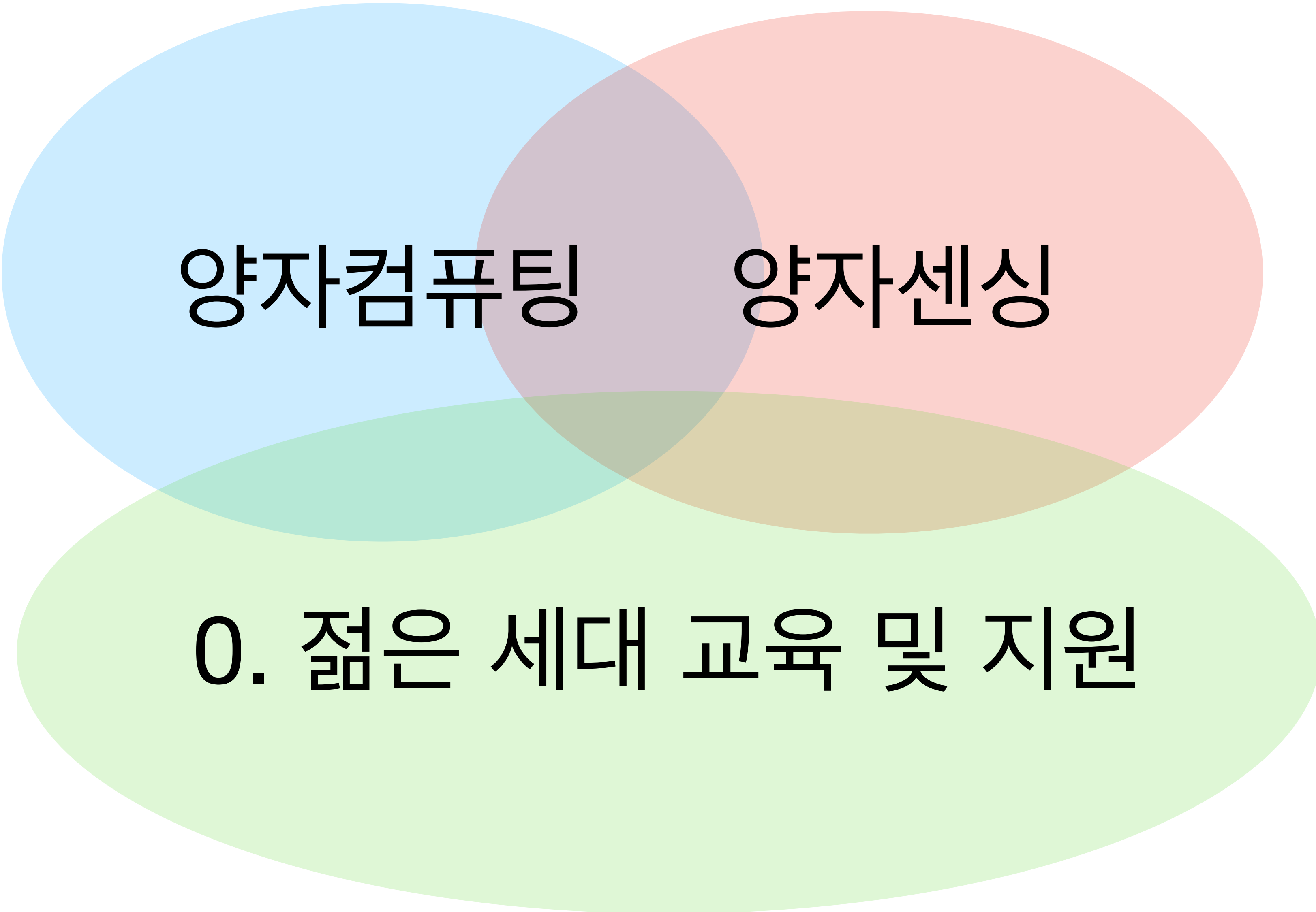
고에너지 물리에서 양자컴퓨팅과 센싱 기술의 가능성

박명훈
(서울과학기술대학교)

한국고에너지물리학회 2025 봄 학술대회
2025. 05.22 - 05.24 인하대학교 정석학술정보관

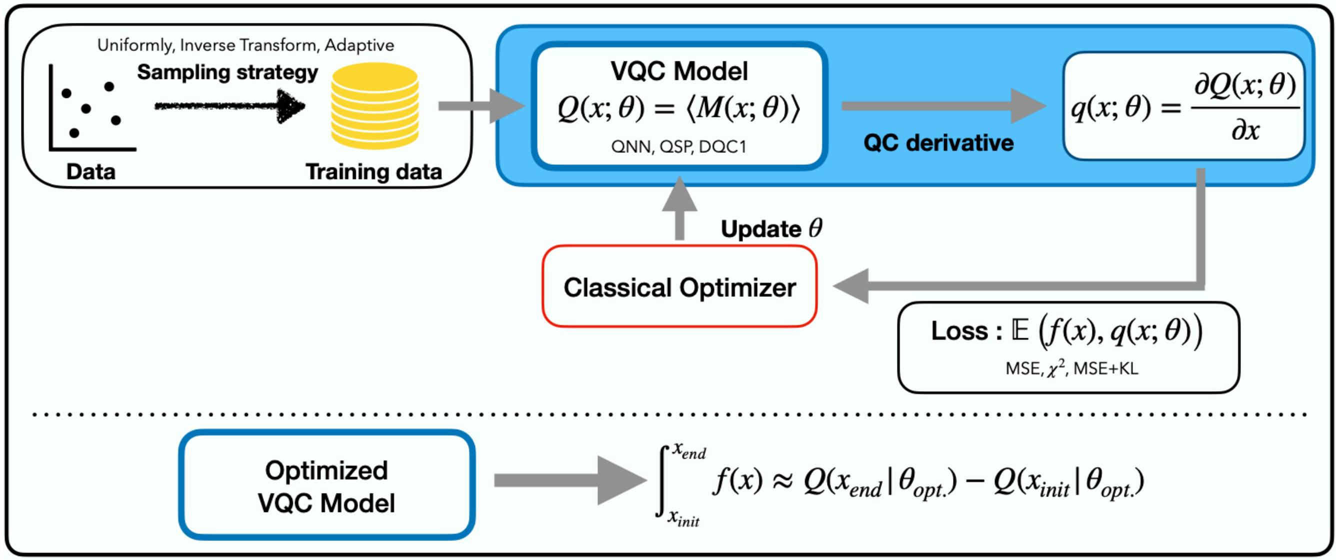

양자컴퓨팅
양자센싱
0. 젊은 세대 교육 및 지원

국내외 교육 기회

- 양자정보연구지원 센터: IonQ 멘토링 프로그램

https://youtu.be/MWsCLjok95I?t=809

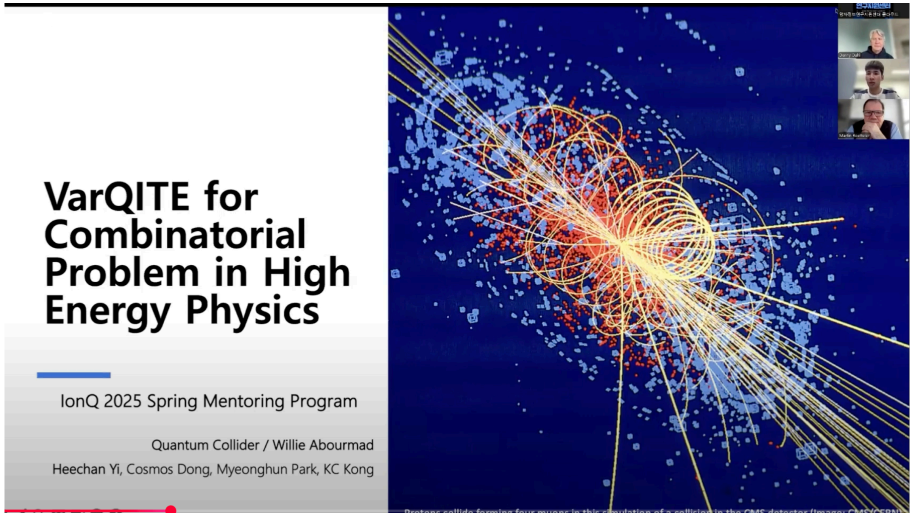
- 참가자: 대학생 (이희찬), 연구원 (반가영),
  공경철 (U.Kansas), 박명훈
  - Mentor: Evgeny Epifanovsky (IonQ)
  Software for the frontiers of quantum chemistry



