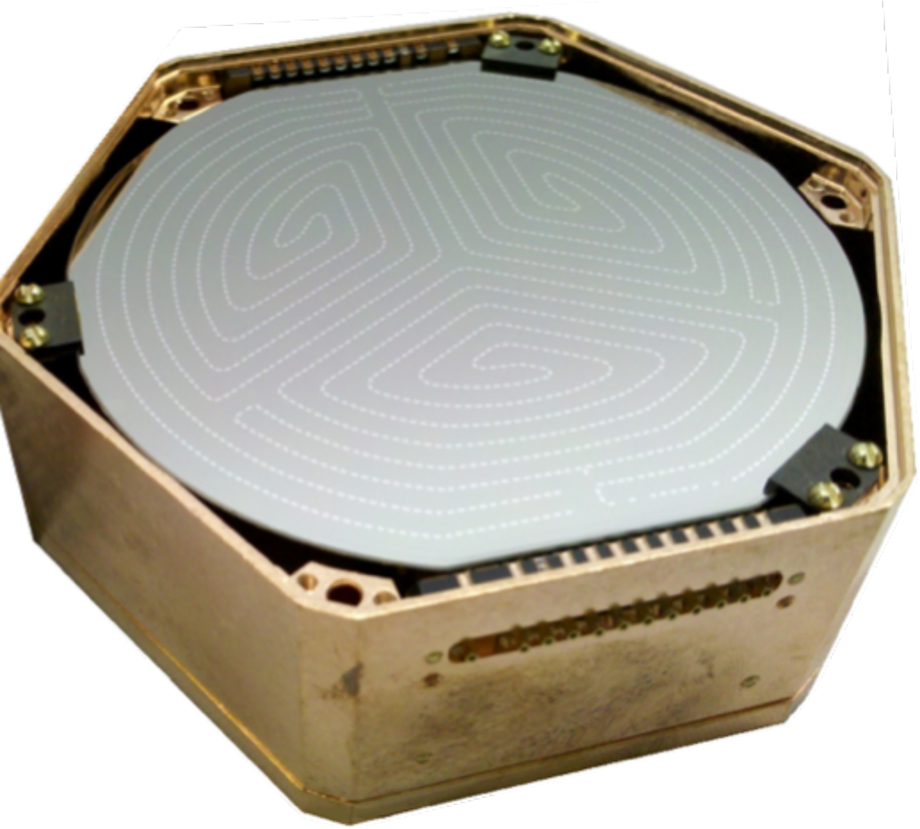
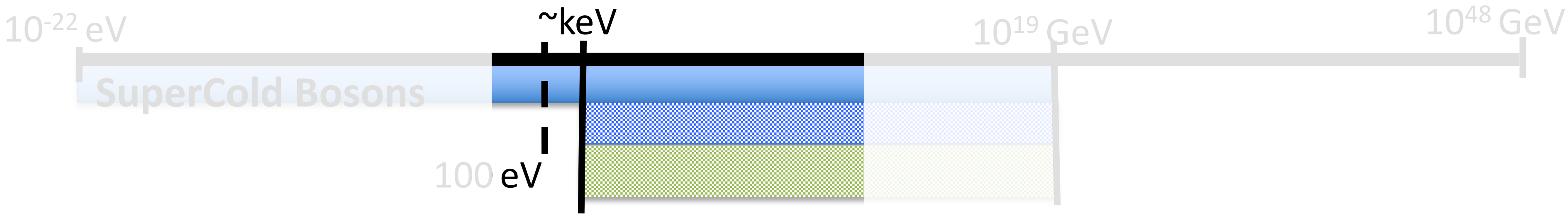
Experimental Techniques to Search for Dark Matter throughout the Range of $10\text{meV} < M_{DM} < 10\text{ GeV}$



Matt Pyle
UC Berkeley
AIT DM School
18/02/18

Design Drivers for 10 meV < M_{DM} < 10 GeV



- Sensitivity to tiny excitations / tiny energy
- Very small dark count rate (Poissonian)
- ~~Exposure:~~ 1 kgyr
- ~~Radioactive~~: 1 evt/kgdkeV

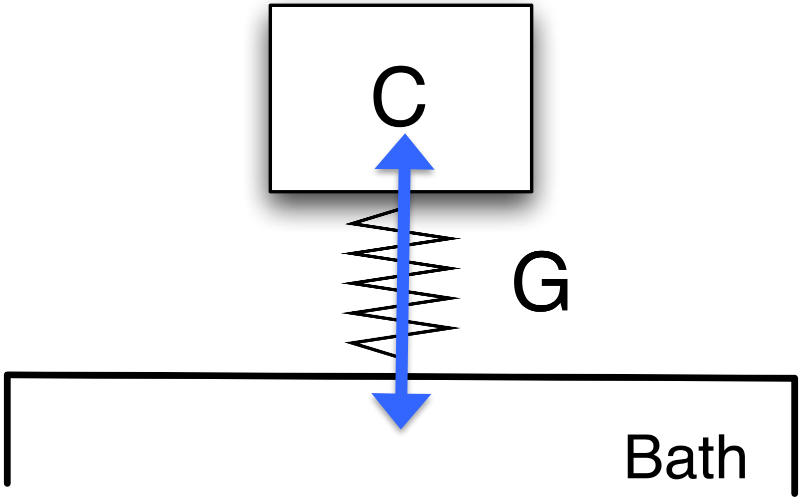
Calorimeter Sensitivity
Detector Physics 101

Calorimeter Sensitivity

$$\sigma^2_{<E>} = \sum_i (E_i - <E>)^2 \frac{e^{-\beta E_i}}{\sum_j e^{-\beta E_j}}$$

$$= \frac{\sum_i E_i^2 e^{-\beta E_i}}{\sum_j e^{-\beta E_j}} - <E>^2$$

$$= -\frac{\partial <E>}{\partial \beta} = \frac{\partial <E>}{\partial T} k_b T^2 = C k_b T^2$$



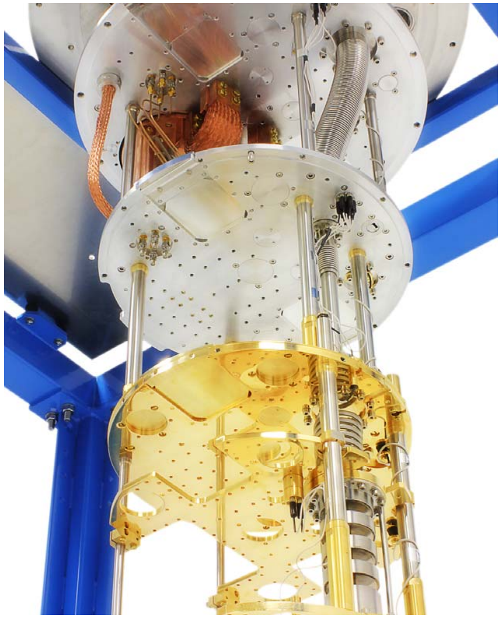
~ Intrinsic Thermal Noise of Calorimeters

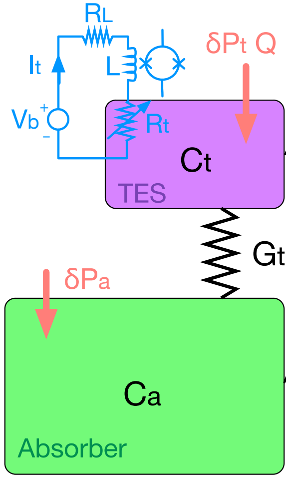
Calorimeter Optimization

$$\sigma^2_{<E>} = C k_b T^2$$

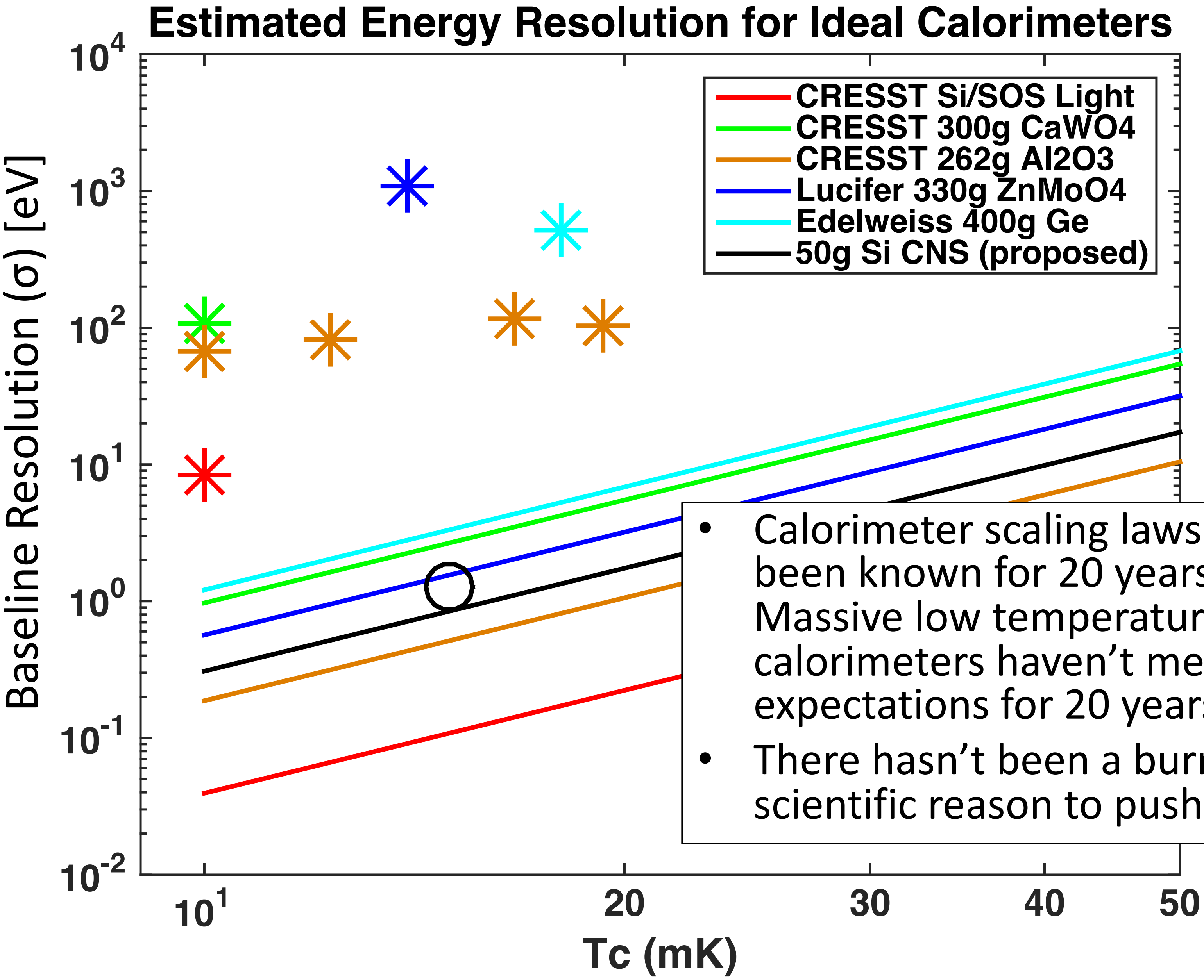
- Minimize T
  - Dilution Refrigerators can cool detectors to 5mK
- Minimize C
  - ~~Small Volume~~
  - Low T
  - Insulators

} Freeze out



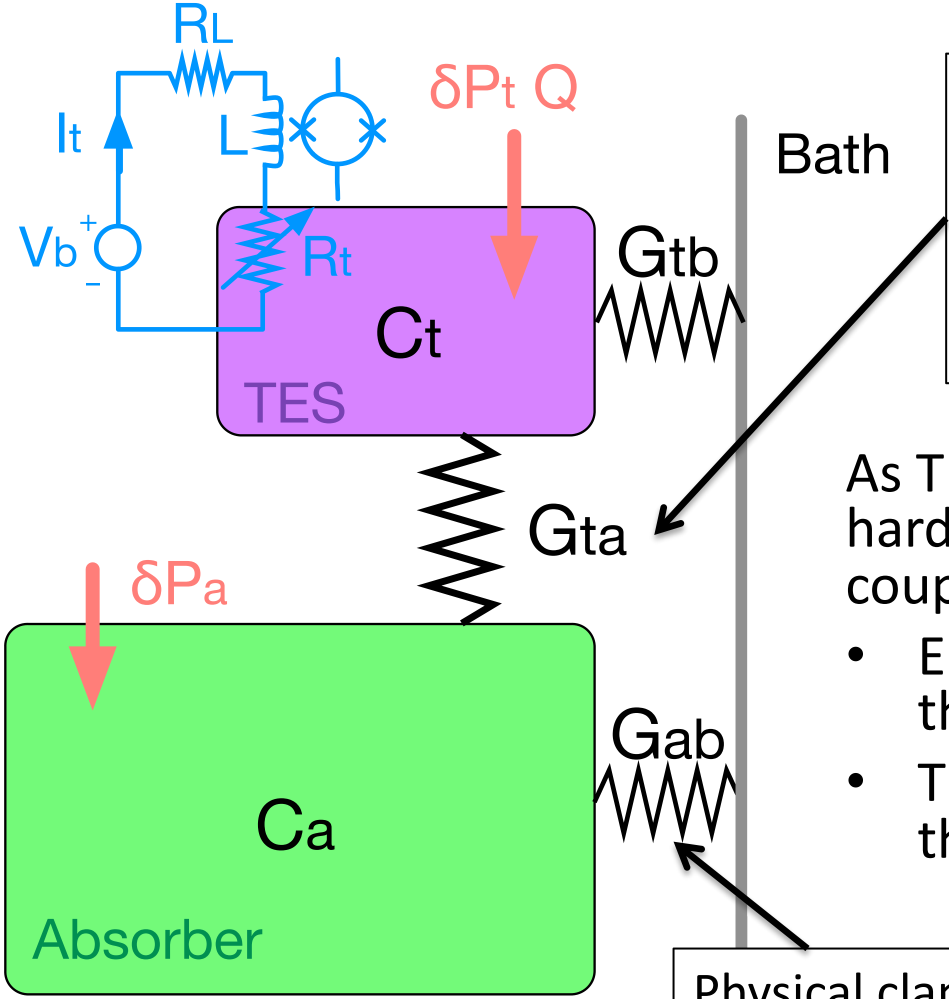


Shouldn’t this be a solved problem?



- Calorimeter scaling laws have been known for 20 years … Massive low temperature calorimeters haven’t met expectations for 20 years
- There hasn’t been a burning scientific reason to push

Engineering Blunder: Decoupling between the Sensor and Absorber



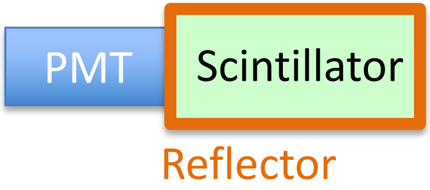
- e^-/phonon thermal conductance scales as T^4
- Kapitza boundary conductance scale as as T^3

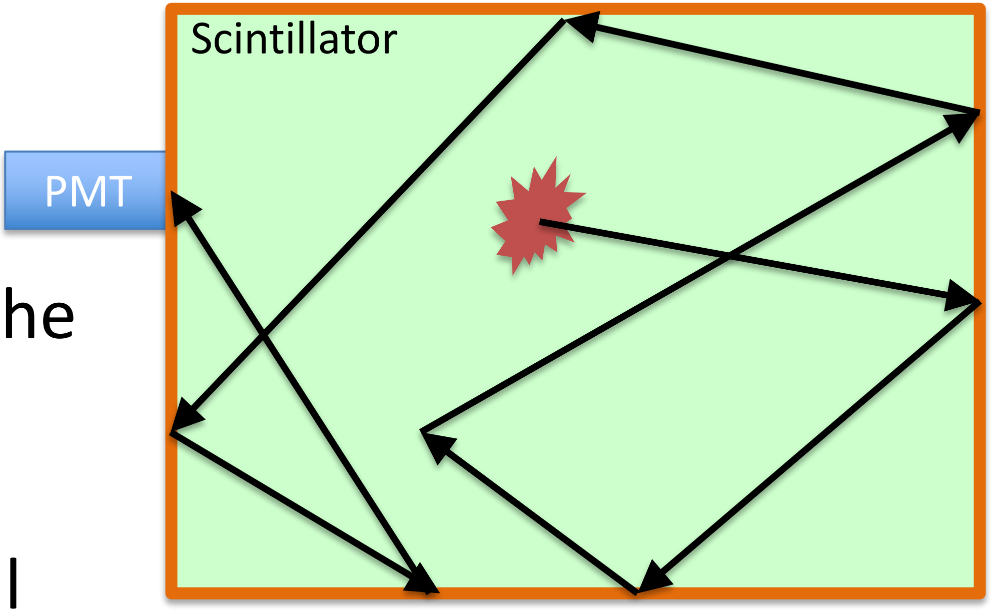
As T is decreased, it's harder and harder to keep the sensor thermally coupled to the absorber

