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Bringing Science Solutions to the World

U.S. DEPARTMENT OF ENERGY
Office of Science

TESSERACT: dark matter detection with transition edge sensors and multiple targets

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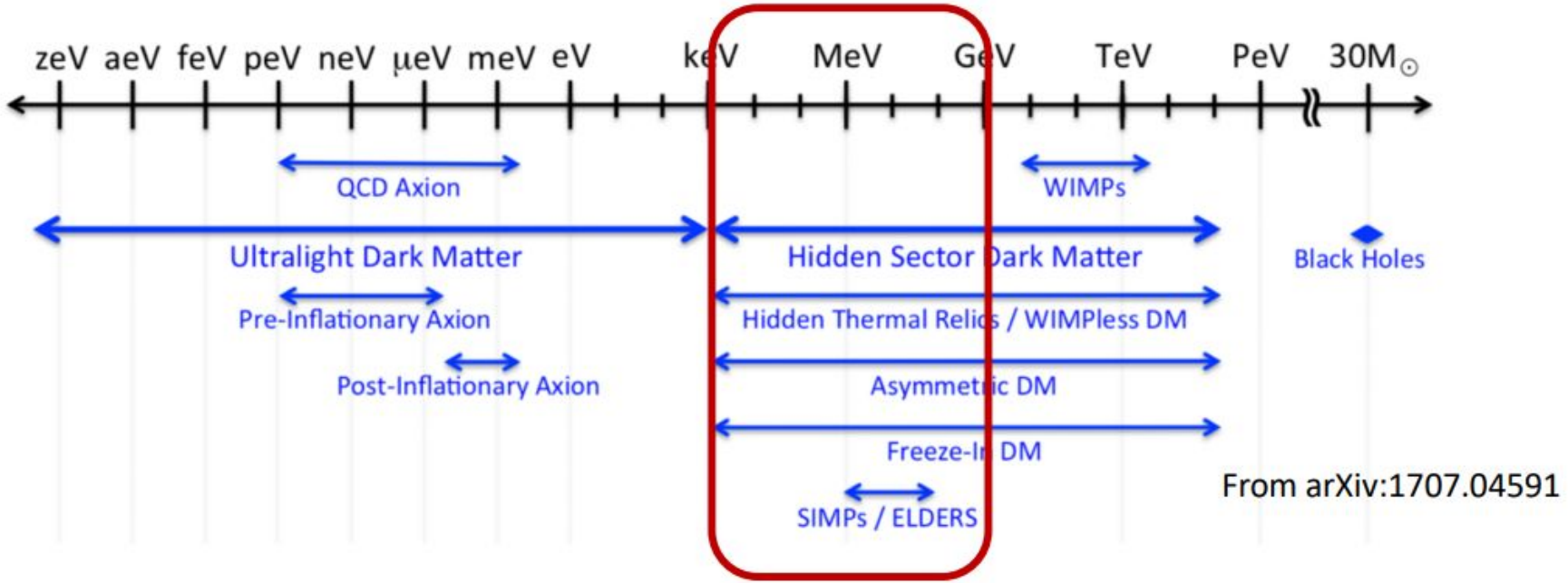
Physics department, Lawrence Berkeley Laboratory
The TESSERACT collaboration

08/22/2024

GUINEAPIG 2024, Toronto, Canada

TESSERACT

Direct detection for low-mass dark matter



Direct detection for low-mass dark matter

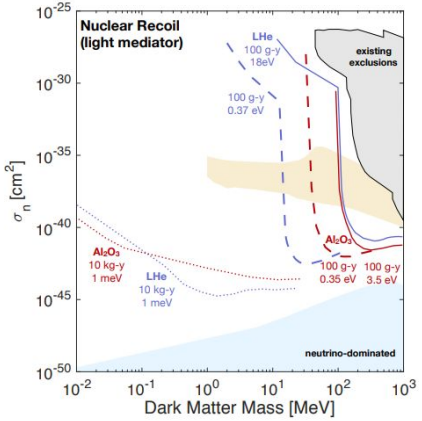
Low threshold

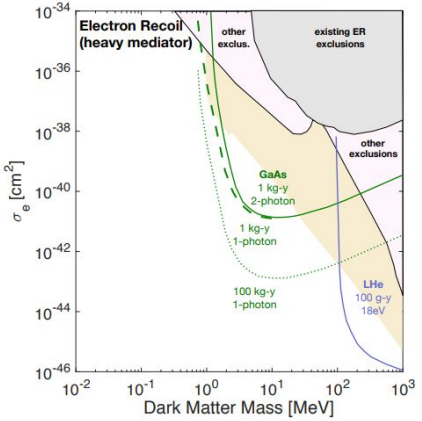
Target with light element

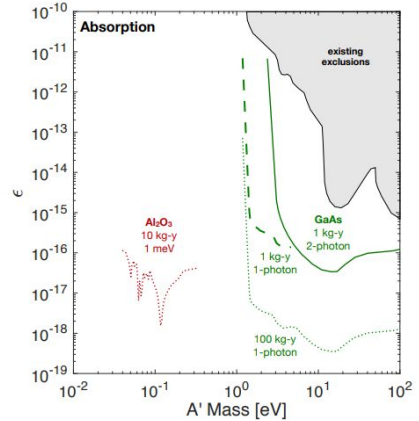
Polar crystal: optical phonons, dark photon coupling.

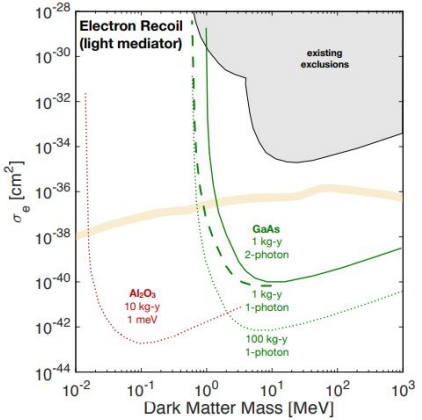
→ **Develop a low-threshold (sub-eV) sensor for multiple cryogenic targets: TES based athermal phonon sensors!**

Snowmass2021 - Letter of Interest
The TESSERACT Dark Matter Project

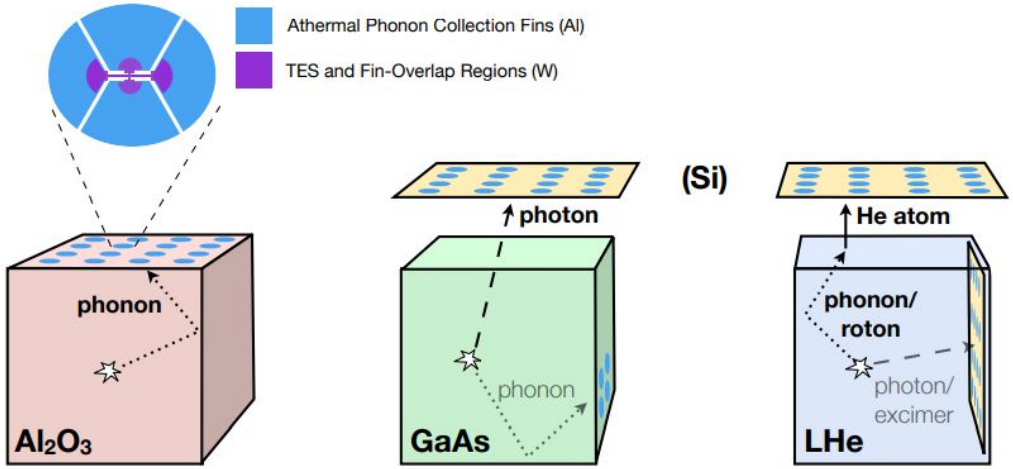








TESSERACT & Athermal phonon sensor



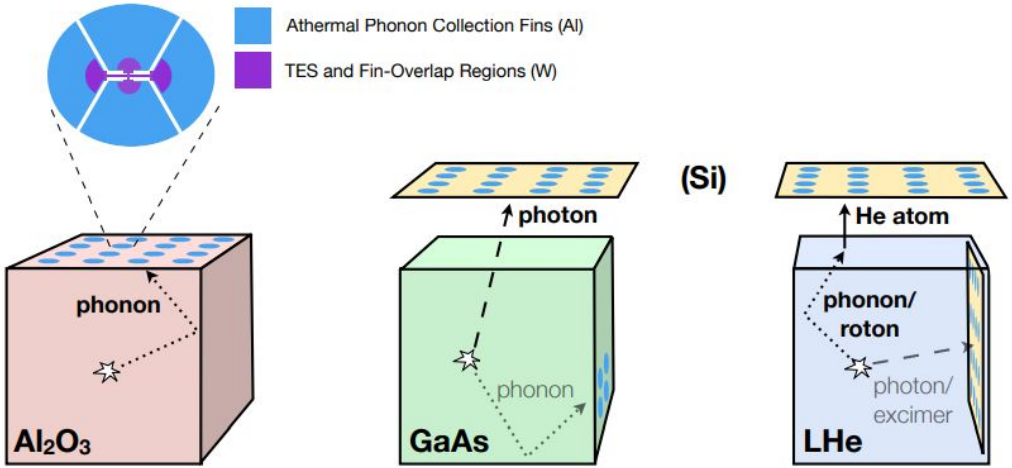
Polar crystals: **SPICE**

Superfluid helium: **HeRALD**

3 new French institutes: Lyon, Grenoble, Orsay

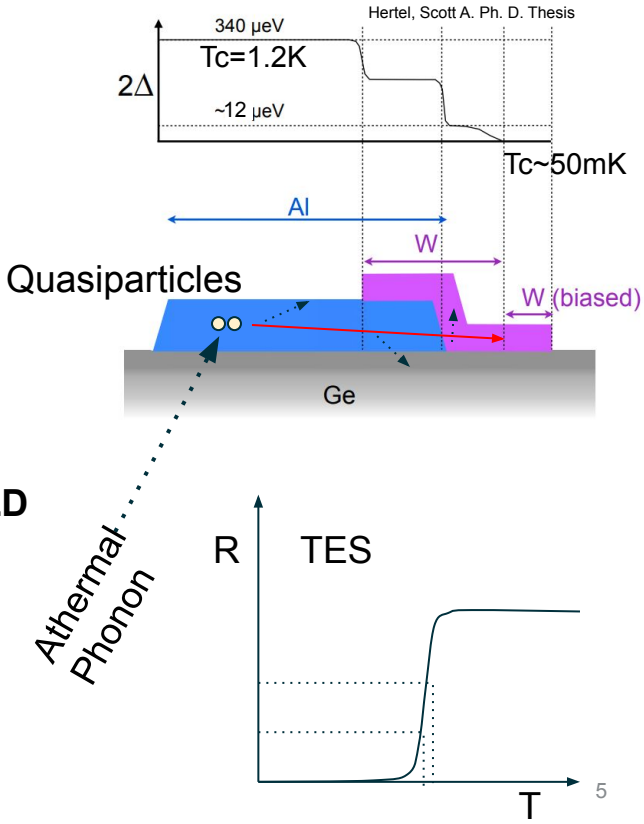
Project funding from DOE & IN2P3

TESSERACT & Athermal phonon sensor



Polar crystals: **SPICE**

Superfluid helium: **HeRALD**



- Fast (~100us) **athermal** phonon signals.
- Quasiparticle trapping

TESSERACT: SPICE

Use polar crystals as targets.

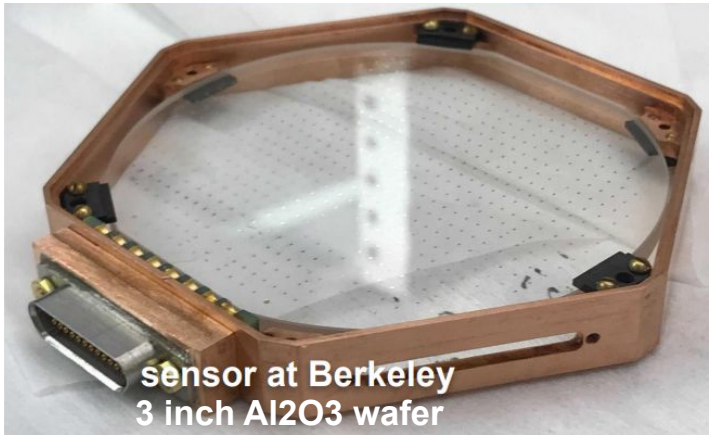
- Al_2O_3
- GaAs

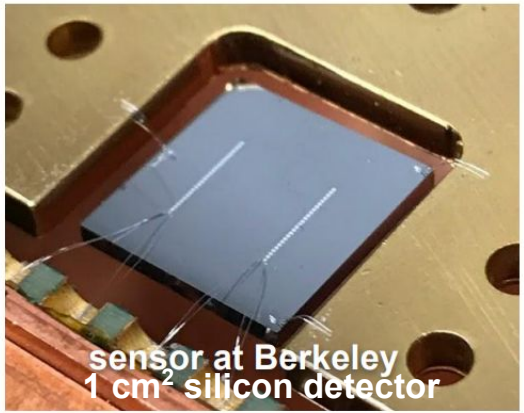
GaAs is also a great cryogenic scintillator, can use photons to do background discrimination.

