Phonon Focusing in Cryogenic Calorimeters

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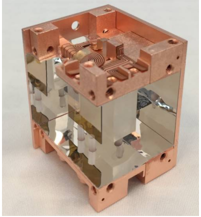
35th IMPRS Workshop – June 28, 2016

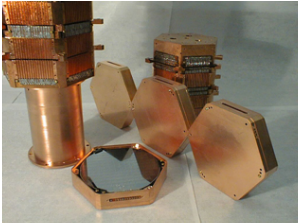
Applications of Cryogenic Calorimeters

Rare-Event Searches

Direct search for dark matter

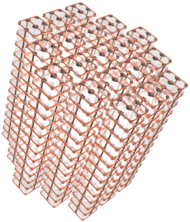
CRESST-III

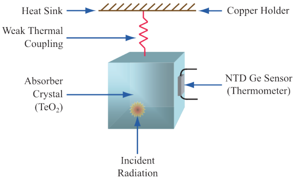




SuperCDMS

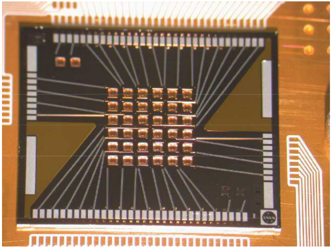
Neutrinoless Double-Beta-Decay



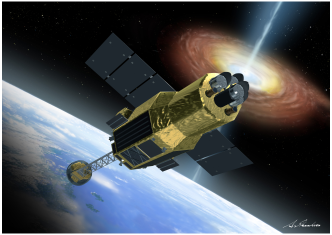


CUORE

Astronomy



Soft X-ray Spectrometer (Hitomi Satellite Mission)



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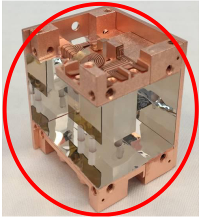

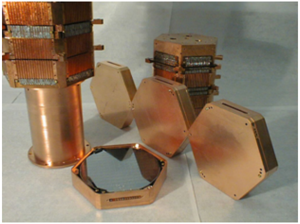

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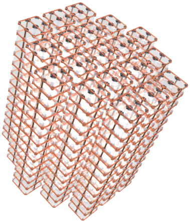

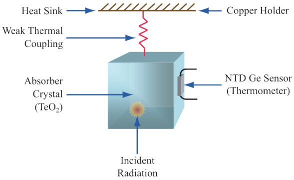

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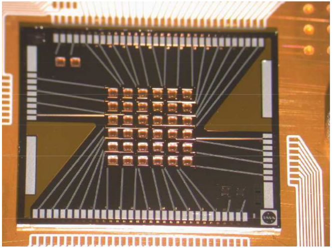

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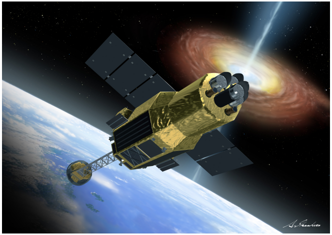
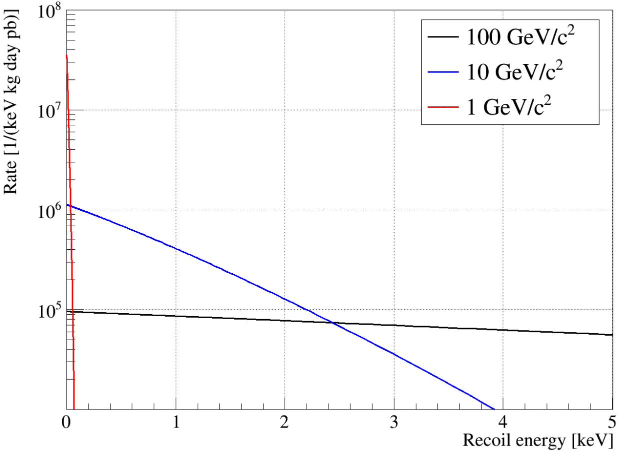


