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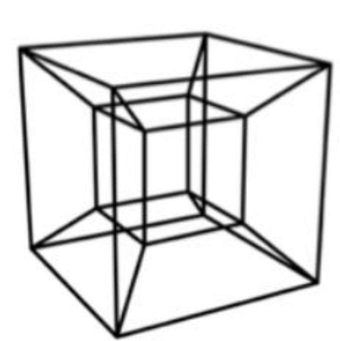
Transition edge sensor developments for the TESSERACT project

Xinran Li
Physics department, Lawrence Berkeley Laboratory
The TESSERACT collaboration

12/01/2022
CPAD 2022, Stony Brook University, Long Island



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The TESSERACT project

- Direct search for low-mass dark matter
- Transition Edge Sensors (TESs) with Sub-EV Resolution And Cryogenic Targets
- Athermal phonon detectors

Low Tc films

- Why lower Tc?
- Current status: 20mK tungsten (W) films
- Next step: low Tc and low stress

Detector performance

- Bare TESs
- 10 gram cryogenic photon detector

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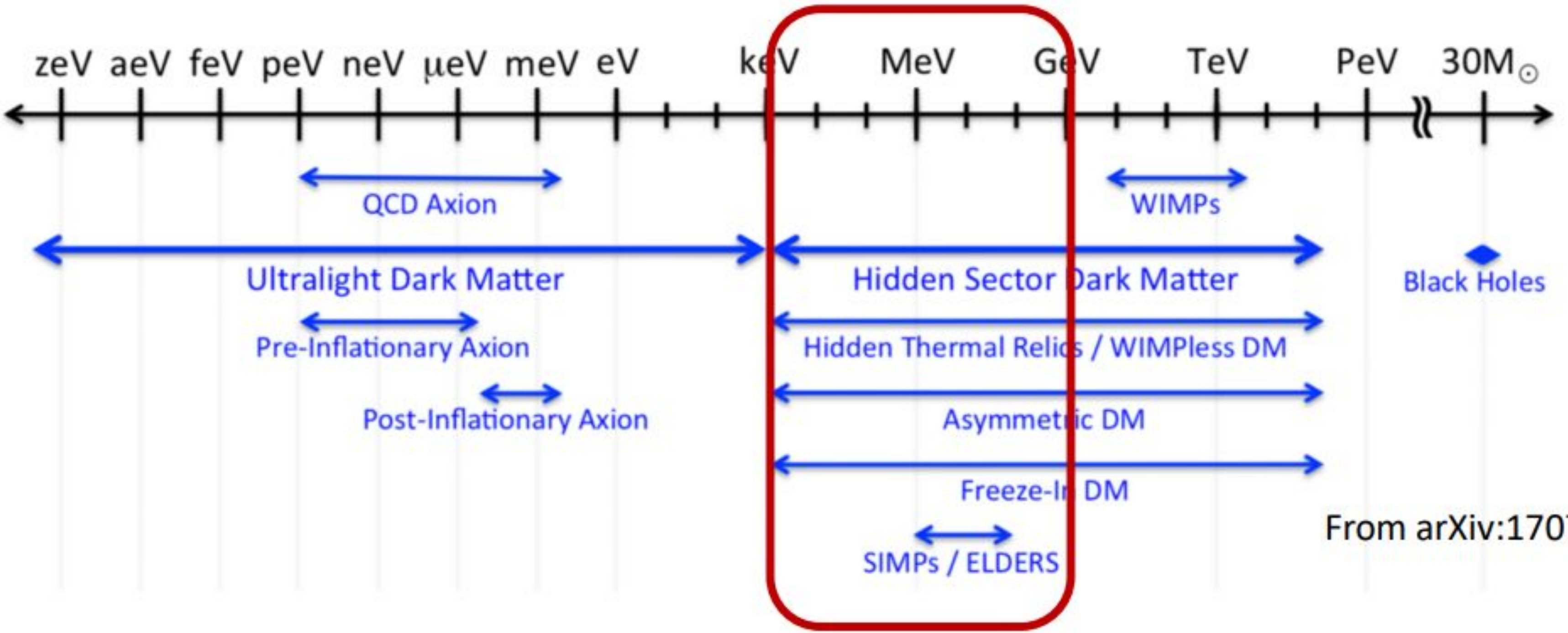
The TESSERACT project

Direct detection for low-mass dark matter



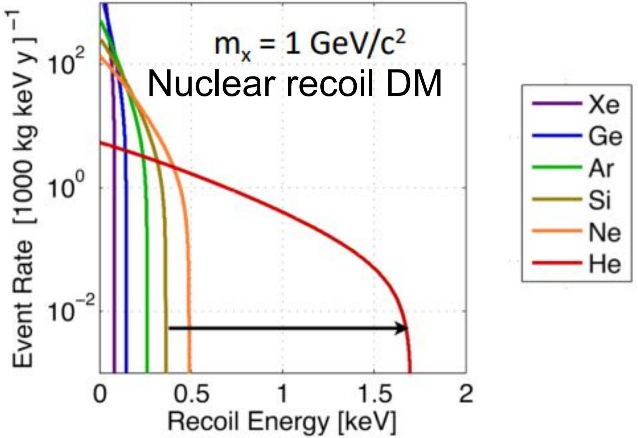
From arXiv:1707.04591

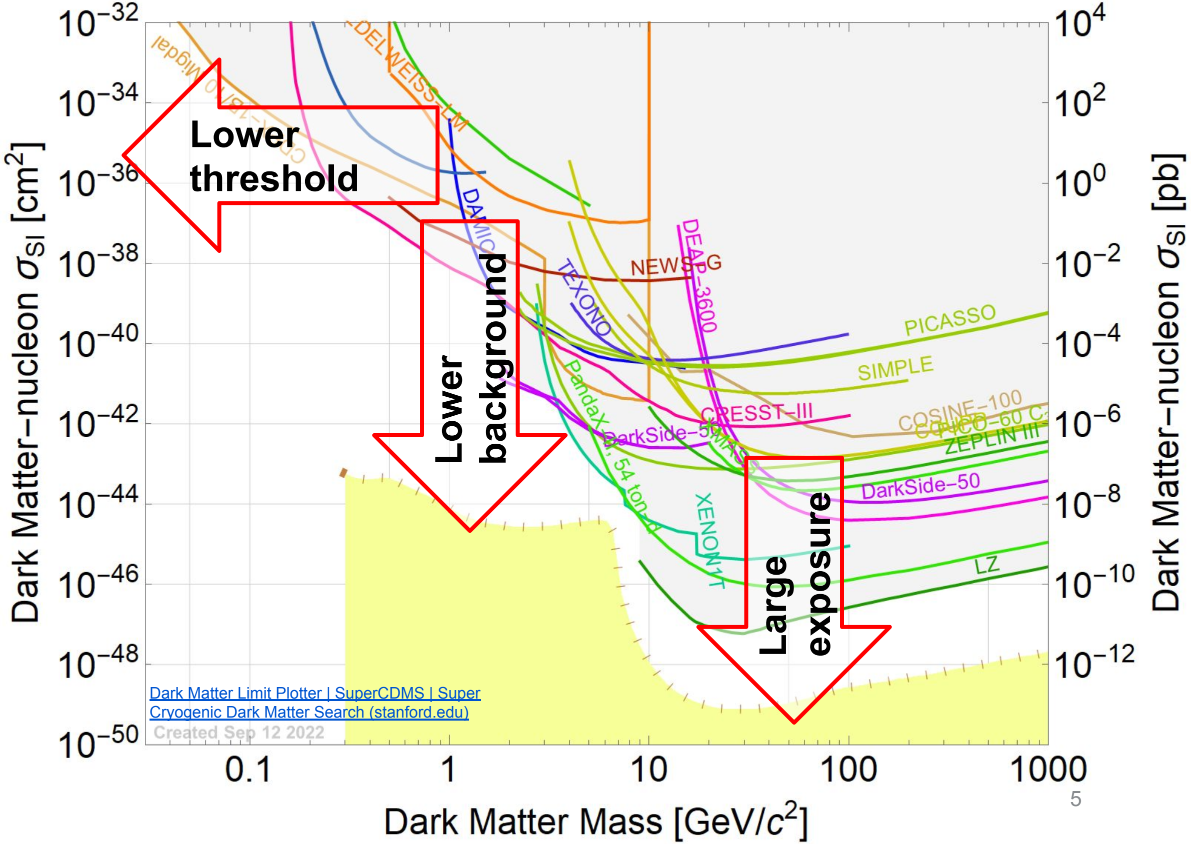
Direct detection for low-mass dark matter

