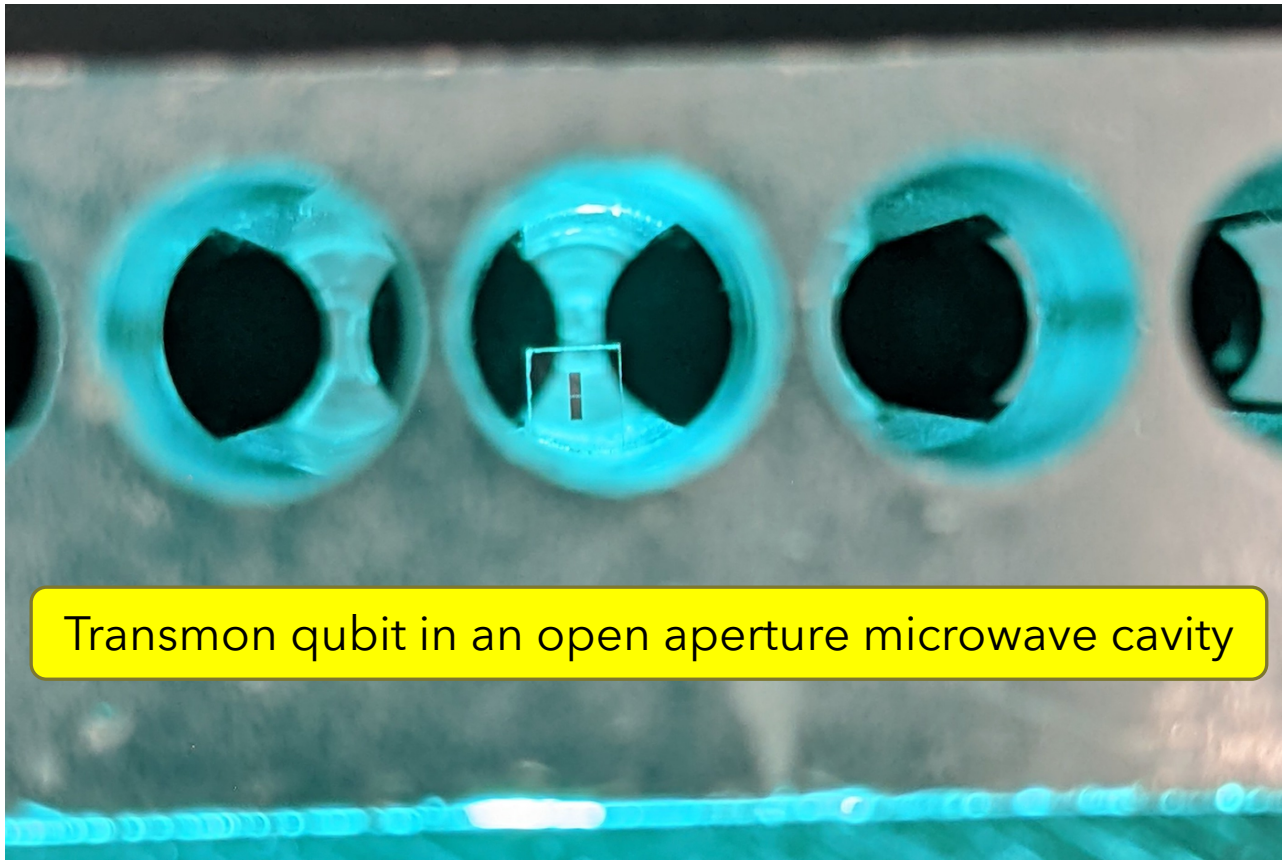
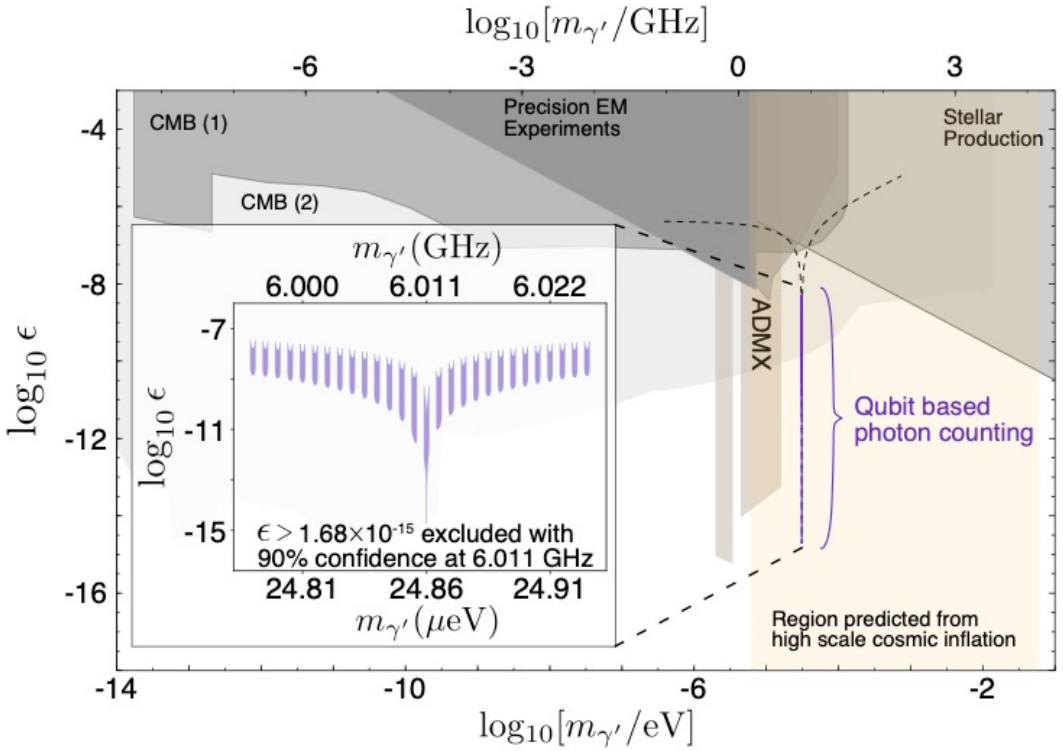
Detecting Dark Matter with a Superconducting Qubit

A. V. Dixit, et al., Phys.Rev.Lett. 126 (2021) 14, 141302





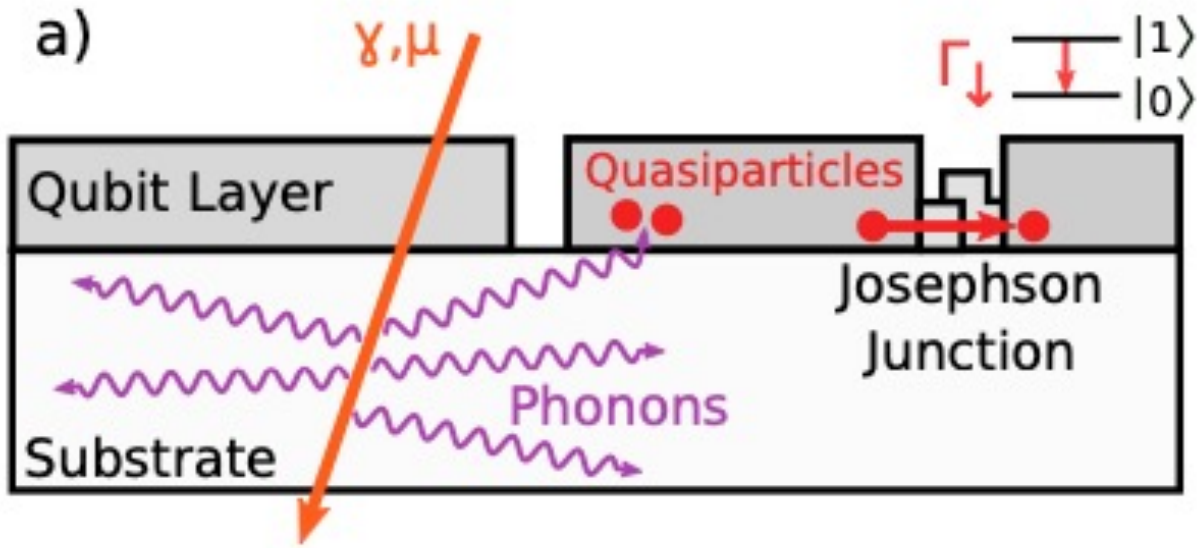
- Dark matter waves deposit spurious single microwave photons into this "quantum RAM."
- The resulting qubit frequency errors can be detected with high fidelity quantum readout