Currently use silicon substrate for fast R&D (SuperCDMS Cryogenic Photon Detector, CPD):

- Tune TES film Tc to achieve sub-eV energy threshold. 55mK Tc → 20mK Tc
- Understand noise and background.

GaAs and Al_2O_3 R&D in parallel.





TESSERACT: HeRALD

Use superfluid helium as target.

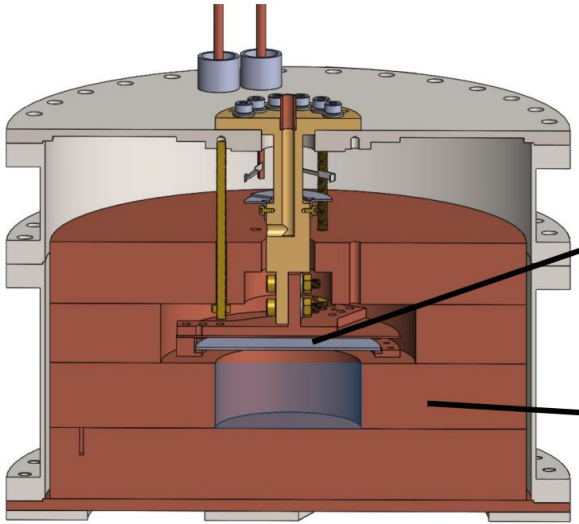
Use silicon CPD as sensor.

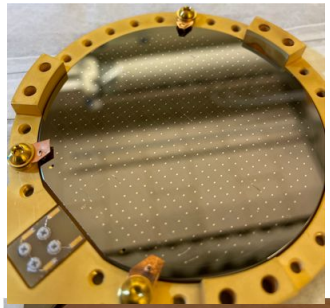
- 16eV scintillation photon
- Quantum evaporation from rotons and phonons

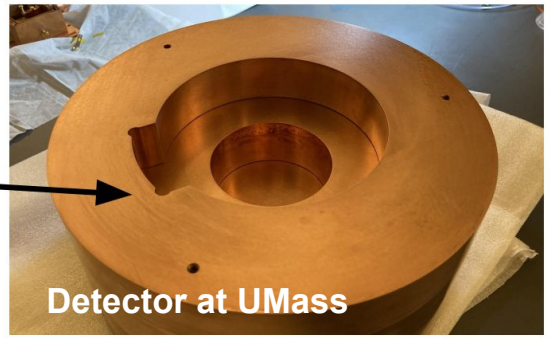
Currently focus on understanding the detector response

- Roton detection efficiency
- Quantum evaporation gain
- Superfluid helium response

arXiv:2307.11877







Recent progress

SPICE

SPICE: ~1eV threshold detector

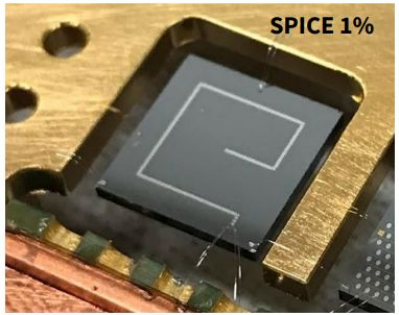
Reduce target mass. Optimize surface coverage.

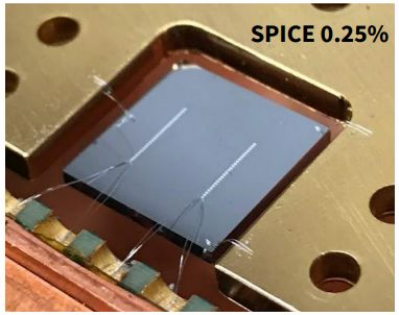
1cm^2 1mm thick silicon detectors.

Free-hanging from wire bonds to reduce stress.

Energy calibrated with optical photons!

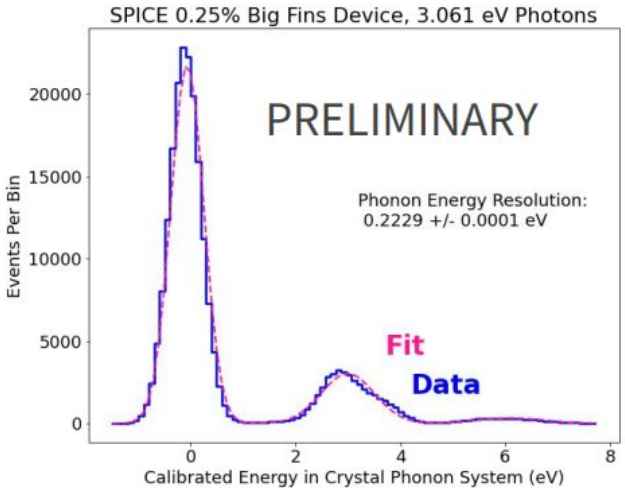
~300meV energy resolution achieved in multiple different designs.

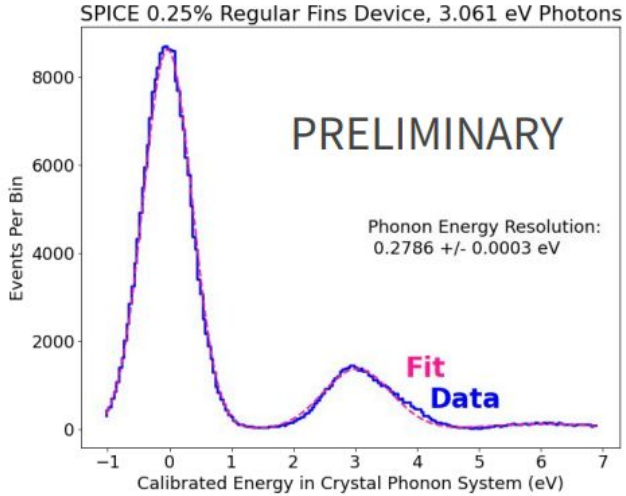


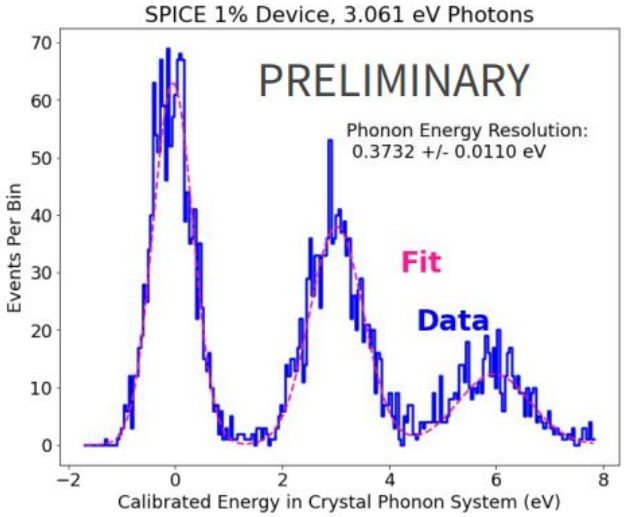


CPAD Talk 2023 (stanford.edu)

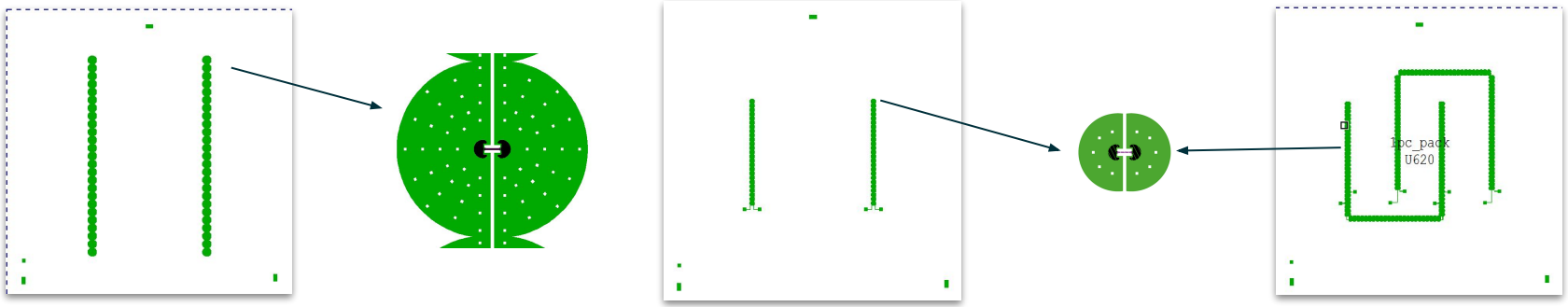
Baseline (sigma) phonon energy resolutions: 300 meV scale







R. K. Romani [IDM Talk 2024 (infn.it)]

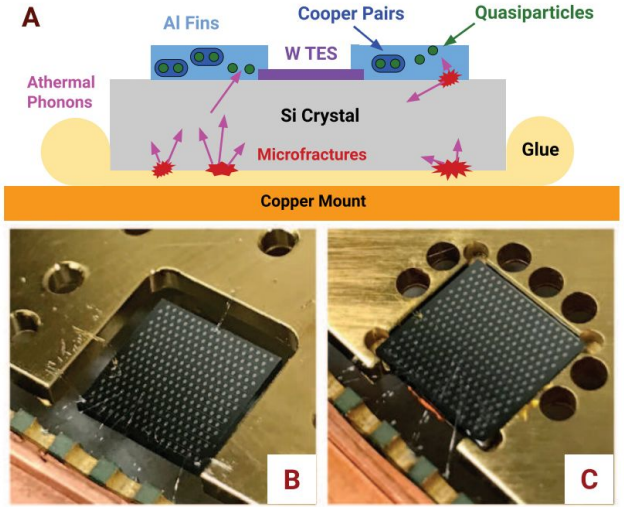


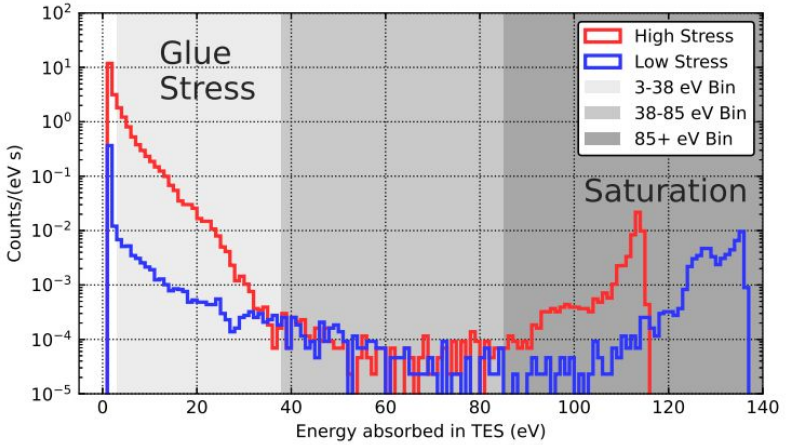
Low energy excess (LEE) events

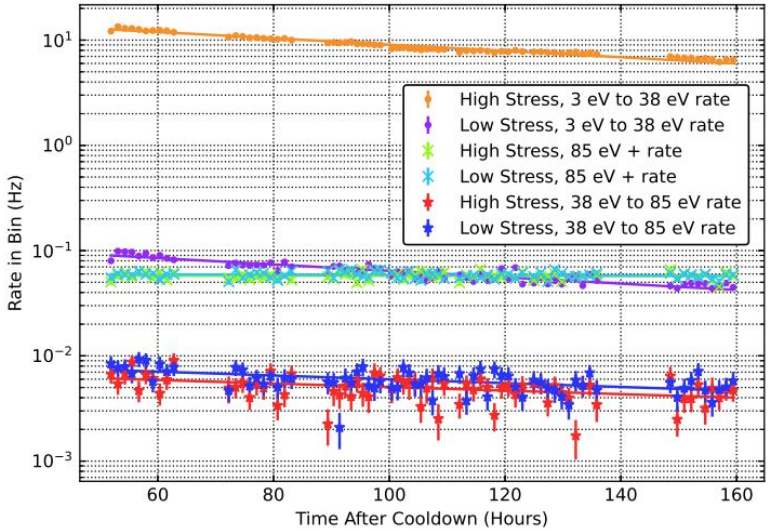
Stress related low energy events.

High stress mounting introduce higher rate.
Rate decays exponentially with cold time.
Events of same spectrum and decay observed in many experiments. Non-ionizing.

→ **Hanging device + low stress film.**







arxiv:2208.02790

Low energy excess (LEE) events

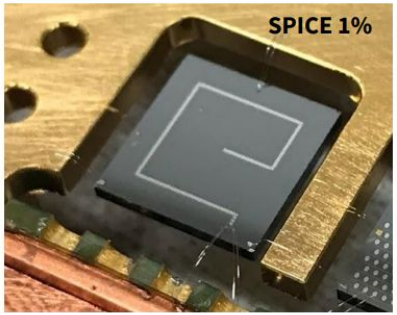
Stress related low energy events.

