Global TOP Strategic Research Center for

Hyper-Connected Scalable

SUPER-QUANTUM COMPUTING

“Beyond Digital to Quantum —
Toward Super-Quantum Computing”

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Korea Research Institute of Standards and Science

KRISS | KIST | ETRI | KISTI

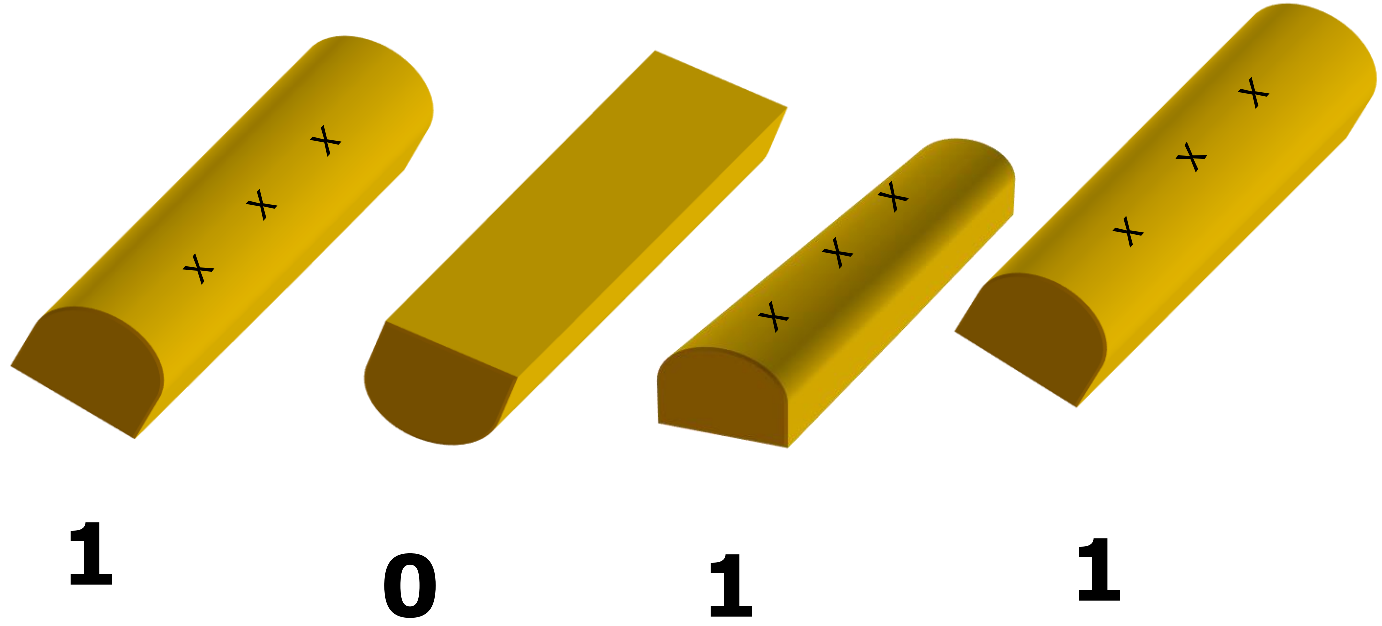
It from Bit

A. Wheeler

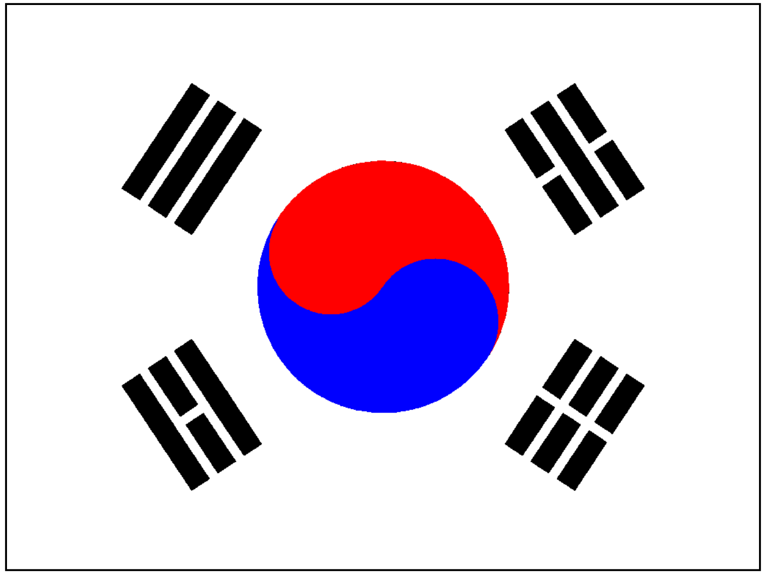
Yin(--) Yang(—)

(易經, Iching, dynamics of universe)

윷 (Yoot = Korean dice)



태극기 Taegeuk-gi (Korean National Flag)



$$|\psi\rangle = a|0\rangle + b|1\rangle$$

Qubit=quantum bit

Contraria sunt complementa

Opposites are complementary.

Complementarity Principle

the coat of arms of Niels Bohr’s family

Brief history of quantum physics

1900: Max Planck introduced the concept of the **quantum** to explain **blackbody radiation**.

1905: Albert Einstein explained the **photoelectric effect** using quantized light (photons).

1913: Niels Bohr proposed **quantized electron orbits** in the hydrogen atom.

1924: Louis de Broglie hypothesized the wave nature of matter (**matter waves**).

1925: Werner Heisenberg developed **matrix mechanics**, the first formulation of quantum mechanics. ➔ **2025, International Year of Quantum Science and Technology**

1926: Erwin Schrödinger introduced **wave mechanics**, providing a differential equation (Schrödinger equation) that describes the quantum state of a system.

1927: Werner Heisenberg formulated the **uncertainty principle**, establishing fundamental limits on the precision of simultaneous measurements of position and momentum.

Measurement Problem

- **The Measurement Problem**
  – Central puzzle in quantum theory:
  How and when does a quantum system "collapse" into a definite outcome?
- **Bohr vs. Einstein**
  – **Bohr**: Emphasized the role of measurement and complementarity; accepted inherent randomness.
  – **Einstein:** Advocated for an underlying deterministic reality; challenged quantum indeterminism.
- **Nondeterminism vs. Determinism**
  – Quantum mechanics predicts probabilities, not certainties.
  – Einstein resisted this, famously stating:
  “God does not play dice with the universe.”
- **1935: Pivotal Thought Experiments**
  – **Einstein, Podolsky, and Rosen (EPR)**: Proposed **entanglement** to argue that quantum mechanics is incomplete.
  – **Erwin Schrödinger**: Introduced the **Schrödinger's Cat** paradox to illustrate the absurdity of quantum superposition at macroscopic scale.

“Shut Up and Just Calculate” → 1st Quantum Revolution

- **Understanding Atomic and Molecular Structure**
  – From **alchemy** to **modern chemistry**
  – Enabled **synthesis of new materials** → Foundation for **energy, chemical, and materials engineering**
  – Revealed quantum basis of **life:**
    . DNA structure
    . Vision and sensory mechanisms (olfactory, gustatory)
    . Photosynthesis and biological energy transfer
- **Technological Applications**
- **Semiconductor devices, lasers**
  – Emergence of **nano** and **digital** technologies
  – Led to the rise of **20th-century information and communication technology (ICT)**

- **Scope and Limitation**
  – Focused primarily on **materials and hardware**
  – Quantum theory used as a **tool** rather than explored for its full conceptual depth

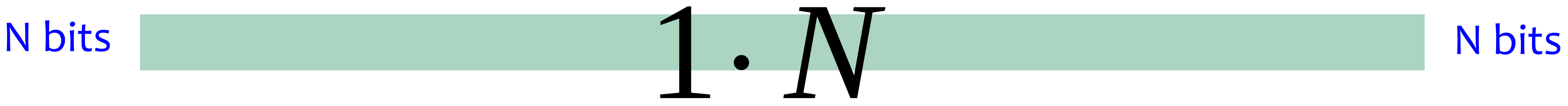
Curiosity-Driven ➔ 2nd Quantum Revolution

- **From Foundational Curiosity to Quantum Technologies**
  – **1964:** John Bell proposed **Bell's Inequality** to test the EPR paradox experimentally
  – **1970s–1990s and beyond:**
  Bell test experiments confirm quantum nonlocality → Quantum mechanics prevails
  → *John Clauser, Alain Aspect, Anton Zeilinger* awarded the **2022 Nobel Prize in Physics**
- **Key Milestones in Quantum Information Science**
  – **1984:** Bennett & Brassard – **Quantum Cryptography (BB84 protocol)**
  – **1985:** David Deutsch – **Quantum Parallelism** and the **first universal quantum computer model**
  – **1993:** Bennett et al. – **Quantum Teleportation**
  – **1994:** Peter Shor – **Quantum Factoring Algorithm**
  – **1995:** Peter Shor – **Quantum Error Correction**
  Lov Grover – **Quantum Search Algorithm**
  – **1999:** Tsai & Nakamura – Demonstration of **Superconducting Qubit**

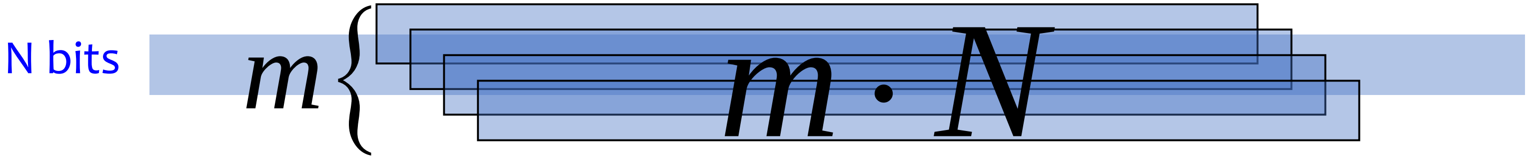
→ *Bennett, Brassard, Deutsch, and Shor :* **2023 Breakthrough Prize in Fundamental Physics**
→ *Bennett and Brassard :* **2026 Alan Turing Prize**

Digital Parallelism
(Distributed Digital Computing)

