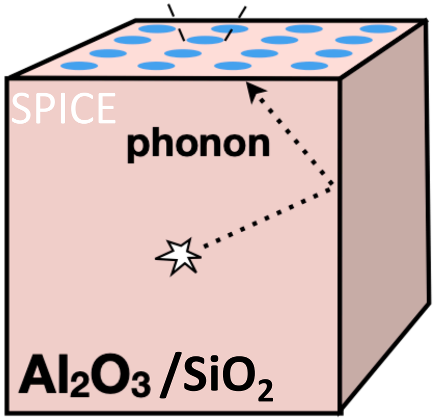
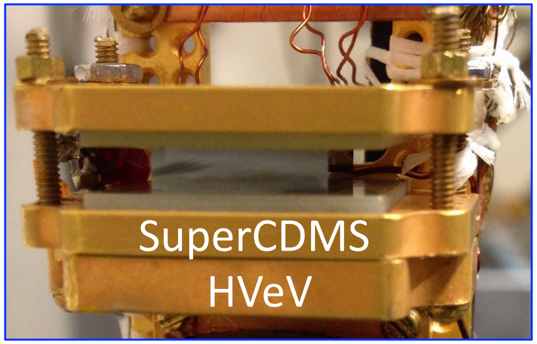
Shared Athermal Phonon Detector Challenges

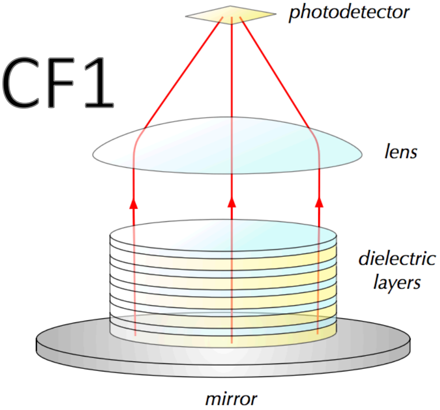
Matt Pyle

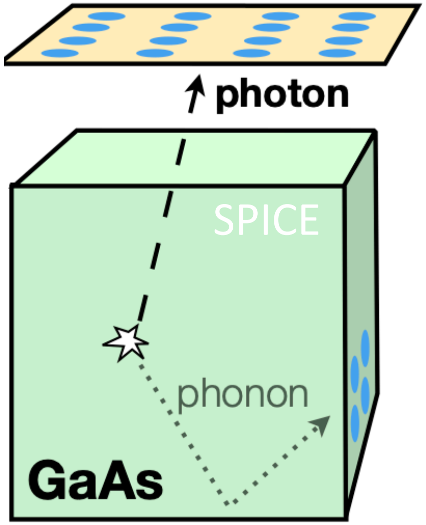
SNOWMASS CF1

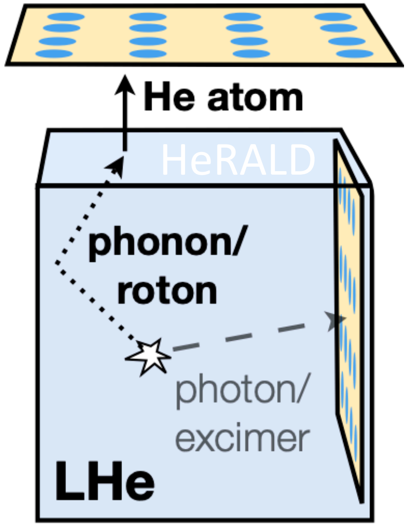
10/01/20

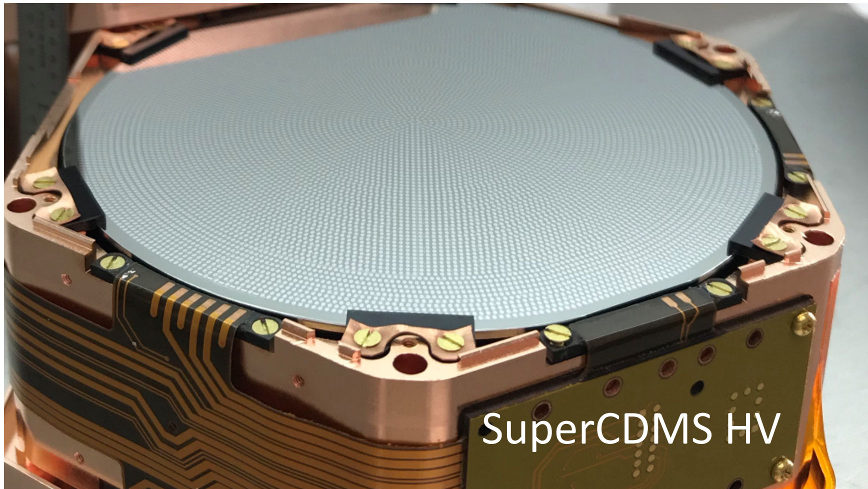










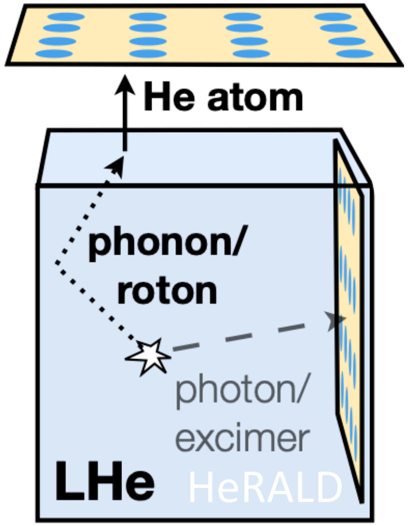


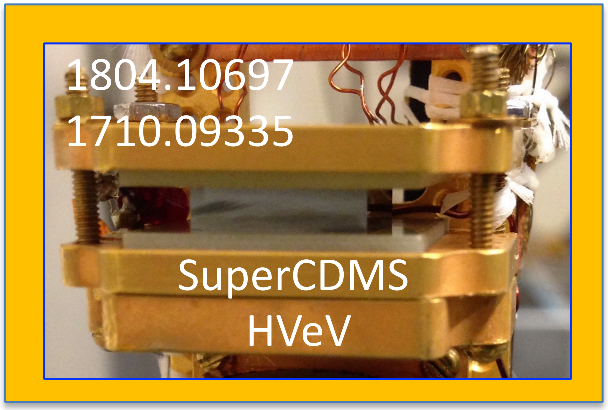
Many Complementary Light Mass Dark Matter Search Applications for Athermal Phonon Sensor Technology

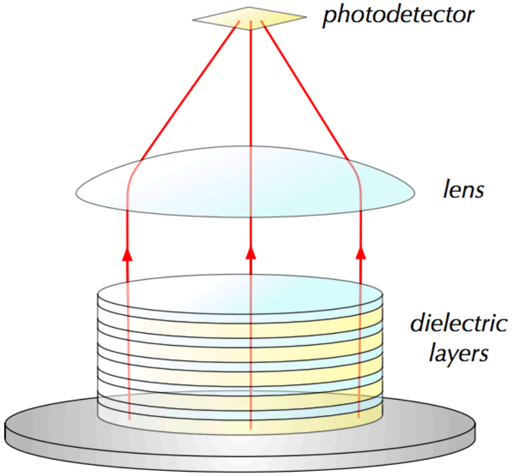

SuperCDMS HV
1509.02448


1712.06598

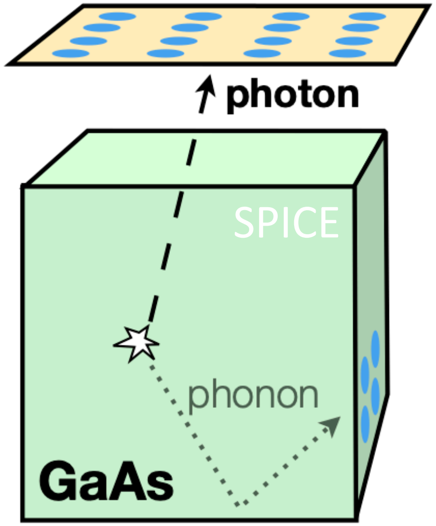
1611.06228



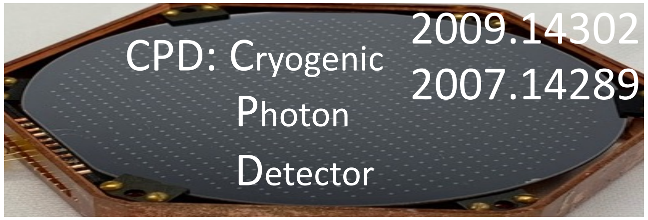

1804.10697
1710.09335
SuperCDMS HVeV



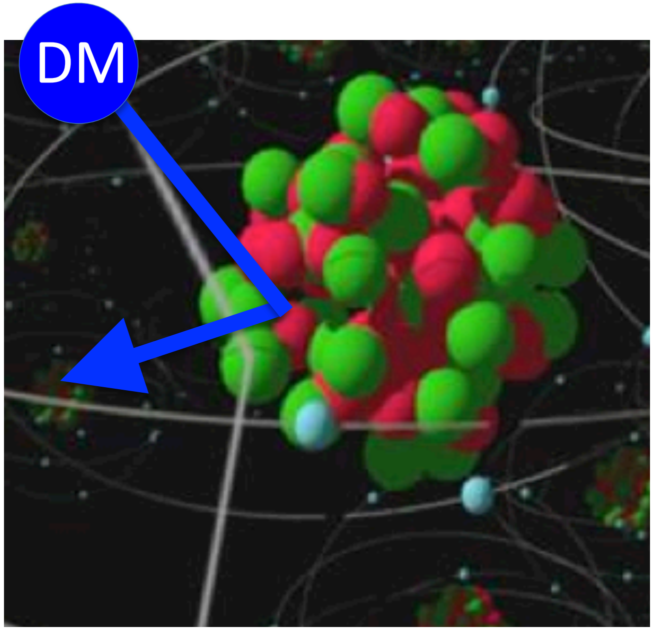
1803.11455

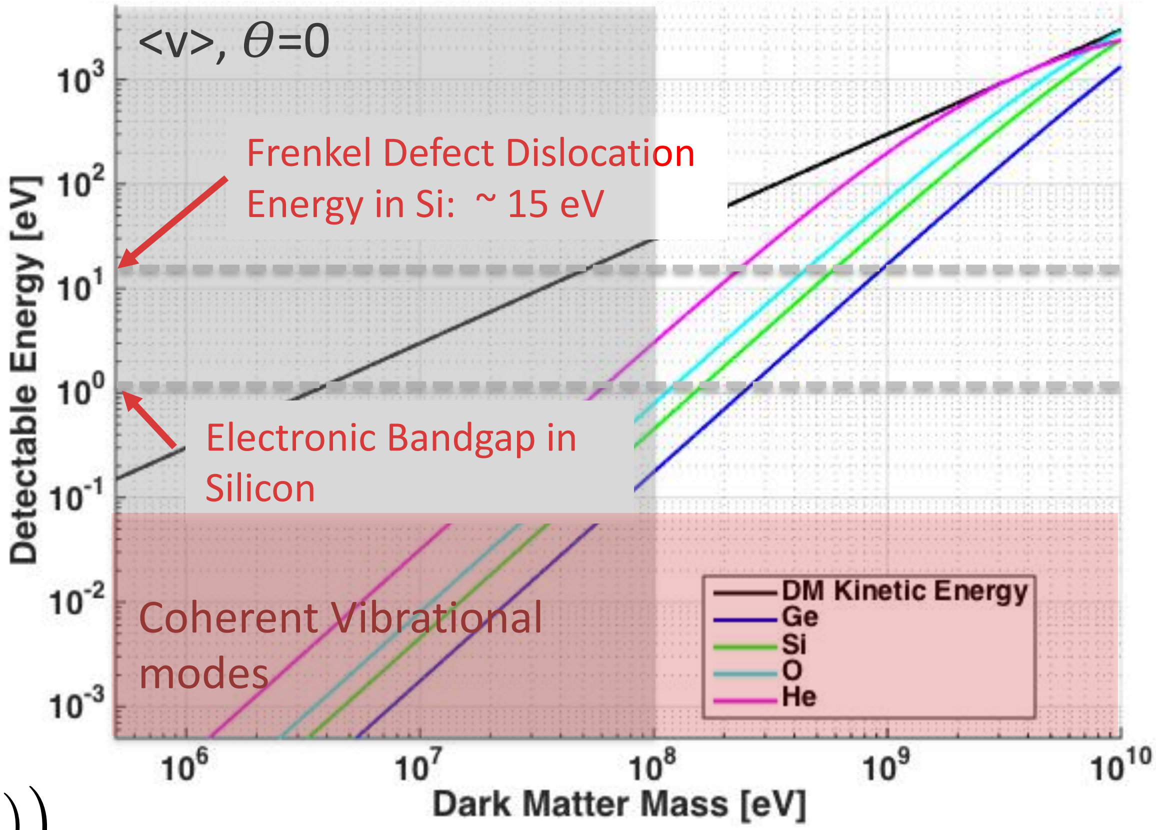


1607.01009


CPD: Cryogenic Photon Detector
2009.14302
2007.14289

2 Body Elastic Nuclear Scattering





Frenkel Defect Dislocation Energy in Si: ~ 15 eV

Electronic Bandgap in Silicon

Coherent Vibrational modes

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

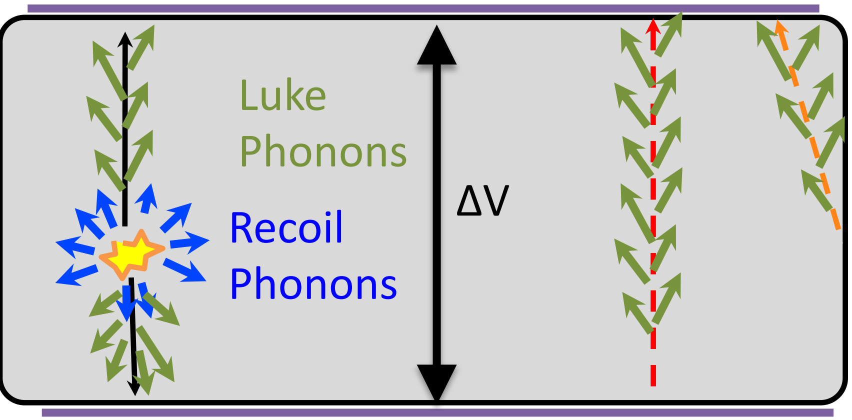
When $M_n >> M_{DM}$

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

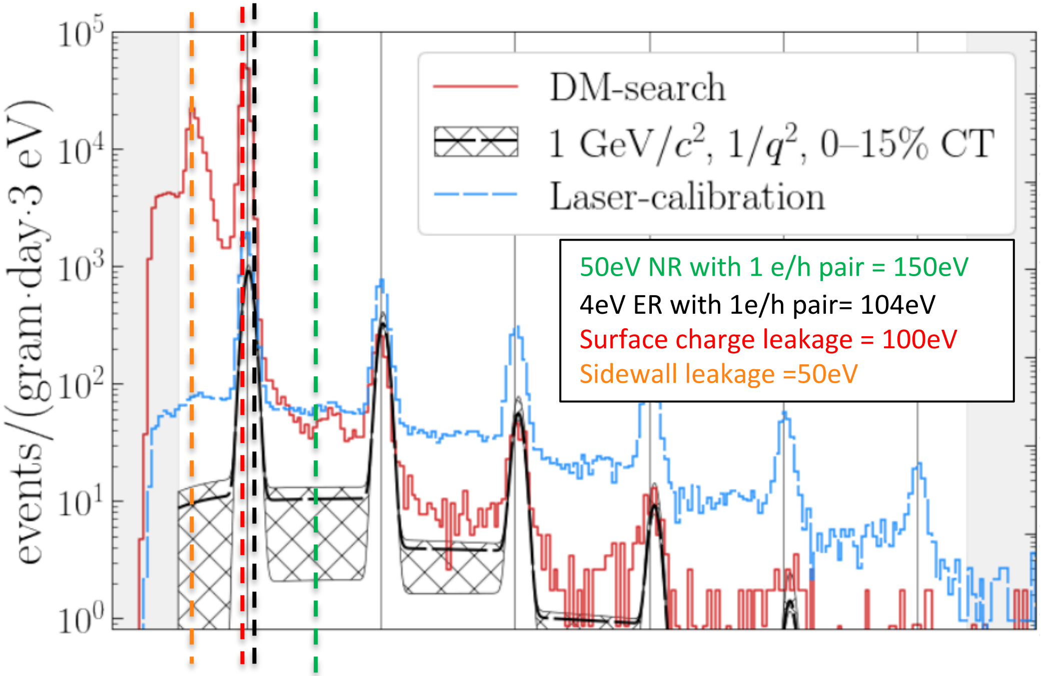
- Energy Sensitivity is the primary design driver for < GeV NR searches
- Below O(100MeV), DM NR won't produce ionization … **phonon detection is largely required**

Inelastic Electronic Recoils: SuperCDMS HVeV

Natural Charge to Phonon Amplification when voltages placed across detector



$$\begin{aligned} E_{total} &= E_{recoil} + E_{luke} \\ &= E_{recoil} + Qe\Delta V \end{aligned}$$



50eV NR with 1 e/h pair = 150eV
4eV ER with 1e/h pair= 104eV
Surface charge leakage = 100eV
Sidewall leakage =50eV

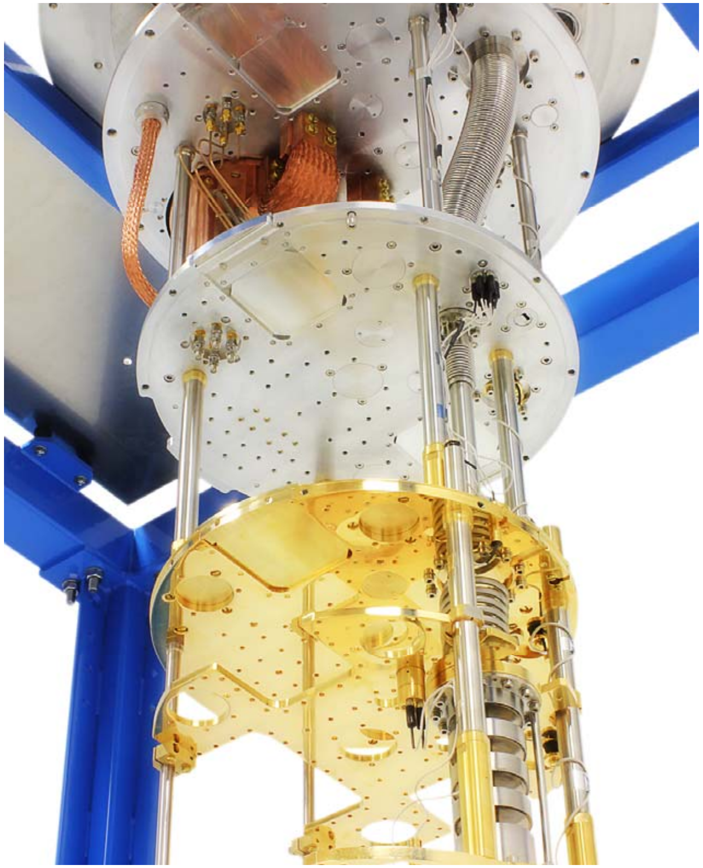
- Lots of competition
  - Si CCDs (SENSEI/DAMIC)
  - SNSPDs (GaAs)
- **Athermal Phonon Detector Technology can potentially discriminate between ERDM signals, NR backgrounds (Pyle), and potentially nearly all detector physics backgrounds (Kurinsky)**

Energy Sensitivity Summary

DM Signal	Experiment	Threshold
>1 GeV NR 0V	SuperCDMS	~ $50eV_t$
<1 GeV NR	SuperCDMS, HeRALD, SPICE	$100meV_t$ – 50eVt
Single Optical and Acoustic Phonons	SPICE	40-100meVt
Inelastic ER	SuperCDMS HV / HVeV	• 20eVt (@100V) • 2eVt (@100V with full background discrimination)
Inelastic ER	SPICE (GaAs)	• 0.8eVt

100meV Vibrational Excitation Sensitivity -> Low Temperature Detectors

- 300K = 26meV
- To sense 100meV excitations we'll need to cool the detector down to near absolute zero
- Use superconducting detector technology
  - MKIDs
  - Phonon Sensitive QUBITs
  - **Transition edge sensors**

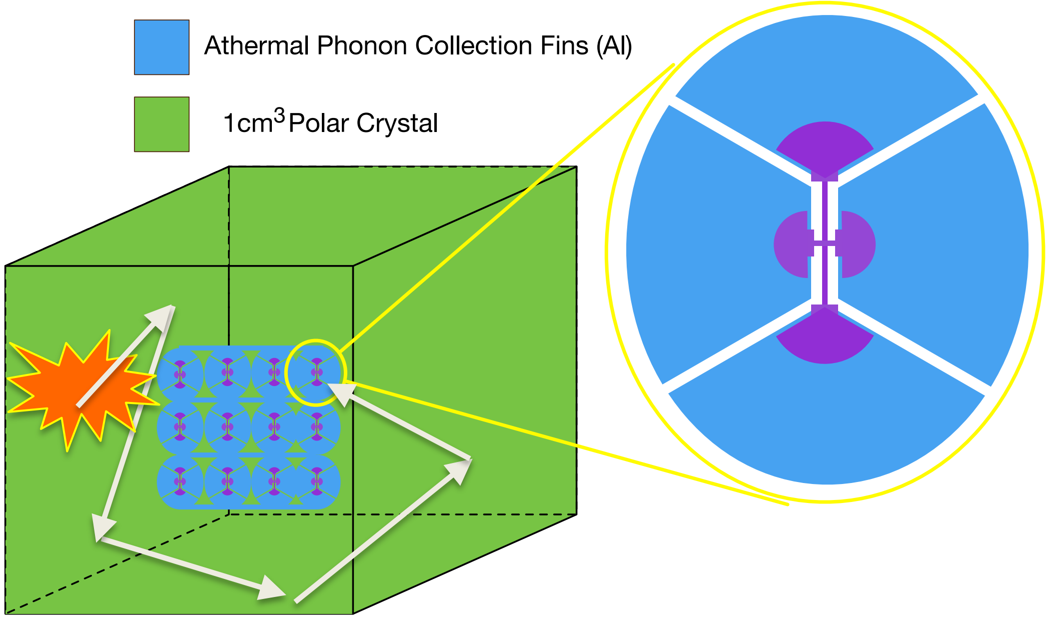


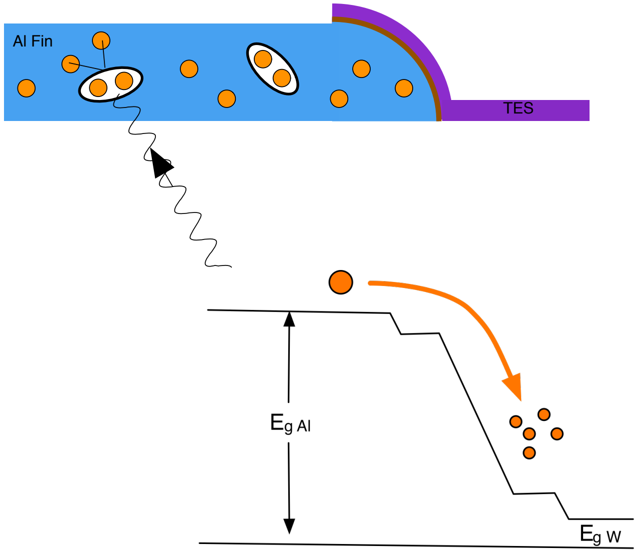
Athermal Phonon Sensor Technology

🟪 TES and QP collection antennas (W)

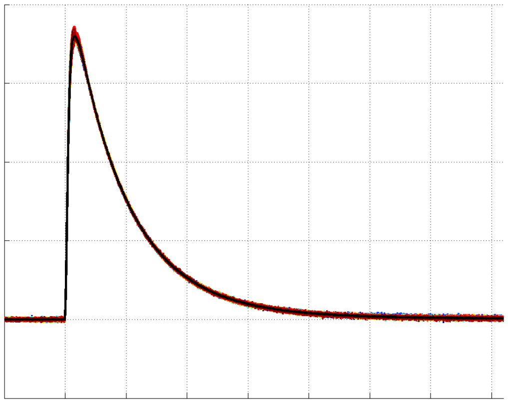
🟦 Athermal Phonon Collection Fins (Al)

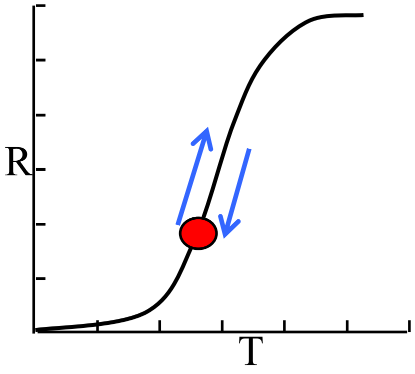
🟩 1cm^3 Polar Crystal



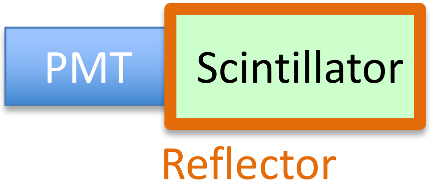


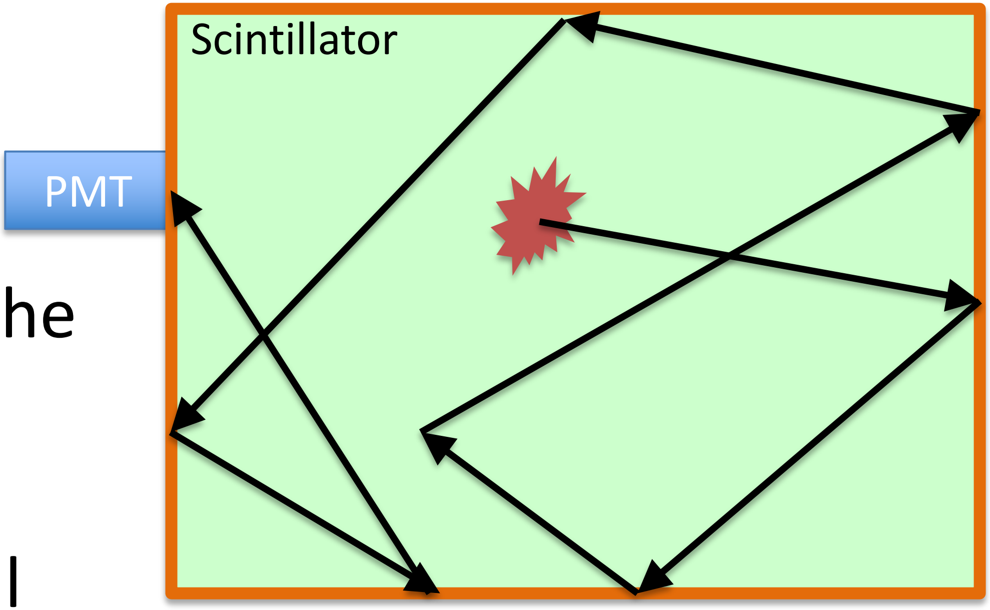
Collect and Concentrate Athermal Phonon Energy into Sensor





Excitation Detectors & Volume Scaling

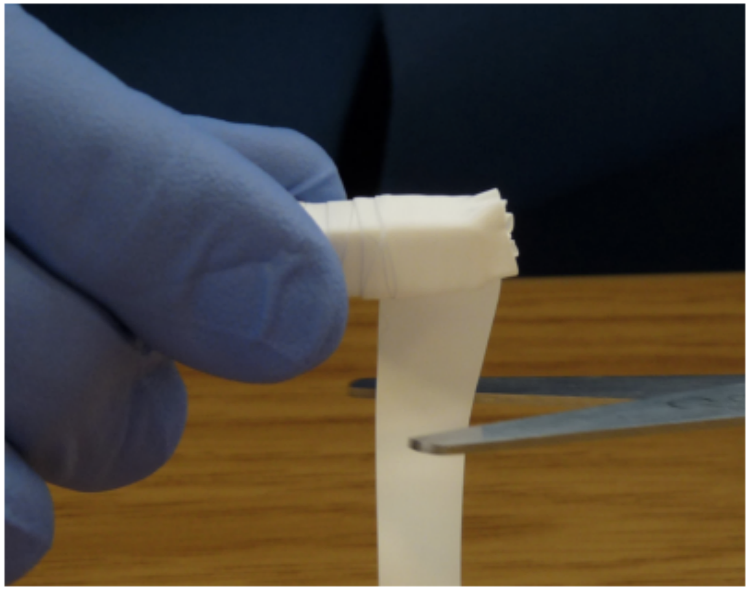




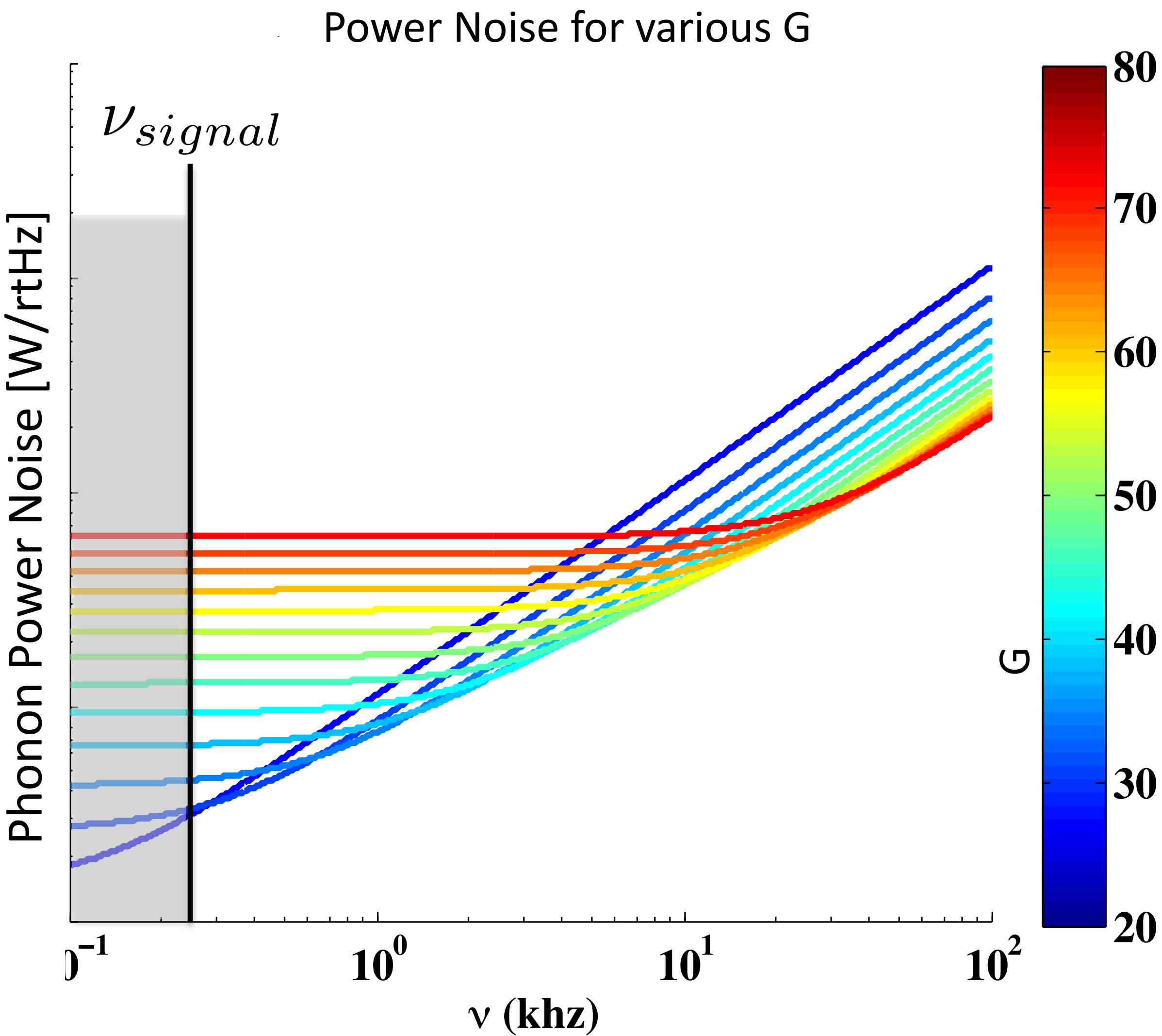
Will these detectors have the same energy sensitivity?

Yes, if:

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



TES Athermal Phonon Sensor Sensitivity Scaling



$$G \propto T_c^4$$

$$S_{p\,t\,f\,n} = 4k_b T_c^2 G$$

$$\propto T_c^6$$

$$\sigma_E \propto T_c^3$$

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

You can always say on $V^{1/2}T_c^{\,3}$ scaling (in principle)

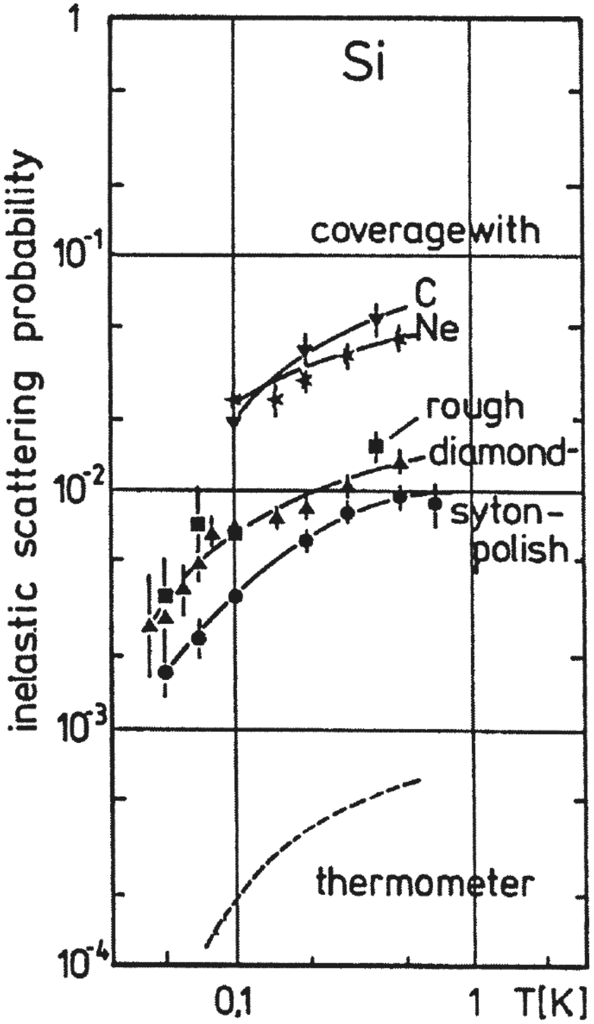
45mK-> 10mK: 2eV -> 20meV

Athermal Phonon Thermalization at Surfaces

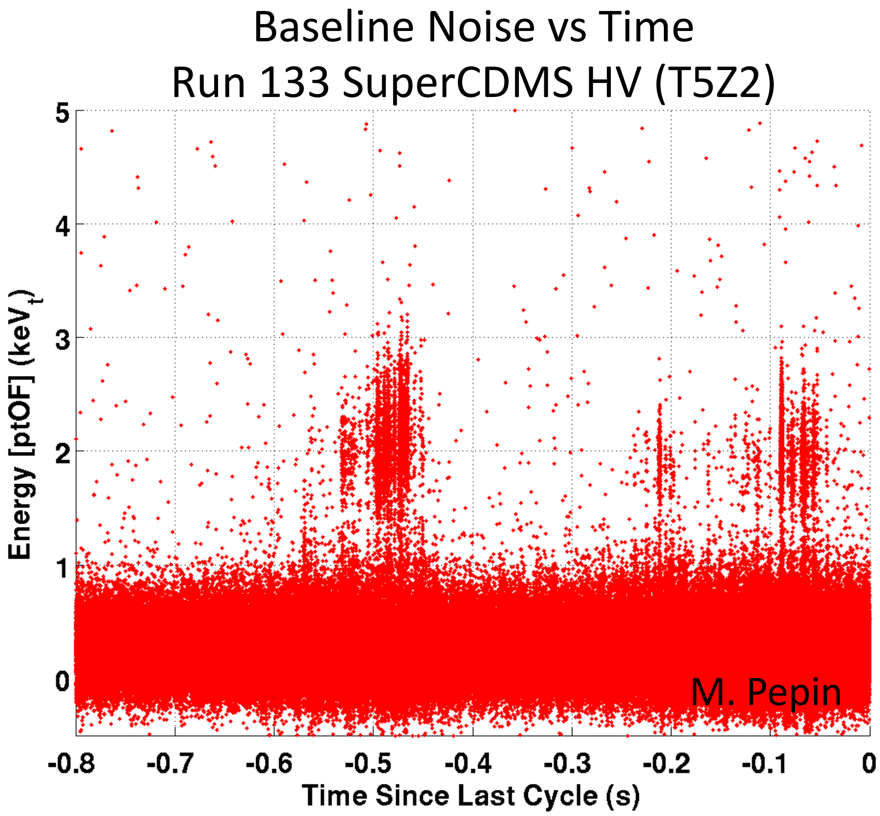
- Athermal phonon surface thermalization probability found to depend upon
  - Crystal
  - Surface roughness
  - Surface cleanliness

(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



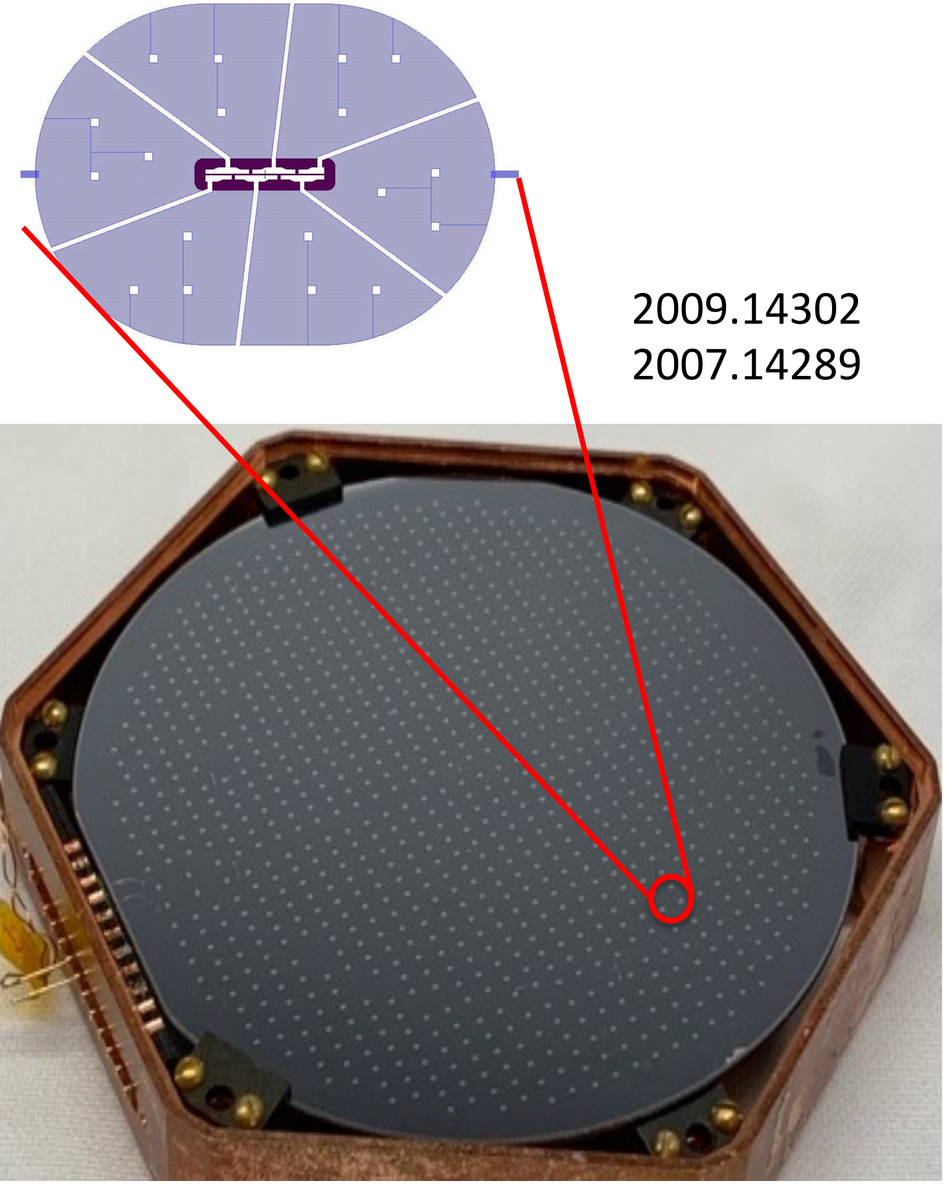
Environmental Vibrational Noise and Residual Stress



Vibrations from the SuperCDMS Soudan cryocooler produced high frequency phonons our detectors which looked like real events.

