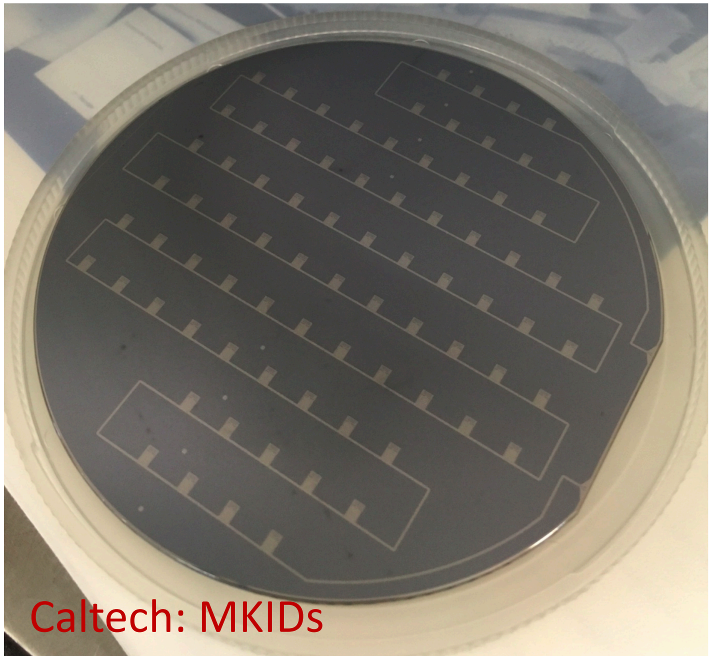
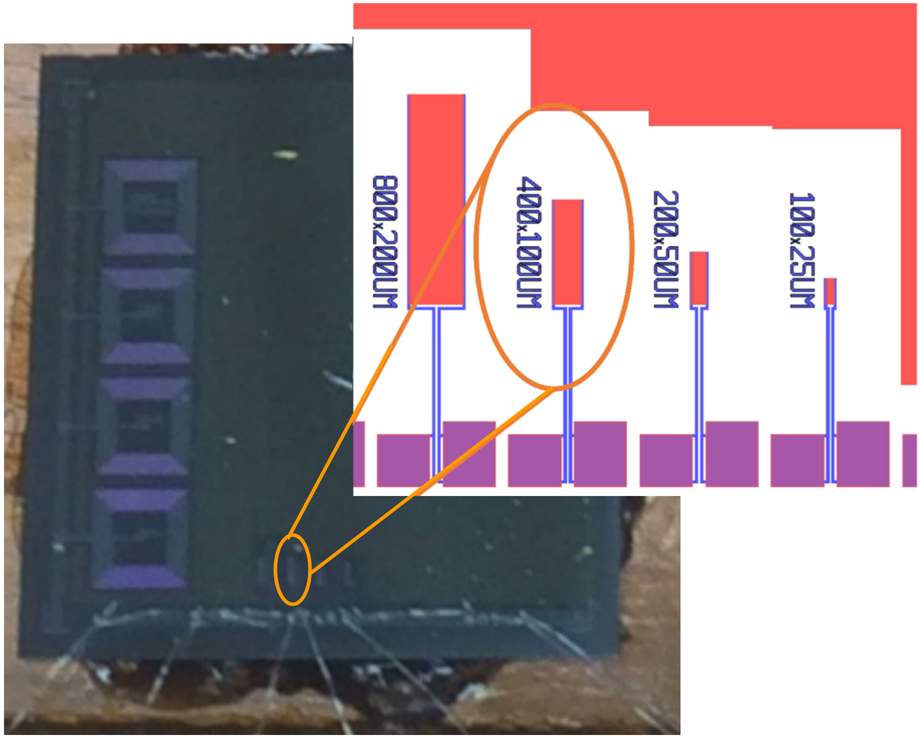
NTD, TES, MKID and SNSPD Sensors in Dark Matter





Matt Pyle

UC Berkeley

New Directions Fermilab

June 4 2019

Outline

- Light Mass Dark Matter Design Drivers
- TES
  - Athermal phonon collection and concentration schemes
- NTDs
- MKIDs
- SNSPDs
  - Energy Reconstruction
- Proposed/Running Experiments

Light Mass Dark Matter Direct Detection Design Drivers

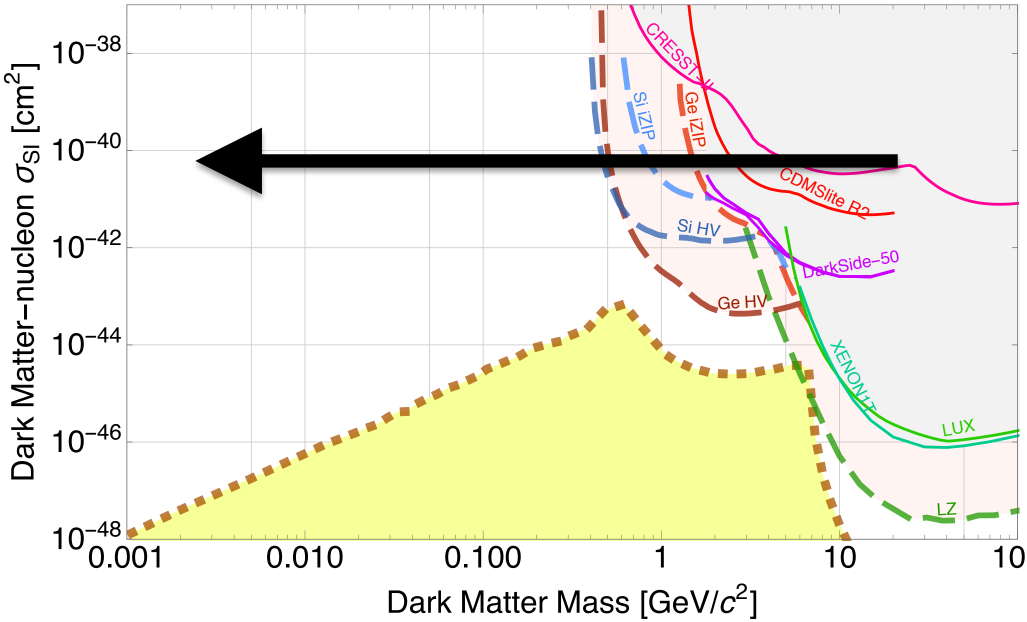
Light Mass DM Design Drivers:

