Title: Searching for Dark Matter with Athermal Phonon Detectors Throughout the Mass Range from 50meV through 500MeV

Speakers: Matt Pyle

Series: Particle Physics

Date: December 10, 2019 - 1:00 PM

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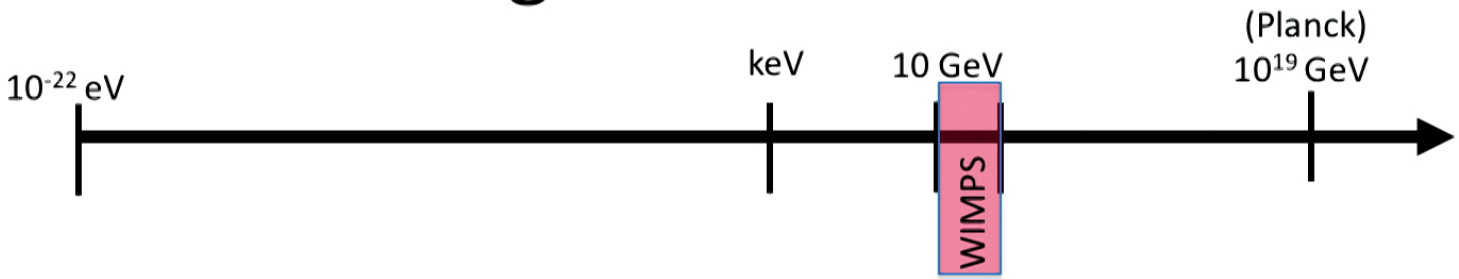
Abstract: Substantial astronomical observations have established that approximately 25% of the energy density of the universe is composed of cold non-baryonic dark matter, whose detection and characterization could be key to improving our understanding of the laws of physics. Over the past three decades, physicists have largely focused on searching for dark matter within the 10 GeV-1 TeV range (WIMPs), unfortunately without success.In this talk, weâ€™ll discuss the experimental requirements when searching for dark matter throughout the mass range from 50meV- 500 MeV. Weâ€™ll also discuss recent R&D breakthroughs in athermal phonon sensor technology that will enable experiments that are being proposed using silicon, polar crystal and superfluid He as the detector material.

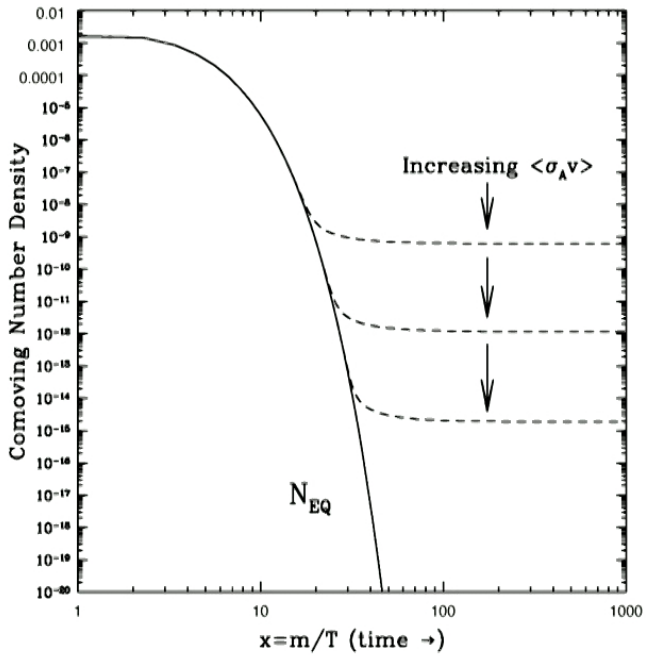

Searching for Dark Matter in the
Mass Range from 100meV–1 GeV
Matt Pyle
UC Berkeley
Perimeter 12/10/19

Outline

- Briefest Theoretical Motivation for Light Mass DM
- Exploration Directions Beyond Funded Experiments
- Experimental Design Drivers for Light Mass Dark Matter
  - Nuclear recoils
  - Acoustic Phonon Production
  - Optical Phonon Production and Dark Photon Models
  - Single Photon Detection
- Athermal Phonon Detection Technology
  - R&D Status
  - DM Search with PD2 in collaboration with SuperCDMS

10 Years Ago: A Focus on WIMPs

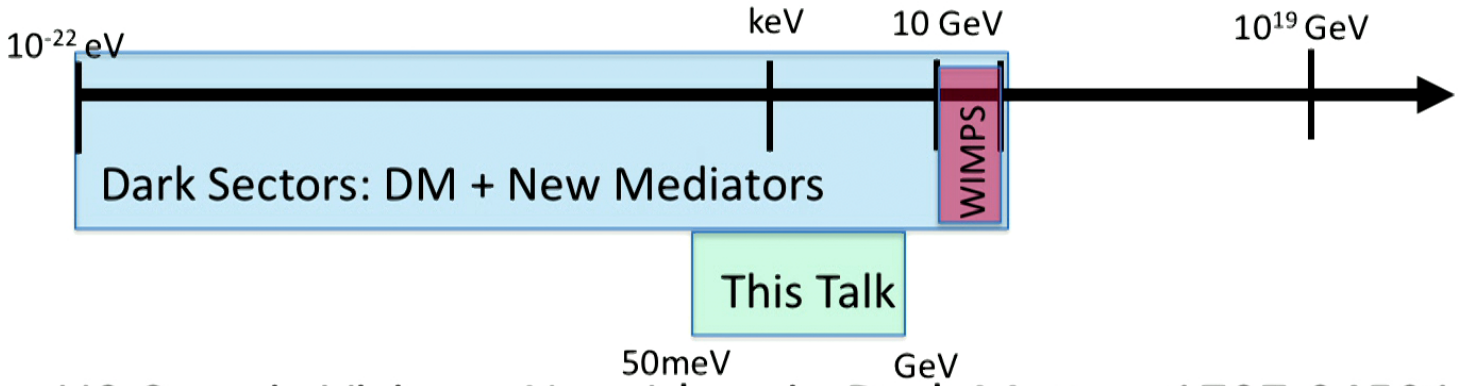




- Relic DM density suggests weak-scale cross sections
- New physics (and particles) at the weak scale could solve the hierarchy problem

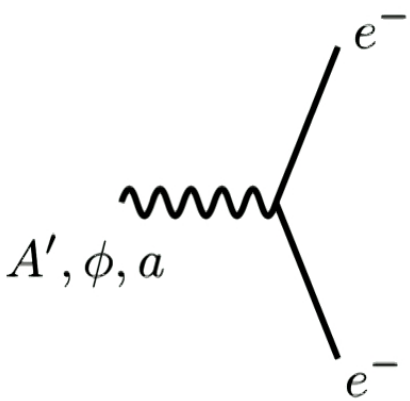
3

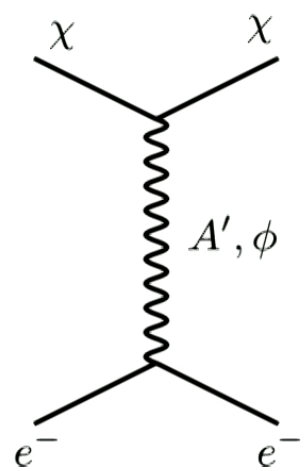
Today: Search for DM Everywhere



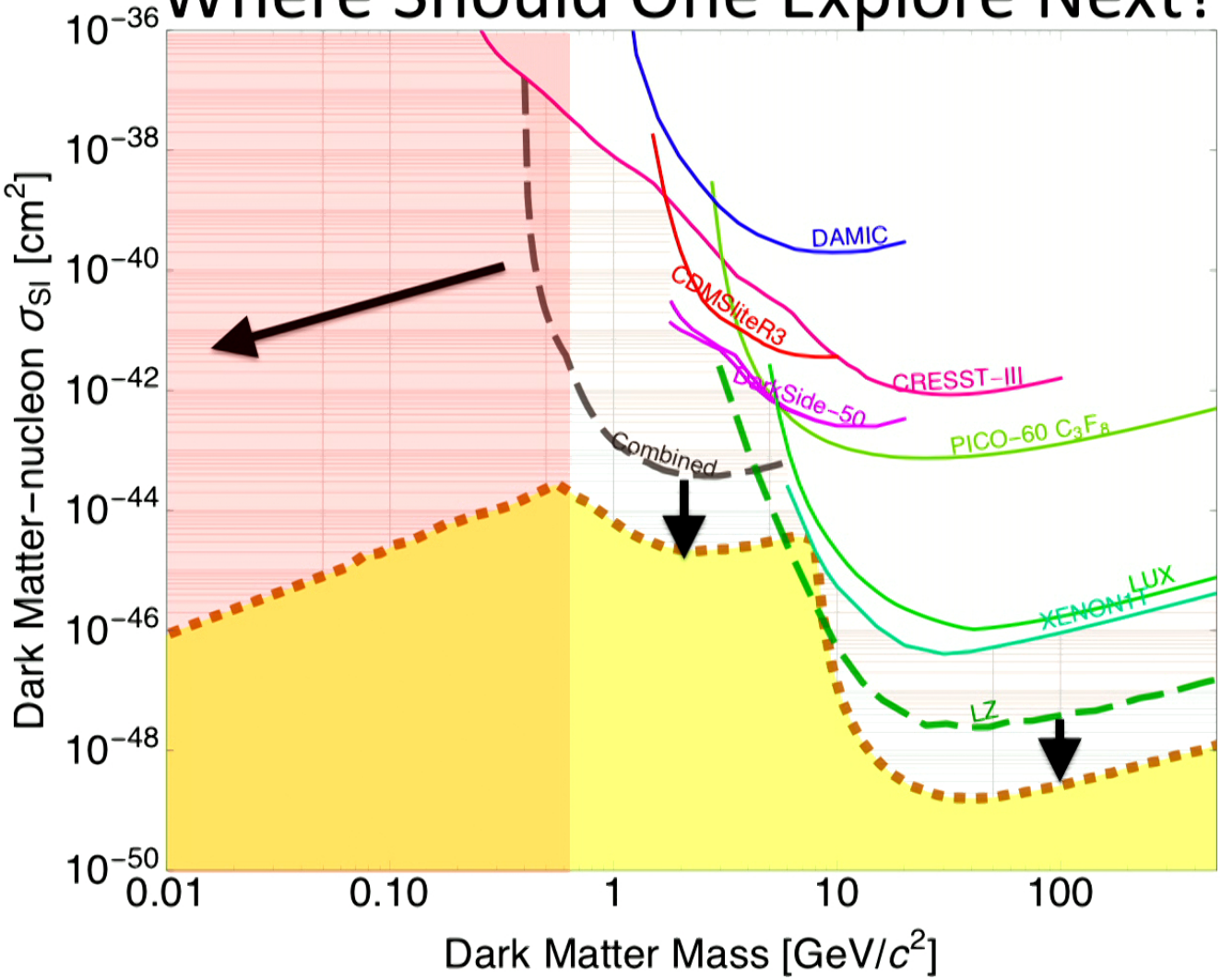
US Cosmic Visions: New Ideas in Dark Matter: 1707.04591

Many Well Motivated DM Models at Light Mass





Where Should One Explore Next?

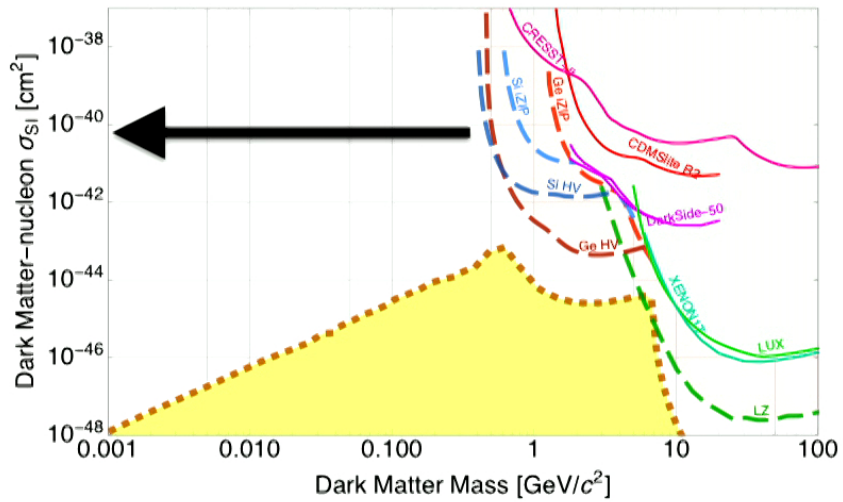


Light Mass DM Design Drivers:

~~Exposure~~

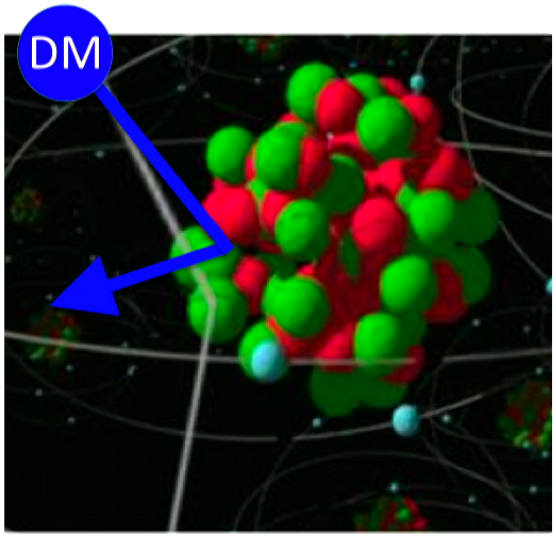
$$R = \sigma n_{DM} v_{DM} N_{exp}$$
$$= \sigma \frac{\rho_{DM}}{M_{DM}} v_{esc} N_{exp}$$

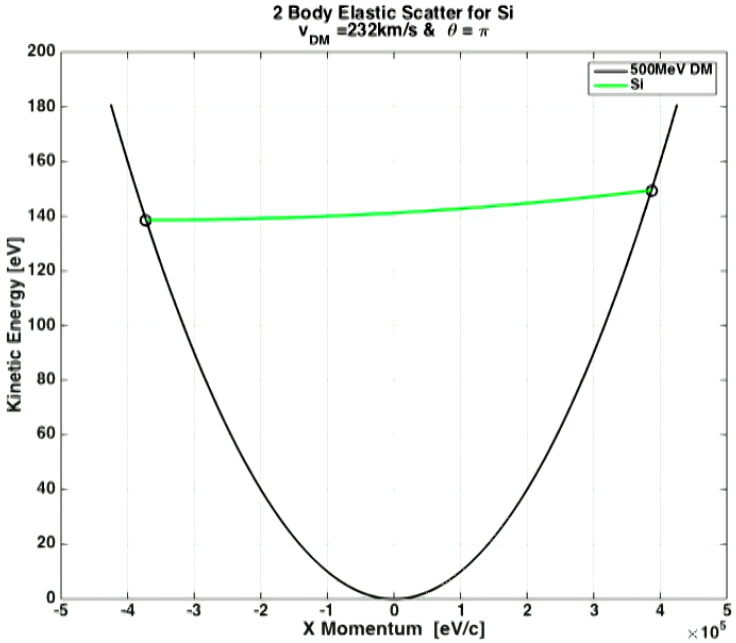
Interaction Rate scales with $1/M_{DM}$



LZ needs 10 tons to get to 10^{-47} cm^2 at 100GeV, Light Mass DM searches only needs 10kg to reach the same level at 100MeV

Kinematics: 2 Body Elastic Nuclear Scattering





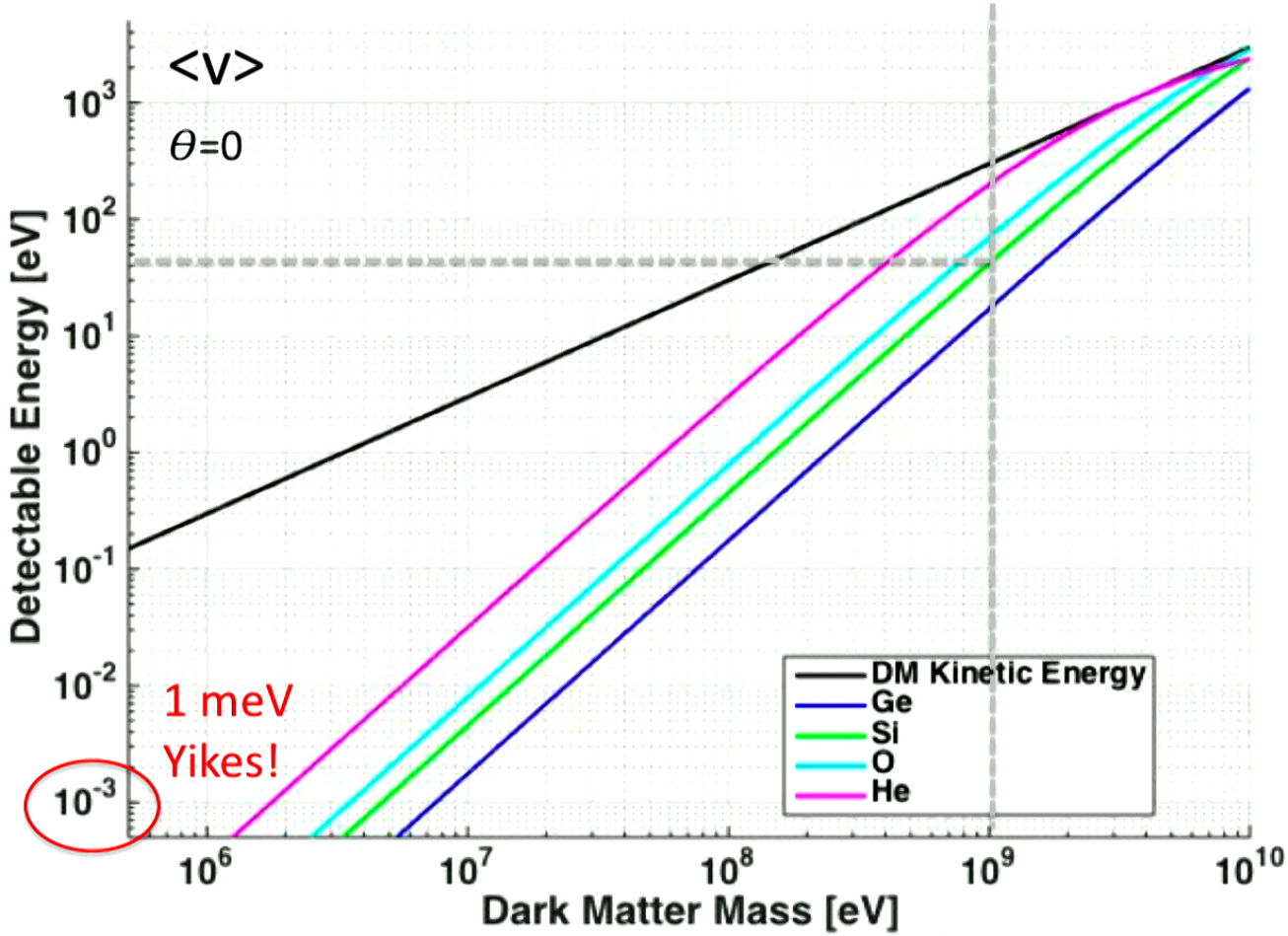
$$K_n = \frac{\mu^2 v_{DMo}^2}{M_n}\left(1 - \cos(\theta)\right)$$