- The smaller the crystal, the less susceptible to vibrational noise (not seen in CPDv0-2 or HVeV)
- Single phonon sensitive detectors will almost certainly need double spring+mass vibration decoupling system

Current Best Measured Performance Athermal Phonon Detector: CPDv0



2009.14302
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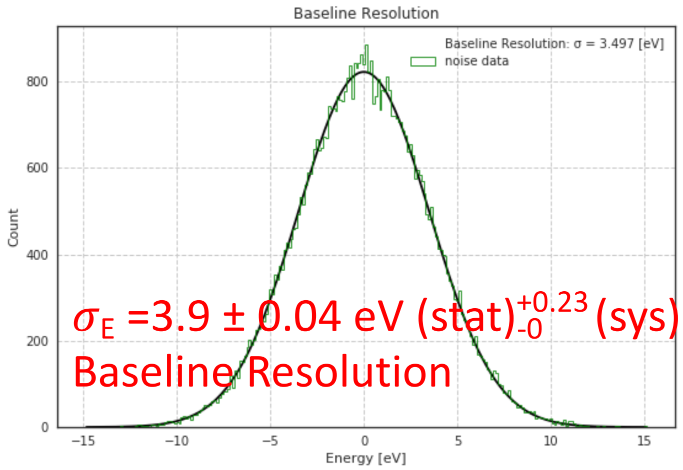
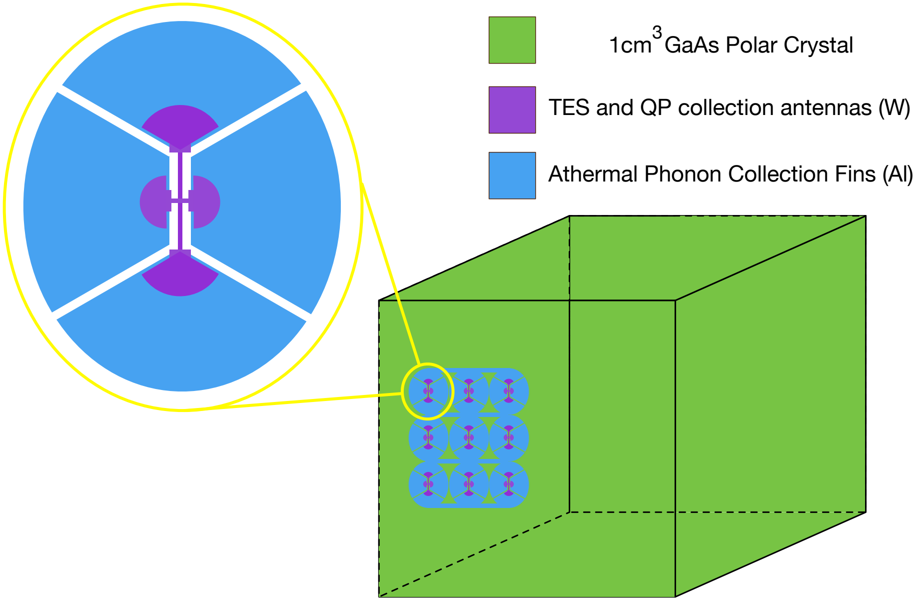
- 3” diameter Si wafer (45.6 cm^2)
- 1mm thick
- 2.5% sensor coverage
- Athermal Phonon collection time: ~20us
- T_c= 41.5mK
- 60us TES falltime



σ_E =3.9 ± 0.04 eV (stat)$^{+0.23}_{-0}$ (sys)
Baseline Resolution

Prototype Design Estimated Sensitivities



🟩 1cm^3 GaAs Polar Crystal

🟪 TES and QP collection antennas (W)

🟦 Athermal Phonon Collection Fins (Al)

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

Summary

- Athermal Phonon Detectors have wide applicability in light Mass Dark Matter searches
- Current Progress:
  - 3” large are photon detector 3.9eV resolution
  - 100x400um TES test chip: 40meV resolution
- Athermal Phonon R&D
  - Surface Down Conversion
  - Vibration Mitigation
- TES R&D
  - Lower Tc ($\boldsymbol{\sigma} \propto V^{1/2} T_c^3$)
  - EMI mitigation

Backup

Athermal Phonon R&D

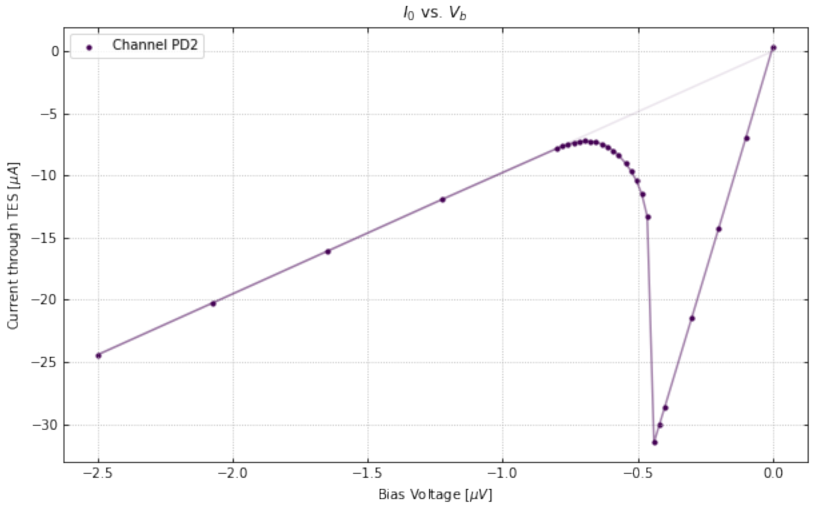
Matt Pyle

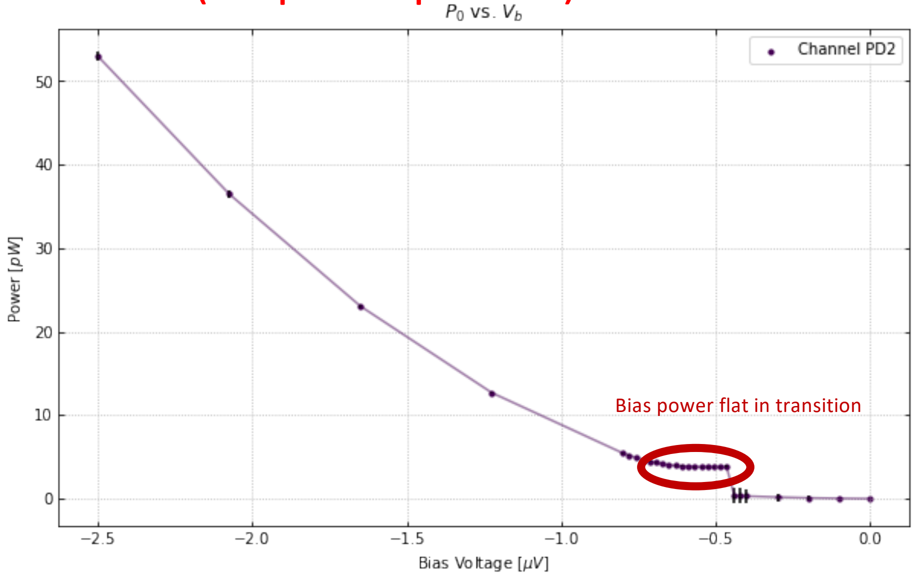
For

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

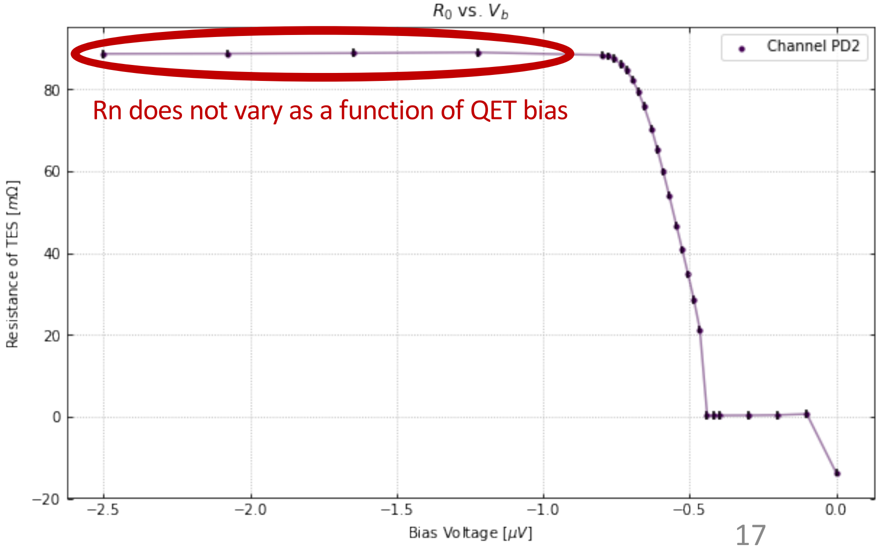
Measured Performance: Tc & IV

- 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)



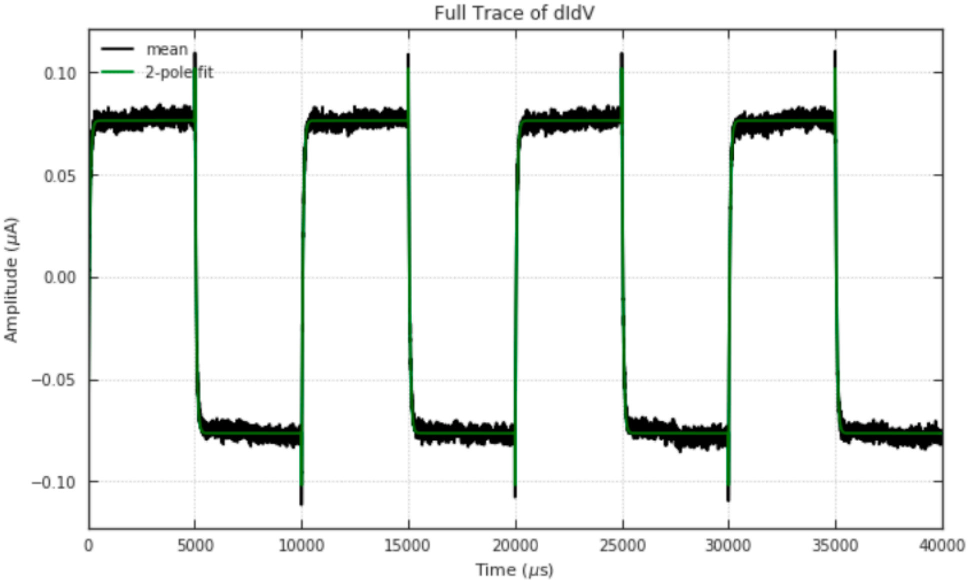


Bias power flat in transition



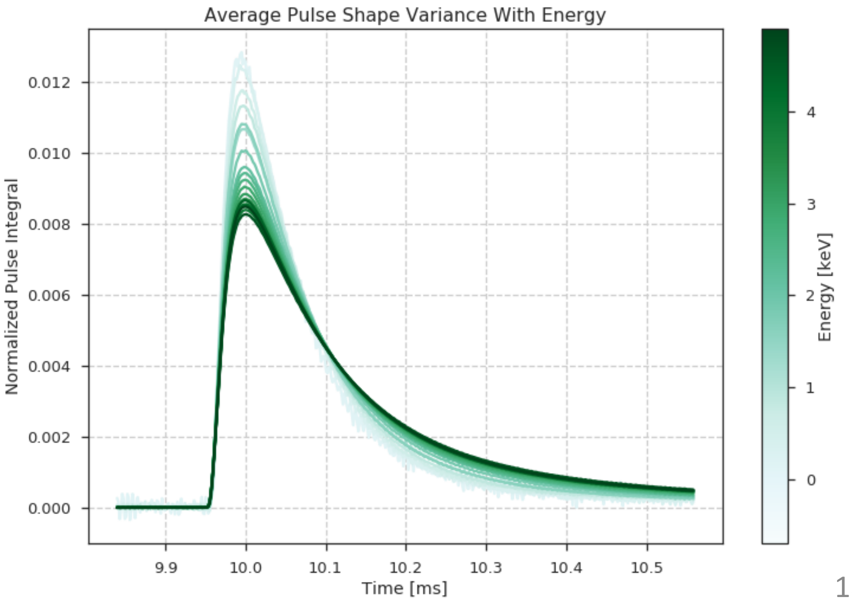
Rn does not vary as a function of QET bias

Measured Performance: dIdV

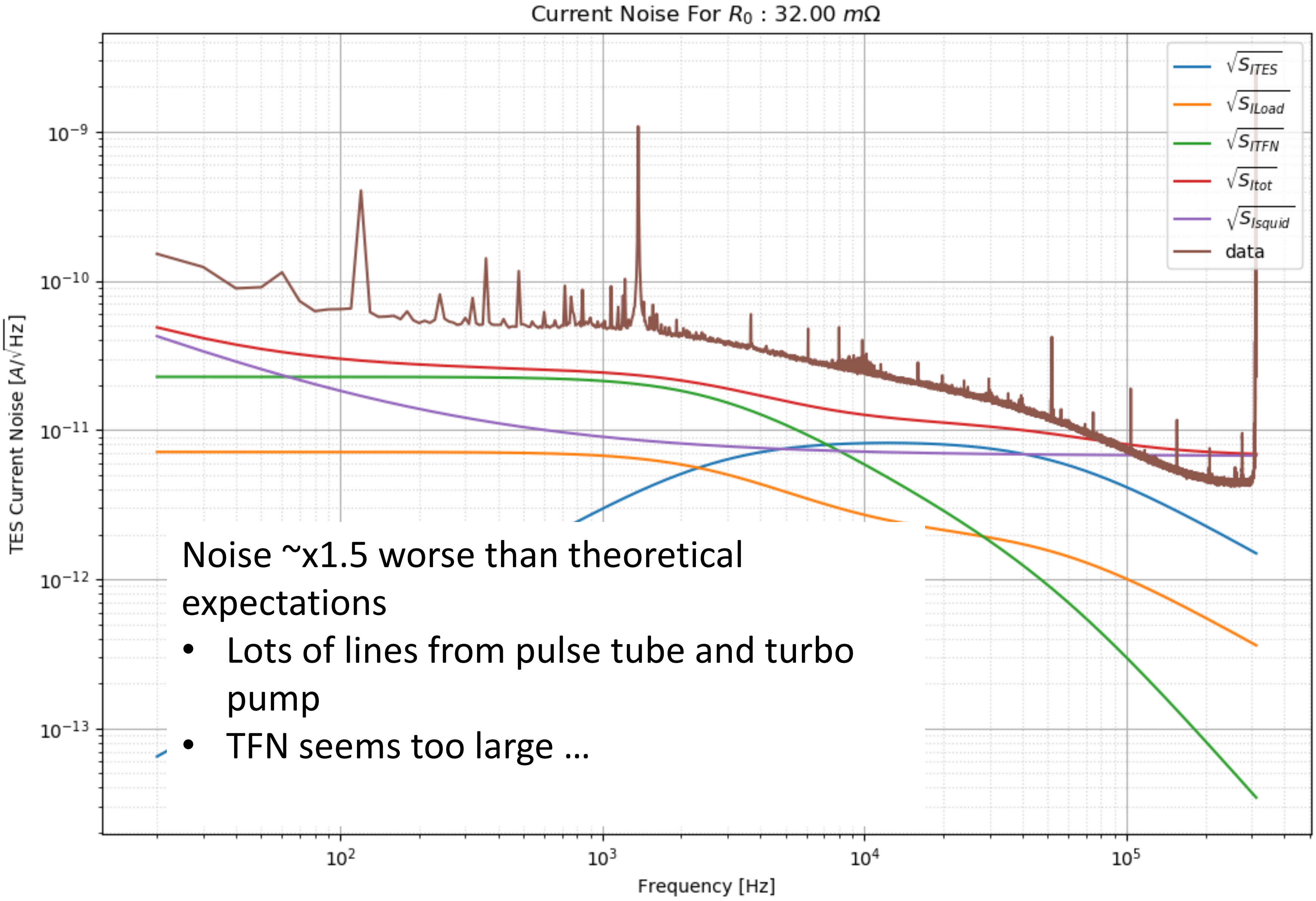


- TES sensor pretty fast @ 60us. However, it's not as fast as the estimated athermal phonon collection (20us)

- 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.



Measured/Theoretical Noise

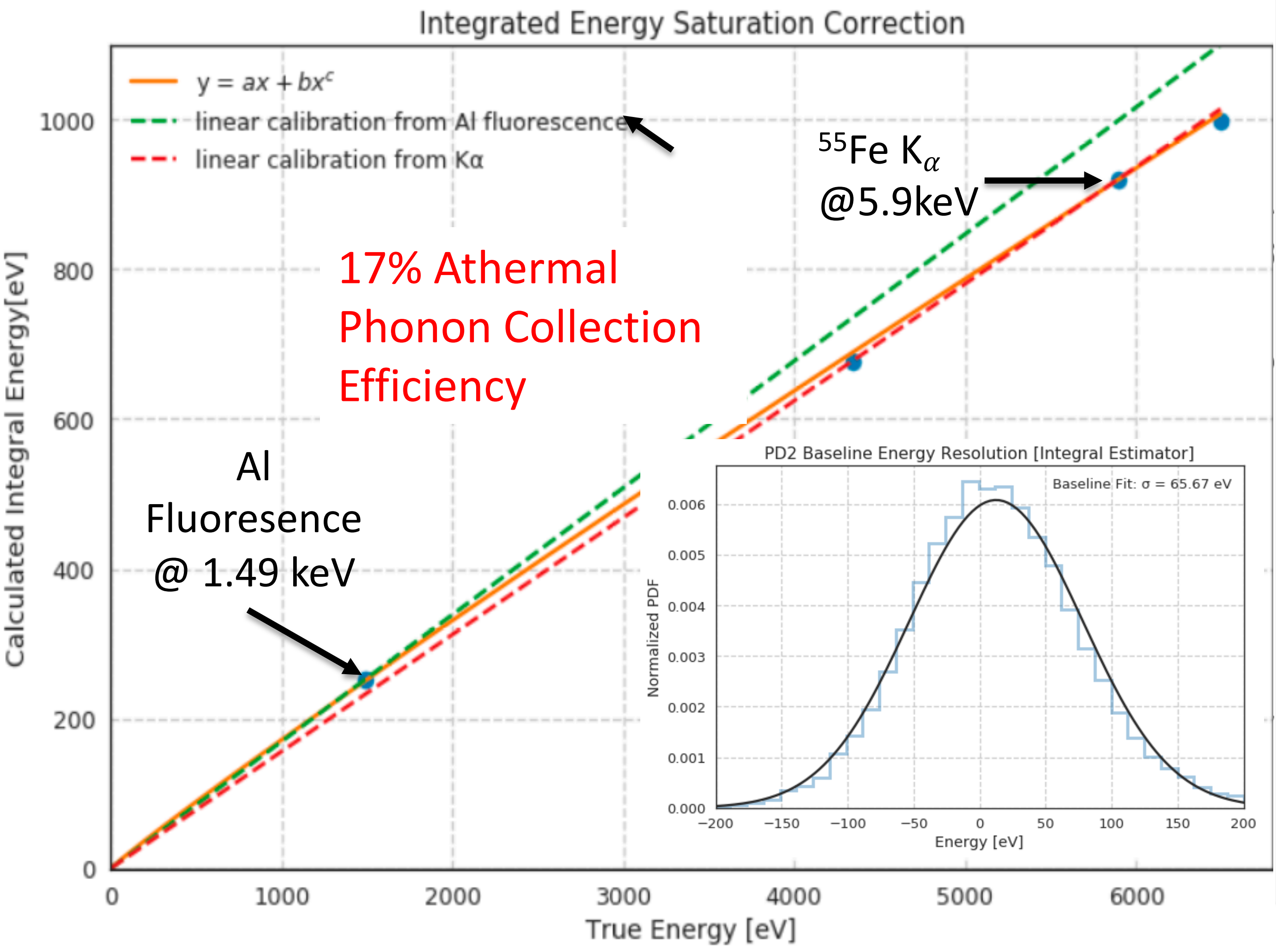


Noise ~x1.5 worse than theoretical expectations

- Lots of lines from pulse tube and turbo pump
- TFN seems too large …

Integral Estimators for relative ^{55}Fe calibration

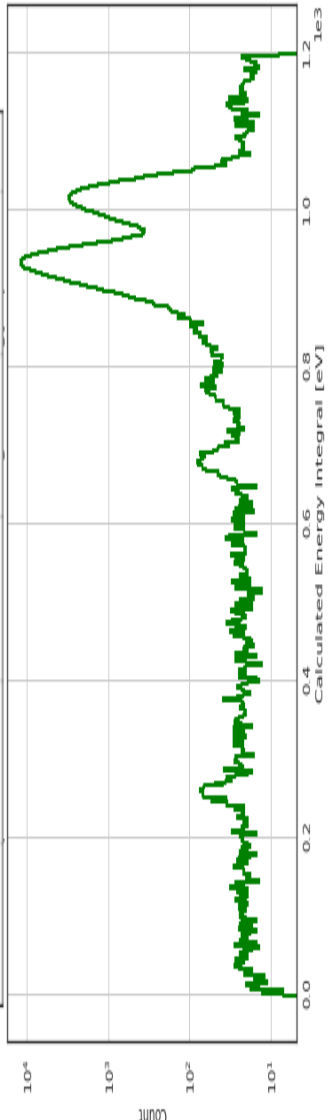
- Since pulse shape has significant variation with energy, we must use noisy but minimally biased DC estimators to fit the ^{55}Fe calibration lines



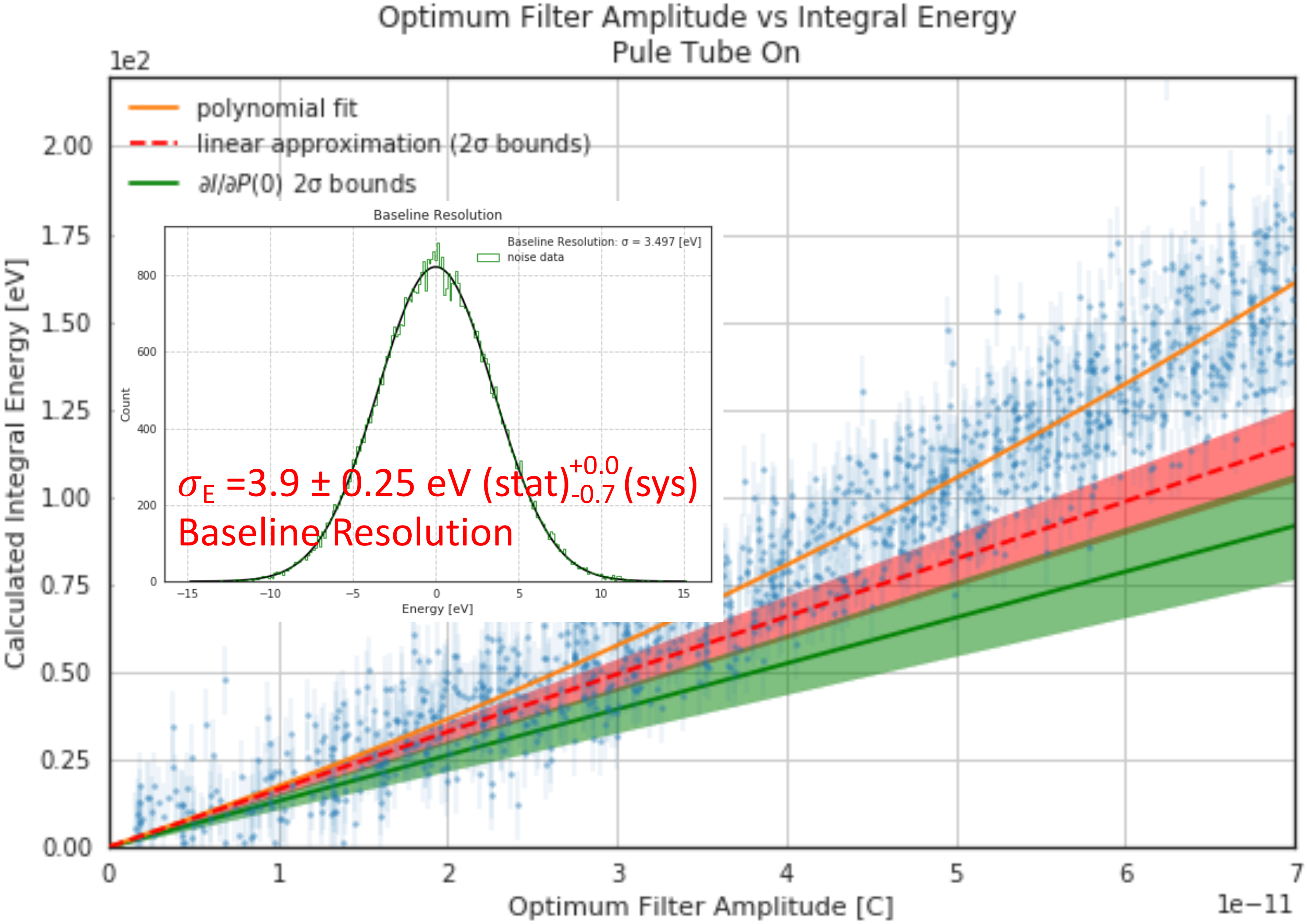
^{55}Fe K_α @5.9keV

17% Athermal Phonon Collection Efficiency

Al Fluoresence @ 1.49 keV



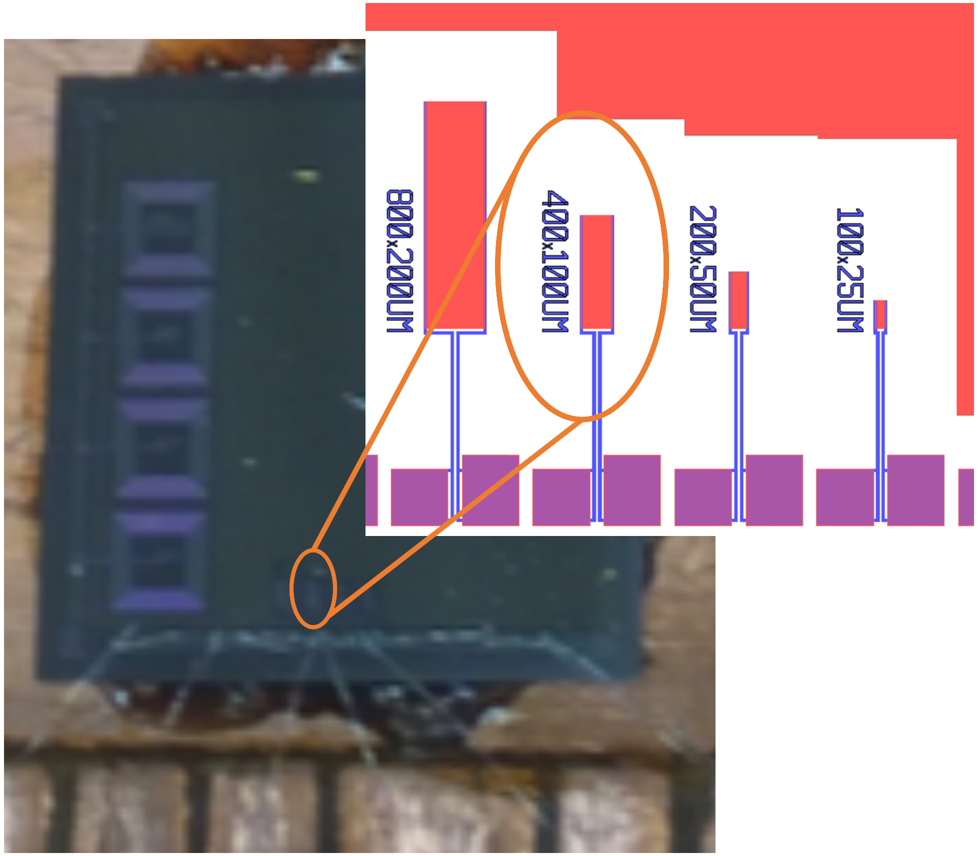
Calibrating Pulse Shape Dependent Energy Estimators to the DC estimator (Pulse Tube On)



$\sigma_E = 3.9 \pm 0.25$ eV (stat)$^{+0.0}_{-0.7}$(sys)

Baseline Resolution

R&D Ultra-Sensitive TES



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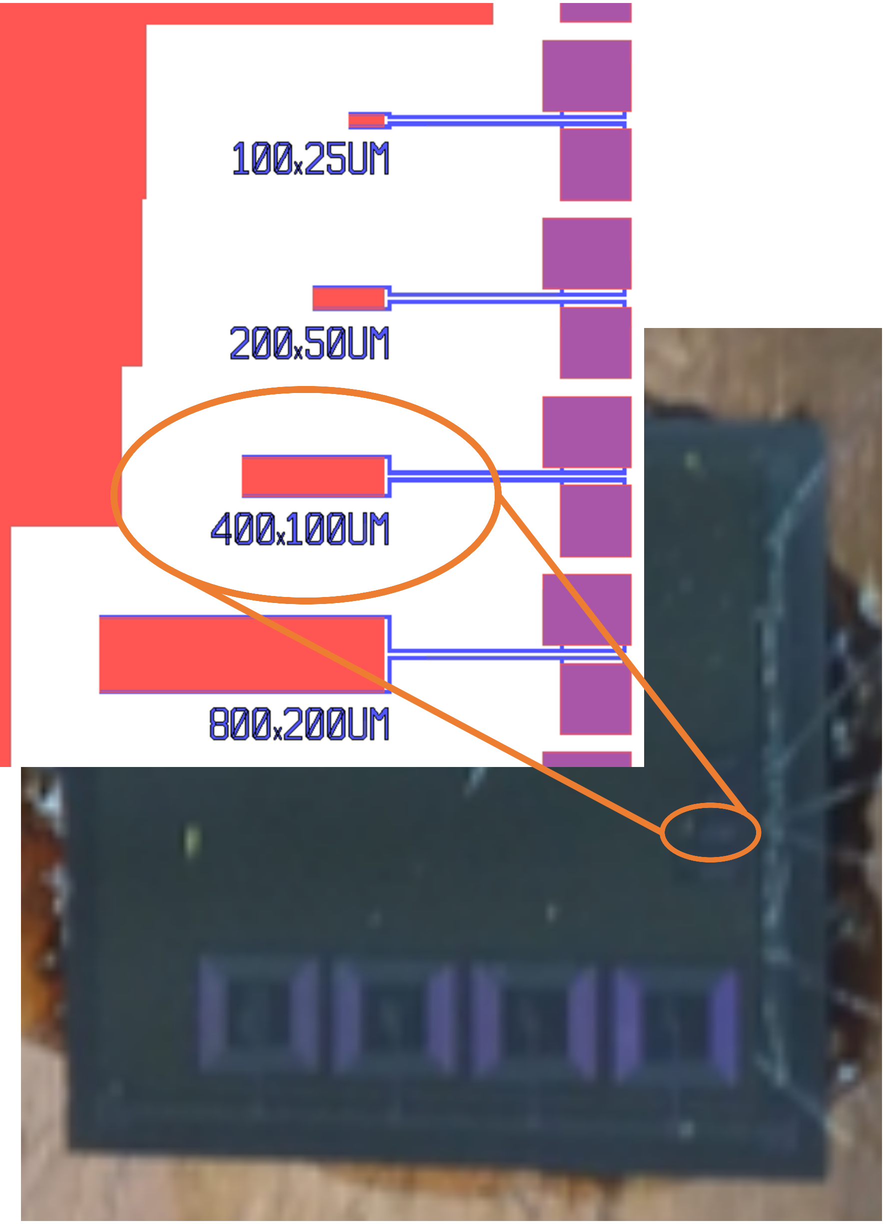
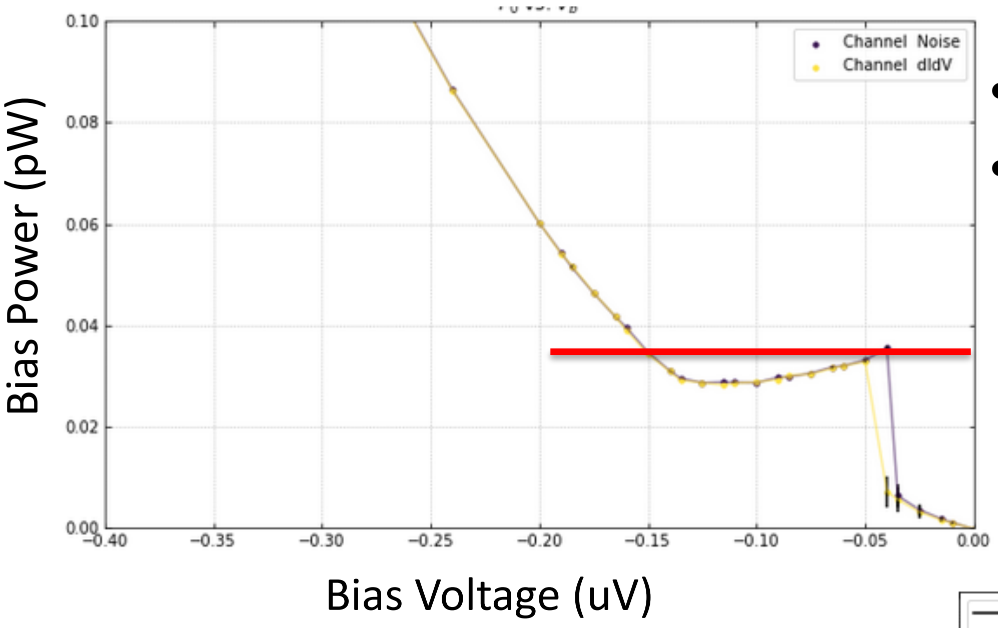
R&D: ultra sensitive TES



- Build and test simple TES test structures for noise is performance
- Tests at SLAC SuperCDMS test facilty (switching to UCB in March)
- Tungsten TES
  - Tc= 41mK
  - 40nm thick

100um x400um TES Characterization

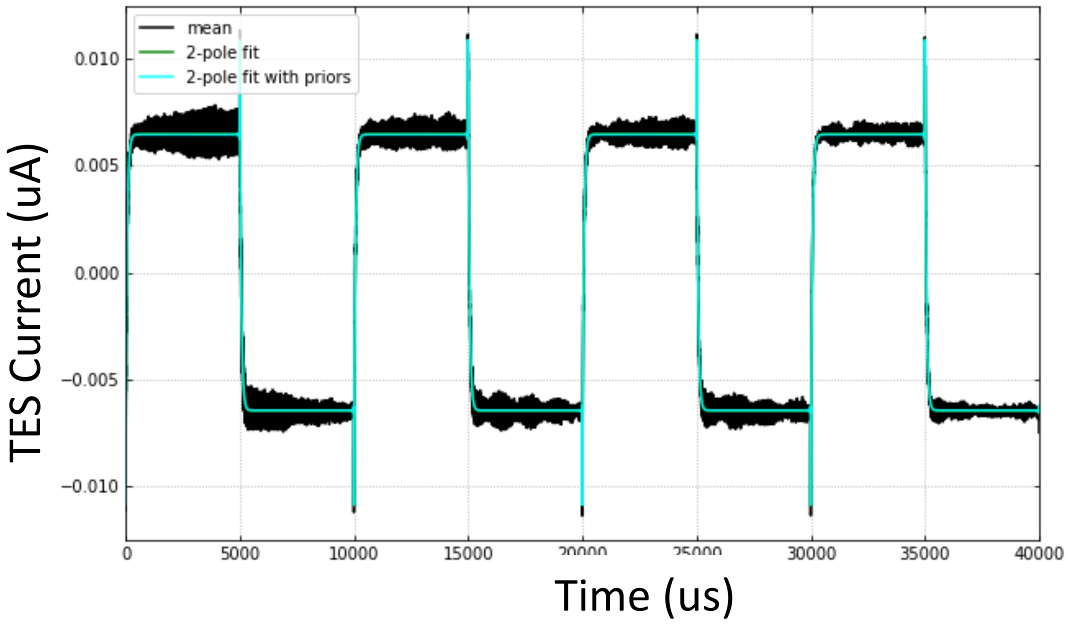
TES Power vs TES Bias Voltage



- Normal Resistance: 630mOhm
- Bias Power: 35fW
  - Your average CMB TES: 1 pW
  - Slight calibration error

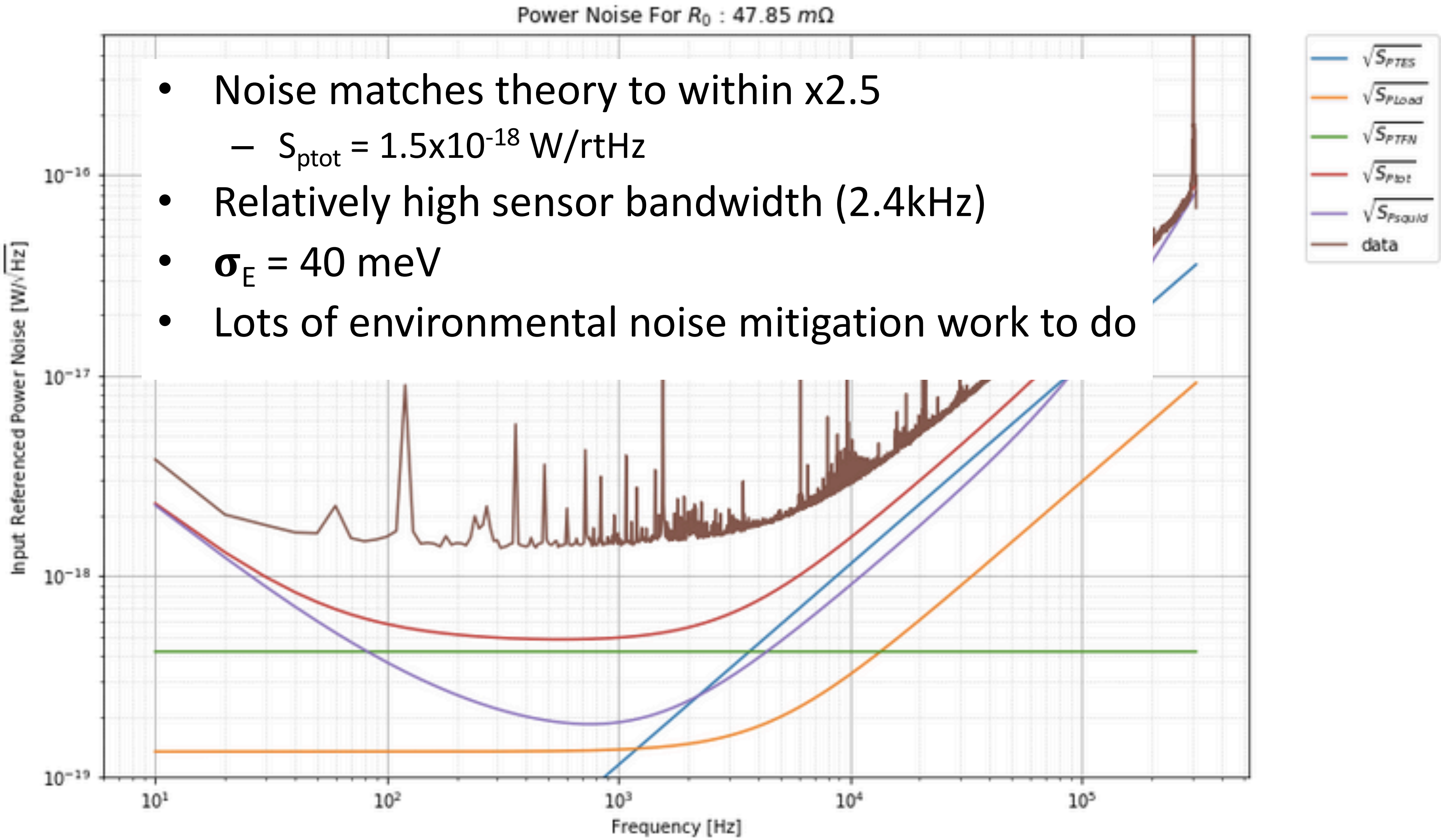
- Complex Impedance
  - Simple 2 pole TES dynamical model perfectly fits response
- TES falltime: ~66us (2.4kHz)
  - Relatively fast

TES Response to Square Wave Jitter

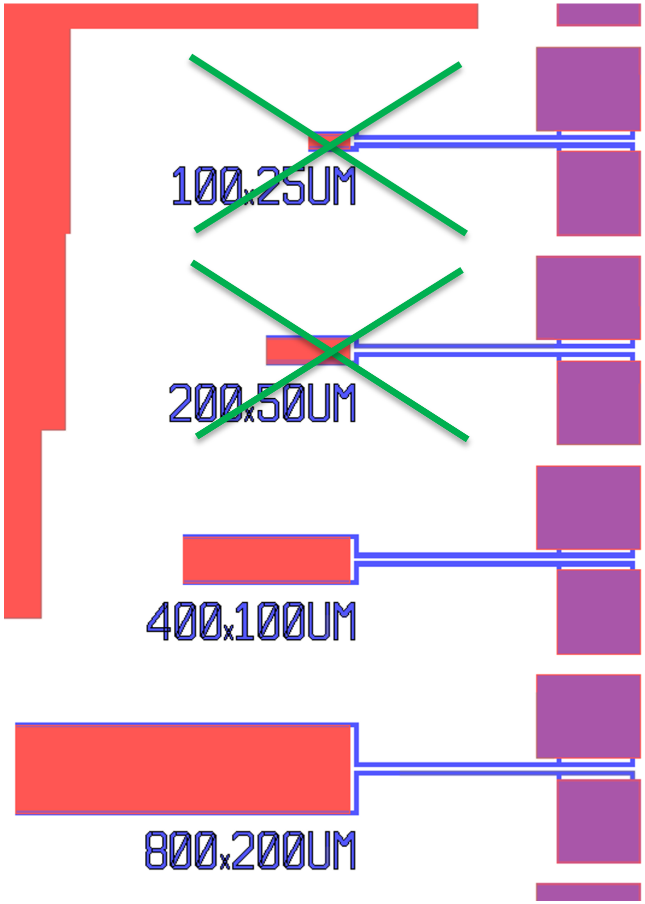


100um x400um TES Noise

- Noise matches theory to within x2.5
    - $S_{ptot} = 1.5\times10^{-18}$ W/rtHz
- Relatively high sensor bandwidth (2.4kHz)
- $\boldsymbol{\sigma}_E$ = 40 meV
- Lots of environmental noise mitigation work to do



More Sensitivity -> Decrease Volume



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

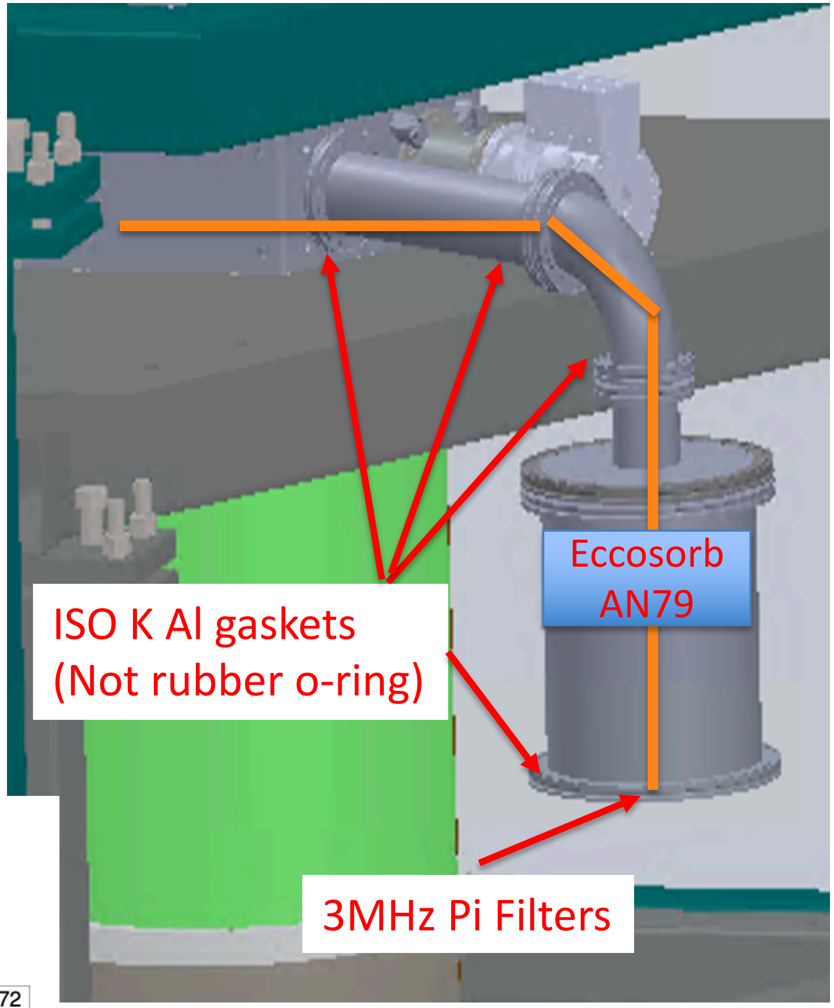
Volume (40nm thick)	Bias Power	Expected Sensitivity
25x25um^2	0.5 fW	5meV
100x25um^2	2.2 fW	10meV
200x50um^2	9 fW	20meV
400x100um^2	35 fW	40meV

- 200x500: barely operates
- 100x25um: completely normal

We have 5 fW of DC environmental parasitic power hitting our TES. Our current primary challenge is to continue to improve environmental isolation!