Outline

Predicting Energy Thresholds

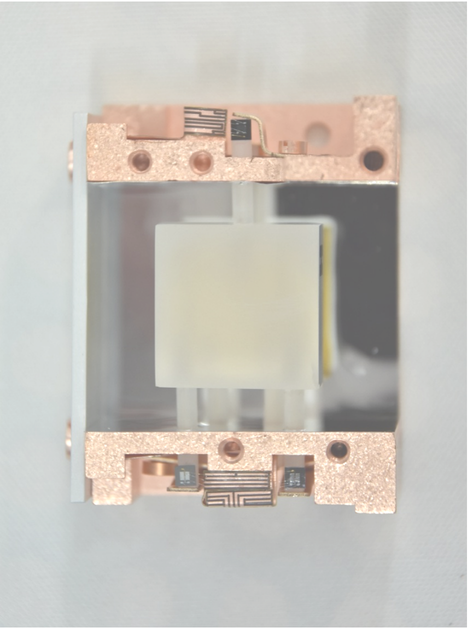
Importance of a Low Energy Threshold



$\longleftarrow$

lower dark matter particle mass

Pulse Height in Cryogenic Calorimeters



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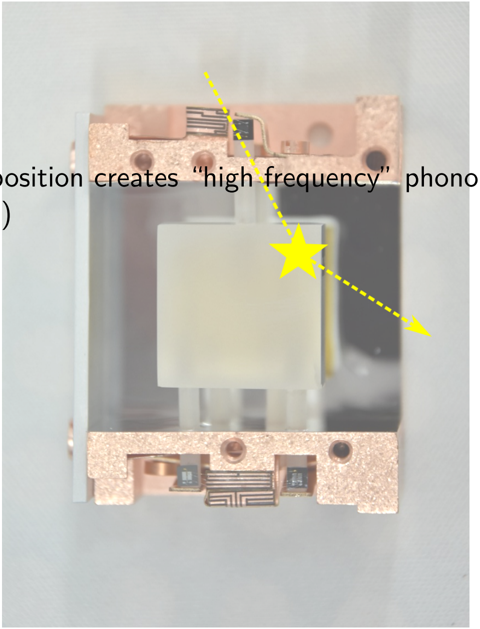
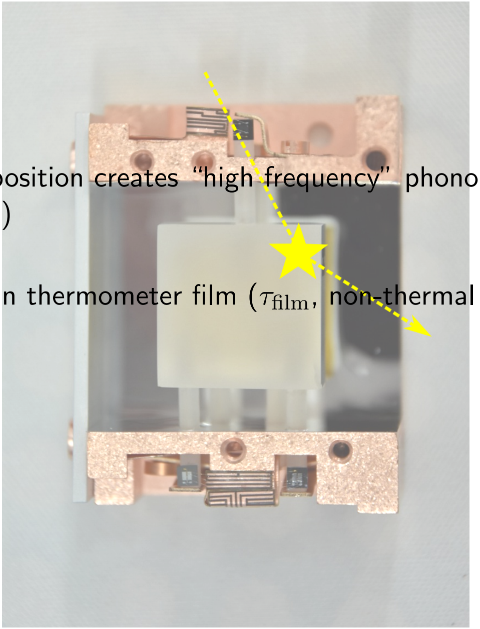


1. Energy deposition creates "high frequency" phonons (out of thermal equilibrium)

Pulse Height in Cryogenic Calorimeters



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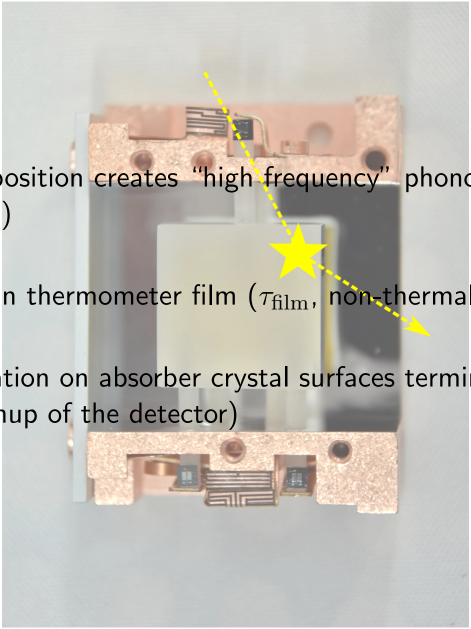
2. Detection in thermometer film ($\tau_{\rm film}$, non-thermal signal)

Pulse Height in Cryogenic Calorimeters



1. Energy deposition creates "high frequency" phonons (out of thermal equilibrium)

2. Detection in thermometer film (τ_{film}, non-thermal signal)

3. Thermalization on absorber crystal surfaces terminates signal (τ_{crystal}, slight warmup of the detector)

Pulse Height in Cryogenic Calorimeters

$$\Delta T = \underbrace{\frac{1/\tau_{\mathrm{film}}}{1/\tau_{\mathrm{crystal}} + 1/\tau_{\mathrm{film}}}}_{\text{collection efficiency}} \cdot \frac{\Delta E}{C_{\mathrm{film}}}$$