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

Physical clamps that support the absorber

Excitation Detectors & Volume Scaling

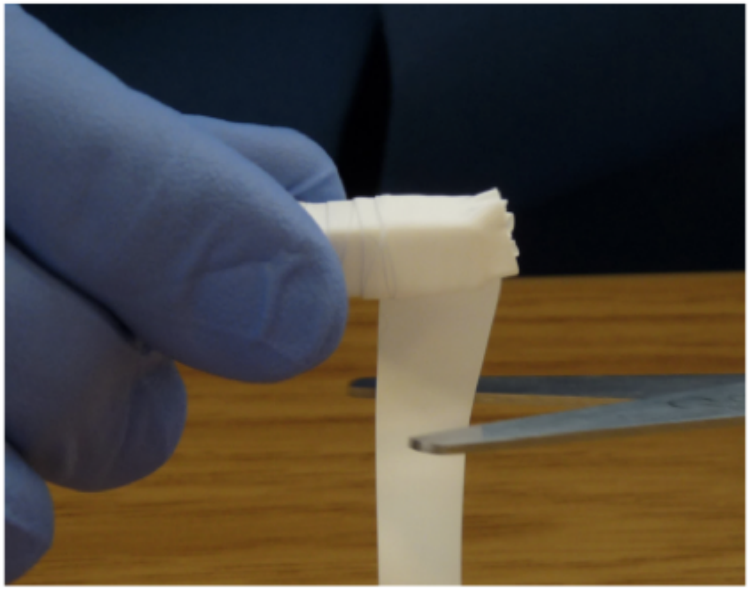




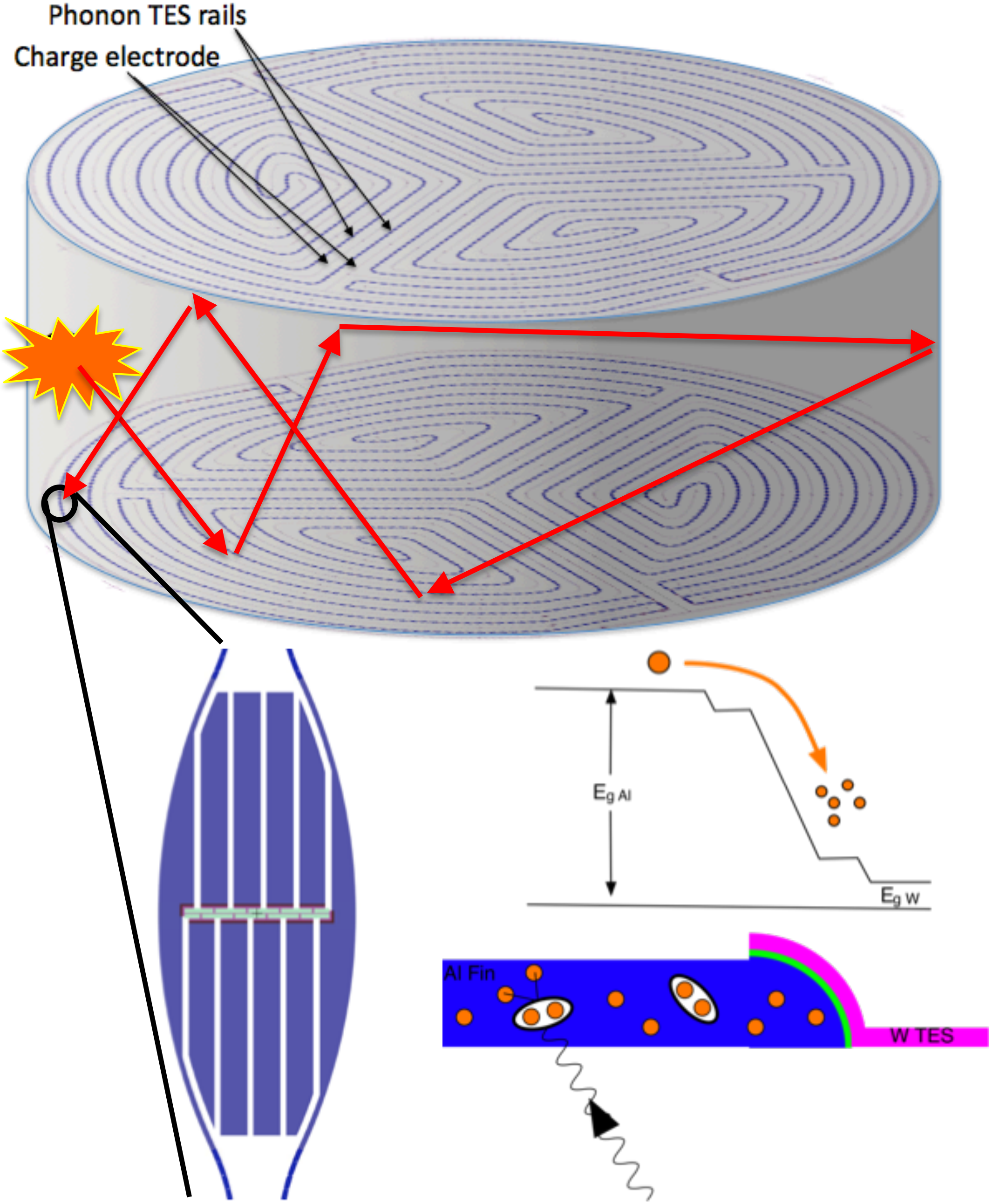
Will these detectors have the same energy sensitivity?

Yes, if:

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

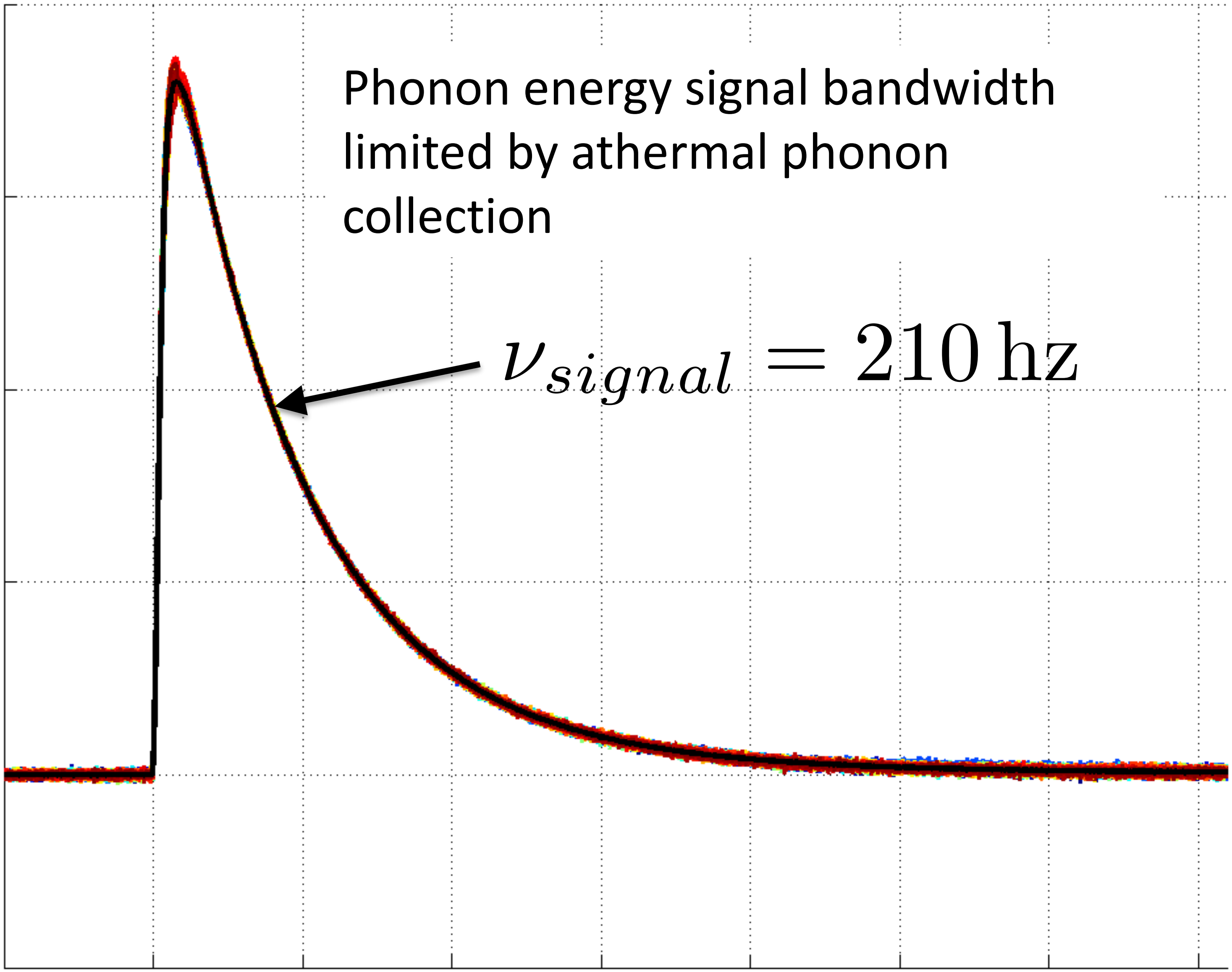


Athermal Phonon Sensors



- Collect and Concentrate Athermal Phonon Energy into small volume W TES
- We’re collecting 4K phonons (e^-phonon coupling still huge)
- Athermal Phonons have very long lifetimes!

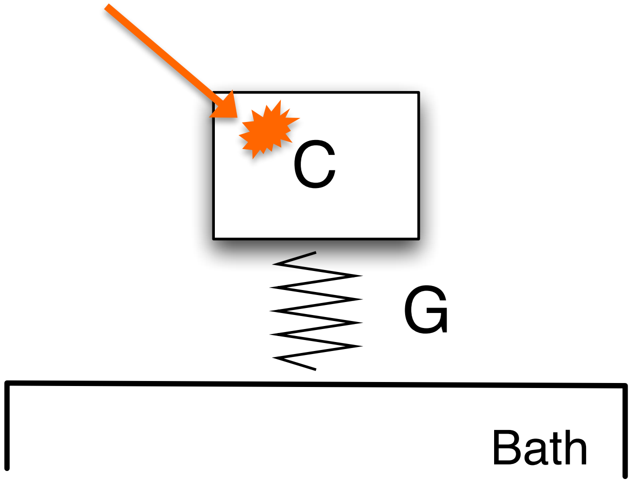
Phonon Signal Bandwidth in SuperCDMS

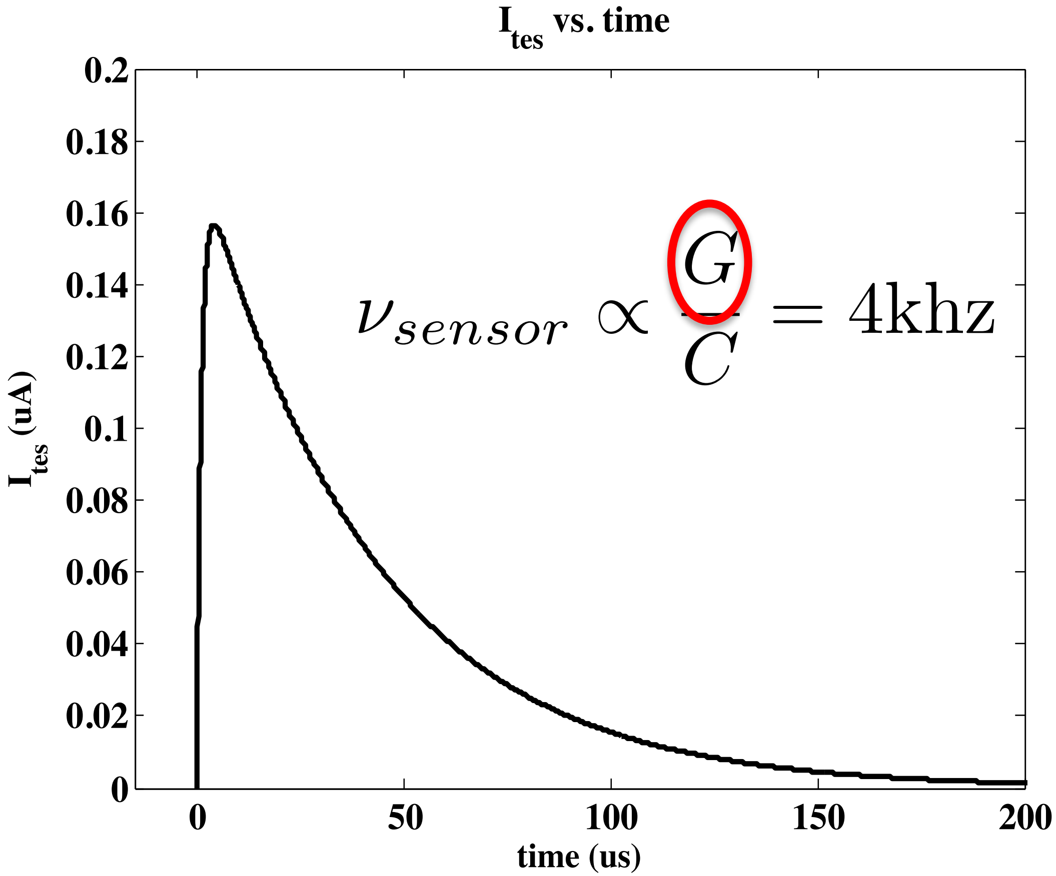


Phonon energy signal bandwidth limited by athermal phonon collection

$$\nu_{signal} = 210\,\mathrm{hz}$$

Transition Edge Sensor: Dynamics

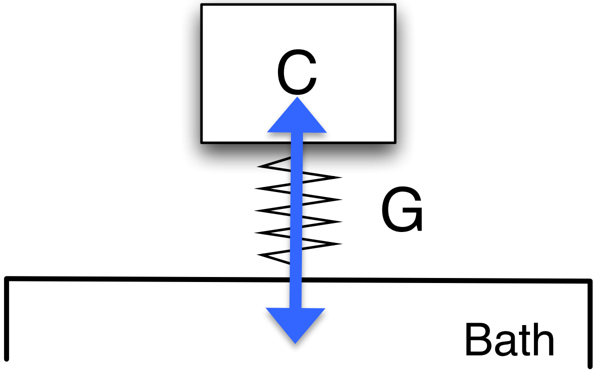




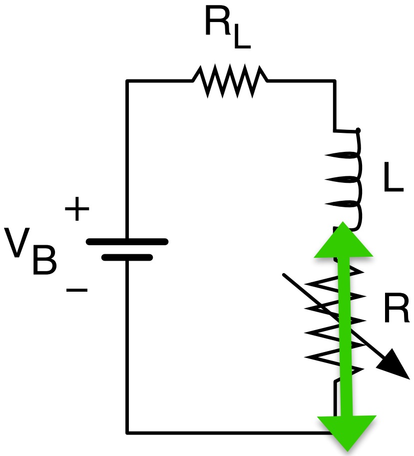
$$\nu_{sensor} \propto \frac{G}{C} = 4\text{khz}$$