Faraday Cage #1 -> Dilution Fridge

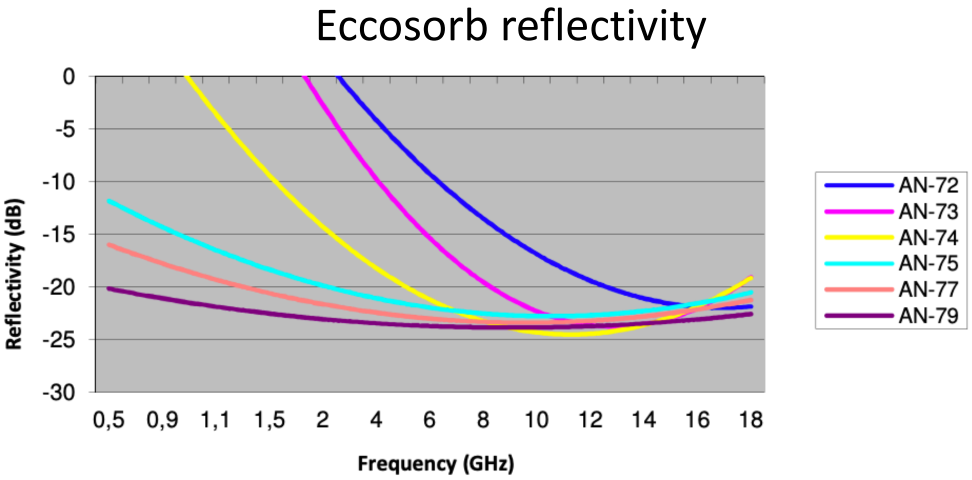
- If your E&M signal can get out, the environmental EMI can get in!
- Need to carefully filter all signal lines breaching the faraday cage



ISO K Al gaskets (Not rubber o-ring)

Eccosorb AN79

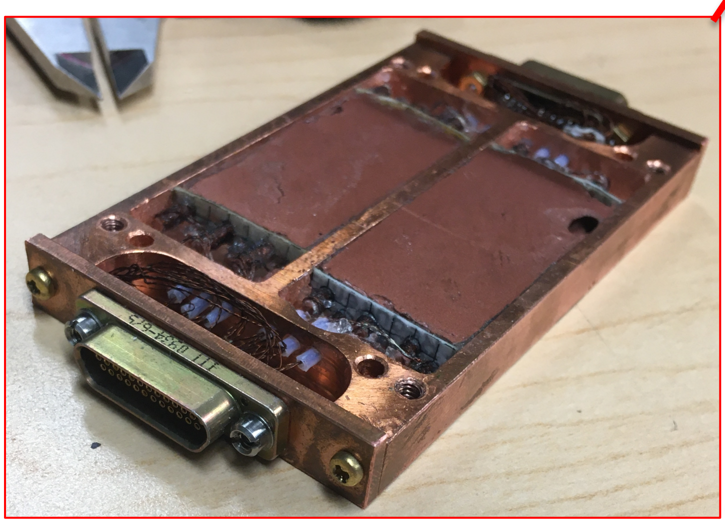
3MHz Pi Filters

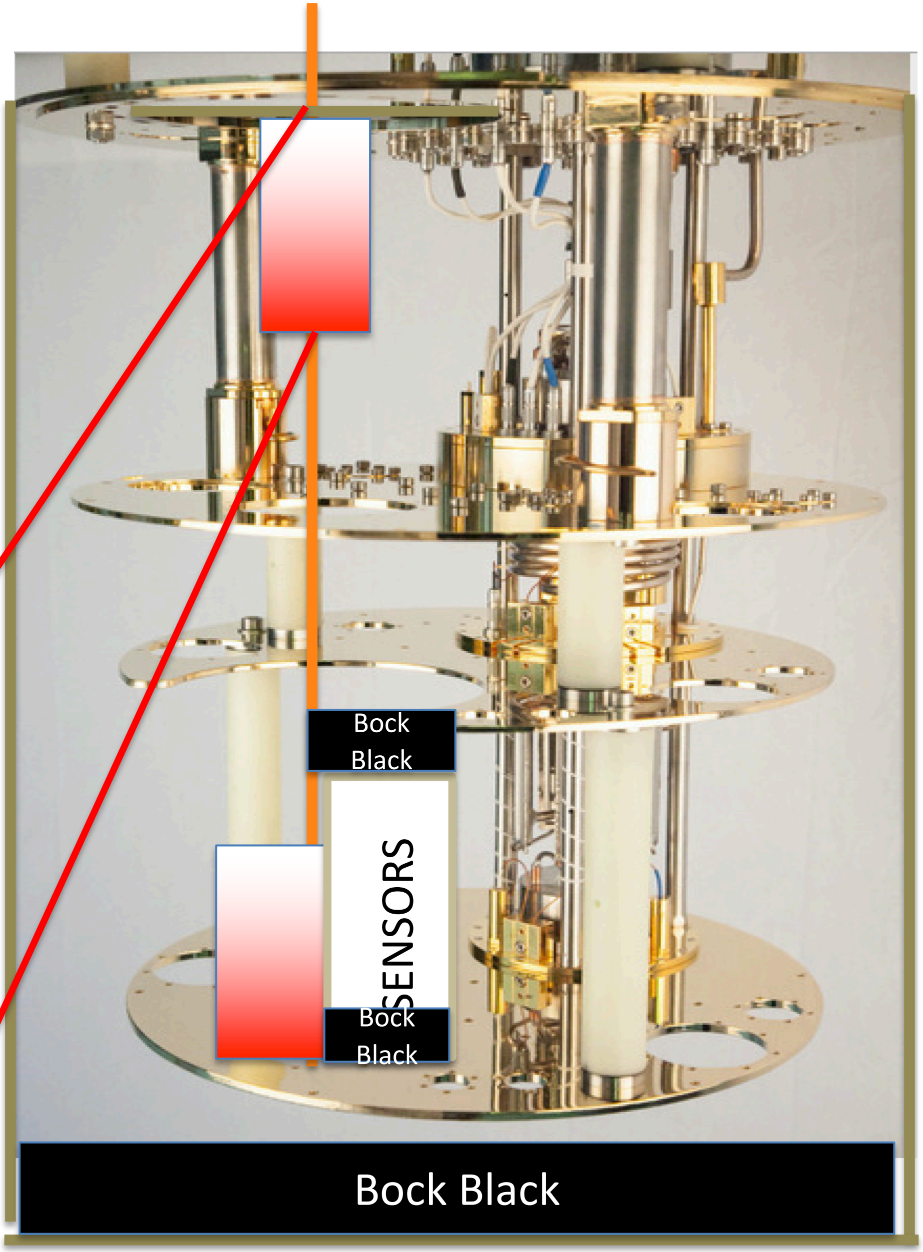


Eccosorb reflectivity

Faraday Cages 2 & 3: 4K & 10mK

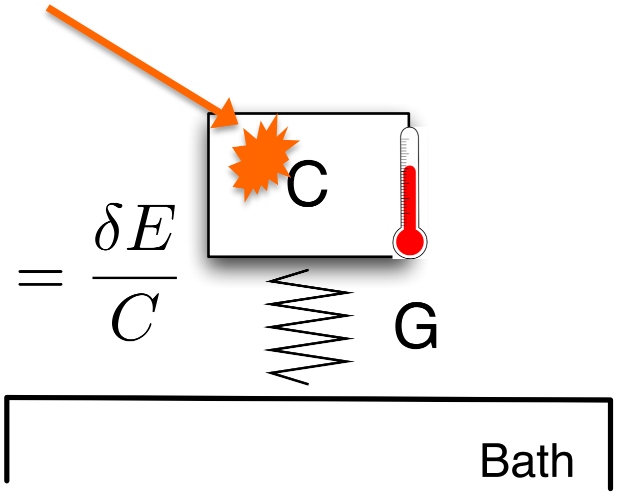
- Inner thermal shields would act as additional Farday Cages … if there were filters on all the lines.
- Bock Black for IR light leaks
- Steal copper powder filter from Martinis, Devoret, Clarke (PRB 35.4682 1987)



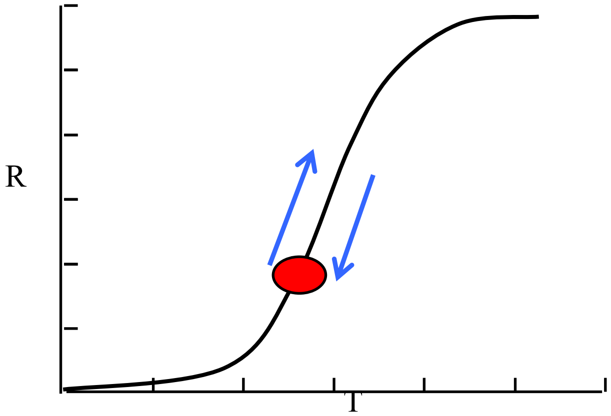


Athermal Phonon Detectors

The Simplest Thermal Calorimeter

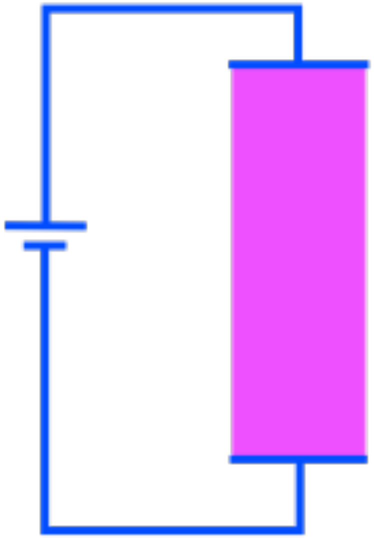


$$\delta T = \frac{\delta E}{C}$$

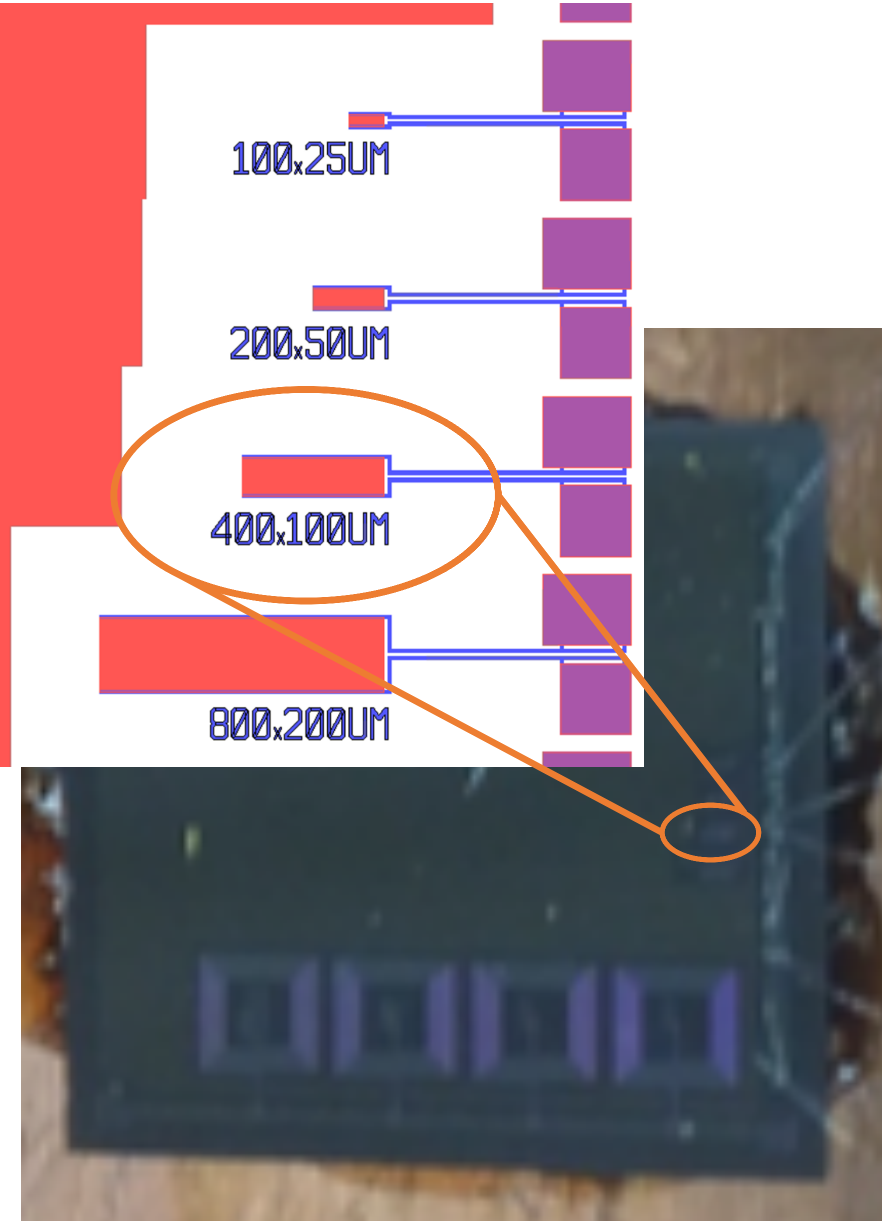


Transition Edge Sensor (TES):

- A superconducting metal film (W) that is externally biased so as to be within its superconducting/normal transition
- $$\sigma_{<E>} \sim \sqrt{C k_b T^2}$$
  $$\propto \sqrt{V T^3}$$
- Must use low Tc and very small volume TES -> hard to get gram-day exposures when your TES (25umx25umx40nm) is 500fg … only directly useful for IR Haloscope

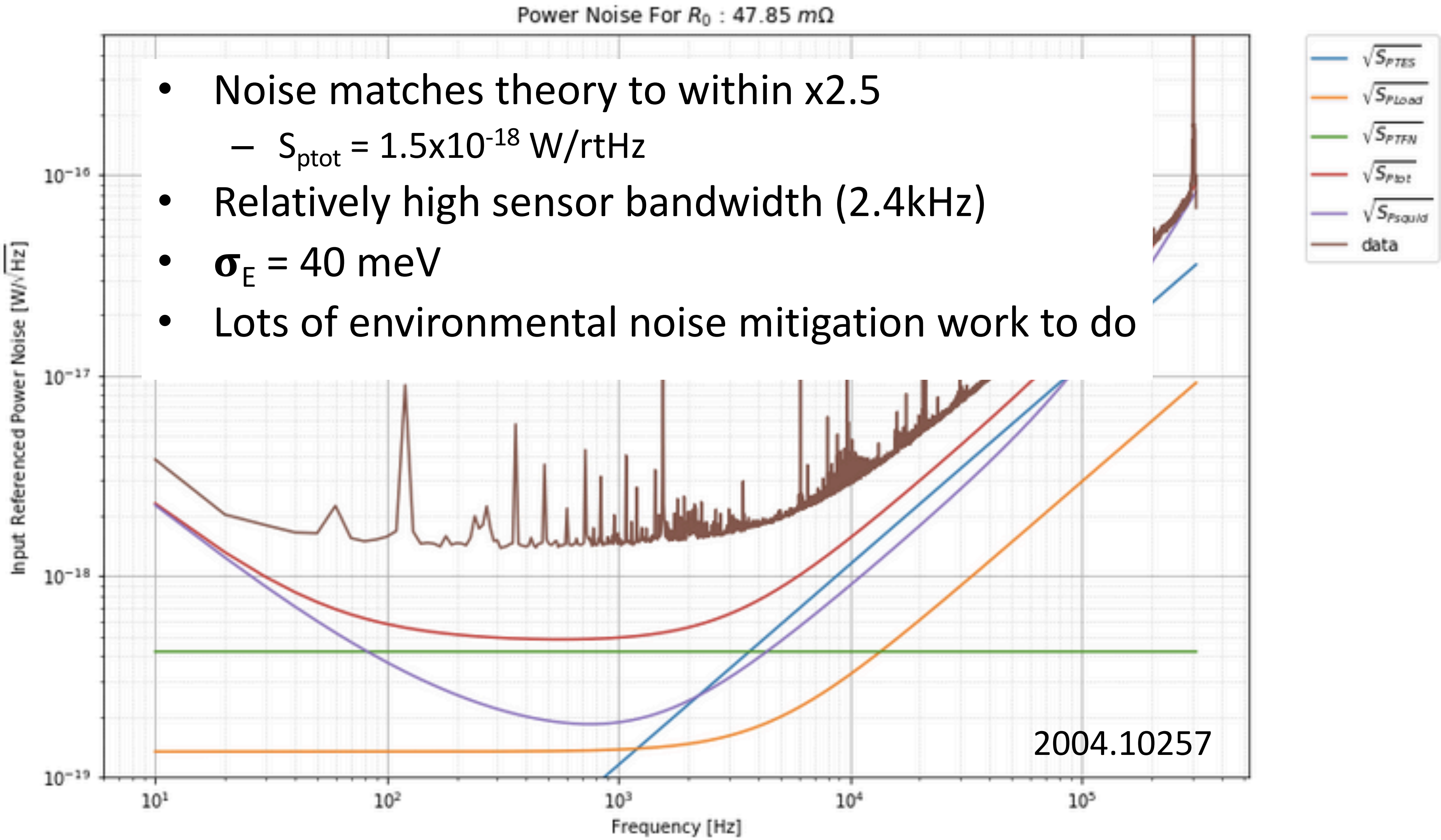


FY20 R&D: ultra sensitive TES



- Build and test simple TES test structures for noise performance
- **2004.10257**
- Tungsten TES
  - Tc= 41mK
  - 40nm thick

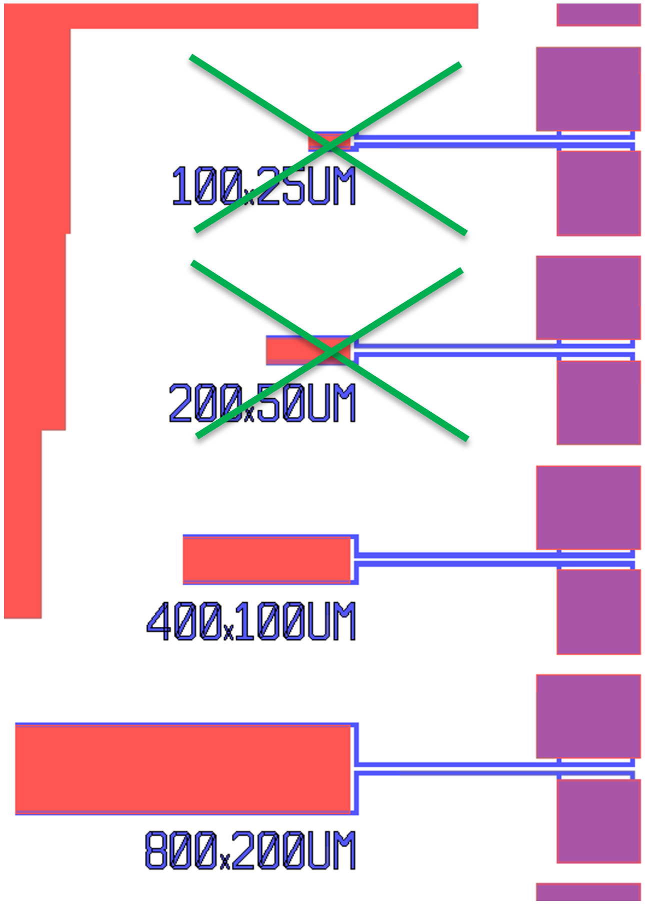
FY20: 100um x400um TES Noise



- Noise matches theory to within x2.5
  - $S_{ptot} = 1.5\text{x}10^{-18}$ W/rtHz
- Relatively high sensor bandwidth (2.4kHz)
- $\boldsymbol{\sigma}_E$ = 40 meV
- Lots of environmental noise mitigation work to do

2004.10257

Sensitivity Limited by Noise



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

Volume (40nm thick)	Bias Power	Expected Sensitivity
25x25um^2	0.5 fW	5meV
100x25um^2	2.2 fW	10meV
200x50um^2	9 fW	20meV
400x100um^2	35 fW	40meV

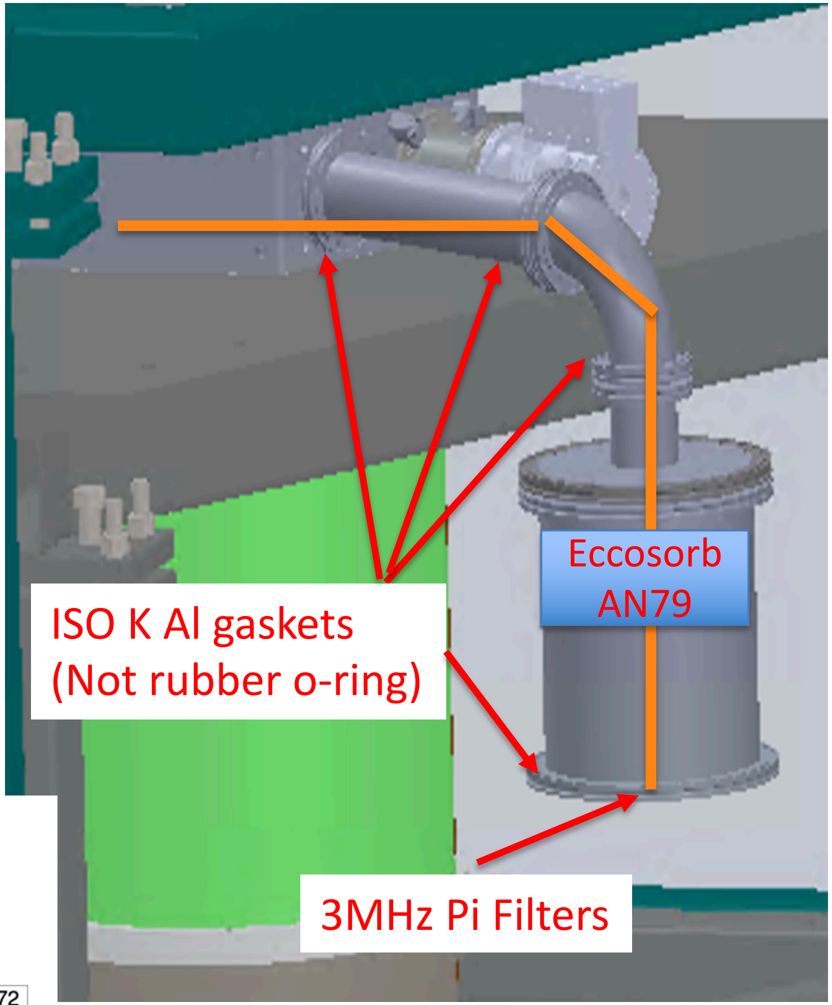
- 200x500: barely operates
- 100x25um: completely normal

We have 5 fW of DC environmental parasitic power hitting our TES. Our current primary challenge is to continue to improve environmental isolation!

2004.10257

300K Faraday Cage -> Dilution Fridge

- If your E&M signal can get out, the environmental EMI can get in!
- Need to carefully filter all signal lines breaching the faraday cage
- FY20: construction
- FY21: test

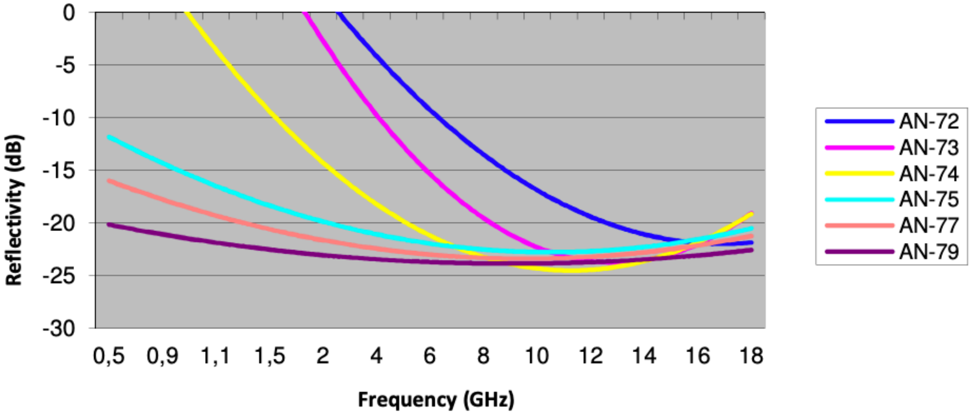


Eccosorb AN79

ISO K Al gaskets
(Not rubber o-ring)

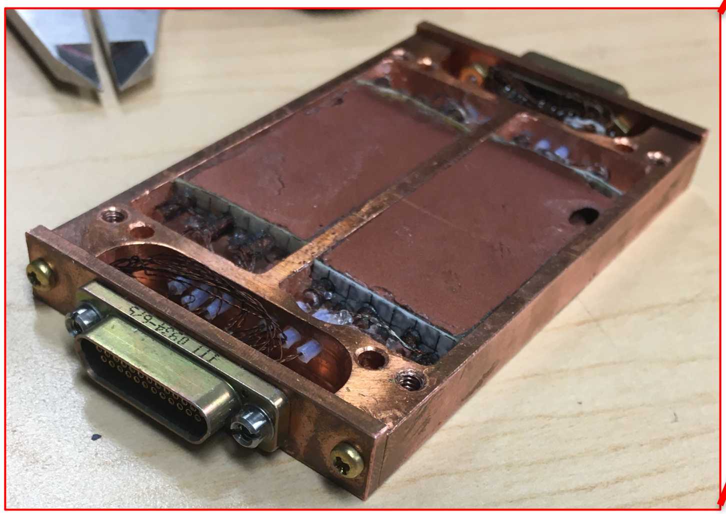
3MHz Pi Filters

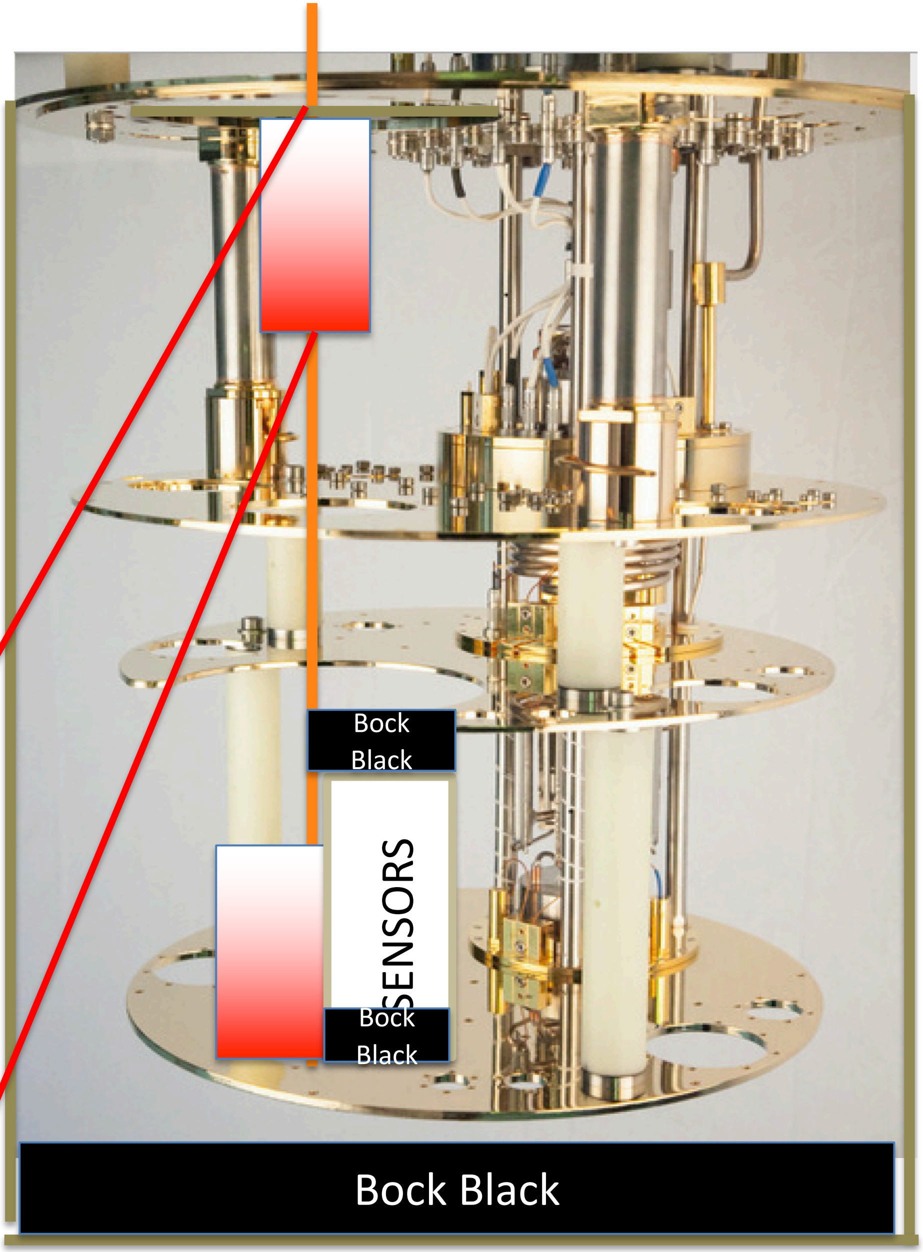
Eccosorb reflectivity



4K and MC Faraday Cages

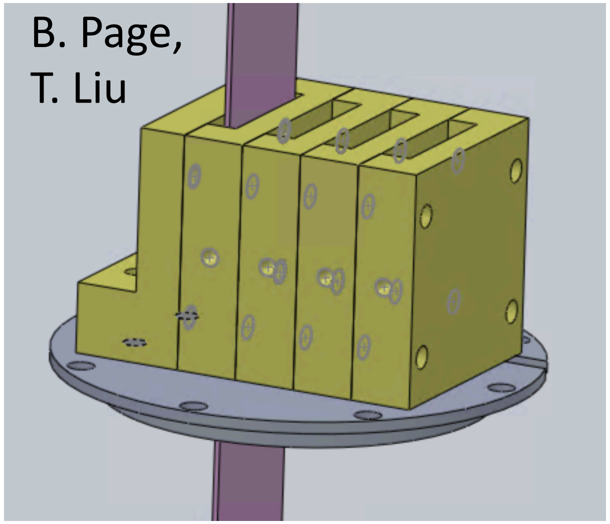
- Inner thermal shields would act as additional Farday Cages … if there were filters on all the lines.
- Bock Black for IR light leaks
- Steal copper powder filter from Martinis, Devoret, Clarke (PRB 35.4682 1987)
    - FY20: design & construction
    - FY21: test



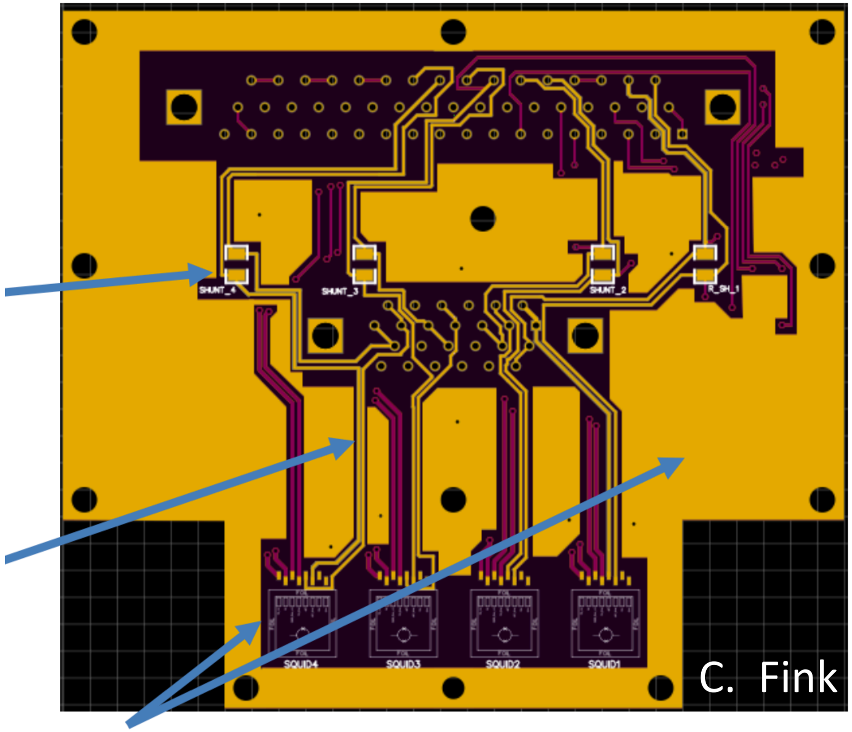


SQUID Electronics Pyle

- W TES noise work done in SLAC fridge. RF shielding mods not possible in DF. Swapping all work to Berkeley / LBL
- CDMS-2 Berkeley system
  - Very fragile, expensive striplines
  - Shunt resistor 20mOhm
  - 4mOhm Parasitic resistance at 4K … dominated noise
  - More robust thermalization
  - Not EMI tight
- FY20: Recycled CDMS-2 setup
  - NbTi(PhBr) wire weaves below 4K
  - New PCB layout
  - EMI tight (MDM connectors)



B. Page, T. Liu

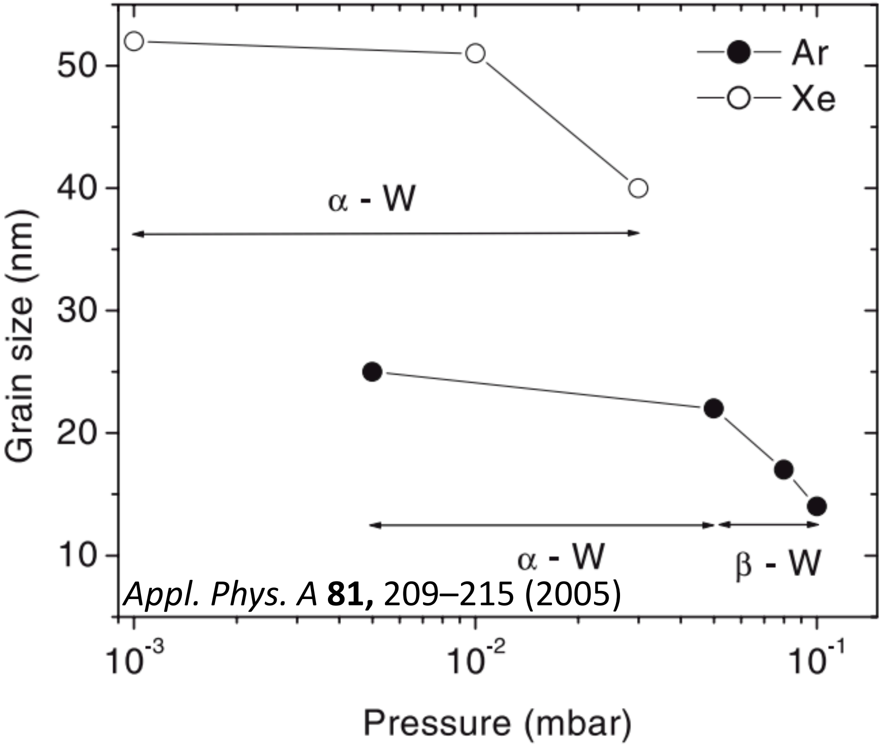


C. Fink

More Sensitivity -> Decrease Temperature

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

- What's set W Tc? 2 crystal configurations
  - Alpha: T_c=10mK
  - Beta: T_c~ 3K
  - Perhaps 40mK films have just a tinge too much beta?
  - Perhaps 40mK films have stress that has increased Tc?
- Goal: produce a stress free, alpha phase W film
- Bouziane et al, *Appl. Phys. A* **81,** 209–215 (2005) says that if you use Xe plasma rather than Ar plasma your alpha film quality improves substantially



Appl. Phys. A **81,** 209–215 (2005)

FY20:

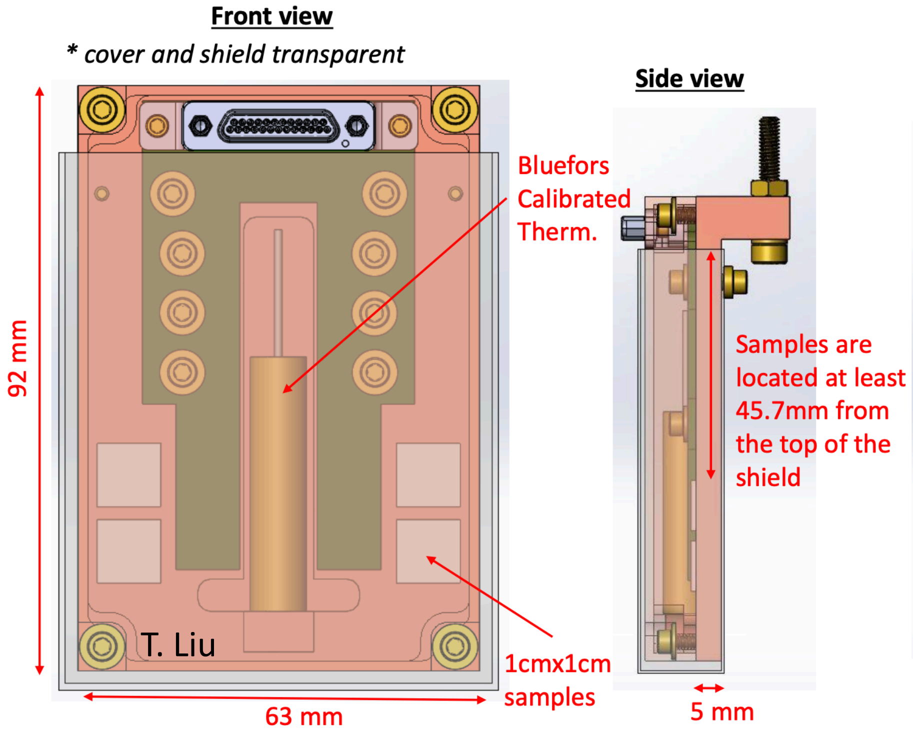
- Add Xe gas option to the RF Sputterer at TAMU
- Very Preliminary Tc measurement: 30mK (beware: lots of systematics)

