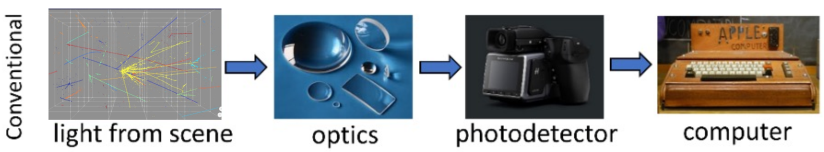
Quantum Physical AI for Compute-in-Sensor

François Léonard, Sandia National Laboratories, CA
Maurice Garcia-Sciveres, Lawrence Berkeley National Laboratory

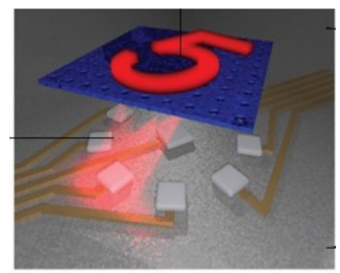
Concept 1: Physical Artificial Intelligence

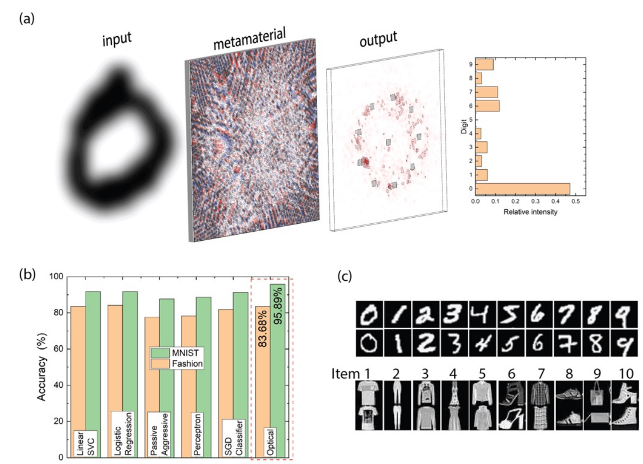


- **Conversion from the field (e.g. photons) to the electronic domain is time consuming and requires energy**

Q: Can we use the physics of the field to accelerate computation and reduce energy needed?

Physical Artificial Intelligence

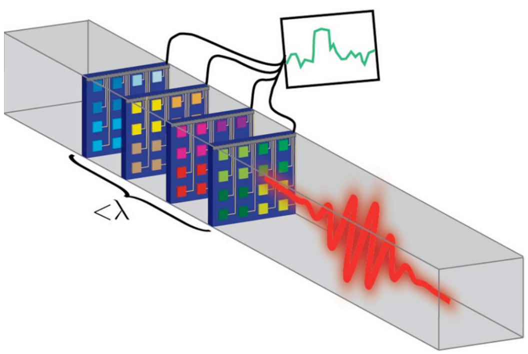


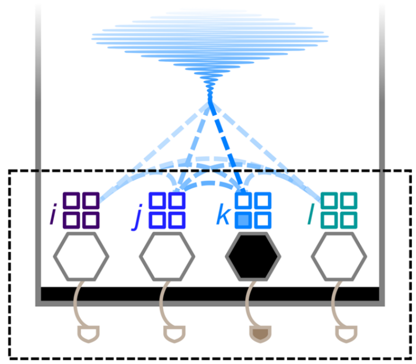


- **High performance possible**
- **Orders of magnitude decrease in time and energy**

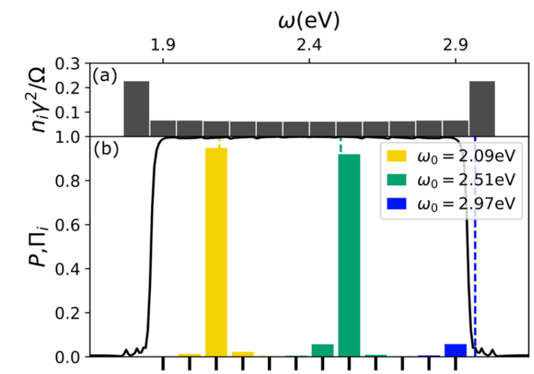
F. Léonard, A.S. Backer, E. J. Fuller, C. Teeter, C. M. Vineyard, *ACS Photonics* (2021)
F. Léonard, E. J. Fuller, C. Teeter, C. M. Vineyard, *Optics Express* (2022)

Concept 2: Quantum Photodetection





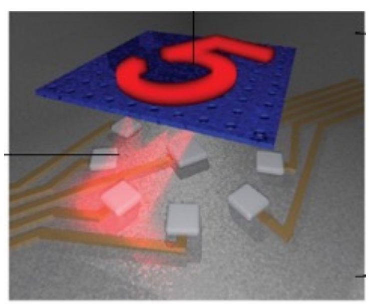
High Efficiency and Frequency Resolution

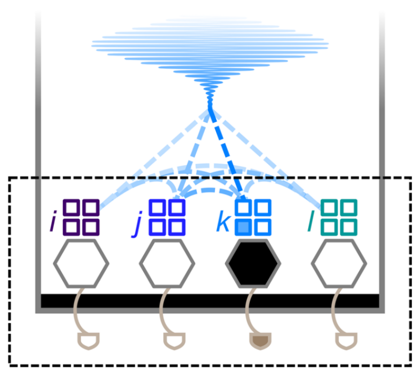


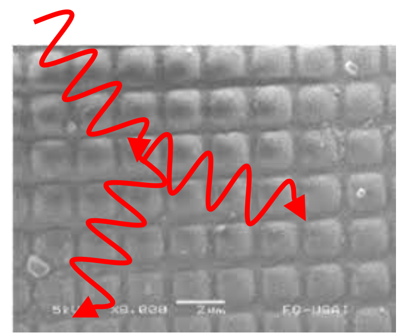
S. Young, M. Sarovar, F. Léonard, Comm. Phys. (2023)
S. Young, M. Sarovar, F. Léonard, ACS Photonics (2021)

➢ **Collective quantum interactions allow us to design the detector for high performance across metrics**

Future Concept: Quantum Physical AI for Compute-in-Sensor



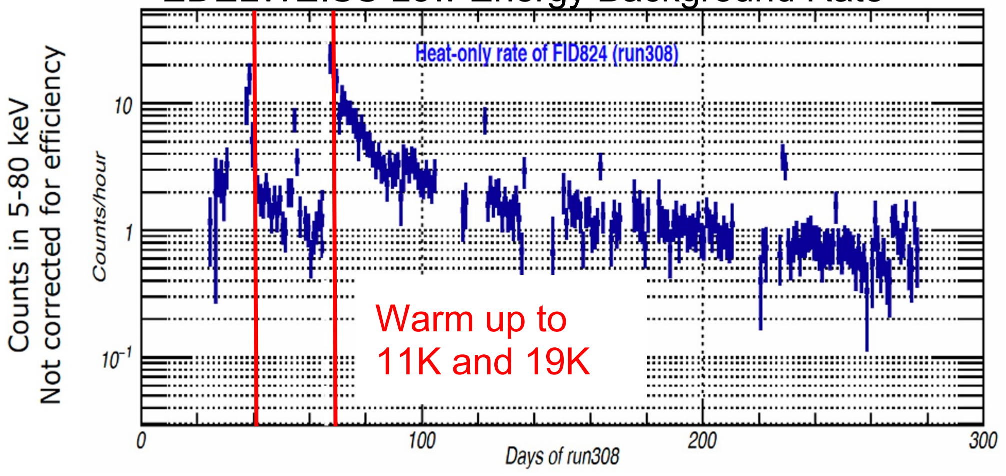




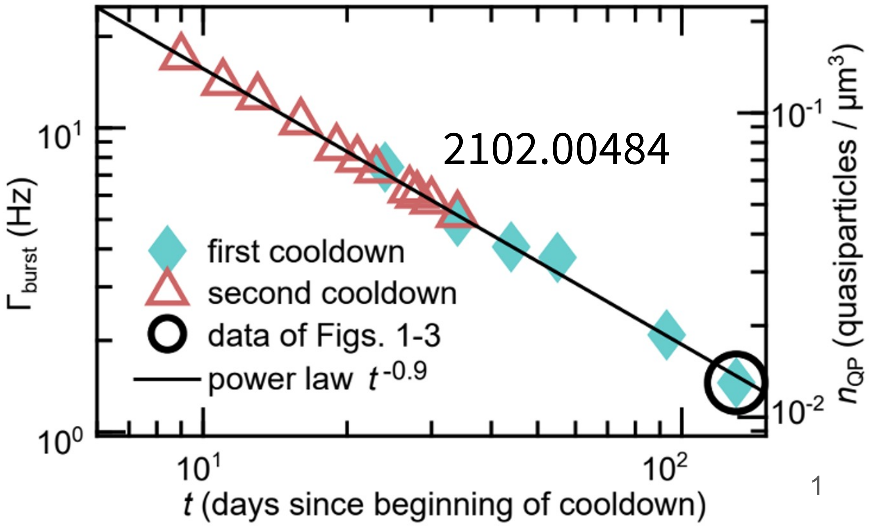
Low Energy Relaxation Events In Solid State Detectors

Matt Pyle

EDELWEISS Low Energy Background Rate

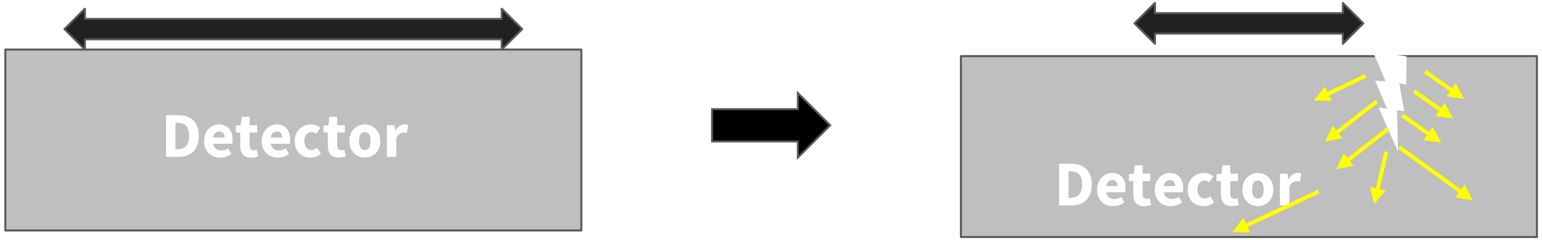


- Background varies with time since fab / time since cooldown
- Background produces no ionization
- Scales largely with surface or sensor area

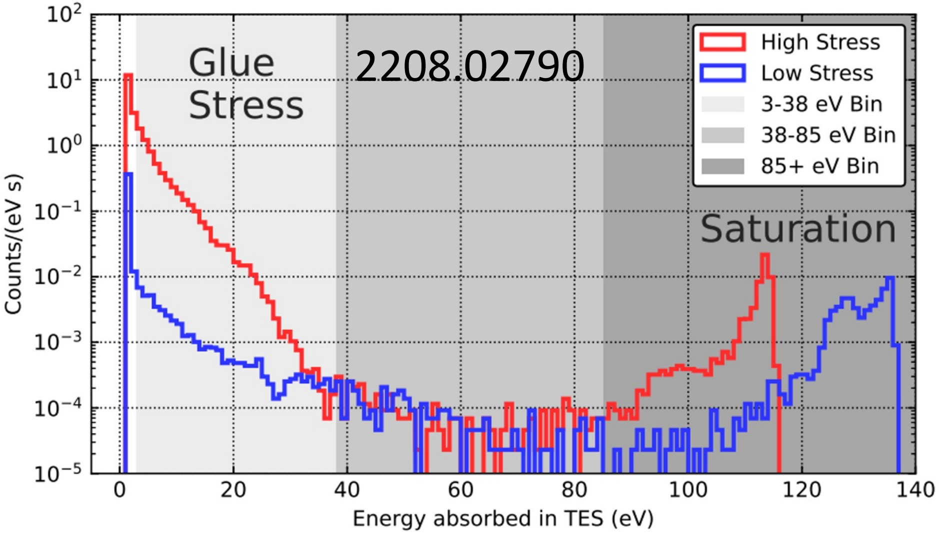


- Similar time dependent backgrounds seen in excess quasiparticle density in some superconducting QUBITs.
- Understanding and minimizing this background is fundamental to fundamental physics (light mass dark matter) and applied physics (long coherence time in QUBITs)

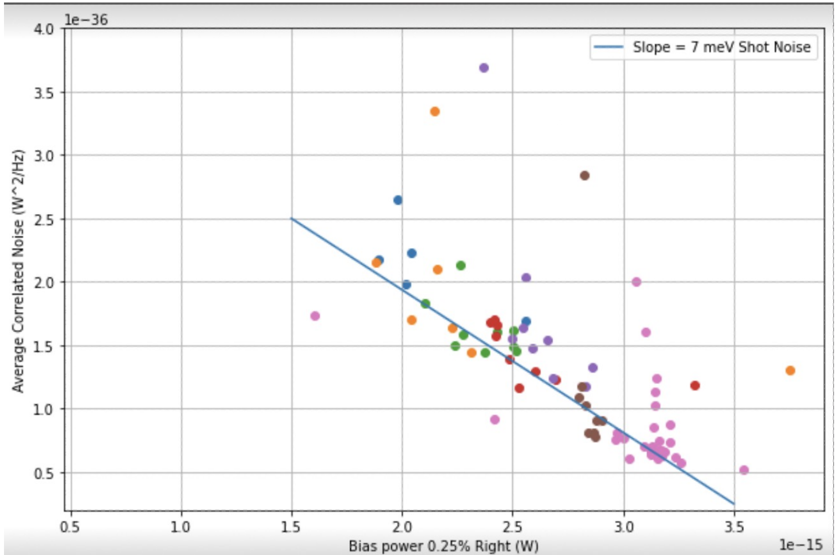
Stress Induced Microfractures?