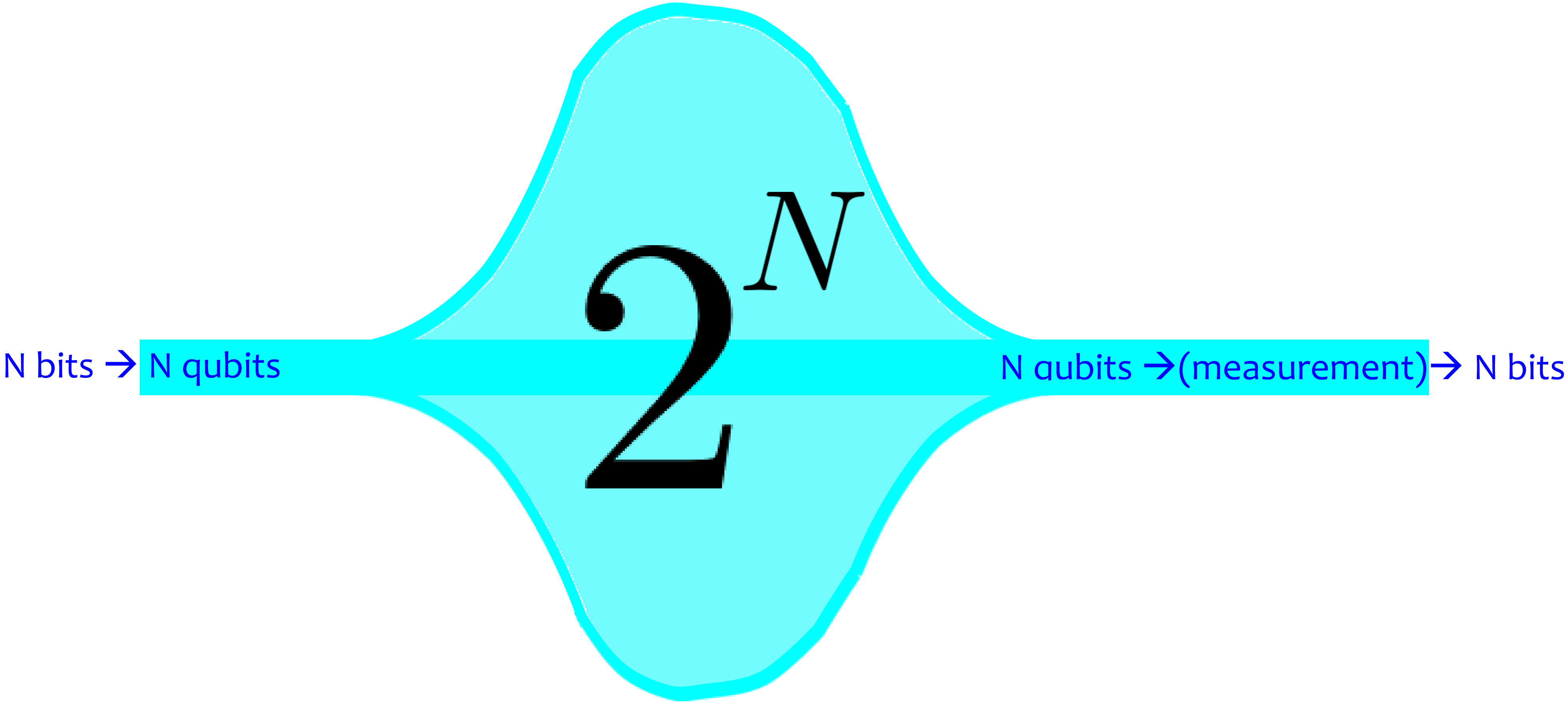
Digital computer



Parallel digital computer (at most linearly parallel)

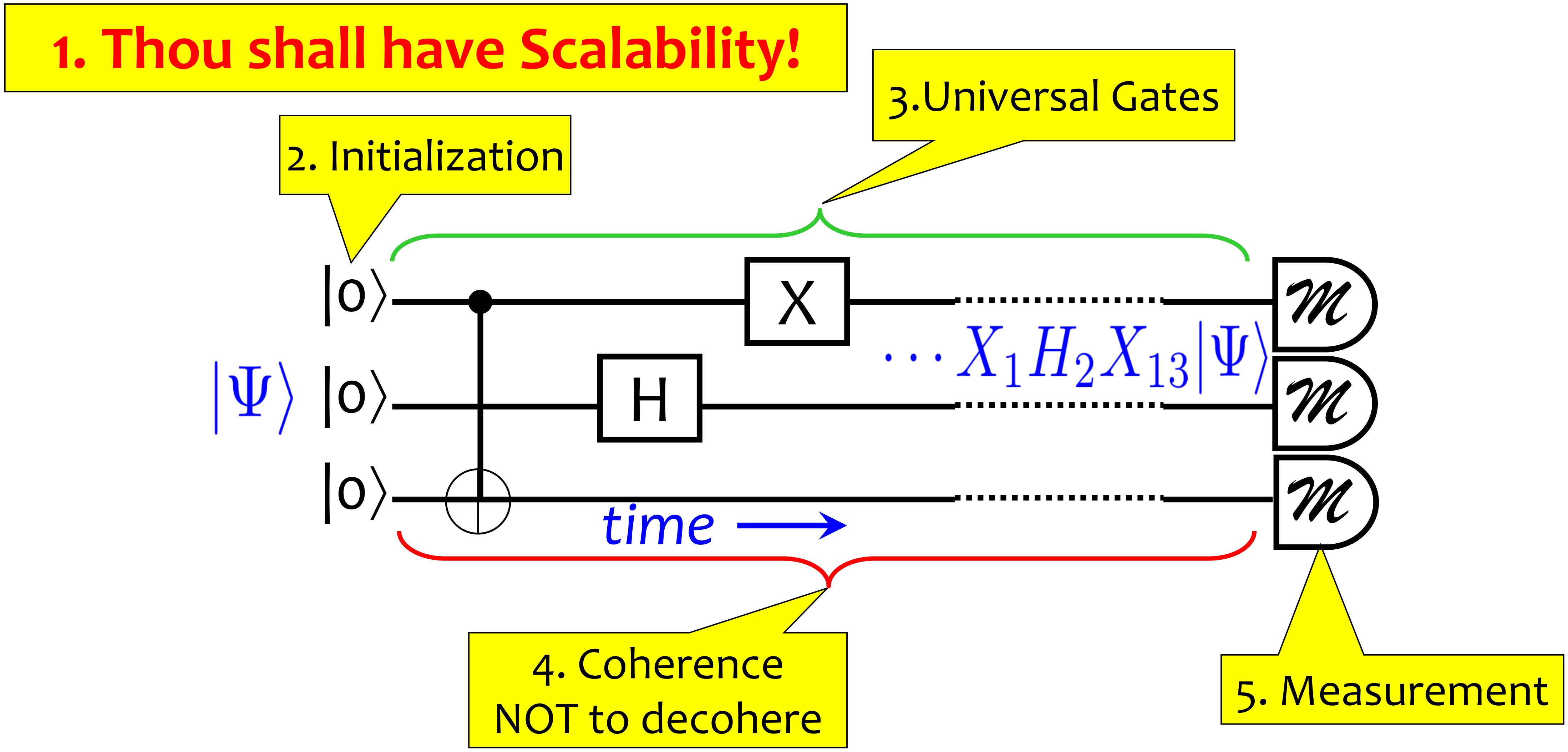


Quantum Parallelism
(Distributed Quantum Computing)



Five Commandments for QPU

DiVincenzo, Qu-Ph/0002077



- Factoring RSA-2000: about 1 million qubits
- New drug or materials discovery: millions of qubits
- Most useful problems of interest: tens to hundreds of millions of qubits

- A single module or system cannot scale indefinitely because of physical limits on the number of qubits.

➔ Quantum Interconnect

Digital → Quantum → Super-Quantum

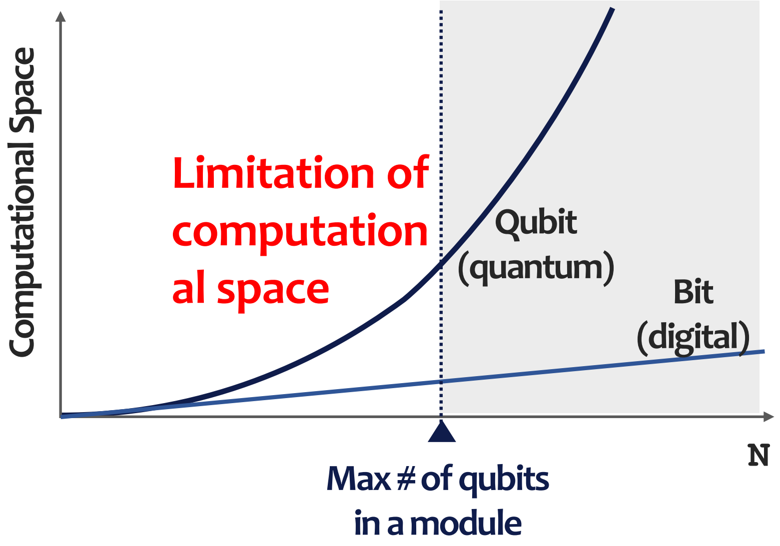
Digital → Quantum

$2N \rightarrow 2^N$

Catch-up research

- Single module quantum processor

※ other quantum computer projects

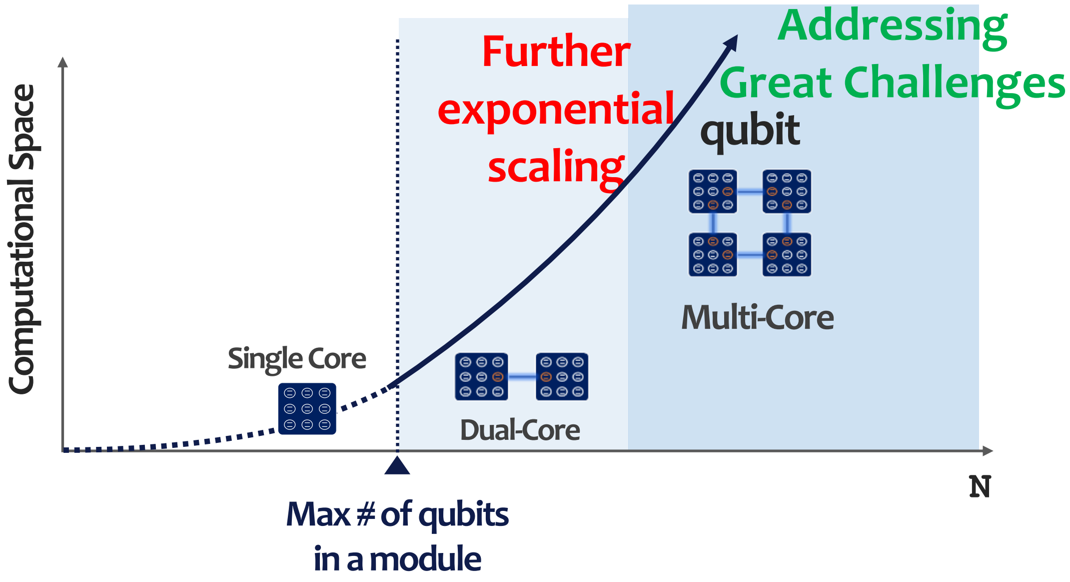


Quantum → Super-Quantum

$2^N \rightarrow (2^N)^{[\# \text{ of Cores}]}$

Pioneering research (First mover)

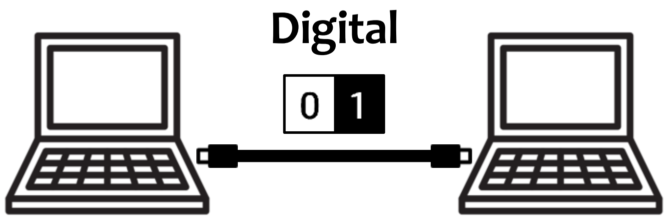
- Multi-core quantum processor



Multi-core quantum processors and Quantum Interconnect

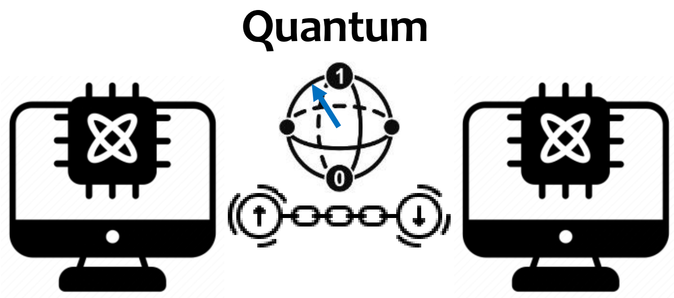
Quantum Interconnect

Digital vs Quantum



Transmission
= copying

(elec, mag, light)

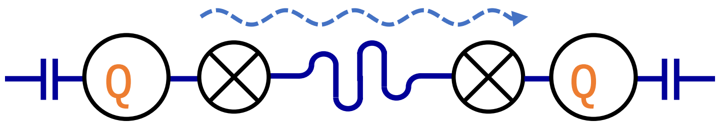


NO cloning theorem
Ultra-Low-Noise operating environment is needed

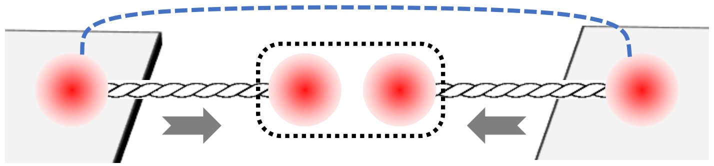
Developing next-generation convergence technologies is essential for advancing quantum information platforms.