Pulse Height in Cryogenic Calorimeters

$$\Delta T = \underbrace{\frac{1/\tau_{\text{film}}}{1/\tau_{\text{crystal}} + 1/\tau_{\text{film}}}}_{\text{collection efficiency}} \cdot \frac{\Delta E}{C_{\text{film}}} \approx \frac{\tau_{\text{crystal}}}{\tau_{\text{film}}} \cdot \frac{\Delta E}{C_{\text{film}}}$$

$$\tau_{\text{crystal}} \ll \tau_{\text{film}}$$

Pulse Height in Cryogenic Calorimeters

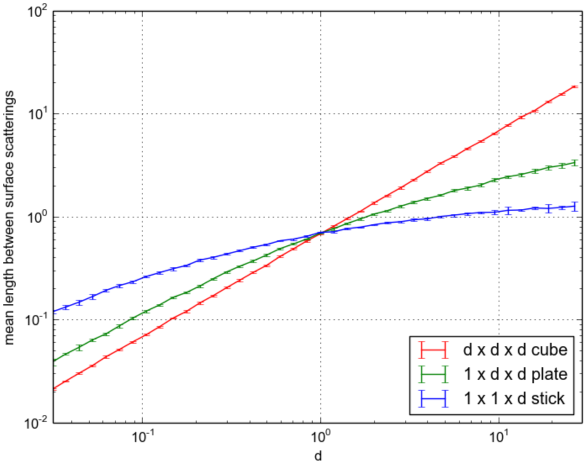
$$\Delta T = \mu \cdot \frac{l_{sc}}{V_a} \cdot \frac{A_t}{V_t} \cdot \Delta E$$

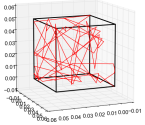
l_{sc}: mean length between surface scatterings

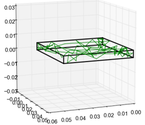
μ: material constant

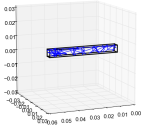
- sound speed
- phonon transmission into thermometer
- thermalization probability at crystal surface

Surface Scattering Lengths for Different Geometries

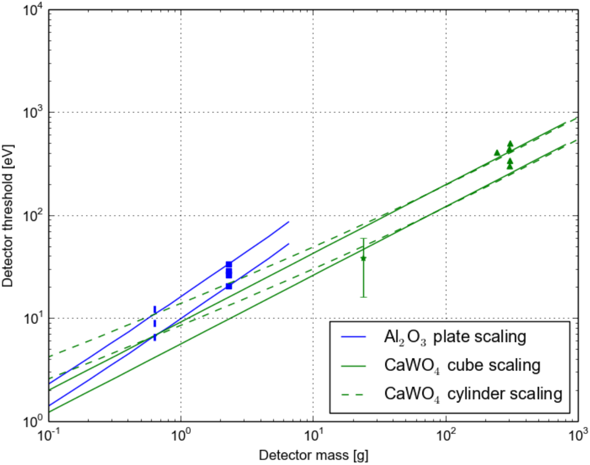








Threshold Predictions



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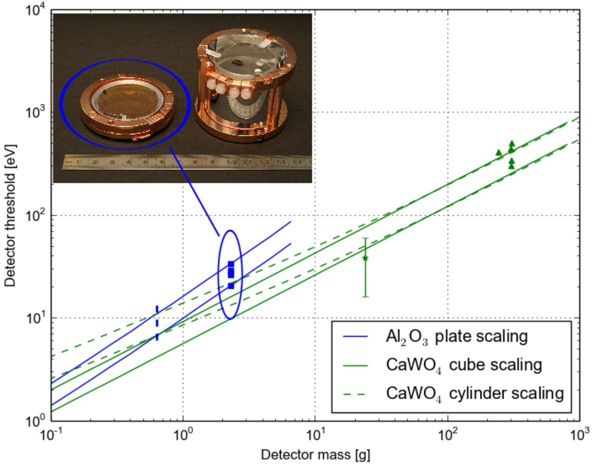
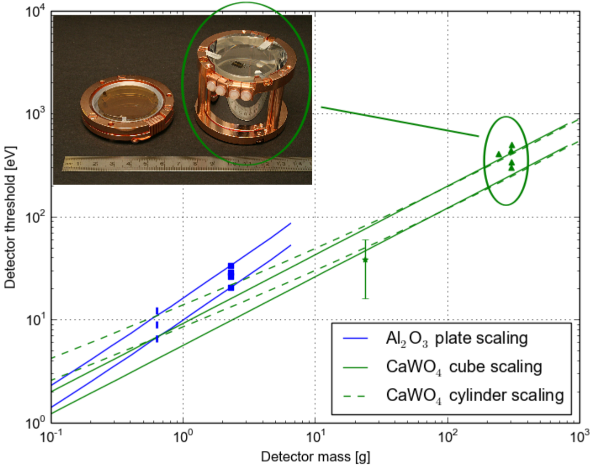