Low threshold

Target with light element

Polar crystal





Direct detection for low-mass dark matter

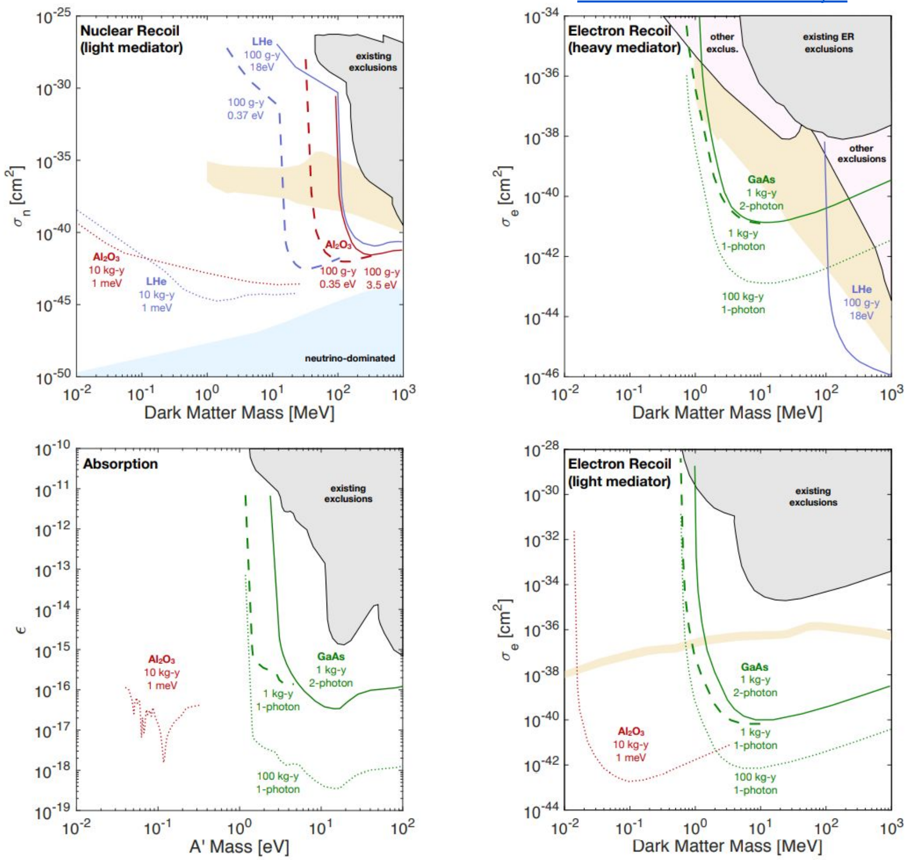
Low threshold

Target with light element

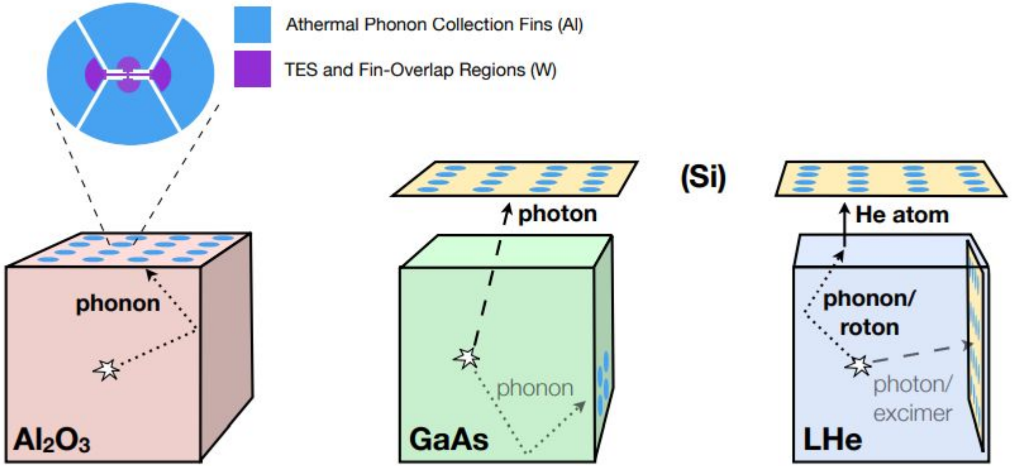
Polar crystal: optical phonons, dark photon coupling.

→ 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**

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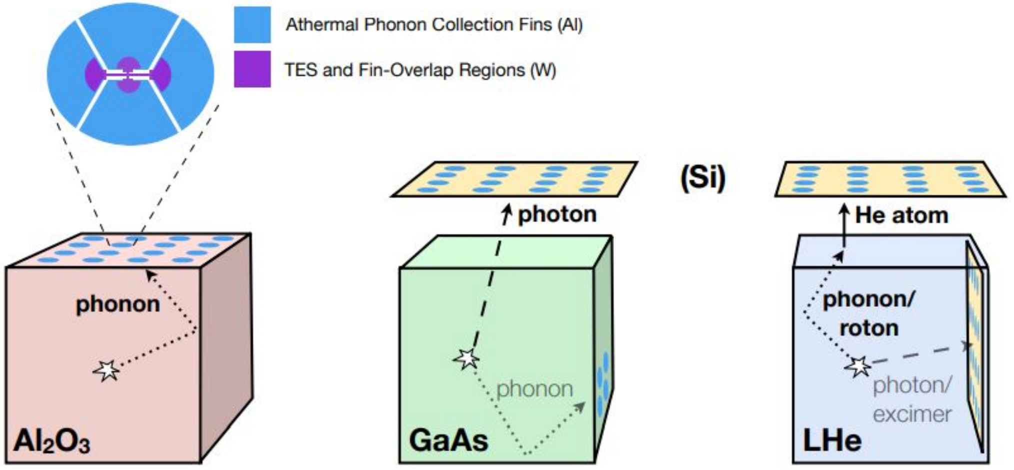
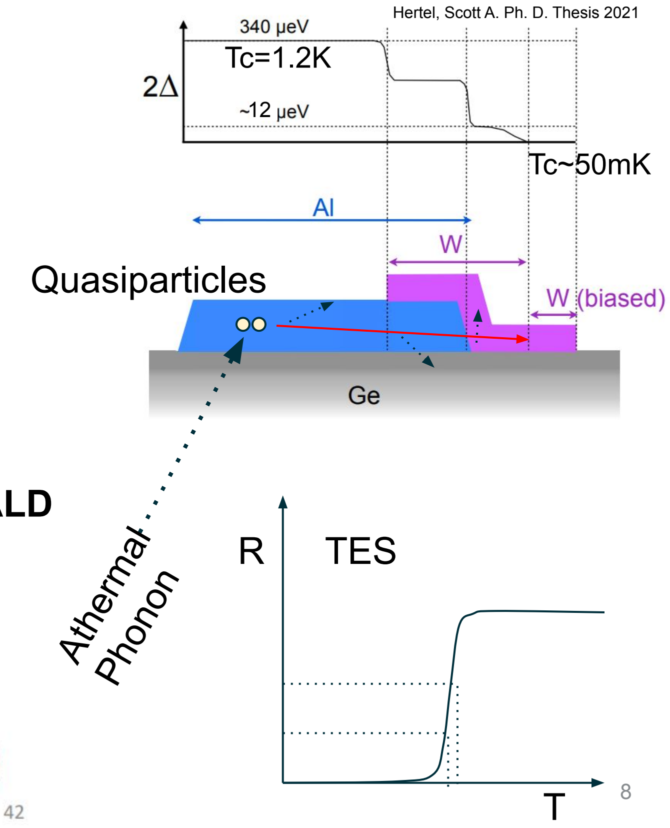
TESSERACT & Athermal phonon sensor