- Quantum Algorithm을 사용하여, Monte-Carlo 적분

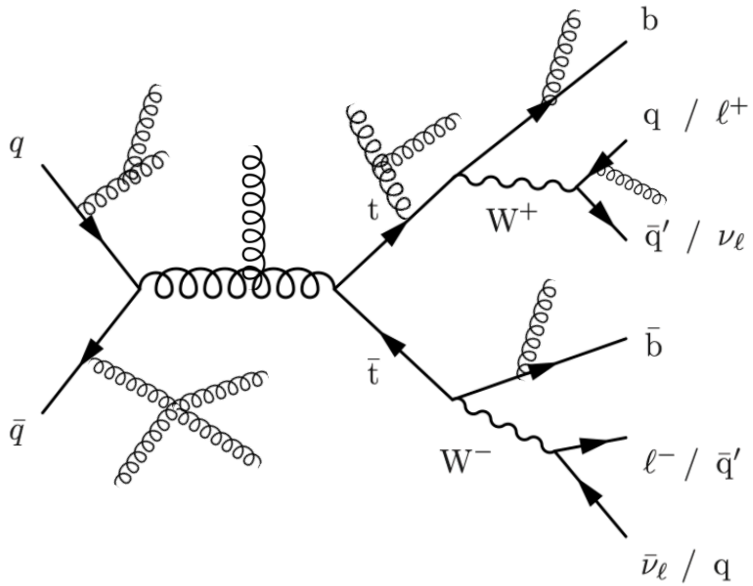
국내외 교육 기회

- 양자정보연구지원 센터: IonQ 멘토링 프로그램



https://youtu.be/YWagYHJKHcI?t=1419

- 참가자: 대학생 (이희찬),
  대학원생 (Zhongtian Dong),
  공경철 (U.Kansas), 박명훈
  - Mentor: Willie Aboumrad (IonQ)
    Mathematician and computational scientist



- Fully hadronic channel: $2^6 = 64$ possibilities for 6 particles in the final state. But in reality, 10-20 jets appear in the final state, leading to 2^{10}-2^{20} possibilities.

Can we use quantum-inspired al
gorithms to resolve the combinat
orial problems?

국내외 교육 기회

- Google Summer of Code (GSoC)

[2024 Program]

Machine Learning for Science (ML4SCI)

Machine learning applications in science

by Sergei Gleyzer (U.Alabama)

https://summerofcode.withgoogle.com/archive/2024/organizations/machine-learning-for-science-ml4sci

Successful Projects

Contributor
Sanya Nanda

Mentor
ToMago, Gopal Ramesh Dahale, KC Kong, Myeonghun Park

Organization
Machine Learning for Science (ML4SCI)

Learning quantum representations of classical high energy physics data with contrastive learning

Data: Quark Gluon Dataset from CMS

This project investigates the fusion of classical data encoding onto quantum models using contrastive learning techniques. The objective is to...

View project details | View code

https://sanyananda.github.io/ML4Sci_QuantumContrastiveLearning/

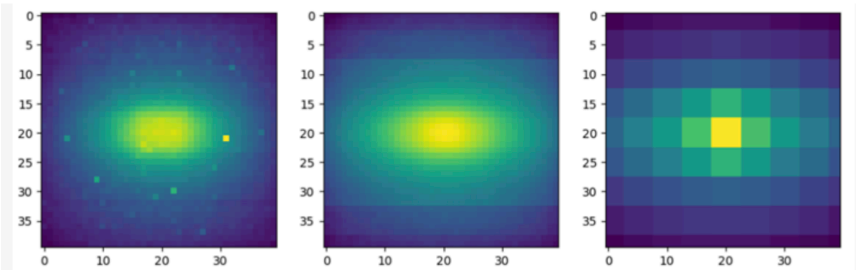
?

!

- 양자컴퓨팅의 활용적인 측면에서, 고에너지 물리학 (기초과학) 응용

  - 물리학과 학생들 뿐만 아니라, **공과계열 학생들도 많은 관심**을 갖음.

  : **"추상적인" 물리학을 실제 "데이터"를 통해 이해**



  - **데이터 과학 측면에서의 상징성 / 도전성**

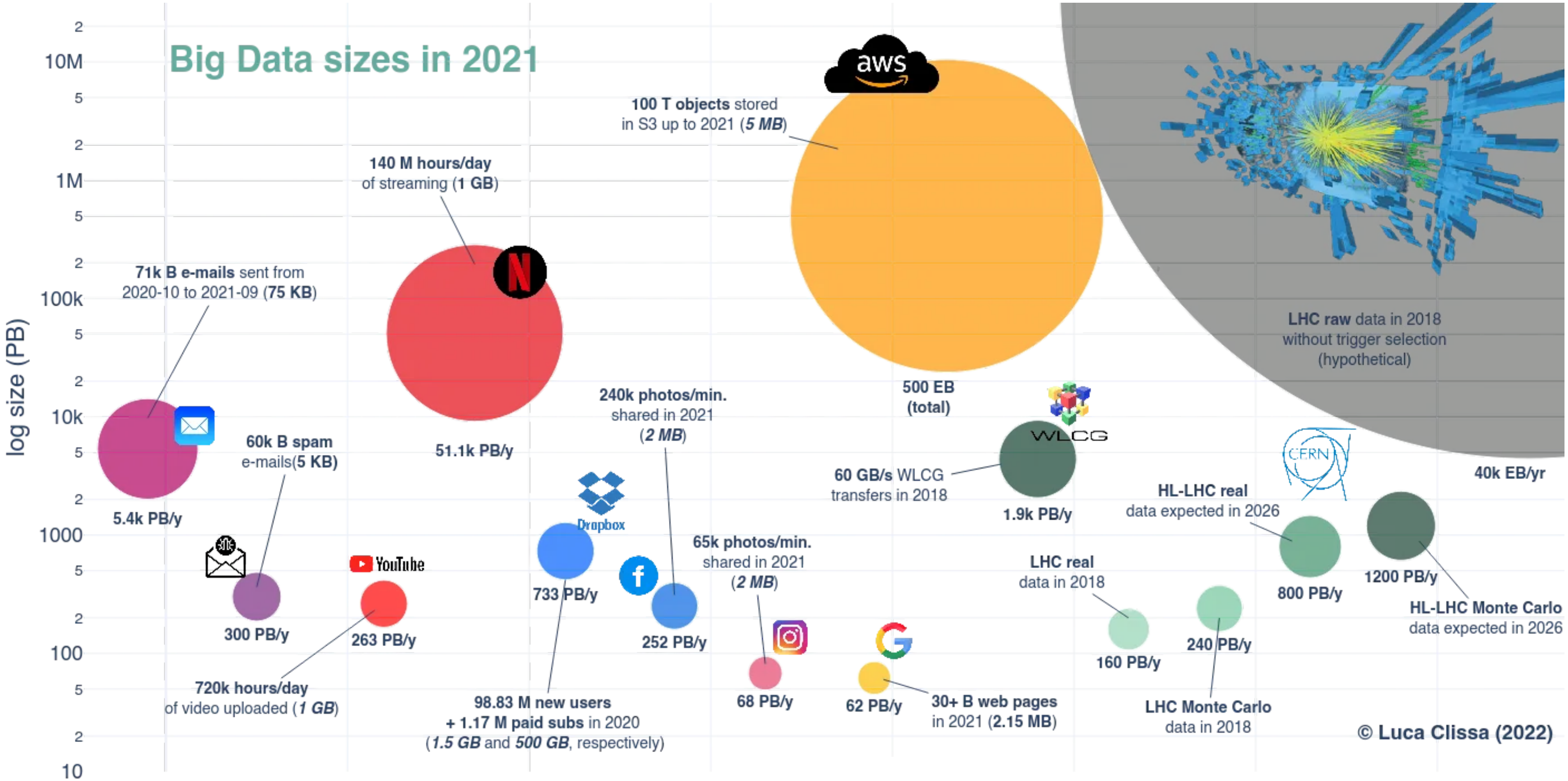
  (알려진 알고리즘의 효용성 확인 / 실질적인 하드웨어 능력 확인)

- 양자컴퓨팅 프로그래밍의 접근성

고에너지 실험과 데이터

- **Data of the (interesting) energy scale:** $\mathcal{O}(100)\,\mathrm{GeV} - \mathcal{O}(10)\,\mathrm{TeV}$

= Data from $\mathcal{O}(10^{-14}) - \mathcal{O}(10^{-10})$ sec just after the "start of our universe"



고에너지 실험과 데이터

Tell us your challenge. We're here to help.

Contact us

CERN analyzes petabytes of data per year, including from experiments on the world's largest particle accelerator. A joint project has shown how it's possible to burst this infrastructure with Google Cloud.

Google Cloud results

- Sped up terabyte-size workloads by reading data at 200 GB per second with Cloud Storage
- Compute power was scaled automatically, as needed, with Google Kubernetes Engine
- Used the public cloud for the public good by making more data open source for researchers, scientists, and educators

Researchers analyze 70 TB Higgs boson data in minutes

CERN openlab

About CERN

The European Organization for Nuclear Research (CERN) uses the world's most complex scientific instruments, including the Large Hadron Collider, to study subatomic particles and advance the boundaries of human knowledge by delving into the smallest building blocks of nature. Founded in 1954, CERN was one of Europe's first joint ventures and now has 23 member states.