Qubit-core Interconnect

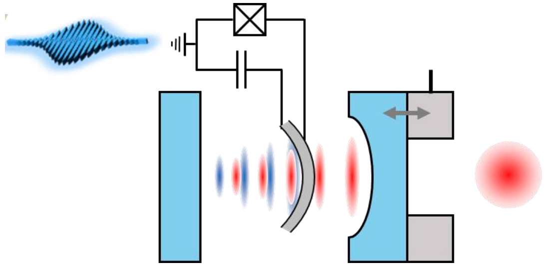
Increasing entanglement complexity between cores



High fidelity entanglement swapping



High efficiency RF-photon conversion



qubit/μ-wave ←→ phonon ←→ photon

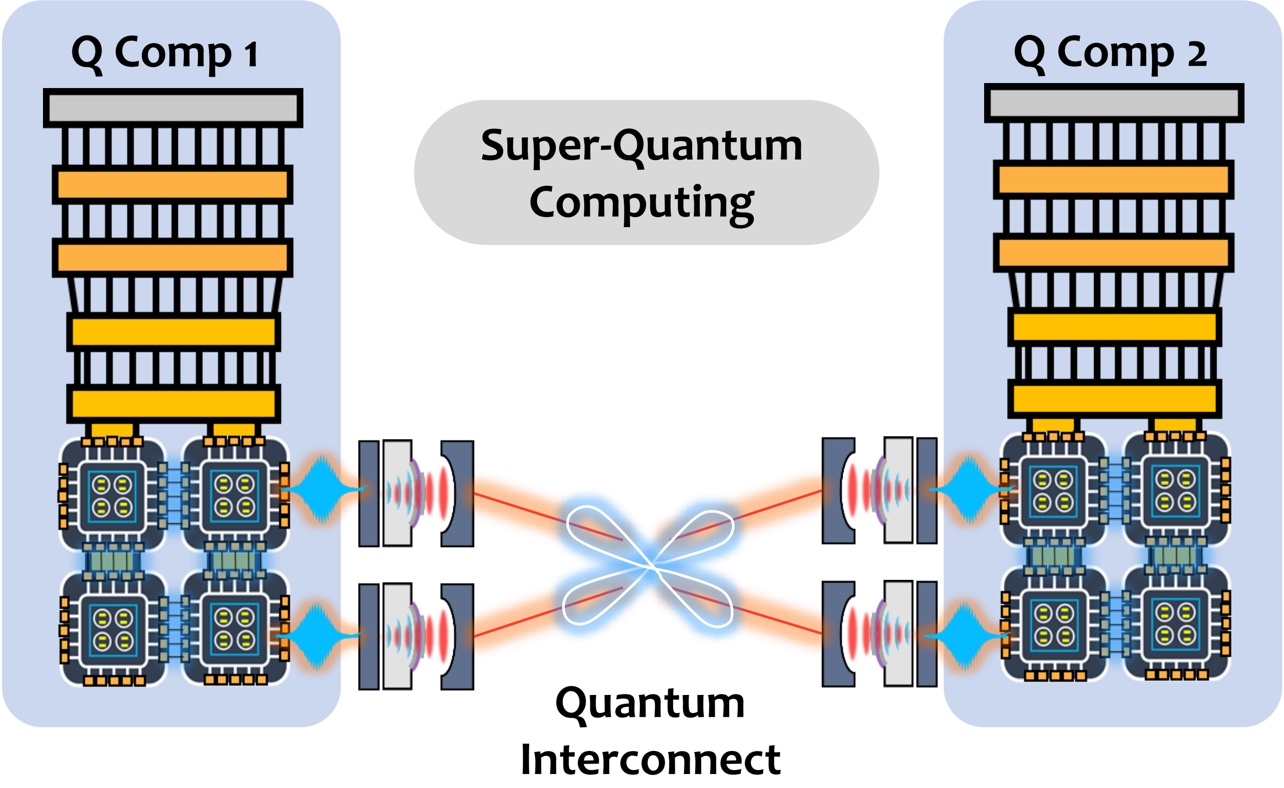
Vision

A New Paradigm of Scaling-Up Quantum Computers

Goal

1) A multi-core quantum processor that overcomes the limit of qubit scalability

2) Super-quantum computing enabled by quantum-interconnecting multiple quantum computers



Goal 1

Scaling Up
the number of qubits
→ Quad-Core
Q Processor prototype

Goal 2

Super-Quantum Computing
quantum-interconnecting
two quantum computers

Quantum National Science and Technology Laboratories

KRISS

Korea Research Institute of Standard and Science (1975)
NMI (national metrology institute) of Korea ; Daejeon

KIST

Korea Institute of Science and Technology (1966)
to build industrial technology for economic growth
Mother of many Korean research institutes; Seoul

ETRI

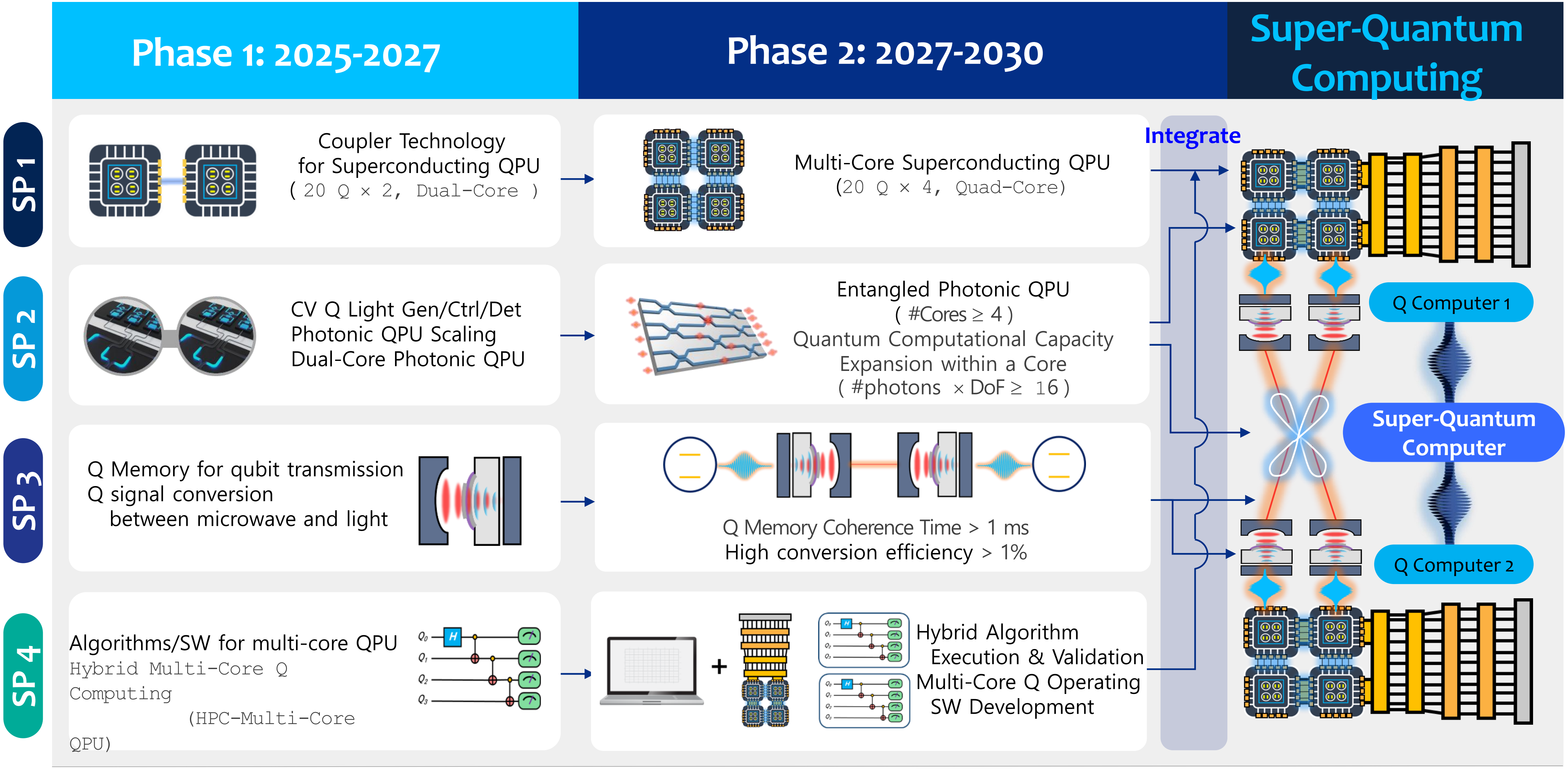
Electronics and Telecommunications Research Institute (1976)
semiconductor chips (DRAM), commercialization of CDMA; Daejeon

KiSTi

Korea Institute of Science and Technology Information (1962)
scientific and technological information services
and high-performance computing; Daejeon

and **Seouls National University** (SNU), **Korea Advanced Institute of Science and Technology** (KAIST), **Hanyang University**, **Jeonbuk University, IdQuantique**, …

$50M/5yrs (2025-2030)


Phase 1: 2025-2027
Phase 2: 2027-2030
Super-Quantum Computing
SP 1
SP 2
SP 3
SP 4
Coupler Technology
for Superconducting QPU
(20 Q × 2, Dual-Core)
Multi-Core Superconducting QPU
(20 Q × 4, Quad-Core)
Integrate
CV Q Light Gen/Ctrl/Det
Photonic QPU Scaling
Dual-Core Photonic QPU
Entangled Photonic QPU
(#Cores ≥ 4)
Quantum Computational Capacity
Expansion within a Core
(#photons × DoF ≥ 16)
Q Computer 1
Super-Quantum Computer
Q Computer 2
Q Memory for qubit transmission
Q signal conversion
between microwave and light
Q Memory Coherence Time > 1 ms
High conversion efficiency > 1%
Algorithms/SW for multi-core QPU
Hybrid Multi-Core Q Computing
(HPC-Multi-Core QPU)
Hybrid Algorithm
Execution & Validation
Multi-Core Q Operating
SW Development

Subproject 1. Jaseung Ku (KRISS)

Superconducting Multi-Core Quantum Processor

Phase 1 – Year 1

Core Technology 1

Superconducting Quantum Processor Design and Fabrication

. High-Performance Qubit Device Fabrication
. Superconducting Quantum Interconnect Module Fabrication

