Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

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

Kelly Stifter - Fermilab Cosmic Physics Center, Quantum Science Center

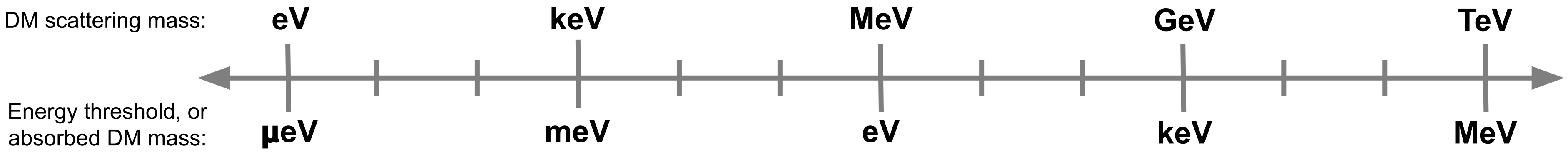
The 14th International Conference on Identification of Dark Matter

7/21/2022

QUANTUM SCIENCE CENTER

The future of low-mass particle dark matter searches

Wide range of particle DM models to explore:



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The future of low-mass particle dark matter searches

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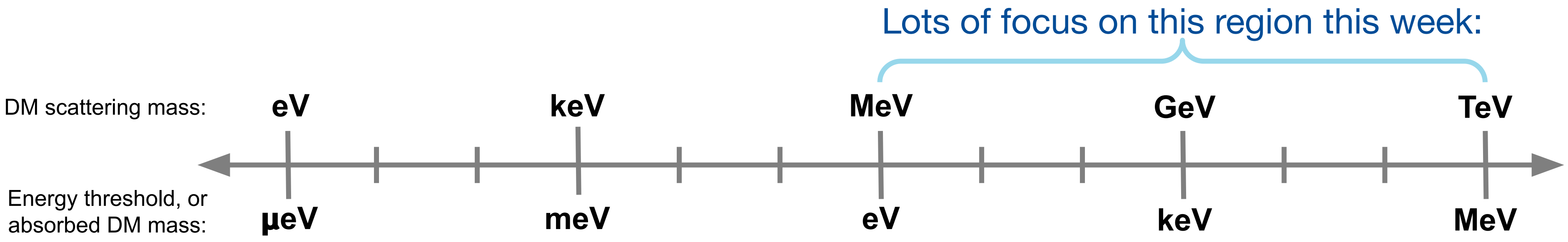

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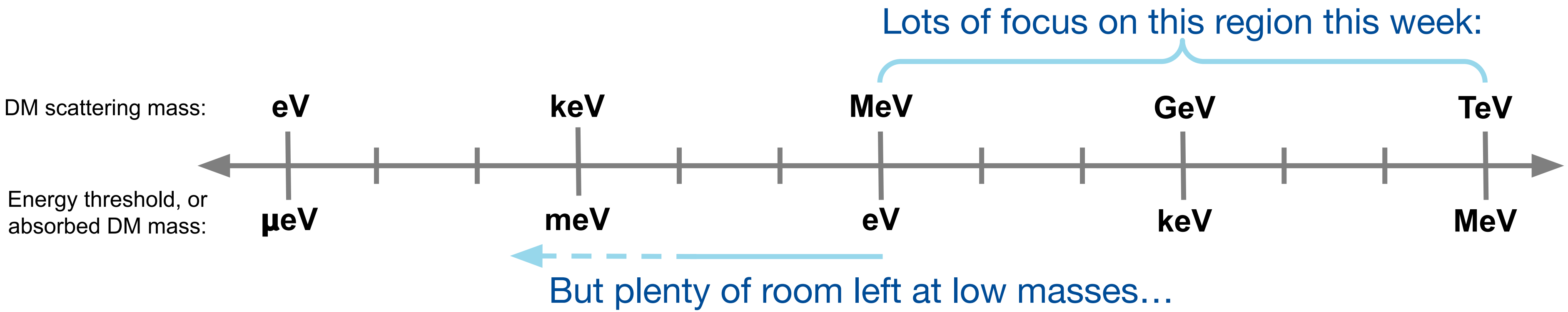

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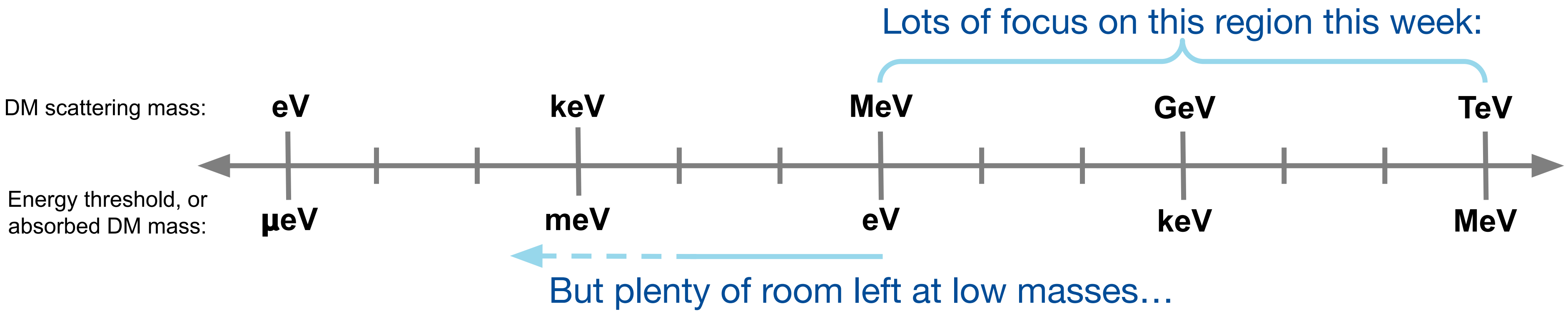

Major R&D challenge: How do we lower the threshold of DM detectors?

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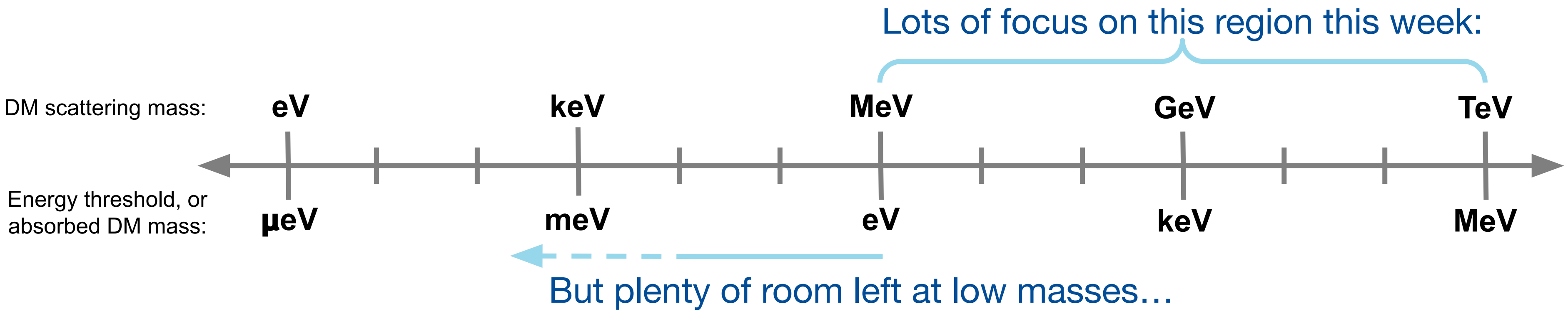

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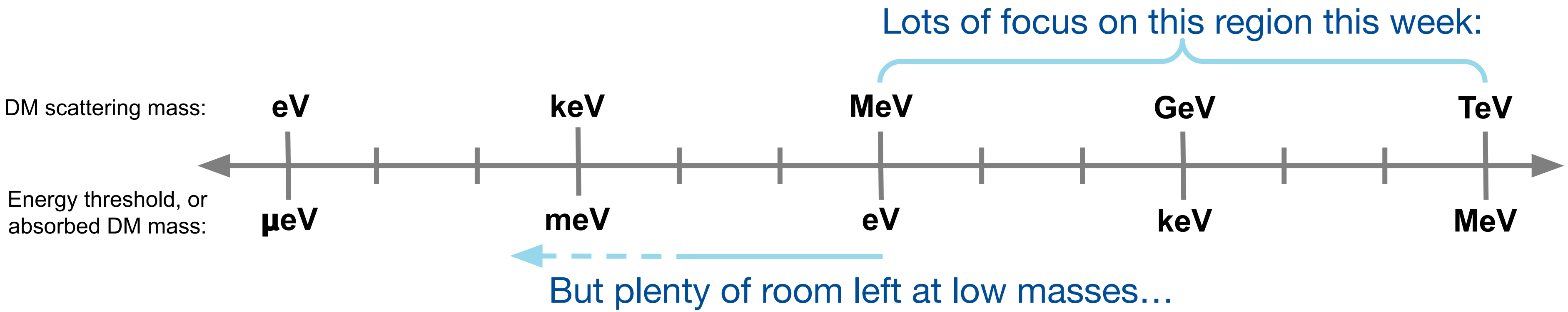
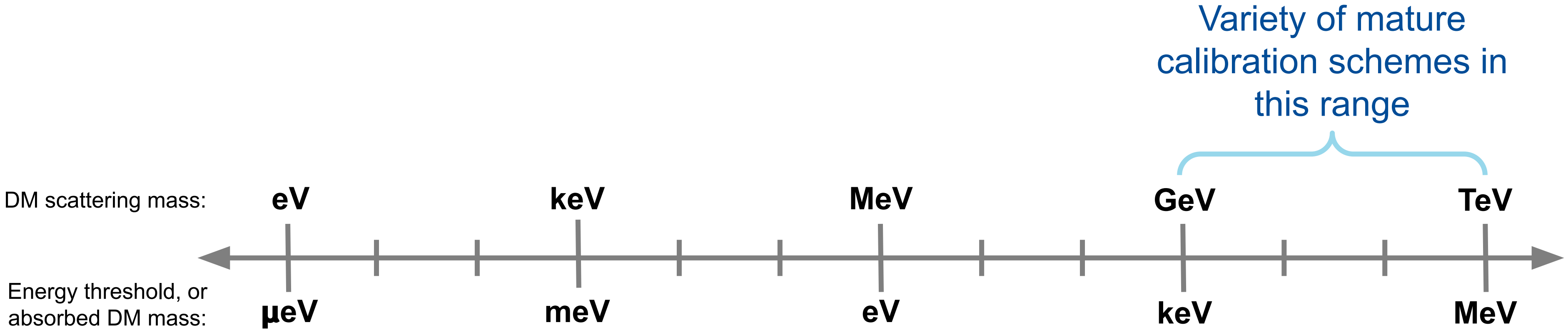


