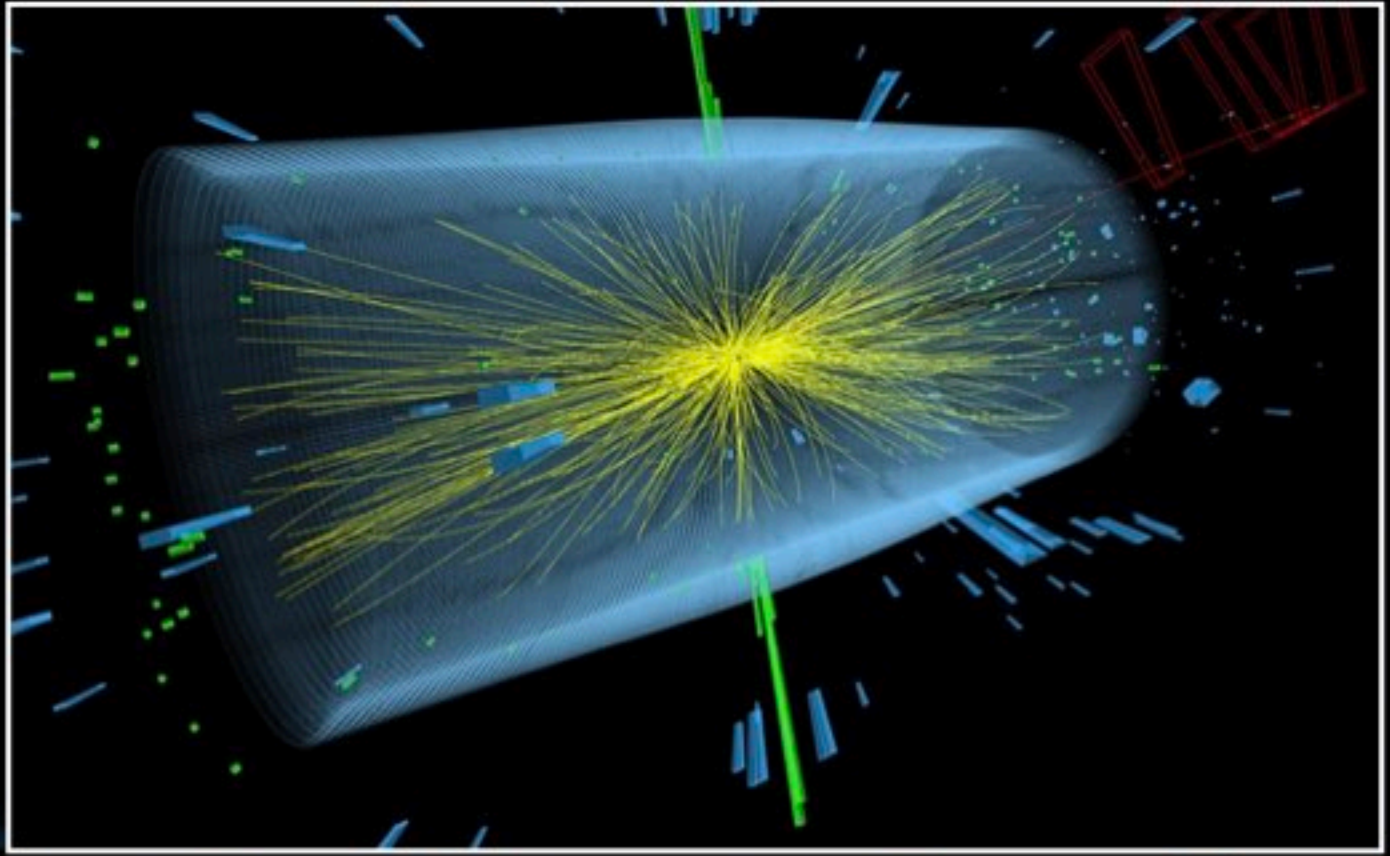
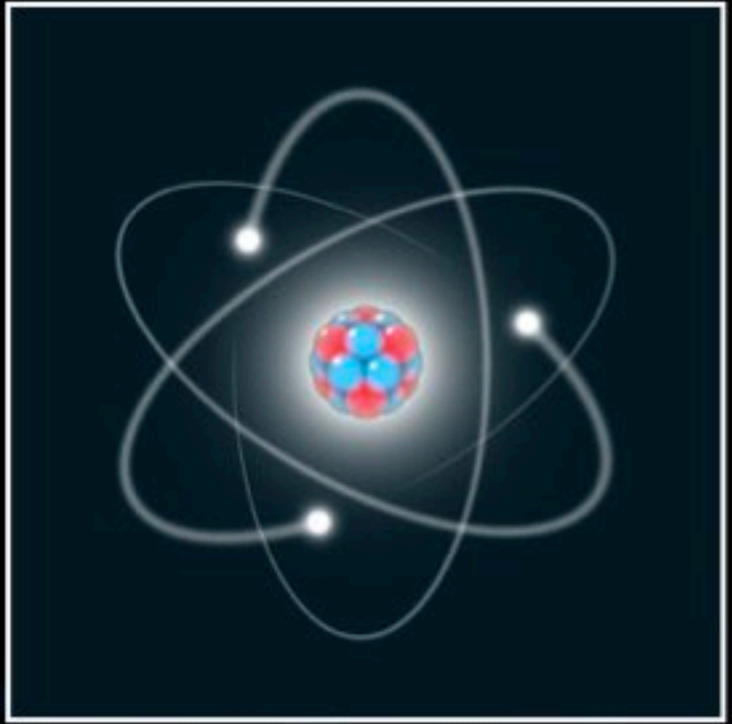
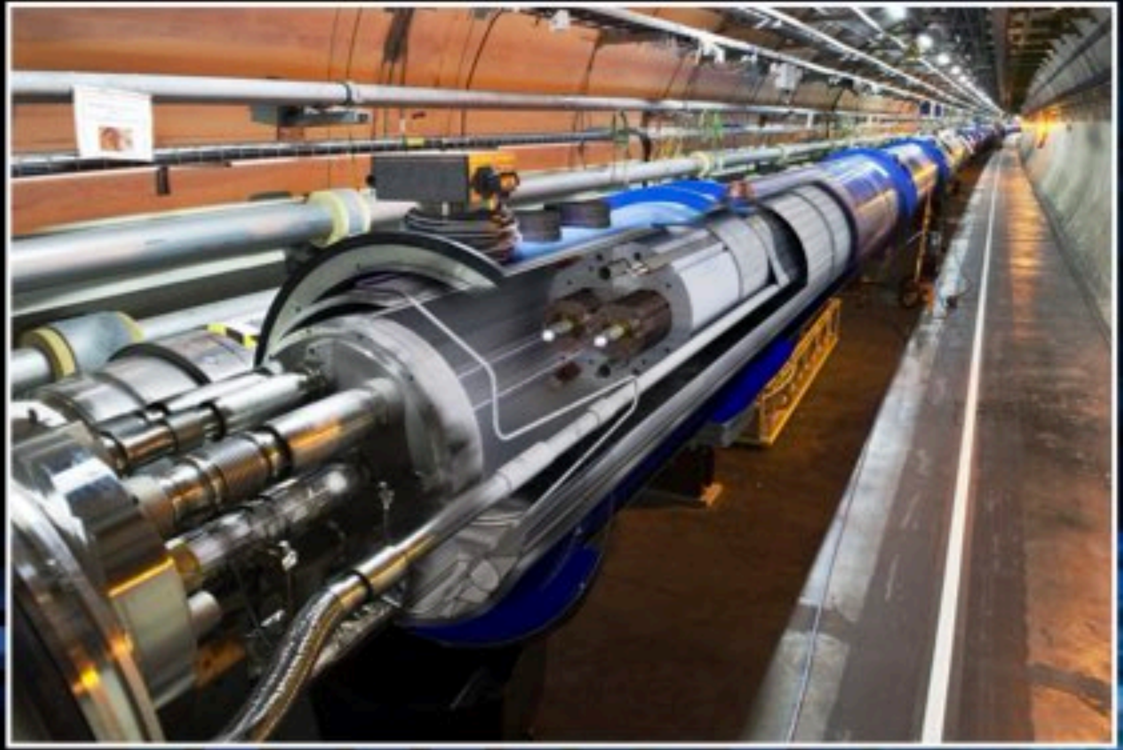
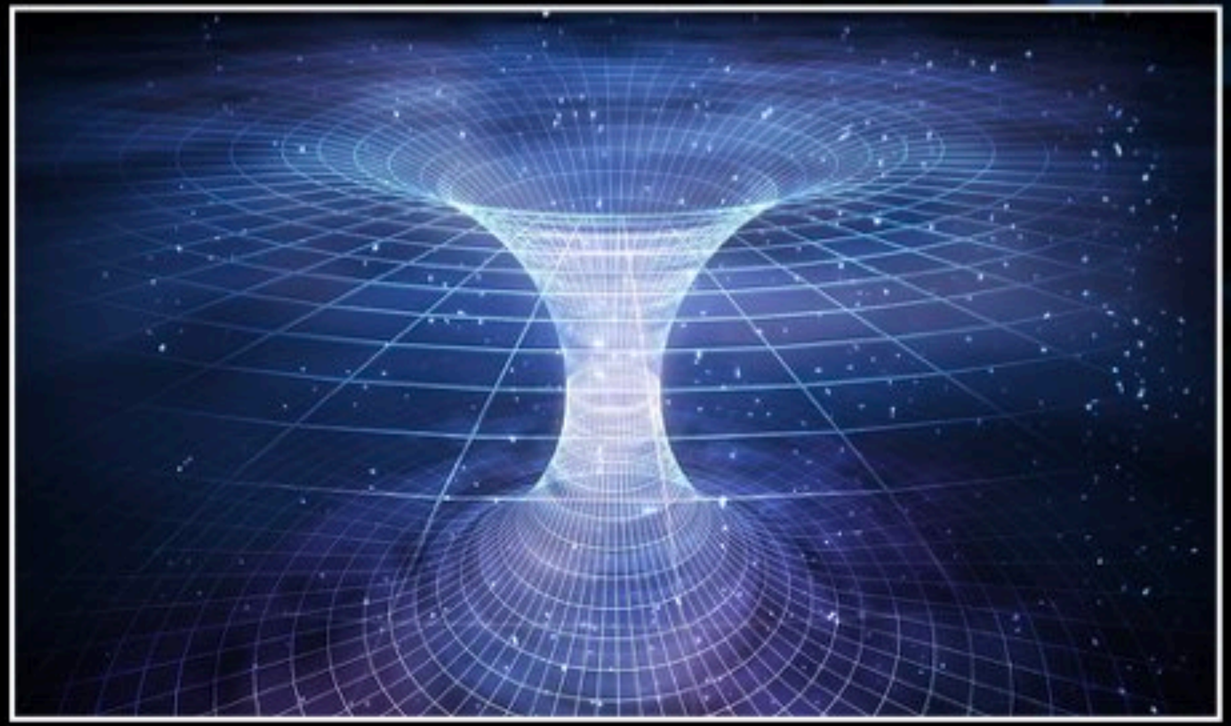
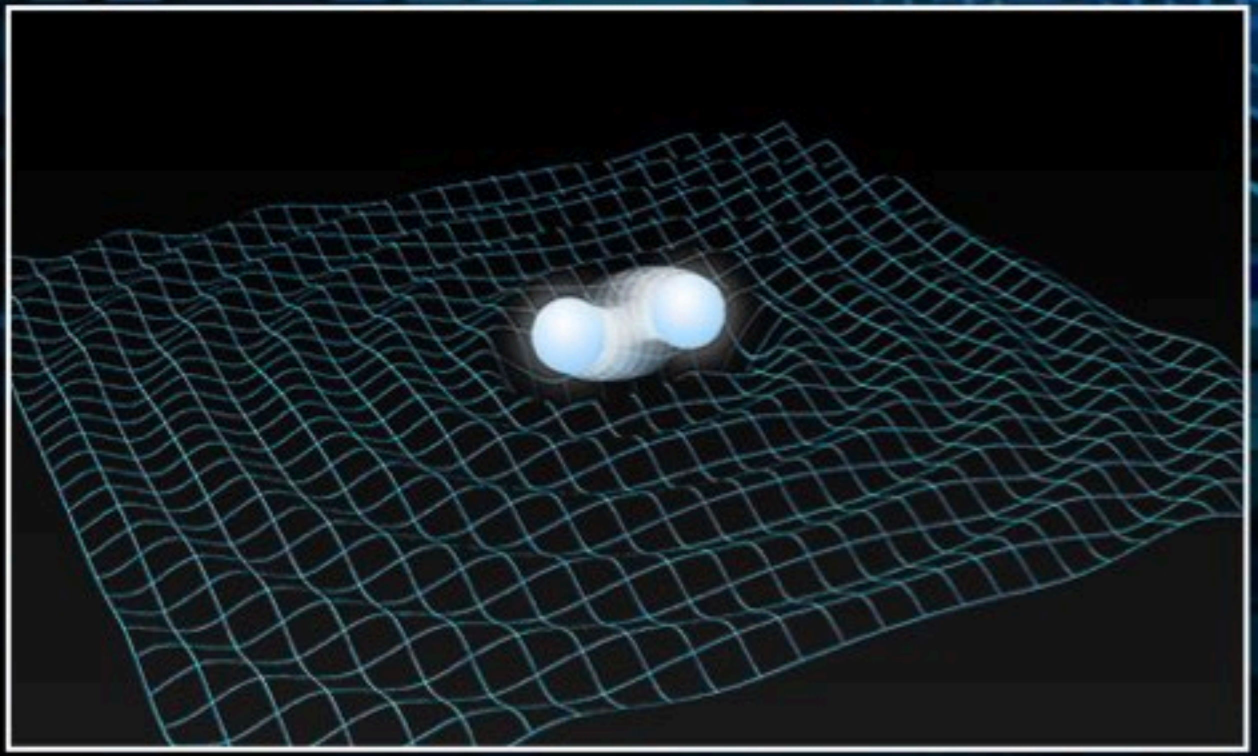