~~Exposure~~

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

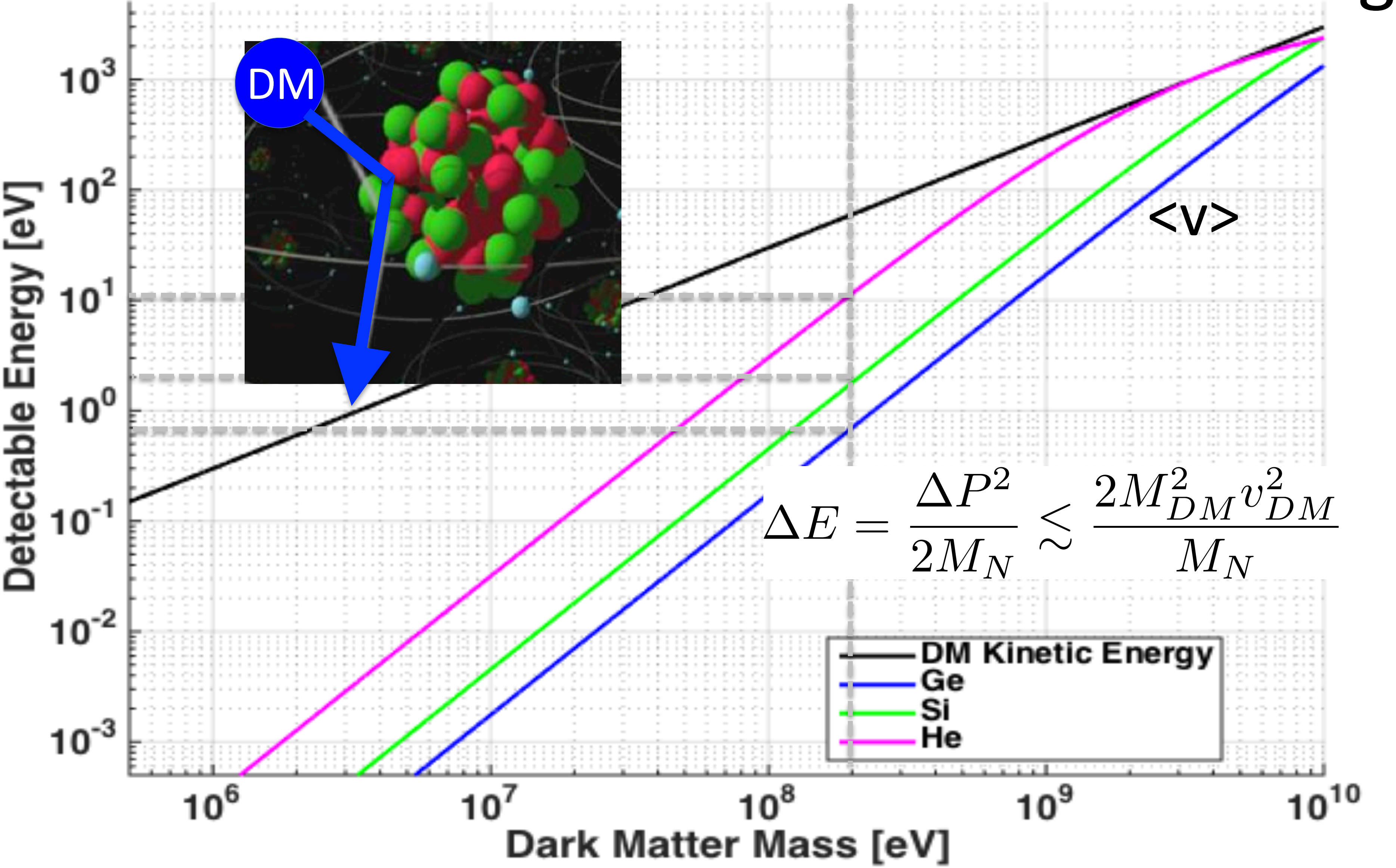
$$= \sigma \frac{\rho_{DM}}{\boxed{M_{DM}}} v_{esc} N_{exp}$$

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 10kg to reach the same level at 100MeV.