When $M_n >> M_{DM}$

$$\sim \frac{2M_{DM}^2 v_{DMo}^2}{M_n} = \frac{(2P_{DMo})^2}{2M_n}$$

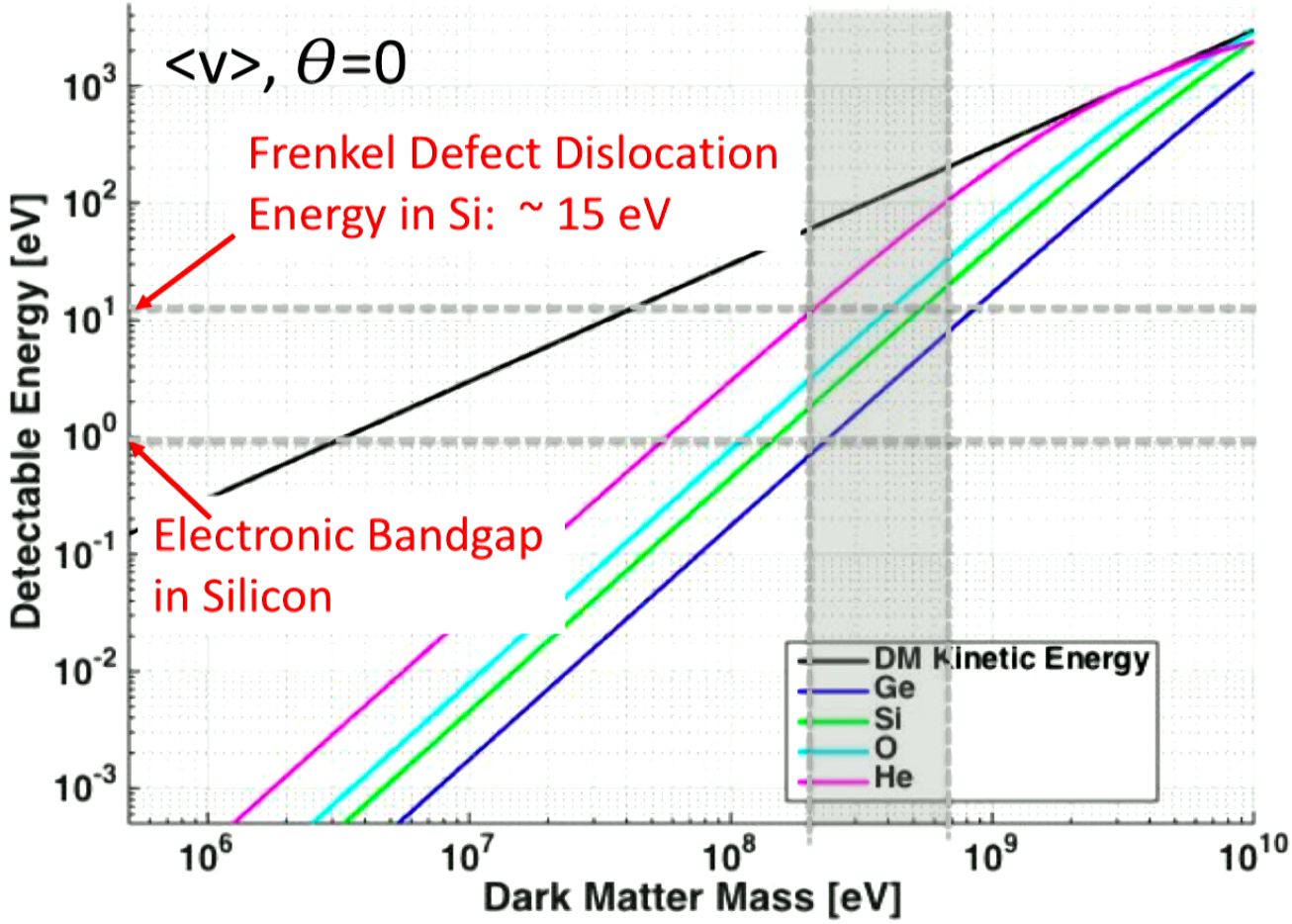
Recoil Energy Scales as M_{DM}^2. Transfer of DM kinetic energy is really inefficient for elastic 2 Body Scatters when $M_n >> M_{DM}$

Light Mass Dark Matter: Elastic Nuclear Scattering



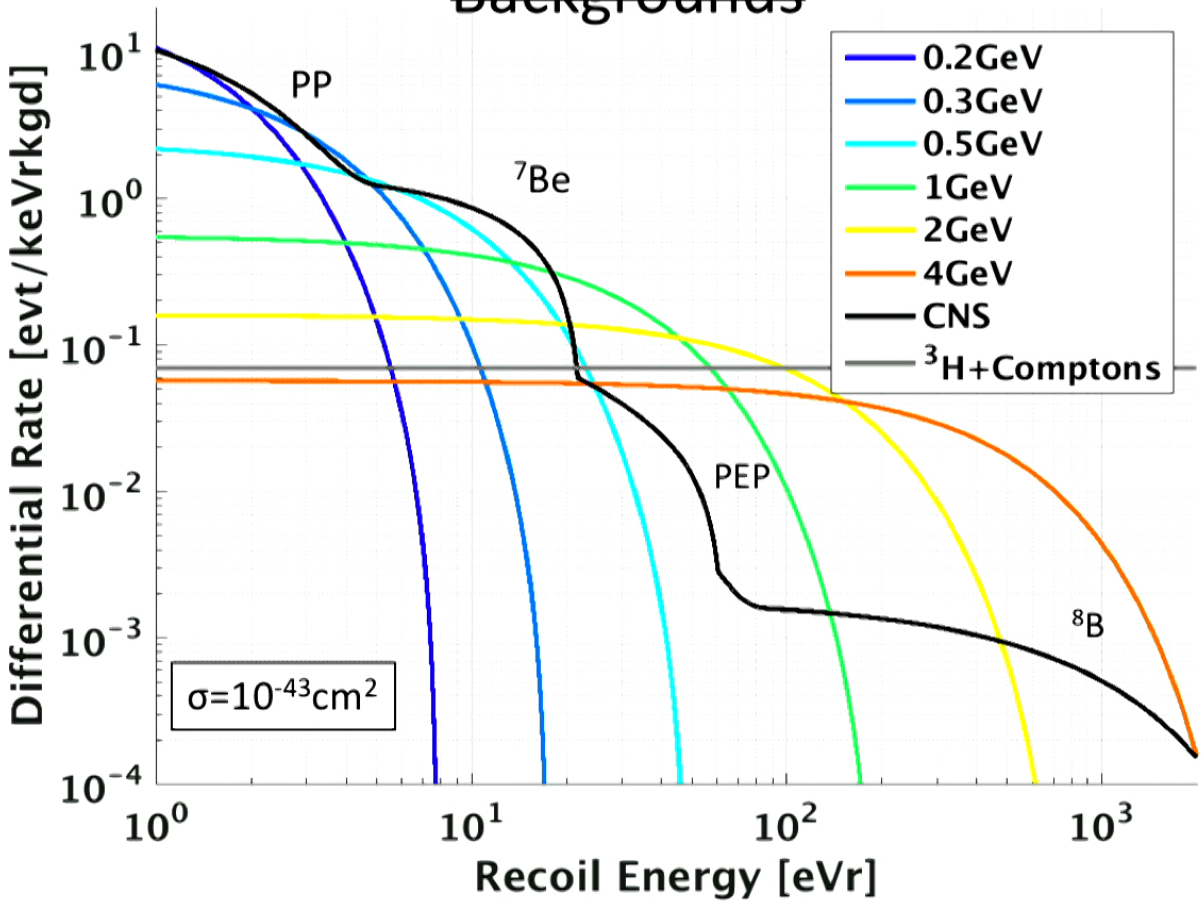
Energy Sensitivity is Primary Design Driver

Ionization Production in eV Scale Nuclear Recoils



For DM <~ 200MeV, no ionization expected from NR

Light Mass DM Design Drivers: ~~Flat Radiogenic Backgrounds~~

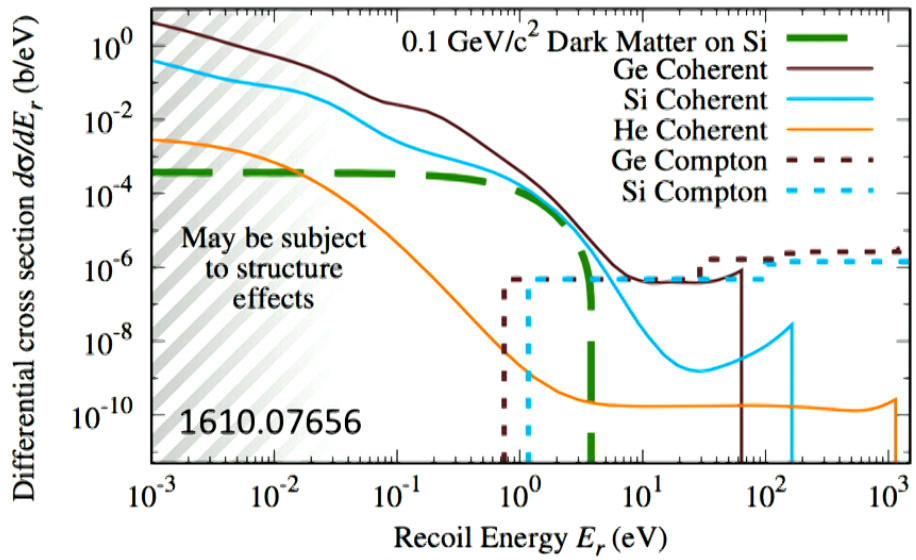


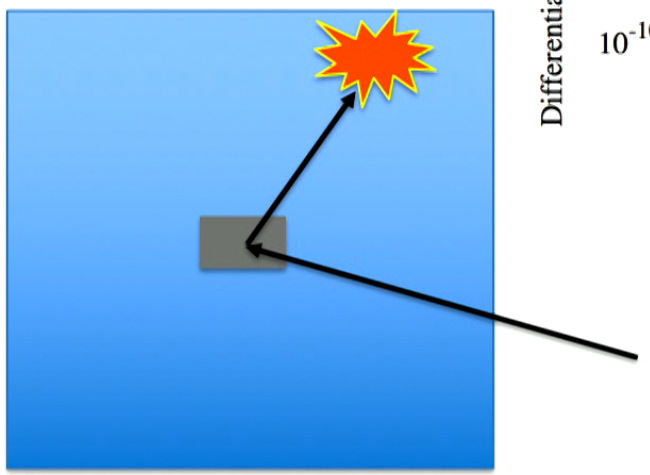
Smaller DM masses have less overlap with flat backgrounds!

Are Backgrounds Really Flat?: Coherent Photon Scattering

- High Energy Photons can coherently elastically scatter off nuclei
- Robinson: 1610.07656