Physics Frontiers with Quantum Science and Technology

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)

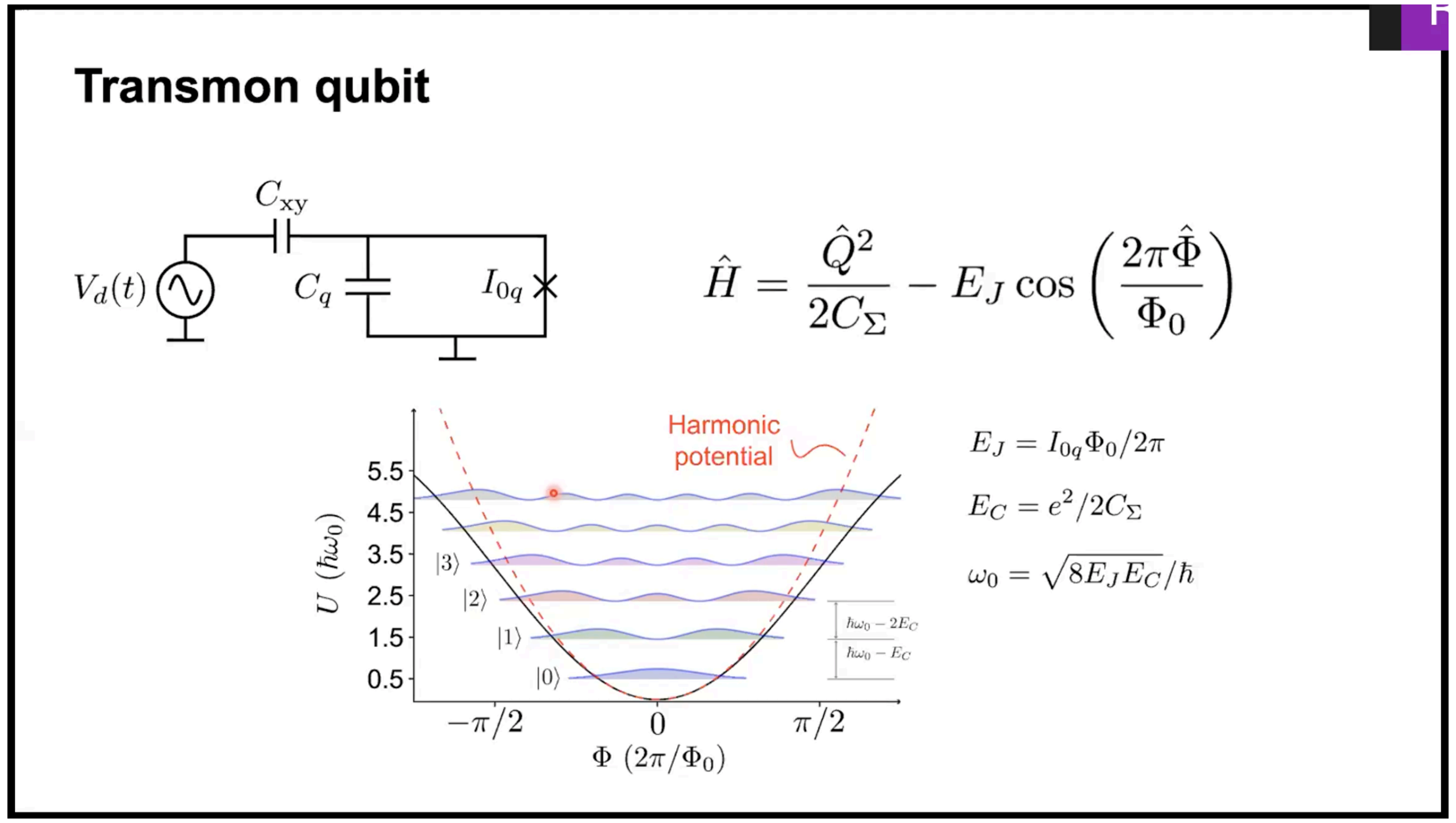
Quantum computer/sensor applications for physics: 1¶
Quantum computer/sensor applications for physics: 2¶

- ➢ Europe-Friendly time (16:00-19:10 JST)

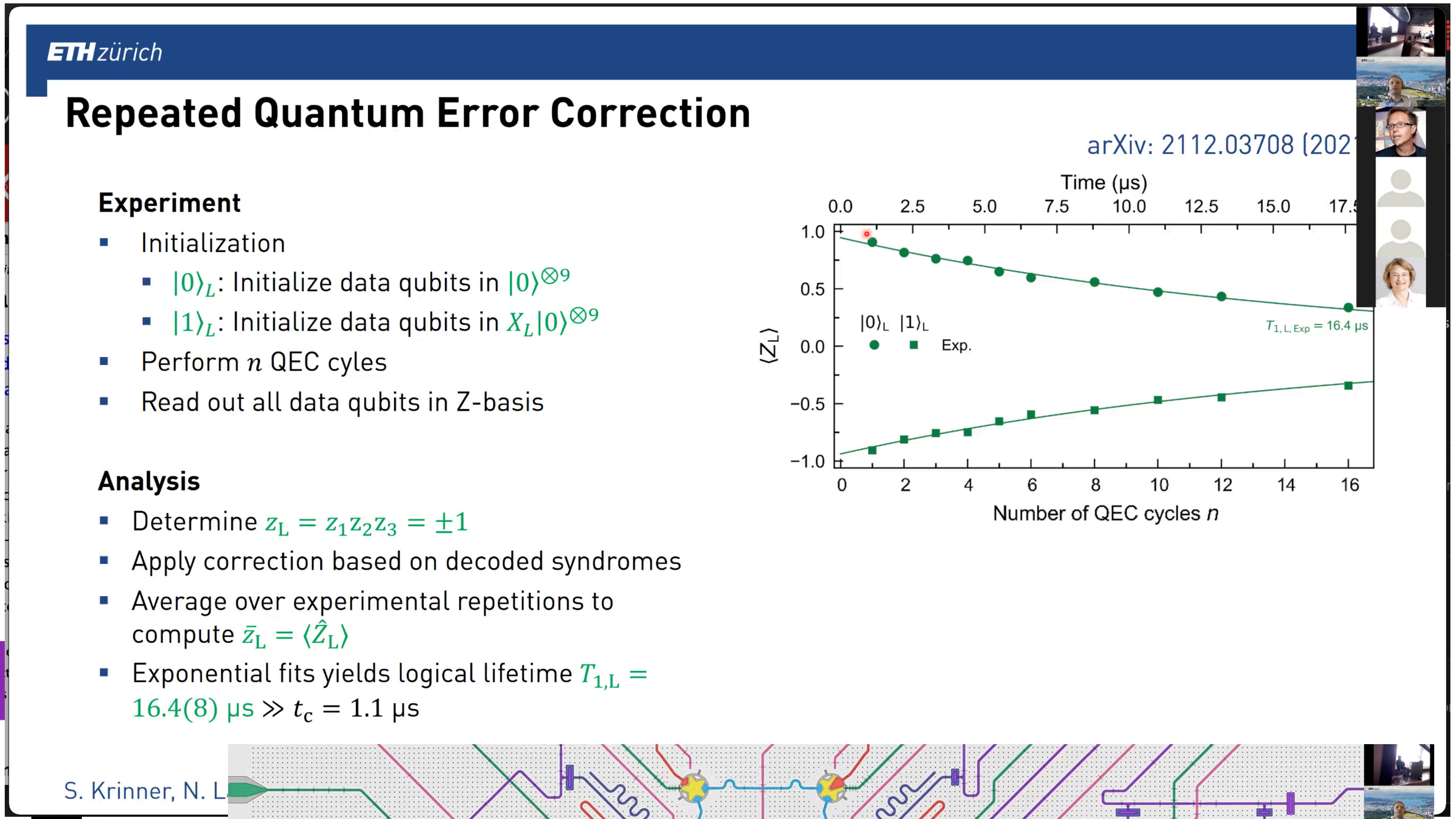
Quantum computer applications for physics: 3¶
Quantum-computer applications for physics: 4¶

19 excellent talks covering a wide range of topics including

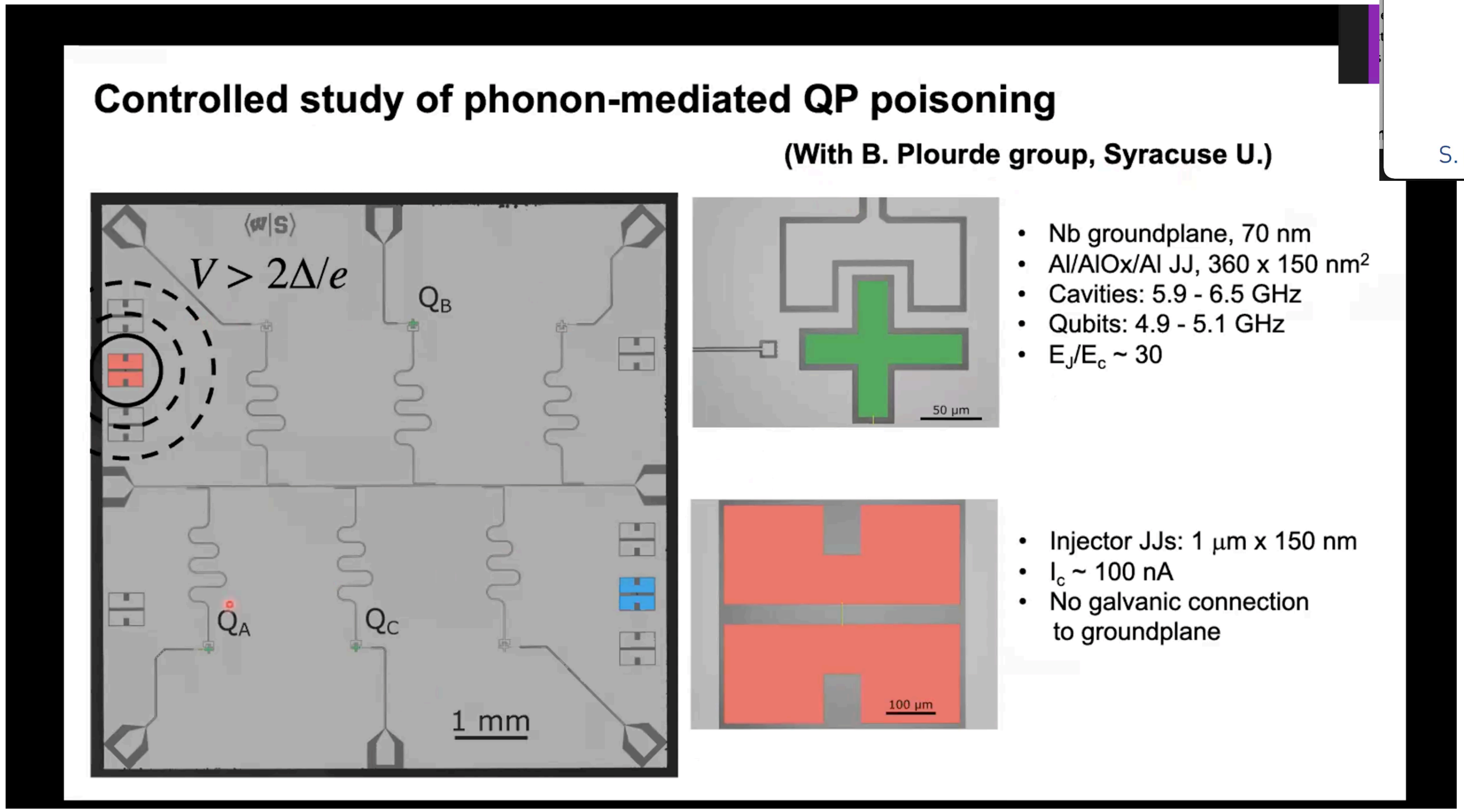
- quantum computing/sensor technologies and recent developments
- applications to particle physics, astrophysics, material science, photon science, ..
- future prospects in quantum technologies