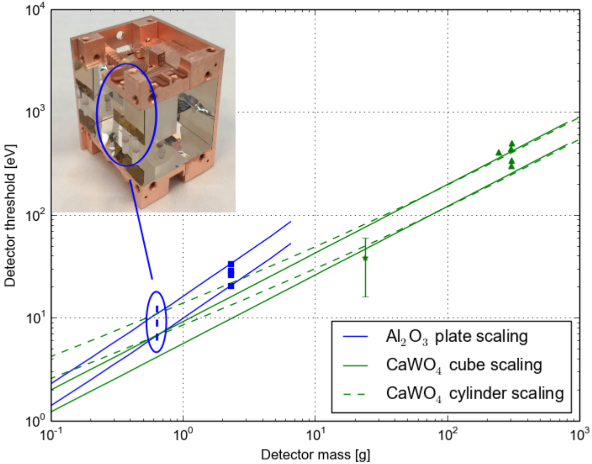
CRESST-II light detectors: predictions scaled to measured thresholds

Threshold Predictions



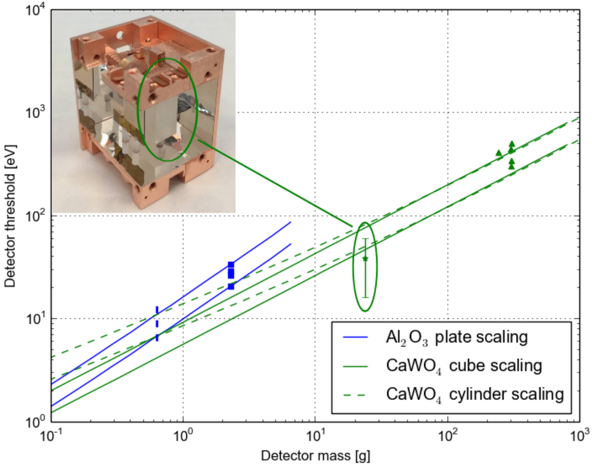
CRESST-II phonon detectors: independent measurement confirms model

Threshold Predictions



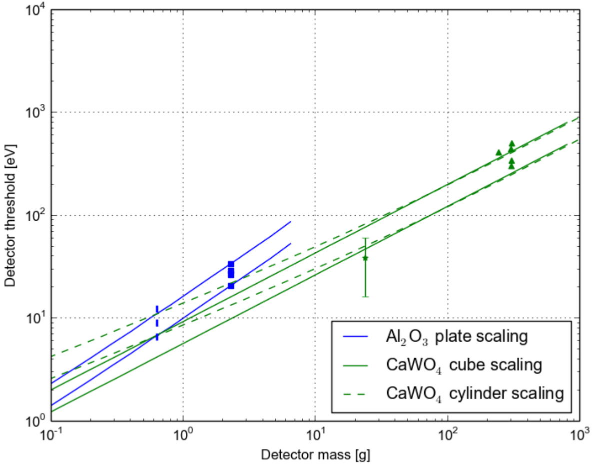
CRESST-III light detector: threshold lowered by a factor of 3 from scaling

Threshold Predictions



CRESST-III phonon detector: threshold < 100 eV (design goal exceeded)

Threshold Predictions

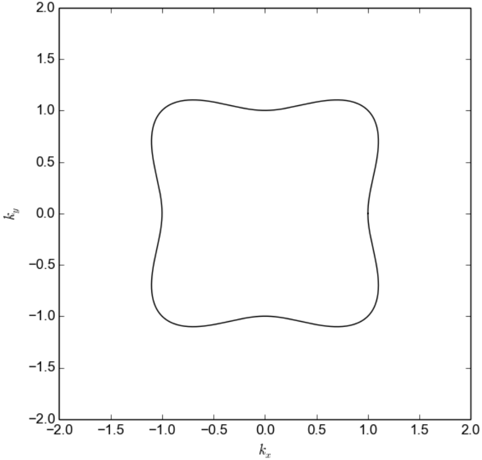


All modeling assumes isotropic phonon propagation!