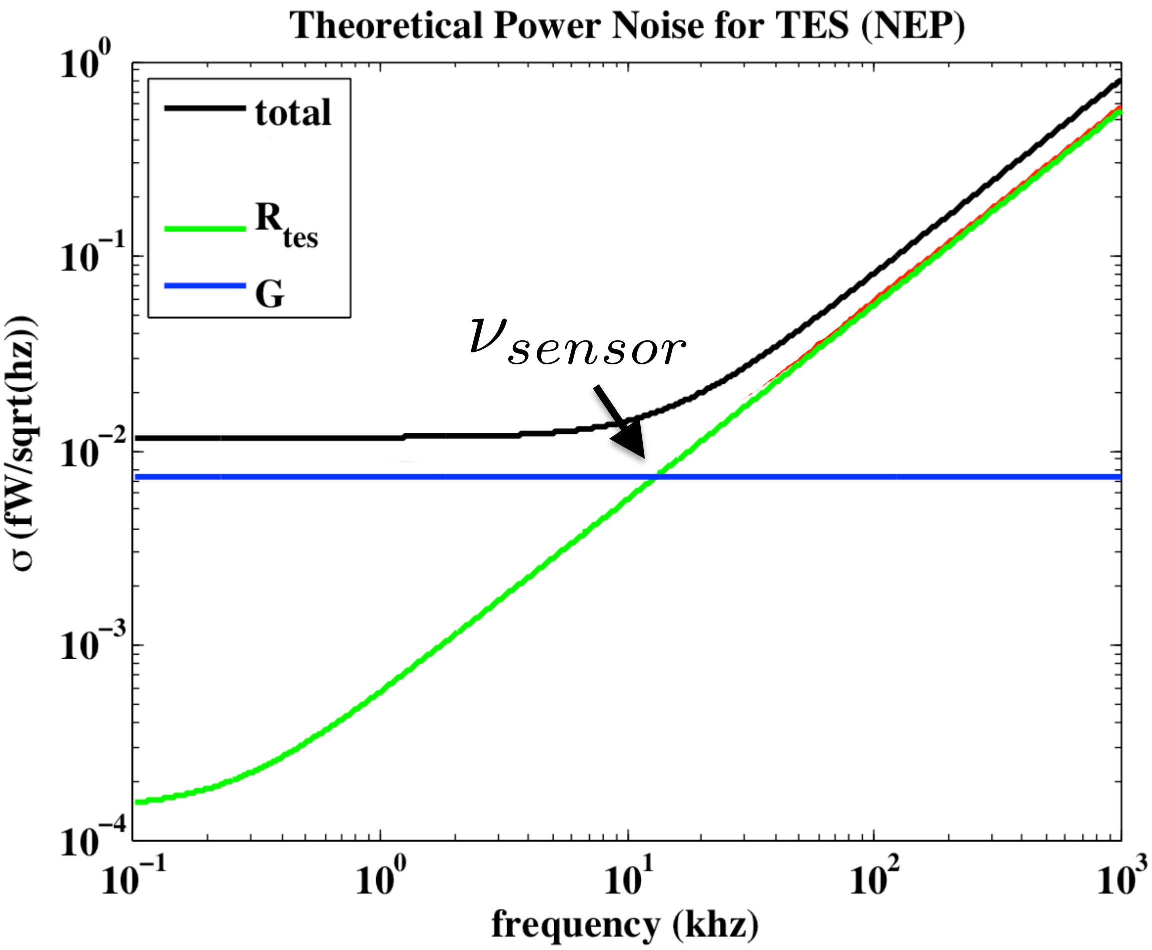
$$\nu_{signal} << \nu_{sensor}$$

Transition Edge Sensor: Noise



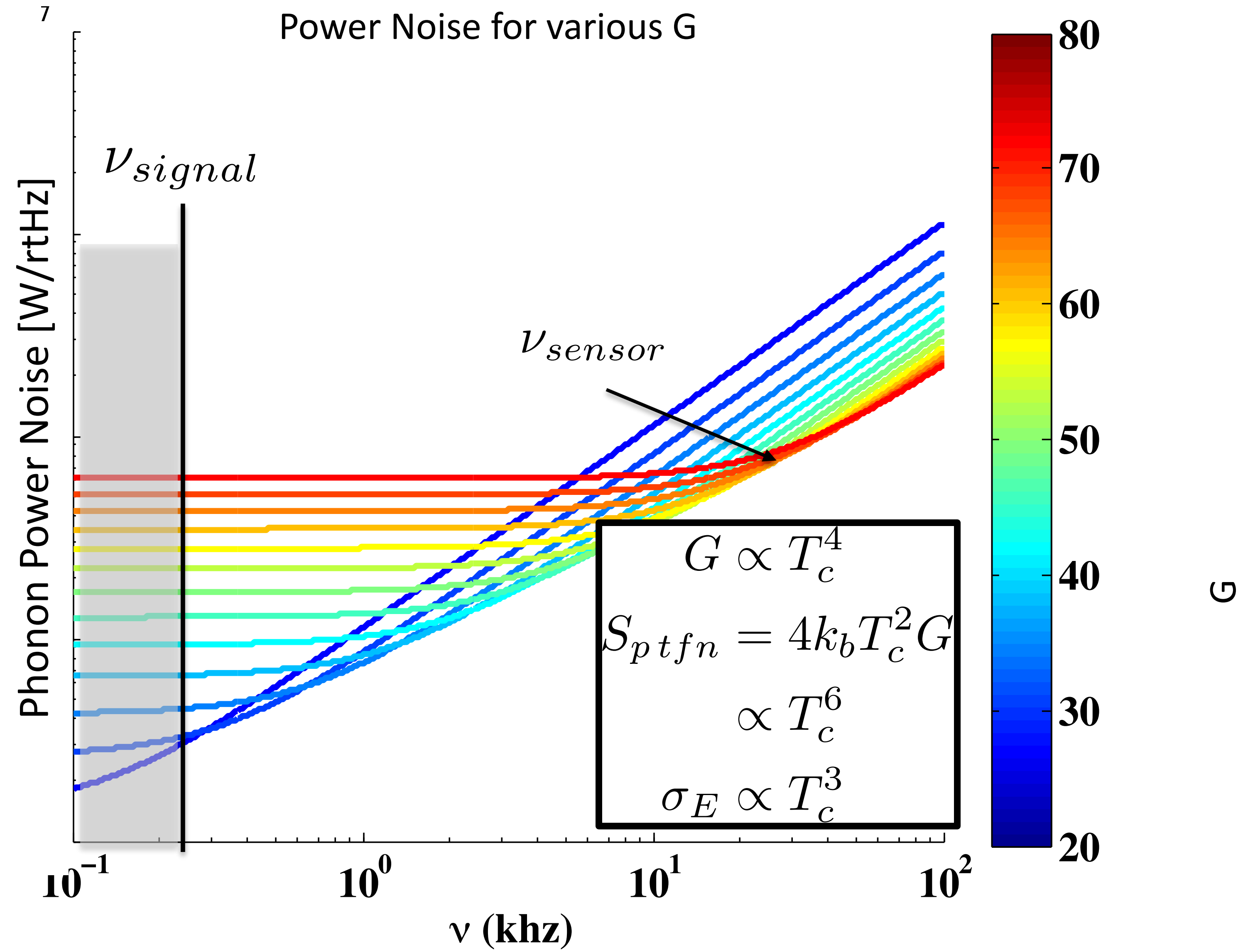
$S_{pG} = 4k_bT^2\mathbf{G}$





DC noise scales with G

Bandwidth Optimization and Tc^3 Sensitivity Scaling



$$G \propto T_c^4$$

$$S_{ptfn} = 4k_b T_c^2 G$$

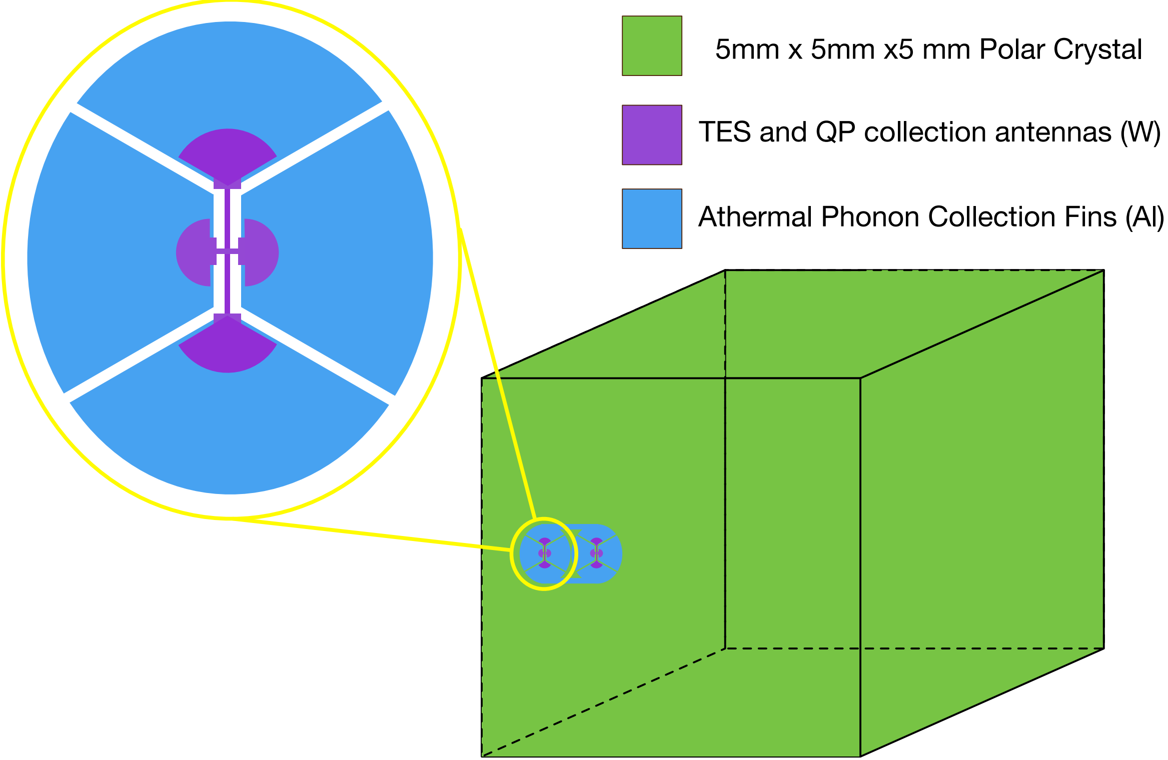
$$\propto T_c^6$$

$$\sigma_E \propto T_c^3$$

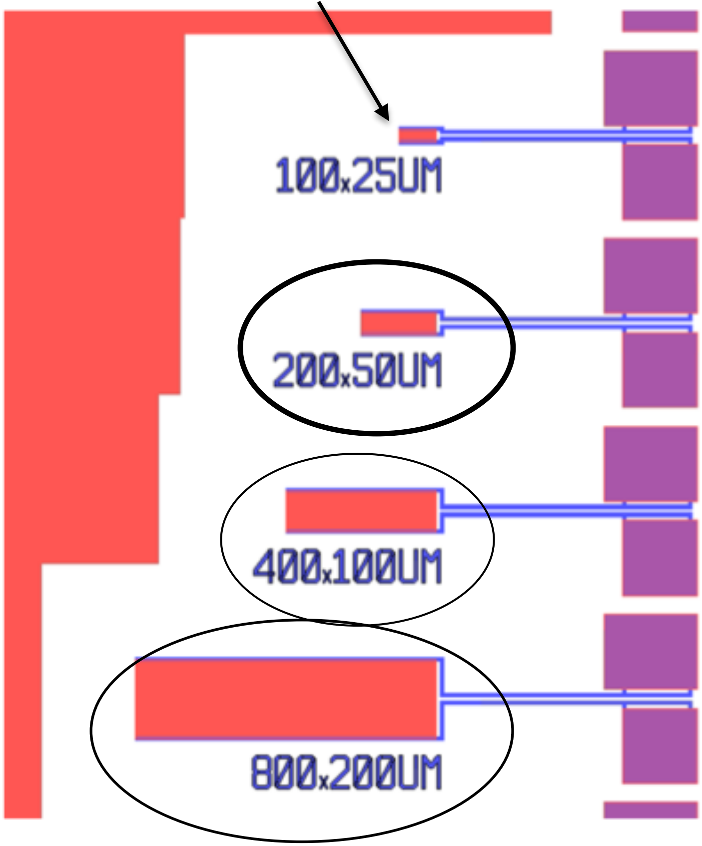
- When $\nu_{sensor} < \nu_{signal}$, Energy Sensitivity scales as Tc^3
- Design Goal: $\nu_{sensor} = \nu_{signal}$

Optical Phonon Sensitive Detector

- SuperCDMS just smaller: 1kg -> 1g
  - Athermal phonons have small probability to thermalize at the crystal surface.
  - Keep fractional sensor coverage at ~1% (more setu)
  - Smaller crystals -> Less phonon sensors



Step 1)Making An Ultra-Sensitive TES

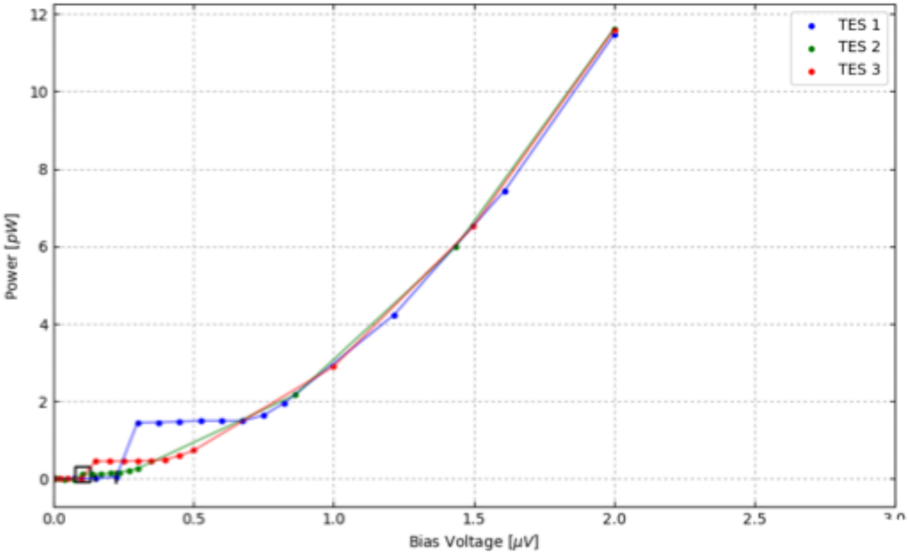


Didn’t run the smallest TES … we were too conservative

- Build and test simple TES test structures for noise is performance
- $\sigma^2_{<E>} = C k_b T^2$
  - small volume TES more sensitive to both DM and environmental backgrounds (RF and vibrations)
- Tc =68mK (a bit high)

50um x200um TES Characterization

TES Power vs TES Bias Voltage

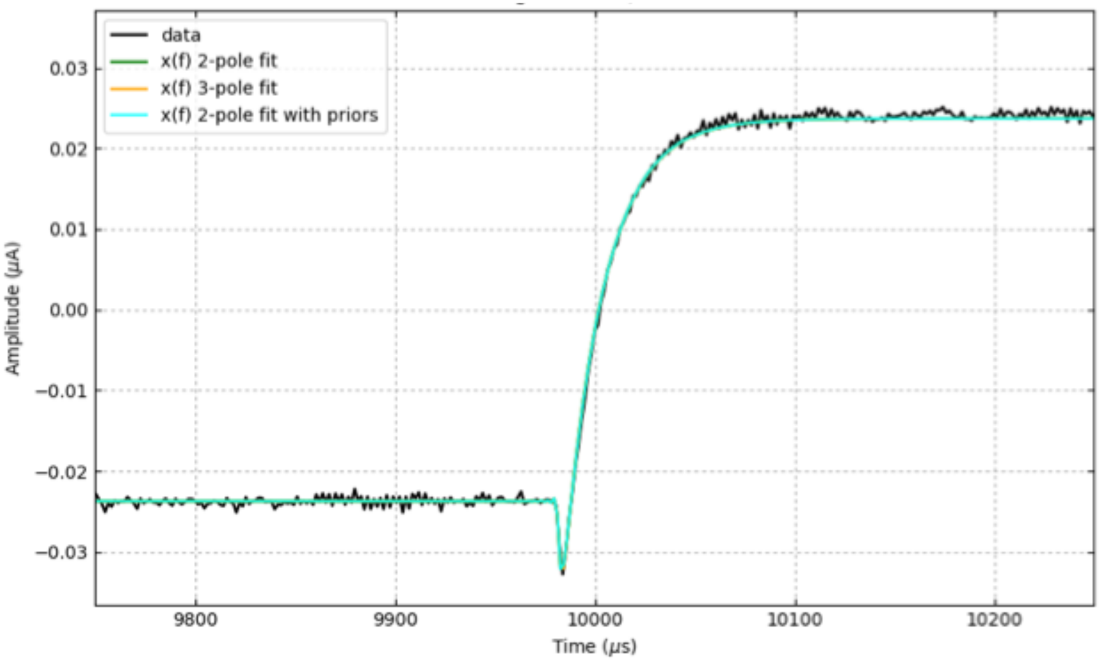


Bias Power: 0.25 pW

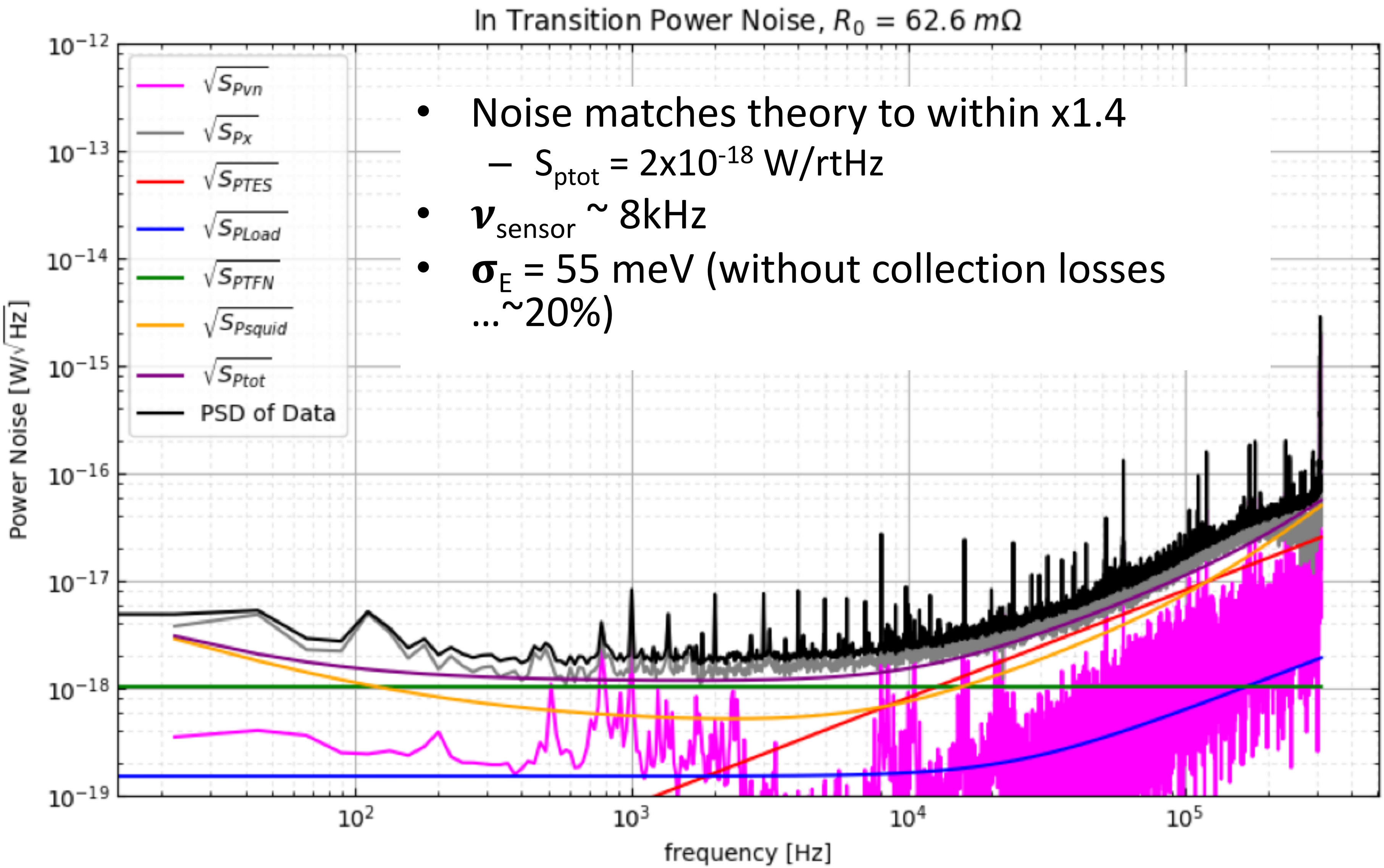
Time Response:

- Simple 2 pole TES dynamical model perfectly fits response
- TES falltime: ~20us (8kHz)
    - we need to slow this down by x10 to match phonon collection bandwidth

TES Response to Square Wave Jitter



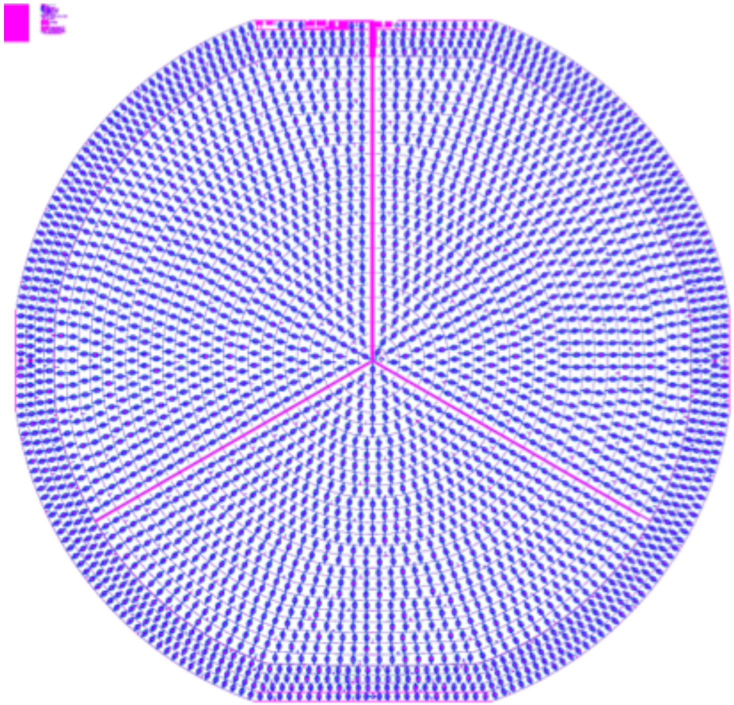
50um x200um TES Noise



- Noise matches theory to within x1.4
  - $S_{ptot} = 2\times10^{-18}$ W/rtHz
- $\boldsymbol{\nu}_{\text{sensor}}$ ~ 8kHz
- $\boldsymbol{\sigma}_E$ = 55 meV (without collection losses …~20%)