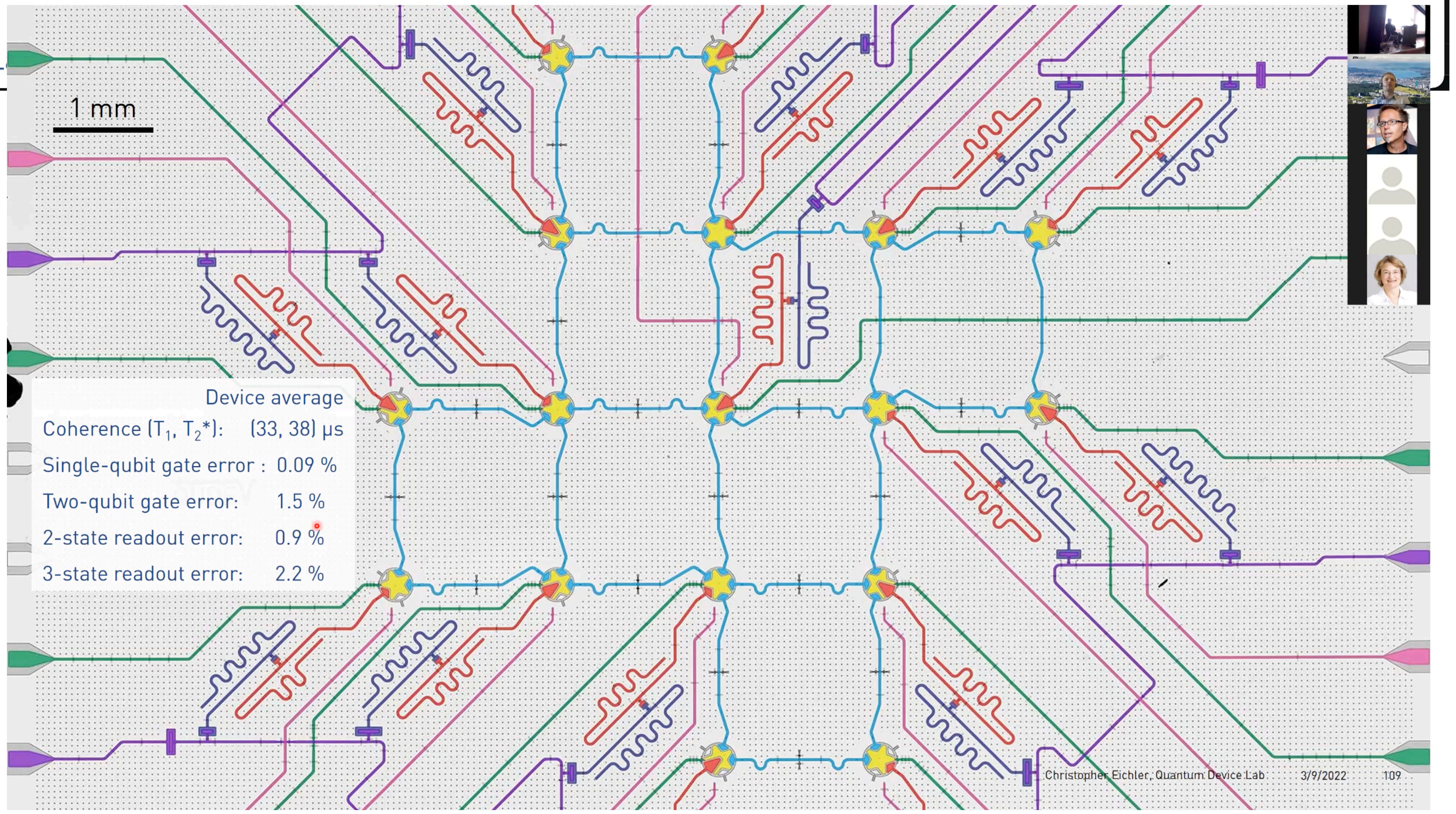


Christopher Eichler (ETH Zurich)



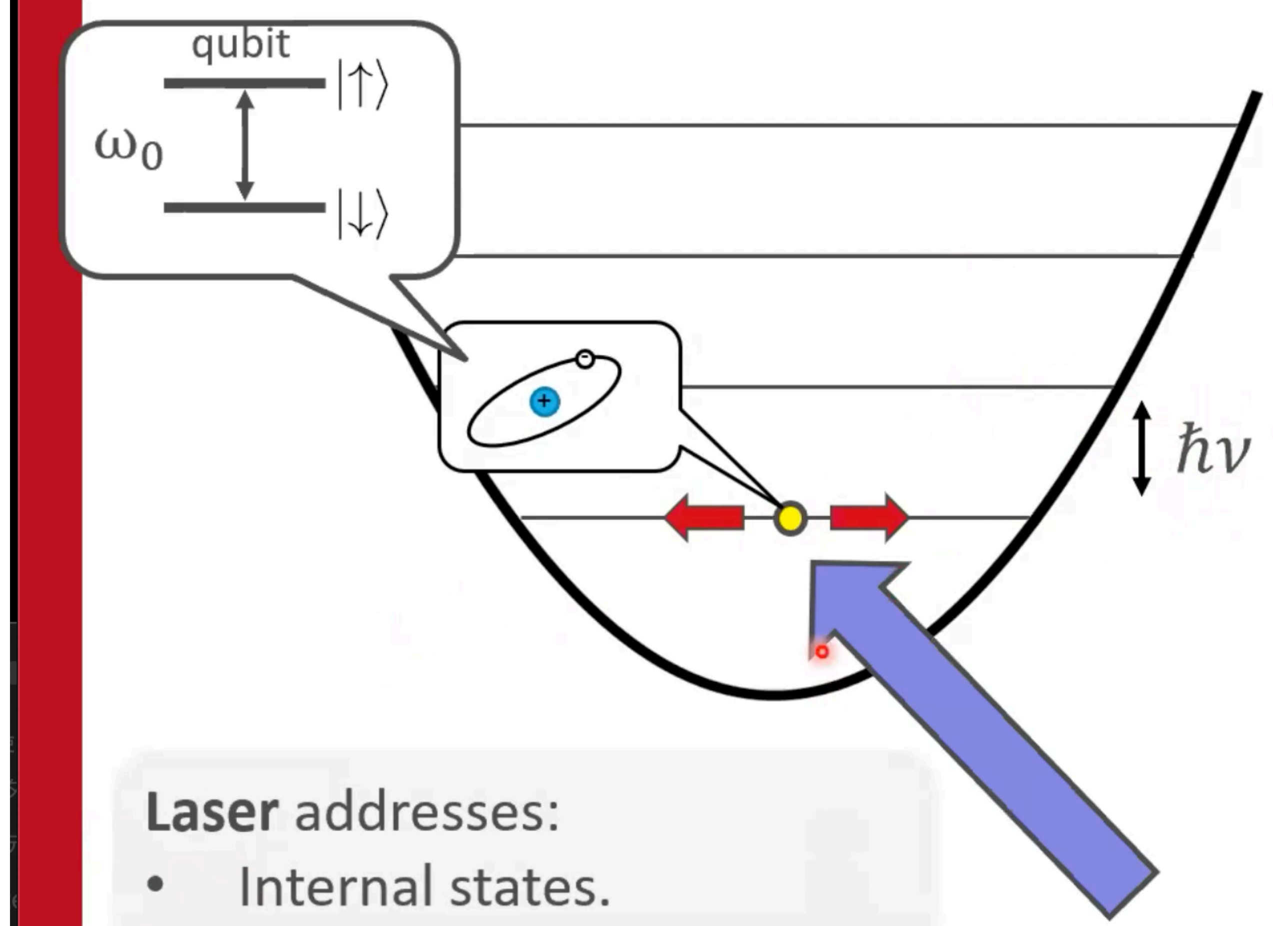
Robert McDermott (U. of Wisconsin Madison)





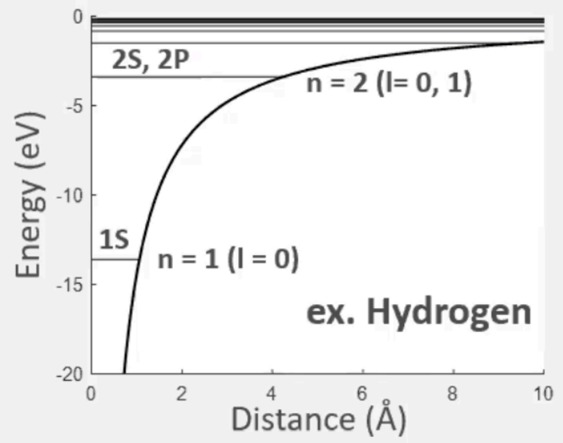
Hiroki Takahashi (OIST)

Qubit in a trap

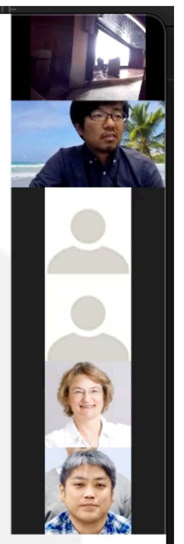


Laser addresses:
- Internal states.
- Motional states (cooling).

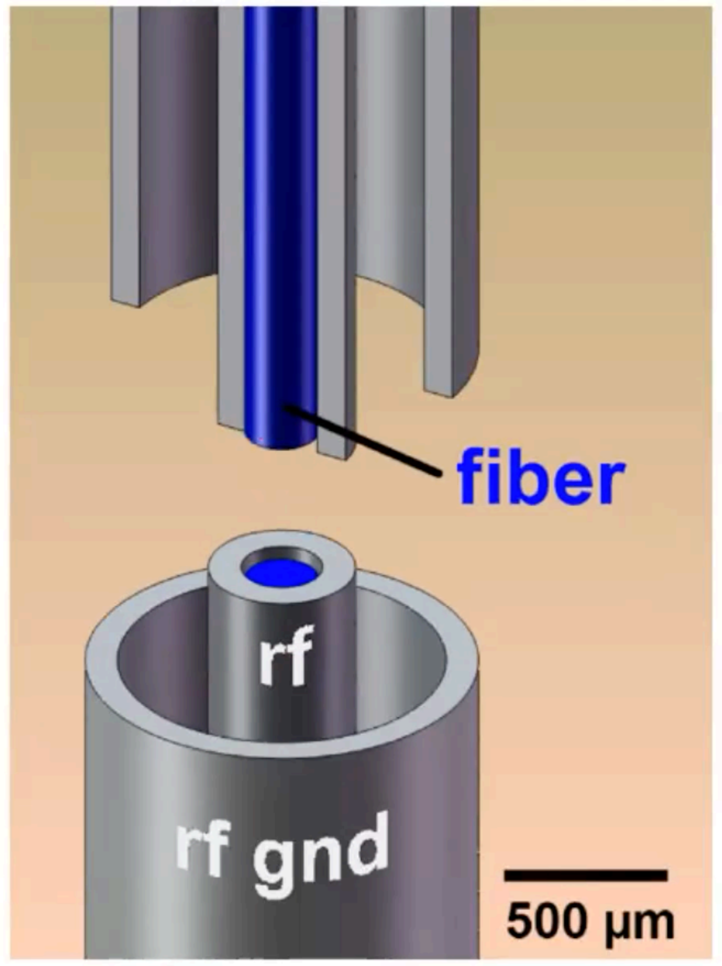
- An ion trapped in **harmonic potential**.
- Quantized energies for **internal states** for **electronic degrees of freedom** (angular momenta, spins).



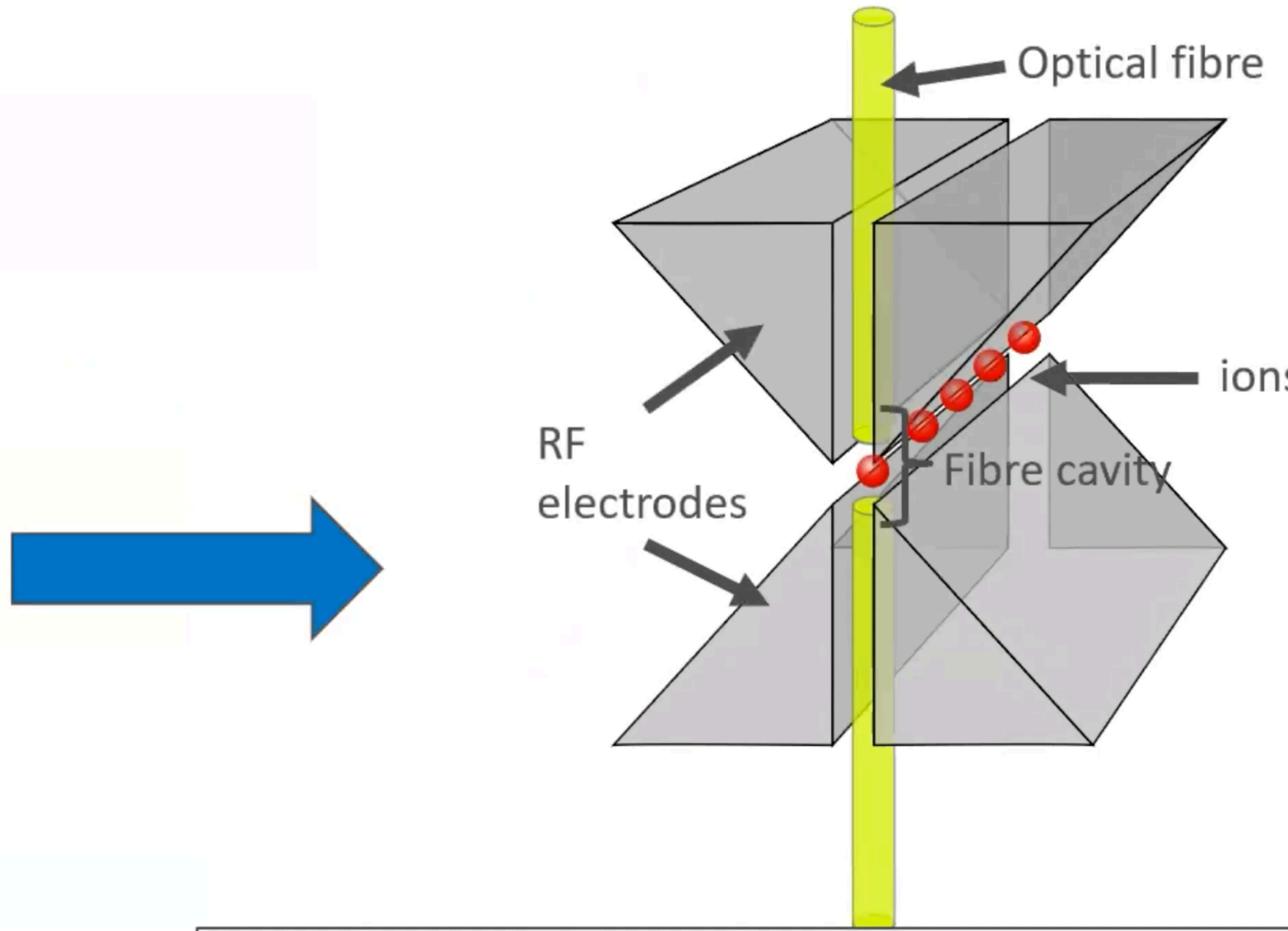
- **Center of mass motion** cooled to a low temperature (<mK) and also quantized.