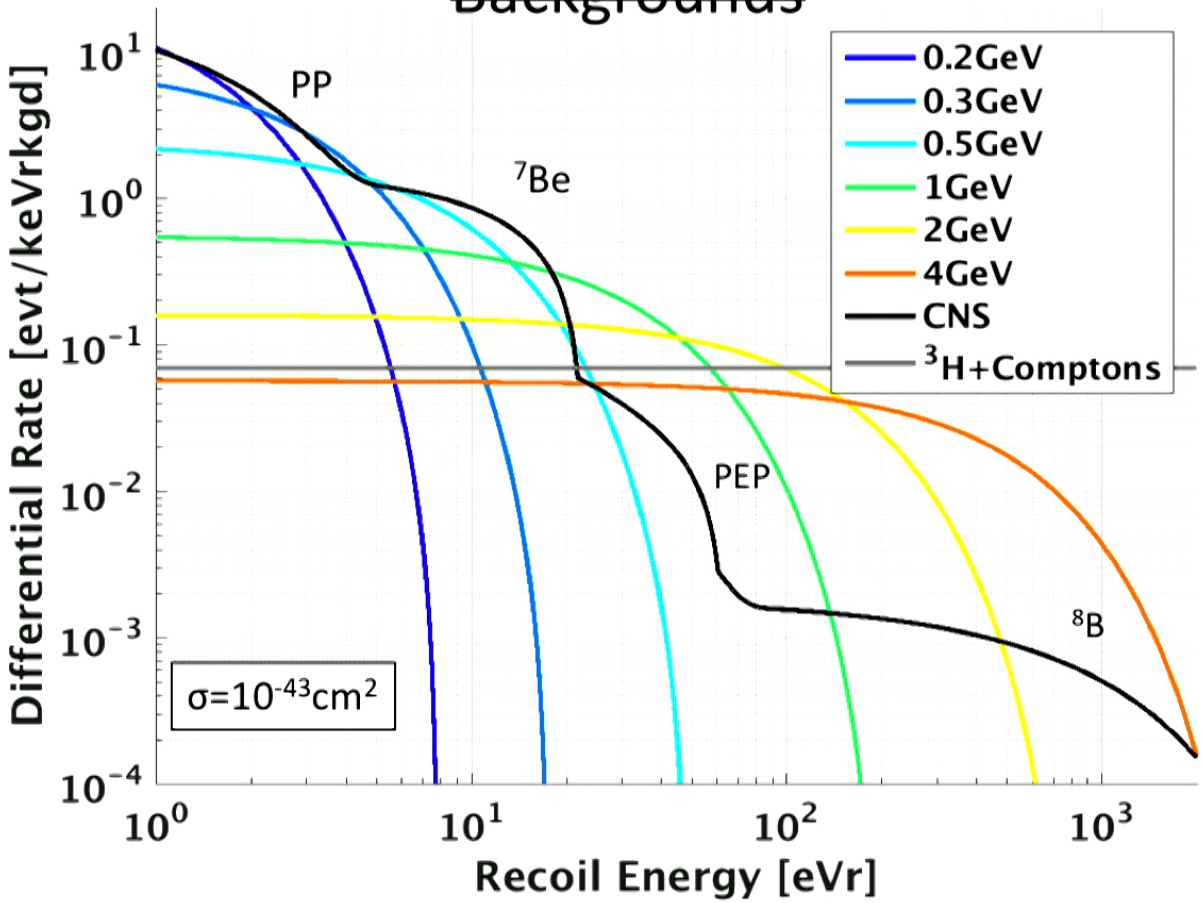
1461keV Photon from ^{40}K





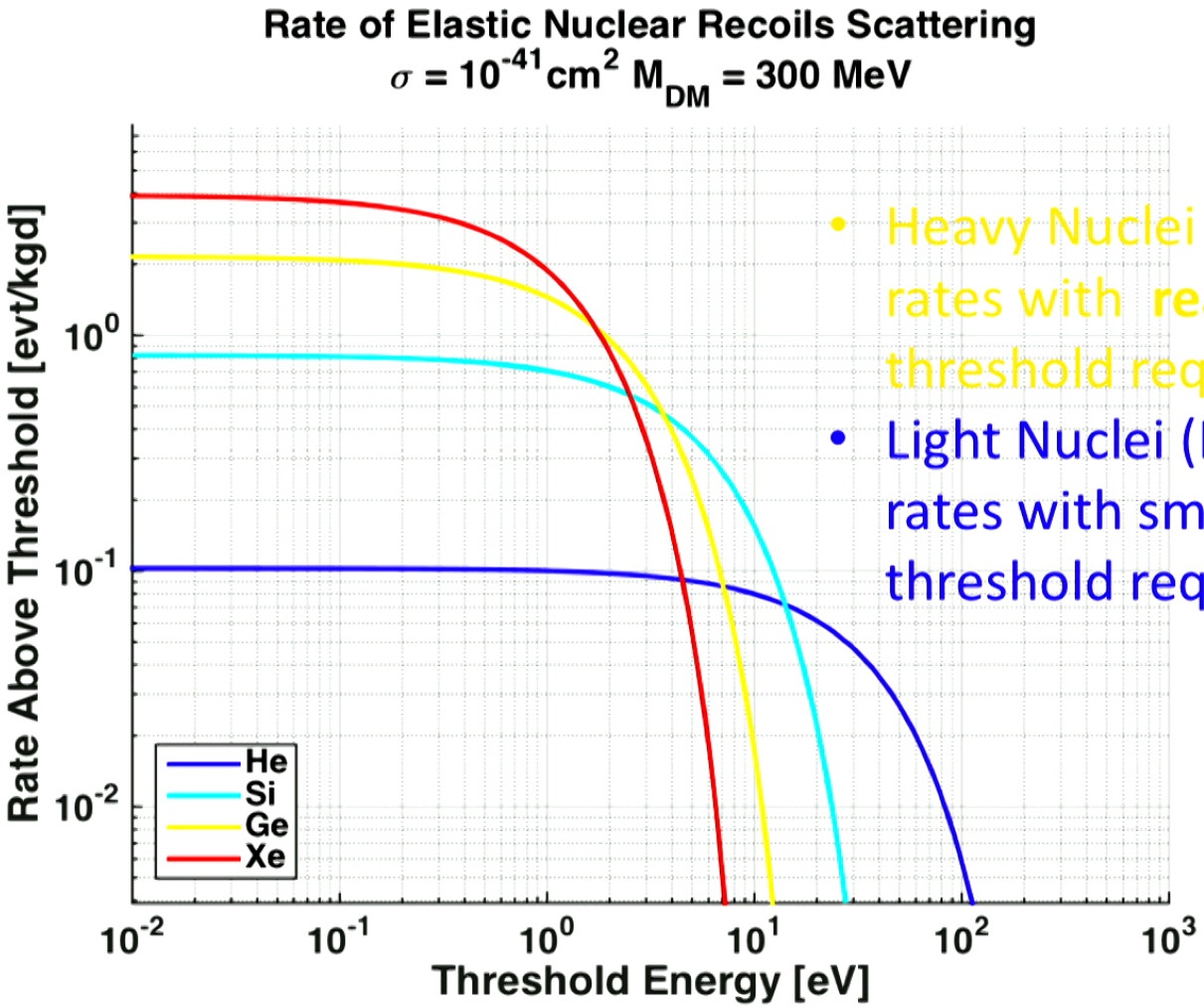
Build a Active Photon Veto

Light Mass DM Design Drivers: ~~Flat Radiogenic Backgrounds~~



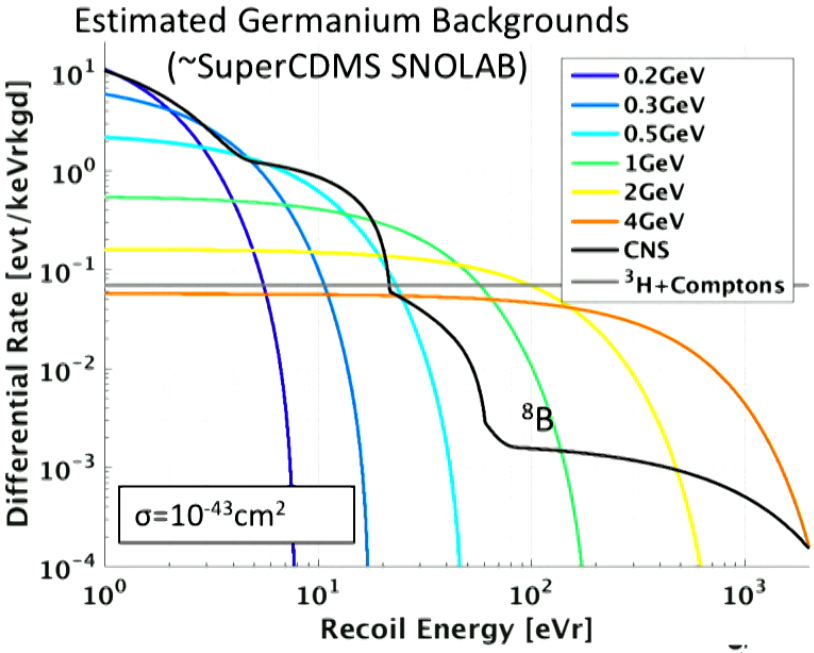
Smaller DM masses have less overlap with flat backgrounds!

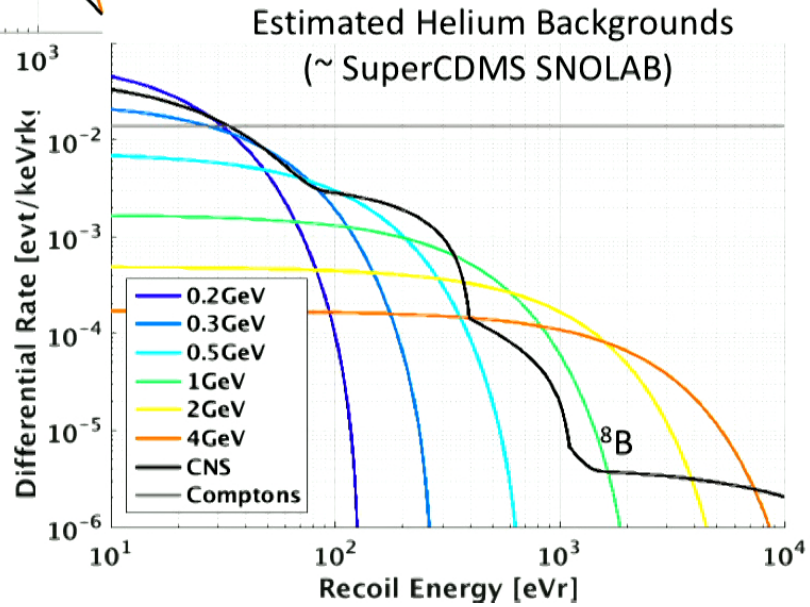
Heavy vs Light Nuclei: Rates



- Heavy Nuclei (Ge): larger rates with **really** small threshold requirements.
- Light Nuclei (He): smaller rates with small threshold requirements

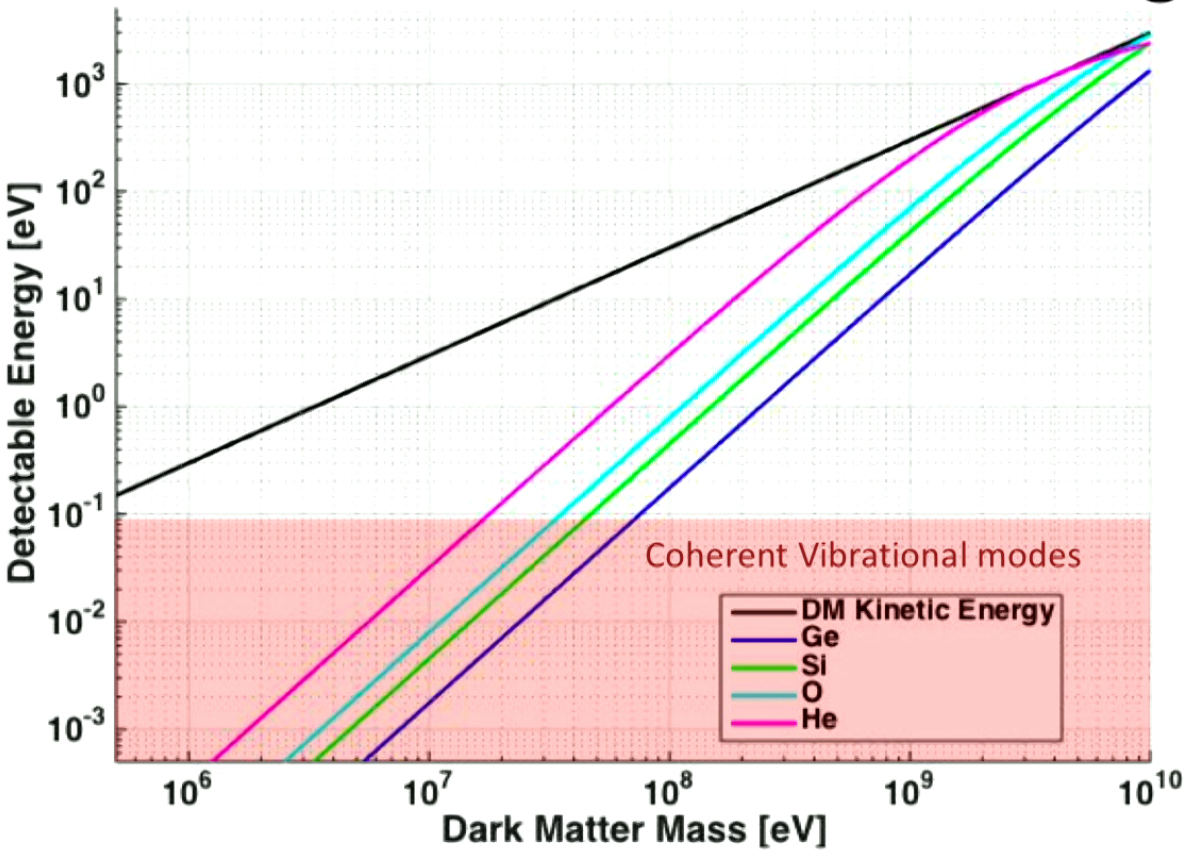
Heavy vs Light Nuclei: Susceptibility to Electronic Recoil Backgrounds





Heavy Nuclei less sensitive to electronic recoil backgrounds

Coherent Vibrational Excitation Regime



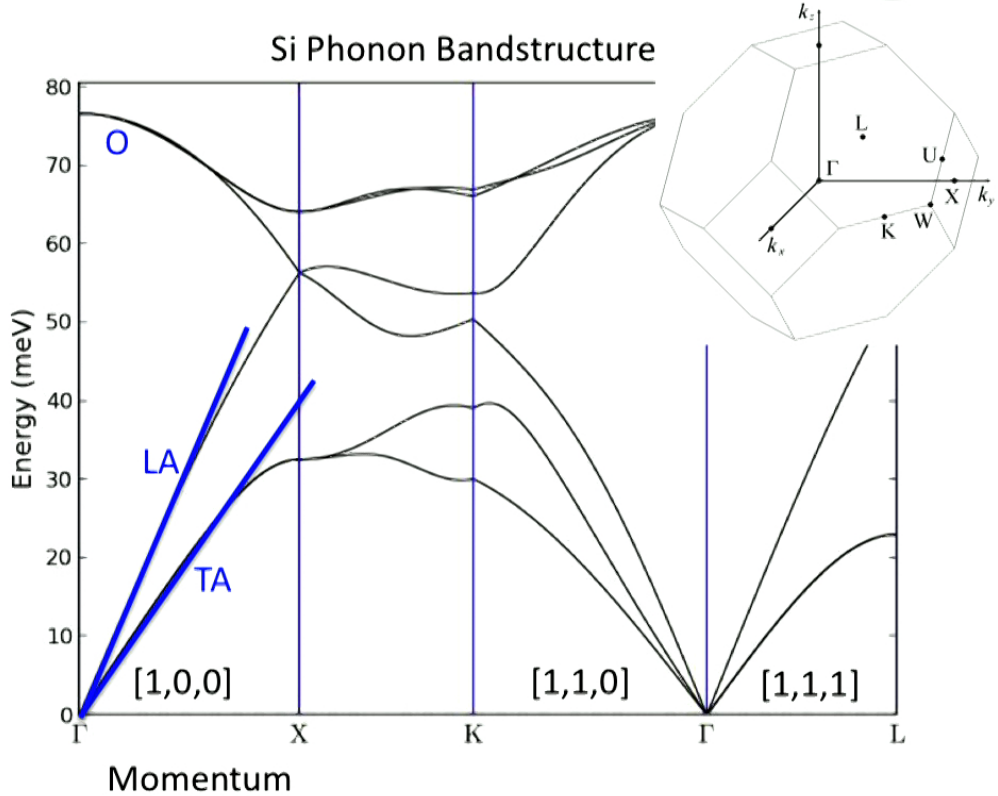
Below O(10 MeV), we need to start thinking about DM nucleus interactions in terms of coherent vibrational mode production

Acoustic Phonons

← 5.4×10^{-10} m →

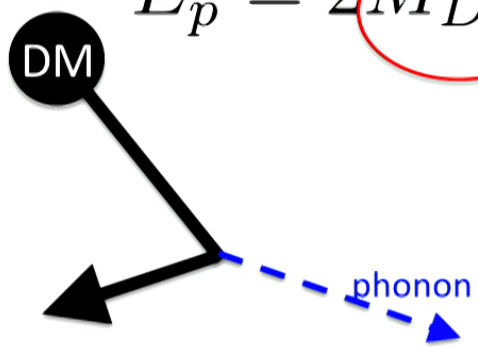
P = h/a = 2.3 keV/c

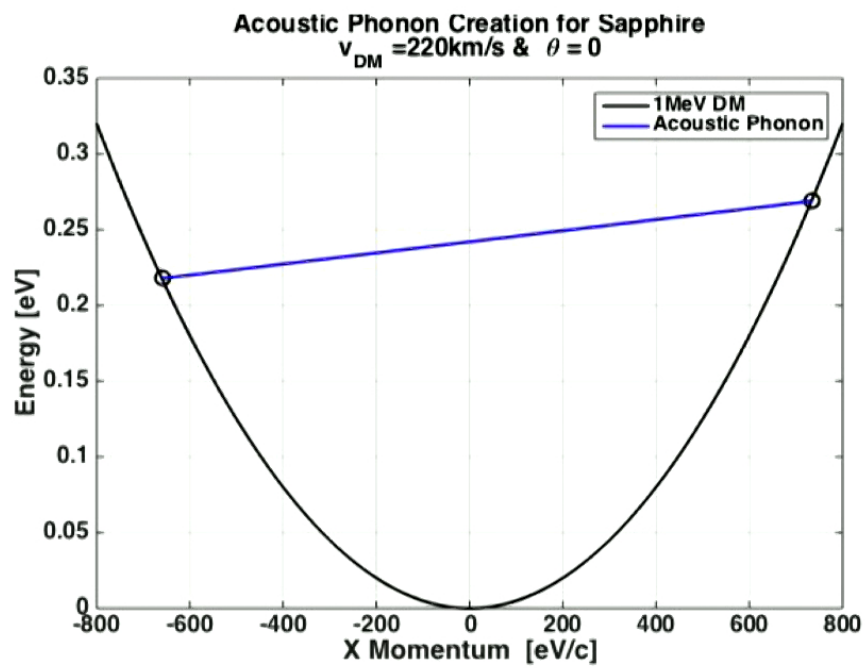
Phonons have momentum from [0,few keV/c]



Kinematics: Acoustic Phonon Production

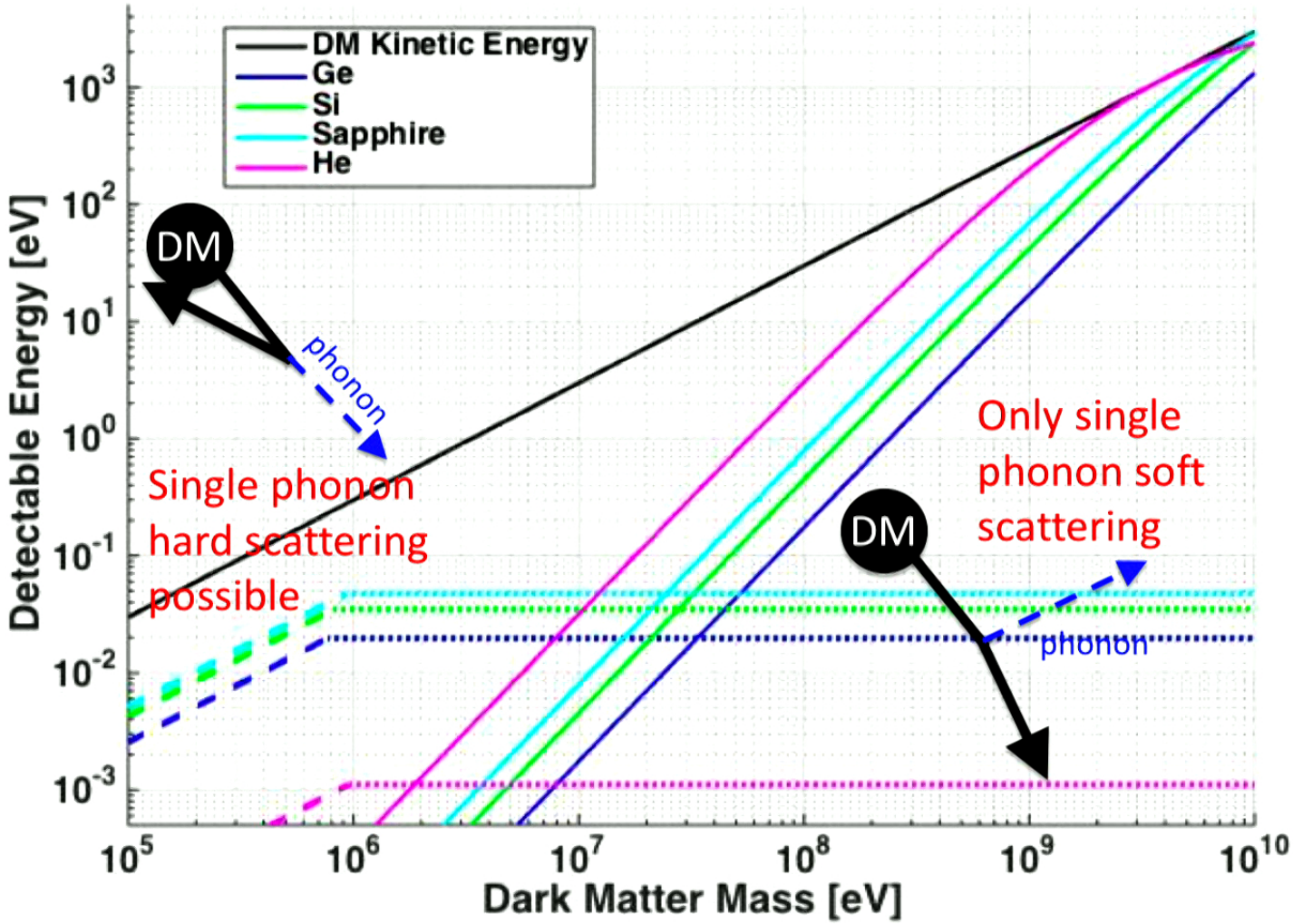
$$E_p = 2M_{DM}v_a\left(v_{DM\,0}\cos(\theta) - v_a\right)$$