DOE-OHEP QuantISED Consortium: Quantum Sensing for Dark Matter

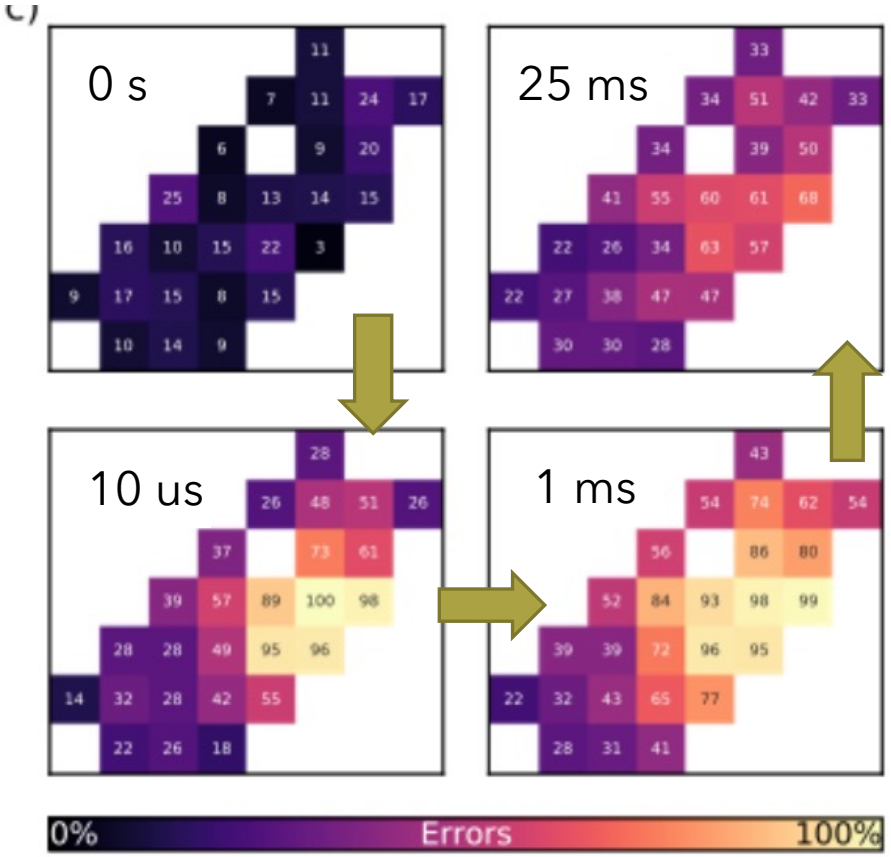
- World record quantum sensor noise suppression 37x below the standard quantum limit for **single microwave photon detection**
- World-leading dark photon sensitivity

Qubits are also ultra low threshold phonon and charge detectors

Aluminum superconducting gap = 10^{-4} eV << 1 eV semiconductor band gap of silicon



The "catastrophic event" is reconstructed in both space and time using the pattern of detected qubit errors



100 keV energy deposit in silicon substrate of Google Sycamore chip.

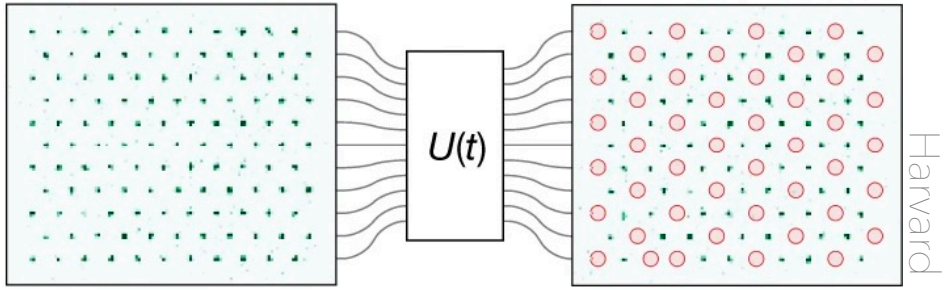
M. McEwen et al., Nature Physics 18 (2022)

QUANTUM SCIENCE CENTER

QSC provides HEP instrumentation and low background underground test stands to make more robust qubits and better dark matter detectors.

Fundamental Building Blocks of Nature

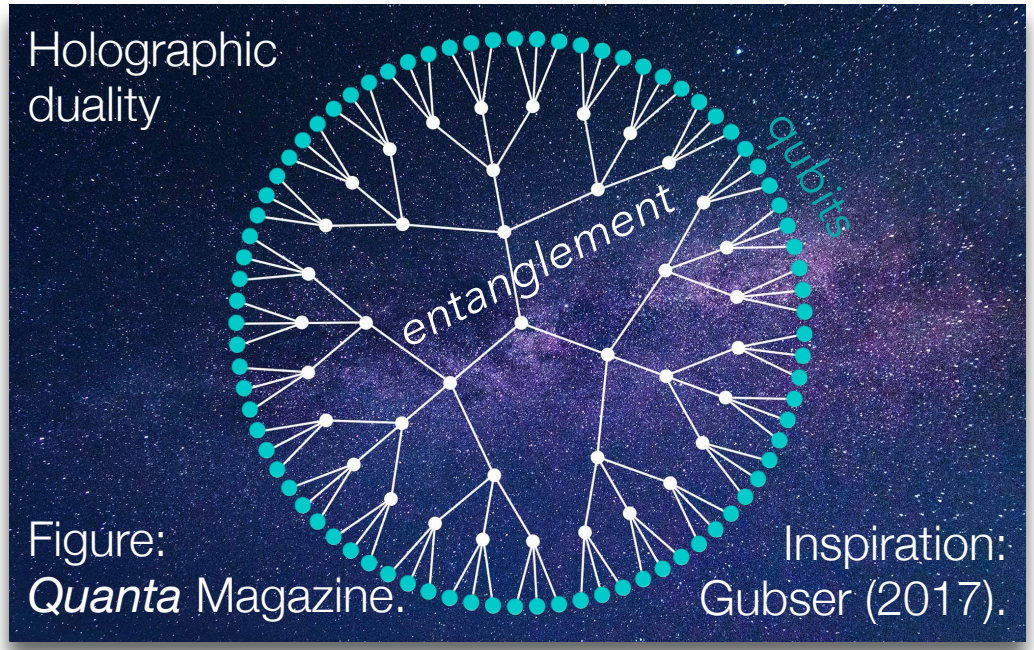
Sweet is by convention
& bitter is by convention,
hot by convention,
cold by convention,
color by convention,
in truth there are but atoms and the void.
—Democritus (b. 460 BC)



Macroscopic behavior emerges from microscopic configuration of atoms

Today: understanding the void

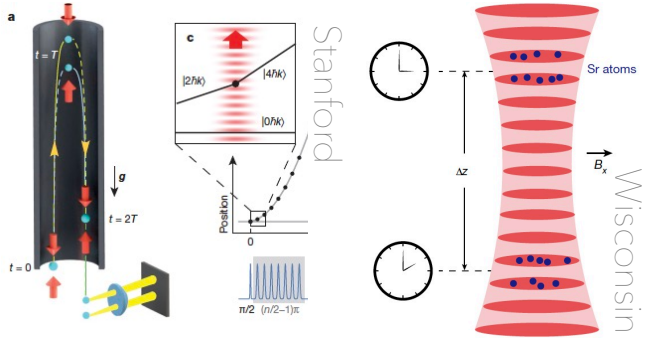
Is spacetime *really* smooth?



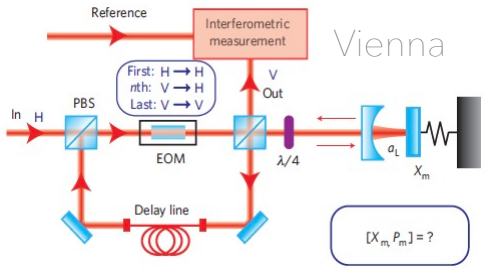
…or do curved space & gravity emerge from discrete constituents?

Quantum Gravity in Table-Top Experiments?