Stress caused by glue increased event rate by x200 at low energy



New: Relaxation shot noise dominates detector sensitivity. We can now measure total relaxation rates



Material science of quantum sensors

non-equilibrium thermodynamics, backgrounds & decoherence

Quantum sensors for HEP April 27 2023

Sergey Pereverzev
LLNL

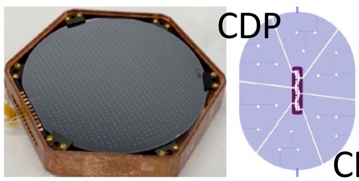
Reference

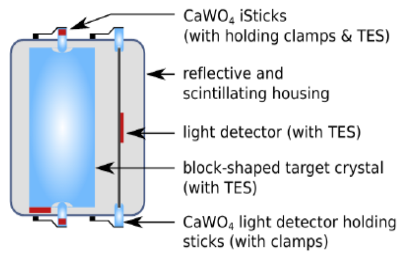
1. arXiv:2212.13964 **[hep-ex]** (2023)
2. Phys. Rev. D **107**, 032010 (2023)
3. arXiv:2204.01919 **[quant-ph]** (2022)
4. Phys. Rev. D **105**, 063002 (2022)

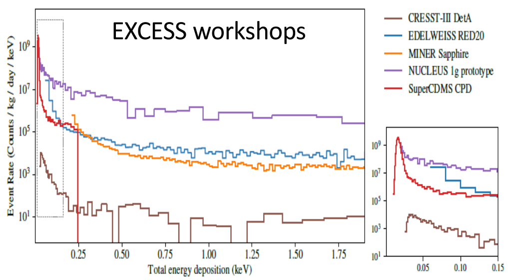
LLNL-PRES-XXXXXX
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

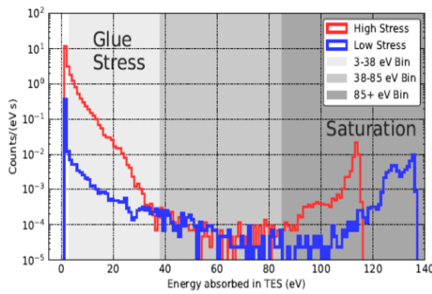
Lawrence Livermore National Laboratory

A decade of increasingly stringent dark matter limits was also a large-scale material physics study – what did we learn ?









cryogenic solid-state and noble liquid detectors, CCDs, NaI(Tl), all reveal broadly similar patterns of access (low-energy) backgrounds

- backgrounds not fully explained by direct particle interactions (Excess workshops)
- Energy accumulation and punctuated release may co-exist with particle interactions
- Excess energy can be pumped - by stress, radioactivity, fields, temperature cycling (glass-like relaxations at low temperatures)
- Common features of this background:
  - rising sharply toward low-energy
  - rises with stress (micro-cracking)
  - slowly decreases after cool-down
  - resets with slight warm-up
  - can be triggered, annealed, quenched... **controlled**

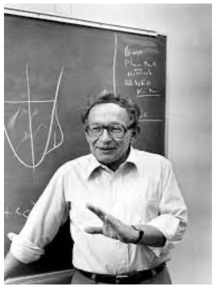
Similar features may be appear in quantum devices/computing

- excess low energy events
- qubit control pumps energy into materials
- dynamic not accounted for in material studies of decoherence;

Bottom line: a rich field of study at the intersection of particle and condensed-matter physics

Materials effects induce backgrounds that matter for dark matter particle searches and quantum devices, but have we a proper models?

In the condensed matter community, non-thermal noise, decoherence, and properties of glasses are is a long-standing robust field of study by an august field of researchers ...
Anderson, Galperin: TLS model; Prigogine- emerging phenomena in systems with energy flow due to internal interactions; Osheroff and Leggett –ultra-low temperature glasses...



Bottom line: TLS models are incomplete**,** Internal interactions are insufficiently known/understood

Let's look for effects predicted by phenomenology analysis /comparison of different systems:

- Up-conversion - "high-energy-like" (keV-scale) relaxation events due to the slow accumulation of low-energy insults; from stress, ionizing radiation, temperature, or field swings
- What mechanisms trigger stored-energy release ?
- what is the relaxation time-scale under various conditions ?

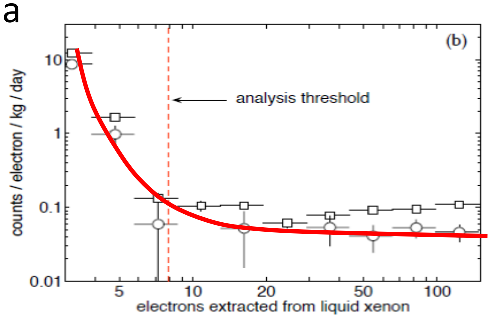
SNSPDs are a good laboratory for these effects in superconductors - (relevant for axion search - project BREAD)
we've also started to find hints in **room temperature NaI(Tl)** (relevant for DAMA/LIBRA, COSINE, others)

The Bottom line, Again: collaboration with BES and the Condensed matter community is helpful and highly advisable !

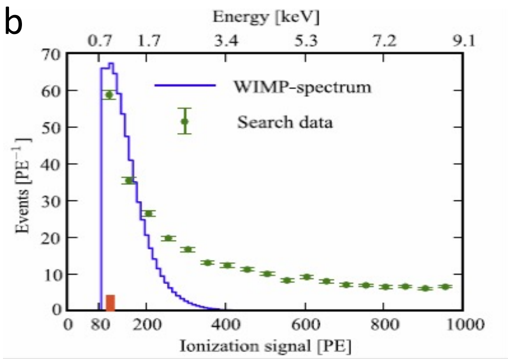
Additional slides

Excess noise: Noble liquid dual-phase detectors, Nai(Tl)

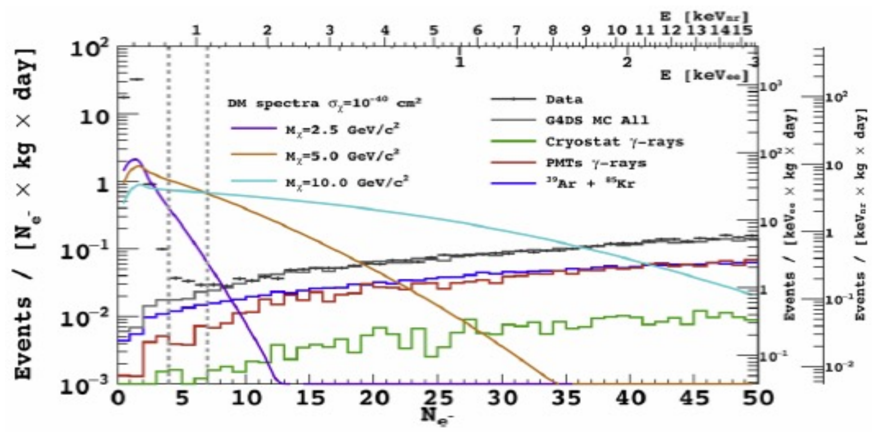
a



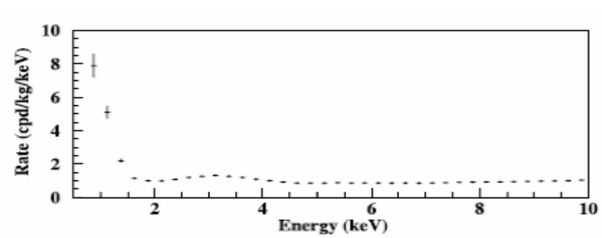
b



c

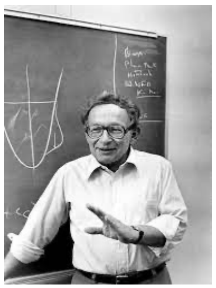


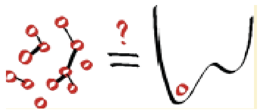
d



a: Xenon 10 experiment,
b: Xenon 100,
c: Dark Side 50 experiment, 50 kg liquid Ar TPC;
d: DAMA-LIBRA experiment, NAI(Tl) scintillator, energy deposition of 1 keV results here in registration 5.5-7.5 photons (David Nygren paper)

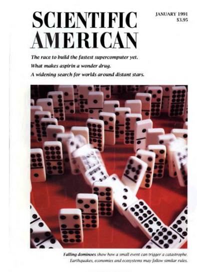
DM searches reveal material science problem: incomplete or untreatable (yet) backgrounds models





Tunneling Two-Level systems introduced to describe glasses, then non-thermal noise & decoherence

P.W. Anderson (Noble Price in Physics 1977), Y.M. Galperin



Ilya Prigogine (Noble Price in Chemistry 1977)

Doug Osheroff and Sir Anthony Leggett
Nobel laureates; Ultra-Low Temperatures, He3

Non-interacting TLS, thermodynamics is applicable, distribution of tunneling parameters leads to an observable effect

Systems with energy flow: thermodynamics not applicable, interactions between energy-bearing states lead to emerging phenomena (correlation in energy release, avalanches (SOC model), etc.

Collaboration with BES is required! Looking for “missed” effect predicted by phenomenology analysis:

- Burst–like emission of photons, phonons, and quasiparticles after energy deposition by stress, ionizing radiation, change of temperature, magnetic and electric fields;
- Up-conversion- significant relaxation events due to exposure to low-energy particles, and photons
- Triggering stored-energy release by below-detection threshold events (yearly modulation?)

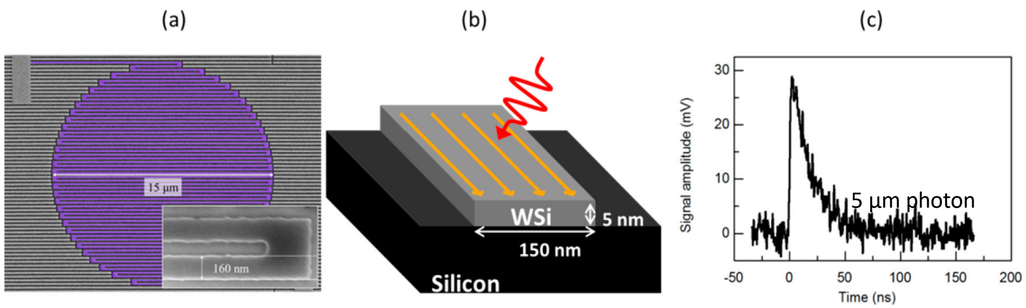
SNSPDs are a good laboratory for these effects in superconductors; direct application for axion search (project BREAD)

DAMA-LIBRA modulation could be due to sub-ev particle events (triggering); are quantum errors rate modulated?

Superconducting Nanowire Single-Photon Detectors

in between thermal equilibrium noise and quantum fluctuations

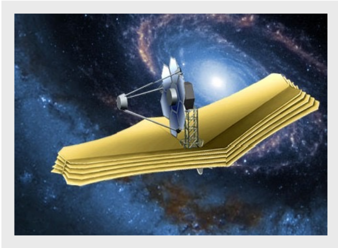
Where we are

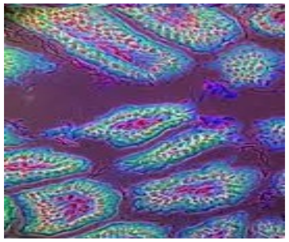


Li Chen et al., Accounts of Chemical Research, V. 50 pp1400-1409 (2017)

(a) SEM image of an SNSPD (b) Absorption of a photon produces a hotspot in a nanowire: destroys superconductivity across the entire width of the nanowire, generate a voltage pulse -(c)
Thermal time constant = ~30 ns; Working temperature = ~250 mK-1.5 K

Where we go





Space microwave telescopes; Axions,
Dark Matter & Neutrino detectors
QI devices, chemical &biophysics sensors.

Nanowire detectors outperform others in response time, energy sensitivity and quantum efficiency, have macroscopic sensor (pixel) areas, require cooling to 250- 300 mK, (1.5 K for Near-IR) ;
In development: large arrays, working temperature 1.5- 2 K, time resolution 30 ps
Growing impact on many sensing technologies (core LLNL competency)

… and why this technology is better than others?