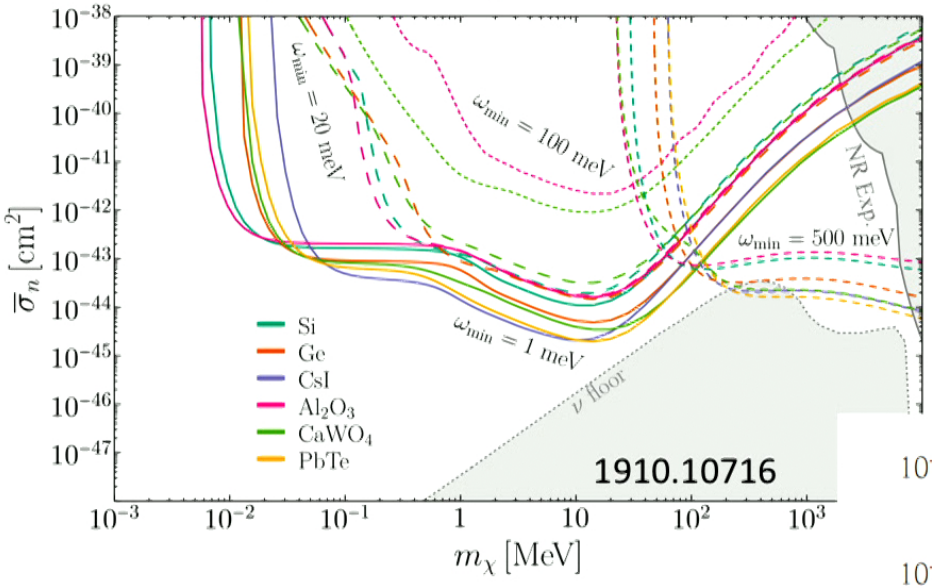
- Characteristic acoustic phonon energy scales as M_{DM} … not quite as bad as for elastic 2 body recoils
- We should use crystals with really large sound speeds (Sapphire, Diamond,…)

Acoustic Phonon Production from DM



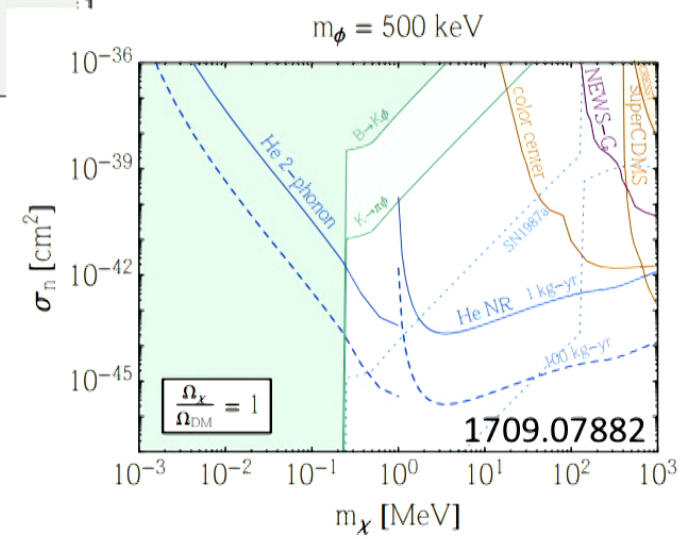
Phonon Sensitivity Curves

Heavy Mediator Single Phonon Sensitivity



- Zurek, Griffin, et al: 1910.10716
- Exposure: 1kgyr
- No Backgrounds

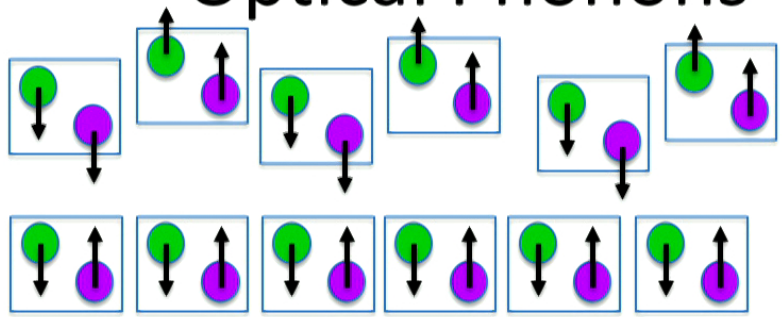
Interaction space pretty constrained by astronomical measurements below 0.1MeV

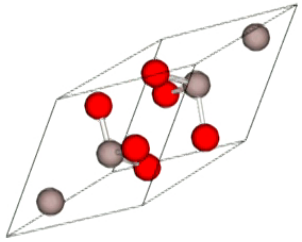


Optical Phonons

Acoustic:

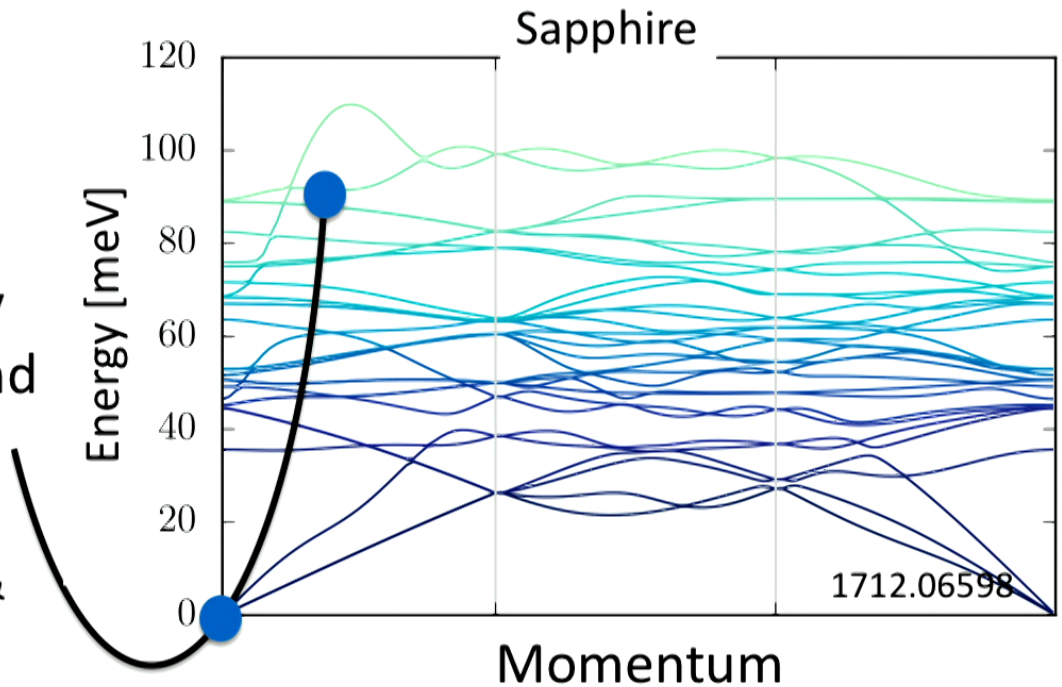
Optical:





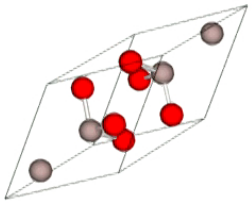
Due to their gapped nature, optical phonons are kinematically matched to IR and light mass DM!

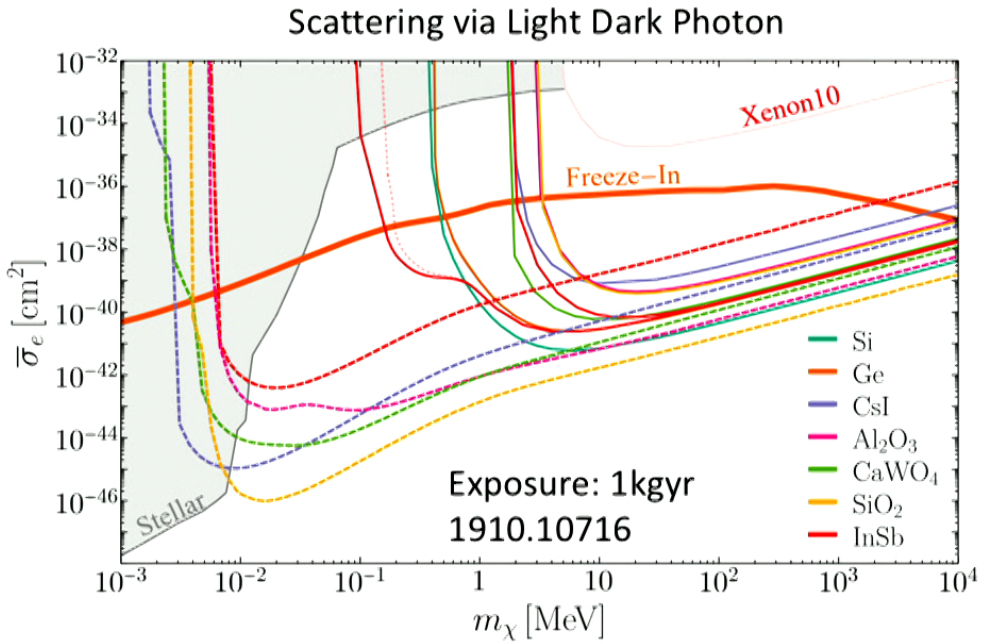
Knapen, Lin, Pyle, & Zurek: 1712.06598



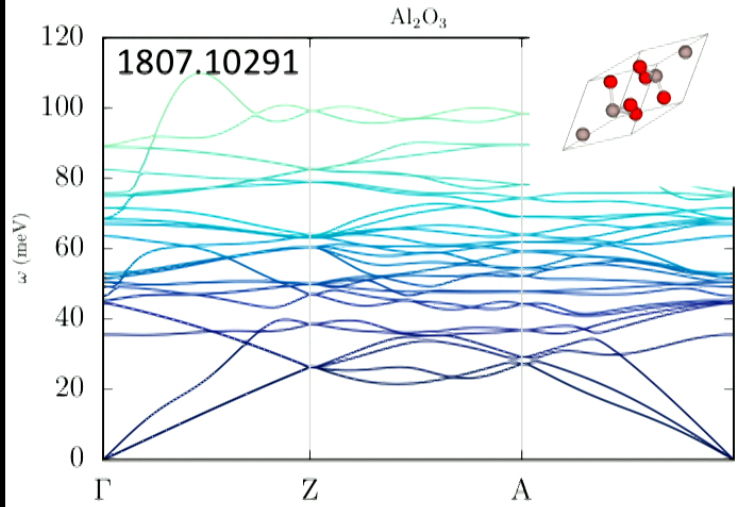
Dark Photon Couplings: Polar Crystals

- In ionic crystals, optical phonons are oscillating electric dipoles!
- Very large coupling to photons (black in the IR)… Very large coupling to the dark photons





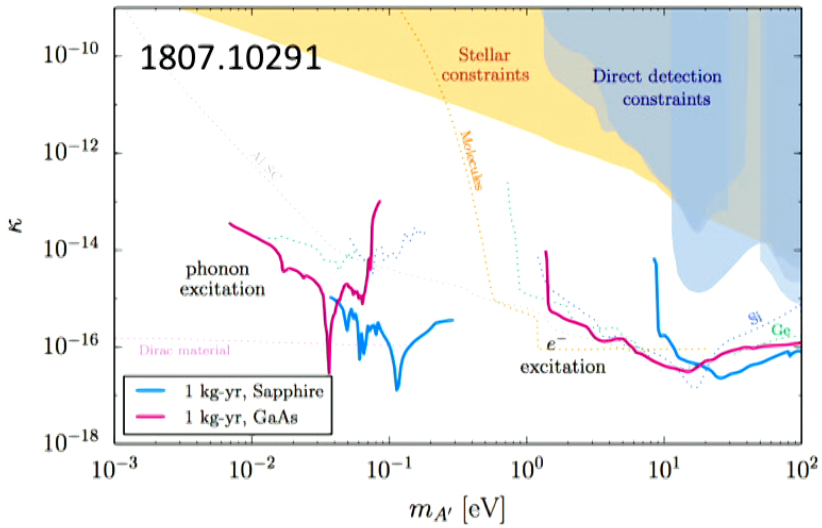
Sapphire: Lot's of Optical Phonon Bands



Sapphire is a complex crystal with 10 atoms in its unit cell. Dark Matter can interact with lots of different modes

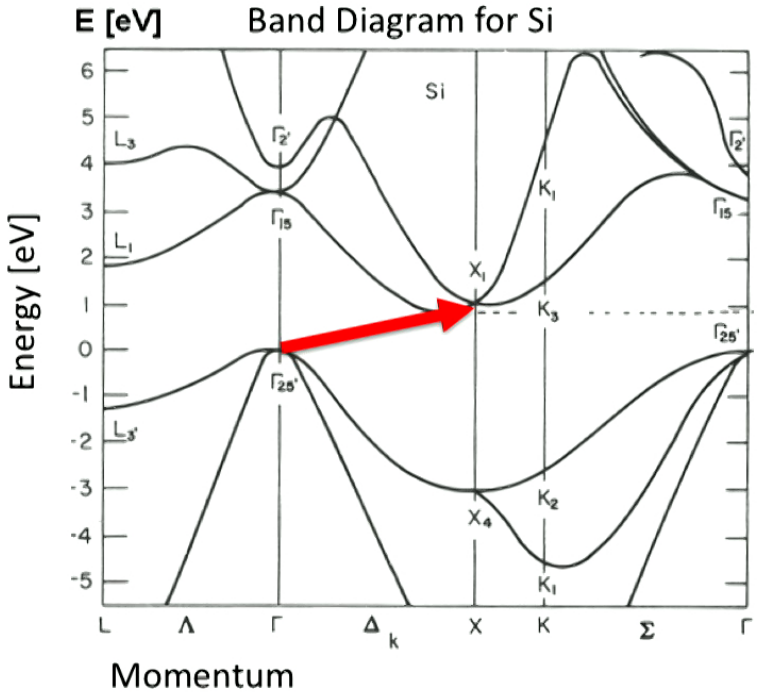
To search for thermal DM down to keV masses via scattering and ultracold bosonic DM to 30 meV, we need a detector sensitive to a single optical phonon

Dark Photon Dark Matter Absorption

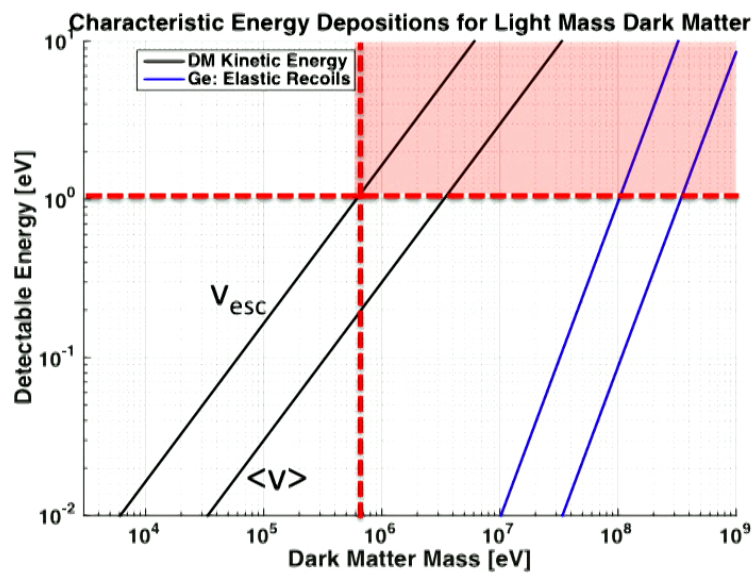


Other Signal Channels for Interacting with Light Mass Dark Matter

Inelastic e⁻ Recoils in Semiconductors

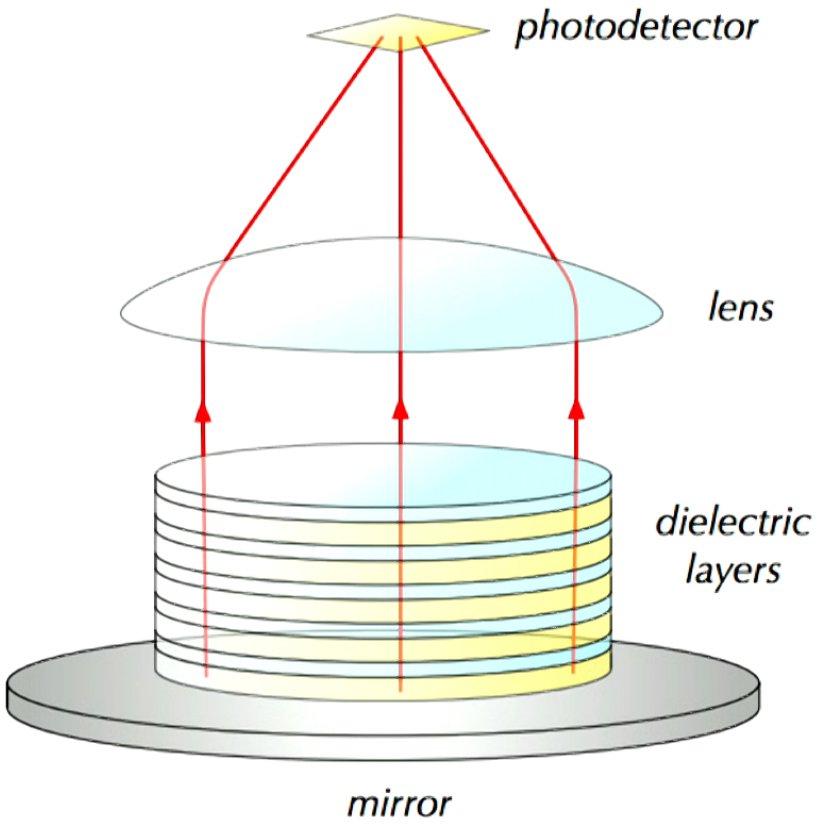


- e- excitation momentum and energy scales in semiconductors well matched to 1 MeV-100MeV DM
- Essig et al: 1108.5383