Precision Measurement

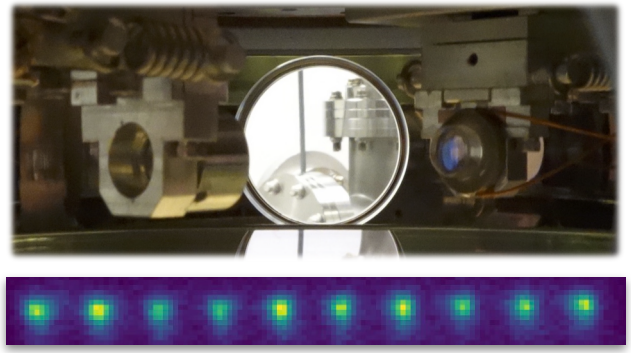


Quantum gravimeters & clocks

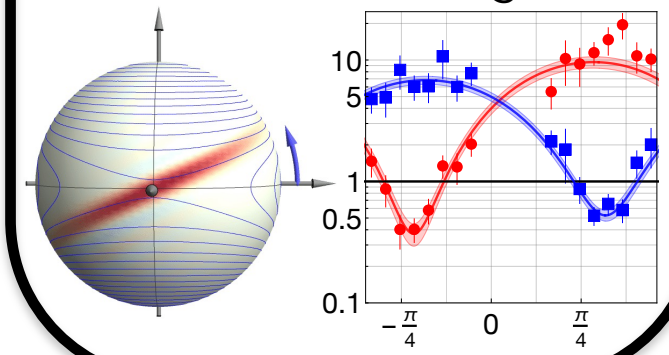


Massive quantum objects

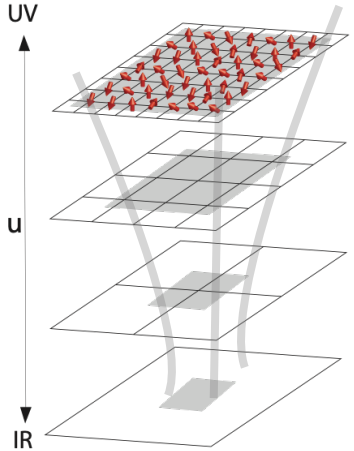
Quantum Engineering



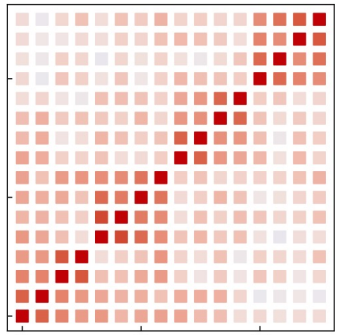
Interactions → Entanglement



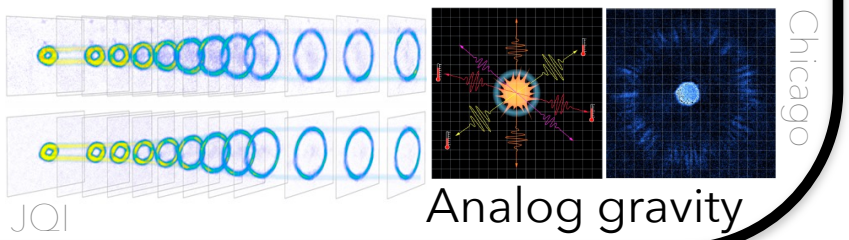
Quantum Simulation



Holographic duality



Build interacting quantum system and probe correlations



Analog gravity

Holographic Quantum Simulation

Can curved space and gravity *emerge* from entanglement?

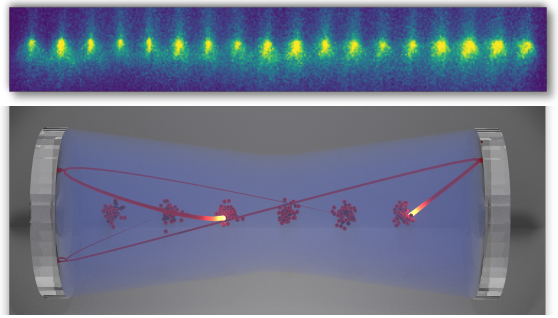
Inspiration: *p*-adic AdS/CFT

Tree graph as discretized version of hyperbolic space (holographic bulk)

Experiment:

Cold atoms & photons

⇒ programmable interactions



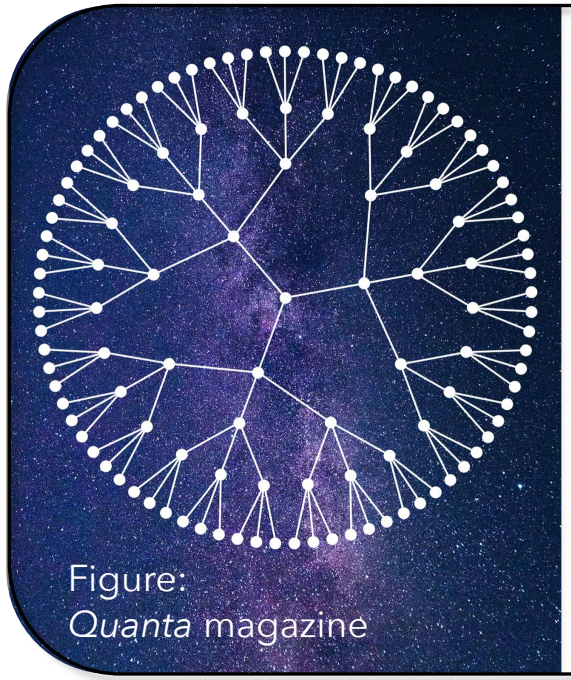
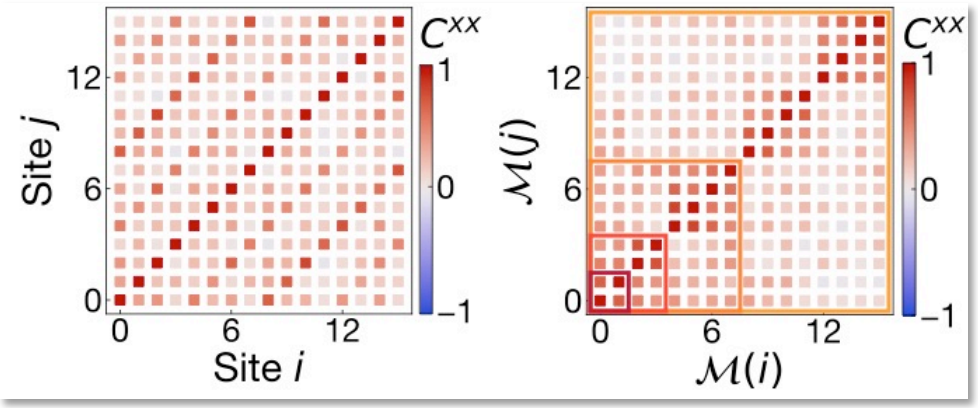
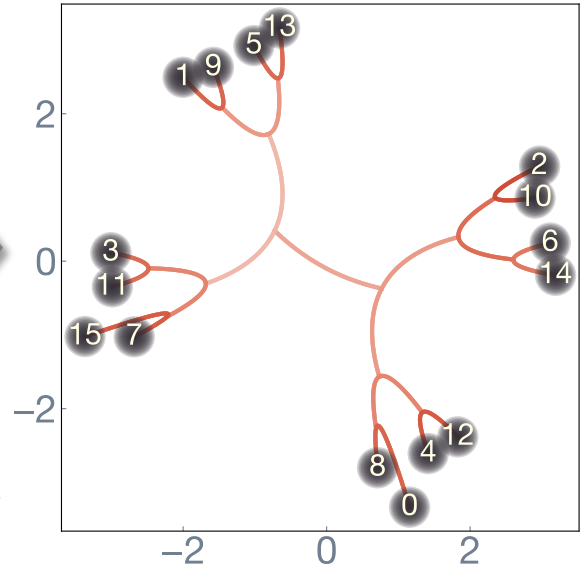


Figure:
Quanta magazine

Treelike bulk geometry emerges from measured spin correlations





Periwal, Cooper, Kunkel, Wienand, Davis & MS-S, *Nature* (2021).

Proposed in: Bentsen, …, Daley, Gubser & MS-S, *PRL* (2019).

Led by Fermilab, $115M
Awarded August 2020

Superconducting Quantum Materials and Systems Center

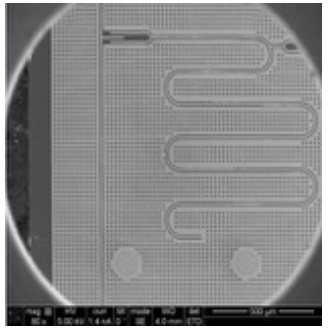
A DOE National Quantum Information Science Research Center

23 Institutions
> 400 Researchers
> 100 students/postdocs

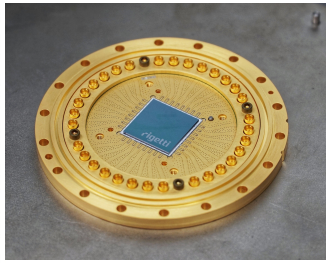
Fermilab
Northwestern University
rigetti
AMES NATIONAL LABORATORY
Creating Materials & Energy Solutions
NASA Ames Research Center
NIST
INFN Istituto Nazionale di Fisica Nucleare
Stanford University
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN
RUTGERS
UNIVERSITÀ DI PISA
University of Colorado Boulder
ILLINOIS INSTITUTE OF TECHNOLOGY
JOHNS HOPKINS UNIVERSITY
Temple University
COLORADO SCHOOL OF MINES
THE UNIVERSITY OF ARIZONA
UNIVERSITY OF MINNESOTA
NYU
Goldman Sachs
LOCKHEED MARTIN
JANIS
Unitary Fund

SQMS Roadmap: a quantum decade leading to new revolutionary tools

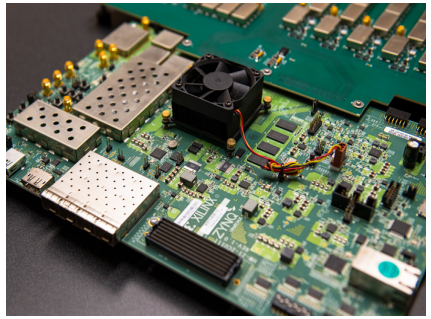
From 1 to 10 high coherence qubits prototype



