Low energy calibration of novel dark matter detectors using a scanning laser device

Kelly Stifter - Fermilab Cosmic Physics Center, Quantum Science Center

Coordinating Panel for Advanced Detectors Workshop 2022
11/30/2022

Wide range of dark matter candidates and detection methods:

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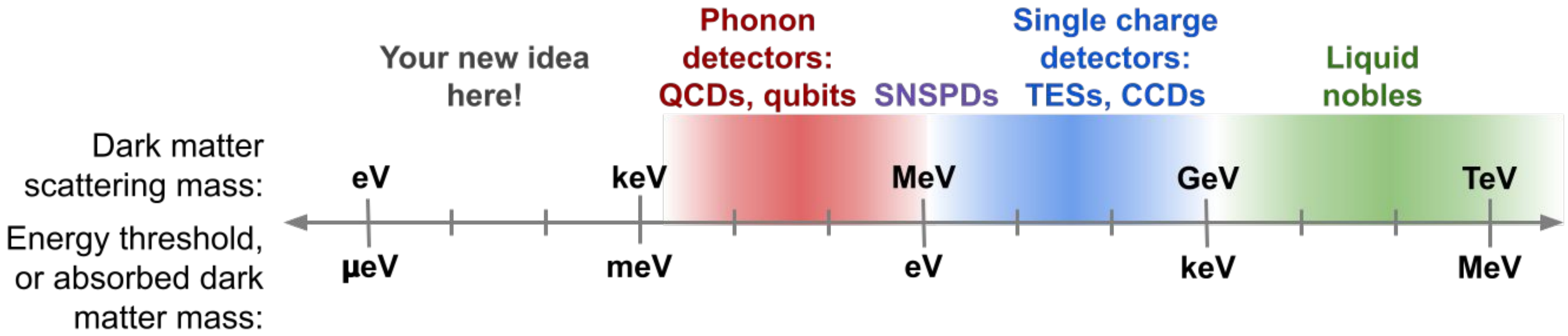

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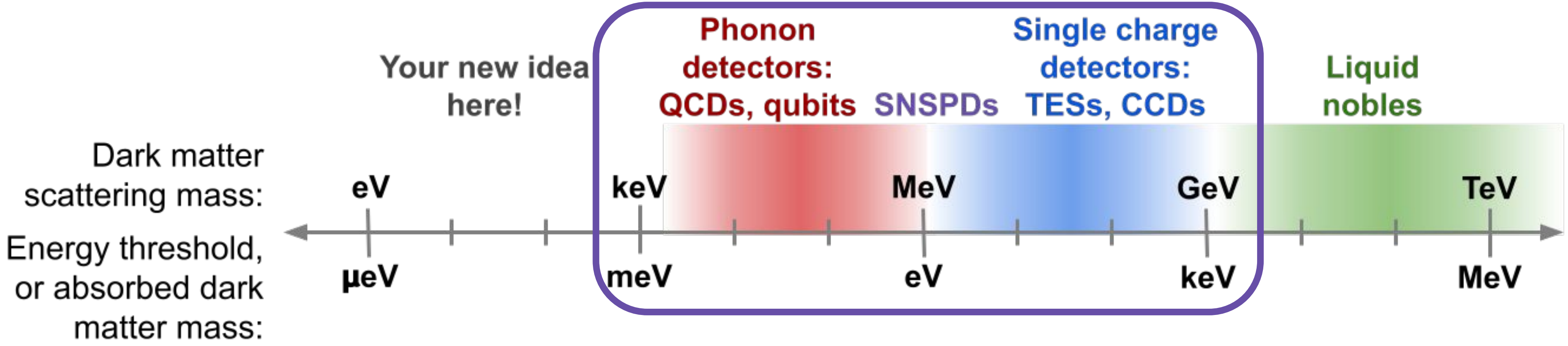

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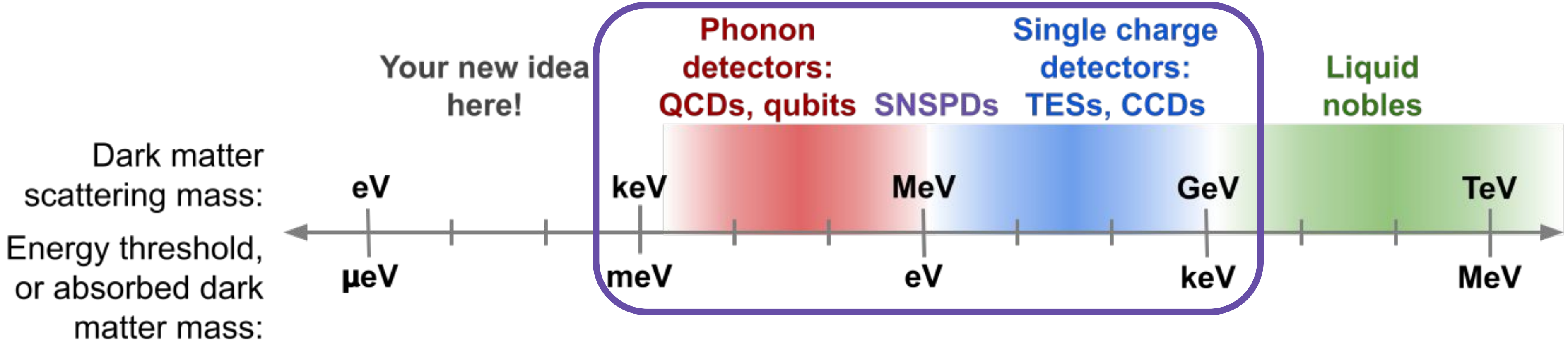

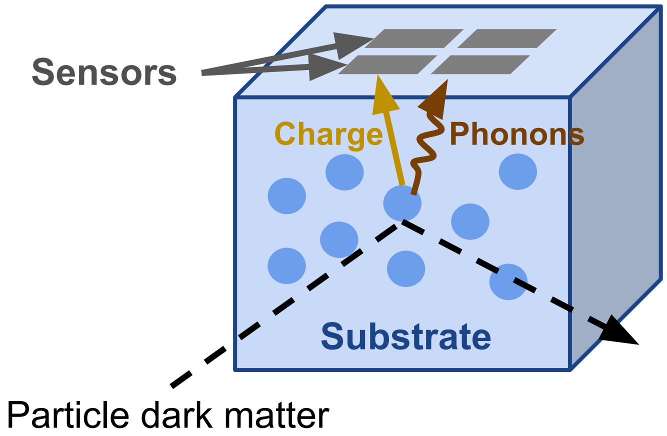

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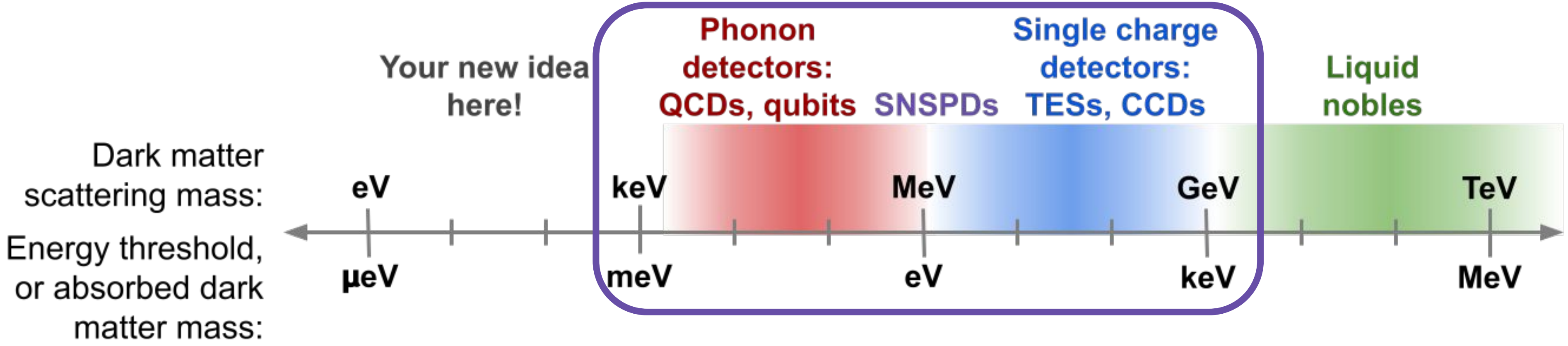

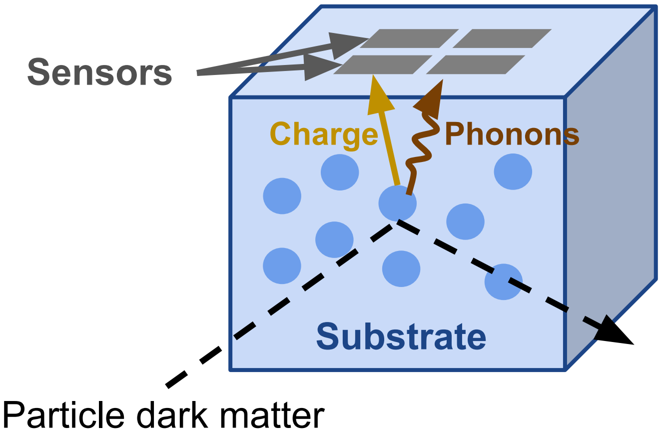

Major R&D challenge: How do we lower the threshold of DM detectors?

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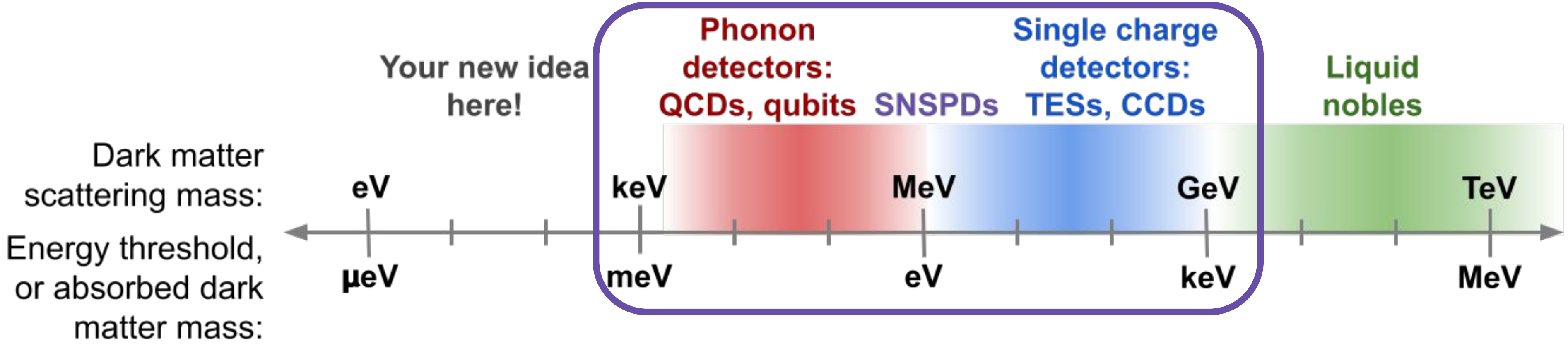

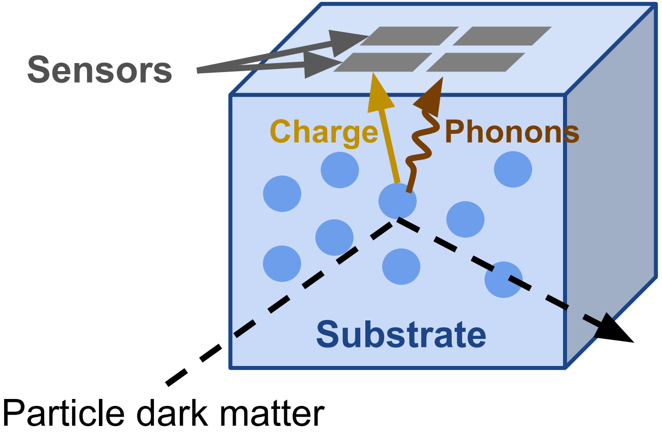

Major R&D challenge: How do we lower the threshold of DM detectors?