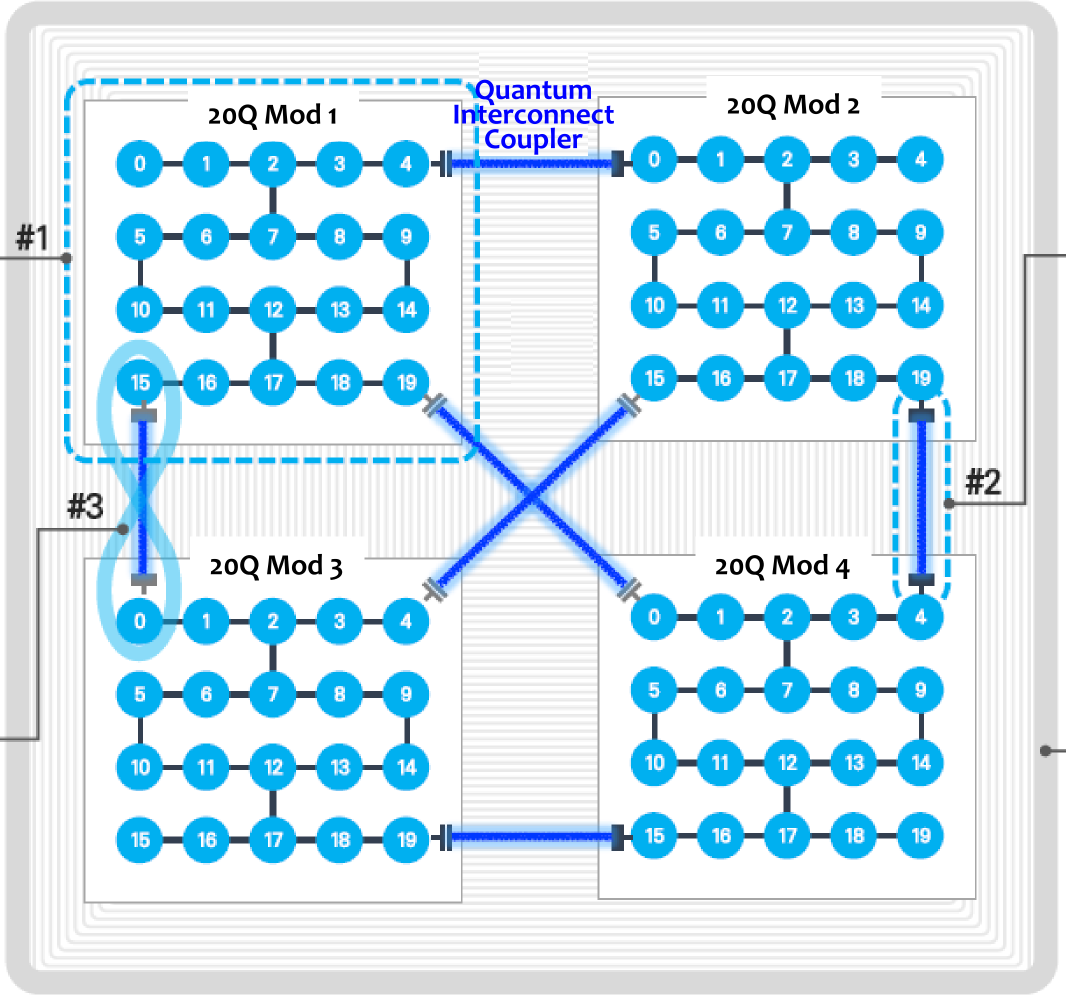
KRISS

Core Technology 3

Quantum Interconnect Entangling Gate Technologies

. Inter-Module Quantum Gate Implementation
. Gate Fidelity Optimization

Lead KRISS Contract 서울대학교



Phase 1 – Year 2

Core Technology 2

Quantum Interconnect Coupler Technologies

. Inter-Module Coupler Integration
. Qubit–Coupler Interface Optimization

Lead KRISS Contract KAIST

Core Technology 2

Multi-Core Quantum Processor System Technologies

. Scaling through Inter-Module Interconnects
. Quantum Processor Performance Optimization

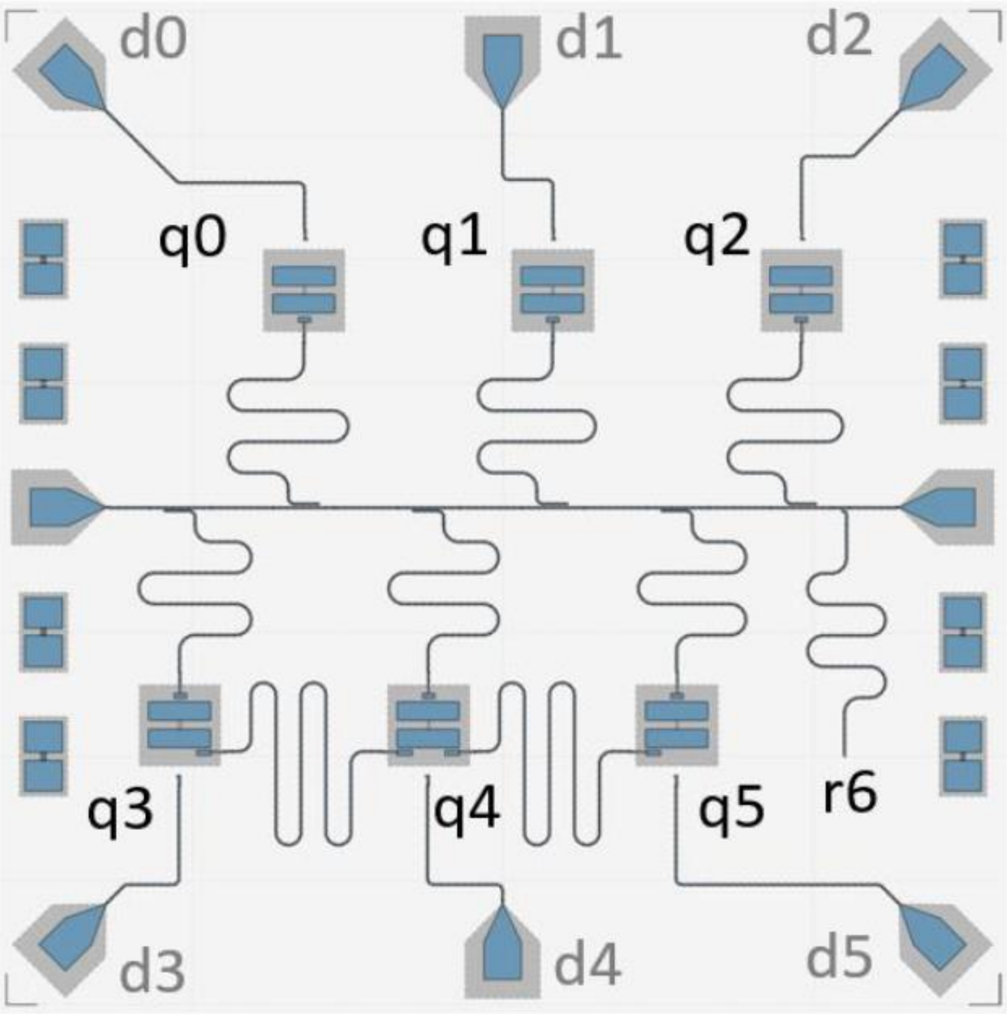
Lead KRISS Partner KISTI

1. Single-Core QPU Design & Fabrication Workflow

6-qubit prototype device design
- 3 isolated fixed-frequency transmons
- 3 fixed-frequency transmons with fixed coupling

Design process
- Set target parameters
- Draw circuit layout using qiskit-metal
- Simulate with Ansys
- Iterate simulation and drawing

Parameters	Symbol	Target Value
Qubit frequency	f_{01}	5 GHz
Anharmonicity	α	-300 MHz
Coupling strength	$g/2\pi$	75 MHz
Dispersive shift	$\chi/2\pi$	0.3 MHz
Readout resonator frequency for qubits	f_r	6.5 – 7.2 GHz
Readout resonator linewidth	$\chi/2\pi$	0.3 MHz
Test resonator	$f_{r,test}$	7.3 GHz
Test resonator coupling quality factor	Q_c	10^6
Exchange coupling strength	$J/2\pi$	2.5 MHz
Bus-qubit coupling strength	$g_{1,b}/2\pi,\ g_{2,b}/2\pi$	110 MHz
Bus Resonator Frequency	f_{bus}	9 GHz



[Chip design with Qiskit-Metal]

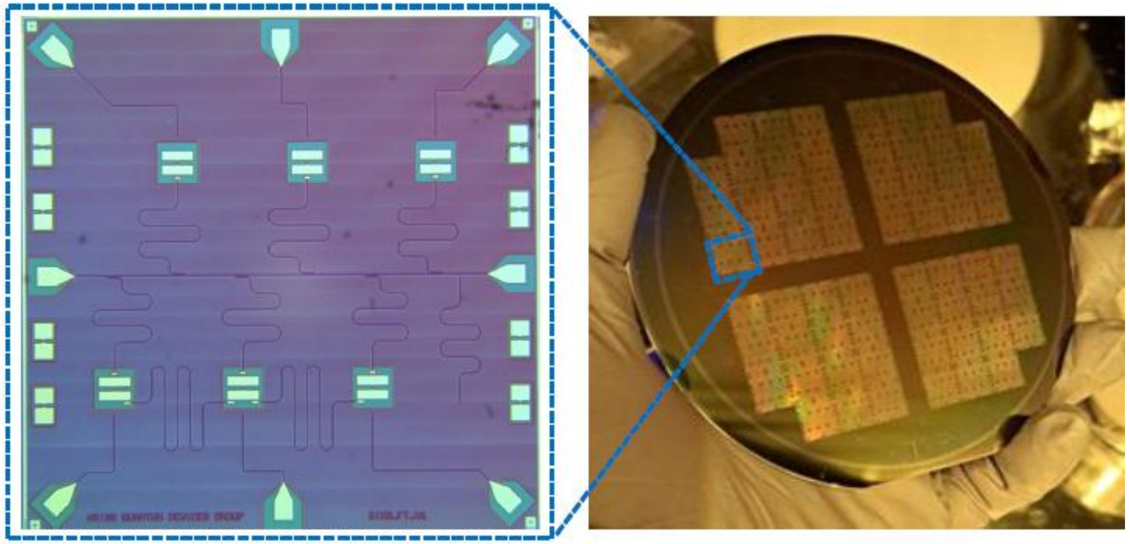
1. Single-Core QPU Design & Fabrication Workflow

- 4 inch wafer-scale fabrication

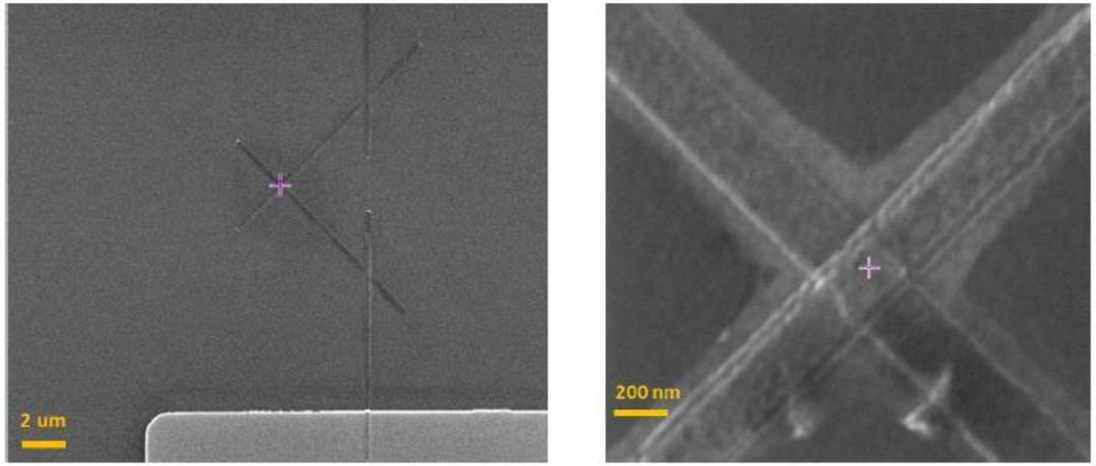
Fabrication Step

- Sputter 200 nm Nb on 4” Si wafer (@KRISS)
- Photolithography (@KRISS)
- ICP RIE etch of Nb (@KRISS)
- E-beam lithography (@KANC)
- JJ evaporation (@SNU)
- Lift-off (@KRISS)
- Dicing and wire-bonding (@KRISS)

* **Important**: Maintaining clean interface is critical for high-coherence qubit



[After photolithography]



[Josephson Junction]