Transmon qubit improvement in coherence > 10



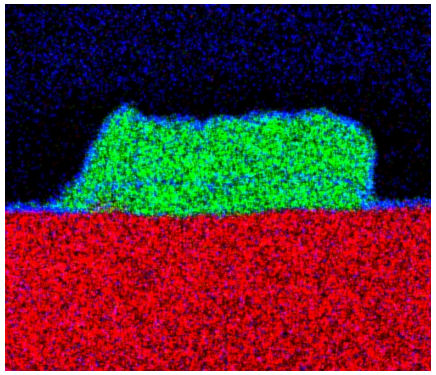
100 qubits Quantum Computer @ Fermilab



Electronics/optimal controls development and scale up

1000 qubits Quantum Computer @ Fermilab

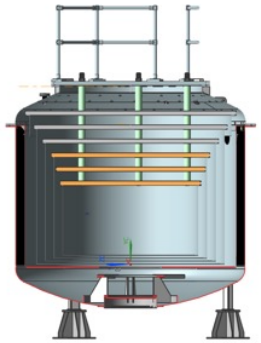
2020-2030: The SQMS Quantum Decade of Technological and Scientific Innovation



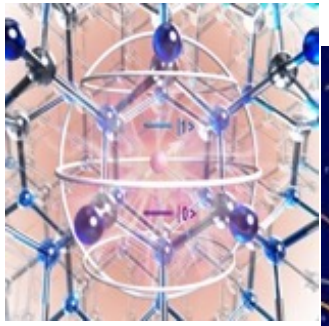
Materials Research for high coherence qubits

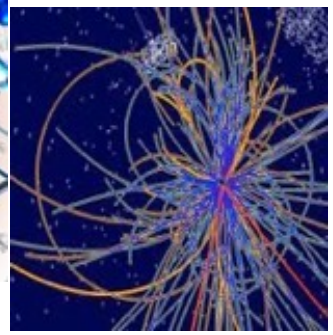
New quantum testbeds commissioned

Quantum Sensors for fundamental physics



Colossal fridge commissioned 20mK





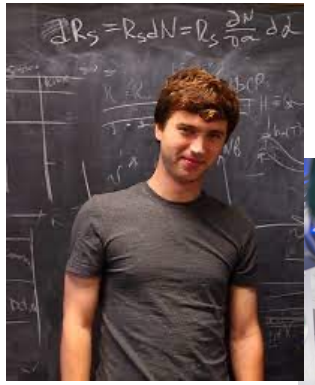
Solving complex problems in HEP, CMP, medicine, climate, national security

Fermilab

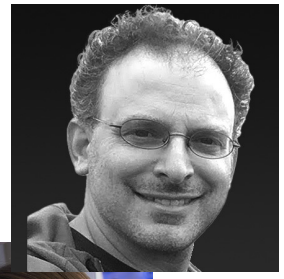
SQMS theorists and experimentalist 'co-design' to develop new experiments

SRF + QIS capabilities enable new particle searches of unprecedented sensitivity and precision

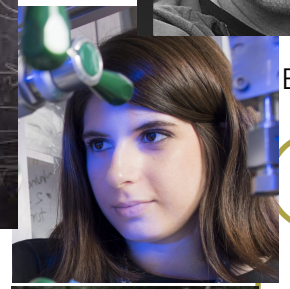
A. Romanenko



R. Harnik



Y. Kahn



B. Giaccone

G. Gabrielse

R. Cervantes

Theory

Options for mode setups + sensitivity

Prototypes

Systems design, testing

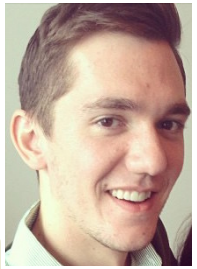
(measure cross-talk, Q for various modes, readout)