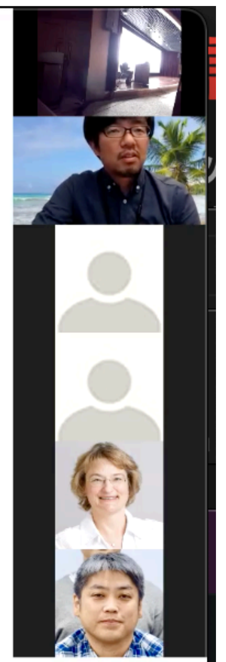
Extension to a linear trap



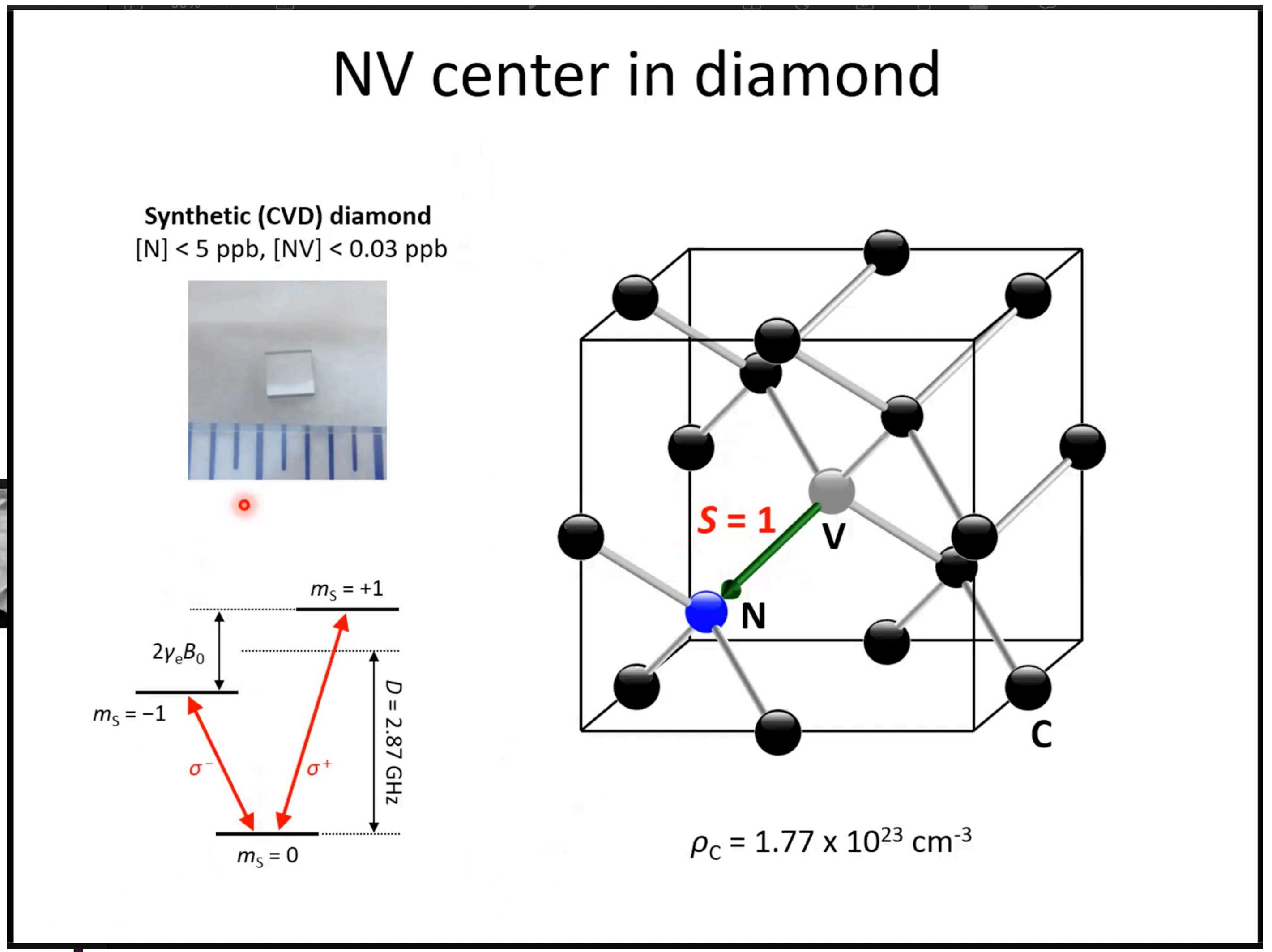
Can only trap a single ion.



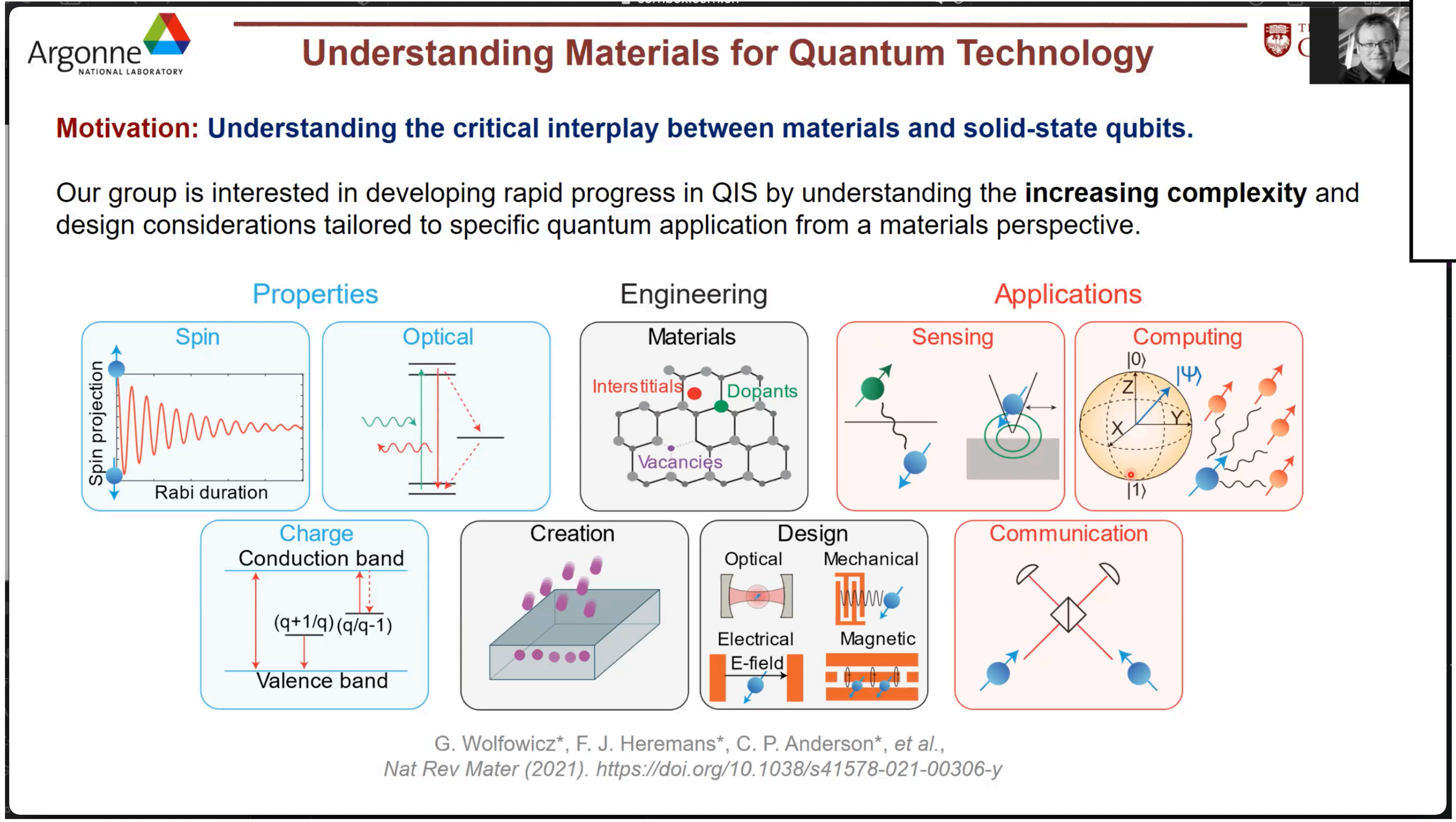
- Cavity coupled to an ion in string.
- Fibers shielded by the electrodes.

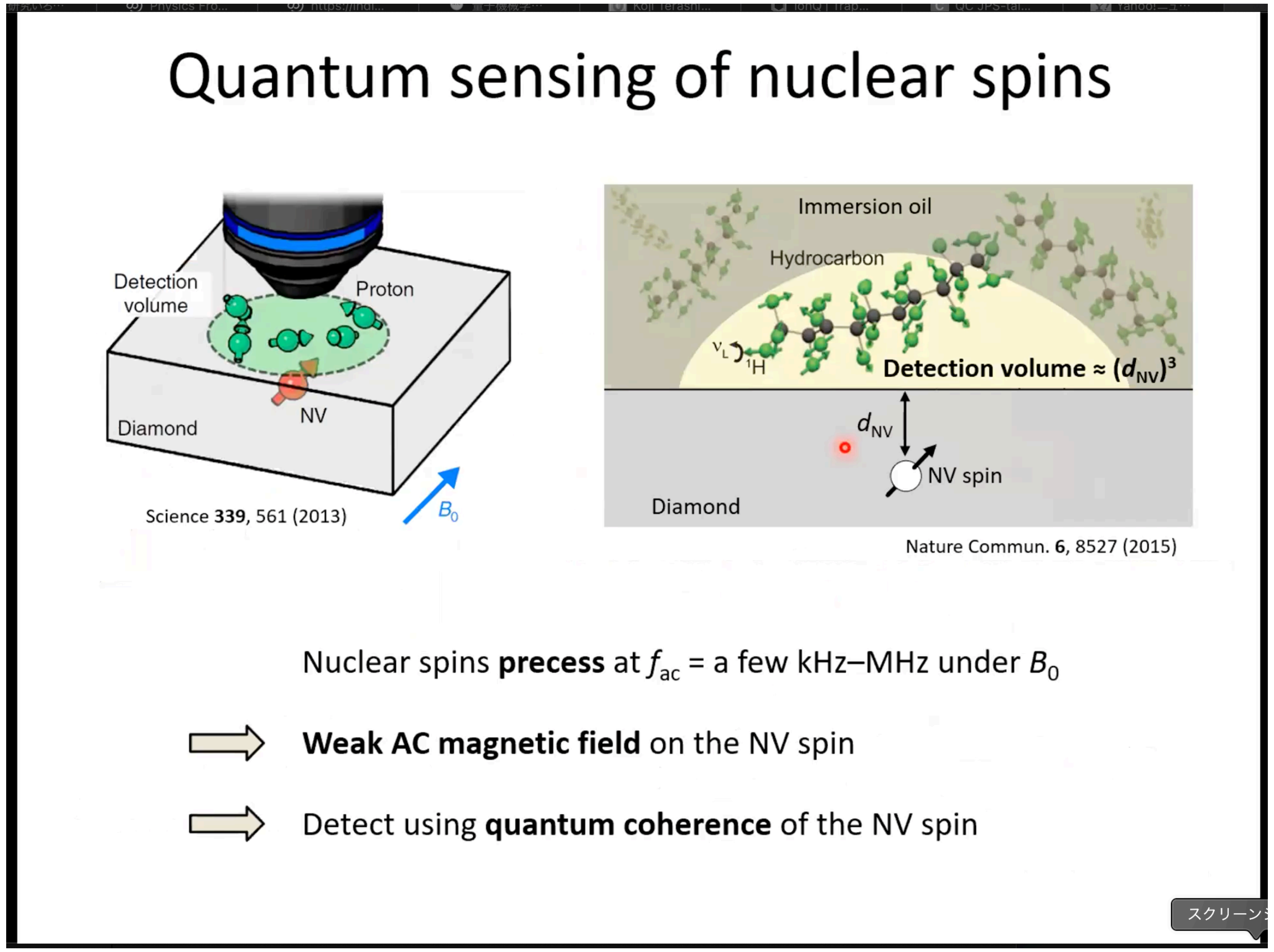


Eisuke Abe
(RIKEN)



Joseph Heremans (U. of Chicago)