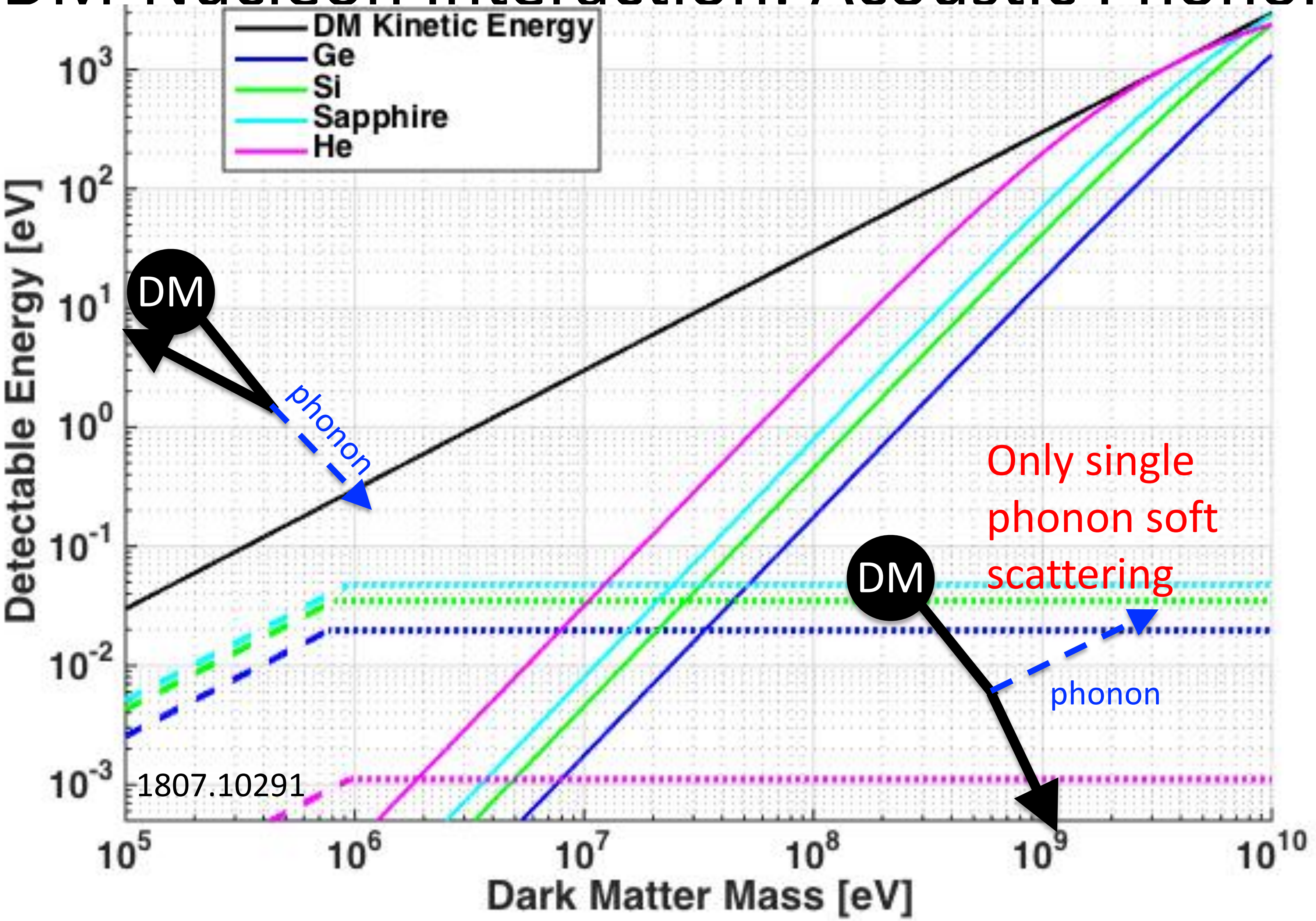
DM-Nucleon Interaction: Elastic Scattering