Detector Requirement:
Sensitivity to single e/h pairs with negligible dark count rate

Optical/IR Haloscope

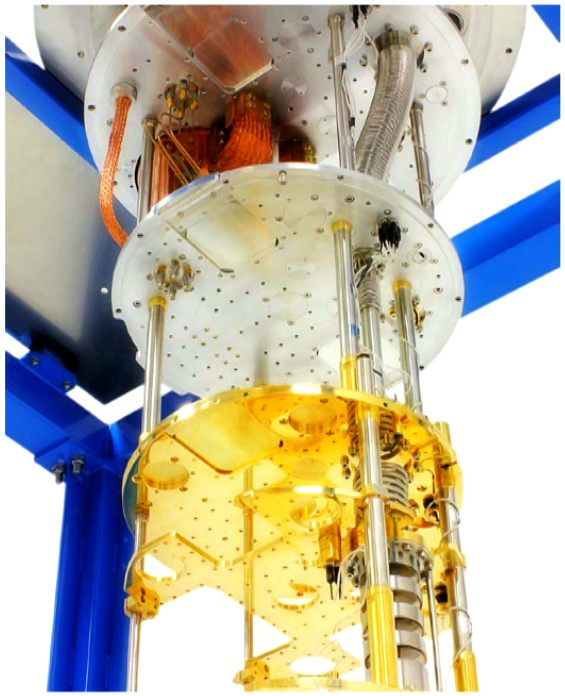


- Baryakhtar, Huang, Lasenby 1803.11455
- Momentum matching via multilayer stack
- Requirements: Single photon sensitivity with no dark counts

Building Detectors with Sensitivity to Single Phonons and Single e/h production (without Luke-Neganov Gain)

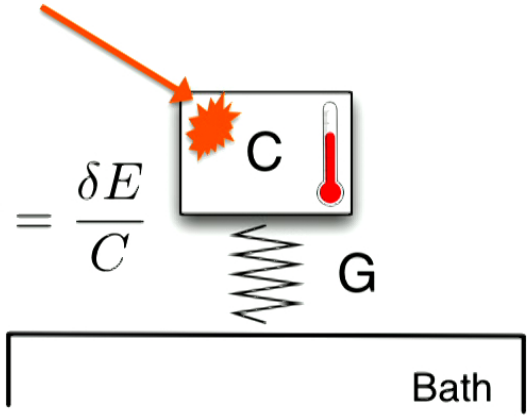
Optical Phonon Sensitivity -> Low Temperature Detectors

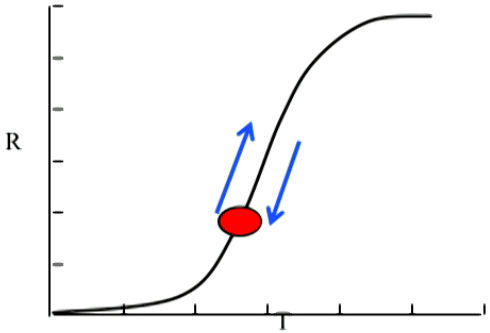
- 300K = 26meV
- To sense single optical phonons we'll need to cool the detector down to near absolute zero
- Use superconducting detector technology
  - MKIDs
  - **Transition edge sensors**
  - SNSPD (only for photon applications)



~~The Simplest Thermal Calorimeter~~

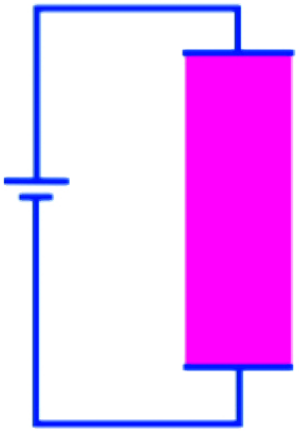
$$\delta T = \frac{\delta E}{C}$$



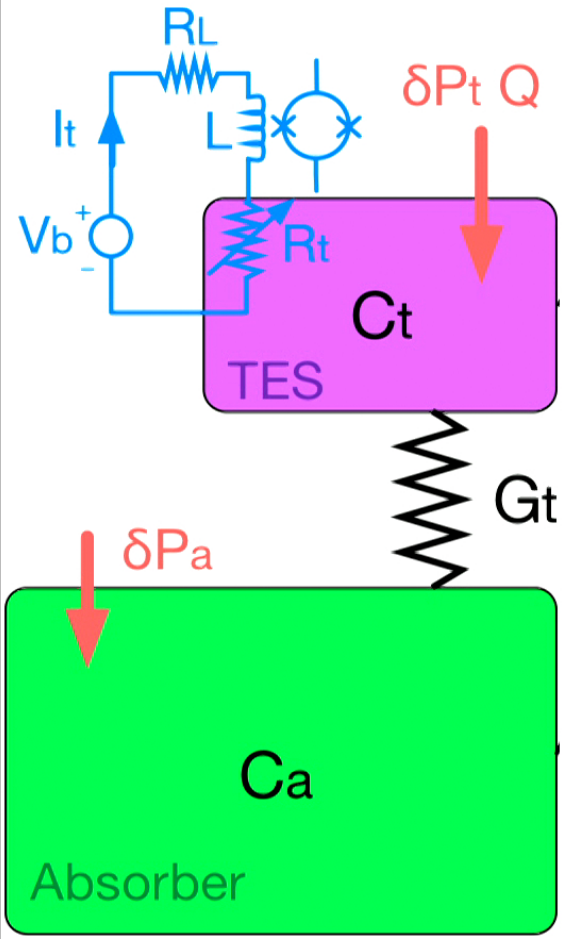


Transition Edge Sensor (TES):

- A superconducting metal film (W) that is externally biased so as to be within its superconducting/normal transition
- $\sigma^2_{<E>} = Ck_bT^2$
- Must use low Tc and very small volume TES -> hard to get gram-day exposures when your TES (25umx25umx40nm) is 500fg

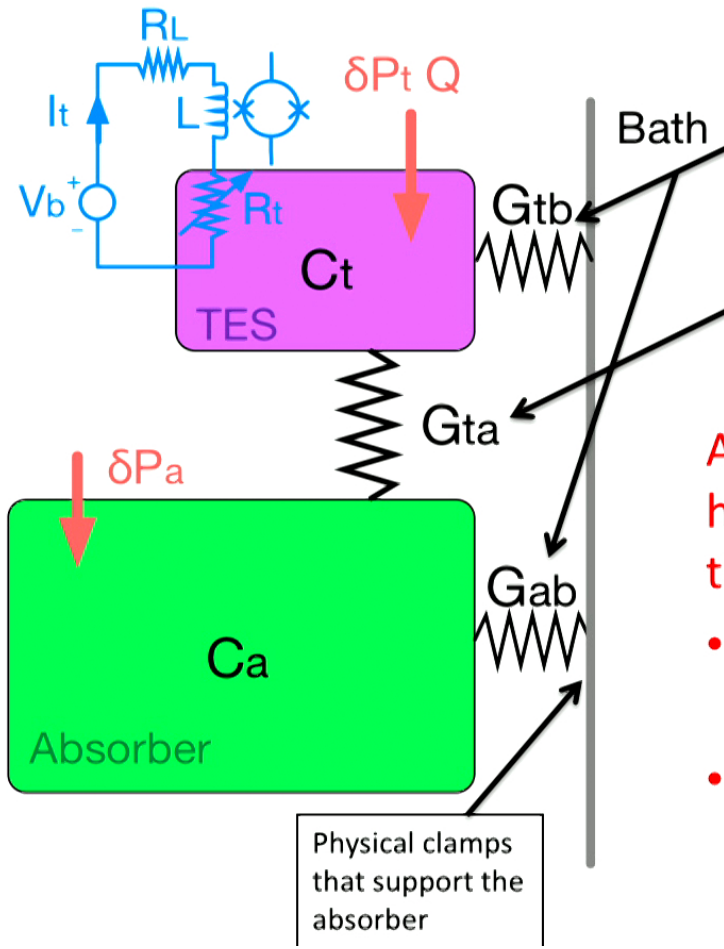


~~2nd most simple thermal calorimeter~~



Couple the sensor to a large volume insulator -> low heat capacity

Problem: Decoupling between the Sensor and Absorber

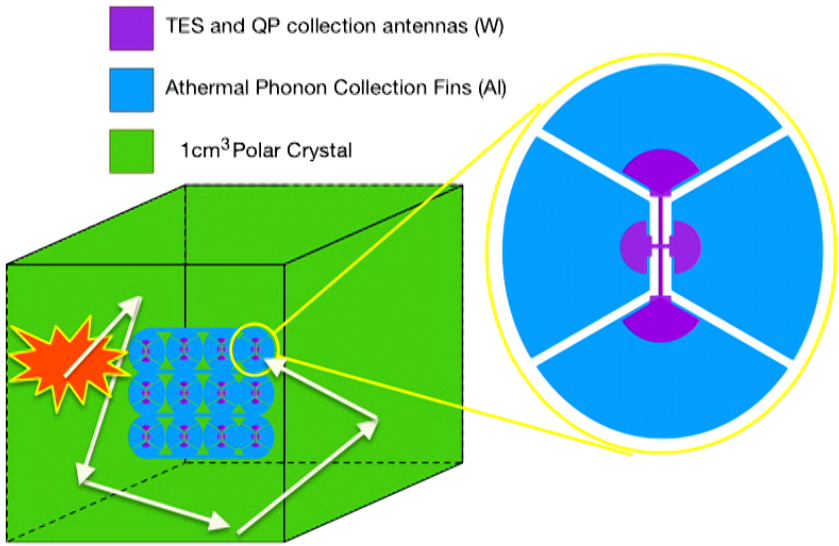


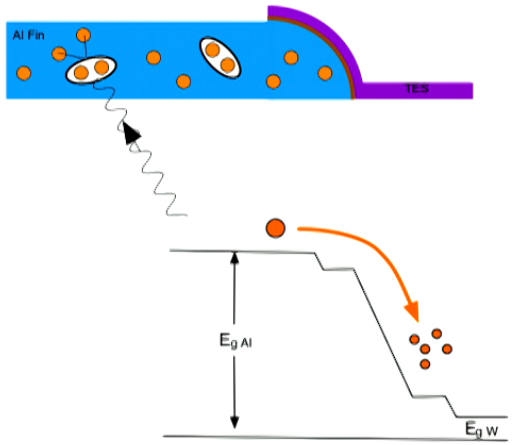
- Kapitza boundary conductance scale as as T^3
- e^-/phonon thermal conductance scales as T^4

As T is decreased, it's harder and harder to keep the sensor thermally coupled to the absorber

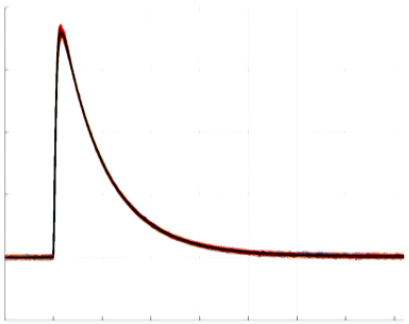
- Energy leaks out of the absorber through G_{ab} before its measured
- TES sensitive to power fluctuations through G_{tb}

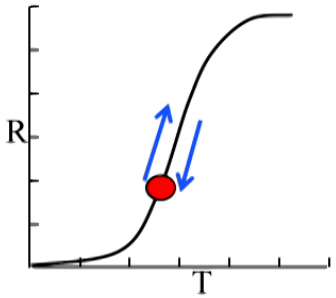
Athermal Phonon Sensor Technology



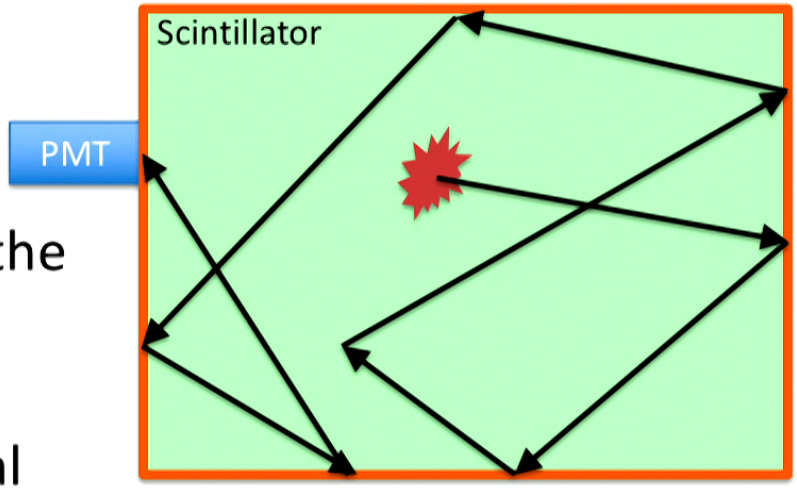


Collect and Concentrate Athermal Phonon Energy into Sensor





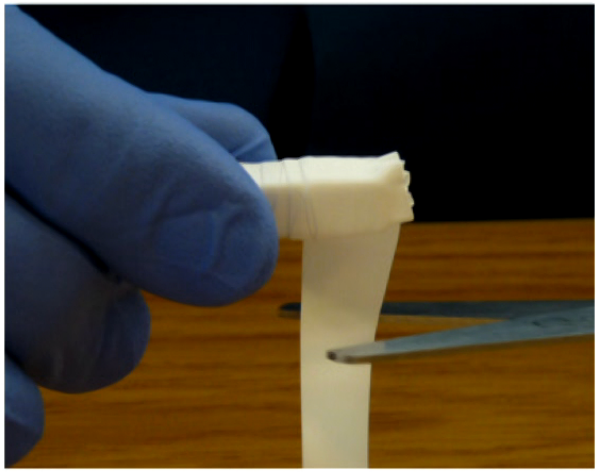
Excitation Detectors & Volume Scaling



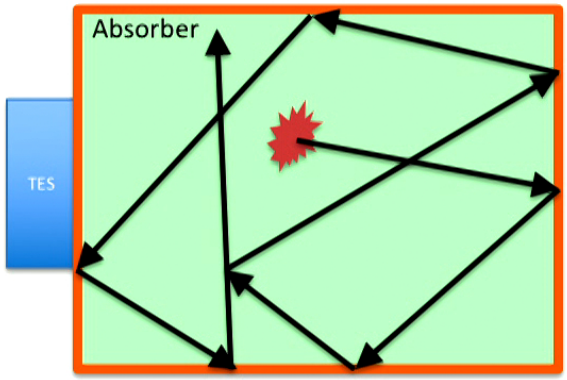
Will these detectors have the same energy sensitivity?