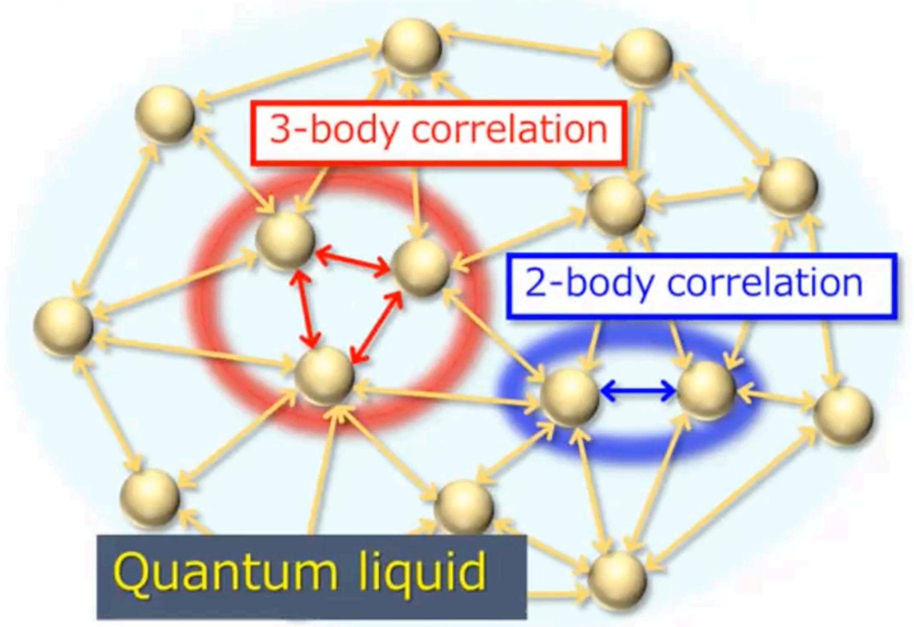


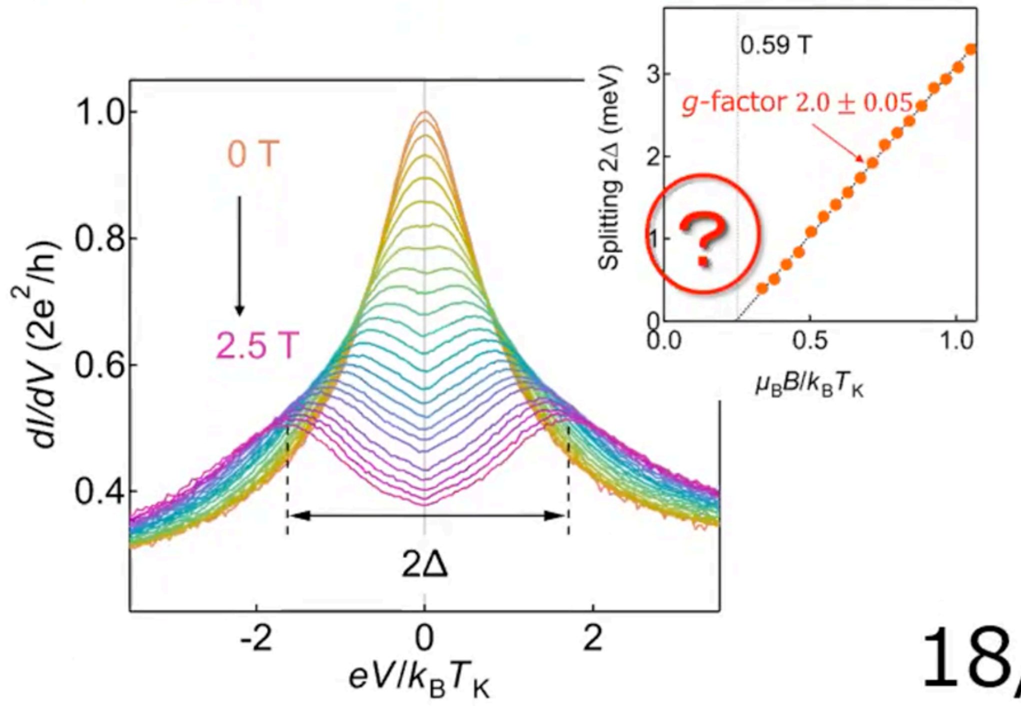
Kensuke Kobayashi (U. of Tokyo)

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





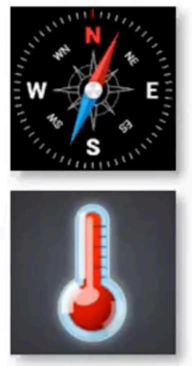
Diamond quantum sensor

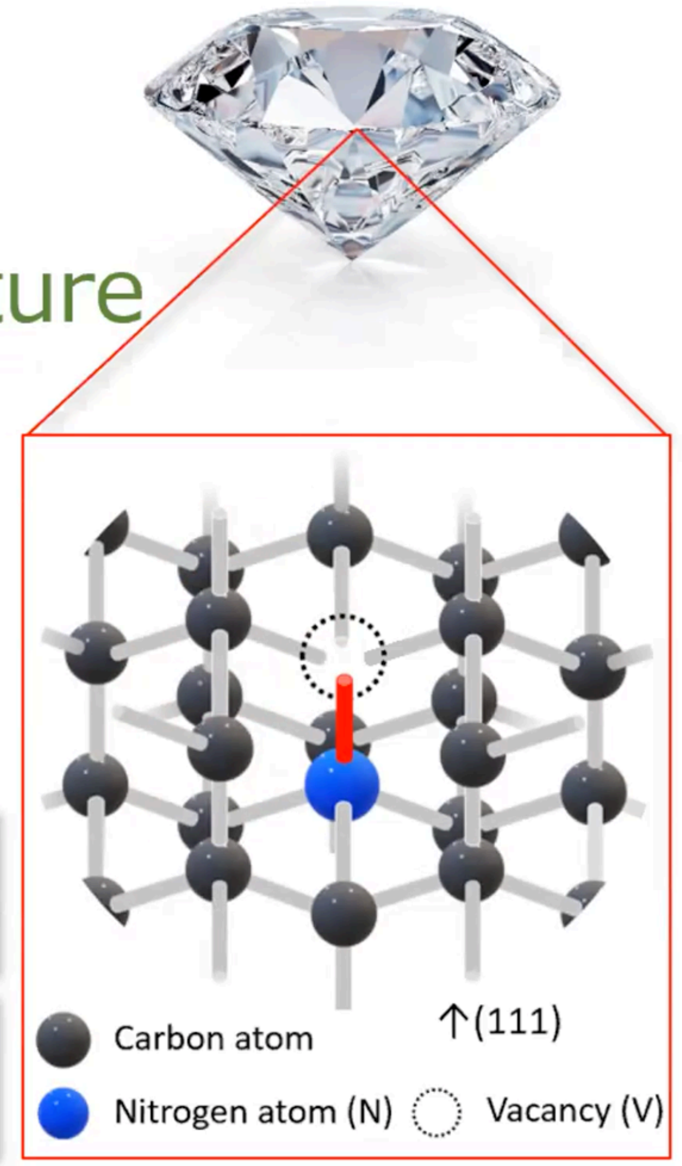
NV (nitrogen-vacancy) center
= Atomic size sensitive sensor
for magnetic field* & temperature

New tool for meso. physics

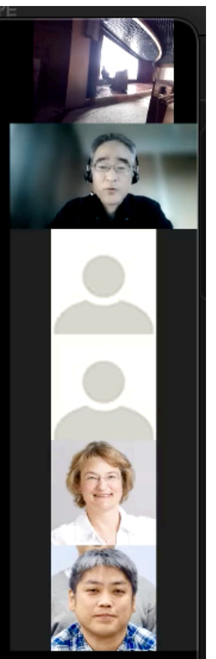
- Non-eq.: heat & spin current
- Nano-magnetism
- Topological edge states
- Phase transitions
- Superconducting vortex ...

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).



Aaron Chou (Fermilab)

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

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

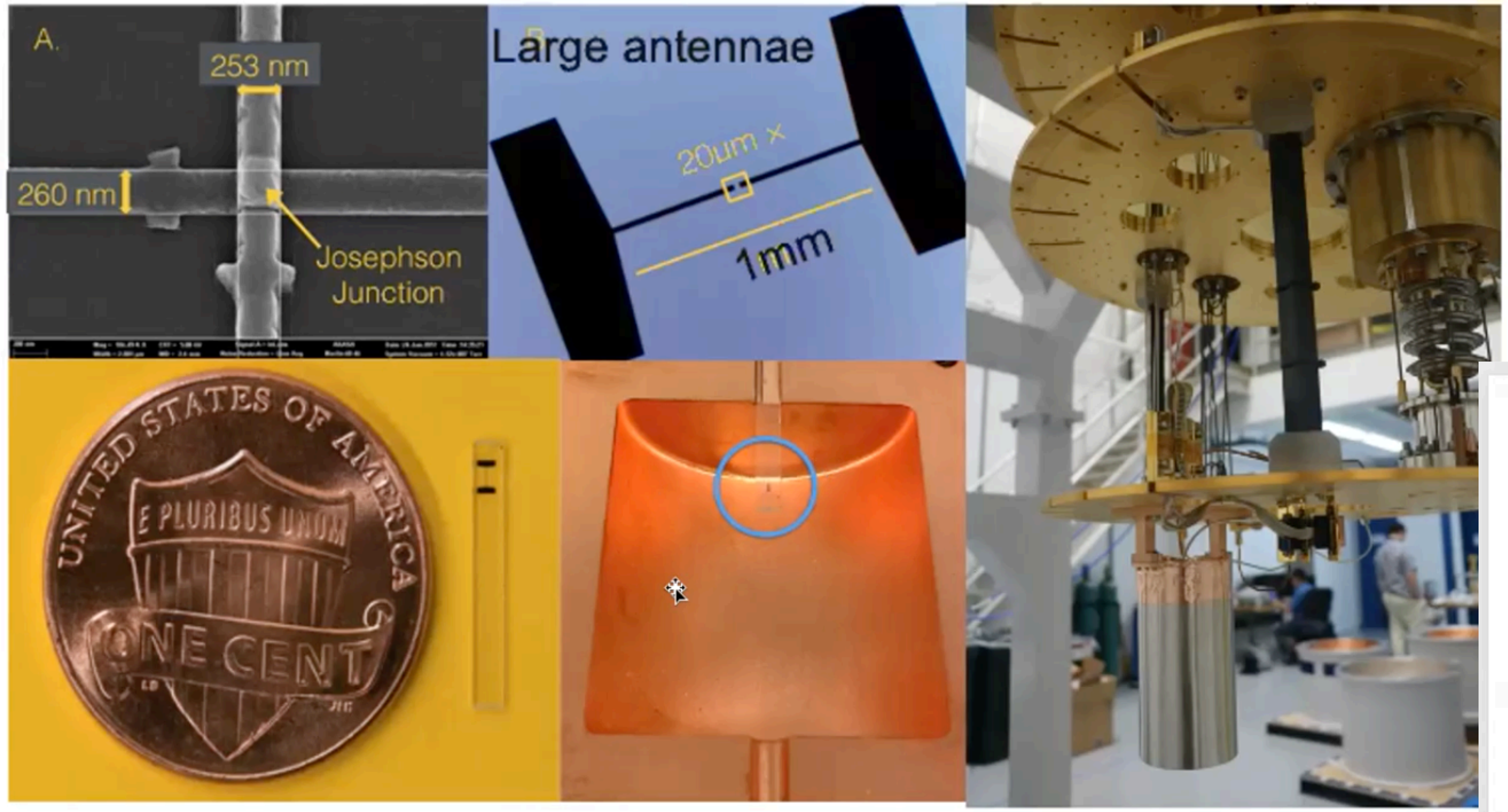
$$H \approx \hbar\omega_r a^\dagger a + \frac{\hbar}{2}(\omega_a' + 2\chi a^\dagger a)\sigma_z$$

Funded by

HEISING-SIMONS FOUNDATION

DOE QuantISED

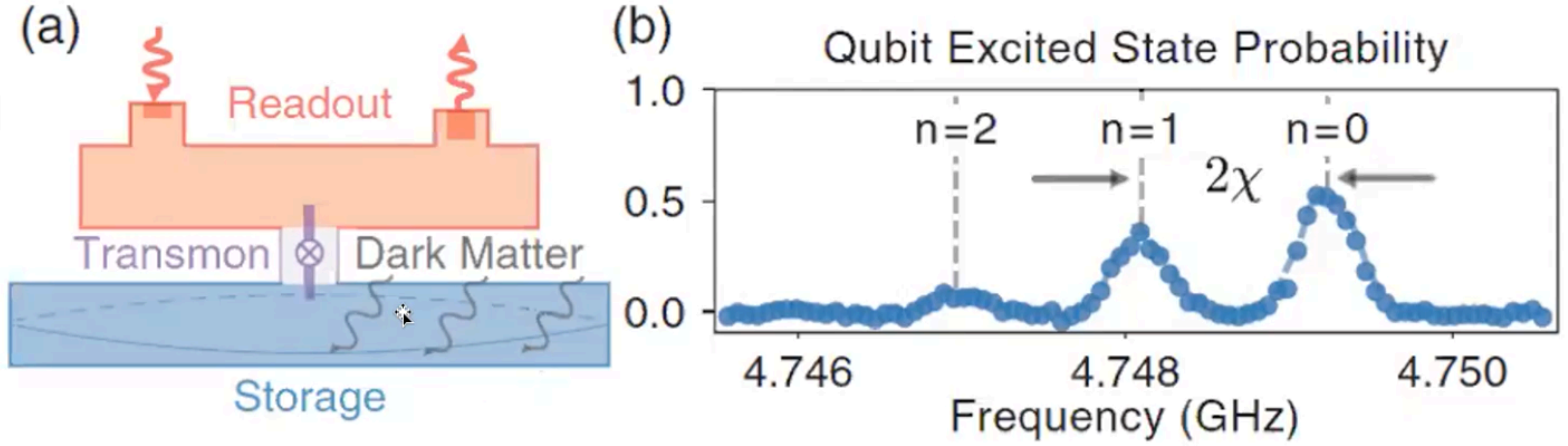
Fermilab LDRD



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.