$$\Delta E = \frac{\Delta P^2}{2M_N} \lesssim \frac{2M_{DM}^2 v_{DM}^2}{M_N}$$

Primary Design Driver: Vibrational Energy Sensitivity

DM-Nucleon Interaction: Acoustic Phonon

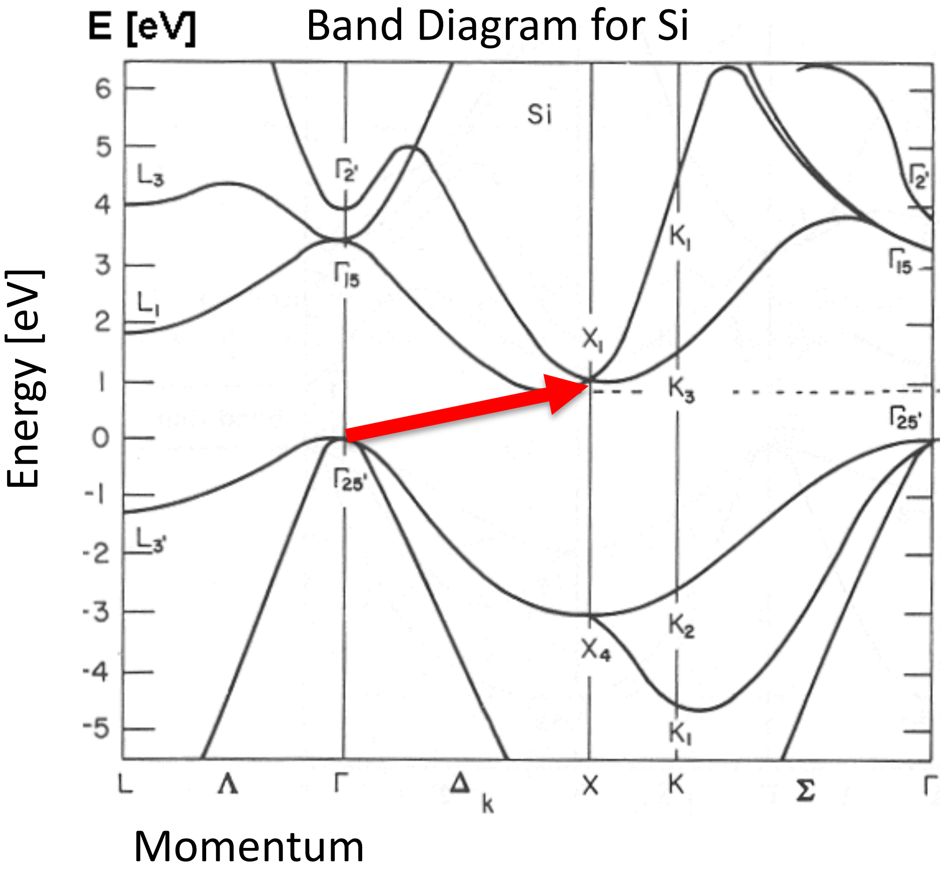


1807.10291

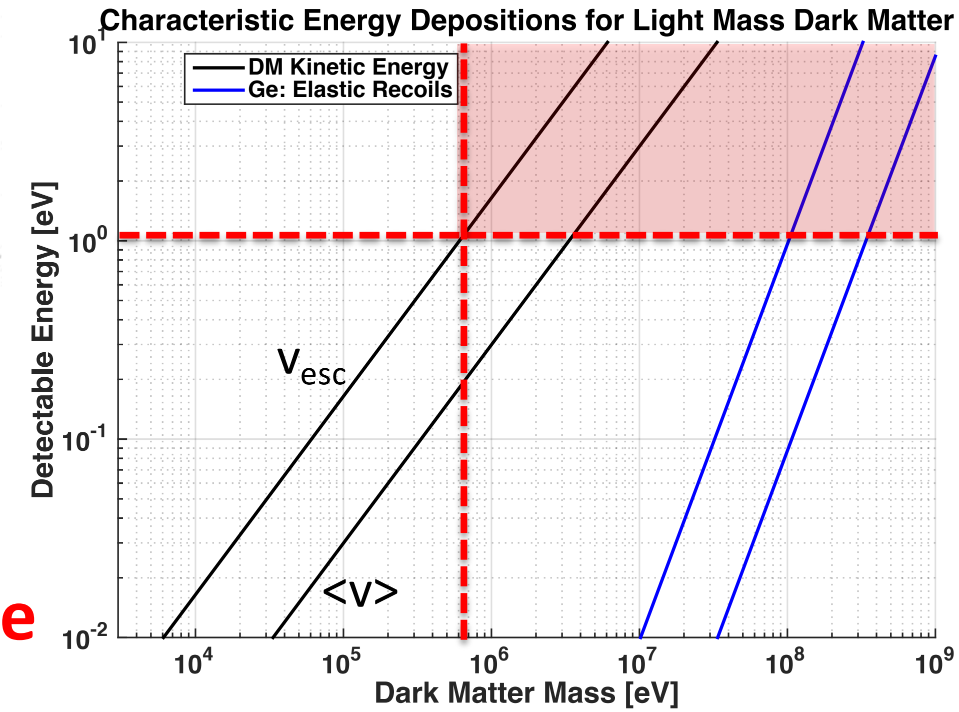
Only single phonon soft scattering

Primary design driver: Still Vibrational Energy Sensitivity

DM-Electronic Interactions: Inelastic e⁻ recoil

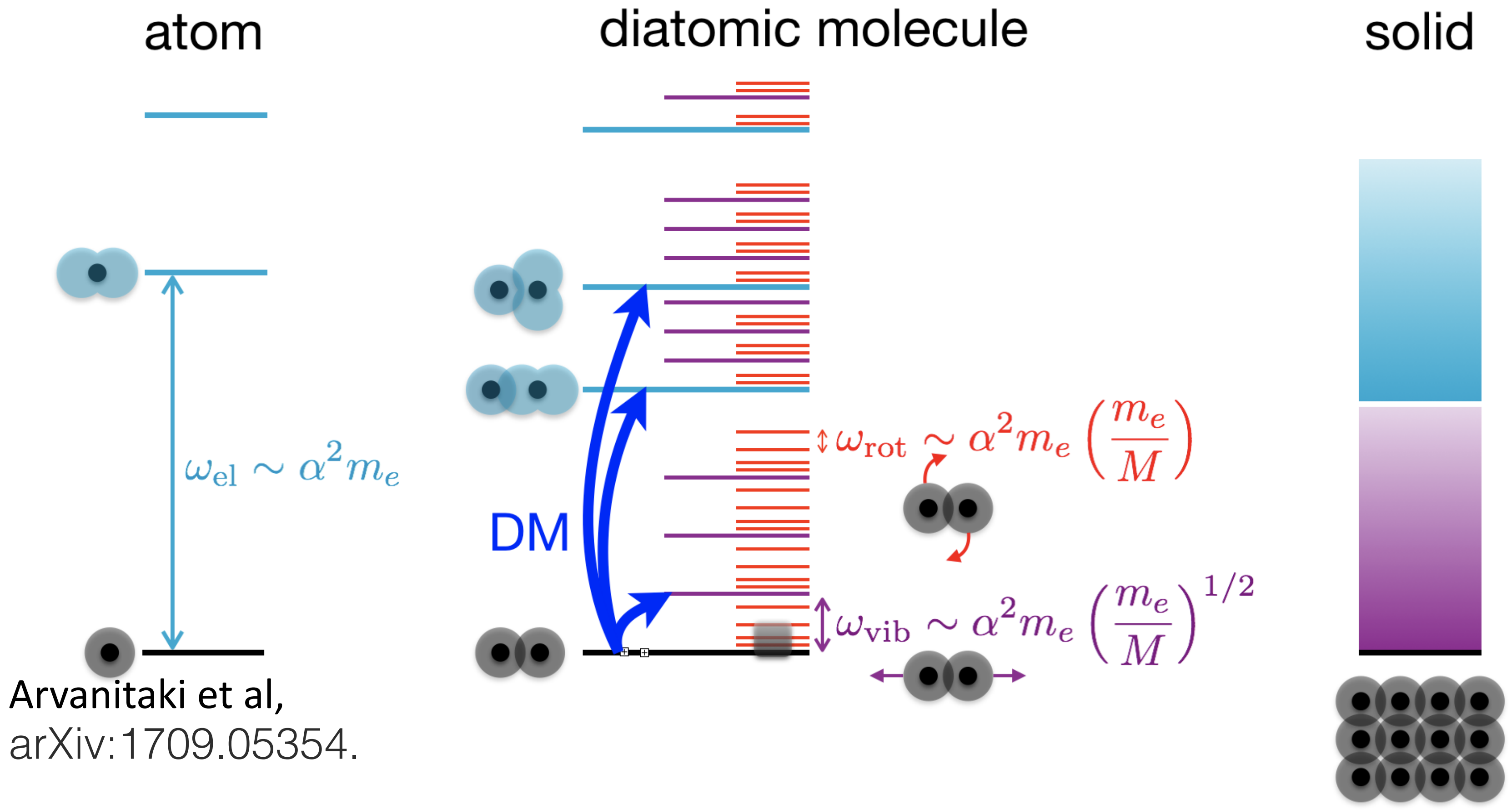


- e- excitation momentum and energy scales in semiconductors well matched to 1 MeV-100MeV DM
- Essig et al: 1108.5383