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



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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: $\tau \sim C_{detector}/G \rightarrow$ $\boldsymbol{\sigma_E \sim Tc^{3/2}}$

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) $\rightarrow$ $\boldsymbol{\sigma_E \sim Tc^3}$

- **Lower Tc**
- **Optimization of phonon and quasiparticle collection efficiency.** (David's talk)

Caleb Fink Thesis

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Low Tc films

Low Tc film R&D

Tungsten (W) has two phases:

α-W: 15mK

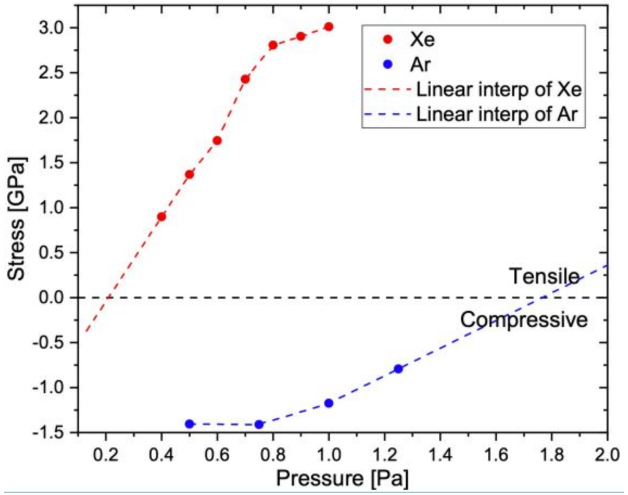
β-W: 1~4 K

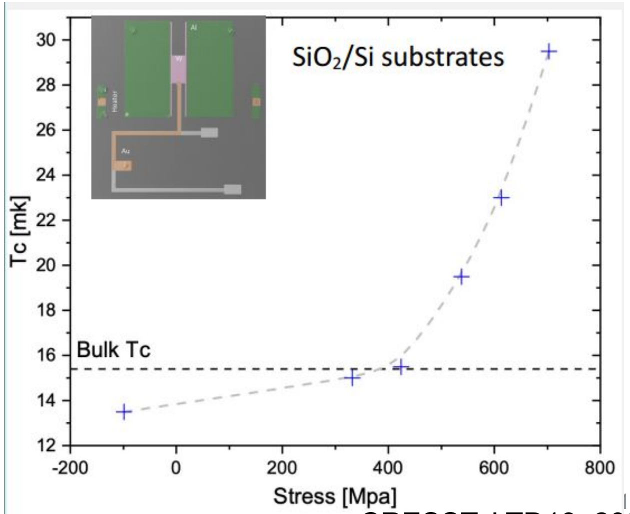
CRESST (right plots) shows evidence of correlation between the pressure of the xenon plasma sputtering deposition, the film stress, and the Tc.

W deposition R&D at Texas A&M University.

Low Tc. Uniformity and Repeatability. Low Tc and low film stress (see Roger's talk)

Argonne : Ir/Pt films

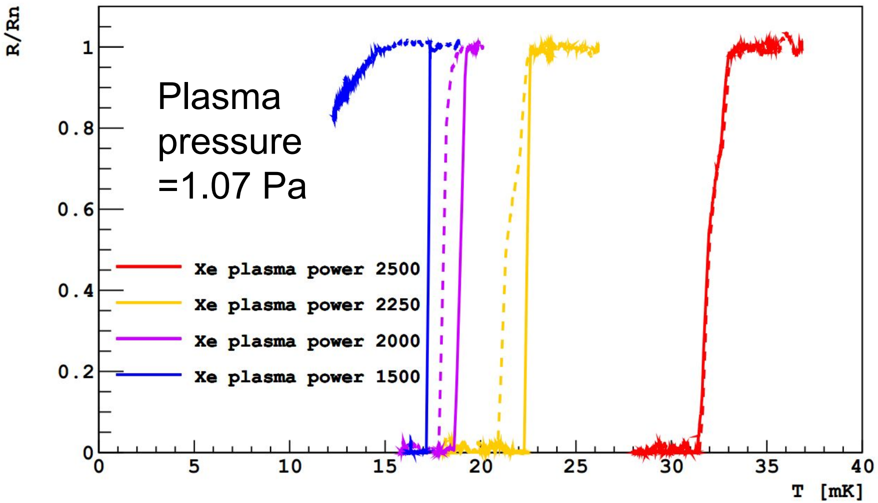


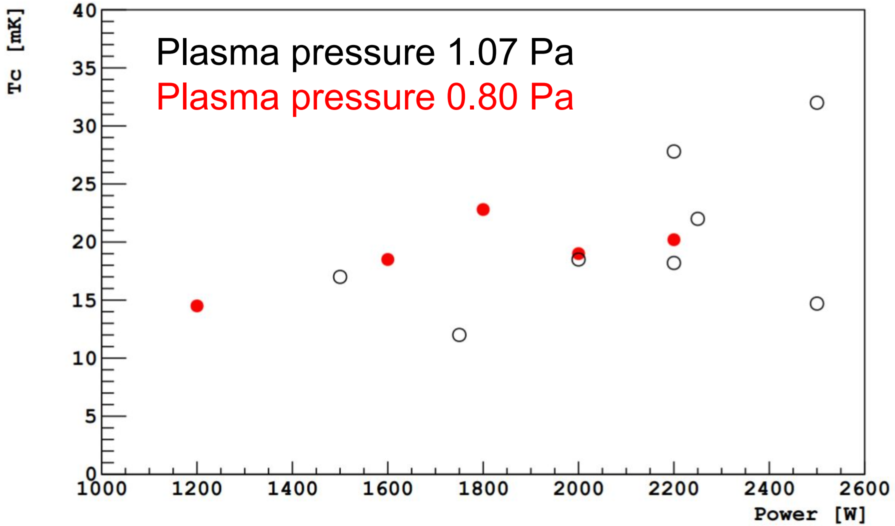


CRESST, LTD19, 2021

Low Tc W films

- Plasma gas: Ar → Xe
- Deposition chamber geometry: A SEGI chamber, an AJA chamber.
- Plasma power
- Plasma pressure
- DC bias on substrate