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 <n>=1

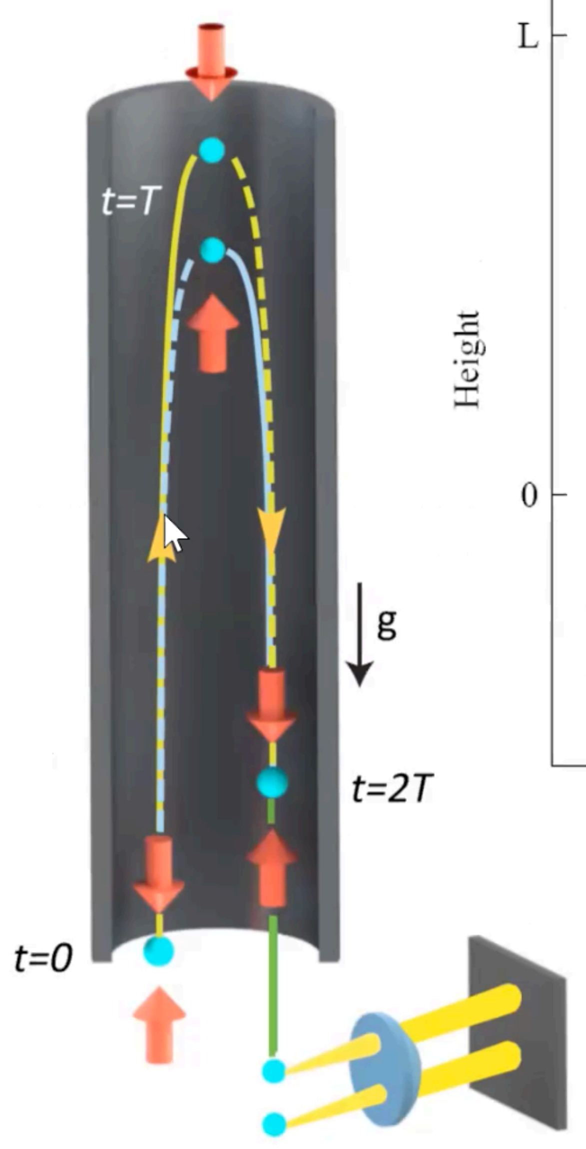


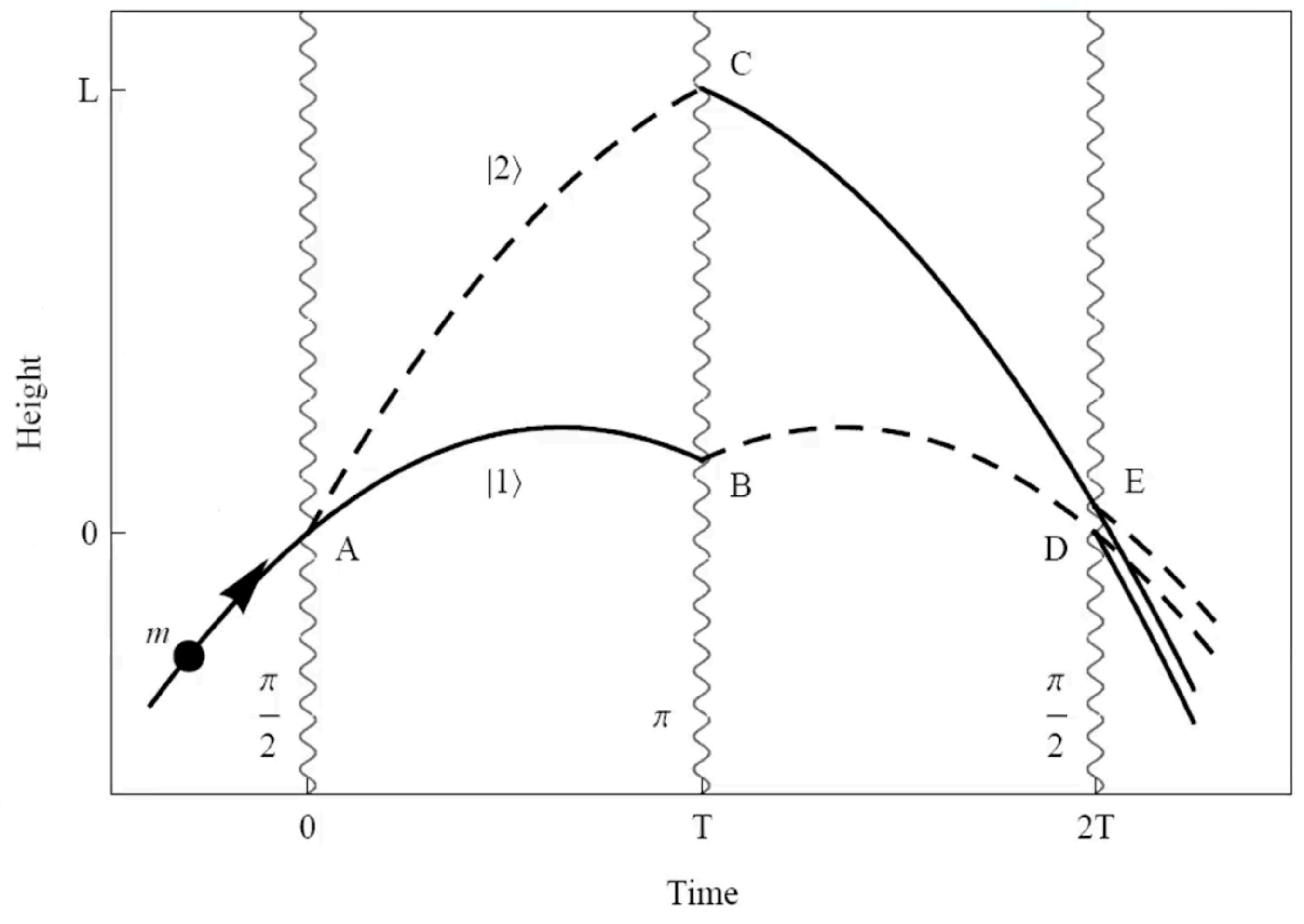
The measured qubit spectrum exhibits a distribution of resonances which are in 1-1 correspondence with the Poisson distribution of the cavity's coherent state.

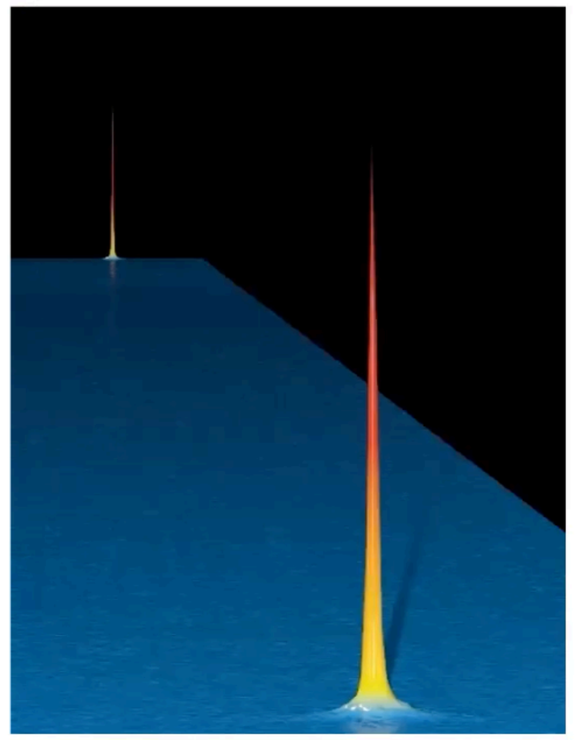
Non-destructively count photons by measuring the qubit's quantized frequency shift.

Jason Hogan (Stanford U.)

Atom interferometry







Rb wavepackets separated by 54 cm

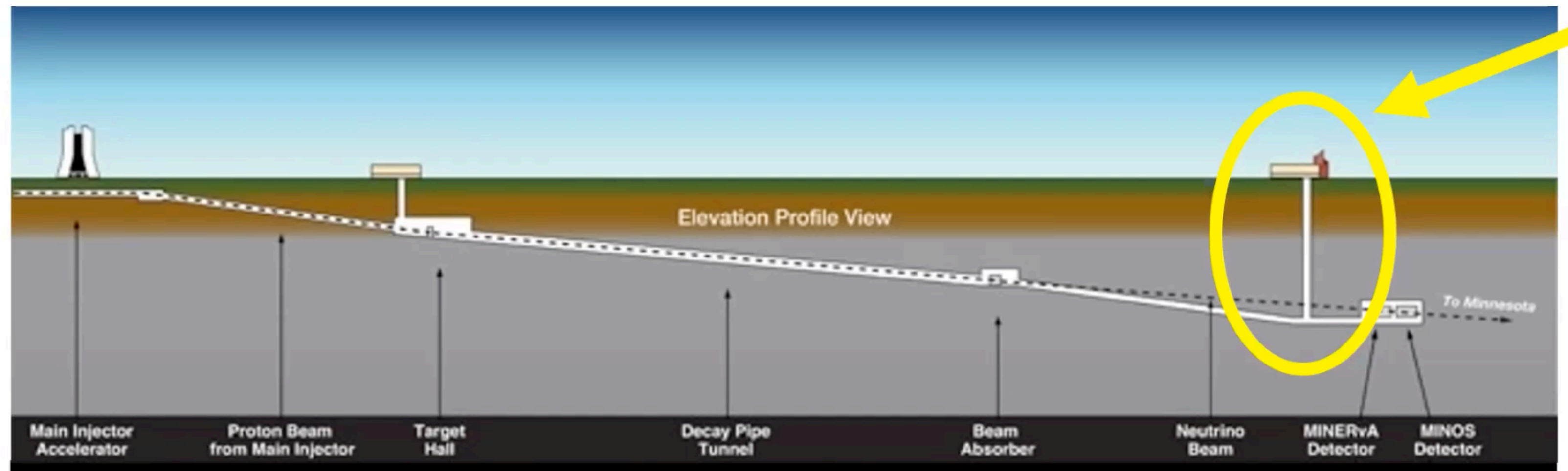
$$\Delta\phi = k_{\mathrm{eff}} g T^2$$

Sensitivity proportional to spacetime area enclosed.

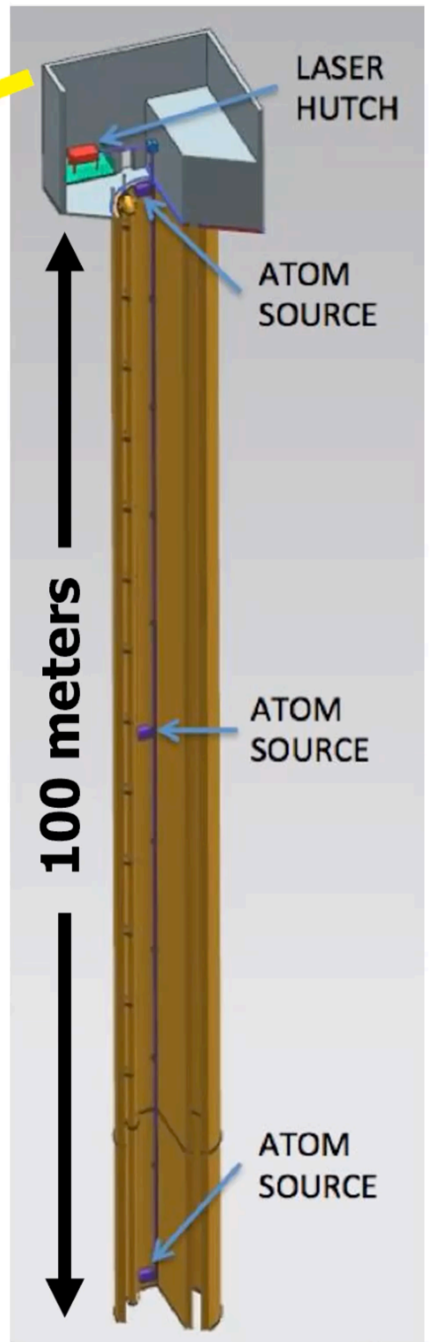
Increase sensitivity using large momentum transfer (LMT) atom optics

MAGIS-100: Detector prototype at Fermilab

Matter wave **A**tomic **G**radiometer **I**nterferometric **S**ensor



Neutrino Beam Line for MINERvA and MINOS Experiments

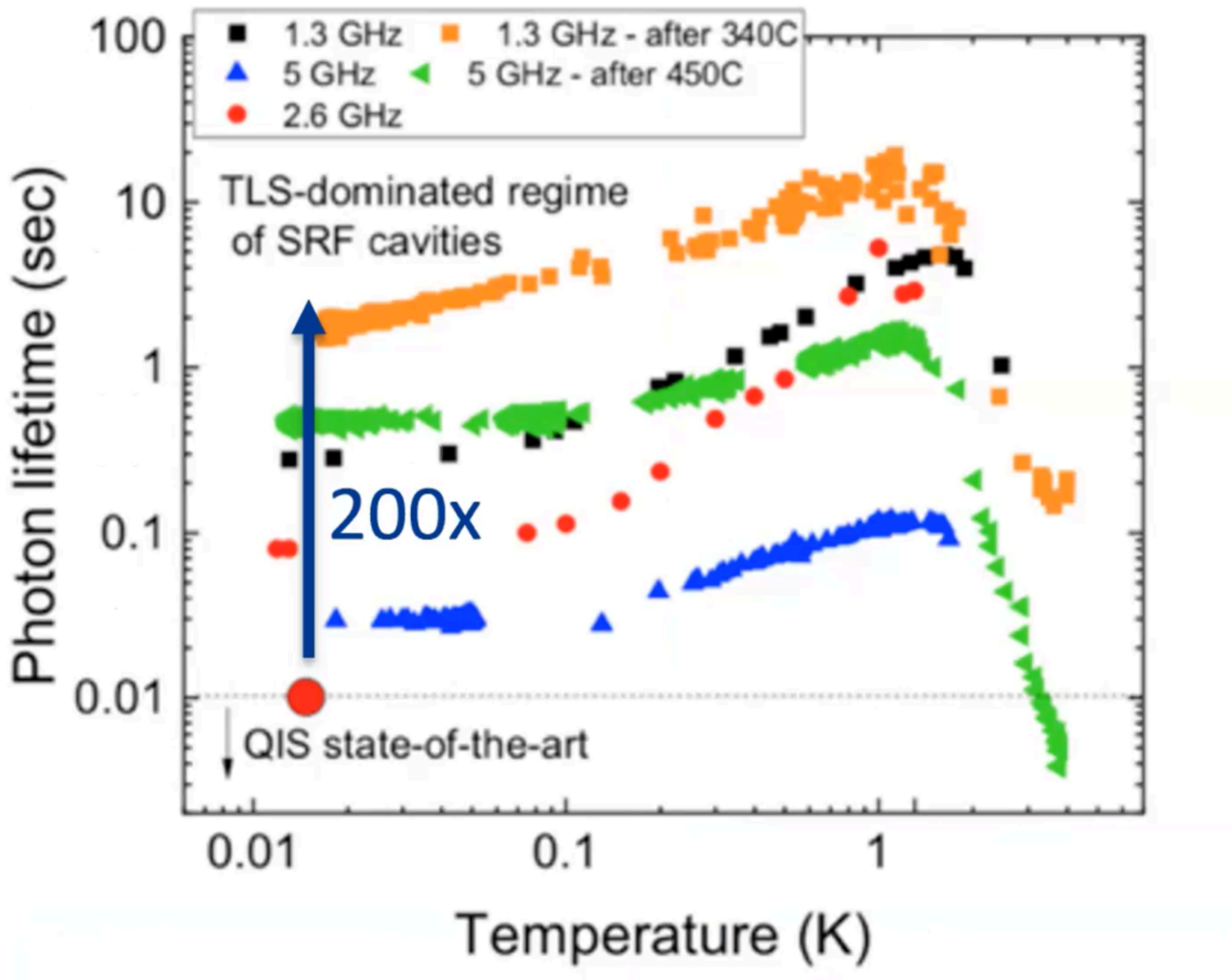


- 100-meter baseline atom interferometry in existing shaft at Fermilab
- Intermediate step to full-scale (km) detector for gravitational waves
- Clock atom sources (Sr) at three positions to realize a gradiometer
- Probes for ultralight scalar dark matter beyond current limits (Hz range)
- Extreme quantum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