TESs (X. Li, L. Chaplinsky, tomorrow)
KIDs (O. Wen, Z. Pan, Thursday)
SNSPDs (M. Shaw, J. Luskin, yesterday, C. Wang, today)
Qubits (D. Baxter, today)
QCDs (K. Ramanathan, P. Echternach, yesterday)

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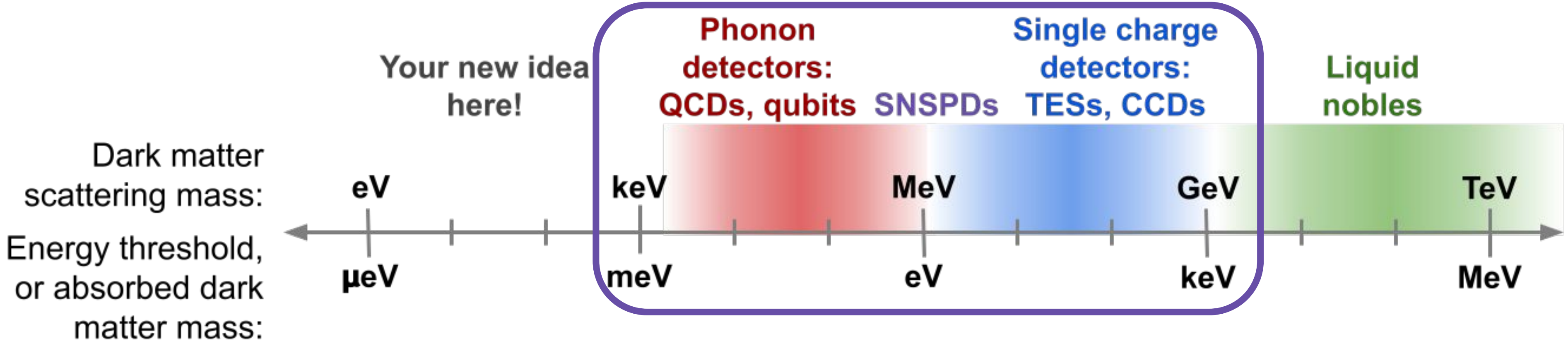

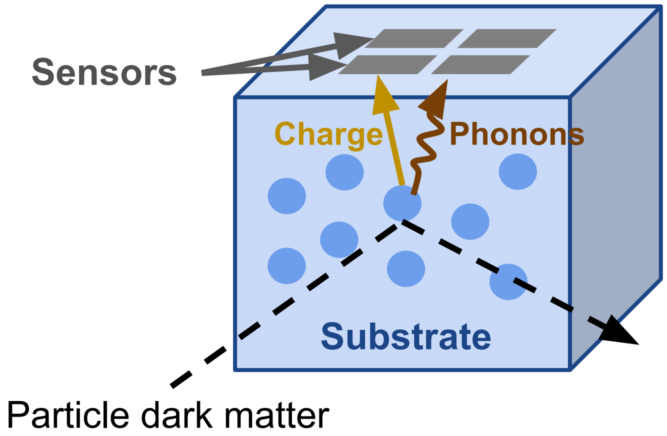

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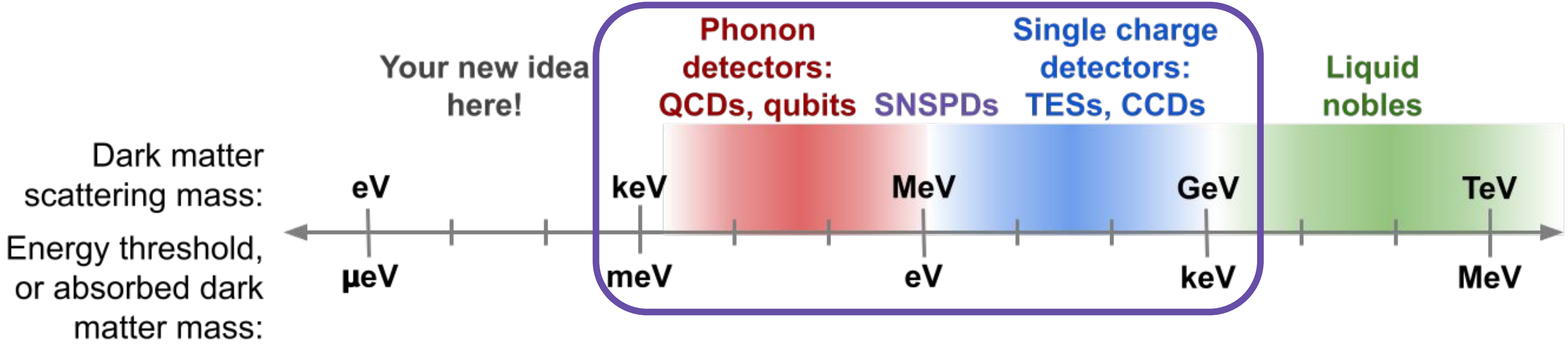

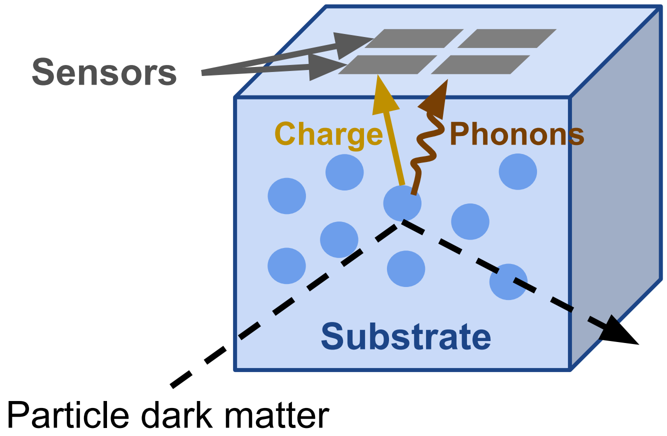

Major R&D challenge: How do we lower the threshold of DM detectors? ✅

How do we calibrate these new, low-threshold detectors?

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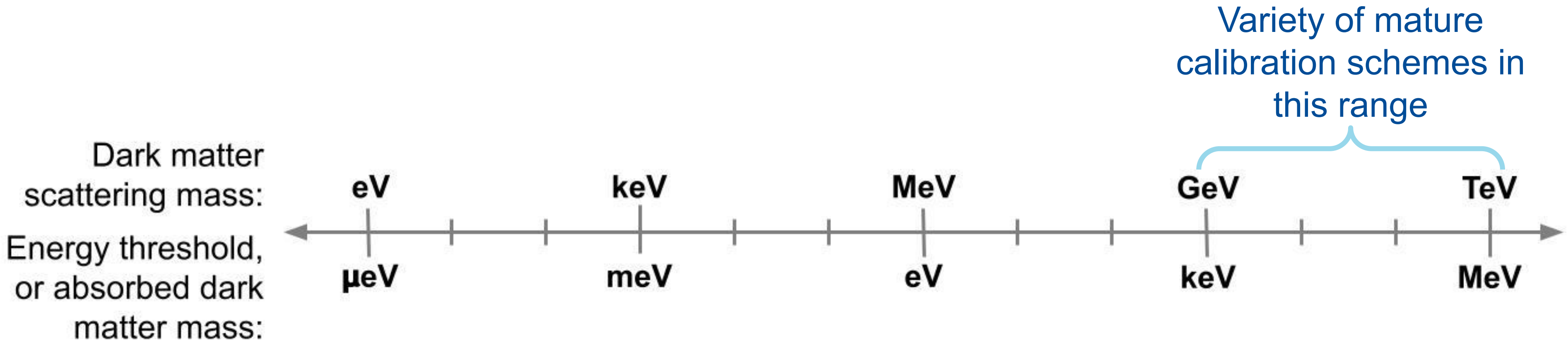
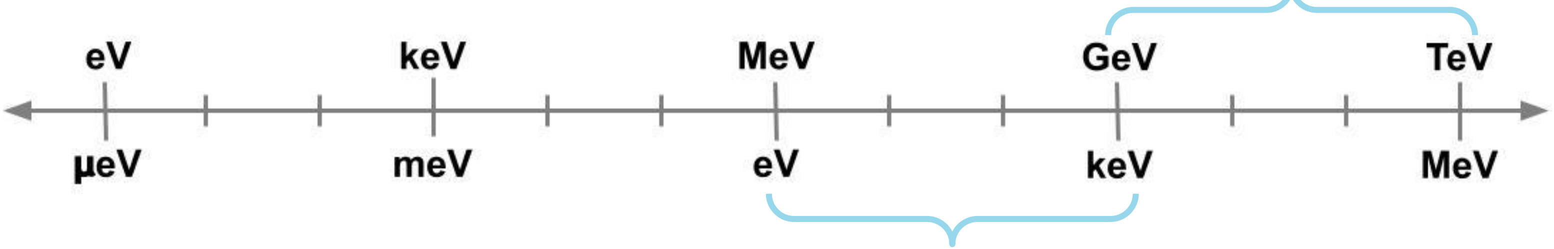


Wide range of dark matter candidates and detection methods:

Variety of mature calibration schemes in this range

Dark matter scattering mass:

Energy threshold, or absorbed dark matter mass:



Fewer options in this range:

- Activation lines
- Compton measurements
- Neutron sources or beams
- Photon pulses

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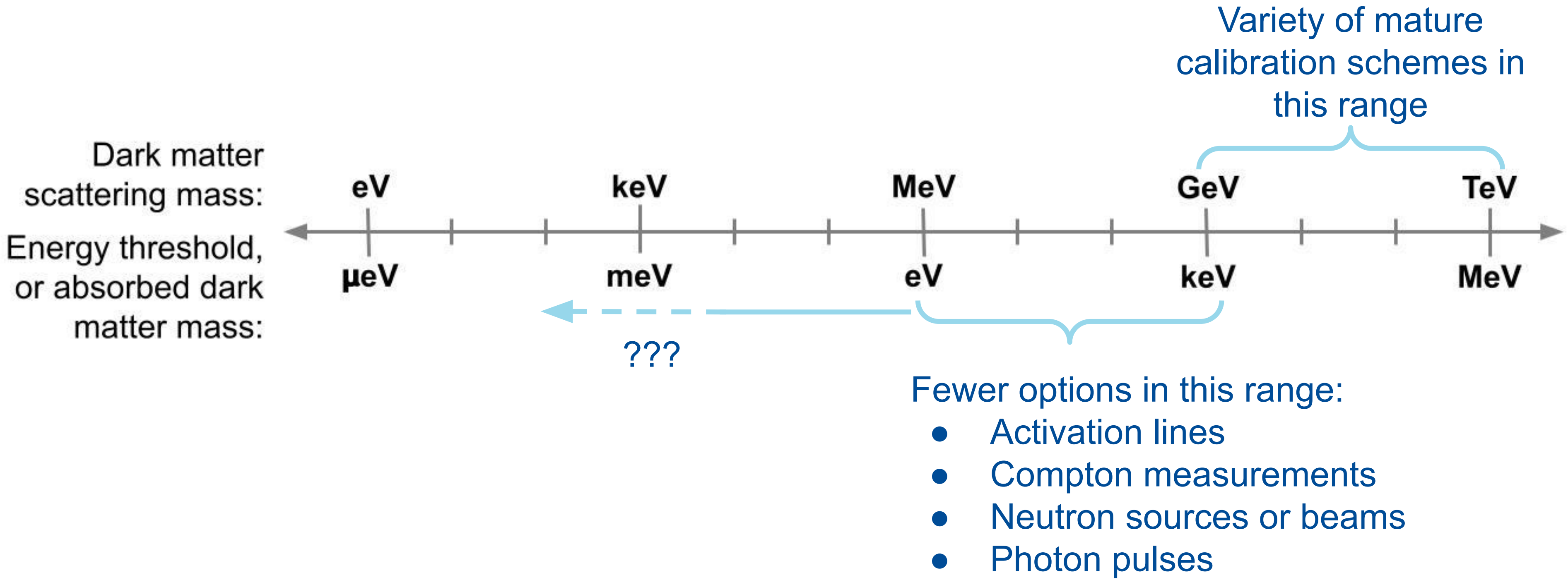

How do we calibrate in the sub-eV regime?

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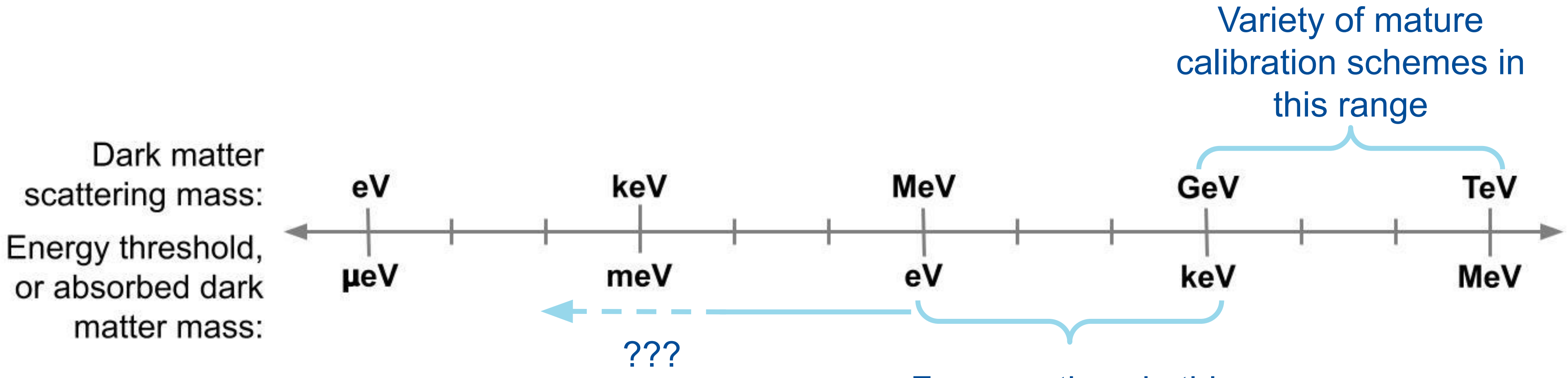


Fewer options in this range:

- Activation lines
- Compton measurements
- Neutron sources or beams
- **Photon pulses**

How do we calibrate in the sub-eV regime?

