Quantum Sensors for HEP

Rakshya Khatiwada

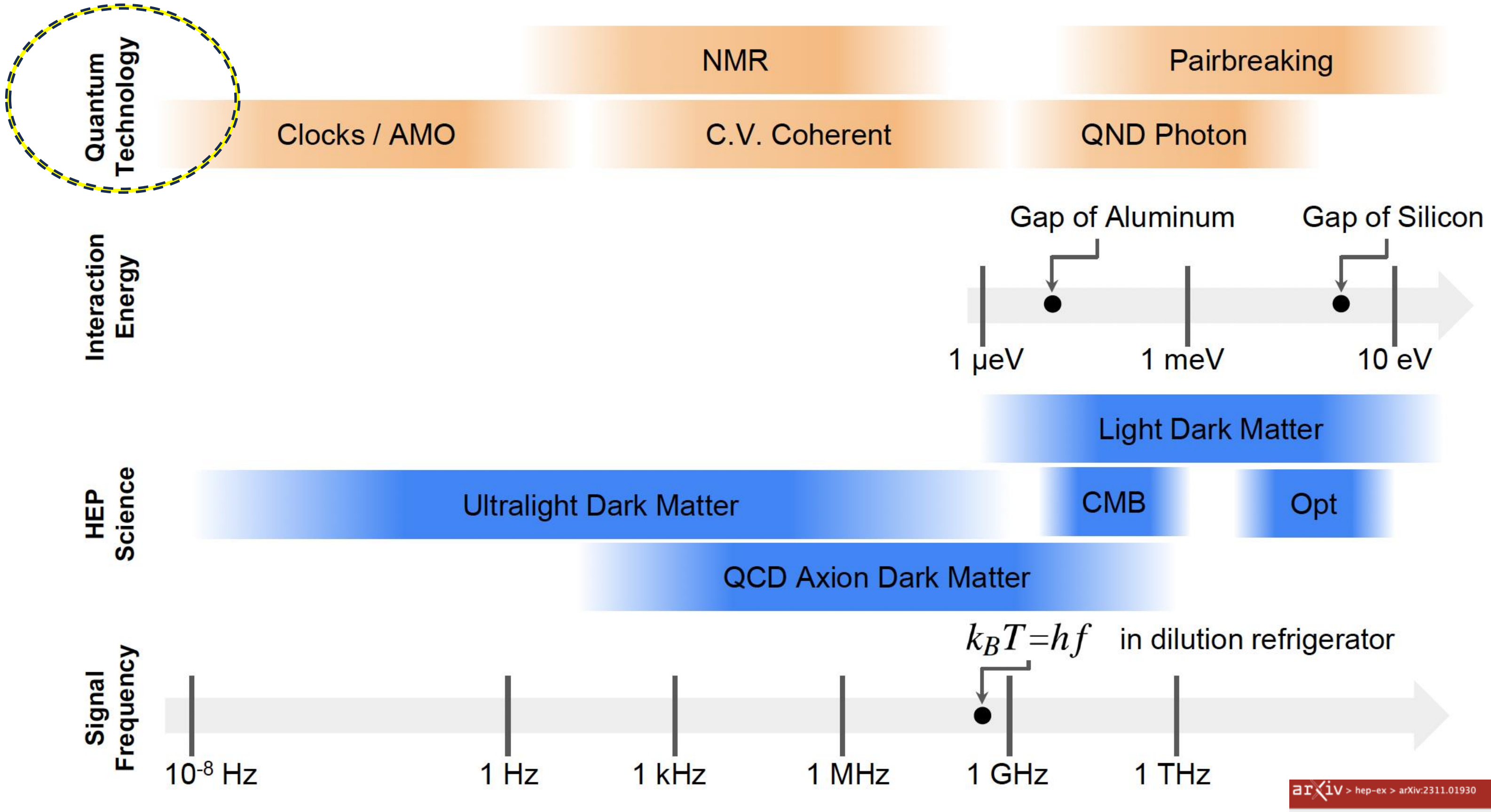
Illinois Institute of technology & Fermilab

Aspen Center for Physics

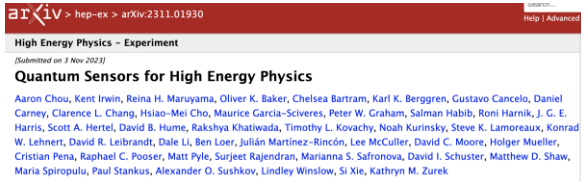
03/26/2024

Motivation to use Quantum Sensors

Science Drivers and Energy Scale



Great for probing sub-eV energy scale!



arXiv > hep-ex > arXiv:2311.01930

Help | Advanced

High Energy Physics – Experiment

[Submitted on 3 Nov 2023]

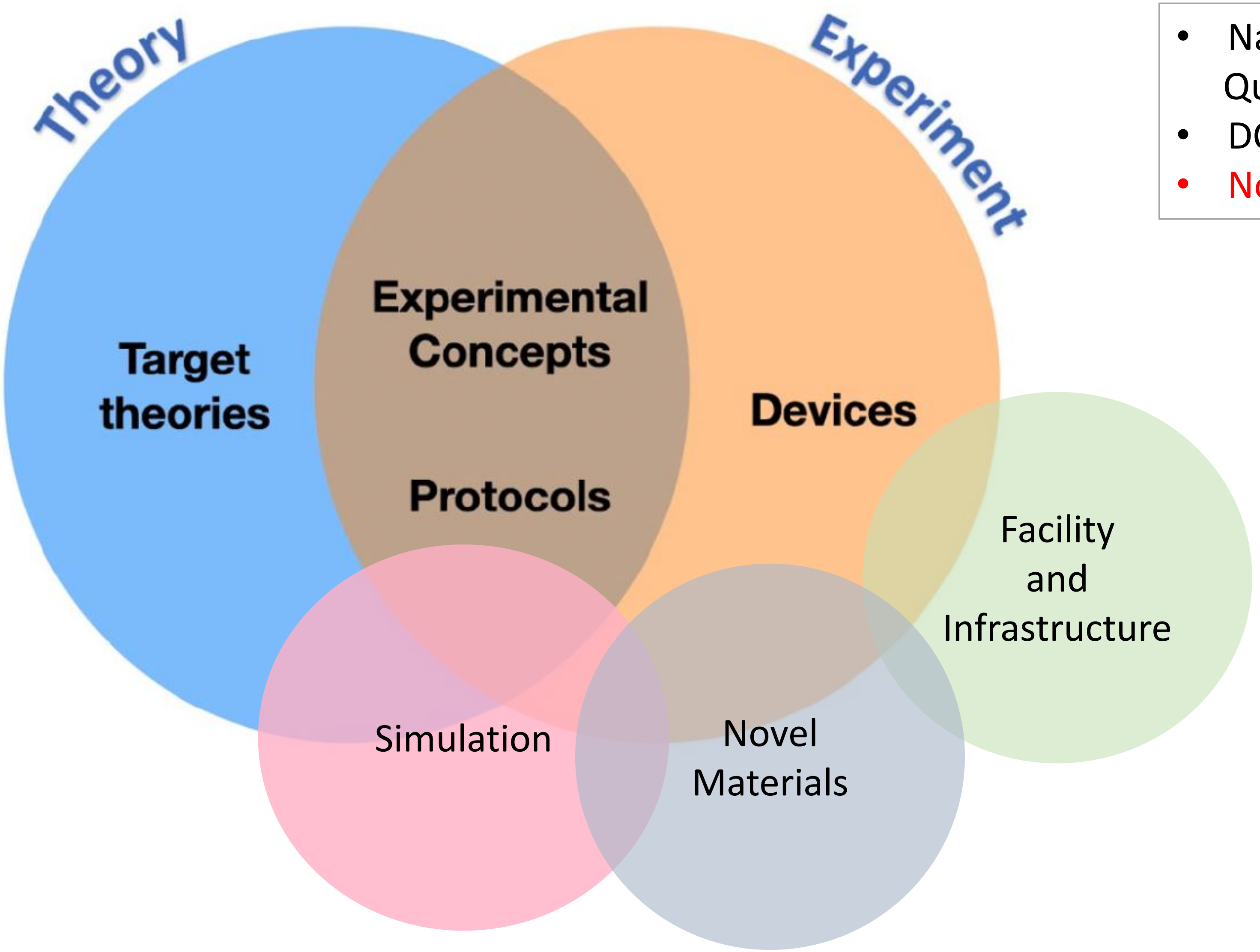
Quantum Sensors for High Energy Physics

Aaron Chou, Kent Irwin, Reina H. Maruyama, Oliver K. Baker, Chelsea Bartram, Karl K. Berggren, Gustavo Cancelo, Daniel Carney, Clarence L. Chang, Hsiao-Mei Cho, Maurice Garcia-Sciveres, Peter W. Graham, Salman Habib, Roni Harnik, J. G. E. Harris, Scott A. Hertel, David B. Hume, Rakshya Khatiwada, Timothy L. Kovachy, Noah Kurinsky, Steve K. Lamoreaux, Konrad W. Lehnert, David R. Leibrandt, Dale Li, Ben Loer, Julián Martínez-Rincón, Lee McCuller, David C. Moore, Holger Mueller, Cristian Pena, Raphael C. Pooser, Matt Pyle, Surjeet Rajendran, Marianna S. Safronova, David I. Schuster, Matthew D. Shaw, Maria Spiropulu, Paul Stankus, Alexander O. Sushkov, Lindley Winslow, Si Xie, Kathryn M. Zurek