Design Driver: Sensitivity to single e/h pairs (eV energy) with negligible dark count rate

DM-Molecular/Atom Absorption: Photon Production

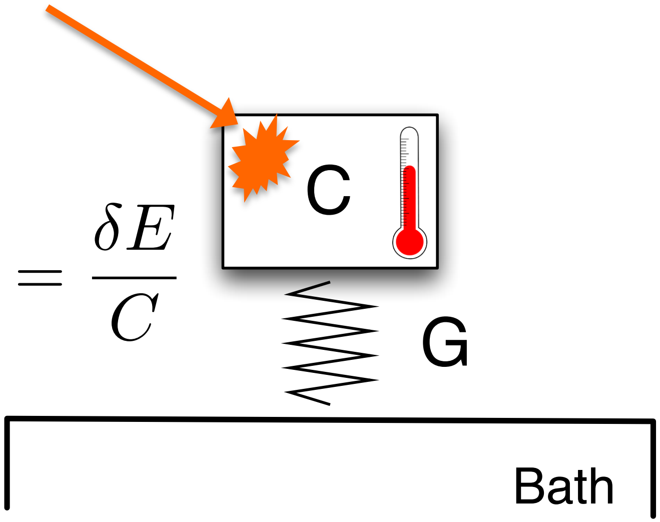


Arvanitaki et al,
arXiv:1709.05354.

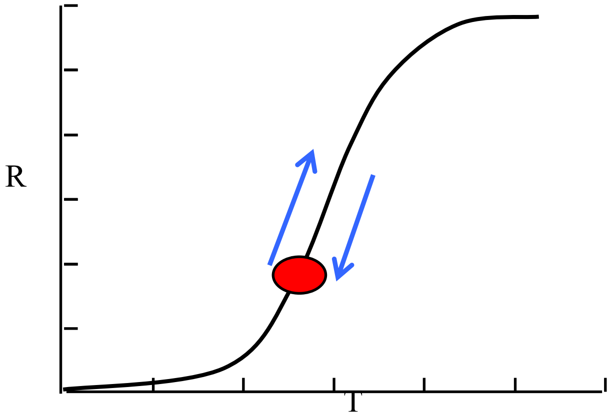
Design Driver: 100meV –eV scale
single photon sensitivity

Transition Edge Sensor

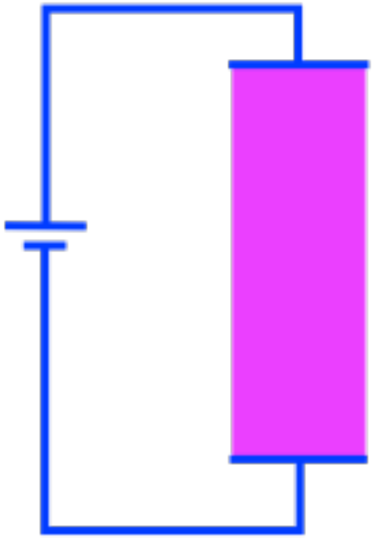
The Simplest Thermal Calorimeter



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



Transition Edge Sensor (TES): A superconducting metal film (W) that is externally biased so as to be within its superconducting/normal transition

