WG4: Quantum and Superconducting Detectors

Michael Jewell, Julian Martinez-Rincon, Cristian Pena

Outline

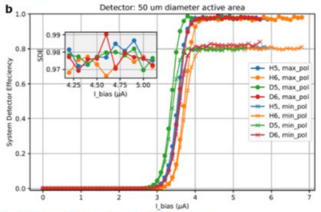
- There are a number of technologies being explored
  - SNSPD: Superconducting Nanowire Single Photon Detectors
  - QCD: Quantum Capacitance Detectors
  - KID: Kinetic Inductance Detectors
  - TES: Transition Edge Sensors
  - Atomic Clocks
  - Atom Interferometry
- Wide range of applications to Fundamental Physics
  - Dark Matter Detection
  - Gravitational Waves
  - Neutrino Scattering

Superconducting Nanowire Single Photon Detectors (SNSPD)

Present State of The Art in SNSPDs

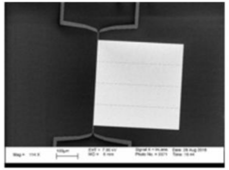
Matt. Shaw's Talk

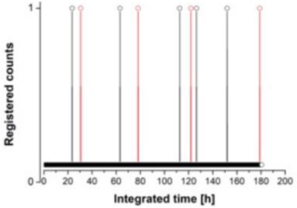
High Efficiency
98% SDE @ 1550 nm (NIST)



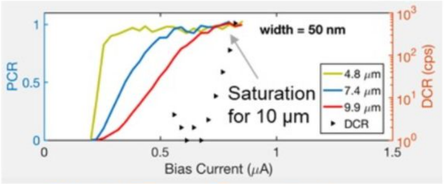
Reddy et al, *Optica* (2018)

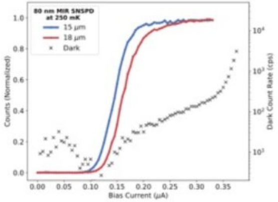
Low Dark Counts
6e-6 cps (MIT/NIST) Chiles et al, *Phys. Rev. Lett.* (2022)



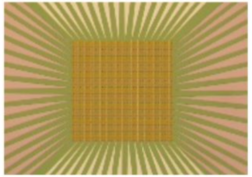


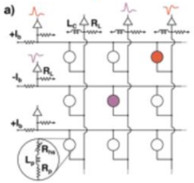
UV – Mid-IR Operation
Photon counting to 18 μm (JPL/MIT/NIST)



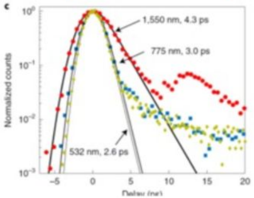


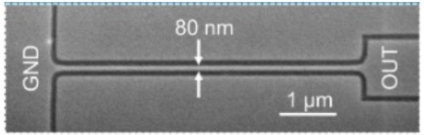
Kilopixel Array Formats
32x32 "row-column" array (NIST/JPL)





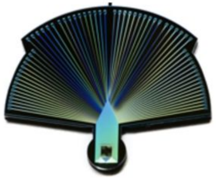
High Time Resolution
2.6 ps FWHM (MIT/JPL/NIST)





Korzh et al, *Nature Photonics* (2020)

High Event Rate Wollman et al, *Optics Express* (2019)
1.4 Gcps in 32-element array (JPL)



NIST
MIT
JPL

SNSPD Advantages for Fundamental Physics

Dark Matter Detection + Axions

- Low dark counts (10^{-5} cps)
- Low energy threshold (70 meV)
- Large active area ($mm^2 \rightarrow cm^2$)

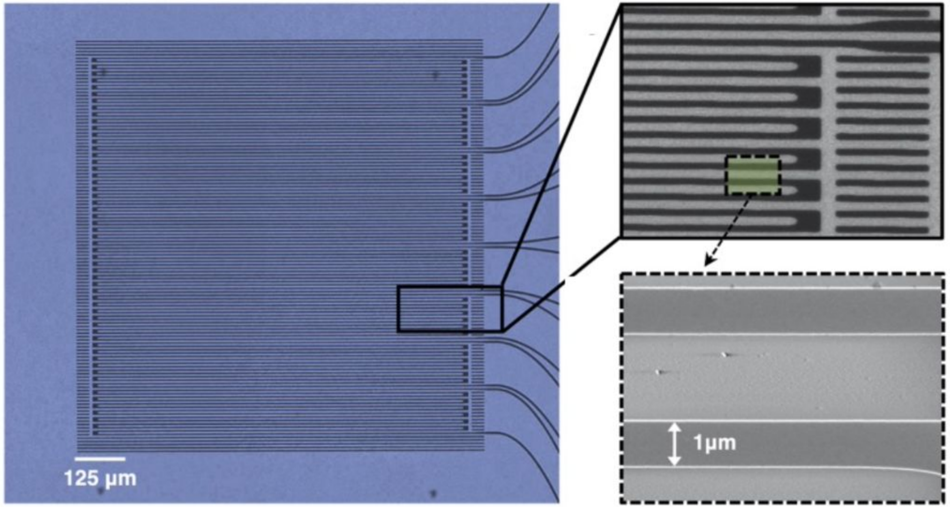
Nuclear Physics and Collider Physics

- High time resolution (3 ps)
- Low dark counts (10^{-5} cps)
- Radiation hardness

Tests of Quantum Gravity

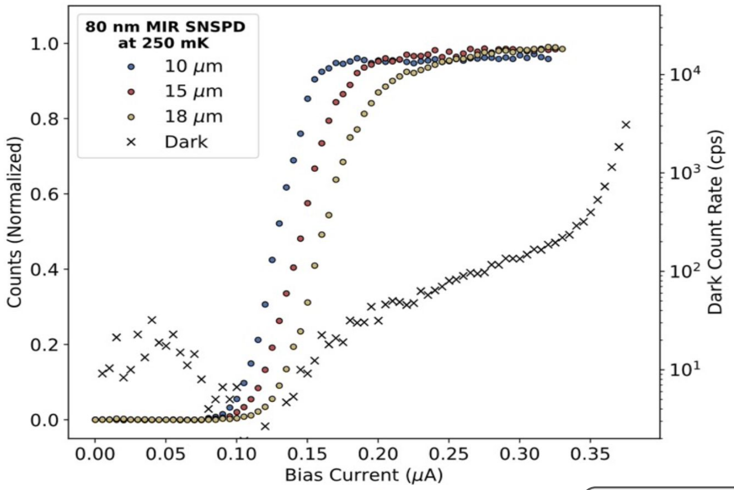
- Low dark counts (10^{-5} cps)
- High efficiency (98% @ 1.5 μm)
- Photon number resolution (1, 2, or many)

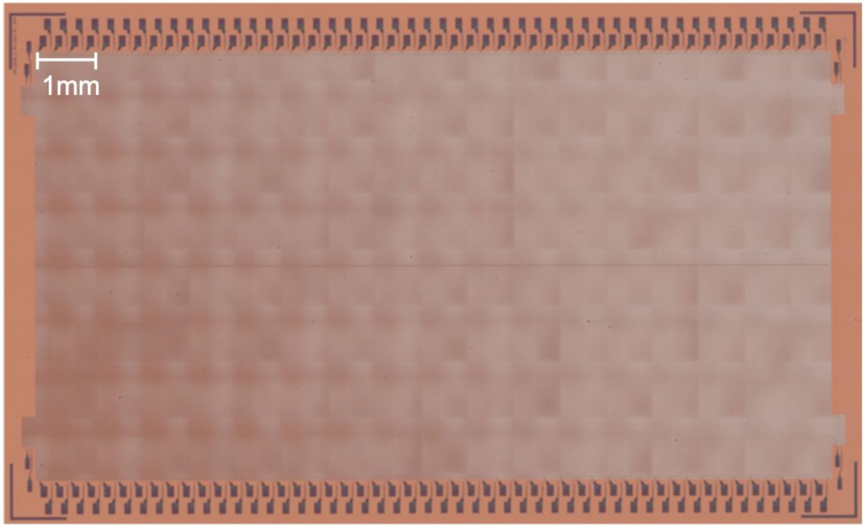
Large Area SNSPD (J. Luskin)