SNSPD: energy accumulation and release effects suppressed, can come close to qubit's energies and noises

CMB and IR photon detectors:

<<< readout 'drive' dissipation <<< Noise equivalent power "energy sensitivity">>>

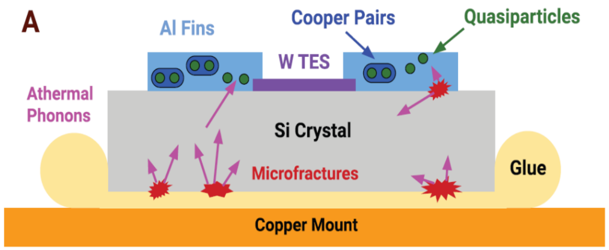
MKIDs	TES with SQUID array readout	Superconducting nanowire
Sensors are integrated into microwave resonant circuits	TES are DC-coupled to array of SQUIDs Frequency multiplexing array redout	DC supercurrent in sensors while waiting for "click"; RSFQ -compatible*
Continuous Dissipation in sensors by microwave readout signals	Some leakage of RF signals to sensors, dissipation by DC current in TES	No dissipation by readout in sensor whole waiting for photon

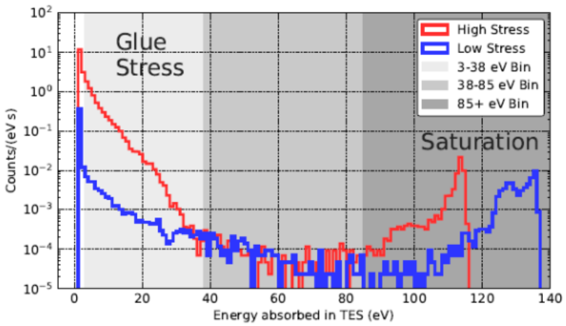
Energy accumulation and release effects are present in all superconducting devices, including STJ detectors and qubits. Focused experiments are required to find the scale of these effects with respect to other "line-widening" and backgrounds effects

- At low temperatures system of interacting charges (on interfaces), spins (localized electrons, impurities, nuclei), nuclear quadrupole moments, etc., **are in the glass-like state**, so one can define a 'generalized excitation' as any non-equilibrium configurations of these systems.
- Time-varying electric or magnetic **fields applied** to materials or **leaking from the environment** can dynamically produce **energetic excitations and decoherence**

No dissipation in SNSPD waiting for signals; less stress in nanowires - SOC-like noise suppressed

Low-temperature solid-state detectors: phonon burst and quasiparticles production by stress and other energy sources





"Stress Induced Source of Phonon Bursts and Quasiparticle Poisoning." https://doi.org/10.48550/arXiv.2208.02790

Excess background in solid-state detectors rising with stress

- Relaxation/ inelastic deformation in single crystals (semiconductors, dielectrics, metals) goes through small dissipative transitions in small volumes: change of crystal structure, formation of twins boundaries, sliding plane, dislocations, dislocation motion, chemical transformation; can be accompanied by light emission and electron emission from the surface.
- In materials where irradiation led to energy accumulation (Thermally-Stimulated luminescence, Exaelectron Emission, Conductivity) one can expect burst of phonon, photons, quasiparticles, exaelectrons, etc. (see: Sergey Pereverzev, "Detecting low-energy interactions and the effects of energy accumulation in materials", Phys. Rev. D 105, 063002 (2022). https://arxiv.org/abs/2107.14397)

We cannot build first principles models yet; we can expect to find new phenomenology, glass-like effects at different energy scales, so our empirical models are incomplete.

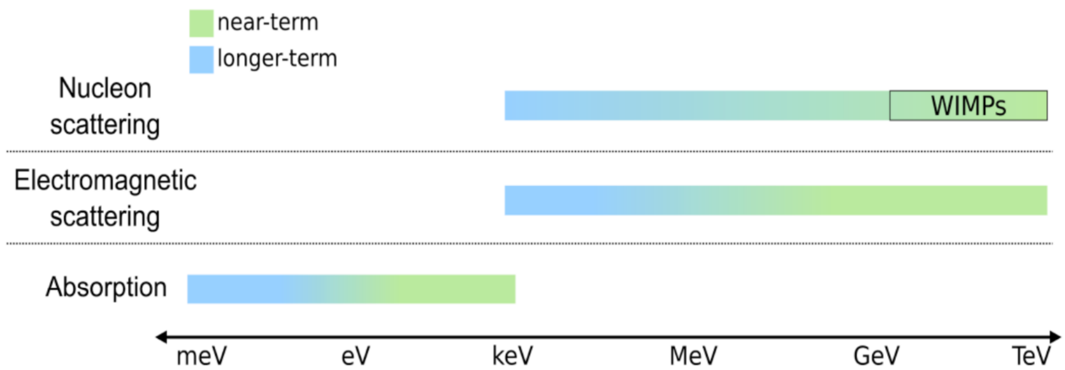
Sapphire substrate qubits for low mass Dark Matter searches

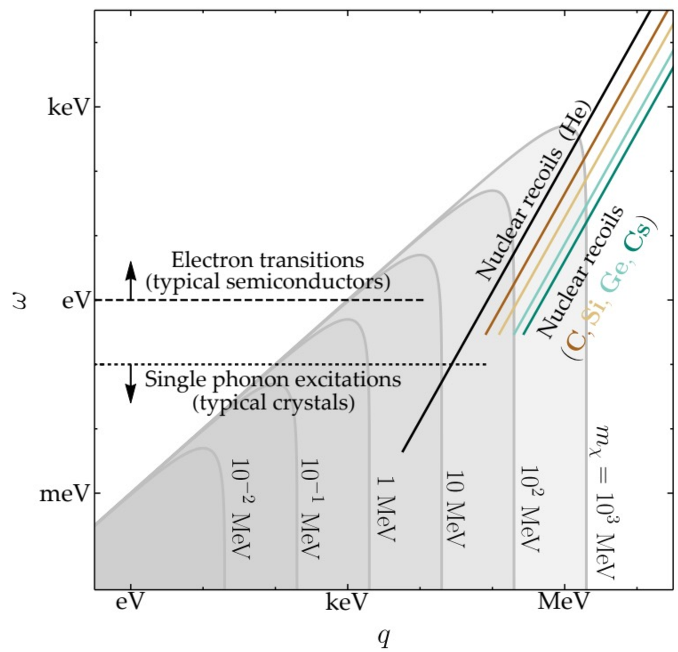
Rakshya Khatiwada

Illinois Institute of Technology

Fermilab

Motivation



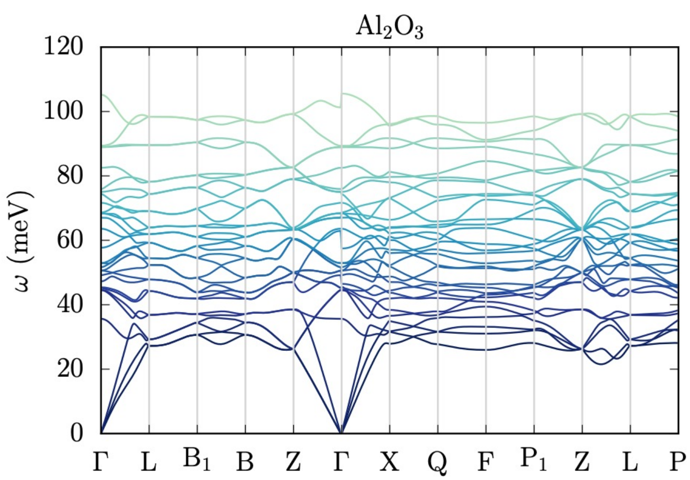


- ➢ How do we look for sub-MeV (scattering) and sub-eV (absorption) Dark Matter?
- ➢ What mechanisms in materials will be able to produce < 1 eV energy excitations?
  - -- phonons (collective excitations of ions) are effective since deBroglie wavelength of sub-MeV Dark Matter > than interatomic spacing
  - -- Polar crystals -- Sapphire
  - -- single phonon excitation modes ~ 100 to 10s of meV

Basic Research Needs for Dark Matter small projects new Initiatives

Trickle, T., Zhang, Z., Zurek, K.M. *et al.* Multi-channel direct detection of light dark matter: theoretical framework. *J. High Energ. Phys.* **2020**, 36 (2020).

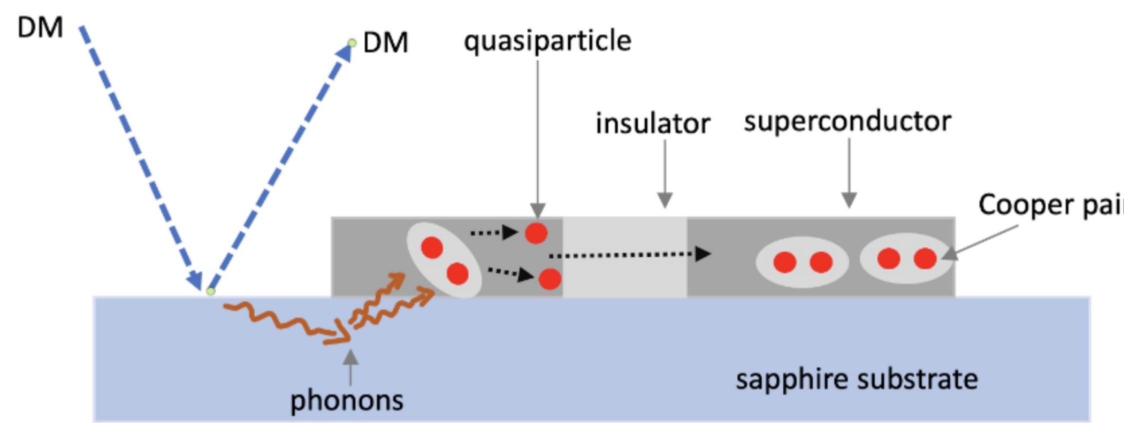
Sapphire substrate qubits-based detector?



Sapphire crystal phonon modes

- Qubits: great potential for low energy radiation/excitation detection
- Sapphire substrate qubits, common technology
- Can produce broken Cooper pairs of electrons in Al when $E > 2\ \Delta_{Al} \sim 0.6$ meV
- Demonstrated sensitivity to a few Δ_{Al} energies already

- Map out: Energy deposited -> phonon excitations and down-conversion -> quasiparticles produced in Al -> qubit readout 'signal' ?



Potential qubit based Dark Matter detector

Sinead Griffin, Simon Knapen, Tongyan Lin, and Kathryn M. Zurek
Phys. Rev. D **98**, 115034 – Published 27 December 2018

Improved strain sensitivity can extend the reach of existing experiments, and can enable new experiments.

Daniel Baxter, Sunil Bhave, Daniel Bowring, Bryan Ramson, Jason St. John, ***Dylan Temples***

Embedded optical strain sensor allows for codeposition of primary detectors: Qubit, MKID, TES, CCD.

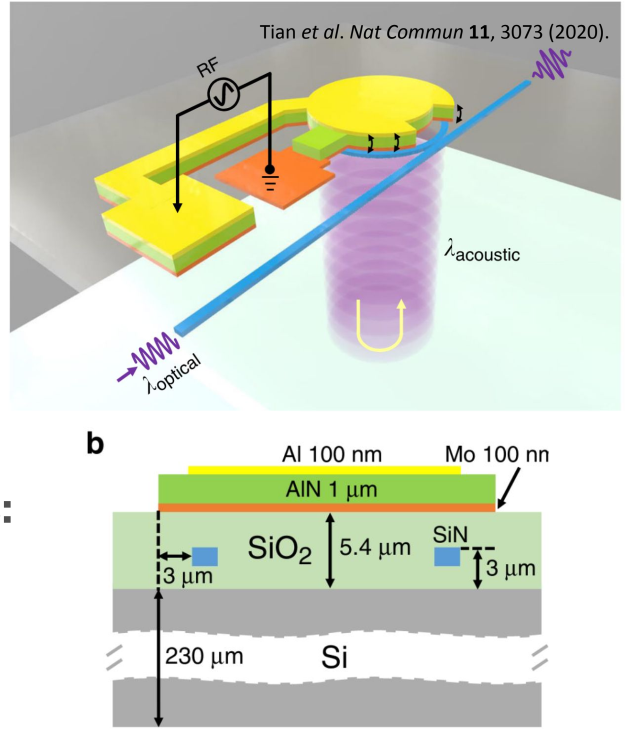
Additional readout channel: stress / substrate deformation

DM: Anticoincidence to reject low energy stress events. Potential for ER/NR discrimination?

QIS: Improve understanding of the role of stress release in quasiparticle poisoning of qubits.

Novel detection strategy for **resonant scattering processes:**

- 0 phonon final state, whole lattice recoils → no quanta
- Sufficient sensitivity to strain can identify these events
- Targeting Mössbauer-like (γ) and neutrino scattering



Fermilab

Full characterization of these devices for use in HEP is needed.