US Particle Physics
https://www.usparticlephysics.org › 2023-p5-report

2023 P5 Report: Exploring the Quantum Universe Recommendation: CMB, DM

Comprehensive Quantum Frontier program



- National Quantum Initiative Quantum Science Centers
- DOE QuantiSED
- No Quantum Frontier yet

Figure modified from Quantum Sensors for HEP arXiv:2311.01930

Quantum and Superconducting sensors

Quantum Sensor (broader definition): any new quantum device or technique that has the potential to achieve greater reach towards beyond-the-standard-model physics than that achievable through conventional techniques traditionally used in HEP. → Not just superposition and entanglement based

Quantum Sensors for HEP
arXiv:2311.01930

Coordinating Panel for Advanced Detectors (CPAD)

US R&D COLLABORATIONS

GOALS:

→ **Provide a roadmap for US Detector R&D program**
→ **Coordinate efforts for funding opportunities**

Coordinate with European effort to avoid redundancy

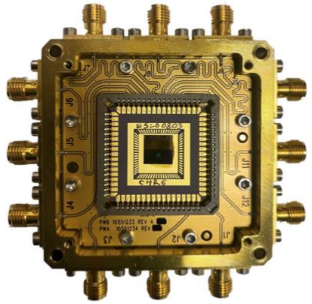
R&D Collaborations

RDC	Topic	Coordinators
1	Noble Element Detectors	Jonathan Asaadi, Carmen Carmona
2	Photodetectors	Shiva Abbaszadeh, Flavio Cavanna
3	Solid State Tracking	Sally Seidel, Tony Affolder
4	Readout and ASICs	Angelo Dragone, Mitch Newcomer
5	Trigger and DAQ	Jinlong Zhang, (TBN)
6	Gaseous Detectors	Prakhar Garg, Sven Vahsen
7	Low-Background Detectors (incl. CCDs)	Noah Kurinsky, Guillermo Fernandez-Moroni
8	Quantum and superconducting Detectors	Aritoki Suzuki, Rakshya Khatiwada
9	Calorimetry	Marina Artuso, Minfang Yeh
10	Detector Mechanics	Andy Jung, Eric Anderssen
11	Fast Timing	Gabriele Giacomini, Matt Wetstein

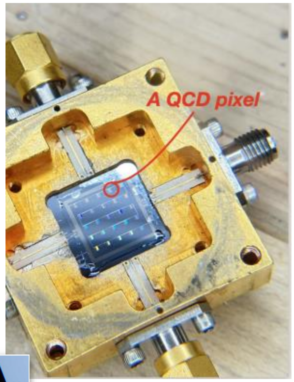
→ RDC8 is quantum and superconducting detectors
→ **Nov 7-11 annual CPAD workshop in SLAC, CA, USA**

Quantum and Superconducting sensors

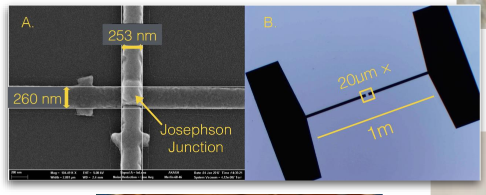
1. Pairbreaking sensors:
Microwave Kinetic Inductance Detectors, Transition Edge Sensors, Superconducting Nanowire Single-Photon-Detectors, Quantum Capacitance Detectors, Superconducting Qubits….

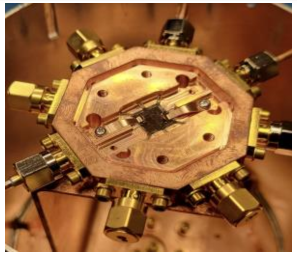


SNSPDs

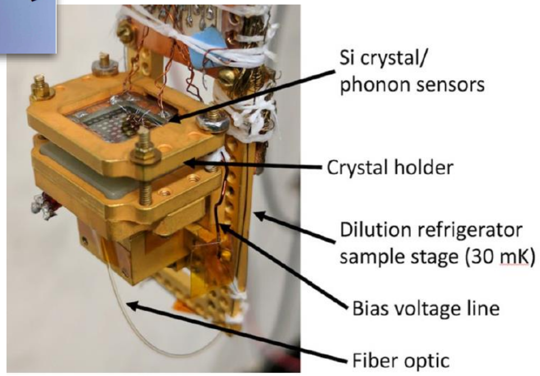


QCDs





Qubits



TESes

Pics: JPL, FNAL, BRN

Principle of Operation
Resistance,
Quantum Capacitance,
Coherence,
Kinetic Inductance

Due to Cooper-pair breaking

Advantage
Single photon counting with lowest dark rate,
Low energy single-excitation sensing,
High quantum efficiency

Enabling Quantum Technology
Standard Quantum Noise evasion

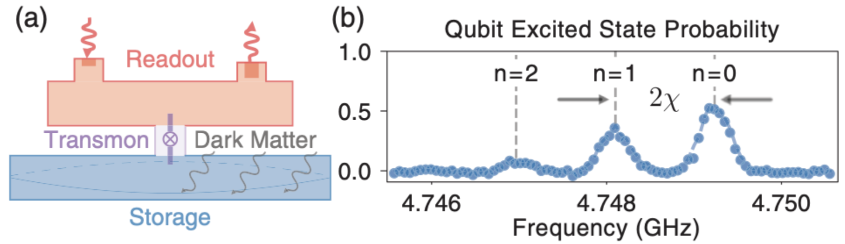
SQL: Similar to $\Delta x \Delta p \geq \hbar/2$
phase and amplitude

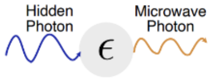
48 mK ($h\omega/k_B$ @1GHz)

Hidden photon Dark Matter search with qubits

QuantiSED

U Chicago/FNAL





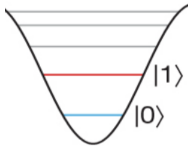
Qubit + 3D cavity – qubit excited state probability due to presence of a DM signal photon

Hidden Markov model to reduce noise to 16 dB below SQL

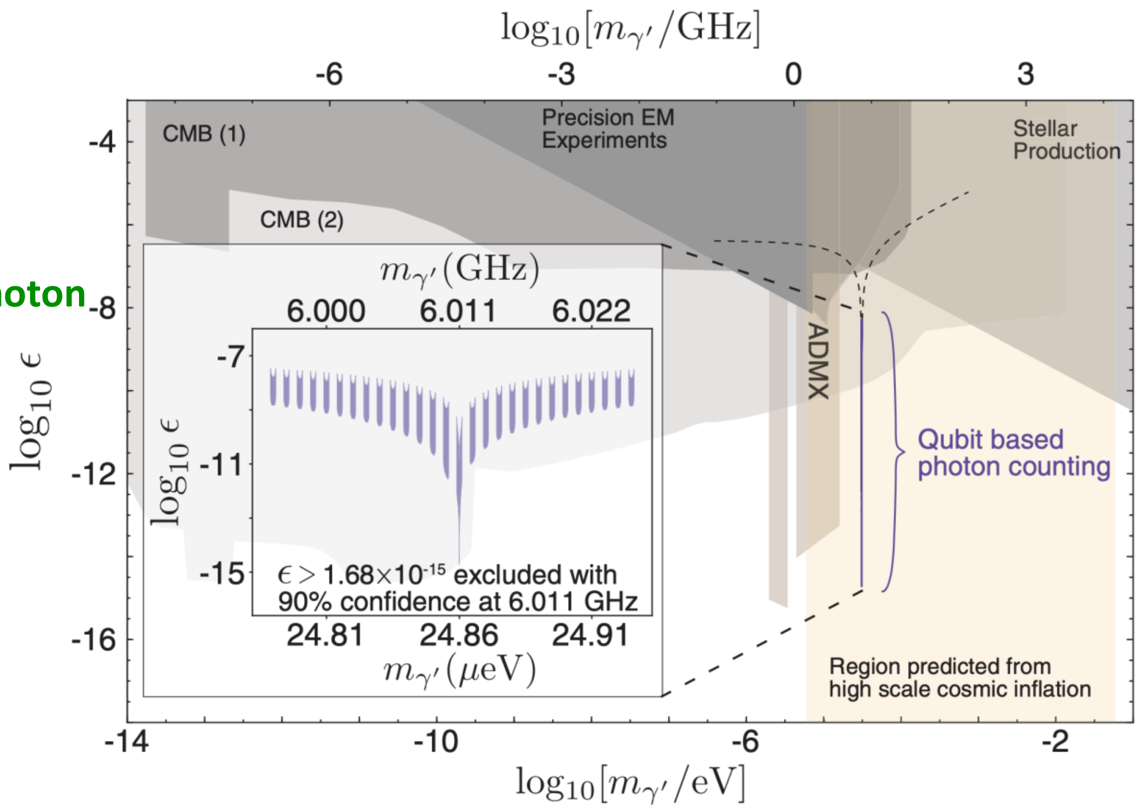
$$H = \omega_c a^\dagger a + \omega_q \sigma_z + 2\frac{g^2}{\Delta} a^\dagger a \sigma_z$$