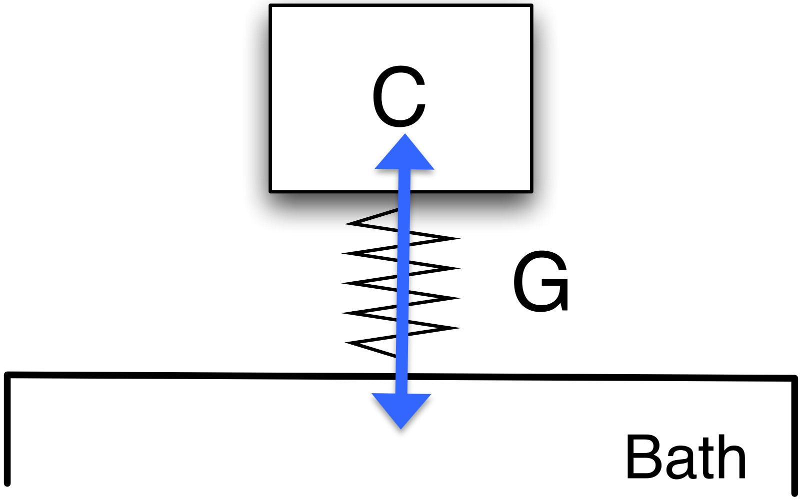


TES Sensitivity

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

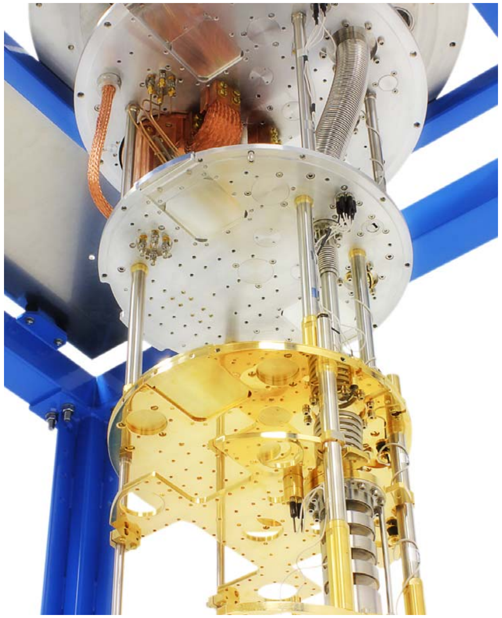
$$= \frac{\sum_i E_i^2 e^{-\beta E_i}}{\sum_j e^{-\beta E_j}} - <E>^2$$

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



~ Intrinsic Thermal Noise of Calorimeters

TES Scaling Laws & Optimization

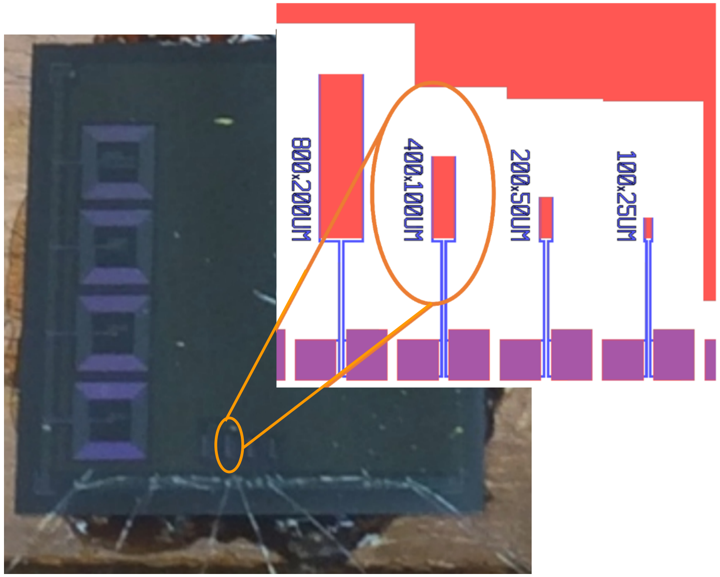


$$\sigma^2_{<E>} = C k_b T_c^2$$

$$\propto V T_c^3$$

- Minimize Temperature
  - Dilution Refrigerators can cool detectors to 5mK
  - T_c -> 1.5x T_{bath}
- Minimize Volume

100meV Threshold TES are really small!



σ_{theory} ~ 20meV

T_c = 41mK

V = 400umx100umx40nm

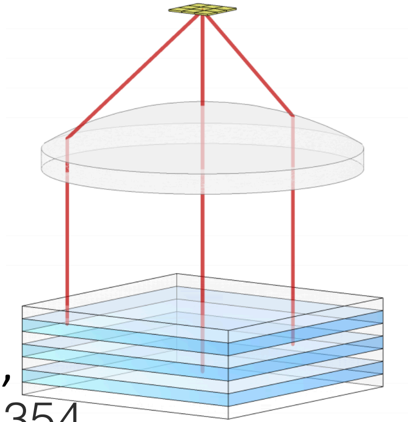
= 1.6 x10^{-9} cm^3

= 30ng

1 gram of active target mass -> 30M channels

1 cm^2 of active area -> 2500 channels

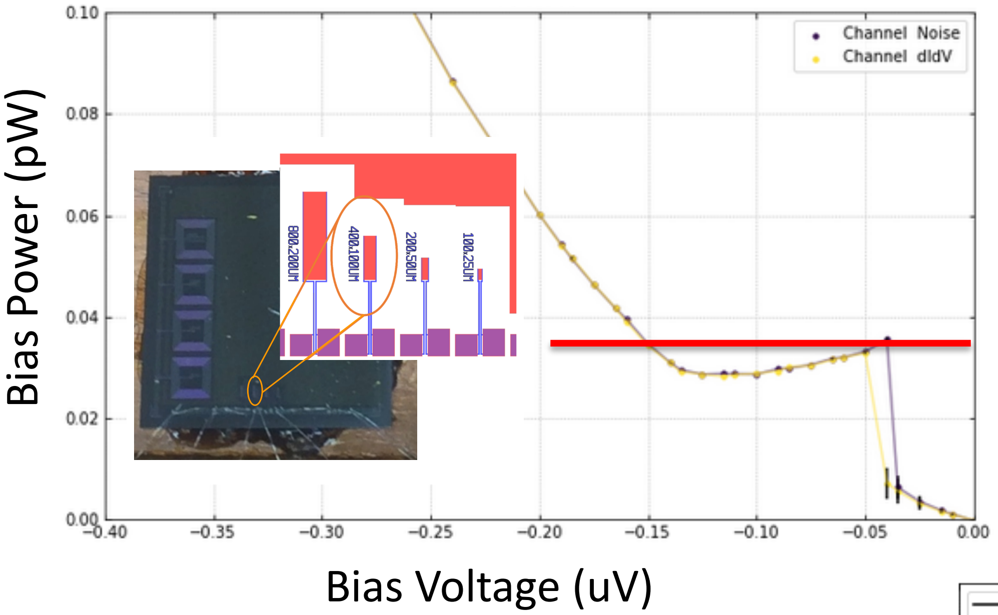
TES can only be used by themselves when photon collecting over a very small area



Arvanitaki et al, arXiv:1709.05354.