Phonon Focusing in Anisotropic Crystals

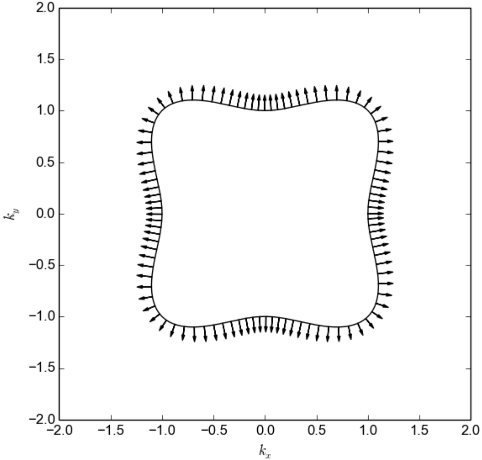
Phonon Focusing: Anisotropic Elasticity

$$\omega(k) \rightarrow \omega(\vec{k})$$



Phonon Focusing: Anisotropic Elasticity

$$\vec{v_g} = \vec{\nabla}_k \, \omega$$



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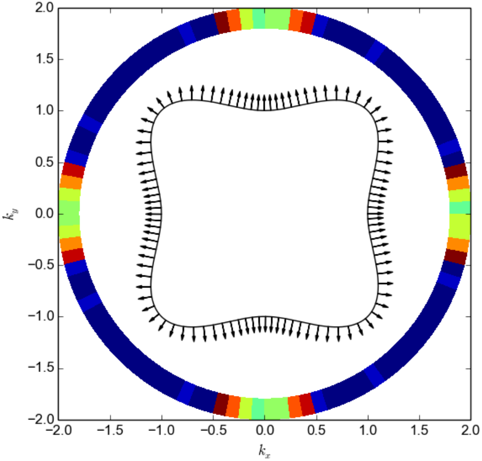
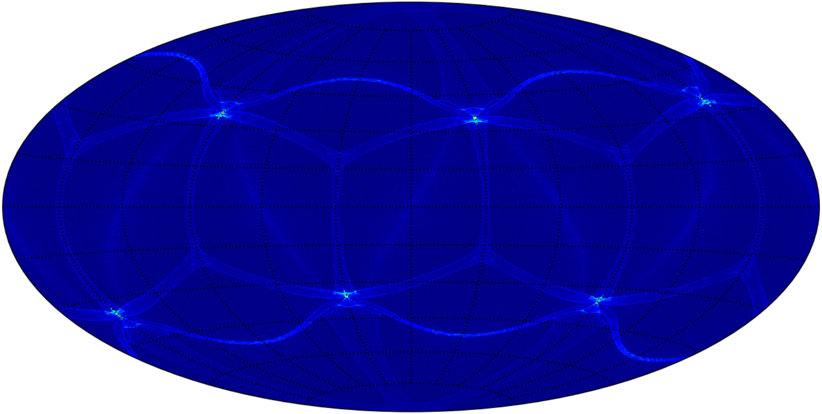


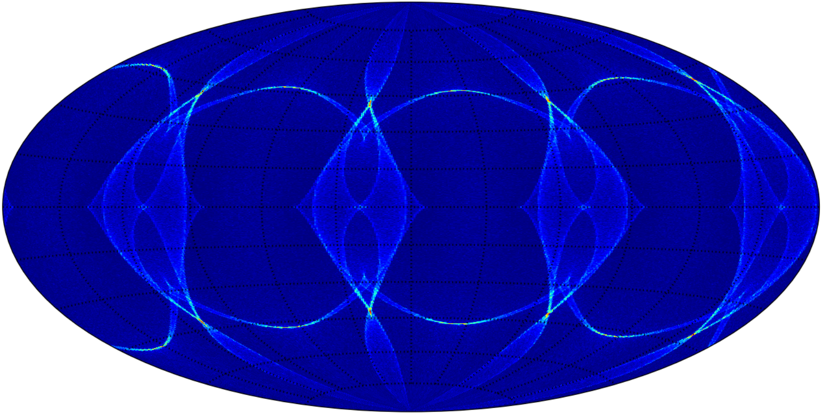
Phonon Focusing: Patterns in CRESST Materials

