Quantum sensing discussion questions

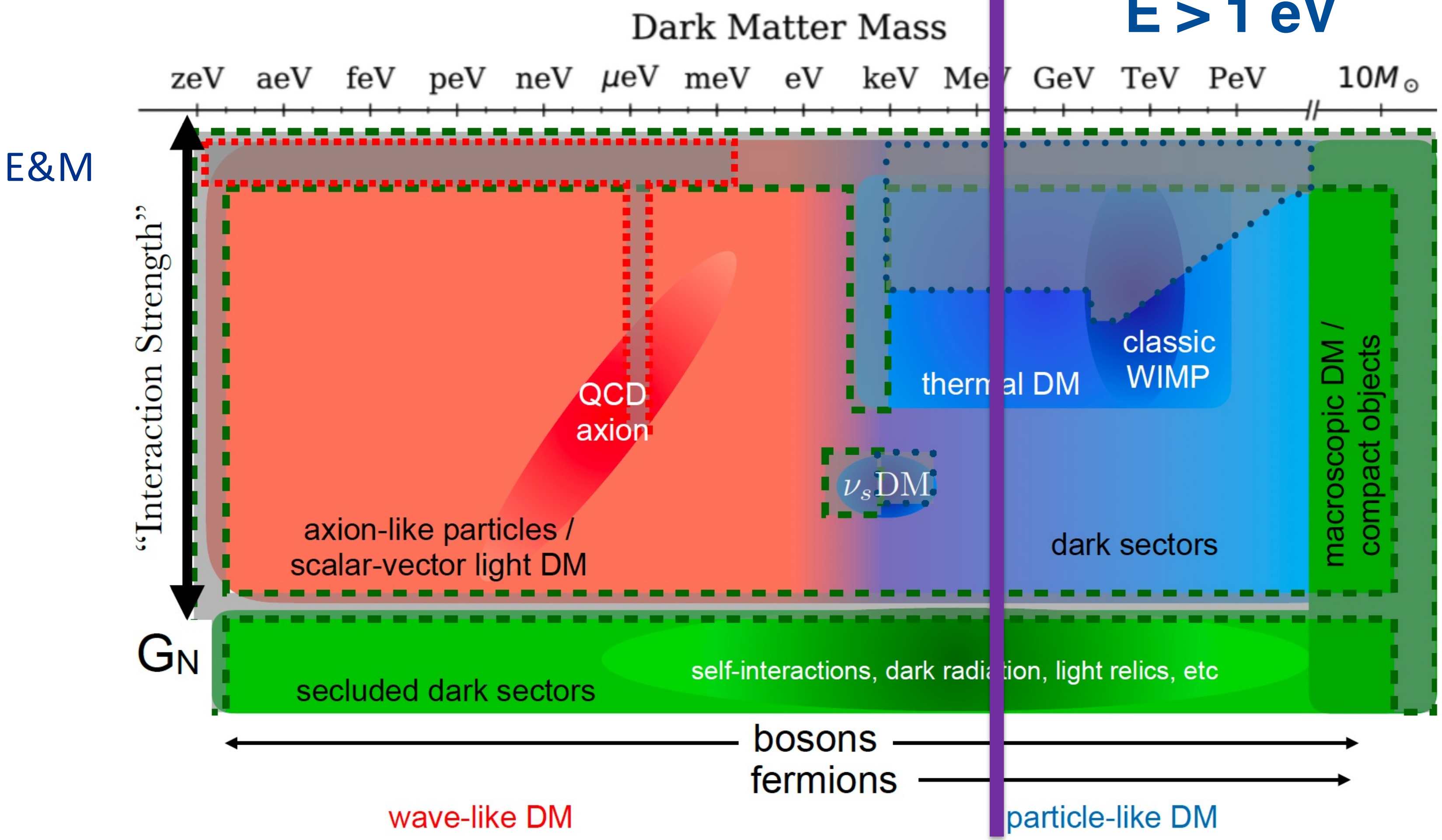
- What is your SNR-limited application, and what are the properties of the detector you wish you had?

- What prevents you from obtaining or inventing this detector? Does it violate any known laws of physics?

- If you had a detector with X energy threshold and Y background or noise rate, what would you do with it?

Quantum sensors: E < 1 eV

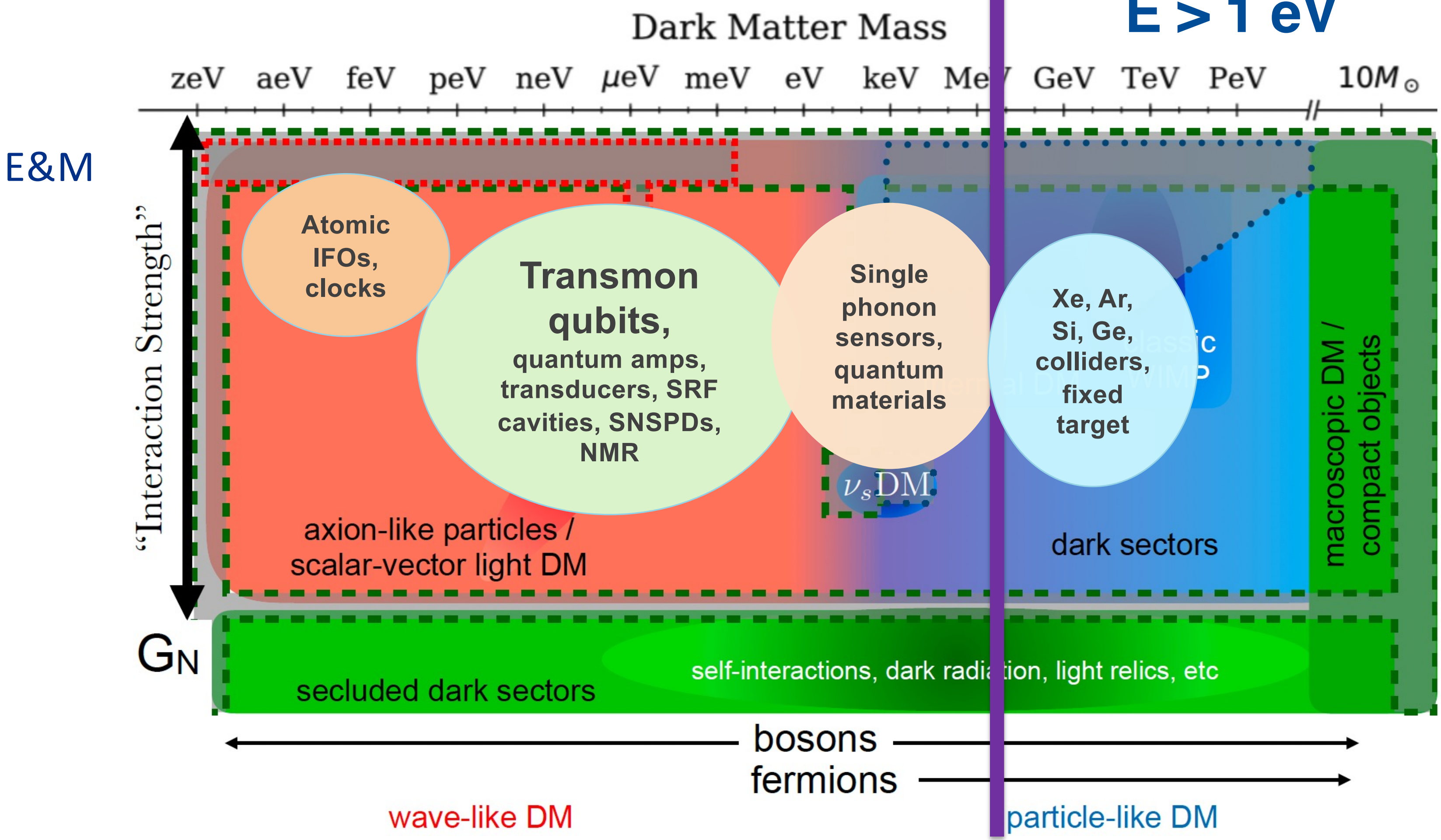
Current HEP tech: E > 1 eV



Cartoon from Snowmass

Quantum sensors: E < 1 eV

Current HEP tech: E > 1 eV



Atomic IFOs, clocks

Transmon qubits, quantum amps, transducers, SRF cavities, SNSPDs, NMR

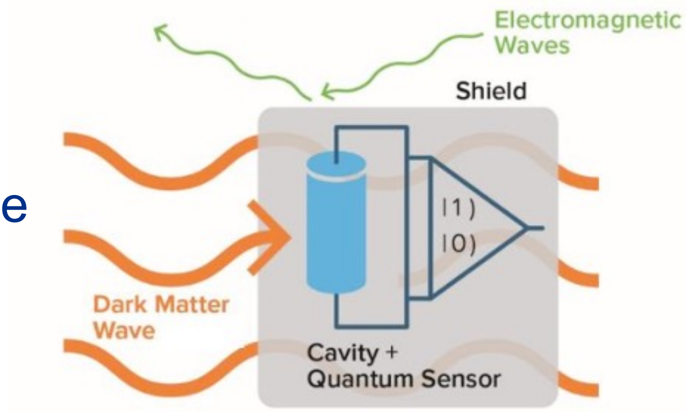
Single phonon sensors, quantum materials

