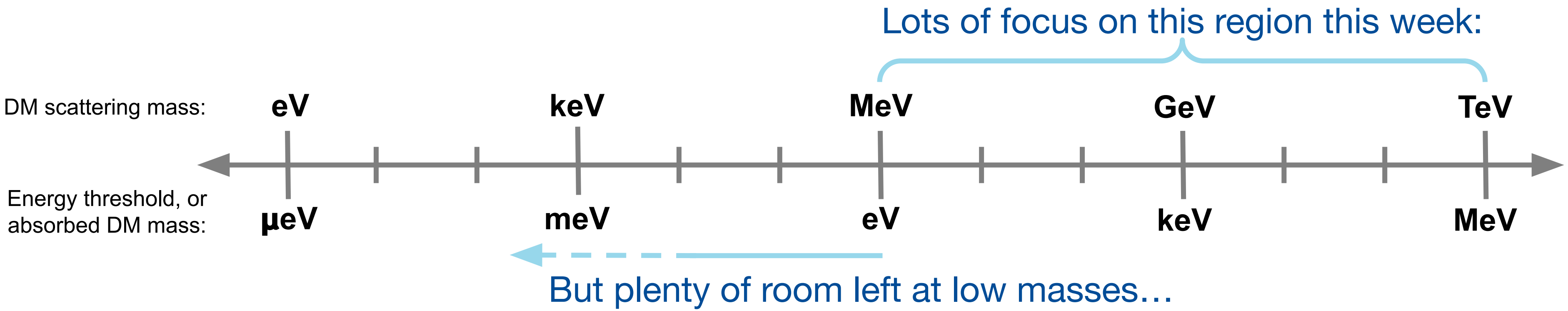
Pulsed laser device for low-energy calibrations

Kelly Stifter - Fermilab Cosmic Physics Center, Quantum Science Center
EXCESS2022 workshop
2/17/2022

The future of low-mass particle dark matter searches

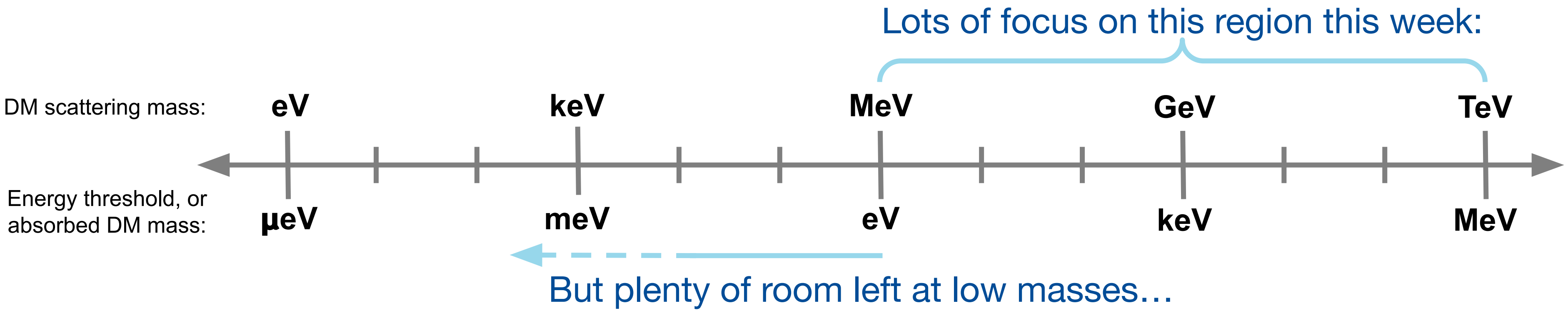
Wide range of particle DM models to explore:



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

The future of low-mass particle dark matter searches

Wide range of particle DM models to explore:



Lots of focus on this region this week:

DM scattering mass: eV keV MeV GeV TeV

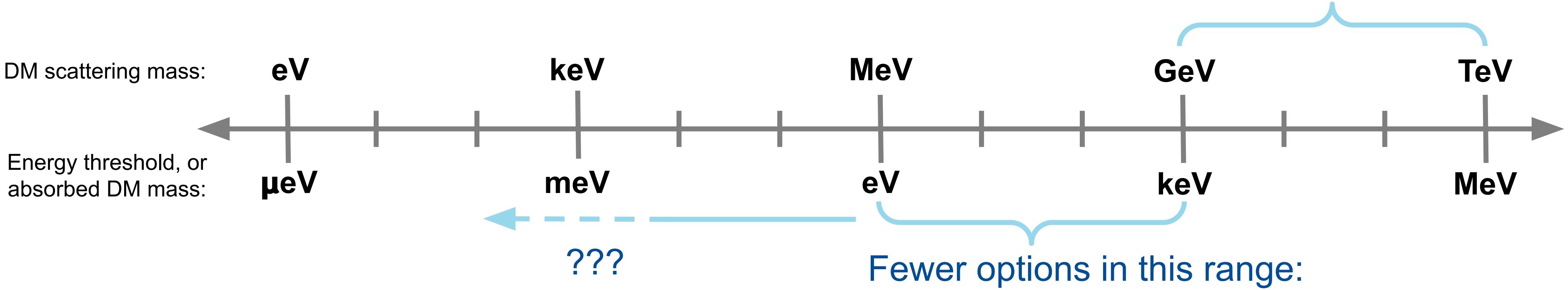
Energy threshold, or absorbed DM mass: μeV meV eV keV MeV