Industries: Government & Public

고에너지 실험과 데이터

Global Researchers and Industry Leaders Pursue Value with IBM Quantum

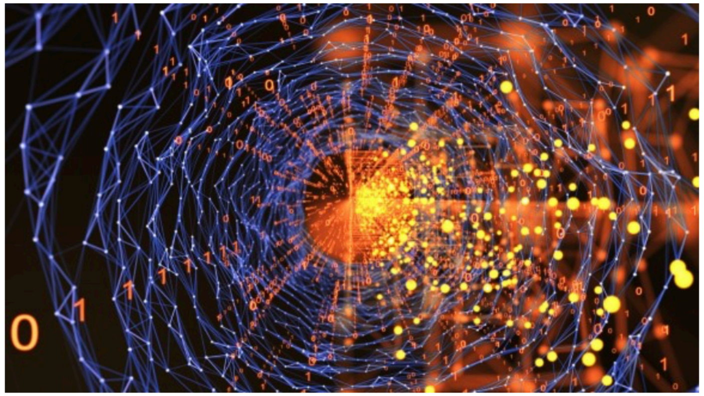
As IBM expands its quantum technology stack, research institutions and private-sector leaders are mobilizing across industries for which quantum holds immediate potential. Equipped with more powerful quantum technology, including advanced hardware and tools to explore how error mitigation can enable accuracy today, pioneering organizations and universities are working with IBM to advance the value of quantum computing.

These working groups that are exploring the potential value quantum computing offers include:

- **Healthcare and Life Sciences:** led by organizations such as **Cleveland Clinic and Moderna,** are exploring applications of quantum chemistry and quantum machine learning to challenges such as accelerated molecular discovery and patient risk prediction models.
- **High Energy Physics:** comprised of groundbreaking research institutions such as **CERN** and **DESY**, are working to identify the best suited quantum calculations, for areas such as identification and reconstruction algorithms for particle collision events, and the investigation of theoretical models for high energy physics.
- **Materials:** spearheaded by the teams at **Boeing**, **Bosch**, **The University of Chicago**, **Oak Ridge National Lab**, **ExxonMobil** and **RIKEN**, aim to explore the best methods to build workflows for materials simulation.
- **Optimization:** aimed at establishing collaboration across global institutions such as **E.ON, Wells Fargo** and others to explore key questions that progress the identification of optimization problems best suited for quantum advantage in sustainability and finance.

Collection

Quantum Technologies and Computing for High-Energy Particle Physics



Submission status
Open

Submission deadline
31 December 2025

Recent advances in quantum technologies are rapidly emerging as powerful tools for pushing the boundaries of High Energy Physics (HEP), offering innovative paradigms for simulating quantum field theories, analysing high-energy processes, and extracting physical observables from complex data. These cutting-edge developments, encompassing quantum computing, simulation, and sensing, hold the promise to unlock fundamental insights into the nature of matter and interactions in regimes that are classically intractable, revolutionising how we address long-standing challenges in particle physics.

This topical collection in *Communications Physics* aims to highlight recent progress in the application of quantum technologies and computing for HEP, bringing together contributions from quantum simulation, quantum algorithms, and quantum sensing tailored to the challenges of particle physics. — show all

1. Quantum Algorithms for HEP

This section focuses on developments in quantum information science and algorithm design tailored to HEP, particularly those not based on direct quantum simulation of physical systems. Topics include:

- Quantum information and entanglement in HEP

- Quantum algorithms in perturbative calculations and Monte Carlo methods

- Quantum simulations of scattering processes and hadronic structure

- Quantum algorithms for data analysis and generation in HEP

2. **Quantum Simulation for HEP**

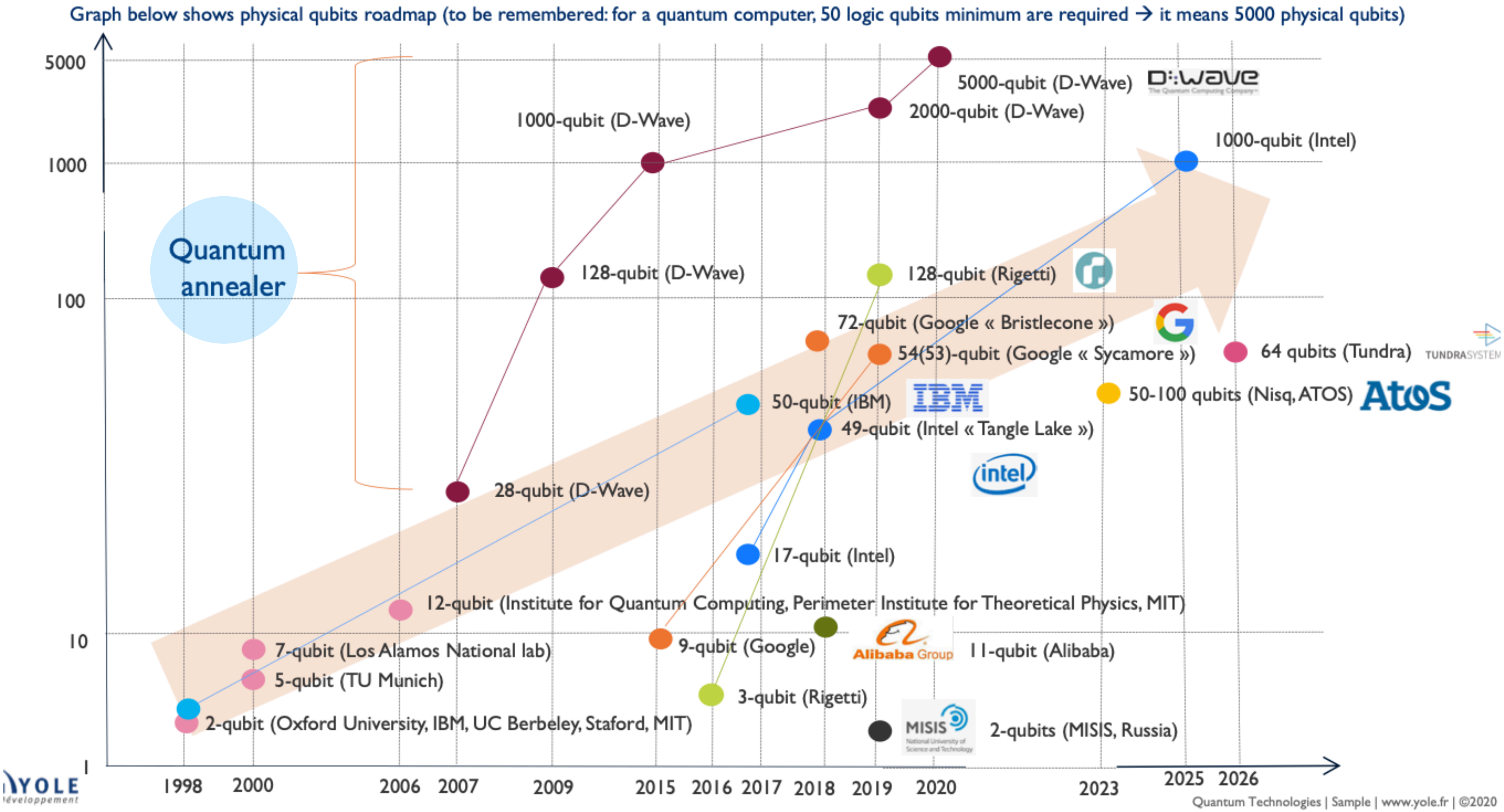
This section highlights efforts to simulate quantum field theories and related phenomena using quantum devices or hybrid workflows. Topics include:

- Quantum simulation of quantum field theories, including real-time dynamics and nonperturbative phenomena

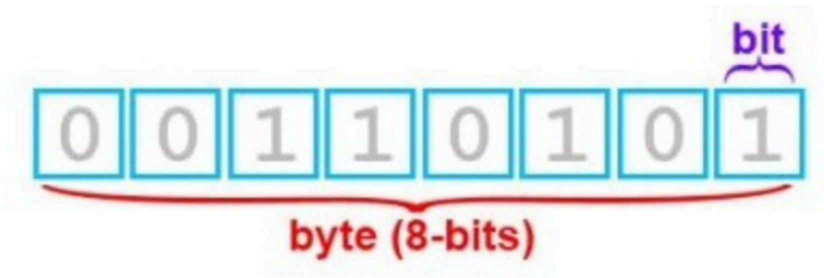
- Lattice gauge theory on quantum processors