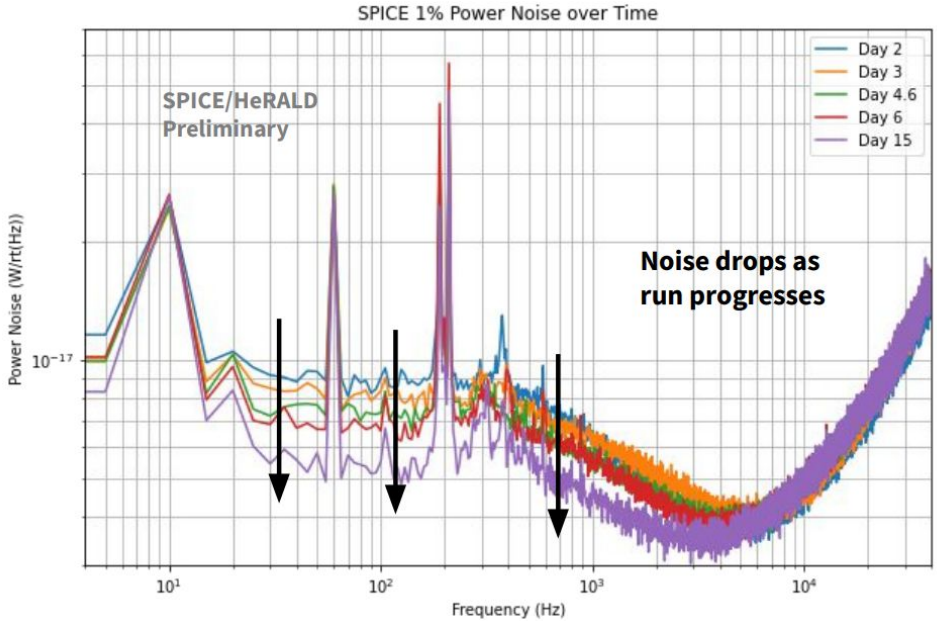
High stress mounting introduce higher rate.
Rate decays exponentially with cold time.
Events of same spectrum and decay observed in many experiments. Non-ionizing.

→ **Hanging device + low stress film.**

The low coverage device's energy resolution improves over time as the LEE rate decreases!

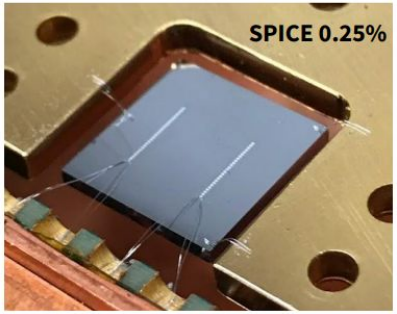
- **The LEE spectrum extends to below threshold.**
- **The LEE also prevent us reaching the theoretical energy resolution.**





CPAD Talk 2023 (stanford.edu)

Low energy excess (LEE) events

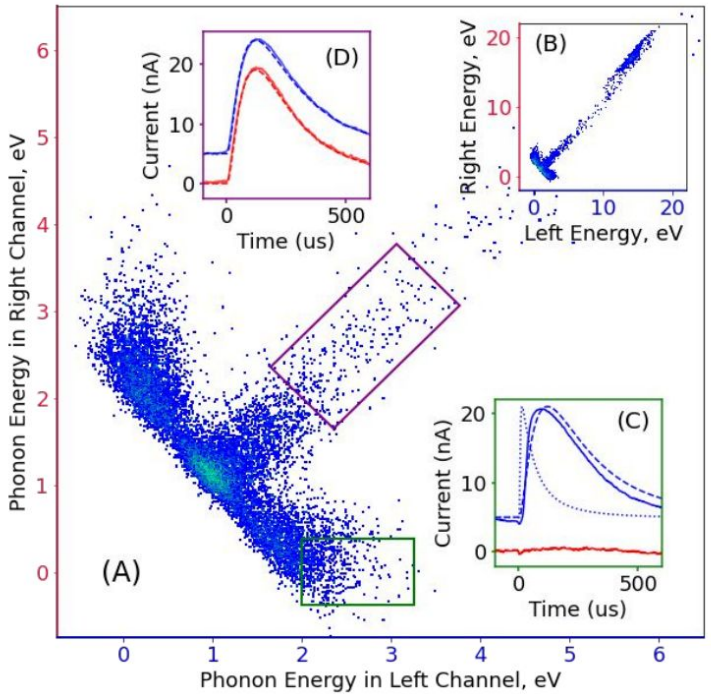


Signatures in correlated signals and noises from a two-channel device

Correlated events has uniformly shared energies.
→ Phonon events from bulk

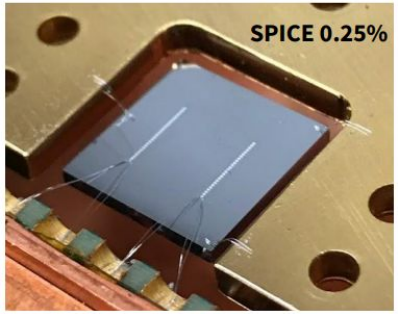
Uncorrelated events (singles) has larger prompt energy fraction.

→ Likely to be metal film stress release.



[IDM Talk 2024 (infn.it)]

Low energy excess (LEE) events

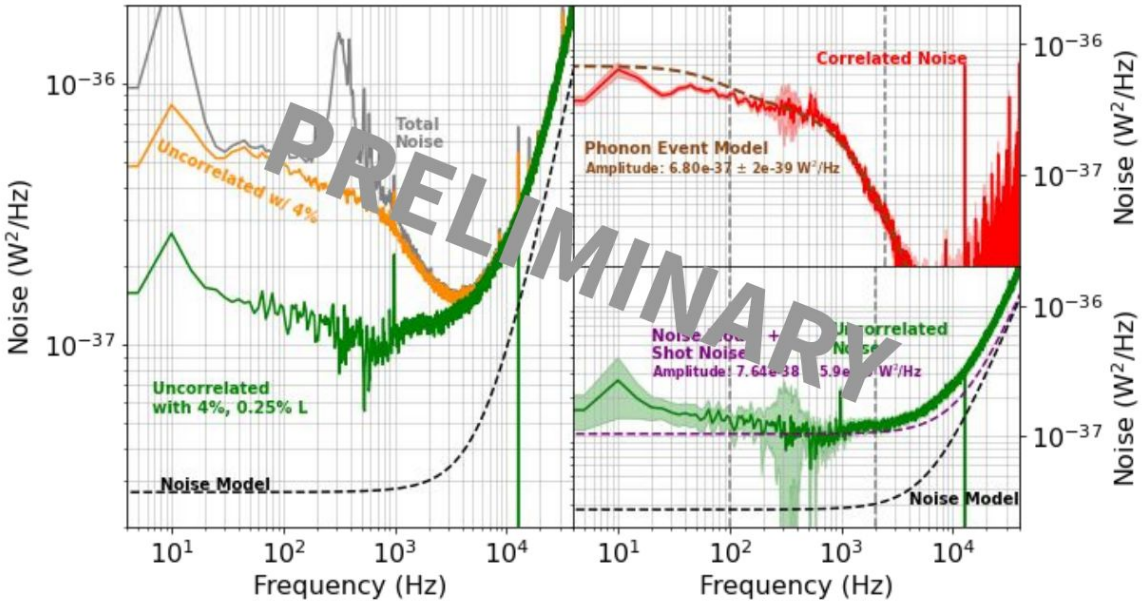


Signatures in correlated signals and noises from a two-channel device

Noise can be decomposed into correlated and uncorrelated components.

Correlated noise shows the phonon signal power spectrum
→ Phonon shot noise.

Uncorrelated noise has flat power spectrum
→ Excess thermal fluctuation noise from external noise power



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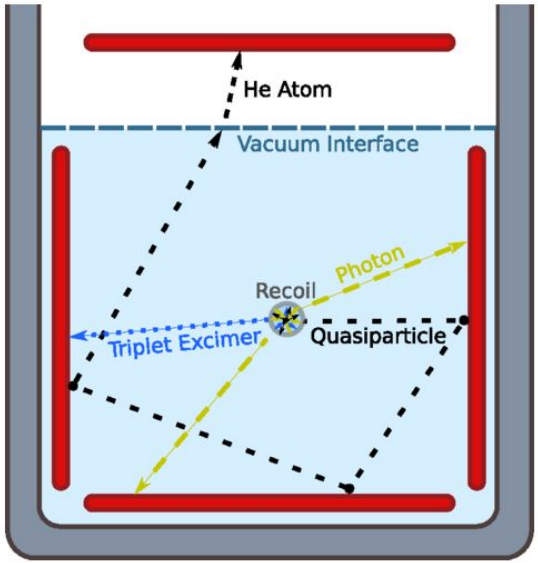
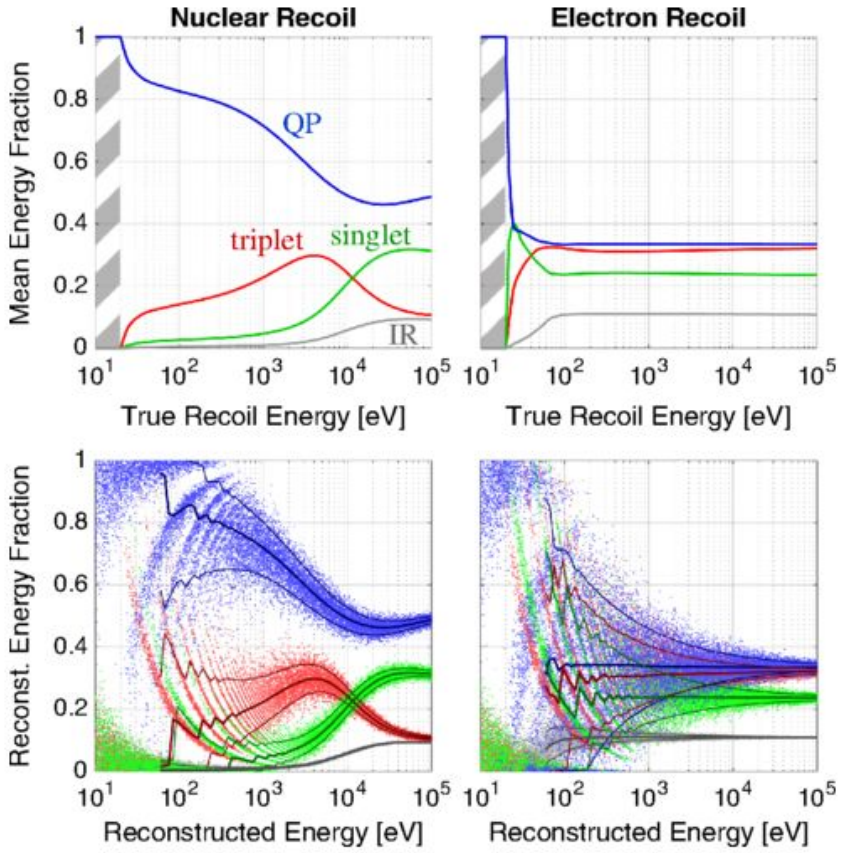
Recent progress

HeRALD

HeRALD detector concept and helium response

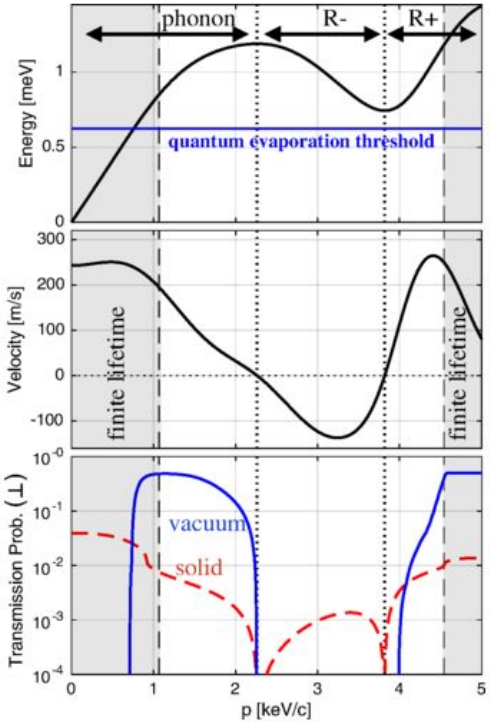
Phys. Rev. D 100, 092007 (2019)