Cavity
Harmonic Oscillator

qubit
two level system



mixed state
g ~ **d.E**:
Δ: ω_q-ω_c
g^2/Δ: Stark shift



Hidden photon world limits set by qubits in 8 s integration time

Searching for Dark Matter with a Superconducting Qubit

Akash V. Dixit, Srivatsan Chakram, Kevin He, Ankur Agrawal, Ravi K. Naik, David I. Schuster, and Aaron Chou
Phys. Rev. Lett. **126**, 141302 – Published 8 April 2021

HEISING-SIMONS FOUNDATION

Quantum and Superconducting sensors

2. Coherent wave sensors:
Josephson Parametric Amplifiers, Travelling Wave PA, Squeezed state receivers, Microwave to optical transducers, Superconducting RF cavities, RF quantum upconverters..

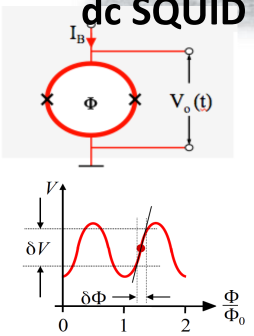
Principle of Operation
Parametric amplification,
High Q resonance cavities/resonators,
kHz-MHz to GHz and GHz to THz up-conversion,

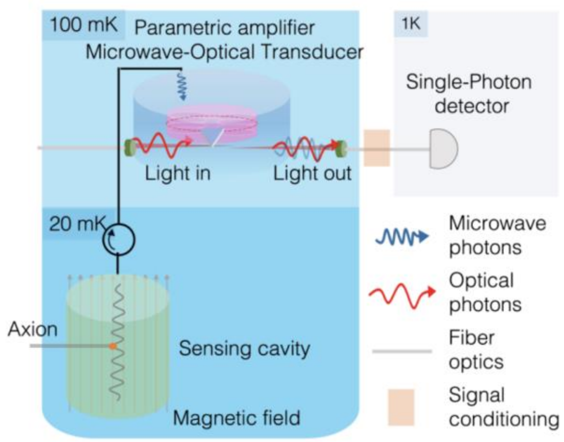
Advantage
low noise readout,
Potential for DM searches with magnetic field and high Q cavity,

Enabling Quantum Technology
Standard Quantum Limit,
Squeezing and backaction evasion extends to kHz to 100s of THz DM

Josephson Parametric Amplifier

dc SQUID



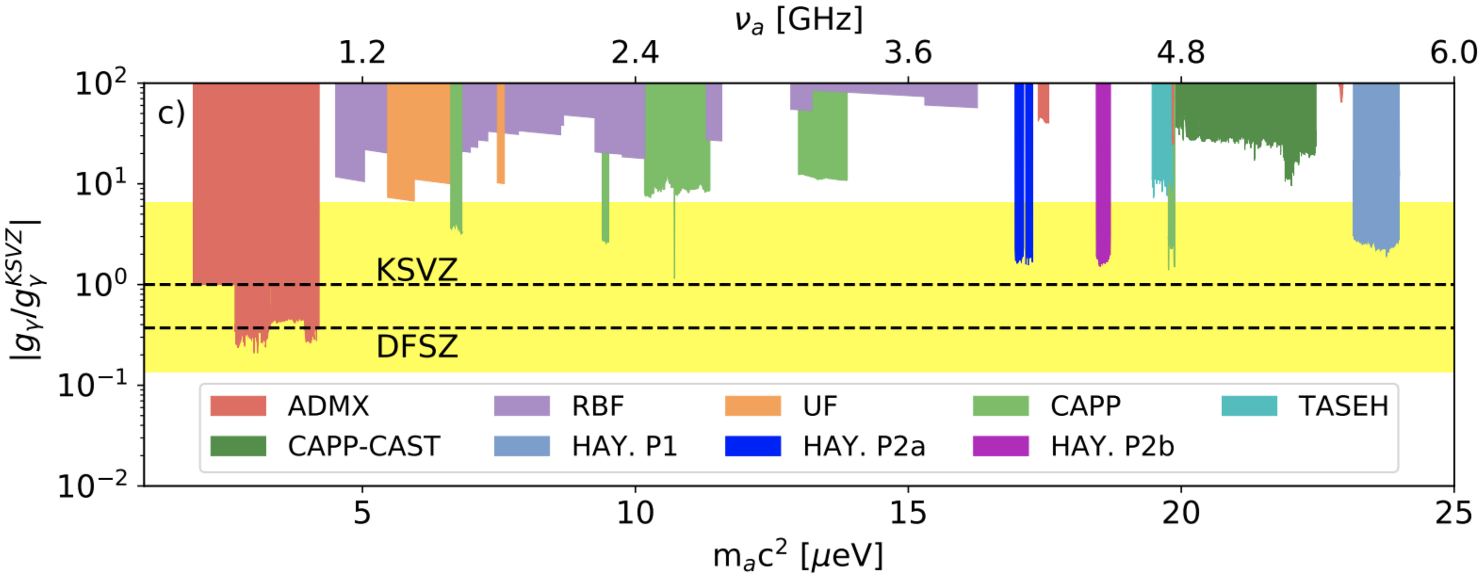


MW to Optical transducer

SRF cavity

Axion search with Squeezed state receiver

HAYSTAC Phase IIb



x2 Scan Speed

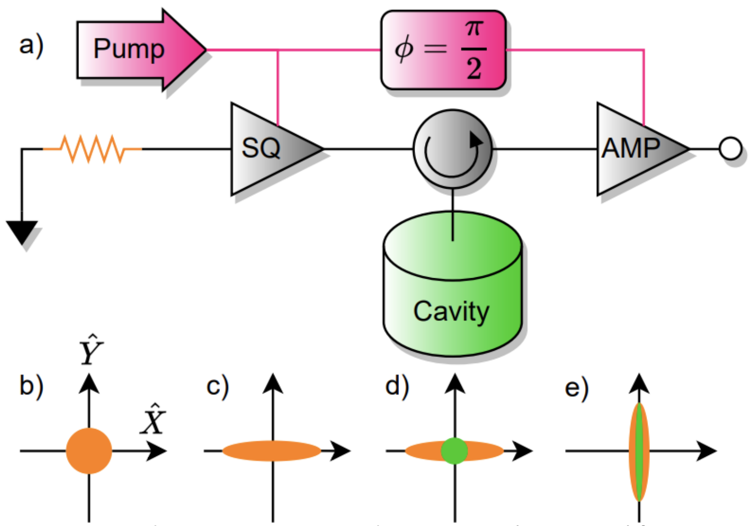
4 dB Squeezing

New results from HAYSTAC's phase II operation with a squeezed state receiver

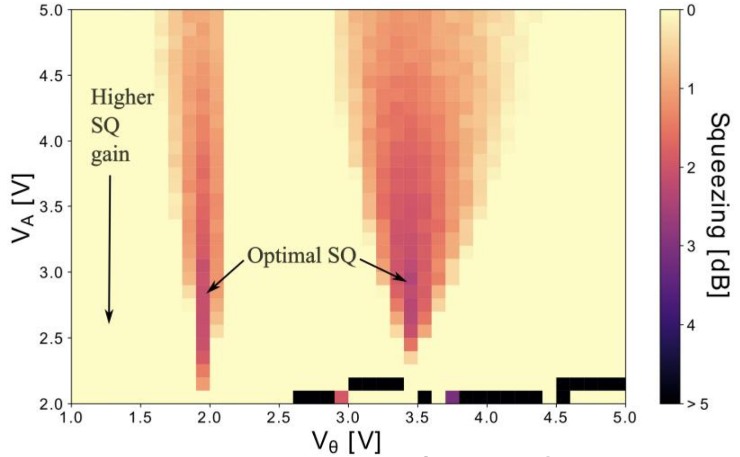
M. J. Jewell *et al.* (HAYSTAC Collaboration)