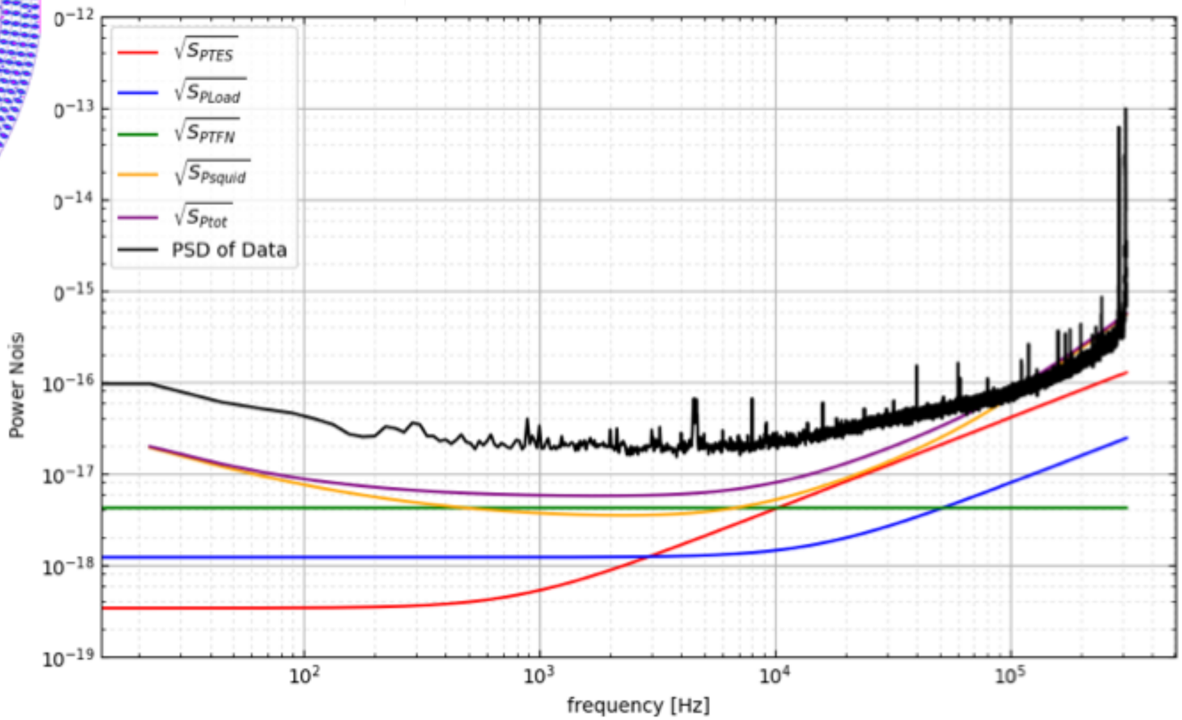
Some Weirdness: SuperCDMS Noise

3” SuperCDMS HV Prototype



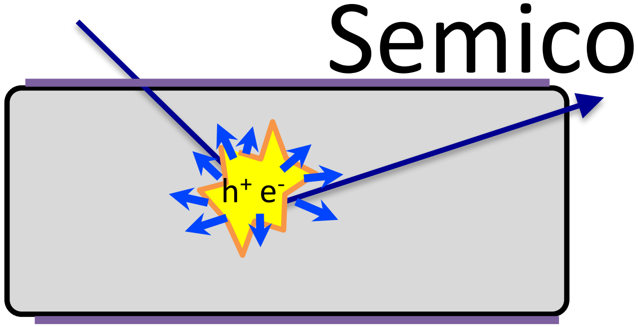
- SuperCDMS 3” HV prototype run in same fridge, same setup as TES test structure
- Noise: 2×10^{-17}W/rtHz

3” Phonon Noise PSD



Luke-Neganov Charge Amplification

Interaction Products in Semiconductors

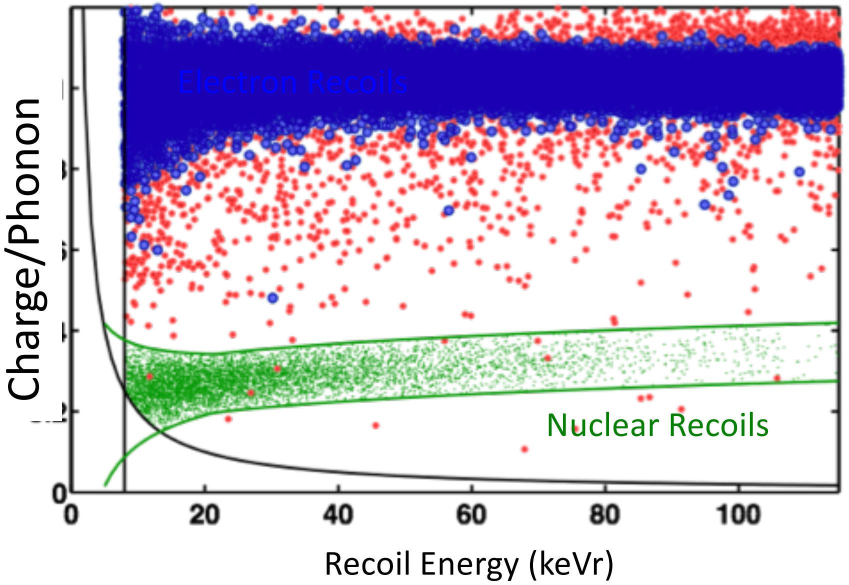


Nuclear Recoils (NR)

- 8% e^-/h^+
- 92% phonons

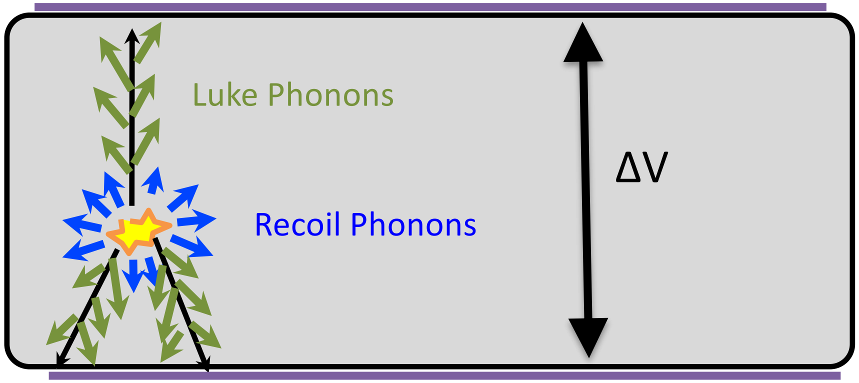
Electron Recoils (ER)

- 25% e^-/h^+
- 75% phonons

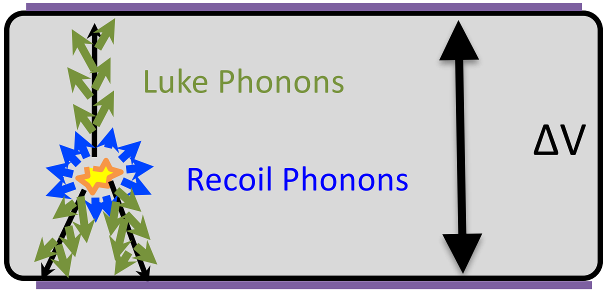


Luke-Neganov Phonon Production In Recoils

- Drifting charges release kinetic energy via Luke-Neganov Phonon Production
- $$\begin{aligned} E_{total} &= E_{recoil} + E_{luke} \\ &= E_{recoil} + Qe\Delta V \end{aligned}$$



Luke-Neganov Ionization Amplifier

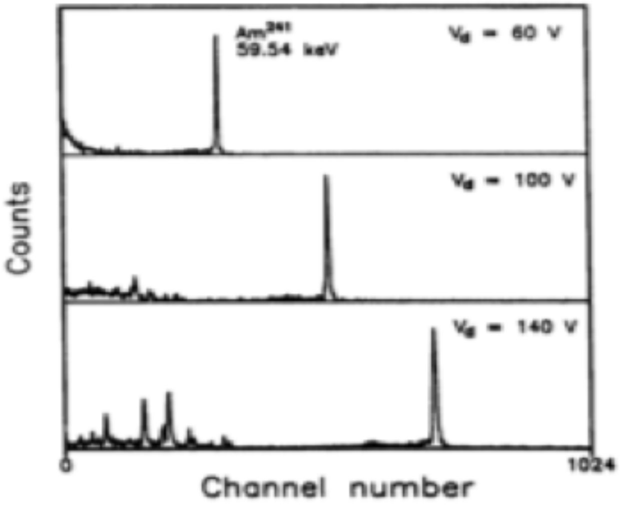


$$\begin{aligned} E_{total} &= E_{recoil} + E_{luke} \\ &= E_{recoil} + Qe\Delta V \end{aligned}$$

$$\lim_{\Delta V \to \infty} E_{total} \propto Q$$

At high voltage

- Bad: No ER/NR discrimination through Ionization Yield
- Good: You've made a phonon amplifier for charge

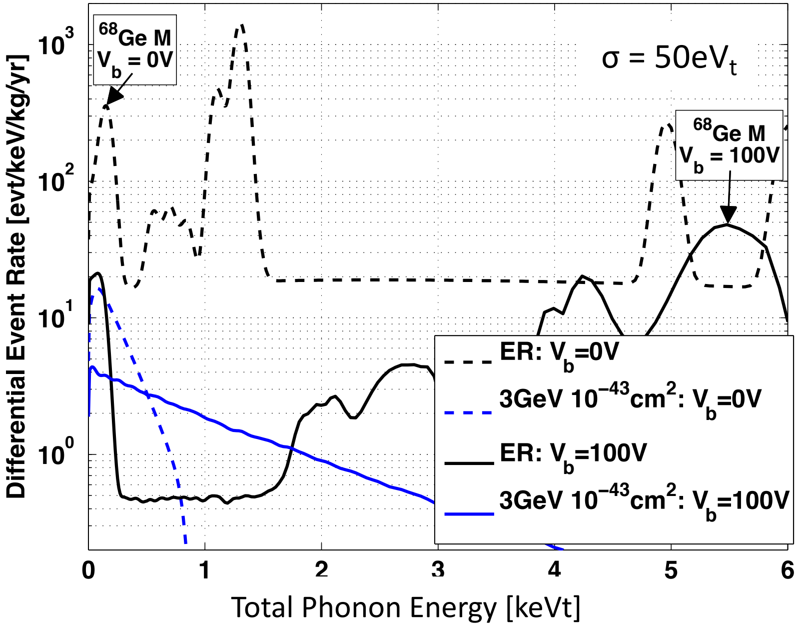


P.N. Luke et al. NIM A289, 405 (1990)

Preferential Stretching of Electronic Recoils

$$
\begin{aligned}
E_{total} &= E_{recoil} + E_{luke} \\
&= E_{recoil} + Qe\Delta V \\
&= E_{recoil}\left(1 + \frac{Ye\Delta V}{< E_{eh} >}\right)
\end{aligned}
$$

Since Electronic Recoils (ER) have larger Ionization Yields than Nuclear Recoils (NR), they have larger Luke Neganov Gain

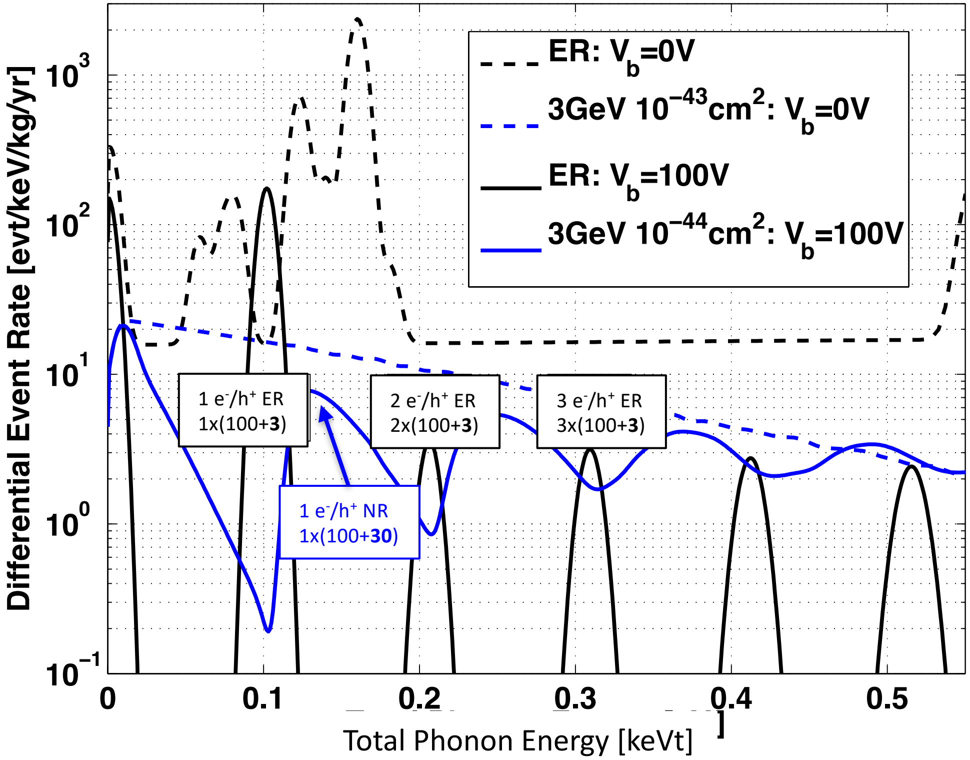


If you have phonon sensitivity to spare, this is great!

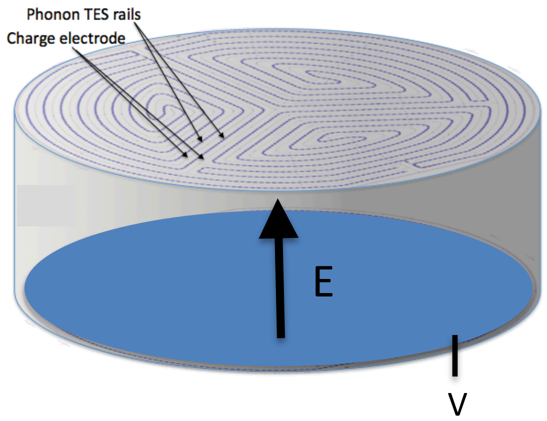
ER/NR Stretching: The Single e^-/h^+ Limit

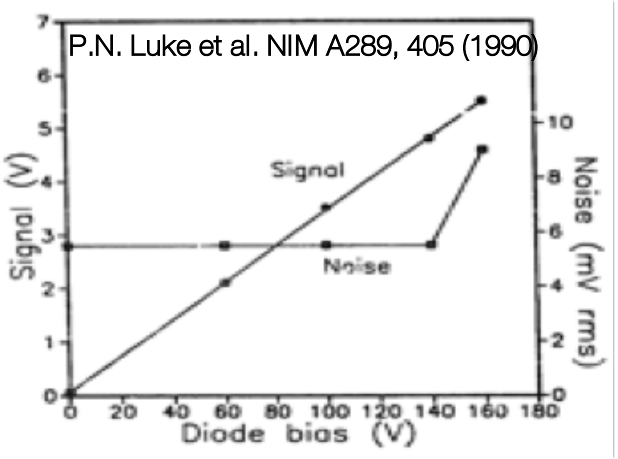
- $\sigma = 5eV_t$
- Single e^-/h^+ Sensitivity
- ER/NR Discrimination

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



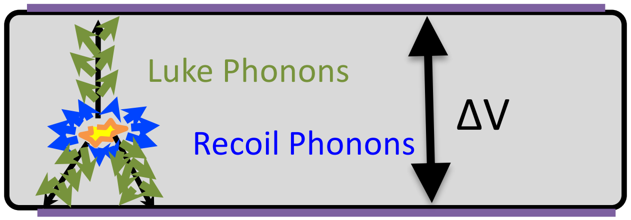
Problem #1: Charge Breakdown



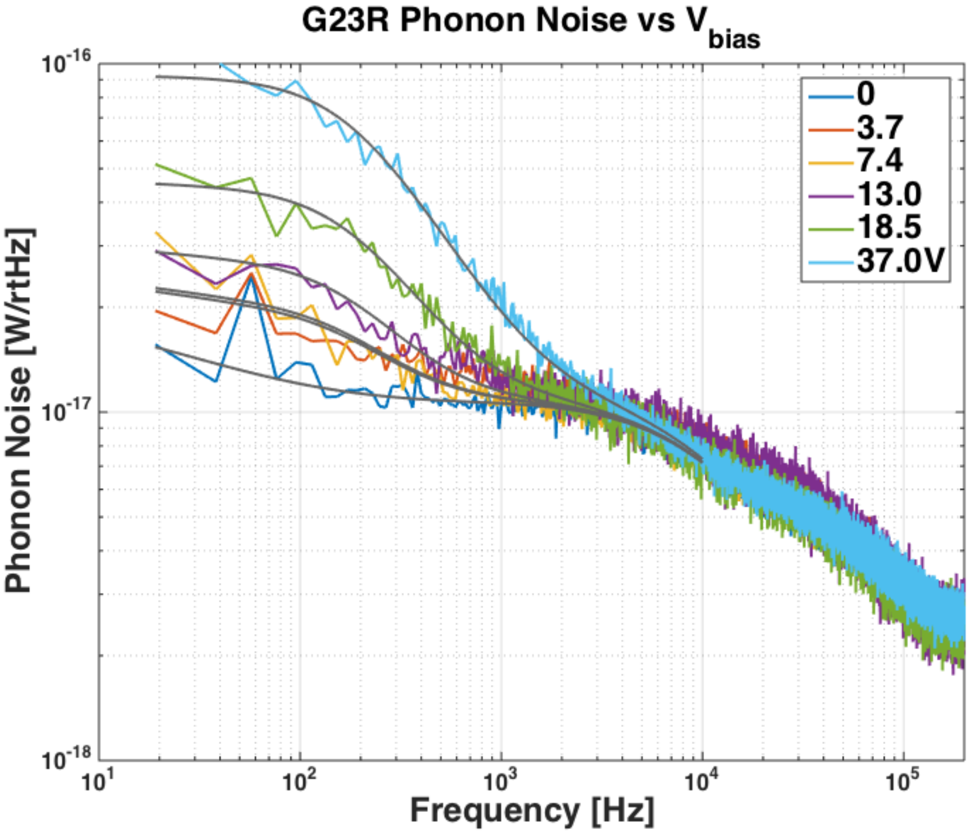

P.N. Luke et al. NIM A289, 405 (1990)

- Luke’s very first attempt saw significant charge breakdown at a certain E-field ☹
- We see this too in SuperCDMS. E-field at which this breakdown occurs varies rapidly between detectors (20 V/cm – 400 V/cm)

Problem #2: Low E-field Dark Current



- Unlike Luke, We see a dark current below the charge breakdown threshold
- Huge variation between detectors 1e-12-1e-15A
- Luke-Neganov Noise Dominates Phonon Sensor Sensitivity.
- Strange: Dark Current nearly independent of E magnitude (IR?)
- We need to understand and mitigate!