FY21:

- 48 depositions that span power/pressure space

Measuring Tc Films

- 12 channel high impedance W film measurement setup at LBL (Toki)
  - FY20: design, construction, installation, first tests
  - FY21: lots of measurements
- Matt similar 8 channel low impedance/ high impedance cross check setup on campus
  - FY20: design, construction, fab, first tests
  - FY21: lots of measurements



DAQ+Control+Data Handling/Processing

- Hertel/McKinsey/Pyle labs share everything downstream of electronics
- FY20: work finished
  - Magnicon electronics drivers
  - Increased DAQ speed:
  - Lots of cleanup, added web interface
- Bruno, Vetri, Suerfu, Fink, Watkins

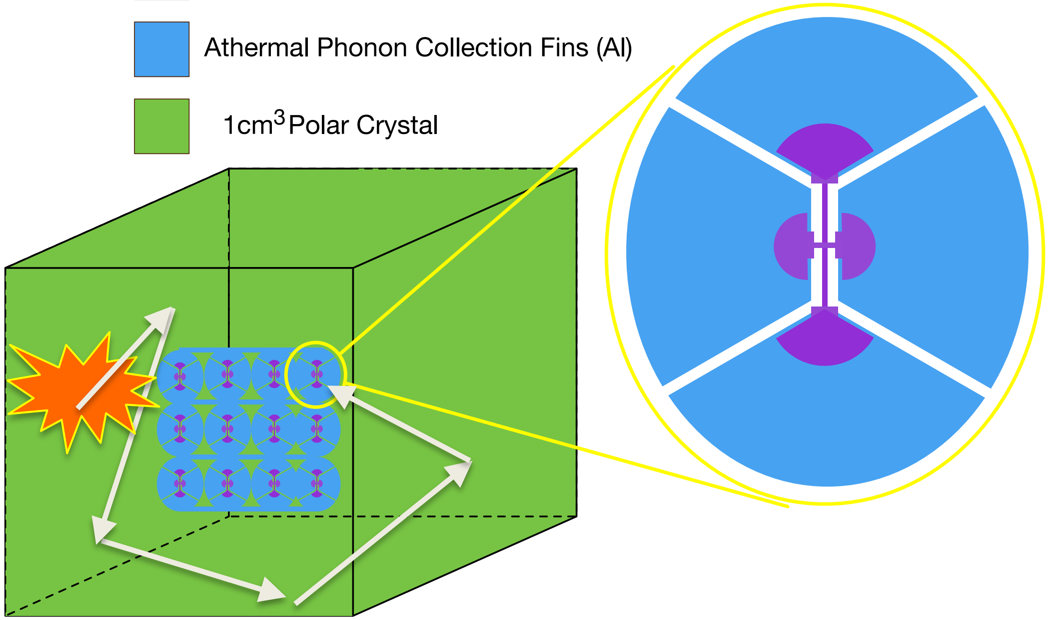
Athermal Phonon Detectors

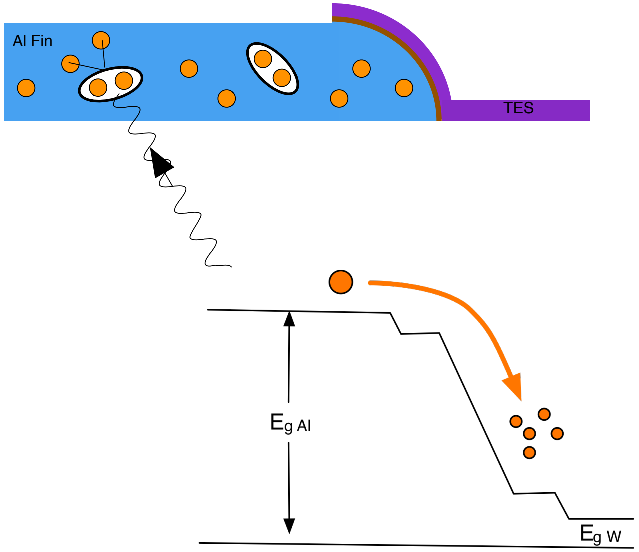
Athermal Phonon Sensor Technology

🟪 TES and QP collection antennas (W)

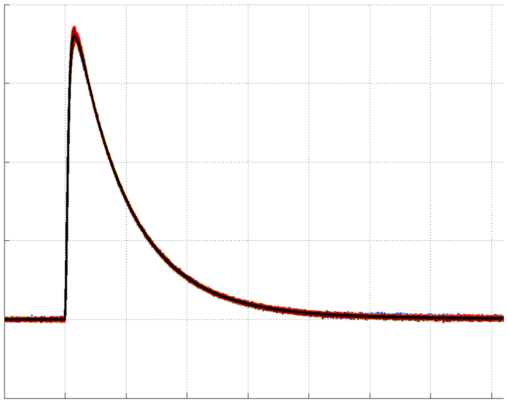
🟦 Athermal Phonon Collection Fins (Al)

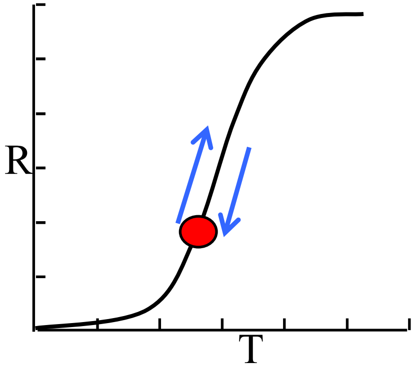
🟩 1cm^3 Polar Crystal



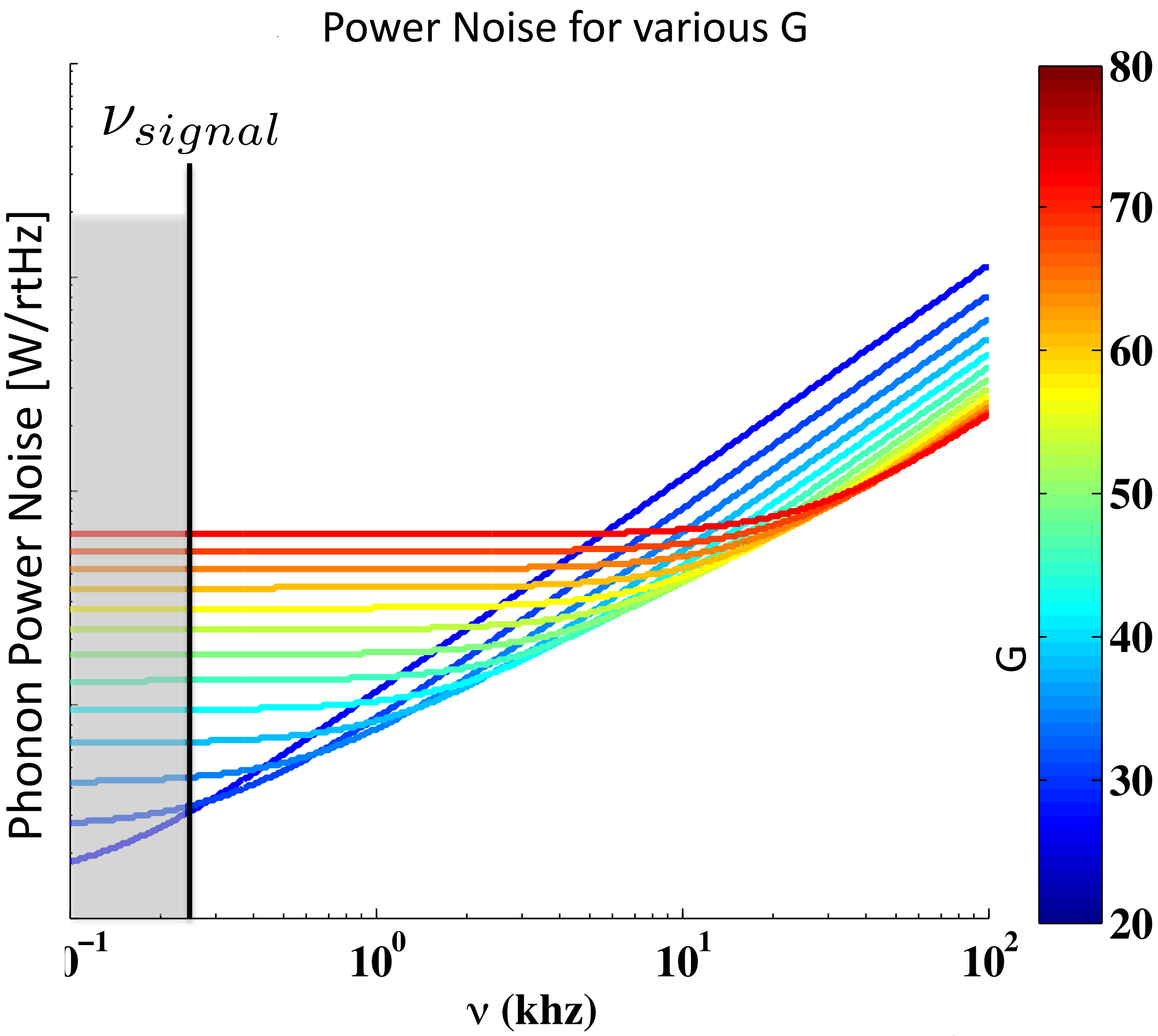


Collect and Concentrate Athermal Phonon Energy into Sensor





Athermal Phonon Sensor Sensitivity Scaling



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

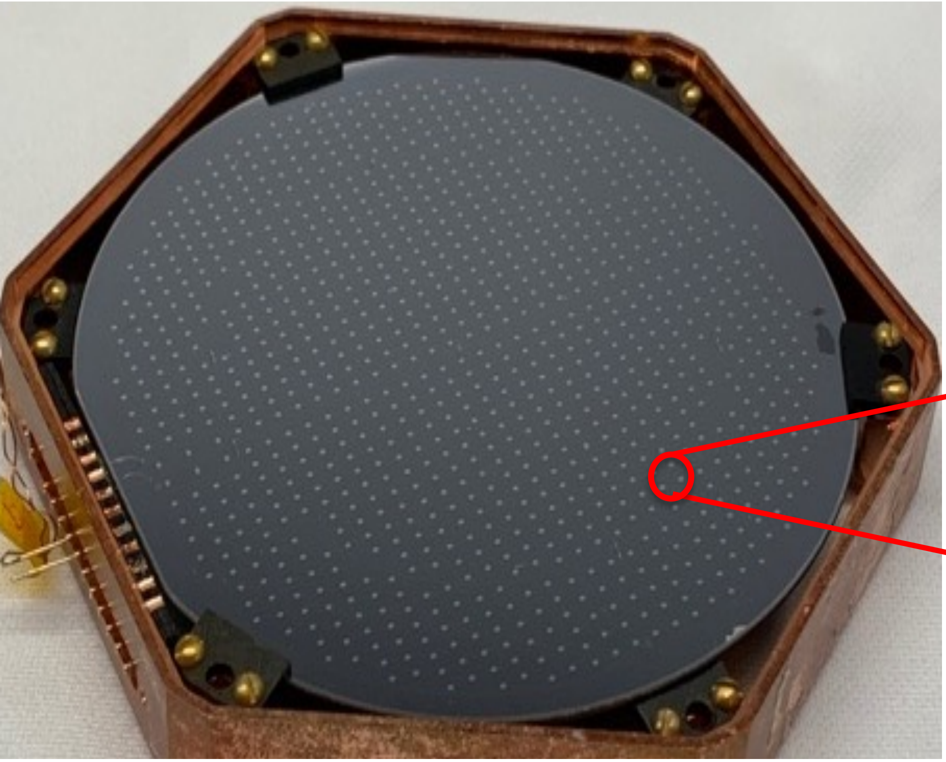
- Lower v_{sensor} (lower T_c) if $v_{\text{signal}} < v_{\text{sensor}}$
- Lower v_{signal} (decrease Al coverage) if $v_{\text{signal}} > v_{\text{sensor}}$

You can always keep VT_c^3 scaling (in principle)

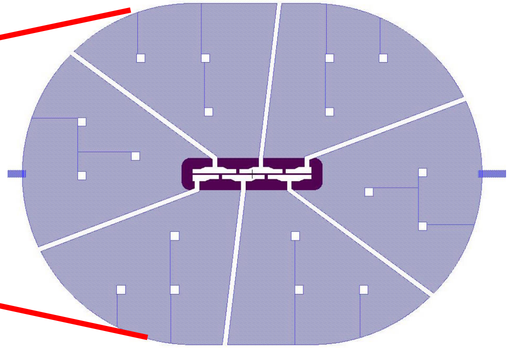
45mK-> 10mK: 2eV -> 20meV

Cryogenic Photon Detector (CPDv0)

- 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

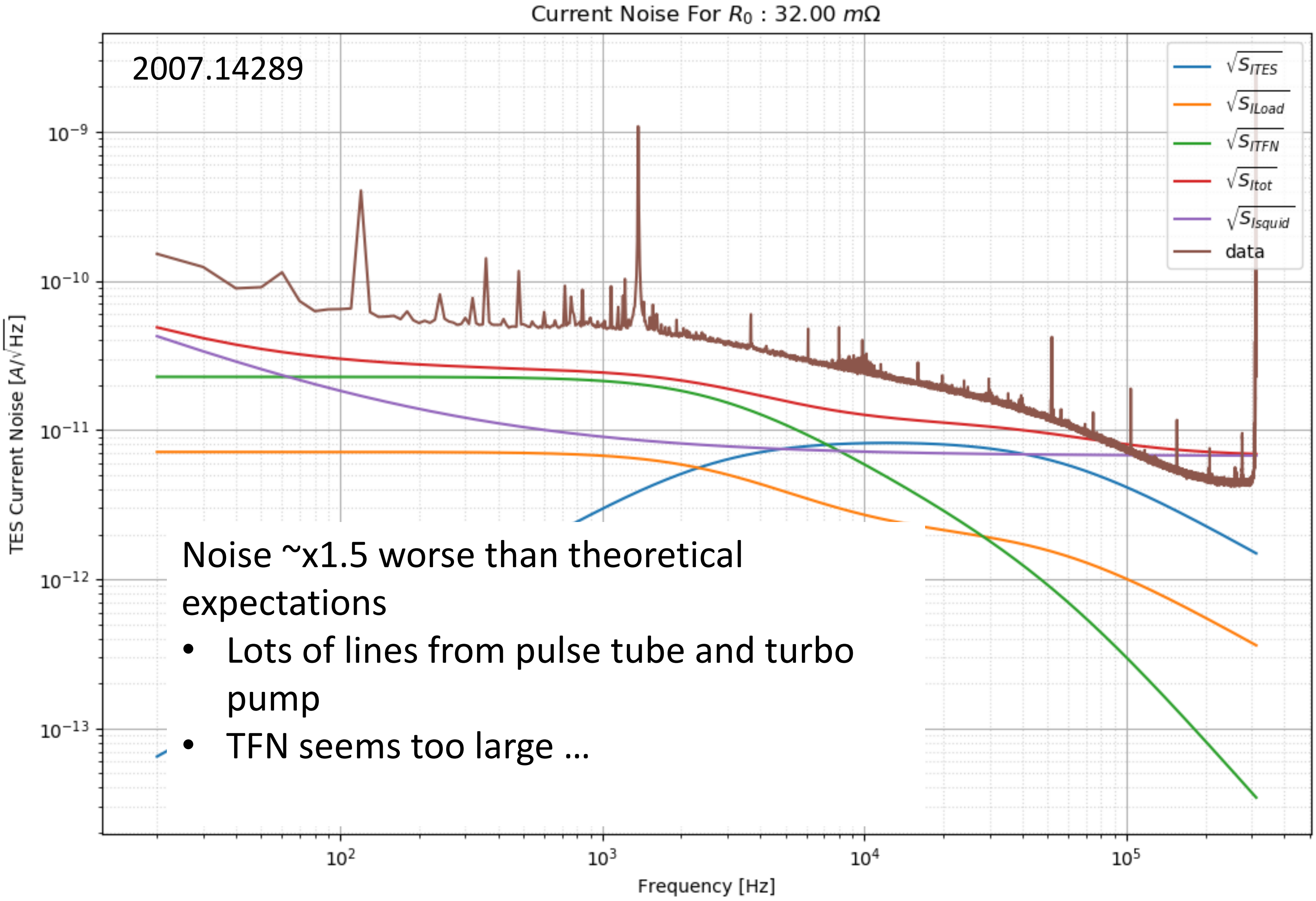


FY20: 2 more CPDv0 were made for various background studies, and for test facilities to run during ramp up.



2007.14289

Measured/Theoretical Noise

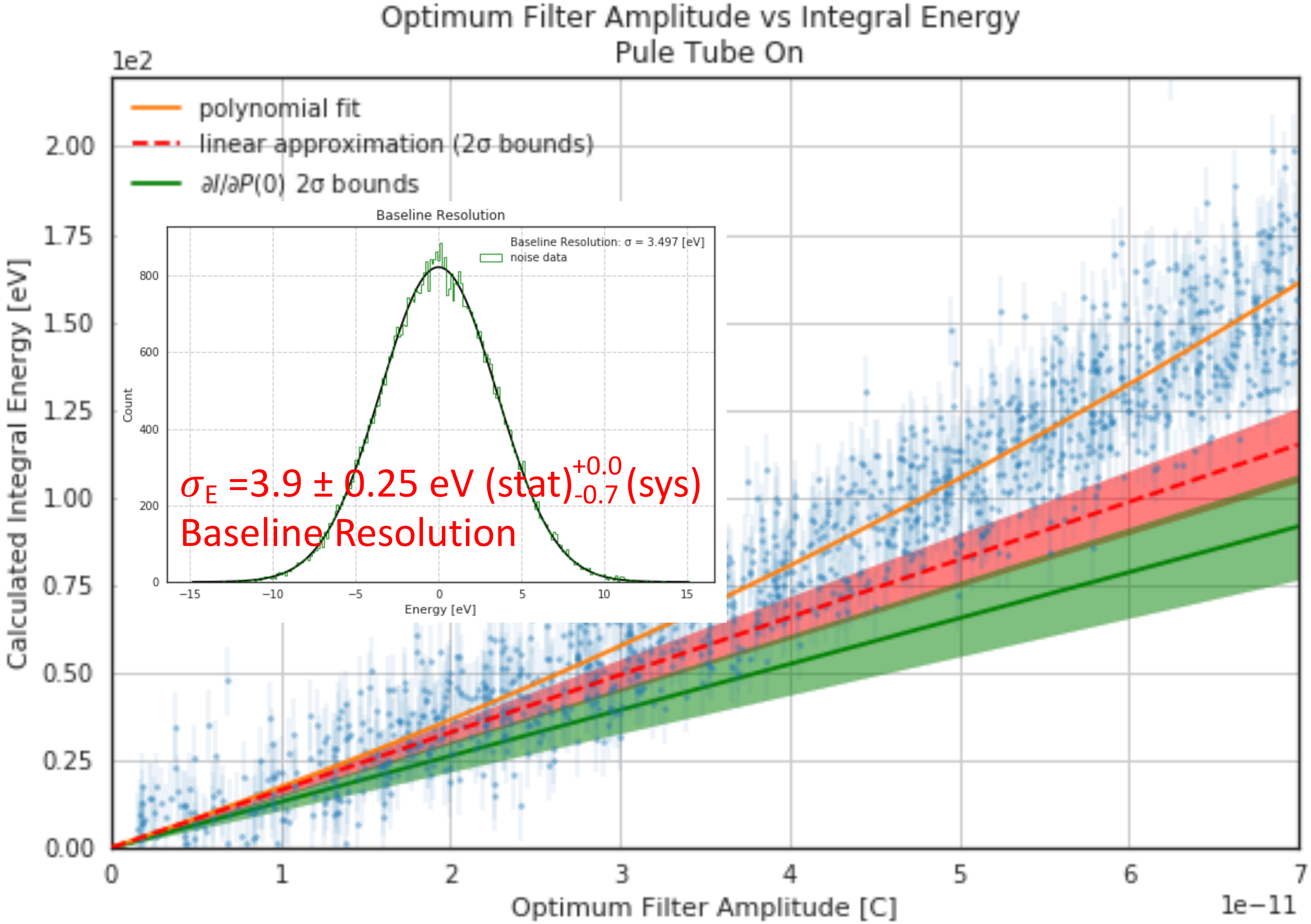


2007.14289

Noise ~x1.5 worse than theoretical expectations

- Lots of lines from pulse tube and turbo pump
- TFN seems too large …

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



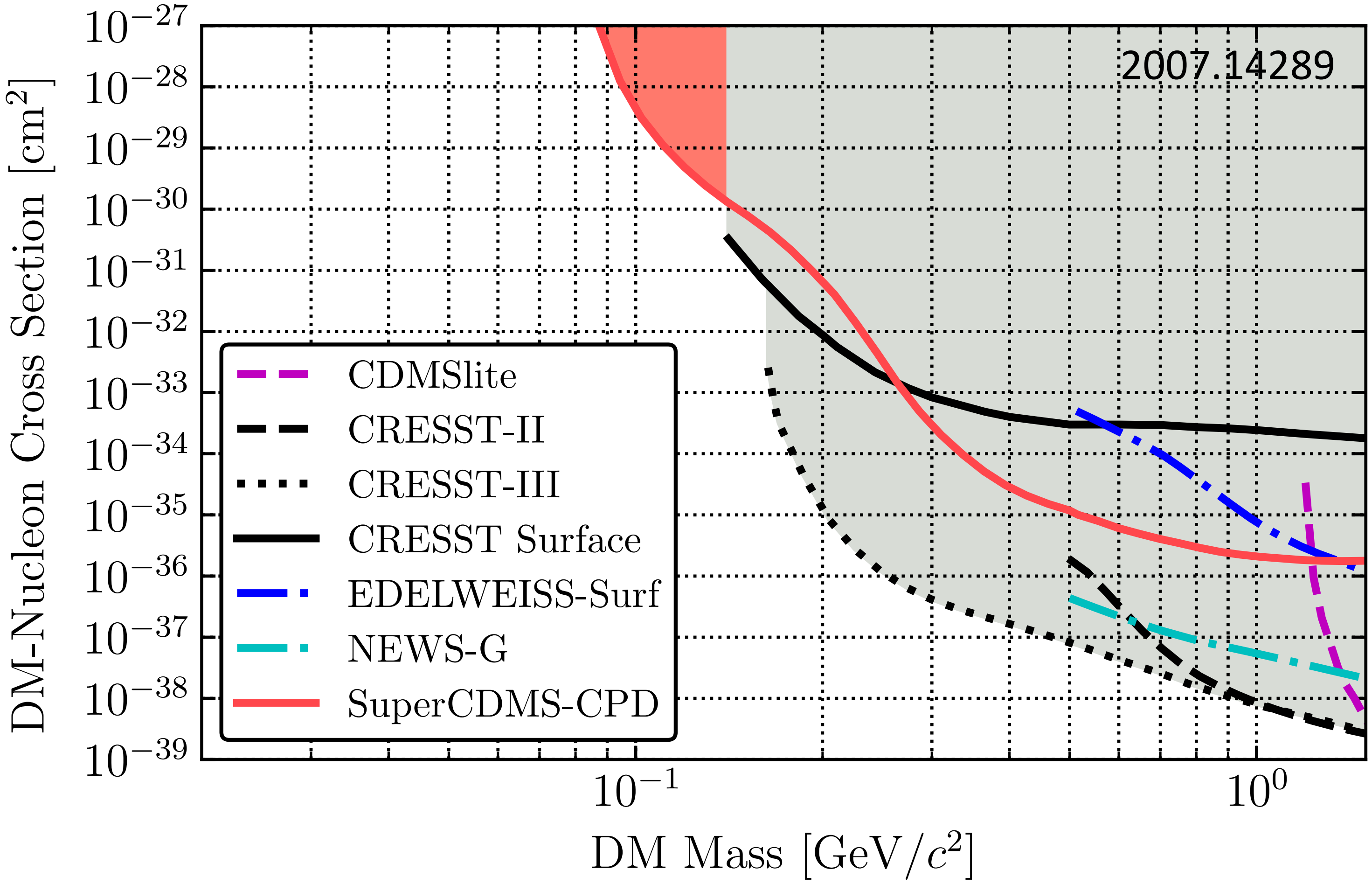
Optimum Filter Amplitude vs Integral Energy
Pule Tube On

$\sigma_E = 3.9 \pm 0.25$ eV (stat)$^{+0.0}_{-0.7}$(sys)
Baseline Resolution

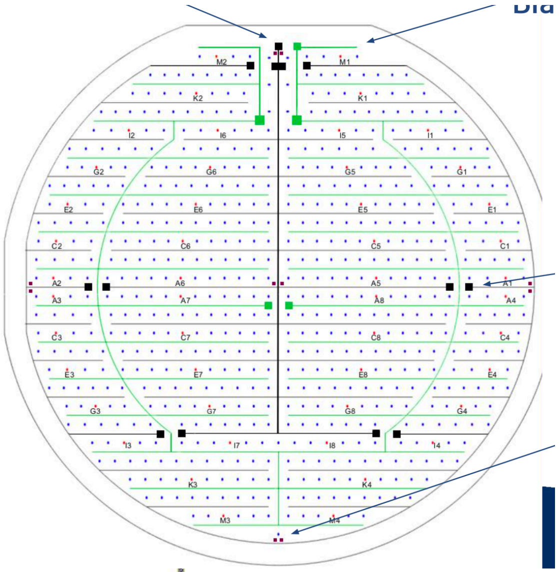
2007.14289

First Dark Matter Search @ SLAC

- In collaboration with SuperCDMS, we ran the CPD detector at the SLAC surface test facility
  - Significantly limited by cosmogenic backgrounds
  - 10gd exposure
- World leading DM sensitivity from 87-140 MeV
- First world leading sensitivity search from LBL QIS program

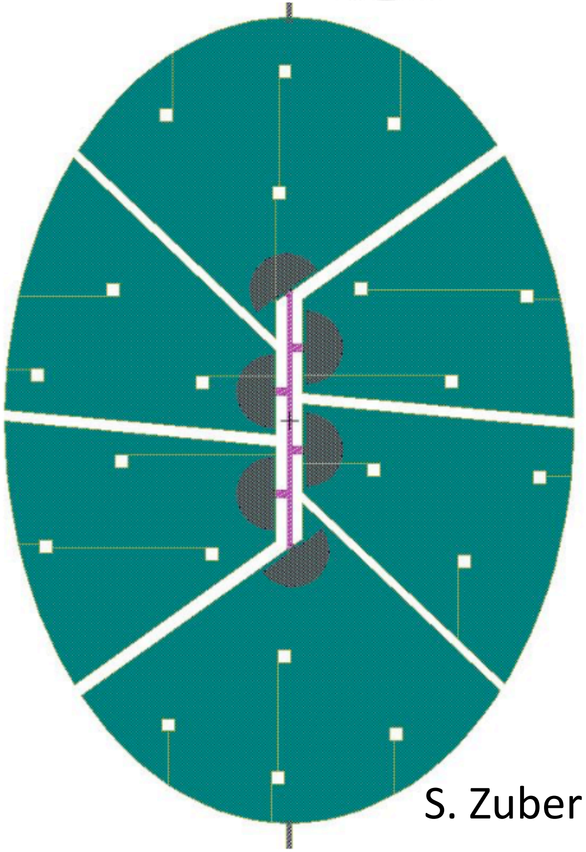


CPDv2



Next Generation CPDv2 Designed. Fabrication in progress (FY20).

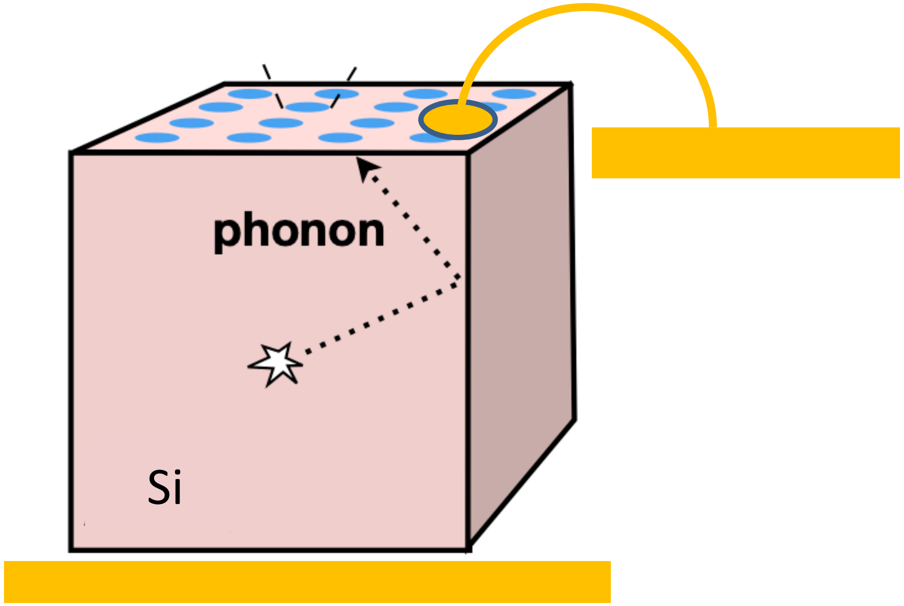
- ~2eV baseline resolution at 40mK expected (doesn't meet the design specs for SPICE/HeRALD)
- Test bed for athermal phonon sensor improvements
- Nice first device for ramping up test facilities … because of its size, it's easier to run than ultimate devices.
- Surface veto for SPICE tower
- Sensor for potential SPICE/HeRALD active veto
- FY21: used for scintillation yield studies of GaAs



S. Zuber

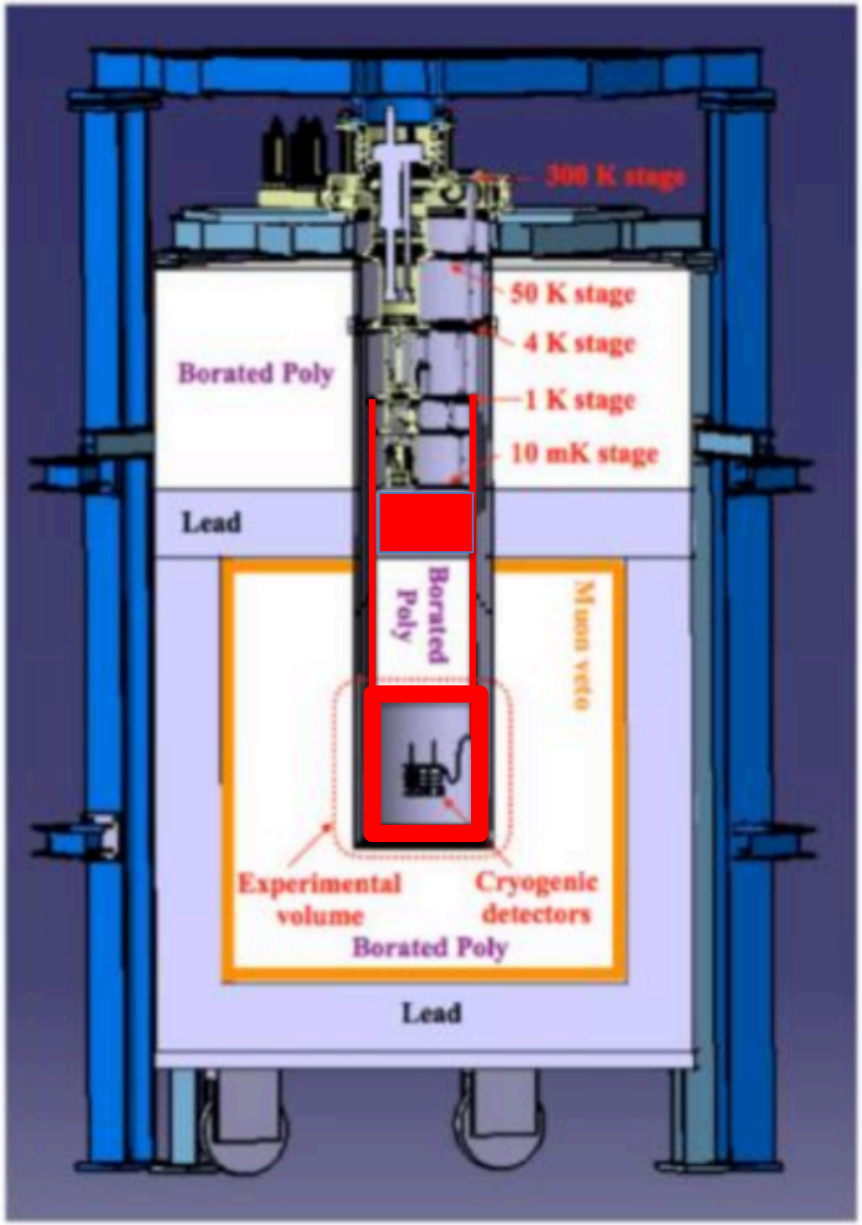
1cm^2 program beginning

- End FY20/Beginning FY21: 1cm^2 program beginning
- Au wire bonds for thermalization with new low stress structural support designs
- Estimated ~200meV resolution (Good enough for GaAs)

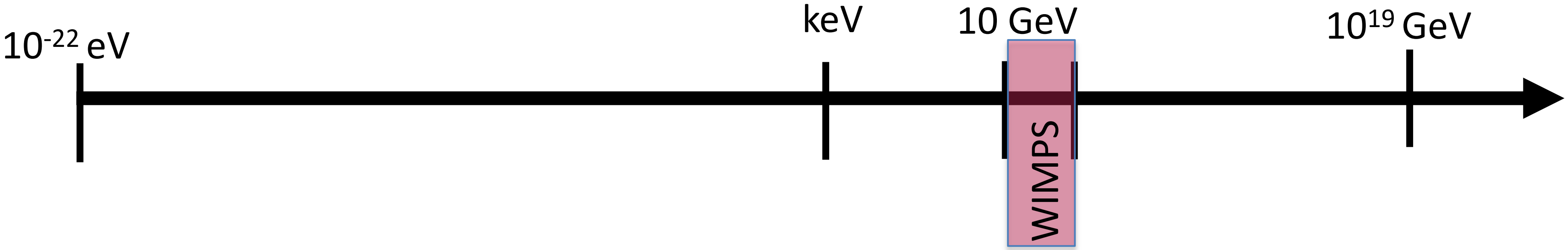


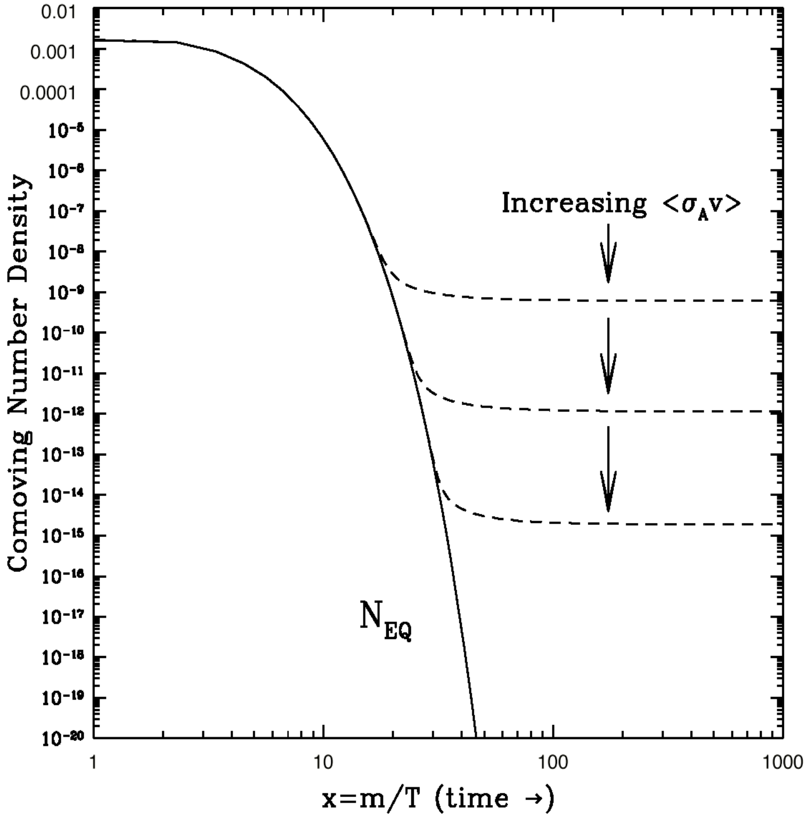
Internal Vibrational Mitigation

- Low stress support structures will almost certainly require very low environmental vibration noise
- Double mass 1K-1K vibration isolator
- FY20 finish design
- FY21 fabricate, install,test in Pyle Fridge



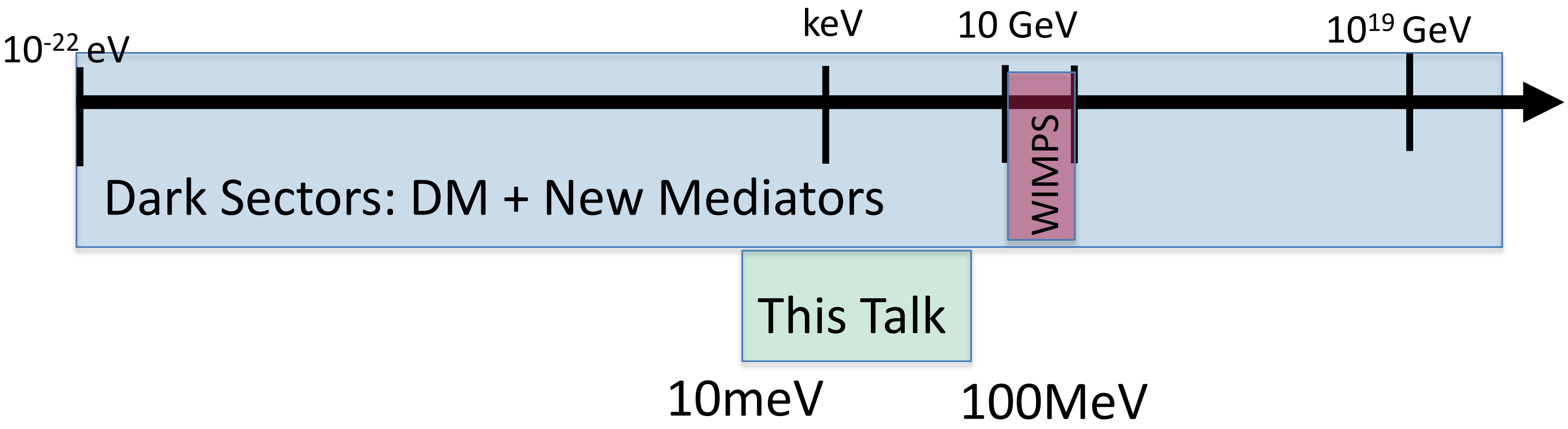
10 Years Ago: A Focus on WIMPs





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

Today: Search for DM Everywhere



10^{-22} eV

keV

10 GeV

10^{19} GeV

Dark Sectors: DM + New Mediators

WIMPS

This Talk

10meV

100MeV

Many Well Motivated DM Models at Light Mass

US Cosmic Visions: New Ideas in Dark Matter: 1707.04591

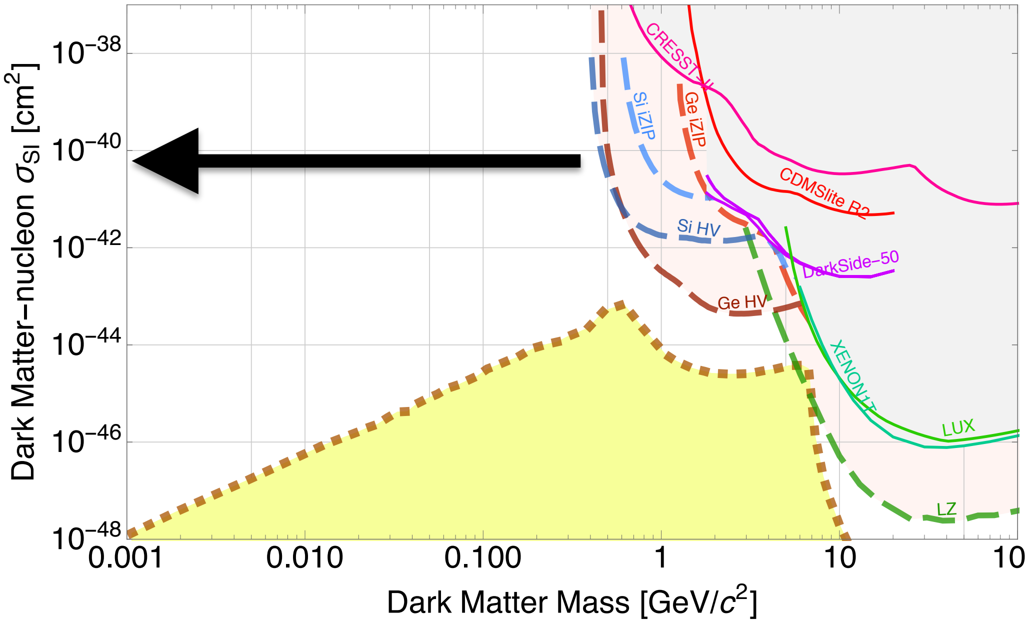
Exploring 10meV-100MeV Dark Matter:
Detection Signatures
and
Experimental Design Drivers

