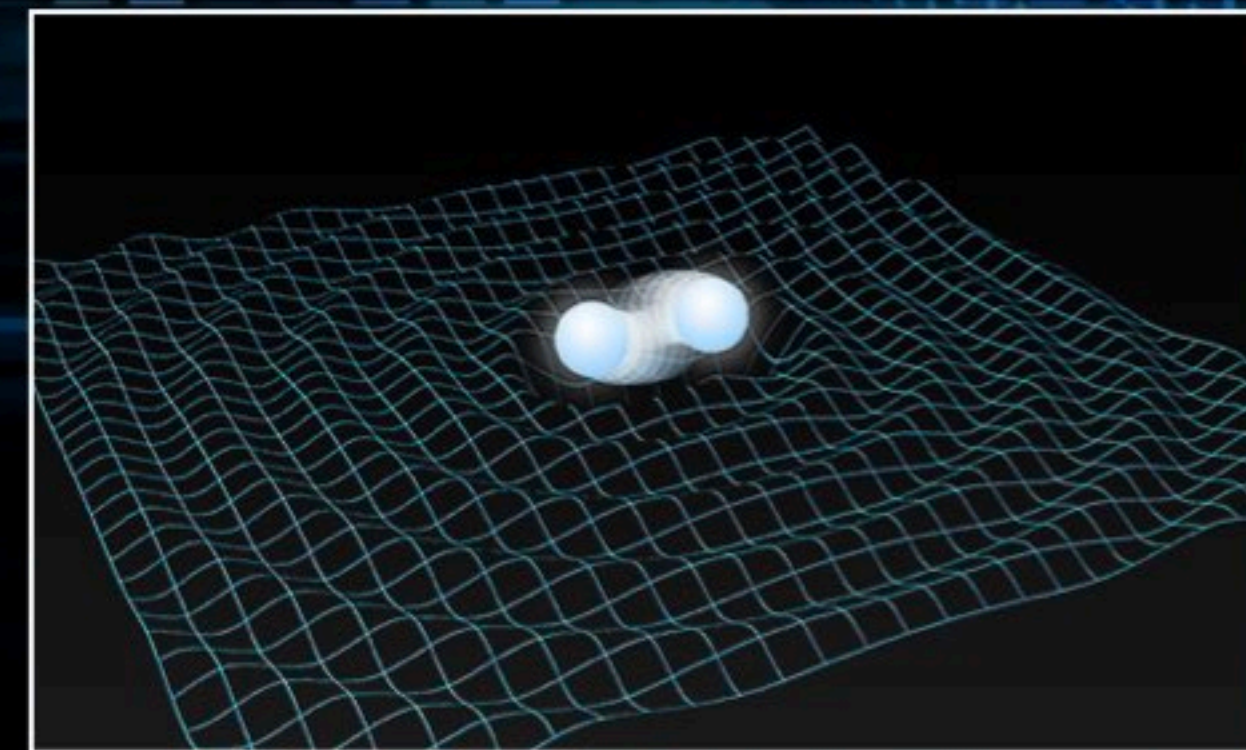



Physics Frontiers with Quantum Science and Technology





Short Summary







Thank you all for joining the workshop and discussion!



9th

- US-Friendly time (8:30-11:10 JST)
Quantum sensor/computer developments and physics applications: 1 
Quantum sensor/computer developments and physics applications: 2 
- Europe-Friendly time (16:00-19:00 JST)
Quantum computer/sensor developments and physics applications: 1 
Quantum computer/sensor developments and physics applications: 2 

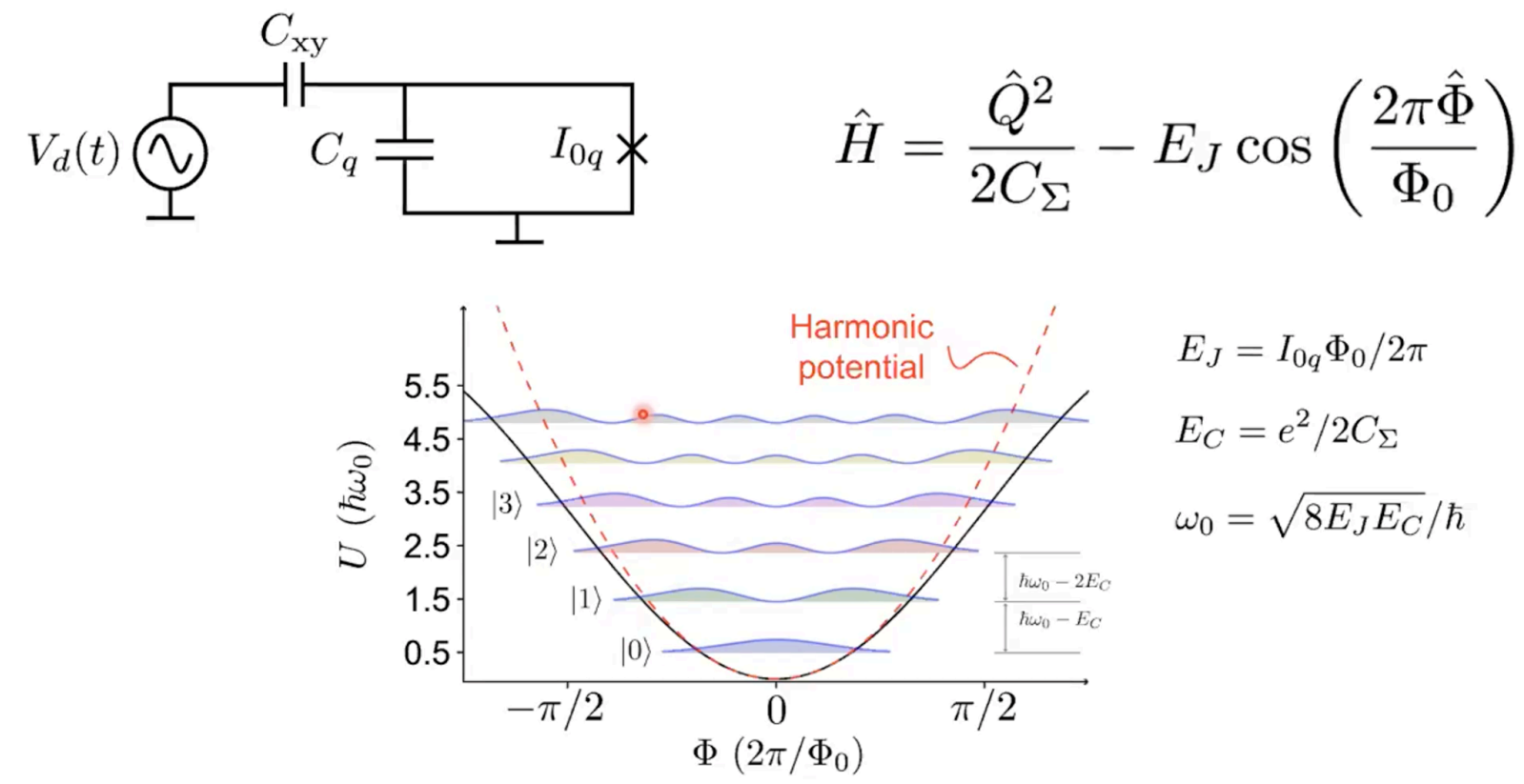
10th

- US-Friendly time (8:00-11:00 JST)
Quantum computer/sensor applications for physics: 1 
Quantum computer/sensor applications for physics: 2 
- Europe-Friendly time (16:00-19:10 JST)
Quantum computer applications for physics: 3 
Quantum-computer applications for physics: 4 

19 excellent talks covering a wide range of topics including

- ▶ quantum computing/sensor technologies and recent developments
- ▶ applications to particle physics, astrophysics, material science, photon science, ..
- ▶ future prospects in quantum technologies

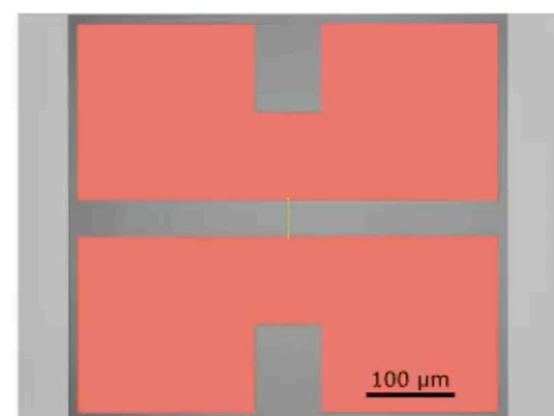
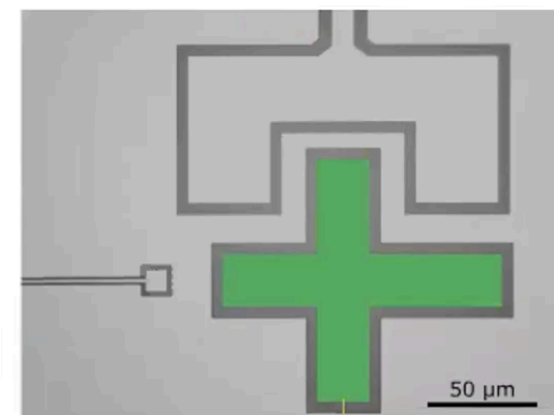
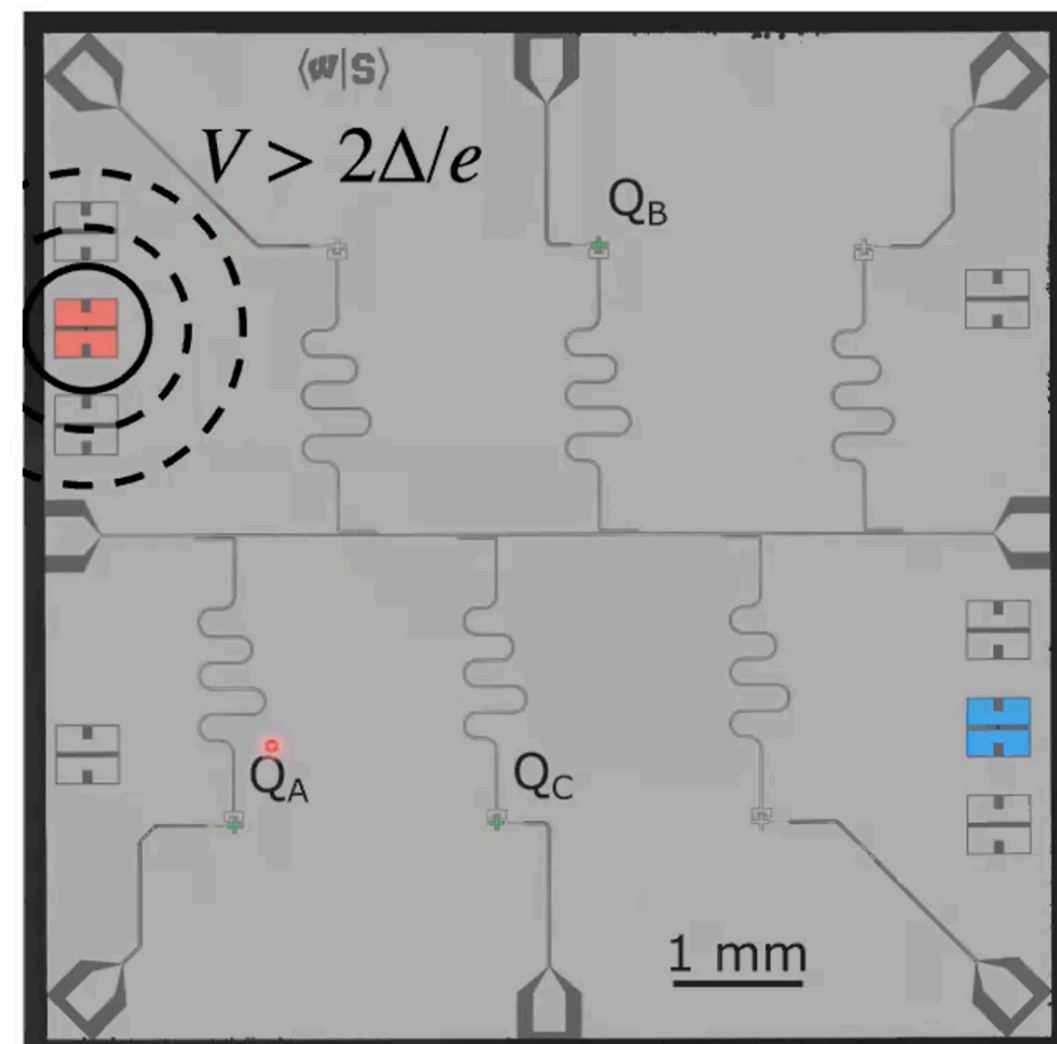
Transmon qubit



Robert McDermott (U. of Wisconsin Madison)

Controlled study of phonon-mediated QP poisoning

(With B. Plourde group, Syracuse U.)