- Hybrid classical-quantum approaches for field-theoretic calculations

다양한 양자 컴퓨터 하드웨어의 발전



양자중첩을 통한 데이터 공간 크기



3 Qubits= 2^3 bit = 8 bit = 1 byte (1B)

43 Qubits=2^{43} bit information = $2^{43}/8 = 2^{40}$ byte =

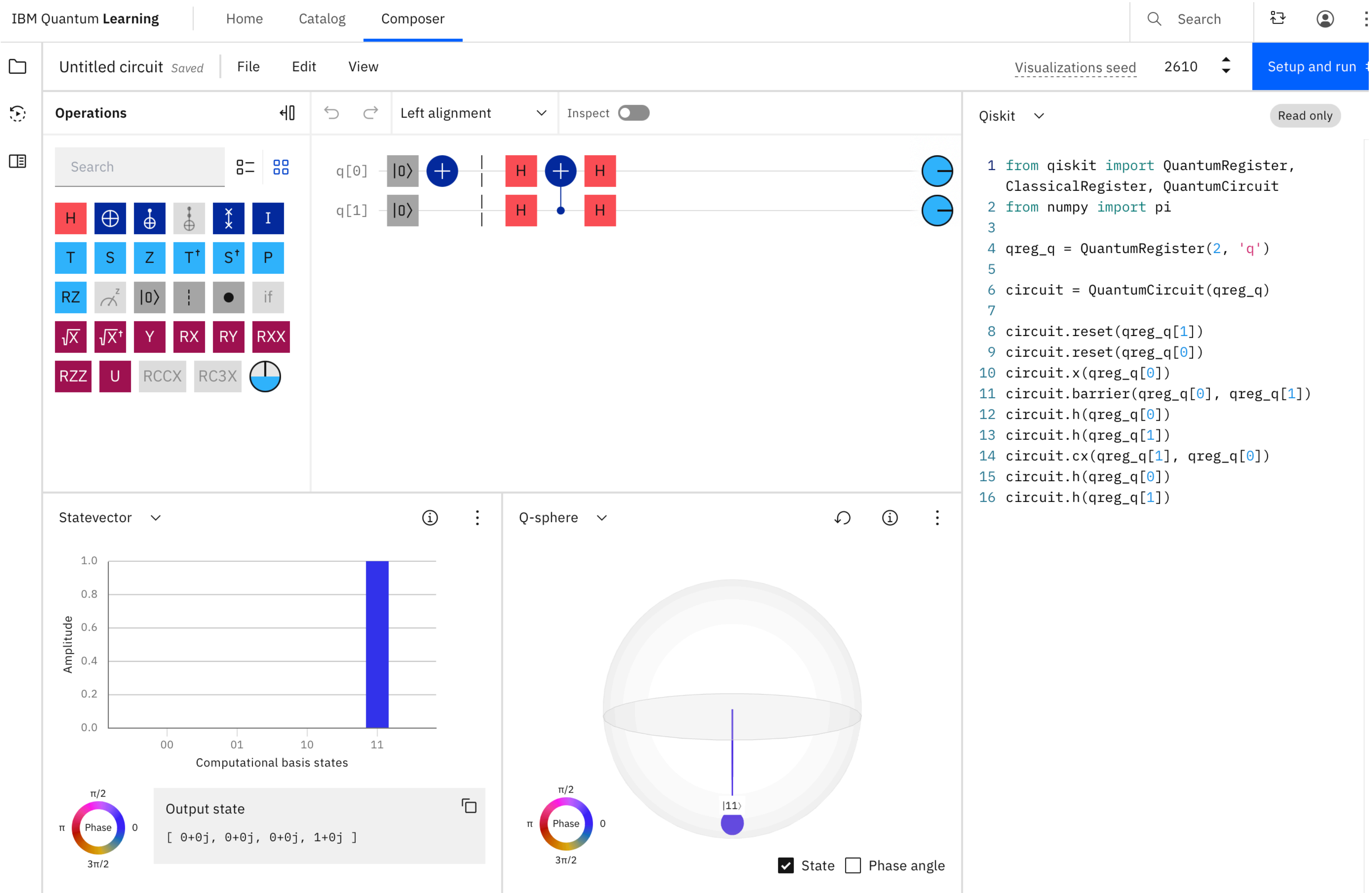
$$\left(2^{10}\times\frac{1\text{KB}}{1\text{Byte}}\right)\times\left(2^{10}\times\frac{1\text{MB}}{1\text{KB}}\right)\times\left(2^{10}\times\frac{1\text{GB}}{1\text{MB}}\right)\left(2^{10}\times\frac{1\text{TB}}{1\text{GB}}\right)=1\text{TB}$$

- **만약** 100 개의 이상적인 큐빗을 사용할 수 있는 경우,

  2^{100} bit $\simeq 2\times 10^{25}$ TB

  즉, 10^{25} TB 상태공간을 준비하고, 처리할 수 있음.

양자컴퓨팅 프로그램 라이브러리: 쉬운 접근



양자컴퓨팅 프로그램 라이브러리: 쉬운 접근

PENNYLANE Why PennyLane ⌄ Getting Started ⌄ Documentation ⌄ Ecosystem ⌄ Search ⌘K Install

Codebook

Learn quantum computing with PennyLane — the leading tool for programming quantum computers. Explore a specific module or follow a guided path to build your skills step-by-step.

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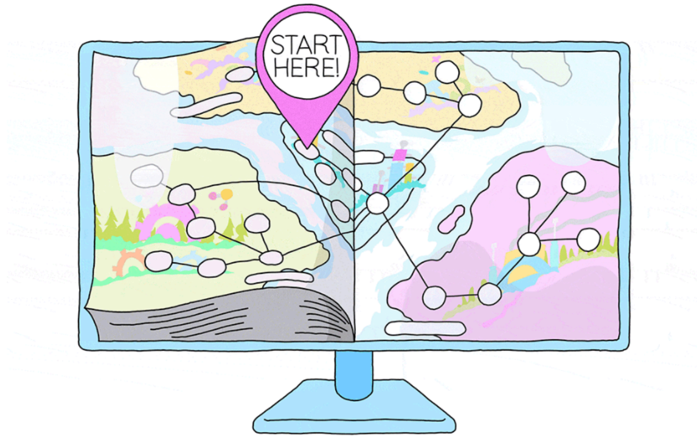
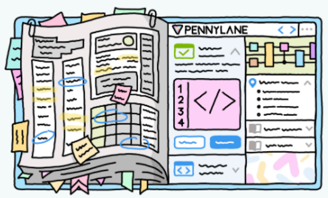




PENNYLANE FUNDAMENTALS CODEBOOK MODULE

Accelerate your quantum research breakthroughs with PennyLane! Quickly learn fundamental functions and practical applications of theoretical concepts in this brand-new module.