co-design

Materials and Devices

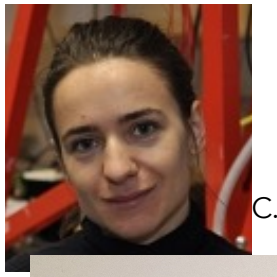
Improved Q, sensitivity, controls

A. Berlin

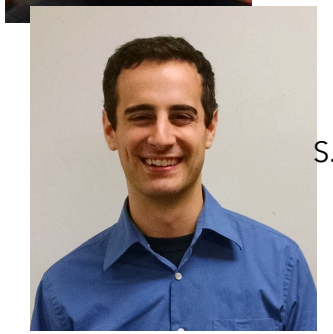


S. Rajendran

P. Graham

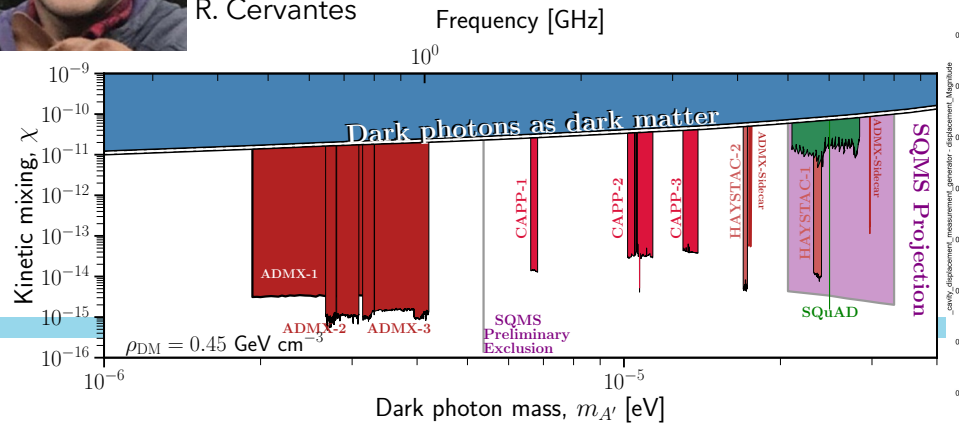


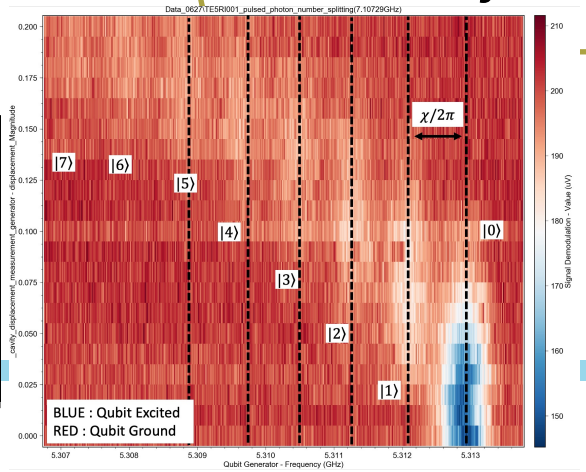
C. Braggio



S. Posen

Best limit for dark photon dark matter



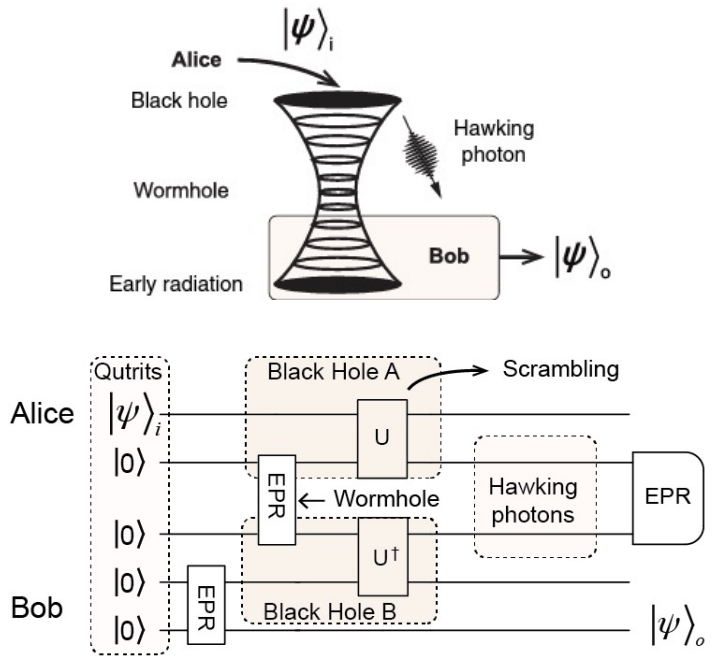


Single microwave photon counter

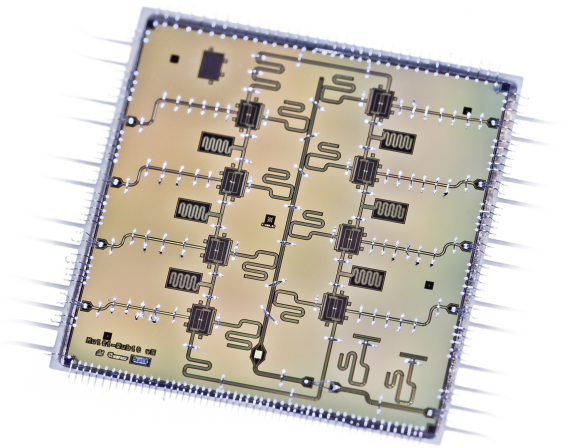
Fermilab

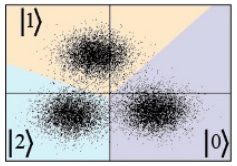
Scrambling with ternary quantum logic

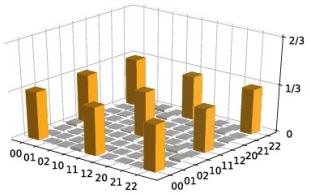
Black hole information paradox



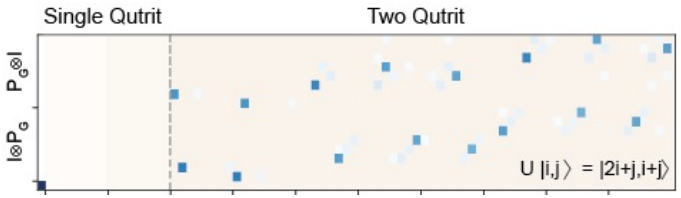
Superconducting qutrit processor

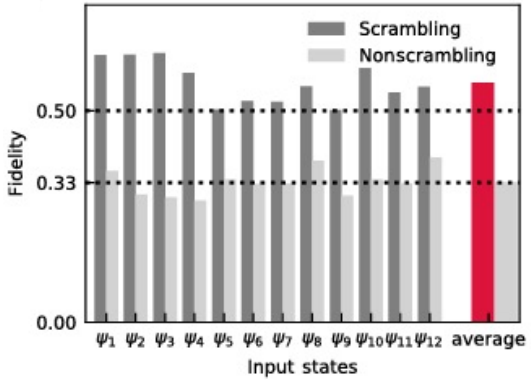






Scrambling and teleportation



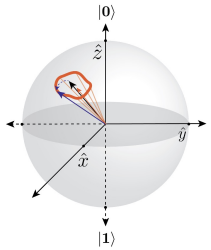


Blok, et. al., PRX (2021)