Light Mass DM: Detector Size

$$R = \sigma n_{DM} v_{DM} N_{exp}$$

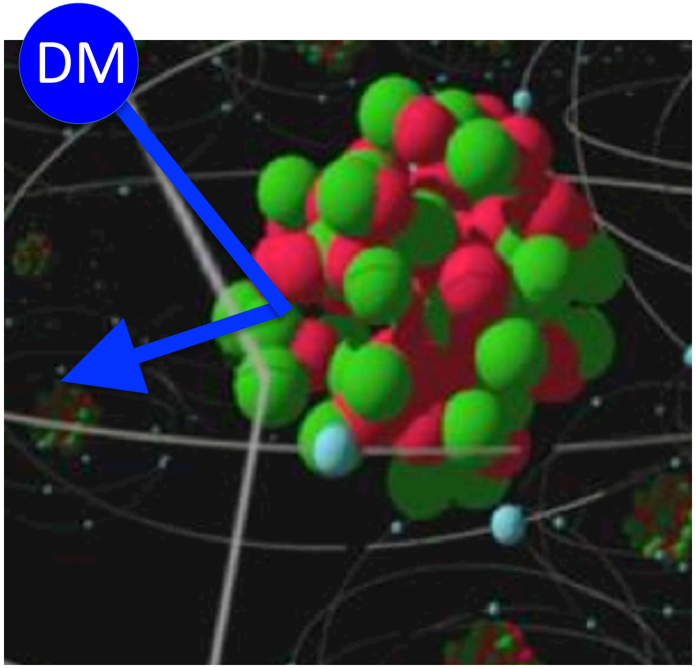
$$= \sigma \frac{\rho_{DM}}{\boxed{M_{DM}}} v_{esc} N_{exp}$$

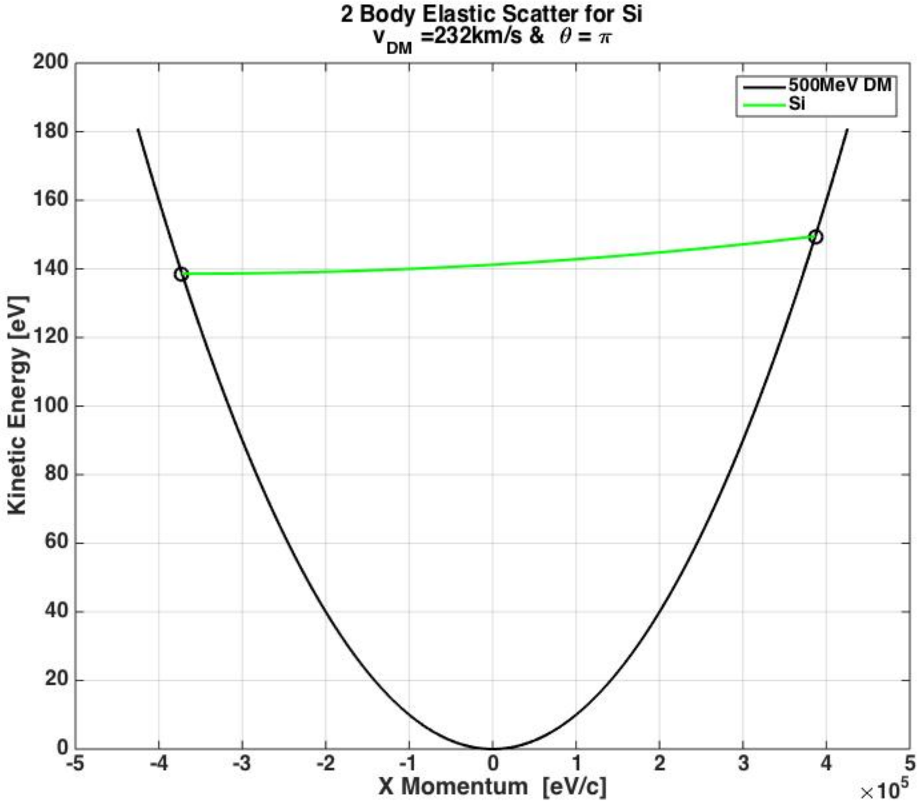
Interaction Rate scales with $1/M_{DM}$



LZ needs 10 tons to get to 10^{-47} cm^2 at 100GeV, Light Mass DM searches only needs 1kg to reach the same level at 10MeV

Kinematics: 2 Body Elastic Nuclear Scattering





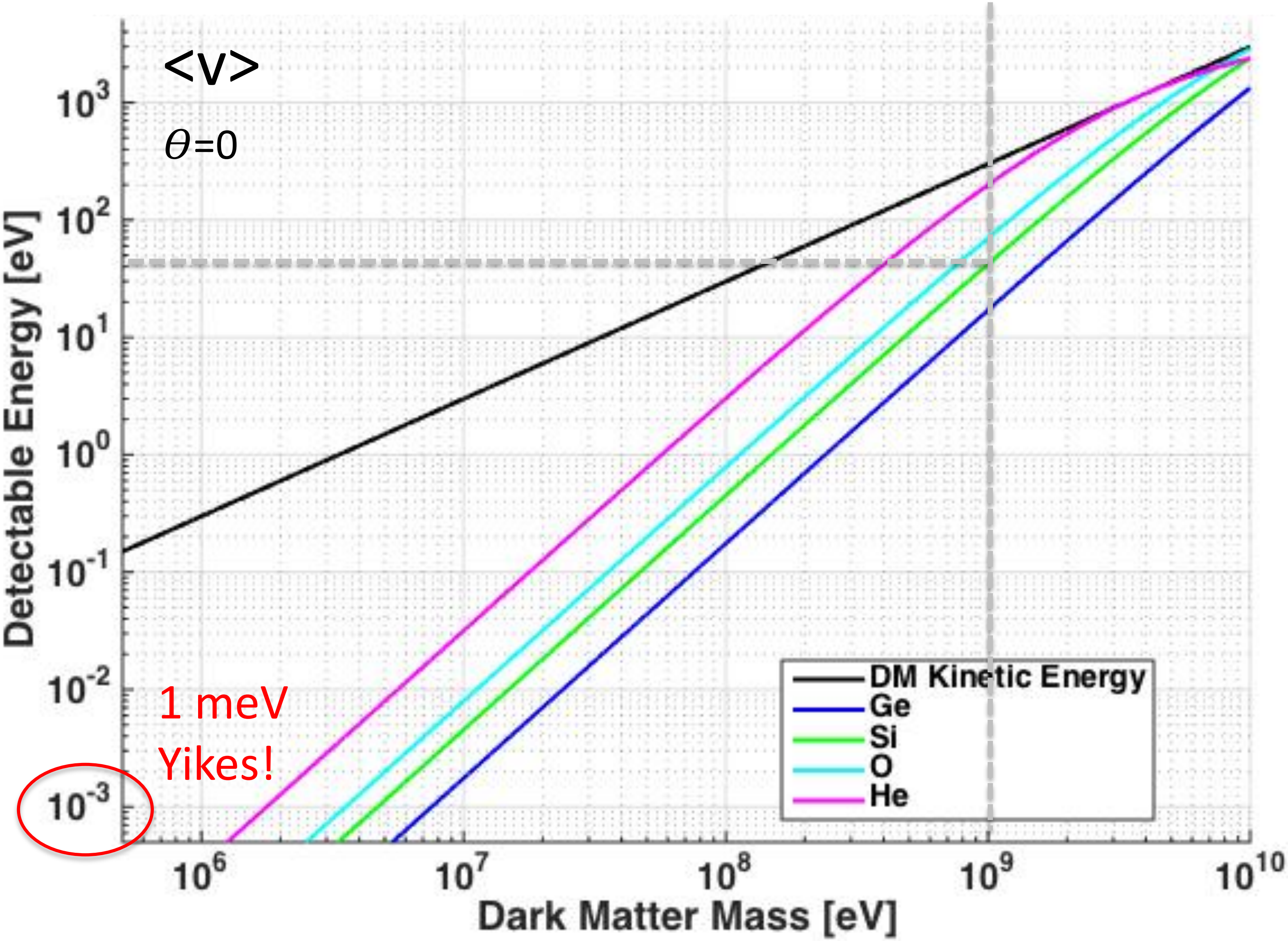
$$K_n = \frac{\mu^2 v_{DMo}^2}{M_n}\left(1 - \cos(\theta)\right)$$

When $M_n >> M_{DM}$

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

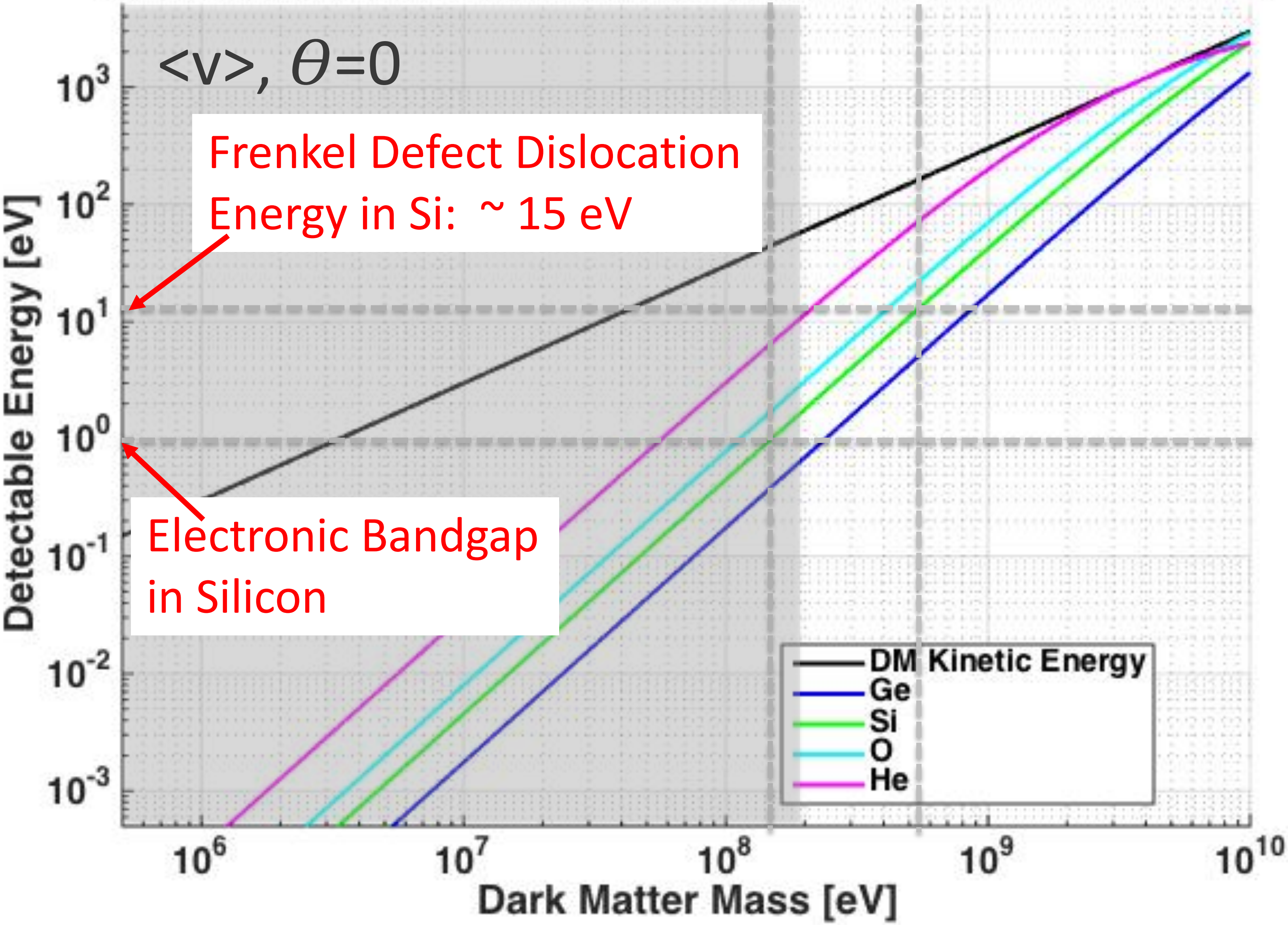
Recoil Energy Scales as M_{DM}^2. Transfer of DM kinetic energy is really inefficient for elastic 2 Body Scatters when $M_n >> M_{DM}$

Light Mass Dark Matter: Elastic Nuclear Scattering



Energy Sensitivity is Primary Design Driver

Ionization Production in eV Scale Nuclear Recoils

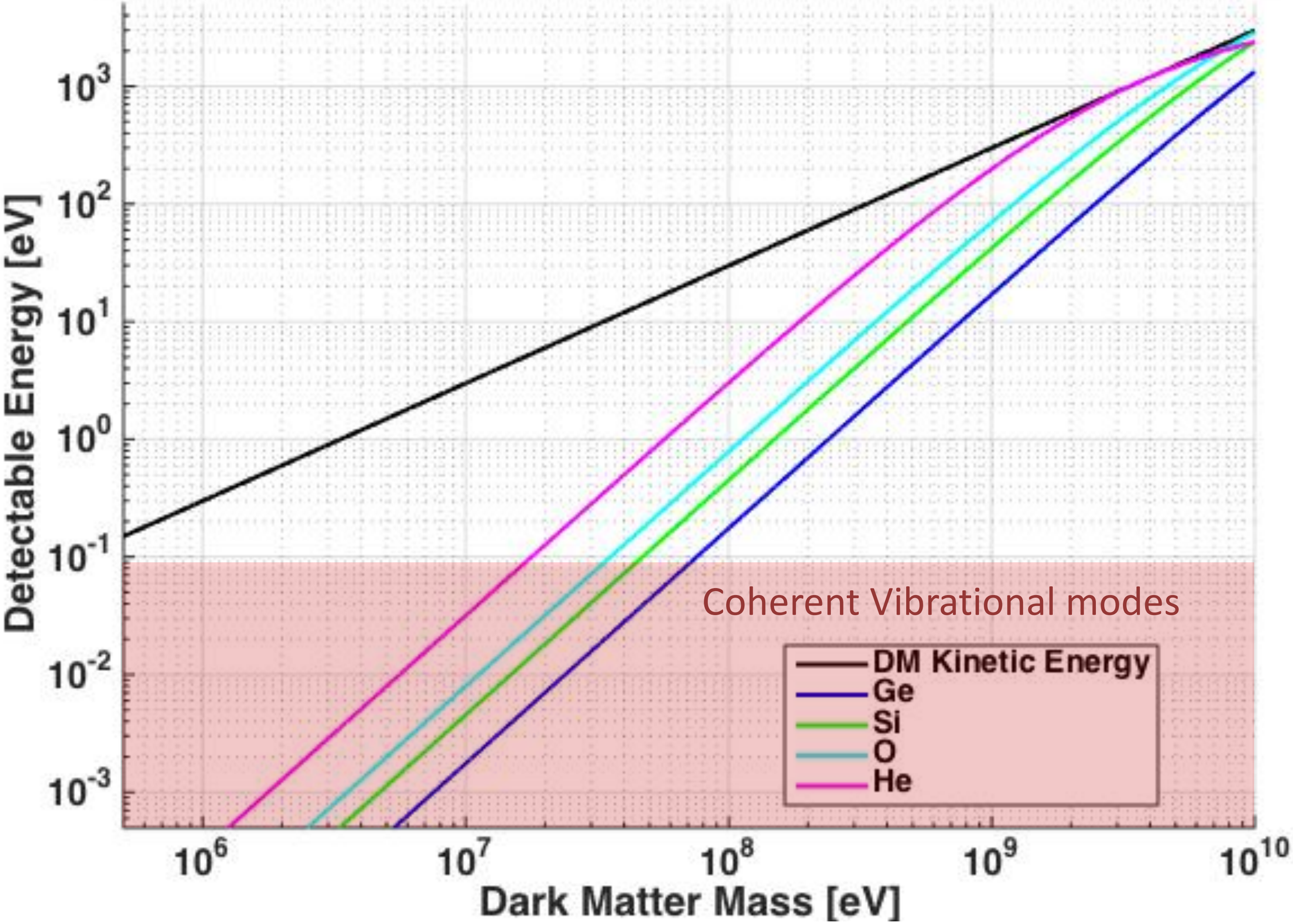


Frenkel Defect Dislocation Energy in Si: ~ 15 eV

Electronic Bandgap in Silicon

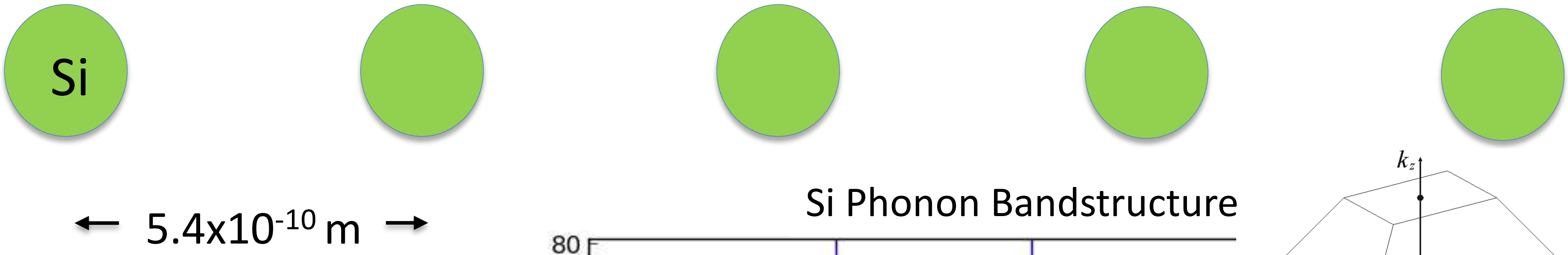
For DM <~ 200MeV, no ionization expected from NR

Coherent Vibrational Excitation Regime



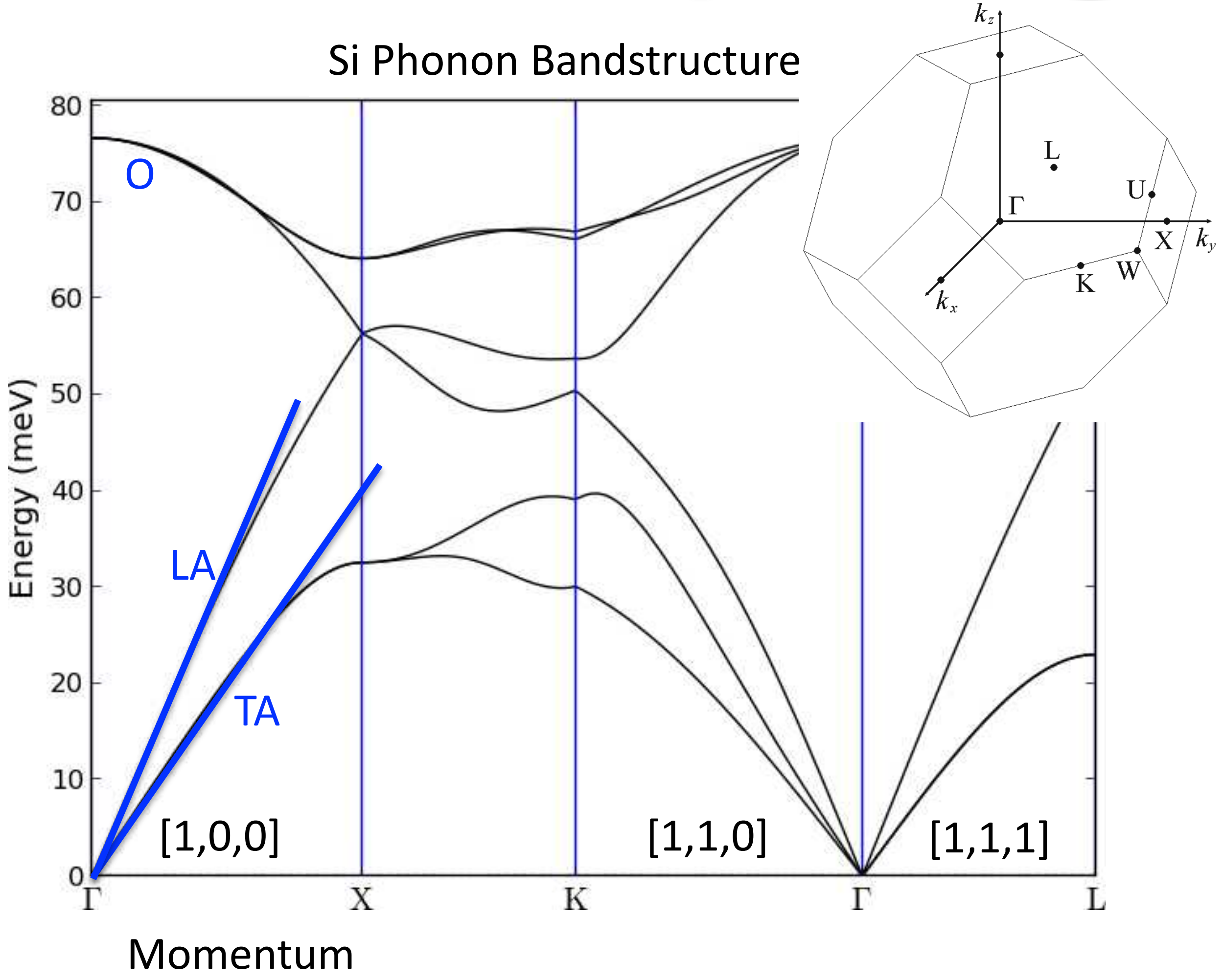
Below O(10 MeV), we need to start thinking about DM nucleus interactions in terms of coherent vibrational mode production

Acoustic Phonons



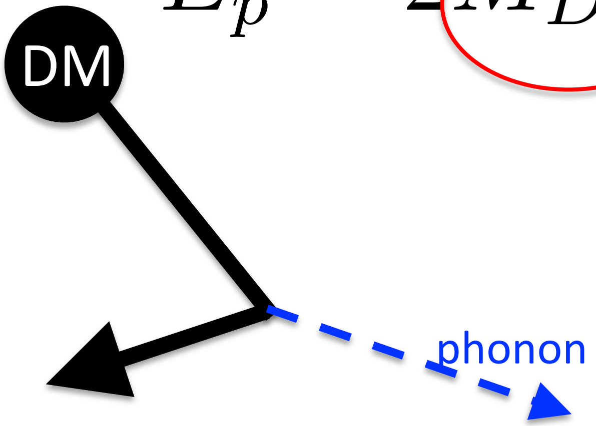
P = h/a = 2.3 keV/c

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

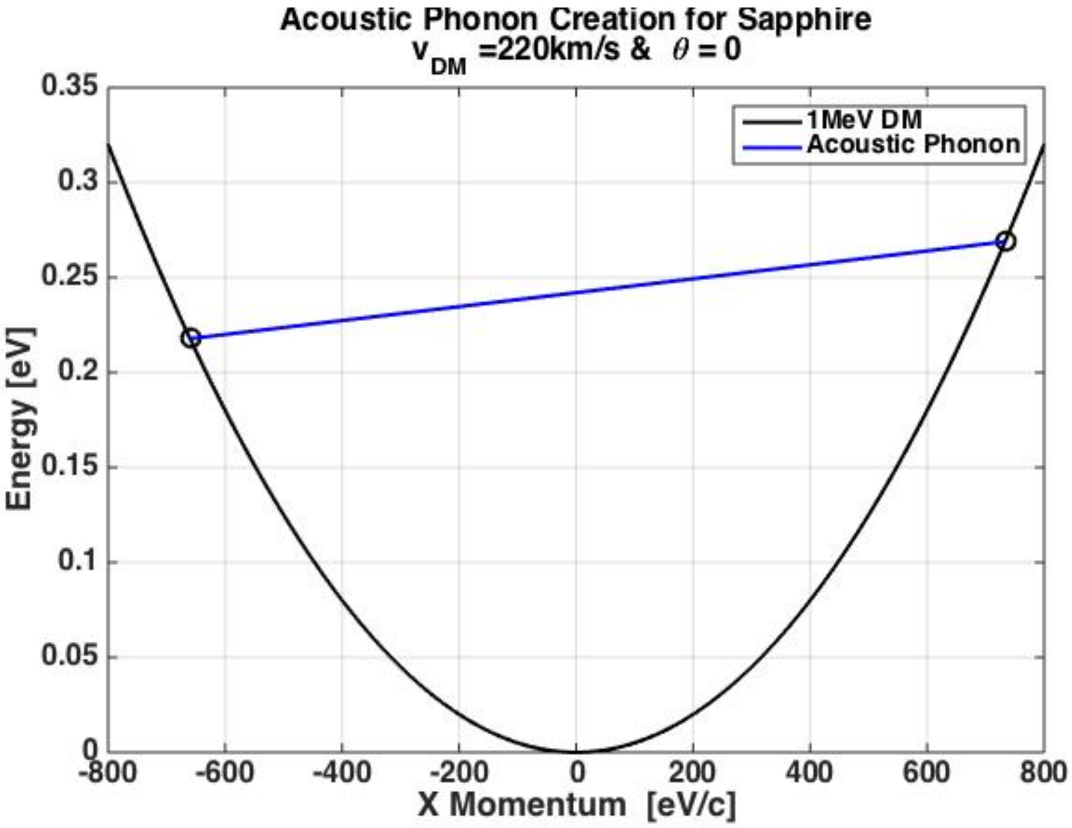


Kinematics: Acoustic Phonon Production

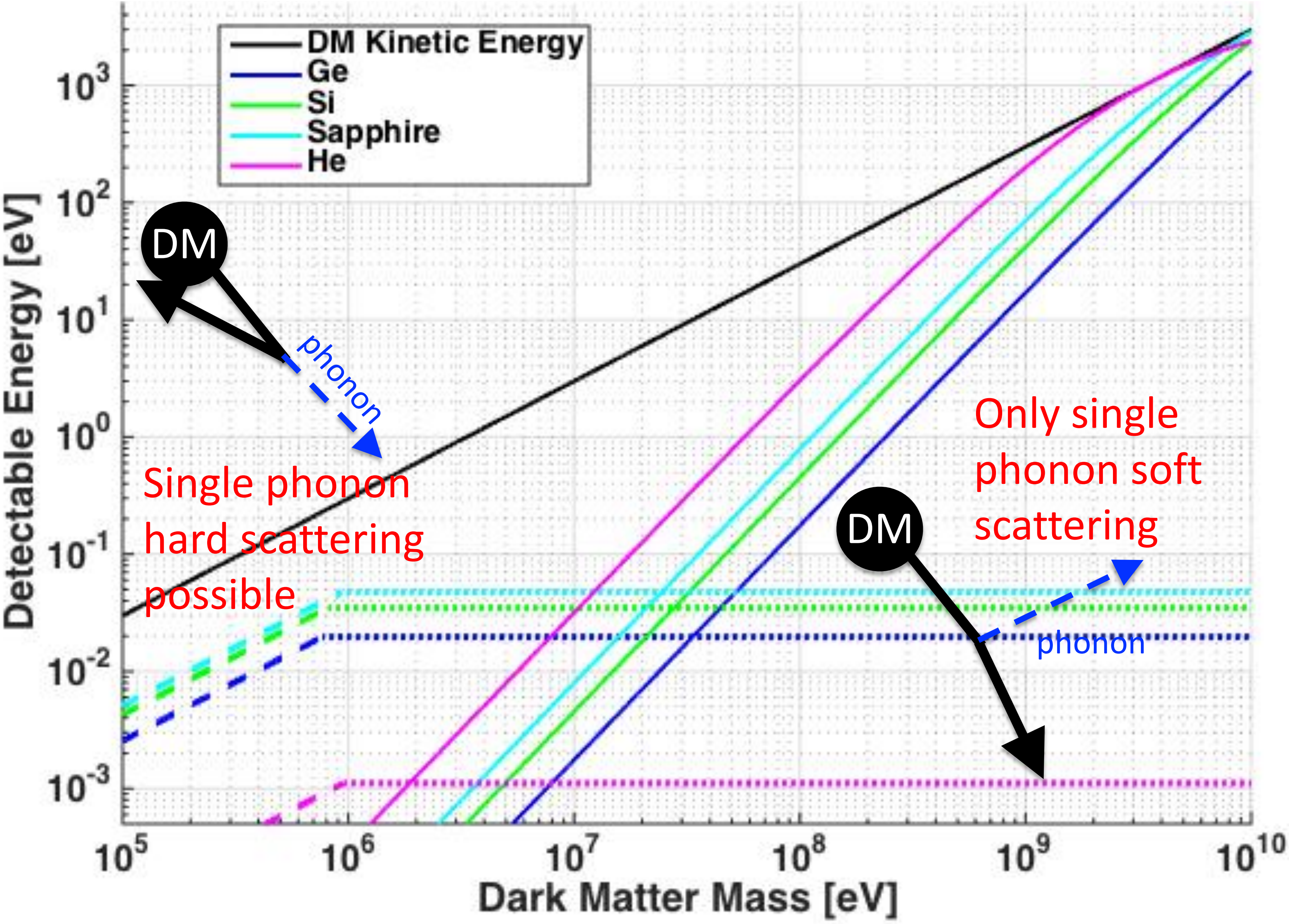
$$E_p = 2M_{DM} v_a (v_{DM\,0} \cos(\theta) - v_a)$$



- 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

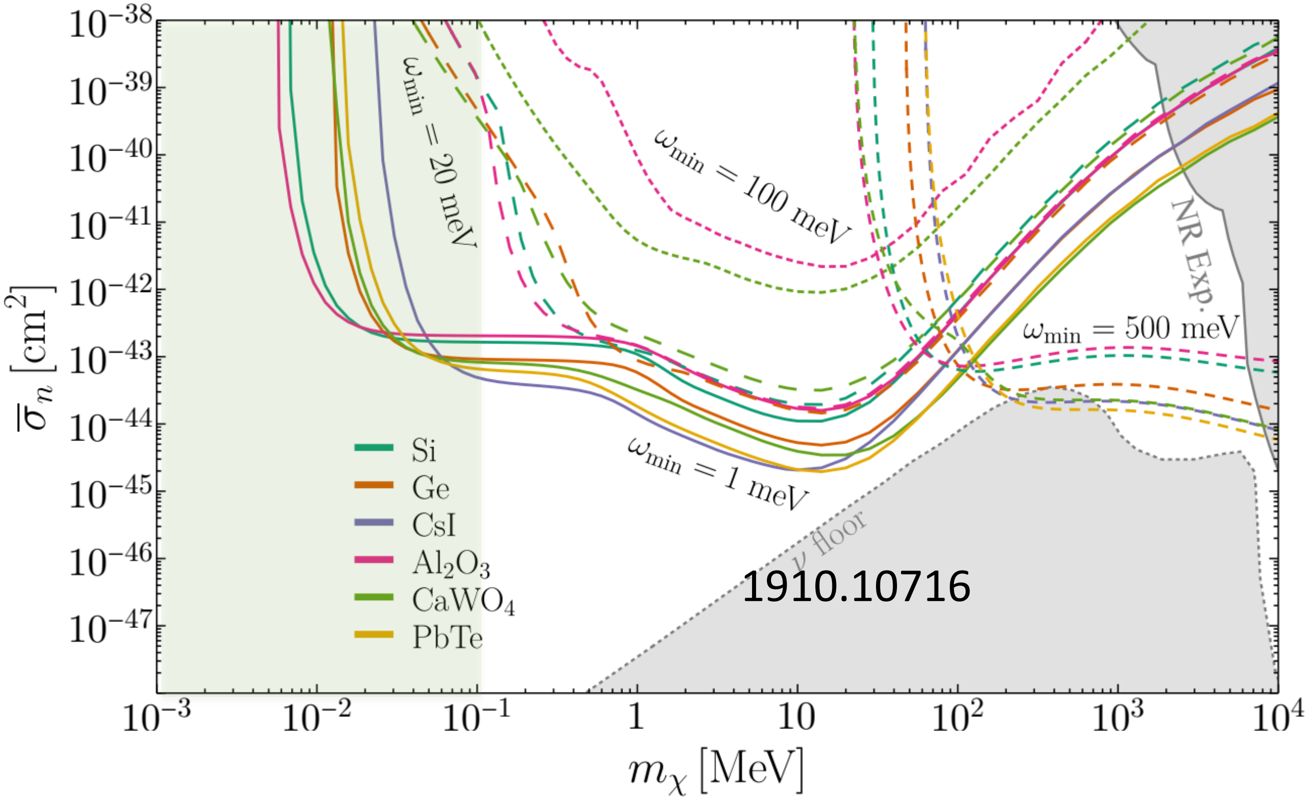


Single phonon hard scattering possible

Only single phonon soft scattering

Phonon Sensitivity Curves

Heavy Mediator Single Phonon Sensitivity



1910.10716

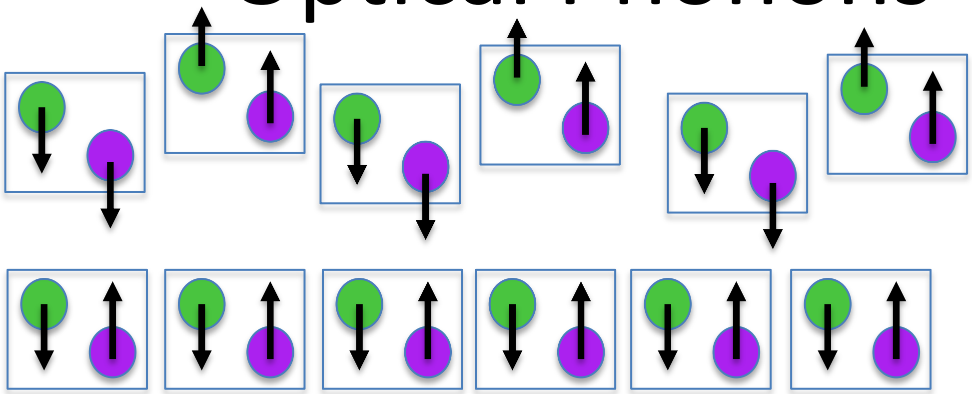
- Zurek, Griffin, et al: 1910.10716
- Exposure: 1kgyr
- No Backgrounds

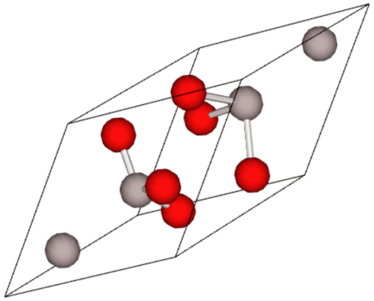
Detectors with ~20meV phonon sensitivity needed to really probe this space

Optical Phonons

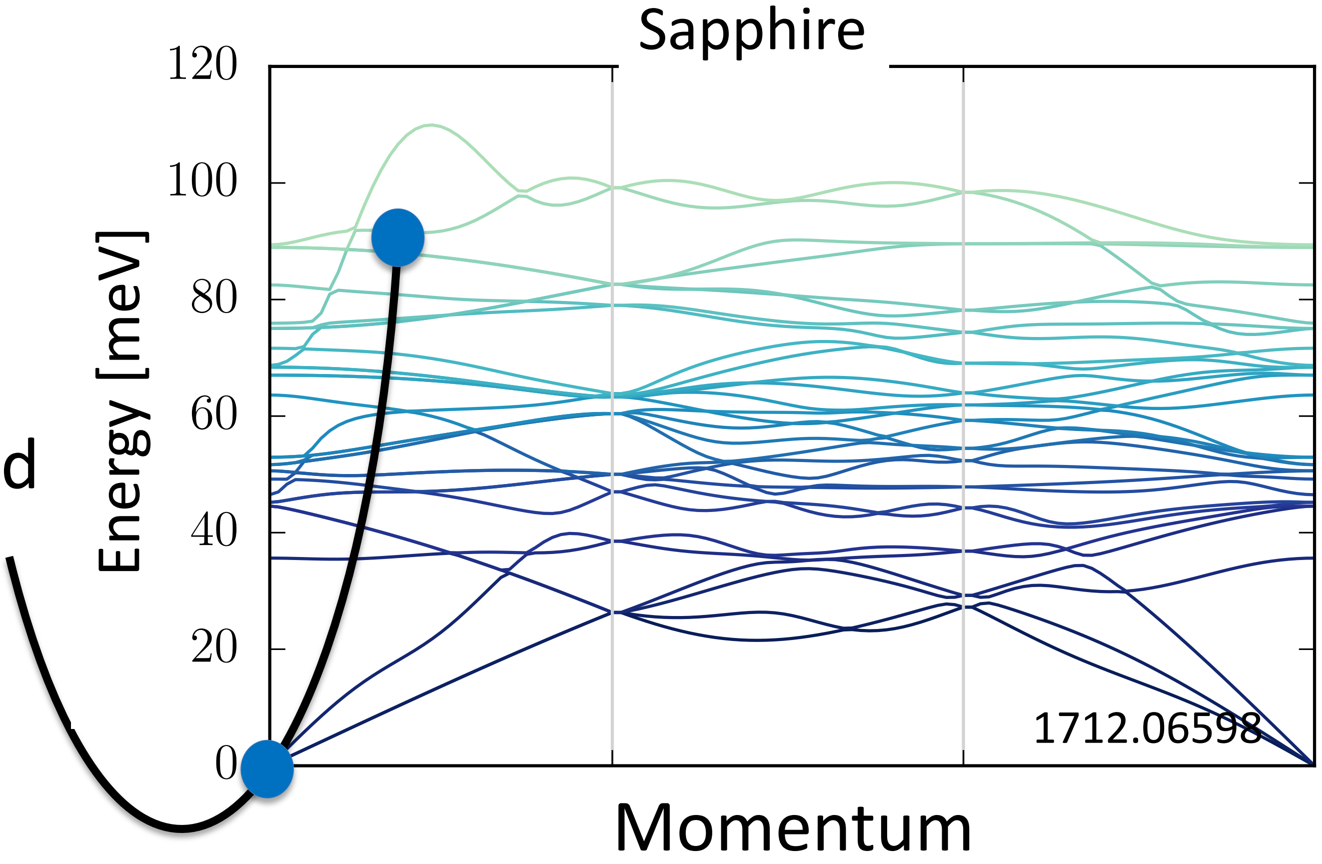
Acoustic:

Optical:





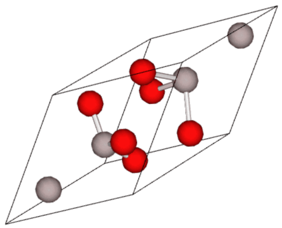
Due to their gapped nature, optical phonons are kinematically matched to IR and light mass DM!