- Nb groundplane, 70 nm
- Al/AlOx/Al JJ, 360 x 150 nm²
- Cavities: 5.9 - 6.5 GHz
- Qubits: 4.9 - 5.1 GHz
- E_J/E_c ~ 30

- Injector JJs: 1 μm x 150 nm
- I_c ~ 100 nA
- No galvanic connection to groundplane

Repeated Quantum Error Correction

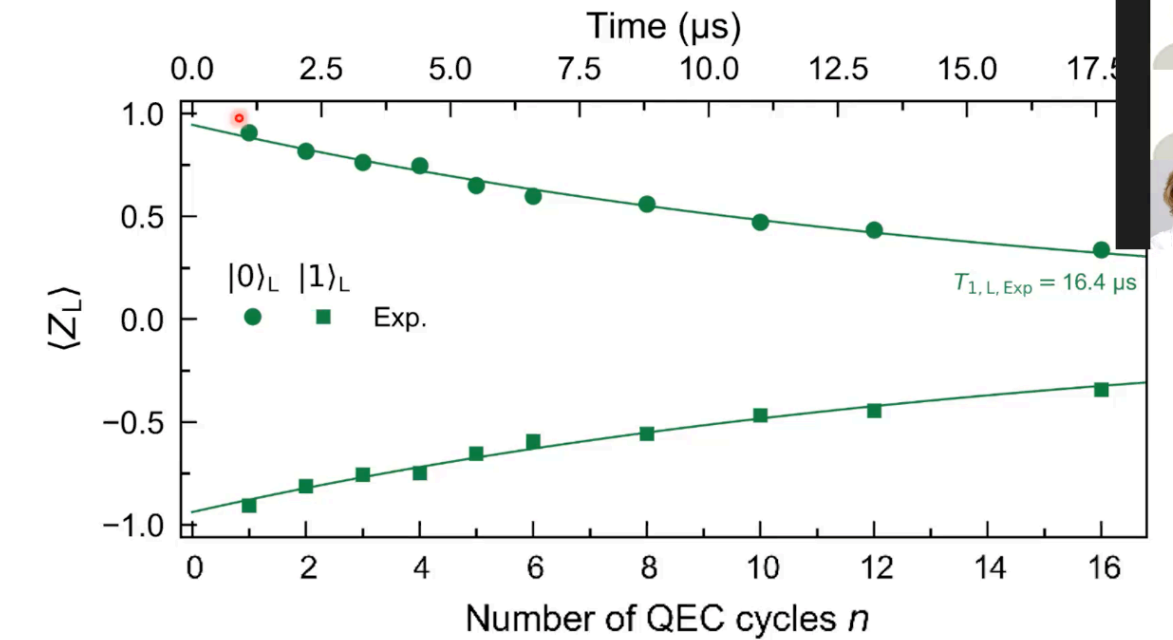
arXiv: 2112.03708 (2021)

Experiment

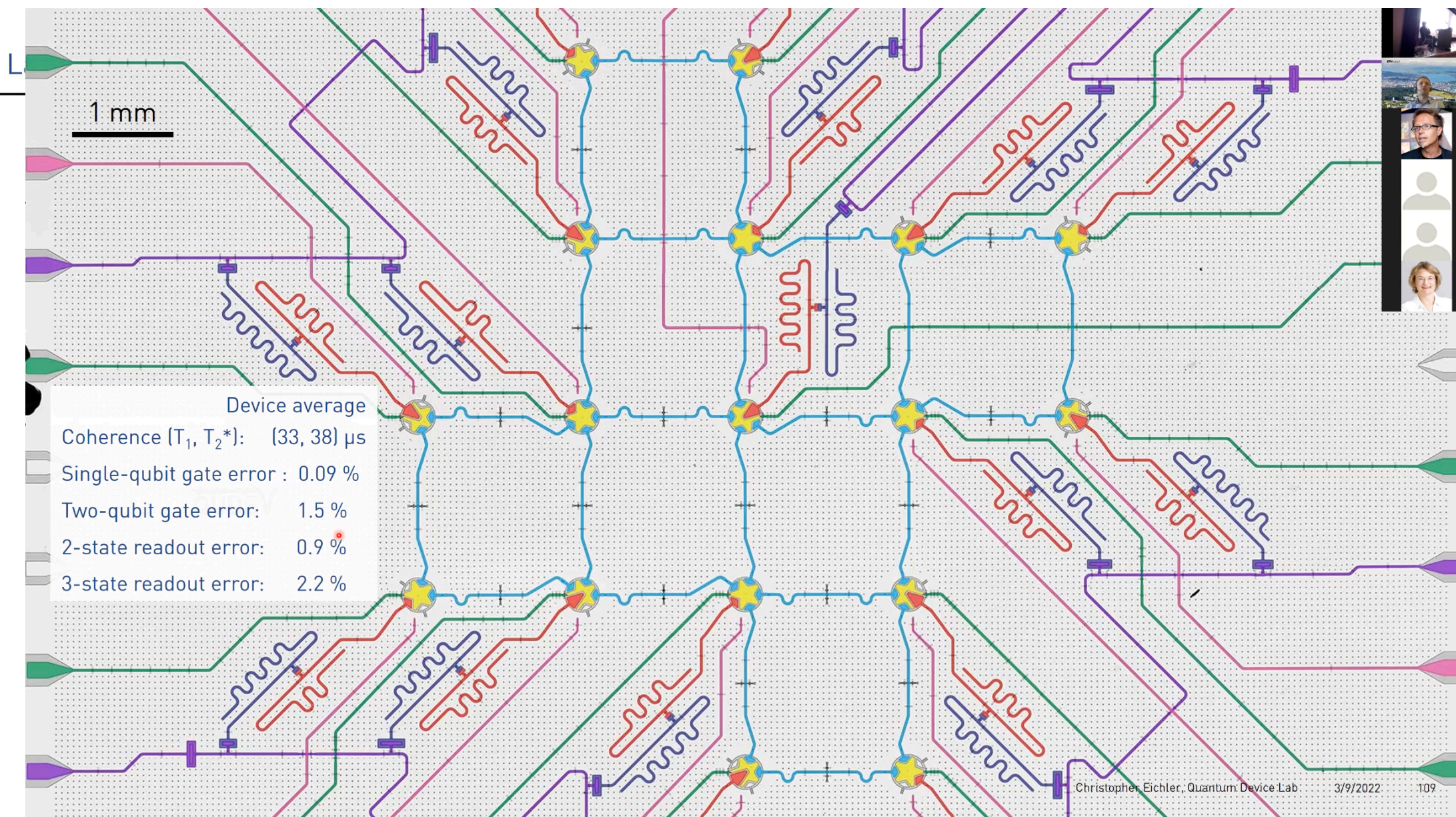
- Initialization
 - $|0\rangle_L$: Initialize data qubits in $|0\rangle^{\otimes 9}$
 - $|1\rangle_L$: Initialize data qubits in $X_L|0\rangle^{\otimes 9}$
- Perform n QEC cycles
- Read out all data qubits in Z-basis

Analysis

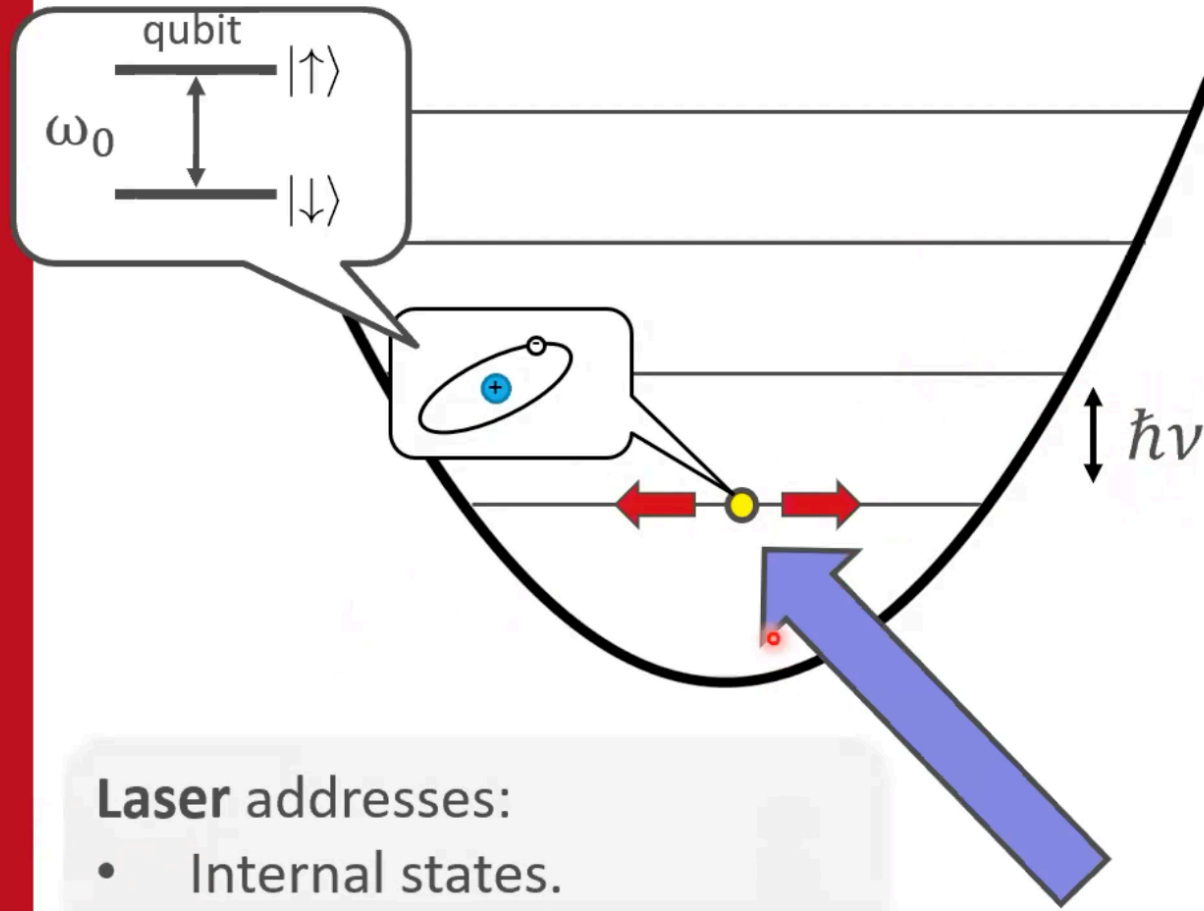
- Determine $z_L = z_1 z_2 z_3 = \pm 1$
- Apply correction based on decoded syndromes
- Average over experimental repetitions to compute $\bar{z}_L = \langle \hat{Z}_L \rangle$
- Exponential fits yields logical lifetime $T_{1,L} = 16.4(8) \mu\text{s} \gg t_c = 1.1 \mu\text{s}$