Xe, Ar, Si, Ge, colliders, fixed target

Cartoon from Snowmass

Hmmm… quantum computing platforms look just like dark matter searches:

DOE-OHEP Basic Research Needs white paper, 2018



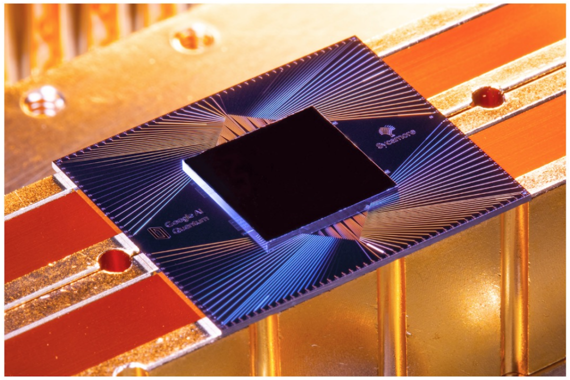
Sensitive single-quantum devices are operated in a cryostat and/or vacuum system and well-shielded from external disturbances (heat, light, sound) in order to maximize their coherence time.

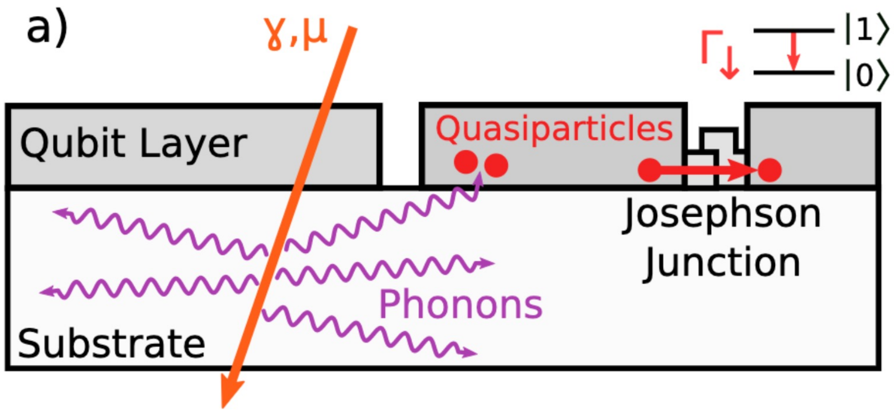
Impossible to shield from the dark matter – the DM interacts so weakly that it flies right through the walls.

If your quantum computer crashes, it could be due to dark matter!
… but as consolation, you'll get a Nobel prize anyway for the discovery.

Quantum Computing and Background Radiation

Several studies have shown that background radiation is very disruptive to superconducting qubits (quasiparticle poisoning causing correlated errors)





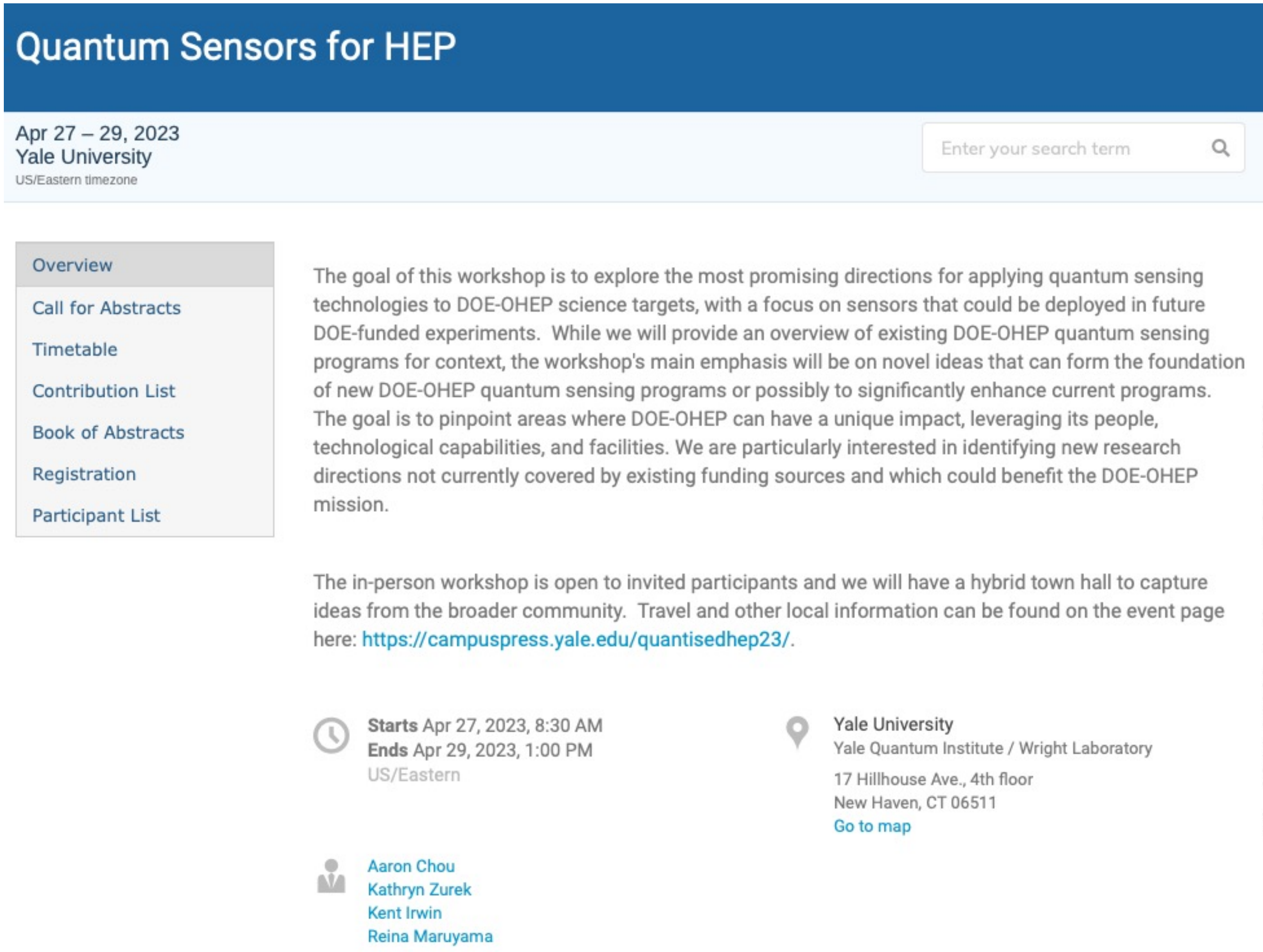
Google Sycamore team: M. McEwen et al., Nature Physics 18 (2022)

Not coincidentally, Matt McEwen's PhD advisor John Martinis was an OG member of CDMS.

Okay, let's use SC qubits as low energy threshold DM detectors!

Detected event = error in quantum computation.

Workshop to define strategy for the US HEP quantum sensors program



Quantum Sensors for HEP

Apr 27 – 29, 2023
Yale University
US/Eastern timezone

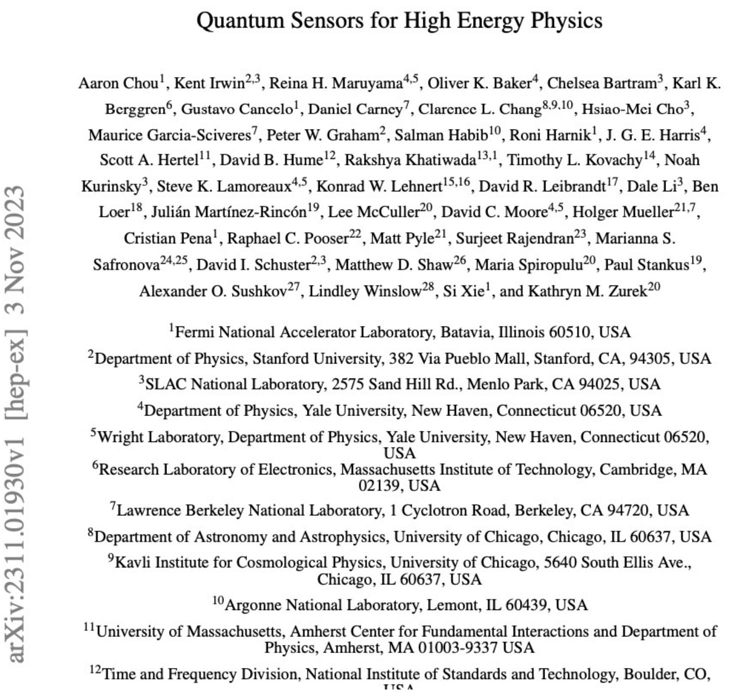
The goal of this workshop is to explore the most promising directions for applying quantum sensing technologies to DOE-OHEP science targets, with a focus on sensors that could be deployed in future DOE-funded experiments. While we will provide an overview of existing DOE-OHEP quantum sensing programs for context, the workshop's main emphasis will be on novel ideas that can form the foundation of new DOE-OHEP quantum sensing programs or possibly to significantly enhance current programs. The goal is to pinpoint areas where DOE-OHEP can have a unique impact, leveraging its people, technological capabilities, and facilities. We are particularly interested in identifying new research directions not currently covered by existing funding sources and which could benefit the DOE-OHEP mission.