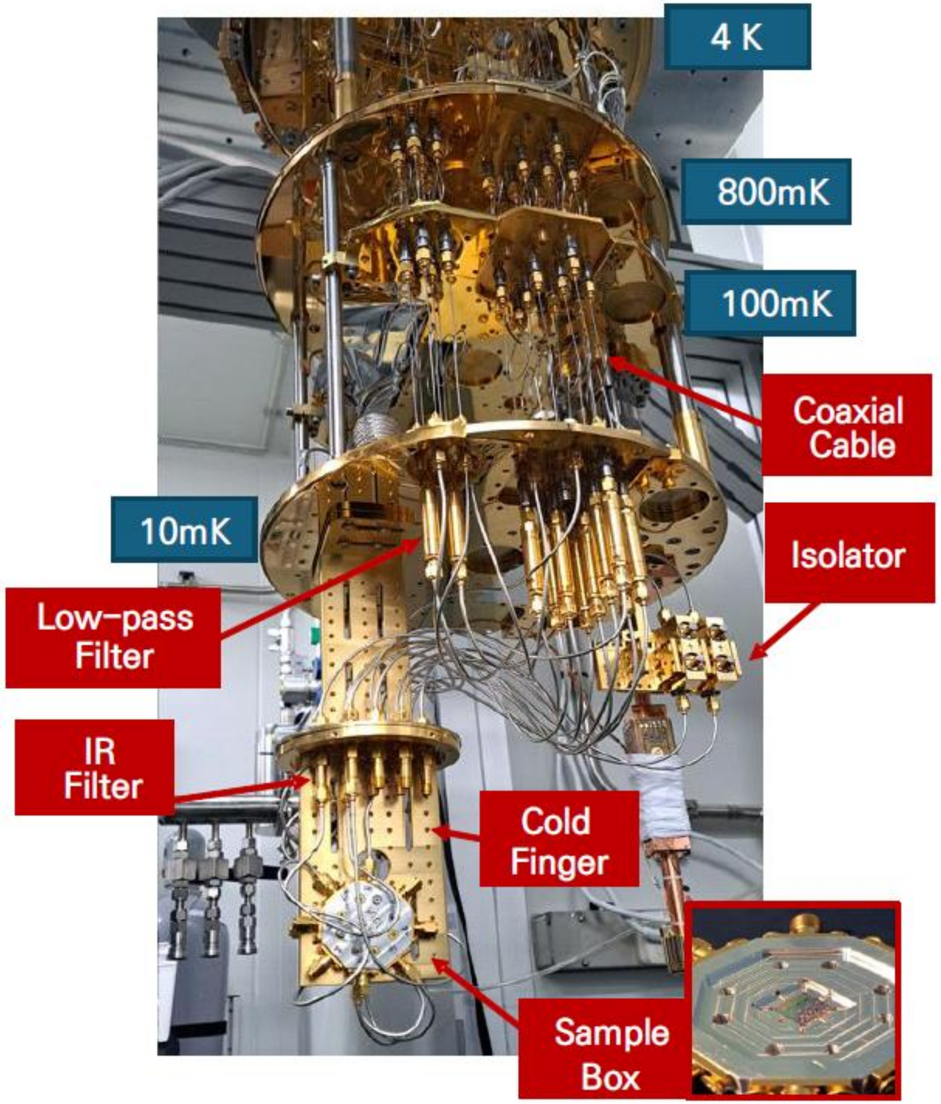
2. Cryogenic RF Setup & Room-Temperature Qubit Readout Setup

극저온 냉동기 저온 RF 셋업 업그레이드

- 듀얼-코어 양자 연결 이중큐비트 게이트 실험 환경 준비 완료
- 고성능 큐비트를 위한 향상된 잡음 환경
- (추가됨) 신호 전송선, 필터, 자기차폐, 새 콜드핑거 (coldfinger)

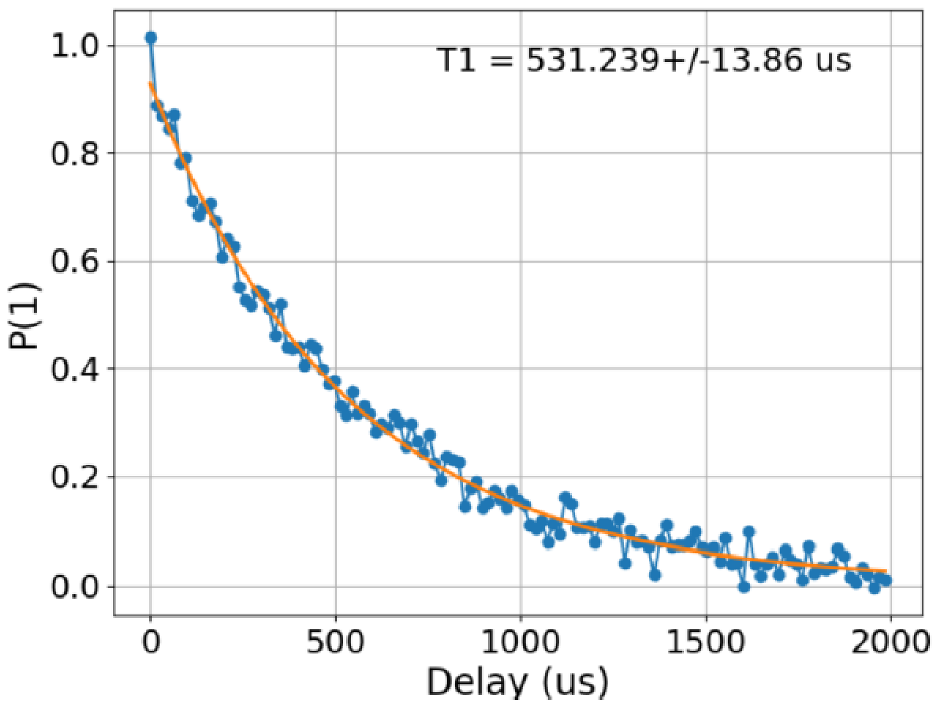
상온 큐비트 제어/측정 셋업

- 큐비트 측정용 상온 하드웨어 셋업 완료
  (Quantum Machines 사 장비)
- 측정용 커스텀 파이썬 라이브러리 개발 (krissqm)

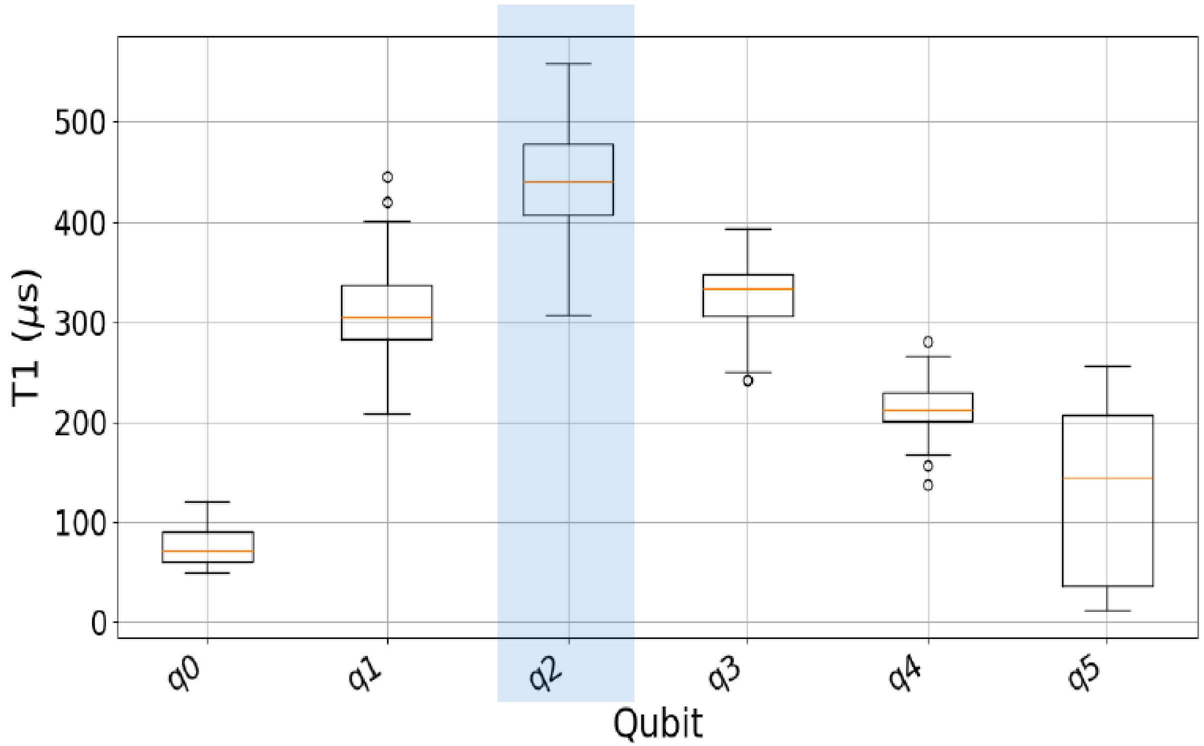


3. Maximum Average Single-Qubit T1 : 440 μs

- Qubit quality factor(Q)~1×10^7 (Highest Q reported ~ 1.5×10^7)
- Qubit design, fabrication and RF setup optimized
- 2차년도에 수행할 초전도 모듈간 양자연결 연구 기반 확립

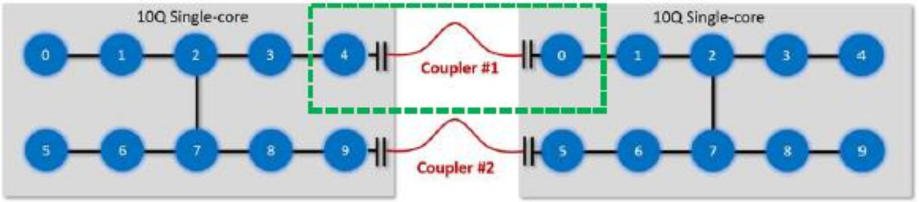


[q2 큐비트의 최대 T1 측정결과]



[6-큐비트 24시간 연속 T1 측정 결과]

2^{nd} Year: Design, Fabrication & Characterization of Quantum Interconnect Devices