Currently Achieved TES Energy Sensitivity: *100um x400umx40nm*

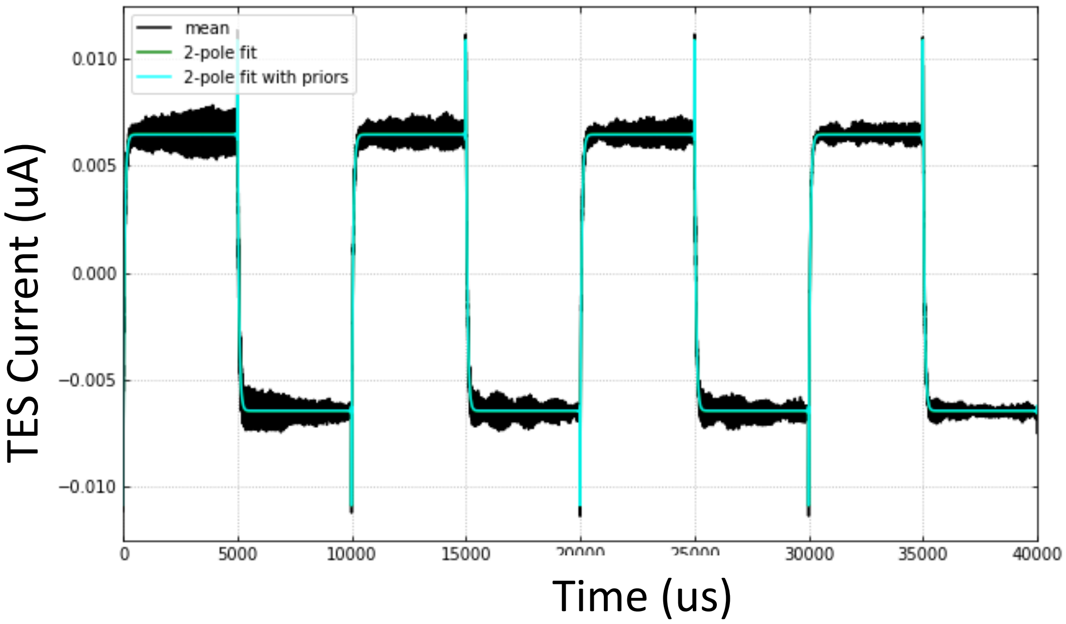
TES Power vs TES Bias Voltage



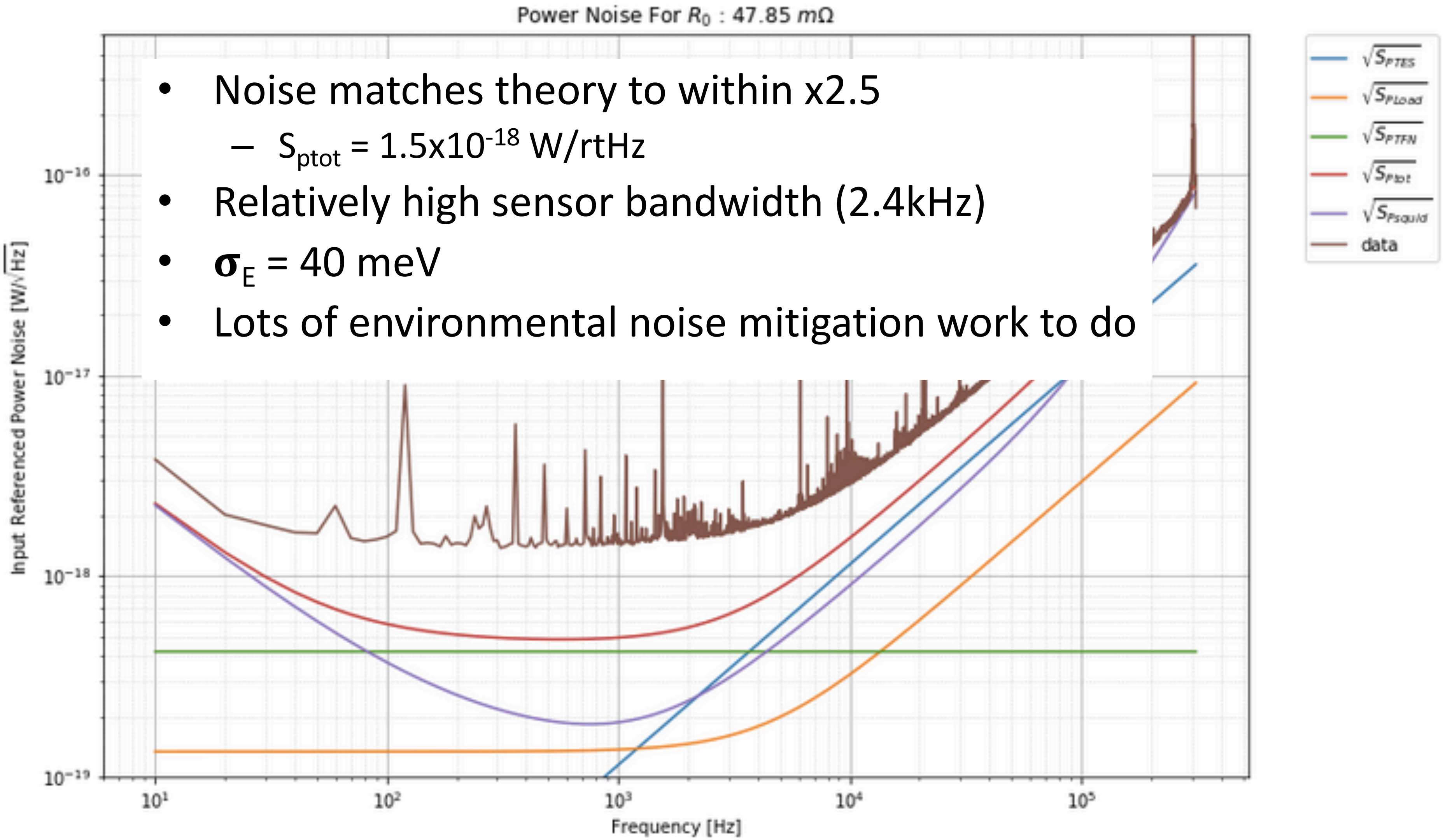
- T. Aramaki, P. Brink, C. Fink, R. Harris, Y. Kolomensky, R. Mahapatra, N. Mirabolfathi, R.Partridge, M. Platt, MP, B. Sadoulet, B. Serfass, S. Watkins
- 100umx400umx40nm W TES
- Tc= 41mK
- Normal Resistance: 630mOhm
- Bias Power: 35fW

