Design and characterization of solid noble bolometers

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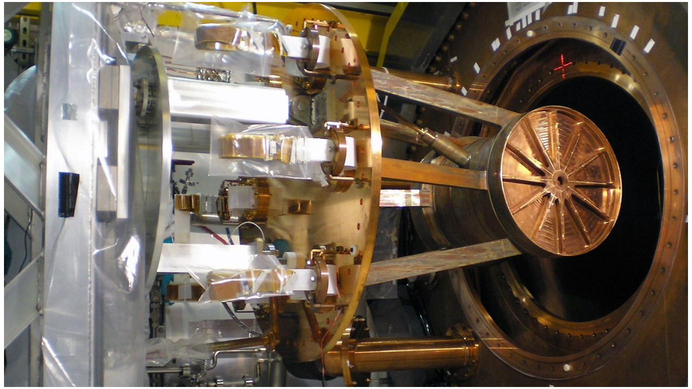
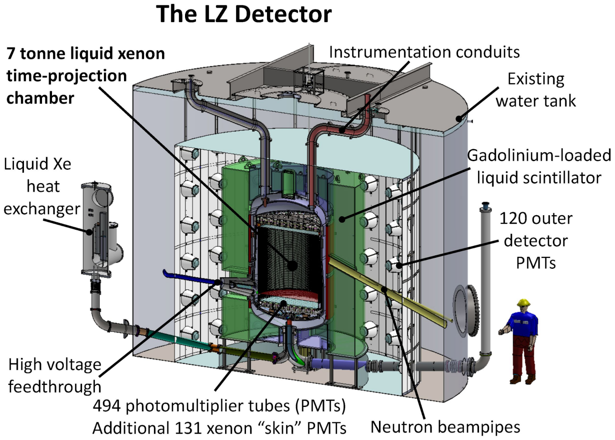
Drexel
UNIVERSITY

Noble Liquid Detectors

- Noble liquid time projection chambers can be used to probe fundamental physics.
    - Direct detection of dark matter
    - Neutrinoless double beta decay
    - Neutrino oscillations
- Typically use liquid argon or xenon.
- These detectors use a combination of scintillation (light) and ionization (charge) signals to reconstruct the position and energy of events.



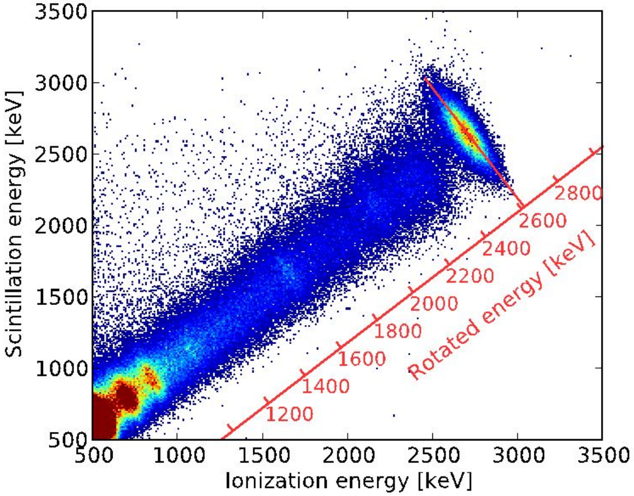
EXO-200: Neutrinoless Double Beta Decay

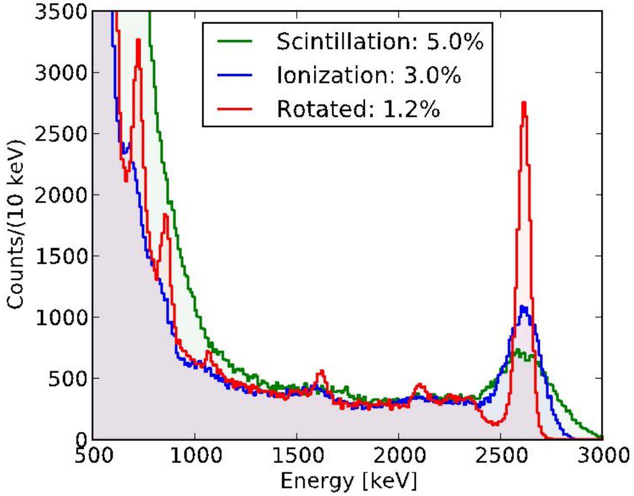


LZ: WIMP Dark Matter

Anti-correlation in liquid xenon detectors

EXO-200 Th-228 source data*:

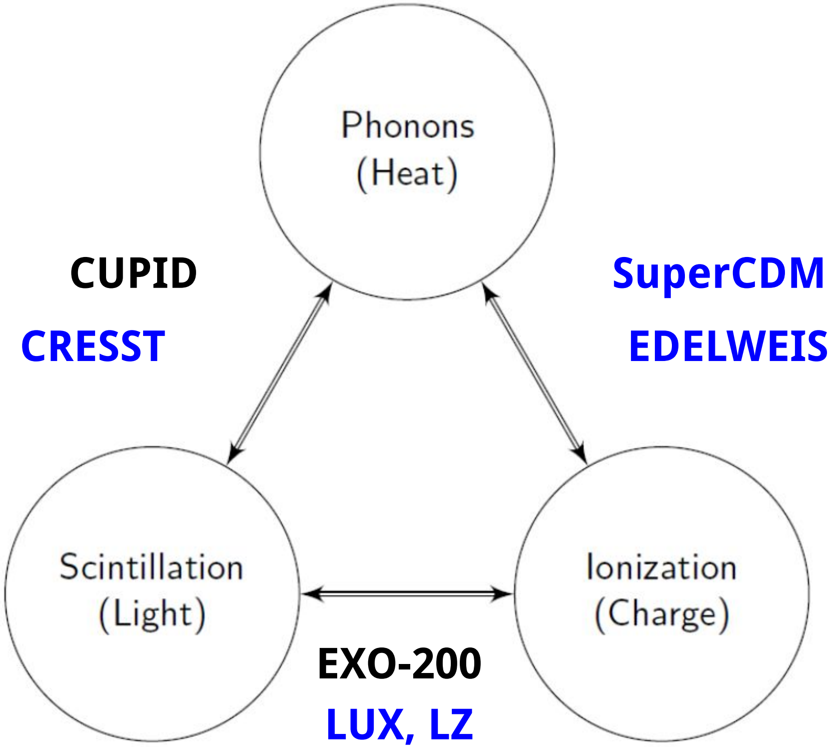




- Microscopic anti-correlation between energy channels seen in many detectors/experiments.
- Modeled well and provides improvements in energy resolution, but not understood from first principles. [NEST, M. Szydagis et al. (2011)].
- Energy measurements in all three channels could provide information about energy partitioning in existing and future detectors.