Sapphire



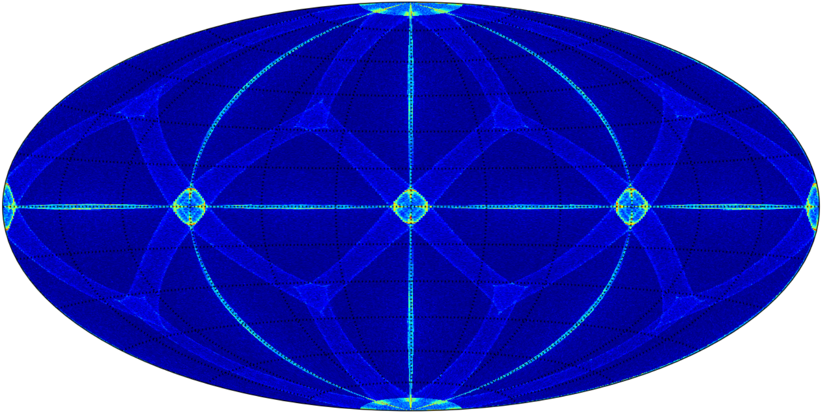
Phonon Focusing: Patterns in CRESST Materials

$CaWO_4$



Phonon Focusing: Patterns in CRESST Materials

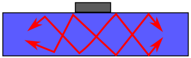
Silicon



Effects in Cryogenic Detectors

Increasing Pulse Height $(\propto \tau_{\mathrm{crystal}}/\tau_{\mathrm{film}})$

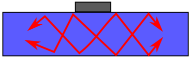
In Planar Geometries:



Maximize in-plane propagation!
(choosing the lattice orientation)

Increasing Pulse Height $(\propto \tau_{\mathrm{crystal}}/\tau_{\mathrm{film}})$

In Planar Geometries:



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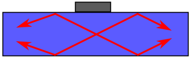
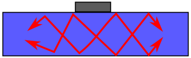


$\Rightarrow \tau_{\mathrm{crystal}}$ grows, but τ_{film} also grows
(longer, but not higher pulses)

Increasing Pulse Height $(\propto \tau_{\mathrm{crystal}}/\tau_{\mathrm{film}})$

In Planar Geometries:



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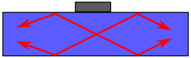

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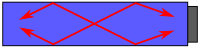
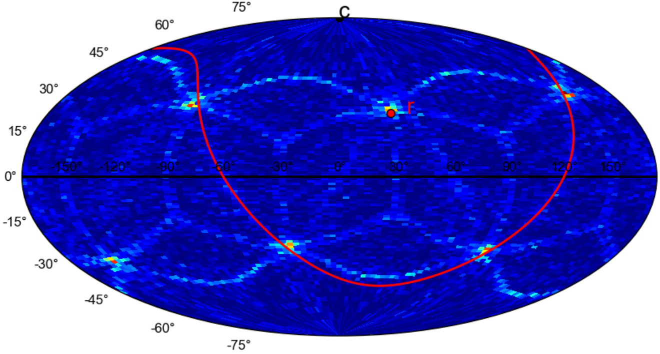


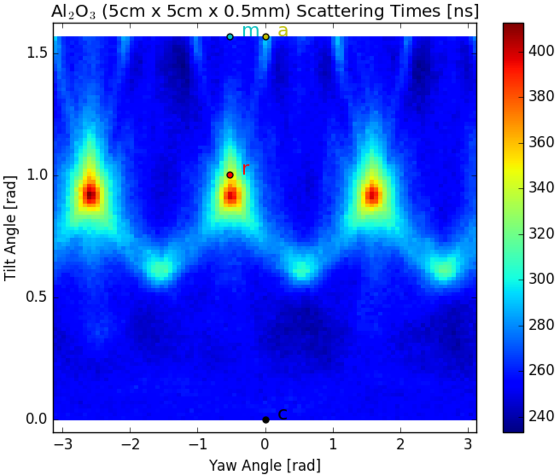
$\Rightarrow$ lowering τ_{film} while keeping τ_{crystal} high