Phys. Rev. D **107**, 072007 – Published 28 April 2023

receiver



unsqueezed noise, JPA squeezed, axion signal, JPA amplification



Squeezing achieved

Quantum and Superconducting sensors

3. AMO, clocks, interferometry, NMR, Optomechanical sensors: neutral atoms, trapped ions, magnetometers, spin precession, optomechanical devices, entangled probes…

Principle of Operation

Atomic energy level shifts,
Strain, acceleration,
Entanglement induced correlation in quantum states,

Advantage

Noise suppression,
High sensitivity,
Long distance quantum coherence,
Long wavelength radiation detection,
Directional resolution of astronomical objects,

Enabling Quantum Technology

Better precision due to entanglement
1/N vs. $1/\sqrt{N}$
(**Heisenberg's limit**),
Squeezing, backaction evasion

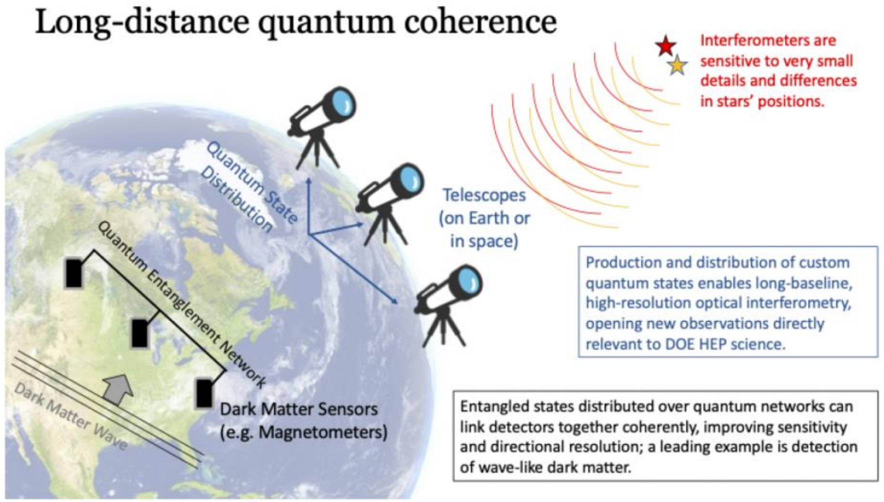
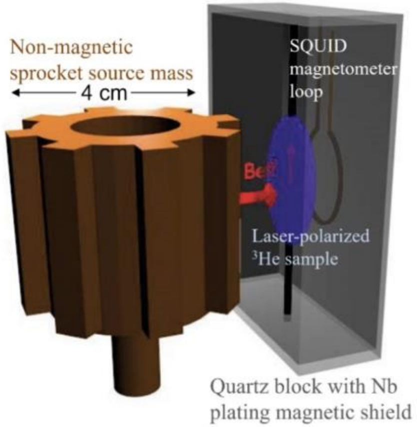


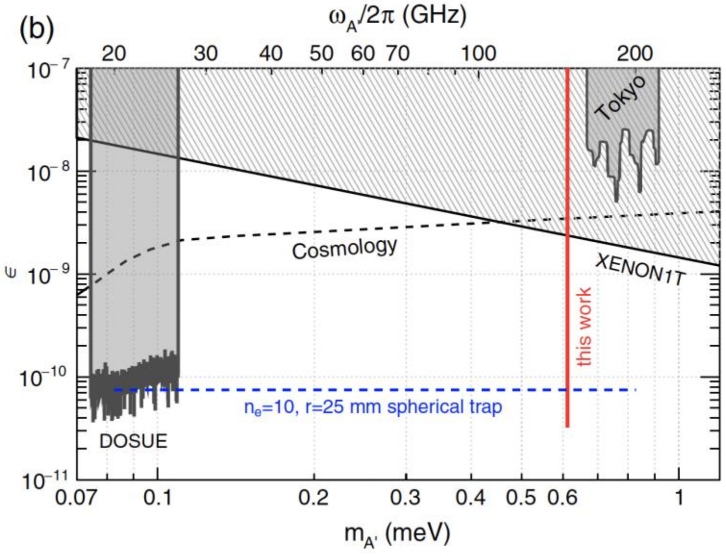
Fig: Quantum Sensors for HEP

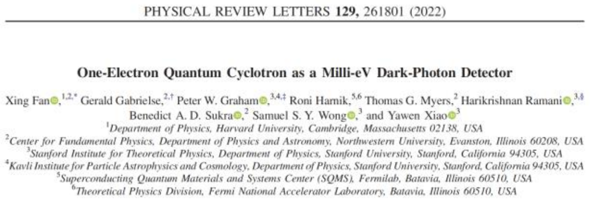
ARIADNE



Demonstrated sensitivity and capabilities

Trapped e- Dark Photon search at 148 GHz





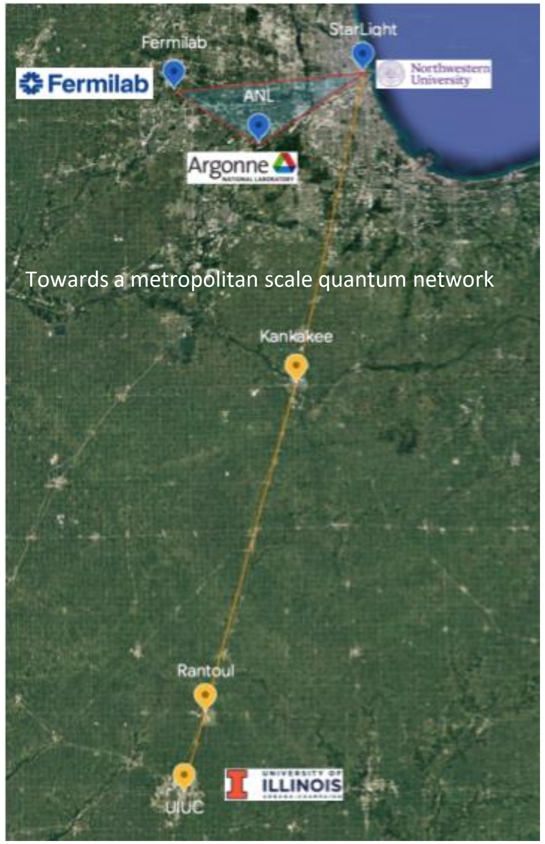
PHYSICAL REVIEW LETTERS **129,** 261801 (2022)

One-Electron Quantum Cyclotron as a Milli-eV Dark-Photon Detector

Xing Fan,[1,2,*] Gerald Gabrielse,[2,†] Peter W. Graham,[3,4,‡] Roni Harnik,[5,6] Thomas G. Myers,[2] Harikrishnan Ramani,[3,§] Benedict A. D. Sukra,[2] Samuel S. Y. Wong,[3] and Yawen Xiao[3]

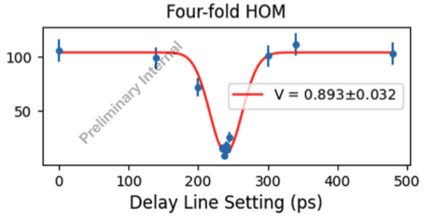
[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*Center for Fundamental Physics, Department of Physics and Astronomy, Northwestern University, Evanston, Illinois 60208, USA*
[3]*Stanford Institute for Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305, USA*
[4]*Kavli Institute for Particle Astrophysics and Cosmology, Department of Physics, Stanford University, Stanford, California 94305, USA*
[5]*Superconducting Quantum Materials and Systems Center (SQMS), Fermilab, Batavia, Illinois 60510, USA*
[6]*Theoretical Physics Division, Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*

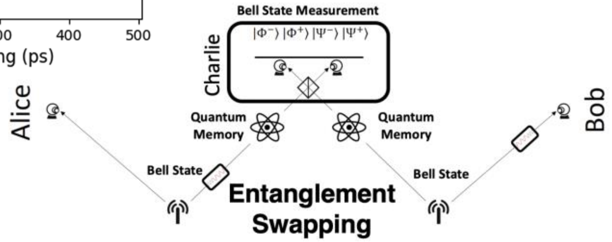
Illinois Express Quantum Network (IEQNET)