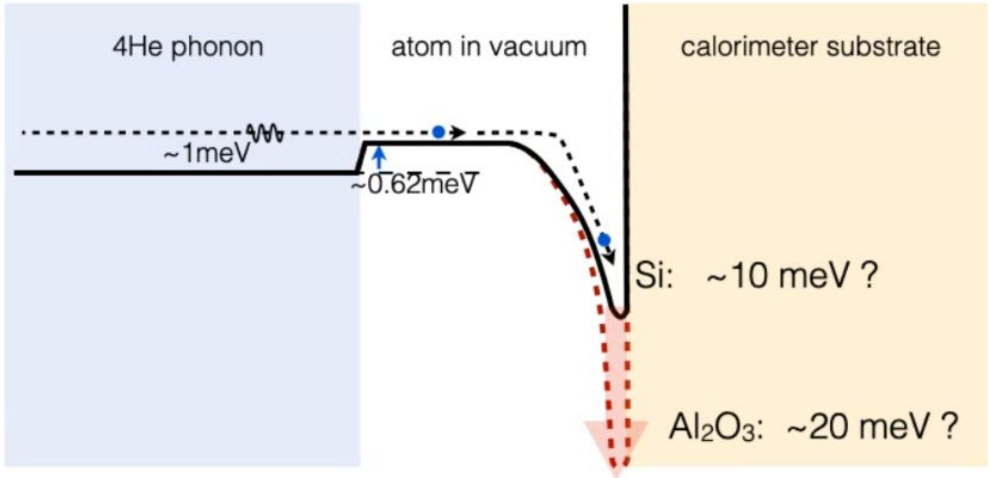




HeRALD detector quantum evaporation

Phys. Rev. D 100, 092007 (2019)





Amplification by surface adsorption

Proof-of-principle HeRALD detector operation

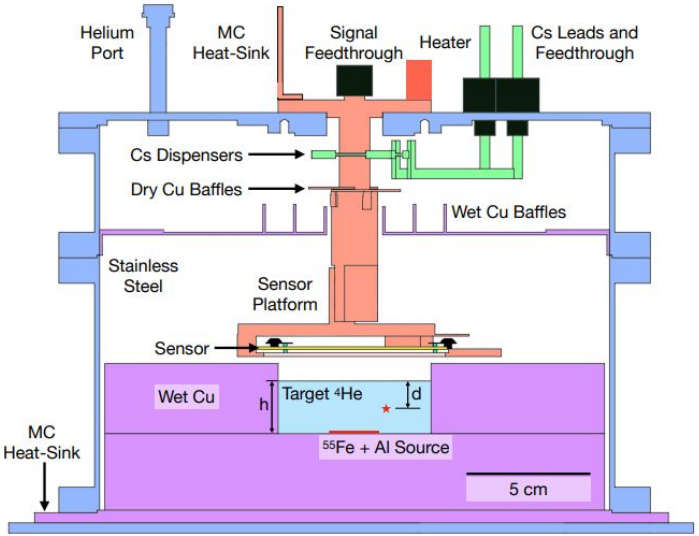
Cs superfluid helium stoper demonstrated.

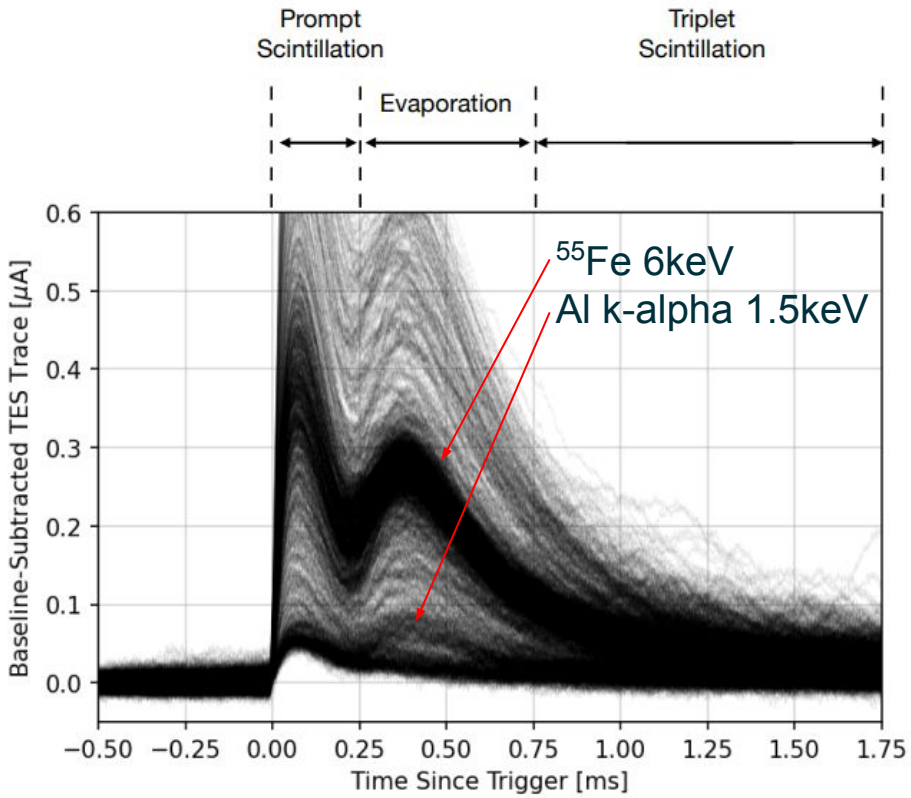
Photon and quantum evaporation signals observed.

145eV energy threshold.

Ready to explore very interesting helium physics!

arxiv: 2307.11877





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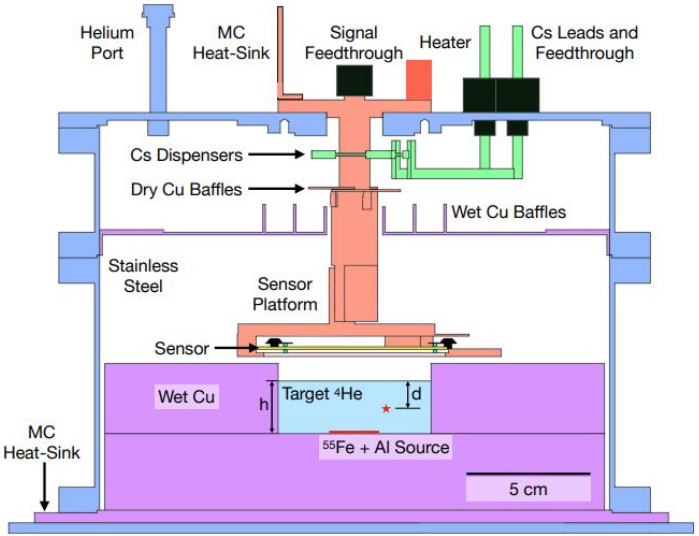

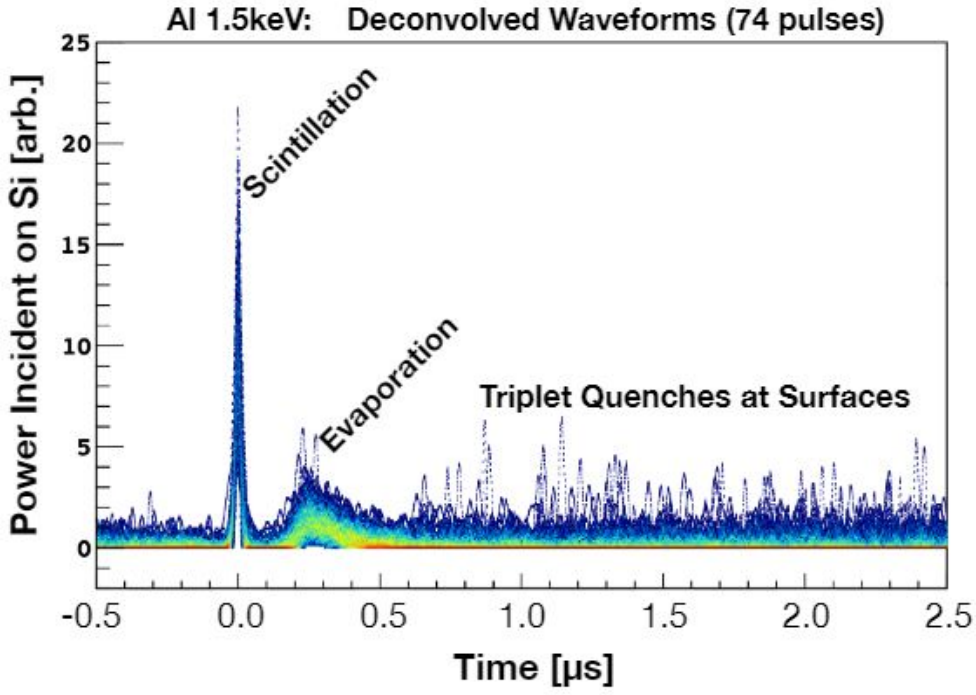

Proof-of-principle HeRALD detector operation

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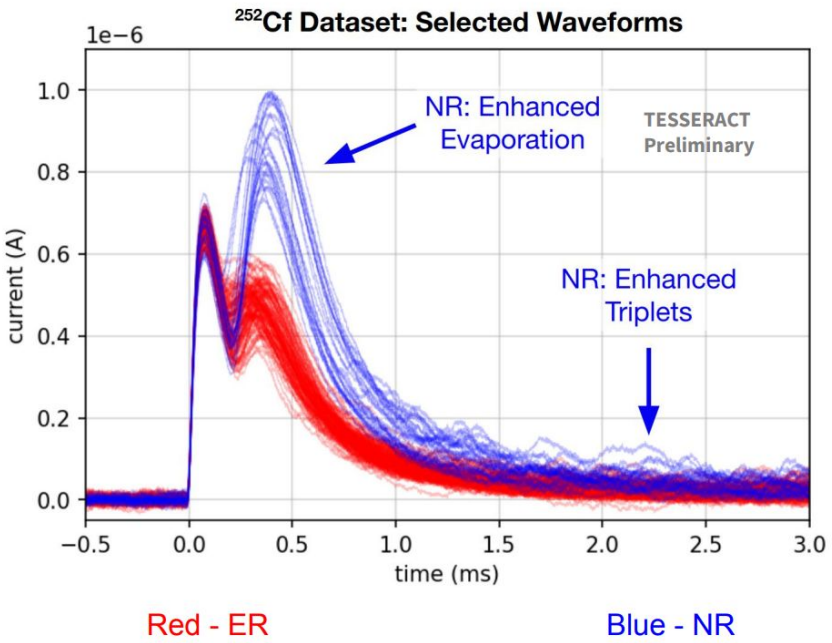
Photon and quantum evaporation signals observed.

145eV energy threshold.

Ready to explore very interesting helium physics!

Clear discrimination between electron recoil and nuclear recoil.



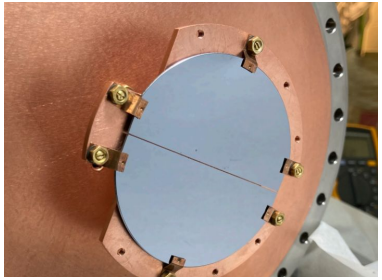
Two-channel HeRALD detector with split-CPD

LEE in crystals never creates correlation between the two channels.

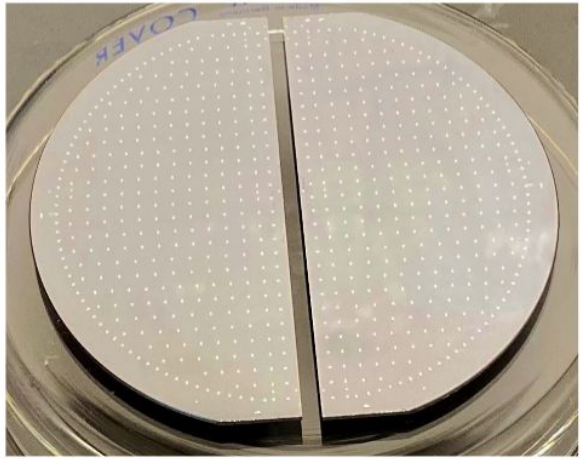
Quantum evaporation will create correlated events.

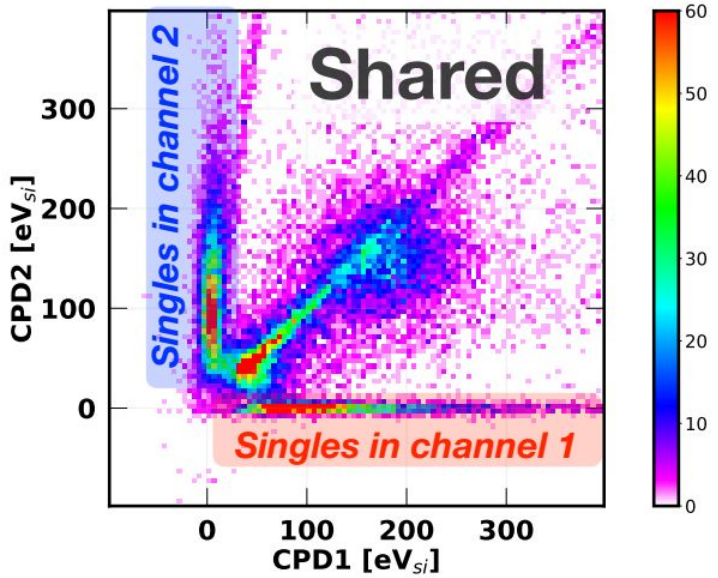
Efficiently remove LEE backgrounds!