Ideal calibration source wishlist:

Works at range of low energies: many wavelengths accessible, from O(eV) down to O(meV) (equivalently: ~1μm - 1000μm, ~250THz - 1THz)

Time-resolved: pulsed operation (~μs resolution)

Position-dependent: steerable, small beam spot (<100μm resolution)

Cryo-friendly: functional at low temps (~10mK), low power dissipation

In-situ: no parasitic backgrounds

Device-independent: flexible, modular

Inexpensive

Calibration source for cryogenic detectors

Goal: pulsed, steerable light source that can couple to a wide variety of cryogenic devices in order to calibrate *electron recoils* (producing e^-/h pairs, phonons)

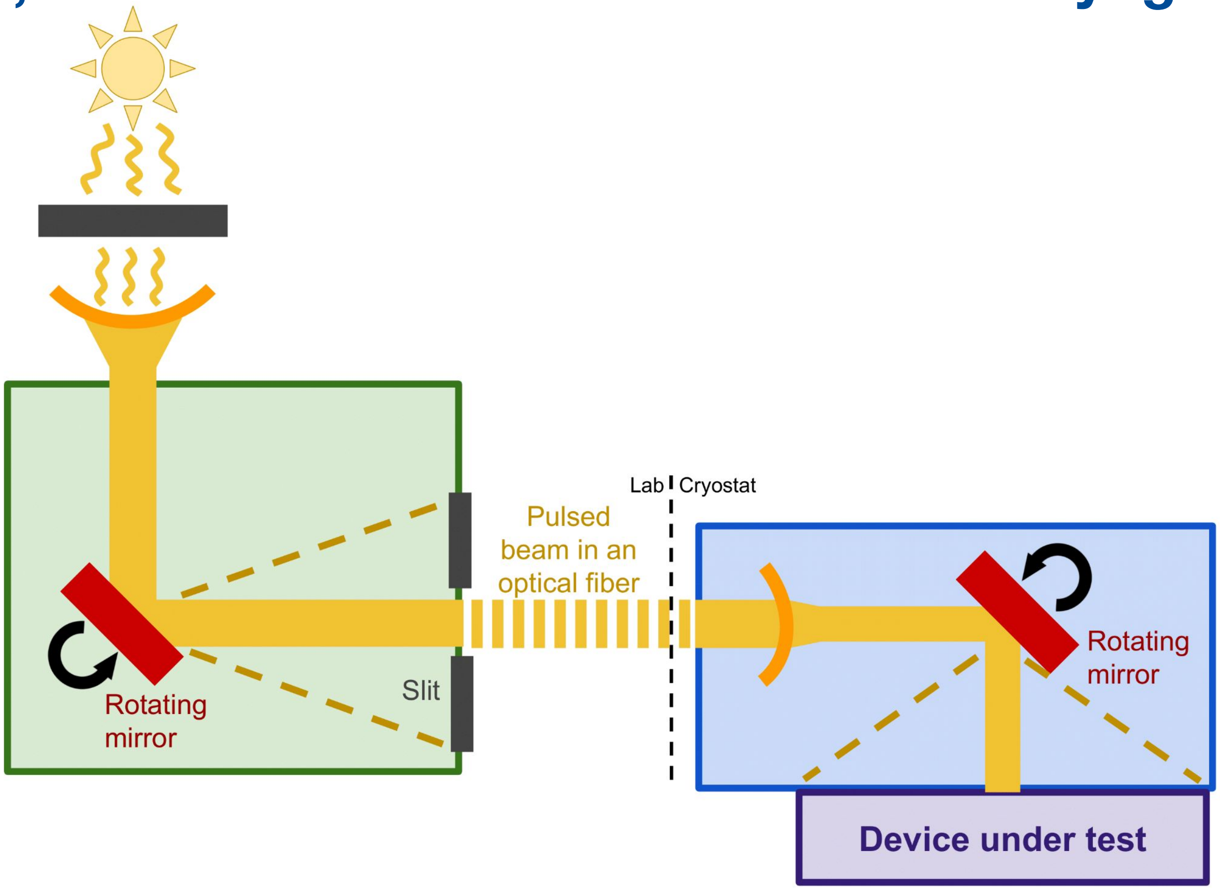
Use to characterize many devices:

- TESs
- KIDs
- SNSPDs
- Qubits
- QCDs
- Your favorite photon-sensitive device

Many important phenomena to investigate:

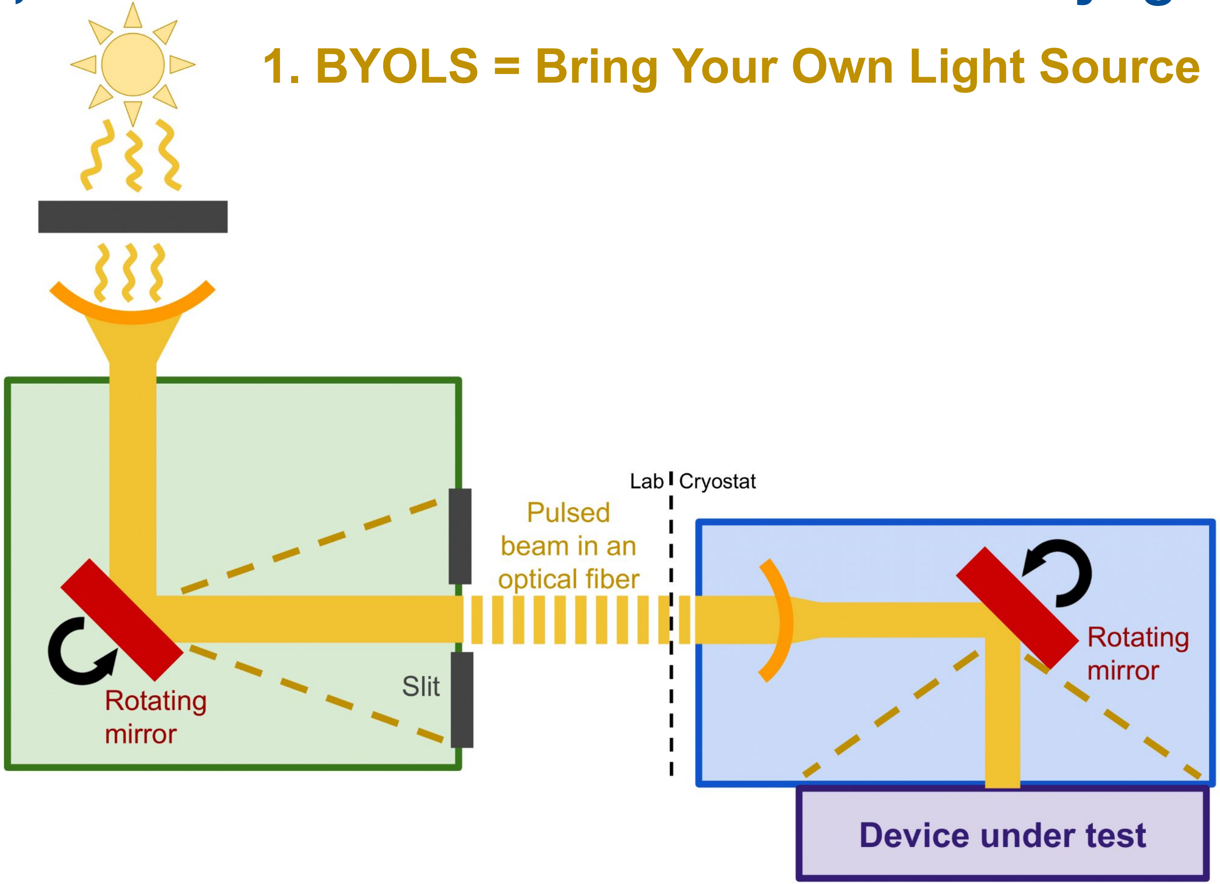
- Sensitivity to ionizing radiation
- Energy detection thresholds
- Quanta collection efficiency
- Position sensitivity of device
- Effect of quasiparticle poisoning
- Detailed phonon propagation

Pulsed, steerable laser device for use with cryogenic devices:



Pulsed, steerable laser device for use with cryogenic devices:

1. BYOLS = Bring Your Own Light Source



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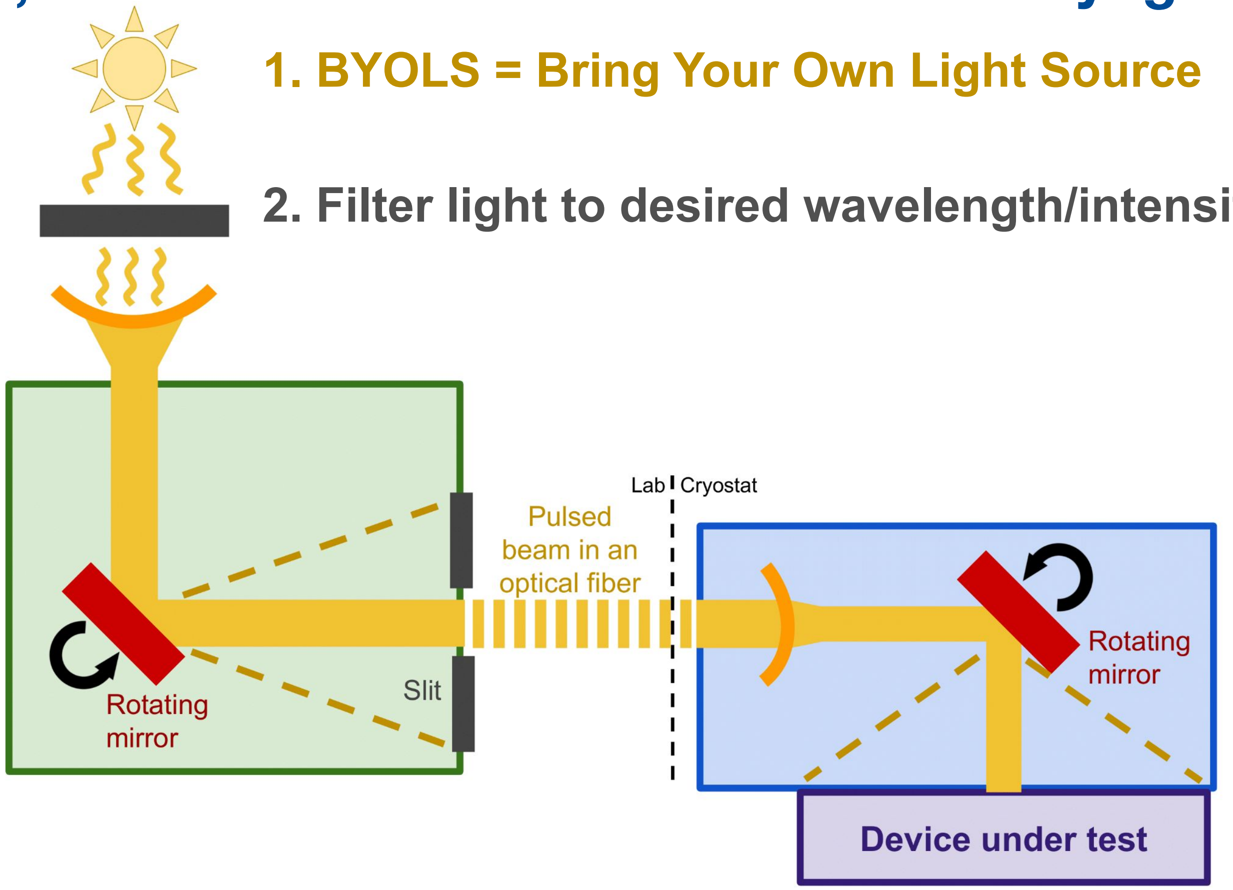
Pulsed, steerable laser device for use with cryogenic devices:

1. BYOLS = Bring Your Own Light Source

2. Filter light to desired wavelength/intensity

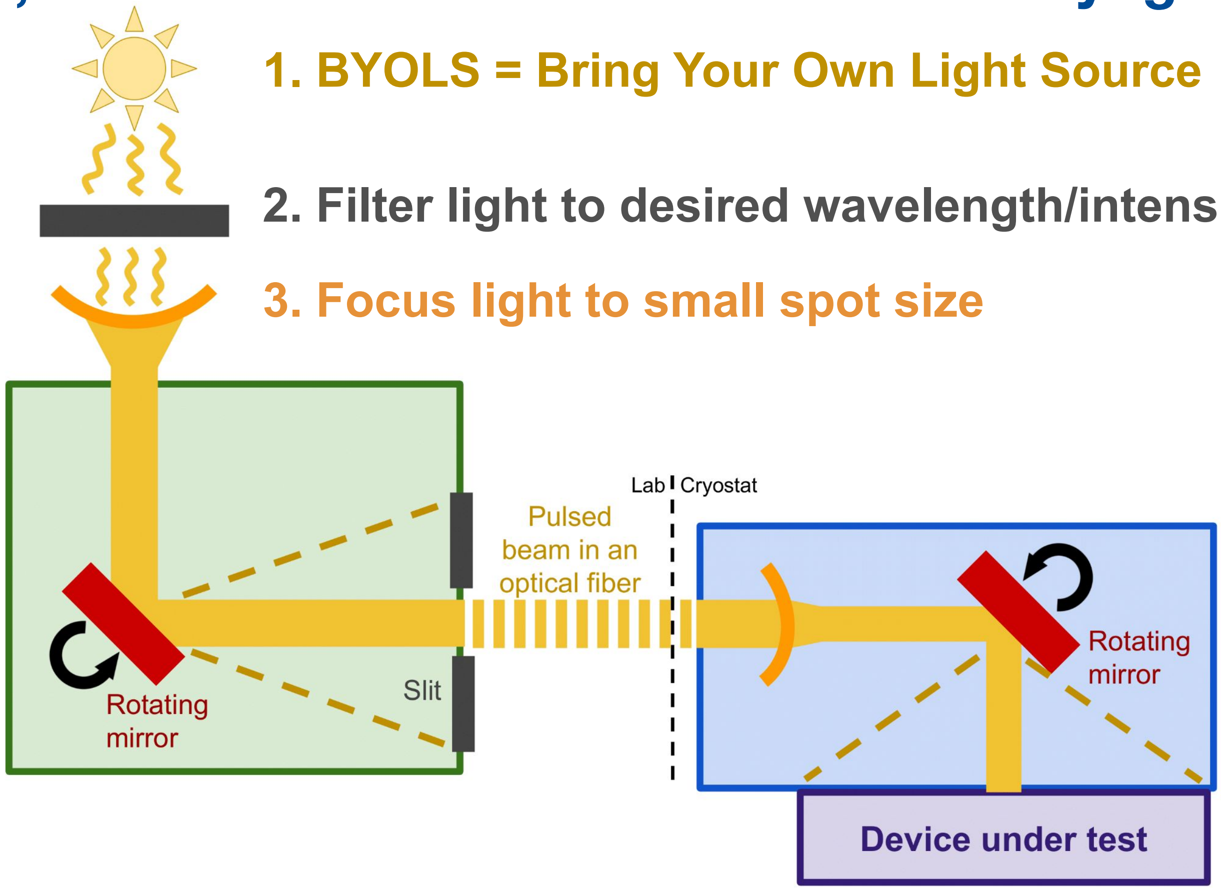


Pulsed, steerable laser device for use with cryogenic devices:

1. BYOLS = Bring Your Own Light Source

2. Filter light to desired wavelength/intensity

3. Focus light to small spot size



Pulsed, steerable laser device for use with cryogenic devices:

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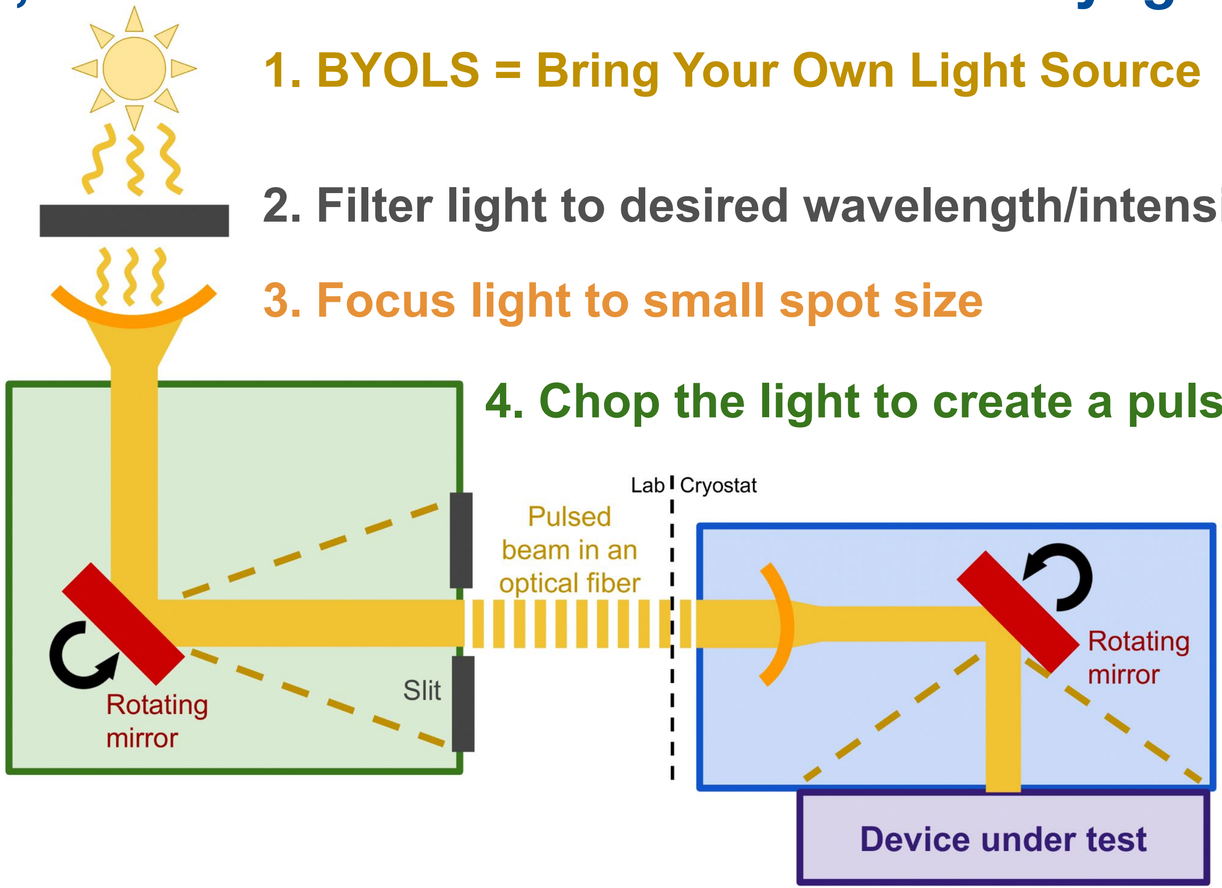
4. Chop the light to create a pulsed beam



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Pulsed, steerable laser device for use with cryogenic devices:

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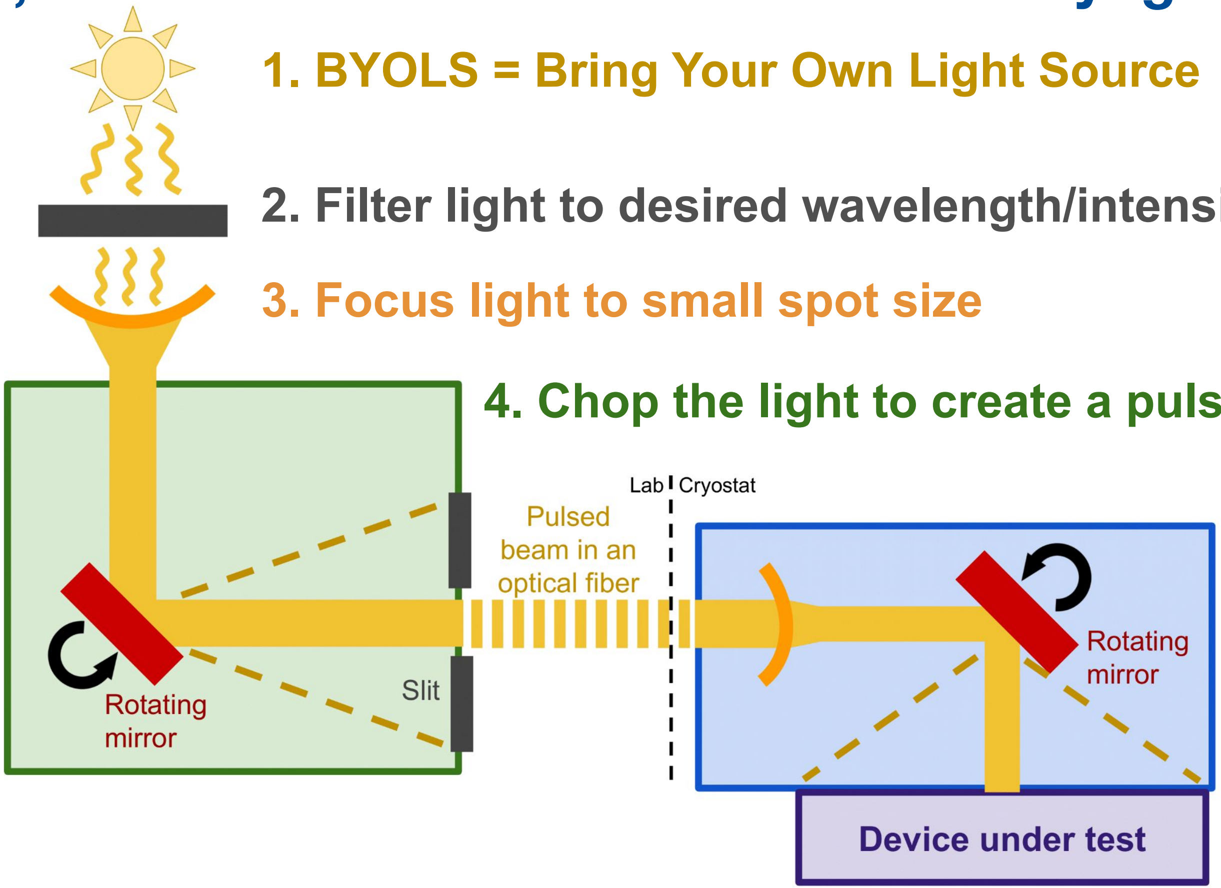
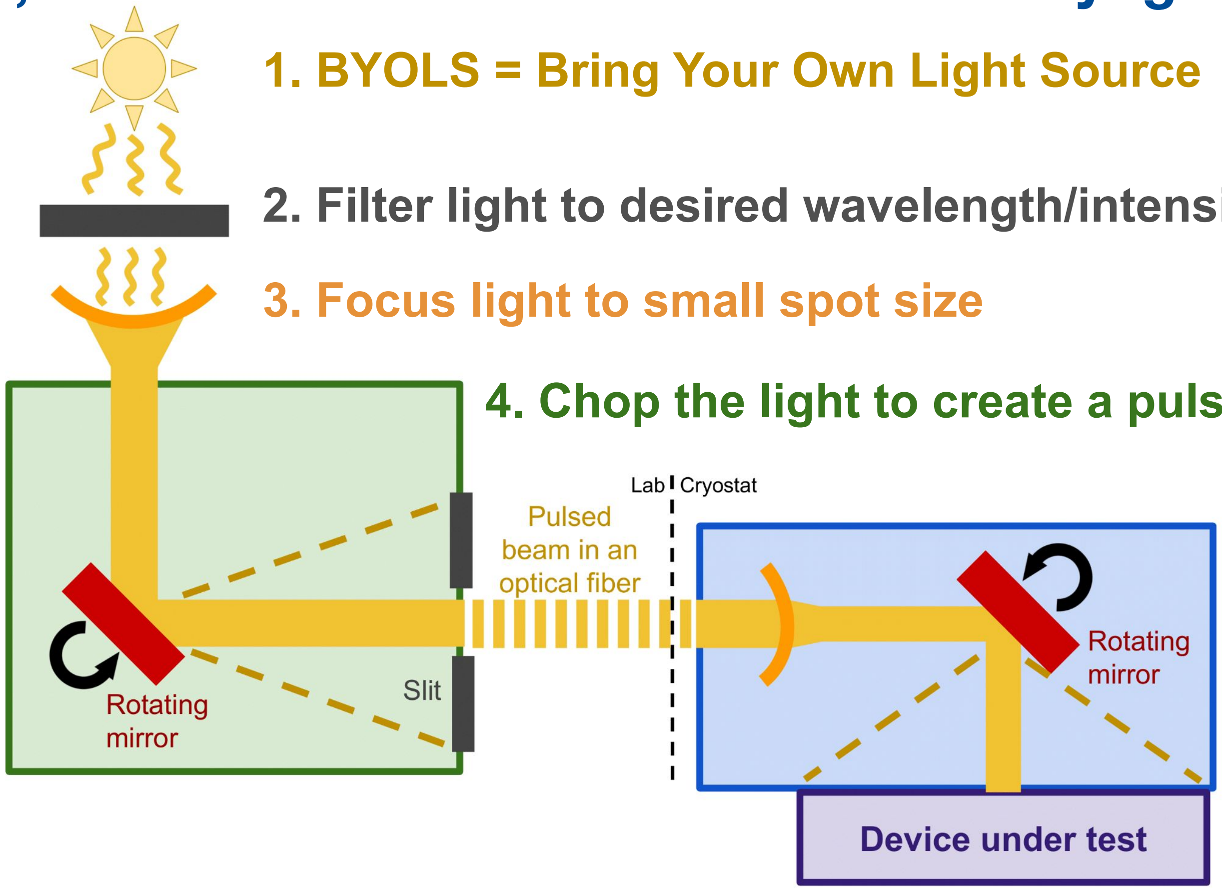
4. Chop the light to create a pulsed beam

5. Steer pulsed beam to desired location…



Pulsed, steerable laser device for use with cryogenic devices:

1. BYOLS = Bring Your Own Light Source
2. Filter light to desired wavelength/intensity
3. Focus light to small spot size
4. Chop the light to create a pulsed beam
5. Steer pulsed beam to desired location…
6. …to produce energy deposits in your device



Technical challenge:

Cryogenic movement

- Power dissipation
- Freeze out of movement mechanisms/control

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Our solution: modified MEMS mirrors (right)