- → **FNAL, Argonne, Caltech, Northwestern**
- → High fidelity **quantum teleportation achieved between multiple nodes (50 km) at Argonne and Fermilab** (2022) using entangled photons
- → Picosecond level entanglement distribution and clock synchronization between two nodes.
- → **Quantum networking over metropolitan distances**

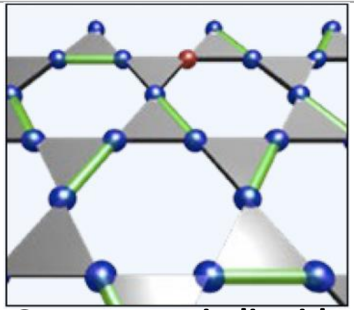
Teleportation of entanglement: entanglement swapping



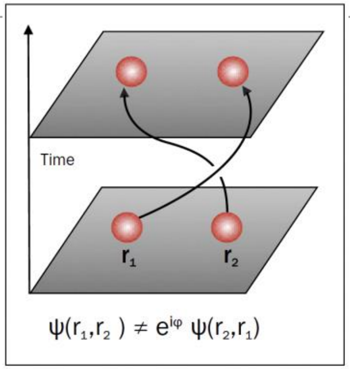


Quantum and Superconducting sensors

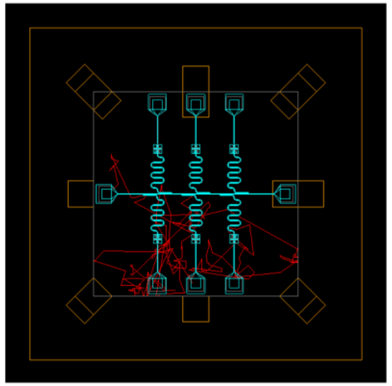
4. Novel materials, Theory and Simulation: Quantum and metamaterials, Low bandgap materials (Dirac, Weyl, Sapphire), High T_C materials, spin liquids, NV centers, topological insulators etc.



Quantum spin liquid

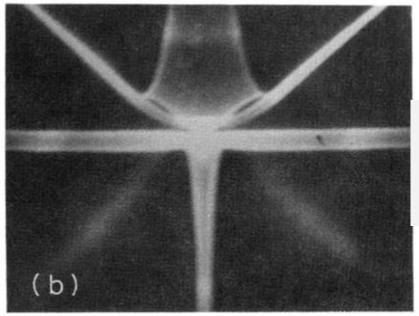


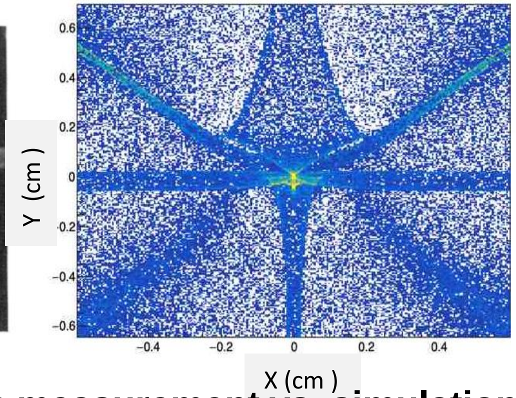
Non-abelian exchange stat.



phonon simulation in a 6-qubit silicon chip (G4CMP)

5 meV





Sapphire Phonon caustic measurement vs. simulation

Host
exotic quasiparticles (magnons, spinons, phonons), and surface properties

Advantage
Quasiparticles boast quantum behaviors,
Harness topological states for surface properties,
Low threshold excitations

Enabling Quantum Technology
coherence, entanglement, quantum transport,
Novel quantum mechanical state

Fig: BRN Quantum materials, IIT/FNAL

HEP and Quantum Synergy

Resolving catastrophic error bursts from cosmic rays in large arrays of superconducting qubits

Matt McEwen, Lara Faoro, Kunal Arya, Andrew Dunsworth, Trent Huang, Seon Kim, Brian Burkett, Austin Fowler, Frank Arute, Joseph C. Bardin, Andreas Bengtsson, Alexander Bilmes, Bob B. Buckley, Nicholas Bushnell, Zijun Chen, Roberto Collins, Sean Demura, Alan R. Derk, Catherine Erickson, Marissa Giustina, Sean D. Harrington, Sabrina Hong, Evan Jeffrey, Julian Kelly, … Rami Barends

+ Show authors

Correlated charge noise and relaxation errors in superconducting qubits

C. D. Wilen, S. Abdullah, N. A. Kurinsky, C. Sta… Ioffe, C. H. Liu, A. Opremcak, B. G. Christensen,

A superconductor free of quasiparticles for seconds

E. T. Mannila,[1,*] P. Samuelsson,[2] S. Simbierowicz,[3,†] J. T. Peltonen,[1] V. Vesterinen,[3] L. Grönberg,[3] J. Hassel,[3] V. F. Maisi,[2] and J. P. Pekola[1]

[1] Centre of Excellence, Department of Applied Physics, Aalto University, FI-00076 Aalto, Finland
[2] Physics Department and NanoLund, Lund University, Box 118, 22100 Lund, Sweden
[3] VTT Technical Research Centre of Finland Ltd, QTF Centre of Excellence, P.O. Box 1000, FI-02044 VTT, Finland

(Dated: February 2, 2021)

A Stress Induced Source of Phonon Bursts and Quasiparticle Poisoning

R. Anthony-Petersen,[1] A. Biekert,[1,2] R. Bunker,[3] C.L. Chang,[4,5,6] Y.-Y. Chang,[1] L. Chaplinsky,[7] E. Fascione,[8,9] C.W. Fink,[1] M. Garcia-Sciveres,[2] R. Germond,[8,9] W. Guo,[10,11] S.A. Hertel,[7] Z. Hong,[12] N.A. Kurinsky,[13] X. Li,[2] J. Lin,[1,2] M. Lisovenko,[4] R. Mahapatra,[14] A.J. Mayer,[9] D.N. McKinsey,[1,2] S. Mehrotra,[1] N. Mirabolfathi,[14] B. Neblosky,[15] W.A. Page,[1,*] P.K. Patel,[7] B. Penning,[16] …D. Pinckney,[7] M. Platt,[14] M. Pyle,[1] M. Reed,[1] R.K. Romani,[1,*] H. Santana Queiroz,[1] …,[1] B. Serfass,[1] R. Smith,[1,2] P. Sorensen,[2] B. Suerfu,[1,2] A. Suzuki,[2] R. Underwood,[8] … Wang,[4] Y. Wang,[1,2] S.L. Watkins,[1] M.R. Williams,[16] V. Yefremenko,[4] and J. Zhang[4]

[1] Department of Physics, University of California, Berkeley, CA 94720, USA
[2] Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
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[5] Department of Astronomy and Astrophysics, University of Chicago, 5640 South Ellis Avenue, Chicago, Illinois 60637, USA
[6] Kavli Institute for Cosmological Physics, University of Chicago, 5640 South Ellis Avenue, Chicago, Illinois 60637, USA
…ment of Physics, University of Massachusetts, Amherst, Massachusetts 01003, USA