S. Krinner, N. L.



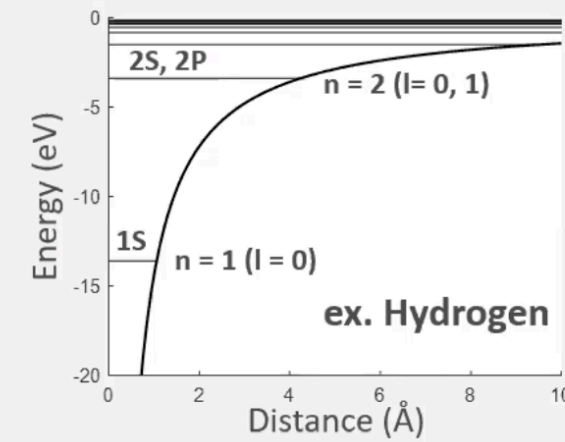
Qubit in a trap



Laser addresses:

- Internal states.
- Motional states (cooling).

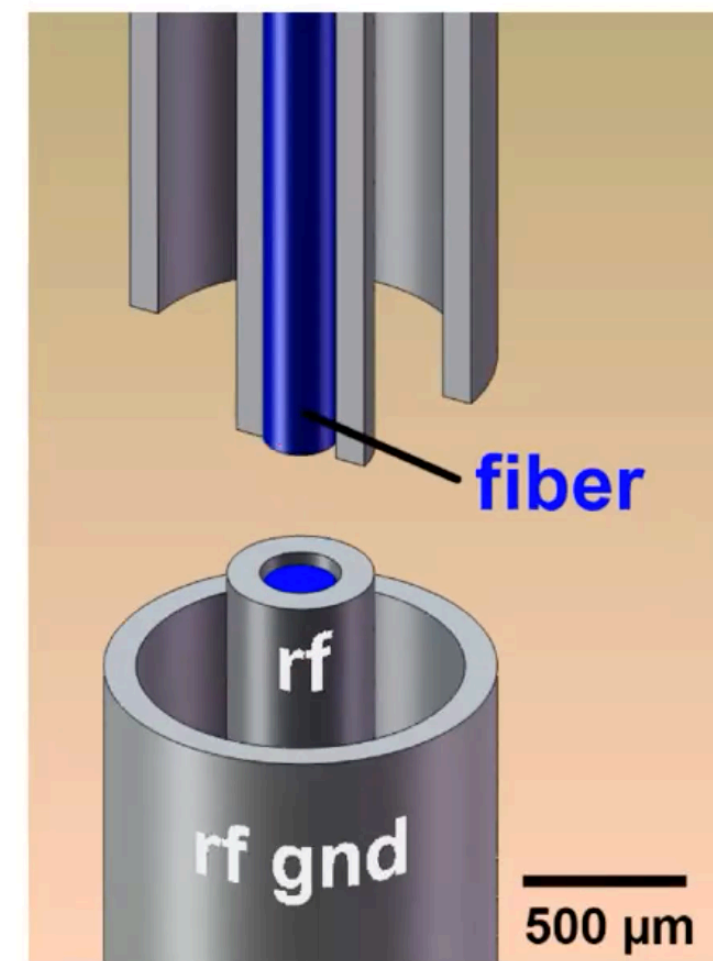
- An ion trapped in **harmonic potential**.
- Quantized energies for **internal states** for **electronic degrees of freedom** (angular momenta, spins).



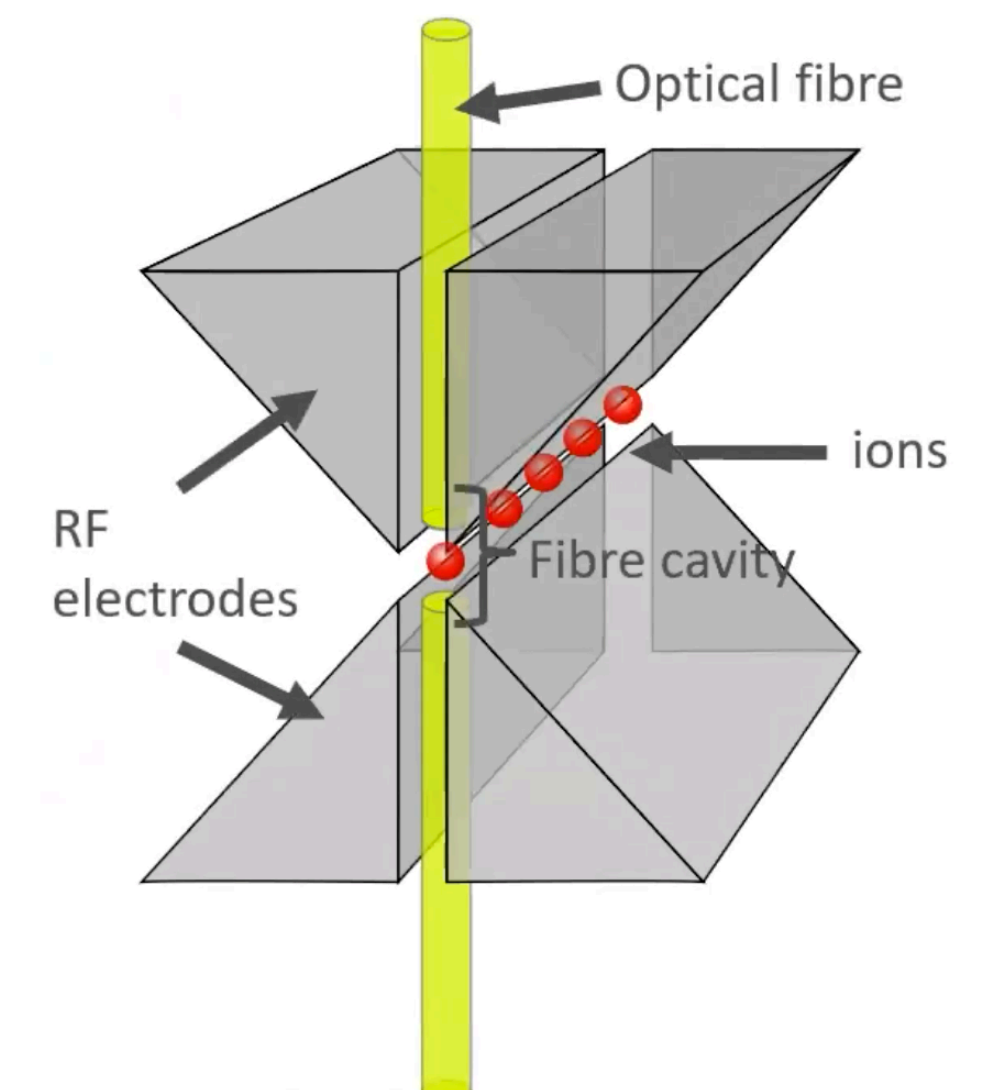
- **Center of mass motion** cooled to a low temperature (<mK) and also quantized.

Hiroki Takahashi (OIST)

Extension to a linear trap



Can only trap a single ion.



- Cavity coupled to an ion in string.
- Fibers shielded by the electrodes.

NV center in diamond

Synthetic (CVD) diamond
[N] < 5 ppb, [NV] < 0.03 ppb

$\rho_c = 1.77 \times 10^{23} \text{ cm}^{-3}$

$D = 2.87 \text{ GHz}$

Joseph Heremans (U. of Chicago)

Argonne NATIONAL LABORATORY

Understanding Materials for Quantum Technology

Motivation: Understanding the critical interplay between materials and solid-state qubits.

Our group is interested in developing rapid progress in QIS by understanding the **increasing complexity** and design considerations tailored to specific quantum application from a materials perspective.

Properties

Spin

Rabi duration

Optical

Engineering

Materials

Applications

Sensing

Computing

Charge

Creation

Design

Optical

Mechanical

Electrical

Magnetic

Communication

G. Wolfowicz*, F. J. Heremans*, C. P. Anderson*, et al.,
Nat Rev Mater (2021). <https://doi.org/10.1038/s41578-021-00306-y>

Quantum sensing of nuclear spins

Science 339, 561 (2013)

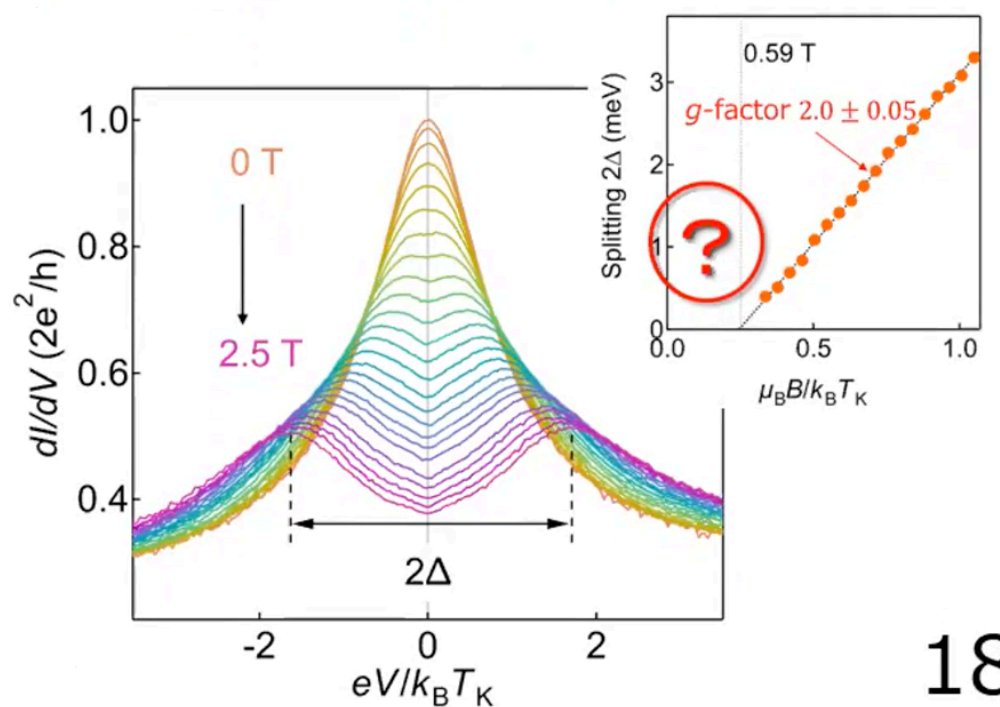
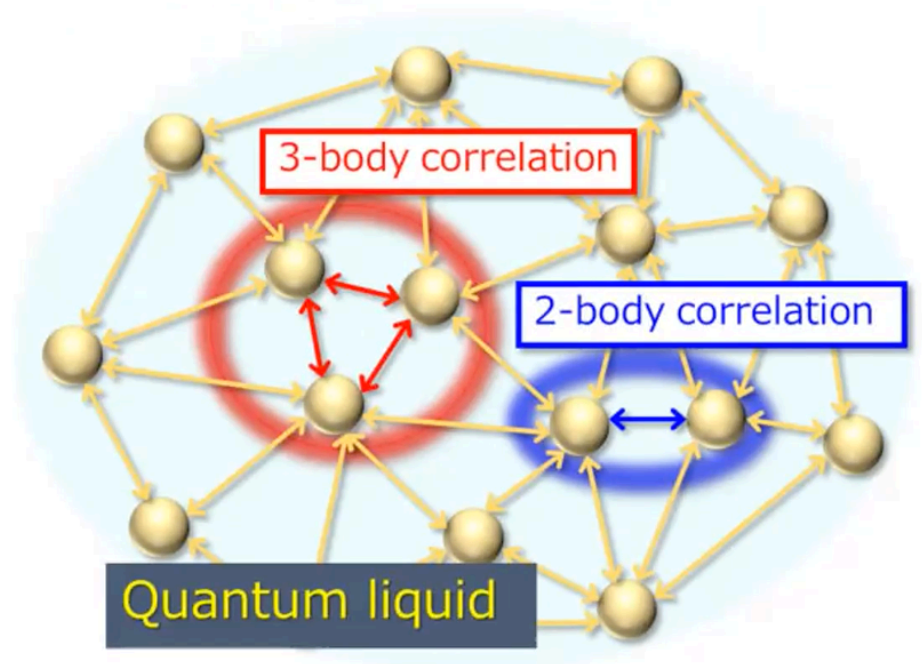
Nature Commun. 6, 8527 (2015)