Stanford, Johns Hopkins University, Northwestern University, Fermilab, SLAC, The University of Chicago, University of Cambridge, Northern Illinois University, University of Oxford, University of Liverpool

Anna Grassellino (Fermilab)

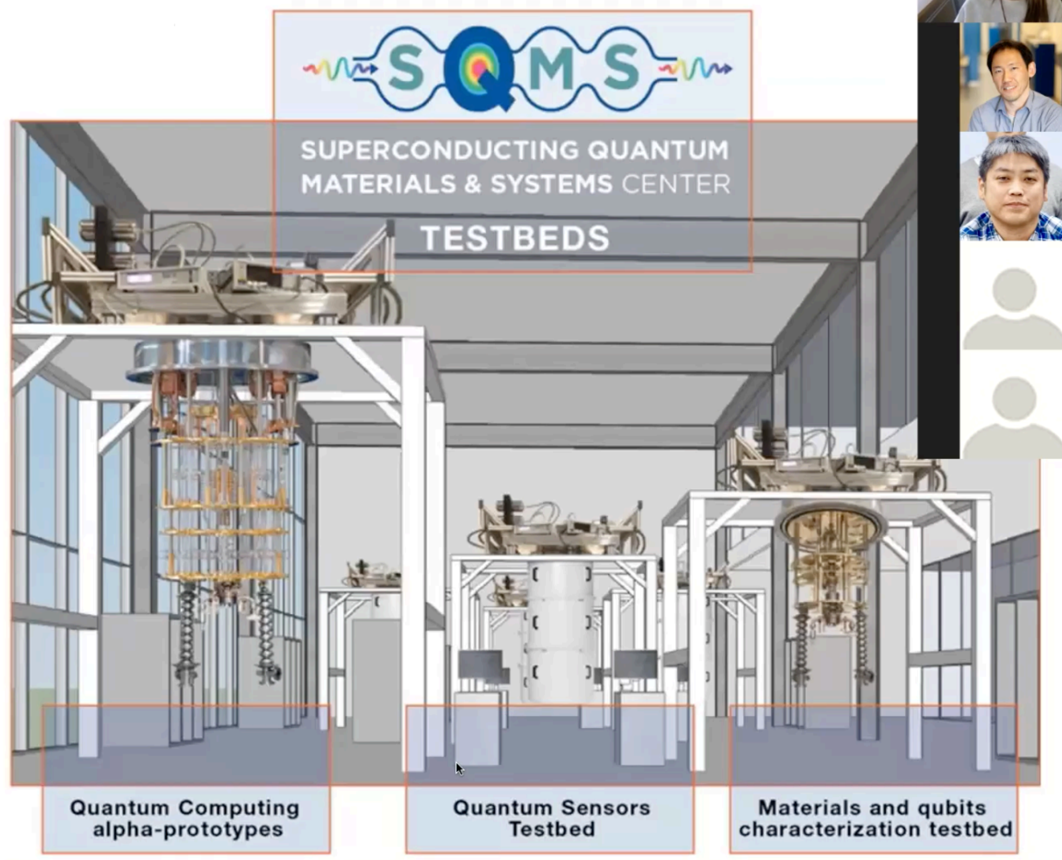
A. Romanenko et al, Phys. Rev. Applied **13**, 034032, 2020



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

Christian Bauer (LBNL)

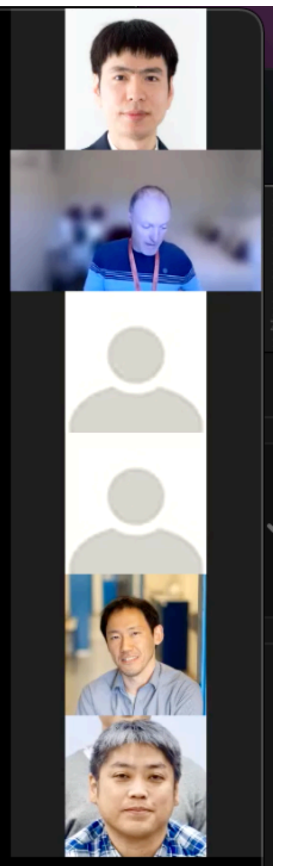
Effective Field Theory treatment to allow quantum simulation of non-perturbative physics

Formulation of Field Theories suited for simulation on quantum devices

HEP Quantum Computing at LBNL

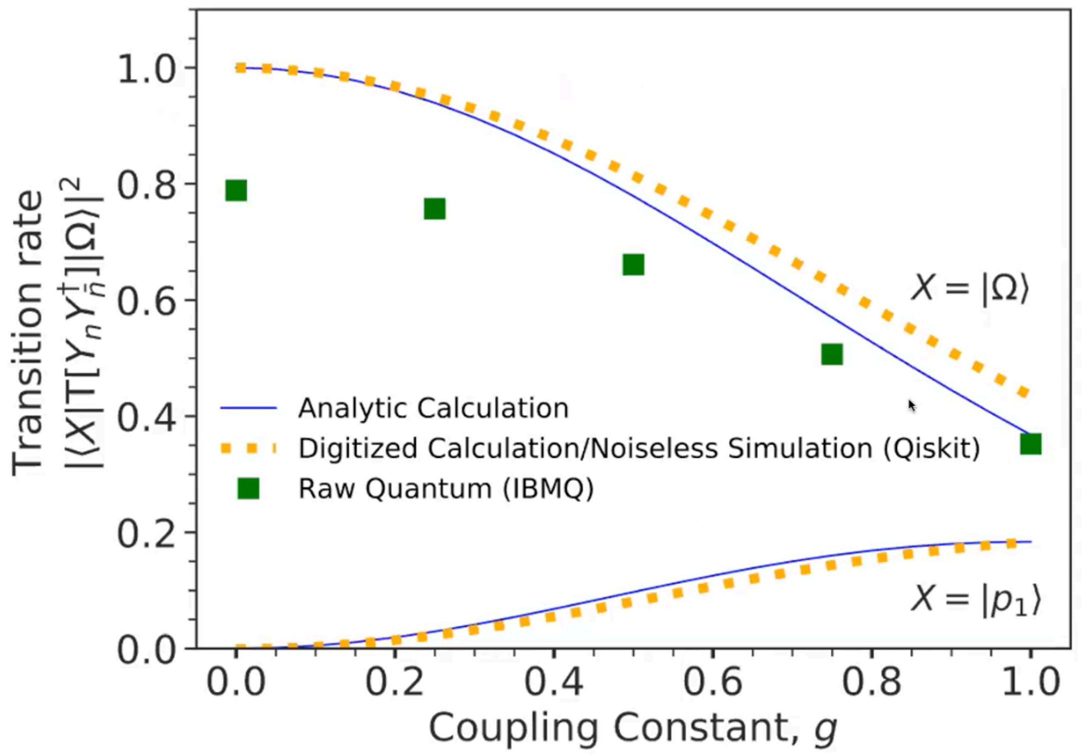
Development of quantum parton showers

Improving techniques to use NISQ devices for near term simulations



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

CWB, Freytsis, Nachman, PRL 127 (2021), 212001



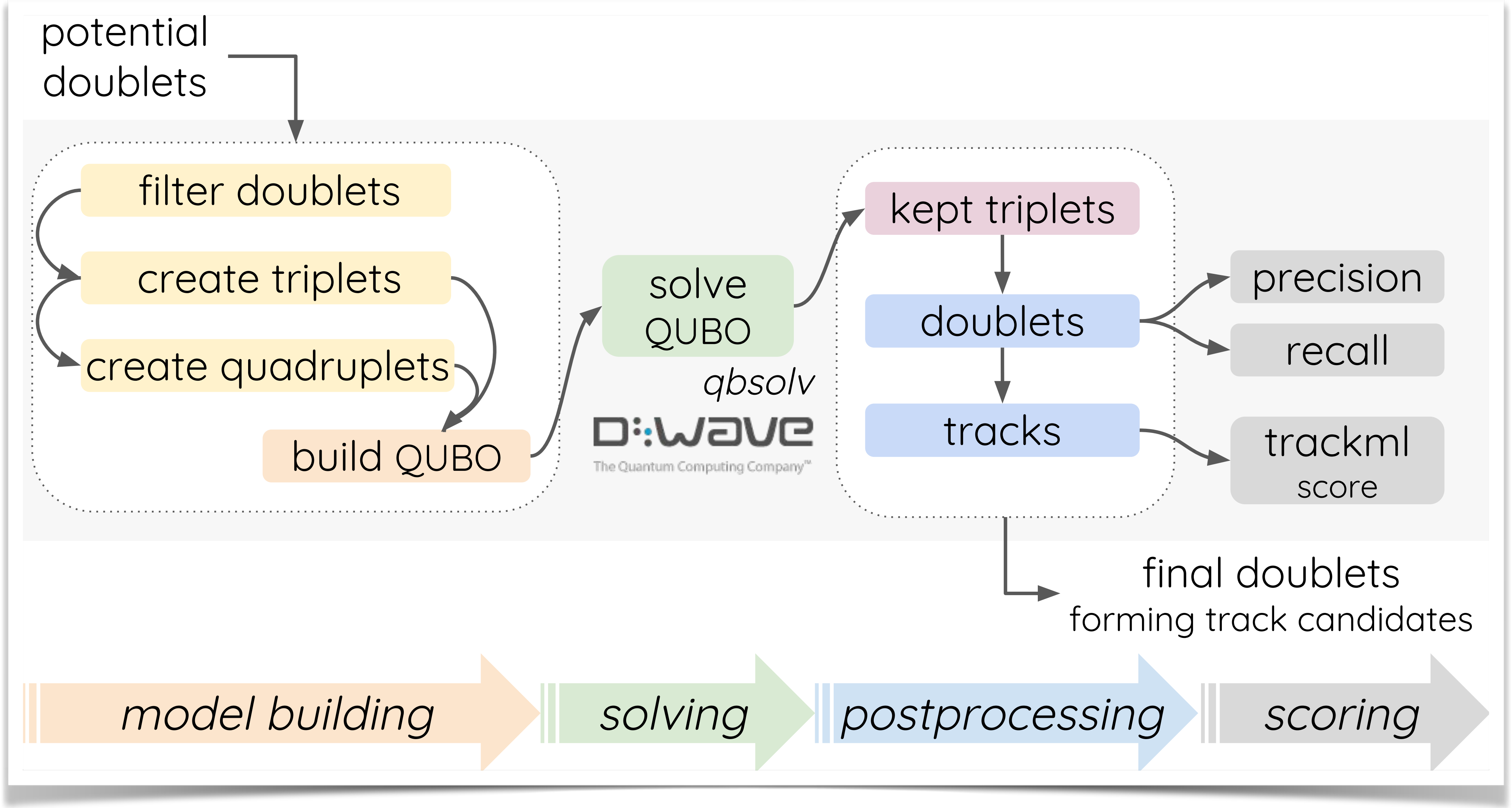
Currently working on implementing of these ideas for U(1) gauge theories

Implementation

arXiv:1902.08324

Heather Gray (UC Berkeley/LBNL)