2eV sigma energy resolution for a single channel.



Pratyush Patel, UMass





Two-channel HeRALD detector with split-CPD

Pratyush Patel, UMass

LEE in crystals never creates correlation between the two channels.

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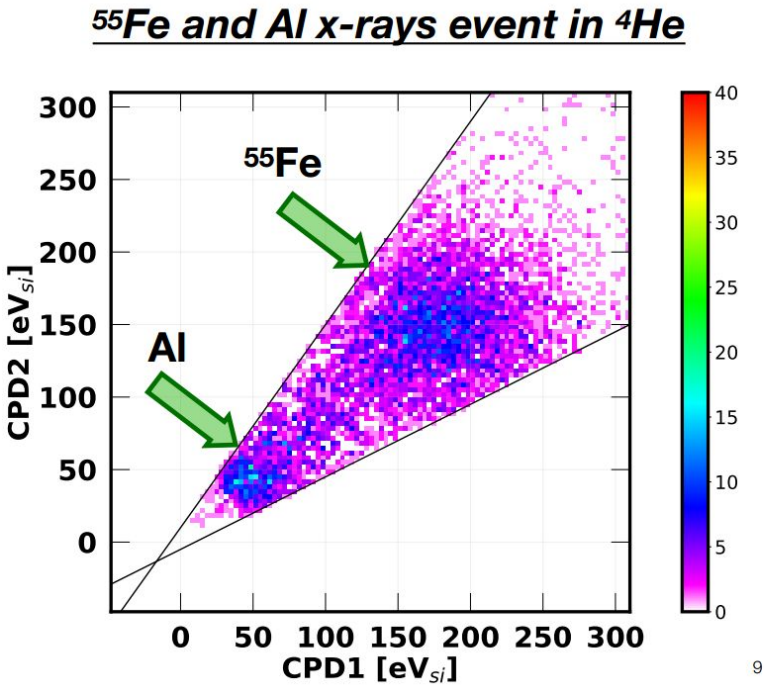
Efficiently remove LEE backgrounds!

Right: Correlated helium events

The key question: Is there LEE in helium?

Next run will be a no-source run!



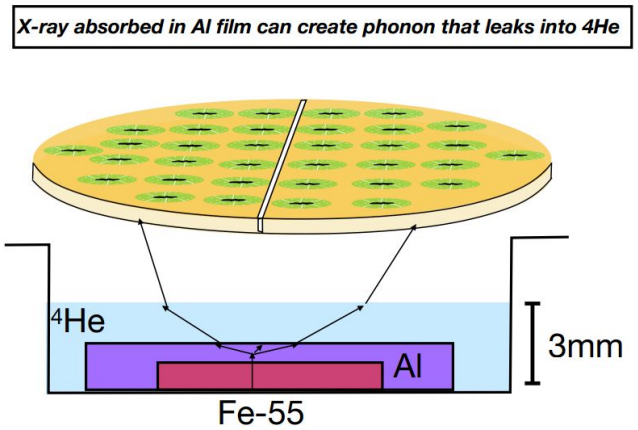
Two-channel HeRALD detector with split-CPD

LEE in crystals never creates correlation between the two channels.

Quantum evaporation will create correlated events.

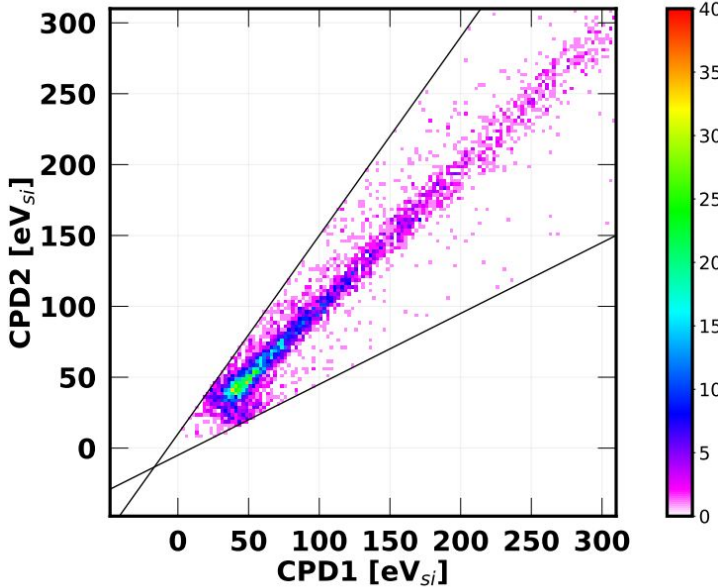
Efficiently remove LEE backgrounds!

Right: Correlated events with slow rising evaporation signal. Energy deposition in Al!



Pratyush Patel, UMass

Slow rising; almost equally shared energy



Two-channel HeRALD detector with split-CPD

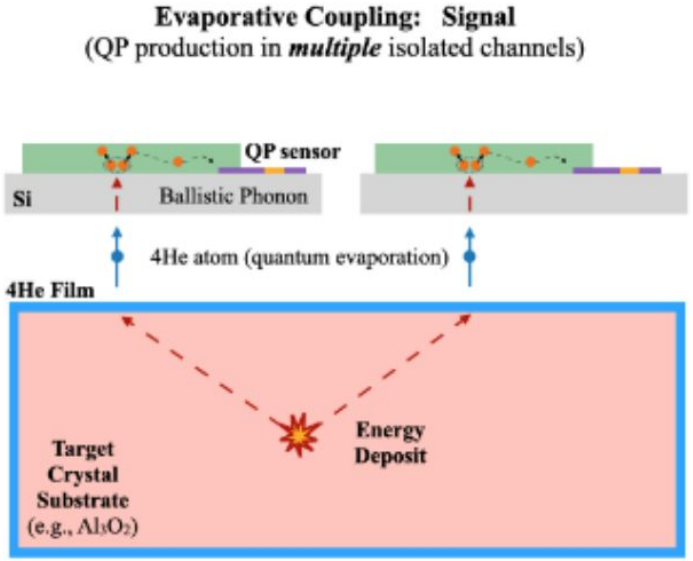
LEE in crystals never creates correlation between the two channels.

Quantum evaporation will create correlated events.

Efficiently remove LEE backgrounds!

Motivates detector with superfluid helium coated crystal targets!
Remove film-stress induced LEE in crystal targets.

Pratyush Patel, UMass



Two-channel HeRALD detector with split-CPD

Pratyush Patel,
UMass

Improved resolution compare to previous full-wafer CPD detector.

16eV peak from triplet events resolved.

Energy resolution and the triplet event line width is under investigation.

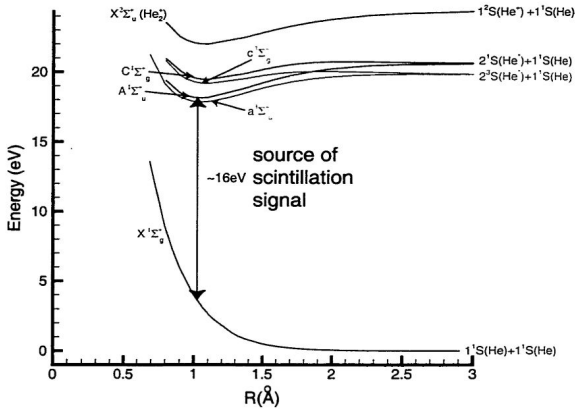
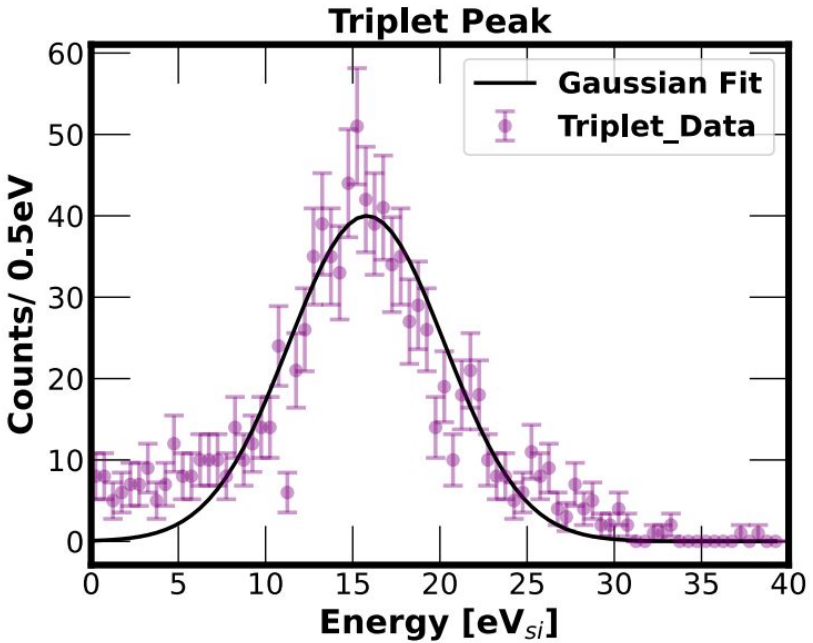


Figure 2.8: The interatomic/molecular potentials for He-He and He_2 dimers. Values are from Sunil et al. [1983], Chabalowski et al. [1989] and Ginter and Battino [1970]



Adams, J. S. Energy deposition by electrons in superfluid helium. (Brown University, 2001).

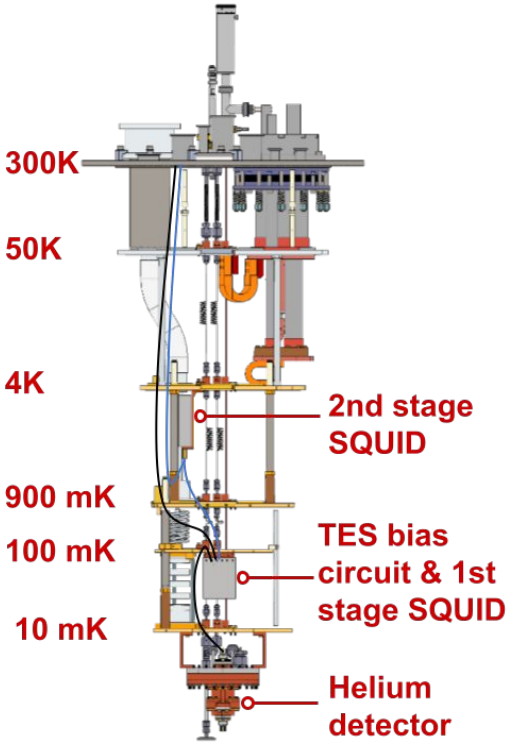
LBL HeRALD 2.0

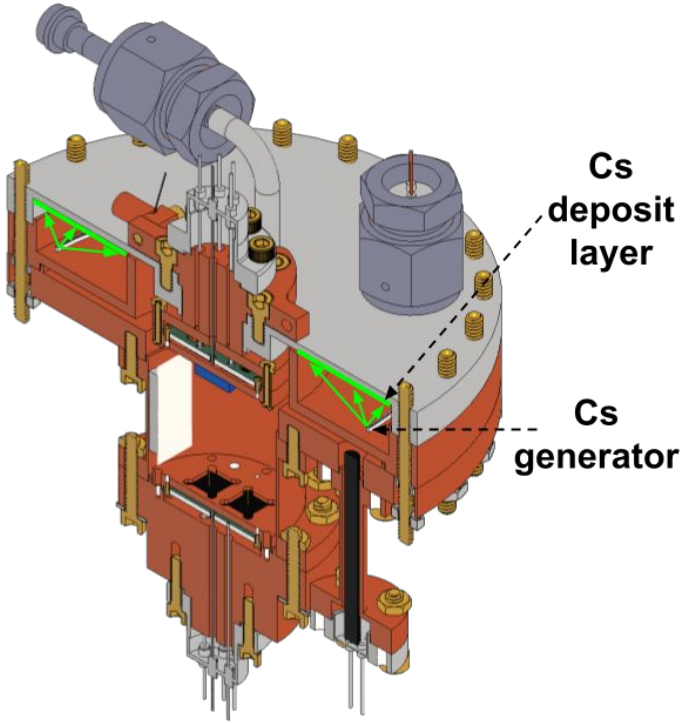
Two-stage SQUIDs.

Helium cell with 4 dry channels and 4 submerged channels.