Quantitative Estimates

Sapphire: maximizing in-plane propagation



Quantitative Estimates



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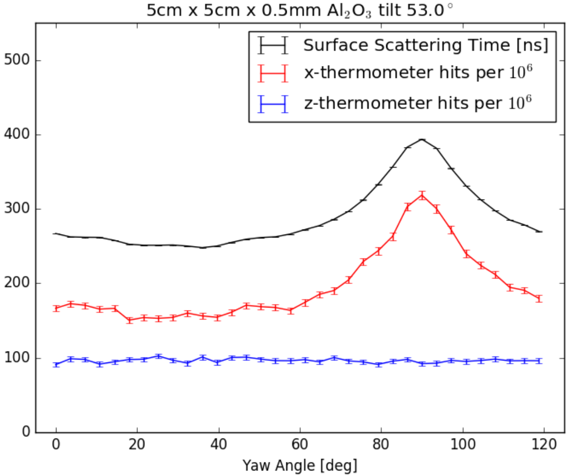
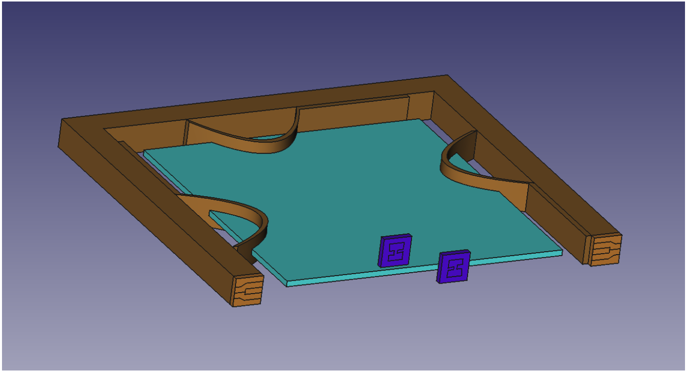


Experimental Testing

Simultaneous comparison:
"face"-thermometer vs. "edge"-thermometer



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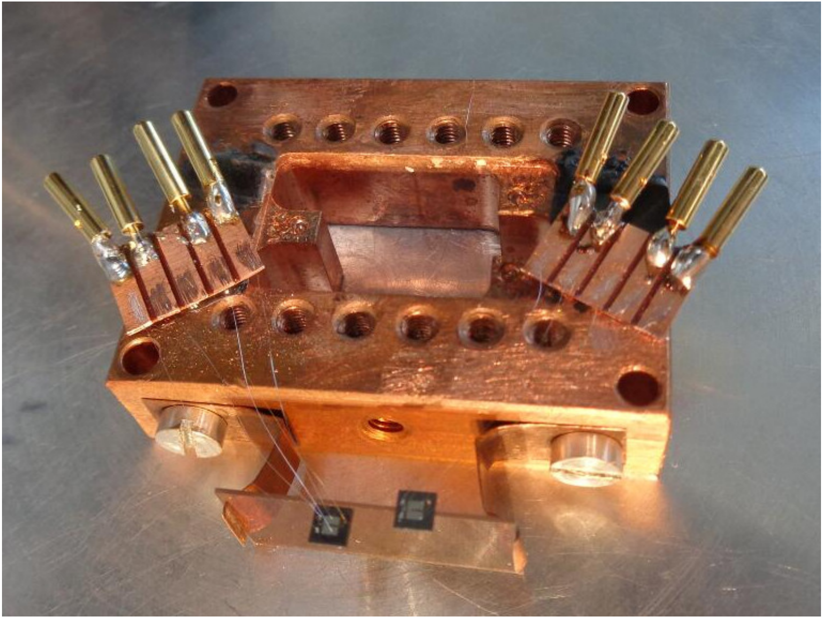