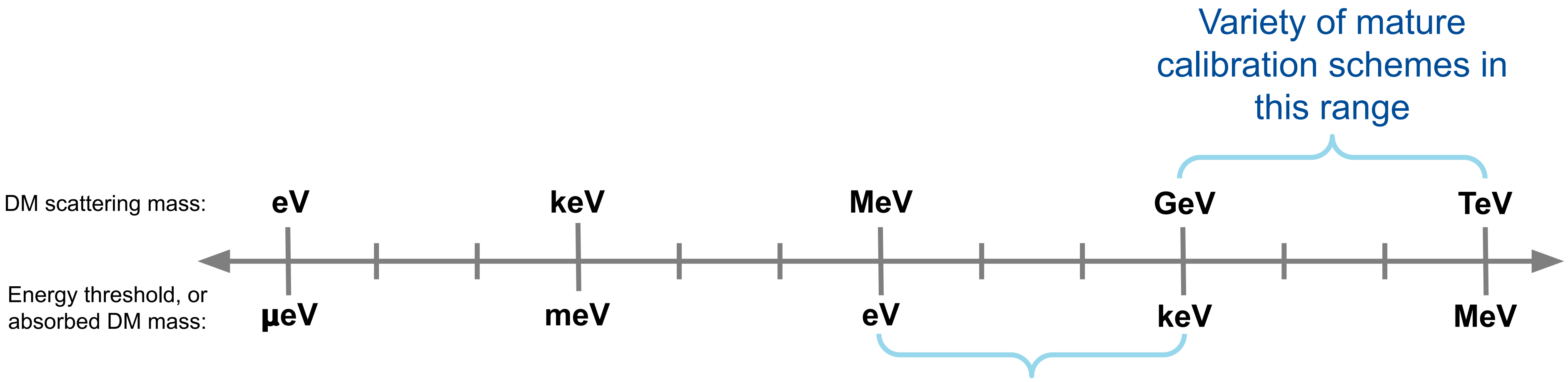
Major R&D challenge: How do we lower the threshold of DM detectors? ✅

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

Calibrating low-threshold detectors



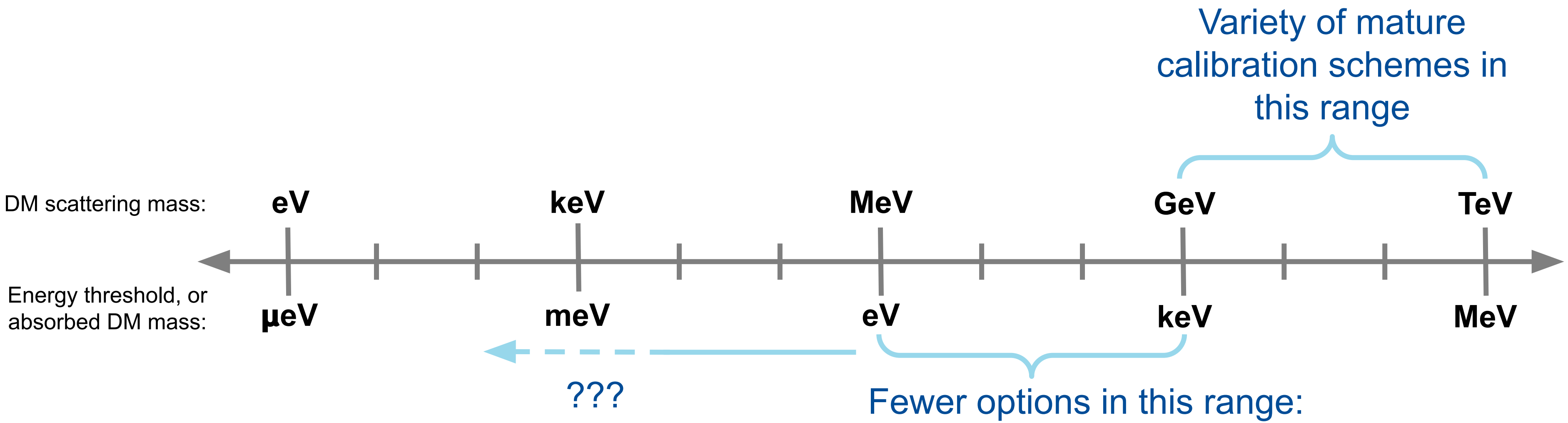
Calibrating low-threshold detectors



Fewer options in this range:

- Activation lines
- Compton measurements (R. Smida, Monday)
- Neutron sources or beams (V. Novati, Monday, V. Wagner, today)
- Photon pulses

Calibrating low-threshold detectors



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How do you calibrate devices below an eV?

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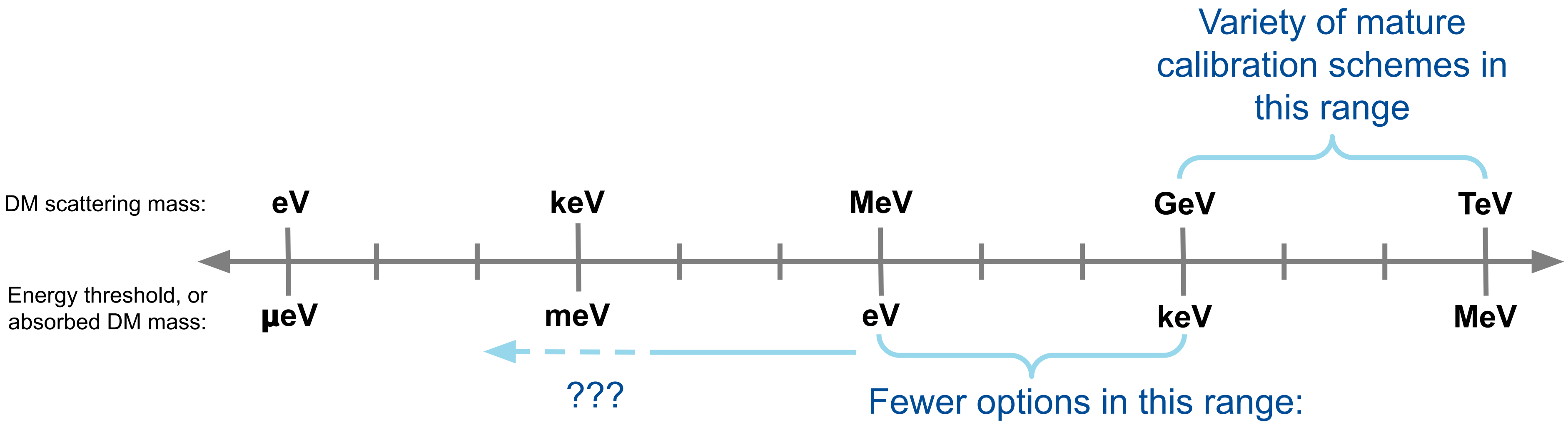
Calibrating low-threshold detectors



Fewer options in this range:

- Activation lines
- Compton measurements (R. Smida, Monday)
- Neutron sources or beams (V. Novati, Monday, V. Wagner, today)
- **Photon pulses**

How do you calibrate devices below an eV?

Calibration 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)

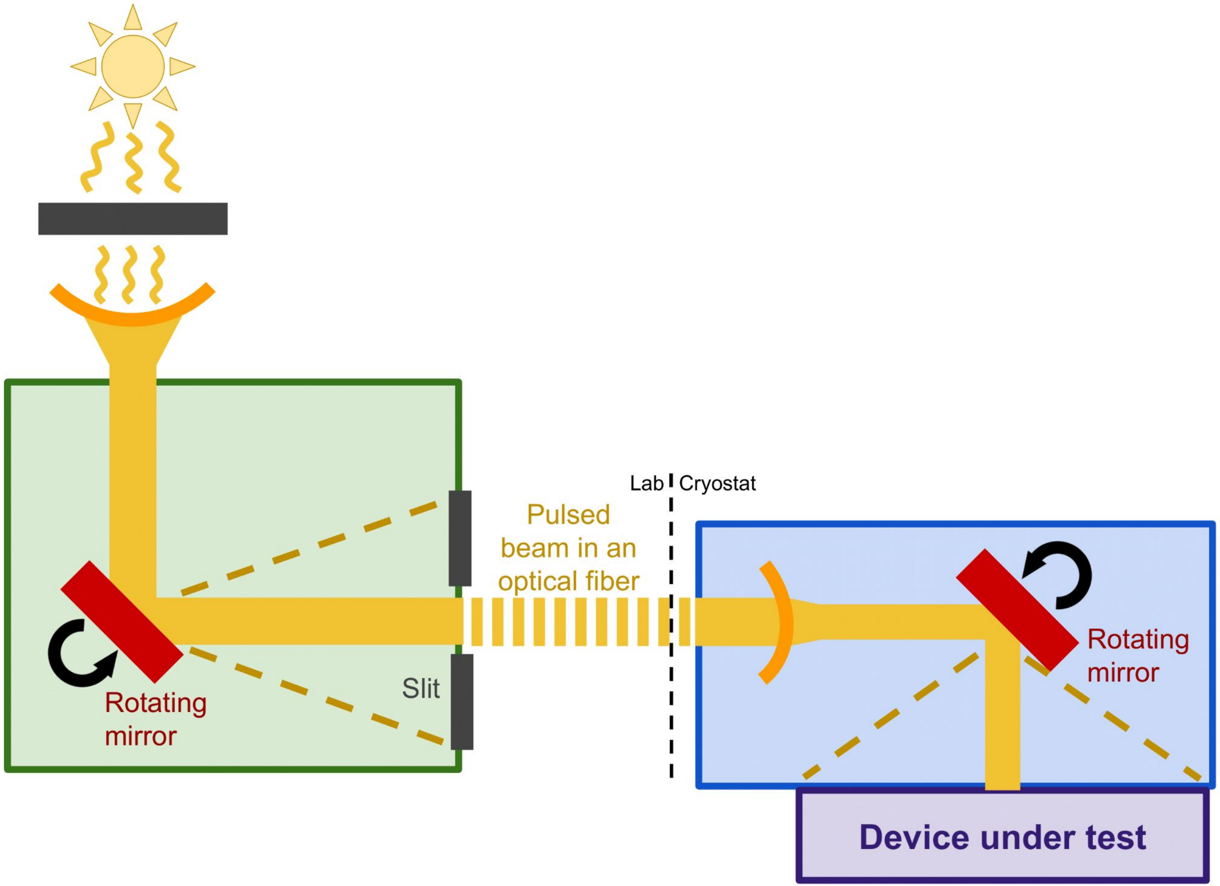
Use to characterize many devices:

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

Many important phenomena to investigate:

- Detection thresholds/readout efficiency
- Position sensitivity of device
- Effect of quasiparticle poisoning
- Sensitivity to ionizing radiation
- Detailed phonon propagation