- Al deposition over doped Si control lines for low-T operation

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Cryogenic movement

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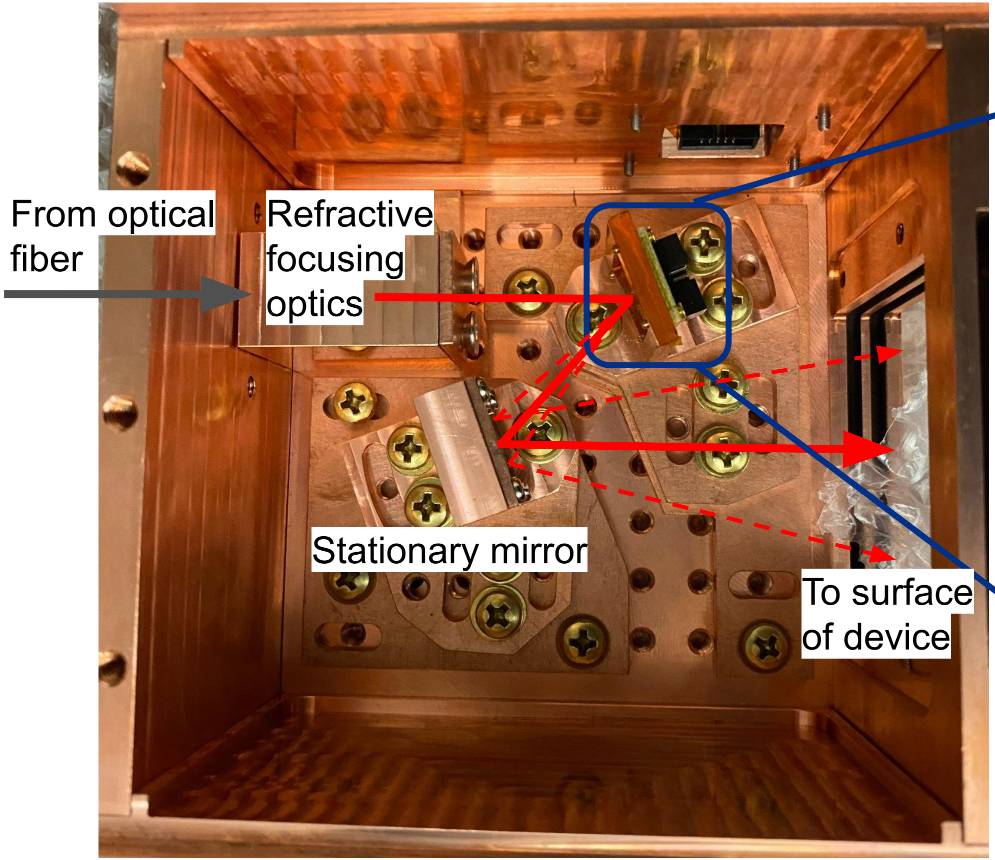
Our solution: modified MEMS mirrors (right)

- Al deposition over doped Si control lines for low-T operation

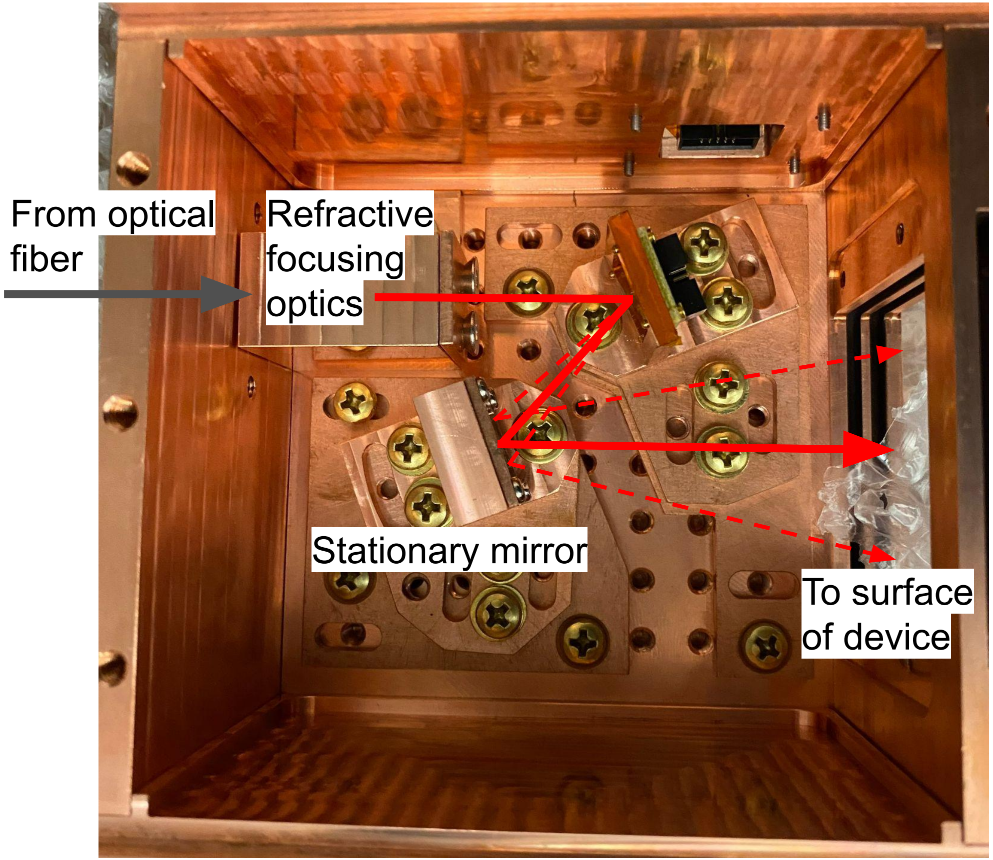
Good because:

- High broadband reflectance
- Relatively large deflection angles
- Effectively no power dissipation while stationary

Scanning unit design using MEMS mirror:

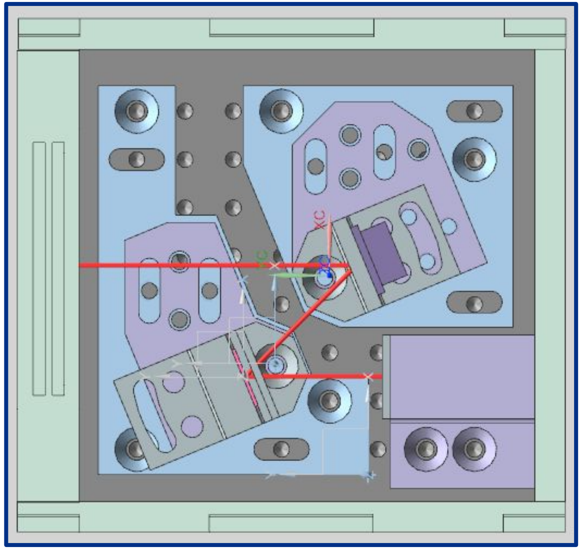


MEMS mirror allows for desired operating specifications:

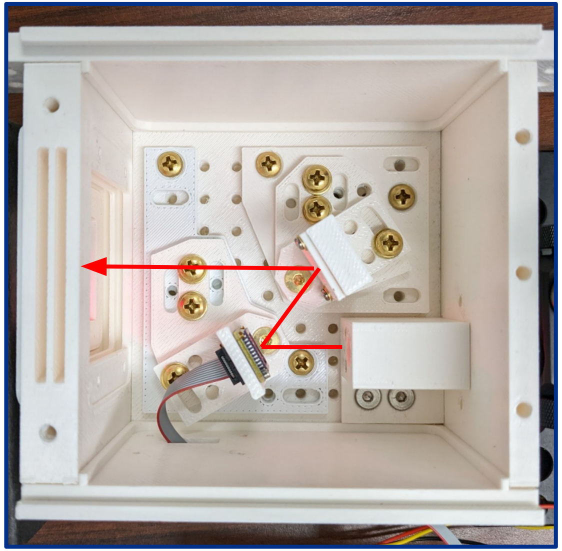


- ~3cm x 3cm scanning area
- <100μm spot size
- ~10μm position resolution
- O(100)Hz scanning speed
- Temperature down to 10mK
- Limits parasitic backgrounds
- Device agnostic
- Single wavelength within 0.6-6.9eV

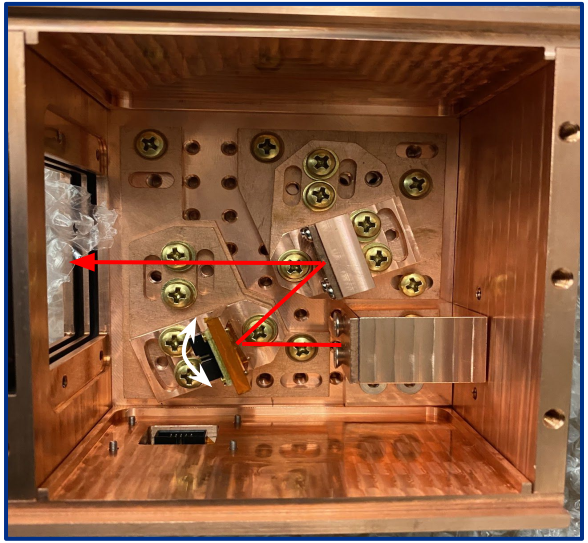
Scanning unit design progression



CAD model of enclosure
(March 2022)



3D-printed prototype
(April 2022)

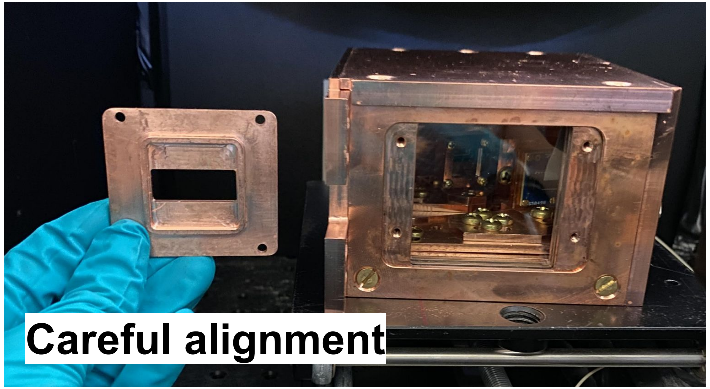


Copper enclosure
(June 2022)

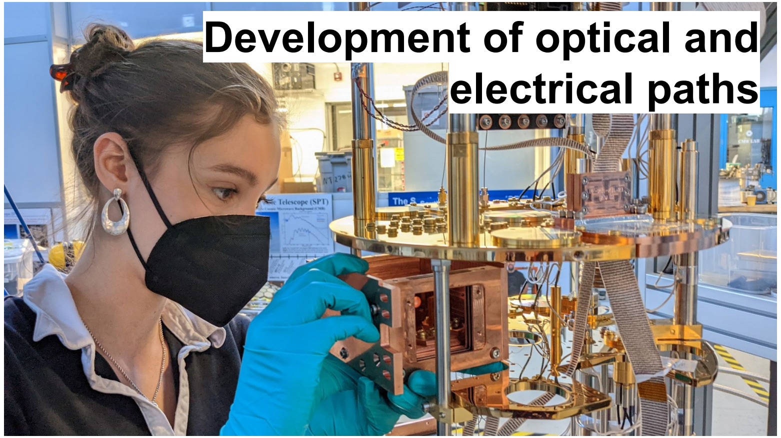
Work by H. Magoon

Warm demonstration and characterization of scanning unit

Steering of MEMS mirror

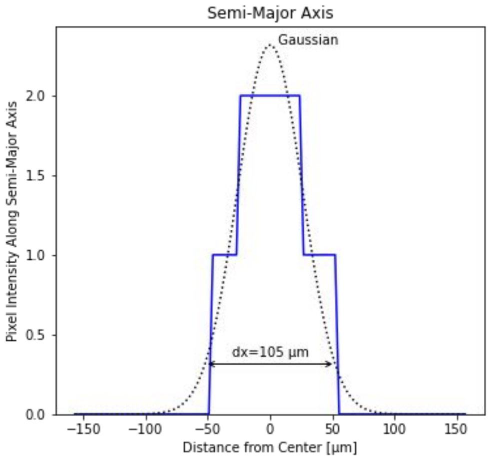


Careful alignment



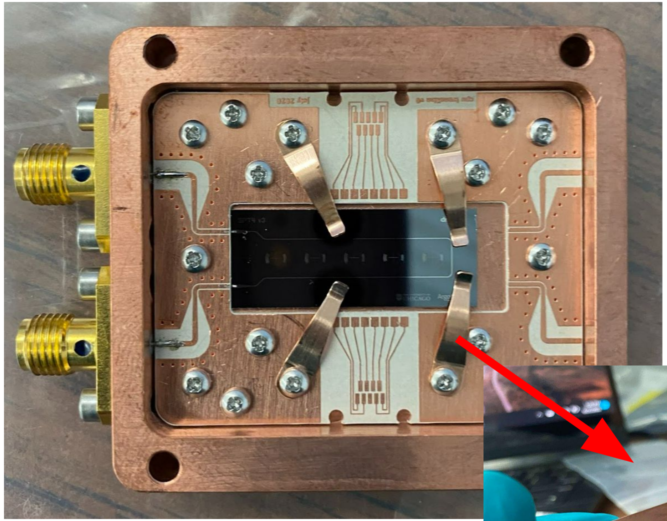
Development of optical and electrical paths