But plenty of room left at low masses…

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



Variety of mature calibration schemes in this range

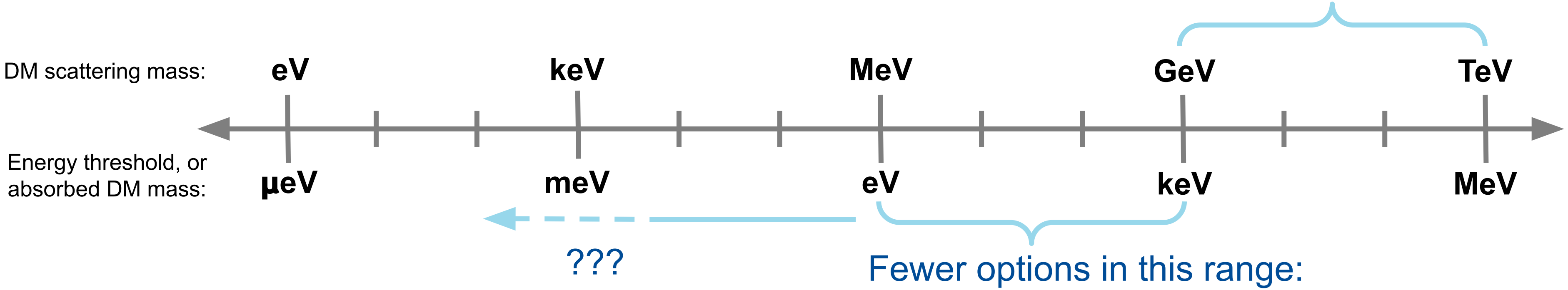
Fewer options in this range:

- Activation lines
- Compton measurements (P. Privitera, yesterday)
- Novel neutron sources (S. Hertel, today)
- Photon pulses

How do you calibrate devices below an eV?

Calibrating low-threshold detectors

Variety of mature calibration schemes in this range



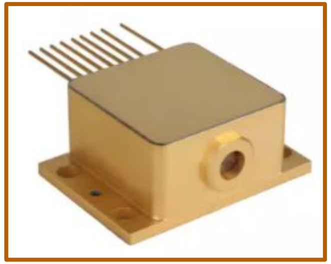
Fewer options in this range:

- Activation lines
- Compton measurements (P. Privitera, yesterday)
- Novel neutron sources (S. Hertel, today)
- **Photon pulses**

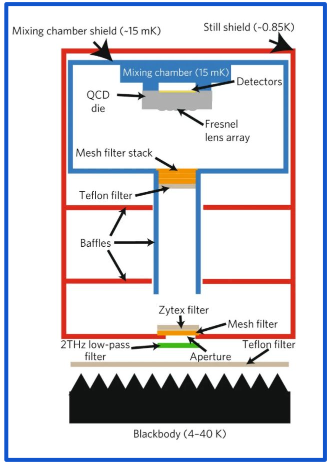
How do you calibrate devices below an eV?

Some available low-energy sources

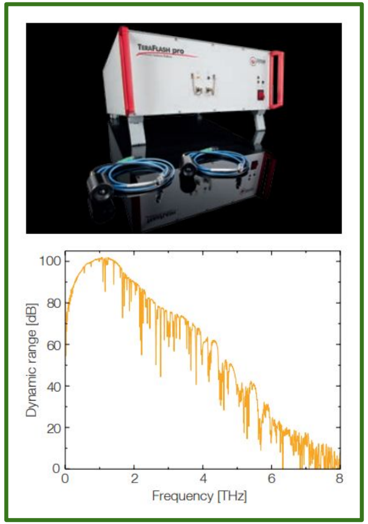
Laser diodes (right): Readily available out to ~2µm (0.62eV)



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]

Possible applications of low-energy laser calibrations

Laser pulses probe electromagnetic interactions → signals are e^-/h pairs, phonons

Can be used to calibrate DM detectors of many types:

- TESs
- CCDs
- KIDs
- Qubits
- QCDs
- Etc…

Many interesting science targets within reach:

- Position sensitivity/energy threshold of novel detectors
- Phonon transport studies and simulations
- Quasiparticle poisoning in superconductors
- IR loading on TESs
- Your favorite application?