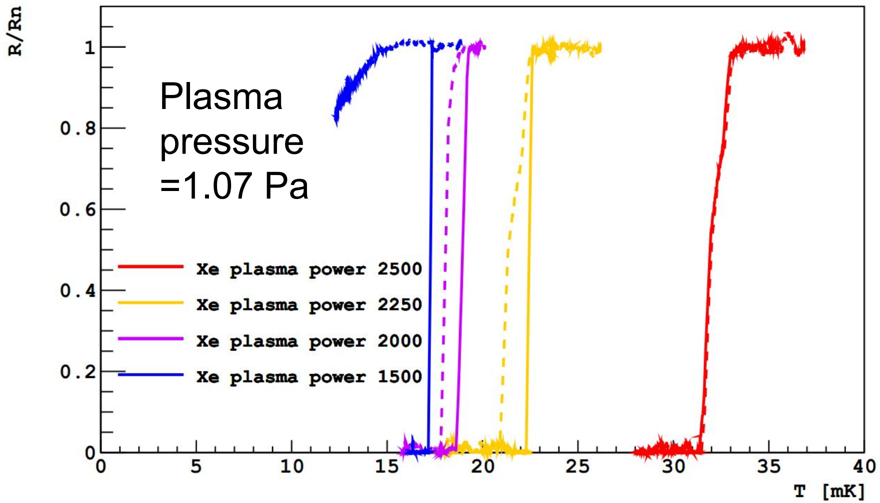


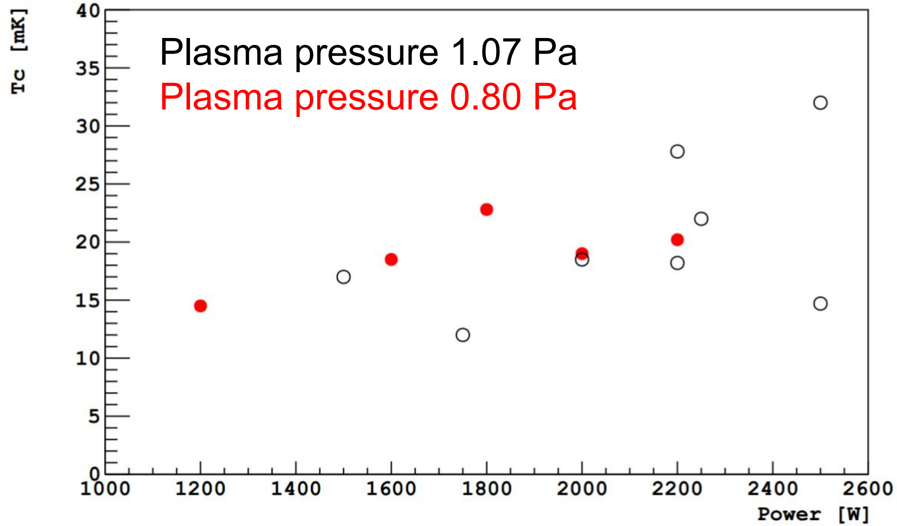
Low Tc W films

- Plasma gas: Ar → Xe
- Deposition chamber geometry: A SEGI chamber, an AJA chamber.
- Plasma power
- Plasma pressure
- DC bias on substrate

Film stress (1~2 GPa) does not show a clear dependence on deposition conditions in the SEGI chamber. We will investigate deposition conditions in the AJA chamber.

Primary goal achieved, working in progress.





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Detector performance

Detector performance

Testing bare TESs

Lower Tc, lower bias power, better sensitivity.

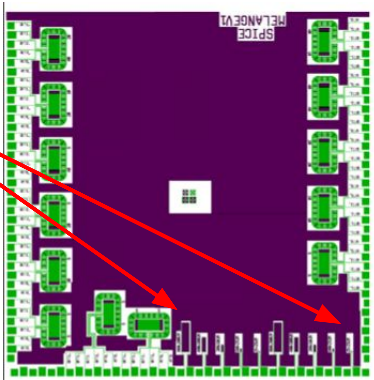


Table from Matt Pyle @UCB

$$\sigma_{<E>} \propto \sqrt{VT^3}$$

Volume (40nm thick)	Tc	Bias Power	Sensitivity (RMS)
25x100um^2	62mK	22.5fW	20meV
200x800um^2	19mK	3.6 fW	-
100x400um^2	19mK	Normal	-
25x25um^2	19mK	Future	est 1.7meV

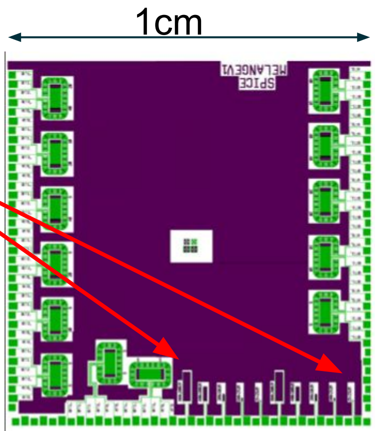
Detector performance

Testing bare TESs

Lower Tc, lower bias power, better sensitivity.

But…

Parasitic background power needs to be reduced!



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25x25um^2	19mK	Future	est 1.7meV

1K black body radiation from 1mm^2 is 56fW!

IR (black body radiation) RF (WiFi/radio/…) EMI (electromagnetic pick-up)

Detector performance

Testing bare TESs

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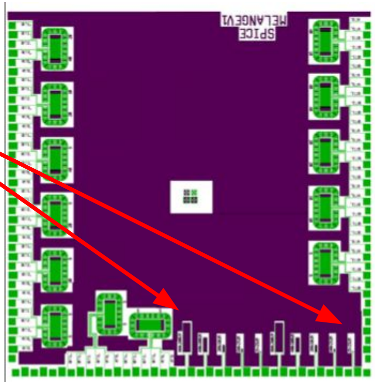
1cm



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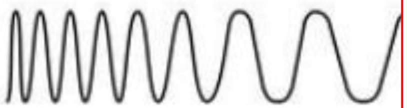

>100GHz 10(0Hz

IR (black body radiation))

- IR tight MC can just tested in Run 22
- Coppercast extrusion techniques for IR tight feedthroughs

Detector performance

Testing bare TESs

Lower Tc, lower bias power, better sensitivity.

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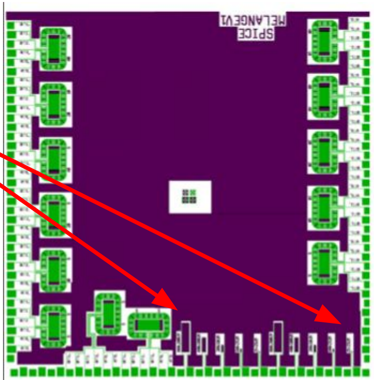

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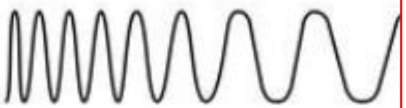
Volume (40nm thick)	Tc	Bias Power	Sensitivity
$25x100um^2$	62mK	22.5fW	20meV
$200x800um^2$	~~19mK~~ 28mK	~~3.6 fW~~ 8.1 fW	?
$100x400um^2$	28mK	Normal	-
$25x25um^2$	28mK	Future	3meV est

1K black body radiation from $1mm^2$ is 56fW!



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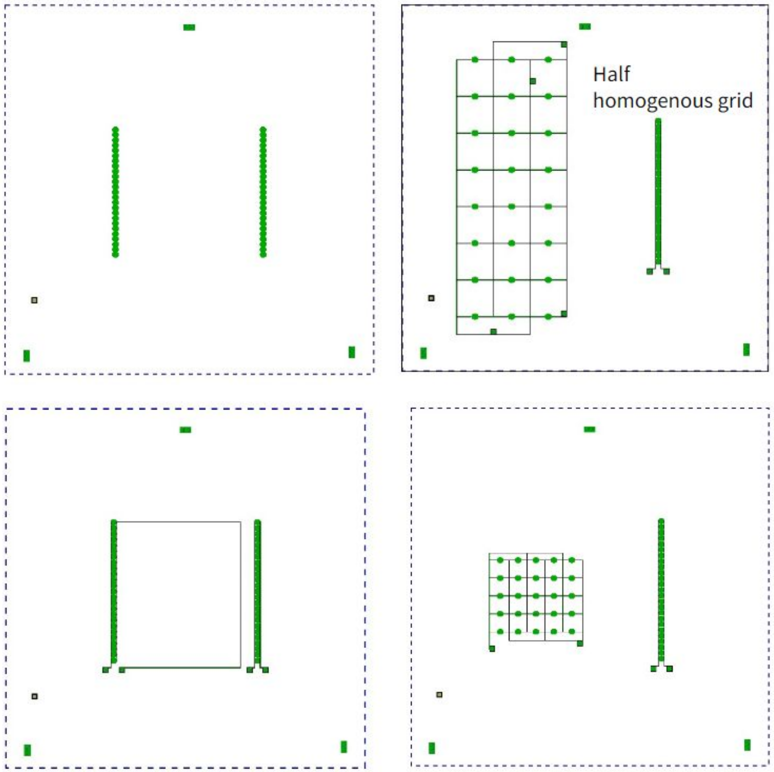
Parasitic power

IR+EMI+RF: Shielding + filtering



Special designs by Roger Romani to verify EMI parasitic power loading. Coming soon.