*Daniel Baxter, Sunil Bhave, Daniel Bowring, Bryan Ramson, Jason St. John, **Dylan Temples***

Currently used in microwave-optical transduction for communication -- we are assessing for HEP applications.

- Do these sensors directly (or indirectly through phonons) respond to radiation?
- What is the spatial resolution of these devices?
- What is their energy resolution and threshold?

Initial device testing at Fermilab planned for later this year.

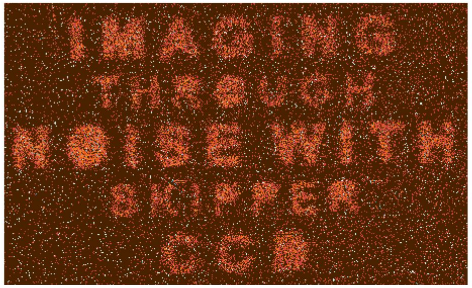
Currently investigating device packaging for deploying in dilution refrigerator.

Optical strain sensors can help us build better, more sensitive detectors, extending the reach of existing experiments, and offer a pathway for novel particle detection techniques.

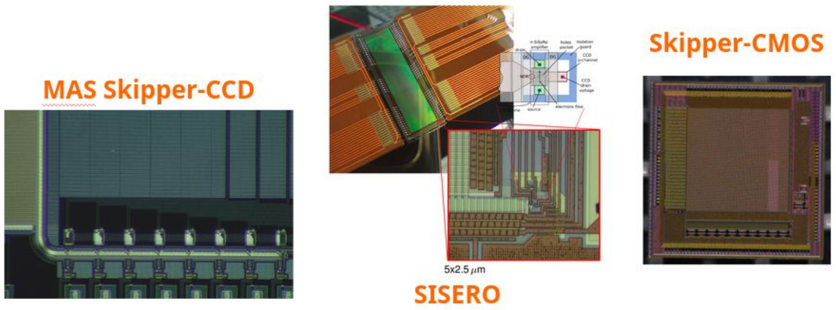
- Investigation of low energy excesses in solid-state DM search experiments.
- Confirmation the origin of non-radiogenic quasiparticle bursts in qubits as due to stress.
- Low-threshold detection of resonant absorption of photons and possibly neutrinos.

Skipper CCDs for Quantum Science

- **Publication:** Infrared photon-number-resolving imager using a Skipper-CCD
    - Accepted at PRApllied. https://arxiv.org/abs/2301.10891



- **Upcoming result:** qudit tomography using a Skipper-CCD
    - Two orders of improvement (less photons needed)
- **Collaboration with Kwiat Lab at UCIC**
    - Effort to build a Quantum IR Spectrograph
    - Installation of a Skipper-CCD pathfinding system at Kwiat Lab upcoming
- **Fermilab is leading the effort to make these detector faster**



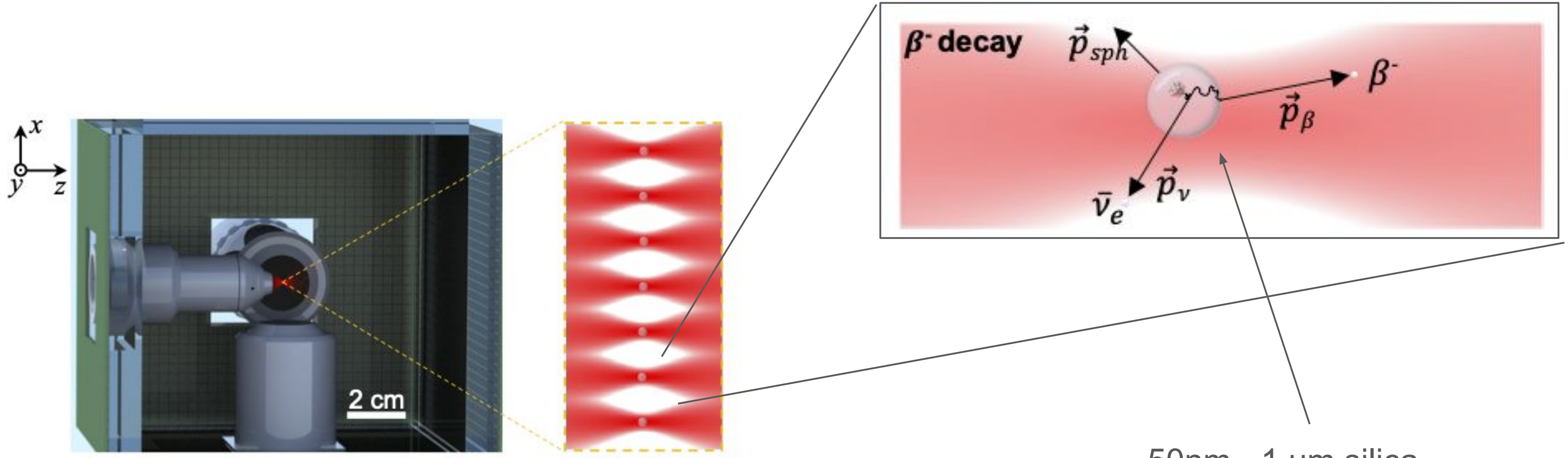
Take home message & vision

Fermilab

- **Very successful HEP-QIS QuantISED**
- **Early adopters are using the Skipper-CCD to produce world leading results**
- **Collaboration with Kwiat Lab at UCIC is growing and accelerating**
    - Killer app: Quantum IR Spectrograph (similar to quantum radar but with IR photons)
- **Effort towards building fast and easy to use compact systems**
    - technology transfer opportunity

By joining forces with established Quantum Science groups, we are leveraging on the Skipper-CCD technology to drive scientific advancements

Quantum Invisible Particle Sensor (QuIPS)



~50nm - 1 um silica

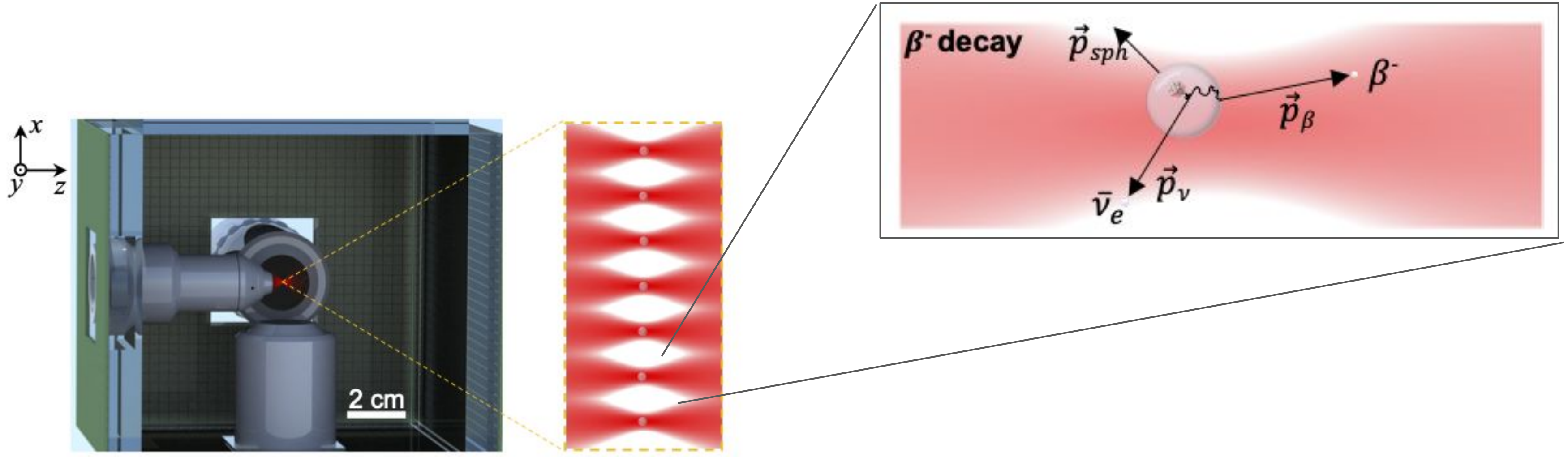
~1% mass-loaded with radioisotope of choice

Targets:

- Heavy sterile neutrinos
- Axions
- Precision EW

Carney, Leach, Moore, PRX Quantum 2023

Quantum Invisible Particle Sensor (QuIPS)



Optical readout @ ~SQL

Pixelated e/photon detector
(e.g., CCD)

$$\begin{pmatrix} E_s \\ \mathbf{p}_s \end{pmatrix} = \begin{pmatrix} E_{s'} \\ \mathbf{p}_{s'} \end{pmatrix} + \begin{pmatrix} E_i \\ \mathbf{p}_i \end{pmatrix} + \begin{pmatrix} E_{B'} \\ \mathbf{p}_{B'} \end{pmatrix}$$

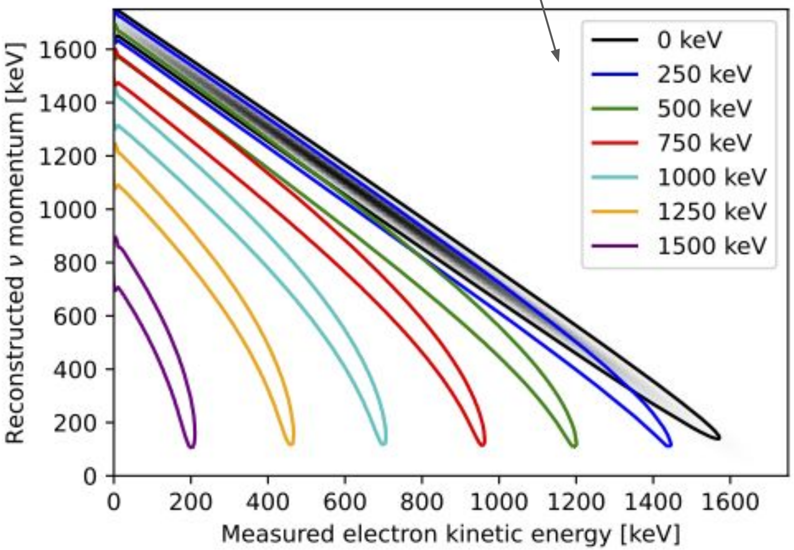
sphere nu other

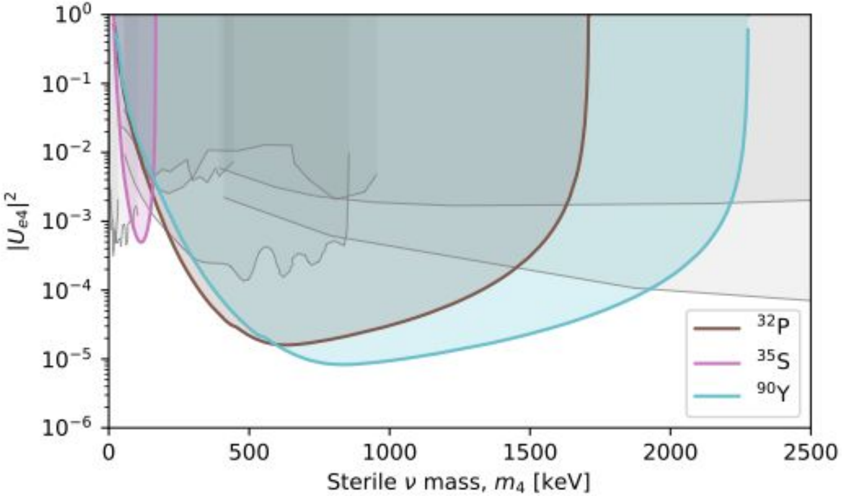
$$\mathbf{p}_i = -(\Delta \mathbf{p}_s + \mathbf{p}_{B'})$$

→ reconstruct neutrino momentum

1-3 year goals

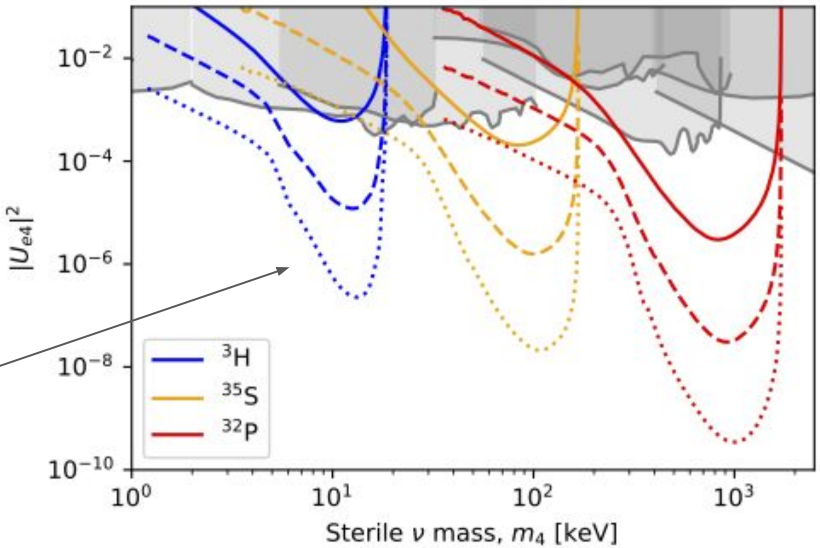
Heavy neutrino mass





Partially funded with LDRD @ LBL (build pixel detector)
Plot: 1 sphere, 1 month exposure