*Plots courtesy of EXO-200

Energy Deposition in Cryogenic Detectors



CUPID

CRESST

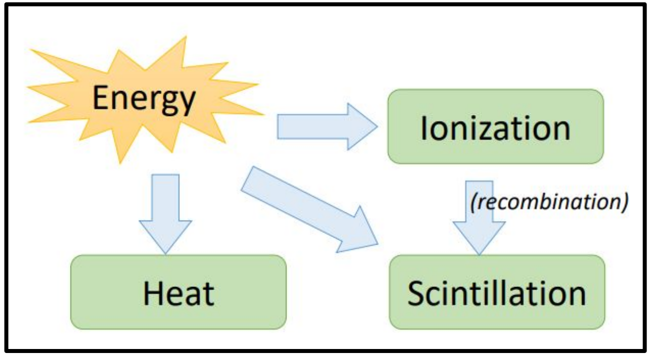
SuperCDMS

EDELWEISS

EXO-200

LUX, LZ

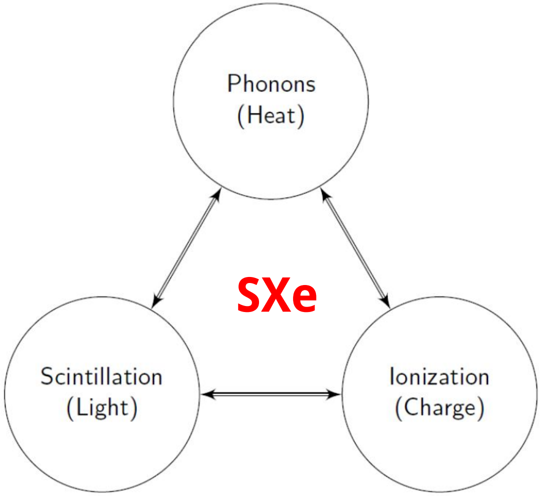
XENON1T/nT

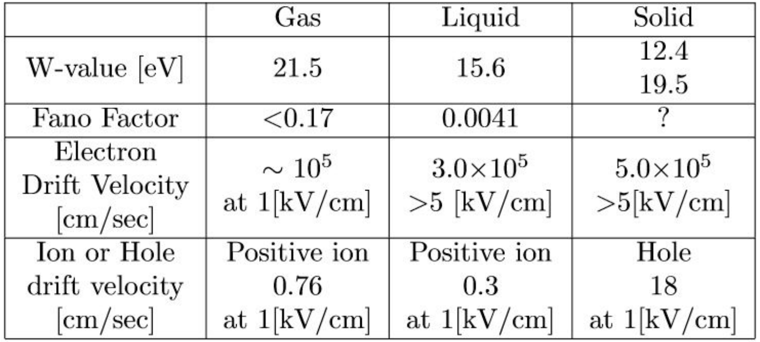


- **Neutrinoless Double Beta Decay**
- **Dark Matter**

...and more.

Solid Xenon Bolometers





	Gas	Liquid	Solid
W-value [eV]	21.5	15.6	12.4 19.5
Fano Factor	<0.17	0.0041	?
Electron Drift Velocity [cm/sec]	$\sim 10^5$ at 1[kV/cm]	3.0×10^5 >5 [kV/cm]	5.0×10^5 >5[kV/cm]
Ion or Hole drift velocity [cm/sec]	Positive ion 0.76 at 1[kV/cm]	Positive ion 0.3 at 1[kV/cm]	Hole 18 at 1[kV/cm]

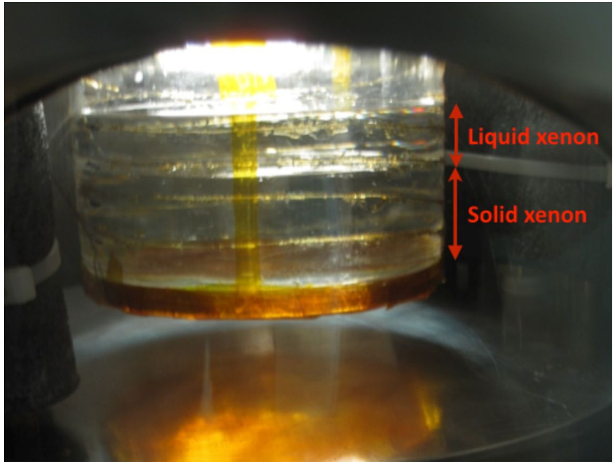
- A solid xenon bolometer could tap into all three energy channels, providing useful information about the anti-correlation phenomenon.
- Solid xenon would retain many of the good qualities that come with a liquid xenon detector, with the additional benefits of a phonon channel.
- ~10,000 phonons / keV
  - Better counting statistics → Better energy resolution

Table values from:
H. Nawa et al., *Proc. of IEEE 13th ICDL (1999)*

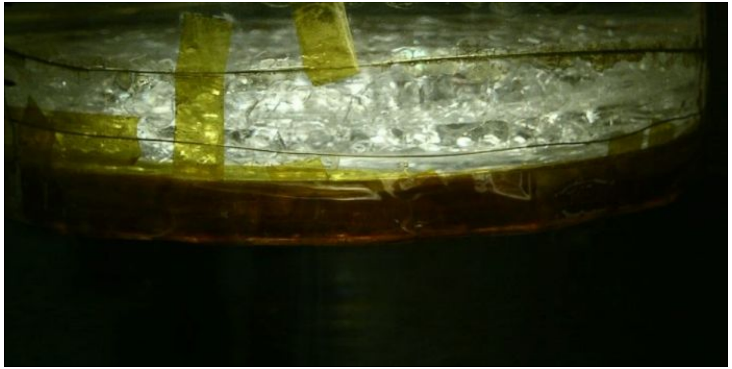
Prior Solid Xenon R&D

A group at Fermilab had a solid xenon R&D platform:

- Used an LN cryostat to condense and freeze xenon in a glass chamber.
- Performed scalability studies for SXe as a detector medium for dark matter, ~1 kg optically transparent sample.
- Demonstrated that SXe growth should be slow to obtain optical transparency.
- Measured electron drift velocities over a range of electric fields in the solid phase.