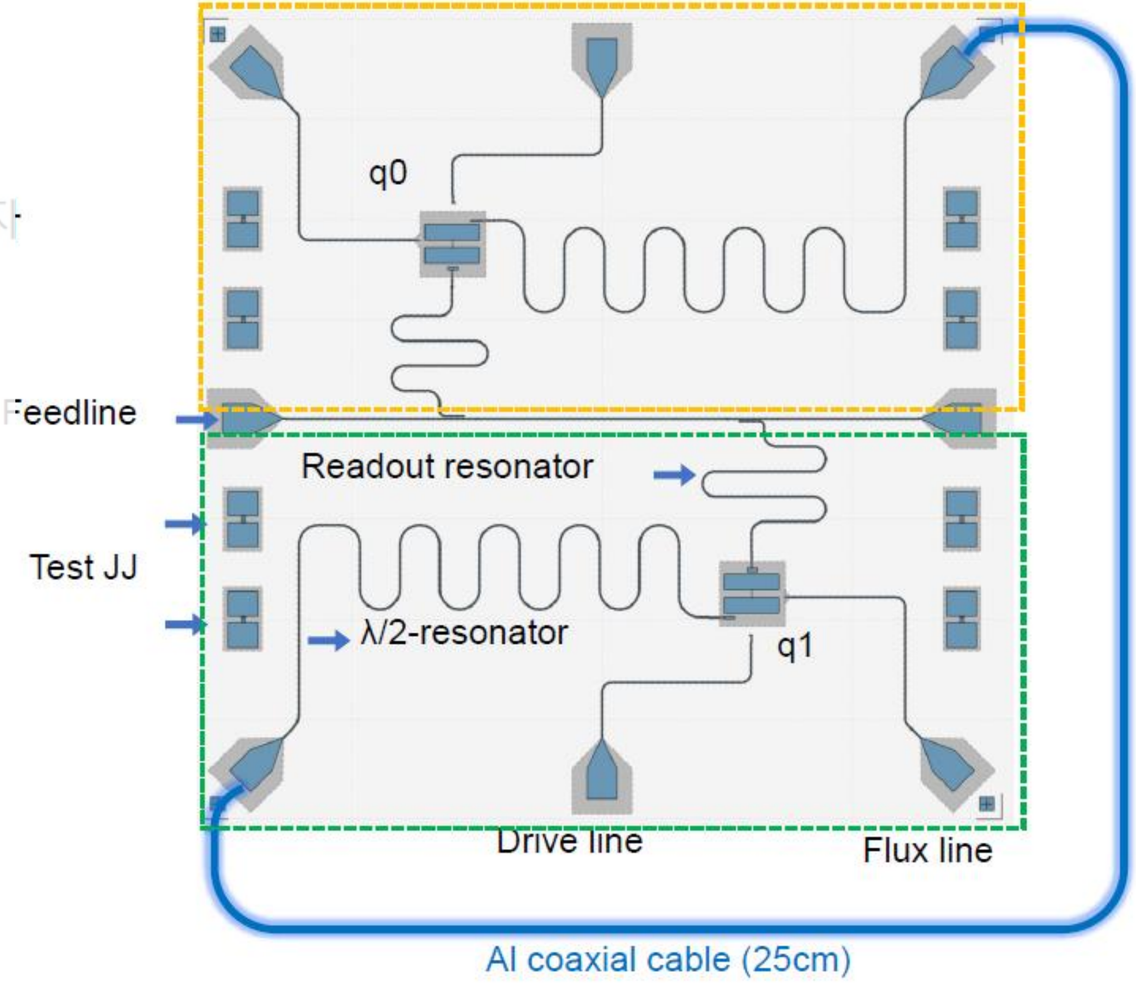


2차년도 계획

- 양자 연결용 소자 (2-qubit) 설계 및 제작
    - 고정 커플러(Bus resonator) 소자
    - 가변 커플러(DTC:Double-Transmon-Coupler) 소자
- 샘플 패키지 제작
- 양자 연결 이중 얽힘 게이트 구현
  (Remote two-qubit entangling gate)
    - Cross-resonance gate (고정 커플러)
    - CZ gate (고정 or 가변 커플러)

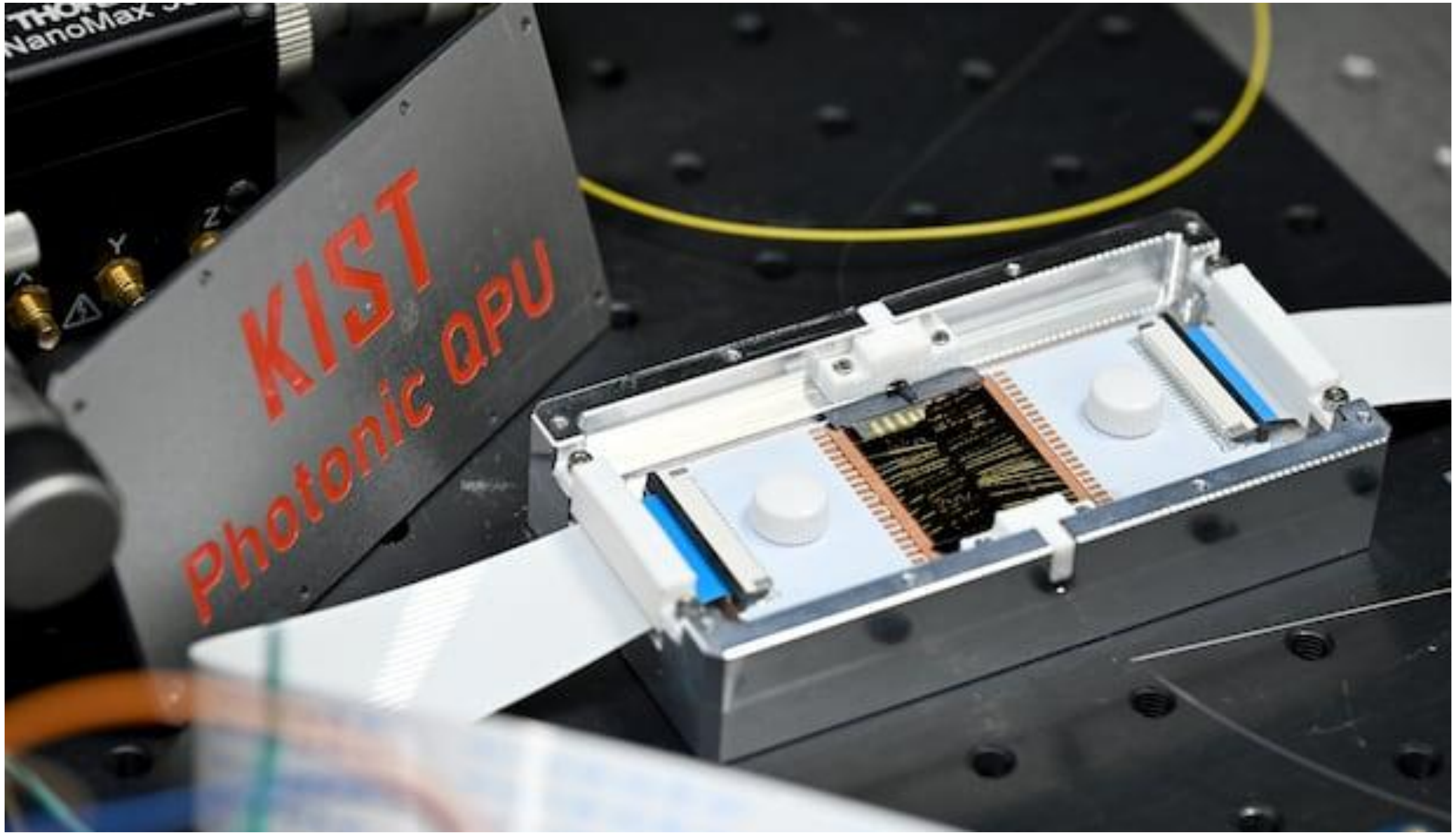
현재 진행상황

- 첫번째 고정 커플러 소자 JJ 증착 완료
- 가변 커플러 소자 시뮬레이션 진행중



Subproject 2. Hyunghan Kwon (KIST)

Photonic Multi-Core Quantum Processor Using Quantum Photonic Integrated Circuits



KLM LOQC (2001)

Linear optics + measurement + gate teleportation

↓

Cluster-State MBQC (Raussendorf–Briegel, 2001)

Large entangled resource + measurement

↓

Fusion-Gate LOQC (Browne–Rudolph, 2005)

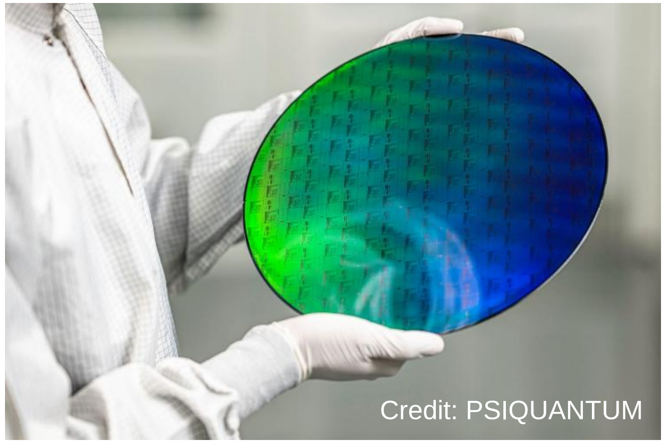
Building clusters by probabilistic fusion

↓

Fusion-Based Quantum Computing (PsiQuantum et al., 2021)

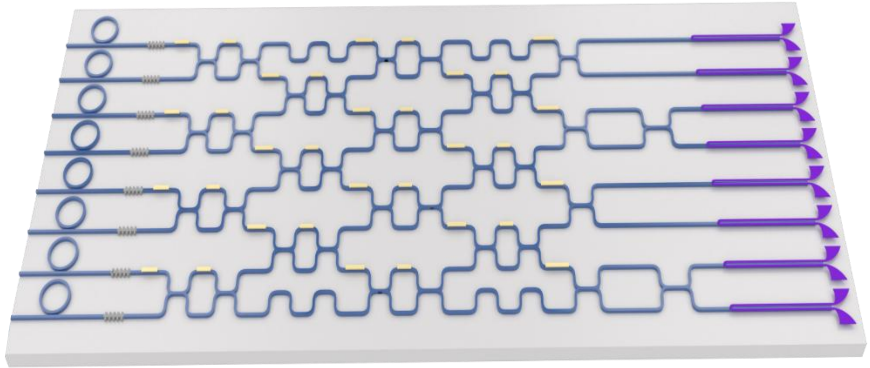
Small resource states + fusion network + integrated fault tolerance