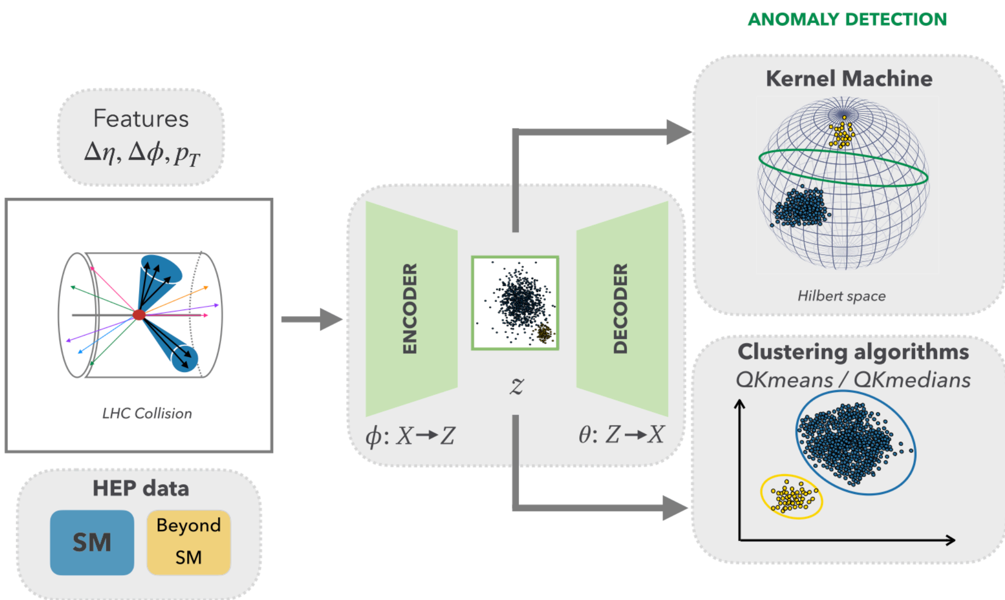
Learn more ›

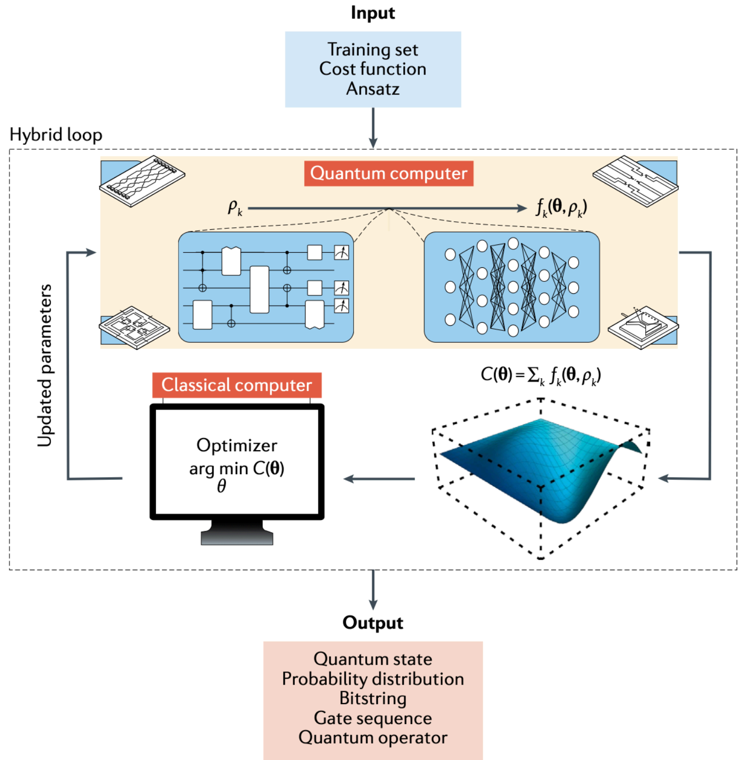
Numbers

NISQ (Noisy Intermediate-Scale Quantum)

- 현재 안정적으로 사용할 수 있는 큐빗의 갯수 $\mathcal{O}(10-100)$.

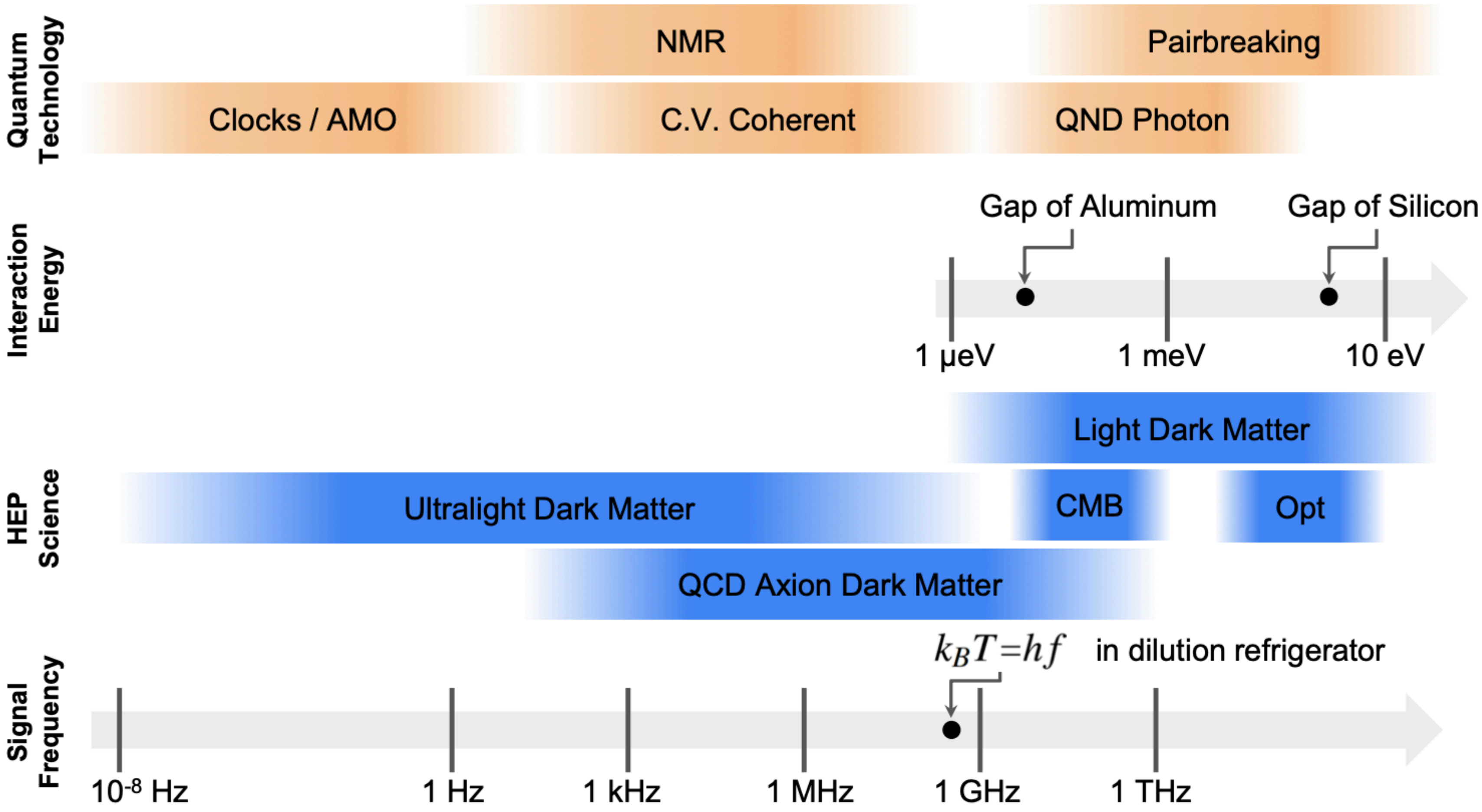
  현재 양자결맞음 시간 $\mathcal{O}(100)\mu s$, 이로인한 회로 깊이의 제한, 대략 $\simeq \mathcal{O}(10-100)$



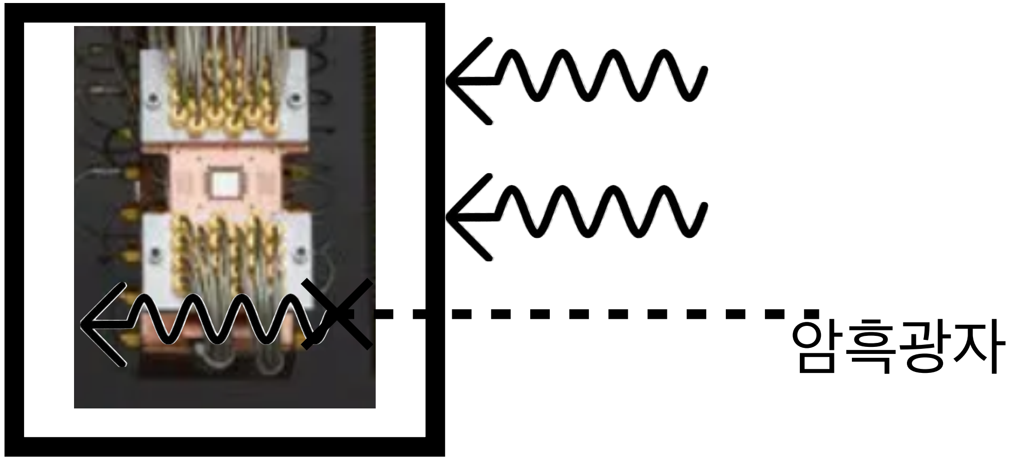


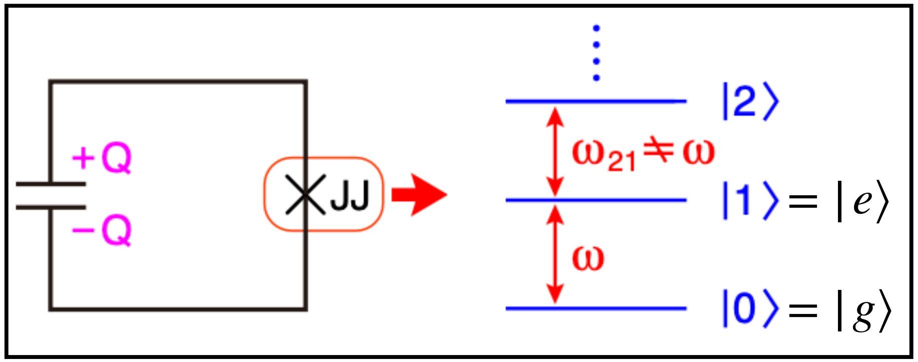
- Classical Machine Learning 과정을 통한 데이터 압축, 또는 Optimization 과정에서의 Classical Optimization 사용

양자센싱

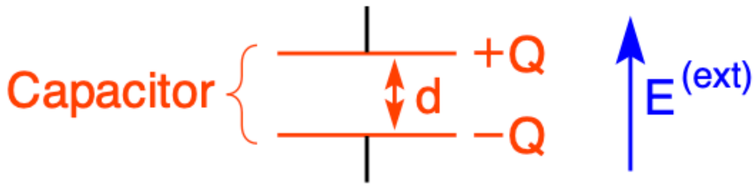

Quantum Technology
NMR
Pairbreaking
Clocks / AMO
C.V. Coherent
QND Photon
Interaction Energy
Gap of Aluminum
Gap of Silicon
1 μeV
1 meV
10 eV
HEP Science
Light Dark Matter
Ultralight Dark Matter
CMB
Opt
QCD Axion Dark Matter
Signal Frequency
$k_B T = hf$ in dilution refrigerator
10^{-8} Hz
1 Hz
1 kHz
1 MHz
1 GHz
1 THz