Optically transparent SXe

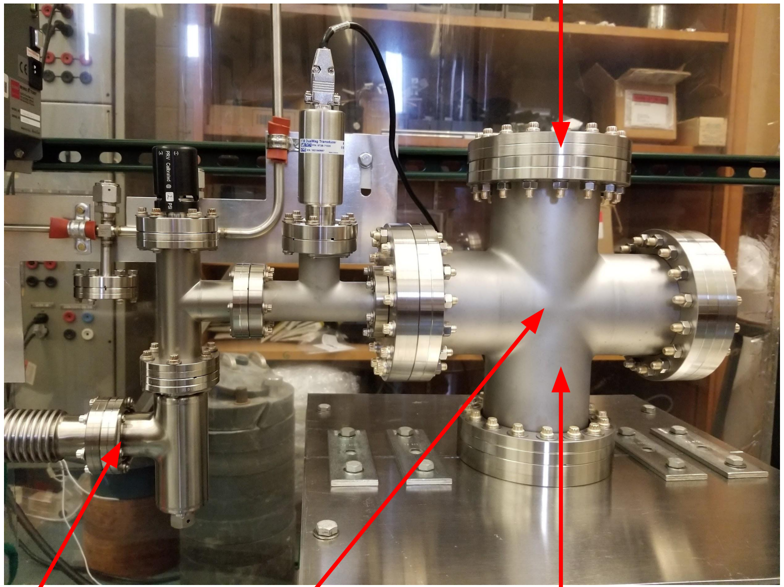


Polycrystalline sample of SXe

Images from Yoo, J. et al. JINST 10 (2015)

Solid Xenon @ Drexel

- Currently working towards the growth of a 1 cm^3 solid sample down to 4.2 K, using vapor deposition and a closed-cycle helium cryocooler.
- Sample growth system almost ready for commissioning.
- This phase will focus on determining the optimal method for growing solid noble samples (argon and xenon).
- Ideal for preliminary scintillation and ionization measurements.



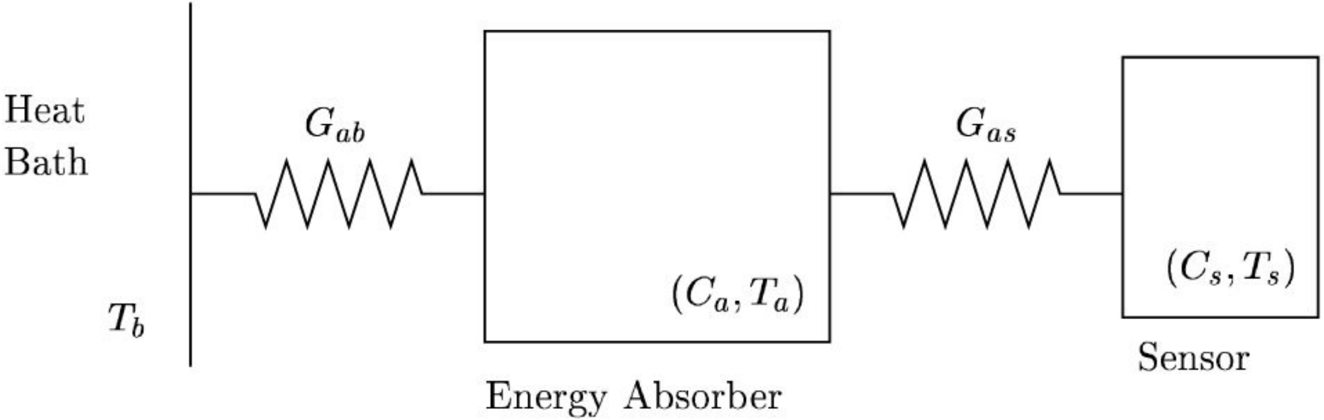
Ar/Xe Gas Inlet

Growth chamber

To vacuum pump

Cryocooler (below)