Go Small! 1g HV R&D detectors @ Stanford

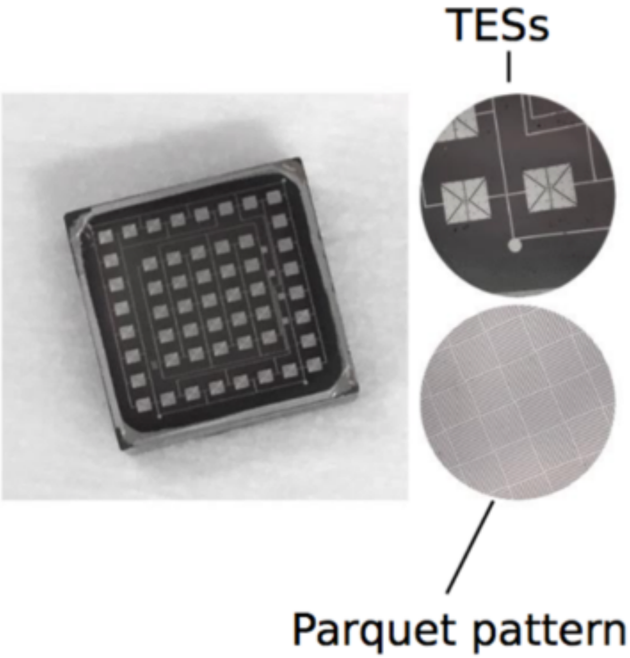
4mm x 1cm x 1cm Si crystal, 20 kohm-cm

Front Pattern:

- 2 TES channels, inner and outer
- Tc ~51 mK
- QET design between Soudan iZIP and SNOLAB HV
- Grounded

Back Pattern:

- "Parquet" pattern, electrode allows light through
- Biased (+/-) relative to fridge ground



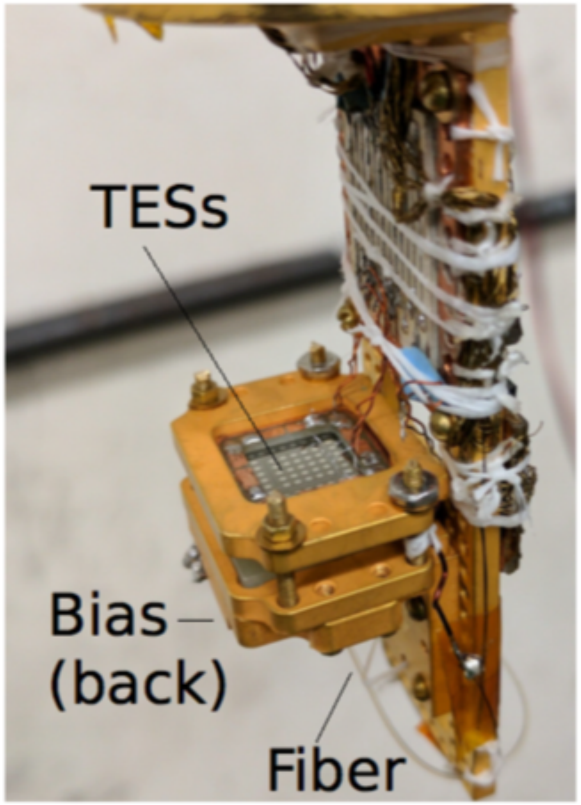
Measuring phonons only!

Romani et. al. 2017 (https://arxiv.org/abs/1710.09335)

Experimental Setup

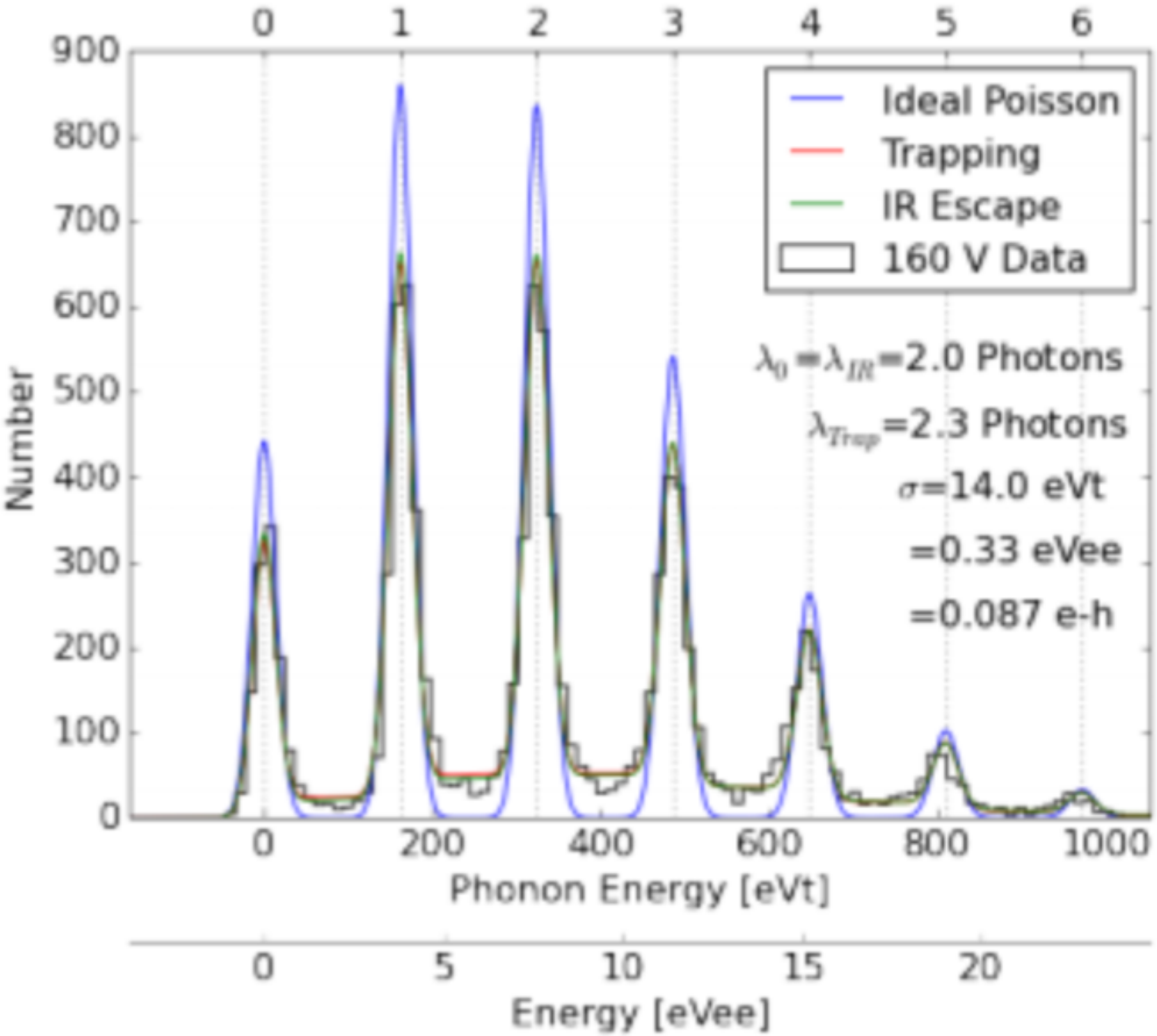
Laser Excitation System:

- Ran fiber from 300 K to sample stage, illuminates crystal backside
- Berkeley Nucleonics laser pulse system, 650 nm photons, pulse widths > 10 ns
- Trigger on the laser pulse
- Standard Si physics:
  - 1.9 eV per photon
  - 1.2 eV to e-h pair
  - 0.7 eV prompt phonons
  - Get full 1.9 eV of phonons back at sensor
- Studied Luke gain under a variety of bias conditions



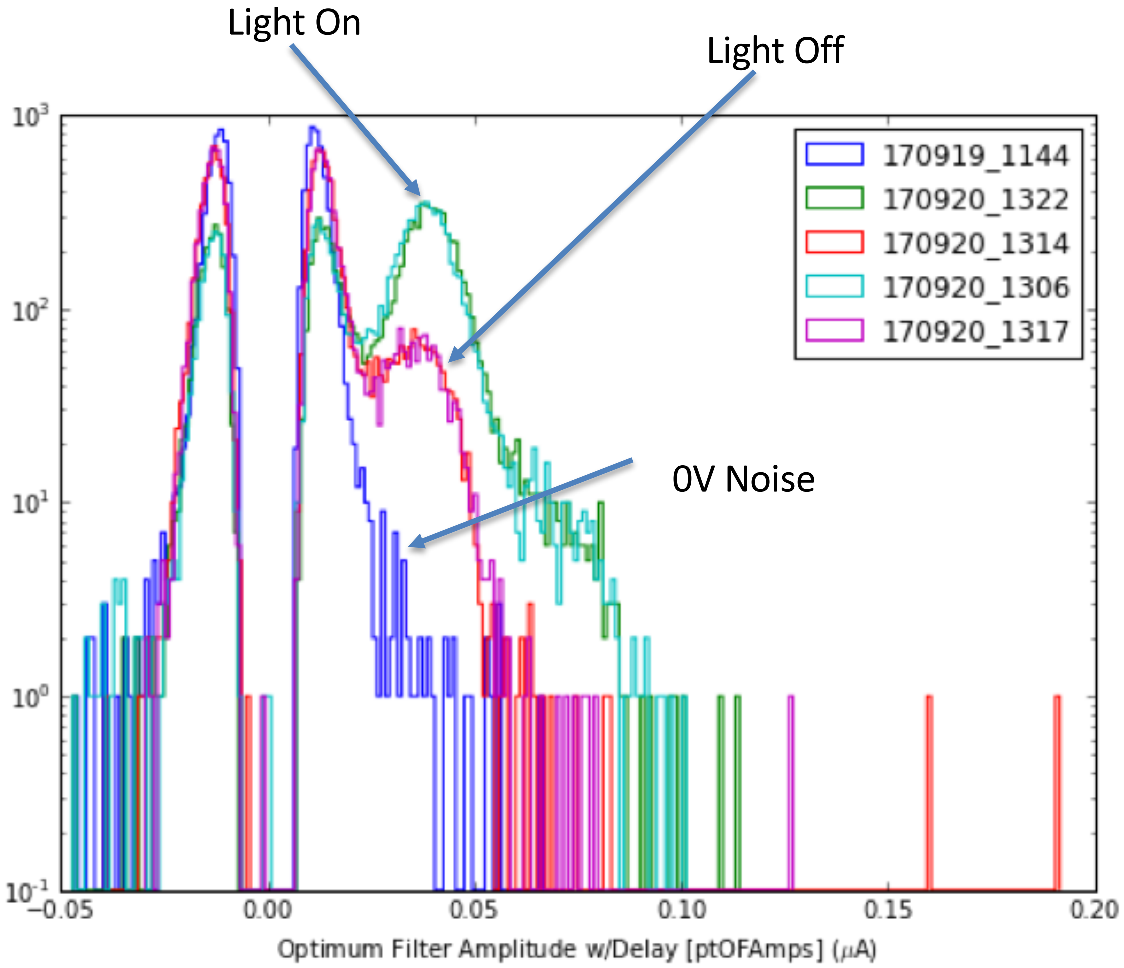
Romani et. al. 2017 (https://arxiv.org/abs/1710.09335)

First observation of single e^-h^+ pair (Si)



Dark Current: Initially Dominated by above gap IR

- Initially, Significant change in dark current rate.
- Improved experimental setup until above gap IR not dominant
- Warning: this doesn't mean that light leaks aren't still an issue!
- Just upgraded setup
  1. multimode fiber -> single mode
  2. IR filters in cryostat
  3. IR absorber surrounding crystal