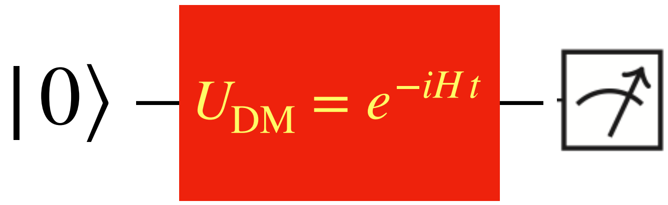
- 암흑광자 X로 인한 외부 전기장 유도 $E^{(\mathrm{ext})} = \epsilon\sqrt{2\rho_{\mathrm{DM}}}\sin m_X t$





$$\mathcal{L}_{\mathrm{int}} = e\bar{\Psi}_e\gamma^\mu(A_\mu + \epsilon X_\mu)\Psi_e,$$





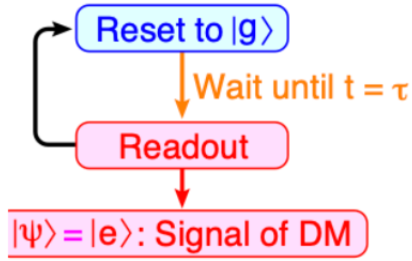
$$i\frac{d}{dt}\begin{pmatrix}\psi_g \\ \psi_e\end{pmatrix} \simeq \begin{pmatrix}0 & -i\eta \\ i\eta & 0\end{pmatrix}\begin{pmatrix}\psi_g \\ \psi_e\end{pmatrix}.$$

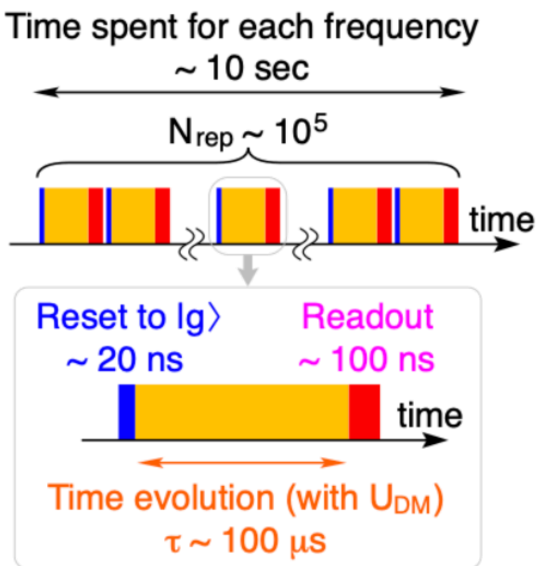
- 암흑물질이 Shield 내부에서 변환된 전자기파가 큐빗의 에너지 상태를 움직임

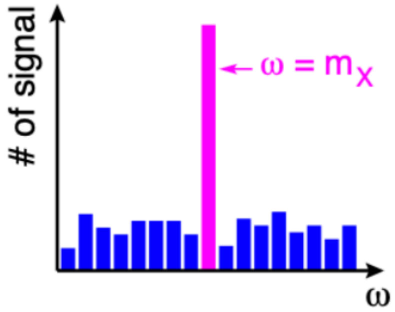
$$|\Psi(t)\rangle \simeq \cos\eta t\,|0\rangle + e^{-\omega t}\sin\eta t\,|1\rangle$$

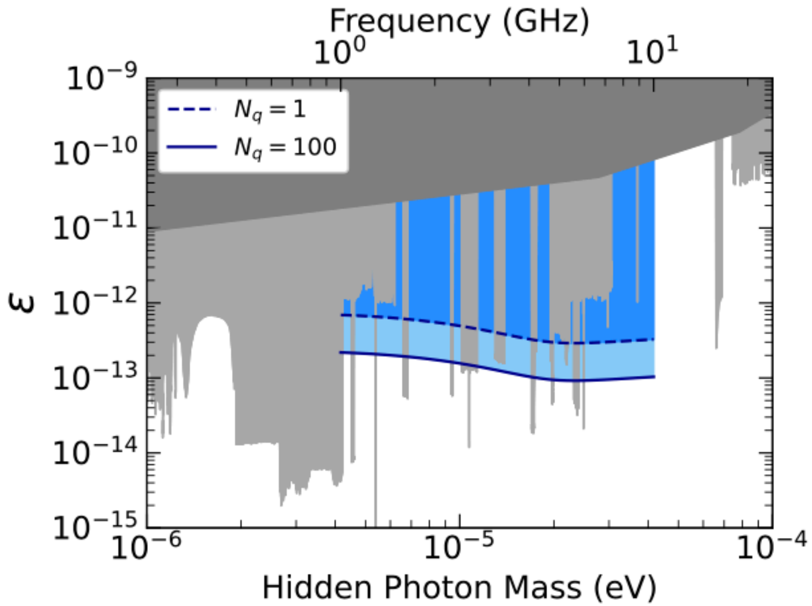
$$= |\langle 1|\Psi(t)\rangle|^2 \simeq \sin^2\eta t \simeq (\eta\tau)^2$$

(τ : 최대 결맞음 시간 μs)



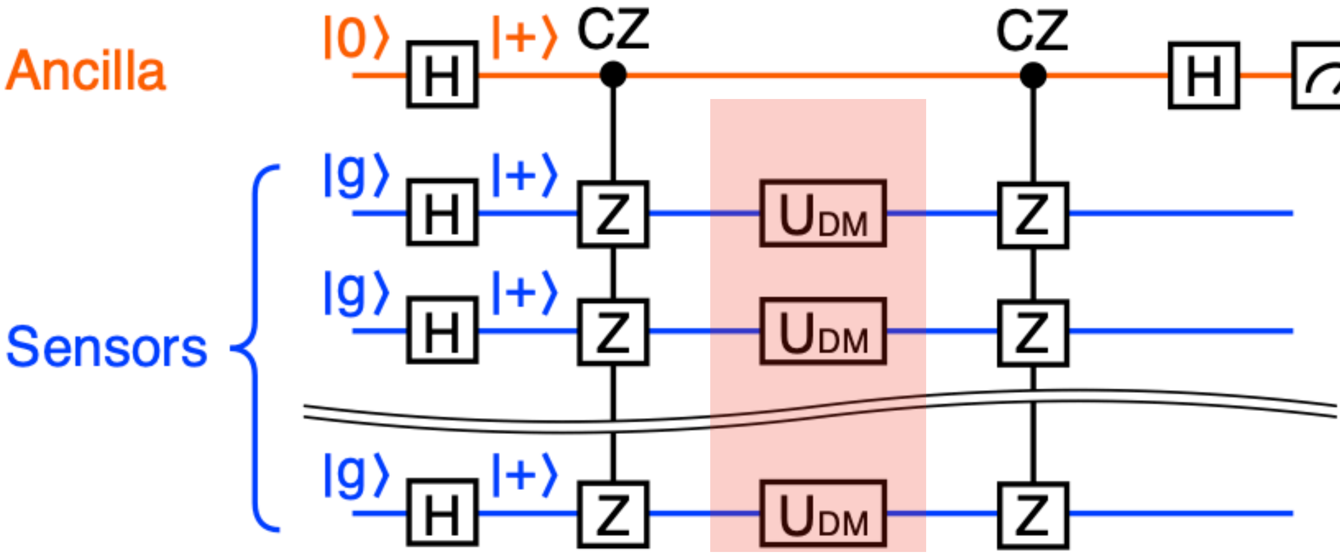






- Takeo Moroi, et.al. PRL 131, 211001 (2023)