Simple bolometer thermal model



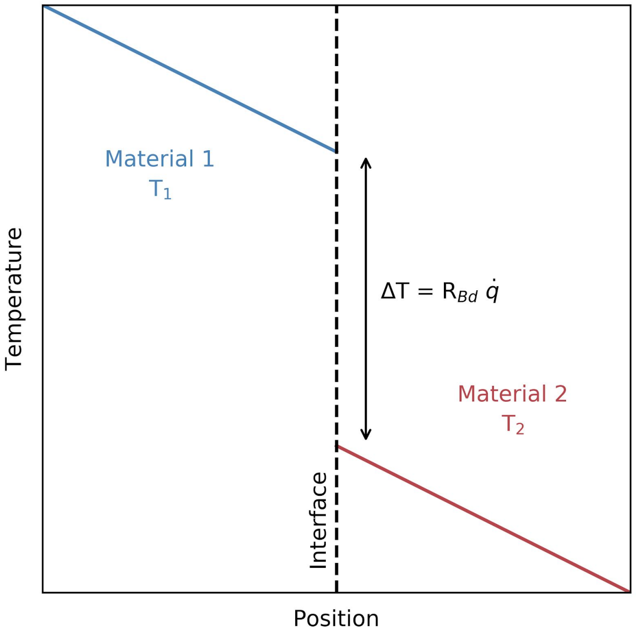
- For a small heat capacity and low temperature, energy deposited by an interaction changes the temperature of the absorber by fractions of a mK.
- This change in temperature is detected by the sensor, and heat flows out of the absorber and sensor into the heat bath, returning to an equilibrium.
- The dynamic behaviour of the system is highly dependent on the values of the thermal conductances.

Image from Marisa Pedretti, PhD. Thesis, Università degli Studi dell'Insubria (2004).

Thermal considerations

Significant design challenge: thermal boundary resistance

- No existing data on the boundary resistance between noble solids (excluding helium) and other materials.
- For a solid noble deposited on a substrate:
  - Total conductance between the absorber and thermal bath will determine time constants for heat pulses.
  - Thermal bonding between absorber and thermistor is also a boundary resistance.
- Acoustic mismatch model (AMM):
  - Assume all phonons specularly reflect/refract/mode convert.
- Diffuse mismatch model (DMM):
  - Assume all phonons scatter diffusely at the interface.



Computing conductance across a boundary (AMM)

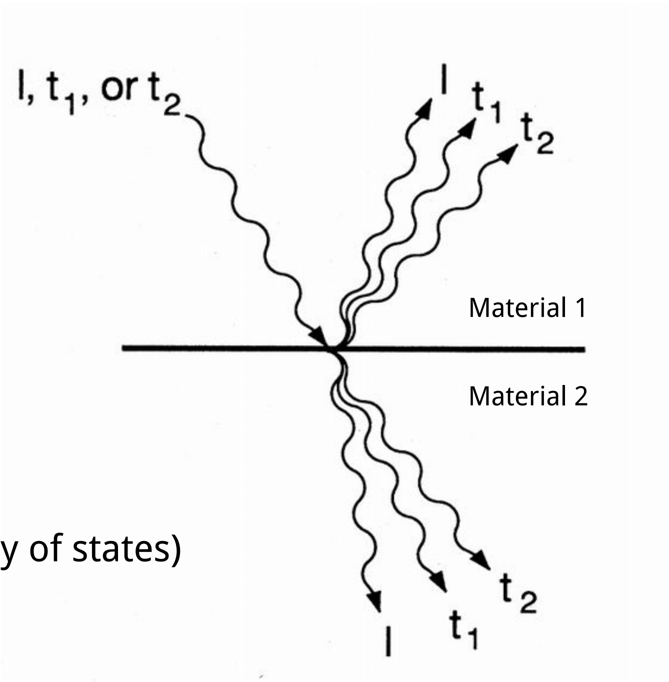
$$\alpha^{\mathrm{AMM}}_{1\to 2,j}(\theta) = \frac{4\rho_1\rho_2 v_{1,j} v_{2,j}}{(\rho_1 v_{1,j} + \rho_2 v_{2,j})^2}$$

$$\Gamma_{1,j} = \int_0^{\pi/2} \alpha_{1\to 2,j}(\theta)\cos(\theta)\sin(\theta)d\theta$$

$$G^{\mathrm{AMM}}_{Bd} = \frac{1}{R^{\mathrm{AMM}}_{Bd}} = \frac{1}{2}\sum_j v_{1,j}\Gamma_{1,j}\int_0^{\omega_{\max}} \hbar\omega \frac{dN_{1,j}(\omega,T)}{dT}d\omega$$

$$G^{\mathrm{AMM}}_{Bd} = \frac{\pi^2 k_b^4}{15\hbar^3}\sum_j \frac{\Gamma_{1,j}T^3}{v_{1,j}^2}$$