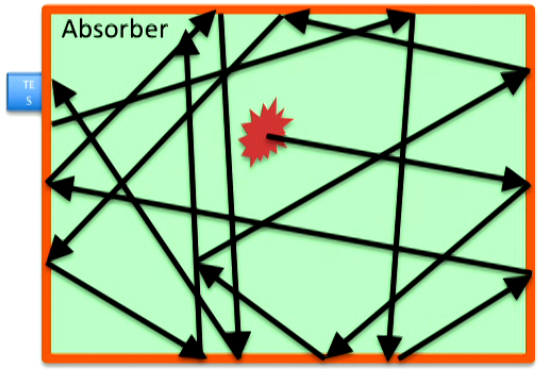
Yes, if:

- Lifetime of the athermal excitation (photon) is really long
- Excitation absorption dominated by sensor
- ~~Position Sensitivity~~



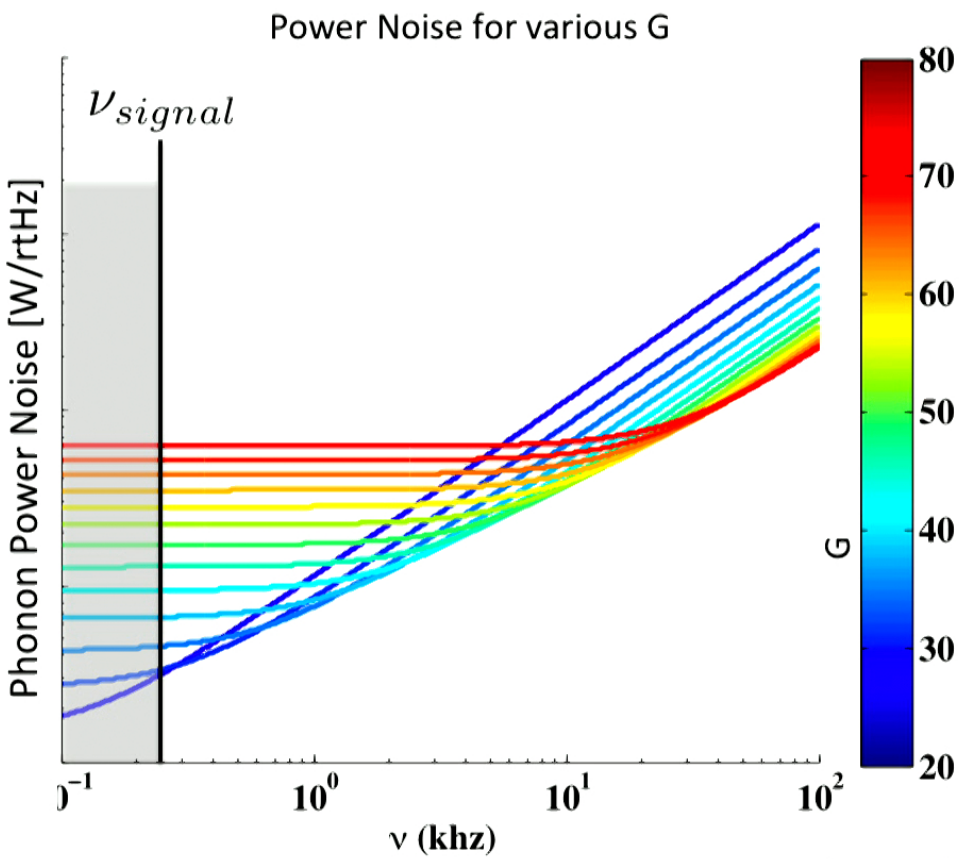
Optimizing the Athermal Phonon Excitation Detectors





Minimize the number/volume of the TES sensors instrumented on the surface to the point that you begin to see the bare surface thermalization rate

Athermal Phonon Sensor Sensitivity Scaling



$$G \propto T_c^4$$
$$S_{ptfn} = 4k_b T_c^2 G$$
$$\propto T_c^6$$
$$\sigma_E \propto T_c^3$$

- Lower v_{sensor} (lower T_c) if $v_{signal} < v_{sensor}$
- Lower v_{signal} (decrease Al coverage) if $v_{signal} > v_{sensor}$

You can always say on VT_c^3 scaling (in principle)

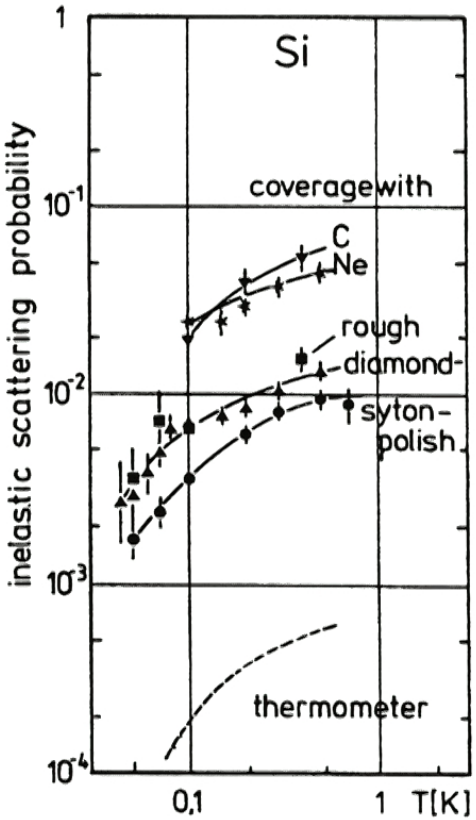
45mK-> 10mK: 2eV -> 20meV

Athermal Phonon Thermalization at Surfaces

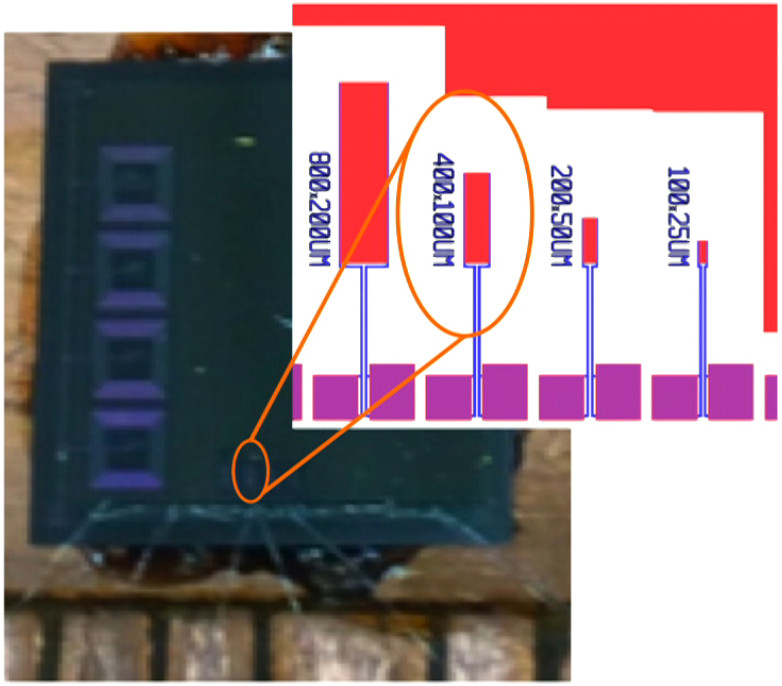
- Athermal phonon surface thermalization probability found to depend upon
  - Crystal
  - Surface roughness
  - Surface cleanliness

(W. Knaak et al, Phonon Scattering in Condensed Matter V,1986)

- 0.1%-1% of the crystal surface covered with athermal phonon sensors … 1/1000-1/100 thermalization probability needed
- Si, Ge -> ok



Making Ultra-Sensitive TES

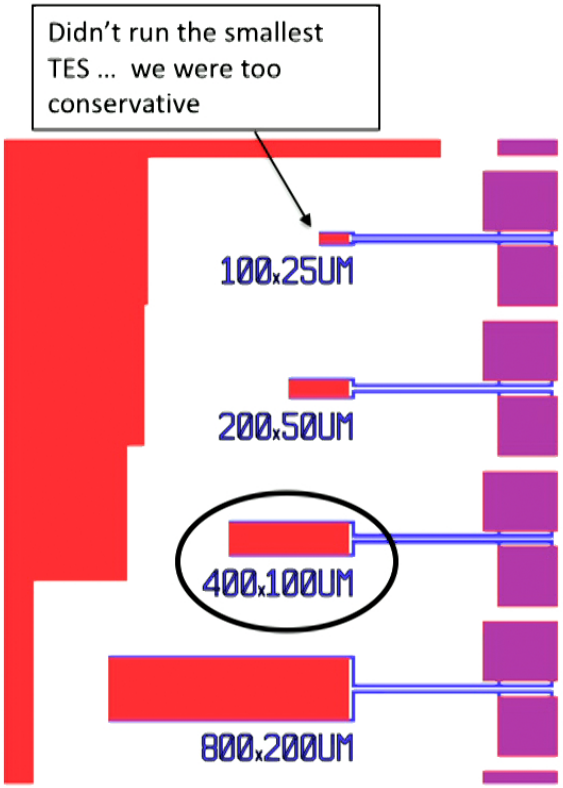


Matt Pyle

For

T. Aramaki, P. Brink, C. Fink, R. Harris, Y. Kolomensky, R. Mahapatra, N. Mirabolfathi, R.Partridge, M. Platt, B. Sadoulet, B. Serfass, S. Watkins

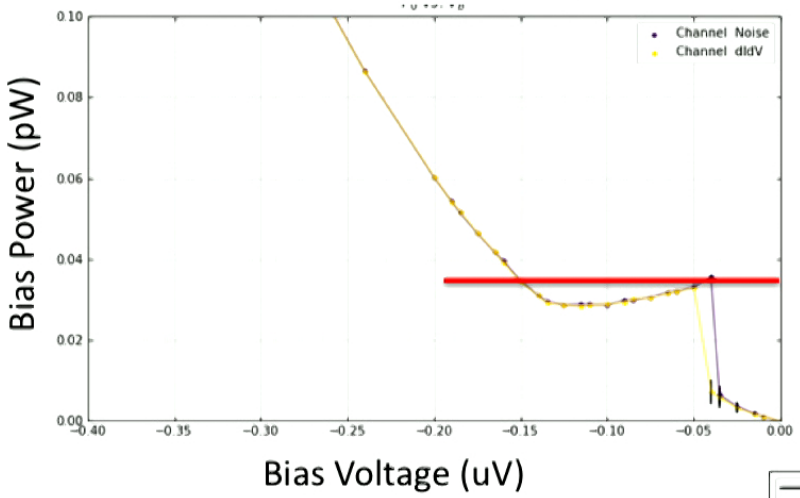
Step 1)Make An Ultra-Sensitive TES



- Build and test simple TES test structures for noise is performance
- $\sigma^2_{<E>} = Ck_bT^2$
  - small volume TES(40nm thick) more sensitive to both DM and environmental backgrounds (RF and vibrations)
- Tc =41 mK

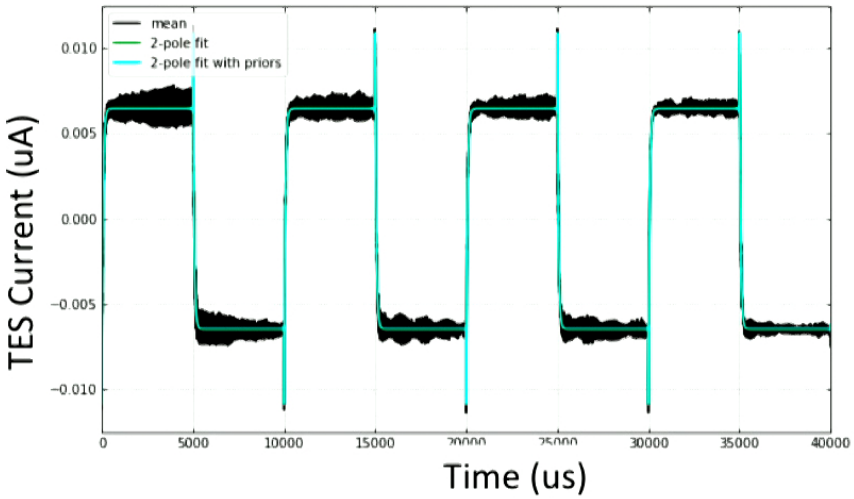
100um x400um TES Characterization

TES Power vs TES Bias Voltage



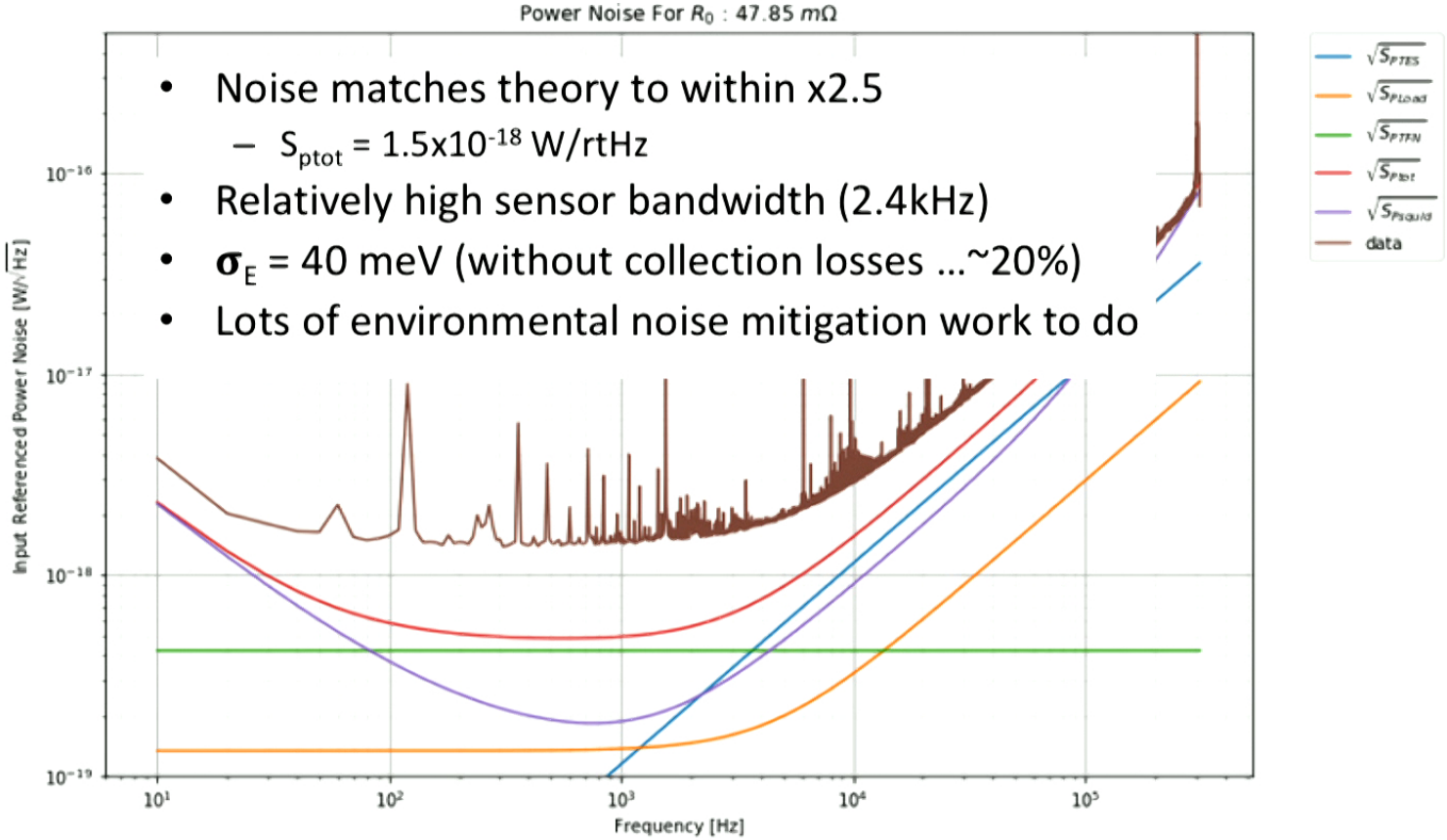
- Normal Resistance: 630mOhm
- Bias Power: 35fW
  - Slight calibration error

TES Response to Square Wave Jitter



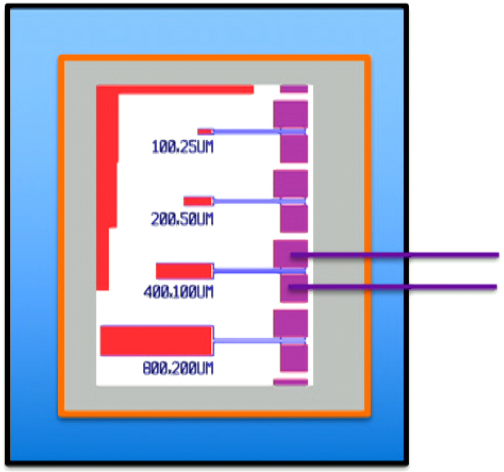
- Complex Impedance
  - Simple 2 pole TES dynamical model perfectly fits response
- TES falltime: ~66us (2.4kHz)
  - Relatively fast
  - Long term -> 1ms and allow athermal phonons to ballistically bounce

100um x400um TES Noise



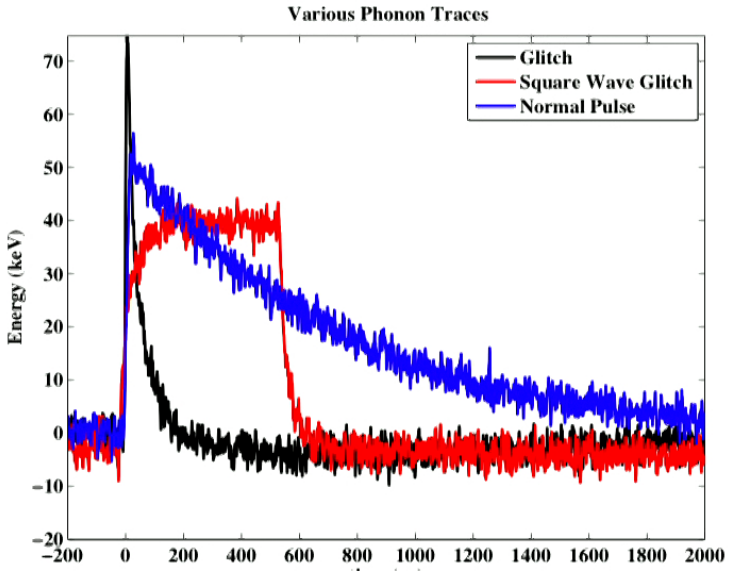
- Noise matches theory to within x2.5
  - S_{ptot} = 1.5x10^{-18} W/rtHz
- Relatively high sensor bandwidth (2.4kHz)
- $\boldsymbol{\sigma}_E$ = 40 meV (without collection losses …~20%)
- Lots of environmental noise mitigation work to do