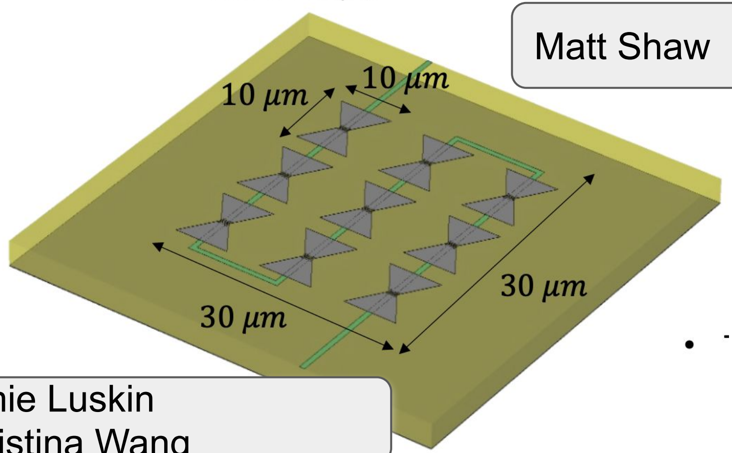
Matt Shaw,
Jamie Luskin

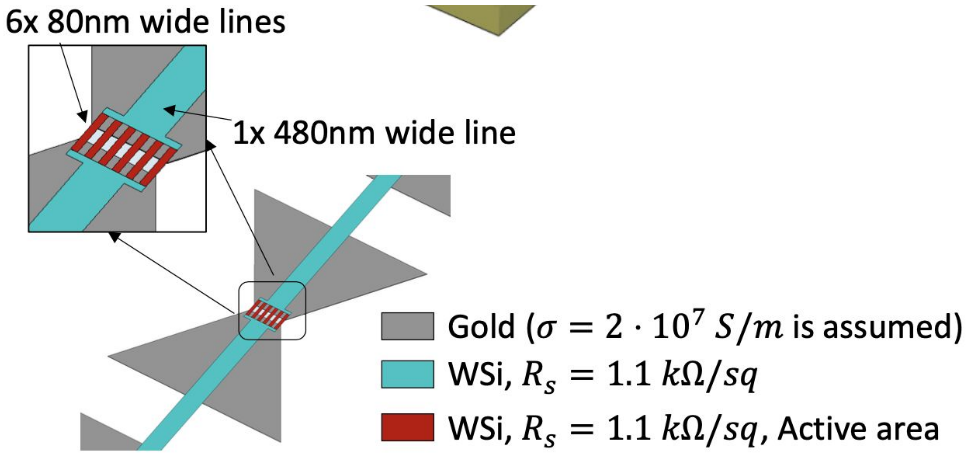
SNSPD New Directions





Matt Shaw



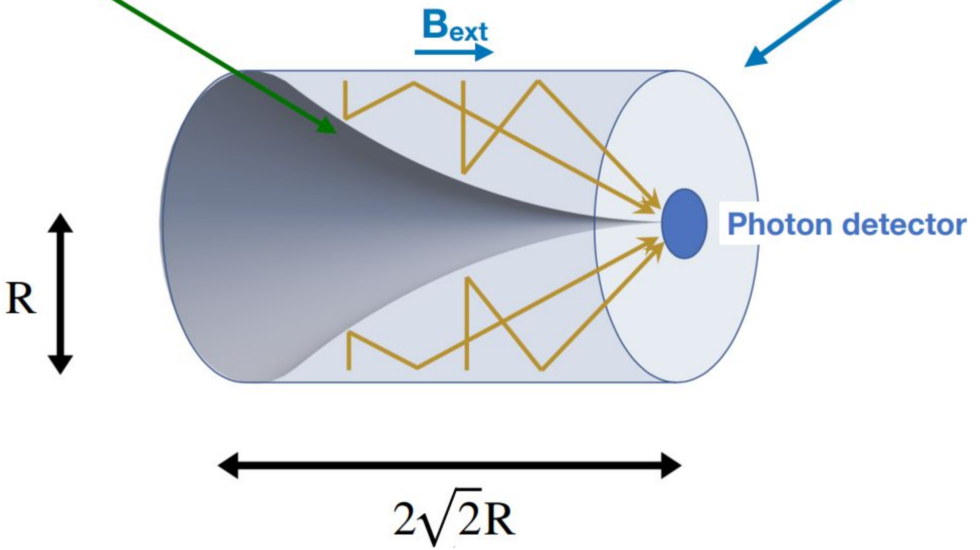


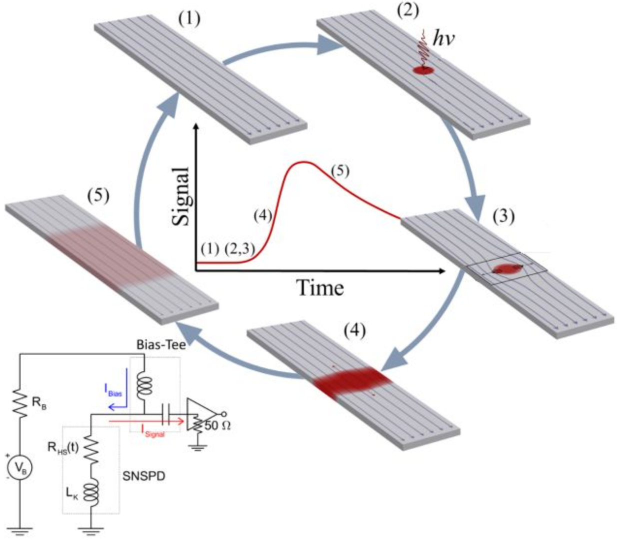
Jamie Luskin
Christina Wang

Direct Applications to Axion/Dark Photon Searches

BREAD Detector Concept

- Since an external B field is needed, its convenient to build a **cylindrical surface** that would fit in a solenoid
- A **parabolic mirror** is added to focus the photons to a vertex





Gabe Hoshino
Christina Wang

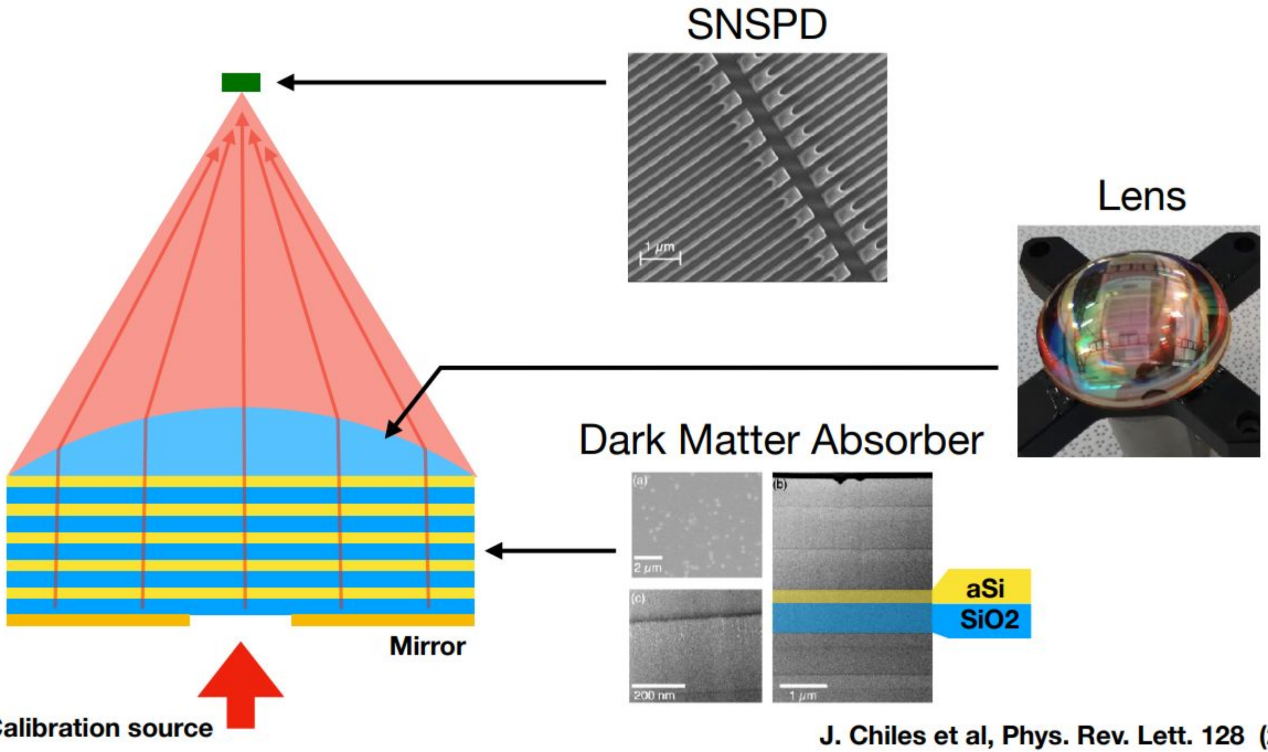
Direct Applications to Axion/Dark Photon Searches