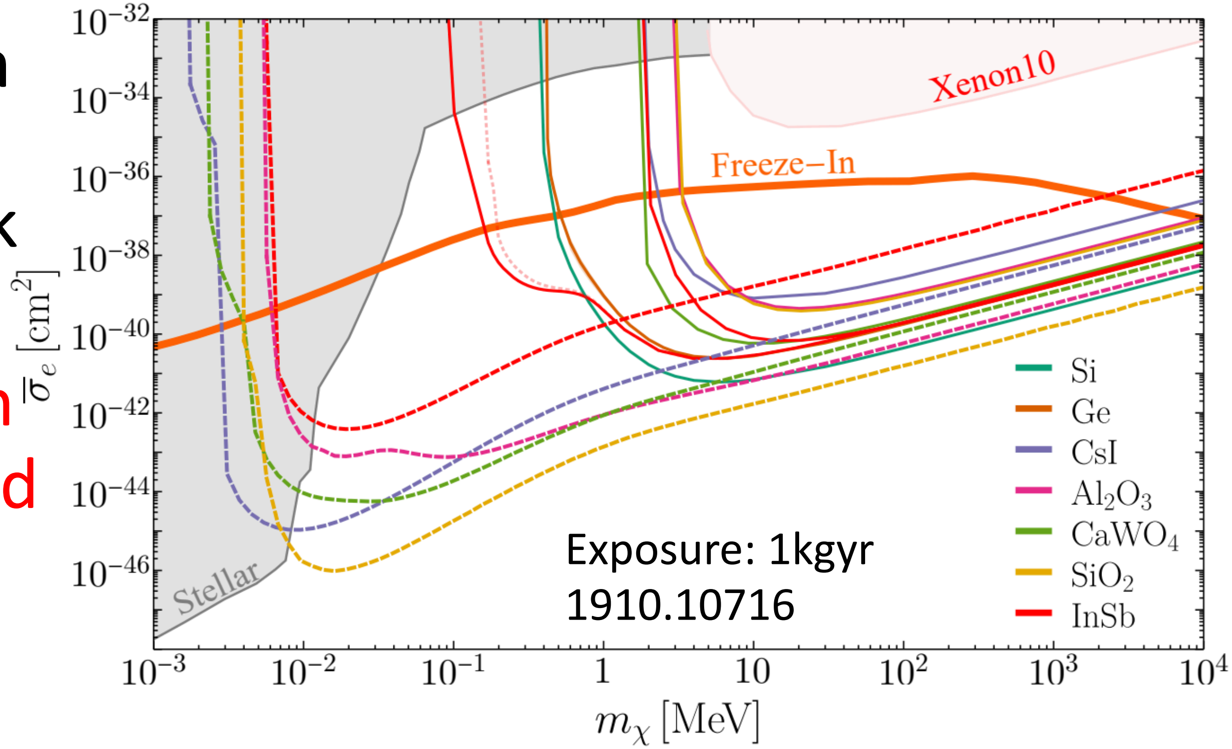
Knapen, Lin, Pyle, & Zurek: 1712.06598

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
- 30-100meV phonon sensitivities required

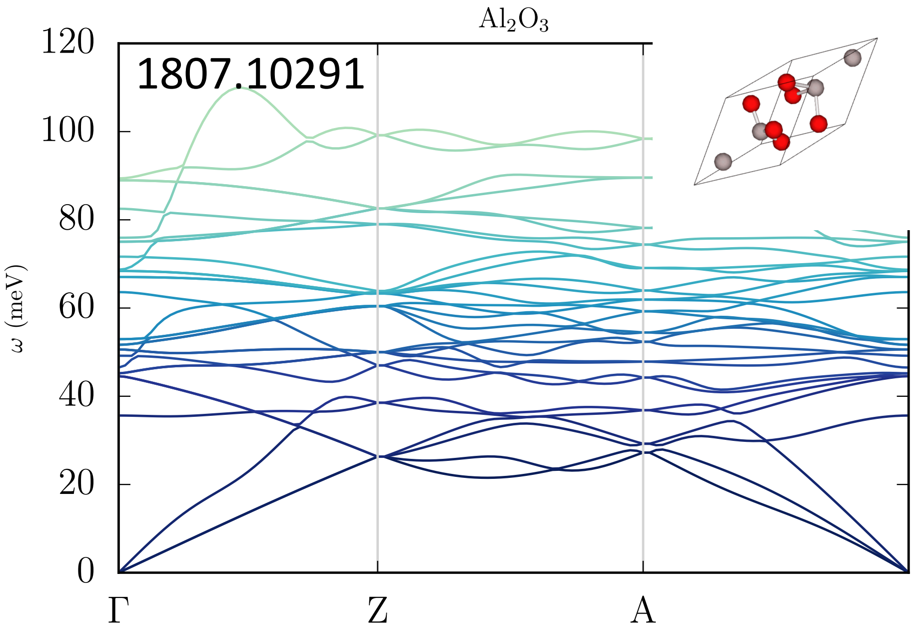


Scattering via Light Dark Photon



Exposure: 1kgyr
1910.10716

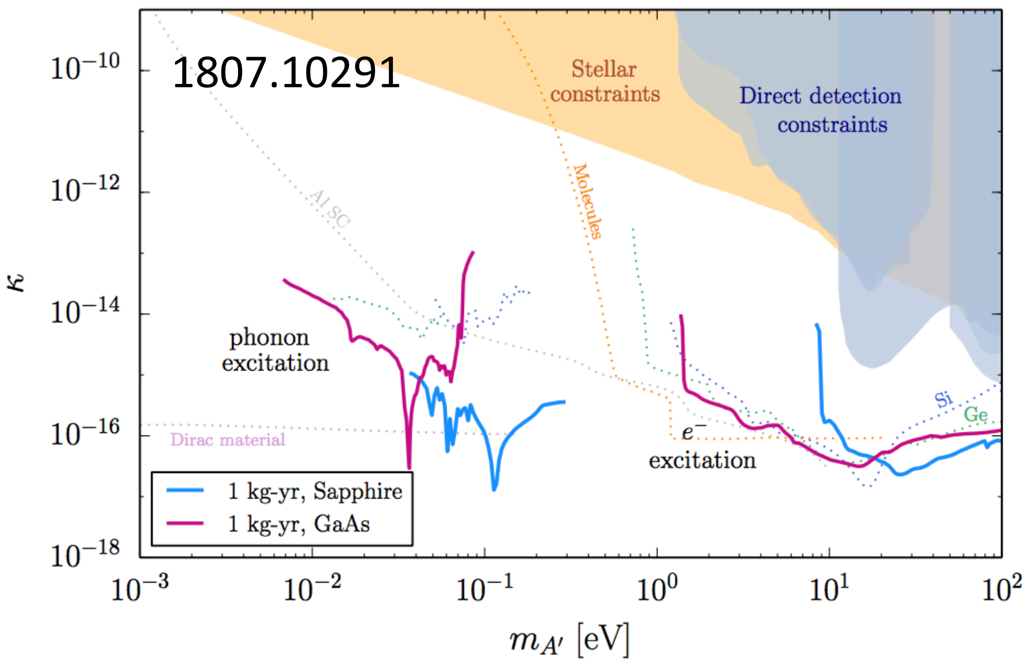
Sapphire: Lot’s of Optical Phonon Bands



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

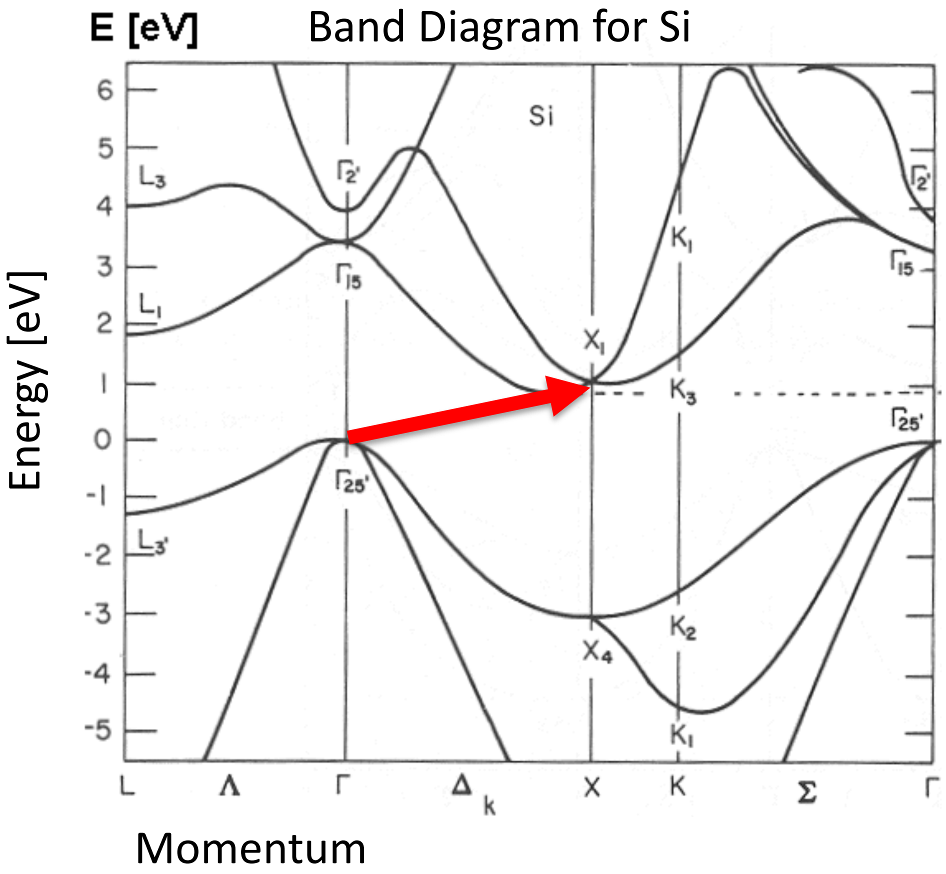
To search for thermal DM down to keV masses via scattering and ultracold bosonic DM to 30 meV, we need a detector sensitive to a single optical phonon

Dark Photon Dark Matter Absorption



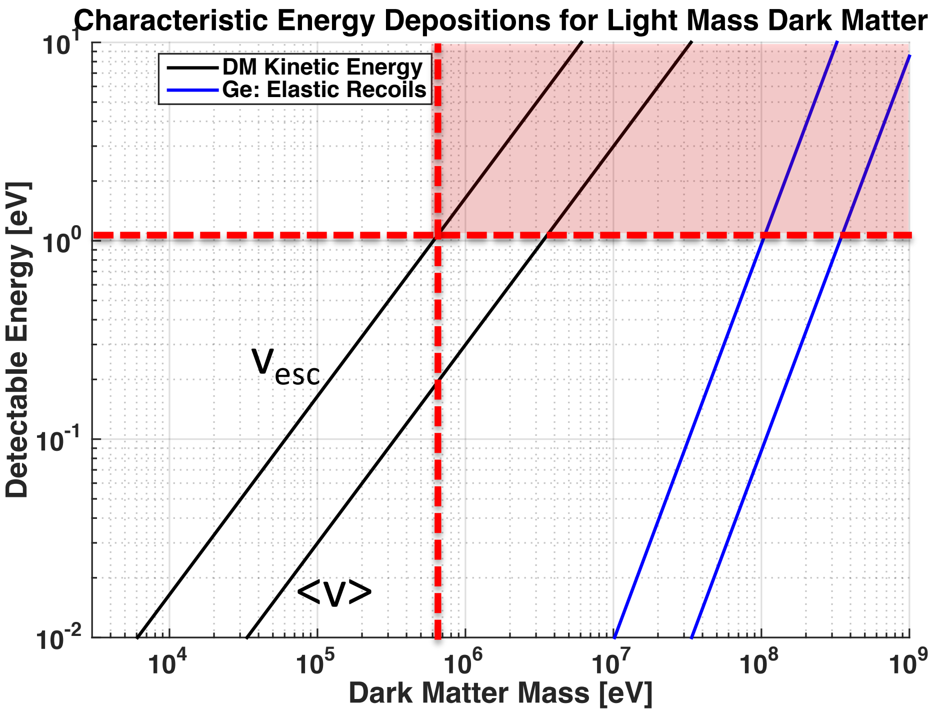
Other Signal Channels for Interacting with Light Mass Dark Matter

Inelastic e$^-$ Recoils in Semiconductors



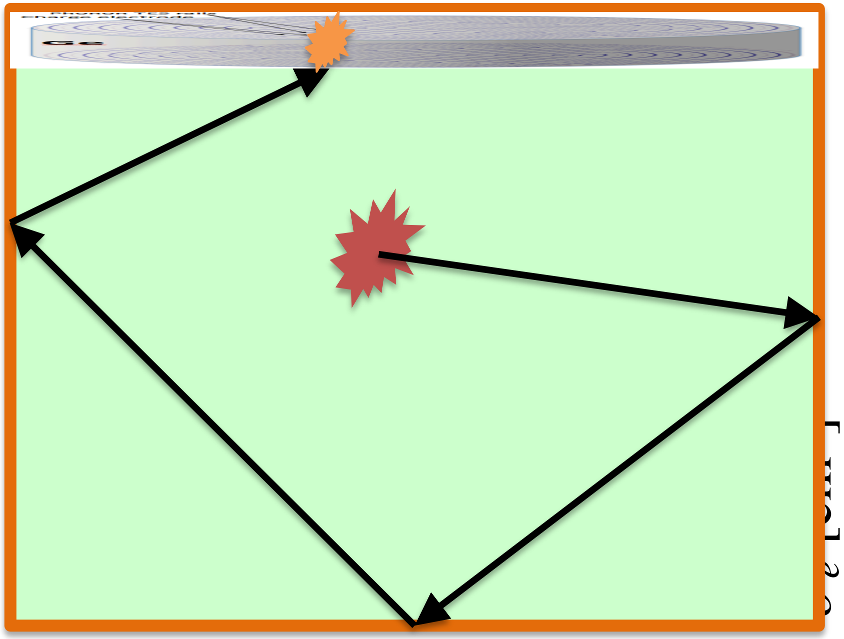
Detector Requirement: Sensitivity to single e/h pairs (1 eV) with negligible dark count rate

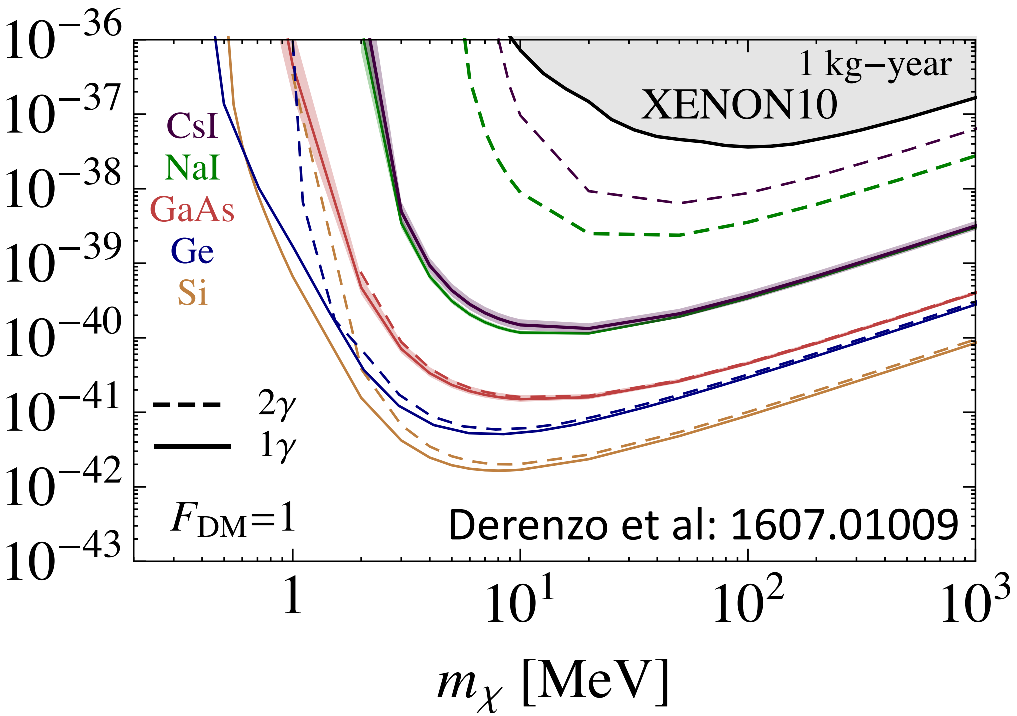
- e- excitation momentum and energy scales in semiconductors well matched to 1 MeV-100MeV DM
- Essig et al: 1108.5383



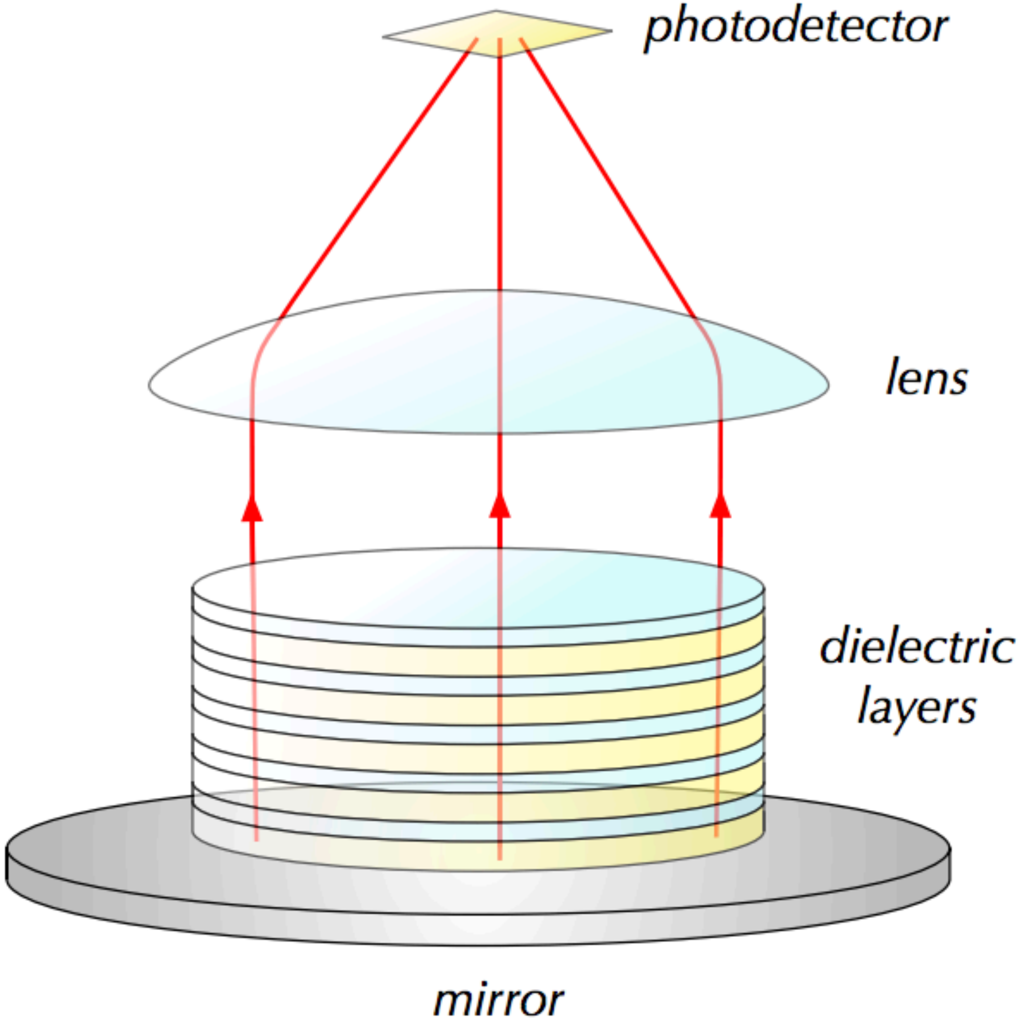
Inelastic e- Recoils: Scintillating Crystals

- Use a low bandgap scintillating crystal (GaAs, NaI) and couple to a single photon sensitive large area detector with no dark count rate
- Penalty: Scintillation Production Efficiency





Optical/IR Haloscope

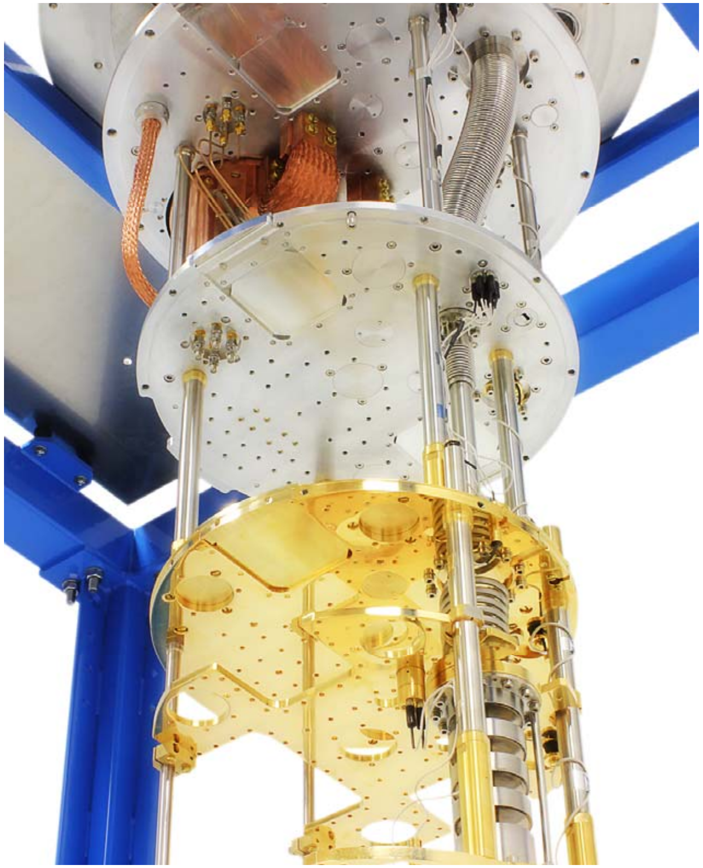


- Baryakhtar, Huang, Lasenby 1803.11455
- Momentum matching via multilayer stack
- Requirements: Single photon sensitivity with no dark counts

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

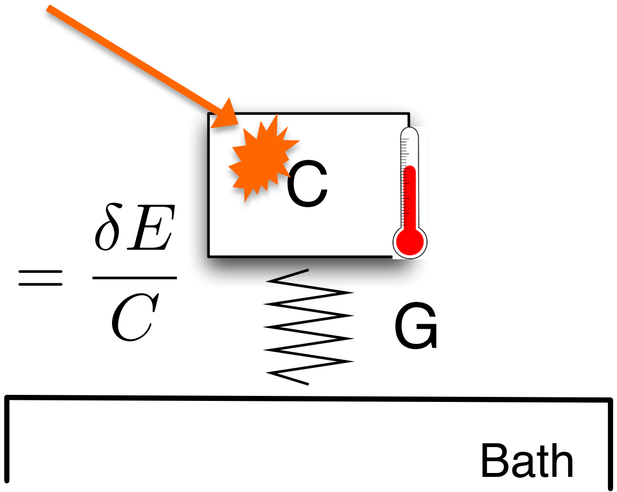
100meV Excitation Sensitivity -> Low Temperature Detectors

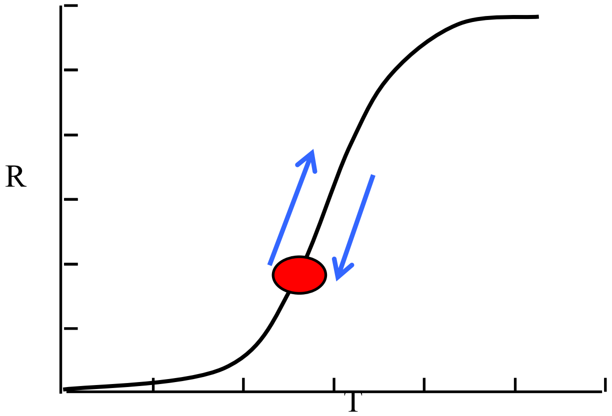
- 300K = 26meV
- To sense 100meV excitations we'll need to cool the detector down to near absolute zero
- Use superconducting detector technology
  - MKIDs
  - **Transition edge sensors**
  - SNSPD (only for photon applications)



The Simplest Thermal Calorimeter

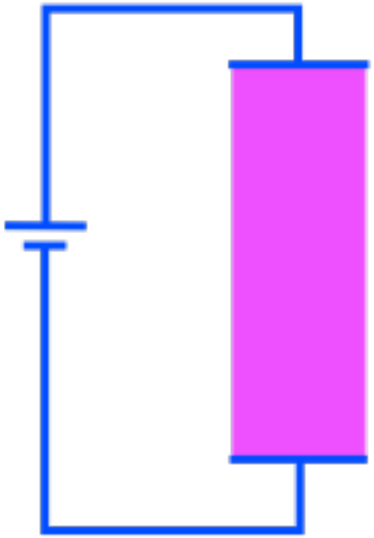
$$\delta T = \frac{\delta E}{C}$$



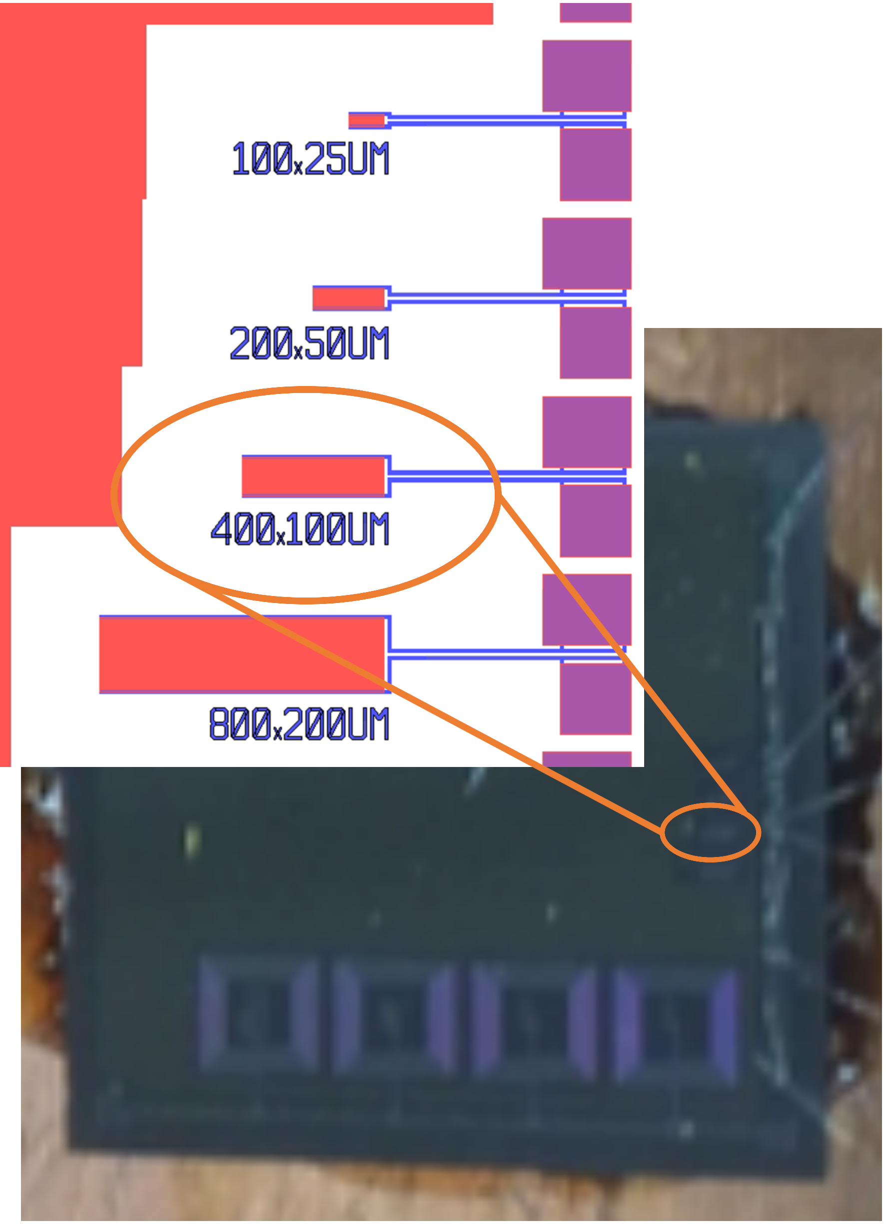


Transition Edge Sensor (TES):

- A superconducting metal film (W) that is externally biased so as to be within its superconducting/normal transition
- $$\sigma_{<E>} \sim \sqrt{C k_b T^2}$$ $$\propto \sqrt{V T^3}$$
- Must use low Tc and very small volume TES -> hard to get gram-day exposures when your TES (25umx25umx40nm) is 500fg … only directly useful for IR Haloscope

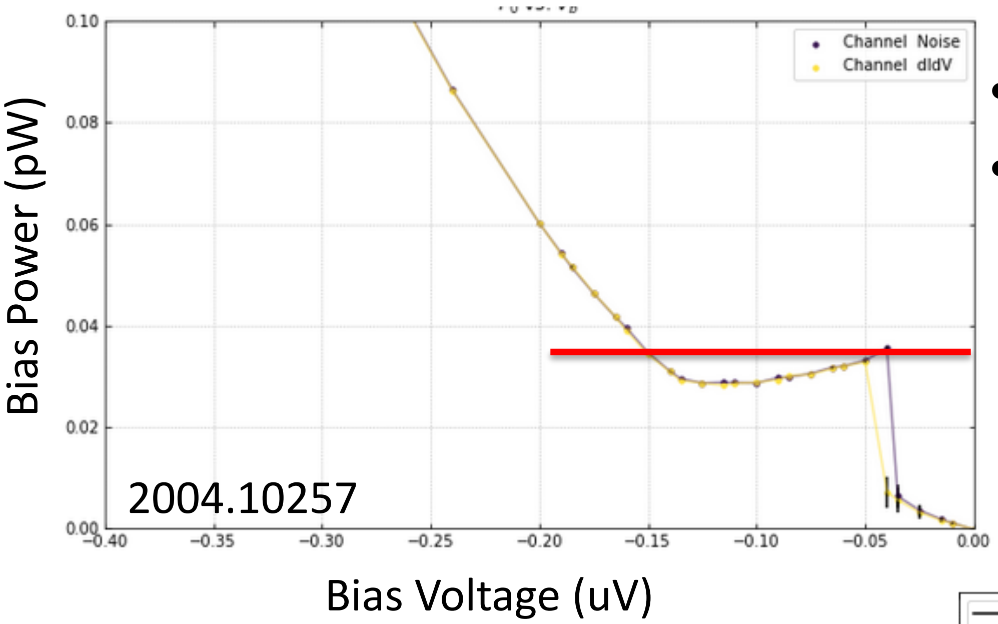


R&D: ultra sensitive TES



- Build and test simple TES test structures for noise is performance
- 2004.10257
- Tungsten TES
  - Tc= 41mK
  - 40nm thick

100um x400um TES Characterization

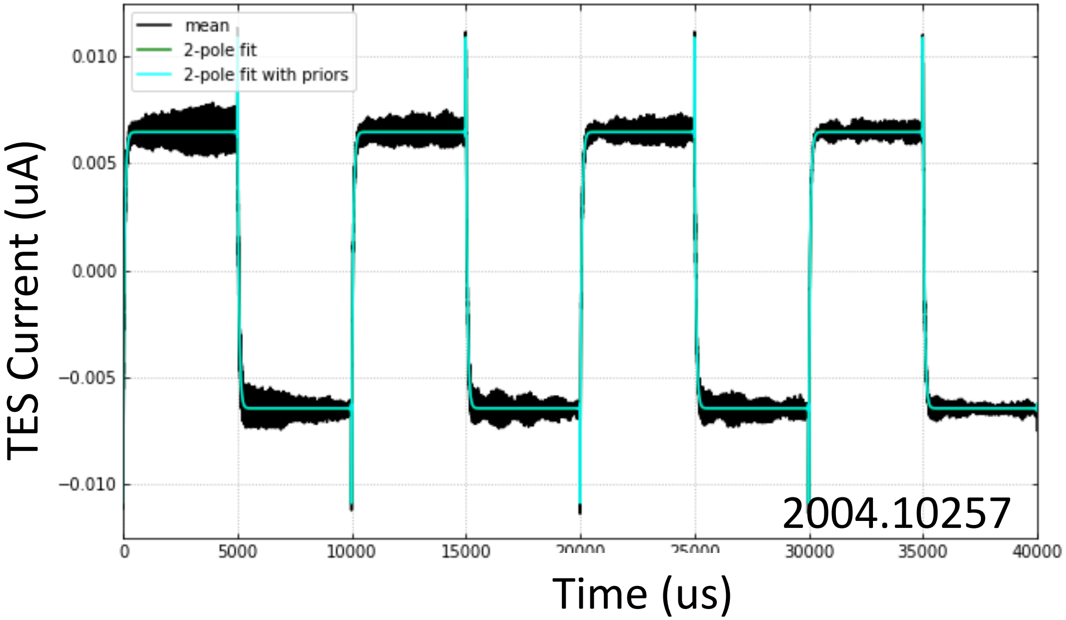

TES Power vs TES Bias Voltage

2004.10257

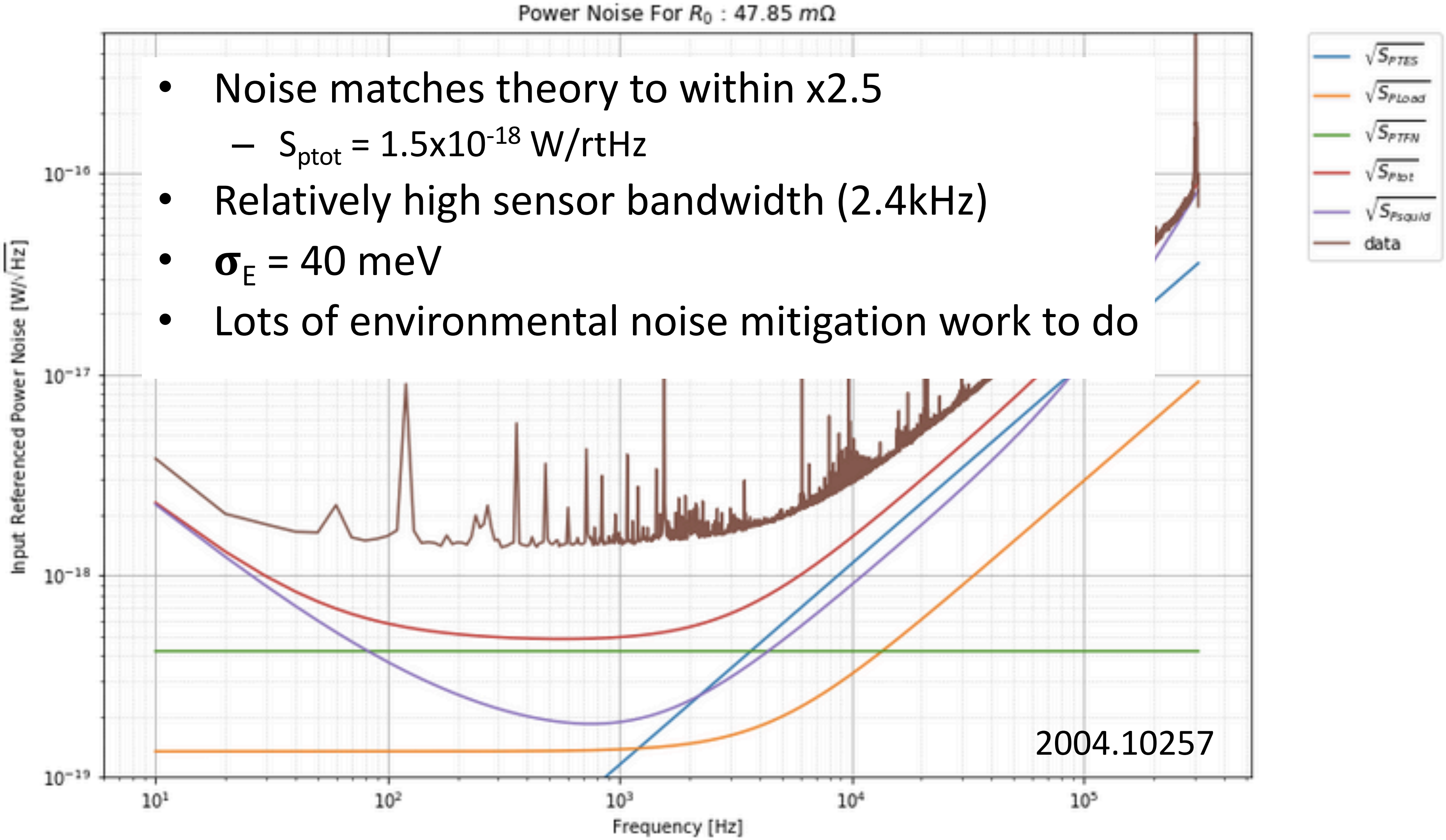
- Normal Resistance: 630mOhm
- Bias Power: 35fW
  - Your average CMB TES: 1 pW
  - Slight calibration error

- Complex Impedance
  - Simple 2 pole TES dynamical model perfectly fits response
- TES falltime: ~66us (2.4kHz)
  - Relatively fast

TES Response to Square Wave Jitter


2004.10257

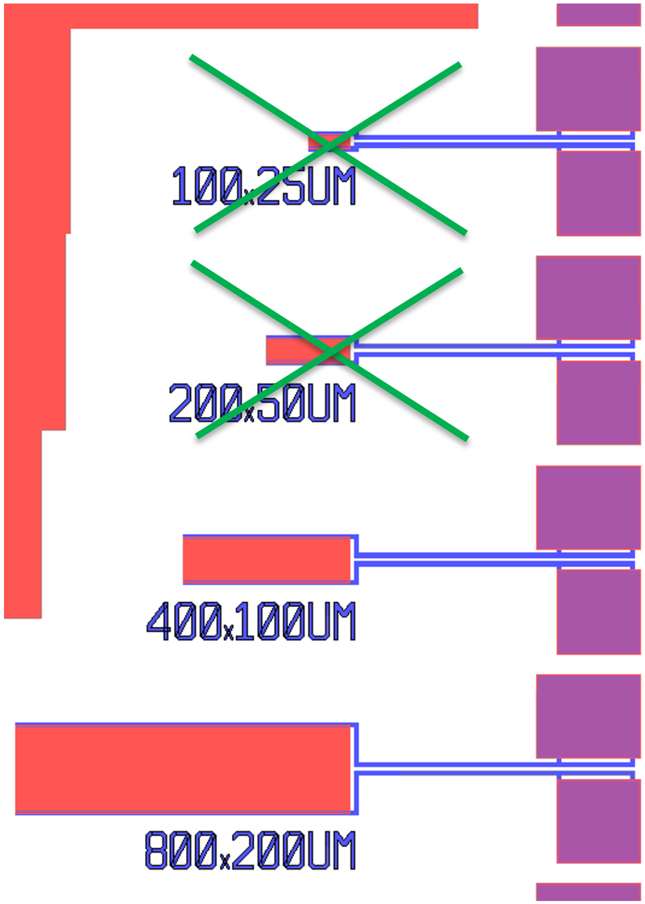
100um x400um TES Noise



- 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
- Lots of environmental noise mitigation work to do

2004.10257

More Sensitivity -> Decrease Volume



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

Volume (40nm thick)	Bias Power	Expected Sensitivity
25x25um^2	0.5 fW	5meV
100x25um^2	2.2 fW	10meV
200x50um^2	9 fW	20meV
400x100um^2	35 fW	40meV

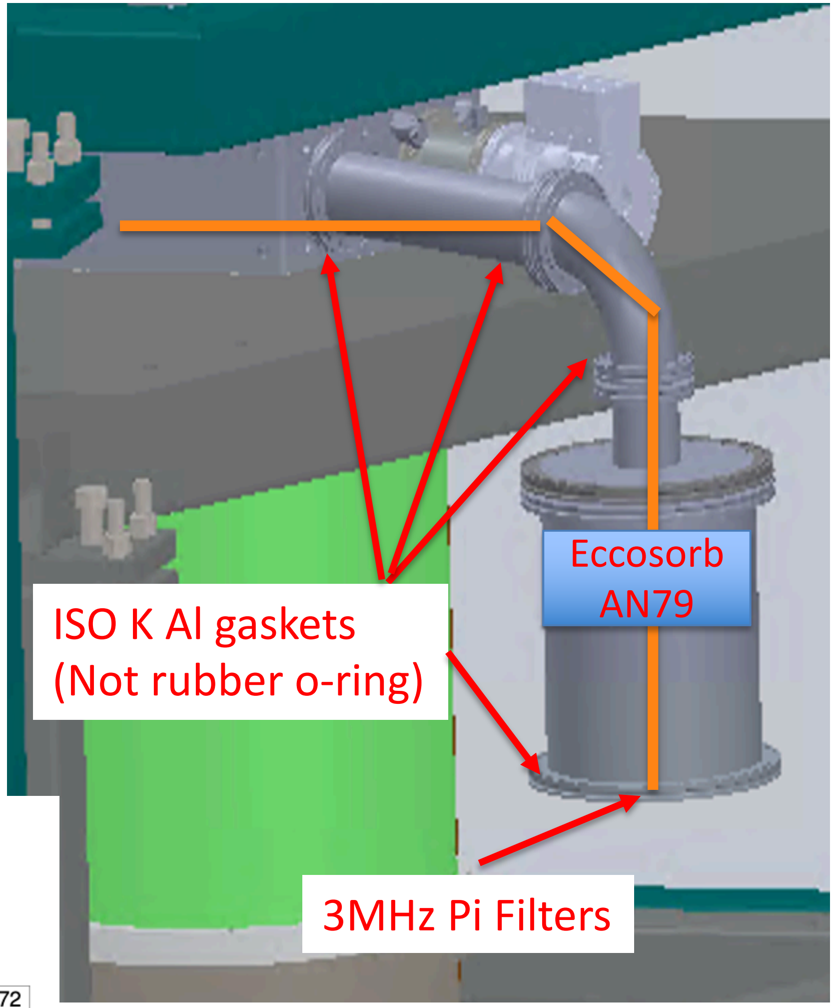
- 200x500: barely operates
- 100x25um: completely normal

We have 5 fW of DC environmental parasitic power hitting our TES. Our current primary challenge is to continue to improve environmental isolation!