As-Is

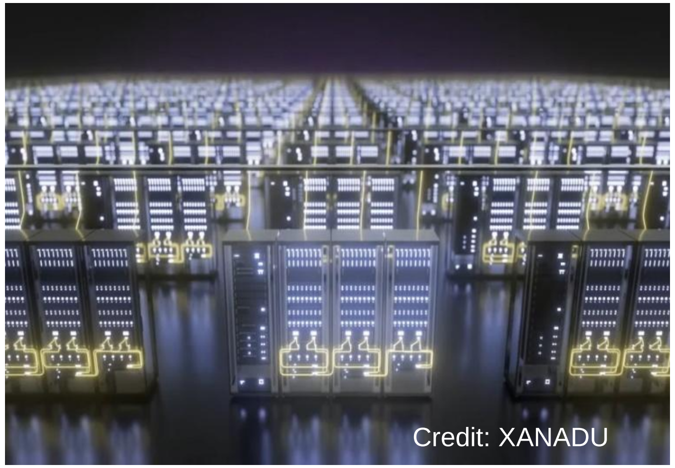


Qubit → **Scalable Qubits**

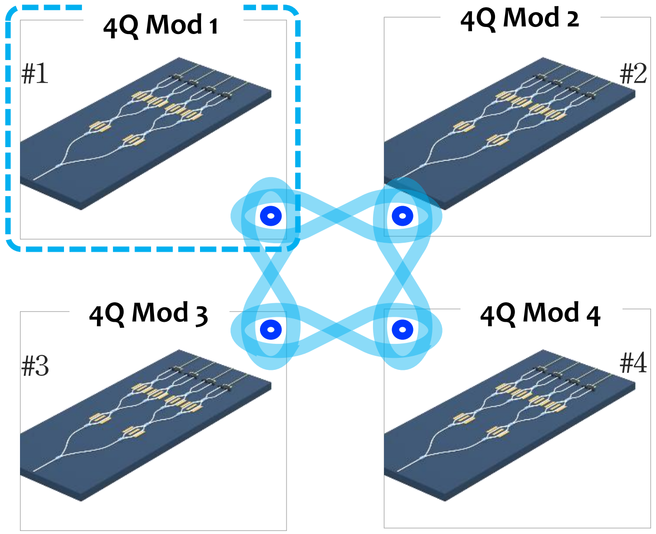
Semiconductor Fabrication Process

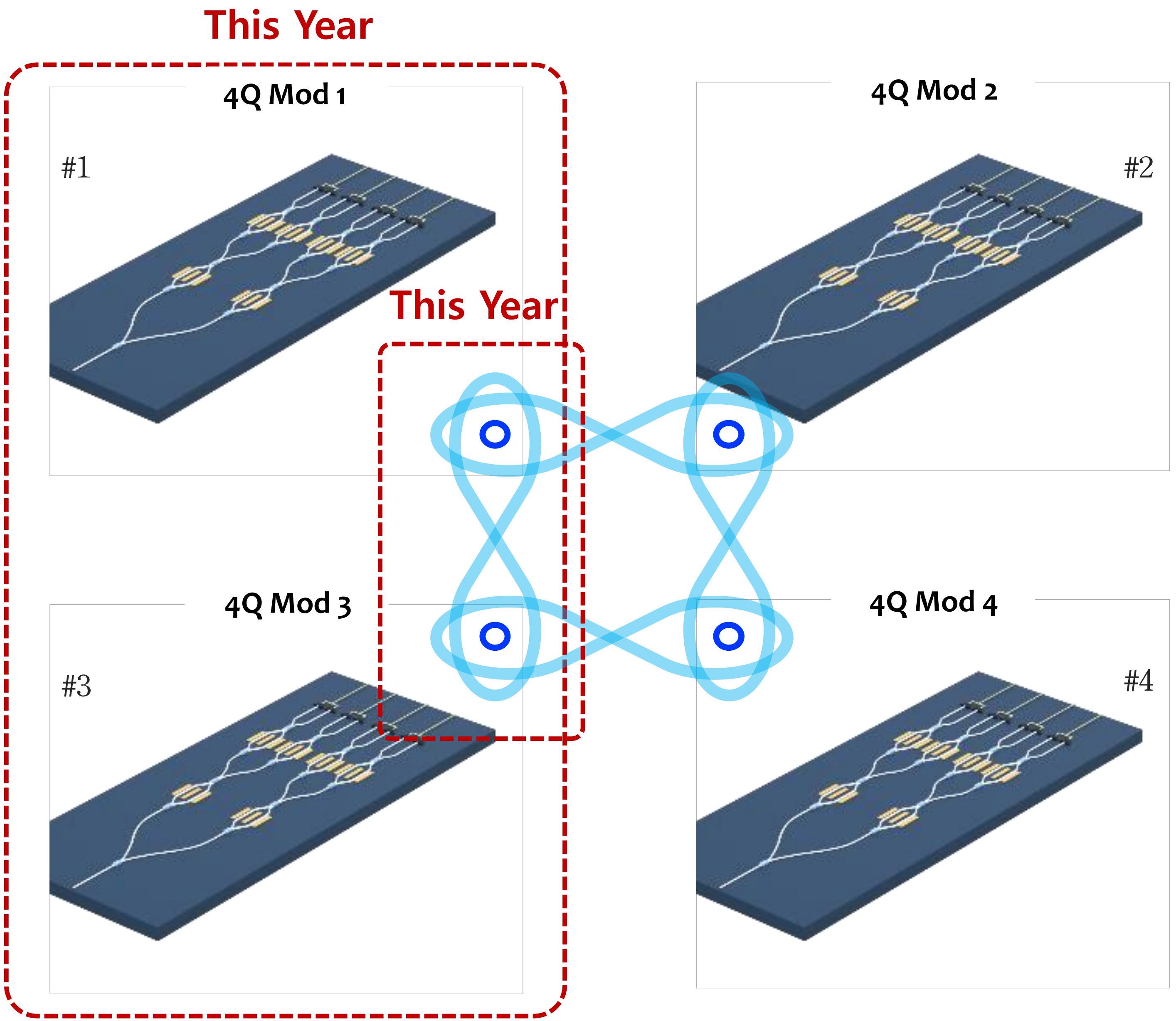


Subproject 2



Overcoming Single-Chip Limitations and Achieving Scalability through Multi-Core Processors





Goal of 2nd year

Execution of Quantum Operations on 4+ Qubits across Two Distributed QPUs via Shared Entanglement

+ **SNSPD**

(Year 1: Material Growth Technology Transfer → Banam Co., Ltd.)

Enhancement of Entanglement Generation Rate via Multiplexing
(KRISS, Hee Su Park)

Multi-Chip Fusion Measurement & Qubit Transfer
(ETRI, Woncheol Shin)

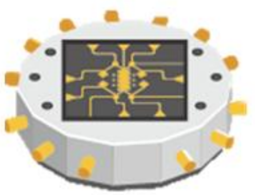
Subproject 3. Byung-Seok Choi (ETRI)

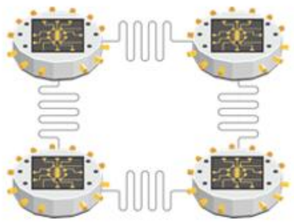
Interconnecting Multiple Quantum Computers

Multi-Core QPU

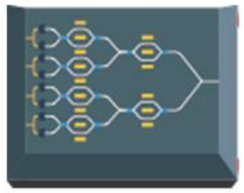
Qubit Scalability Limitations
→ Qubit Modularization & Quantum Interconnect

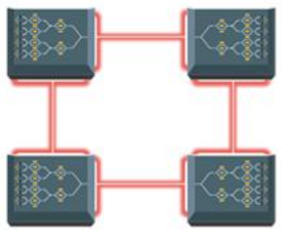
Super-conducting





Photonic

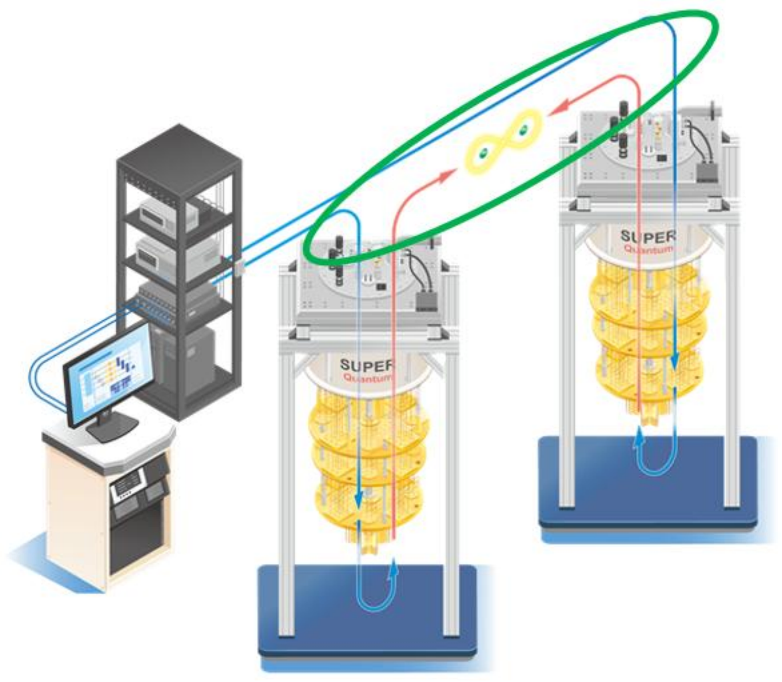




Multi-Core QPU

Interconnecting Multiple Quantum Computers

Long-Distance Interconnection of Quantum Computers
→ Quantum Interconnect Based on Quantum Memory and Quantum Signal Conversion



cf. Lightsynq (diamond SiV)

Modularized Quantum Computer

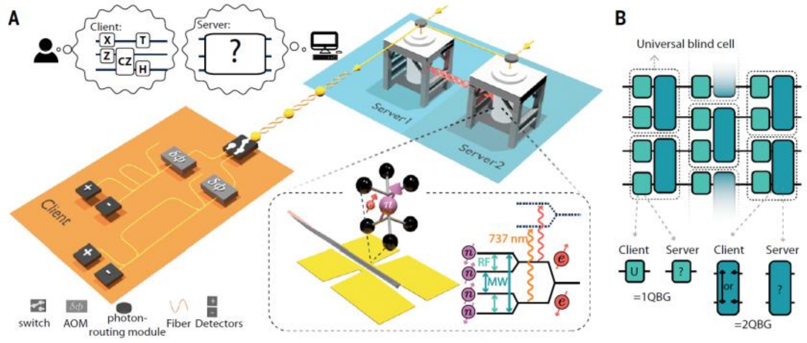


Fig. 1. Distributed BQC with a two-node quantum network with SiVs. (**A**) (Top left) High-level schematic diagram of BQC. (Middle) The client receives photons from the servers and performs measurements. Each server operates a [29]SiV inside a nanophotonic cavity within a dilution refrigerator. (Bottom right) The [29]SiV energy-level diagram shows the MW and RF transitions in the two-qubit manifold (straight arrows) and spin-conserving optical transitions (wavy arrows). (**B**) BQC circuits are constructed from repeated universal blind cells. A universal blind cell can be implemented from two subunits: 1QBG and 2QBG. 1QBG allows the client to perform an arbitrary gate within the universal single-qubit gate set *U*. 2QBG allows the client to apply either a maximally entangling or a nonentangling gate, such as *CZ* or Identities (*I*).

Heralded Quantum Memory

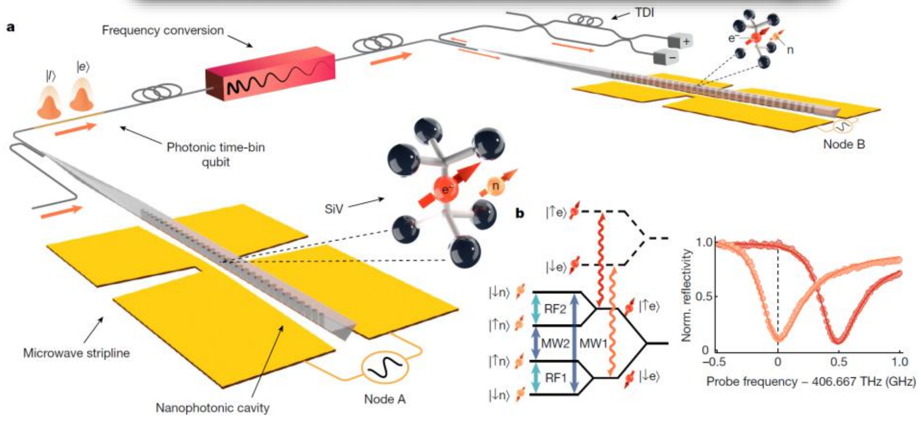
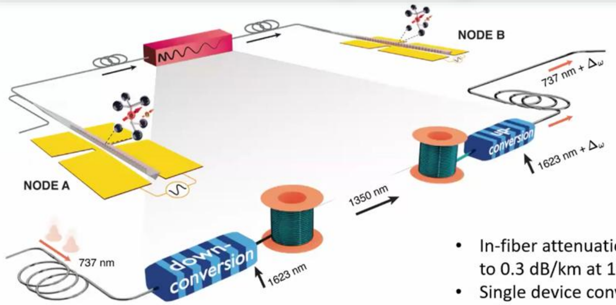


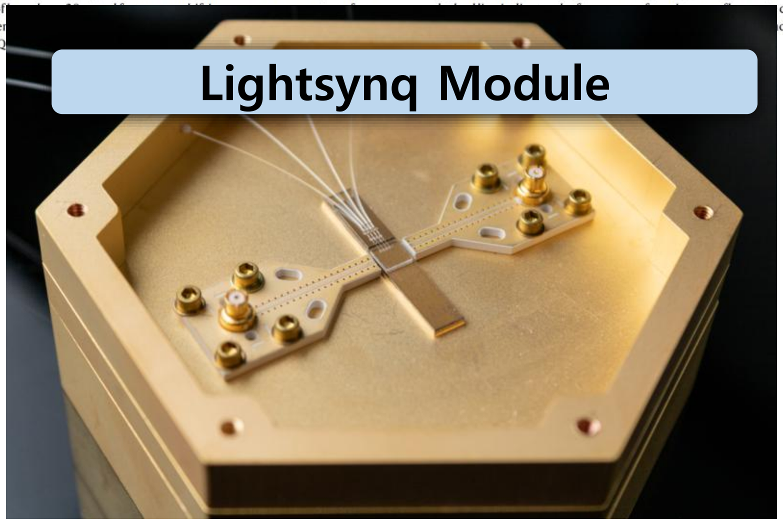
Fig. 1 | A two-node quantum network of cavity-coupled solid-state emitters. **a**, Experimental setup. Each SiV is localized in a nanophotonic cavity within an individually operated cryostat held at temperatures below 200 mK in two separate laboratories. The line-of-sight distance between the two SiVs is 6 m. A gold coplanar waveguide is used to deliver microwave and radio-frequency pulses to the SiV. Both quantum network nodes are connected by an optical fibre of ... differen... using Q... performed at node B using a time-delay interferometer (TDI), which measures the time-bin qubit in the basis $|\pm\rangle \propto (|e\rangle \pm |l\rangle)$. **b**, Left, energy levels of [29]SiV showing the microwave and radio-frequency transitions in the two-qubit manifold (blue and turquoise arrows) and the spin-conserving optical transitions (red and orange). Right, the reflection spectrum of cavity QED system of node A shows the electron-spin-dependent cavity reflectance. The ... contrast, which ... d the photonic

Quantum Frequency Conversion



- In-fiber attenuation reduced from > 4 dB/km at 737 nm to 0.3 dB/km at 1350nm.
- Single device conversion efficiency ~ 30%.
- 2.5 Hz measured noise counts.