Longer term goals



1000 spheres x 1 year

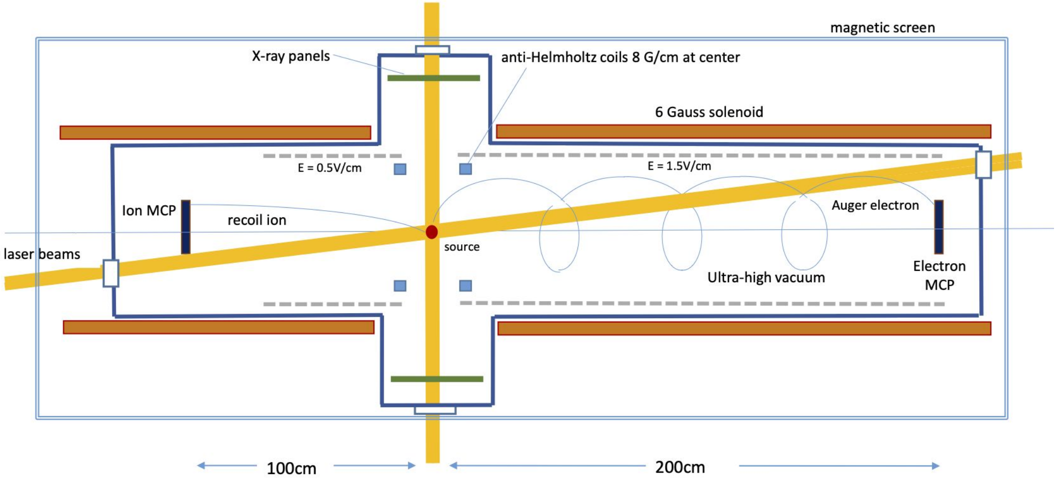
Partially funded via DOE-NP (sub-SQL readout)
Multi-sphere trap currently under development at Yale

(Backup slide) Brief comparison to AMO approach

HUNTER/various others: trap cold parent nuclei directly, no sphere

Difficulties:

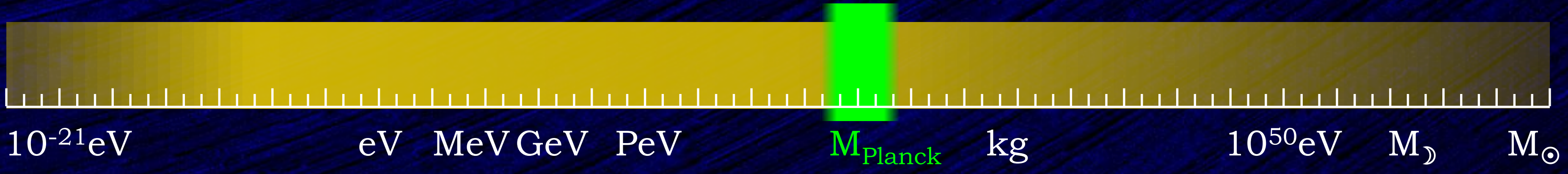
- Daughter kicked out of trap, kinematic reconstruction hard
- Angular resolution challenging
- Can only use optically trappable isotopes (**huge** limitation)
- Can only trap so many atoms…



HUNTER experiment
(image: https://indico.cern.ch/event/653314/contributions/2825747)

The Windchime Project:
Towards Gravitational Detection of Dark Matter in the Lab

arXiv:2203.07242

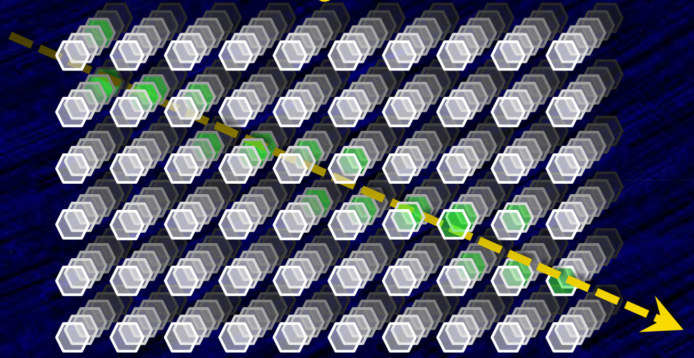


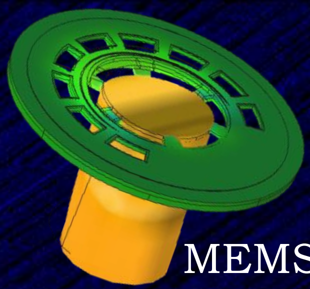
✓ Planck mass uniquely motivated
✓ Still accessible in lab
✓ Gravitational detection feasible

thanks to recent advances in quantum sensing. Need

- sensitive accelerometers
- quantum-enhanced readout
- large array

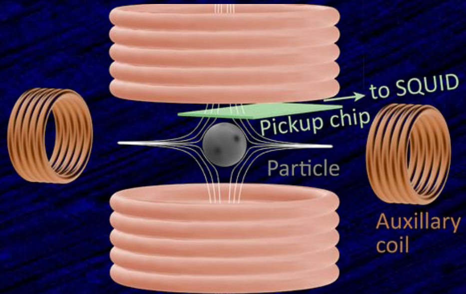
Search for Track in Array of Accelerometers



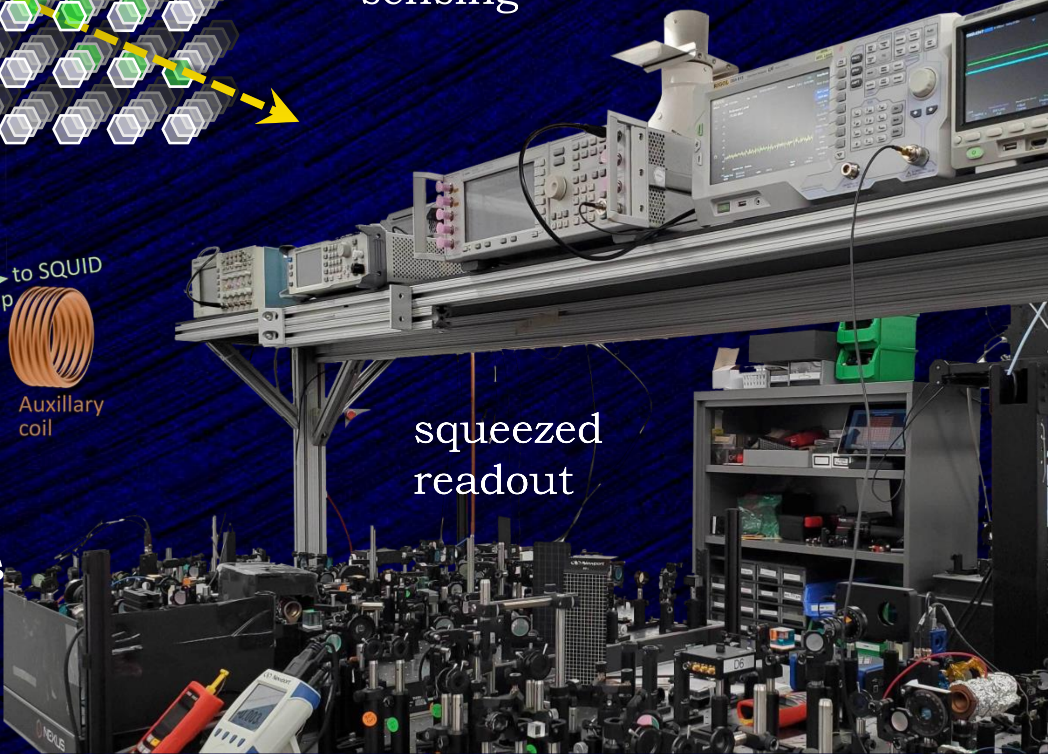


velocity sensing

MEMS accelerometers



levitated superconductors



squeezed readout

U.S. DEPARTMENT OF ENERGY Office of Science

QUANTUM SCIENCE CENTER

PURDUE UNIVERSITY Purdue Quantum Science and Engineering Institute

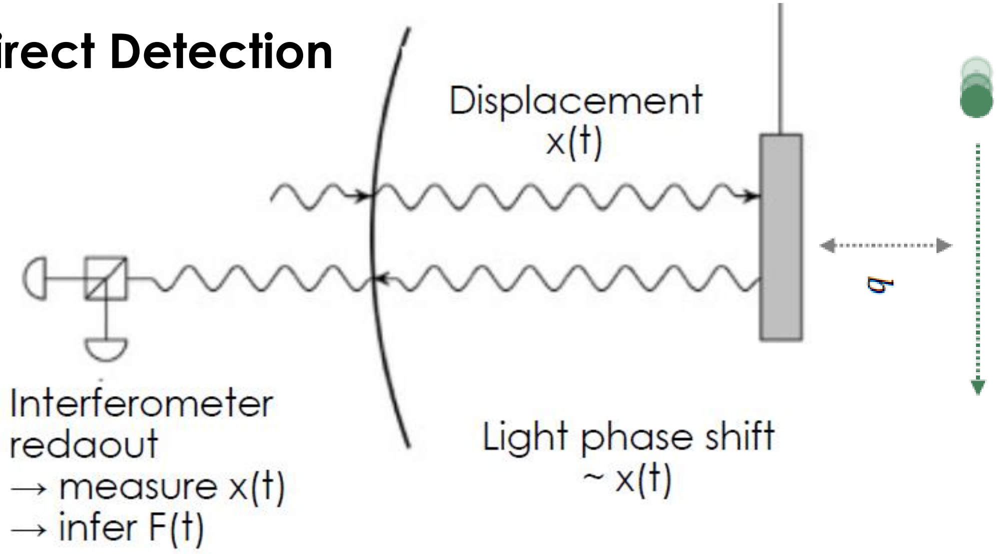
Rafael Lang (Purdue): Windchime

Back action evasion and quantum noise reduction in quantum magnetometers for particle and field detectors

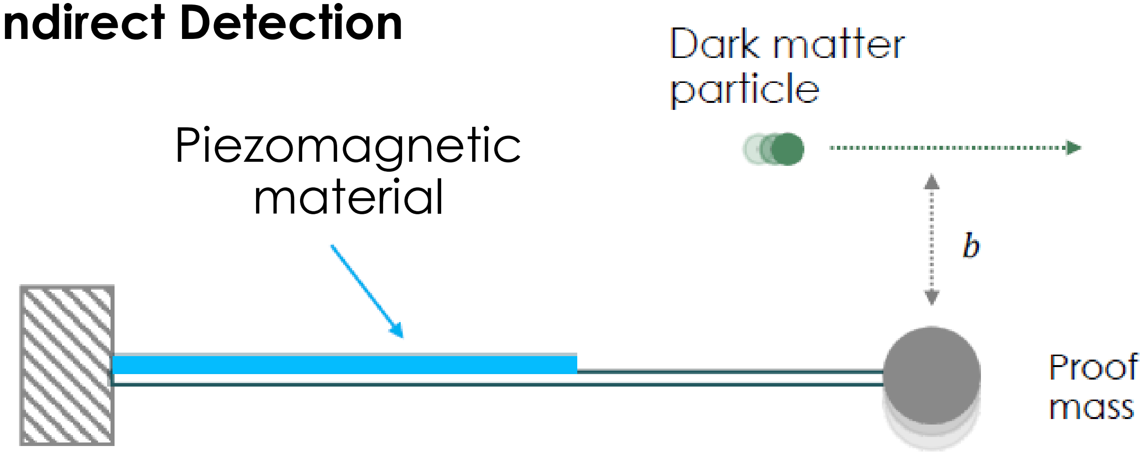
Claire Marvinney, Alberto Marino, Michael Febbraro, Andrea Delgado, Raphael Pooser, Nicholas Peters, Marcel Demarteau
Oak Ridge National Laboratory

Goal: Leveraging quantum-noise reduction techniques (squeezed light and back-action evasion) to obtain sensitives beyond the standard quantum limit with ***scalability decoupled from quantum resource scaling***