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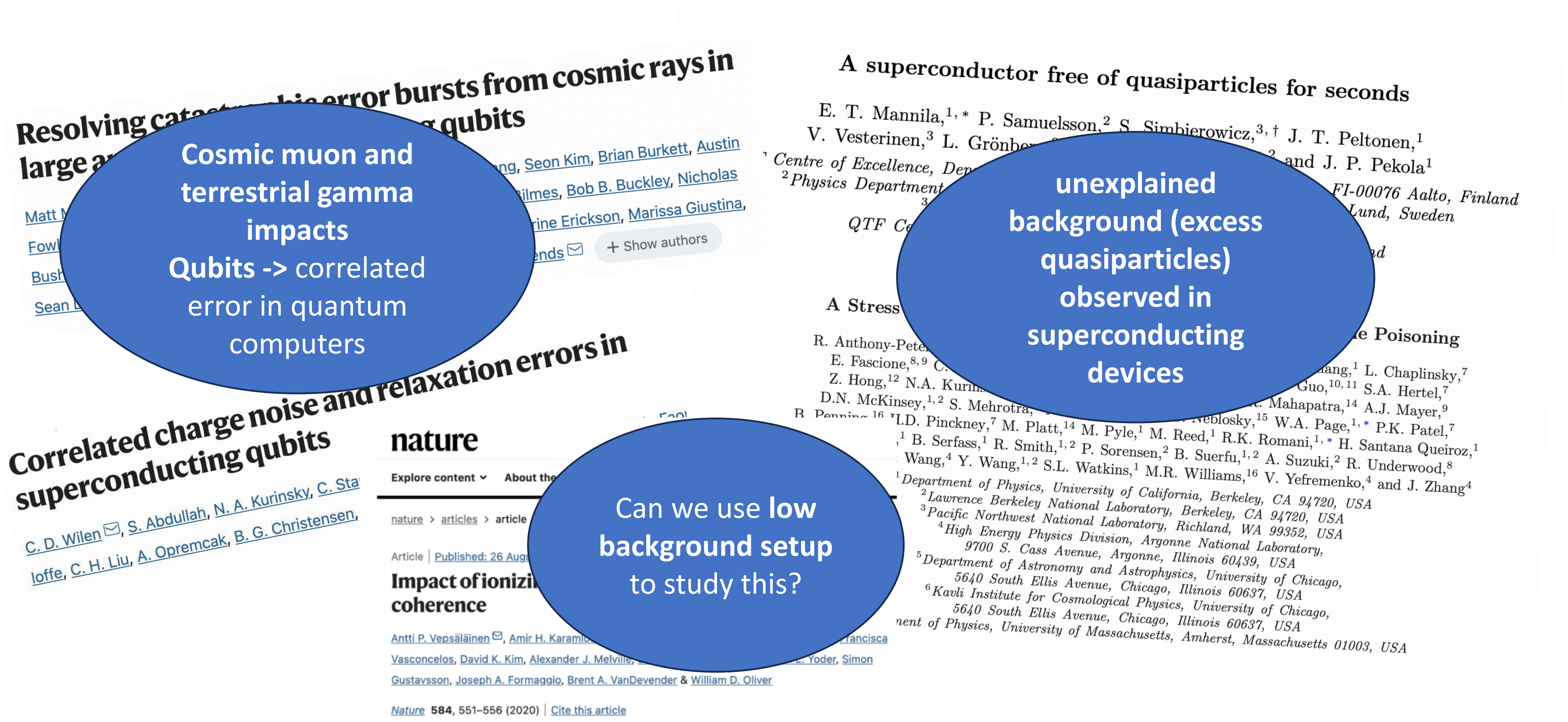
Article | Published: 26 August 2020

Impact of ionizing radiation on superconducting qubit coherence

Antti P. Vepsäläinen, Amir H. Karamlou, John L. Orrell, Akshunna S. Dogra, Ben Loer, Francisca Vasconcelos, David K. Kim, Alexander J. Melville, Bethany M. Niedzielski, Jonilyn L. Yoder, Simon Gustavsson, Joseph A. Formaggio, Brent A. VanDevender & William D. Oliver

Nature 584, 551–556 (2020) | Cite this article

HEP and Quantum Synergy



Conclusion

- Broad application in HEP
- Need a base program in QIS– especially relevant for Early Career
- Coordinated effort in Detector R&D ongoing
- Great potential to advance HEP

THE END

FERMILAB-SLIDES-23-323-ETD

Acknowledgement

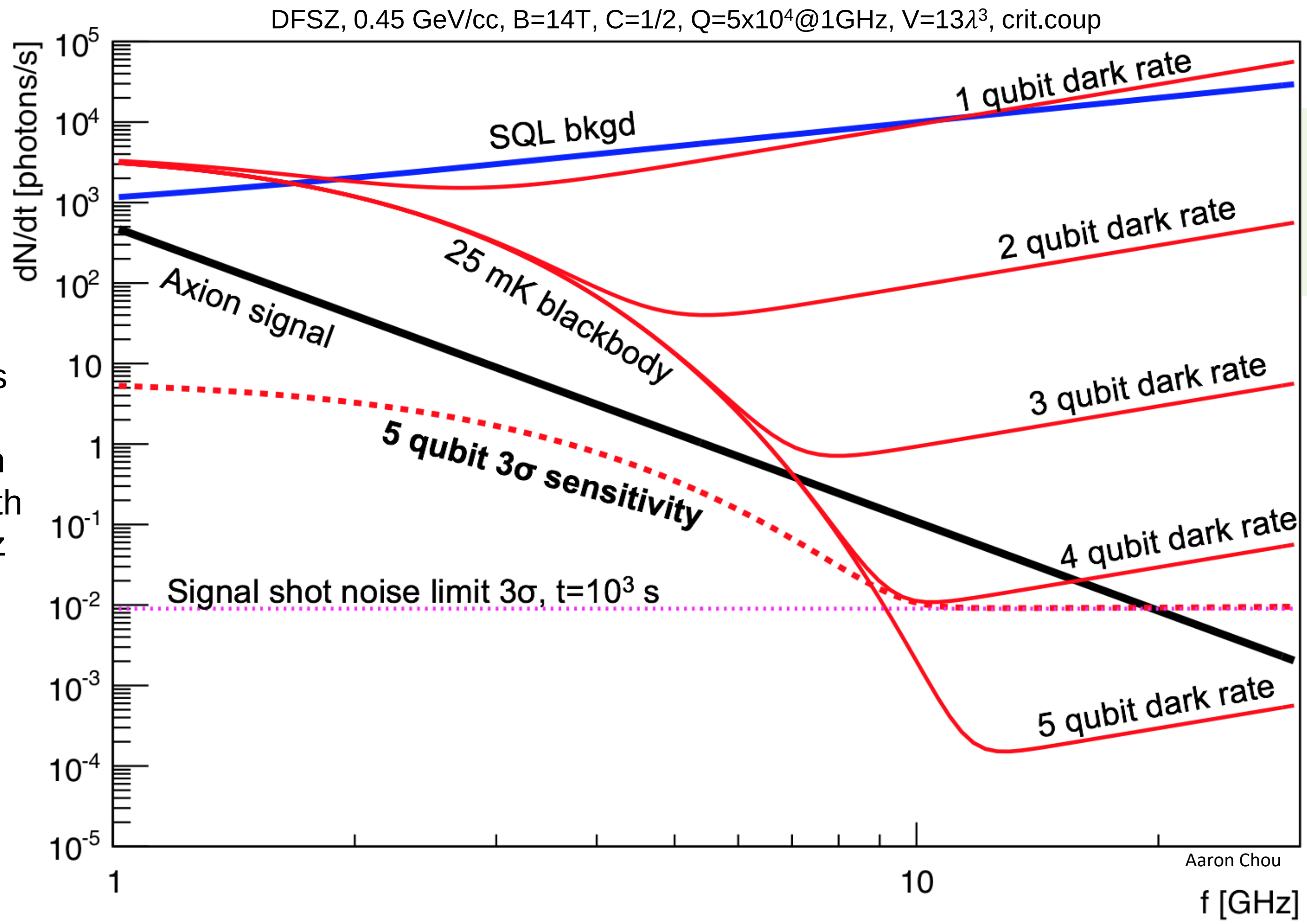
This material is based upon work supported by the U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers, Quantum Science Center.

DOE-OHEP-QuantiSED

- This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

Supplementary Slides

Signal and noise rate



Assumes axion detection bandwidth $\Delta f \sim$ MHz

N QND measurements
dark rate = $(10^{-2})^N \Delta f$

Sensitivity limited only by signal photon shot noise.

NQI Program Component Areas

- **Quantum Sensing and Metrology (QSENS)** refers to the use of quantum mechanics to enhance sensors and measurement science. This can include uses of superposition and entanglement, non-classical states of light, new metrology regimes or modalities, and advances in accuracy and precision enabled by quantum control, for example with atomic clocks.
- **Quantum Computing (QCOMP)** activities include the development of quantum bits (qubits) and entangling gates, quantum algorithms and software, digital and analog quantum simulators using programmable quantum devices, quantum computers and prototypes, and hybrid digital plus analog, as well as quantum plus classical computing systems.
- **Quantum Networking (QNET)** includes efforts to create and use entangled quantum states, distributed over distances and shared by multiple parties, for new information technology applications and fundamental science; for example, networking of intermediate scale quantum computers (modules) for enhanced beyond-classical computing capabilities.
- **QIS for Advancing Fundamental Science (QADV)** includes foundational efforts to invoke quantum devices and QIS theory to expand fundamental knowledge in other disciplines; for example, to improve understanding of biology, chemistry, computation, cosmology, energy science, engineering, materials, nuclear matter, and other aspects of fundamental science.
- **Quantum Technology (QT)** catalogues several topics: work with end-users to deploy quantum technologies in the field and develop use cases; basic R&D on supporting technology for quantum information science and engineering, e.g., infrastructure and manufacturing techniques for electronics, photonics, and cryogenics; and efforts to understand and mitigate risks raised by quantum technologies, e.g., post-quantum cryptography (see Box 4.1).