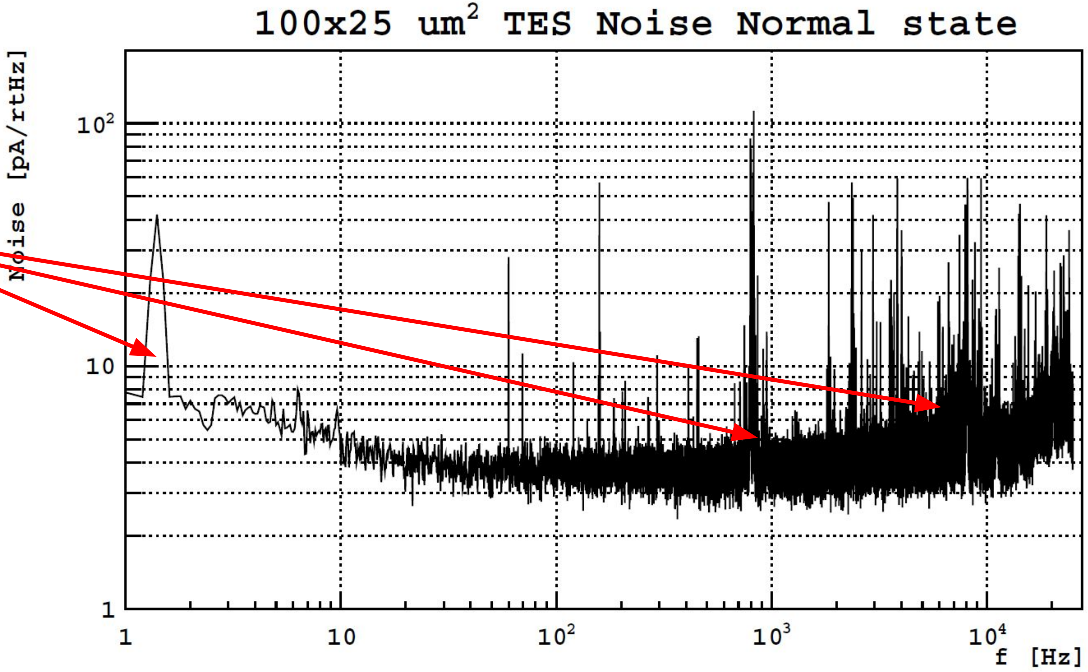
Parasitic power

IR+EMI+RF: Shielding + filtering

Vibration:

Correlated with the dilution refrigerator pulse tube

Could be vibration, Could be EMI as well.



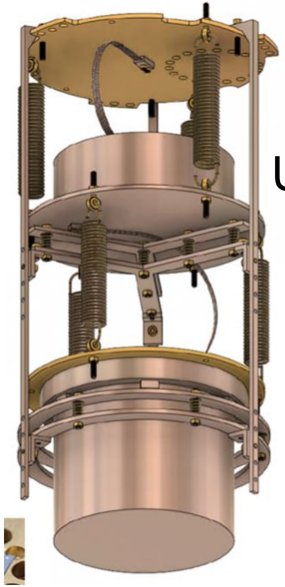
Parasitic power

IR+EMI+RF: Shielding + filtering

Vibration:
Helium battery (~4hr pulse tube off operation)
Hanging device (Roger's talk) & vibration decoupler at cold stage

BlueFors CRYOGENICS

LBL



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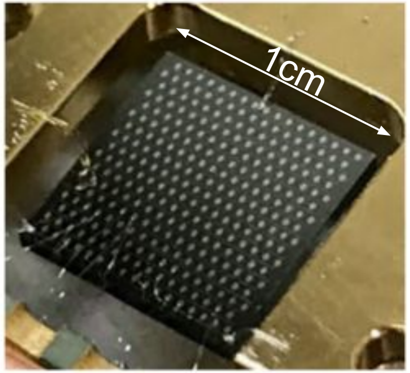

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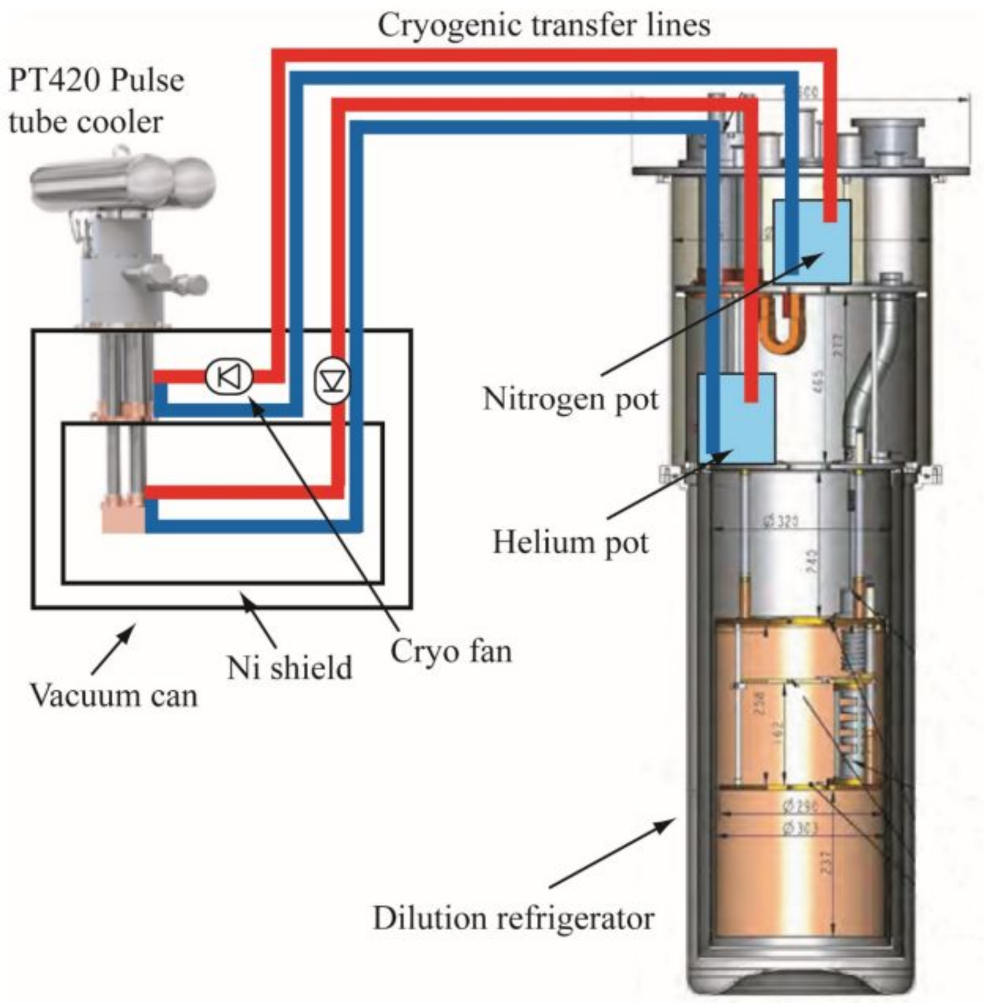
Dilution refrigerator with remote pulse tube (Matt Pyle, Wei Guo, Cryomech Inc, SBIR)



