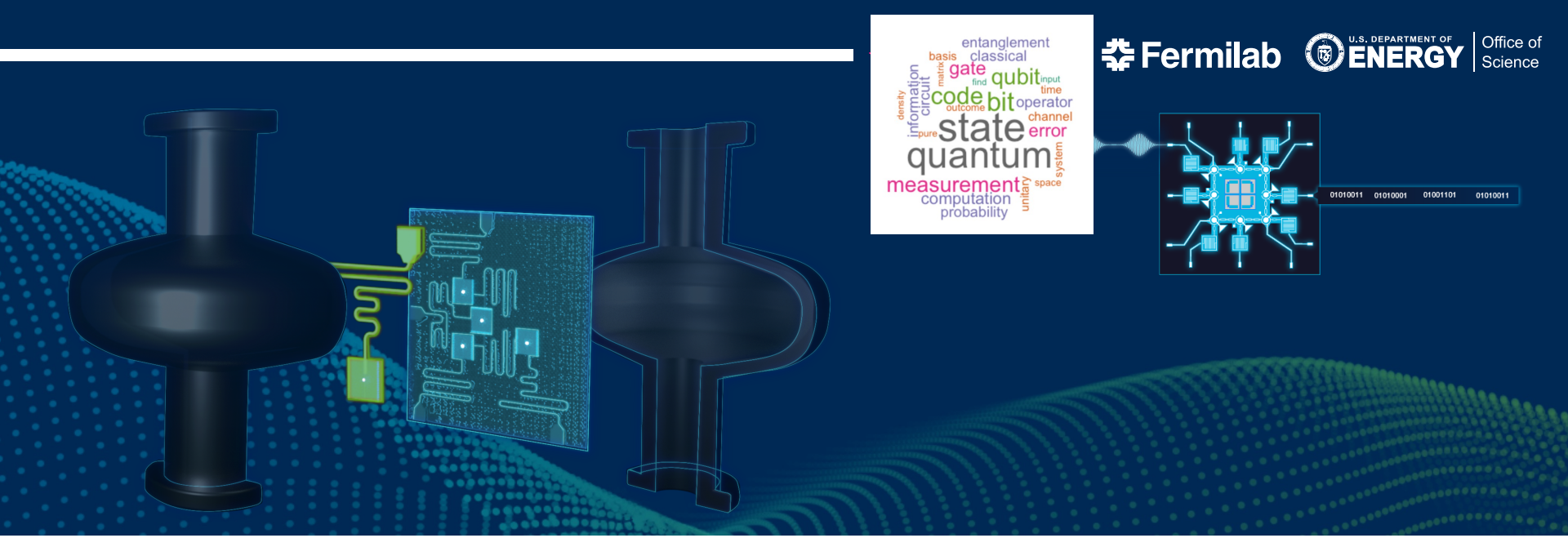


Fermilab Quantum Institute -> Quantum Division

Joe Lykken
Director, Quantum Division
Emerging Technologies Directorate

Outline

- Quantum sensors for dark matter detection
- The MAGIS-100 cold atom gradiometer experiment
- QUIET: our underground qubit testing facility
- QICK, the Quantum Instrumentation Control Kit
- Quantum teleportation networks

Didn’t we already have the quantum talk yesterday???