Direct Detection



Indirect Detection



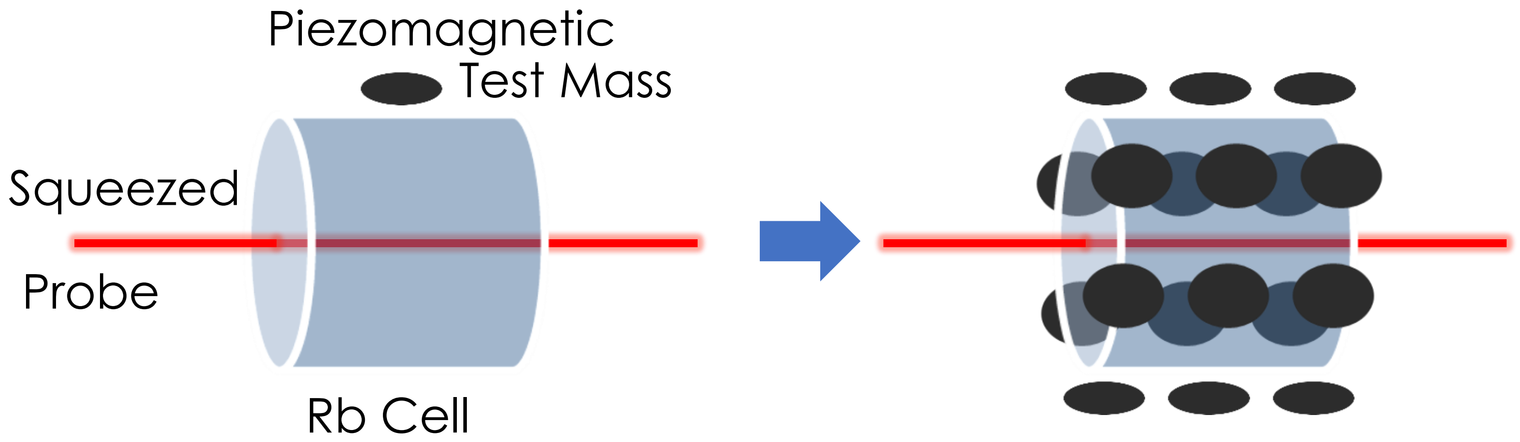
Alternative approach to back-action evasion: instead of directly reading out the position of the proof mass, can transduce response of proof mass

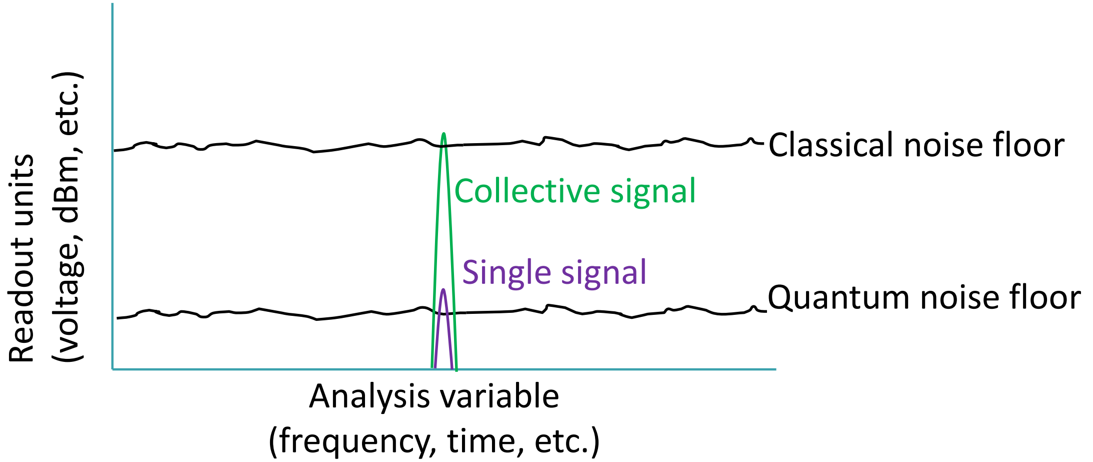
- Piezoelectric materials
  - Stress -> electric field
- Piezomagnetic materials
  - Stress -> magnetic field

Scalable sensitivity enhancement through collective oscillation of sensor array with single quantum enhanced readout

Initial Approach:
Single device, single quantum enhanced readout

Collective Approach:
Array of devices,
Single quantum-enhanced readout





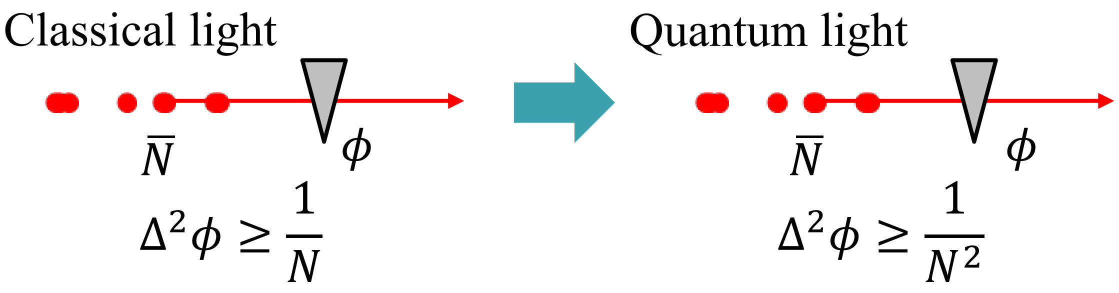
- ***Benefits:***
  - No required scaling of quantum resources for improved sensitivity
  - Readout for multi-axis accelerometers
- ***Challenges and limitations:***
  - Piezomagnetic coating quality and field strength
  - Optimal measurement and data analysis strategies to capture directionality
  - Avoiding spin-noise projection back-action with counter-propagating scheme

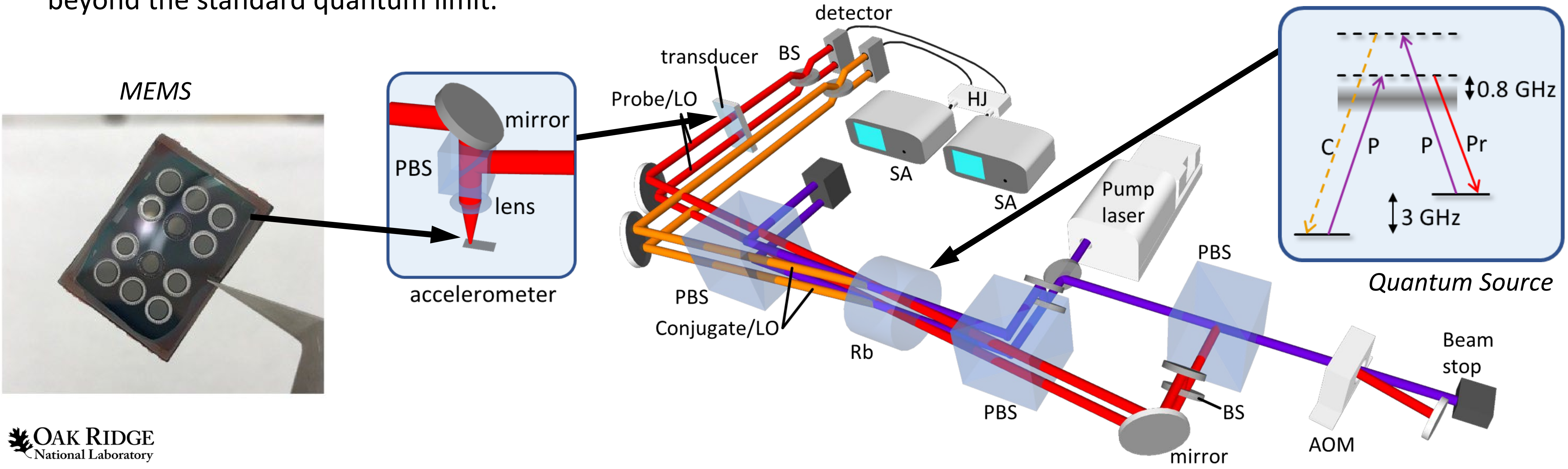
Quantum Enhanced Detection of Quantum Fields and Particles through Networked Entangled Sensors

Alberto Marino, Claire Marvinney, Michael Febbraro, Andrea Delgado, Raphael Pooser, Nicholas Peters, Marcel Demarteau
Oak Ridge National Laboratory

- ***Goal:*** Develop a distributed array (network) of entangled optomechanical sensors for proxy-force detection that enables the sensitivities needed for DM detection and BSM physics.
- Short term: leverage quantum-noise reduction techniques (squeezed light and back-action evasion) to obtain sensitives beyond the standard quantum limit.

Classical sensor | **Quantum sensor**

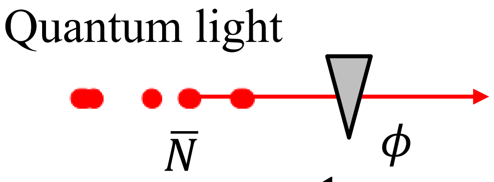




OAK RIDGE National Laboratory

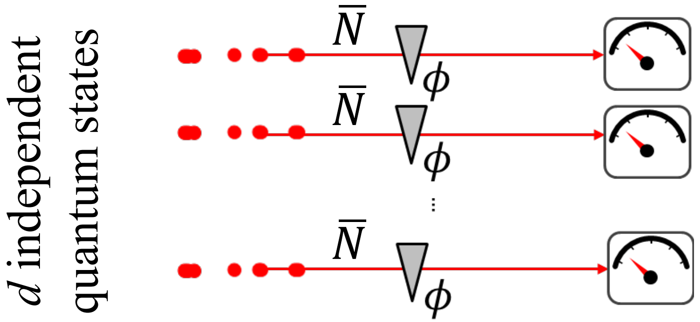
- Longer term: extend quantum sensing configuration to distributed array (network) of entangled sensors.

Quantum sensor



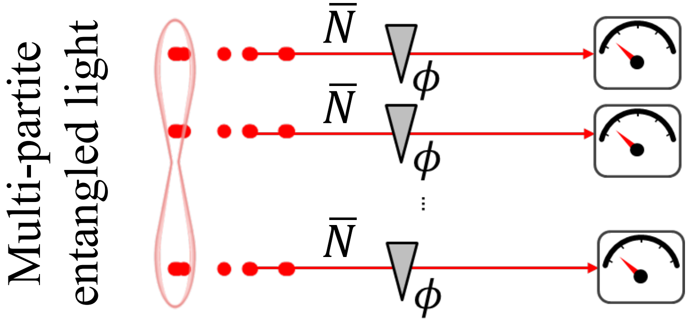
$$\Delta^2\phi \geq \frac{1}{N^2}$$

Array of d quantum sensors



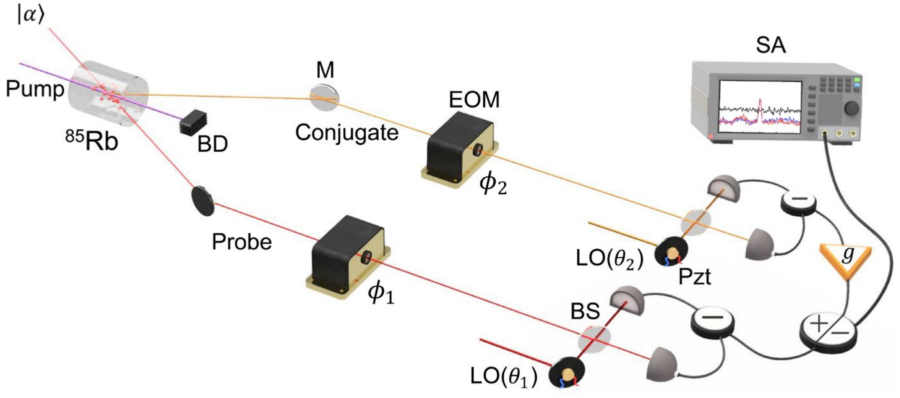
$$\Delta^2\phi \geq \frac{1}{dN^2}$$

Entangled network of d quantum sensors



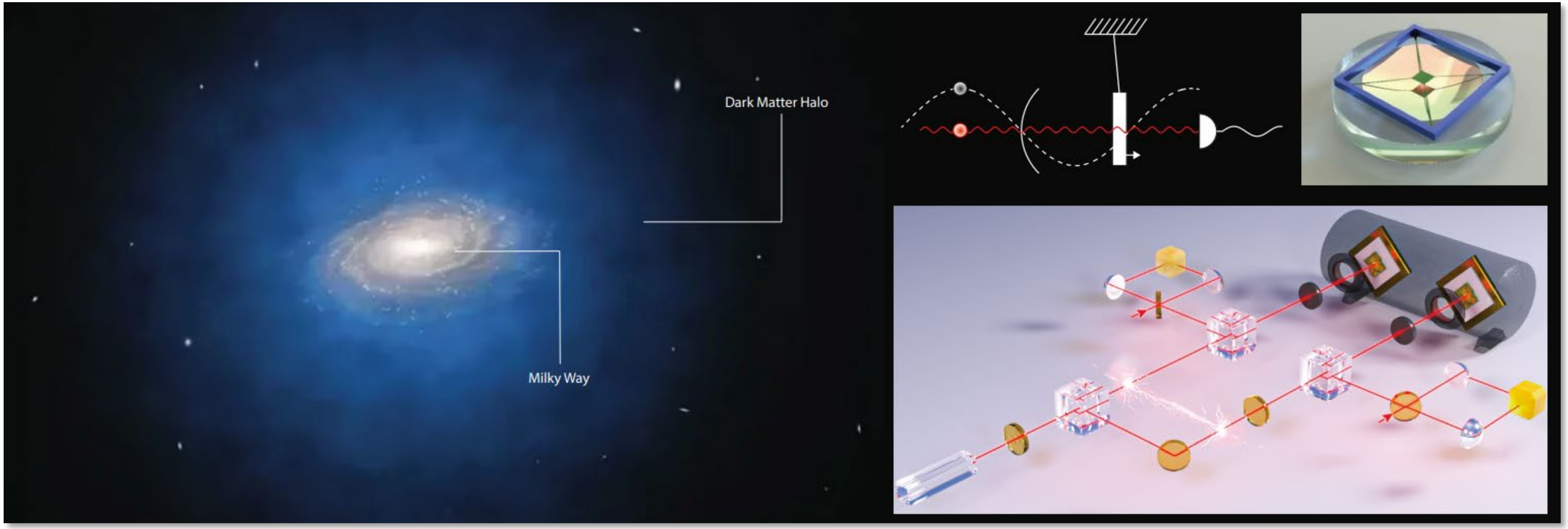
$$\Delta^2\phi \geq \frac{1}{d^2N^2}$$

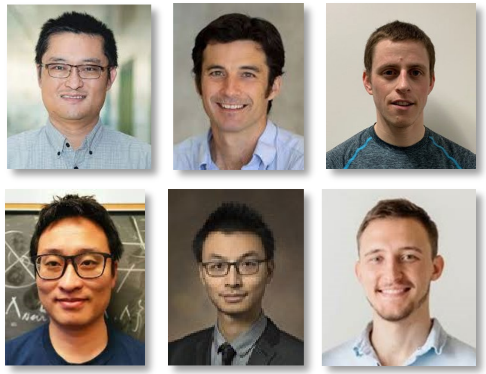
- ***Challenges and limitations:***
  - Scalable source of multi-partite entanglement.
  - Distribution of quantum resources.
  - Optimal measurement and data analysis strategies (QCRB, QML, etc.).
  - Scalability and limitations of imperfections.