Axion production

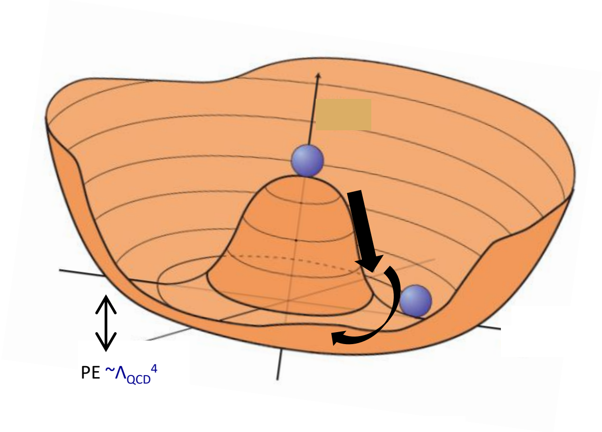
- Global symmetry broken at scale f_a
  -- axion produced through misalignment mechanism
  -- during QCD phase transition, trough tilted by Λ_{QCD}^4
- PE $\sim\Lambda_{QCD}^4$ released, makes up dark matter

  -- oscillation of the QCD θ angle about its minimum--vacuum energy to axions

- QCD axion mass $m_a \sim \Lambda_{QCD}^2/f_a$
  $\sim (200\ \text{MeV})^2/f_a$

  --- f_a unknown

$\Rightarrow$ **GHz frequencies at $f_a \sim 10^{13}$ GeV scale**



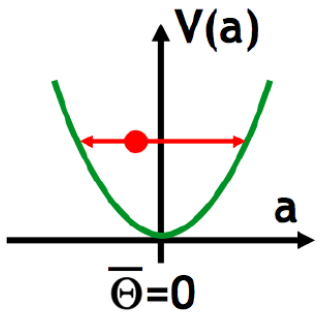
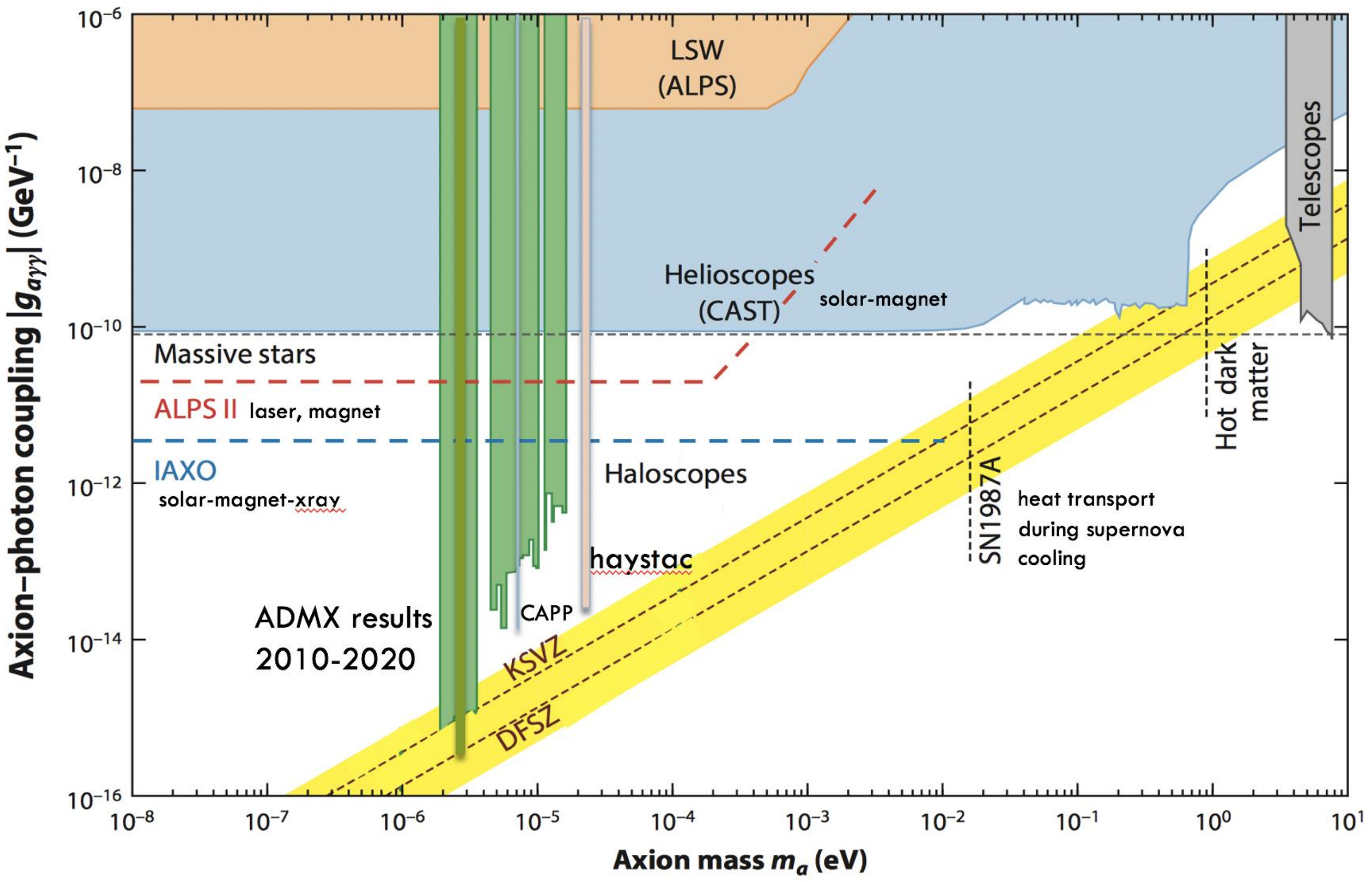


Fig 1:J. Ellis et al; arxiv:1201.6045v1

Axion searches overview



Graham, et. al (2016)

Quantum amplifiers

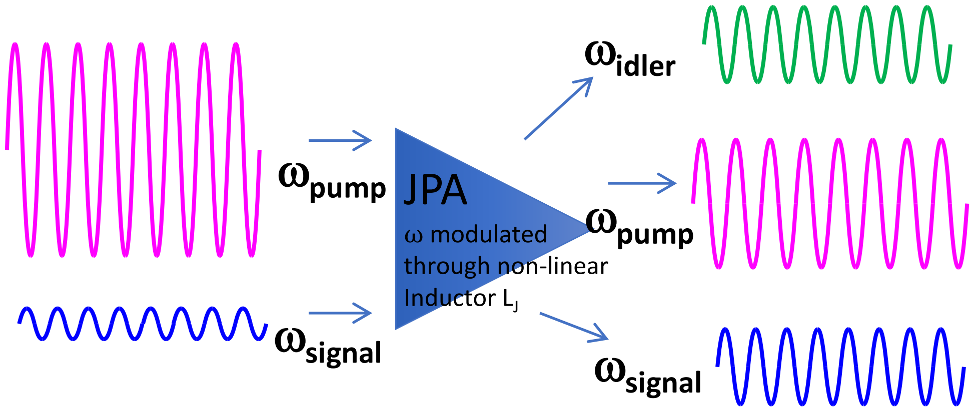
Why quantum amps.?

Intrinsically low noise (superconducting technology)
⇒ low resistance elements
⇒ low thermal dissipation
⇒ Add very low added noise during amplification
=> Tunable in frequency

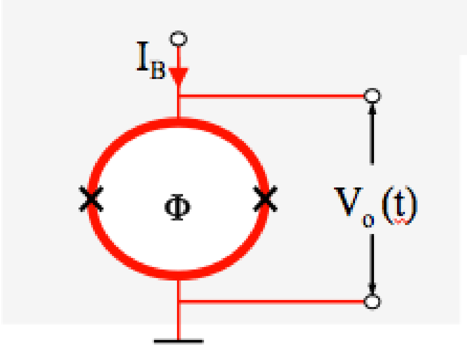
Josephson Parametric Amplifier

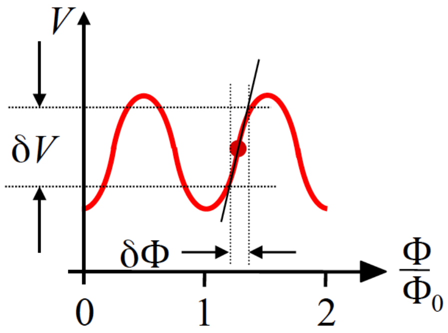
JPA

- Energy transfer from pump to two normal modes of swing



dc SQUID





Only limited by Quantum Noise

What's causing these dark counts?