SQMS

31 Partner Institutions

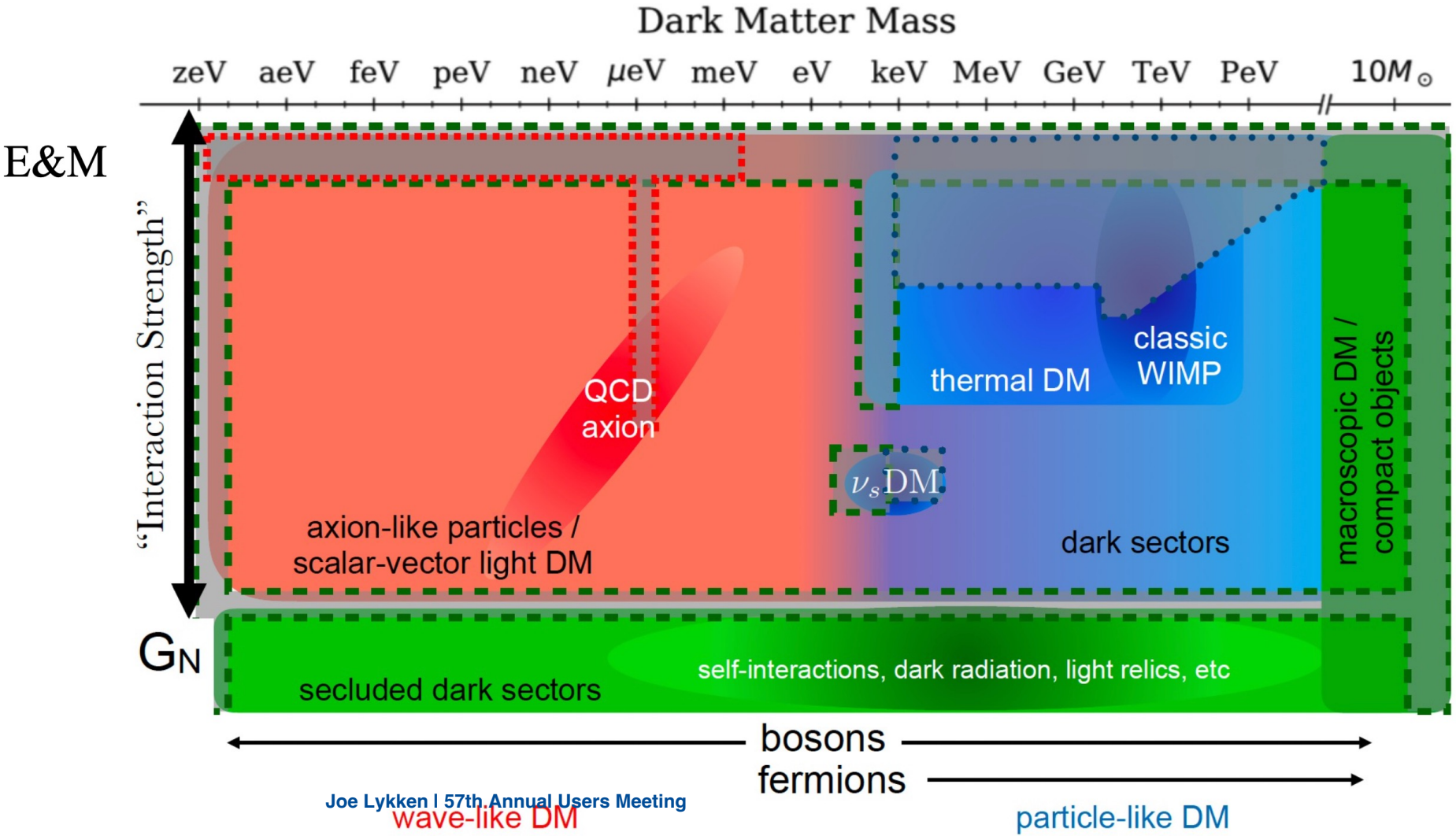
>535 Collaborators, $112M

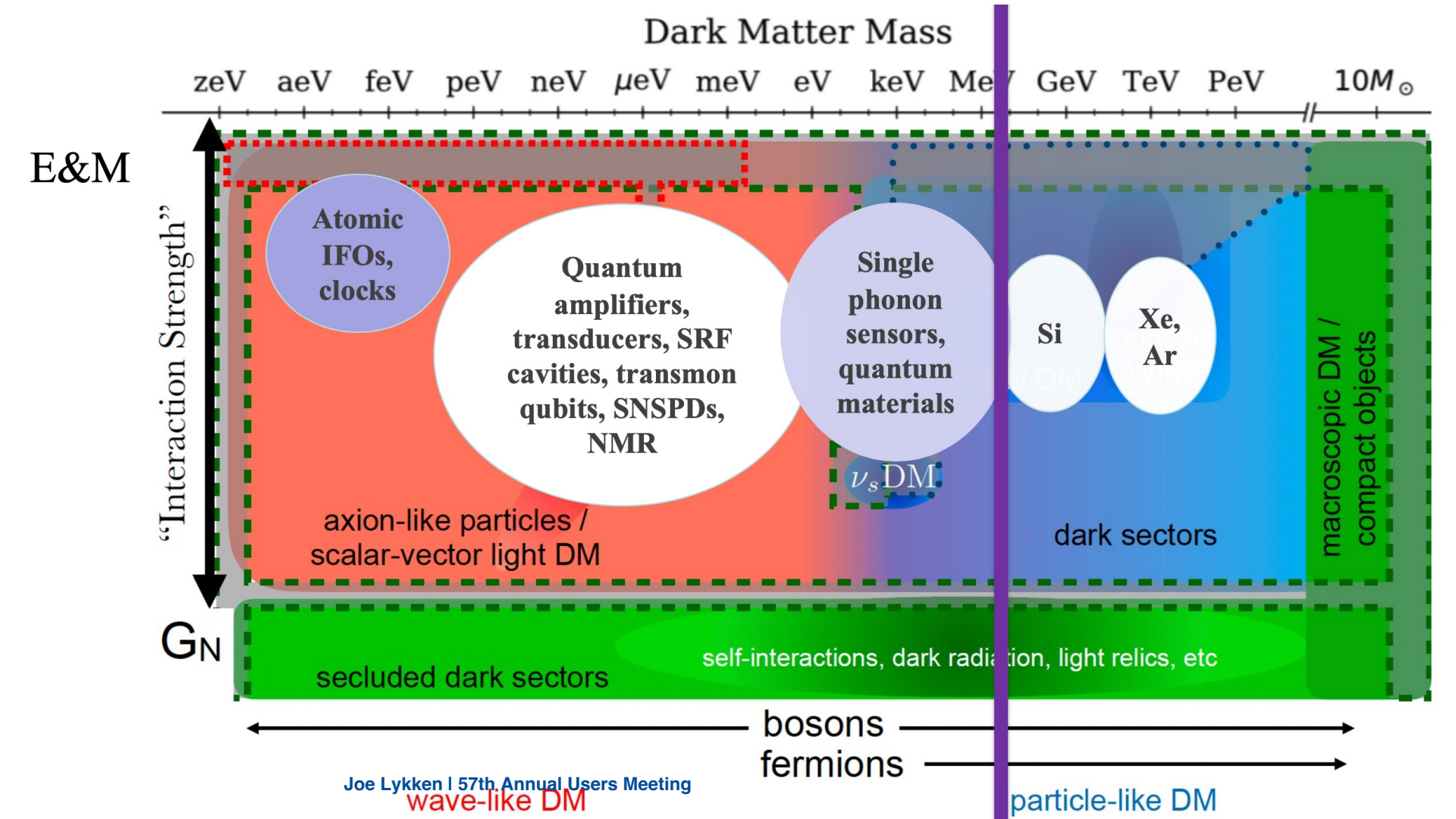
A DOE National Quantum Information Science Research Center, led and host by Fermilab