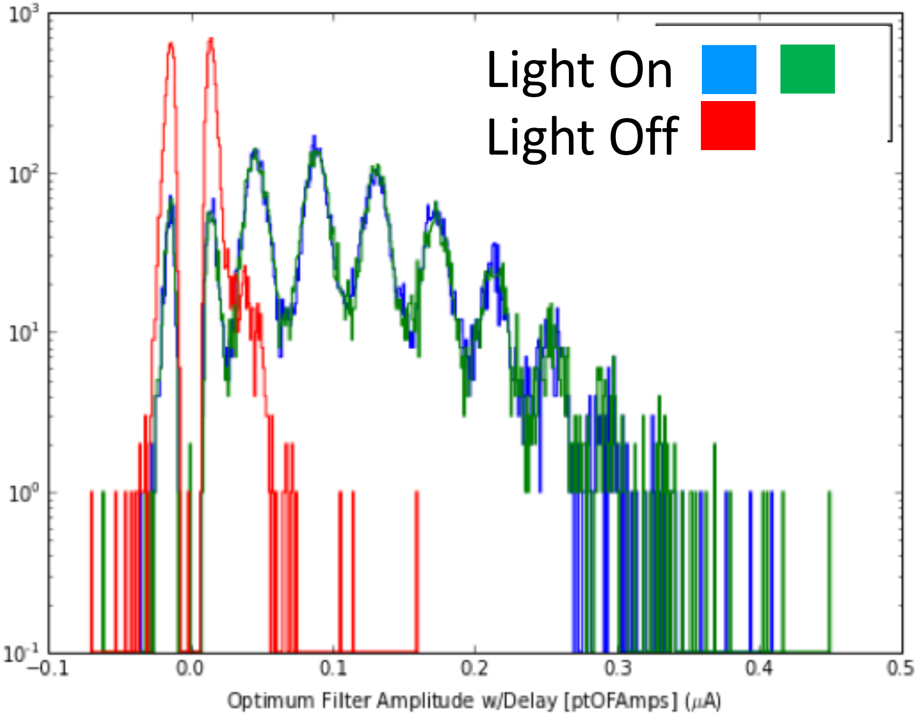

Light On

Light Off

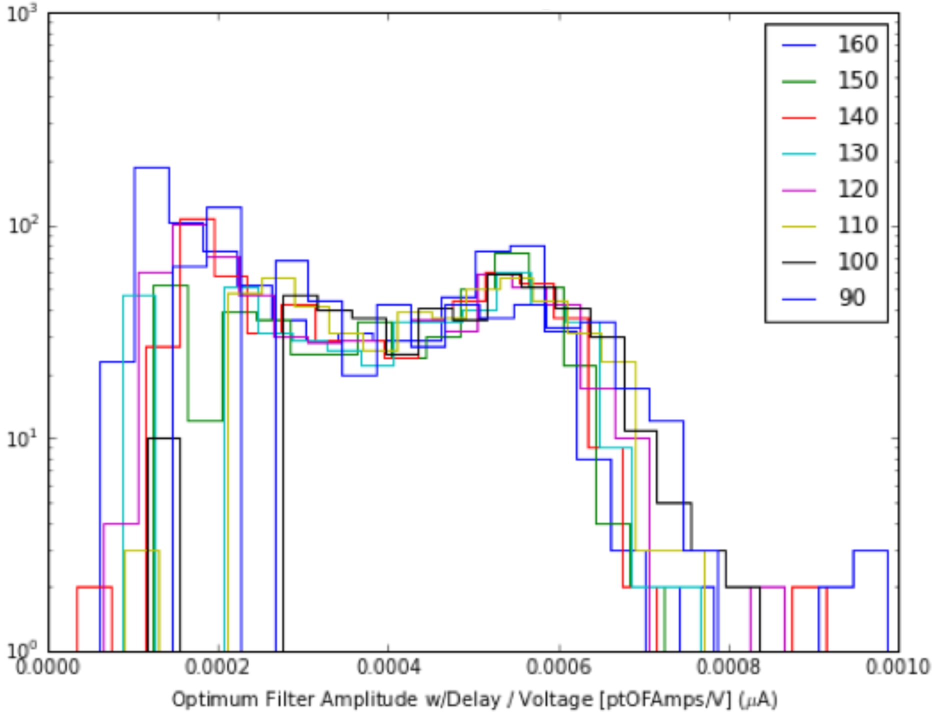
0V Noise

Dark Current

Event Histograms w/ & w/o light



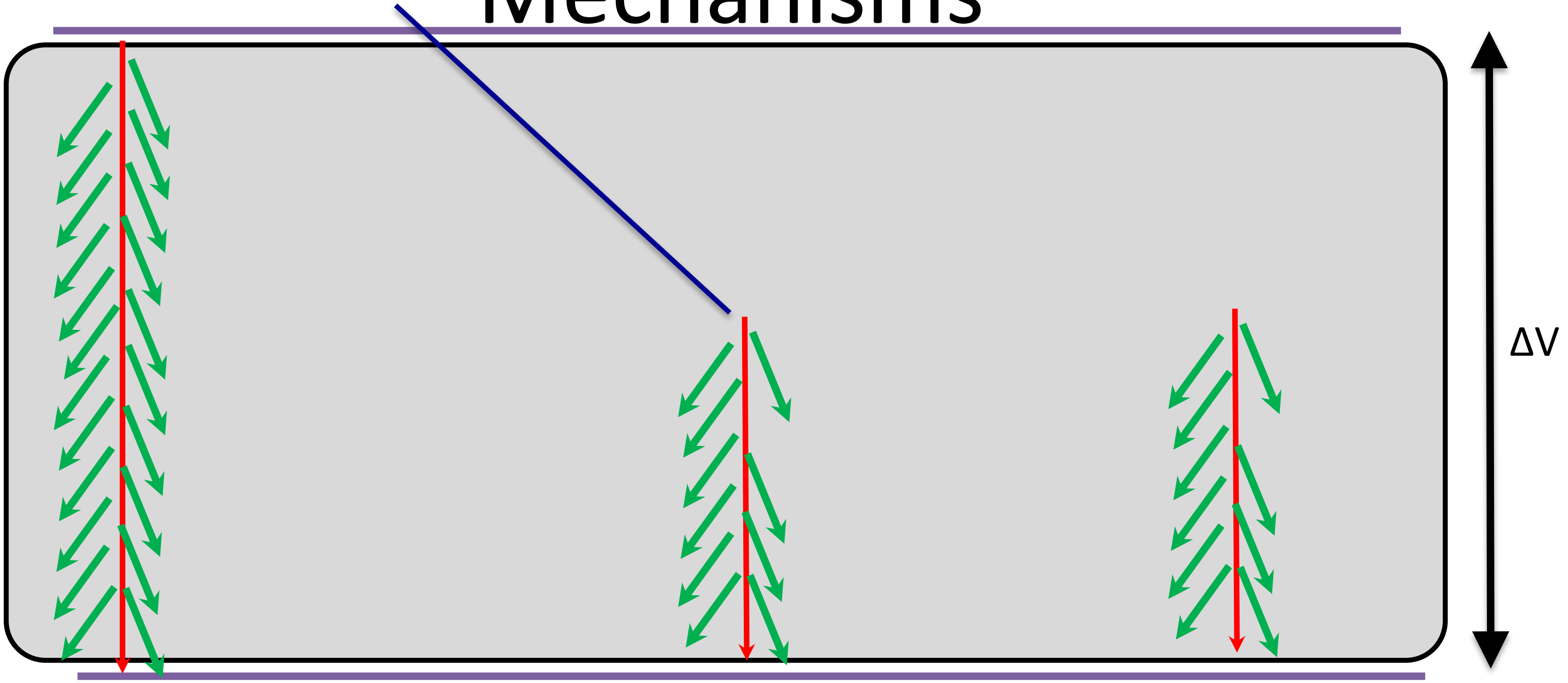
Histograms with 0V Noise Subtracted



Remaining dark count background

- isn't peaked!
- is independent of E-field magnitude

Possible "Bulk" Dark Current Production Mechanisms



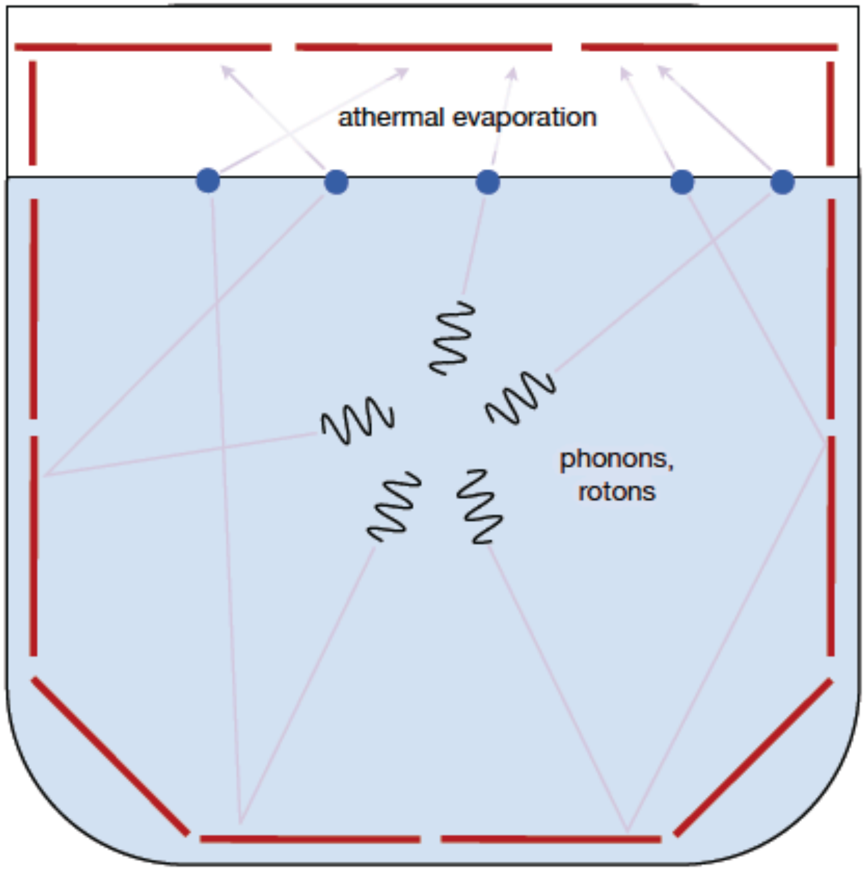
"Surface Leakage"
- Above gap IR/optical
- Surface Tunneling

Subgap IR Photon
Excitation of Impurity

Autoionization
Excitation of Impurity

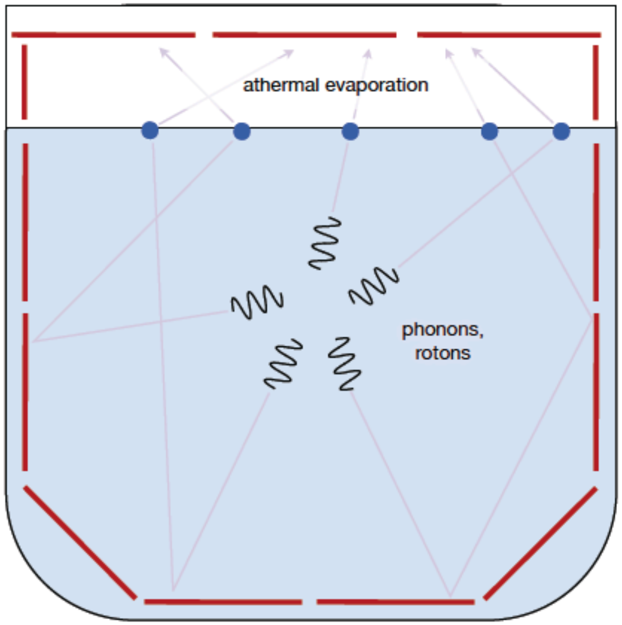
Adsorption Amplification

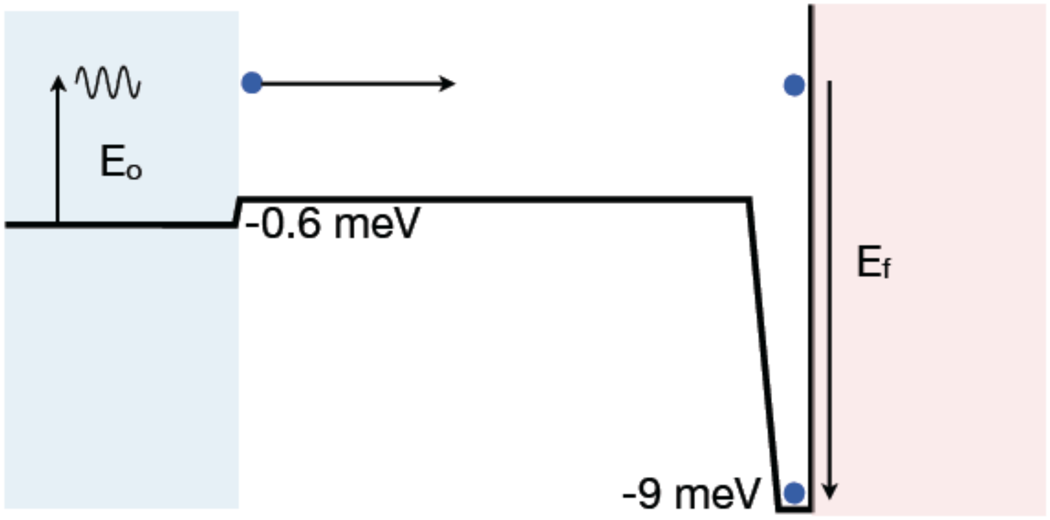
Superfluid He



- Superfluid He: Many Long Lived Excitations
  - D. McKinsey, S. Hertel, HERON (G. Seidel, H. Maris, …), K. Zurek, T. Lin
  - Photons & Triplet Excimers: ~ 18 eV
  - Phonons & Rotons: 1 meV
  - x10 gain due to adsorption on bare surface
- Excitation Detector
  - Bounce until they are collected by the sensor

Amplification Through Adsorption



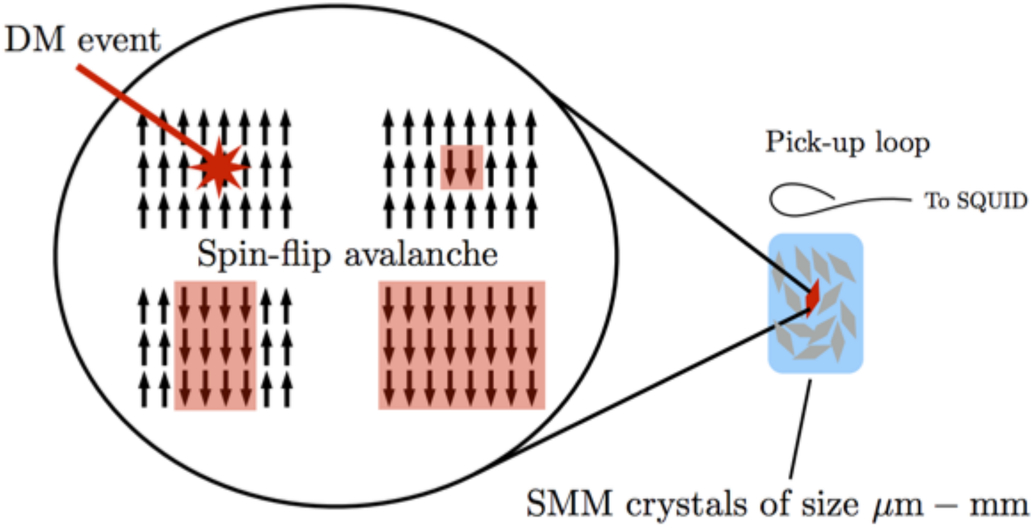


- ~x10 gain due to adsorption on bare surface
- Dark Count Rate … naively dark count free

Phase Transition Amplification

Magentic Bubble Chambers

- Prepare a magnet in a non-equilibrium state with spin anti-aligned to external B-field. Energy from dark matter interaction heats the magnet and flips the state releasing lots of energy
- Bunting, Gratta, Melia, Rajendran 1701.06566



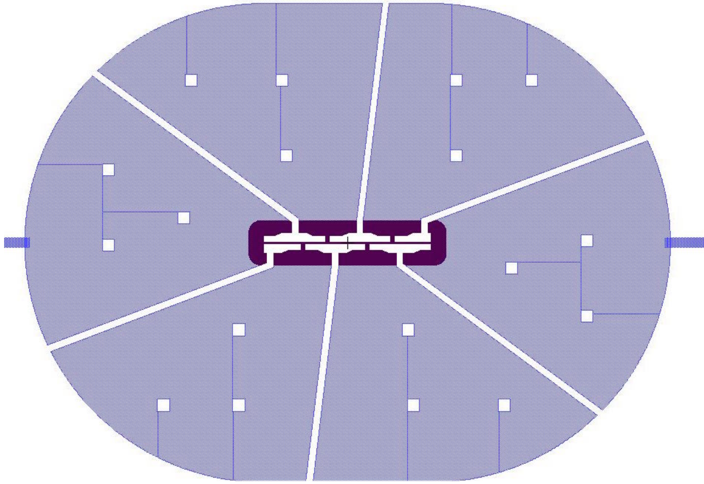
Conclusions

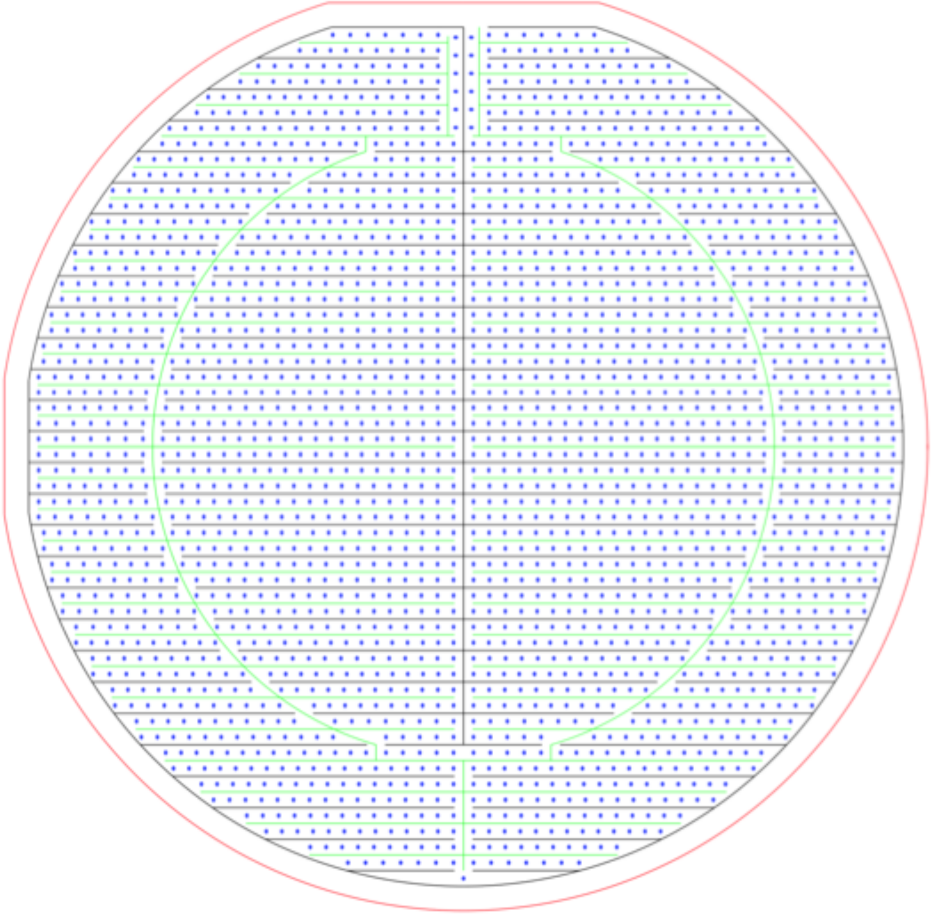
- Direct Detection of 10meV < M_{DM} < 10 GeV requires
  - Energy sensitivity
  - Detector Backgrounds / Dark count rates small
  - Exposure & Radiogenic Background requirements relaxed compared to high mass WIMP searches
- Athermal Phonon sensor technology
  - 10meV<M_{DM}<6 GeV
  - Potentially dark count free
  - Potential path to vast improvements in energy sensitivity
- Luke-Neganov Amplification
  - Single e/h pairs now seen!
- Phase Transition Amplification