S. Hong, et al., *in preparation* (2023).

Entanglement-enhanced optomechanical dark matter detectors



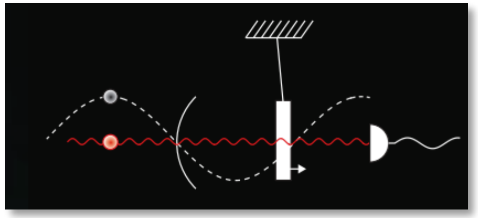


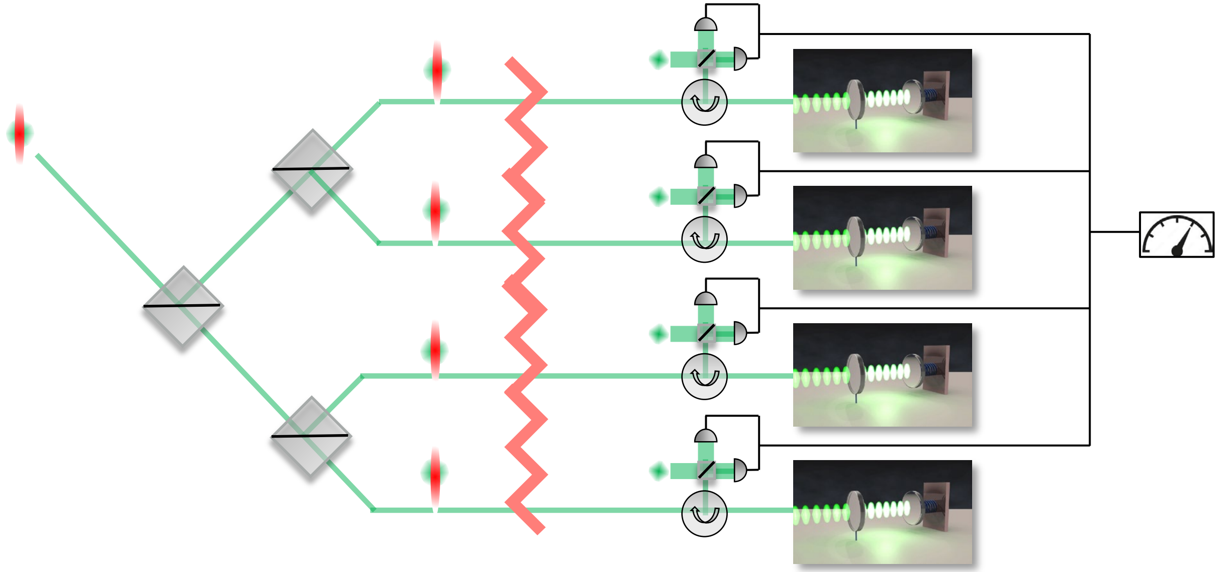
"Entanglement-enhanced optomechanical sensing." *Nat. Phot.* 1-8 (2023)

"Entanglement-enhanced optomechanical sensor array for dark matter searches." *arXiv preprint arXiv:2210.07291* (2022)

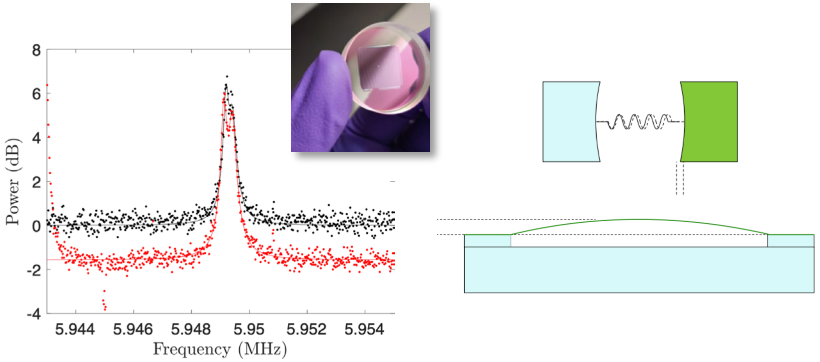
"Searching for vector dark matter with an optomechanical accelerometer." *Physical Review Letters* 126.6 (2021): 061301.

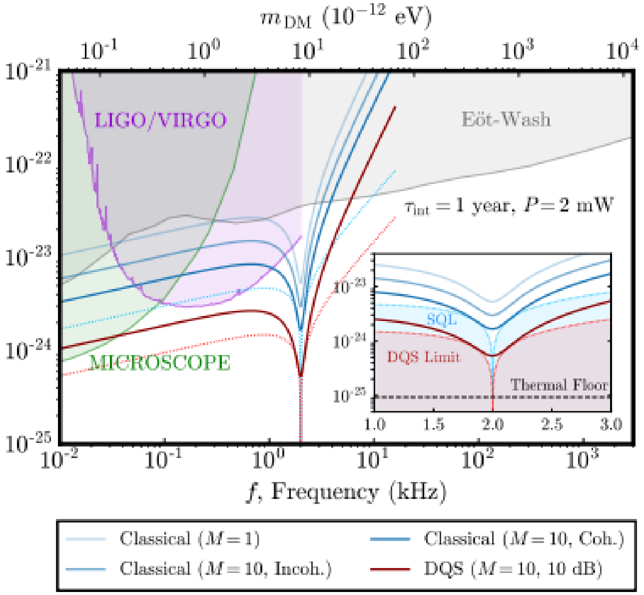
Entanglement-enhanced optomechanical dark matter detectors



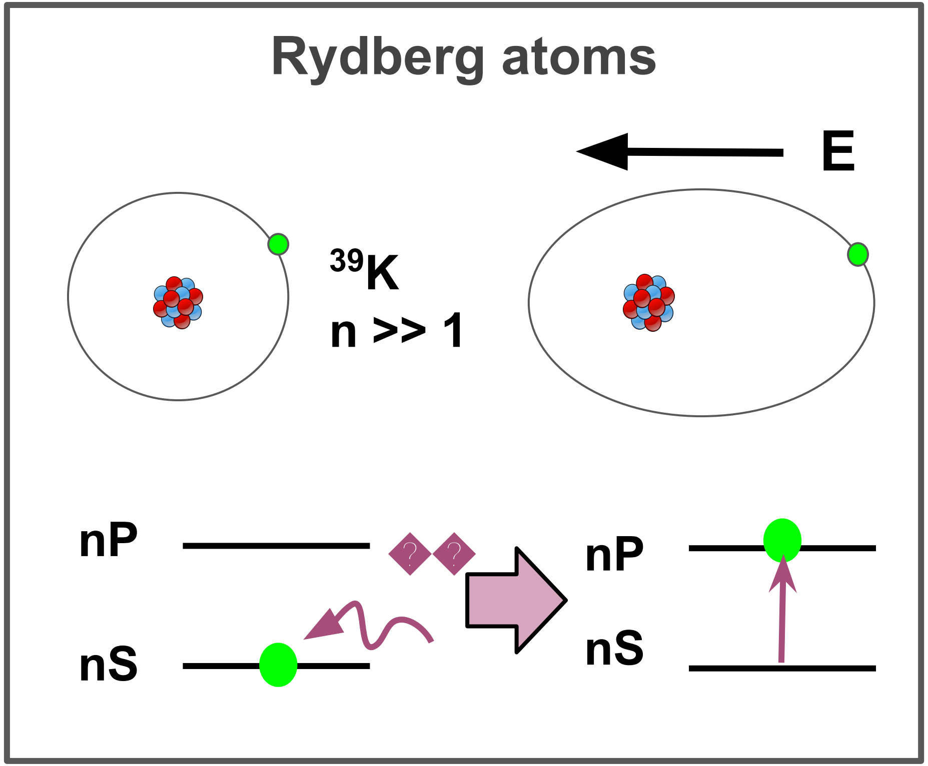


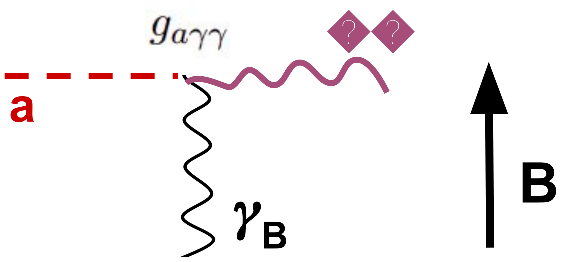
$$\mathrm{SNR}_{+} = M \frac{x_{\mathrm{sig}}}{\langle x_{\mathrm{shot}}^2 \rangle} \rightarrow M^2 \frac{x_{\mathrm{sig}}}{\langle x_{\mathrm{shot}}^2 \rangle}$$





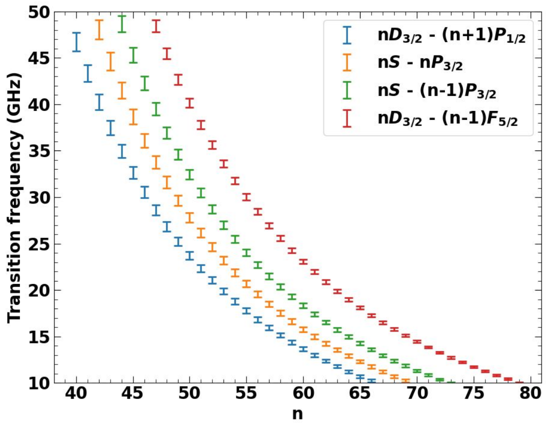
Rydberg Atoms as Single-Photon Detectors for Axions

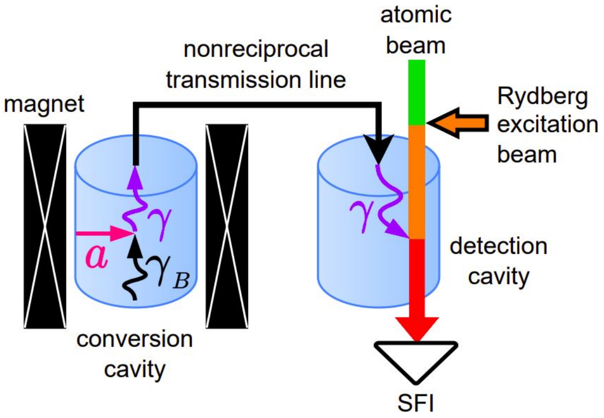


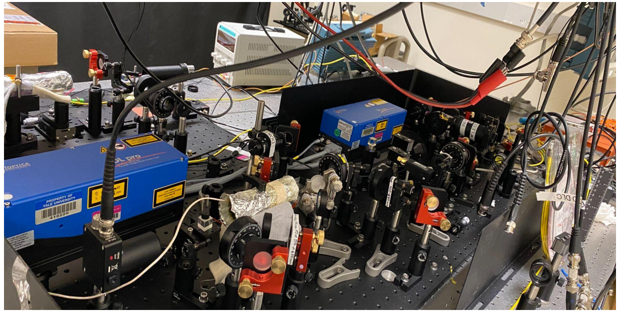


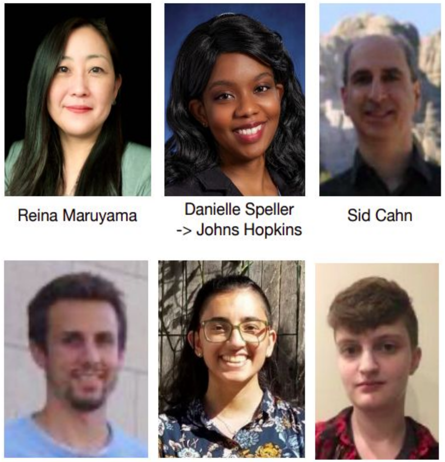
$\gamma \gtrsim$ **10 GHz: single-photon detector advantage**