The in-person workshop is open to invited participants and we will have a hybrid town hall to capture ideas from the broader community. Travel and other local information can be found on the event page here: https://campuspress.yale.edu/quantisedhep23/.

Starts Apr 27, 2023, 8:30 AM
Ends Apr 29, 2023, 1:00 PM
US/Eastern

Yale University
Yale Quantum Institute / Wright Laboratory
17 Hillhouse Ave., 4th floor
New Haven, CT 06511

Aaron Chou
Kathryn Zurek
Kent Irwin
Reina Maruyama



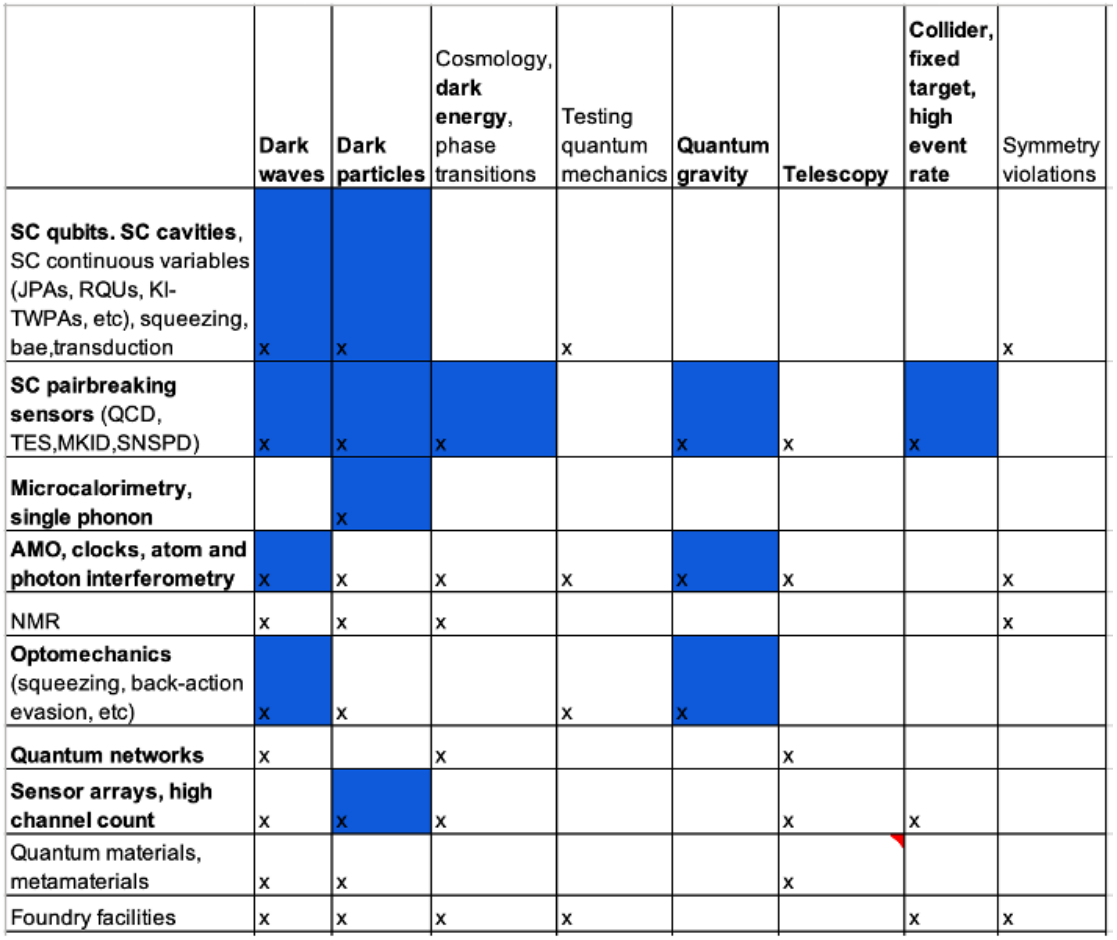
arXiv:2311.01930v1 [hep-ex] 3 Nov 2023

Quantum Sensors for High Energy Physics

Aaron Chou[1], Kent Irwin[2,3], Reina H. Maruyama[4,5], Oliver K. Baker[4], Chelsea Bartram[3], Karl K. Berggren[6], Gustavo Cancelo[1], Daniel Carney[7], Clarence L. Chang[8,9,10], Hsiao-Mei Cho[3], Maurice Garcia-Sciveres[7], Peter W. Graham[2], Salman Habib[10], Roni Harnik[1], J. G. E. Harris[4], Scott A. Hertel[11], David B. Hume[12], Rakshya Khatiwada[13,1], Timothy L. Kovachy[14], Noah Kurinsky[3], Steve K. Lamoreaux[4,5], Konrad W. Lehnert[15,16], David R. Leibrandt[17], Dale Li[3], Ben Loer[18], Julián Martínez-Rincón[19], Lee McCuller[20], David C. Moore[4,5], Holger Mueller[21,7], Cristian Pena[1], Raphael C. Pooser[22], Matt Pyle[21], Surjeet Rajendran[23], Marianna S. Safronova[24,25], David I. Schuster[2,3], Matthew D. Shaw[26], Maria Spiropulu[20], Paul Stankus[19], Alexander O. Sushkov[27], Lindley Winslow[28], Si Xie[1], and Kathryn M. Zurek[20]

[1]Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
[2]Department of Physics, Stanford University, 382 Via Pueblo Mall, Stanford, CA, 94305, USA
[3]SLAC National Laboratory, 2575 Sand Hill Rd., Menlo Park, CA 94025, USA
[4]Department of Physics, Yale University, New Haven, Connecticut 06520, USA
[5]Wright Laboratory, Department of Physics, Yale University, New Haven, Connecticut 06520, USA
[6]Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[7]Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA
[8]Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637, USA
[9]Kavli Institute for Cosmological Physics, University of Chicago, 5640 South Ellis Ave., Chicago, IL 60637, USA
[10]Argonne National Laboratory, Lemont, IL 60439, USA
[11]University of Massachusetts, Amherst Center for Fundamental Interactions and Department of Physics, Amherst, MA 01003-9337 USA
[12]Time and Frequency Division, National Institute of Standards and Technology, Boulder, CO,