TES: Environmental Noise Susceptibility



- TES is a resistor … you can heat a resistor with an E&M wave of any frequency
- 5fW of DC Environmental EMI coming down the TES bias lines
- Lots of AC power glitches seen too

Big Challenge: Need to continue to improve Environmental Isolation

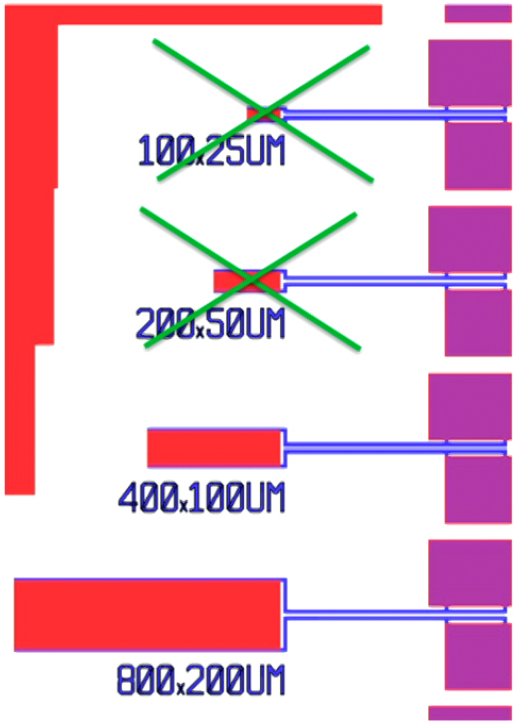


TES R&D

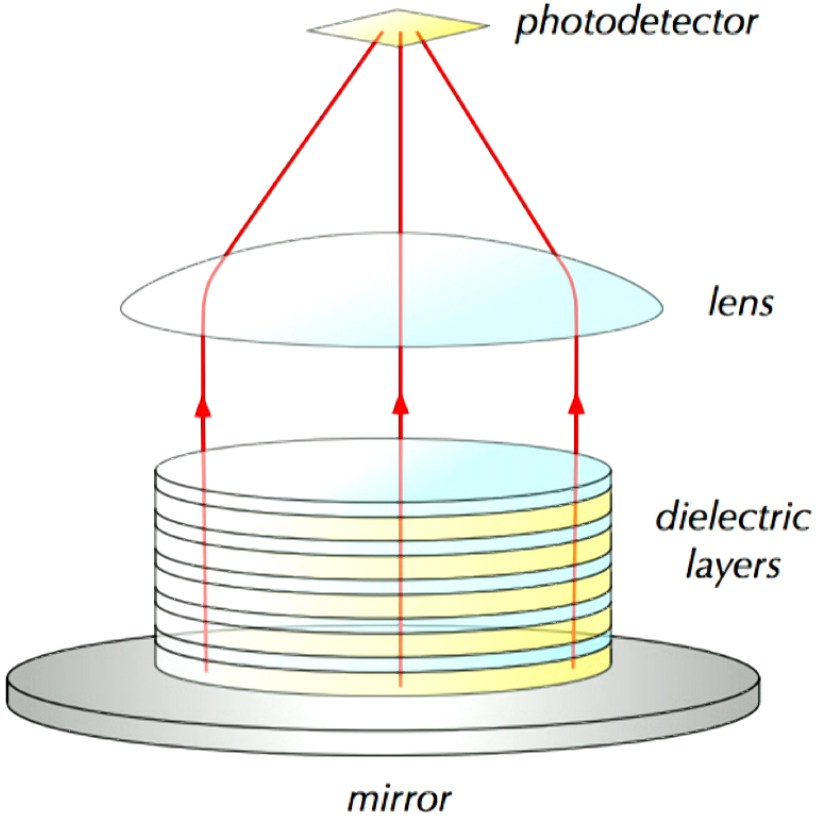
Energy Sensitivity: 40meV -> 1meV

R&D Work Plan

- Lower T_c from 40mK -> 10mK.
  - x8 sensitivity improvement
- Lower volume by x16
  - x4 sensitivity improvement
- Decrease environmental noise by 50dB … there is a reason I'm not showing the performance of the 200umx50um TES

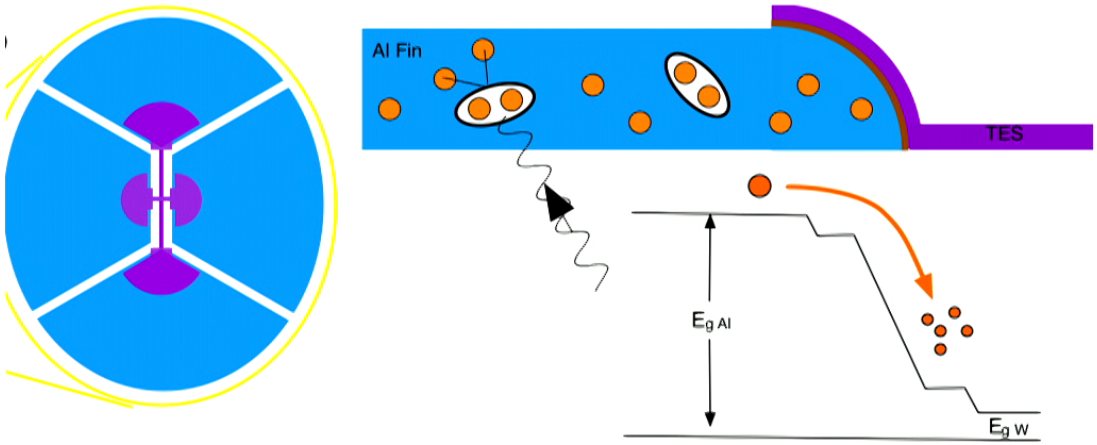


Finished: Optical/IR Haloscopes

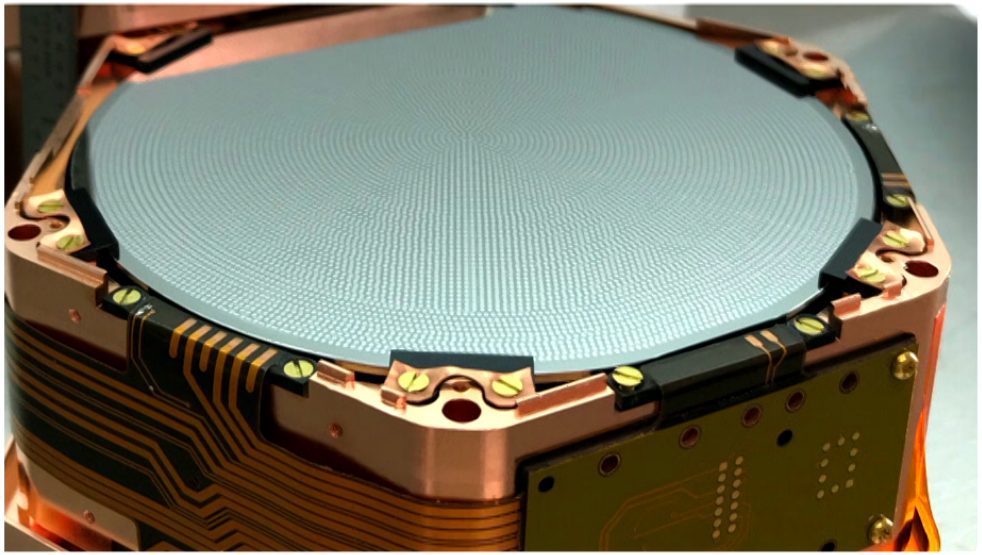


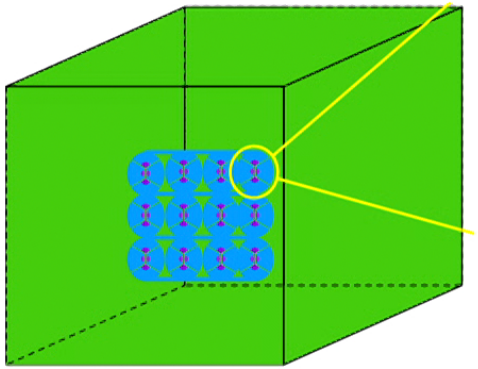
Step 2: Make the Athermal Phonon Sensor

- Measured Phonon Collection Efficiency = 20% -> 40% (theoretical limit)
- R&D Work Plan
  - Optimize Collector/TES (W/Al) interface
  - Improve quasi-particle trapping in collector fin



Step 3: Fabricate Sensors on Crystal





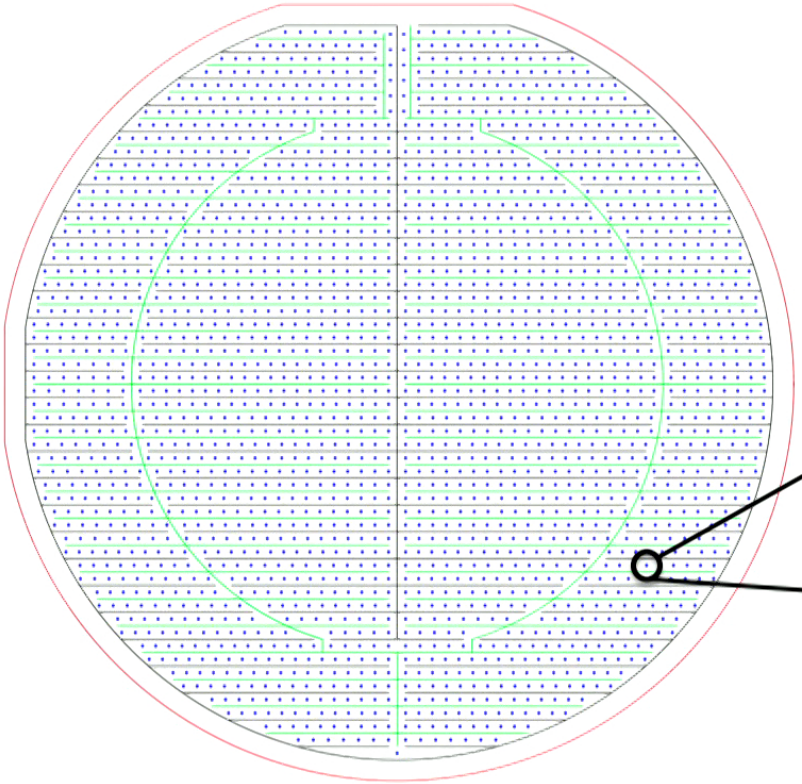
Cryogenic Large Area Photon Detectors For Use In Dark Matter Searches and Neutrinoless Double Beta Decay

Matt Pyle

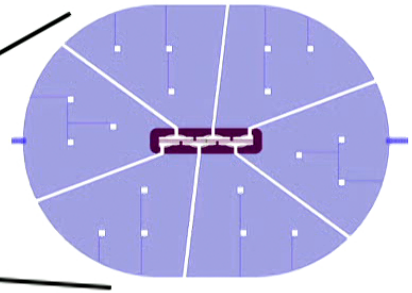
For

T. Aramaki, P. Brink, J. Camilleri, C. Fink, R. Harris, Y. Kolomensky, R. Mahapatra, N. Mirabolfathi, R.Partridge, M. Platt, B. Sadoulet, B. Serfass, S. Watkins, T. Yu

Current Progress: Large Area Photon Detector

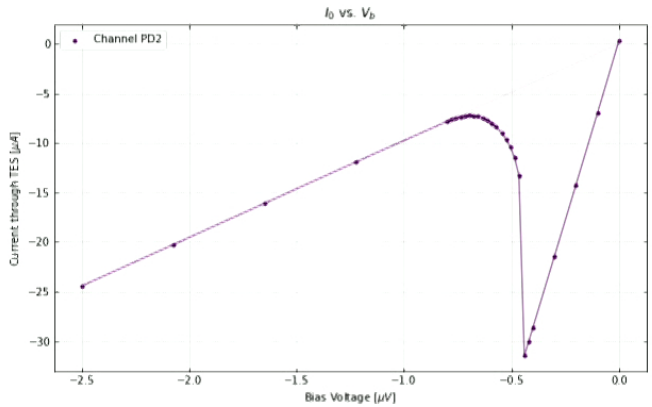


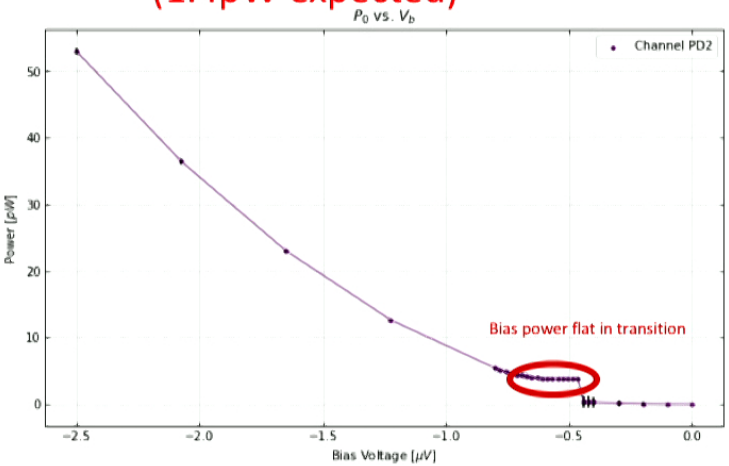
- 3” diameter Si wafer (45.6 cm^2)
- 1mm thick
- Distributed athermal phonon sensors minimize phonon collection time (as fast as it can be for its size)
  - Athermal Phonon collection time estimated to be ~20us
  - 2.5% sensor coverage

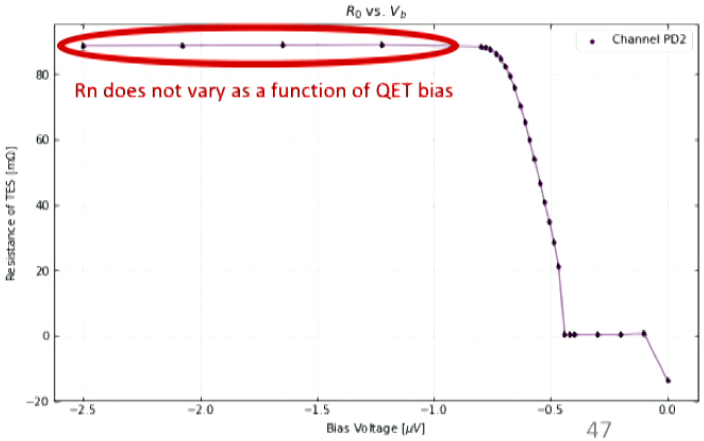


Measured Performance: Tc & IV

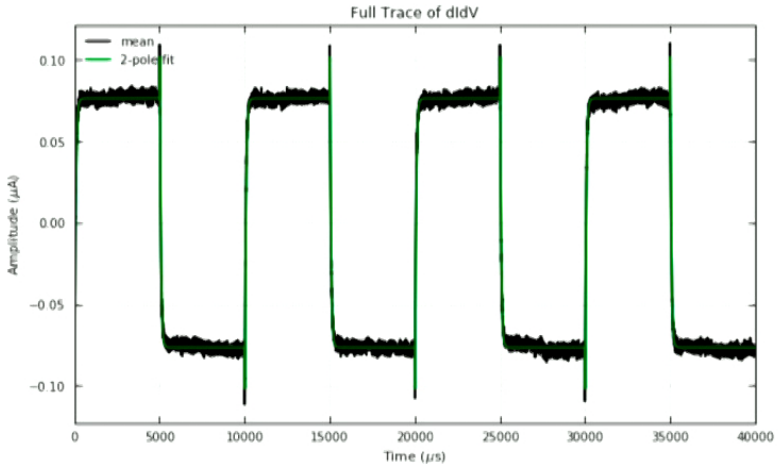
- T_c= 41.5mK
- IV curves show that the detector and electronics are behaving well
  - Rn = 88 mOhms (300mOhm Expected … TES too wide!)
  - Rp = 8 mOhms
  - Bias Power (P_0) = 3.9 pW (1.4pW expected)