LAMPOST

Light A’ Multi-layer Periodic Optical SNSPD Target

Ilya Charaev

Jeffrey Chiles



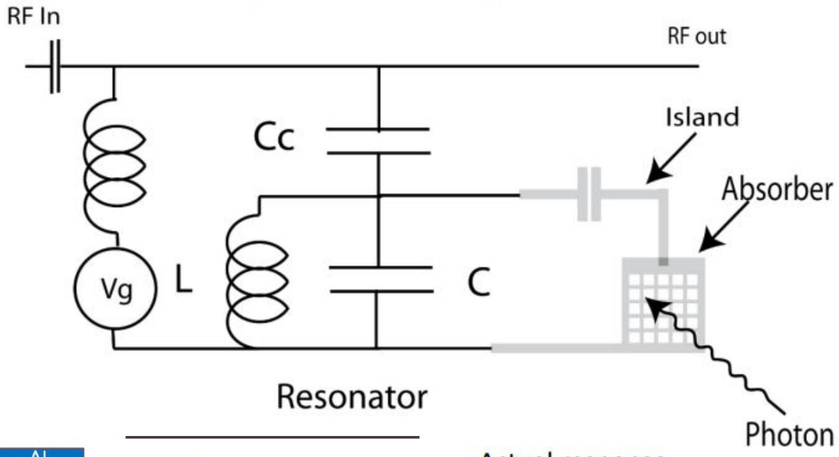
J. Chiles et al, Phys. Rev. Lett. 128 (2022)

Stewart A. Koppell

P.M. Echternach
Karthik Ramanathan

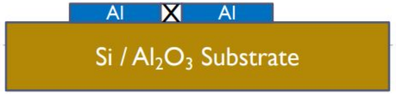
Jet Propulsion Laboratory
California Institute of Technology

Quantum Capacitance Detector Concept

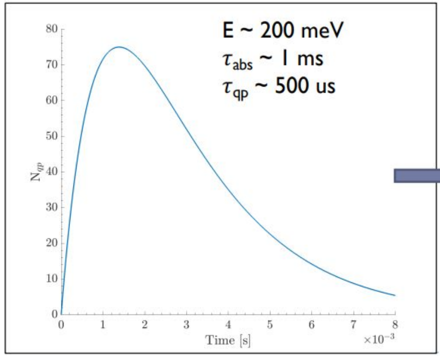


- Make the ground a photon absorbing structure (antenna or metal mesh)
- Insert the SCB in a resonating circuit
- A photon strikes, generating unpaired electrons
- Electrons tunnel to the island, changing its capacitance
- The change in capacitance shifts the resonator frequency