Fermilab · Northwestern University · rigetti · AMES National Laboratory · NASA Ames Research Center · NIST · Colorado School of Mines · Coppin State University · FormFactor · Goldman Sachs · Illinois Institute of Technology · INFN · Jefferson Lab · Johns Hopkins University · Lockheed Martin · Lawrence Livermore National Laboratory · LSU · NYU · Royal Holloway University of London · Rutgers · Spelman College · University of Colorado Boulder · UIC · AMES

Fermilab

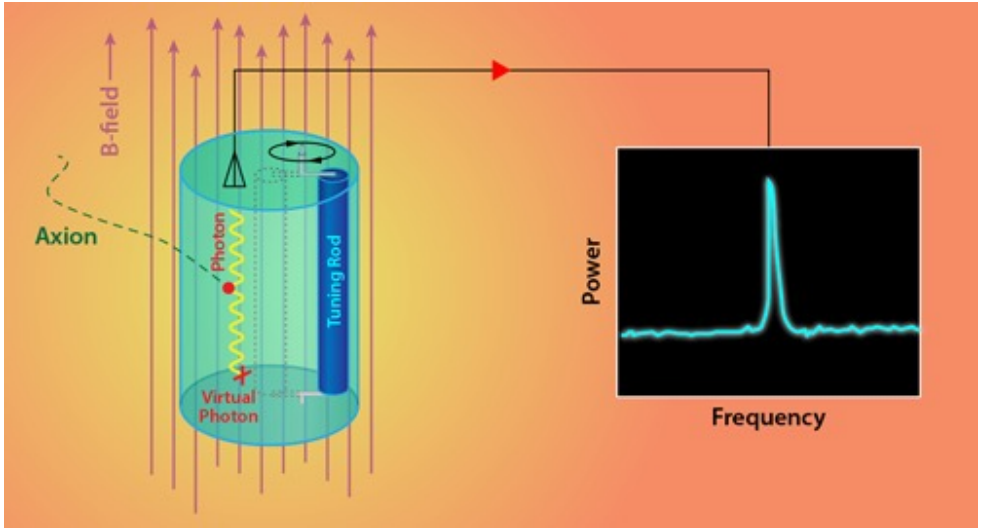
Quantum sensors for dark matter detection

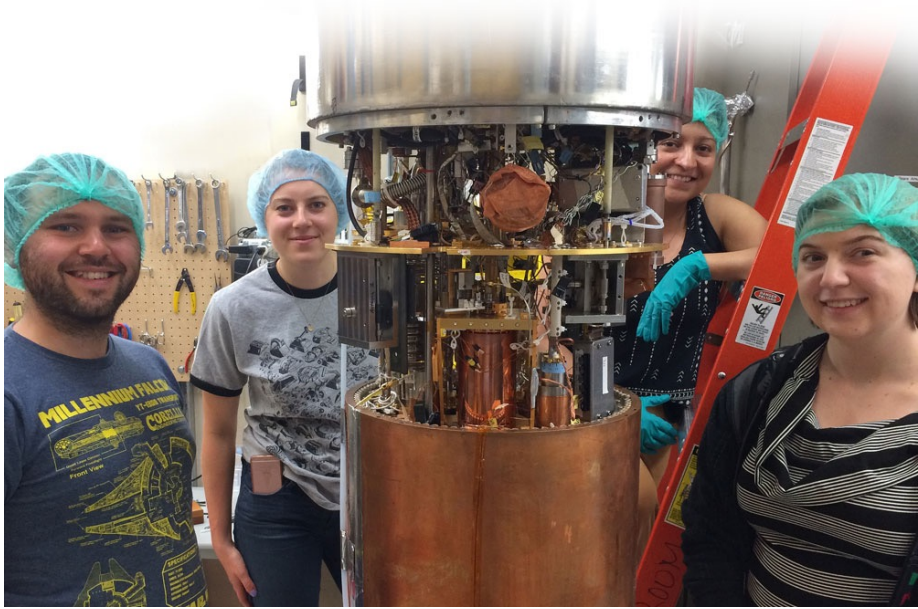

Dark Matter Mass
zeV
aeV
feV
peV
neV
μeV
meV
eV
keV
MeV
GeV
TeV
PeV
10M⊙
E&M
"Interaction Strength"
GN
QCD axion
axion-like particles / scalar-vector light DM
thermal DM
classic WIMP
ν_sDM
dark sectors
macroscopic DM / compact objects
secluded dark sectors
self-interactions, dark radiation, light relics, etc
bosons
fermions
wave-like DM
particle-like DM