양자 알고리즘을 통한 신호 증폭



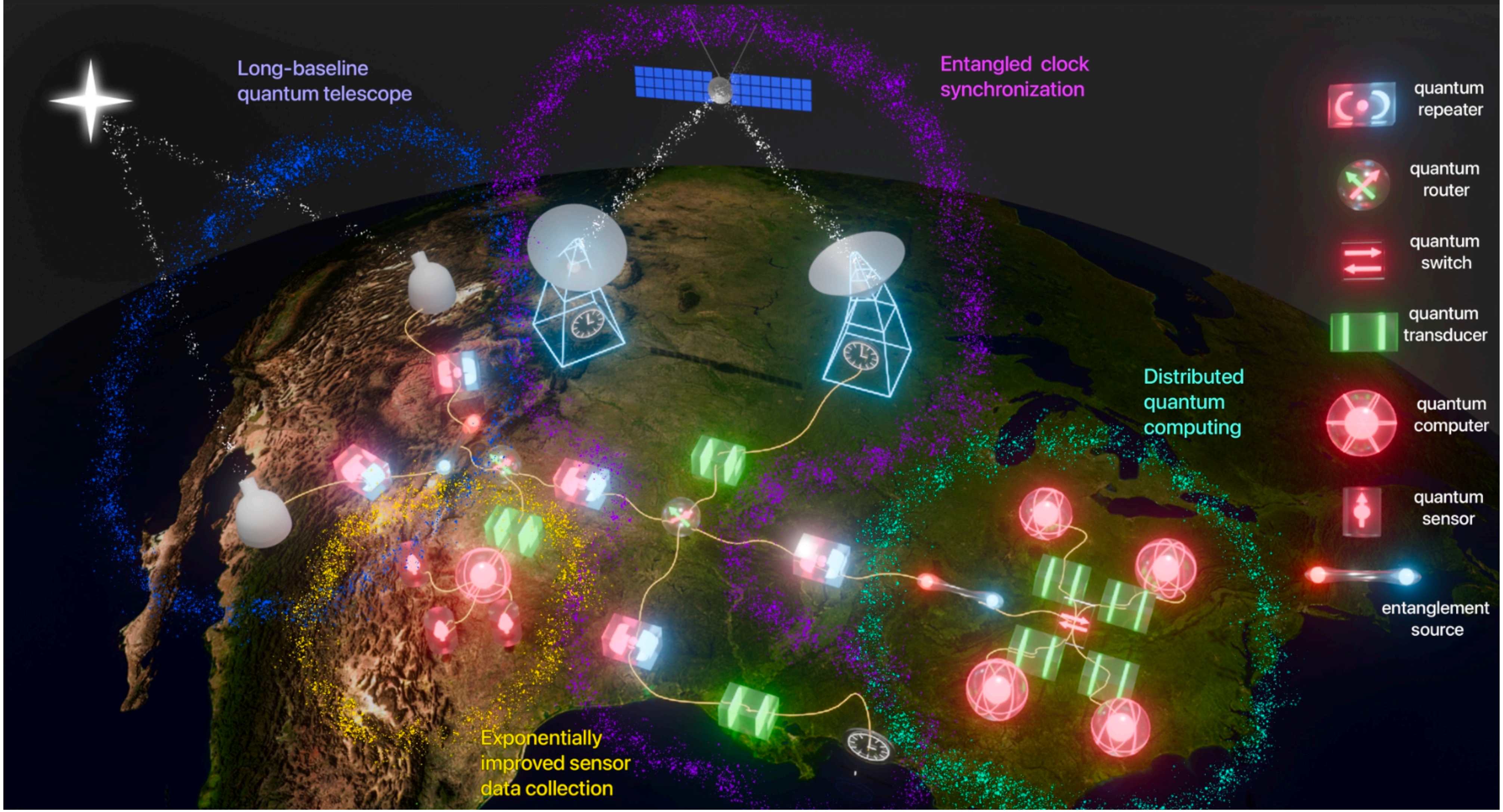
- N_s 개의 큐빗 센서들이 암흑물질의 영향에 노출: $U_{\rm DM}|\pm\rangle = e^{\pm i\delta}|\pm\rangle$ with $\delta = \eta\tau$

- 측정을 통해, $M = |\langle 1|\psi\rangle|^2 = |\sin N_s\delta|^2 \simeq N_s^2\delta^2$: 신호 강도가 N_s^2 로 증가

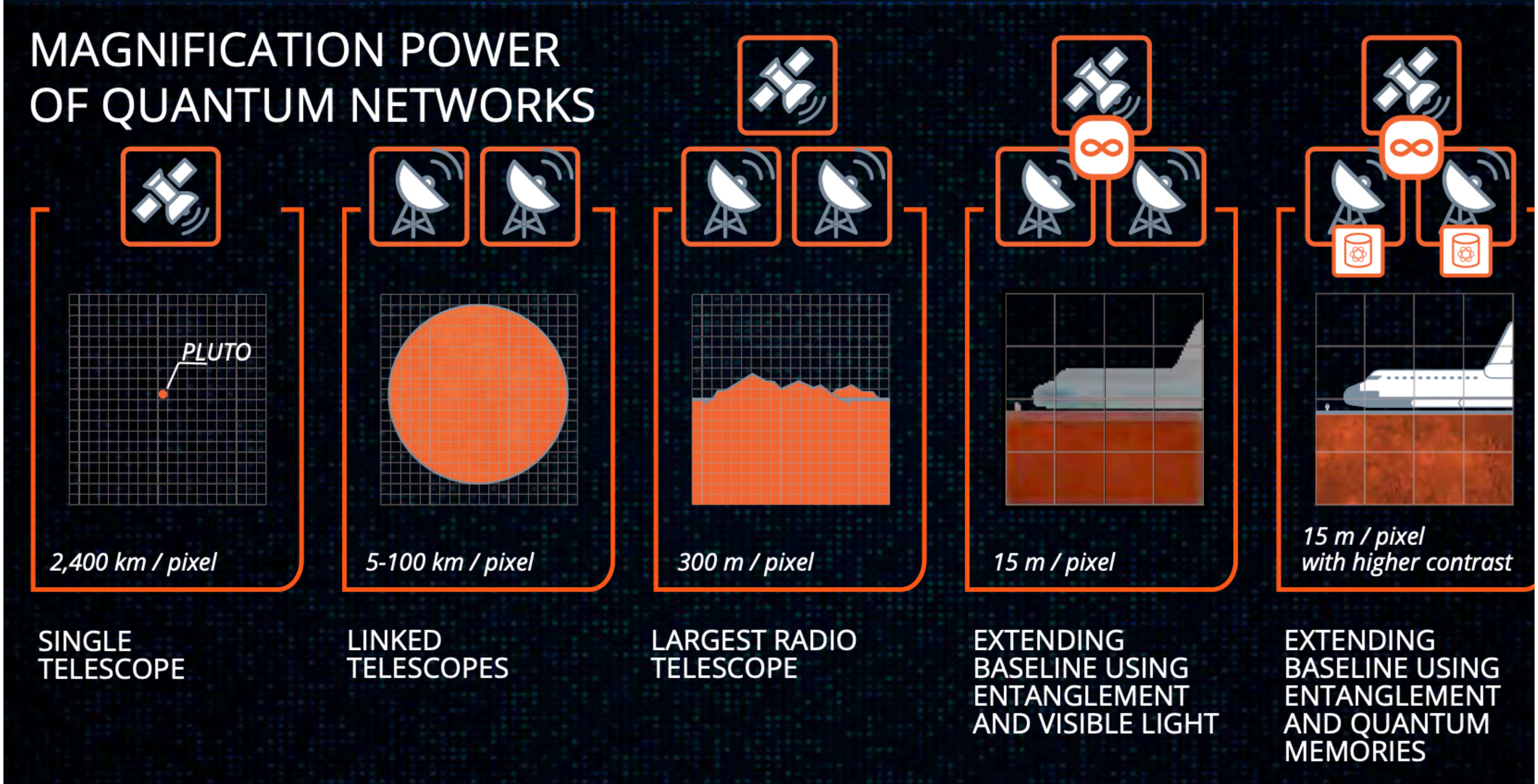
  (고전 센서의 경우, N_s 개의 서로 다른 센서들의 신호 감지 $\propto N_s$)

• Takeo Moroi, et.al. *PRL* 133 (2024) 2, 021801

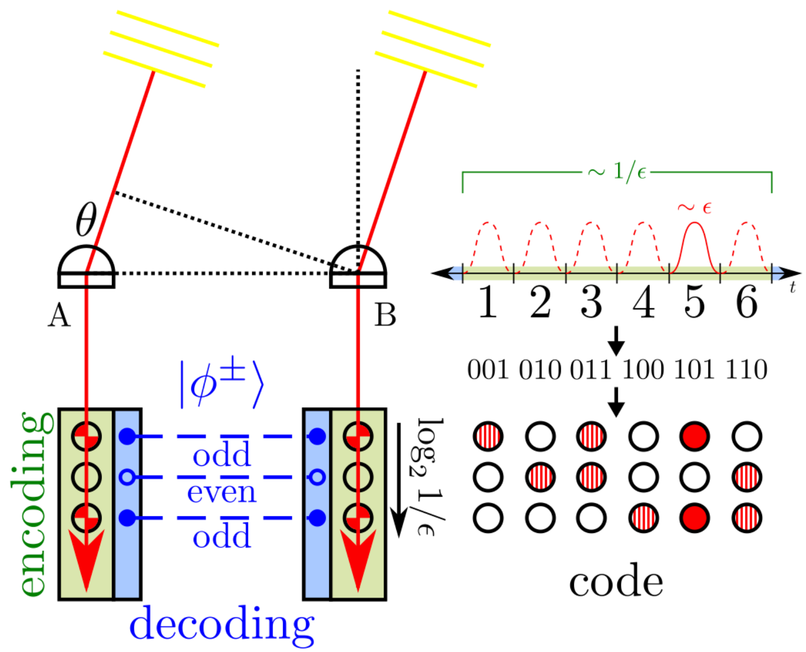
양자 네트워크를 통한 측정 정확도 확장



- 양자 얽힘을 이용한 천체관측 해상도 (예: 명왕성, 대략 40AU)