Spot size of ~100μm

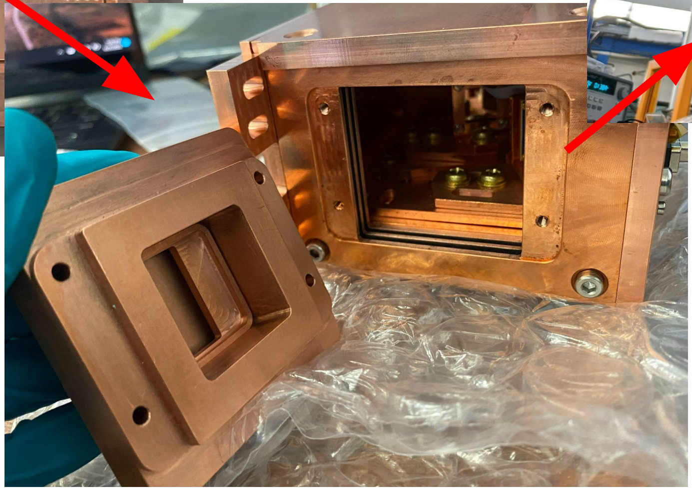


Work by H. Magoon

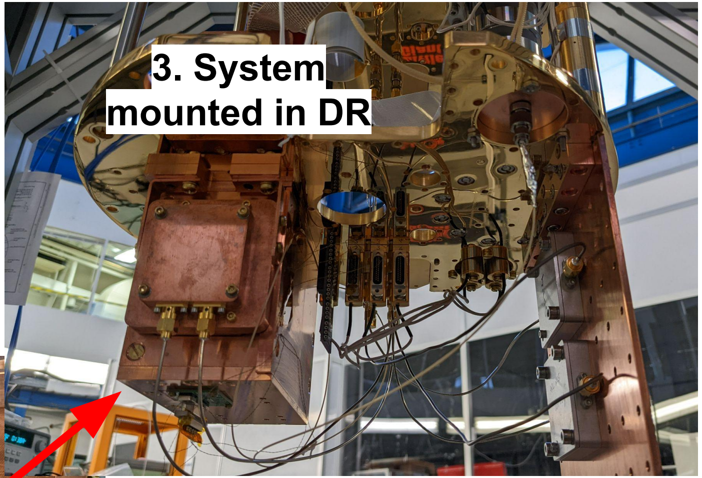
First 10mK test of scanning unit



1. MKID sensor borrowed from colleague A. Anderson



2. Device mounted onto scanning unit



3. System mounted in DR

Work by H. Magoon

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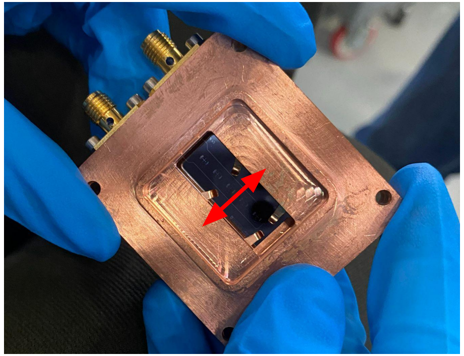
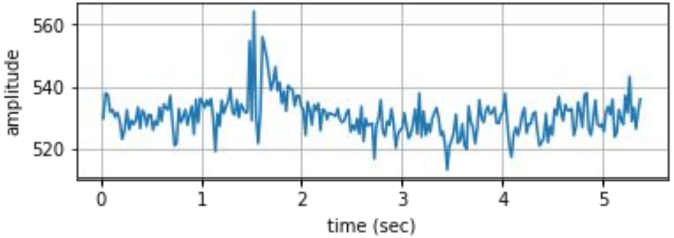
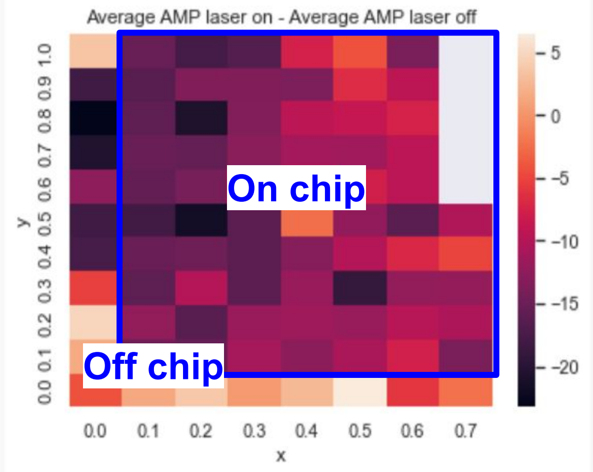
First 10mK test of scanning unit successful!



Clear indication of laser scanning across the chip:





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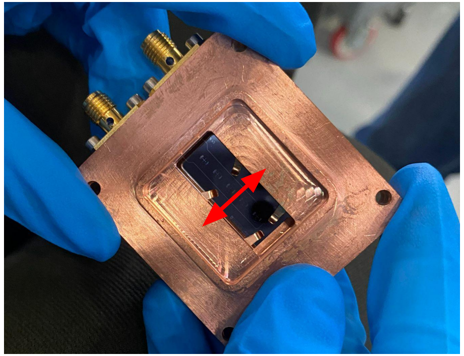

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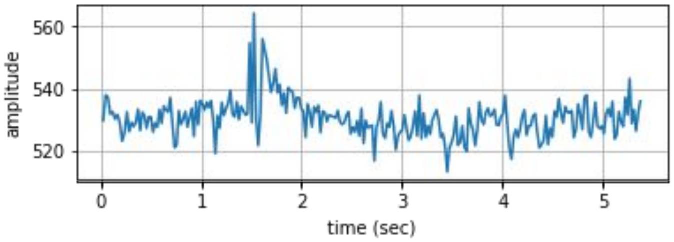
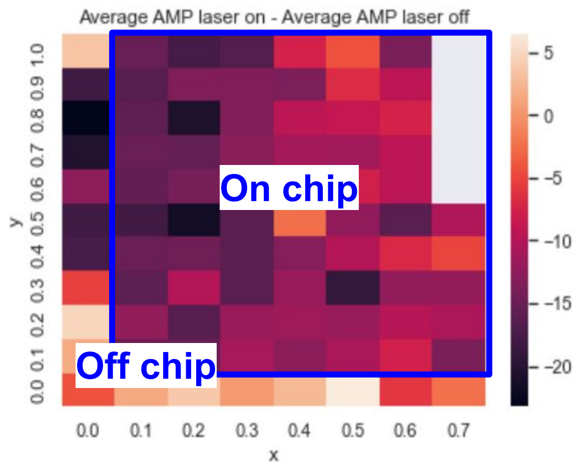
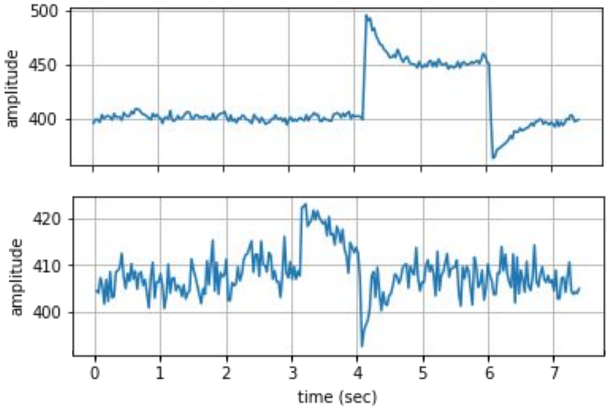


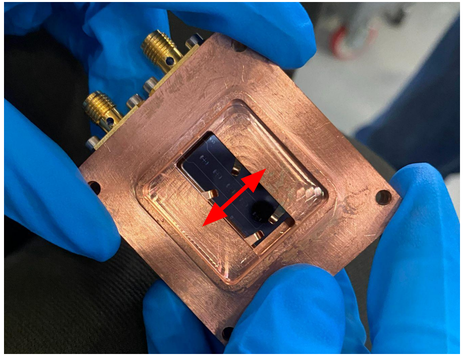


Can easily tune interaction energy:



Work by H. Magoon

First 10mK test of scanning unit successful!



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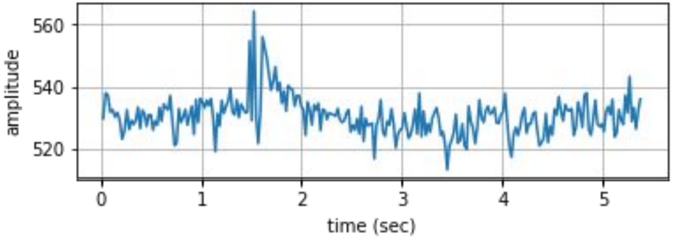

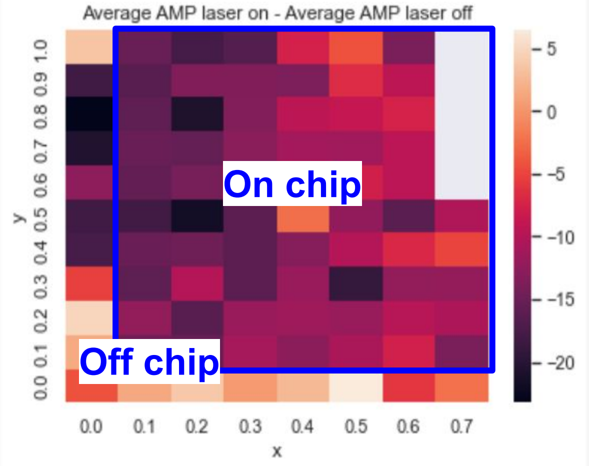

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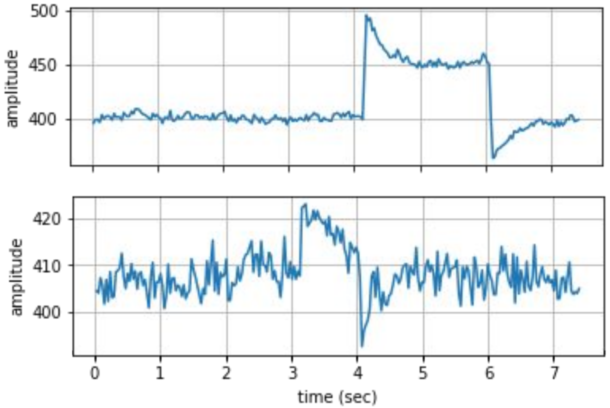
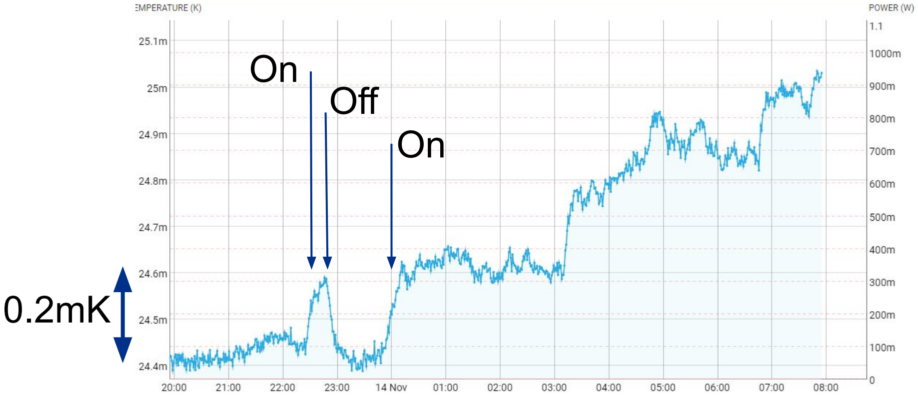


Minimal temperature disruption observed:

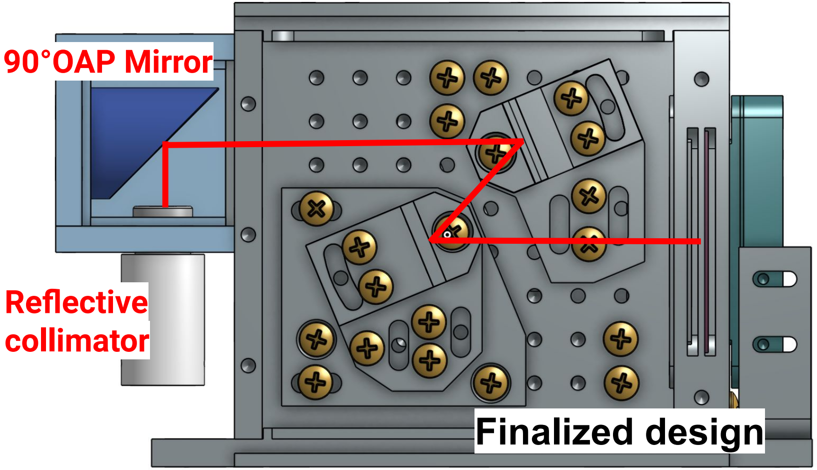


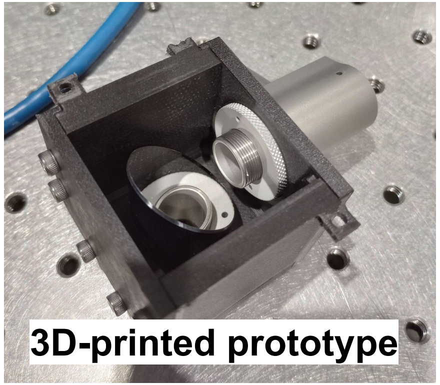
Work by H. Magoon

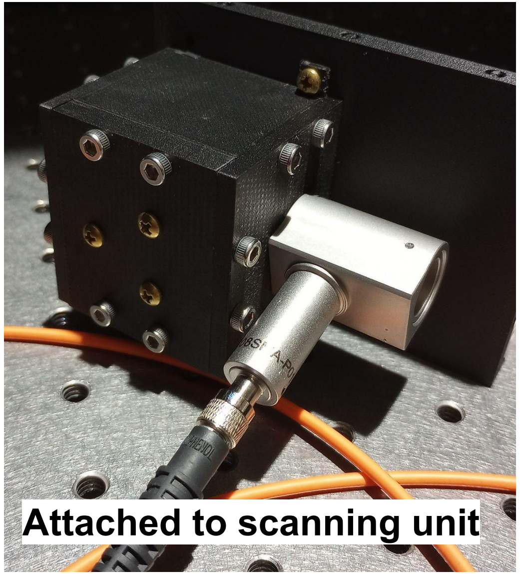
Future upgrade: Expanded energy range through reflective focusing