Dark Matter Mass
zeV
aeV
feV
peV
neV
μeV
meV
eV
keV
MeV
GeV
TeV
PeV
10M⊙
E&M
"Interaction Strength"
Atomic IFOs, clocks
Quantum amplifiers, transducers, SRF cavities, transmon qubits, SNSPDs, NMR
Single phonon sensors, quantum materials
Si
Xe, Ar
ν_sDM
axion-like particles / scalar-vector light DM
dark sectors
macroscopic DM / compact objects
G_N
secluded dark sectors
self-interactions, dark radiation, light relics, etc
bosons
fermions
wave-like DM
particle-like DM

ADMX experiment

- 7 Tesla magnet surrounds a resonant copper cavity cooled to ~100 mK
- If cavity frequency matches axion mass, should get a microwave photon signal ~ 10^{-22} watts





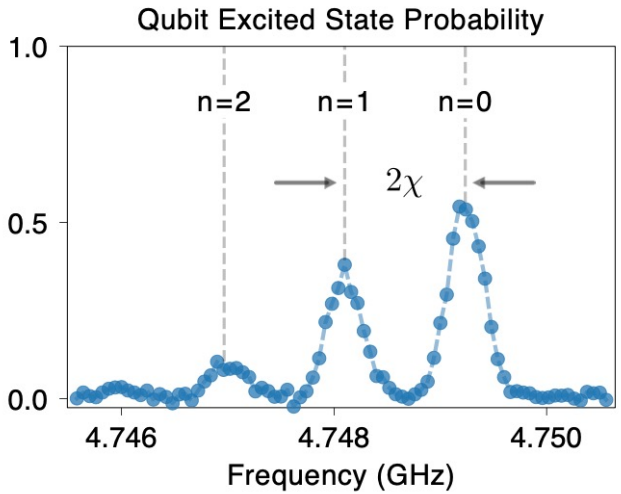
So far ruling out QCD axions as dark matter in mass range ~ 2.6-4.2 μeV

Qubit readout for axion haloscopes

PHYSICAL REVIEW LETTERS **126,** 141302 (2021)

Featured in Physics

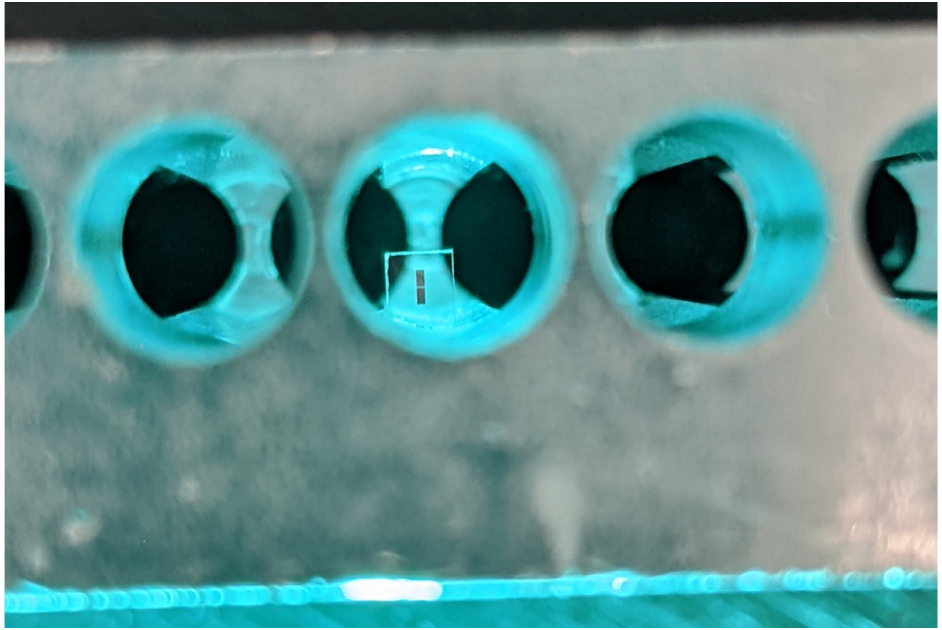
It works! Have already reached a factor of 40 below the Standard Quantum Limit