A superconductor free of quasiparticles for seconds

E. T. Mannila,[1,*] P. Samuelsson,[2] S. Simbierowicz,[3,†] J. T. Peltonen,[1]
V. Vesterinen,[3] L. Grönberg,[3] J. Hassel,[3] V. F. Maisi,[2] and J. P. Pekola[1]

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(Dated: February 2, 2021)

Microfractures due to GE Varnish and mounting glue on Si substrate causing phonon bursts breaking cooper pair -> qp poisioning

Eliminated cosmic muon and radioactive background from suspects since qp poisoning suppressed over longer ~ a week cooldown period

Used similar device to charge parity device like QCD

A Stress Induced Source of Phonon Bursts and Quasiparticle Poisoning

R. Anthony-Petersen,[1] A. Biekert,[1,2] R. Bunker,[3] C.L. Chang,[4,5,6] Y.-Y. Chang,[1] L. Chaplinsky,[7]
E. Fascione,[8,9] C.W. Fink,[1] M. Garcia-Sciveres,[2] R. Germond,[8,9] W. Guo,[10,11] S.A. Hertel,[7]
Z. Hong,[12] N.A. Kurinsky,[13] X. Li,[2] J. Lin,[1,2] M. Lisovenko,[4] R. Mahapatra,[14] A.J. Mayer,[9]
D.N. McKinsey,[1,2] S. Mehrotra,[1] N. Mirabolfathi,[14] B. Neblosky,[15] W.A. Page,[1,*] P.K. Patel,[7]
B. Penning,[16] H.D. Pinckney,[7] M. Platt,[14] M. Pyle,[1] M. Reed,[1] R.K. Romani,[1,*] H. Santana Queiroz,[1]
B. Sadoulet,[1] B. Serfass,[1] R. Smith,[1,2] P. Sorensen,[2] B. Suerfu,[1,2] A. Suzuki,[2] R. Underwood,[8]
V. Velan,[1,2] G. Wang,[4] Y. Wang,[1,2] S.L. Watkins,[1] M.R. Williams,[16] V. Yefremenko,[4] and J. Zhang[4]

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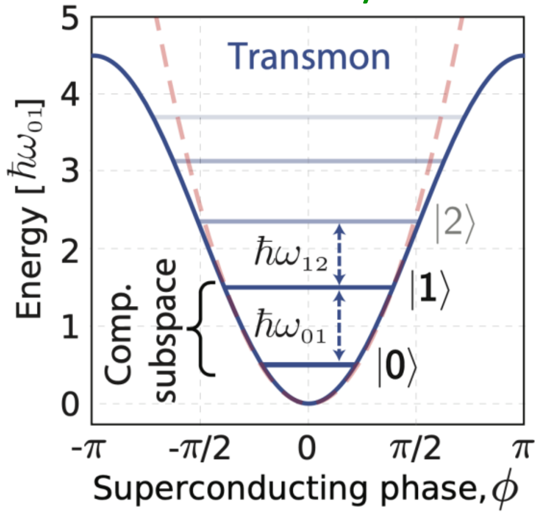
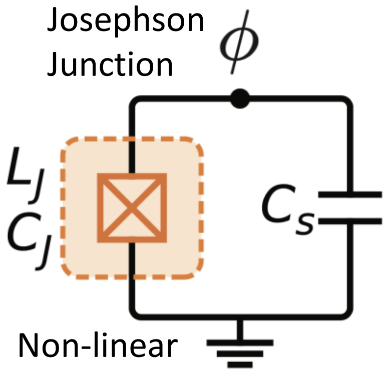
[7]*Department of Physics, University of Massachusetts, Amherst, Massachusetts 01003, USA*

4 Aug 2022

What is a qubit?

two level system

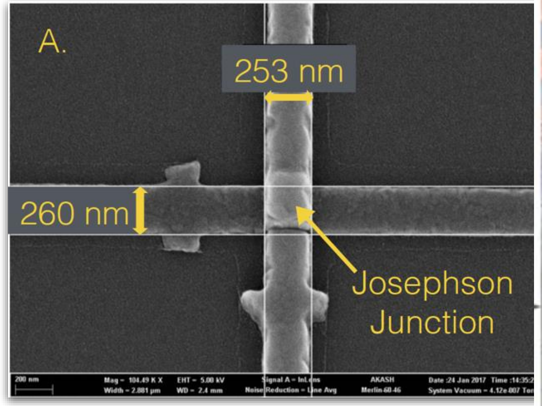


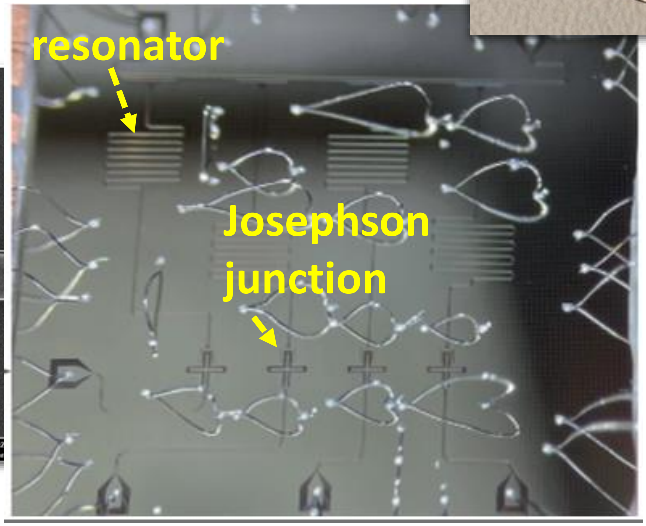


Non-linear dissipation less circuit element

$E_J \gg E_C$
$E_c = e^2/2C$ charging energy
$E_J = I_c\Phi_0/2\pi$ Josephson energy
where $\Phi_0 = h/2e$ magnetic flux quantum

Quadratic energy potential of QHO reshaped by Josephson Inductance to sinusoidal potential





Qubit and resonator circuit on a Si substrate

--Superconducting Transmon and its variants ***can be utilized for Dark Matter detection through several mechanisms of coupling***

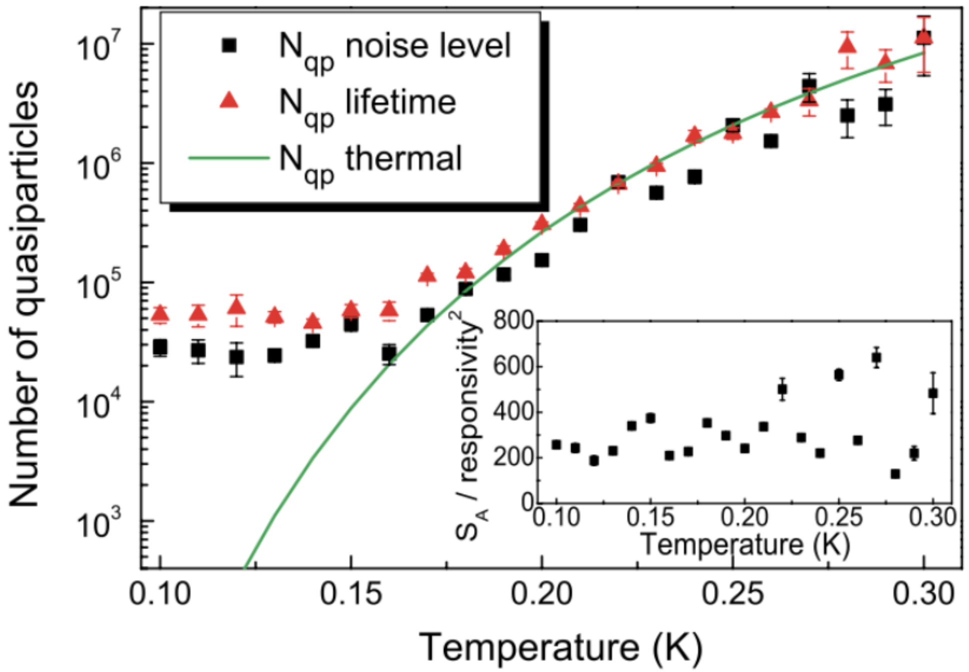
App. Phys. Rev., **6**, 2, 10.1063 (2019).

Excess quasiparticle density

Potential Limitations on Threshold: Quiescent QP Density

Measurements of quasiparticle recombination times suggest a possible excess "nonequilibrium" quasiparticle density at low temperatures.

- Estimates at 25-55 μm^3
- Source not well understood
- If true, could place limit on qubit threshold



Source: P. J. de Visser, J. J. A. Baselmans, P. Diener, S. J. C. Yates, A. Endo, and T. M. Klapwijk
"Number Fluctuations of Sparse Quasiparticles in a Superconductor,"
Phys. Rev. Lett. 106, 167004 – Published 22 April 2011