Pulsed, steerable laser device for use with cryogenic devices:



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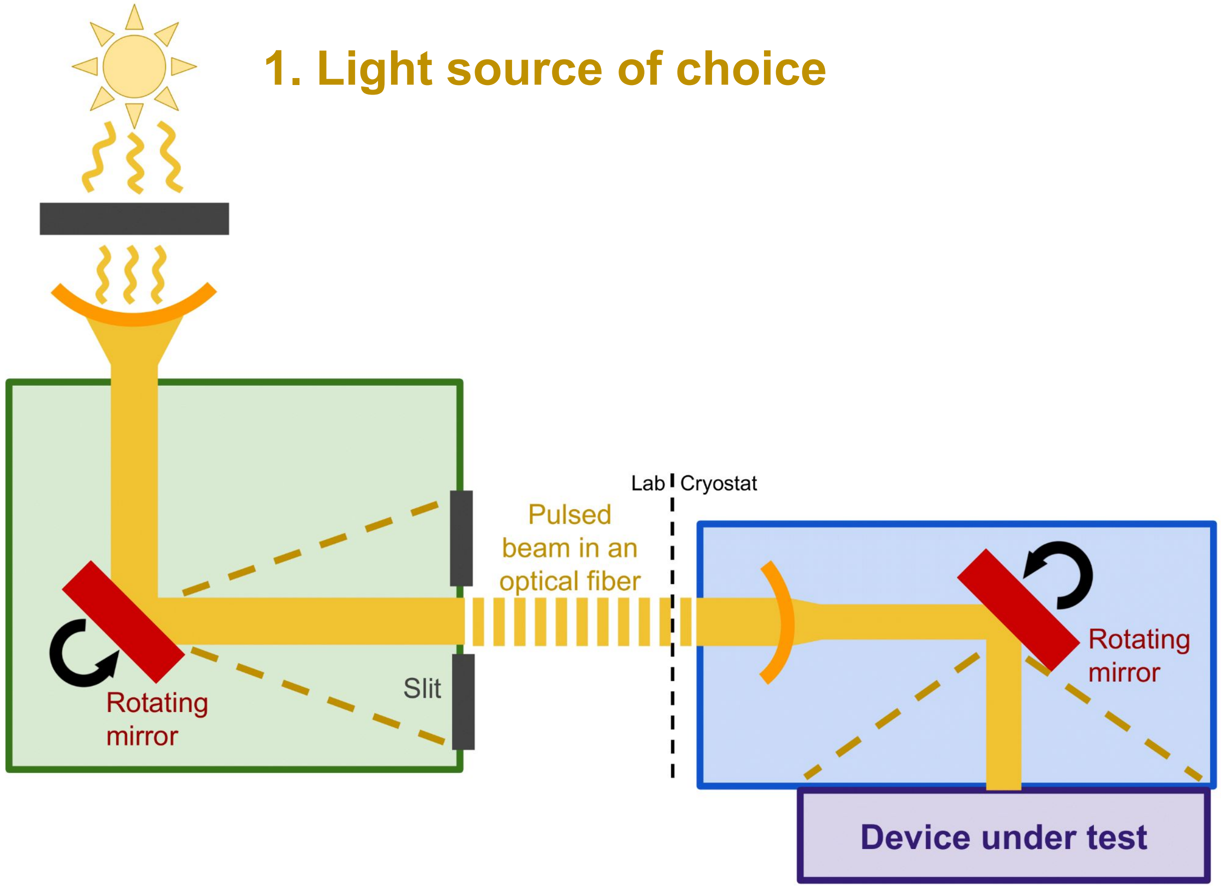
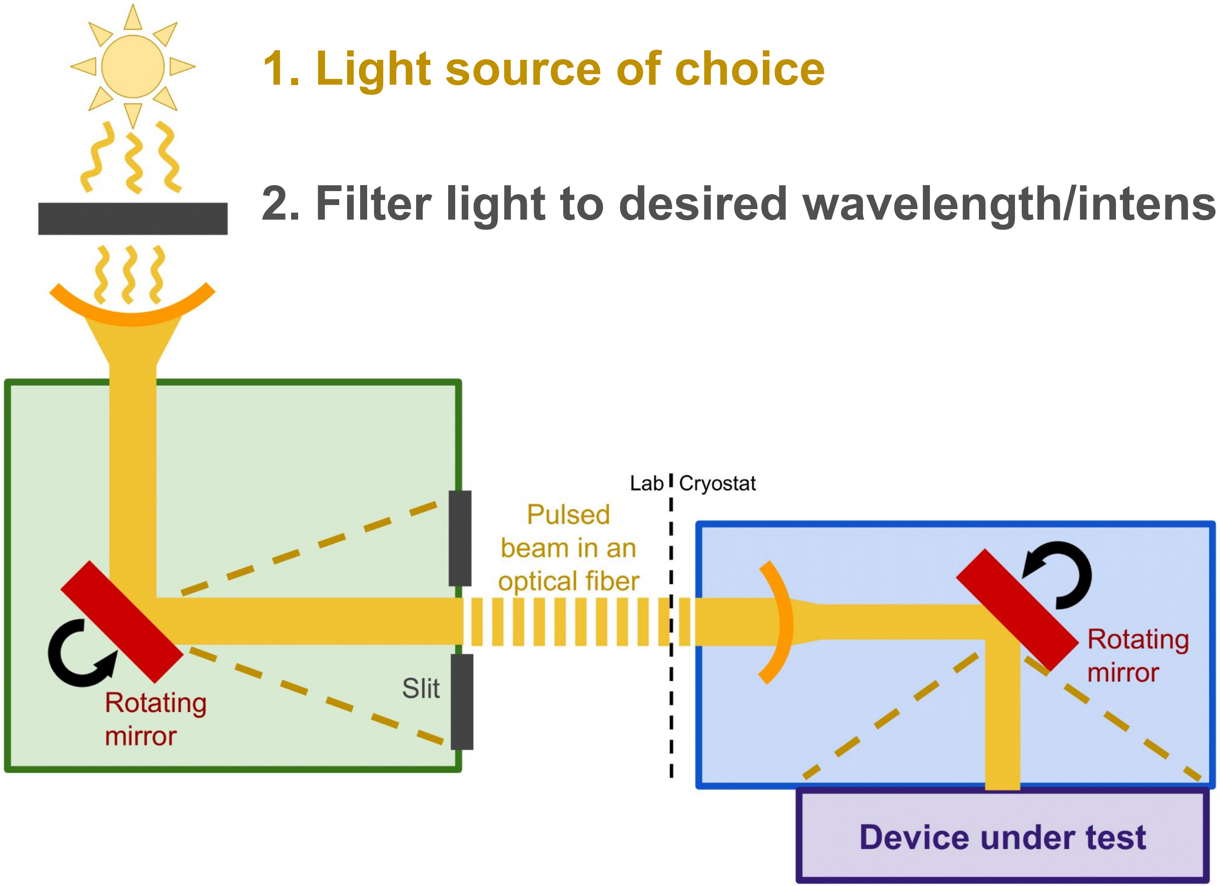


Pulsed, steerable laser device for use with cryogenic devices:

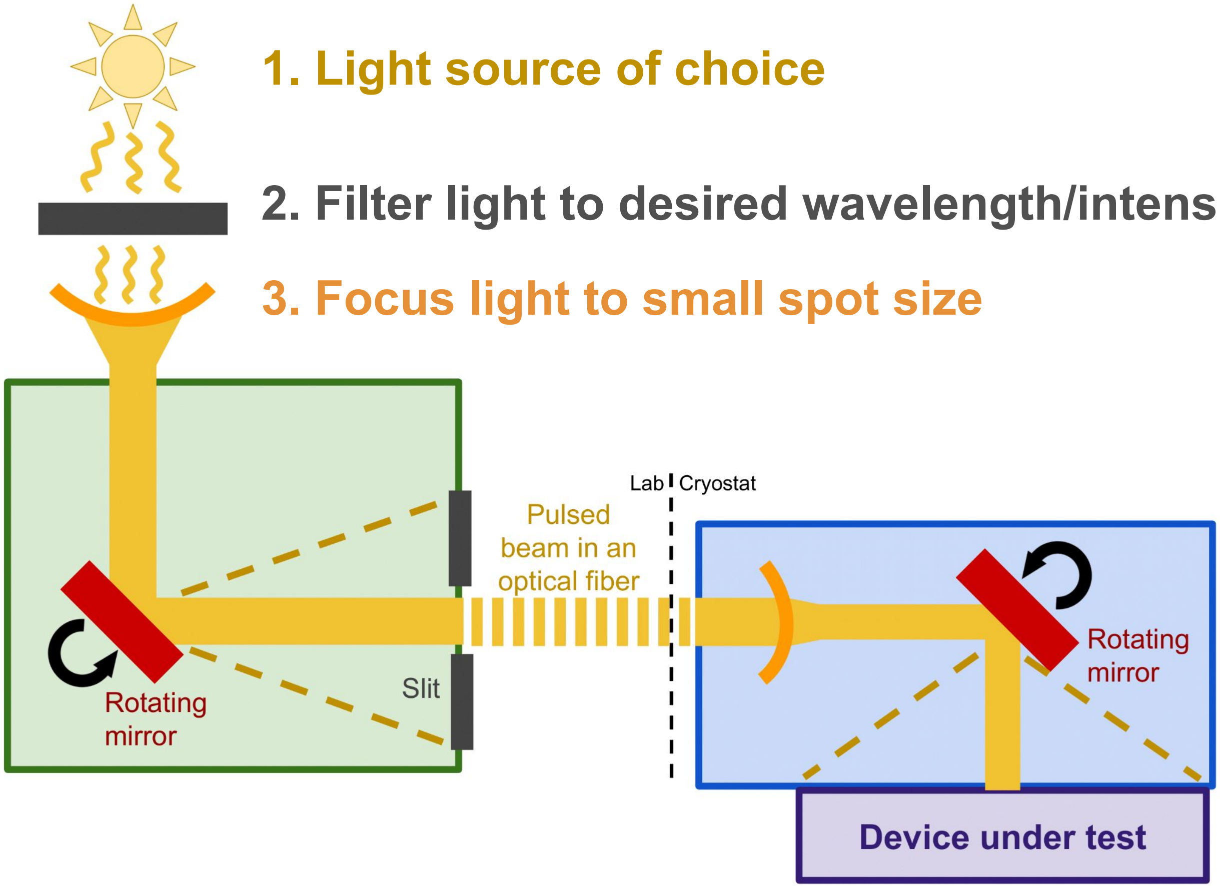
1. Light source of choice

2. Filter light to desired wavelength/intensity



Pulsed, steerable laser device for use with cryogenic devices:

1. Light source of choice
2. Filter light to desired wavelength/intensity
3. Focus light to small spot size



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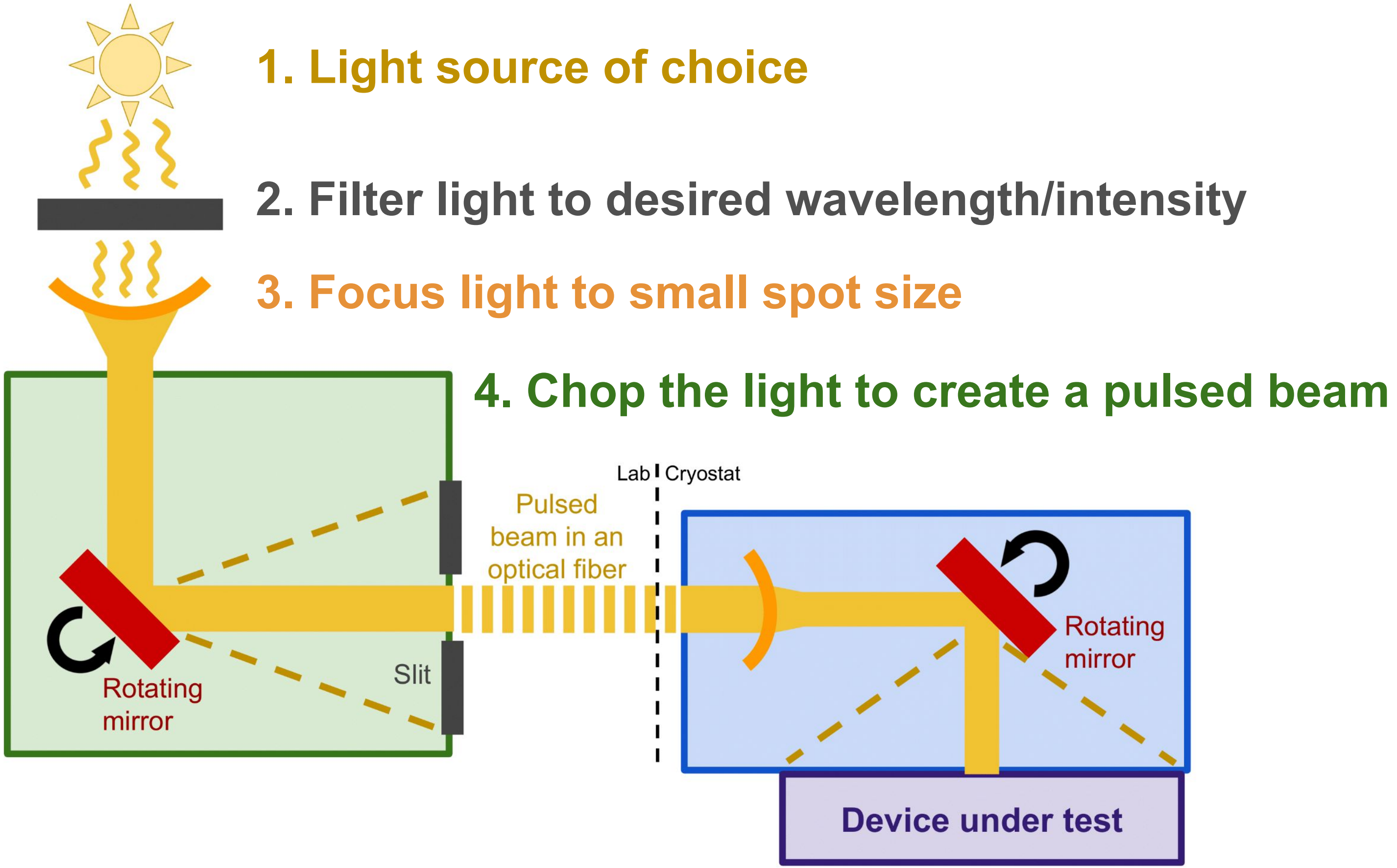
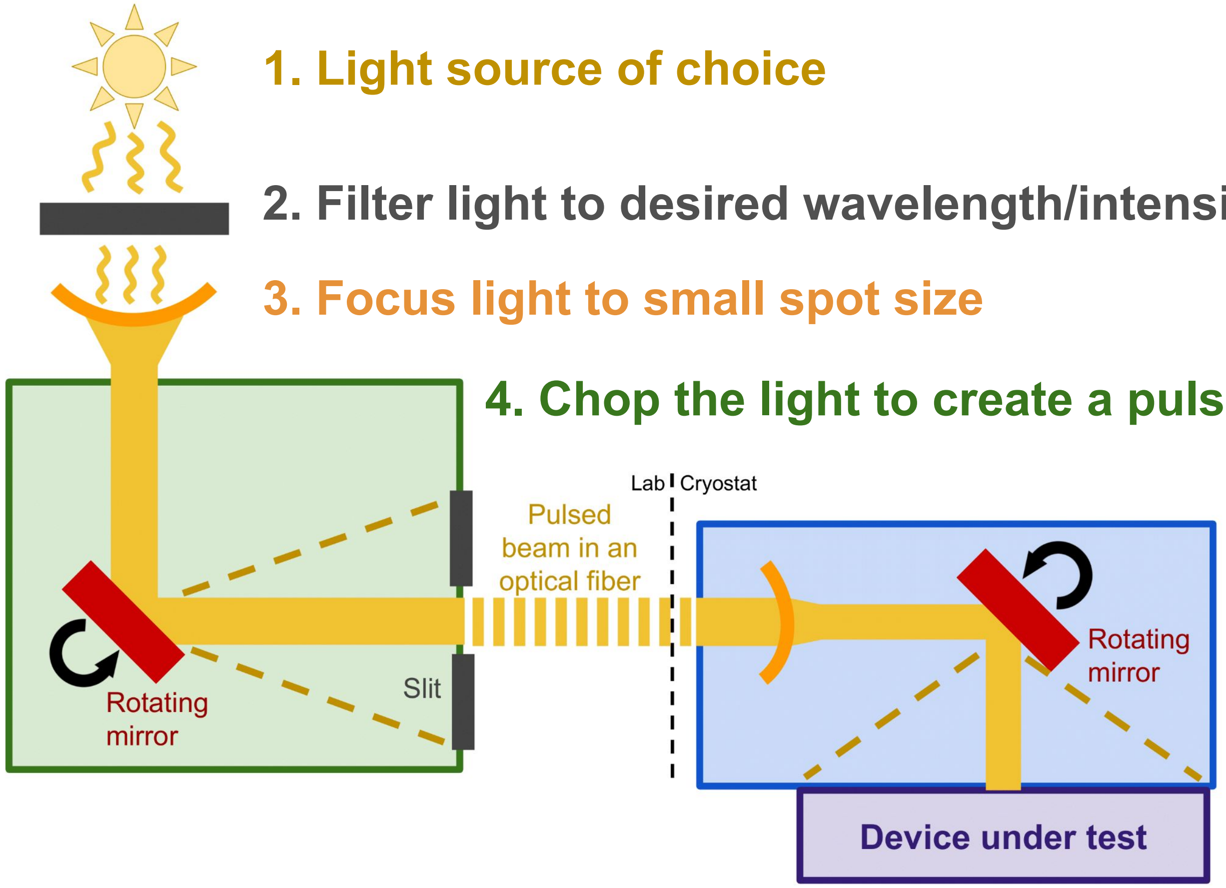


Pulsed, steerable laser device for use with cryogenic devices:

1. Light source of choice
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…



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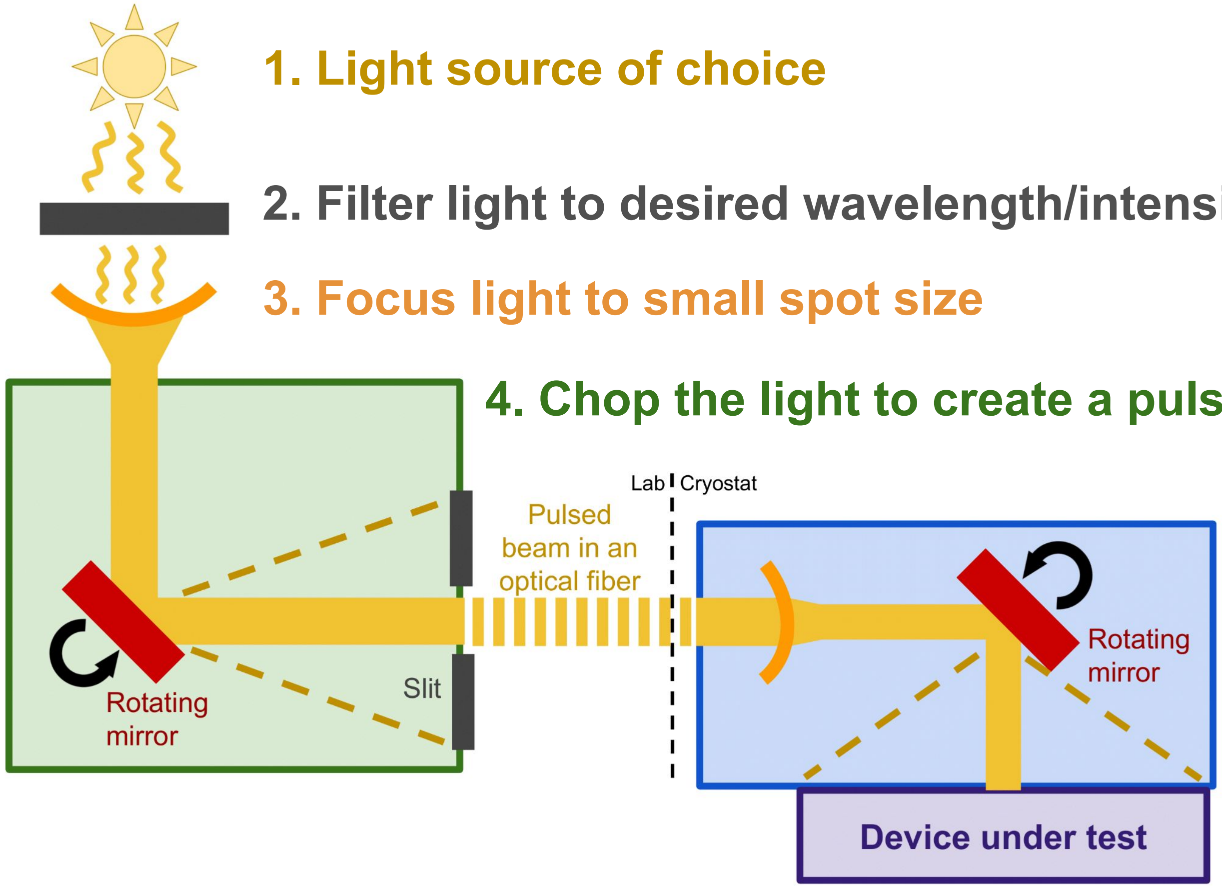