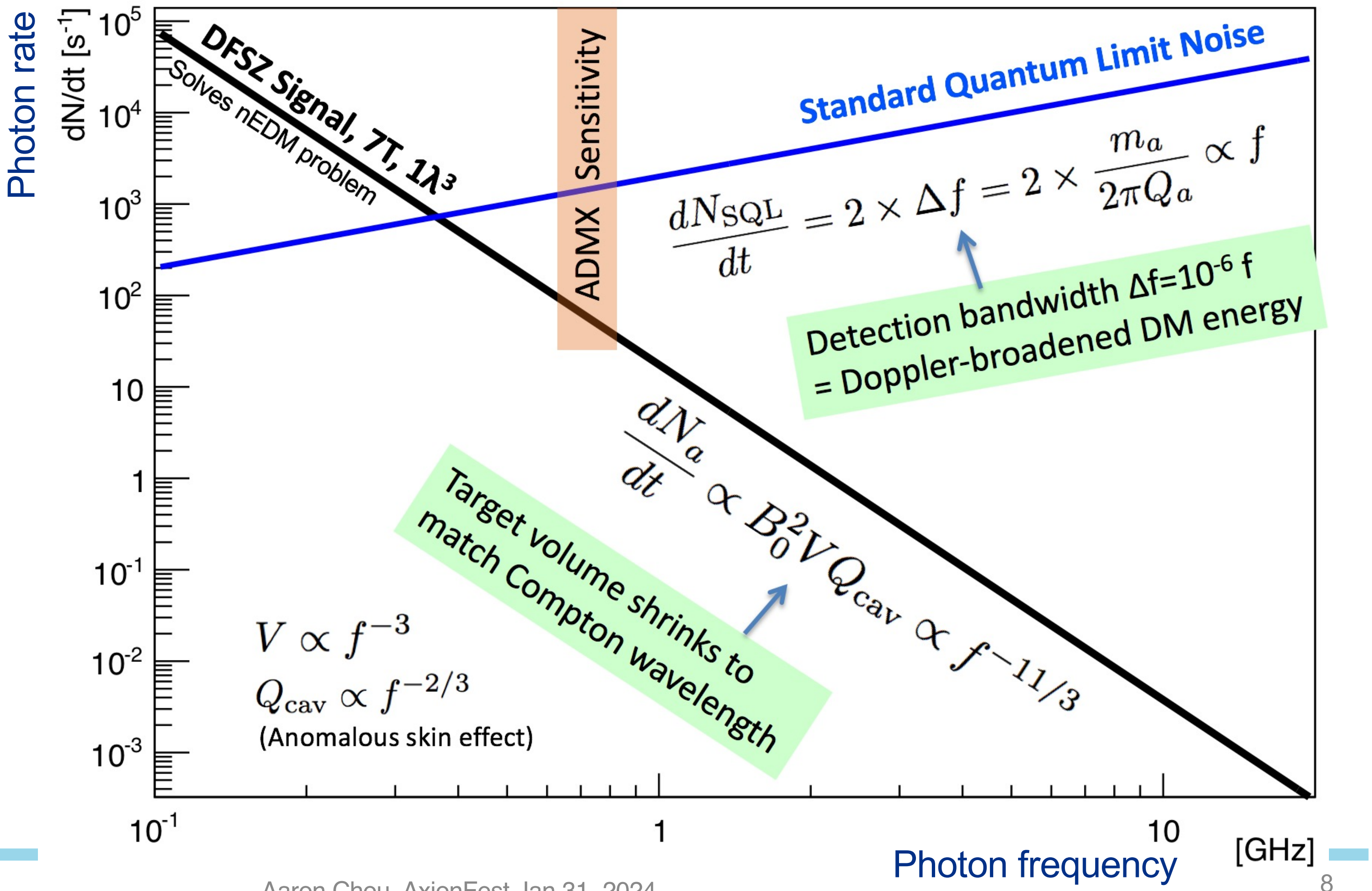
Workshop report: QIS technology vs HEP science application



	Dark waves	**Dark particles**	Cosmology, **dark energy**, phase transitions	Testing quantum mechanics	**Quantum gravity**	**Telescopy**	**Collider, fixed target, high event rate**	Symmetry violations
SC qubits. SC cavities, SC continuous variables (JPAs, RQUs, KI-TWPAs, etc), squeezing, bae,transduction	🟦 x	🟦 x		x				x
SC pairbreaking sensors (QCD, TES,MKID,SNSPD)	🟦 x	🟦 x	🟦 x		🟦 x	x	🟦 x	
Microcalorimetry, single phonon		🟦 x						
AMO, clocks, atom and photon interferometry	🟦 x	x	x	x	🟦 x	x		x
NMR	x	x	x					x
Optomechanics (squeezing, back-action evasion, etc)	🟦 x	x		x	🟦 x			
Quantum networks	x		x			x		
Sensor arrays, high channel count	x	🟦 x	x			x	x	
Quantum materials, metamaterials	x	x				x		
Foundry facilities	x	x	x	x			x	x

Blue = Fermilab activities

The predicted axion DM signal/noise ratio plummets as the axion mass increases → SQL readout is not scalable.



Need much larger signal/noise ratio in many searches for new physics.

Increase signal?

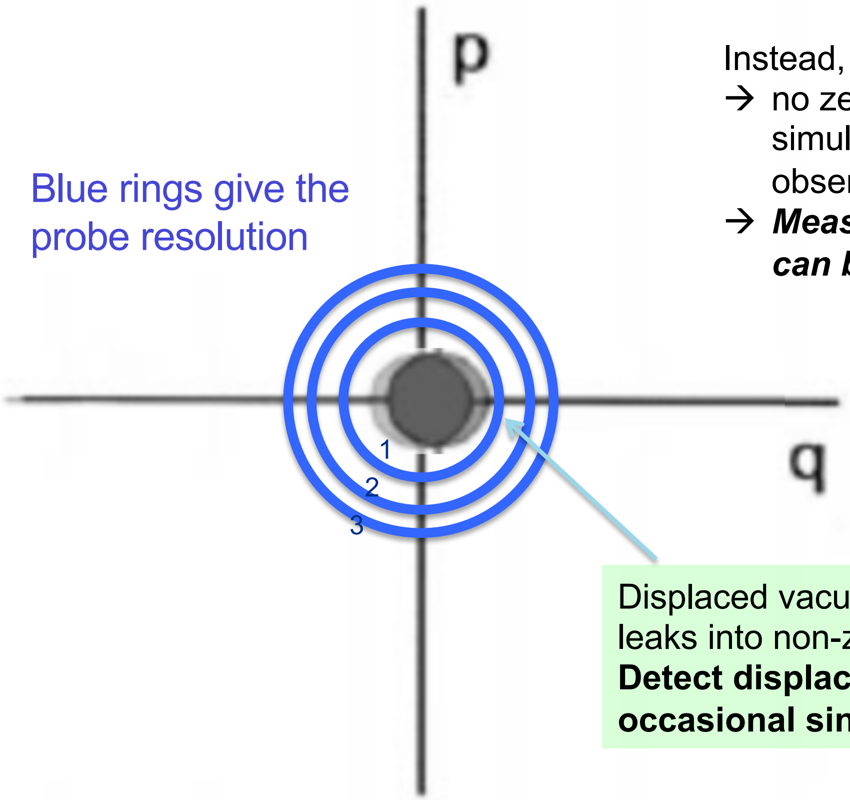
We do need more magnets, but these are expensive and have long lead time.

Reduce noise?

Many quantum tricks are possible, but must be tailored to the application.

To reduce readout noise, use photon counting to measure displacement using the Fock basis, i.e. number eigenstates

Previously we measured *both amplitude and phase*, but this is dumb since the dark matter phase is randomized every coherence time. Useless information obtained at high cost!



Blue rings give the probe resolution

Instead, measure only displacement amplitude

→ no zero-point noise since we are not simultaneously measuring non-commuting observables

→ ***Measurement noise, e.g. from dark counts can be arbitrarily low***

Displaced vacuum state exponentially leaks into non-zero Fock number.
Detect displacement by counting the occasional single photon.

SC qubits as single photon detectors. No quantum noise!

Fermilab/Chicago/Stanford

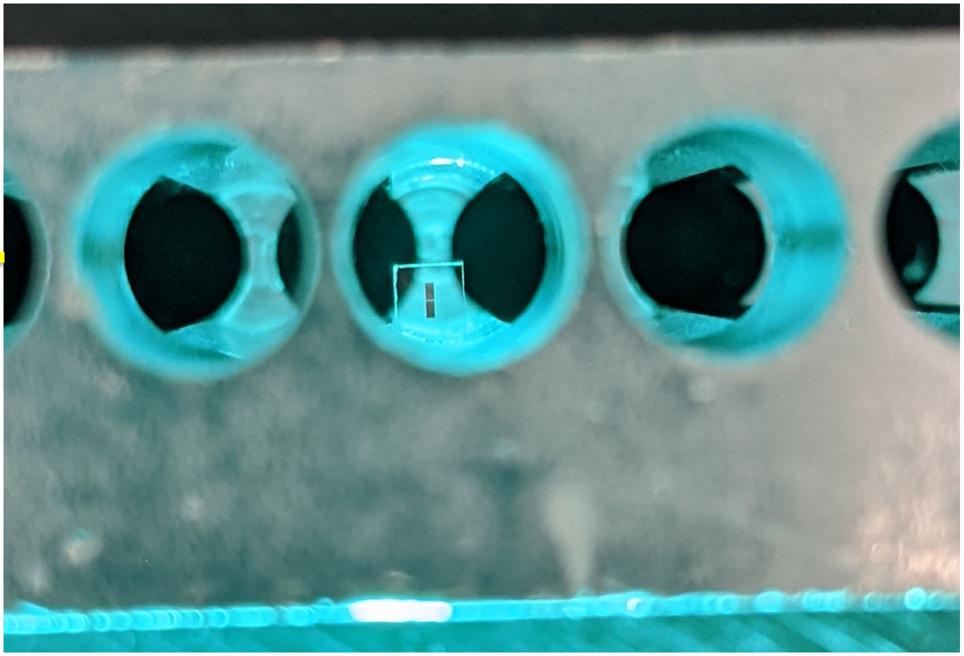
Nested sapphire cavity compatible with high B field needed for axion search: $Q>10^6$,
¼-wave layers reflect photon waves back to center

(based on design from INFN/QUAX)

SQuAD
(Superconducting Qubits for Axion Darkmatter)

Installed in 10 mK dilution refrigerator and 14T solenoid magnet at SiDet Lab B.