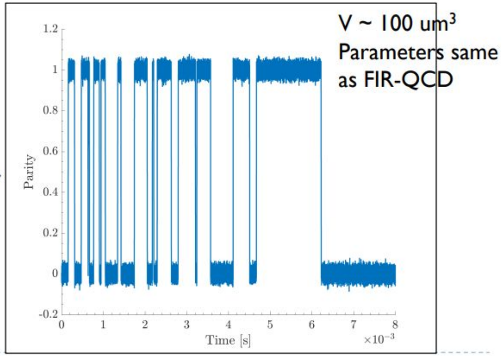
Dark Matter QCDs



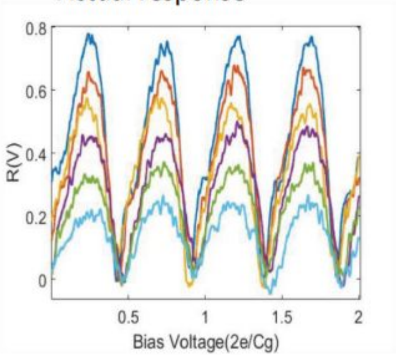
Quasiparticle production in absorber

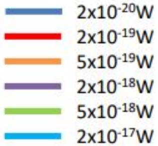


Parity signal observed



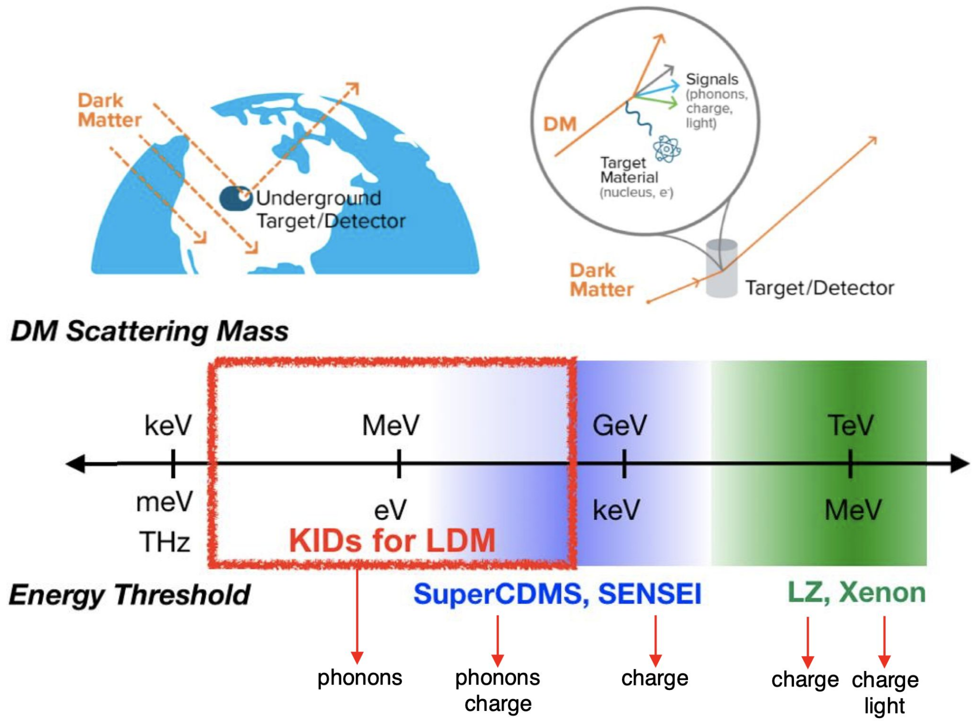
Actual response

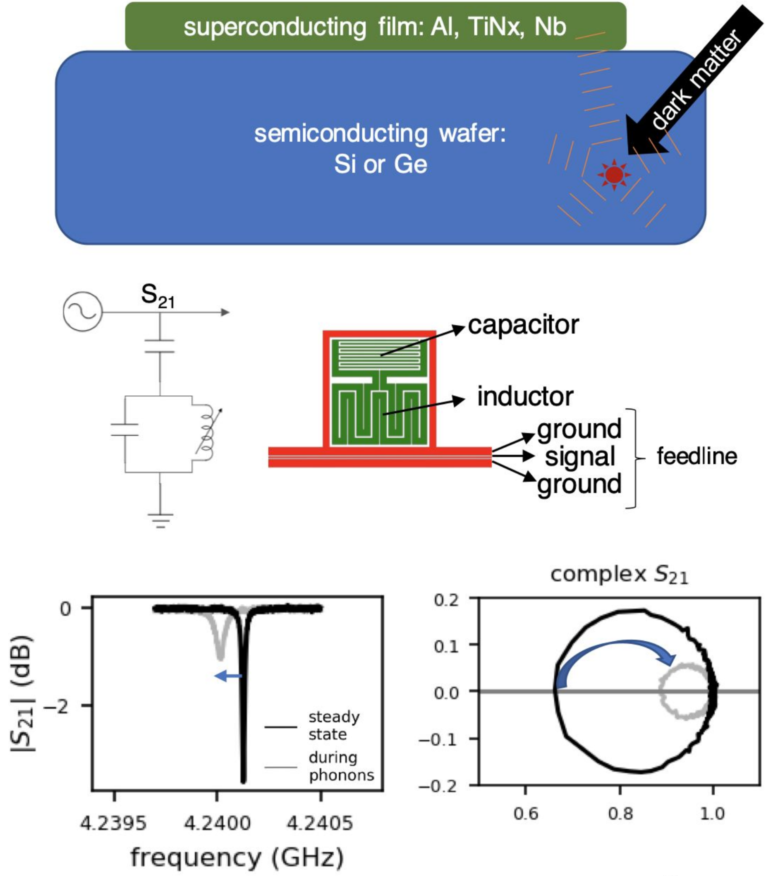




Kinetic Inductance Detector for sub-GeV DM

Osmond Wen



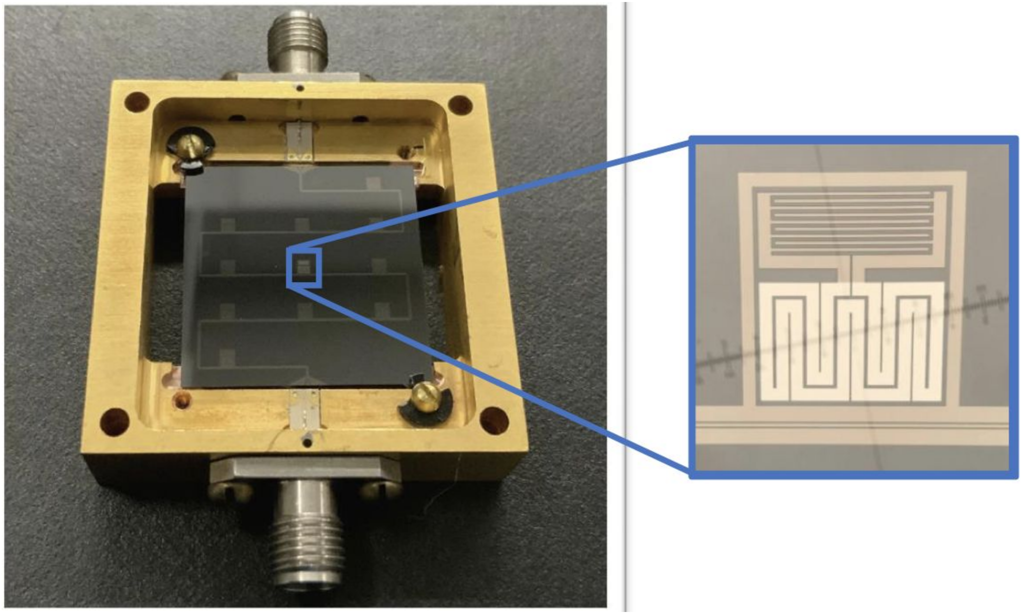


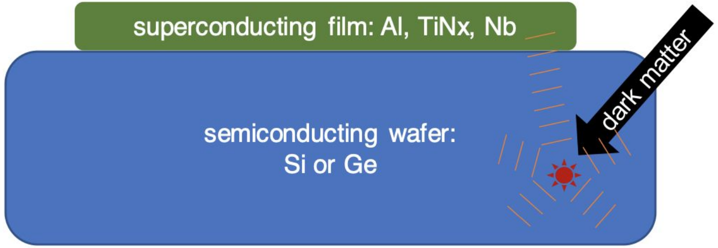
Sub-GeV dark matter particles deposit eV-scale energy in a silicon detector

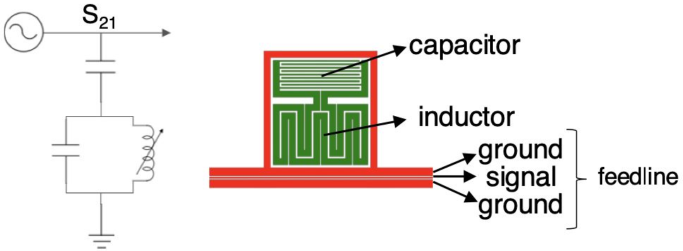
KID allows for large multiplexing

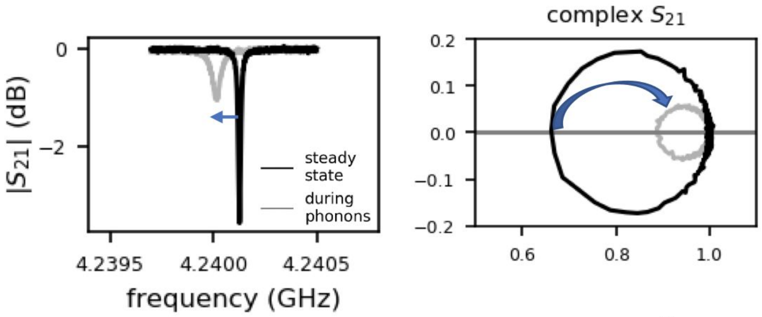
Kinetic Inductance Detector for sub-GeV DM

Osmond Wen









KID allows for large multiplexing

MKIDs as detectors

An example: sub-mm photometers for SPT4 camera

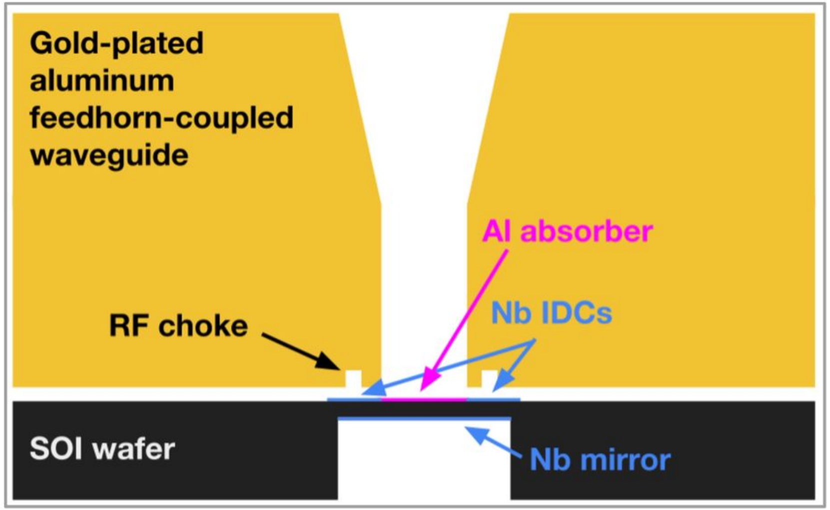
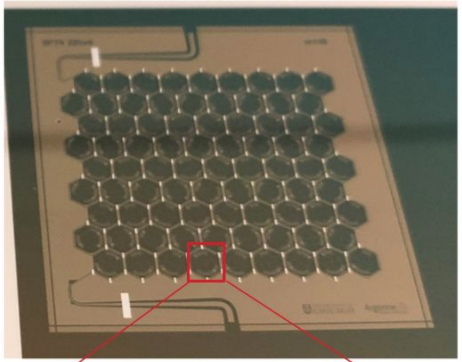


Figure from Dibert et al. ASC2022

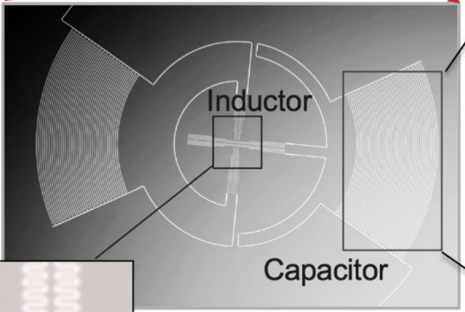
- The optical signal collected by the telescope is coupled to MKIDs detectors via feedhorns.
- The RF choke and Nb mirror enhances the optical coupling and reduce optical leakage.

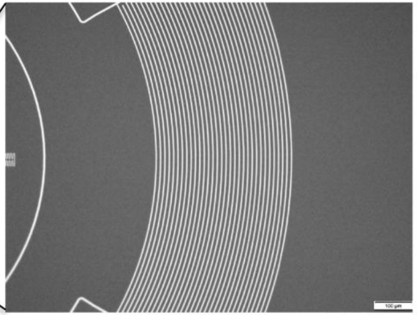


A fabricated detector array

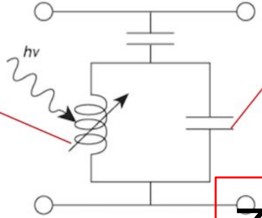
- One single readout line is coupled to multiple pixels, each of which contains two detectors at two polarizations.
- Each detector has an inductor and a capacitor, forming a resonant circuit.