Nuclear spins **precess** at $f_{ac} =$ a few kHz–MHz under B_0

- ➡ **Weak AC magnetic field** on the NV spin
- ➡ Detect using **quantum coherence** of the NV spin

Short summary Hata et al., Nature Comm. 12, 3233 (2021).

- First detection of 3-body correlations in quantum liquids
- Solved 20-years mystery of Kondo splitting
- Step toward more complex quantum many-body systems in non-eq. regime



18/

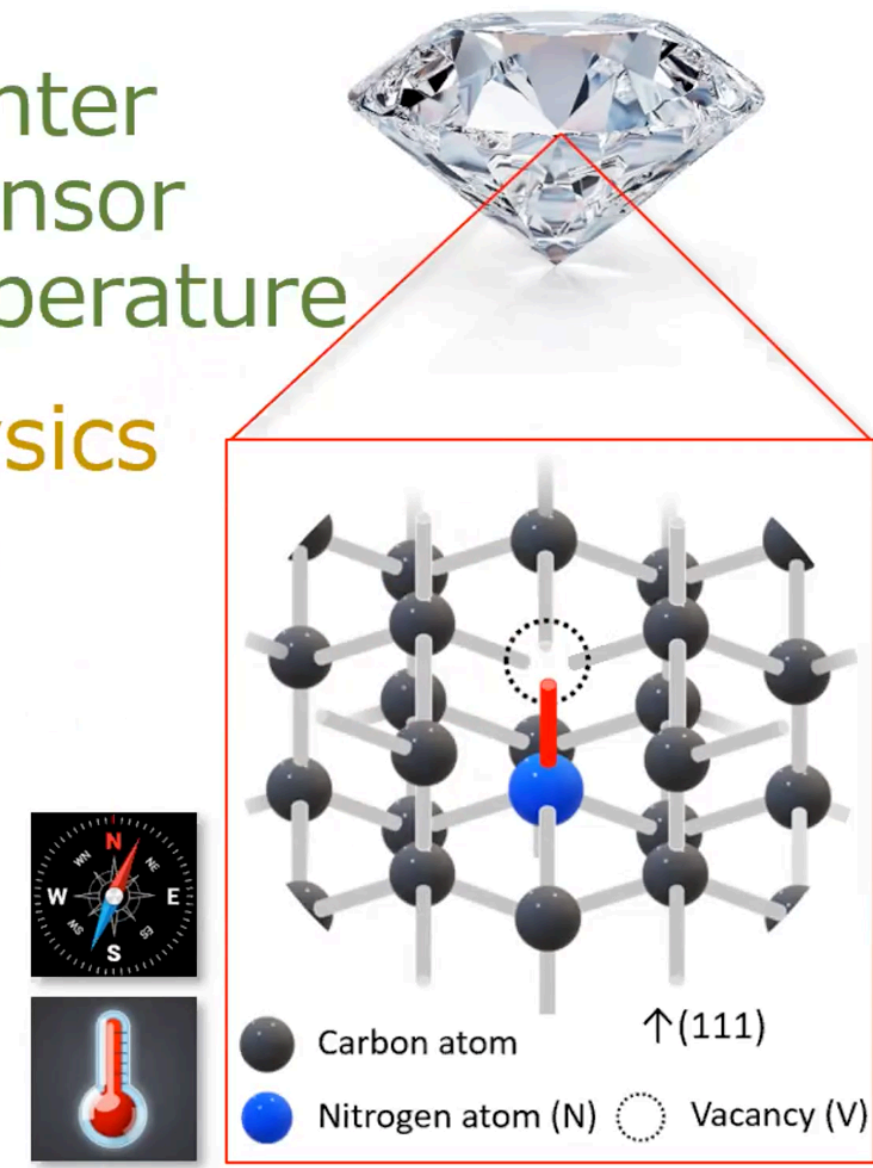
Diamond quantum sensor

NV (nitrogen-vacancy) center = Atomic size sensitive sensor for magnetic field* & temperature

New tool for meso. physics

- Non-eq.: heat & spin current
- Nano-magnetism
- Topological edge states
- Phase transitions
- Superconducting vortex ...

At the atomic level in real time



*Proposal: Maze et al., Nature 455, 644 (2008); Degen, Appl. Phys. Lett. 92, 243111 (2008); Taylor et al., Nature Phys. 4, 810 (2008); Balasubramanian et al., Nature 455, 648 (2008).

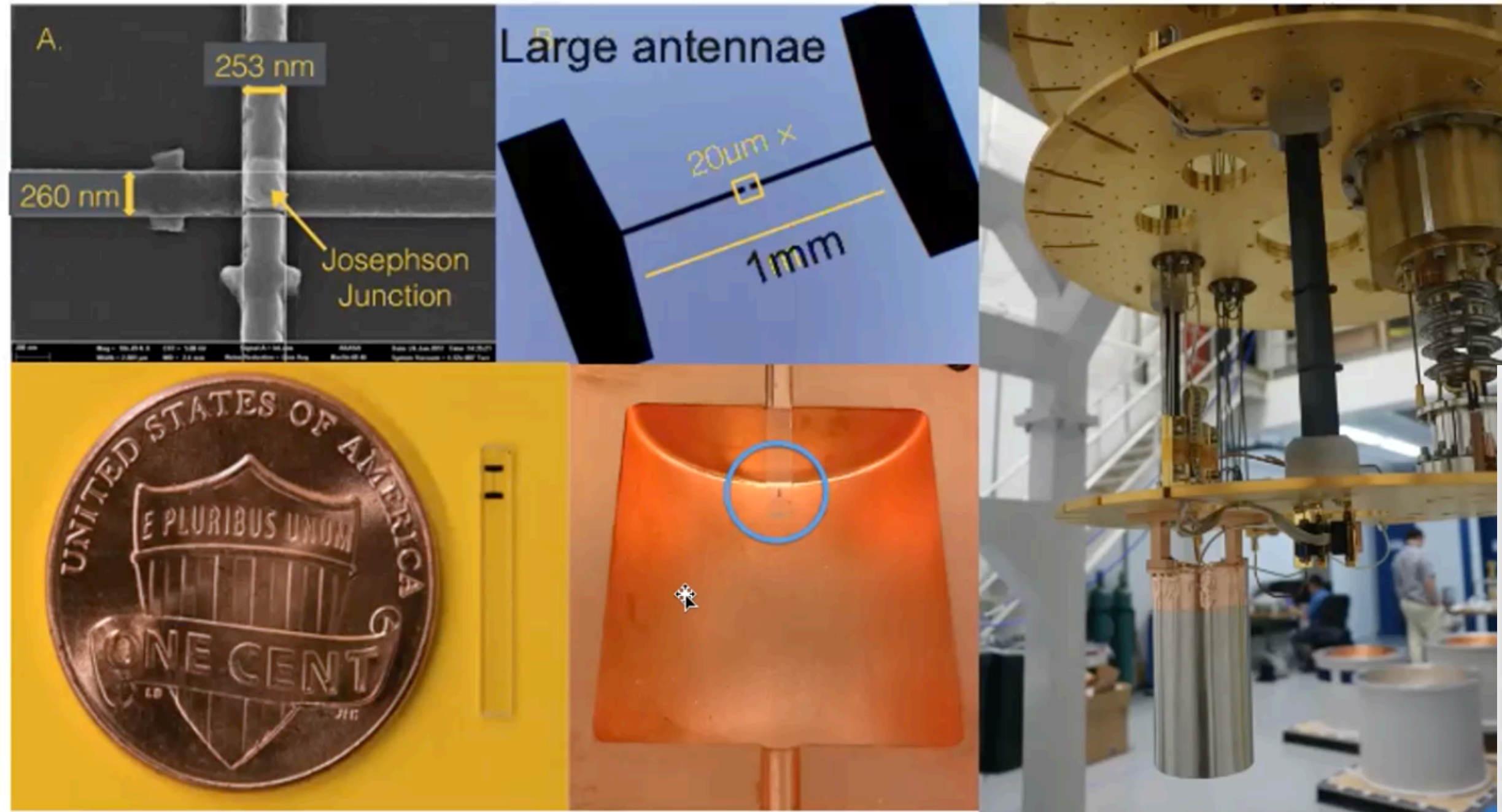


Use artificial atoms made of superconducting “transmon” qubits to nondestructively sense photons

A.S. Chou, Dave Schuster, Akash Dixit, Ankur Agrawal, ...

$$H \approx \hbar\omega_r a^\dagger a + \frac{\hbar}{2}(\omega'_a + 2\chi a^\dagger a)\sigma_z$$

Funded by



DOE QuantISED

Fermilab LDRD

The electric field of individual photons exercises the nonlinear inductance of the Josephson junction. **Photon number is transduced into frequency shifts of the $|g\rangle \rightarrow |e\rangle$ transition.** Same as Lamb shift, but for finite photon number.