Quantum readout electronics in remote, magnetically-shielded region



Transmon qubit performs quantum non-demolition single photon counting with noise **36x lower than zero-point noise, 1300x speed-up.**
Achieved 1 Hz DCR.

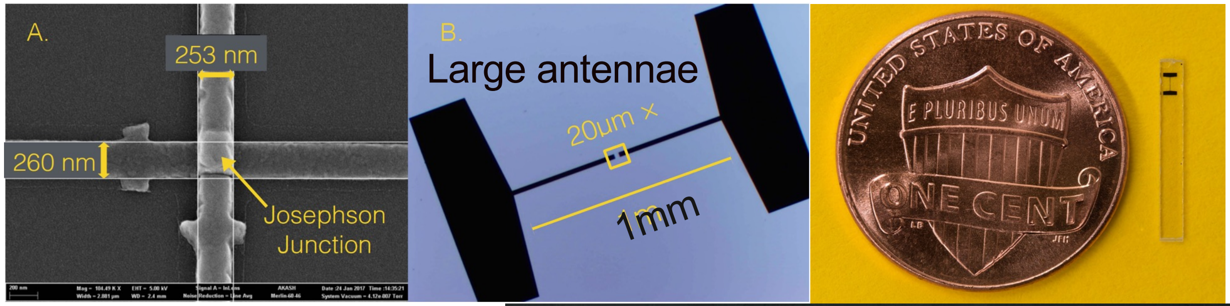
A.V. Dixit et al., *Phys.Rev.Lett.* 126 (2021)

Patrice’s talk!

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

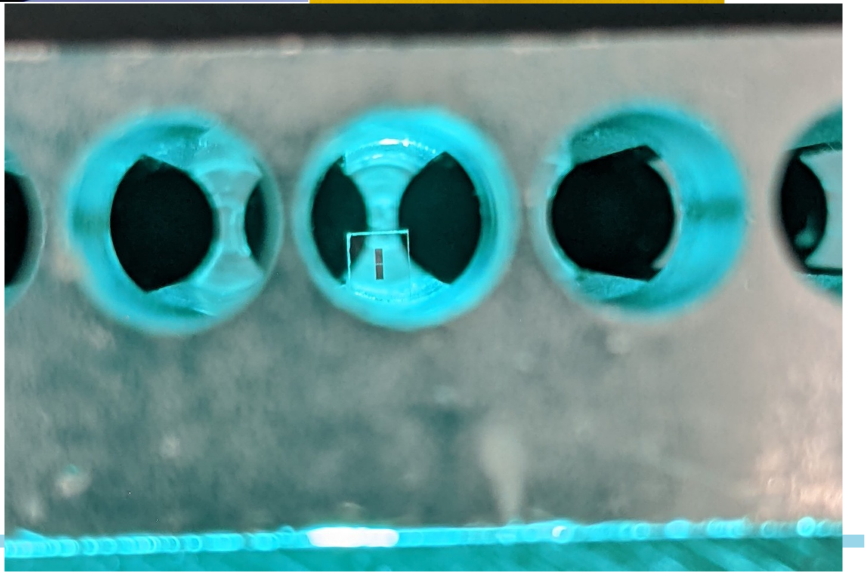
A.S. Chou, Dave Schuster, Akash Dixit, Ankur Agrawal, …

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



The electric field of individual photons drives a tunneling current and exercises the nonlinear inductance of the Josephson junction.

Photon number is transduced into frequency shifts of the $|g\rangle \rightarrow |e\rangle$ transition of this nonlinear LC oscillator.

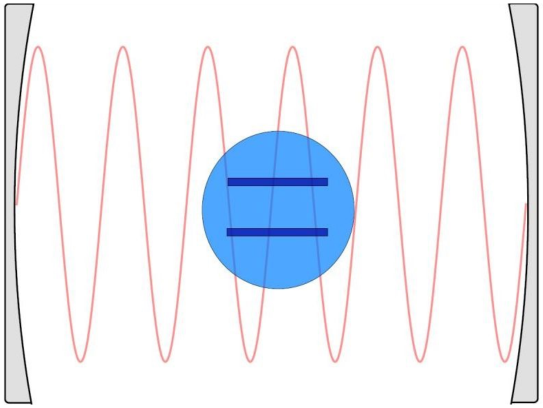


Transmon qubit in pan flute cavity (photo credit: Akash Dixit)

Cavity QED:
Use 2-level atom to measure cavity photon population

Linear cavity

Number operator = $a^\dagger a$



2-level "atom"

Number operator = σ_z

The electric field of the cavity photons stretches the atom oscillator and changes its resonant frequency:

$$H \approx \hbar\omega_{\mathrm{r}}\left(a^\dagger a + 1/2\right) + \frac{\hbar}{2}\left(\underbrace{\omega_{\mathrm{a}} + \boxed{\frac{2g^2}{\Delta}a^\dagger a} + \frac{g^2}{\Delta}}_{}\right)\sigma_{\mathrm{z}}$$

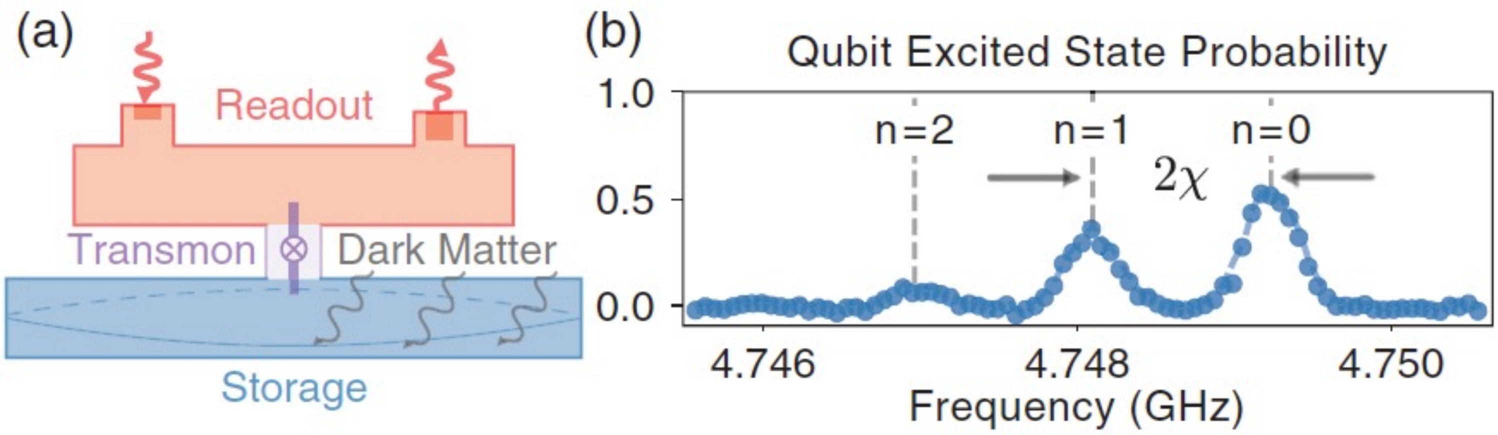
$$g \approx \vec{d}\cdot\vec{E}_0 \approx d\sqrt{\omega/V}$$

$\Delta=\omega_r-\omega_a$

The atom frequency depends on the cavity resonator's occupation number!
Quantized frequency shift of $2\chi = 2g^2/\Delta$ per photon in the cavity mode.
This product of number operators commutes with H and allows QND measurement.