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

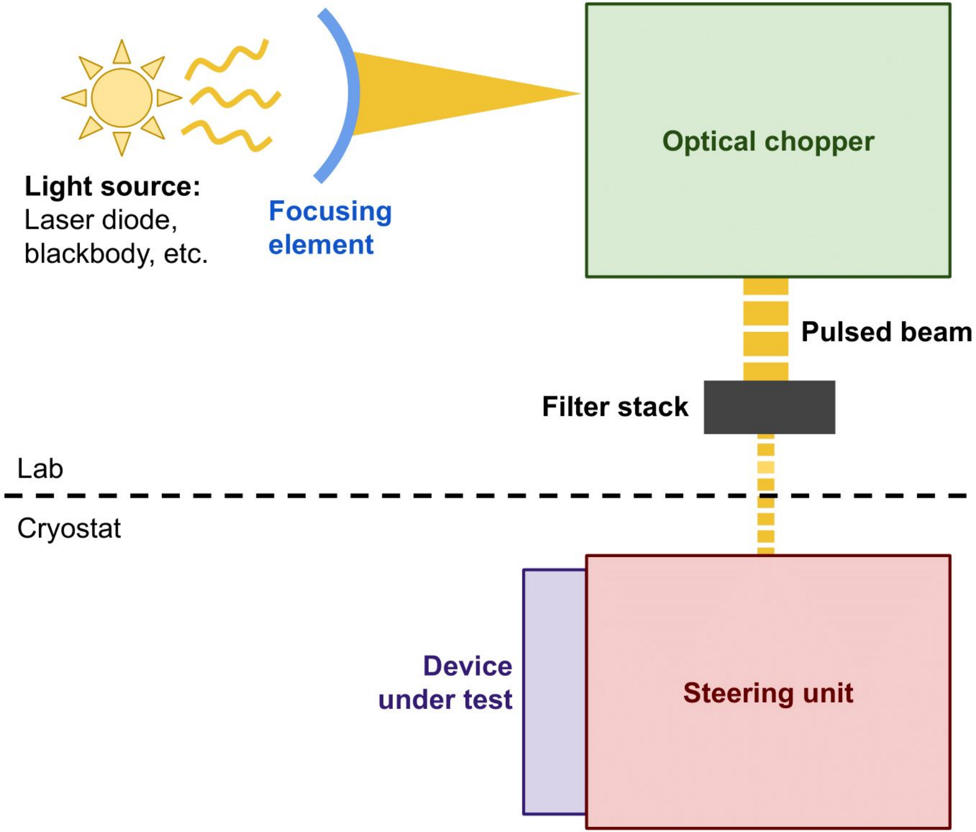
Device-independent: flexible, modular

Inexpensive

Low energy calibration device design

1. Start with light source of choice (in desired energy regime)
2. Focus and collimate the light into a beam
3. Chop the light to create a pulsed beam
4. Filter the beam to desired intensity and bandwidth
5. Inject beam into cryostat
6. Steer beam to desired XY location

End result: A pulsed, steerable beam with easily configurable bandwidth, intensity, and pulse characteristics



MEMS mirrors

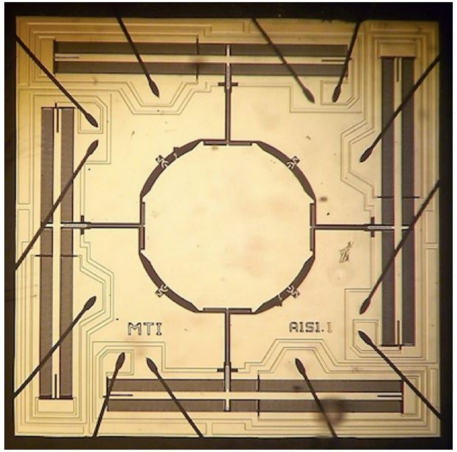
Micro-electro-mechanical systems (MEMS) mirrors, aka micromirrors or microscanners

Very low power consumption during actuation and at static position

Aluminum reflecting surface → high broadband reflectance

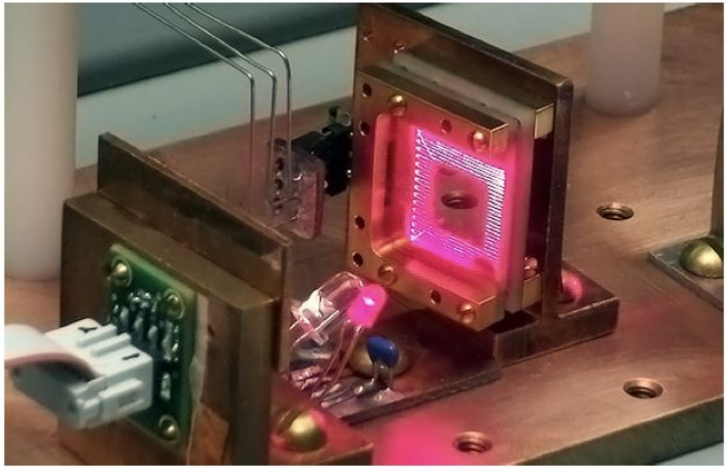
High scan speed with good tilt range, position resolution, repeatability