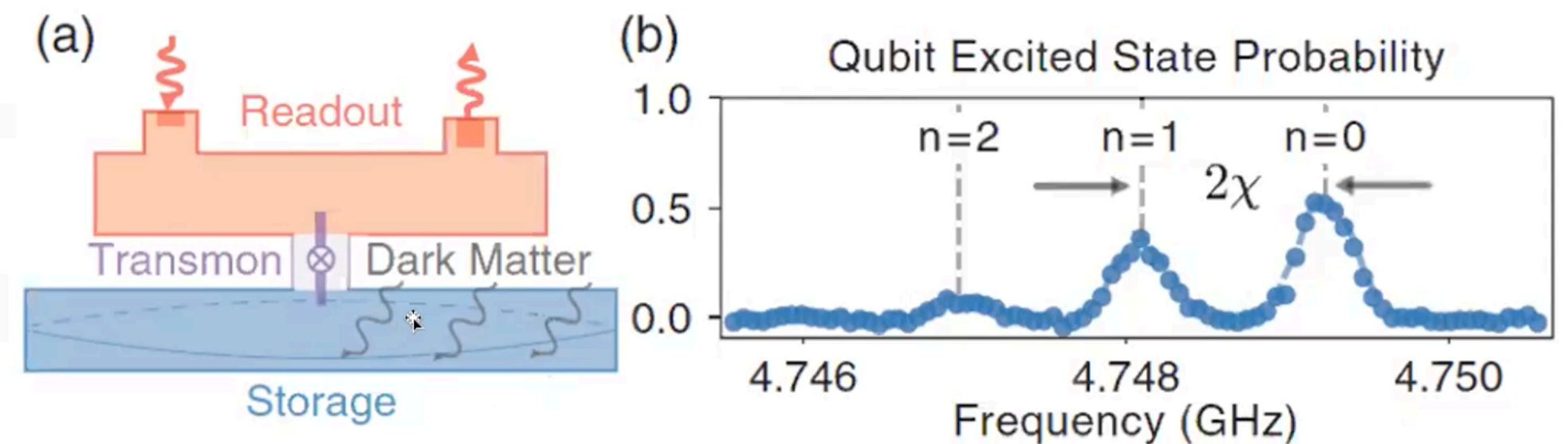
Aaron S. Chou, [U.Tokyo workshop](#), March 9, 2022

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Aaron Chou (Fermilab)

Single photon resolution:

Measure qubit $|g\rangle \rightarrow |e\rangle$ transition frequencies after weakly driving the primary cavity mode into a Glauber coherent state with $\langle n \rangle = 1$



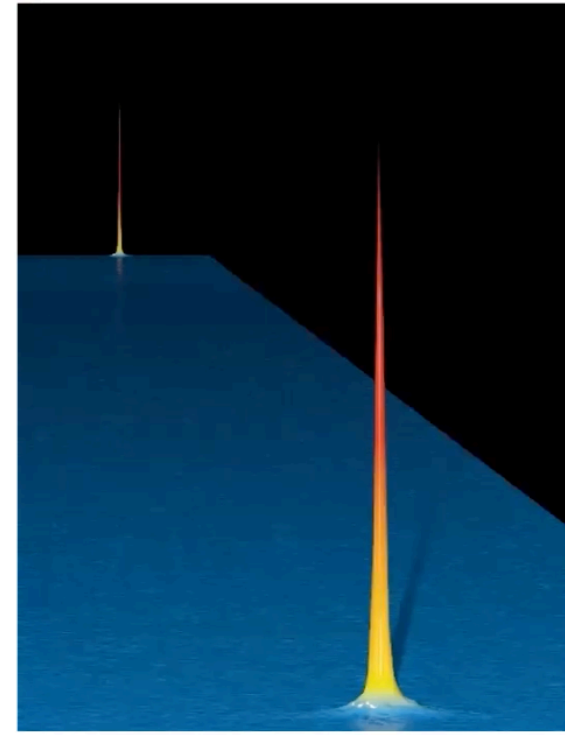
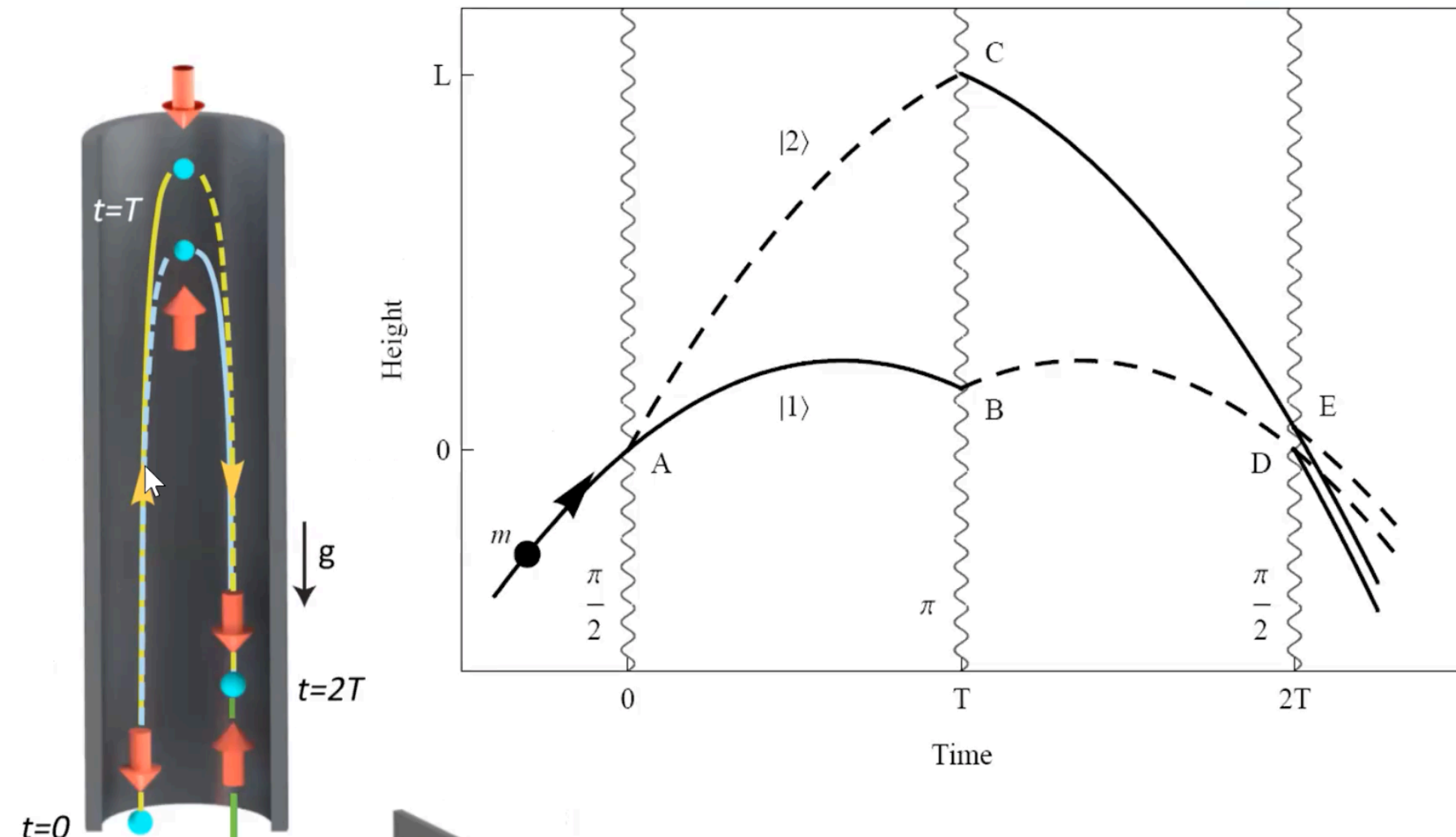
The measured qubit spectrum exhibits a distribution of resonances which are in 1-1 correspondence with the Poisson distribution of the cavity's coherent state.

Non-destructively count photons by measuring the qubit's quantized frequency shift.

Aaron S. Chou, [U.Tokyo workshop](#), March 9, 2022

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Atom interferometry



Rb wavepackets separated by 54 cm

$$\Delta\phi = k_{\text{eff}} g T^2$$

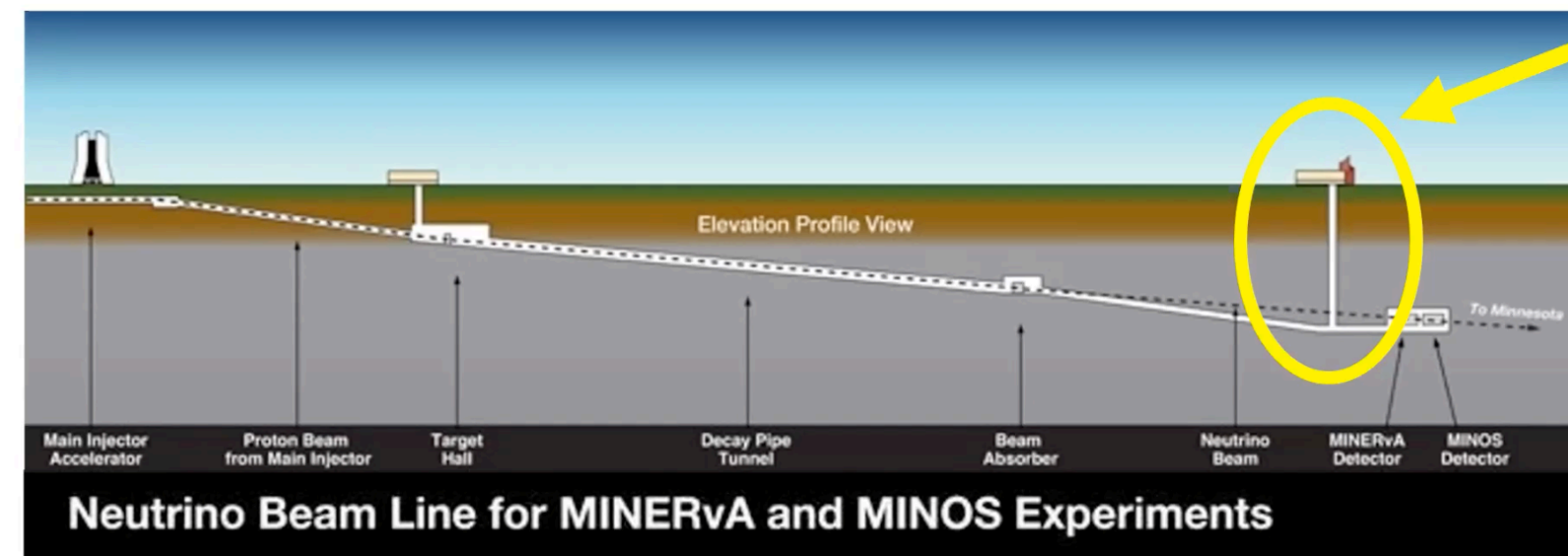
Sensitivity proportional to spacetime area enclosed.