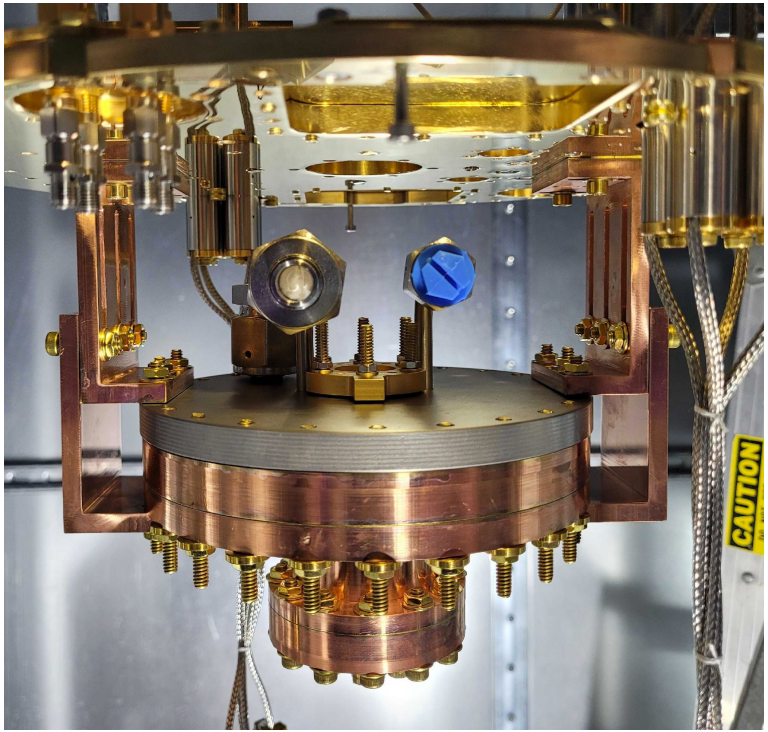
Thin wall for external gamma and neutron source calibration.

Improved Cs film stopper design.

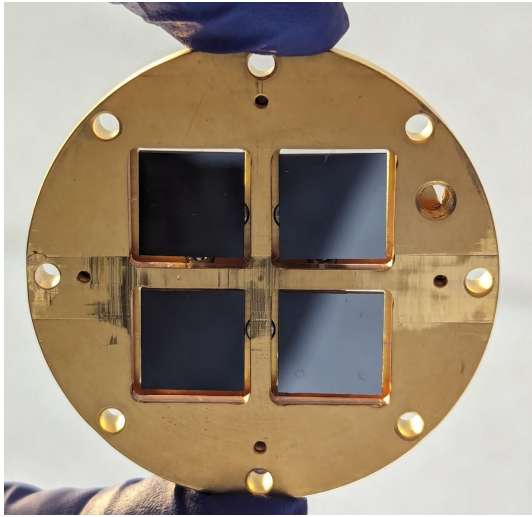


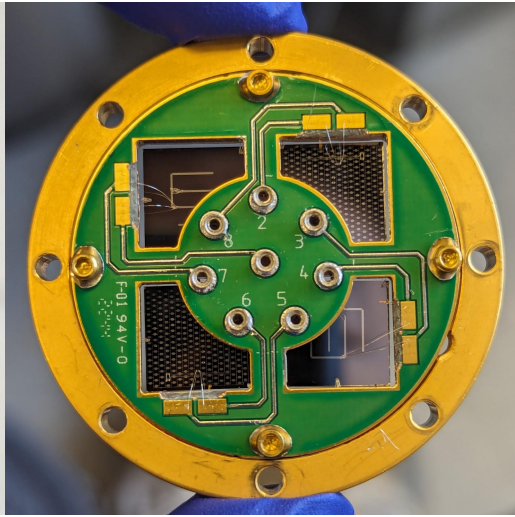


LBL HeRALD 2.0



4-channel hanging devices





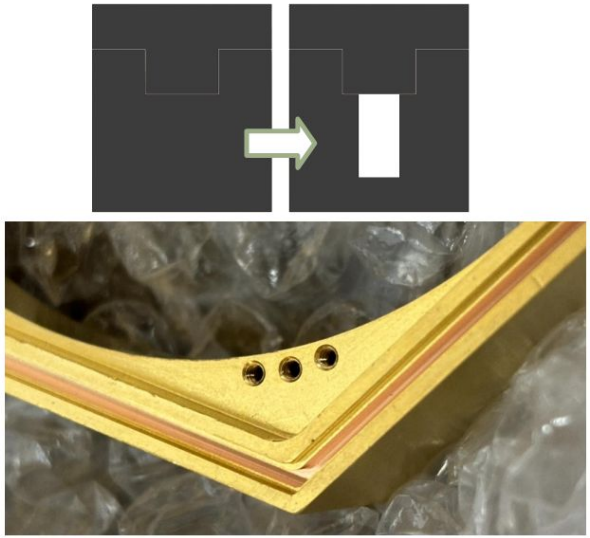
Recent progress

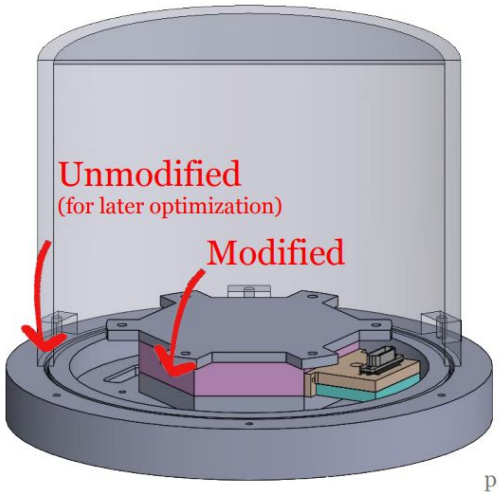
Reducing parasitic noise power

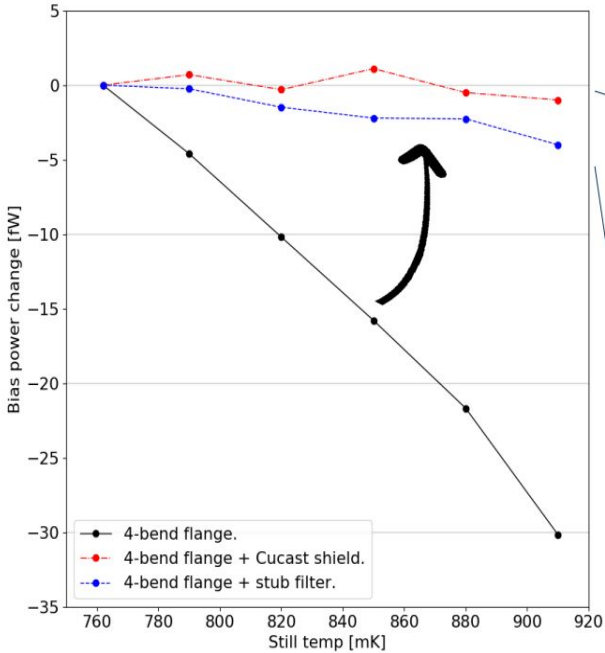
Path to even better sensitivities

Shielding black body radiation

- Retrofitted an 1×2 mm groove into detector housing's tight flange.







Yen-Yung Chang RISQ 2024

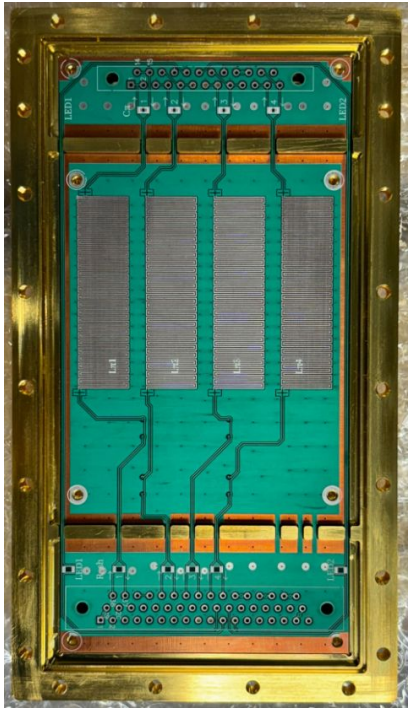
Path to even better sensitivities

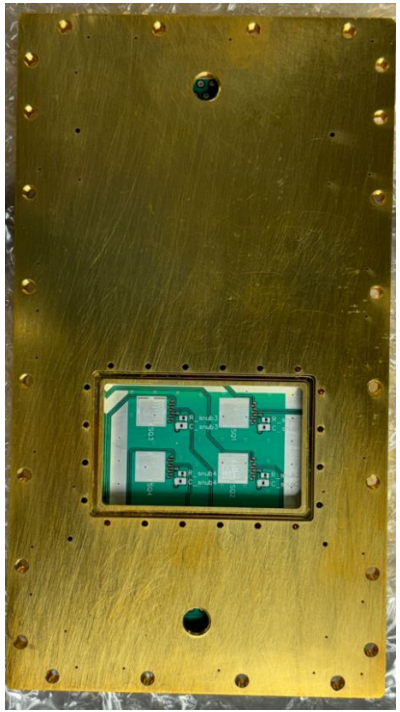
Filtering TES bias power -- Remove MHz to GHz noise powers.

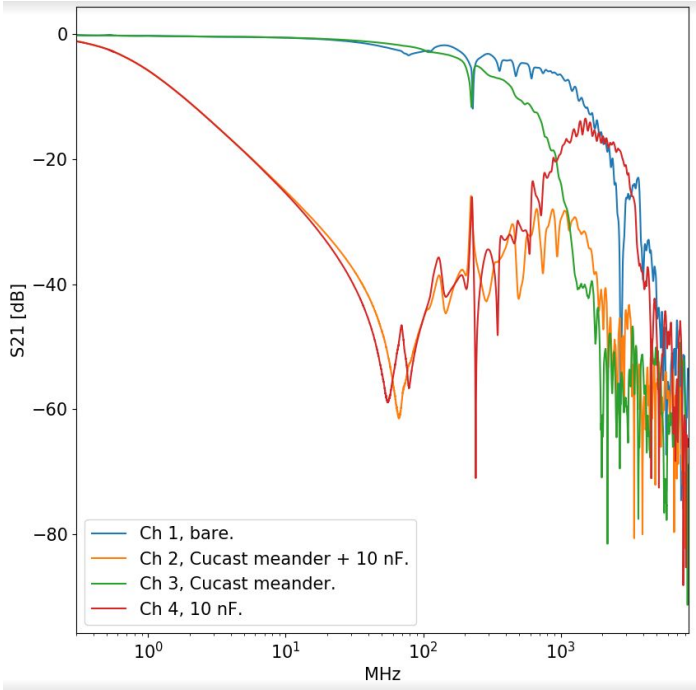
To TES

SQUID Filtering Chamber: Copper dust + Lumped RC

To warm stages







Yen-Yung Chang

Coming up next

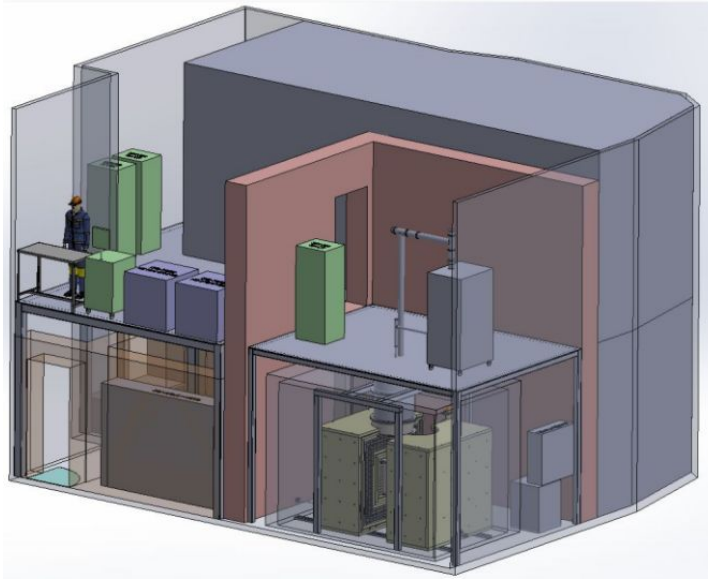
Underground experiment preparation

Underground labs

France - Modane - LSM

Planning for 1~2 payloads.

Simulation and engineering in progress.