transmon qubit in a 6 GHz cavity

Searching for Dark Matter with a Superconducting Qubit

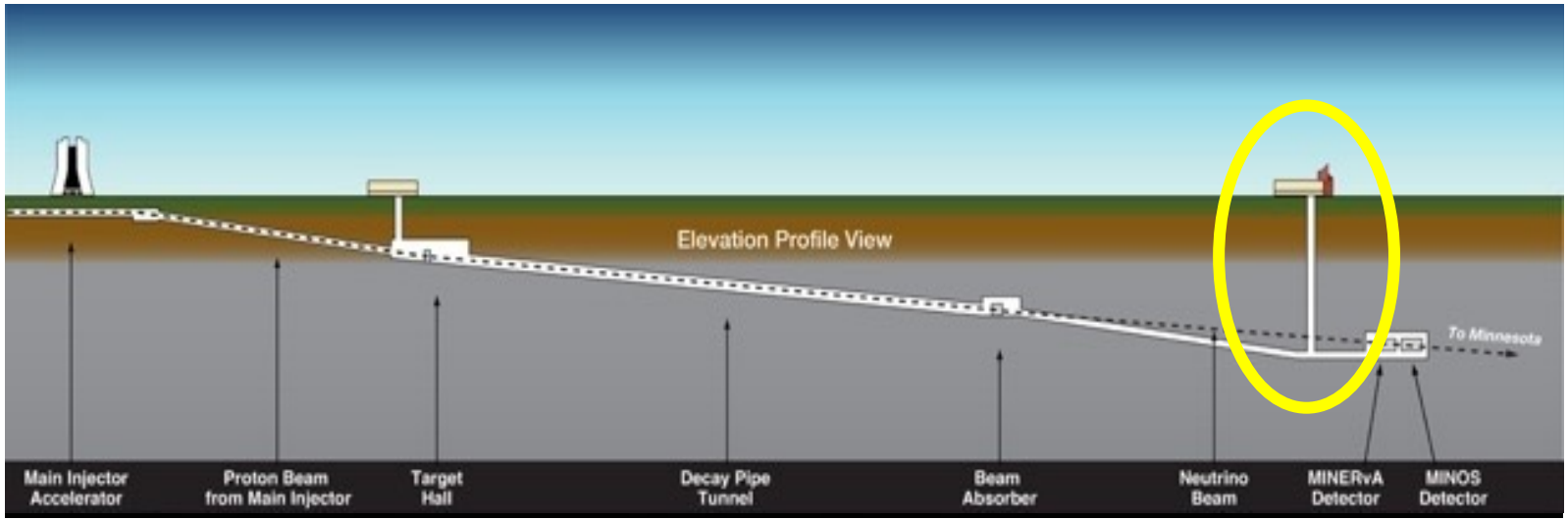
Akash V. Dixit,[1,2,3,*] Srivatsan Chakram,[1,2,4] Kevin He,[1,2] Ankur Agrawal,[1,2,3] Ravi K. Naik,[5] David I. Schuster,[1,2,6] and Aaron Chou[7]



The MAGIS-100 experiment

See talk today by Lederman Fellow Dylan Temples, 5:20 pm

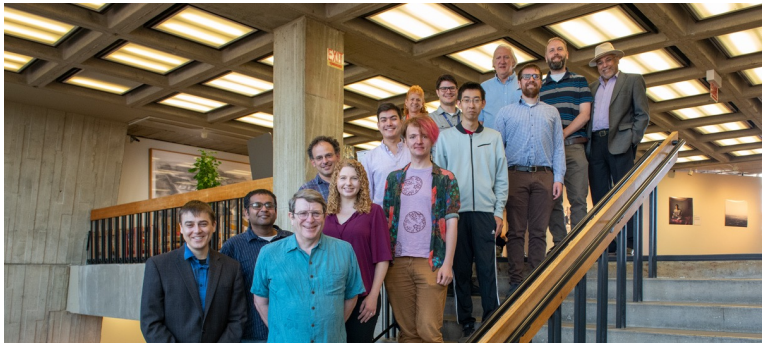
MAGIS-100: large scale atom interferometry at Fermilab



Use existing 100-meter shaft from the neutrino program

MAGIS-100 Collaboration



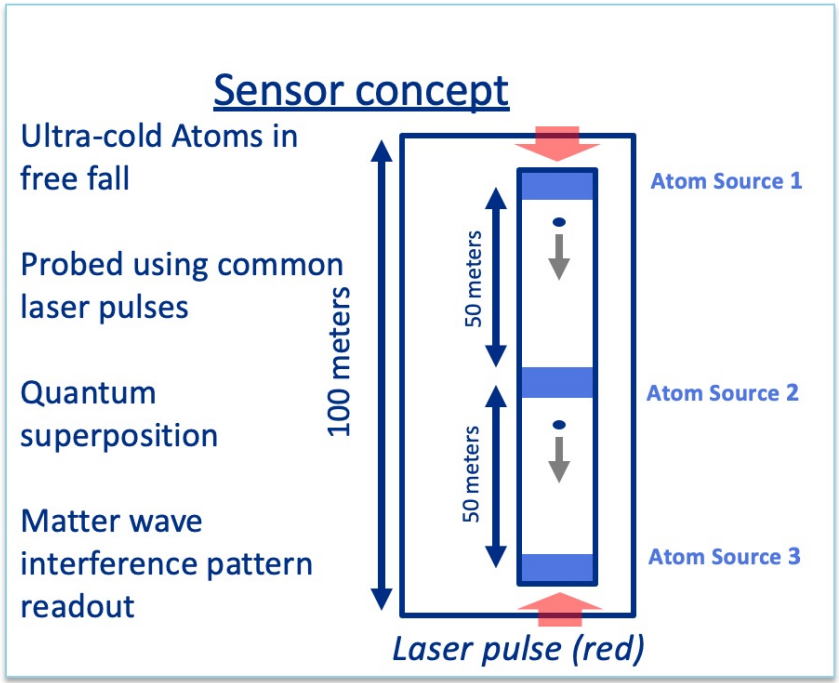
Stanford · Johns Hopkins University · Northwestern University · Fermilab · SLAC · Old Dominion University