1. Light source of choice
2. Filter light to desired wavelength/intensity
3. Focus light to small spot size
4. Chop the light to create a pulsed beam
5. Steer pulsed beam to desired location…
6. …to produce energy deposits in your device

Technical challenge:

Cryogenic movement

- Power dissipation
- Freeze out of movement mechanisms/control

Our solution: modified MEMS mirrors (right)

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Cryogenic movement

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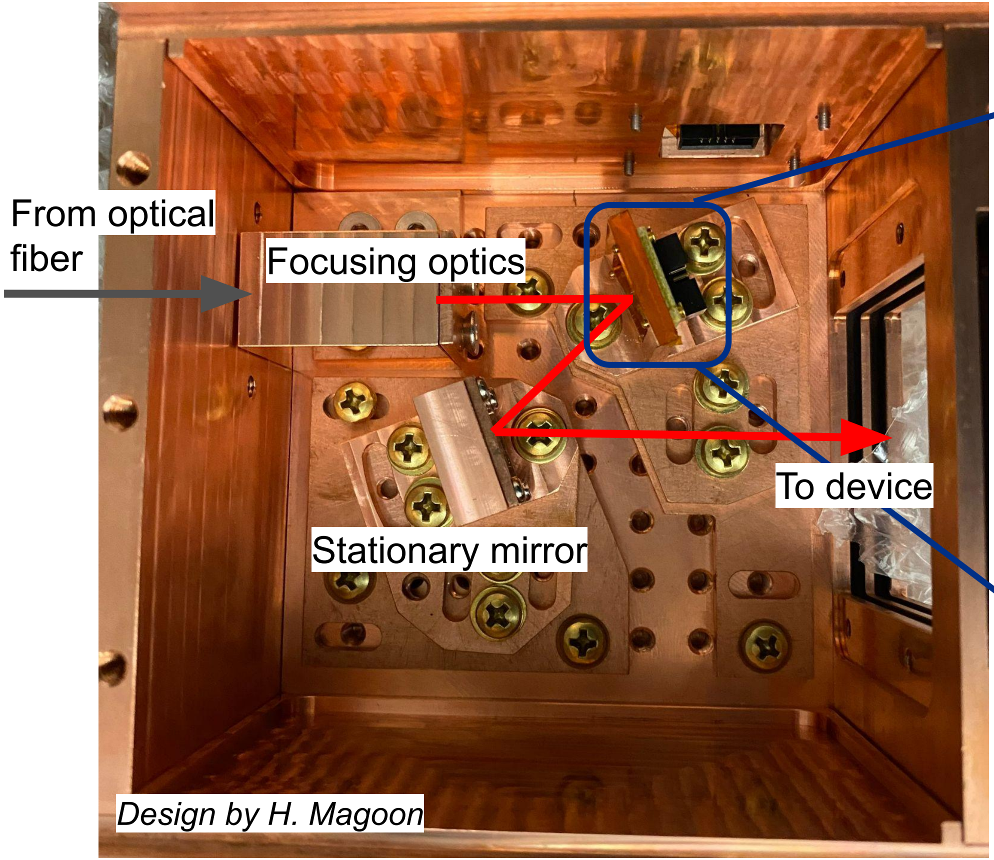
- Freeze out of movement mechanisms/control

Our solution: modified MEMS mirrors (right)

Good because:

- High broadband reflectance
- Relatively large deflection angles
- No power dissipation while stationary
- **Modification:** Al deposition over doped Si control lines for low-T operation

Scanning unit design using MEMS mirror:



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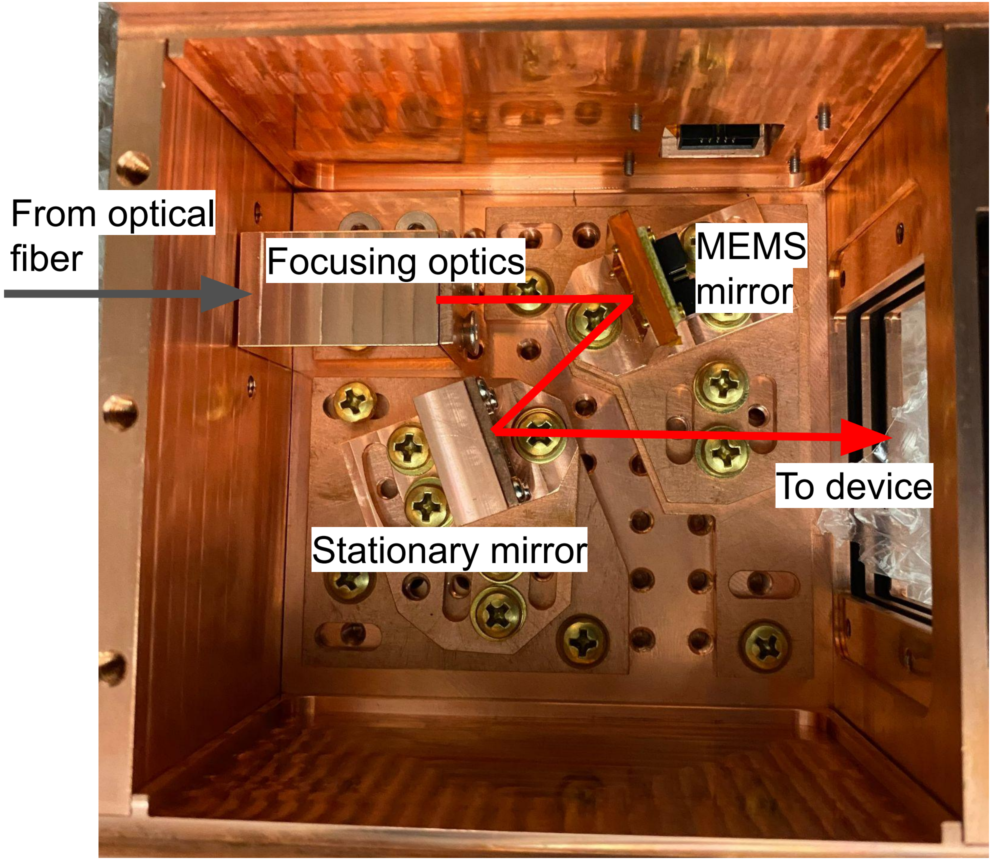
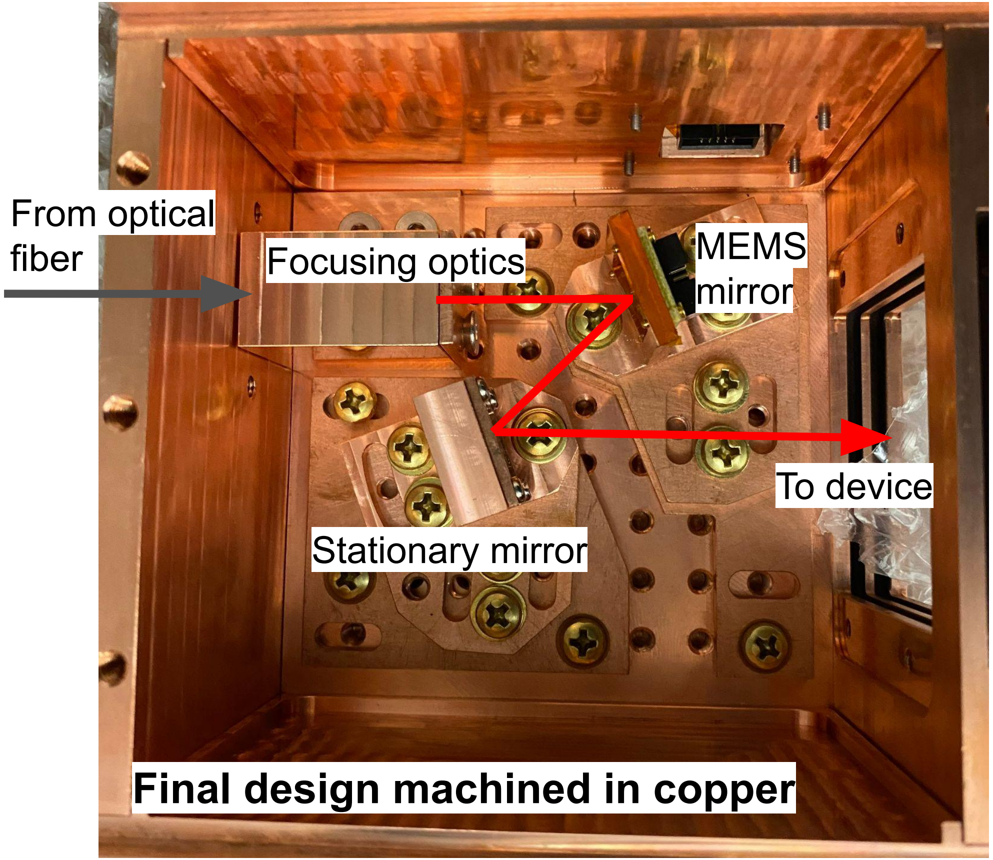
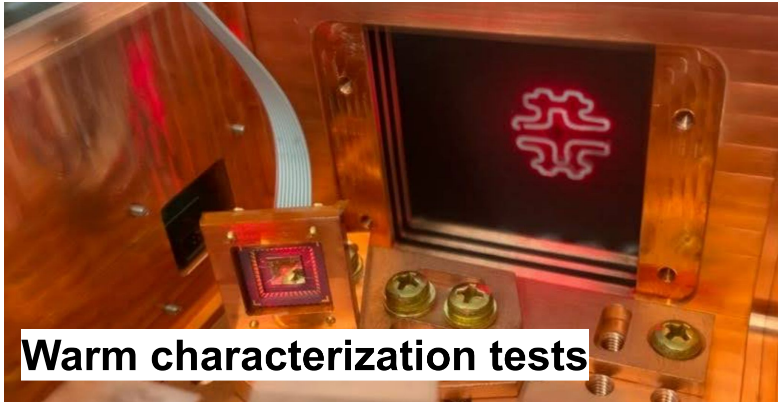
MEMS mirror allows for desired operating specifications:

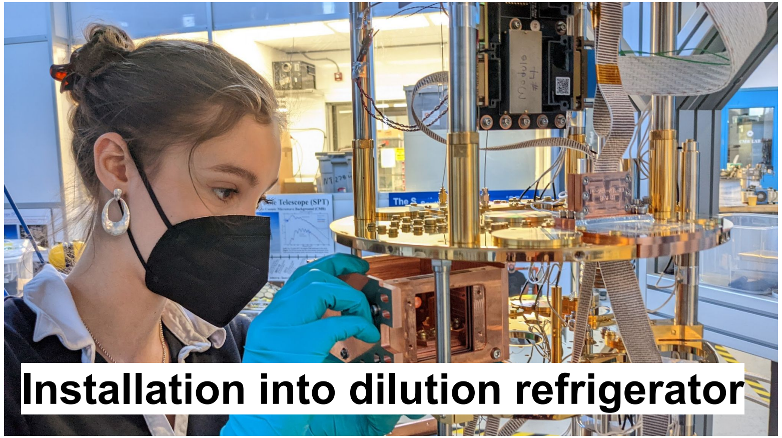


- ~3cm x 3cm scanning area
- <100µm spot size
- ~10µm position resolution
- O(100)Hz scanning speed
- O(µs) pulse width
- Temperature down to 10mK

Current status: scanning unit ready for first 100mK test





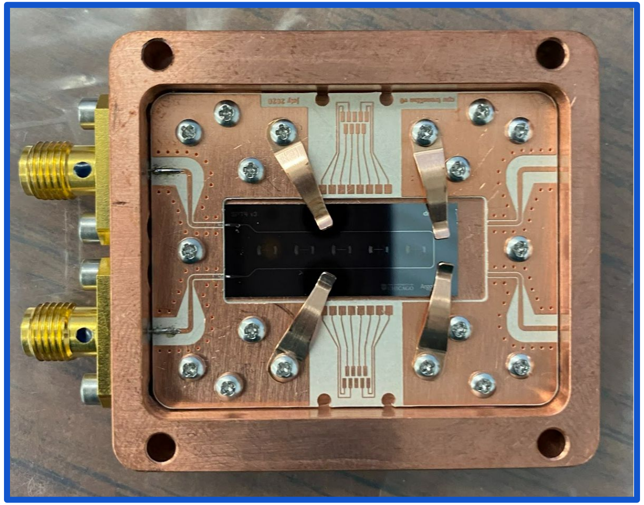


Early science program

Many impactful studies within reach:

- Functionality demonstration of modified MEMS mirrors at 100mK
- Measurement of phonon transport and collection to inform simulations of variety of quantum devices and detectors
- Study of quasiparticle poisoning in qubits in the **LOUD/QUIET facilities** at FNAL *(see D. Baxter's talk in next session)*
- Investigation of **MKID detector** position sensitivity *(see K. Ramanathan's talk in next session)*

Upper: LOUD dilution refrigerator installed @FNAL this week



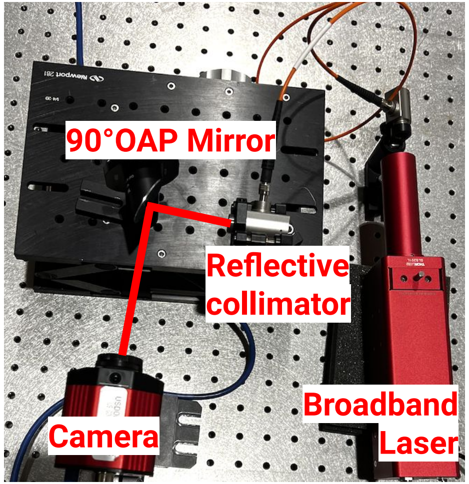
Lower: MKID detector (from A. Anderson) to be used for initial tests

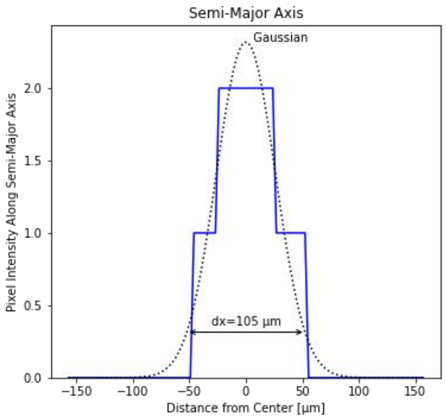
Chopping unit in development @ SLAC:

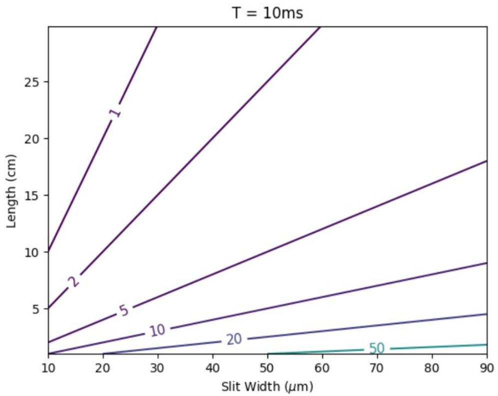
Two current paths of investigation:

1. Reflective focusing system to expand energy range of device while maintaining small spot size
   a. Will allow 62meV - 5eV with predicted spot size of 60µm

2. Optimization of chopping setup + measurement of pulse widths





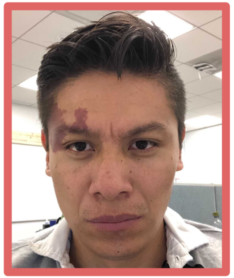


Upper left: Reflective collimation setup with an off-axis parabolic mirror and fiber-coupled reflective collimator
Upper right: Beam spot of 100µm demonstrated, limited by resolution of camera
Lower left: Calculations show pulse widths of O(µs) are possible with realistic slit sizes and focal lengths

Work by A. Nunez and H. Magoon

Thanks to:




Calibration device team:
Kelly Stifter (Lederman Fellow)
Hannah Magoon (Tufts undergrad)
Anthony Nunez (Stanford undergrad)
Israel Hernandez (IIT grad)
Noah Kurinsky (SLAC Scientist)

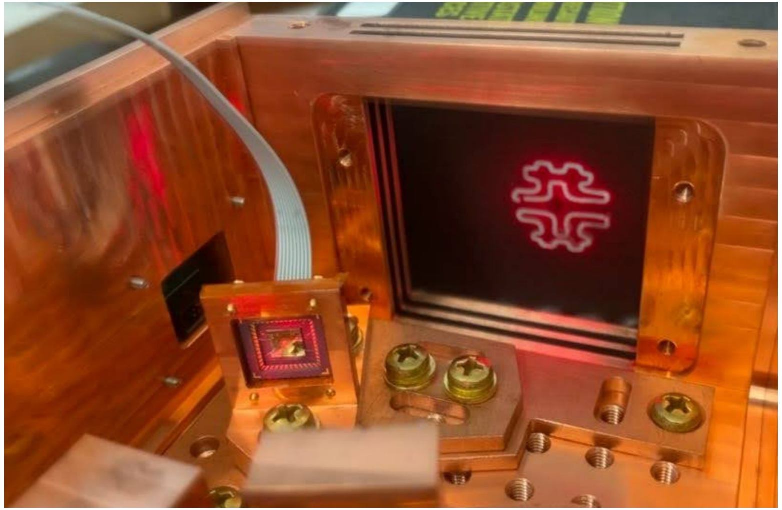


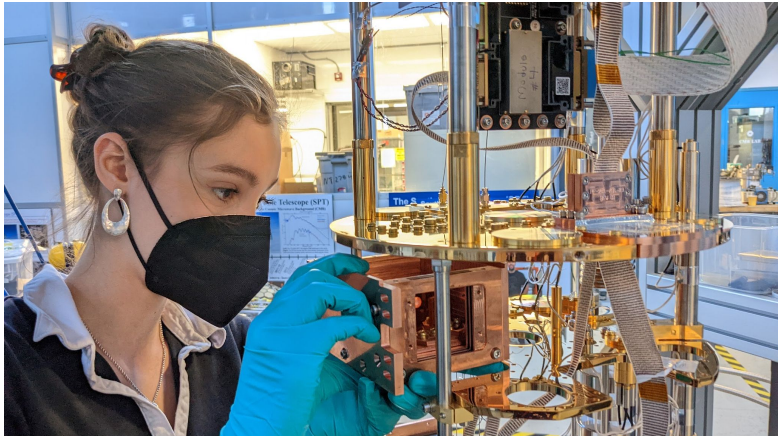


Fermilab QSC group:
Dan Baxter (Scientist)
Daniel Bowring (Scientist)
Lauren Hsu (Scientist)
Rakshya Khatiwada (Scientist)
Dylan Temples (Lederman Fellow)

Summary

- Novel low-threshold detectors will require very low energy calibrations
- MEMS mirror-based design can provide pulsed, steerable beam with easily configurable bandwidth, 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**

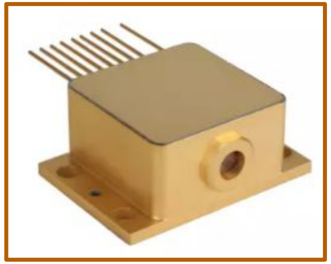




Backup

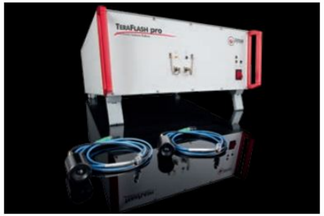
Some available low-energy sources

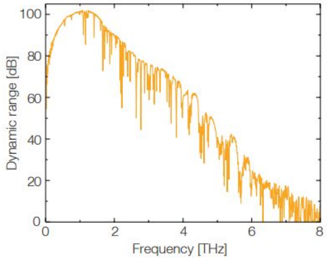
Laser diodes (right): Readily available out to ~2μm (0.62eV)

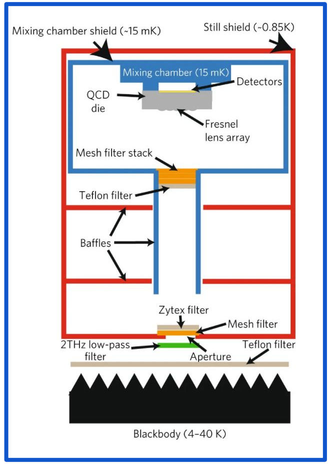


Quantum cascade lasers (left): Out to ~16μm (0.08 eV)

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)

Single 1.5THz photon detection w/ QCD

MEMS mirrors

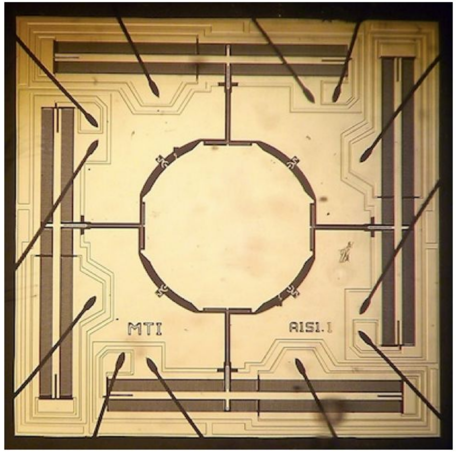
Micro-electro-mechanical systems (MEMS) mirrors, aka micromirrors or microscanners