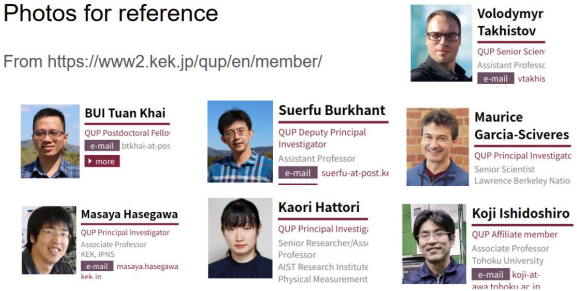


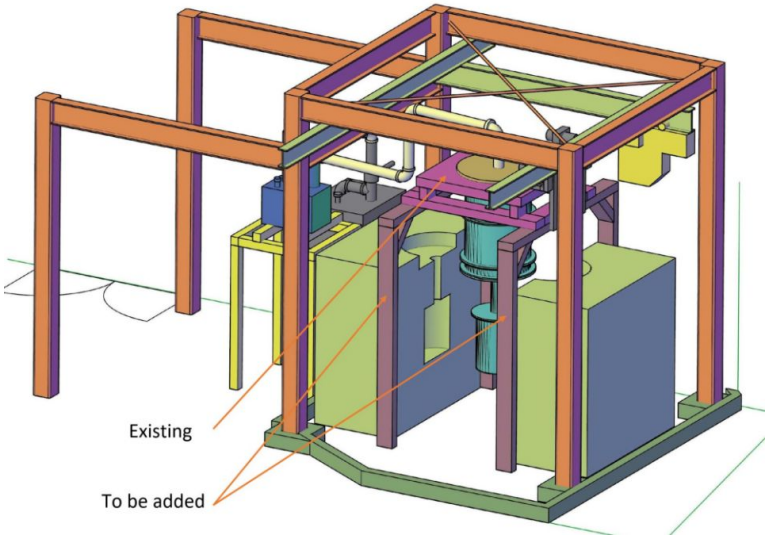
Japan - Kamioka

Science payload:
~10g-yr exposure
~20eV threshold.

Photos for reference

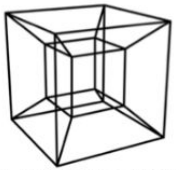
From https://www2.kek.jp/qup/en/member/





BERKELEY LAB

Bringing Science Solutions to the World



Conclusion

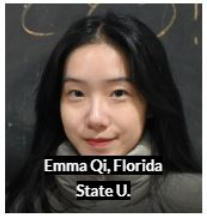
- The goal is to explore the large parameter space from 1GeV to 1keV dark matter mass with various target materials.
- TESSERACT has been project funded by DOE and IN2F3
- We have successfully demonstrated ~1eV threshold silicon devices.
- Successfully demonstrated superfluid helium detector with film stopper and quantum evaporation signals. Triplet signals resolved.
- Understanding the effect of low energy excess (LEE) events as backgrounds and noise power, both in crystal detectors and in helium detectors.
- Underground experiments is in preparation.

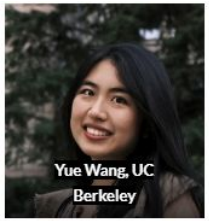
Thank you!
Questions?

BERKELEY LAB

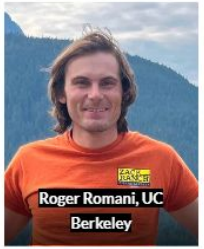
Bringing Science Solutions to the World

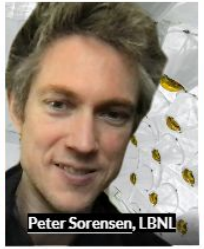

Matt Pyle, UCB & LBNL


Emma Qi, Florida State U.


Yue Wang, UC Berkeley


Kathryn Zurek, Caltech


Roger Romani, UC Berkeley

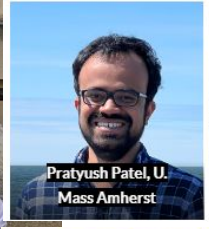

Peter Sorensen, LBNL

Burkhant Suerfu, QUP

Aritoki Suzuki LBNL

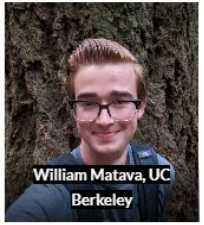

Tuan Khai Bui, QUP


Clarence Chang, ANL


Pratyush Patel, U. Mass Amherst


Wei Guo, Florida State U.


Rupak Mahapatra, Texas A&M U.

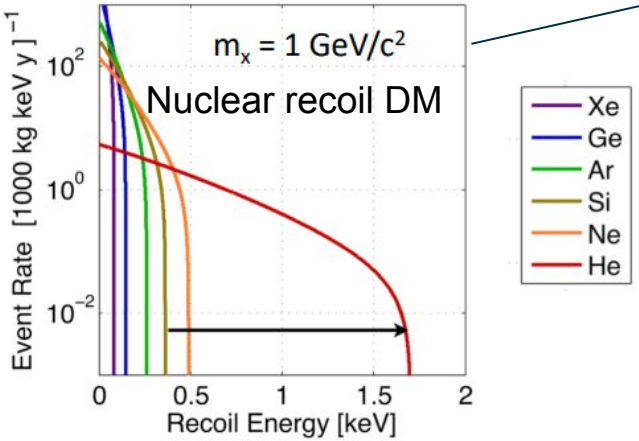

William Matava, UC Berkeley

Back up

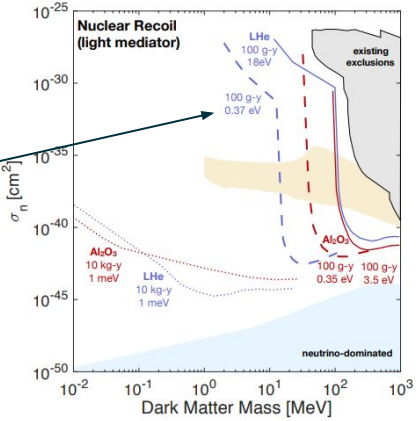
Direct detection for low-mass dark matter

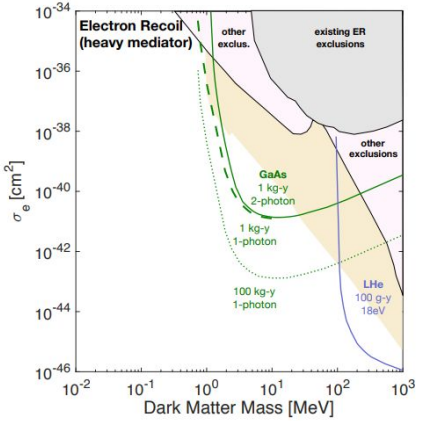
Low threshold

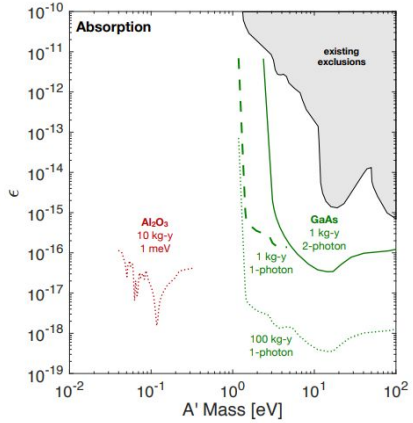
Target with light element: He

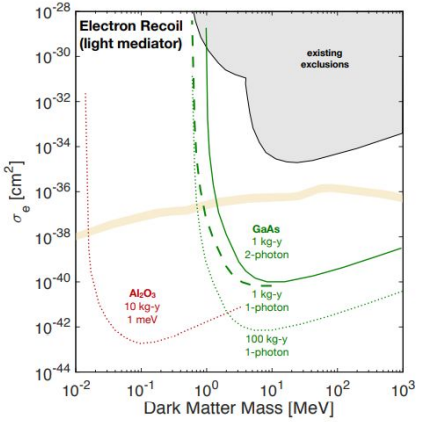


Snowmass2021 - Letter of Interest
The TESSERACT Dark Matter Project









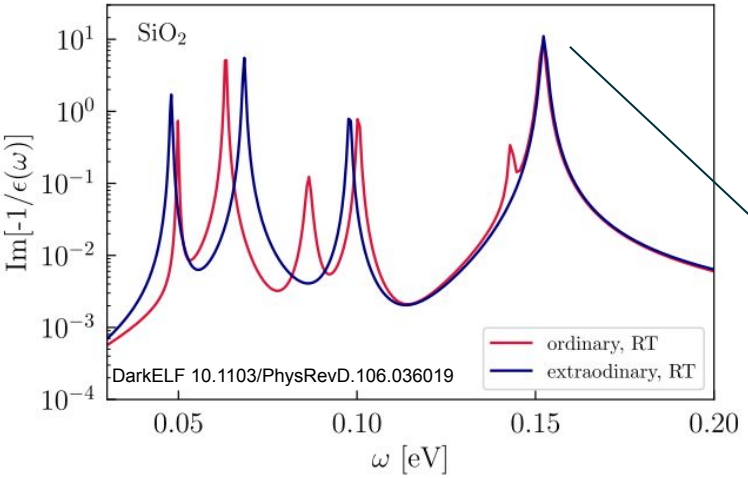
Direct detection for low-mass dark matter

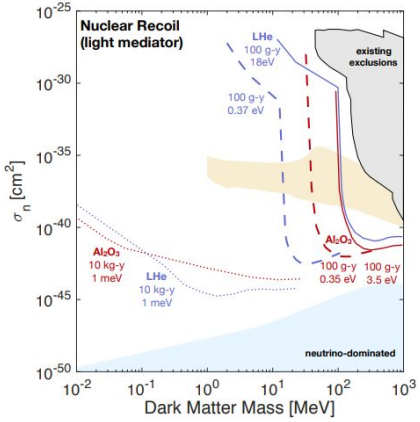
Low threshold

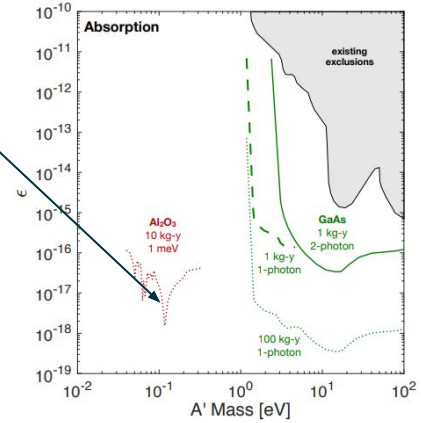
Target with light element: He

Polar crystal: optical phonons, dark photon coupling.

Dark photon coupling







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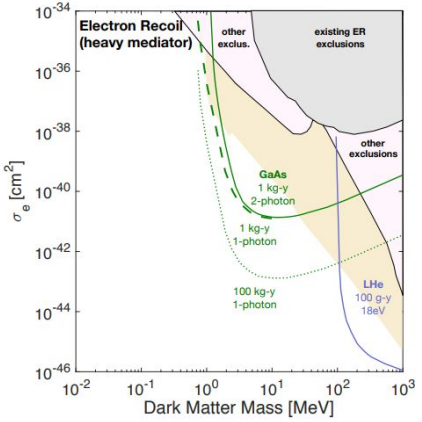
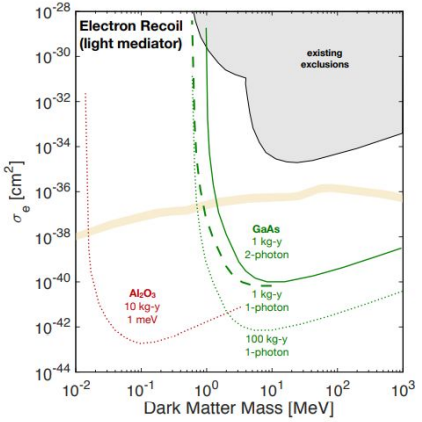
The TESSERACT Dark Matter Project



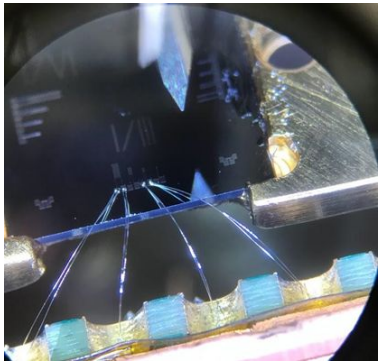


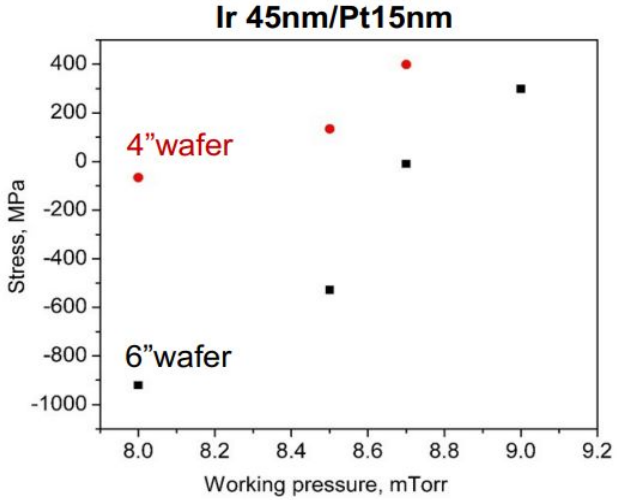
Low stress low Tc films

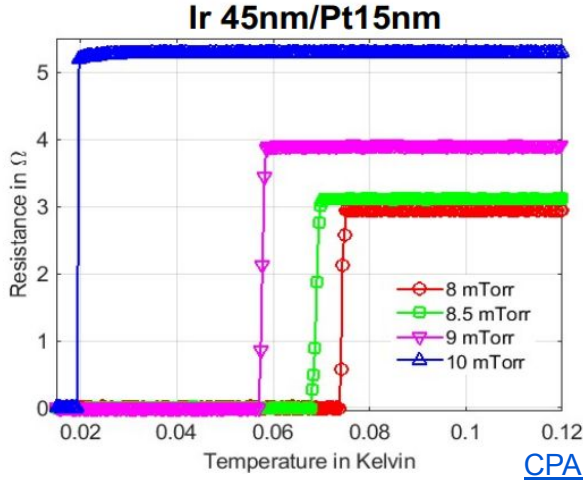
First attempt with tungsten film.
Low Tc achieved. Not low stress.