Increase sensitivity using large momentum transfer (LMT) atom optics

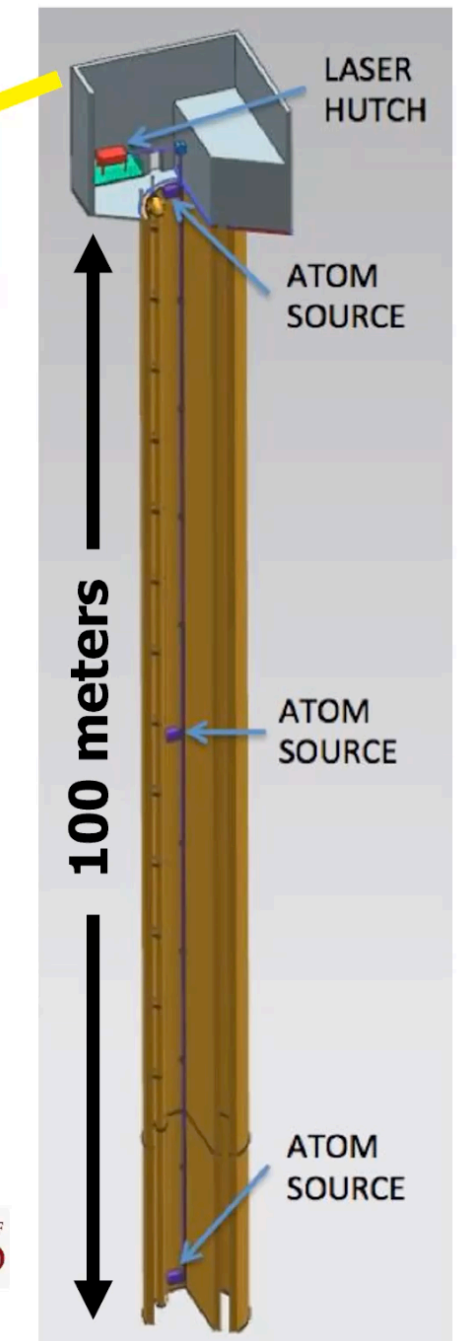
Jason Hogan (Stanford U.)

MAGIS-100: Detector prototype at Fermilab

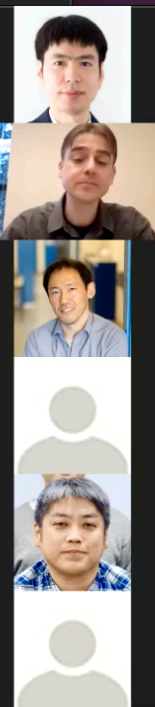
Matter wave Atomic Gradiometer Interferometric Sensor



Neutrino Beam Line for MINERvA and MINOS Experiments



- 100-meter baseline atom interferometry in existing shaft at Fermilab
- Intermediate step to full-scale (km) detector for gravitational waves
- Clock atom sources (Sr) at three positions to realize a gradiometer
- Probes for ultralight scalar dark matter beyond current limits (Hz range)
- Extreme quantum superposition states: >meter wavepacket separation, up to 9 seconds duration



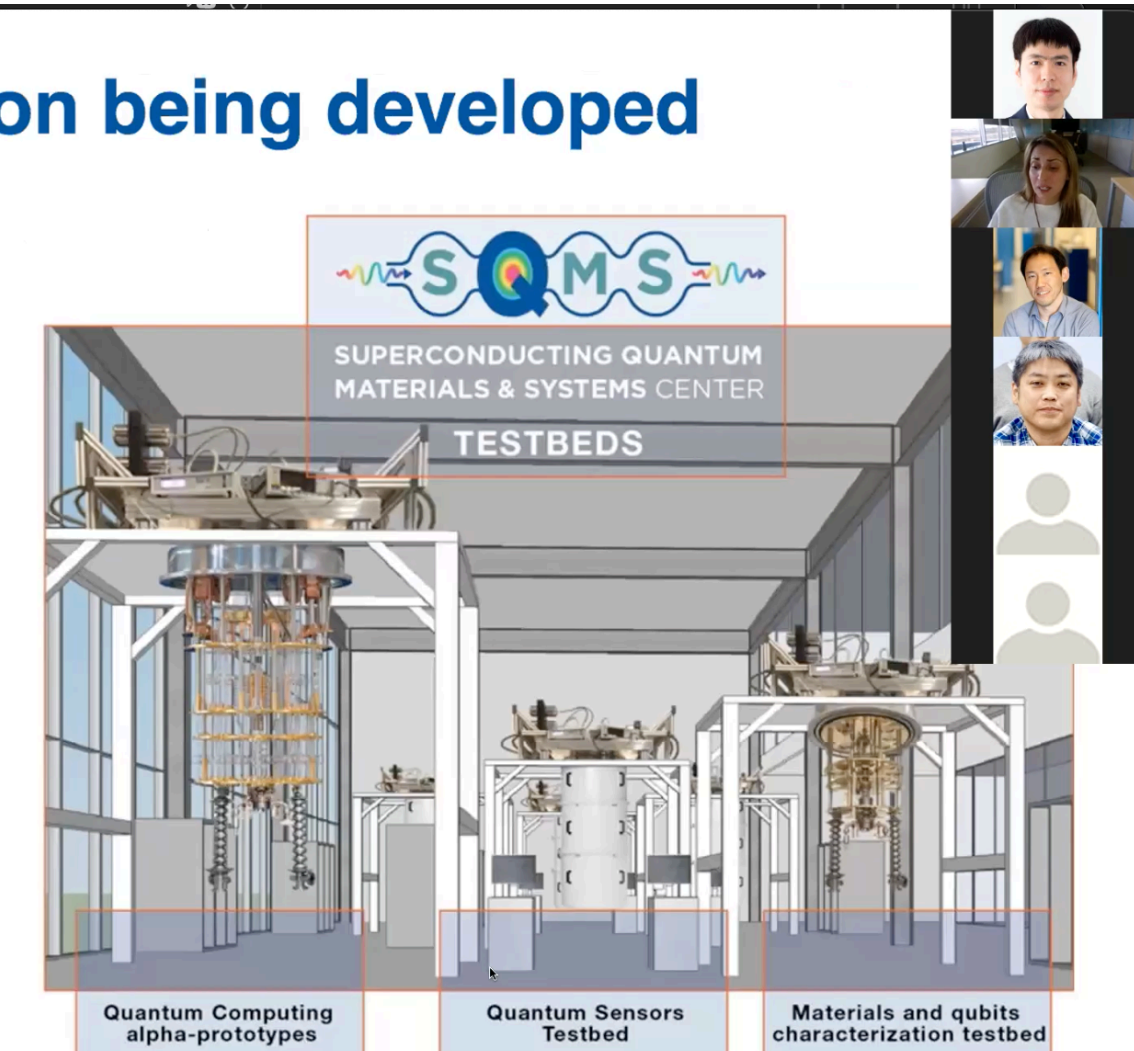


SQMS Mission Statement: "bring together the power of national labs, industry and academia to achieve transformational advances in the major cross-cutting challenge of understanding and eliminating the decoherence mechanisms in superconducting 2D and 3D devices, with the goal of enabling construction and deployment of superior quantum systems for computing and sensing."

SQMS new facilities and instrumentation being developed

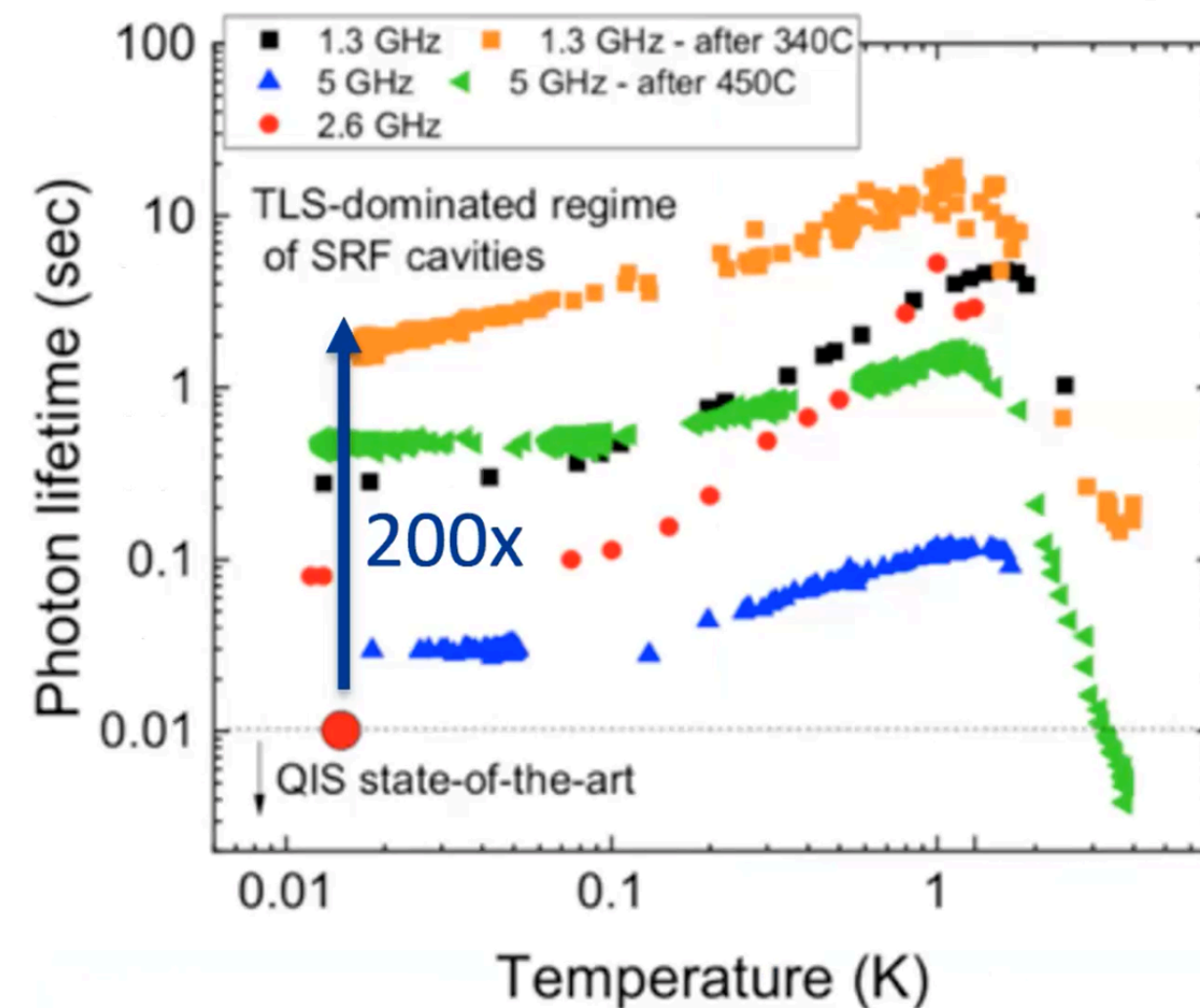
Developing and delivering tangible, unique platforms/instrumentation for QIS fabrication, computing and sensing:

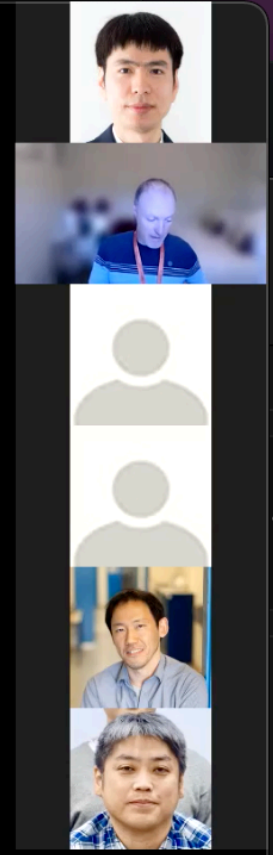
- **Foundries:** New high-flexibility nanofabrication facility at FNAL
- **Materials/Devices testbeds:** Qubits and quantum materials measurements in the most precise and sensitive environments
 - Upgrades to existing characterization facilities to cryogenic environments
 - Novel cavity geometries and configurations
- **Physics Testbeds:** Platforms enabling new particle searches/sensing experiments
 - New cavity shapes and materials for record coherence in high B fields
- **Computing Testbeds:** 2D and 3D-based quantum computer prototypes, including a record sized DR
- **Workforce Development Testbeds:** training platforms