2004.10257

Faraday Cage #1 -> Dilution Fridge

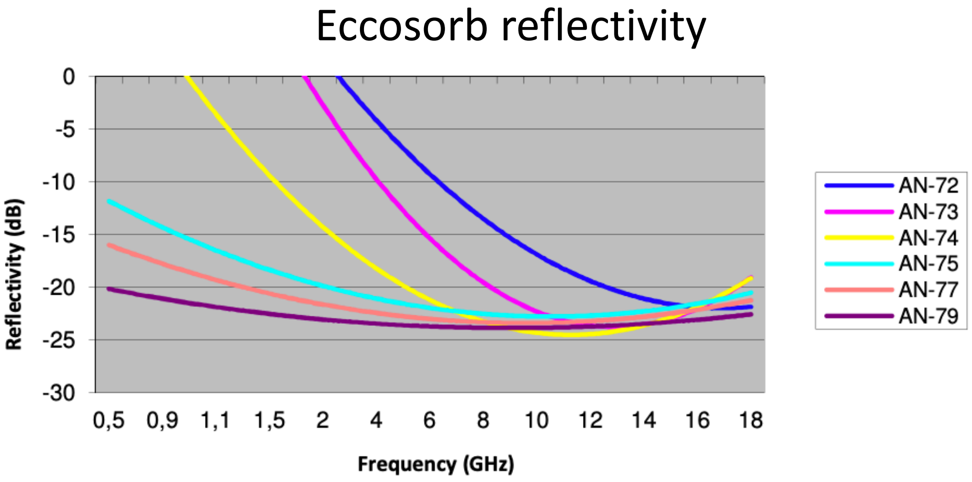
- If your E&M signal can get out, the environmental EMI can get in!
- Need to carefully filter all signal lines breaching the faraday cage



Eccosorb AN79

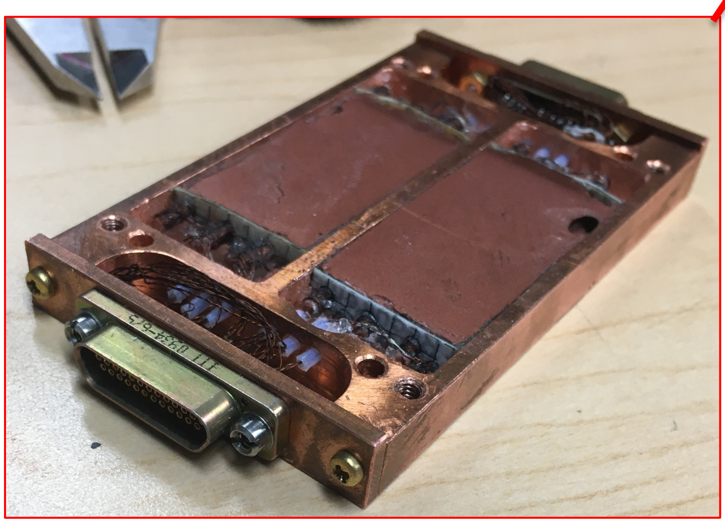
ISO K Al gaskets (Not rubber o-ring)

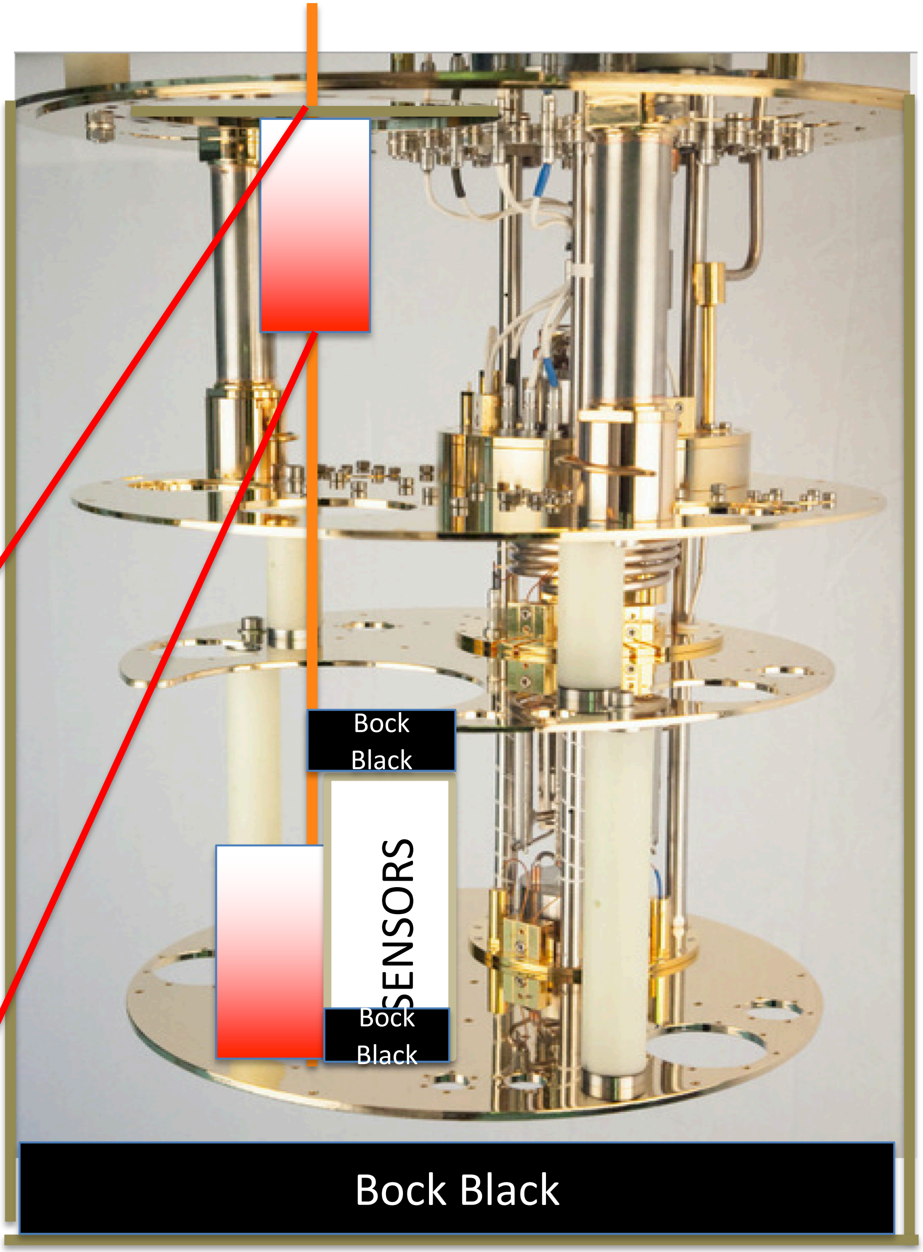
3MHz Pi Filters



Faraday Cages 2 & 3: 4K & 10mK

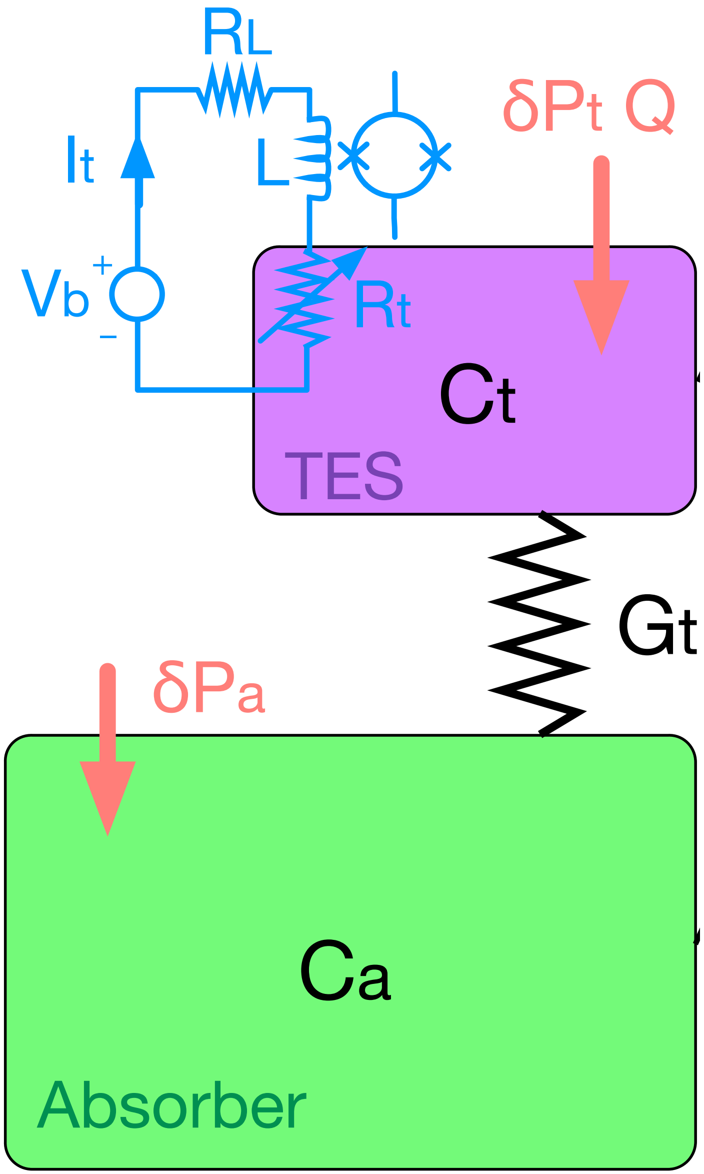
- Inner thermal shields would act as additional Farday Cages … if there were filters on all the lines.
- Bock Black for IR light leaks
- Steal copper powder filter from Martinis, Devoret, Clarke (PRB 35.4682 1987)





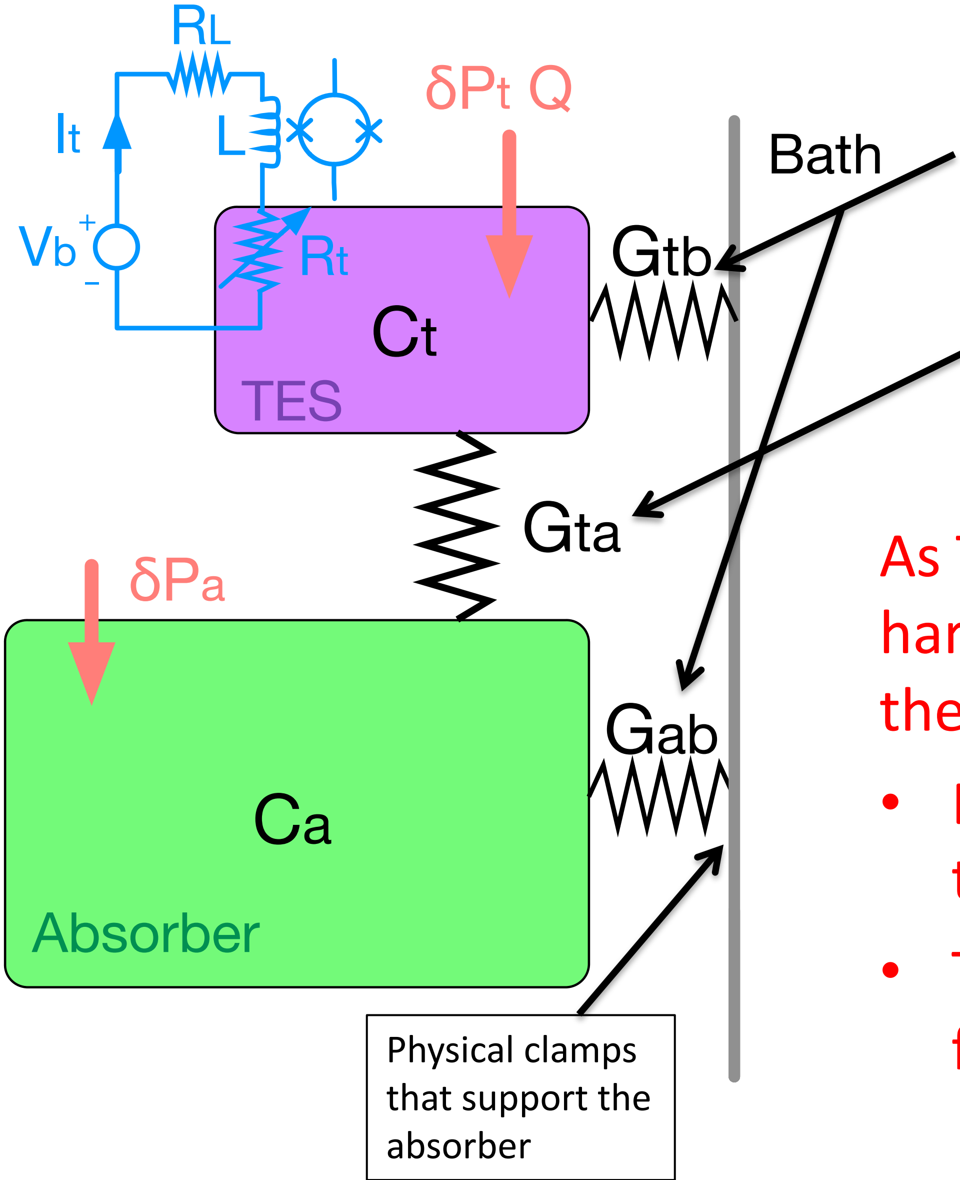
Phonon Detectors

~~2nd most simple thermal calorimeter~~



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

Problem: Decoupling between the Sensor and Absorber



Physical clamps that support the 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

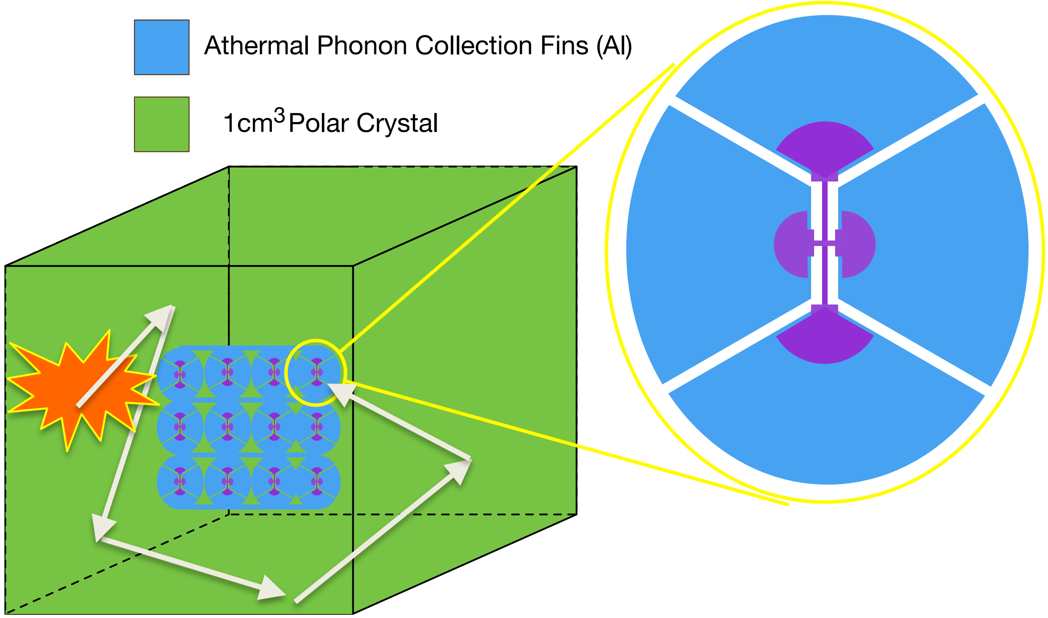
- Energy leaks out of the absorber through G_{ab} before its measured
- TES sensitive to power fluctuations through G_{tb}

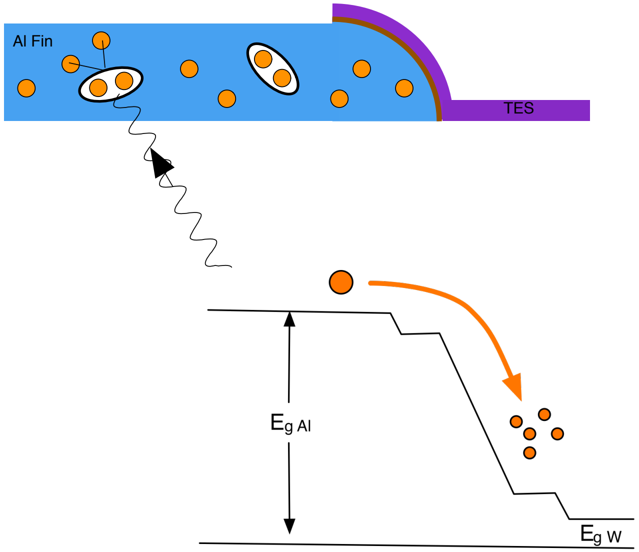
Athermal Phonon Sensor Technology

🟪 TES and QP collection antennas (W)

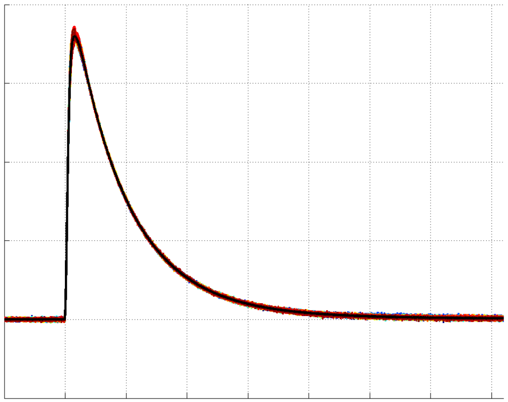
🟦 Athermal Phonon Collection Fins (Al)

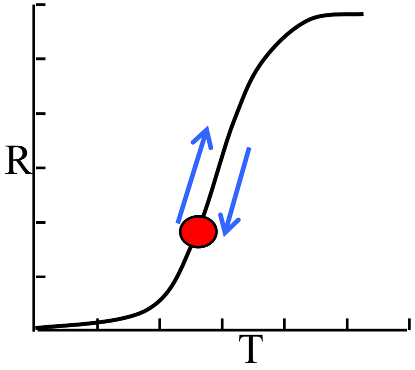
🟩 1cm^3 Polar Crystal



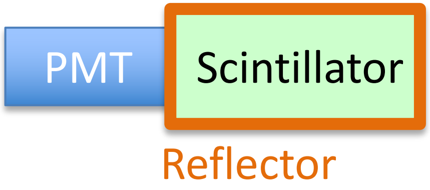


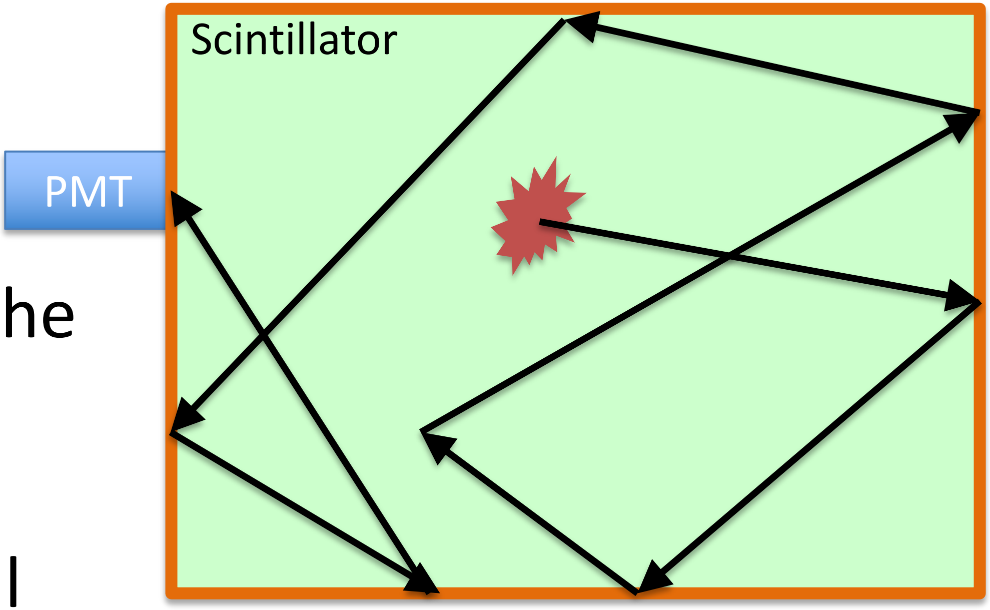
Collect and Concentrate Athermal Phonon Energy into Sensor





Excitation Detectors & Volume Scaling

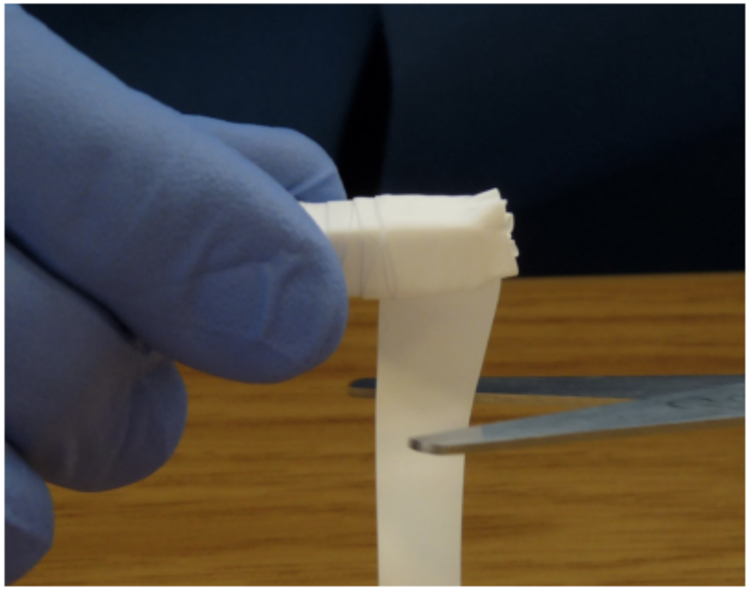




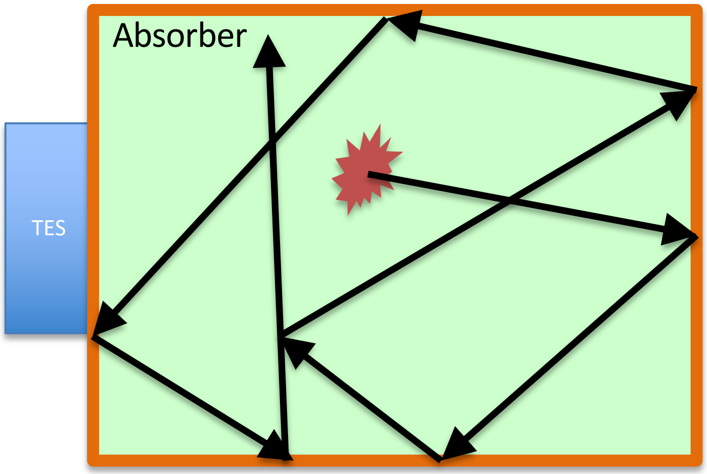
Will these detectors have the same energy sensitivity?

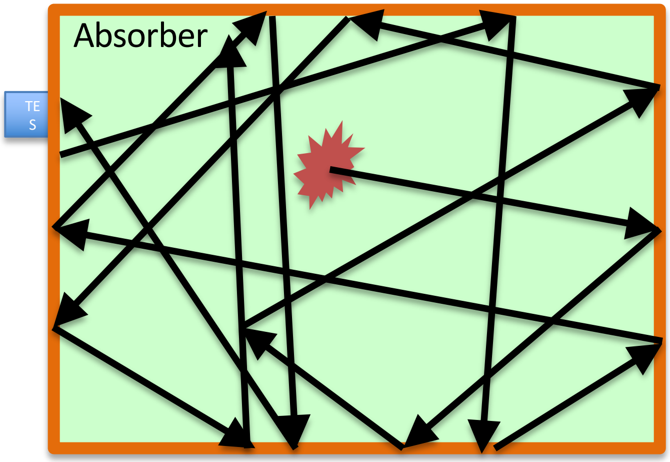
Yes, if:

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



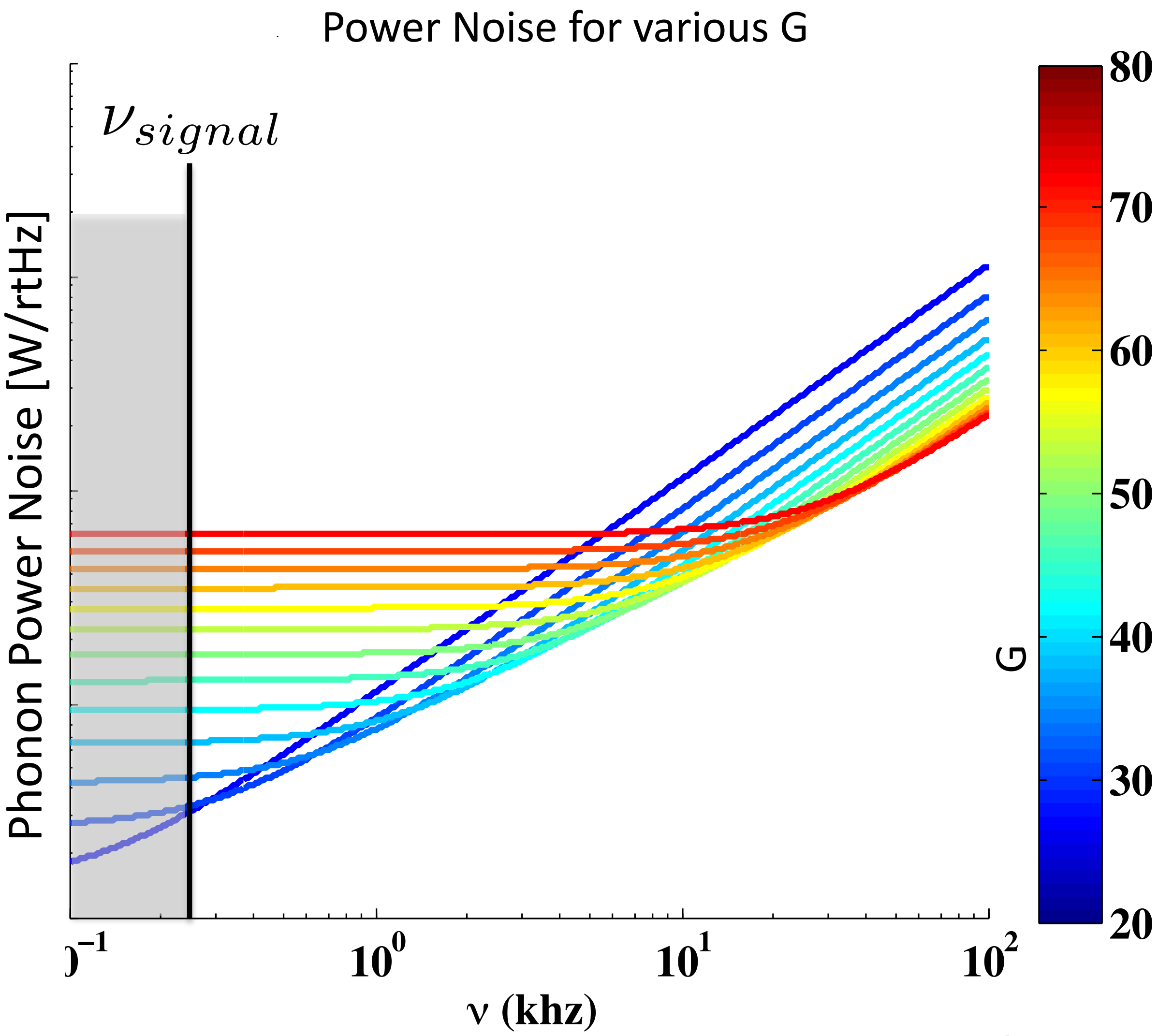
Optimizing the Athermal Phonon Excitation Detectors





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



$$G \propto T_c^4$$

$$S_{ptfn} = 4k_bT_c^2G$$

$$\propto T_c^6$$

$$\sigma_E \propto T_c^3$$

- Lower υ_{sensor} (lower T_c) if $\upsilon_{\text{signal}} < \upsilon_{\text{sensor}}$
- Lower υ_{signal} (decrease Al coverage) if $\upsilon_{\text{signal}} > \upsilon_{\text{sensor}}$

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

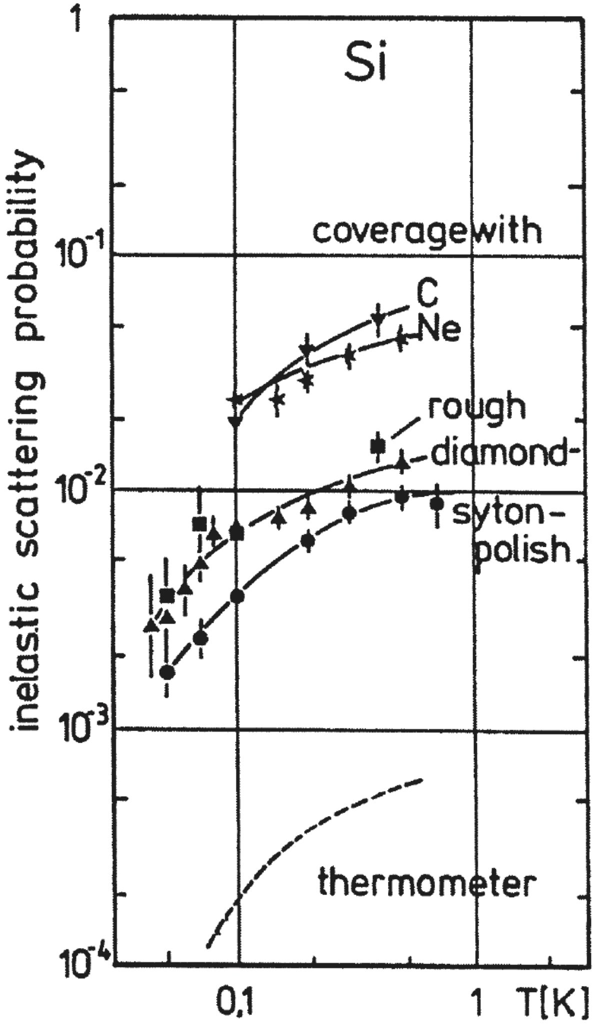
45mK-> 10mK: 2eV -> 20meV

Athermal Phonon Thermalization at Surfaces

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

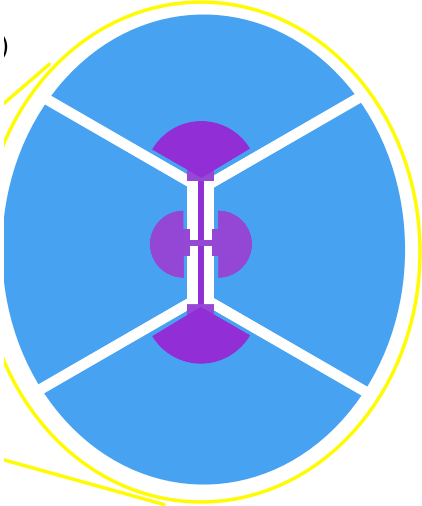
(W. Knaak et al, Phonon Scattering in Condensed Matter V,1986)

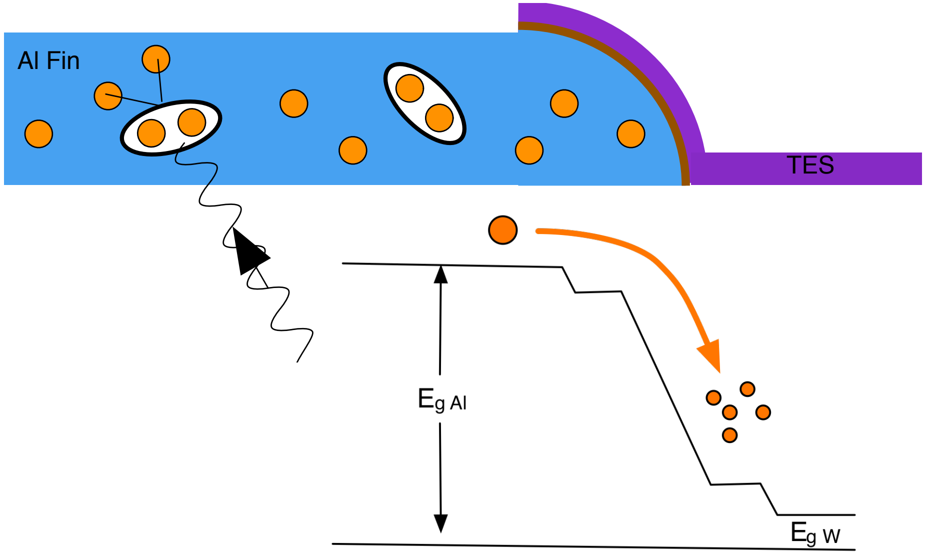
- 0.1%-1% of the crystal surface covered with athermal phonon sensors … 1/1000-1/100 thermalization probability needed
- Si, Ge -> ok



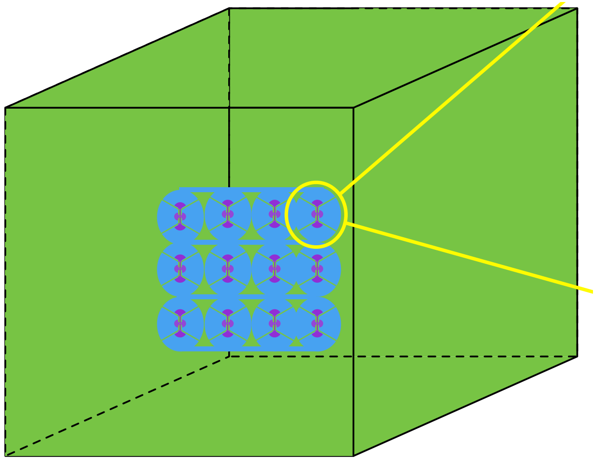
Step 2: Make the Athermal Phonon Sensor

- 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



Athermal Phonon R&D

Matt Pyle

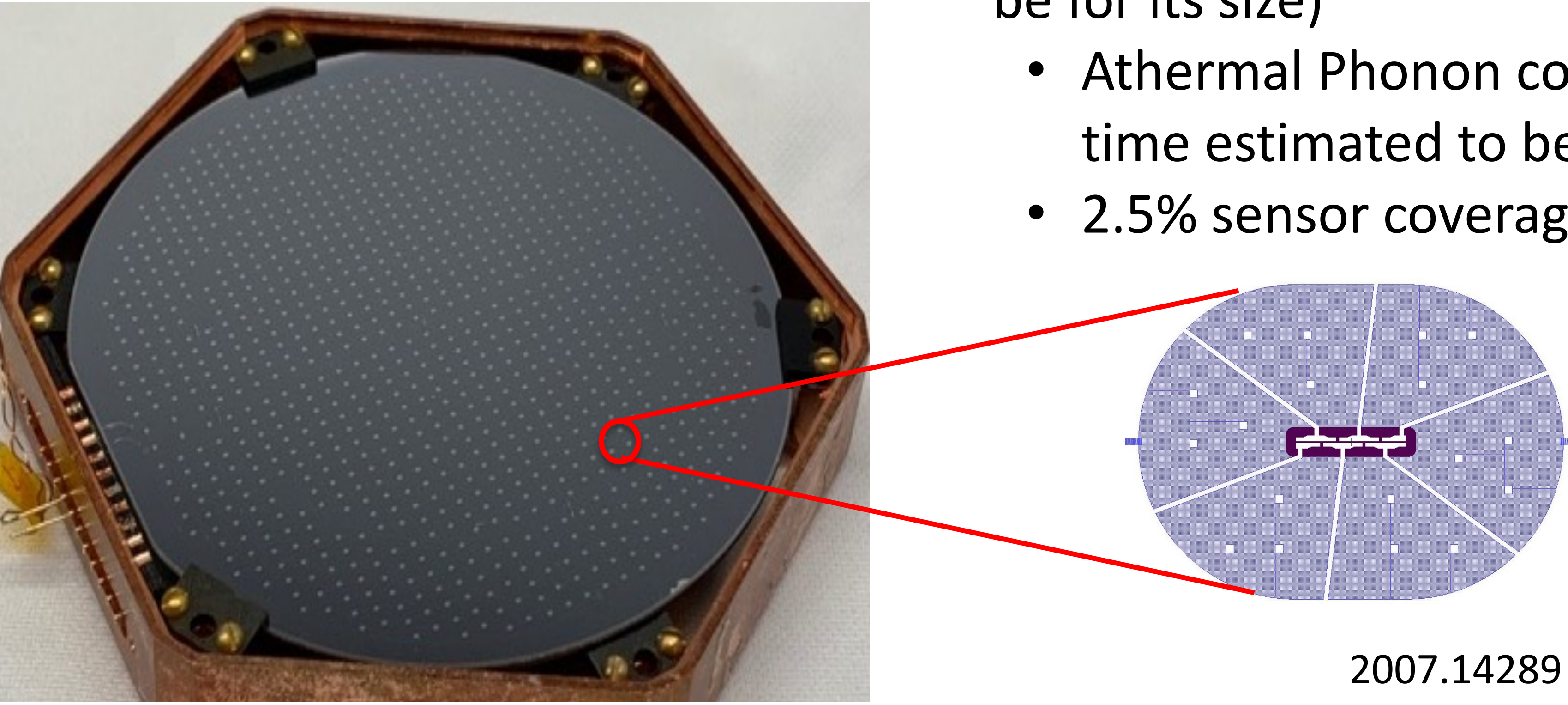
For

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

2007.14289

Cryogenic Photon Detector (CPD)

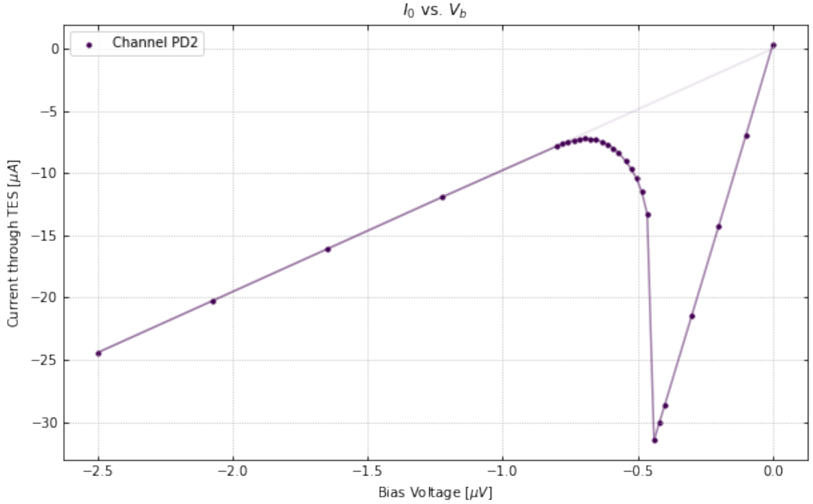
- 3” diameter Si wafer (45.6 cm^2)
- 1mm thick
- Distributed athermal phonon sensors minimize phonon collection time (as fast as it can be for its size)
  - Athermal Phonon collection time estimated to be ~20us
  - 2.5% sensor coverage

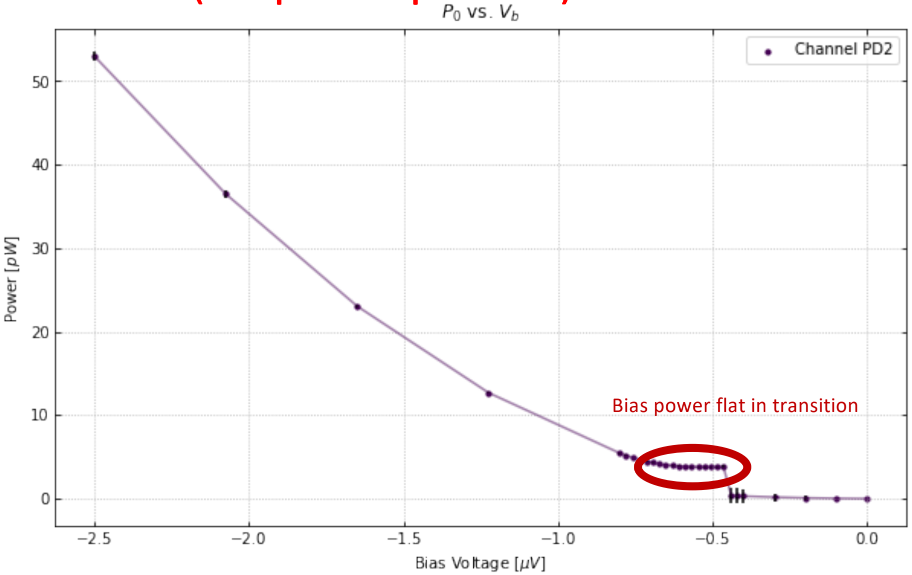


2007.14289

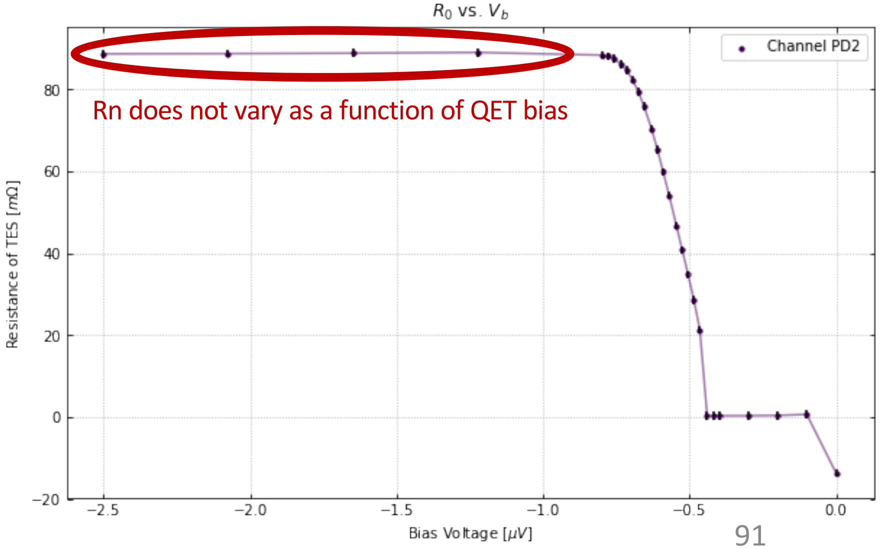
Measured Performance: Tc & IV

- 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)





Bias power flat in transition



Rn does not vary as a function of QET bias

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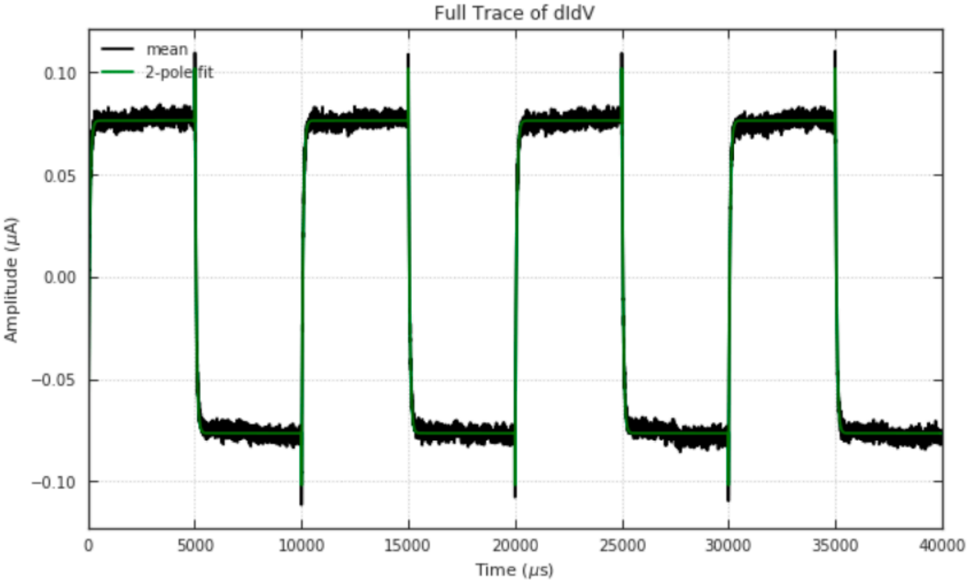
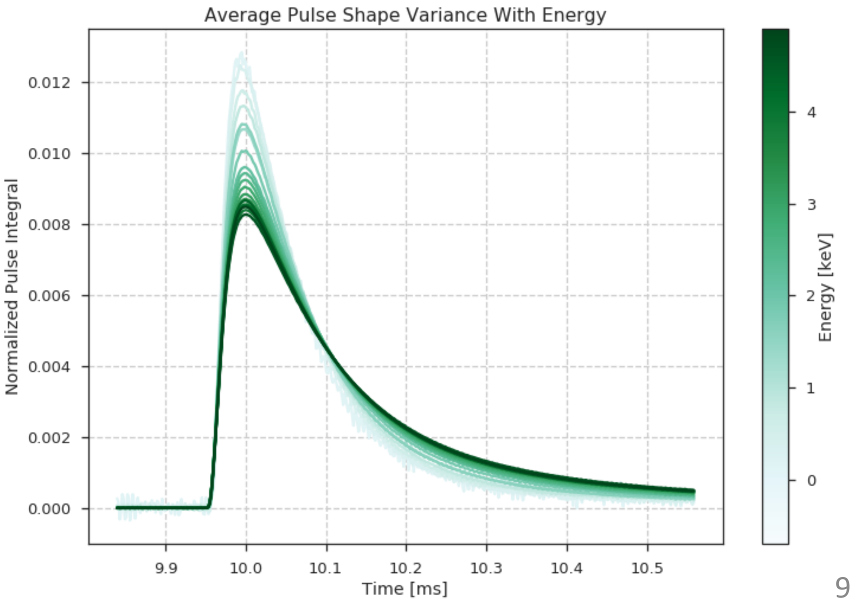
Measured Performance: dIdV



- 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.