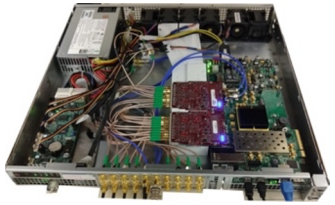
Nuclear physics simulations on AQT

Collaborative research laboratory

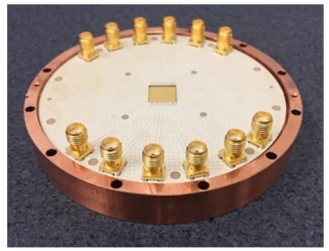
Versatile software stack



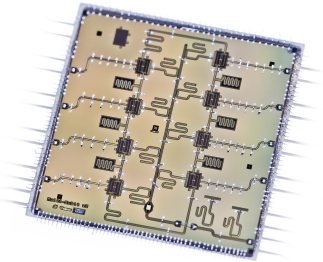
Custom FPGA controls



Cryogenic platform

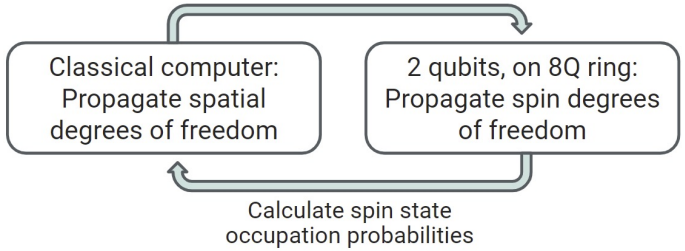


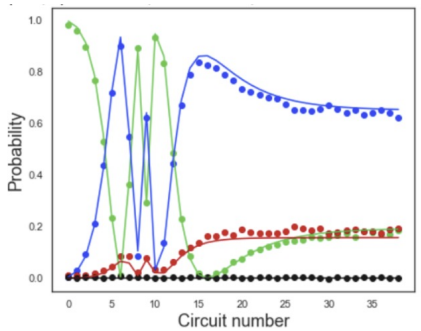
Superconducting processors

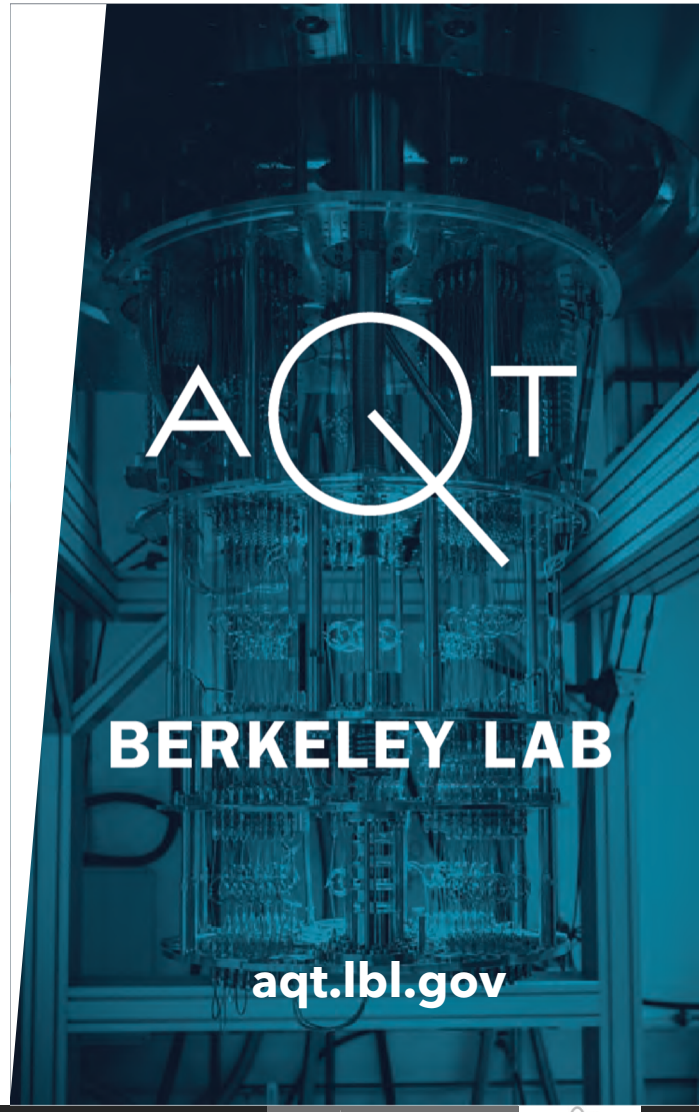


Evolution of interacting neutrons

User project collaboration with Sofia Quaglioni, LLNL





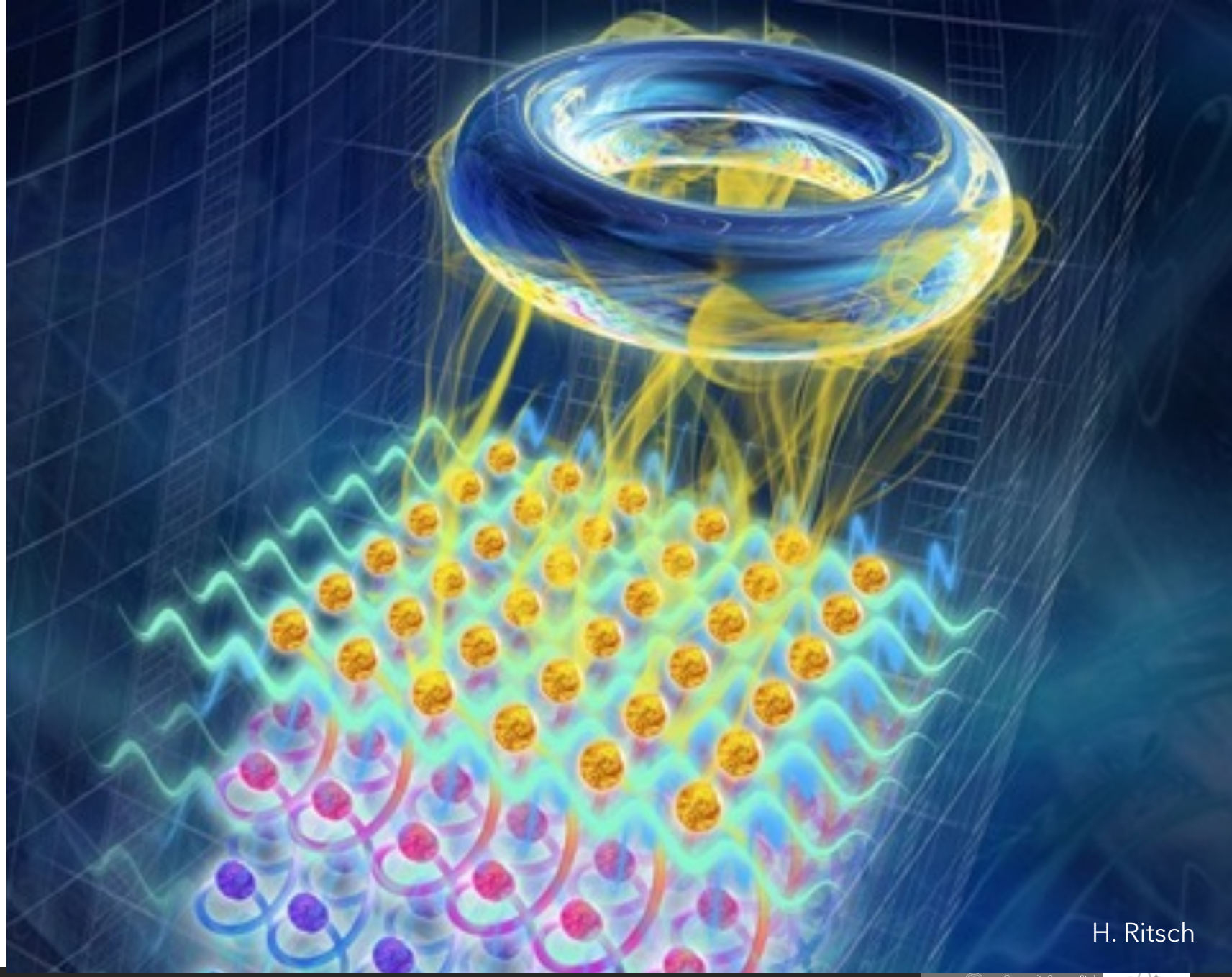


A Culture of Quantum Computing

The paradigm of quantum information

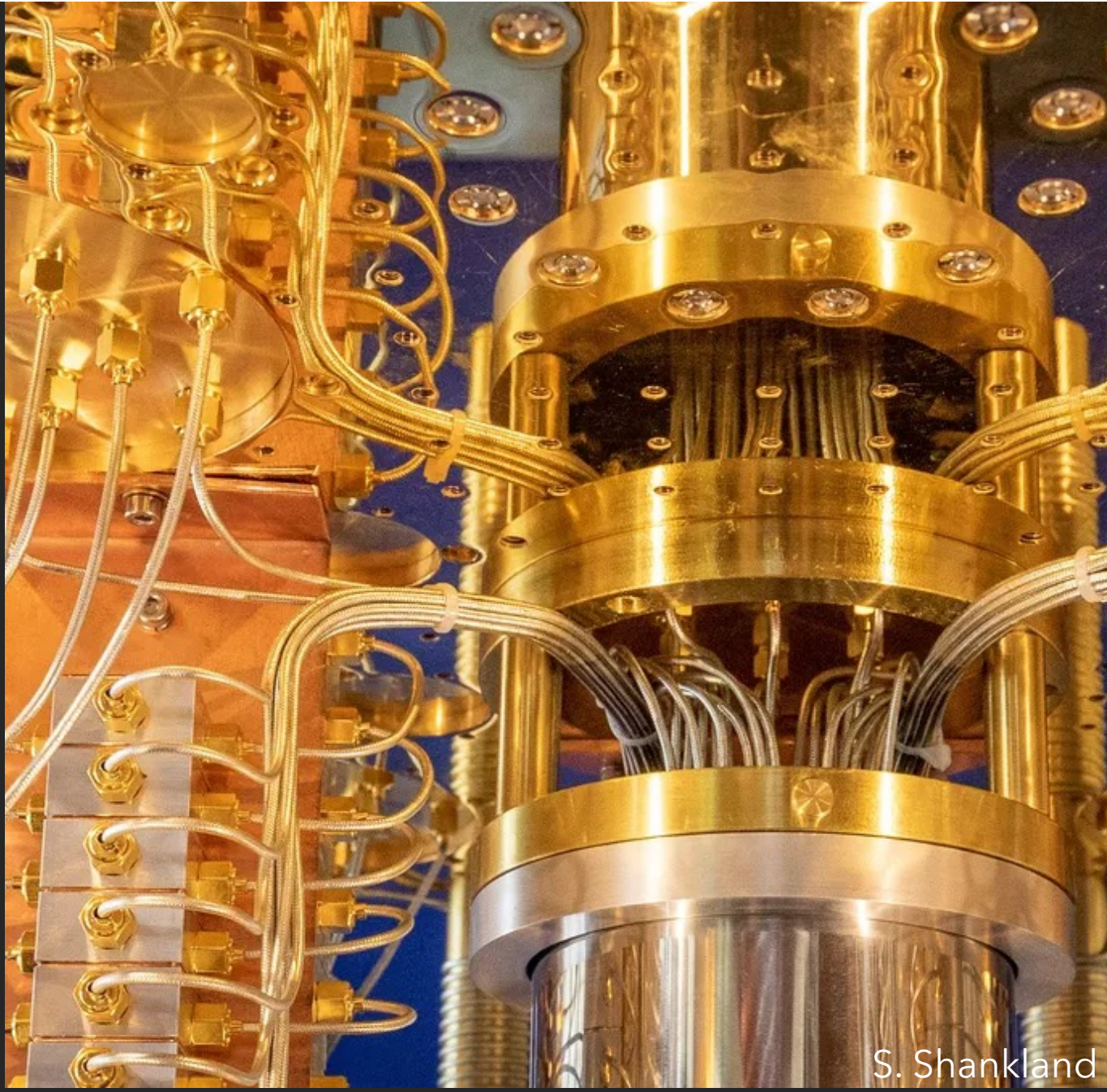
The connection between quantum technology and its scientific drivers

The promise of discovery and innovation



Connecting quantum technology with its scientific drivers

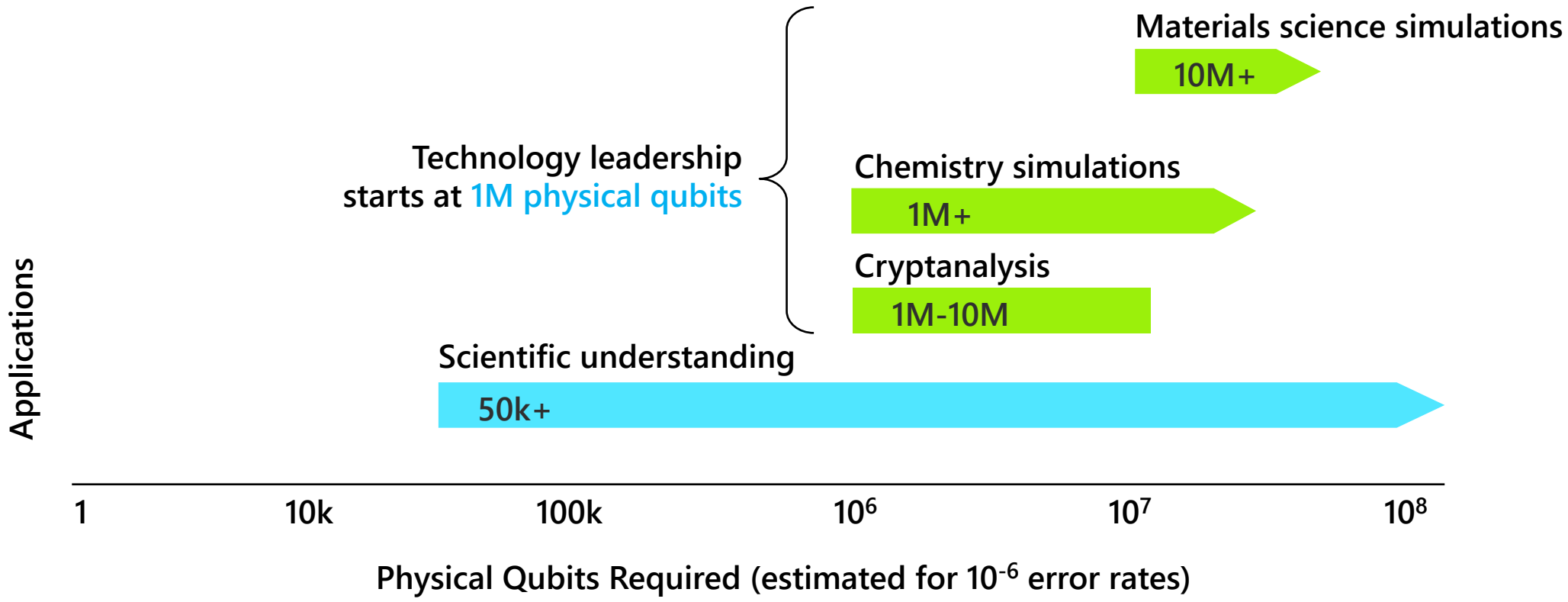
- Modeling and simulation, data mining and machine learning
- Software, systems, tools and techniques
- Networks, workflows, interfaces and infrastructure