Purchasing, developing, fabricating, commissioning: 8 new dilution fridges, dozens of new cavities, dozens of chips, control electronics and wiring, hundreds of custom device ancillary parts, a world record size DR and a new clean room nanofabrication facility with cluster tools

A. Romanenko et al, Phys. Rev. Applied **13**, 034032, 2020





Formulation of Field Theories suited for simulation on quantum devices

Effective Field Theory treatment to allow quantum simulation of non-perturbative physics

HEP Quantum Computing at LBNL

Development of quantum parton showers

Improving techniques to use NISQ devices for near term simulations

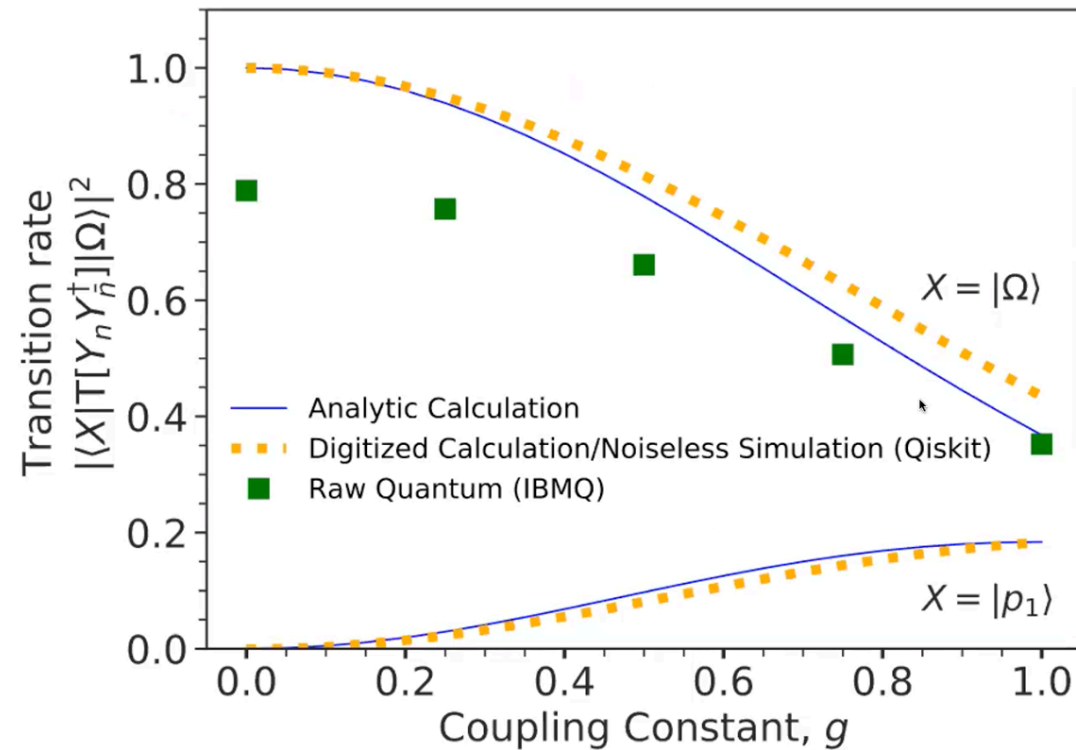


Christian Bauer
QC Applications to HEP Applications



Soft function is the expectation value of a “Wilson line” operator between initial and final state

[CWB, Freytsis, Nachman, PRL 127 \(2021\), 212001](#)



Currently working on implementing of these ideas for U(1) gauge theories



Christian Bauer
QC Applications to HEP Applications

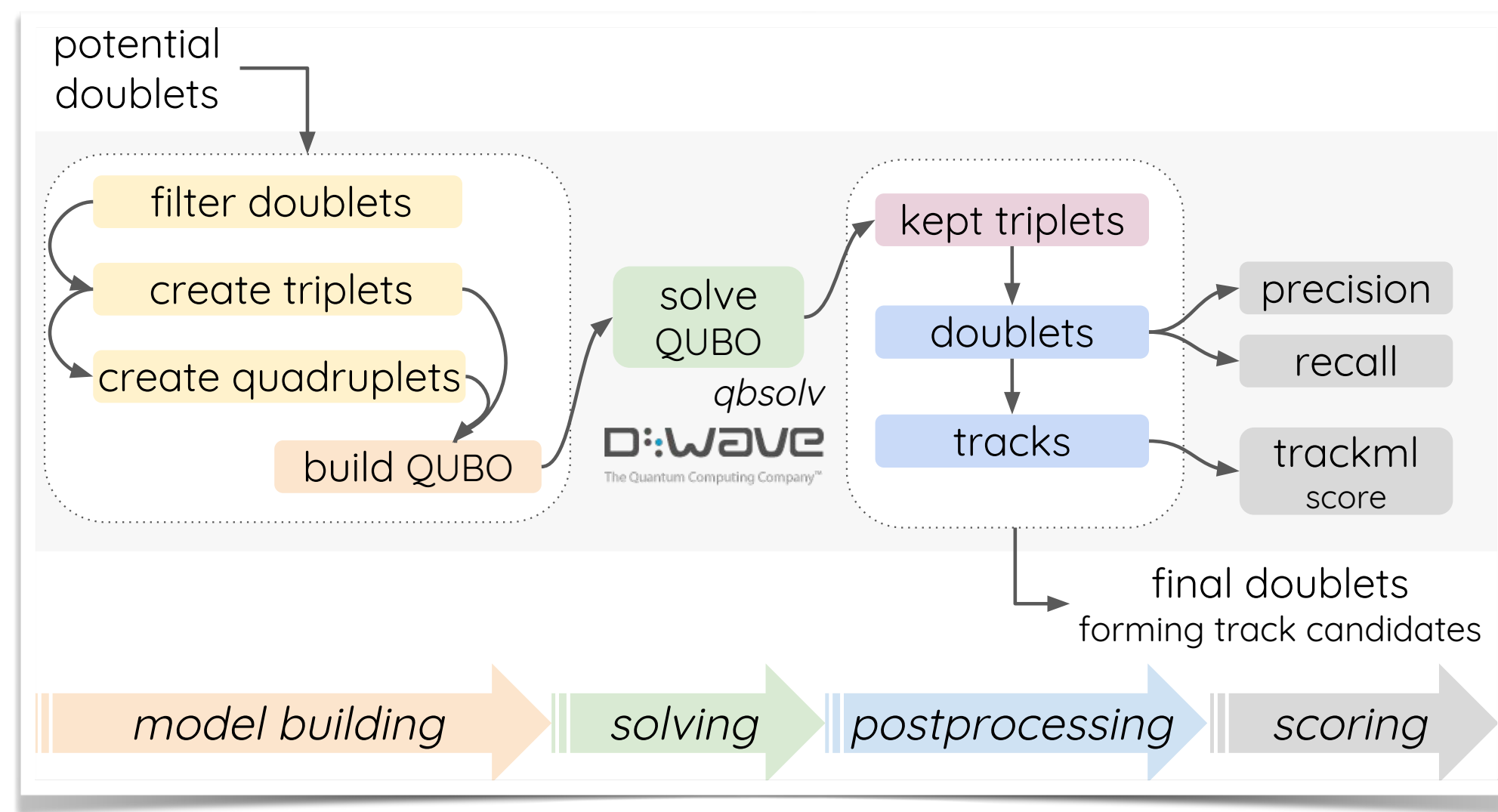


Implementation

- Dataset: simplified TrackML dataset, focus on barrel, 1+ GeV, at least 5 hits
 - Toy dataset, but representative of expected conditions at the HL-LHC
- QUBO solvers: qbsolv (D-Wave + simulation), neal (classical)
- D-Wave 2X (1152 qubits), D-Wave 2000Q (2048 qubits)

17
arXiv:1902.08324

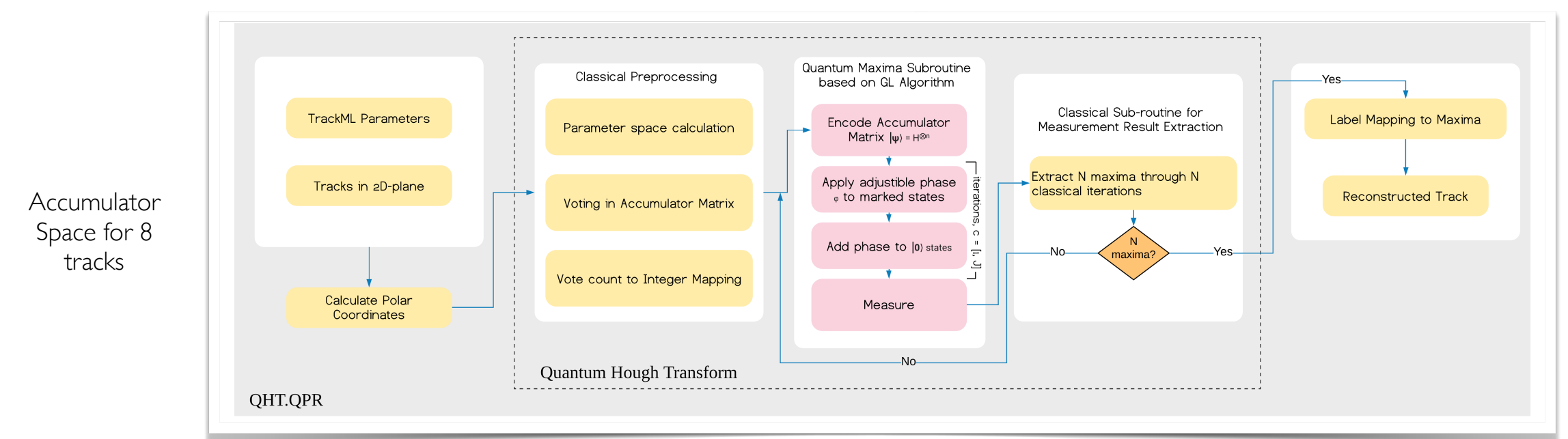
Heather Gray (UC Berkeley/LBNL)



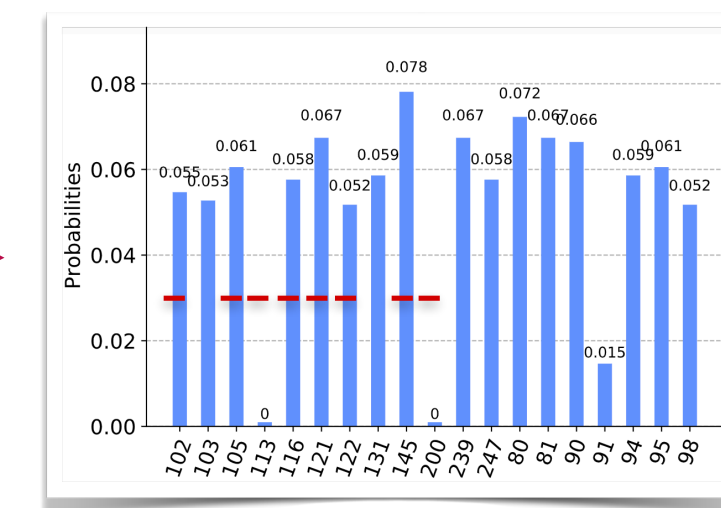
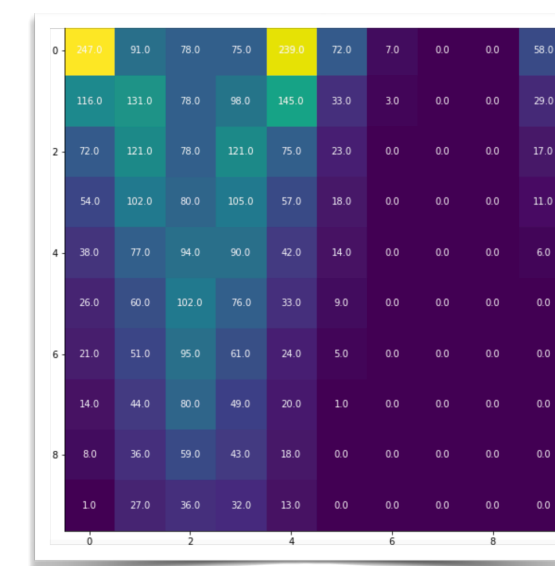
Implementation & Preliminary Results