Parasitic power

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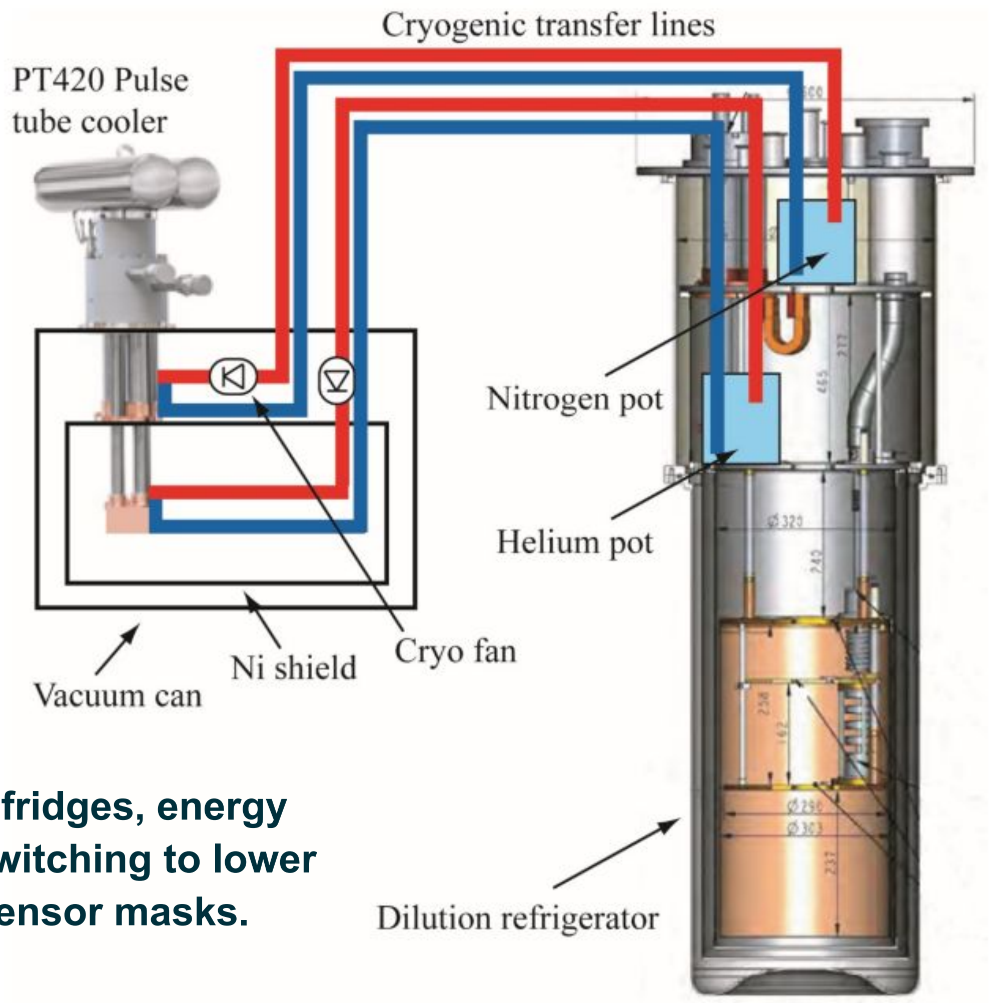


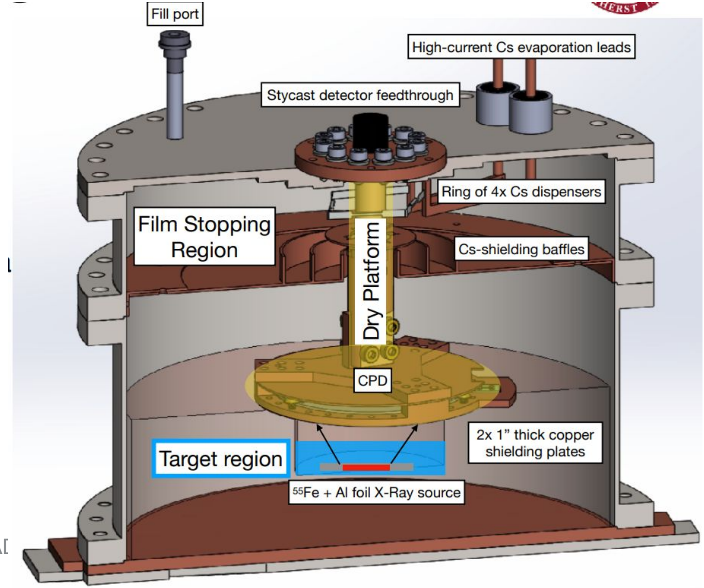
As we lowering the parasitic power in our fridges, energy resolution can be instantly improved by switching to lower Tc films with the same athermal phonon sensor masks.

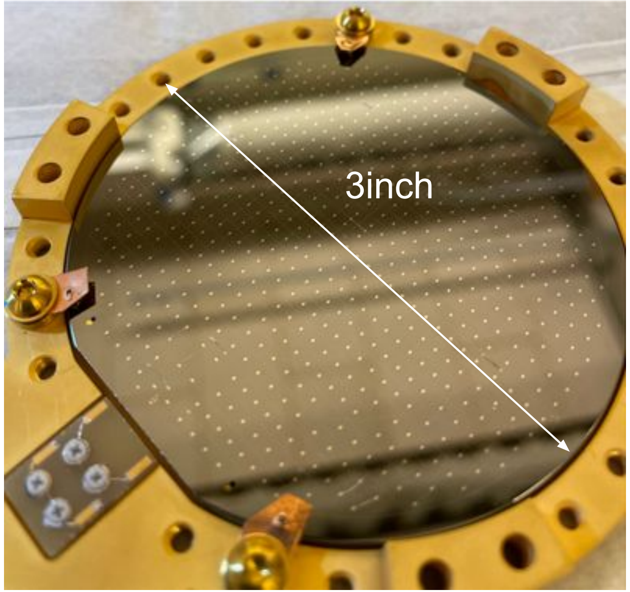
Cryogenic photon detector (CPD-v2)

Running @ UMass

Run as a Si detector first. Now running as a single channel readout for the superfluid helium target. See [Doug's presentation]

10.6g, 51mK Tc, 0.47pW bias power, active surface coverage 0.68%



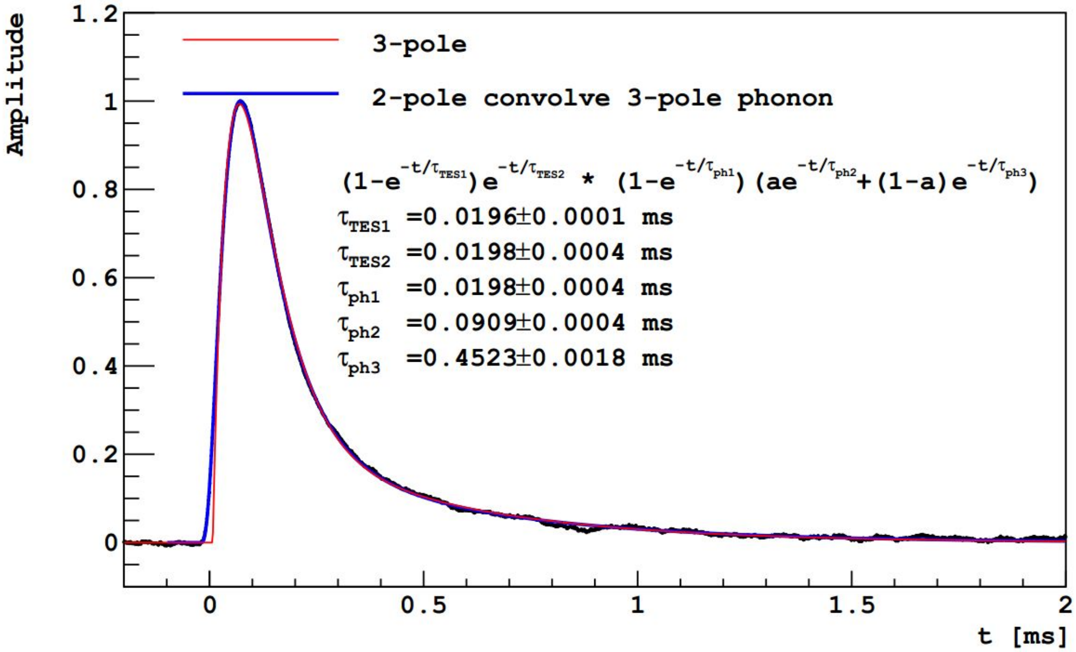


CPD performance -- pulse shape

Average of clean low-energy pulses.