Very low power consumption during actuation and at static position

Aluminum reflecting surface → high broadband reflectance

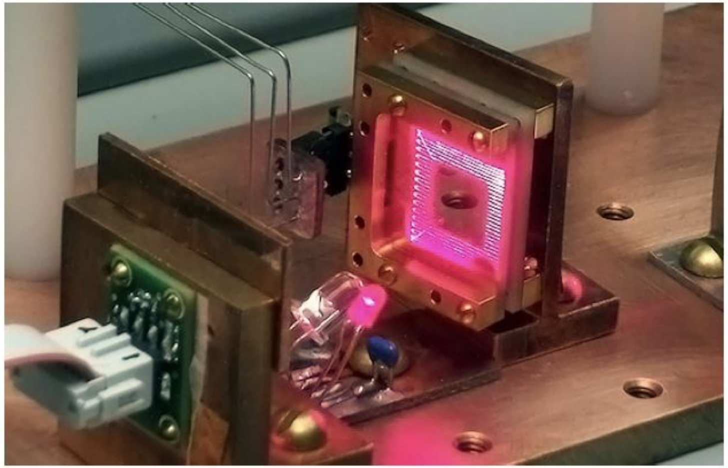
High scan speed with good tilt range, position resolution, repeatability

- 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



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Previous work

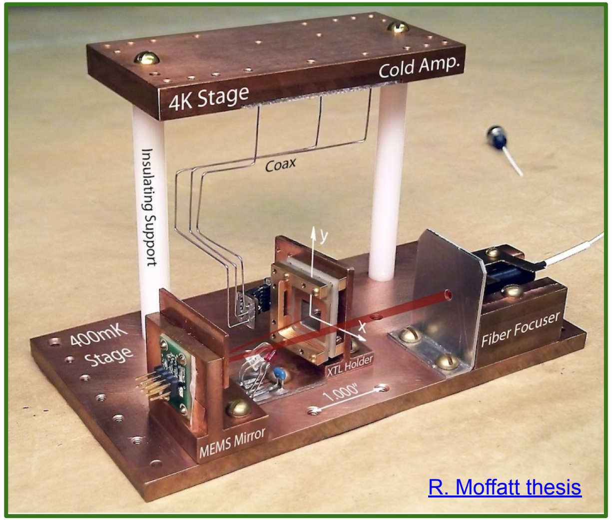
Cryogenic scanner previously built & operated at Stanford (400mK)

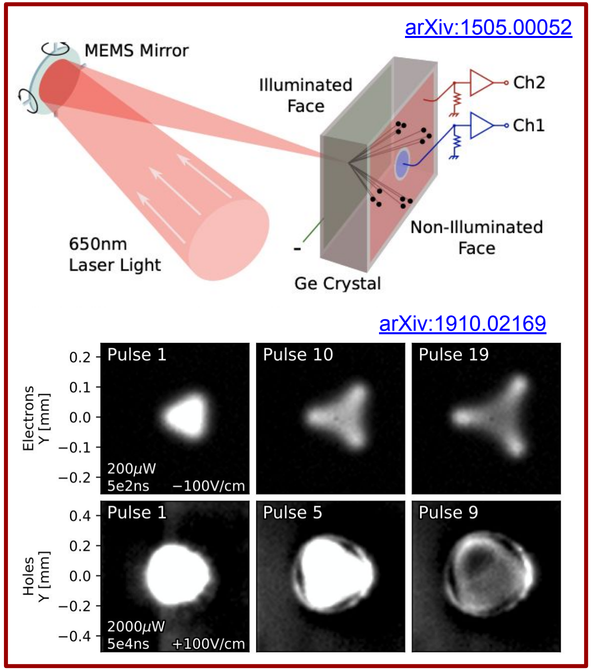
- Used to map charge collection vs. position in Si & Ge

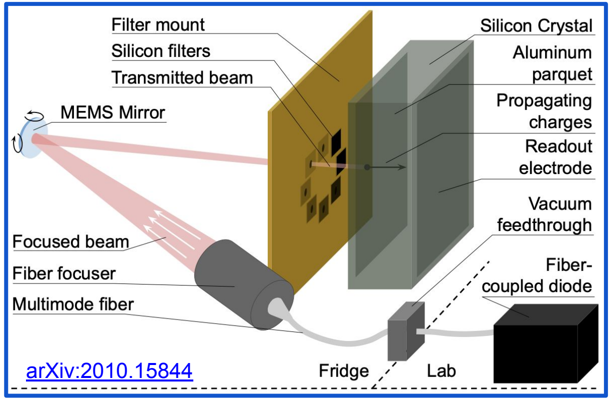
Also used to measure transmission through Si thin films → photoelectric effect

- 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

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 (~μm resolution)

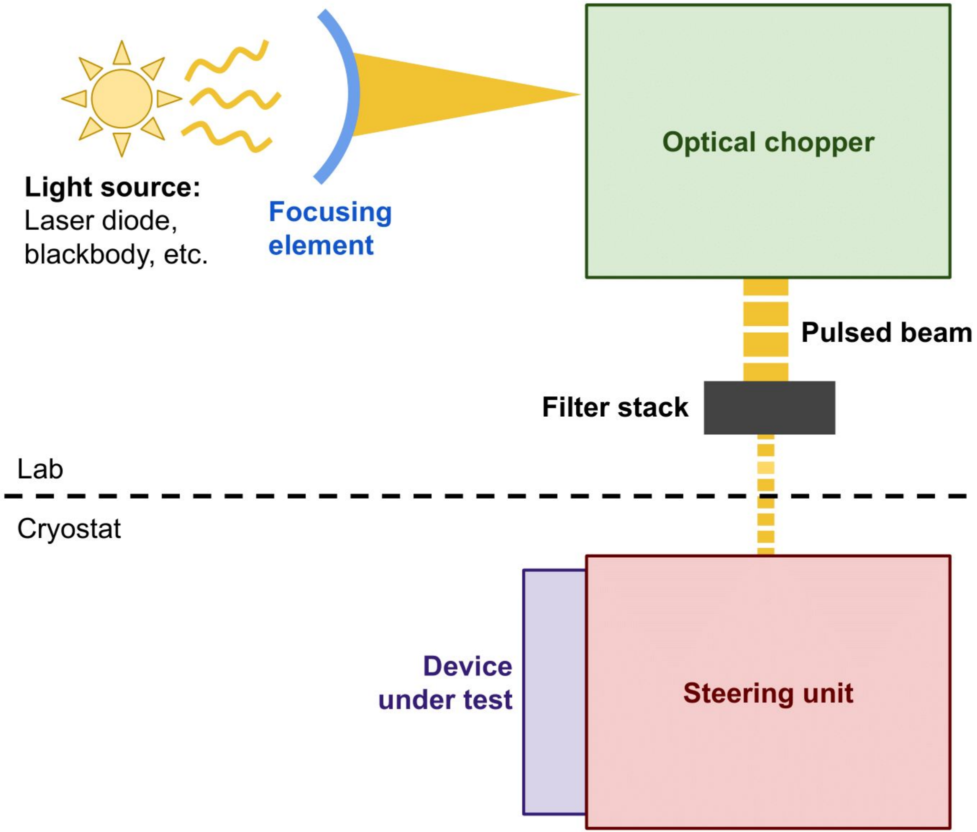
Cryo-friendly: functional at low temps (~10mK), low power dissipation