Zoom in one pixel





Capacitor structure with interdigitated fingers

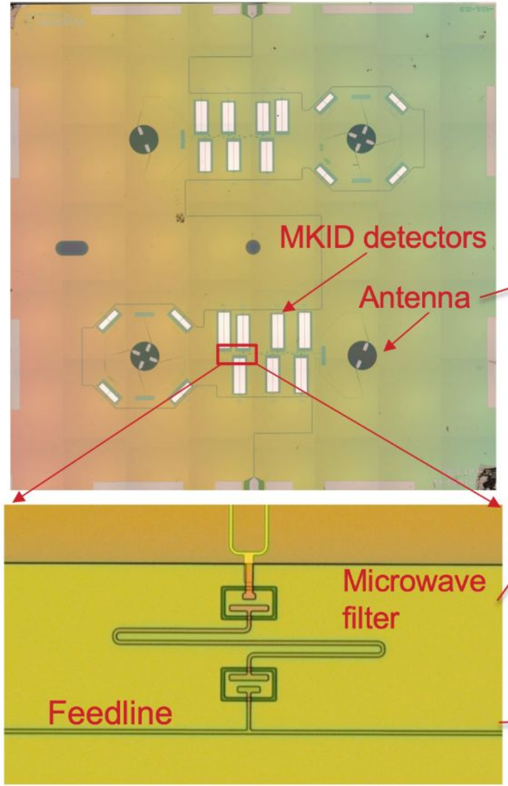


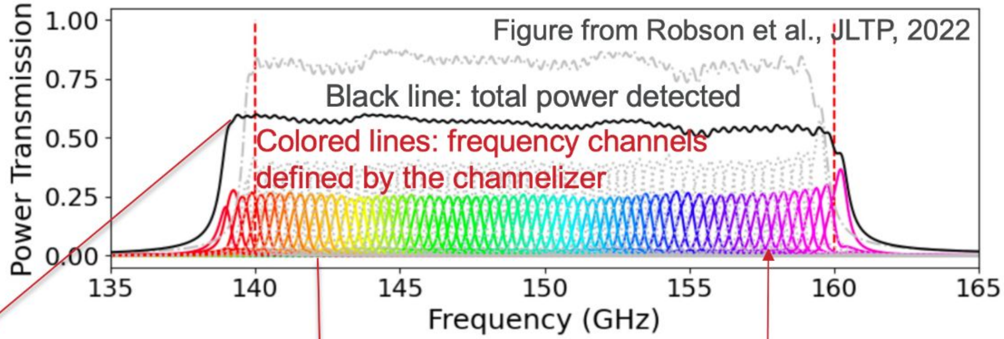
The inductor is below the feedhorn and also serves as the optical signal absorber

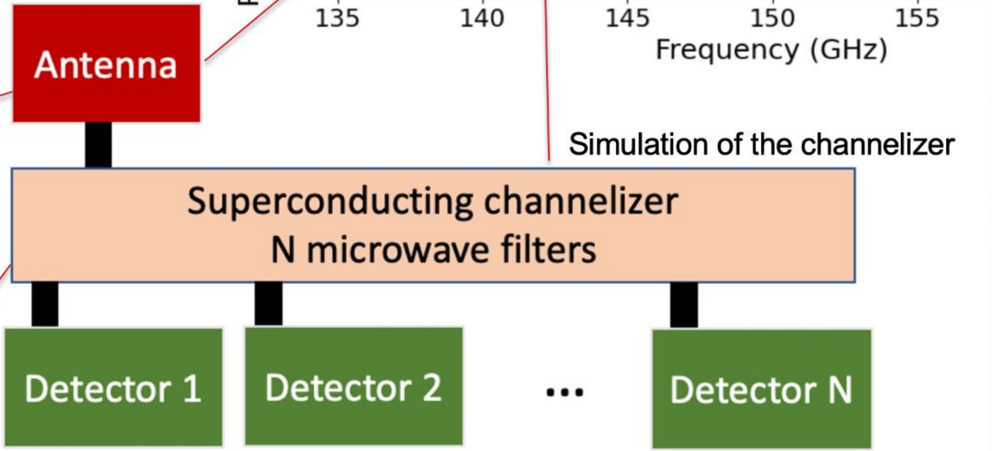
Zhaodi Pan

MKIDs-based spectrometers

Prototype spectrometer by ANL, for SPT-SLIM (see Adam's talk)





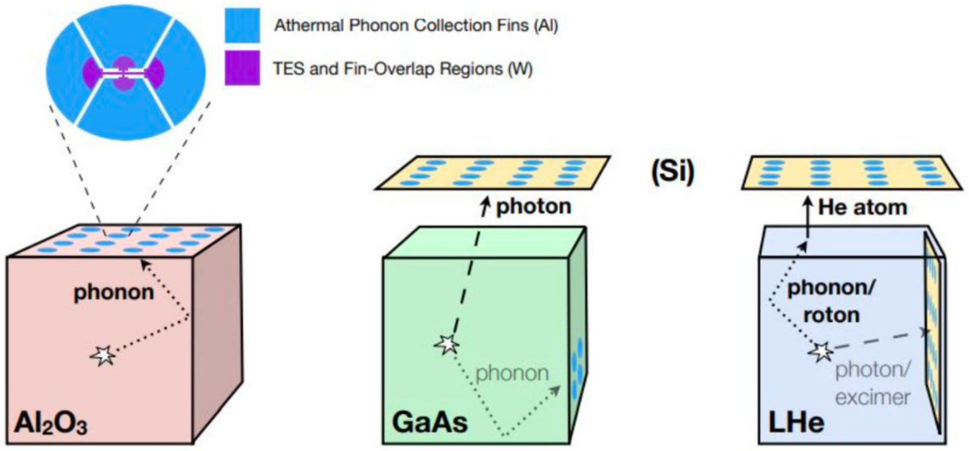


Each **microwave filter** defines a **frequency channel (one colored line)**
Repeat N times to get N channels

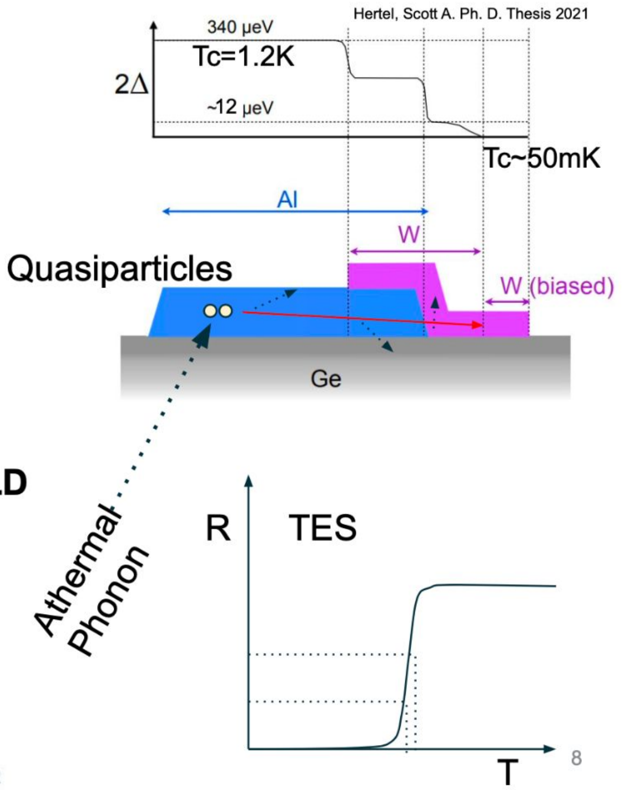
Transition Edge Sensors for DM detection