- O(1kHZ) 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

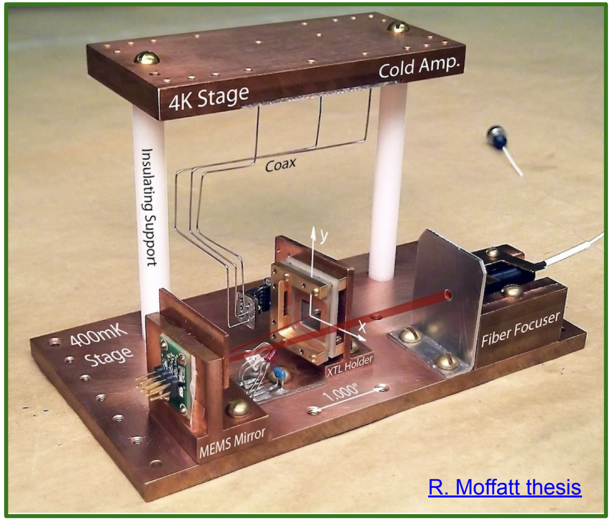
Cryogenic scanner previously built & operated at Stanford (400mK)

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

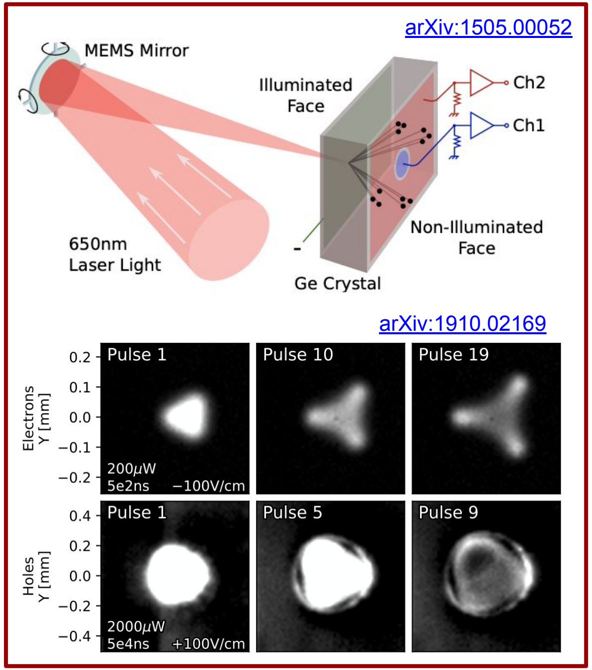
Also used to measure transmission through Si thin films → photoelectric effect

- Realized scanning across aperture acts like a shutter

Original setup open to 4K photon bath (right)