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Preliminary implementation within QISKit



Testing within a quantum simulator



vote counts

Local Maxima Detection using Grover-Long Algorithm

```

track_index
array([array([13, 19, 22, 28, 35, 48, 52]),
       array([ 2,  5, 16, 36, 40, 69]),
       array([23, 29, 30, 32, 43, 53, 54]),
       array([17, 18, 23, 30, 33, 39, 45, 50]),
       array([17, 18, 23, 29, 30, 33, 39, 50]),
       array([ 0,  9, 14, 34, 38, 42]), array([ 1, 11, 12, 20, 24, 27]),
       array([ 7,  8, 15, 37, 46, 57]), array([17, 23, 28, 30, 32, 54]),
       array([17, 29, 32, 43, 53, 54]), dtype=object)
    
```

Chen et al, arXiv:1908.07943

Slide Credit: A.Yadav

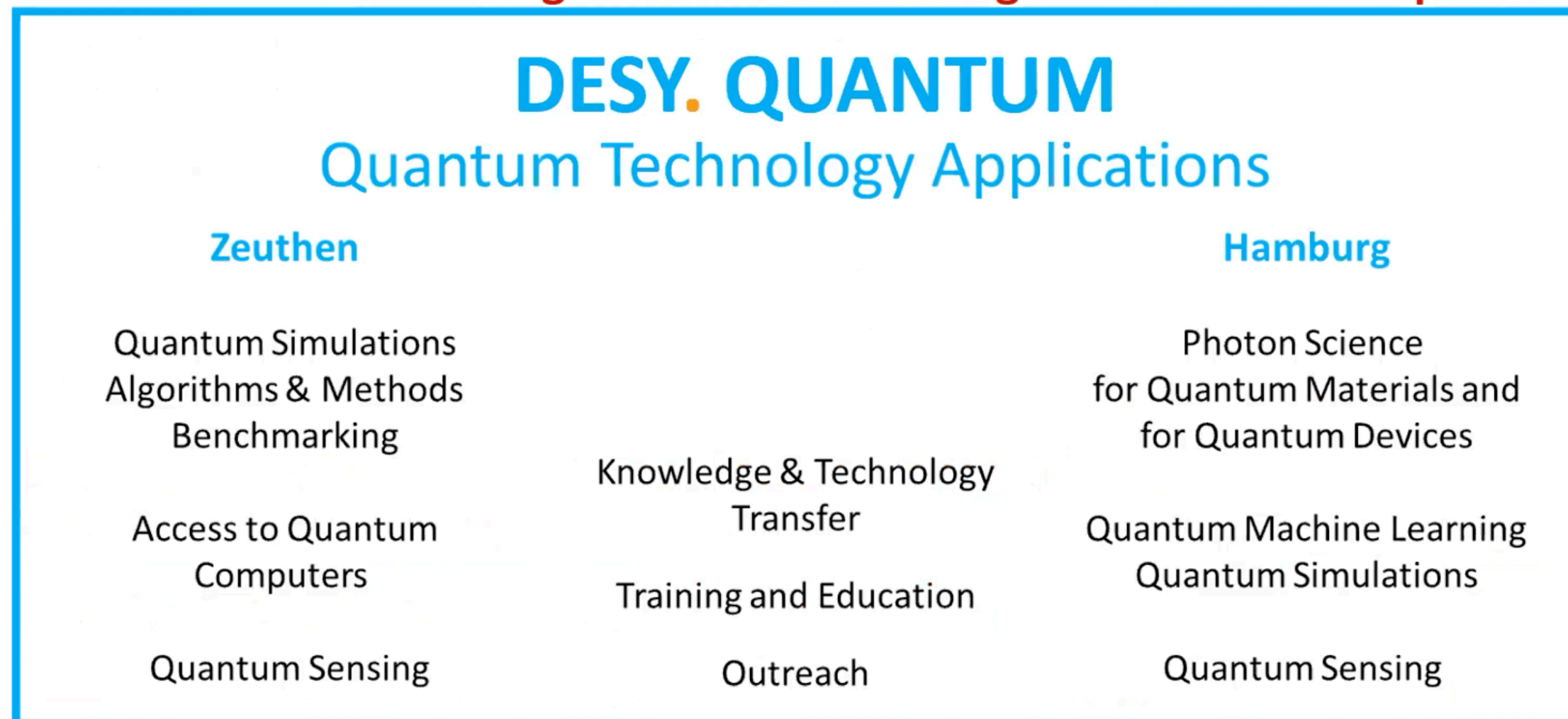
Kerstin Borrás

(DESY/ RWTH Aachen University)

Quantum Technologies at DESY

Overview

Overarching Goal: employ novel Quantum Technologies to enhance and enable cutting-edge science in all divisions
 → DESY wide organization connecting inside and to Campus Partners



Michael Doser (CERN)

Quantum sensors for low energy particle physics

quantum sensors & particle physics: what are we talking about?

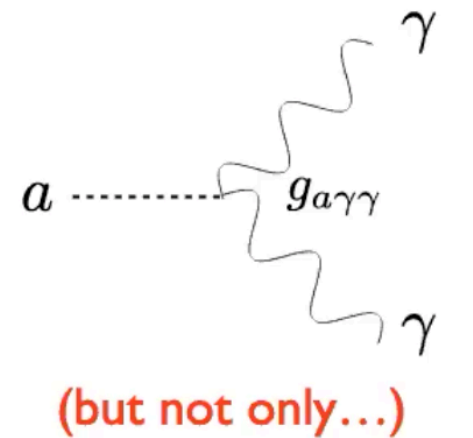
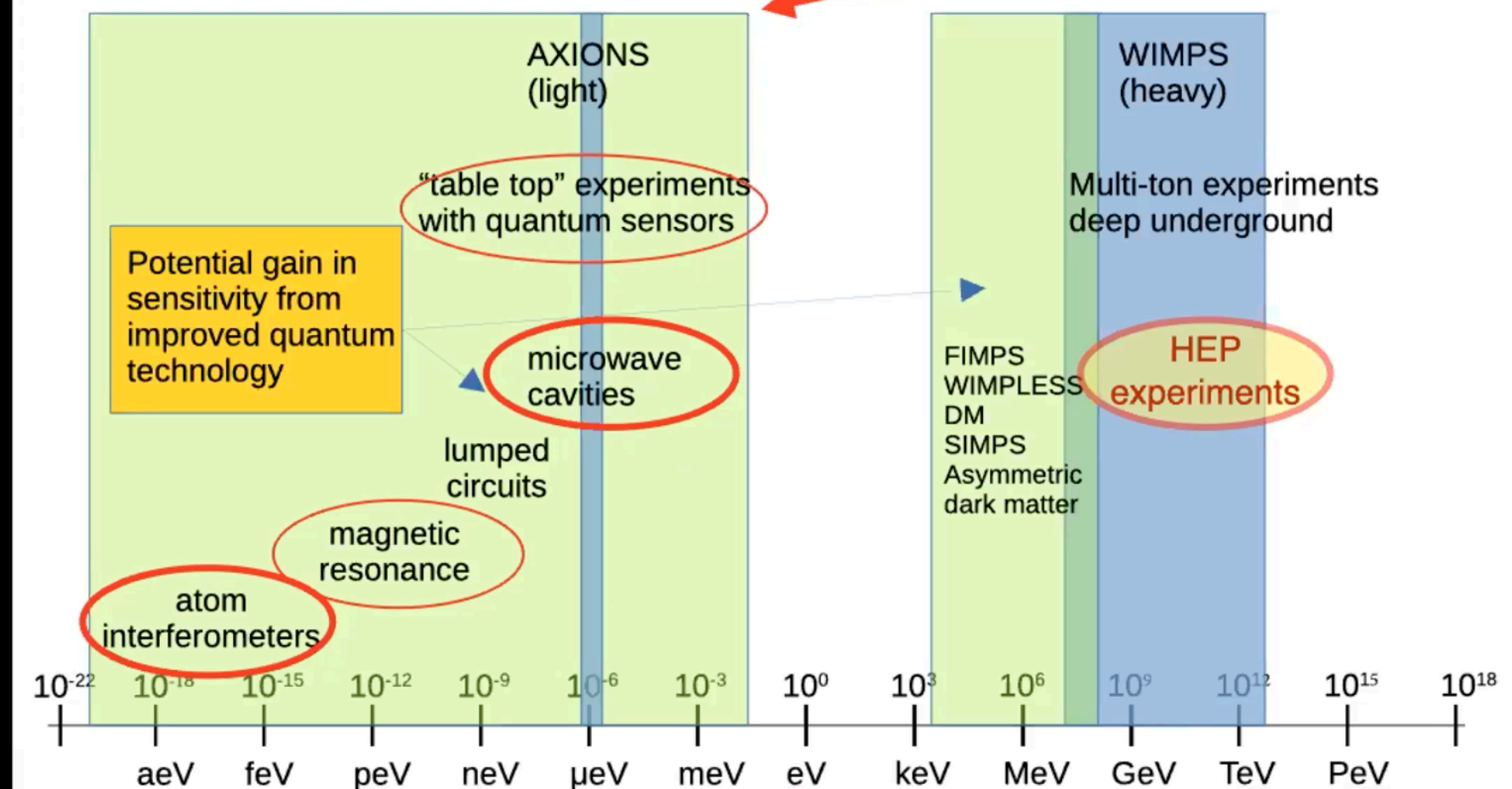
Axions, ALP's, DM & non-DM UL-particle searches



cavity size = axion size
axion mass = unknown

$$F \sim g_{a\gamma}^2 m_A^2 B^4 V^2 T_{sys}^{-2} G^4 Q$$

system noise temperature
cryo-amplifiers JJPA



Extreme Universe of spacetime and matter from quantum information
Tadashi Takayanagi (Kyoto U.)

Quantum simulation and theory for high-energy physics at CERN
Dorota Maria Grabowska (CERN)

Quantum machine learning and algorithm development
Kousuke Mitarai (Osaka University)

Quantum computing applications to high-energy physics at CERN
Sofia Vallecorsa (CERN)

Quantum computing developments and future prospects at IBM
Tamiya Onodera (IBM Research, Tokyo)

Next Steps...

Propose to **continue this workshop in a regular basis (e.g, annually)**

- ▶ **Focused workshops/meetings on selected topics** (e.g, hardware, applications, algorithms) can be foreseen
- ▶ Appreciated if you have any suggestion for future planning
- ▶ Stay in touch for **continuing discussion and future collaboration!!**