Fit with a pulse model with two TES time constants and three phonon time constants.

χ^2 between signal and this template shows very good agreement.

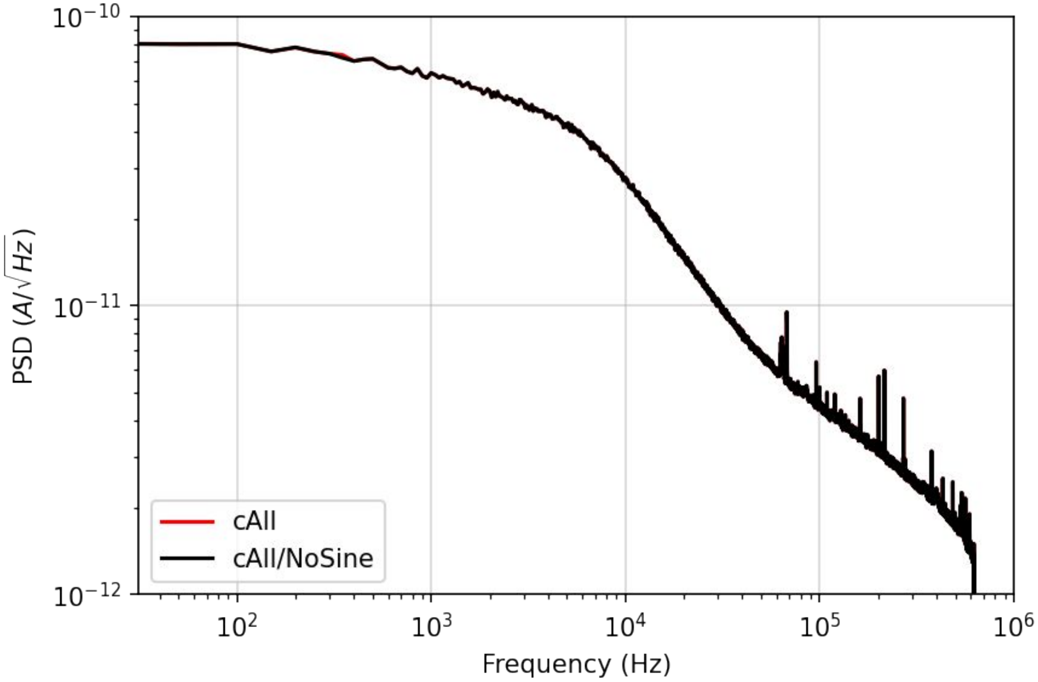


CPD performance -- noise

Noise PSD of flat baseline.

No identifiable EMI or vibration noise in the signal frequency band.

Higher noise than expected below 10kHz.
Further investigation needed.



Plots by Jack Nelson & Richard Germond

CPD performance -- energy calibration

Event true energy: Total energy deposition

Absorbed energy: Joule energy from the TES electrical-thermal feedback.

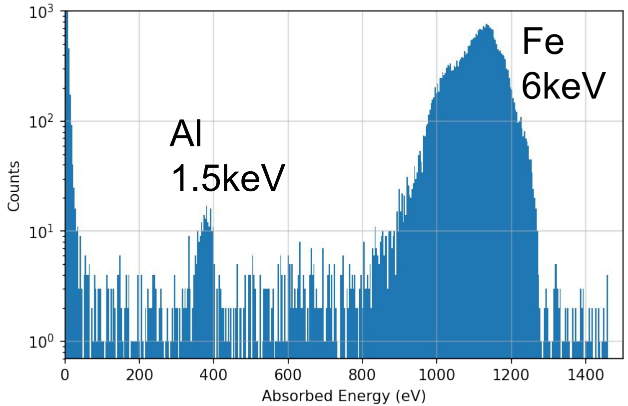
$$E_{absorbed} = \int \left[I(V_b - 2I_0R_L) - I^2R_L \right] dt = \text{total energy} * \eta$$

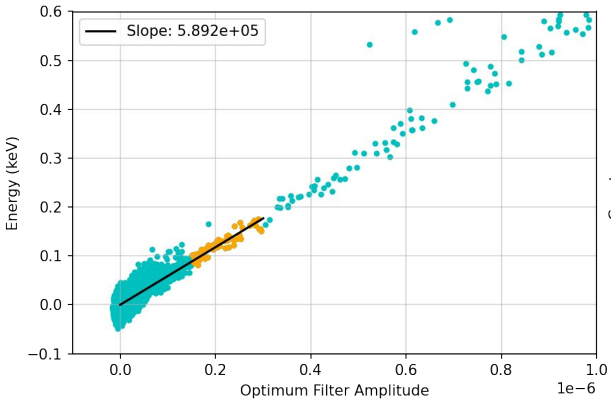
1.5keV Al calibration, η=25.4%

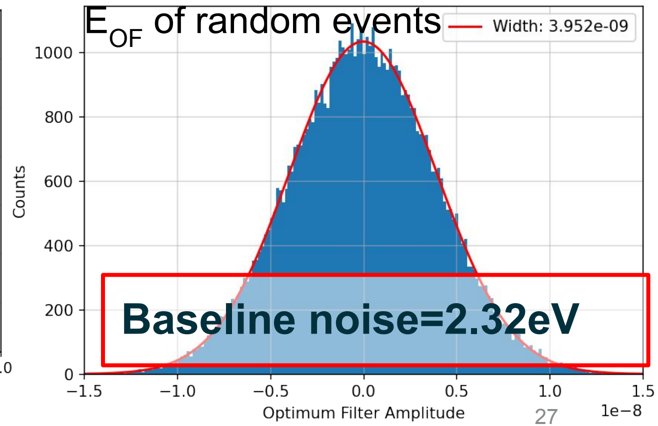
Optimum filtered amplitude: Best signal amplitude estimator.

$$E_{OF} = E_{absorbed}/\eta * k$$

Template pulse shape







Plots by Jack Nelson & Richard Germond

Detector event spectrum

Event energy spectrum of the CPDv2 detector.