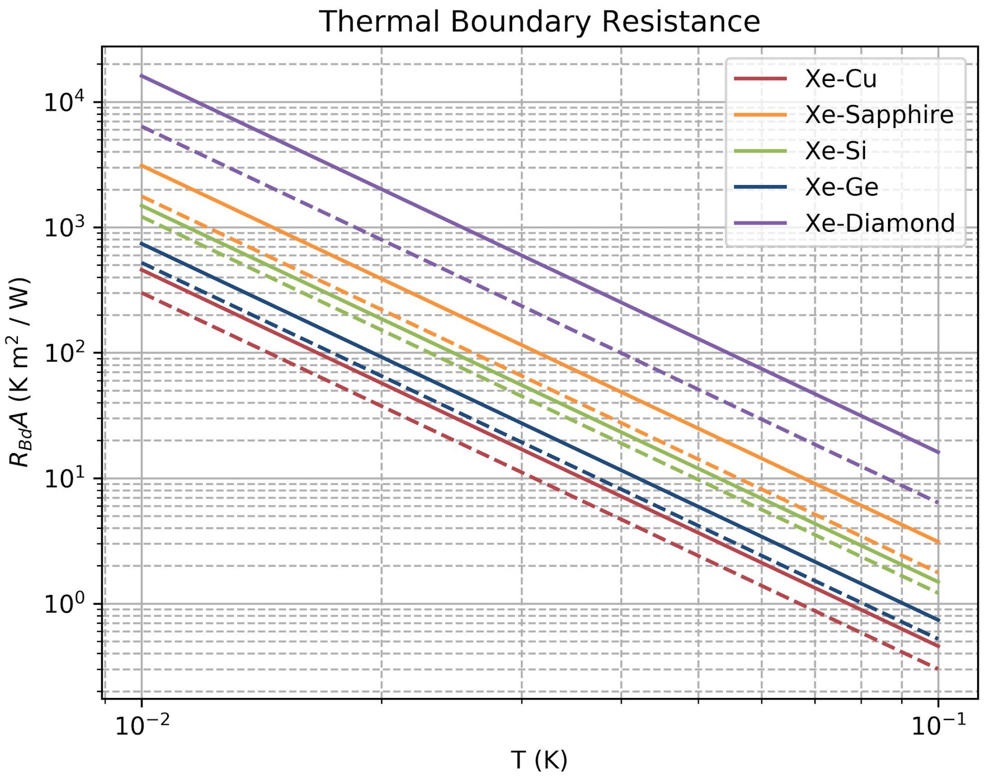
(For Debye density of states)



The calculation for DMM is very similar, the only change is the transmission probability

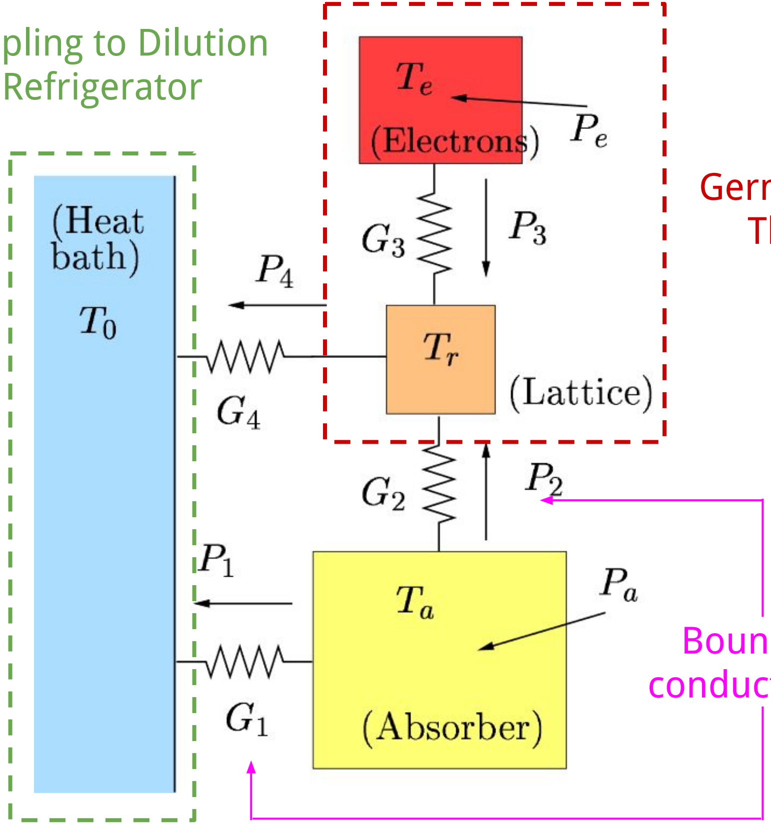
For a review of AMM and DMM, see Swartz and Pohl, Rev. Mod. Phys., Vol. 61, No. 3, (1989)