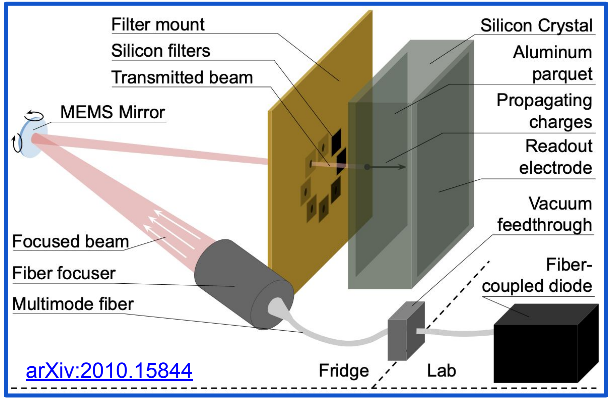


R. Moffatt thesis



arXiv:1505.00052

arXiv:1910.02169



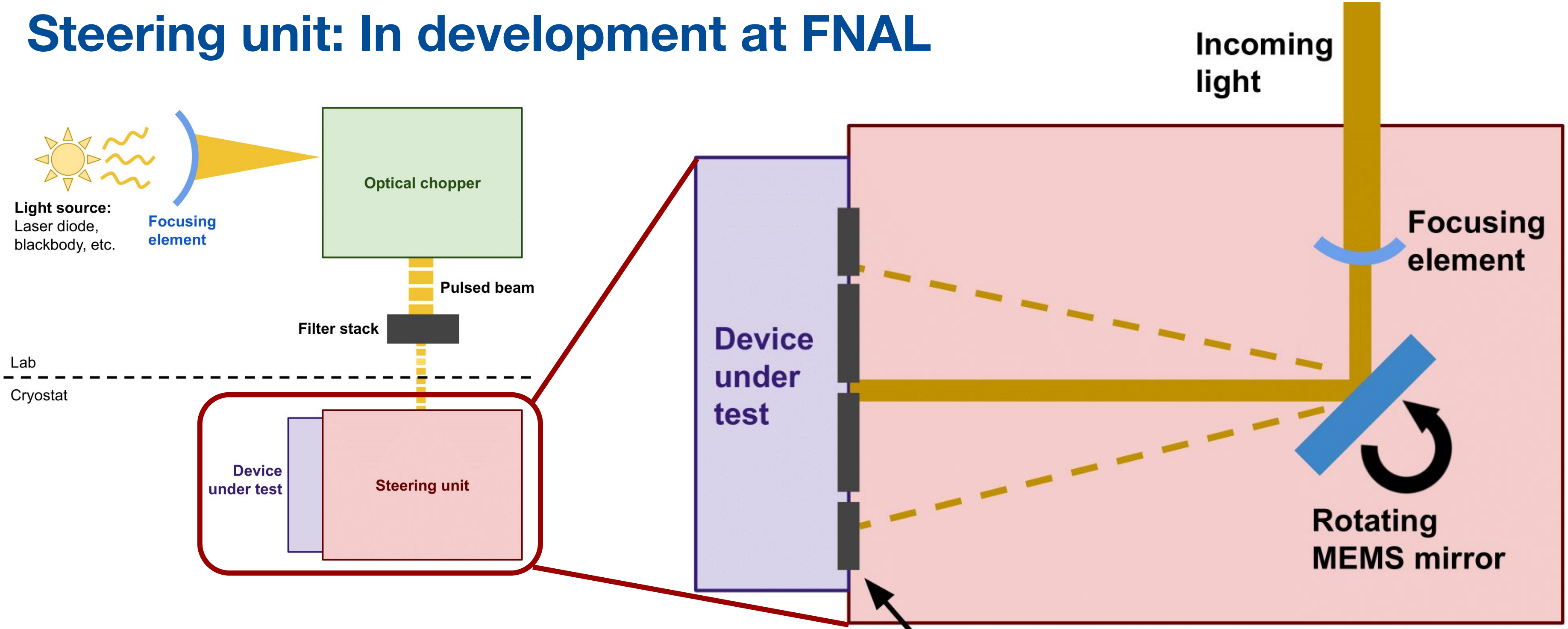
arXiv:2010.15844

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

Steering unit: In development at FNAL



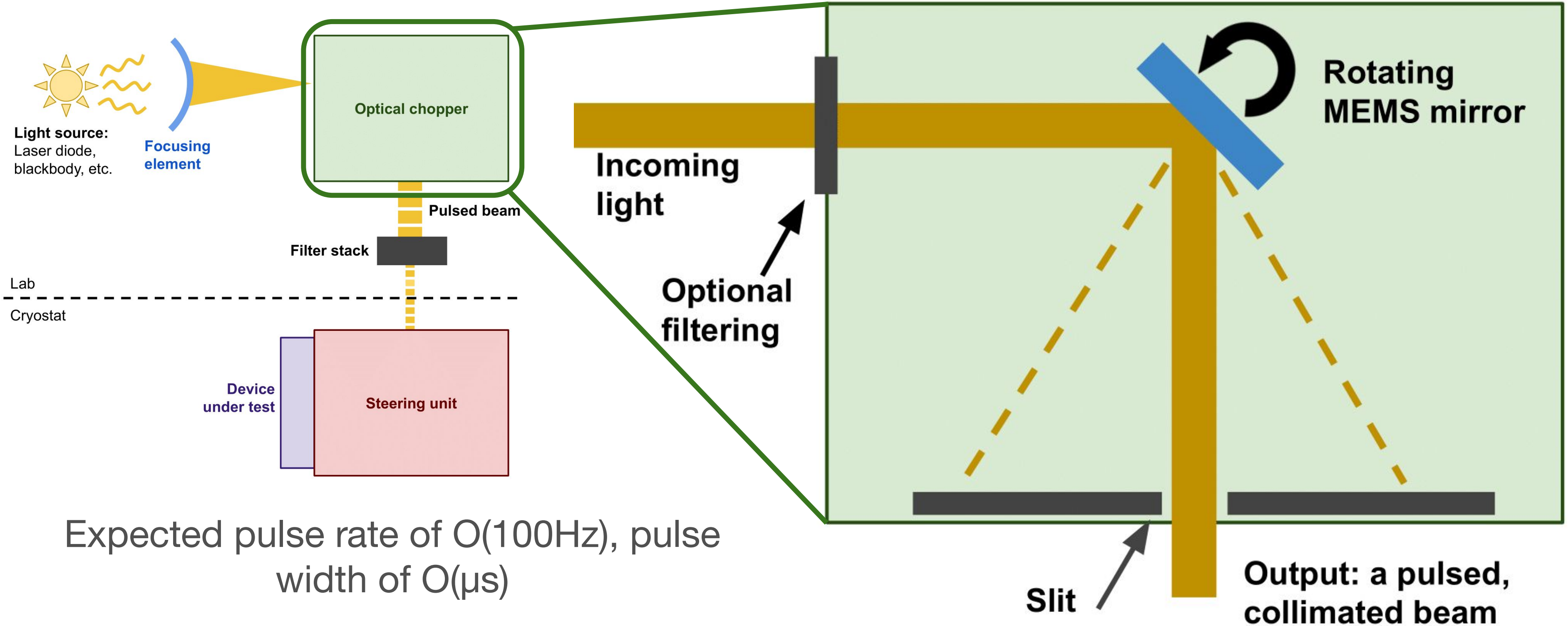
Interface from steering unit can either:

- Be open to allow access to all XY points
- Have holes to allow access to specific XY points

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

Enclosure should limit photon leakage in *and* out

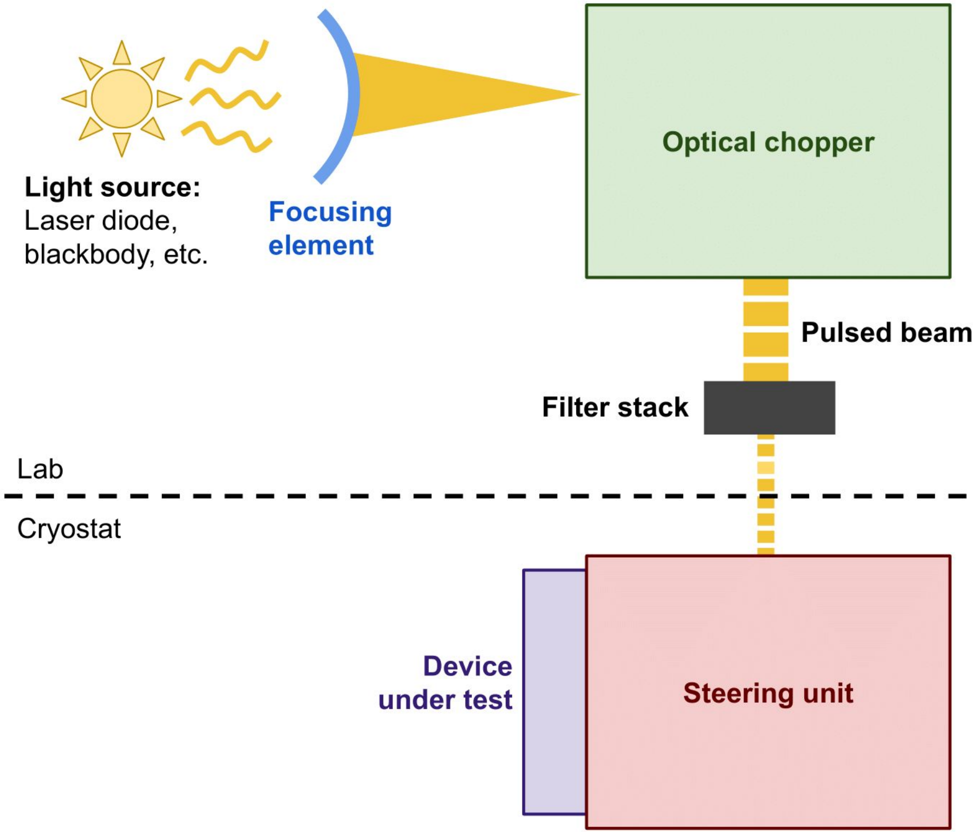
Optical chopper unit: In development at SLAC



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

Tunable through size of slit and scan speed of MEMS mirror

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**

Design challenges

MEMS functionality at low temps (10mK)

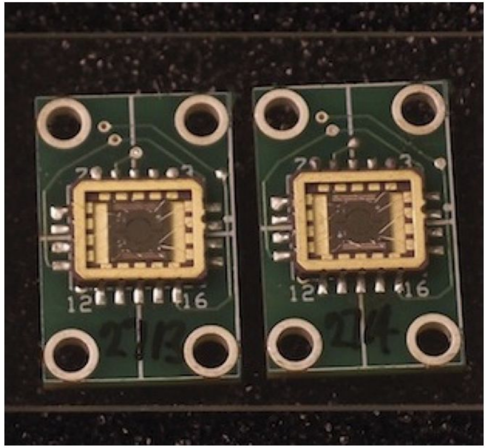
- Original design used doped silicon control lines, freezes out at low temperatures
- Worked with Mirrorcle Inc. to deposit Al over control lines → allows for low temp use

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

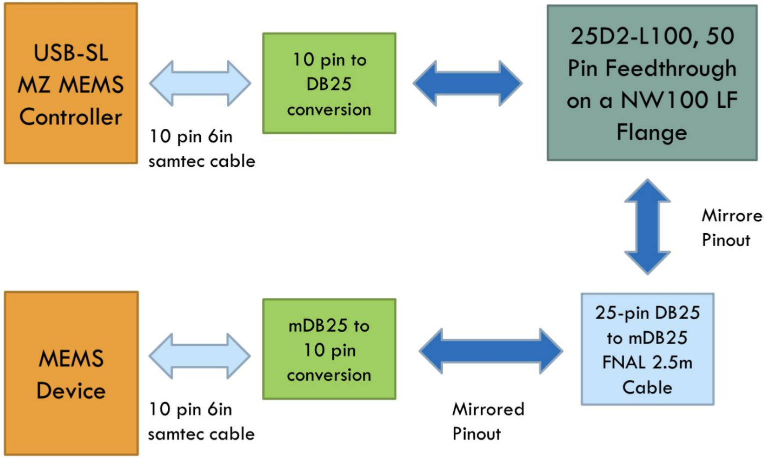
- Ensure housing of steering unit is photon-tight, while still keeping footprint small for operation in DR



mirrorcle TECHNOLOGIES, INC.