TESSERACT & Athermal phonon sensor

Xinran Li's talk

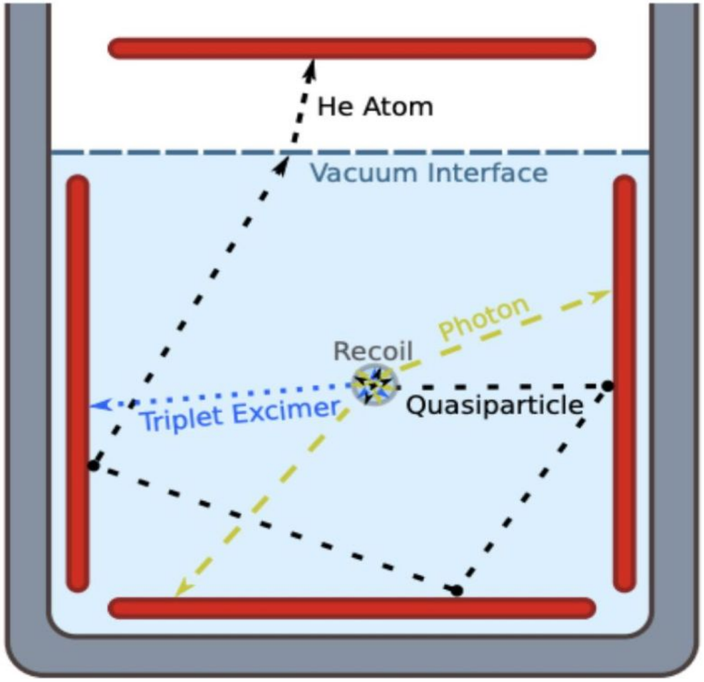


Polar crystals: **SPICE** Superfluid helium: **HeRALD**



TES for Detecting DM with Helium Target

HeRALD: Helium Roton Apparatus for Light Dark matter



Searching for sub-GeV dark matter using a superfluid He target

Three signal channels

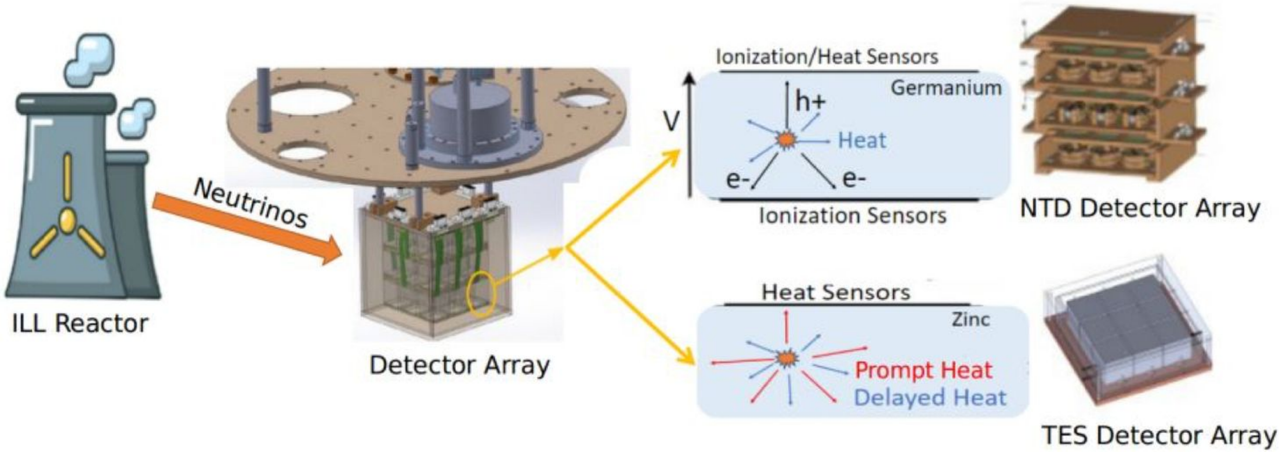
1. Photons - from He singlet excimers decaying with 10ns half-life
2. Triplet excimers - 13s half-life, propagate ballistically, quench on walls
3. Quasiparticles - ~1meV energy, can evaporate He atom from surface for 10x gain

Doug Pinckney
David Osterman

TES for Coherent Neutrino Scattering

Luke Chaplinsky

The RICOCHET Experiment



- **Will place cryogenic solid-state detectors near the ILL research reactor in Grenoble, France to make precision measurements of CEνNS rate and spectrum.**
- **Cryostat will house two different detector payloads.**
  - CryoCube will consist of an array of 18-27 germanium crystals.
  - Q-Array will consist of 9 cubes of superconducting zinc crystals.
- **Total detector target mass of approximately 1 kg.**
- **First CEνNS exposure will begin in 2024.**

Infrastructure to Test/Characterize New Technology

Quantum Science Center

QUANTUM SCIENCE CENTER

- US Department of Energy recently funded five National Quantum Information (NQI) Science Research Centers to advance QIS technologies in the US
- ORNL hosts the Quantum Science Center (QSC) which includes as one of its three thrusts the goal of ensuring some of this investment goes back into discovery science (led by FNAL)

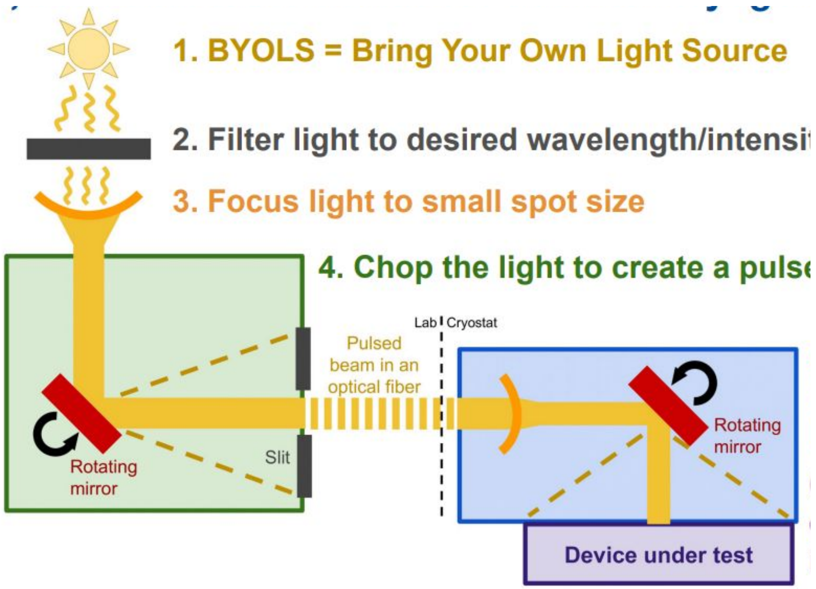
Thrust 3: Quantum Devices and Sensors for Discovery Science

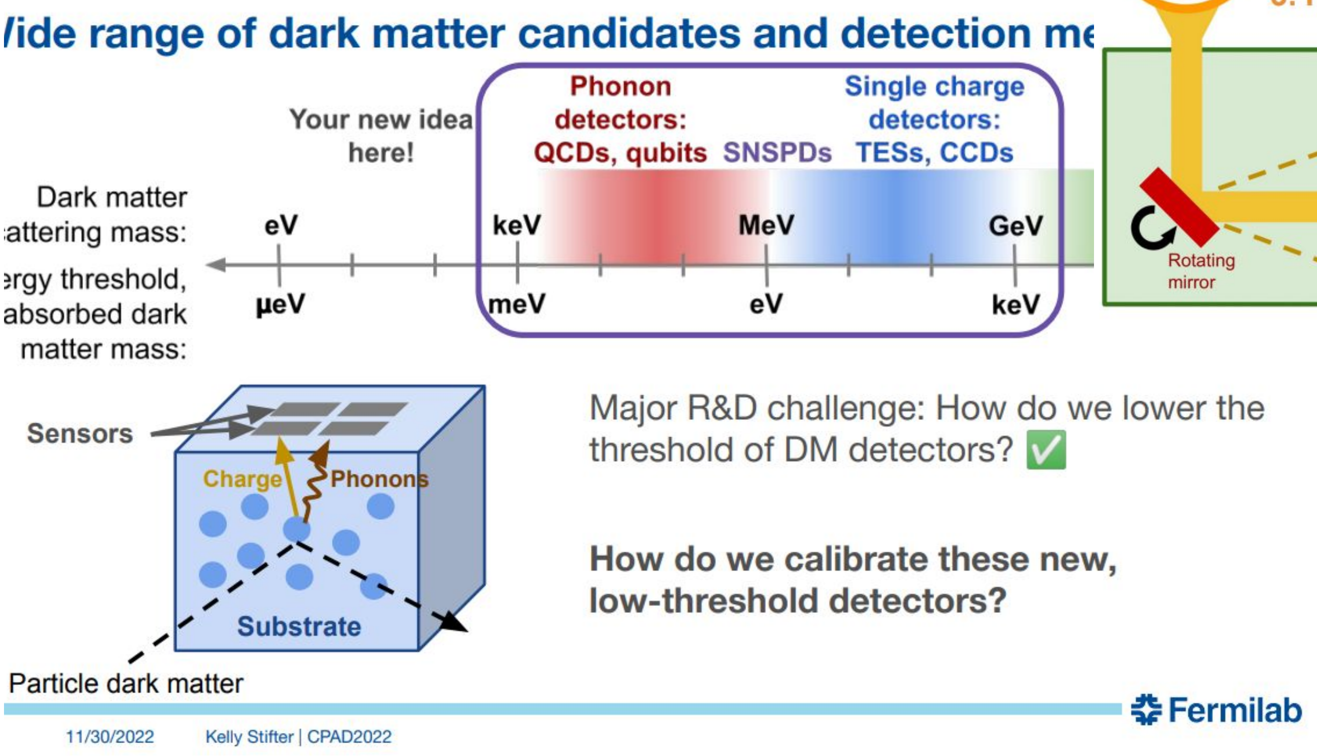
Thrust 3 develops an understanding of fundamental sensing mechanisms in high-performance quantum devices and sensors. This understanding allows QSC researchers, working across the Center, to co-design new quantum devices and sensors with improved energy resolution, lower energy detection thresholds, better spatial and temporal resolution, lower noise, and lower error rates. Going beyond proof-of-principle demonstrations, the focus is on implementation of this hardware in specific, real-world applications.