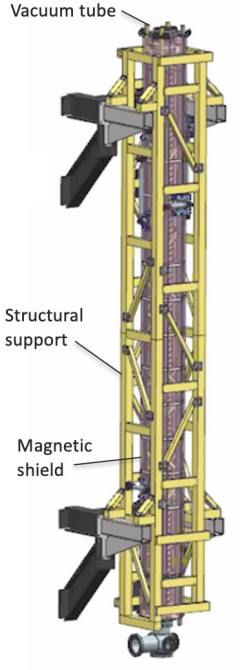
University of Cambridge · Northern Illinois University · University of Oxford · University of Liverpool

Supported by:

Moore Foundation · DOE QuantISED · UK STFC · Kavli Foundation

MAGIS-100:
Multiple atom interferometers on a 100-meter scale





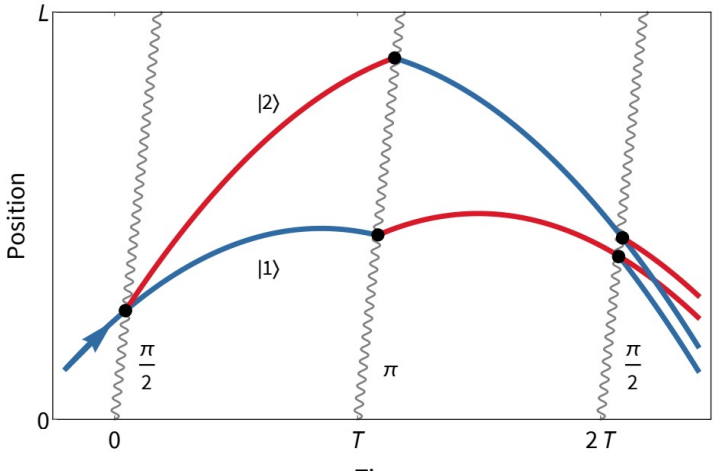
Modular Section x 17

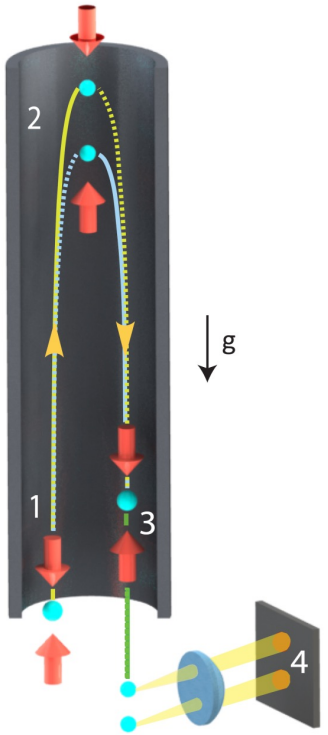
Fermilab

Fountain atom clocks and atom interferometers

- A “fountain” atomic clock is very similar to the Stanford atom interferometer
- A fountain of cold atoms travel up through a region that applies a pi/2 pulse, then fall back again to get the second pi/2 pulse
- The atoms are in freefall in a vacuum chamber

An atom interferometer using strontium has sensitivity to disturbances along its path similar to the precision of a strontium clock ~ 1 part in 10^{16}





MAGIS-100 will be quantum sensor for ultralight dark matter and:

No current agency supported experiments

Well suited for atom interferometry

Goal 5: Pathfinder h ~ $10^{-14}/Hz^{1/2}$

Rich Science Case

Degree scale localization for LIGO sources with ~ 10^5 s lead time, enabling multi messenger astronomy


QUIET
Proteox

QUIET: our underground qubit testing facility

QUANTUM SCIENCE CENTER

a place to study qubits shielded from the effects of cosmic rays

QICK: the quantum instrumentation control kit

Jim Siegrist circa 2014: there is a national quantum initiative coming and HEP should have a major role in it. At the very least we should be the ones to figure out how to do quantum controls...

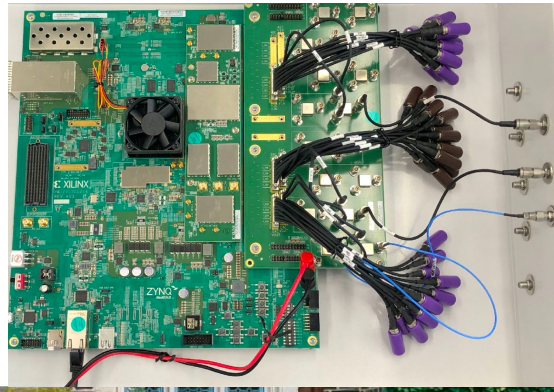
QICK: the quantum instrumentation control kit

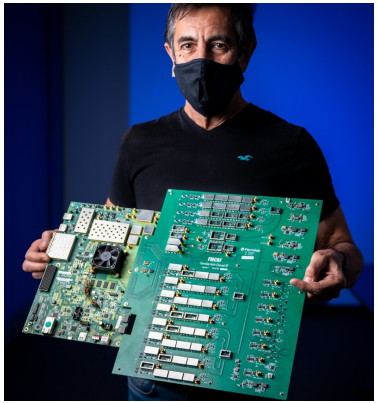
An open-source quantum controls and readout system developed by Gustavo Cancelo's team at Fermilab

Already the world's dominant quantum controls solution, widely adopted by academia, industry, and all five DOE quantum centers

The Houck lab's contributions to QICK

- Founding members of the collaboration
- Developed new Xilinx dev boards for QICK (ZCU216)
- Beta-testers of new QICK boards and firmwares
  - Multiplexed readout
  - Multi-qubit systems