Lightsynq Module



Quantum-Memory-Based Inter-Module Entanglement

Core Technology 1

Design/Fab Tech for SiC-based Q-memory device

. SiC-based quantum memory
. Nano-device fabrication

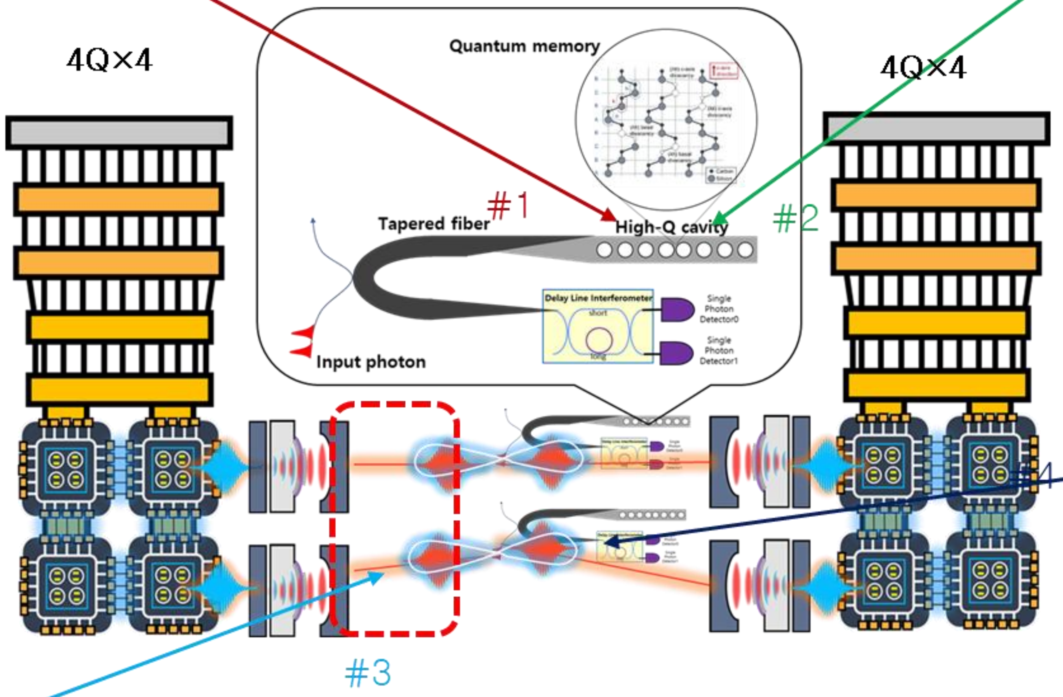
Lead ETRI Partner KIST

Core Technology 2

Design/Fab Tech for NV-based Q-memory device

. Control for interconnect
. Spin-photon CNOT gate
. Entangling photon ecoding

Lead ETRI Partner KIST



qubit/μ-wave←→phonon←→photon

Core Technology 3

Quantum Frequency Conversion

. PPLN-based QFC
. SiN PIC or TFLN-based QFC

Lead ETRI Partner KIST

Core Technology 4

Photon entangled with memory

. Entanglement btw. modules
. Verification of entangled photon indistinguishability
. Verification of asynchronous Bell State Measurement

Lead ETRI Partner KRISS KIST

Subproject 4. Junghee Ryu (KISTI)

Multi-Core Quantum Operating Softwares and Algorithms

Core Technology 1

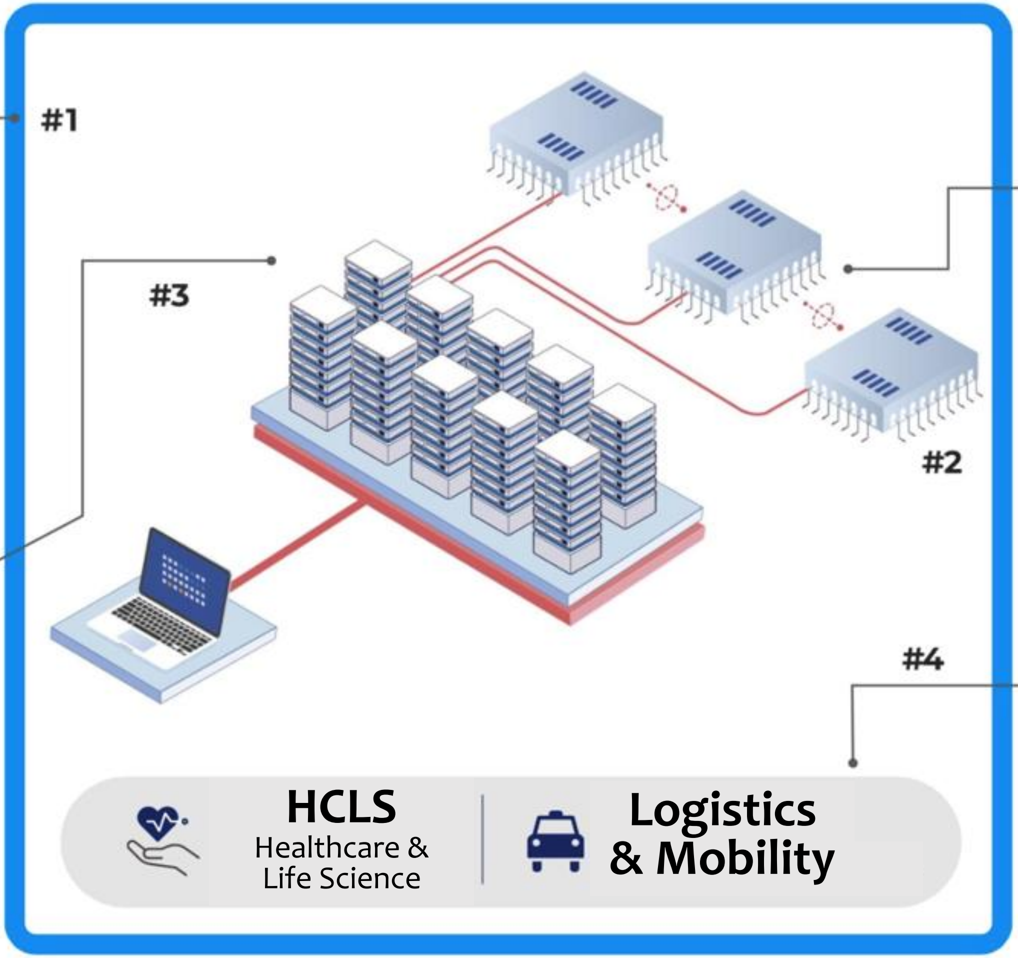
Quantum-HPC Hibrid Computing

KISTI

Core Technology 3

System SW for Modularized QPU

Lead KISTI Contract 서울대학교 XANADU



Core Technology 2

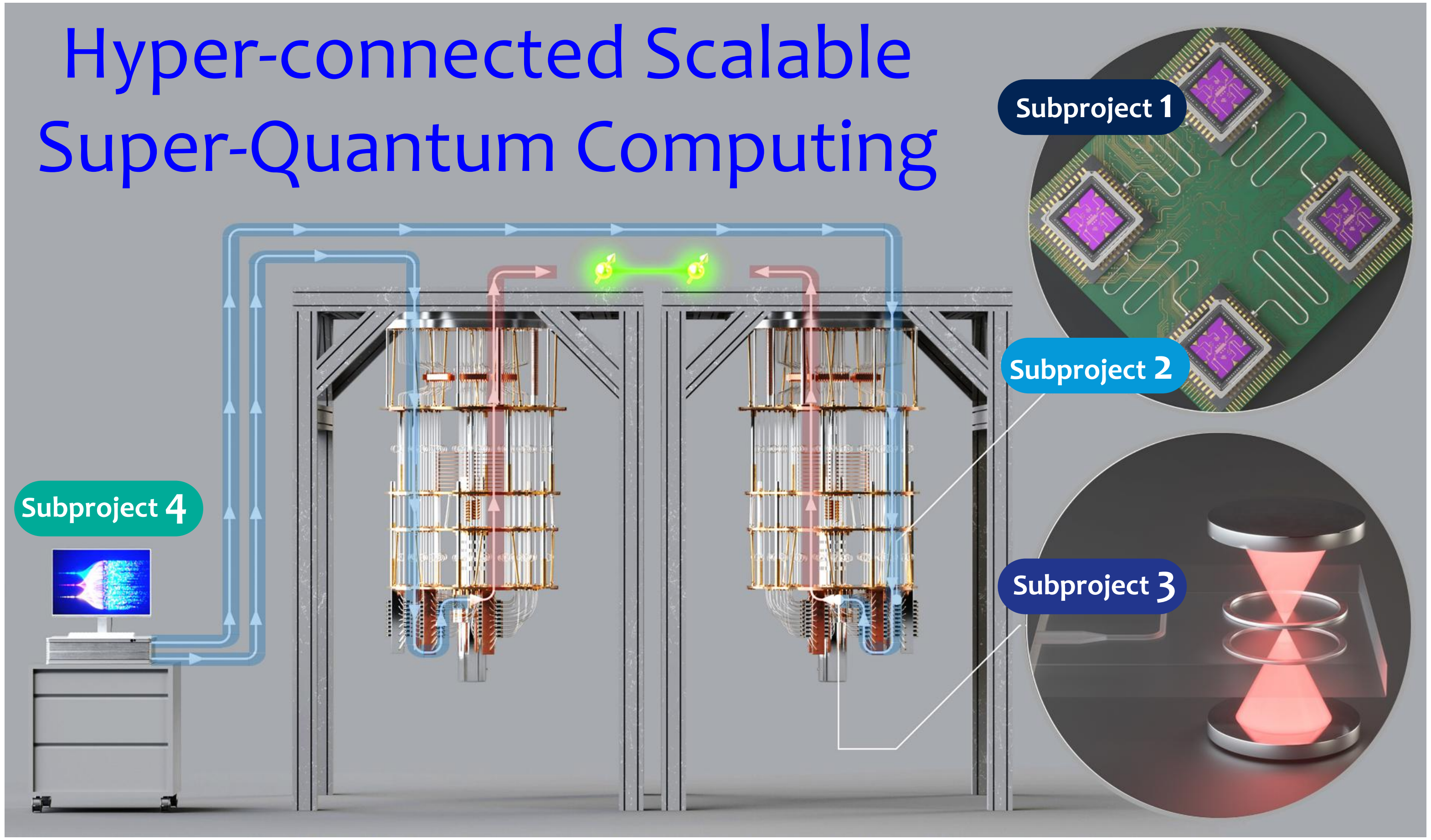
Quantum Algorithms for Modularized QPU

Lead KISTI Partner KRISS

Core Technology 4

Utility of Modular QPUs

Lead KISTI Contract GIST



Subproject 1.
Superconducting Multi-Core Quantum Processor

Subproject 2.
Photonic Multi-Core Quantum Processor

Subproject 3.
Interconnecting Multiple Quantum Computers

Subproject 4.
Multi-Core Quantum Operating Softwares and Algorithms


2026년도 상반기
초연결 확장형 슈퍼양자컴퓨팅 전략연구단 워크숍
일자 2026. 6. 11.(목) ~ 6. 12.(금)
장소 익산 웨스턴라이프 호텔

ThanQ you so much!

KRISS | KIST | ETRI | KISTI