Refractive focusing limits energy range to 0.6-6.9eV

Solution: Reflective focusing @SLAC allows for 0.06-5eV and reduces spot size to ~50μm



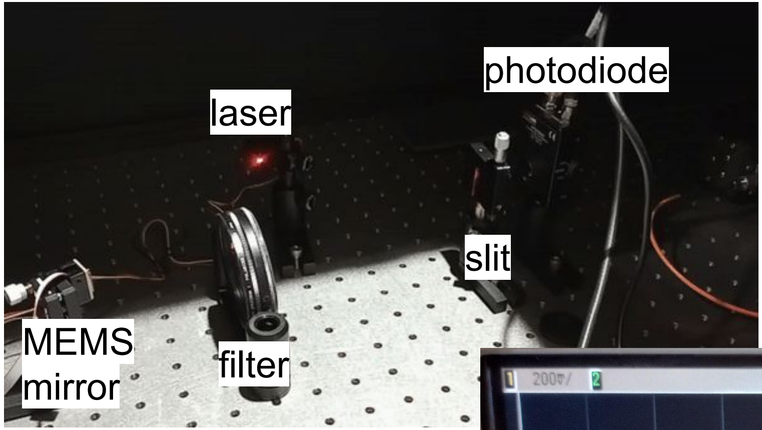




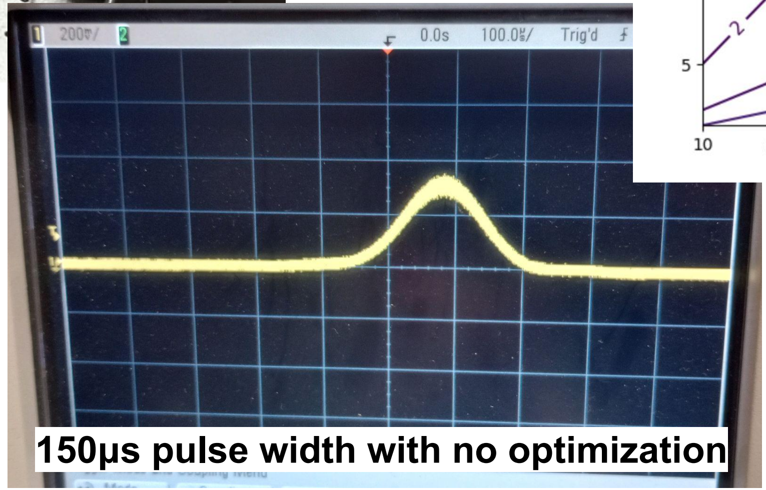
Next step: Optimize spot size, demonstrate energy range

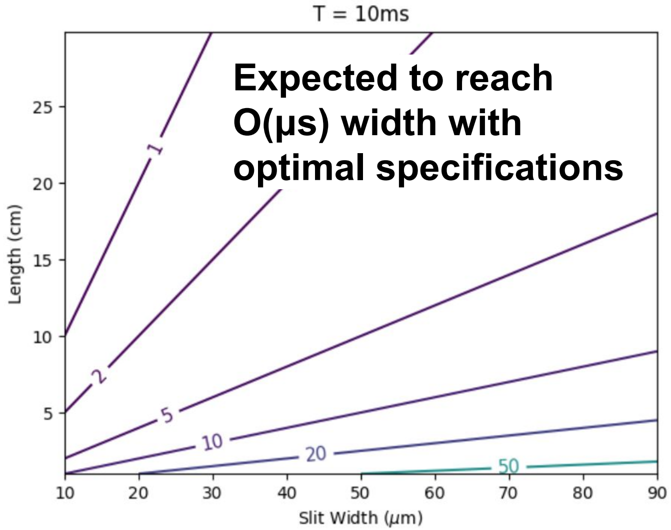
Work by A. Nunez

Future upgrade: Pulsed beam through chopping



Warm chopping setup functional @ SLAC



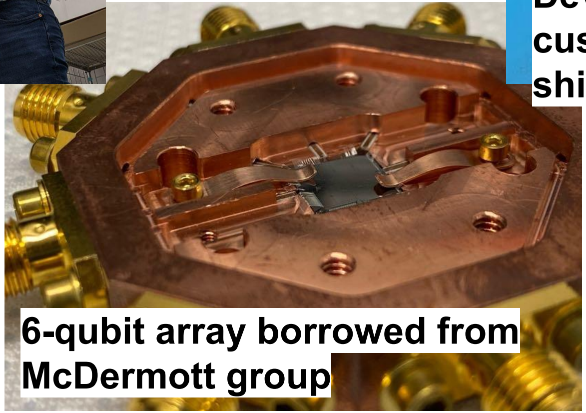


Next step: Optimization of slit width, scan speed, and spot size

Work by G. Perez

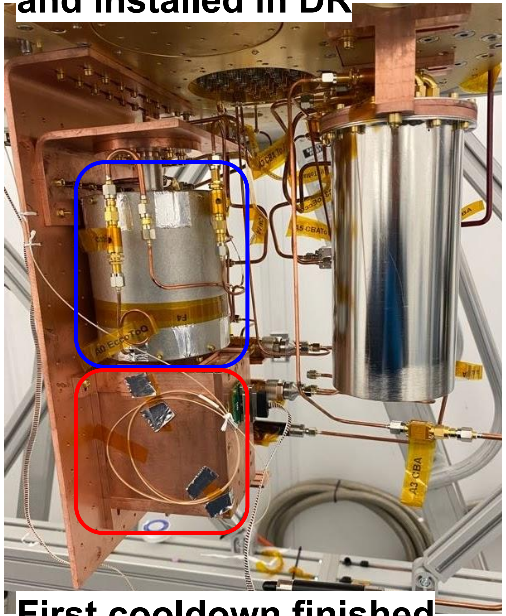
Early science target: Effect of photon interactions on qubit coherence


New DR installed at FNAL


6-qubit array borrowed from McDermott group


Device installed in custom magnetic shielding

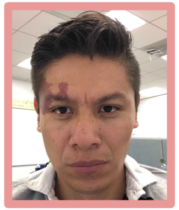
Magnetic shielding coupled to scanning unit and installed in DR


First cooldown finished this week!

Calibration system team:
Kelly Stifter (Lederman Fellow)
Hannah Magoon (Tufts ugrad)
Anthony Nunez (Stanford ugrad)
Giana Perez (Stanford ugrad)
Israel Hernandez (IIT grad)
Noah Kurinsky (SLAC Scientist)



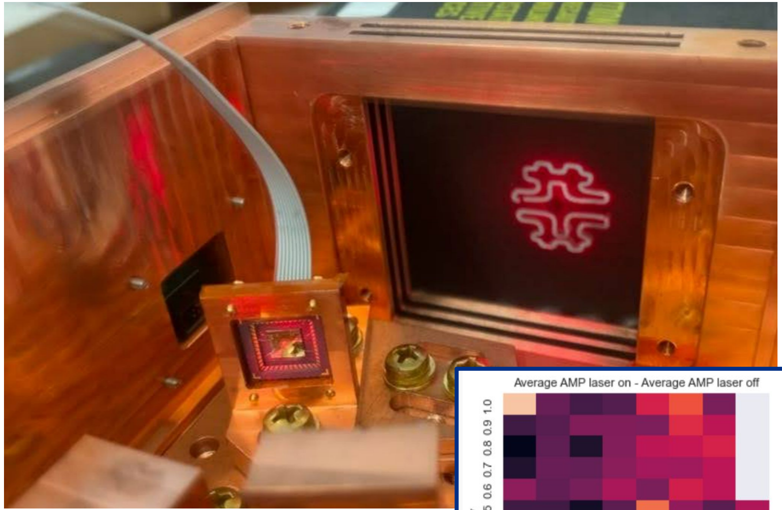


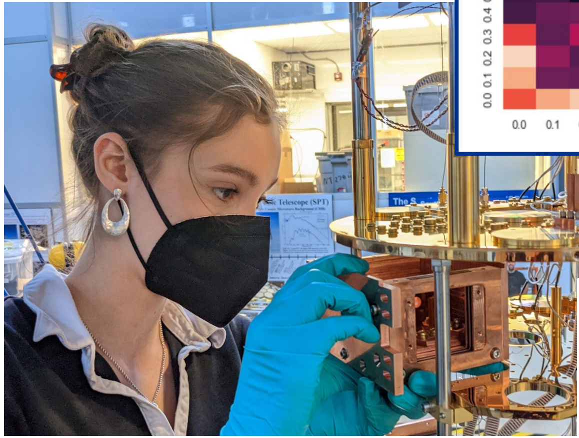


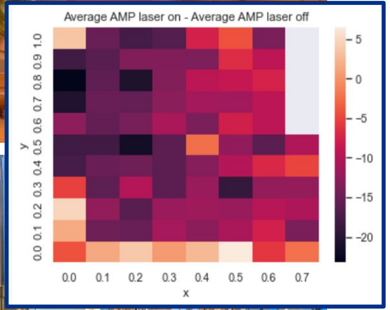

Fermilab QSC group:
Dan Baxter (Scientist)
Daniel Bowring (Scientist)
Lauren Hsu (Scientist)
Rakshya Khatiwada (Scientist)
Adam Anderson (Scientist)
Tali Figueroa (NW faculty)
Dylan Temples (Lederman Fellow)
Ryan Linehan (Postdoc)
Sami Lewis (Postdoc)
Kester Anyang (IIT grad)
Jialin Yu (IIT grad)

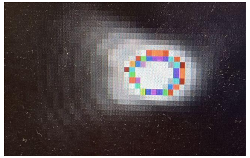
Summary

- Novel low-threshold detectors will require very low energy calibrations
- MEMS mirror-based design can provide pulsed, steerable beam in sub-eV regime with easily configurable intensity and pulse characteristics in a cryo-friendly way
- Can be coupled to wide variety of low-threshold devices
- **Many impactful science topics to be explored**





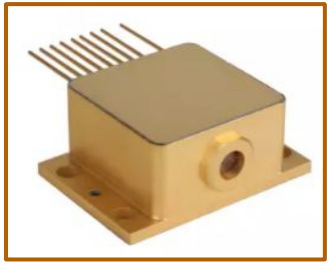




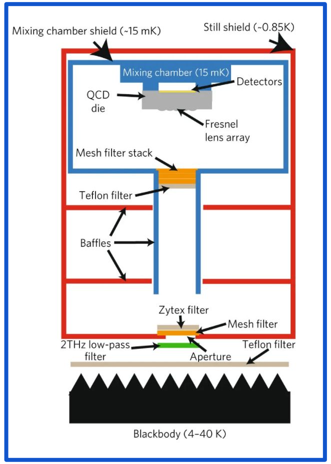
Backup

Some available low-energy sources

Laser diodes (right): Readily available out to ~2μm (0.62eV)

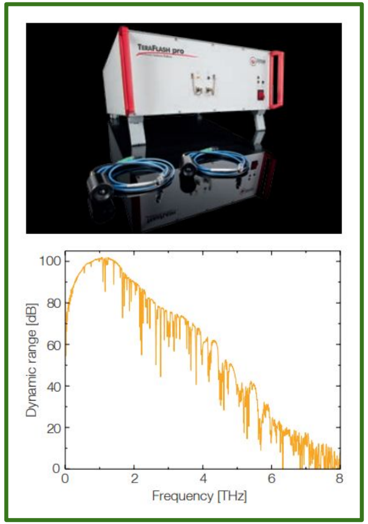


Quantum cascade lasers (left):
Out to ~16μm (0.08 eV)