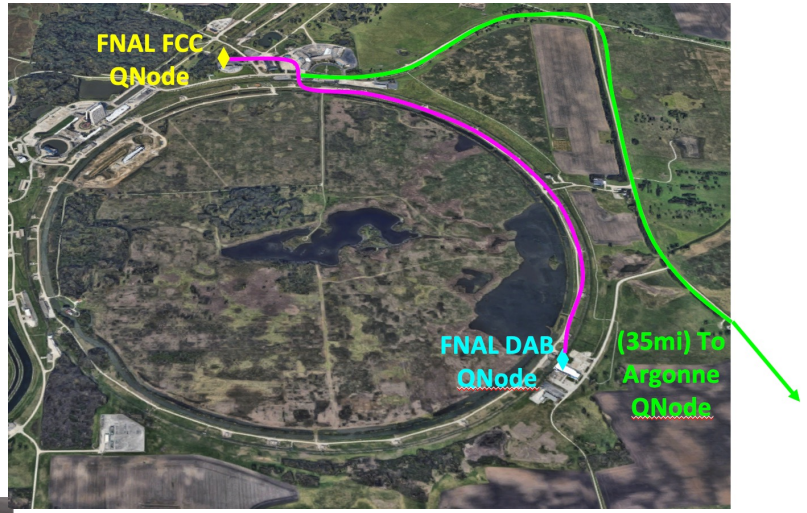


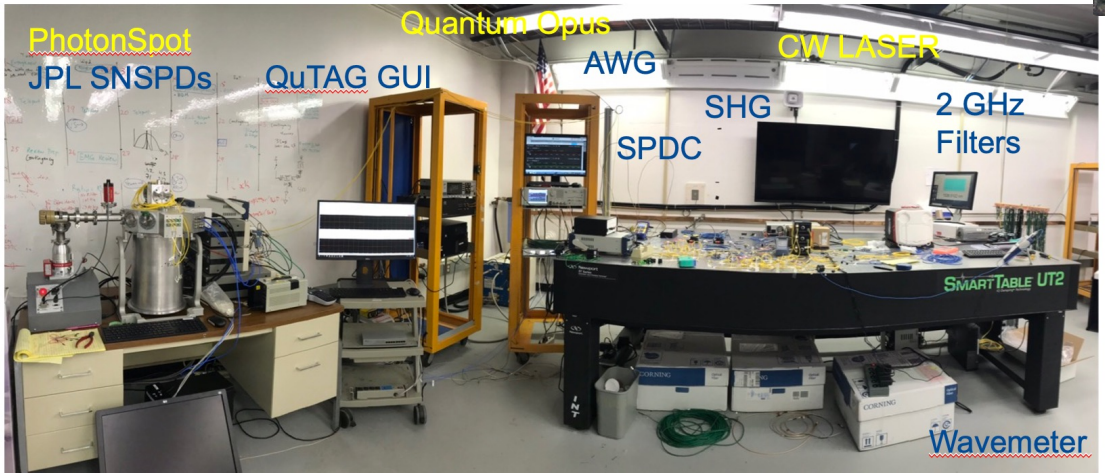


Quantum teleportation networks

Quantum teleportation at Fermilab

- Quantum teleportation is something we know how to do in a lab
- At Fermilab we have a high-fidelity, high-rate quantum teleportation network connecting nodes 2 km apart with ordinary commercial fiber





Teleportation nodes of the Fermilab Quantum Network

Quantum teleportation at Fermilab and Caltech

Possible applications include networking of quantum computers and quantum sensors, as well as provably secure communications

It works!

PRX QUANTUM
a Physical Review journal

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Open Access

Teleportation Systems Toward a Quantum Internet

Raju Valivarthi, Samantha I. Davis, Cristián Peña, Si Xie, Nikolai Lauk, Lautaro Narváez, Jason P. Allmaras, Andrew D. Beyer, Yewon Gim, Meraj Hussein, George Iskander, Hyunseong Linus Kim, Boris Korzh, Andrew Mueller, Mandy Rominsky, Matthew Shaw, Dawn Tang, Emma E. Wollman, Christoph Simon, Panagiotis Spentzouris, Daniel Oblak, Neil Sinclair, and Maria Spiropulu