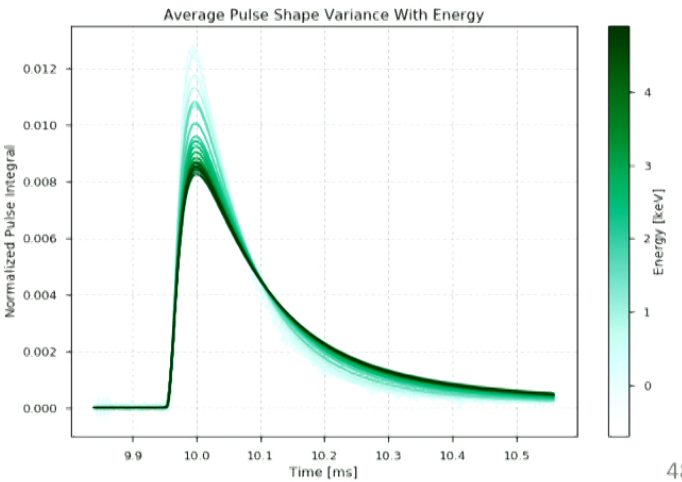


Measured Performance: dIdV



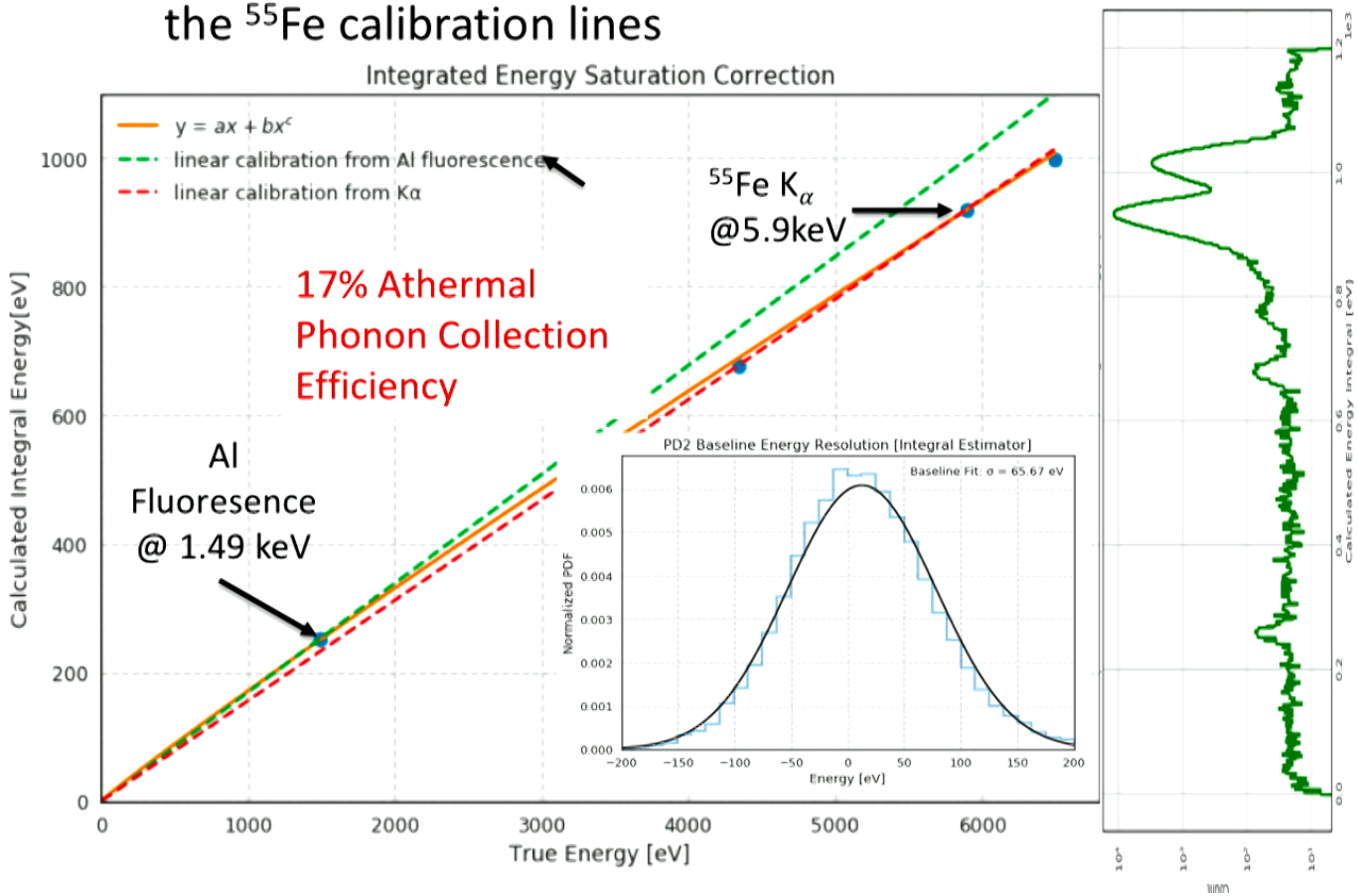
- TES sensor pretty fast @ 60us. However, it's not as fast as the estimated athermal phonon collection (20us)

- Therefore, we expect phonon signals to have a 20us rise time (athermal phonon collection) and a 60us fall time. **Seen for low energy comptons in average pulse shape!**
- Pulse shape varies with energy due to local TES saturation.

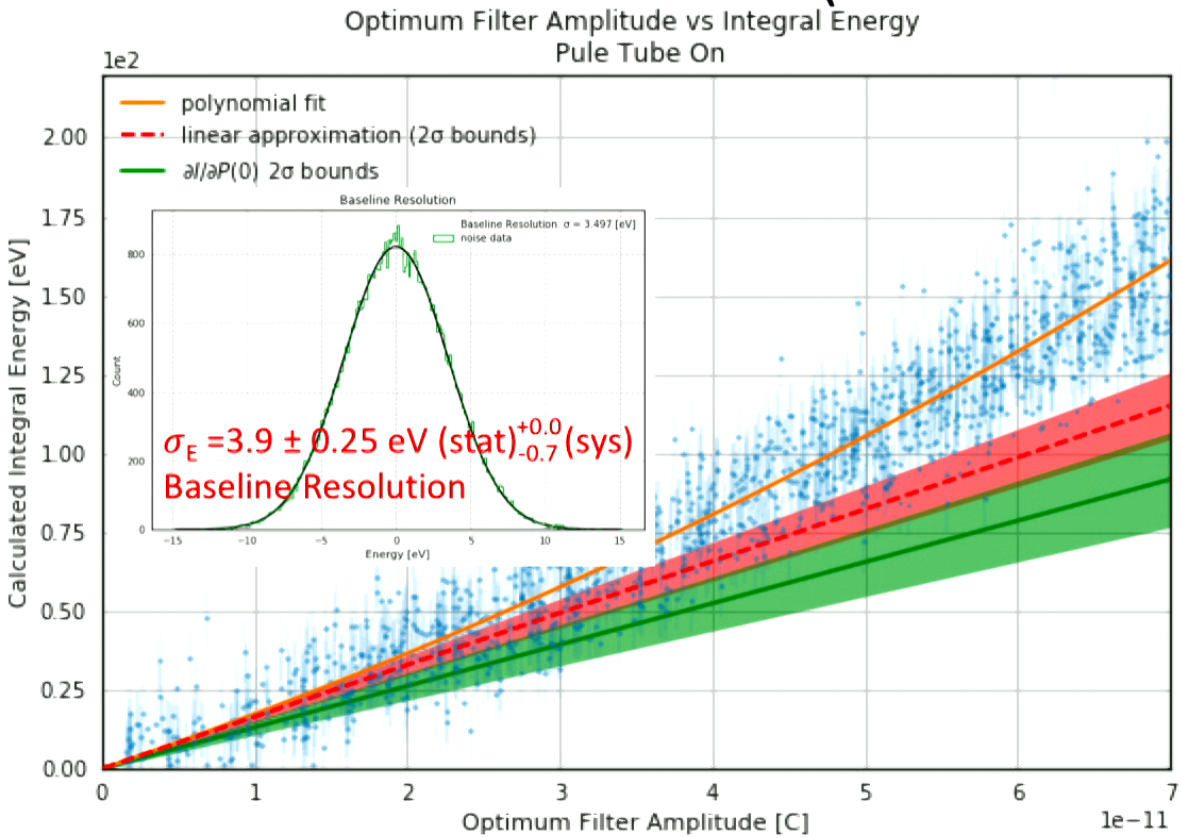


Integral Estimators for relative ^{55}Fe calibration

- Since pulse shape has significant variation with energy, we must use noisy but minimally biased DC estimators to fit the ^{55}Fe calibration lines

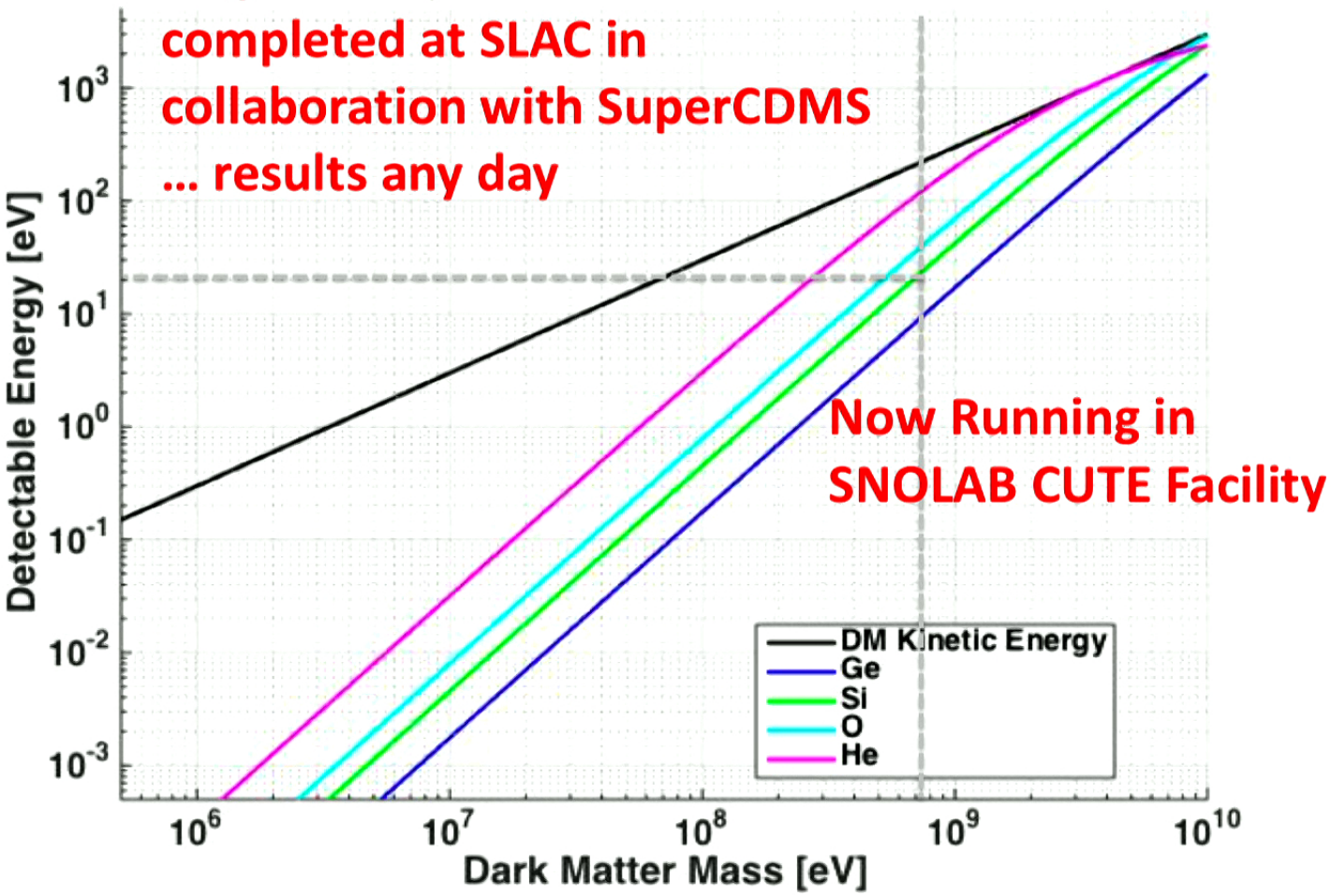


Calibrating Pulse Shape Dependent Energy Estimators to the DC estimator (Pulse Tube On)

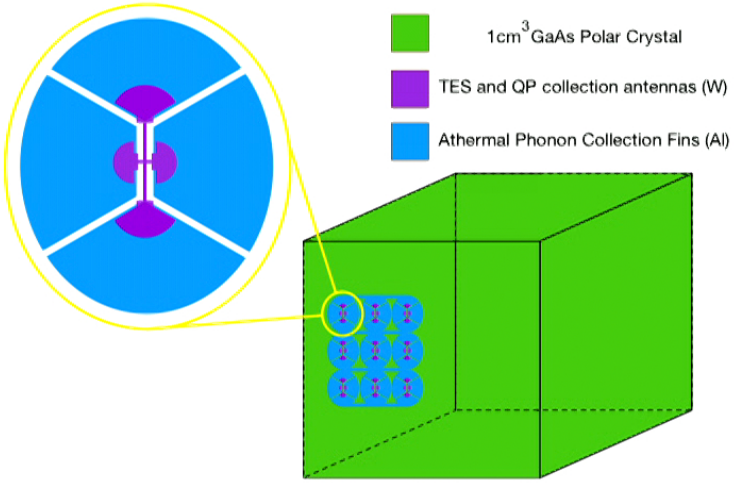


First Dark Matter Search

20 gram-day DM search completed at SLAC in collaboration with SuperCDMS … results any day



Now Running in SNOLAB CUTE Facility



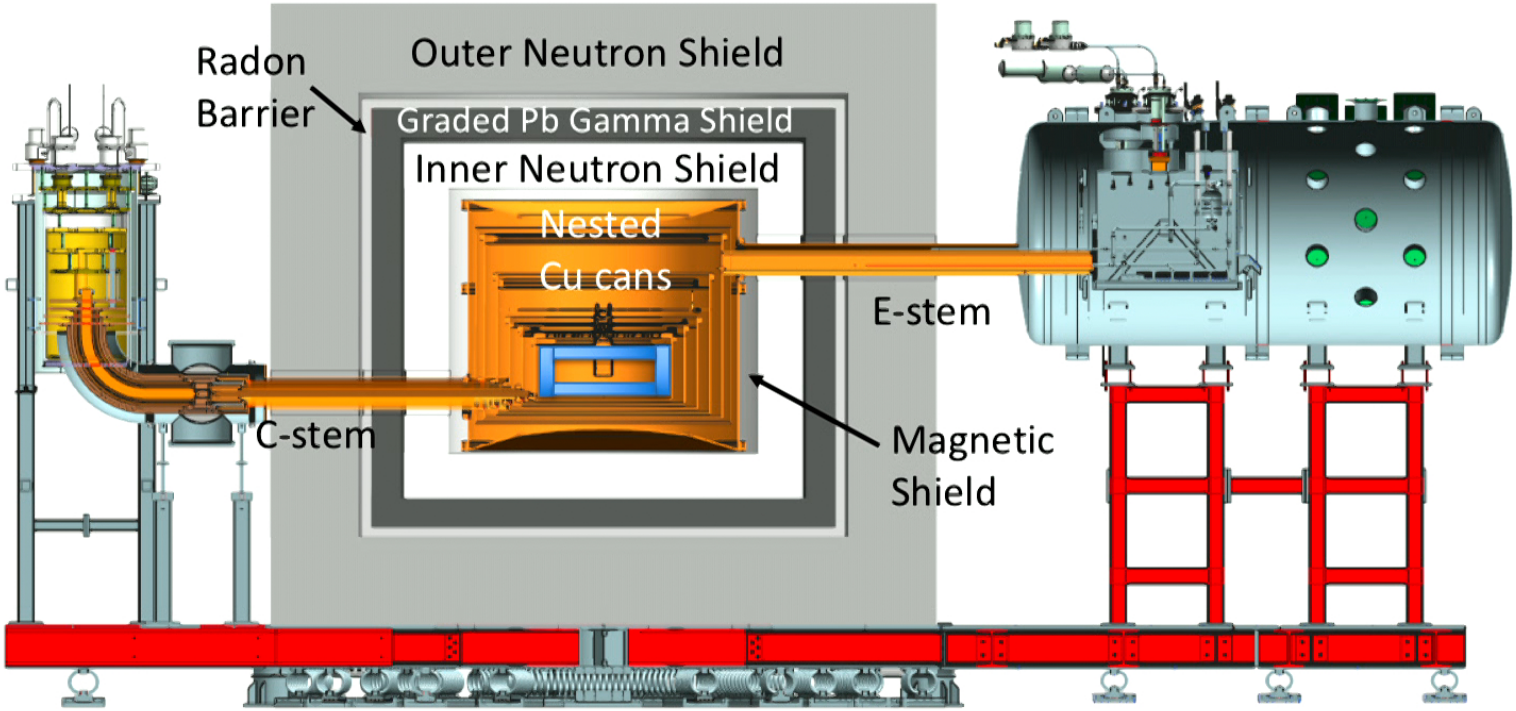
Prototype Design Estimated Sensitivities

New 1cm^3 Prototype Test Design

# TES	**100**
TES Dimensions	50um x 2um x40 nm
TES Rn	320mOhm
Fin Length	125um
W/Al Overlap	15um
Fractional Al Coverage	1%
Tc	40mK
Bias Power	48fW
Power Noise	5.1e-19 W/rtHz
Phonon absorption time	106us
Sensor fall time	97us
Collection efficiency	19%
σ_E	**219 meV**

- With a Si Absorber: single e/h sensitivity without Luke-Neganov gain. Can be used for inelastic electronic recoil DM
- World Leading Elastic Nuclear Recoil DM search potential

Running in SuperCDMS SNOLAB



- Internal Active Photon Veto
- Improved filtering

Summary:

- Athermal Phonon Small Volume detectors are a promising technique to search for 10meV-1GeV Dark Matter
- Current Progress:
  - 3” large are photon detector 3.9eV resolution
  - 100x400um TES test chip: 40meV resolution
  - Running photon detector at CUTE soon
- R&D Plan: Towards single phonon sensing
  - Increase TES sensitivity: lower Tc
  - Improve Collection efficiency: optimize W/Al interface
  - Fabricate on a variety of crystal substrates (SiO_2)
  - Study how phonon surface themalization depends on surface roughness.