Led by Fermilab's Aaron Chou

Daniel Baxter

Infrastructure to Test/Characterize New Technology



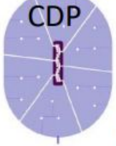


Kelly Stifter

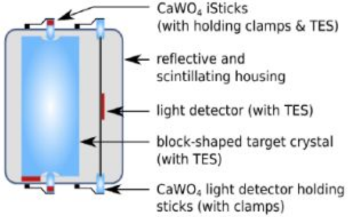
Challenges at Lower Threshold

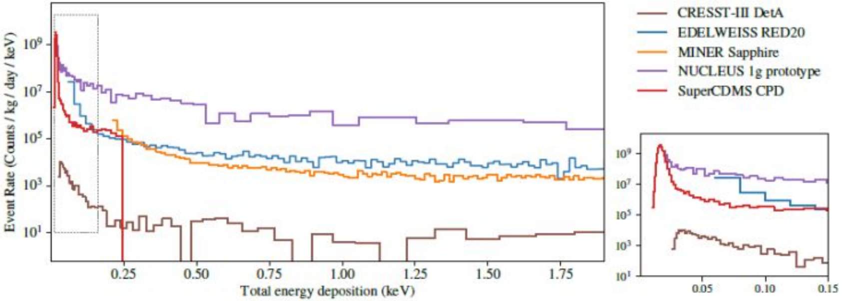
Excessive low-energy background (dark matter and coherent neutrino scattering) Variety of detectors and readout techniques

Super-SDMS-CDP

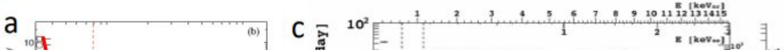


CRESTIII

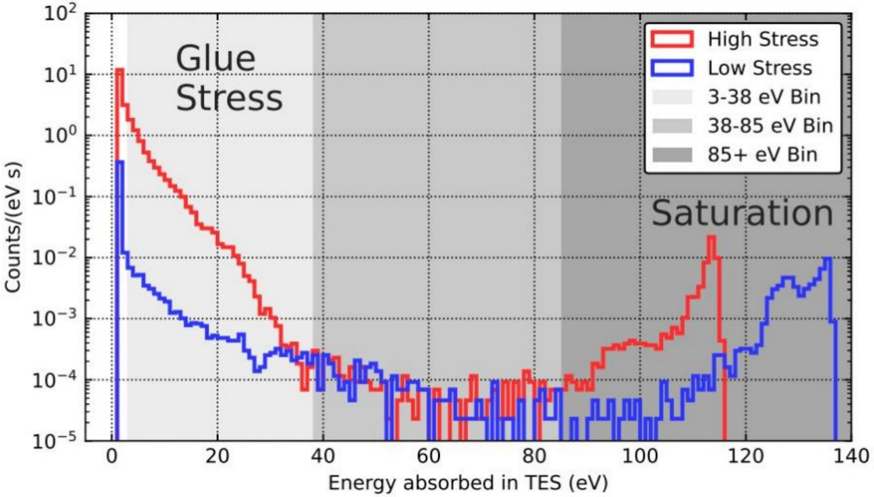




EXCESS workshop: Descriptions of rising low-energy spectra arXiv:2202.05097



Stress Causes LEE like Events: Results



Sergey Pereverzev
Roger K. Romani

Quantum Astrometry

DOE QuantISED project

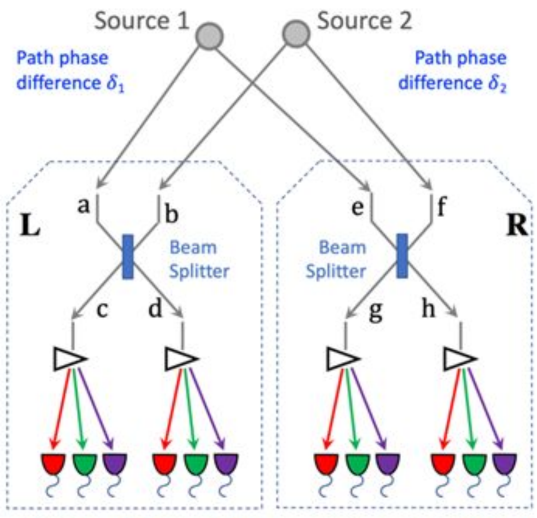
- Measure photon phase difference teleporting it to another station, similar to quantum repeaters in quantum networks
- **Enables long baselines and could improve astrometrical precision by orders of magnitude**
- Great impact on astrophysics and cosmology

- Photons must be indistinguishable to interfere →

indistinguishable means: $\Delta E * \Delta t \sim h/2\pi$

requires detectors with excellent time & spectral binning

$\Delta E * \Delta t \sim$ 0.1nm * 10ps

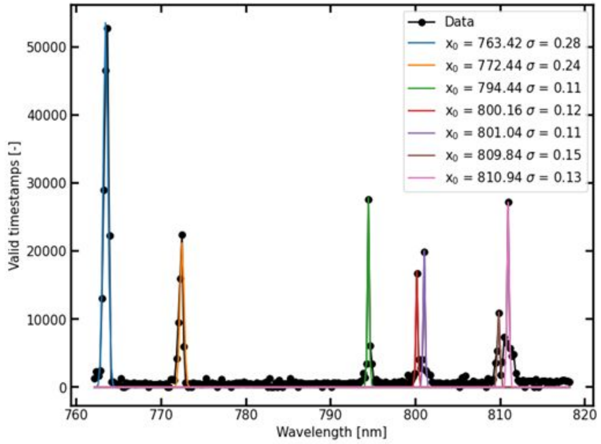


DOE QuantISED project

www.quantastro.bnl.gov

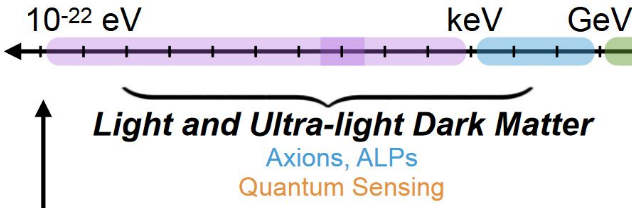
P.Stankus et al, arxiv:2010.09100
A.Nomerotski et al, arxiv:2012.02812, SPIE Proceedings
Y Zhang et al, Phys Rev A 101 (5), 053808 (2020)
P Svihra et al, Appl. Phys. Lett. **117**, 044001 (2020)
A.Nomerotski et al, arxiv: 2107.09229, TIPP Proceedings

Achieved 0.1 nm spectral and 50 ps timing resolution

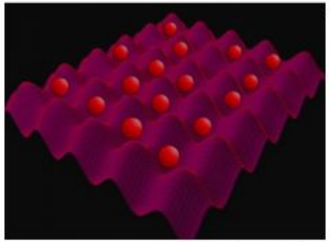


Andrei Nomerotski’s talk

Atomic sensors



Atomic clocks

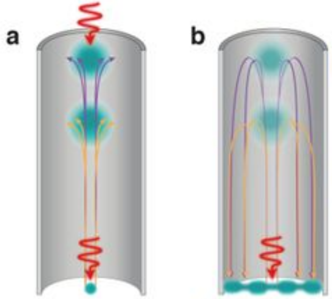

J. Ye Group website

Time keeping for:

- Define unit of time: second
- Communication and GPS positioning
- Many-body physics
- Search for dark matter

QSNET Collaboration
(Network of Clocks)

Atom interferometers

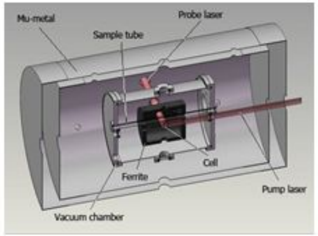


APS/Carin Cain

Free-space inertial sensors:

- Gravity sensors (gravity field monitoring)
- Inertial measurements for navigation
- Precision measurements (EP, GW detection)