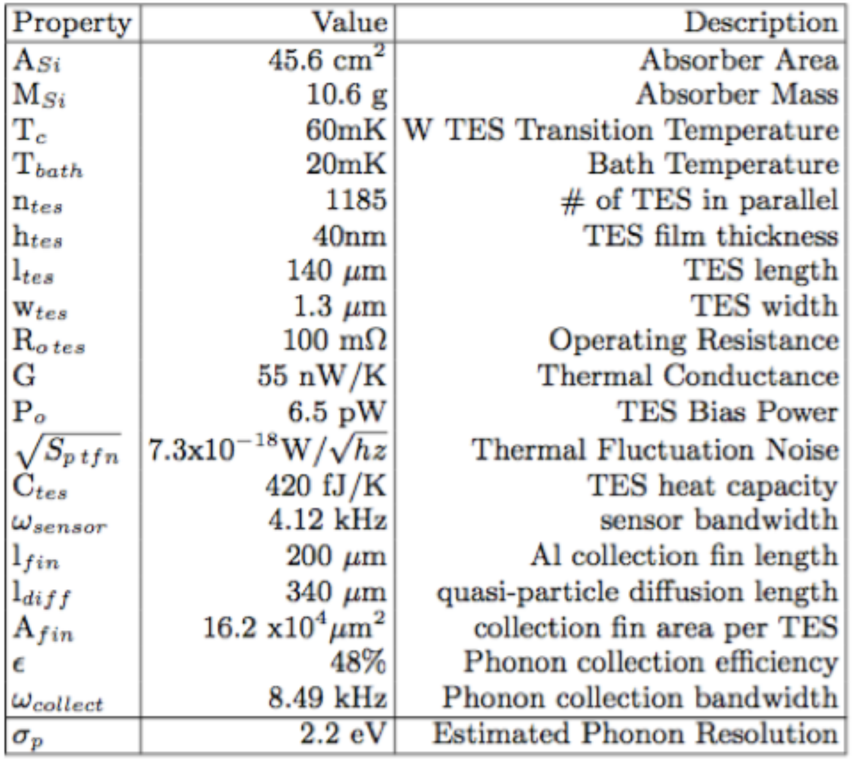
Backup

Photon Detector Preliminary Design

Optimized Phonon Collection Fin Design

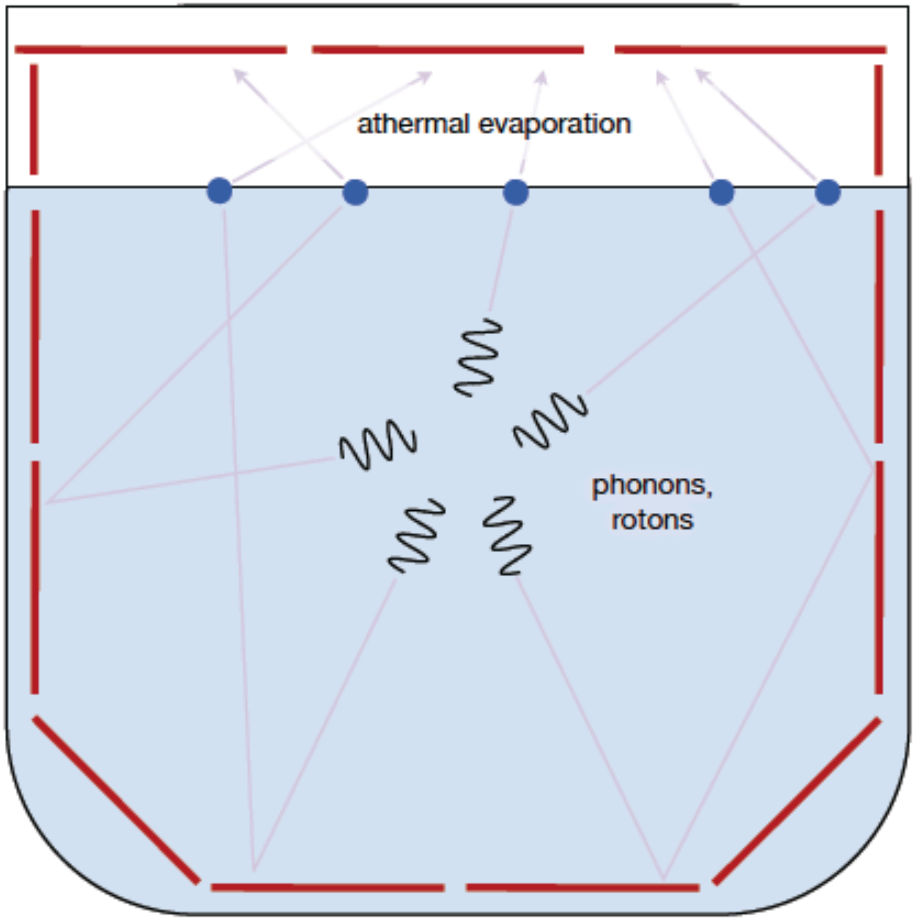






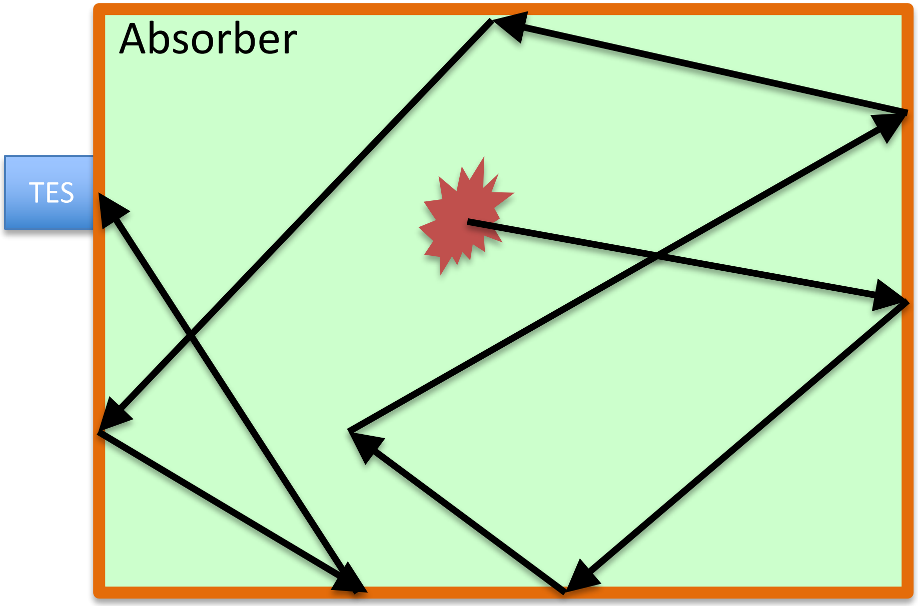
Property	Value	Description
A_{Si}	45.6 cm^2	Absorber Area
M_{Si}	10.6 g	Absorber Mass
T_c	60mK	W TES Transition Temperature
T_{bath}	20mK	Bath Temperature
n_{tes}	1185	# of TES in parallel
h_{tes}	40nm	TES film thickness
l_{tes}	140 μm	TES length
w_{tes}	1.3 μm	TES width
$R_{o\,tes}$	100 mΩ	Operating Resistance
G	55 nW/K	Thermal Conductance
P_o	6.5 pW	TES Bias Power
$\sqrt{S_{p\,tfn}}$	$7.3\text{x}10^{-18}$W/$\sqrt{hz}$	Thermal Fluctuation Noise
C_{tes}	420 fJ/K	TES heat capacity
ω_{sensor}	4.12 kHz	sensor bandwidth
l_{fin}	200 μm	Al collection fin length
l_{diff}	340 μm	quasi-particle diffusion length
A_{fin}	16.2 $\text{x}10^4 \mu m^2$	collection fin area per TES
ϵ	48%	Phonon collection efficiency
$\omega_{collect}$	8.49 kHz	Phonon collection bandwidth
σ_p	2.2 eV	Estimated Phonon Resolution

Superfluid He Detector



- D. McKinsey (1302:0534)
- Superfluid He: Many Long Lived Excitations
  - Photons & Triplet Excimers: ~ 18 eV
  - Phonons & Rotons: 1 meV
- Photon Detection Requirements: Large area, high QE, Single Photon Sensitivity

Pushing the Limit?

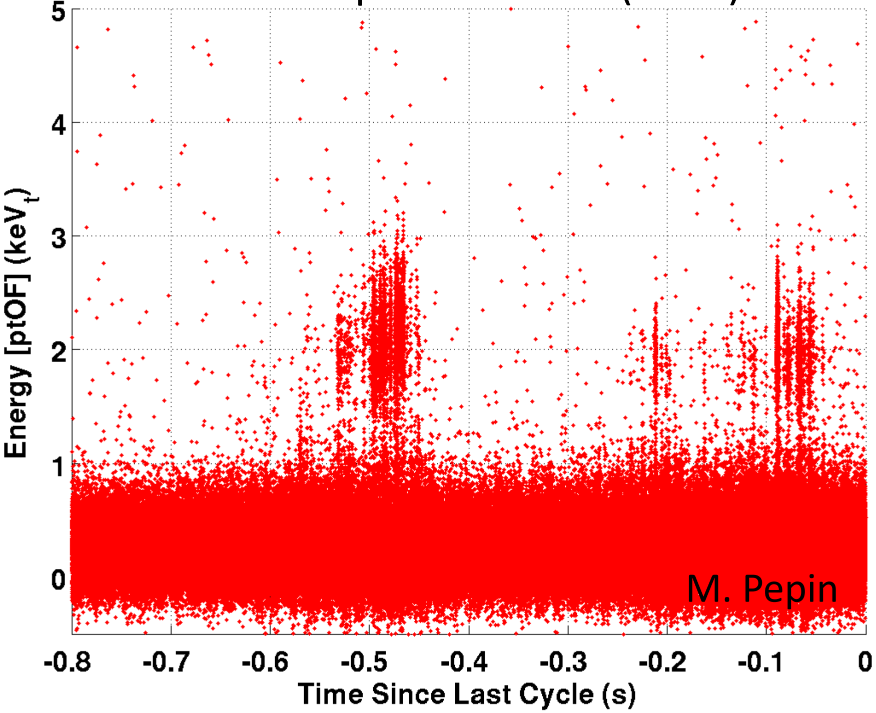


- How many bounces before an athermal phonon down converts?
- How much time before anharmonic downconversion in the bulk?

- If TES bandwidth engineering correctly done, these questions set the TES volume / fin collector size
- Is meV scale sensitivity possible?
  Are keV < M_{DM} < MeV detectors possible?

Why So Large: Vibrational Noise!

Baseline Noise vs Time
R133 SuperCDMS HV (T5Z2)

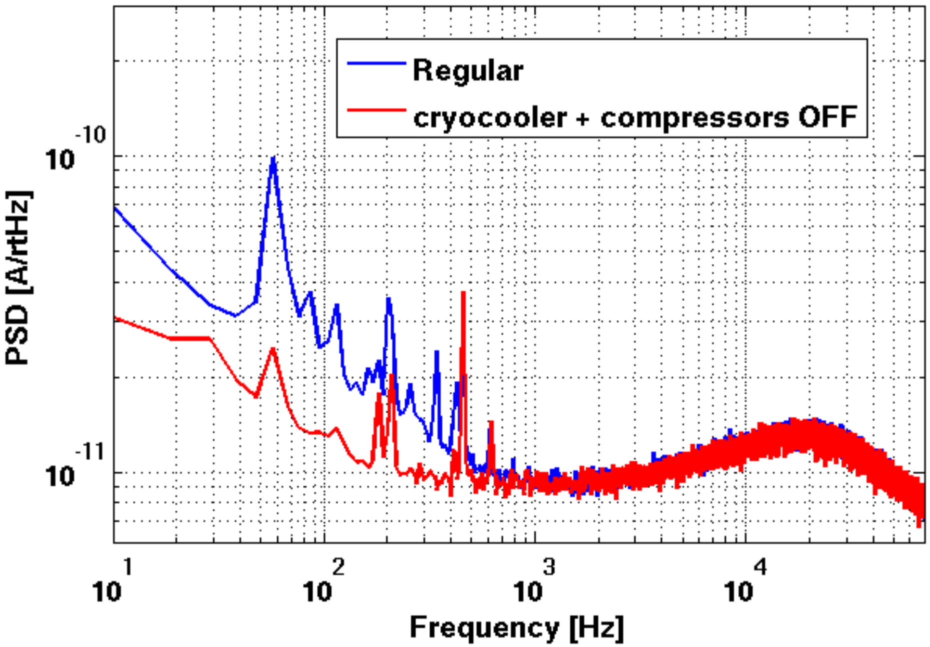


Vibrations from the cryocooler produce high frequency phonons within our detectors which look like real events.

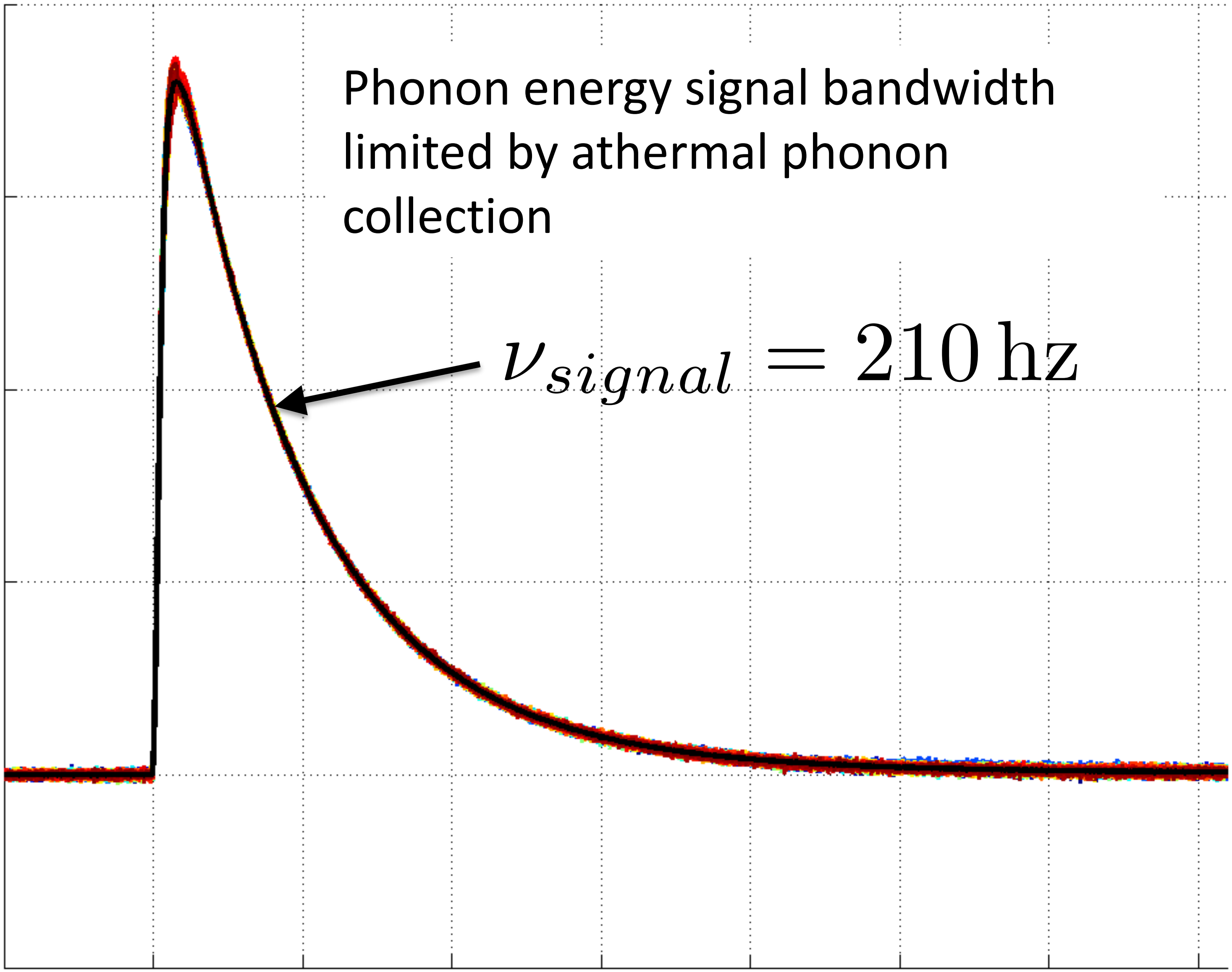
Toggle CryoCooler ON/OFF

- Threshold: $12\sigma_{pt}$ → $7\sigma_{pt}$ (?)
- $\sigma_{pt:}$ 340eVt → 90eVt
- Caveats:
  - Study done at 0V
  - Trigger vs Analysis Threshold

Baseline Noise PSD (T5Z2D)



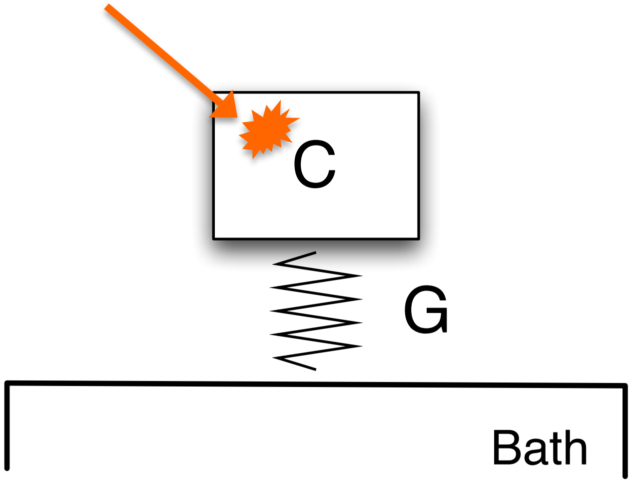
Phonon Signal Bandwidth

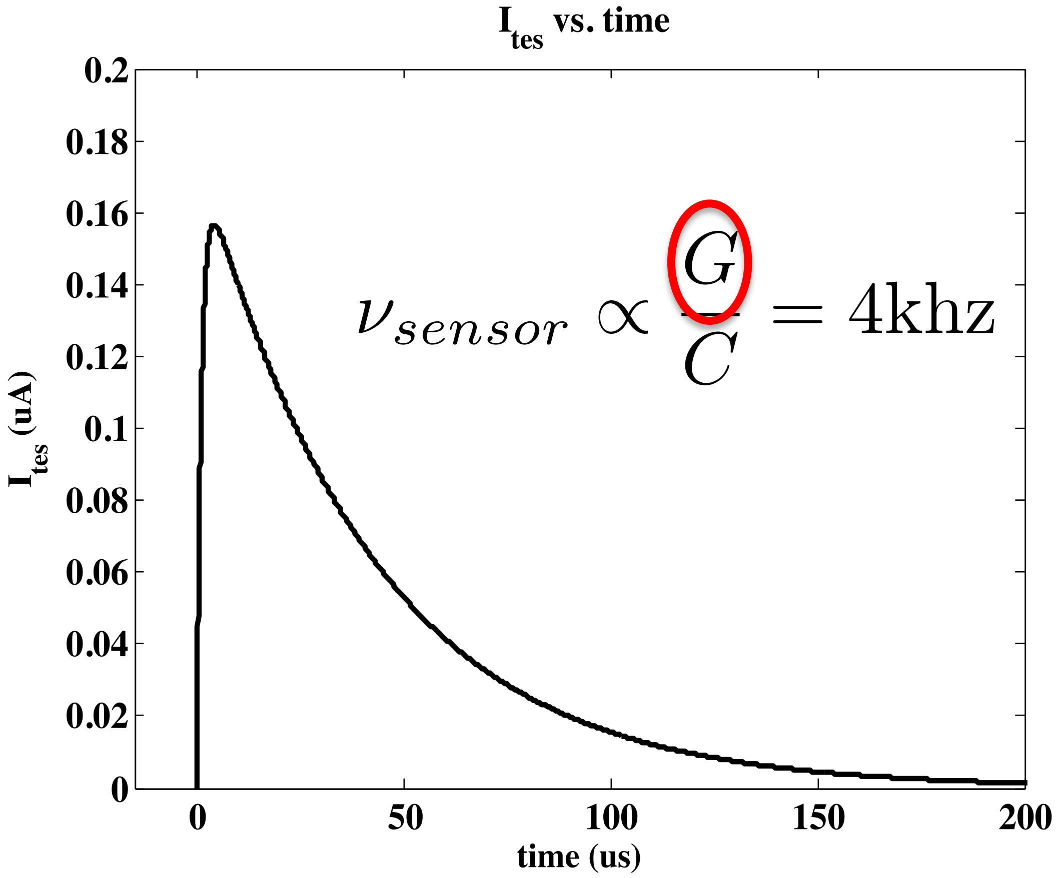


Phonon energy signal bandwidth limited by athermal phonon collection

$$\nu_{signal} = 210\,\mathrm{hz}$$

Transition Edge Sensor: Dynamics

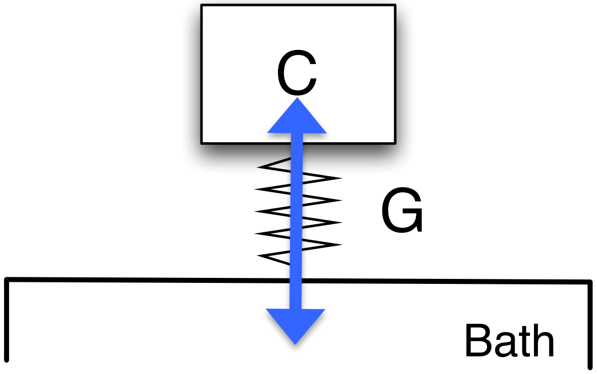




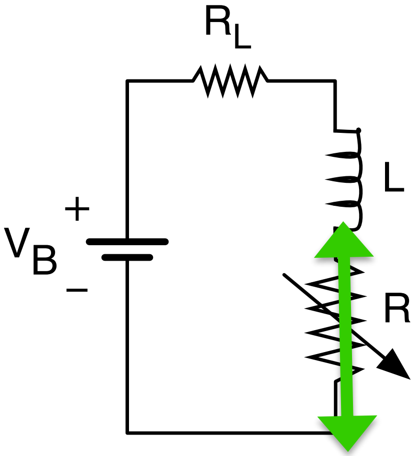
$$\nu_{sensor} \propto \frac{G}{C} = 4\text{khz}$$