S. Shankland

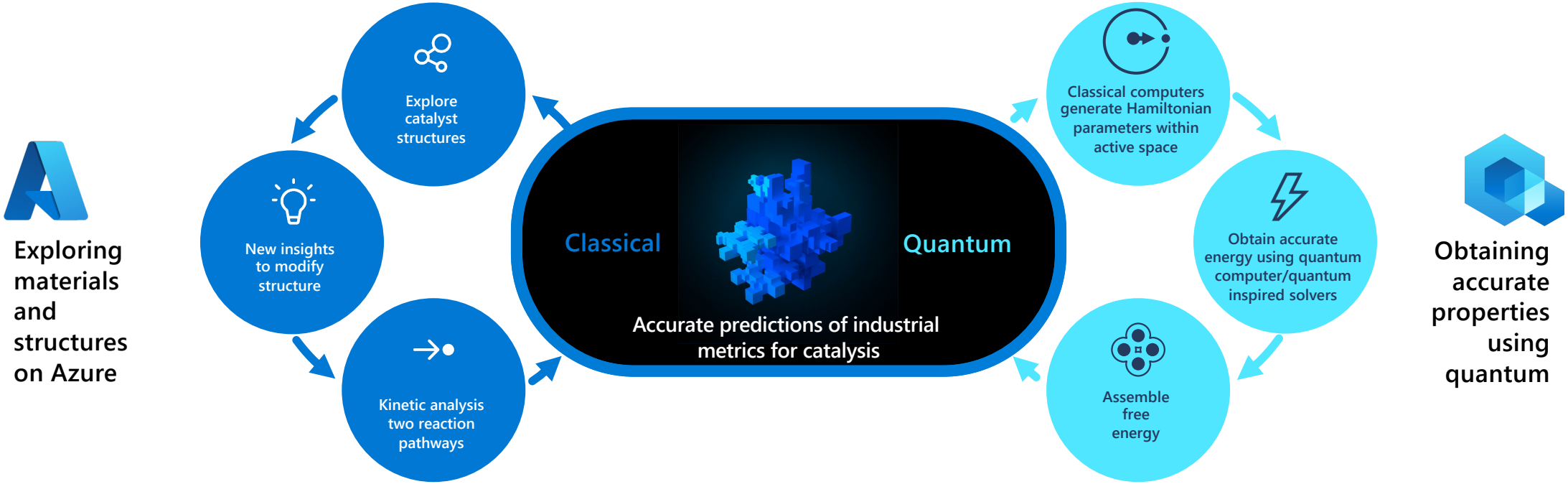
KrystaS

Impactful applications require at least 1M qubits



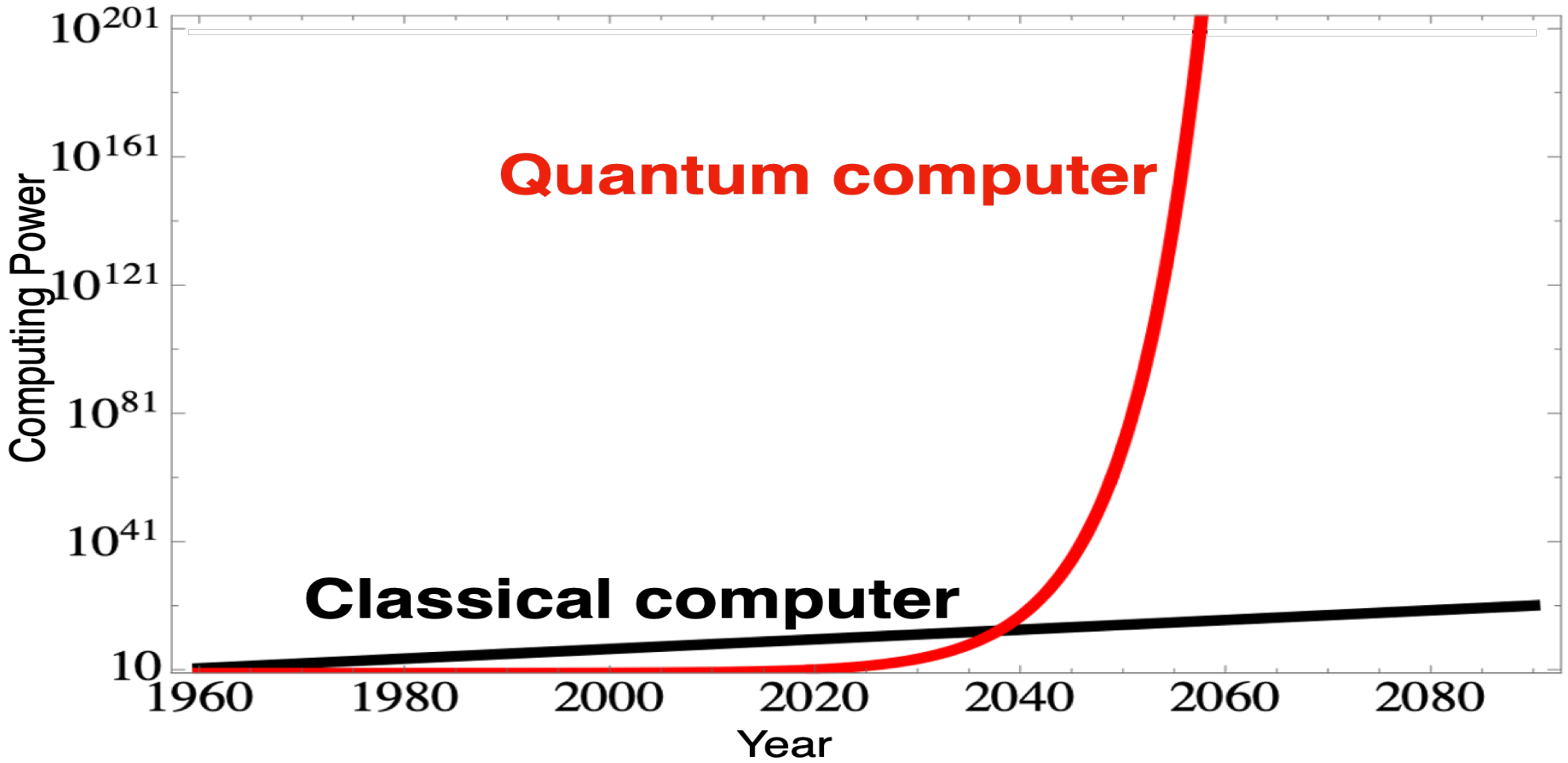
High-performance hybrid quantum computing

Quantum computers are an accelerator of future computational solutions.