In-situ: no parasitic backgrounds

Device-independent: flexible, modular

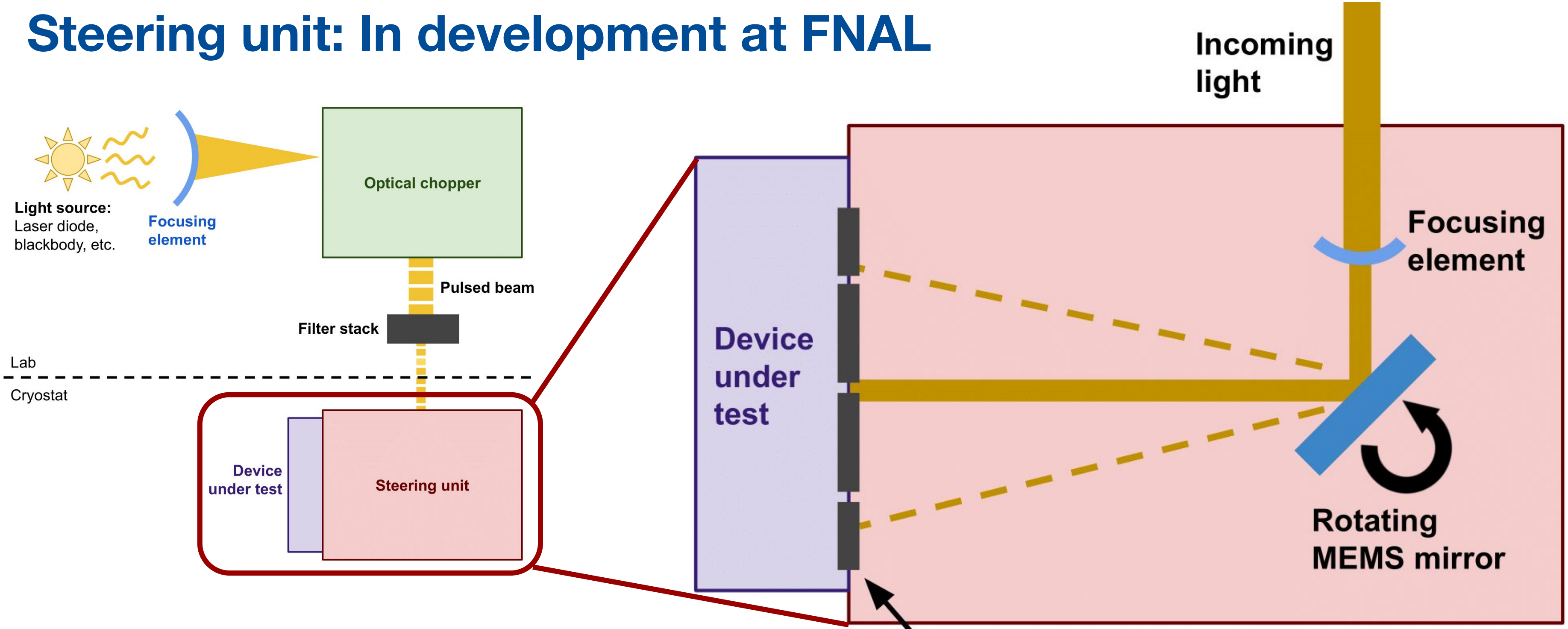
Inexpensive

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**

Steering unit: In development at FNAL

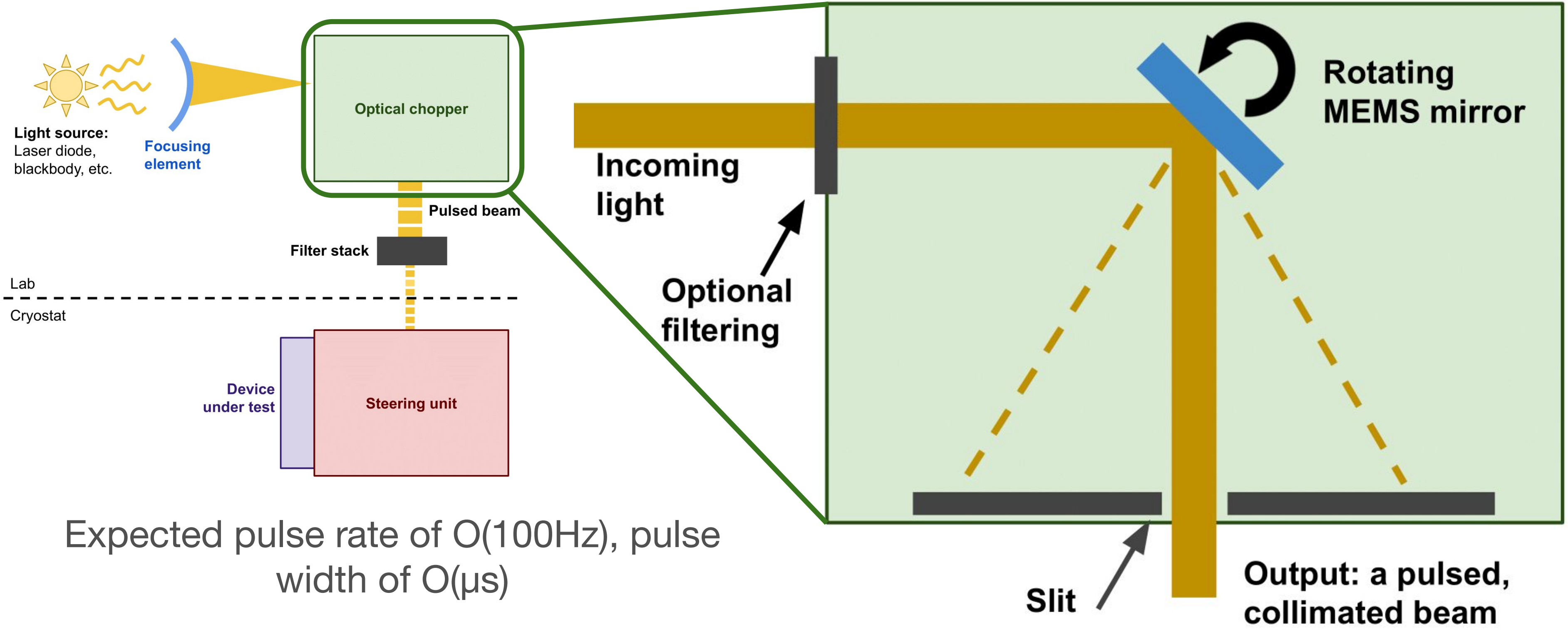


Scanning area of ~1”x1”, resolution of ~10μm → can be adjusted based on distance from mirror

Enclosure should limit photon leakage in *and* out

Interface from steering unit can either:
- Be open to allow access to all XY points
- Have holes to allow access to specific XY points

Optical chopper unit: In development at SLAC



Expected pulse rate of O(100Hz), pulse width of O(μs)

Tunable through size of slit and scan speed of MEMS mirror

Design challenges

MEMS functionality at low temps (10mK)

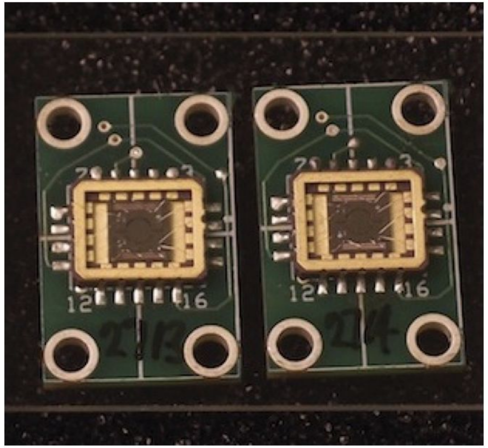
- Original design used doped silicon control lines, freezes out at low temperatures
- Worked with Mirrorcle Inc. to deposit Al over control lines → allows for low temp use

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

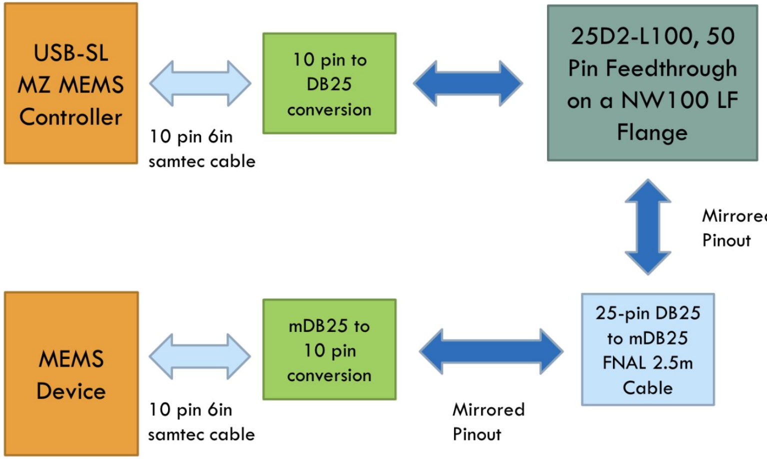
- Ensure housing of steering unit is photon-tight, while still keeping footprint small for operation in DR



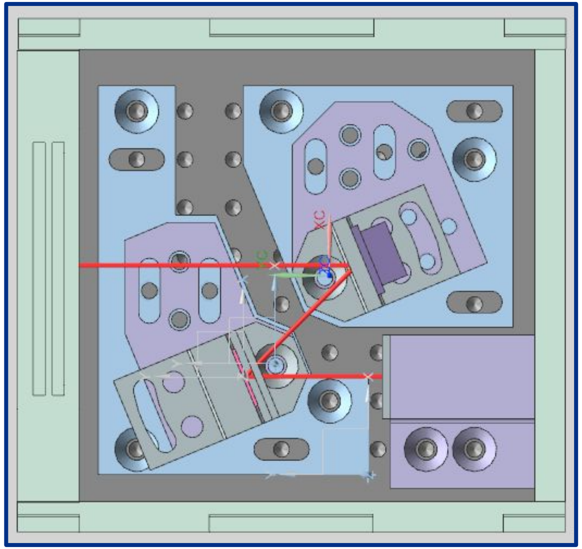
mirrorcle TECHNOLOGIES, INC.

Left: MEMS mirrors mounted on PCB

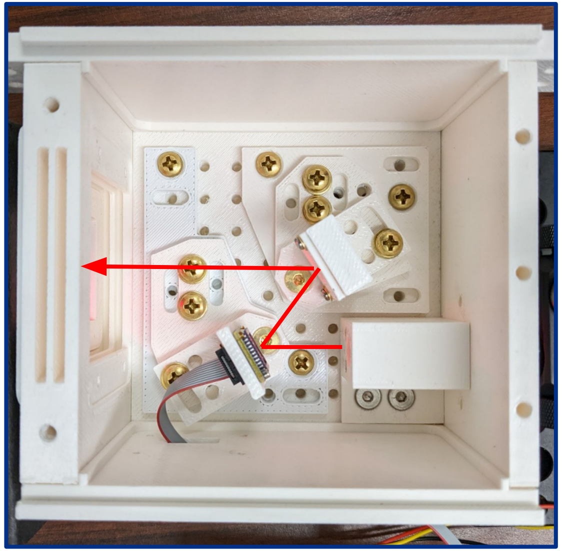
Below: cabling schematic for cryo-friendly MEMS setup



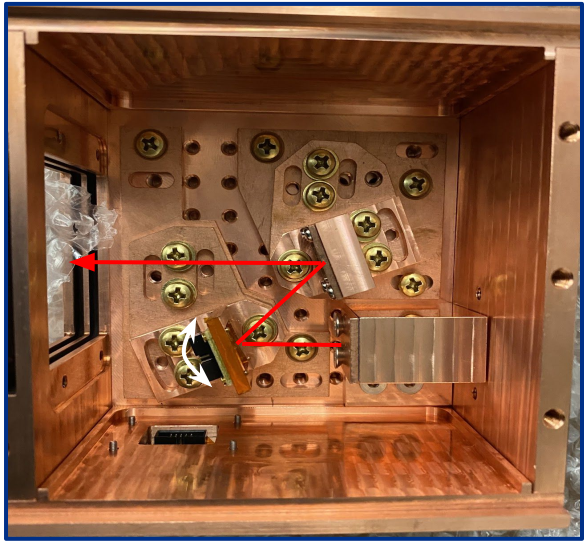
Calibration Device Design Progression



CAD model of enclosure



3D print prototype
(April 2022)



Copper enclosure
(June 2022)

Sample application: Phonon transport and simulation

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

arXiv:1505.00052

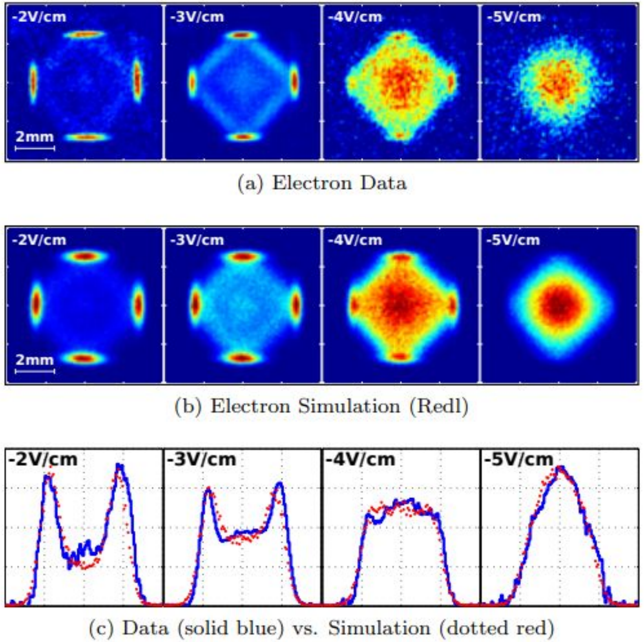


FIG. 3. **Electron Charge Density Patterns:** (a): Data. (b): Redl simulation. (c): One-dimensional projection of charge density onto a diagonal axis. The data (solid, blue) are compared to the Redl simulation employing the Herring-Vogt approximation (dotted, red). The horizontal scale ranges from -4mm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