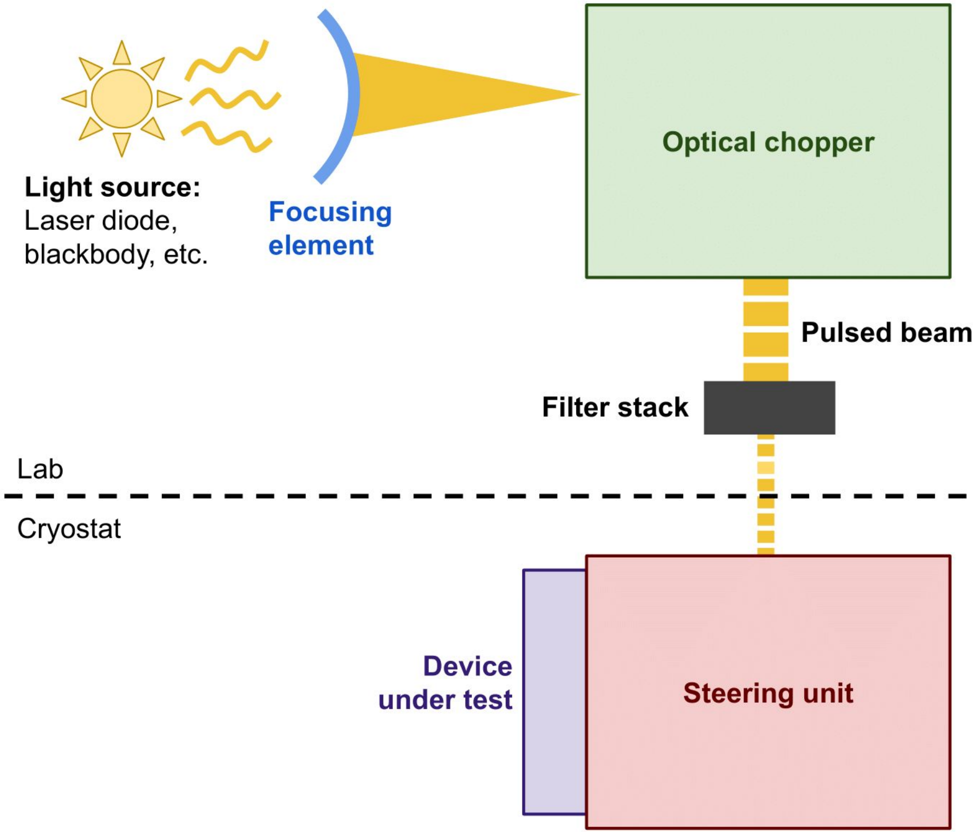
[Single 1.5THz photon detection w/ QCD]

Auston (photoconductive) switches (right):
~THz regime (300μm, 4meV), device under test must be sensitive to magnitude of E-field



Filtered blackbody (left): Previously used at 1.5THz (200μm, 6meV)

Benefits of modular MEMS-based design



- **Wide energy range:** can access sub-eV range and simulate arbitrary deposition of eV-keV
- **Small pulse width with good position resolution and repeatability**
- **In-situ:** Cryo-friendly, shouldn't introduce parasitic backgrounds
- **Customizable:** easy to swap source and filters mid-operations, can mount variety of devices at output
- **Flexible:** individual modules should be "plug-and-play", either could be cryogenic
- **Cheaper, more flexible, or more functional than other options**

MEMS mirrors

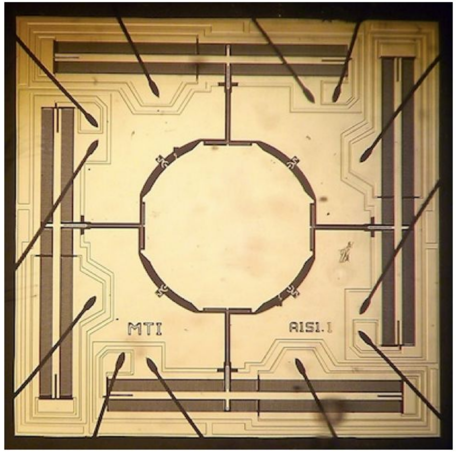
Micro-electro-mechanical systems (MEMS) mirrors, aka micromirrors or microscanners

Very low power consumption during actuation and at static position

Aluminum reflecting surface → high broadband reflectance

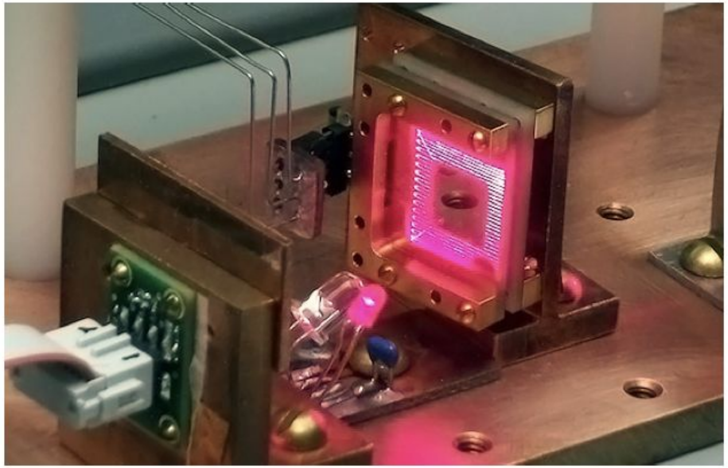
High scan speed with good tilt range, position resolution, repeatability

- O(100)Hz max scan speed, mechanical tilt range of ±6°, 0.005° resolution



Left: MEMS mirror under microscope

Below: photo of a raster scan using MEMS mirror



Previous work

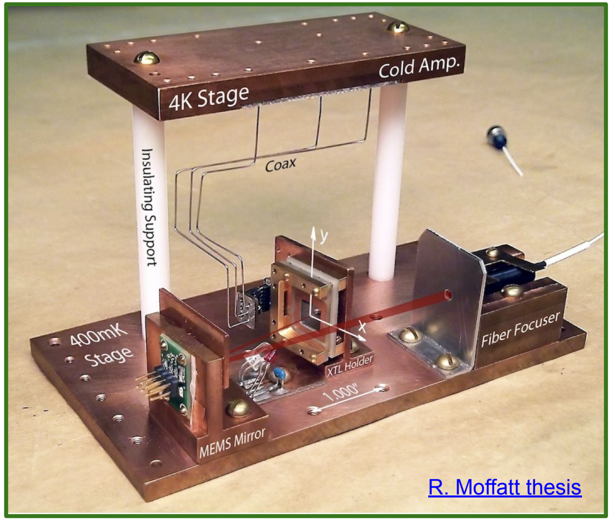
Cryogenic scanner previously built & operated at Stanford (400mK)

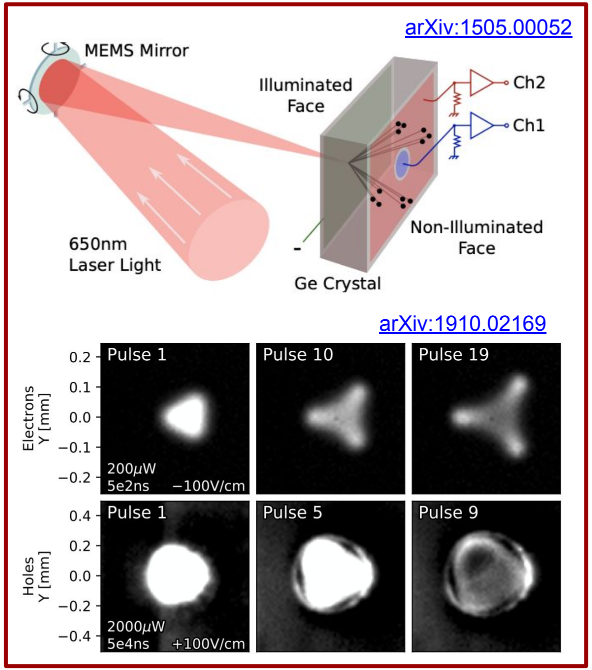
- Used to map charge collection vs. position in Si & Ge

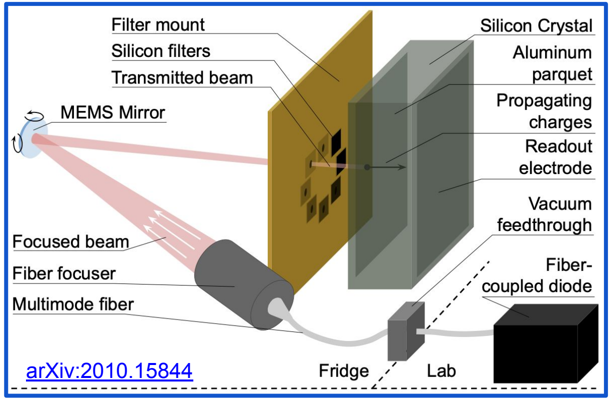
Also used to measure transmission through Si thin films → photoelectric effect

- Realized scanning across aperture acts like a shutter

Original setup open to 4K photon bath (right)







Upper left: photo of scanning device used for charge transport measurements

Upper right: schematic of scanning apparatus and result of charge transport measurement in Si

Lower left: schematic of scanning device used in Si photoelectric effect measurement

Technical design challenges

MEMS functionality at low temps (10mK)

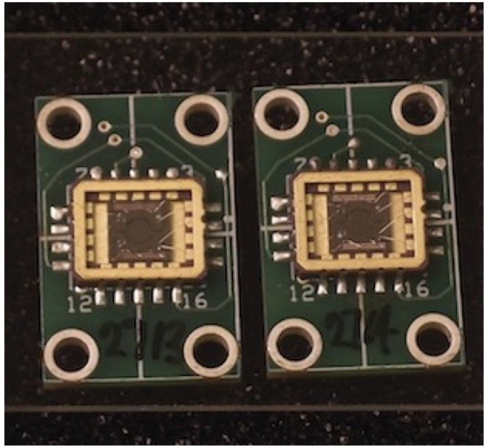
- Original design used doped silicon control lines, freezes out at low temperatures
- Worked with Mirrorcle Inc. to deposit Al over control lines → allows for low temp use

Control hardware functionality with long cryo-cabling with high impedance

- Modified voltage delivery
- Developed adapter boards for DR feedthroughs

Laser coupling to device without degrading performance or admitting excess IR

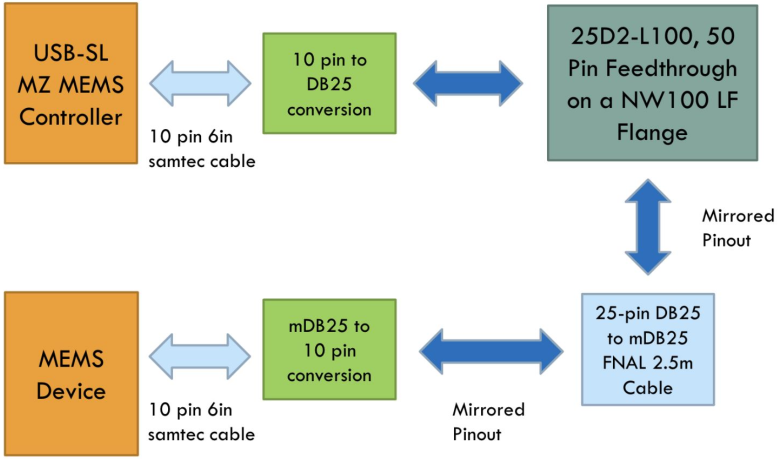
- Ensure housing of steering unit is photon-tight, while still keeping footprint small for operation in DR



mirrorcle TECHNOLOGIES, INC.

Left: MEMS mirrors mounted on PCB

Below: cabling schematic for cryo-friendly MEMS setup



Sample application: Phonon transport and simulation

arXiv:1505.00052

Previous charge transport measurements were used to tune charge transport simulations

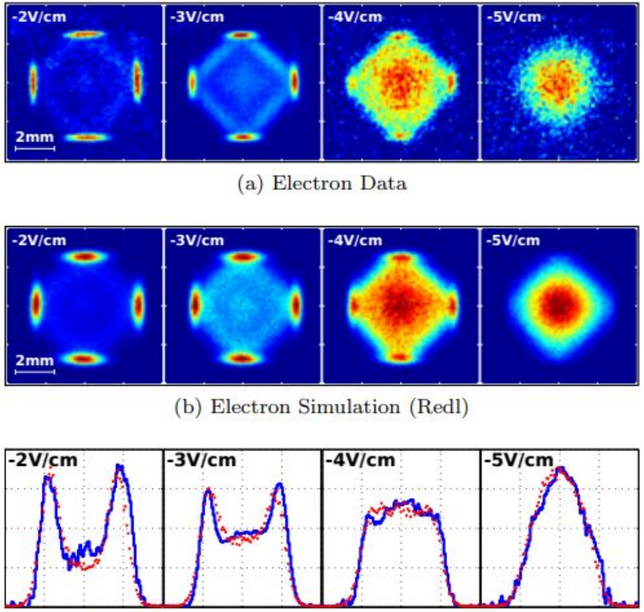
- Excellent agreement was shown (right)

Can repeat measurement, but for phonon transport, and similarly tune simulations

- Will feed into simulation of quantum sensors

Previous scanning setup (see slide 32) requires modifications for this task:

- Low temperature operation (10mK)
- Improved background mitigation
- Increased wavelength range



(a) Electron Data

(b) Electron Simulation (Redl)

(c) Data (solid blue) vs. Simulation (dotted red)

FIG. 3. **Electron Charge Density Patterns:** (a): Data. (b): Redl simulation. (c): One-dimensional projection of charge density onto a diagonal axis. The data (solid, blue) are compared to the Redl simulation employing the Herring-Vogt approximation (dotted, red). The horizontal scale ranges from -4mm to +4mm. The vertical scale is arbitrary.