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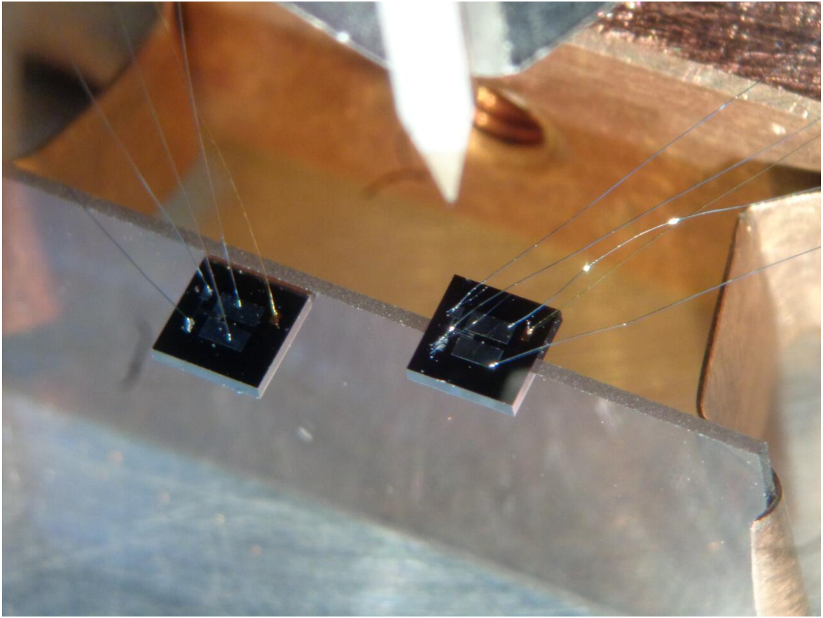
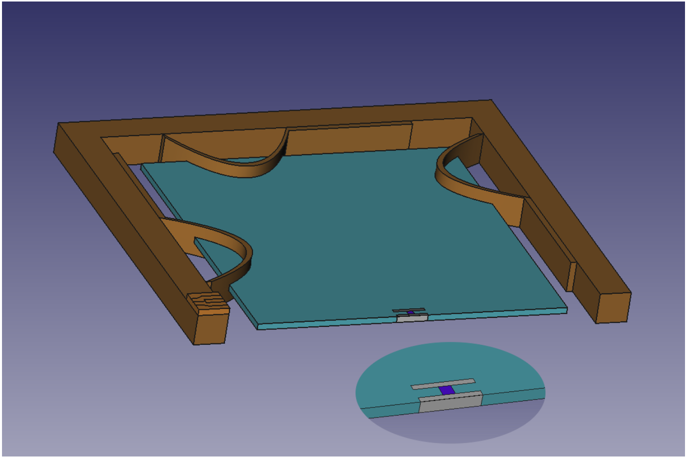
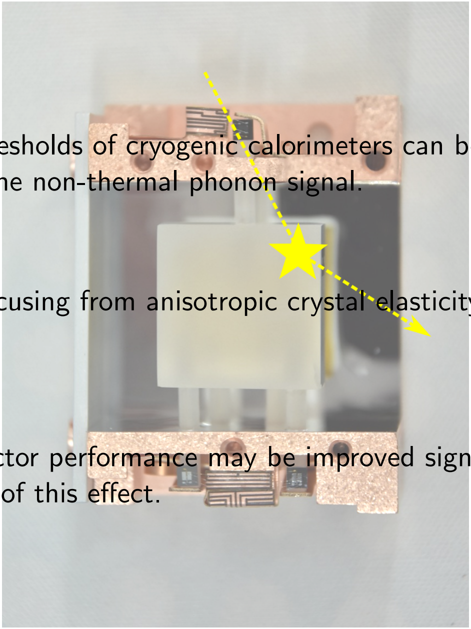


A Future Light Detector Concept

Phonon-focusing assisted light detector:
phonon collector on the side

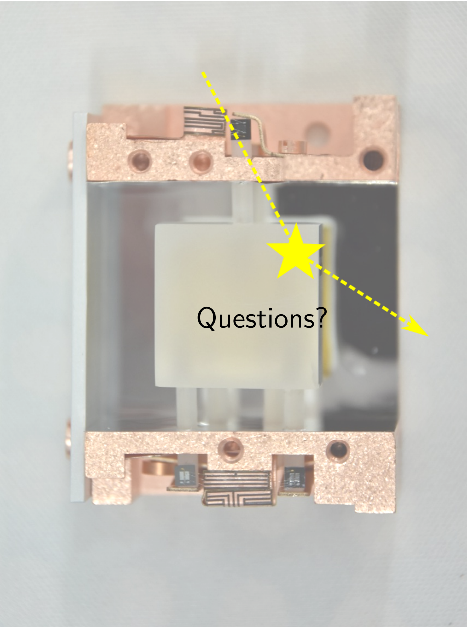


Summary



- Energy thresholds of cryogenic calorimeters can be predicted from a model of the non-thermal phonon signal.
- Phonon focusing from anisotropic crystal elasticity can influence this signal.
- Light detector performance may be improved significantly taking advantage of this effect.

Thank you!



Non-Thermal and Thermal Component