Good results from Ir/Pt bilayer samples from Argonne National Laboratory.

TES fabrication finished. Tests on going!







Athermal phonon sensor energy resolution

TES noise is limited by the thermal fluctuation noise of the thermal link G between the TES and the bath.

$$\sigma_E \sim \frac{\sqrt{4k_b T_c^2 G(\tau_{collect} + \tau_{sensor})}}{\epsilon_{collect}\epsilon_{sensor}}$$

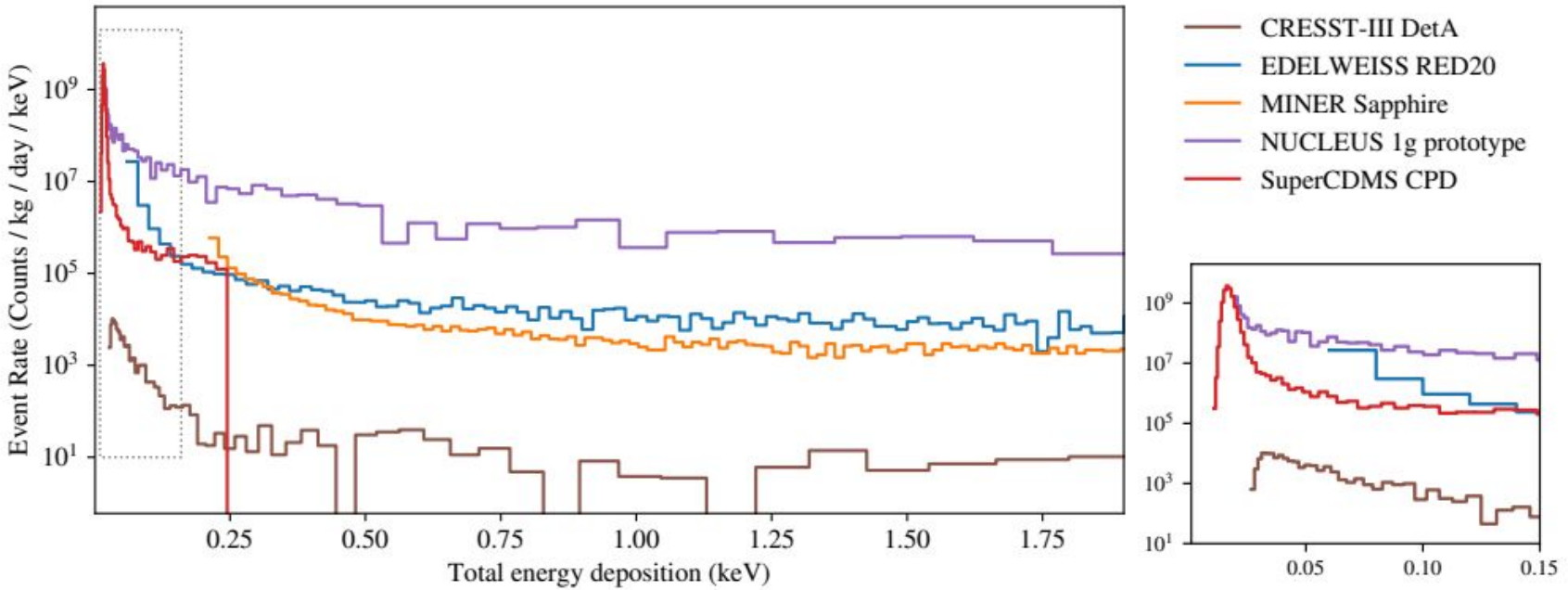
Thermal phonon TES sensor: $\tau \sim C_{detector}/G \rightarrow \boldsymbol{\sigma_E \sim T_c^{3/2}}$

Athermal phonon sensor: Thanks to extra freedoms from the phonon collection fins, $\tau_{collect}$ can be engineered to match τ_{sensor} (the time scale of electrical-thermal feedback) $\rightarrow \boldsymbol{\sigma_E \sim T_c^{3}}$

- **Lower Tc**
- **Optimization of phonon and quasiparticle collection efficiency.**

Caleb Fink Thesis

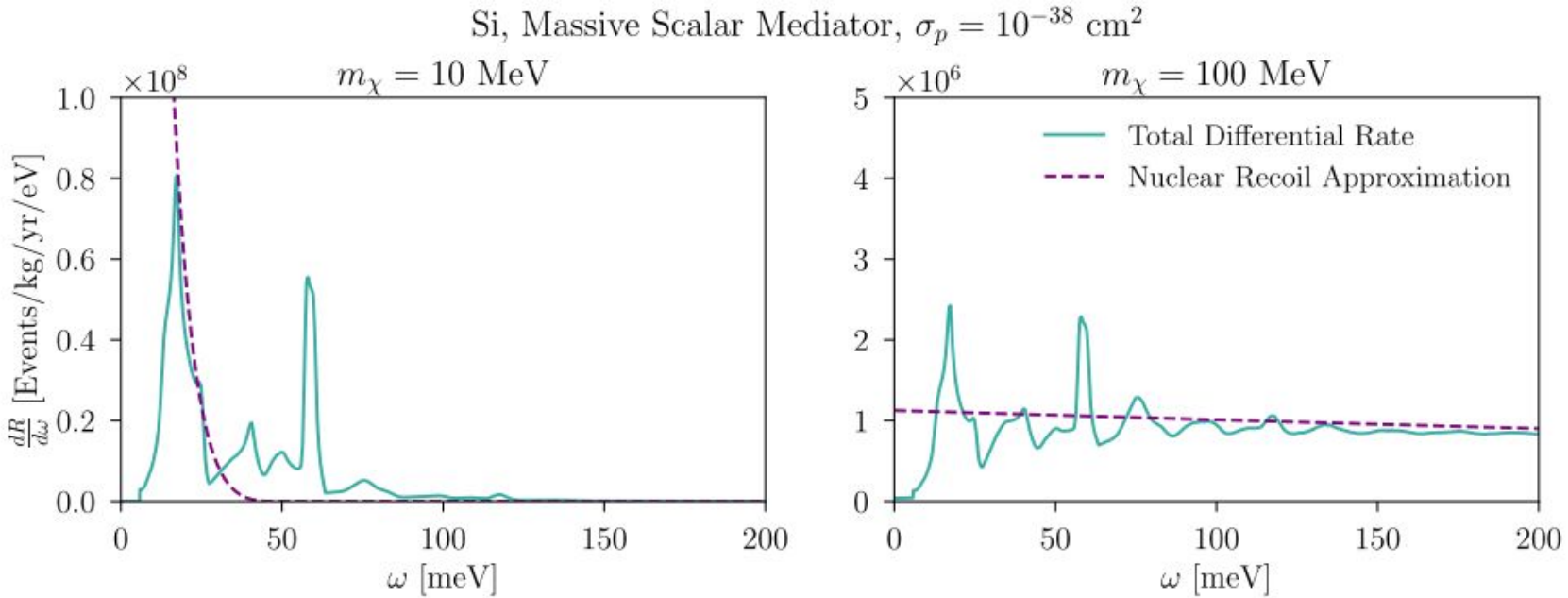
LEE event spectra from various experiments.



arxiv: 2202.05097

Multi-phonon creation in crystals

Gains additional sensitivity at sub-eV

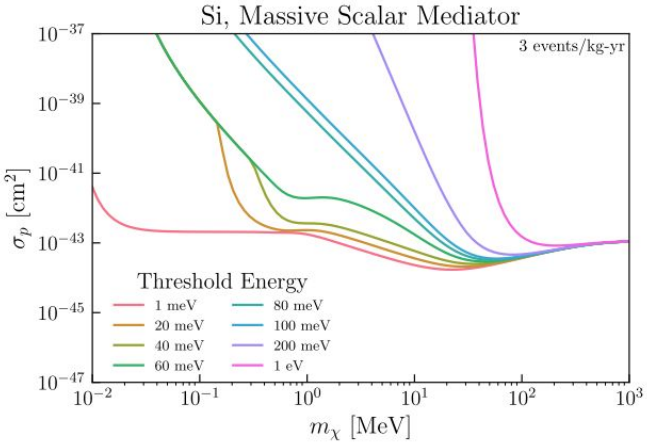


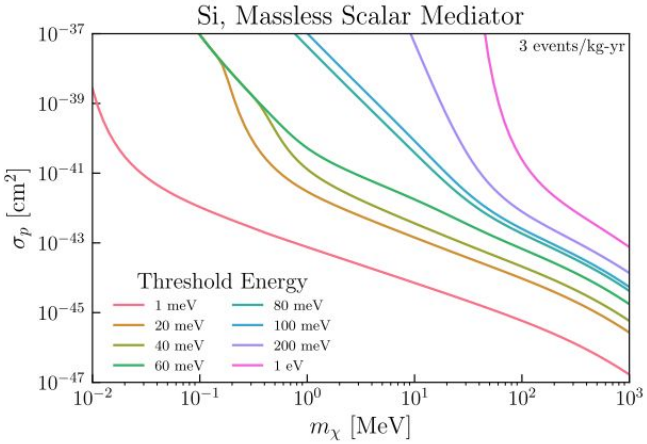
DOI: 10.1103/PhysRevD.106.036019

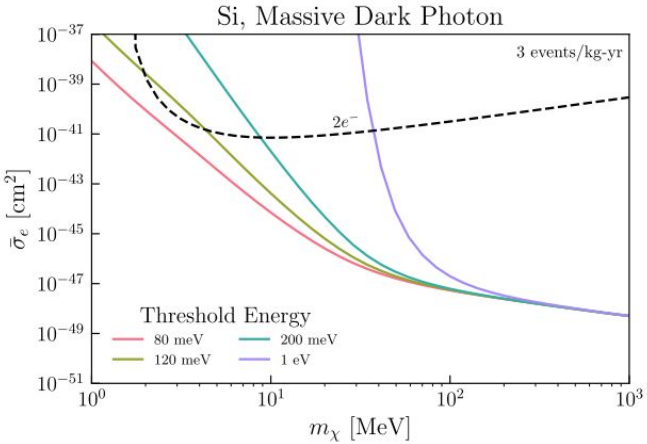
DOI: 10.1103/PhysRevD.106.036019

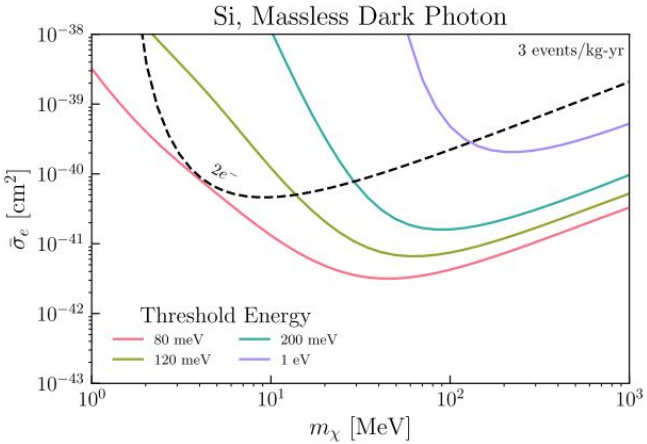
Multi-phonon creation in crystals

Gains add

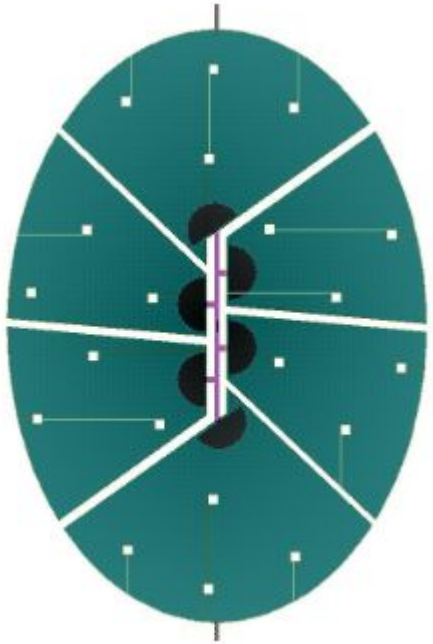








CPDv2 design



TES length	140 µm
TES Thickness	40 nm
TES width	2.5 µm
n_{fin}	6
Fin Length	150 µm
Fin Thickness	600 nm
Al/W Overlap	20 µm
N_{qet}	673
Active Surface Area	0.68%
Passive Surface Area	0.18%
R_n	200 mΩ
QP Abs Efficiency	52%
Tot Efficiency	18% (Simulated)