Calculated thermal boundary resistances



Solid lines: AMM
Dashed lines: DMM

Bolometer thermal model

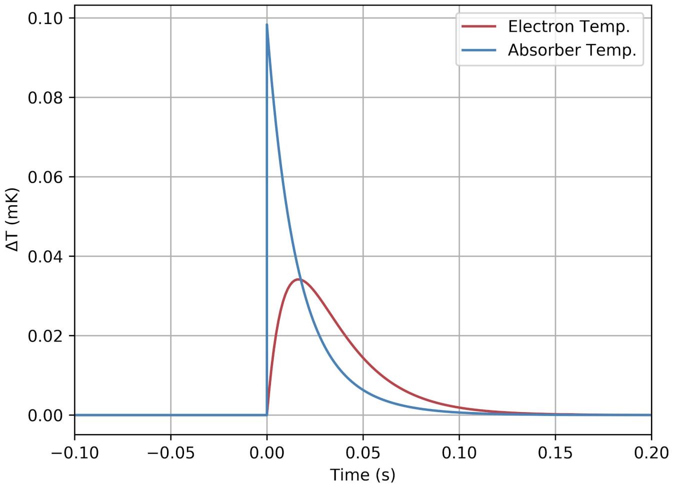


Coupling to Dilution Refrigerator

Germanium NTD Thermistor

Boundary conductances

1.0 MeV energy deposition @ 20 mK for a preliminary SXe bolometer design



- 1 cm^3 sample of solid xenon thermally coupled to a quartz substrate.
- Conductances between Xe-Quartz and Xe-Ge calculated from AMM.

Image and thermistor values from Marisa Pedretti, PhD. Thesis, Università degli Studi dell'Insubria (2004).

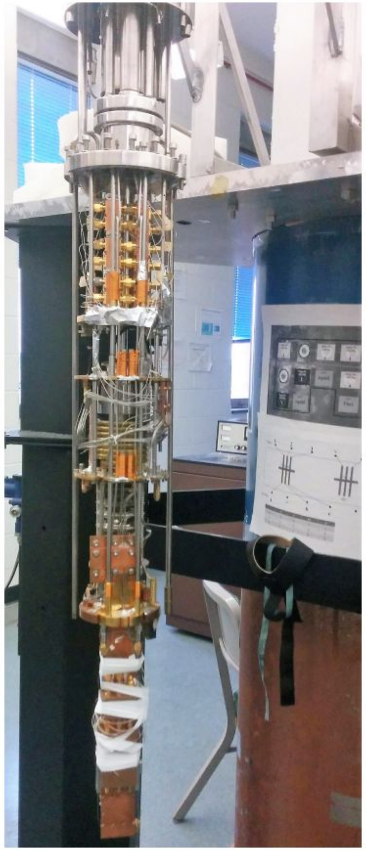
Solid Xenon @ Drexel

<u>Now:</u>

- Finalizing construction of the growth apparatus
- Interfacing with existing noble gas purification hardware

<u>In the future:</u>

- Sample growth studies with argon and xenon
  - How fast can a sample be grown using vapor deposition?
- In situ growth of samples onto instrumentation (for charge and light)
- Move setup to the Drexel dilution refrigerator (~20 mK)
- Finalize detector/bolometer design and instrument all three energy channels



Drexel dilution refrigerator

Summary

- Anti-correlation between energy channels is well modeled and used to improve energy resolution, but not understood from first principles.
- Current work at Drexel aimed towards developing an R&D platform for solid argon and xenon sample growth and instrumentation.
- A bolometer model for phonon readout that uses theoretical thermal conductances has been developed.
- Our goal is to read out all three energy channels (heat, charge, light) from these samples to further the understanding of energy deposition in current and future detectors.