Optical magnetometers

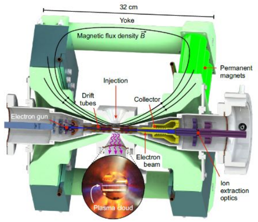


Romalis Group Webpage

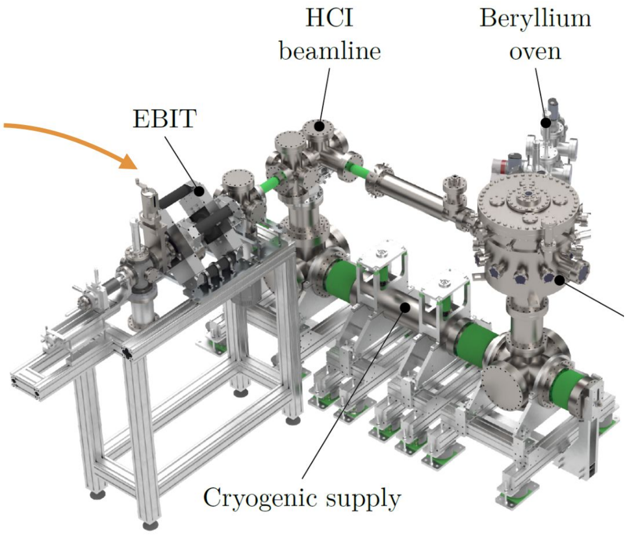
- Biological and medical sensing
- New interest for fundamental research (HEP)
- Room temperature operation!


GNOME Collaboration
(Network of Magnetometers)

Highly charged ions (Steven Worm's talk)



Compact EBIT @ MPIK



MK → μK

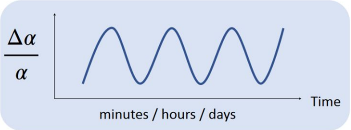
Search for Variations at Different Timescales

- Slow drifts

$\frac{\Delta\alpha}{\alpha}$ — Time — Year 1, Year 2, Year 3

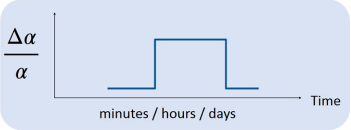
➡ New physics

- Oscillations

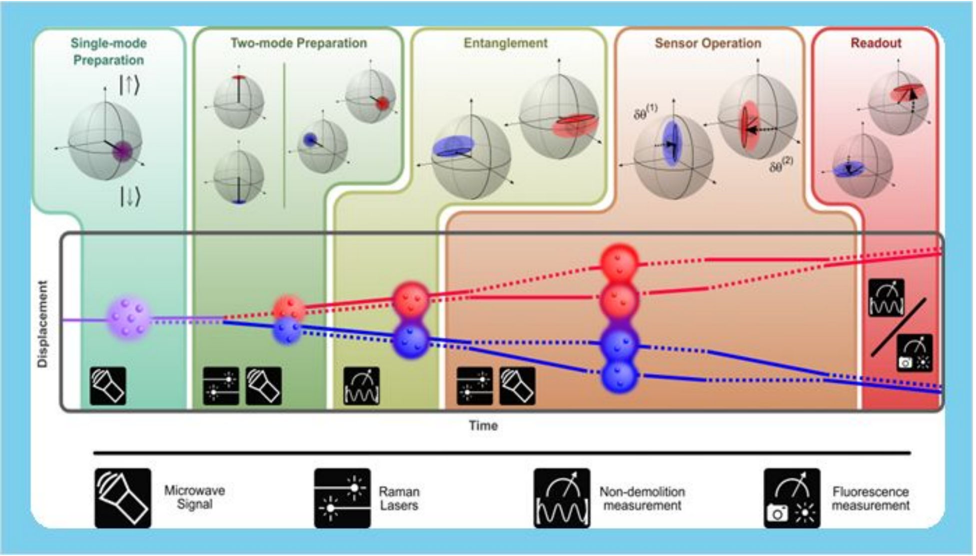


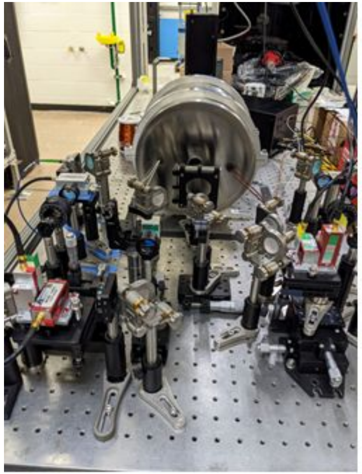
➡ Very light dark matter

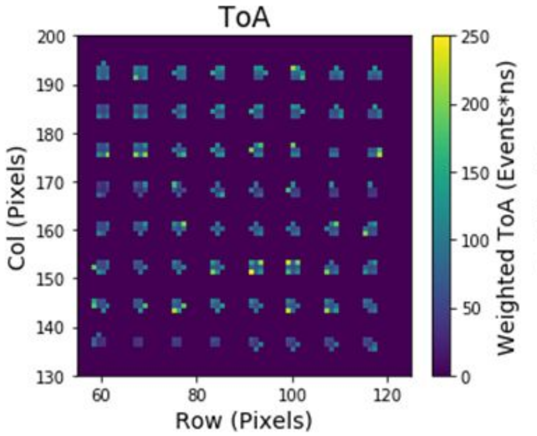
- Fast transients



➡ Dark matter, topological defects







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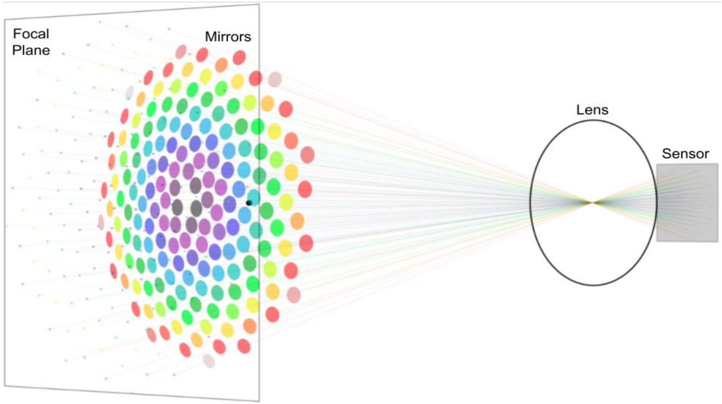
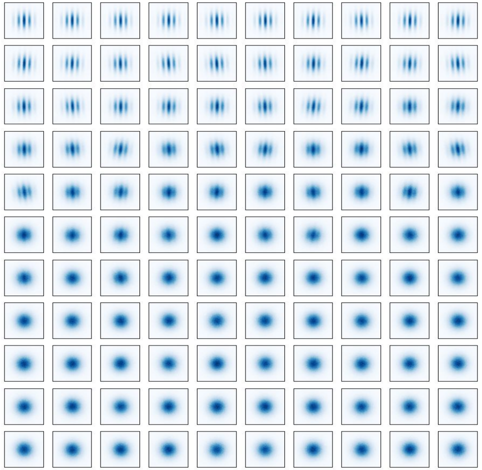
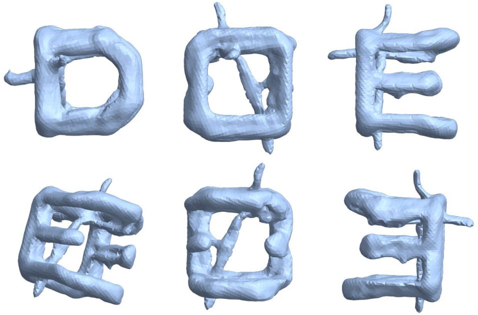
Julian Martinez-Rincon's talk

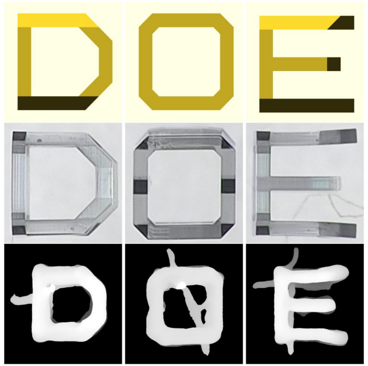
Spatially Multiplexed Light Field Imaging







Images of different views through different mirrors



Sanha Cheong’s talk

Summary of the Summary

- There are a number of cutting edge Quantum/SC detectors being explored
- Helped by the advancement in Quantum Computing
- These technologies can be leveraged to do Fundamental Physics