PRX Quantum **1**, 020317 – Published 4 December 2020

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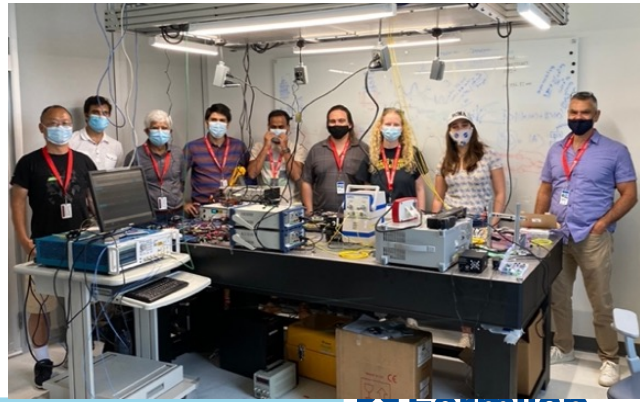
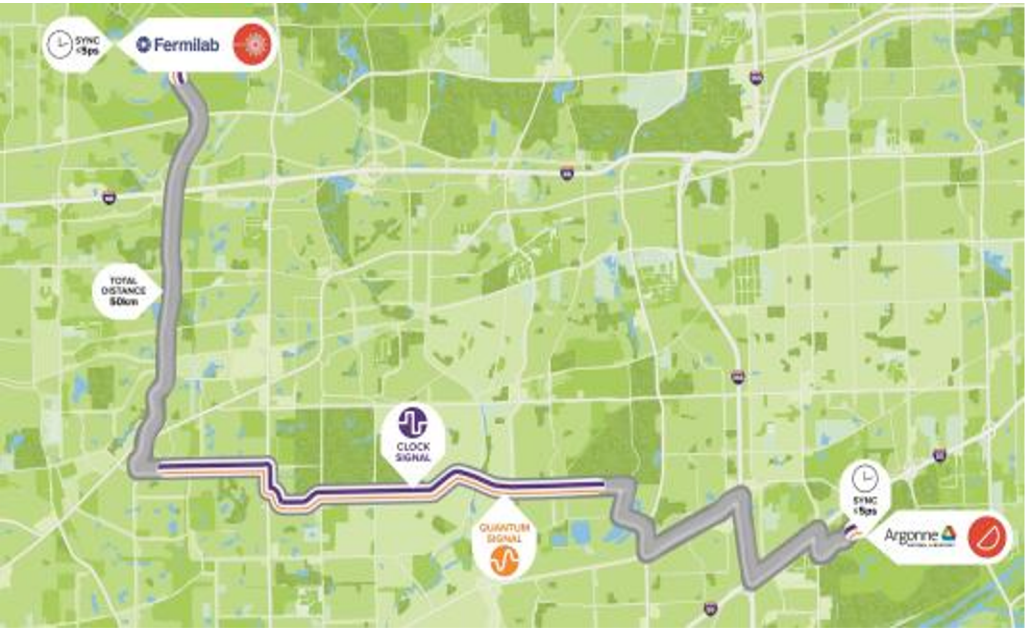
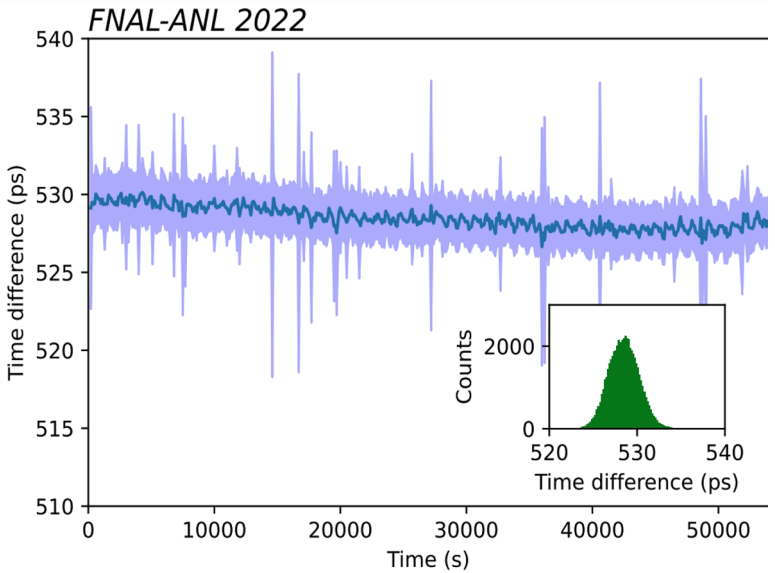


Quantum teleportation network between Fermilab and Argonne

- Key challenge: synchronize the clocks between the quantum nodes
- We developed in-house a picosecond synchronization system with the classical clock signal and photonic qubits co-existing on the same fiber





Quantum internet blueprint

- The DOE Quantum Internet initiative was announced at the University of Chicago, July 2020
- Goal is to connect all 17 national labs with a high-performance quantum teleportation optical fiber network
- Can also provide cybersecurity for the energy grid
- Supported by DOE ASCR

Quantum scientists of tomorrow

Quantum scientists of tomorrow

Annual Quantum Computing for Physics Undergraduates Internship

summer school + year-long internship

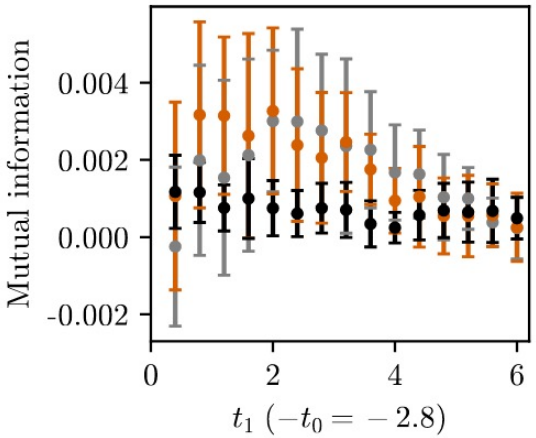
hosted by the Quantum Theory Department

Outlook

This is, and will continue to be, an exciting area to work in

Quantum activities at Fermilab that I didn't have time to cover:

- Wormhole teleportation
- Quantum algorithms
- Cryogenic electronics
- Quantum imaging




Thank you for your attention