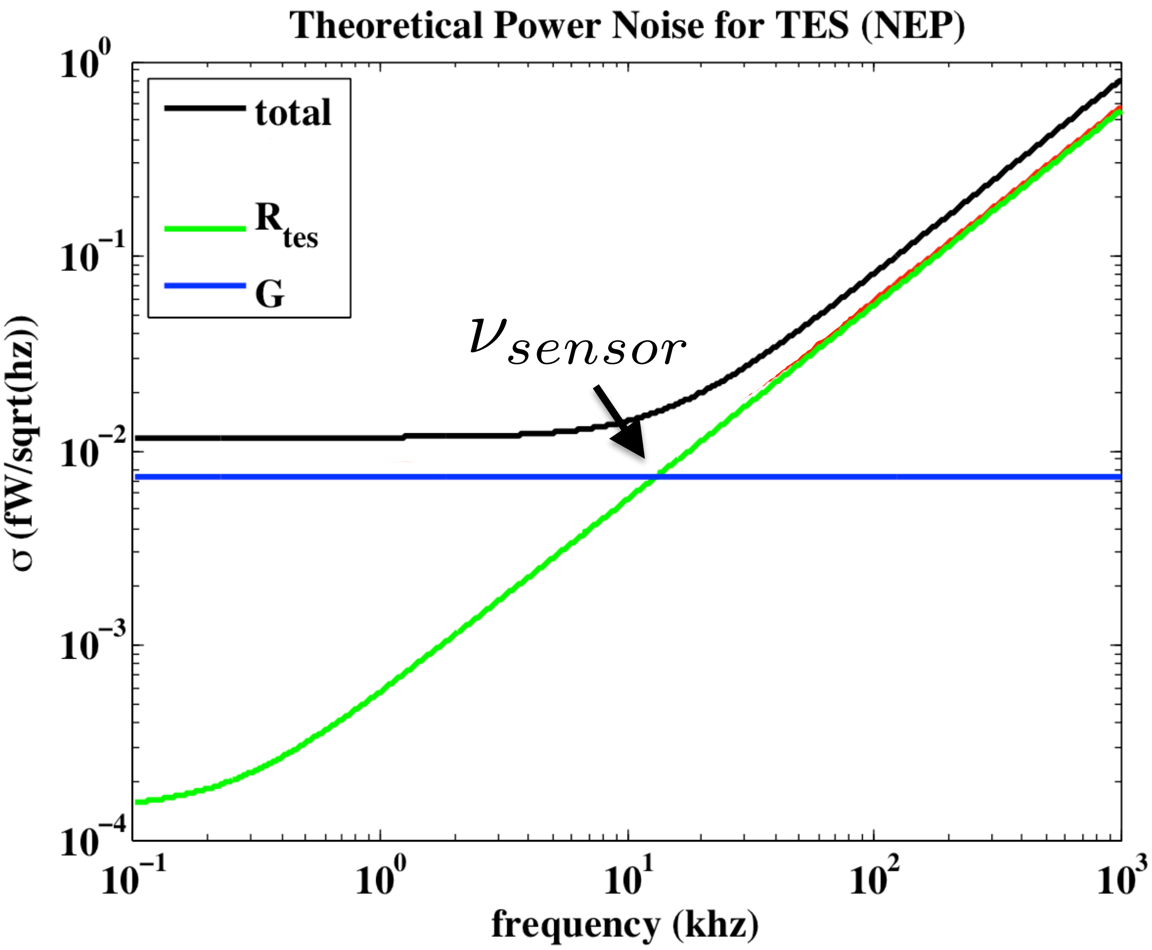
$$\nu_{signal} << \nu_{sensor}$$

Transition Edge Sensor: Noise



$S_{pG} = 4k_bT^2\mathbf{G}$

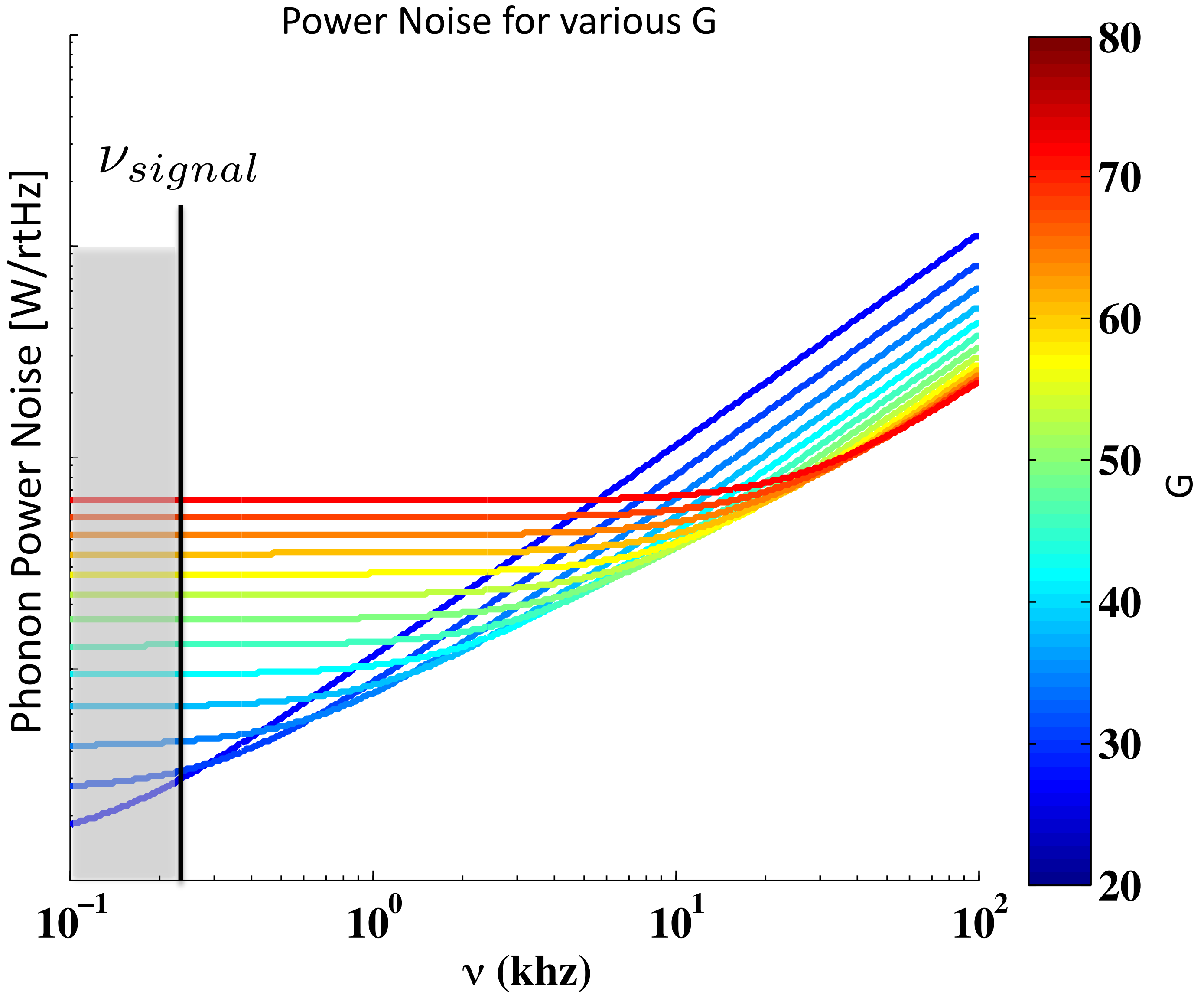




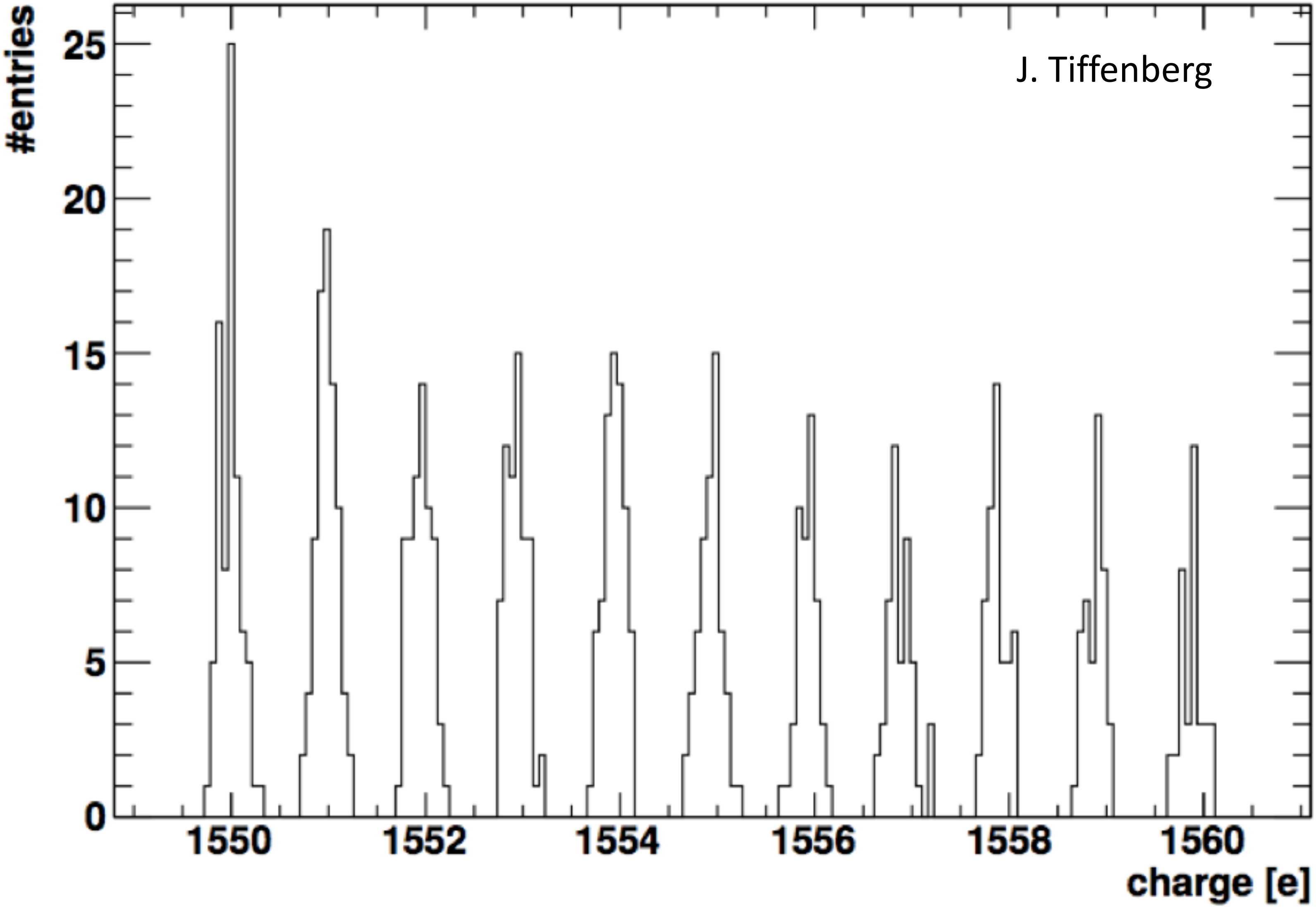
DC noise scales with G

Bandwidth Optimization Rule

$$\nu_{sensor} < \nu_{signal}$$

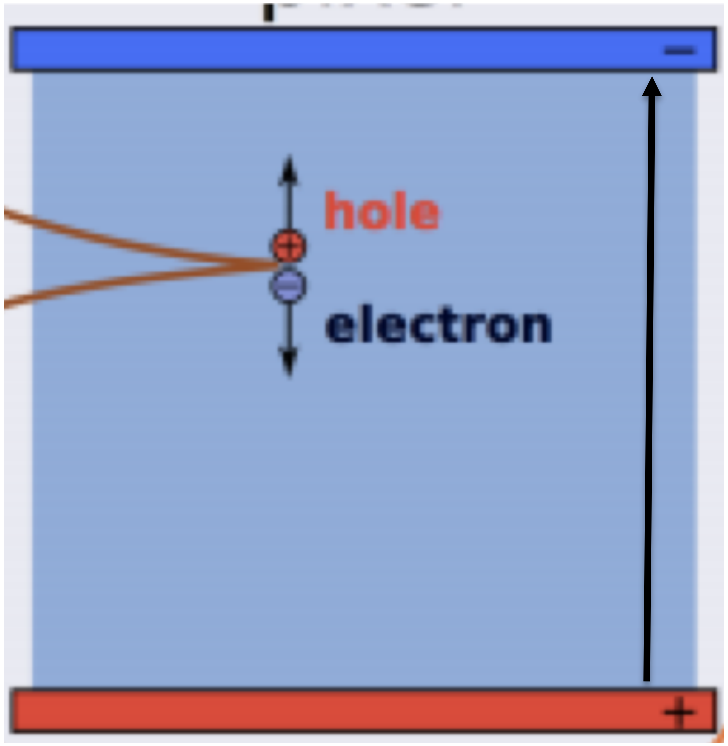


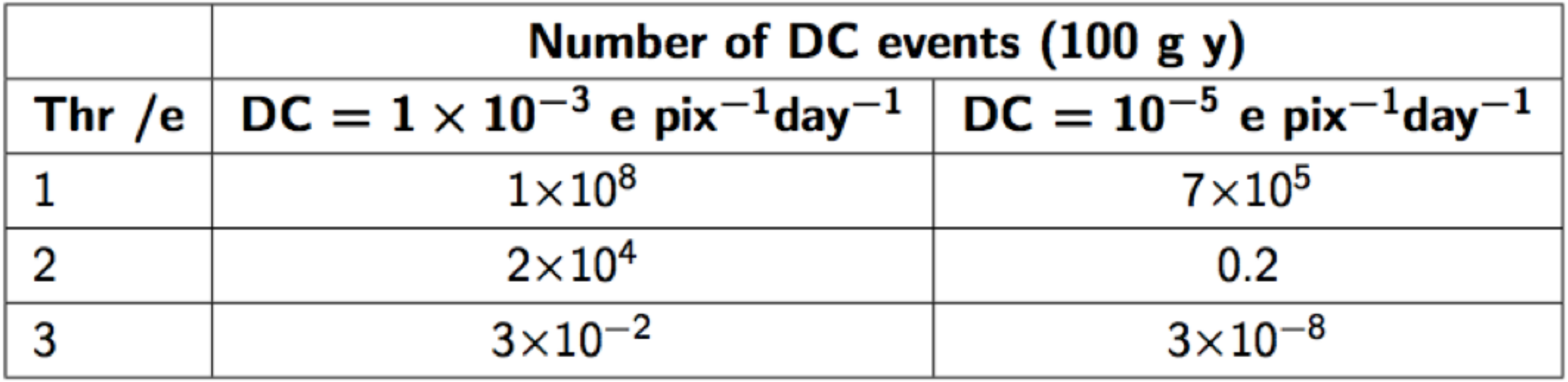
SINSEI/DAMIC: Meets Single e^-/h^+ Sensitivity



SINSEI/DAMIC: Dark Current

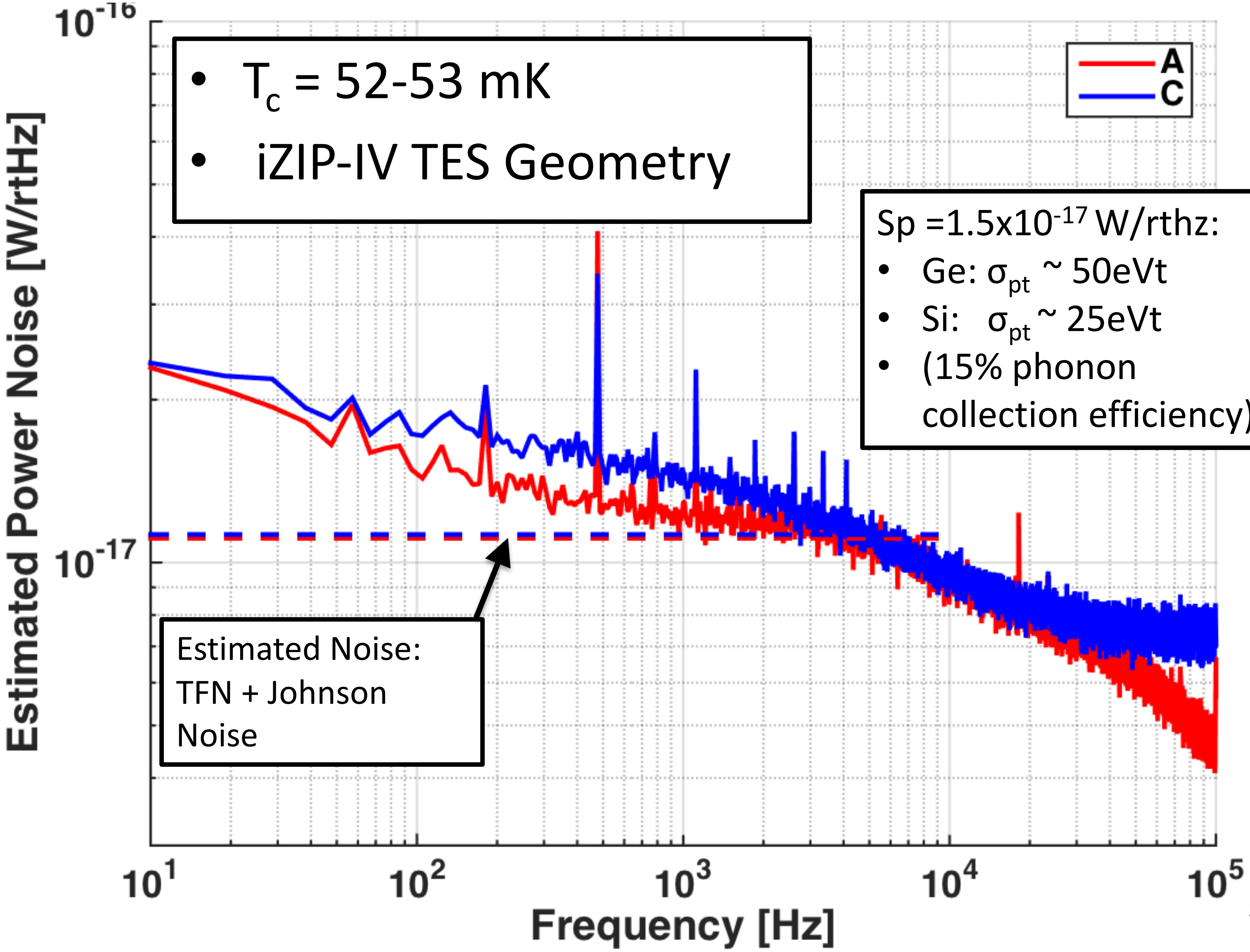
Dark Current: < 10-3 e/d/pixel (arXiv:1611.03066)





	Number of DC events (100 g y)	
Thr /e	**DC = 1×10^{-3} e pix^{-1}day^{-1}**	**DC = 10^{-5} e pix^{-1}day^{-1}**
1	1×10^{8}	7×10^{5}
2	2×10^{4}	0.2
3	3×10^{-2}	3×10^{-8}

Noise of G23R Test Device



- T_c = 52-53 mK
- iZIP-IV TES Geometry

Sp =1.5×10^{-17} W/rthz:

- Ge: σ_{pt} ~ 50eVt
- Si: σ_{pt} ~ 25eVt
- (15% phonon collection efficiency)

Estimated Noise:
TFN + Johnson
Noise