Single photon resolution:

Measure qubit $|g\rangle \rightarrow |e\rangle$ transition frequencies after mimicking the dark matter by weakly driving the primary cavity mode into a coherent state with <n>=1



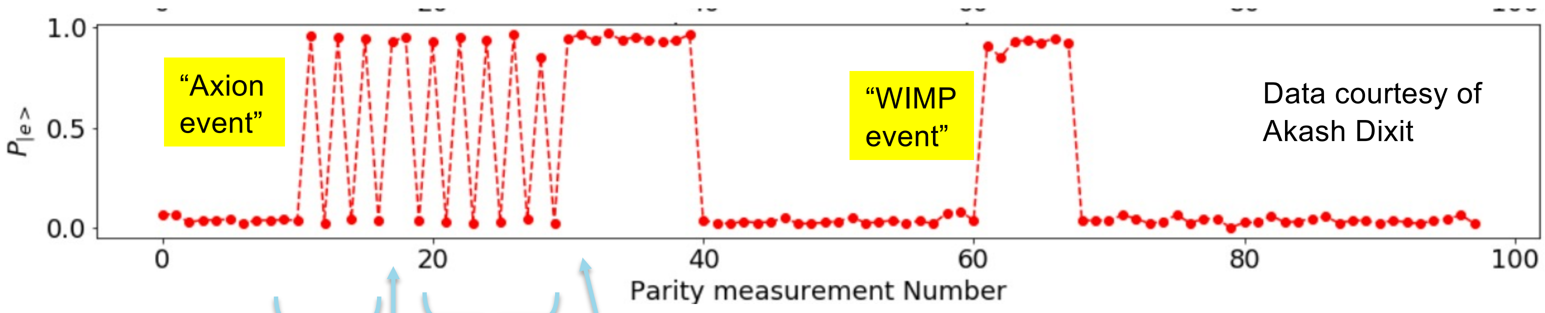
The measured qubit spectrum exhibits a distribution of resonances which are in 1-1 correspondence with the **Poisson distribution** of the cavity's population.

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

Measure spectral response by applying pi-pulse to the qubit at the postulated shifted frequency to see if it absorbs the photon.

Repeated quantum non-demolition measurements ensure high fidelity tagging of single photon events, rejects quasiparticle backgrounds

Signature of a single signal photon is many sequential successful qubit “spin-flips” from $|g\rangle \leftrightarrow |e\rangle$



Data courtesy of Akash Dixit

Single photon injected, repeated successful qubit spin flips

Failed spin-flip = readout error

More successful readouts

Photon decays, qubit stuck in $|e\rangle$ state

Qubit decays

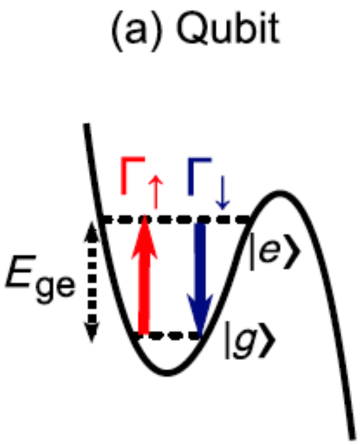
Many failed spin-flips indicate that no photon is present.

Qubit spontaneously excited and then decays. Does not mimic photon event since subsequent spin-flip attempts fail.

Backgrounds for single photon / phonon detectors

Unwanted electron-like quasiparticles from broken Cooper pairs are a direct background for qubit-based photon/phonon detectors. They scramble the information stored these single quantum Cooper pair oscillators.

Potential energy diagram for qubit



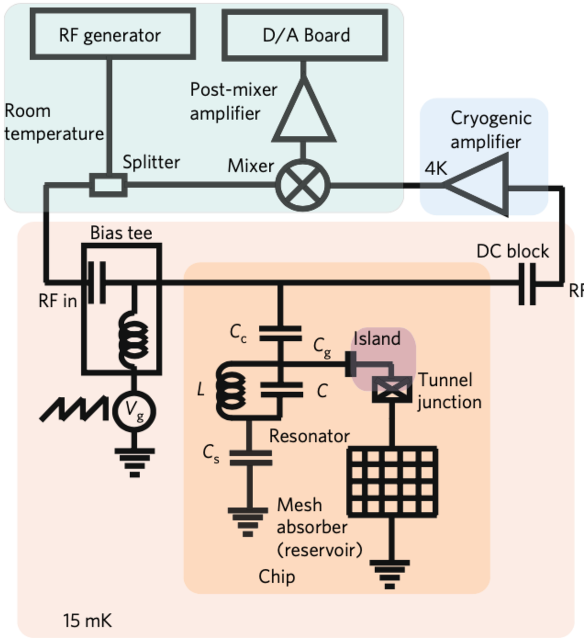
J. Wenner, et al., PRL 110, 150502 (2013)

No fair playing Dodgeball when kid is stuck in the swing!

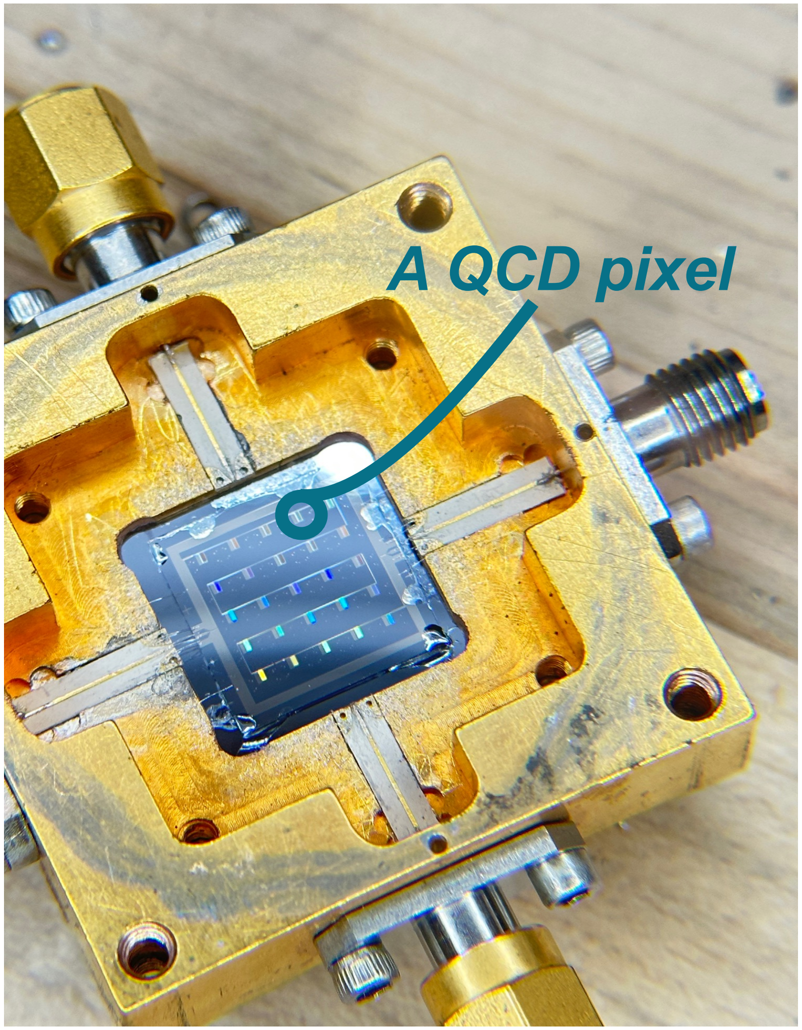
A quasiparticle tunneling through the Josephson junction transfers energy/momentum from/to the qubit oscillator. This changes the qubit's state and creates a false positive detection.

Quantum Capacitance Detector based on charge-parity switching in charge qubit.

Detect QPs from broken Cooper pairs after absorption of single THz photon.