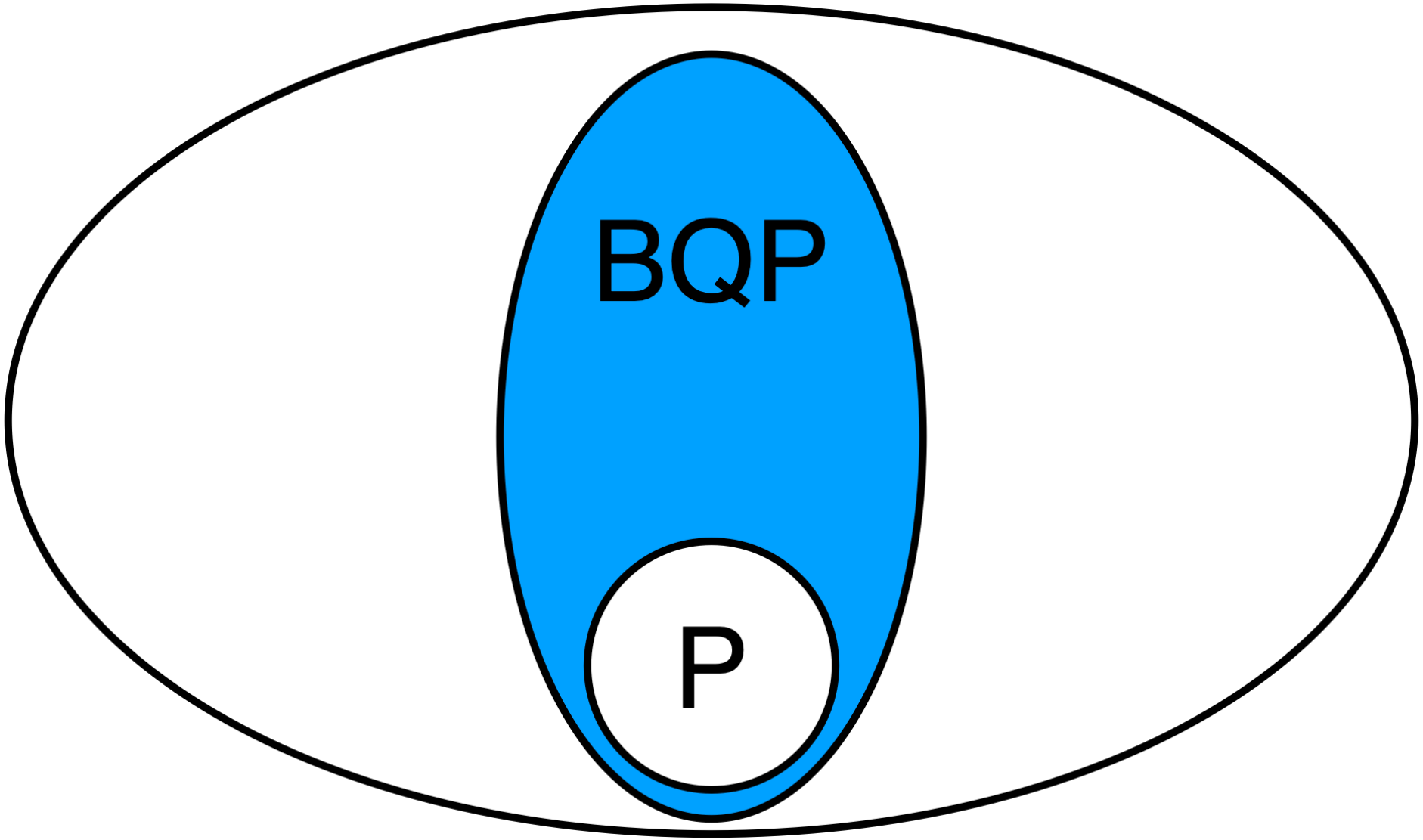


PR Research 3, 0330555 (2021), *Editor's Choice*

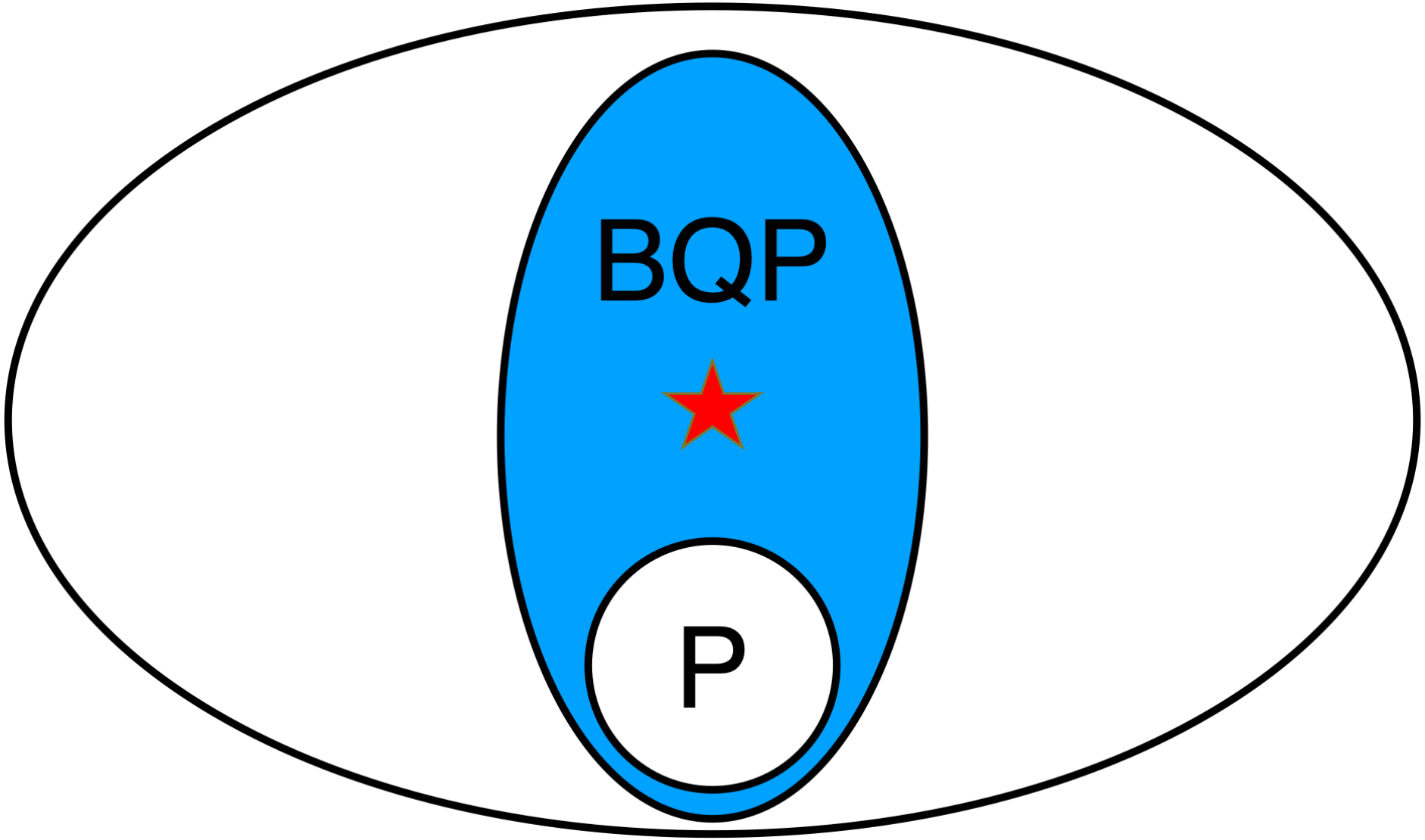
Standard argument for quantum computers



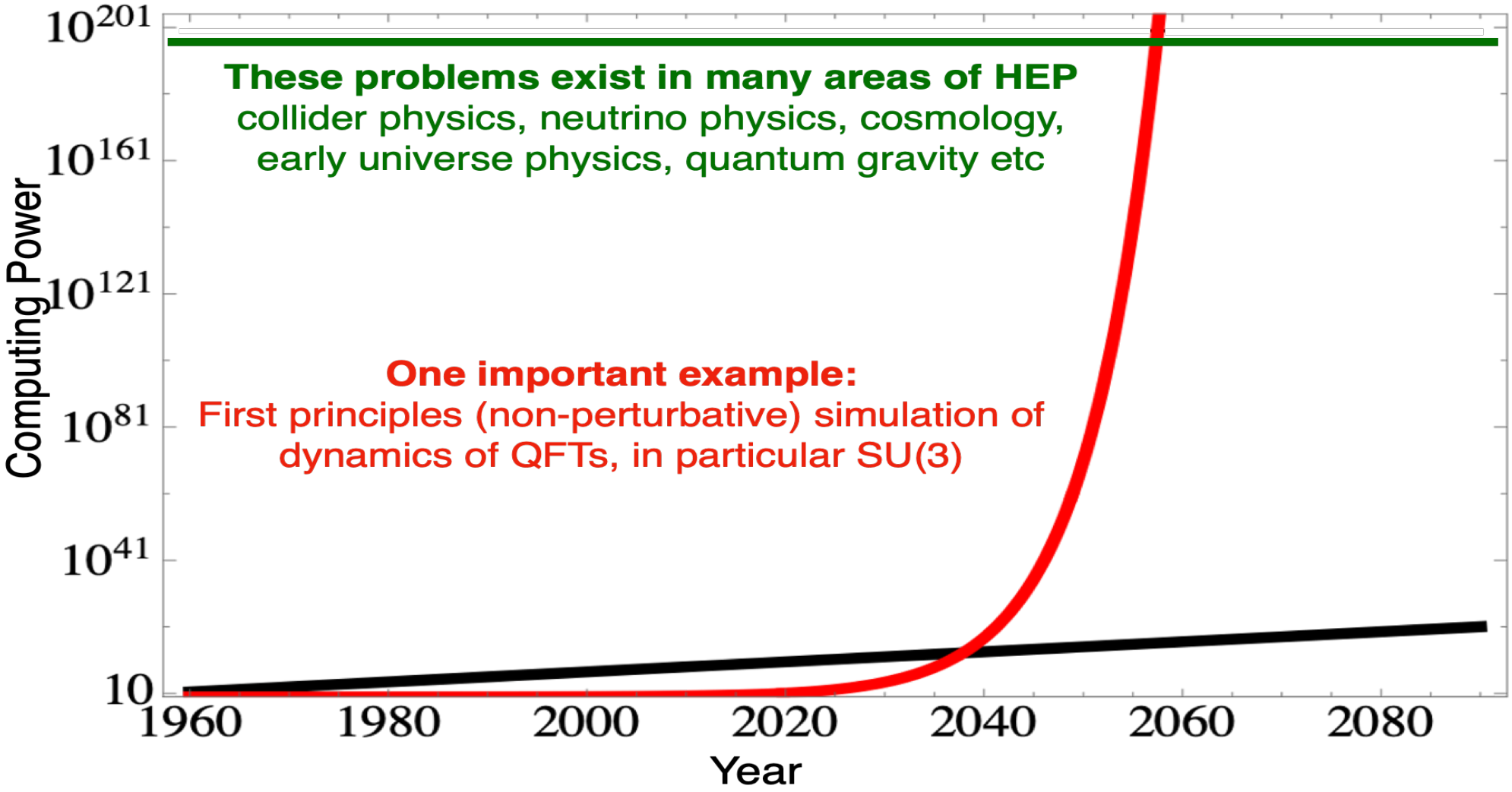
But quantum computers can't solve all problems



Need HEP problems where they shine



Such transformational HEP problems exist



Need to spend the effort to study this in detail to see if / how / when this can become a reality

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HEP on Quantum Machine Learning (QML)

HEP Drivers

- HL-LHC
- DUNE
- Cosmology

ML success on HEP

- Surrogate Models
- Data Analytics (reconstruction, classification, anomaly detection, …)
- Data Compression

ML Challenges

- High Volume
- High Velocity
- Sparse Data

Quantum Machine Learning

- Potential Quantum Advantage
- Exponential / quadratic speed-ups

HEP on Quantum Machine Learning (QML)

QML Limitations & Challenges

- Large qubit simulation slow
- QC Hardware
  - Limited qubit
  - Noises
  - Short qubit coherence time
  - Limited access time
  - Long queue
  - Long execution time (initialization and measurement)
- IO (input / output)

QML Opportunities

- Better simulation SWs
- Bright roadmaps (IBM, IonQ, Google, etc)
  - 1000 qubits (2023, 2028, 2029)
- Quantum-classical hybrid
  - 10^5 qubit to 10^3 qubit
- Quantum Sensing / Network

Challenges and opportunities in quantum machine learning for high-energy physics

Sau Lan Wu[1] ✉ and Shinjae Yoo[2]