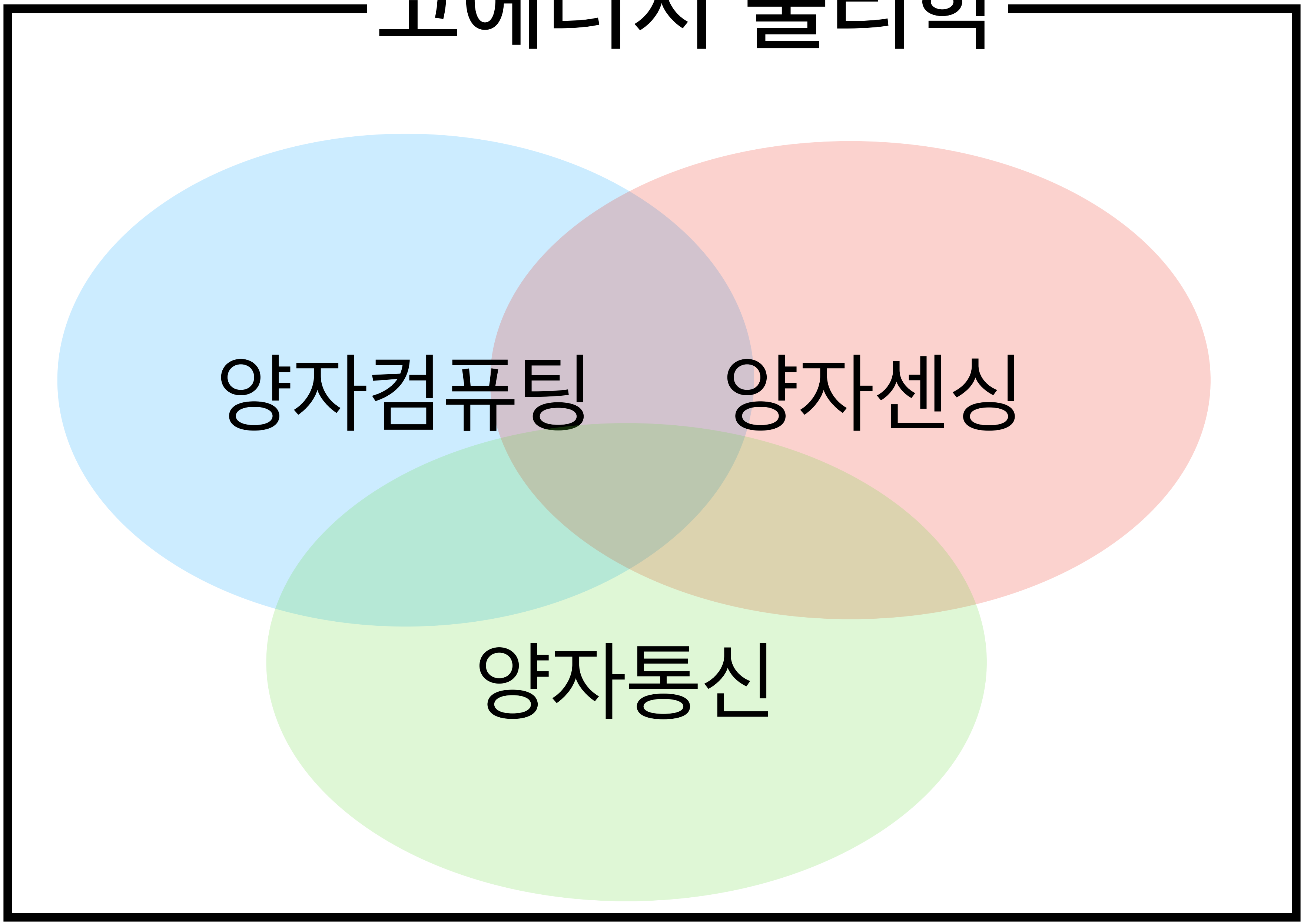
양자 얽힘 기반 광간섭계의 개념도



- 광자의 **도착 시간**을 큐비트에 저장하여 상태를 준비
  → 양쪽 메모리를 **얽힘 쌍과 연결**
  → **비국소적 측정**을 통해 두 관측 지점의 위상차 θ 추출

- **광자 전송 없이도 간섭계 효과 구현 가능 (직접 간섭 없이 위상 추출 가능)**
  이에 따라, 더 멀리 떨어진 망원경 간에도 위상차 측정 가능
  → long-baseline interferometry의 구현 가능성

고에너지 물리학



Quantum Initiative
in
High Energy Physics

Mega funded

DOE Announces $71 Million for Research on QIS Enabled Discoveries in High Energy Physics

POSTED ON JANUARY 16, 2025

(January 16, 2025) The U.S. Department of Energy announced $71 million in funding for 25 projects in high energy physics that will use the emerging technologies of quantum information science to answer fundamental questions about the universe. Awards funded under this program will advance theories of gravity and spacetime, develop quantum sensors that can see previously undetectable signals, and build pathfinder experiments to demonstrate increased discovery reach in searches for dark matter and other new particles and phenomena. The projects were selected by competitive peer review under the DOE Funding Opportunity Announcement for Quantum Information Science Enabled Discovery 2.0 (QuantISED 2.0).

Projects include efforts to use the burgeoning field of quantum information science to enable new discoveries in fundamental physics:

- Theoretical work using existing and near-future quantum devices like computers and simulators to explore the nature of spacetime, perform data analysis at particle colliders, and solve advanced problems in quantum field theory.
- Leveraging quantum information science technologies – such as superconducting qubits, atomic sensors, and quantum states of light – to enhance the sensitivity of experiments searching for new phenomena, including detecting particles that could make up the dark matter in the universe.
- Creation of new experimental platforms using quantum information technologies, such as entanglement or precise control of quantum states, to track and observe microscopic physical processes, like individual radioactive decays or the measurement of gravity between masses as small as a milligram.

고에너지물리(HEP)와 양자정보(QIS) 융합

- 미국, 유럽, 중국 등은 QIS 기반 HEP 연구에 대규모 투자를 단행 중

  \- 양자센싱 기반 암흑물질 탐색, QFT 계산(Lattice), 데이터과학등 실제 활용 확대

- 해외 다양한 Quantum initiative 연구소에 대응 / 교류할 주체 확보 필요

  \- 다양한 교류 프로그램 / 연구자 파견 / 신진 인력 양성

- QIS는 핵물리, 입자물리, 천체물리 전반에 걸쳐 적용되고 있으며,

  고에너지물리 커뮤니티가 Quantum Initiative를 선도할 수 있는 전략적 위치에 있음:

  1) 기초과학 분야

  2) 초빅데이터, 초고에너지, 초거대스케일 영역에서 양자기술의 핵심적 역할을 입증하고,

  기술도를 측정할 수 있는 중요 적용분야

참고

- 한국양자정보학회 (2022년 사단법인) 이후, 학술대회를 포함한 다양한 활동

정기 워크샵
Close
제28회 한국양자정보학회 정기워크샵
2025. 04. 25 ~ 2025. 04. 25
[온·오프라인 동시 진행] 서울바이오허브 지역열린동 컨퍼런스홀B
Shortcut

국내 학술행사
Close
2025 한국양자정보학회 정기학술대회 및 정기총회
2025. 02. 17 ~ 2025. 02. 19
부산항국제전시컨벤션센터 (BPEX)
Shortcut

정기 워크샵
Close
제27회 한국양자정보학회 정기워크샵:...
2024. 12. 20 ~ 2024. 12. 20
서울 스위스그랜드호텔 (서울 서대문구 연희로 353)
Shortcut

정기 워크샵
Close
제26회 한국양자정보학회 정기워크샵
2024. 11. 01 ~ 2024. 11. 01
서울바이오허브 컨퍼런스홀B
Shortcut

정기 워크샵
Close
제25회 한국양자정보학회 정기워크샵
2024. 08. 30 ~ 2024. 08. 30
서울바이오허브 컨퍼런스홀B
Shortcut

정기 워크샵
Close
제24회 한국양자정보학회 정기워크샵
2024. 06. 07 ~ 2024. 06. 07
KIST, L8 Conference Room1 (한국과학기술연구원, 서울 성북구 화랑로14길 5)
Shortcut

- 양자컴퓨팅 (QFT 시뮬레이션), 양자머신러닝 (데이터 분석), 양자센싱 (암흑물질·중력파 탐지등) 등 분야에서 고에너지물리와의 협력·교류 가능성 매우 높음