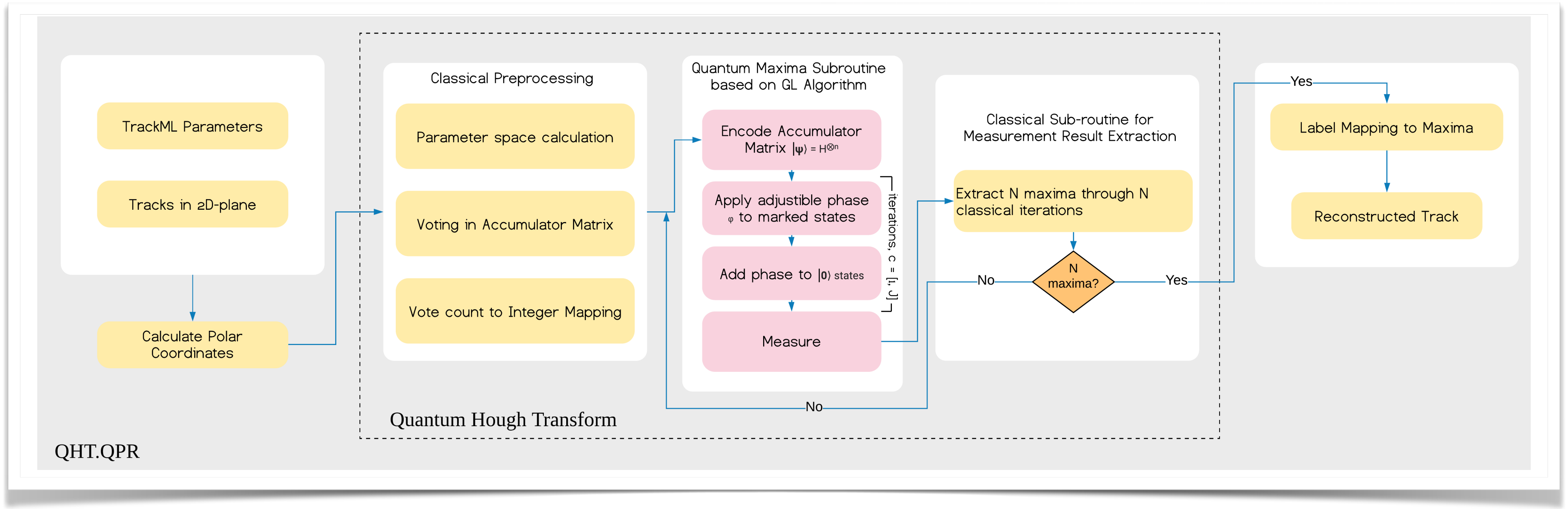
- Dataset: simplified TrackML dataset, focus on barrel, 1+ GeV, at least 5 hits
  - Toy dataset, but representative of expected conditions at the HL-LHC
- QUBO solvers: qbsolv (D-Wave + simulation), neal (classical)
- D-Wave 2X (1152 qubits), D-Wave 2000Q (2048 qubits)



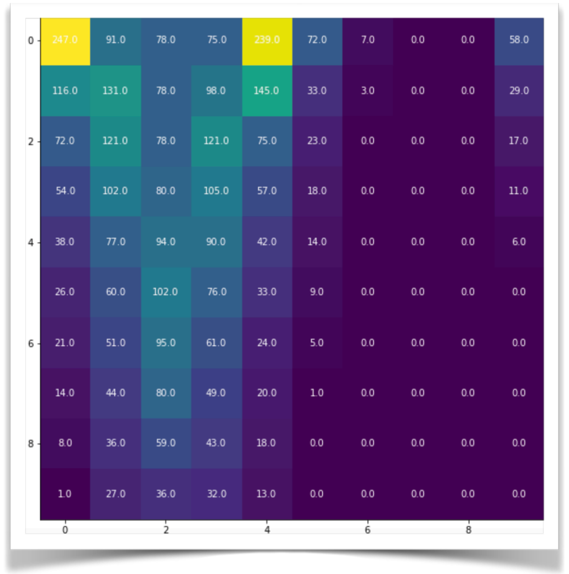
Implementation & Preliminary Results

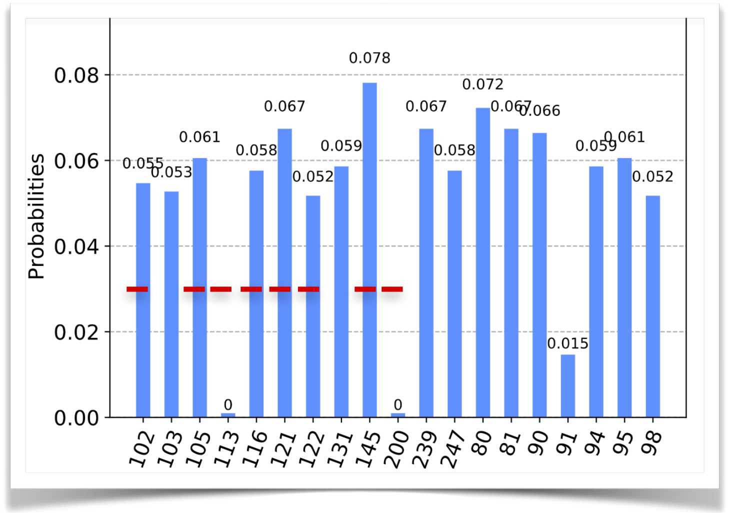
Preliminary implementation within QISKit

Accumulator Space for 8 tracks



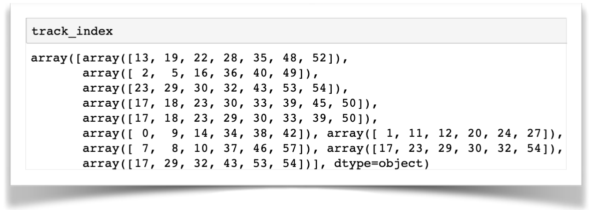
Testing within a quantum simulator





vote counts

Local Maxima Detection using Grover-Long Algorithm



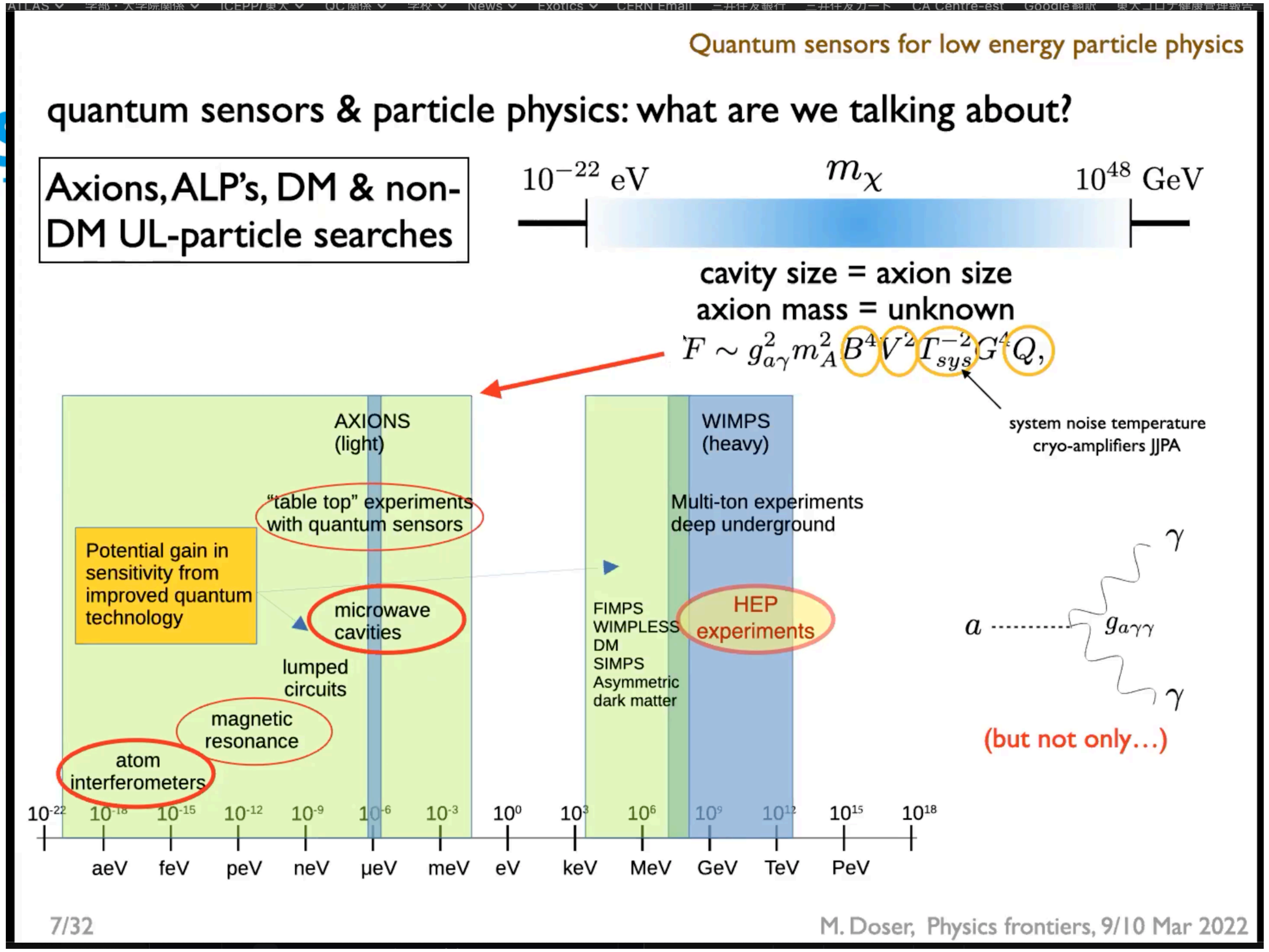
```
track_index
array([array([13, 19, 22, 28, 35, 48, 52]),
       array([ 2,  5, 16, 36, 40, 49]),
       array([23, 29, 30, 32, 43, 53, 54]),
       array([17, 18, 23, 30, 33, 39, 45, 50]),
       array([17, 18, 23, 29, 30, 33, 39, 50]),
       array([ 0,  9, 14, 34, 38, 42]), array([ 1, 11, 12, 20, 24, 27]),
       array([ 7,  8, 10, 37, 46, 57]), array([17, 23, 29, 30, 32, 54]),
       array([17, 29, 32, 43, 53, 54])], dtype=object)
```

Chen et al, arXiv:1908.07943

Slide Credit: A. Yadav

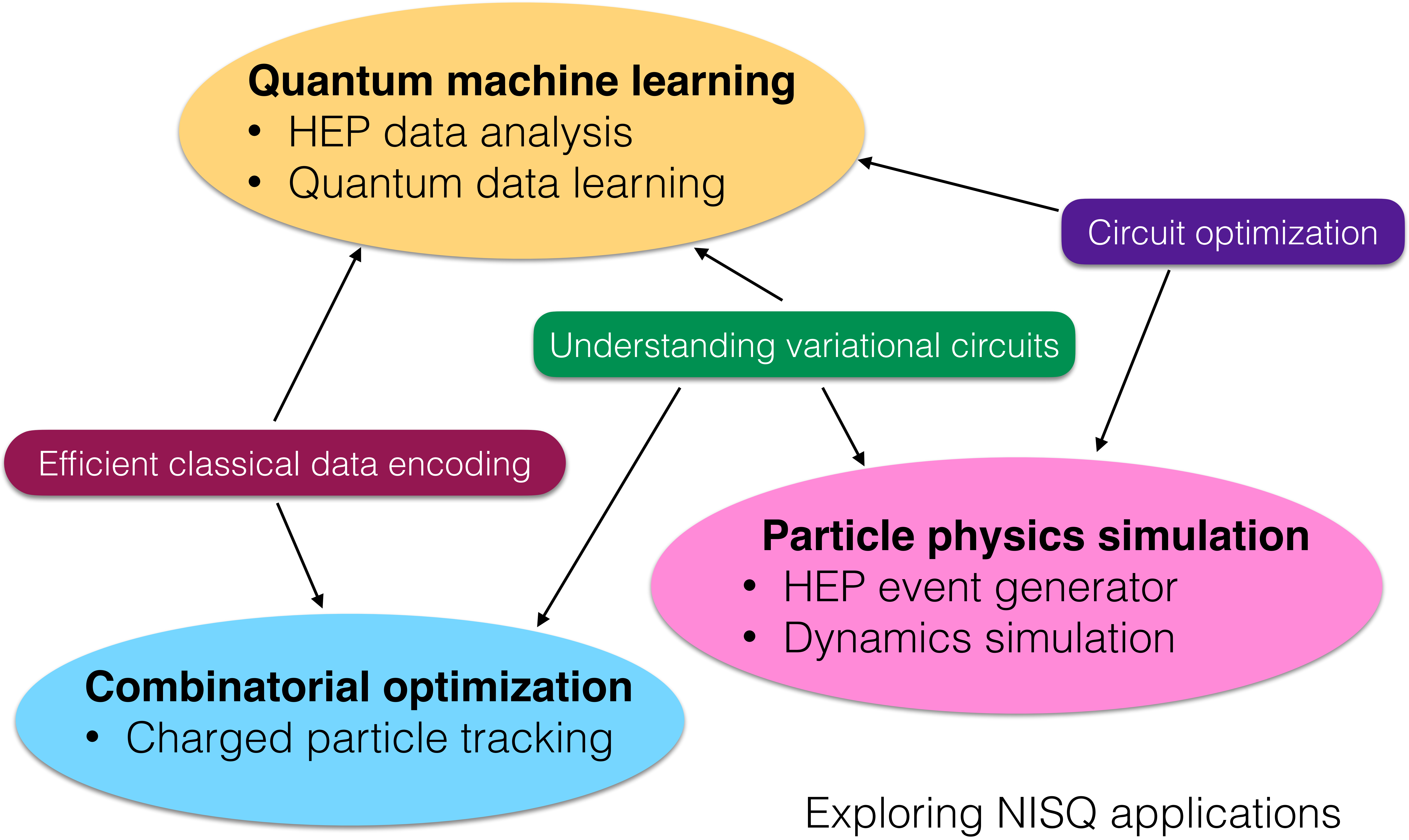
Kerstin Borras
(DESY/ RWTH Aachen University)

Michael Doser (CERN)



Yutaro Iiyama
(ICEPP, U. of Tokyo)

Main research thrusts



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!!