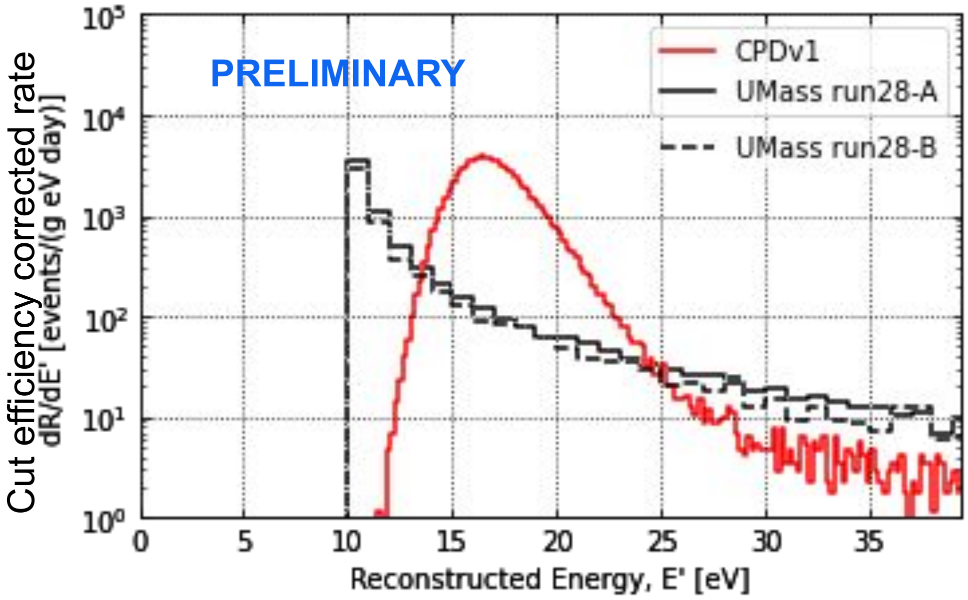
Run28A: 6 g*day

Run28B: 1.8 g*day

Trigger threshold = 4.5 σ = 10.4eV

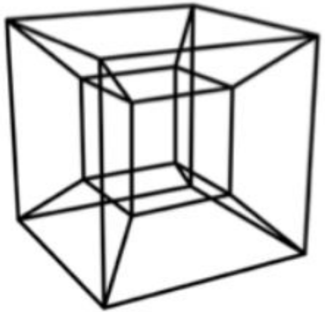
CPDv1 (PRL 127, 061801 (2021)) shown in red.

Data analysis in progress



Conclusion

- TES based low energy threshold athermal phonon sensor is a promising technique for low mass dark matter detection with different targets.
- Athermal phonon detector energy resolution scales as Tc^3.
- We have established stable fabrication processes to deposit W films of Tc's around 20mK. We will further looking for low-Tc low-stress W film deposition protocols.
- TESs fabricated with the low Tc films are tested. We are intensively working on parasitic power reduction in the dilution refrigerators.
- The 10g CPDv2 operating at UMass has a world-leading 2.32eV energy resolution.



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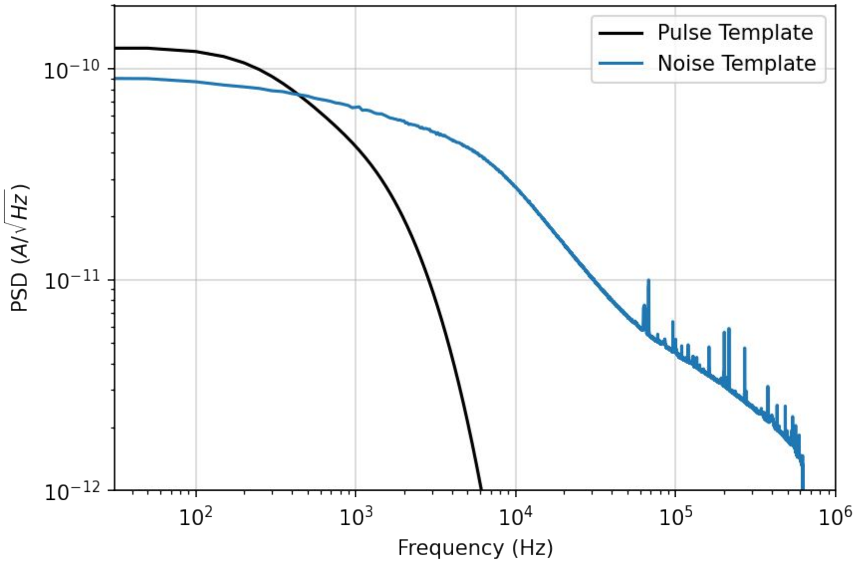
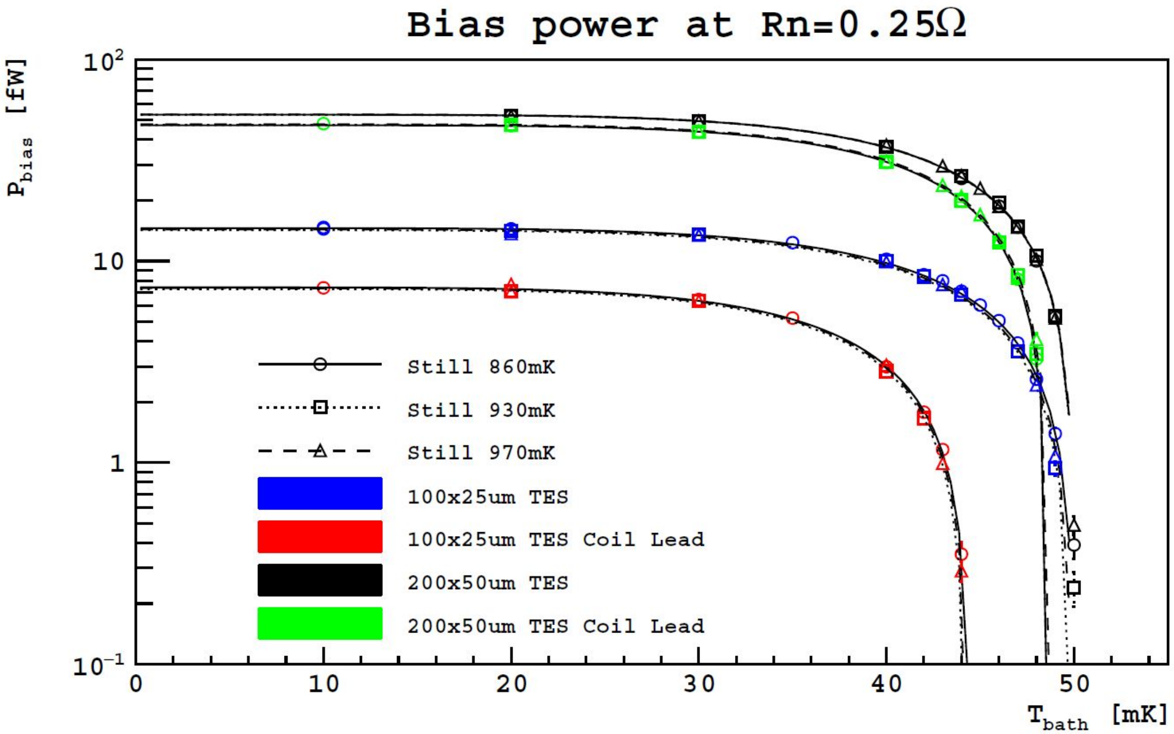
Back up

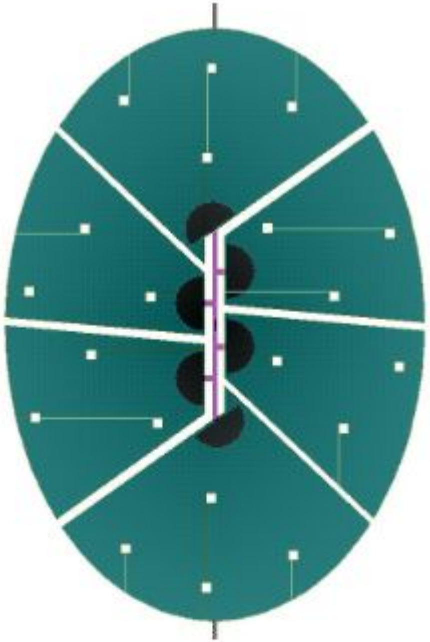
Noise PSD vs signal PSD



IR loading power test



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)