Rydberg/Axions at Yale (RAY)





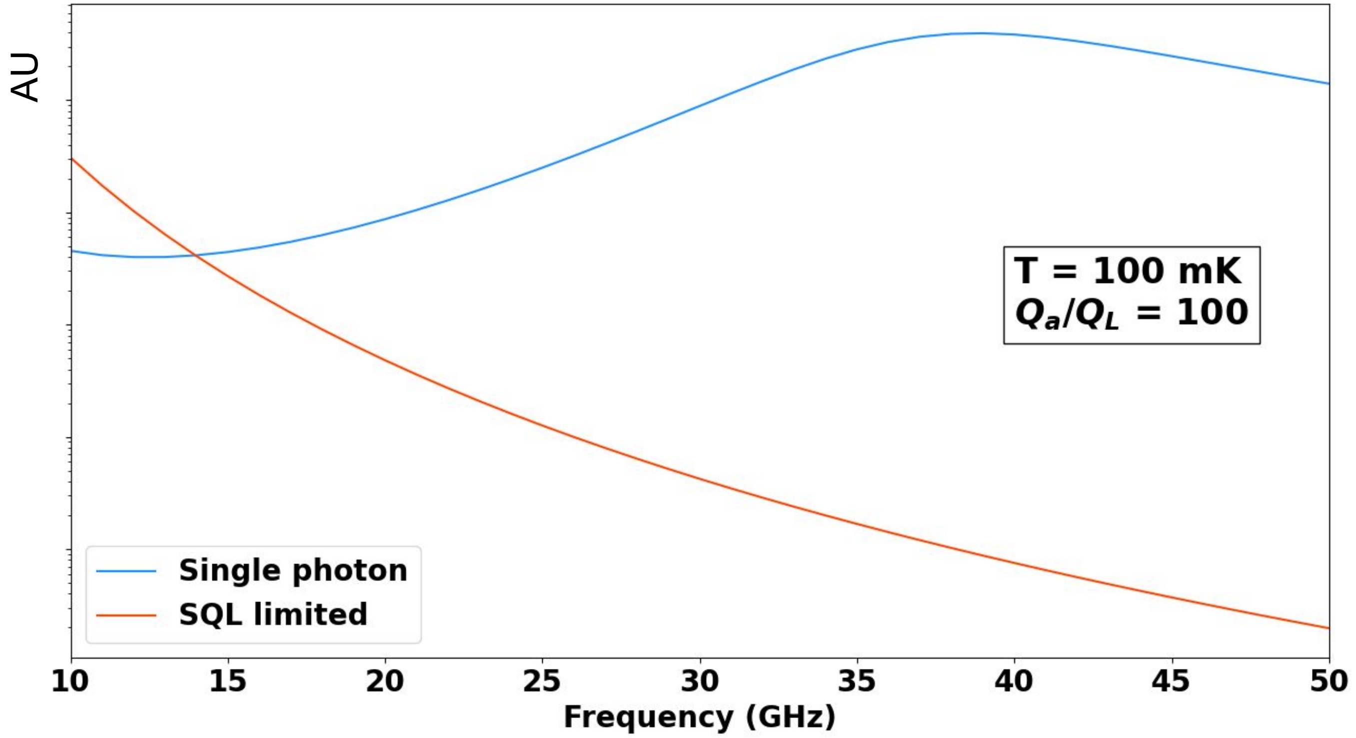




Reina Maruyama
Danielle Speller -> Johns Hopkins
Sid Cahn
Mike Jewell
Sumita Ghosh
Eleanor Graham

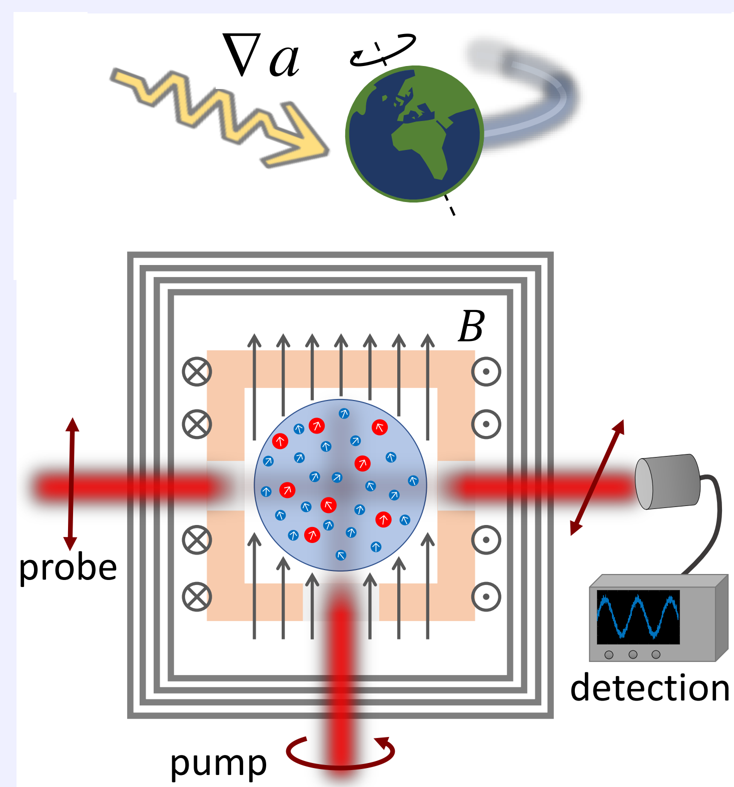
Wright Laboratory

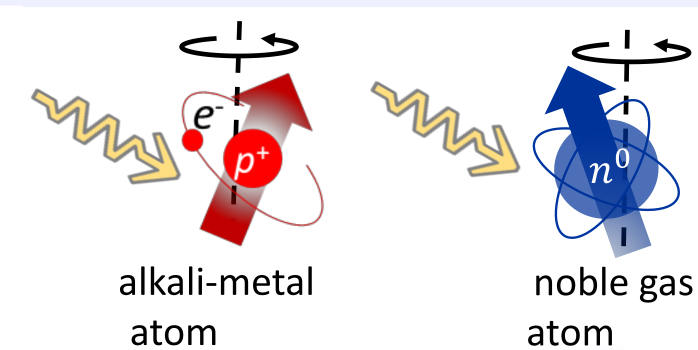
Backup: Single Photon vs. Linear Amplifier



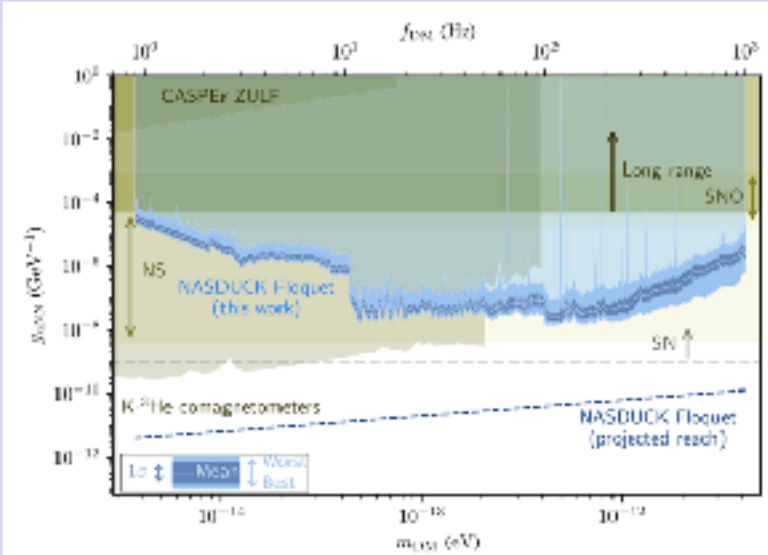
Noble and **A**lkali **S**pin **D**etectors for
Ultralight **C**oherent dar**K** matter

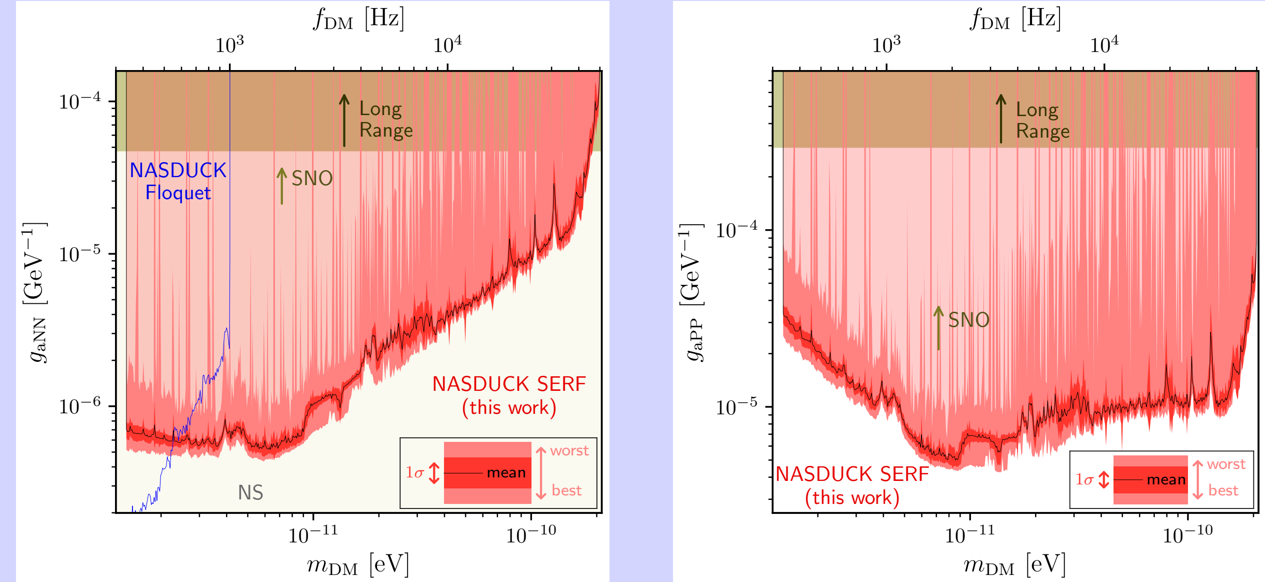
NASDUCK

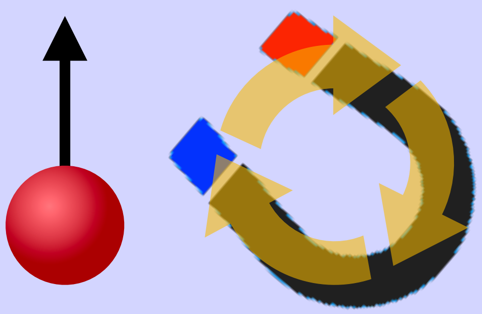




(Sensitive to ALP-proton, ALP-neutron, and ALP-electron interactions)

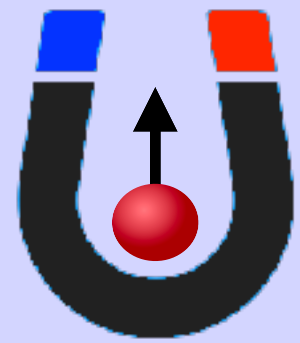






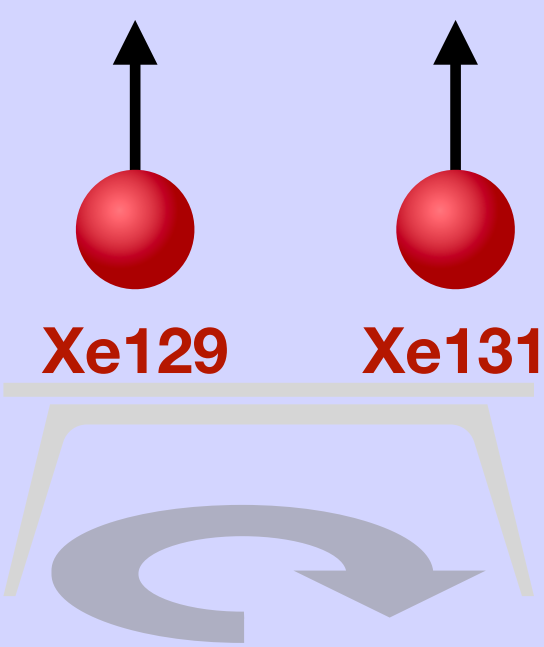
NASDUCK Floquet

[*Sci.Adv.* 8 (2022) 5]



NASDUCK SERF

[2209.13588]



NASDUCK Modulated

And more!