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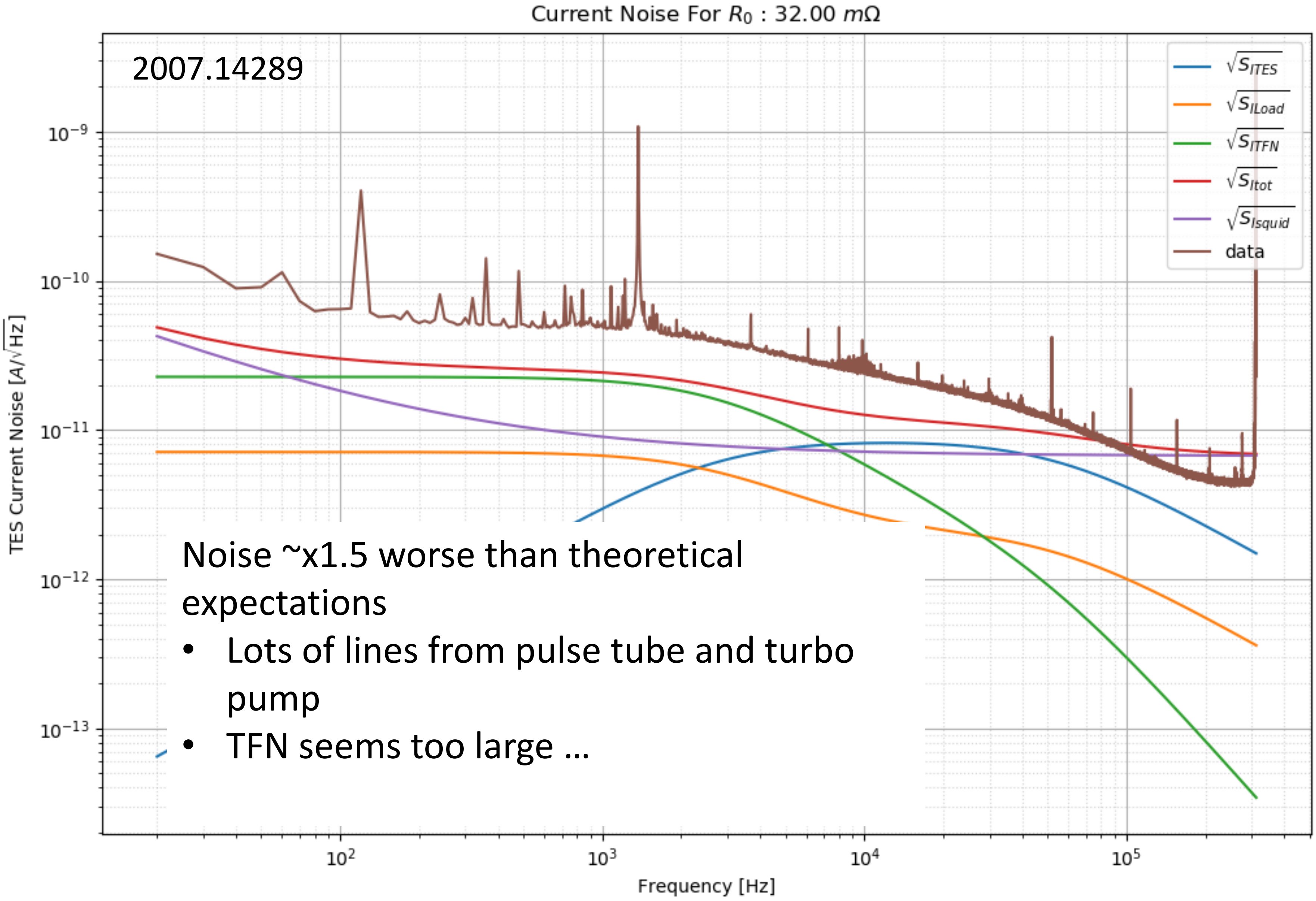
Measured/Theoretical Noise

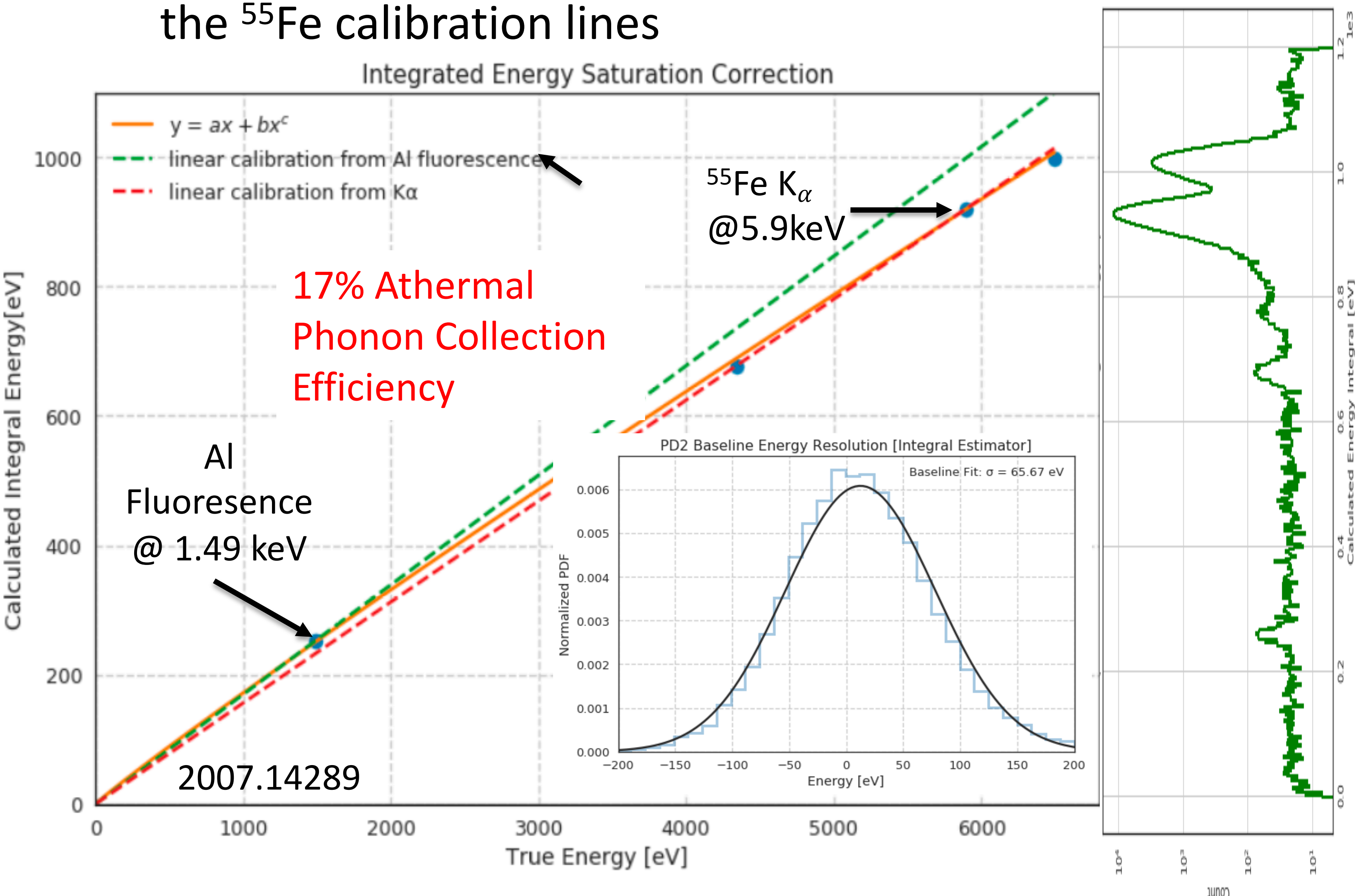


Noise ~x1.5 worse than theoretical expectations

- Lots of lines from pulse tube and turbo pump
- TFN seems too large …

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



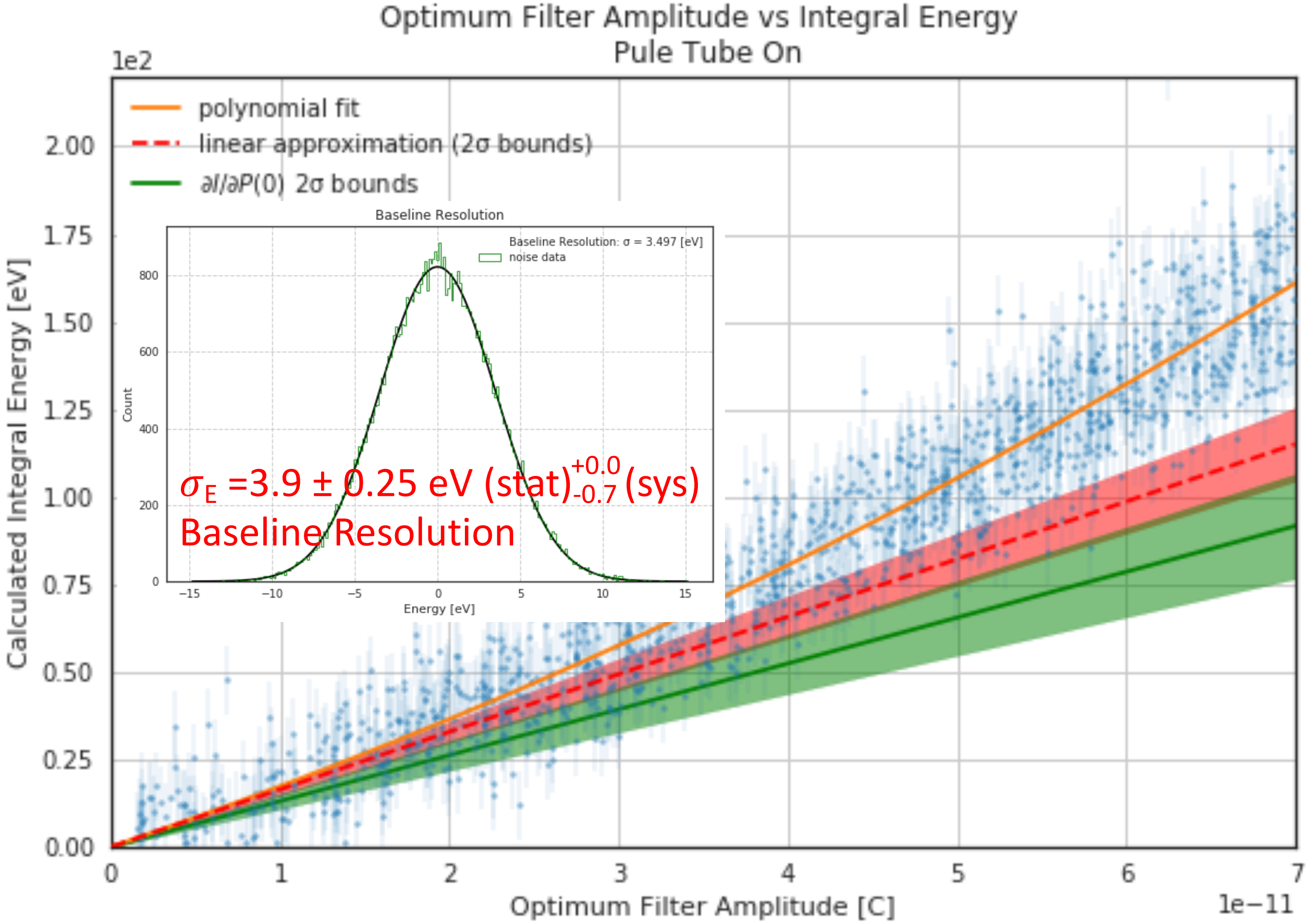
^{55}Fe K_{α}
@5.9keV

17% Athermal Phonon Collection Efficiency

Al
Fluoresence
@ 1.49 keV

2007.14289

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



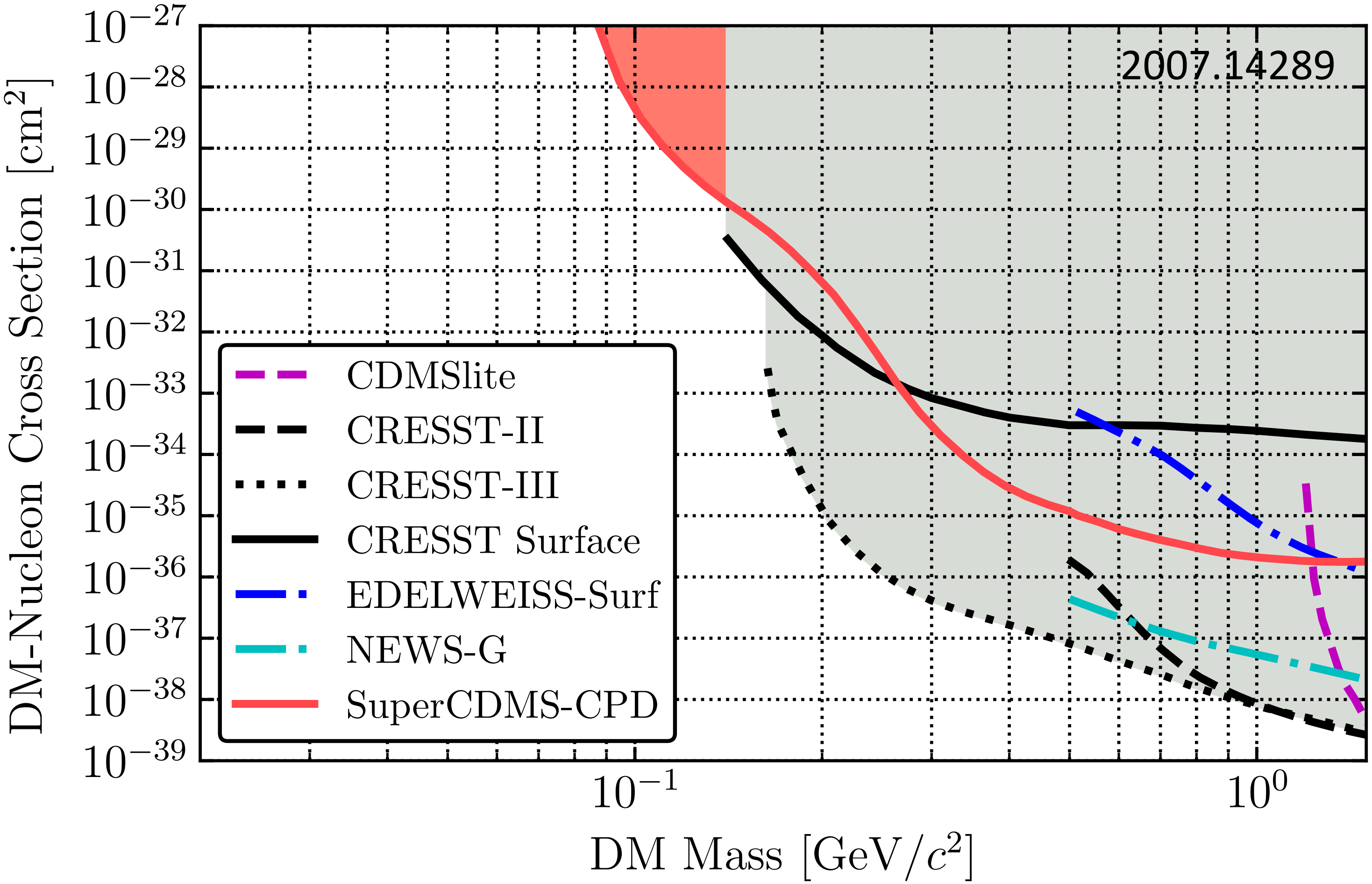
$\sigma_E = 3.9 \pm 0.25$ eV (stat)$^{+0.0}_{-0.7}$(sys)

Baseline Resolution

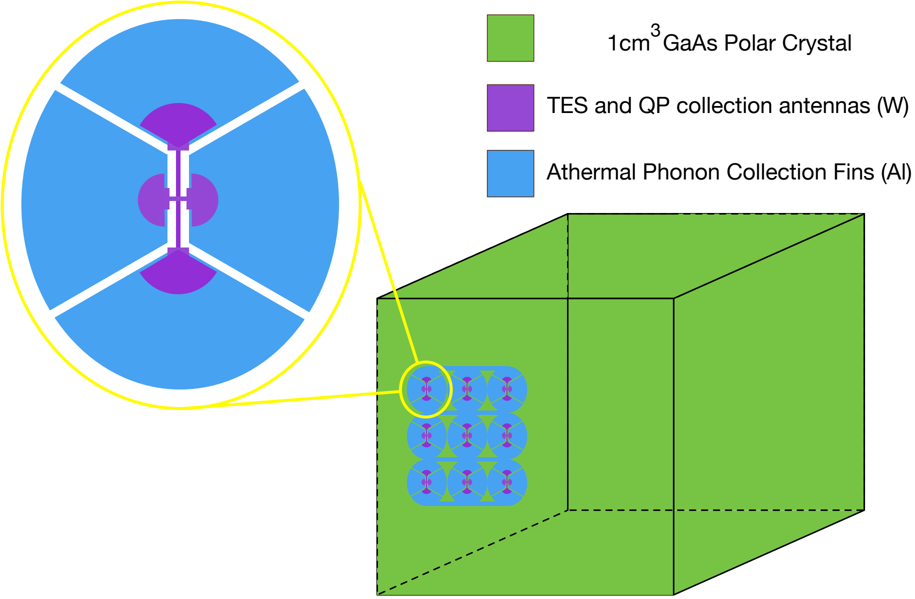
2007.14289

First Dark Matter Search

- In collaboration with SuperCDMS, we ran the CPD detector at the SLAC surface test facility
  - Significantly limited by cosmogenic backgrounds
  - 10gd exposure
- World leading DM sensitivity from 87-140 MeV
- Just the beginning …



Prototype Design Estimated Sensitivities



- 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

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**

Summary:

- Far IR photon detectors, and Athermal Phonon Small Volume detectors are a promising technique to search for 10meV-100meV 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/single phonon sensing
  - Decrease environmental noise
  - Increase TES sensitivity: lower Tc
  - Fabricate on a variety of crystal substrates (SiO_2)
  - Study how phonon surface themalization depends on surface roughness.
  - Improve Collection efficiency: optimize W/Al interface

Backup

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

Matt Pyle

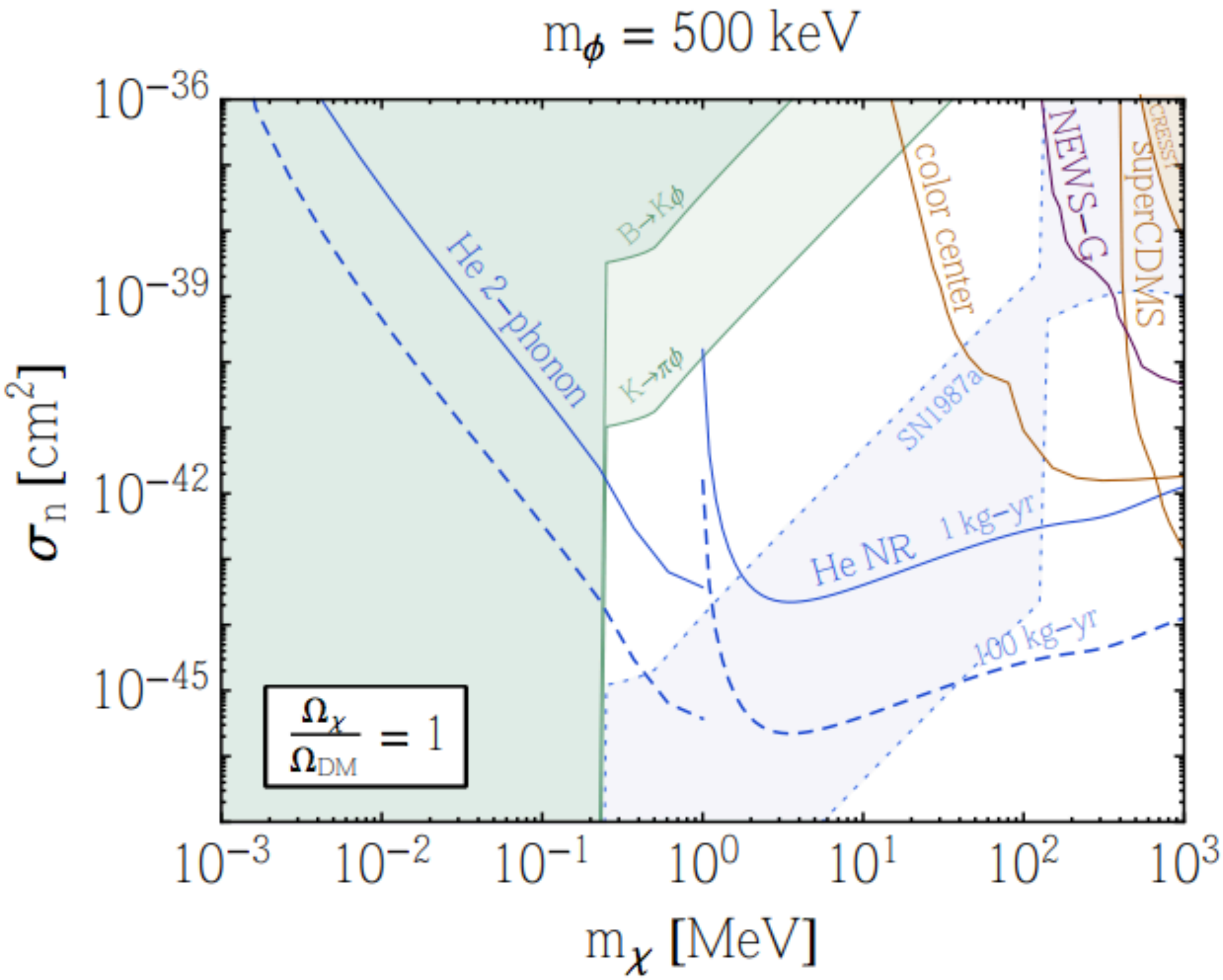
For

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

Other Constraints

Phonon Sensitivity Curves

Heavy Mediator Single Phonon Sensitivity

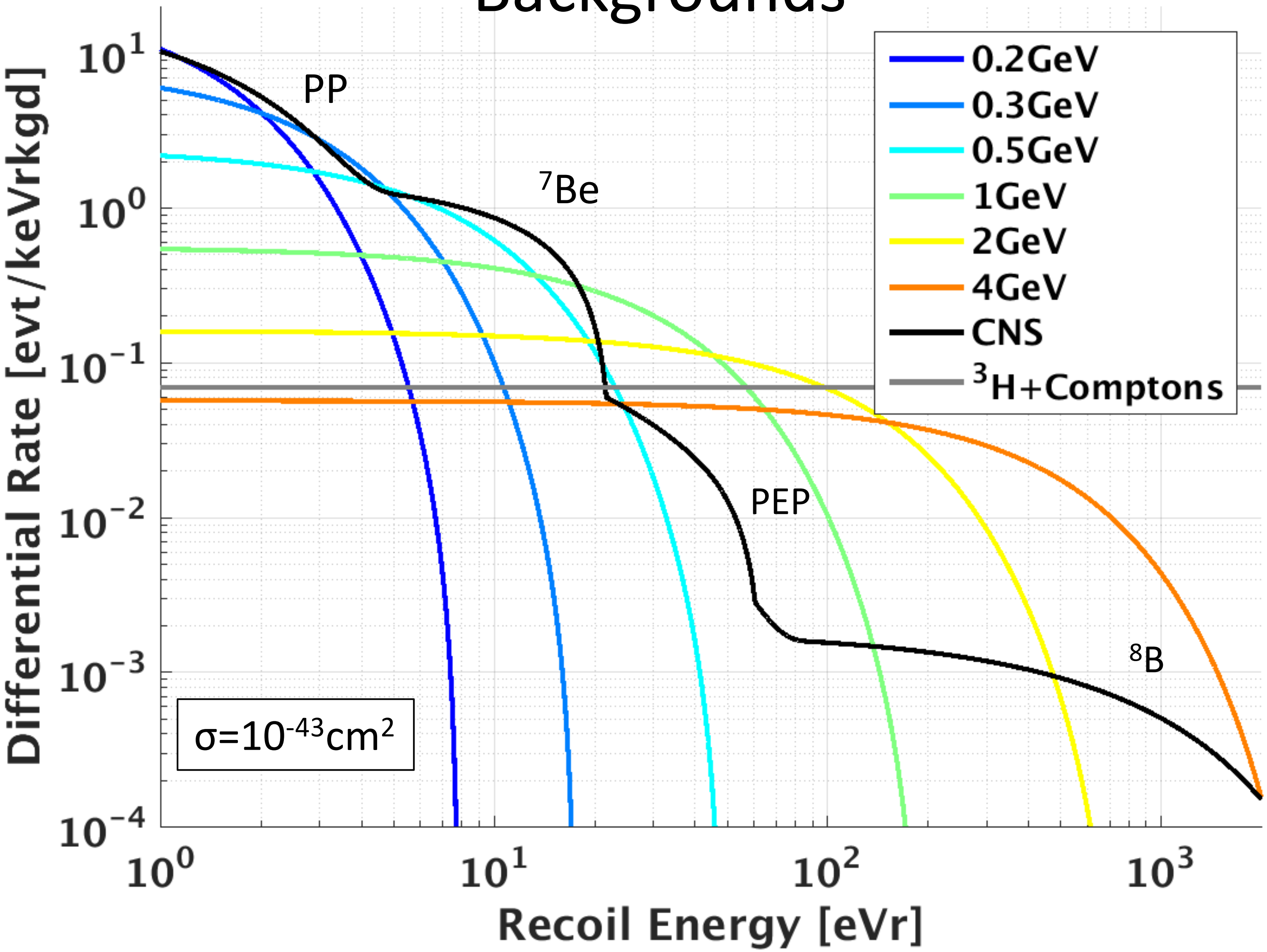


K Zurek et al: 1709.07882

Interaction space pretty constrained by astronomical measurements below 0.1MeV

Backgrounds

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

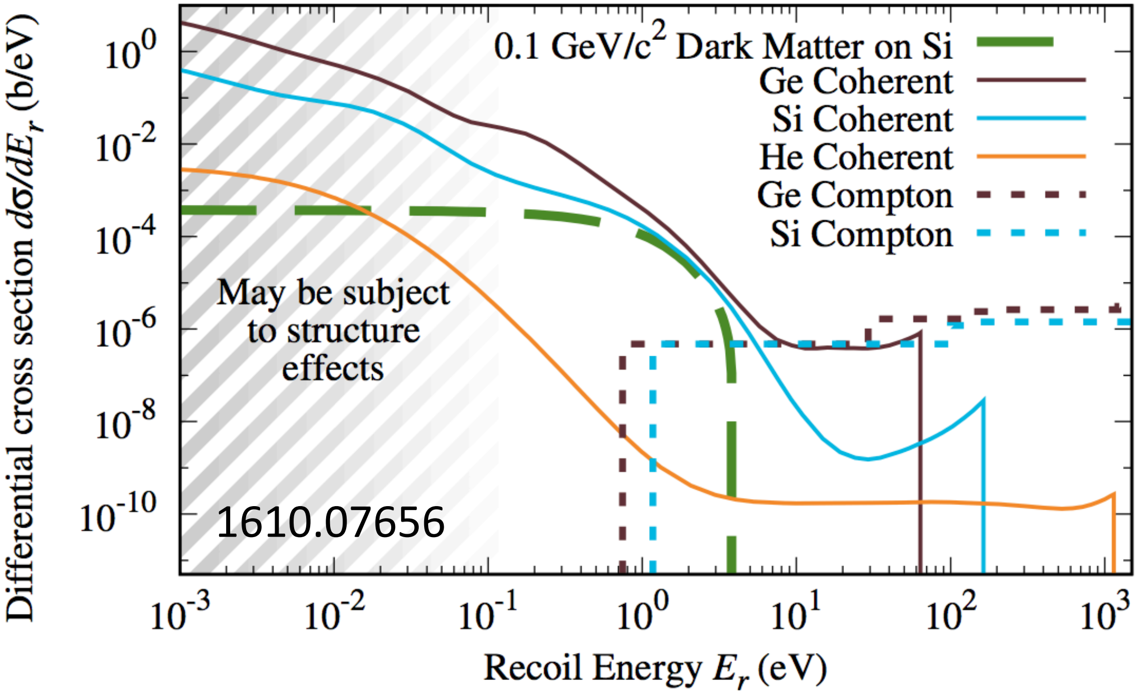


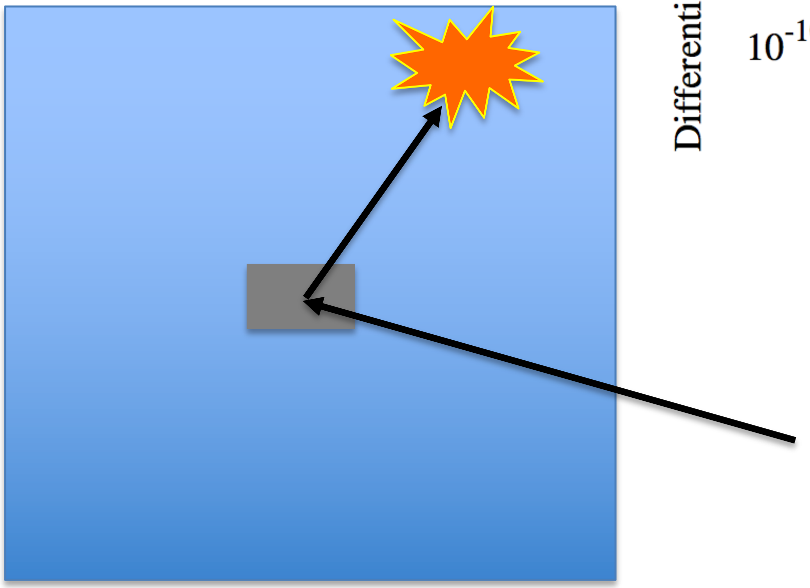
Smaller DM masses have less overlap with flat backgrounds!

Are Backgrounds Really Flat?: Coherent Photon Scattering

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

1461keV Photon from ^{40}K



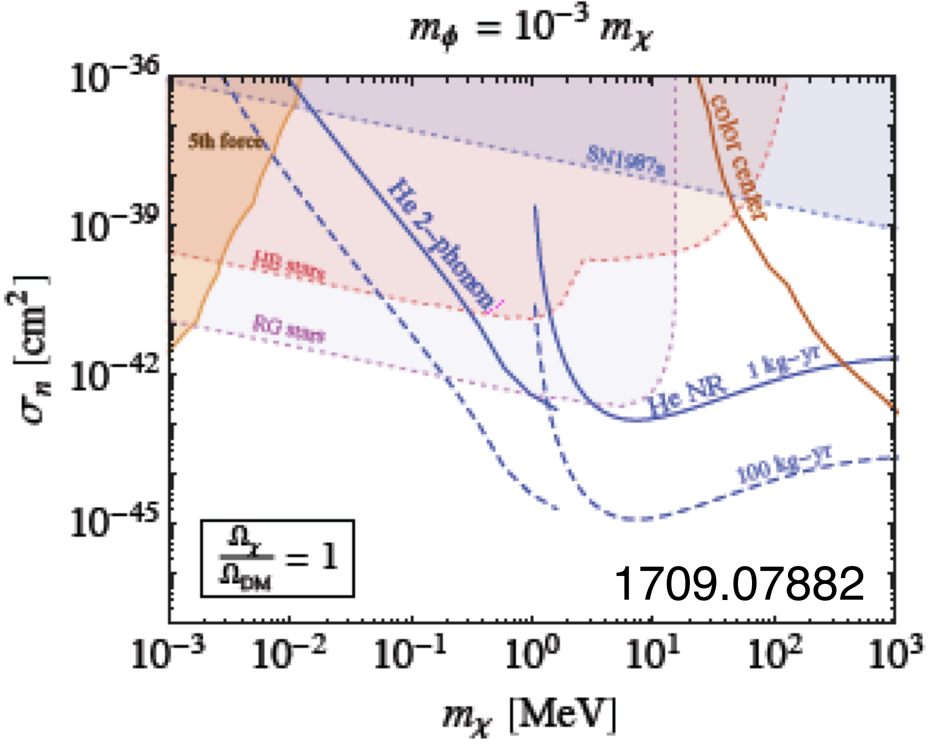


Build a Active Photon Veto

Acoustic Phonon Sensitivity Curves

Work In Progress by Zurek, Knapen, Lin

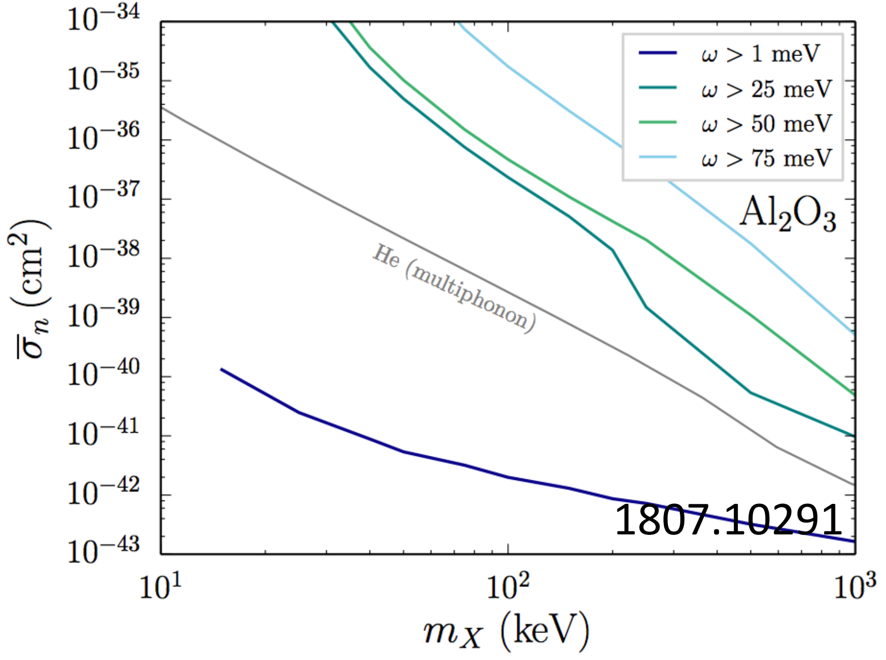
- **Umklapp processes**
- **multiphonon excitations**



1709.07882

- Nominal meV Threshold
- No Backgrounds

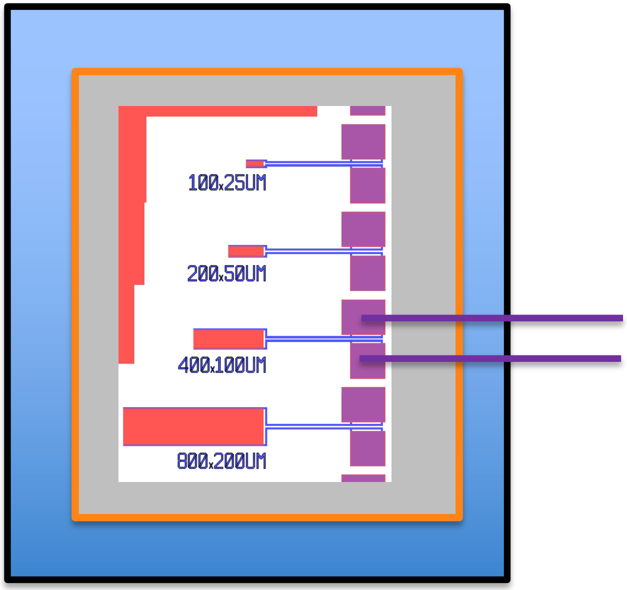
Acoustic Phonons in Sapphire



1807.10291

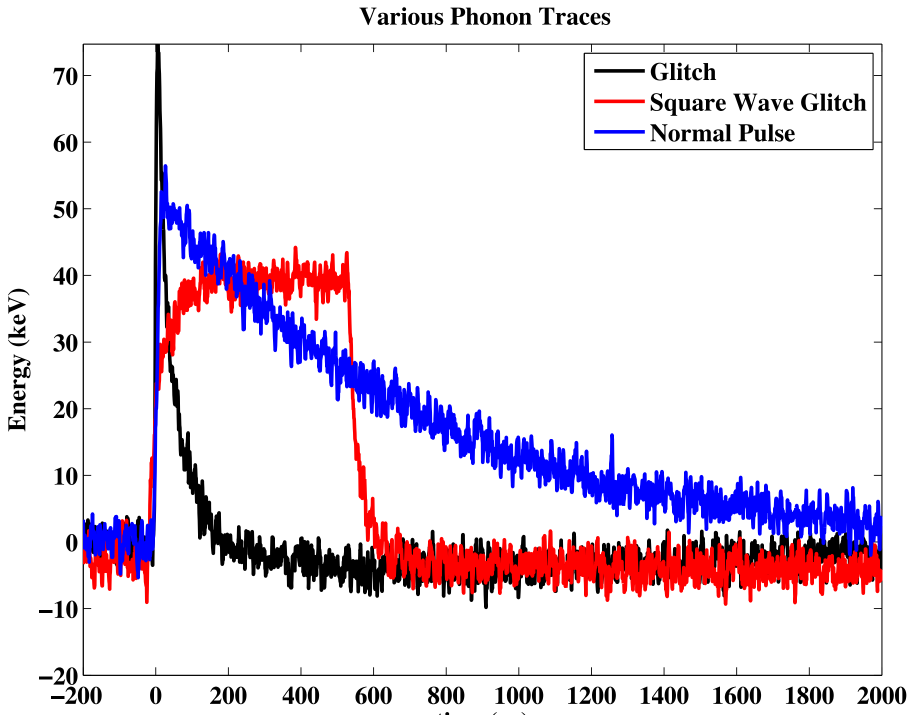
- Various Phonon Energy Thresholds
- 1kgyr
- No Backgrounds

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