Lowest noise-equivalent power of any THz sensor, DCR = 1 Hz

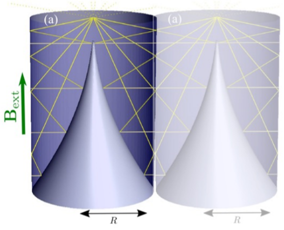

A QCD pixel

P. Echternach, A. Beyer, and C. Bradford (2021)
https://doi.org/10.1117/1.JATIS.7.1.011003

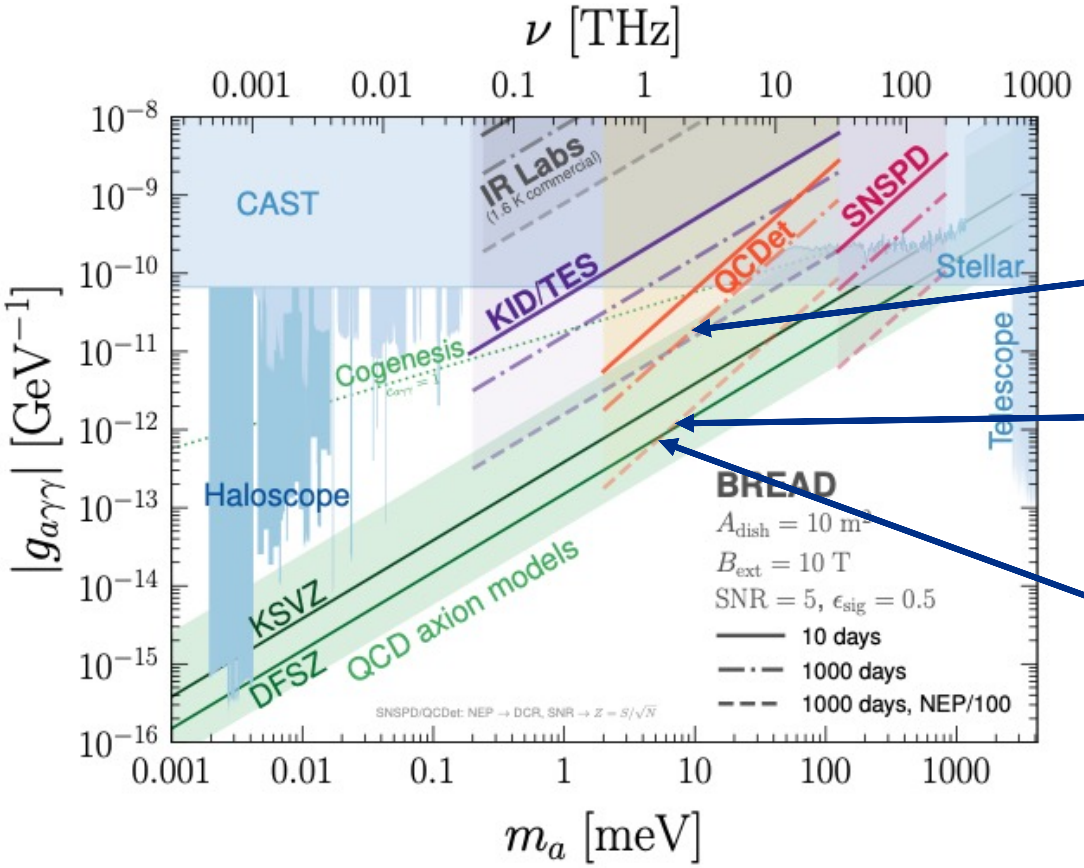
Echternach, P. M., et al. *Nature Astronomy* 2.1 (2018): 90-97.

Cannot reject QP backgrounds in detectors that rely on Cooper pair-breaking!

BREAD experiment: Need to reduce best qubit SPD dark count rates by factor 10^4 !!!



photon-axion coupling



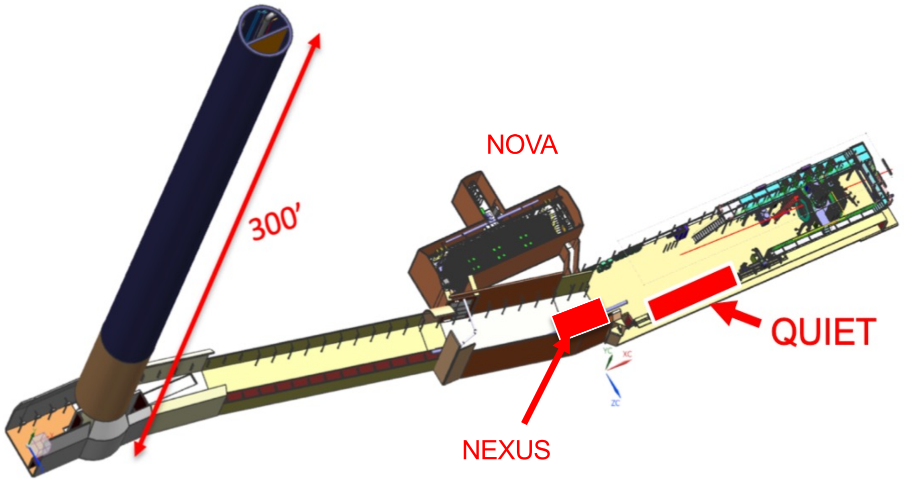
Dark Count Rates:

DCR=1 Hz
10^8 counts in t=10^8 s

DCR=10^{-4} Hz **(!)**
10^4 counts in t=10^8 s

Signal rate
$R_s \sim 10^{-6}$ Hz
100 counts in t=10^8 s
R_s limit ~ sqrt(R_b / t)

To avoid ionizing radiation backgrounds, must go underground and apply lead shielding



Shallow underground labs located in Fermilab's neutrino beamline.
Reduces cosmic ray flux by 1000x

Qubits are also great phonon sensors:

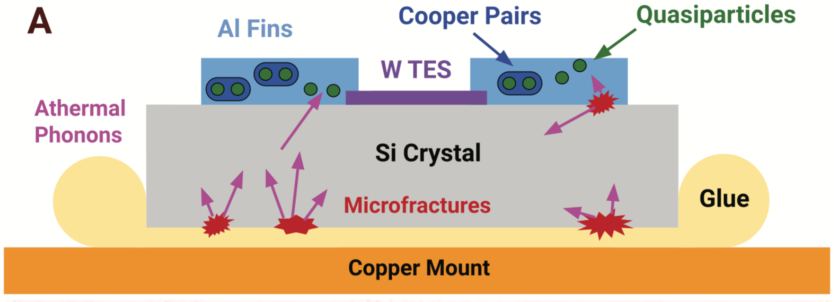
Acoustic noise from substrate microfracture events are currently far worse than ionizing radiation!

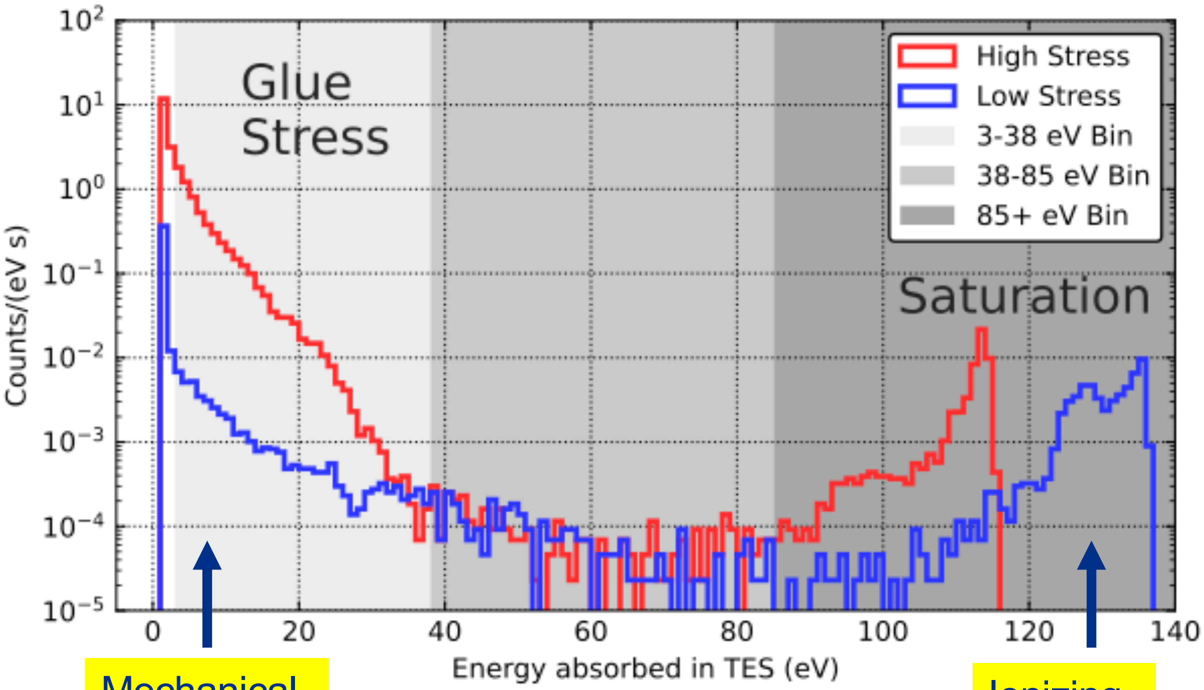
R. Anthony-Petersen… M. Pyle, et al.,
arxiv:2208.02790

Measure spectrum using tiny, cold, low heat capacity TES sensors developed for the SuperCDMS dark matter search.

Next-generation microcalorimeters will reduce thresholds to milli-eV, provide first look at sub-eV spectrum.

Mitigating these low energy disturbances will be critical to achieving low dark count rates in low threshold single photon/phonon detectors.