Left: MEMS mirrors mounted on PCB

Below: cabling schematic for cryo-friendly MEMS setup



Current status

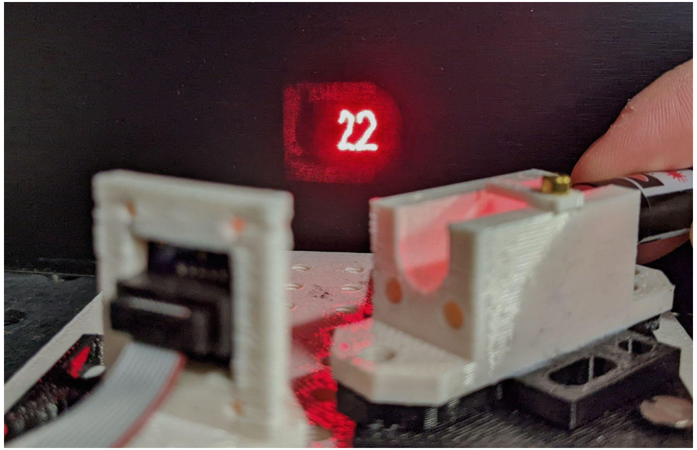
MEMS mirrors in hand & warm validation complete

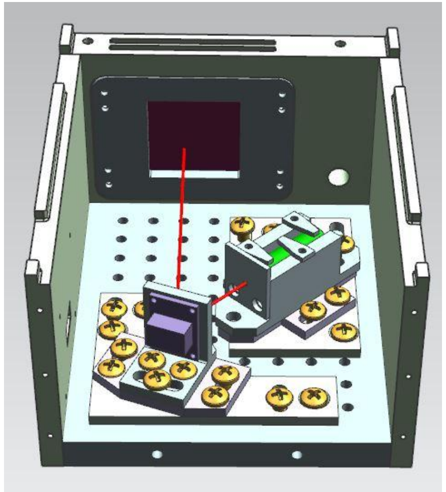
- Auxiliary measurements in progress: beam spot size vs. tilt angle, position resolution, spectral component analysis, etc.

Steering unit housing design near completion

- V1: Produced by Hannah Magoon (Tufts undergrad), based on early bench tests by Israel Hernandez (IIT graduate student)
- V2: 3D printed model pointed to several required changes, currently underway

Control hardware validation and device housing design underway in preparation for first functionality (cold) test with KID device





Above: Warm MEMS validation with 3D-printed version - MEMS is in foreground, reflecting a red laser

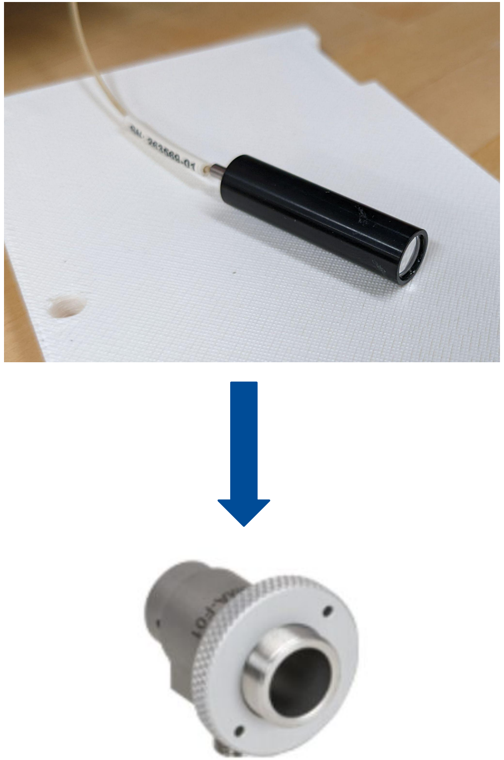
Left: CAD drawing of steering unit housing V1 (Hannah Magoon), same orientation as above

Future development

Several changes must be made to expand viable wavelength range:

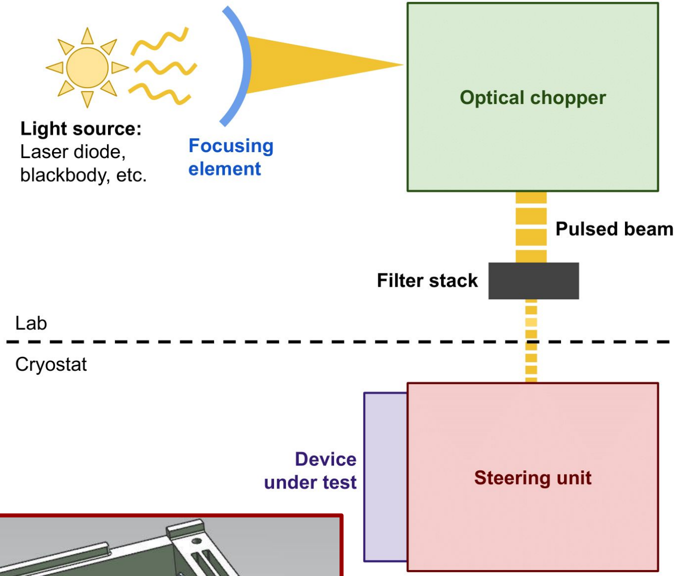
1. Move to reflective focusing technique
   a. Current focusing element (upper right) is refractive → internals must be swapped for each new wavelength
   b. No well-suited commercial options available, have design for home-brew solution

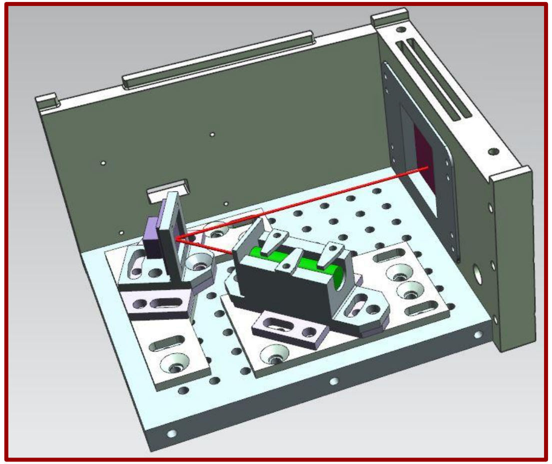
2. Move from fibers to THz waveguides
   a. Current multimode fibers will work out to ~20μm



Summary

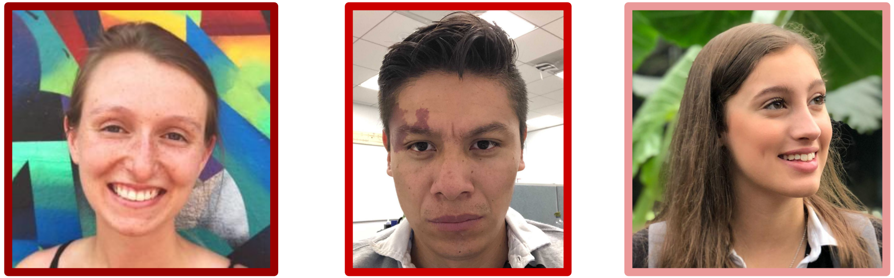
- Novel low-threshold detectors will require very low energy calibrations
- MEMS mirror-based design can provide pulsed, steerable beam with easily configurable bandwidth, intensity, and pulse characteristics in a cryo-friendly way
- Can be coupled to wide variety of low-threshold devices
- **Many impactful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





Thanks to:

Scanner team:
Kelly Stifter (Lederman Fellow)
Israel Hernandez (IIT grad)
Hannah Magoon (Tufts undergrad)



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

Chopper team:
Noah Kurinsky (SLAC Scientist)
Anthony Nunez (Stanford undergrad)

Backup

Sample application: Phonon transport and simulation

arXiv:1505.00052

Previous charge transport measurements were used to tune charge transport simulations

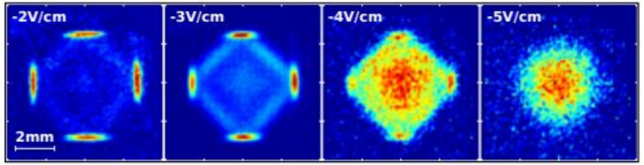
- Excellent agreement was shown (right)

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

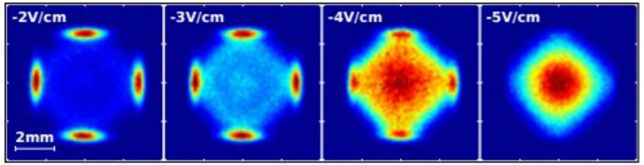
- Will feed into simulation of quantum sensors

Previous scanning setup (see slide 11) requires modifications for this task:

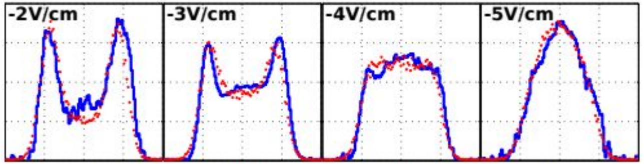
- Low temperature operation (10mK)
- Improved background mitigation
- Increased wavelength range



(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.