Mechanical noise

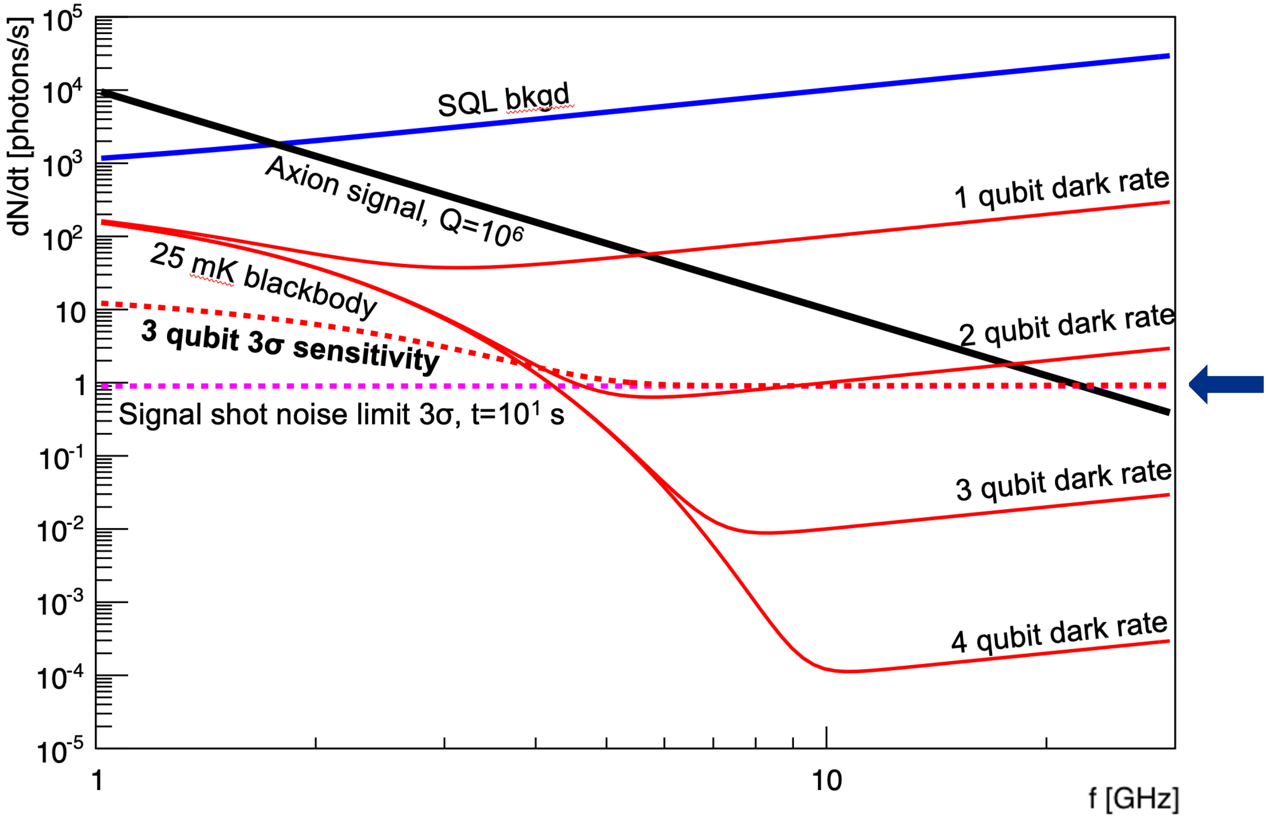
Ionizing radiation

Signal rate sensitivity is determined by the integration time budget:

if $Q=10^6$ then have maximum t=10 s at each tuning to get 1 octave in mass, i.e. using 10^6 tunings in 1 year

Assume that quantum sensors will continue to improve until experiments are no longer background-limited.

Demonstrated qubit DCR=1 Hz is already *nearly* good enough for background-free operation in 10 s integration budget.



For t = 10 s, the minimum observable signal rate is R_s=1 Hz

(Signal shot noise limit, need to count 9 ± 3 photons for 3σ)

Cavity experiments are signal limited: Need larger B^2V or stimulated emission to go above 20 GHz.

Quantum tricks like squeezing, stimulated emission will give a little boost to SNR, but eventually, we still need to buy/obtain big magnets **to avoid being signal-limited**!

First step: Dark Wave Lab @FNAL

First 9 T, warm bore MRI magnet ~$7M to be moved to Fermilab this year for ADMX-EFR. Can host other experiments.

PW8 building can house 2 magnets

Fermilab Dark Wave Lab Workshop

Apr 15 – 16, 2024
Fermilab
US/Central timezone

In this workshop, we will discuss plans for creating a shared facility for axion search experiments at Fermilab.

Goals:

- Identify experiments and collaborations that could benefit from common magnet and cryogenic infrastructure.
- Begin to gather requirements for desired lab features and equipment.
- Explore options for early use of the 9.4 Tesla x 800 mm bore solenoid being installed for the ADMX-EFR project. The magnet is expected to be available beginning in 2025, with full ADMX-EFR operations not anticipated before 2028.
- Discuss longer-term options for higher field and larger volume magnets.

Quantum sensing discussion questions

- What is your SNR-limited application, and what are the properties of the detector you wish you had?

  e.g. no sensing technology currently exists for single 100 GHz photons...

- What prevents you from obtaining or inventing this detector? Does it violate any known laws of physics?

- If you had a detector with X energy threshold and Y background or noise rate, what would you do with it?

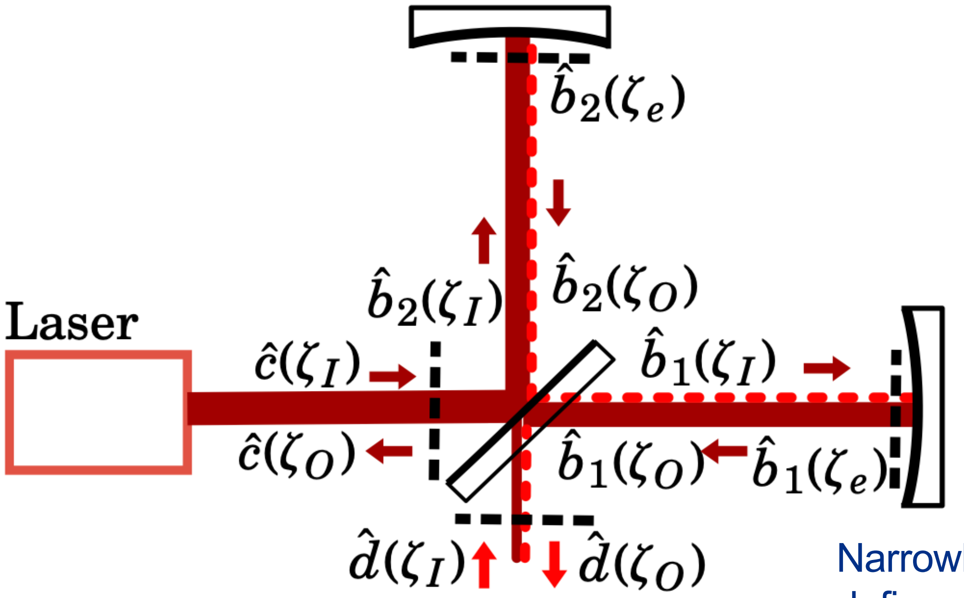
GQuEST: Single photon counting readout for gravitational wave interferometers

Fermilab, Caltech, JPL

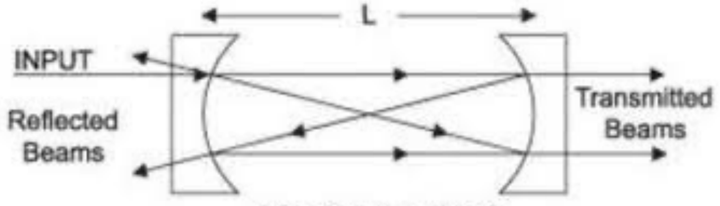
Pathway towards 50 dB below SQL?
Enables search for stochastic GW backgrounds.

Exotic sources include early universe phase transitions, cosmic string decays, space-time noise from quantum gravity.

Fermilab provides cryogenic engineering for fiber-coupled SNSPD, QICK IFO controls.

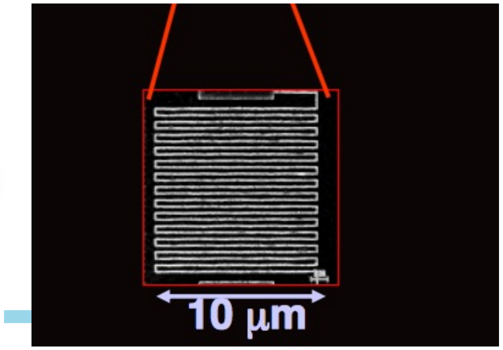


Narrowband filter cavity defines the mode linewidth



CONFOCAL CAVITY
"Bowtie" Mode
FIGURE 1

Low dark rate single photon detector



Lee McCuller, arXiv:2211.04016