- 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

TES Response to Square Wave Jitter

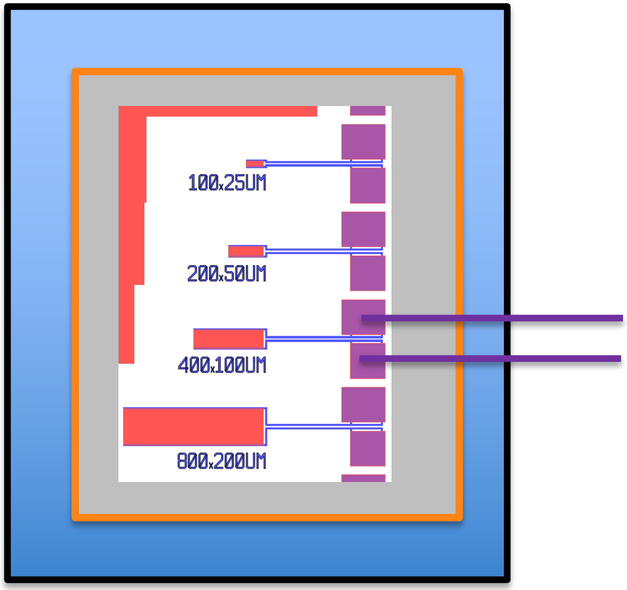


100um x400um TES Noise



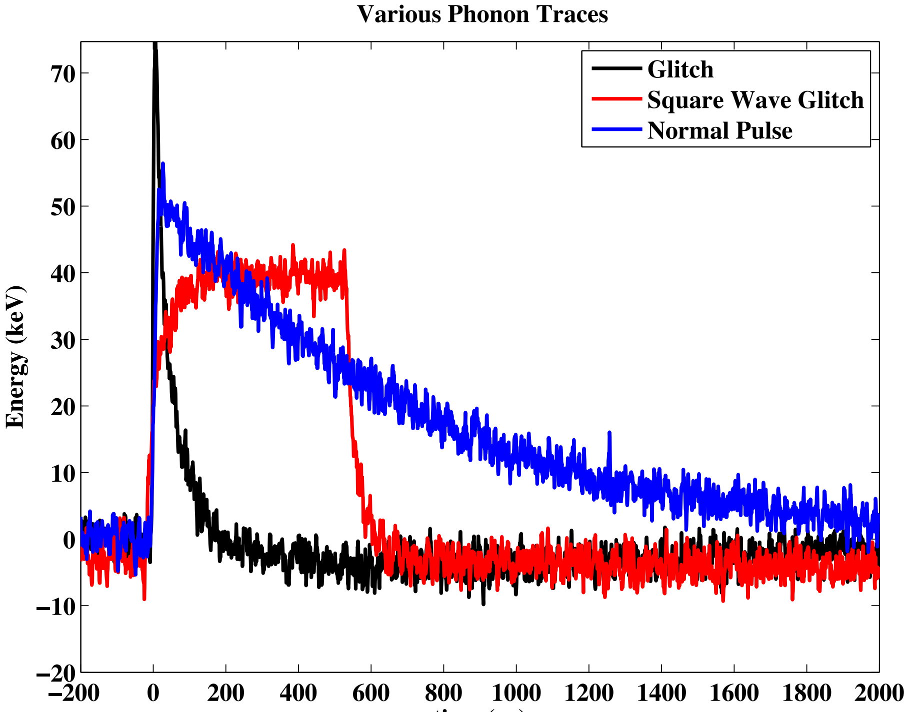
- Noise matches theory to within x2.5
  - S_{ptot} = 1.5x10^{-18} W/rtHz
- Relatively high sensor bandwidth (2.4kHz)
- **σ_E** = 40 meV
- Lots of environmental noise mitigation work to do

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

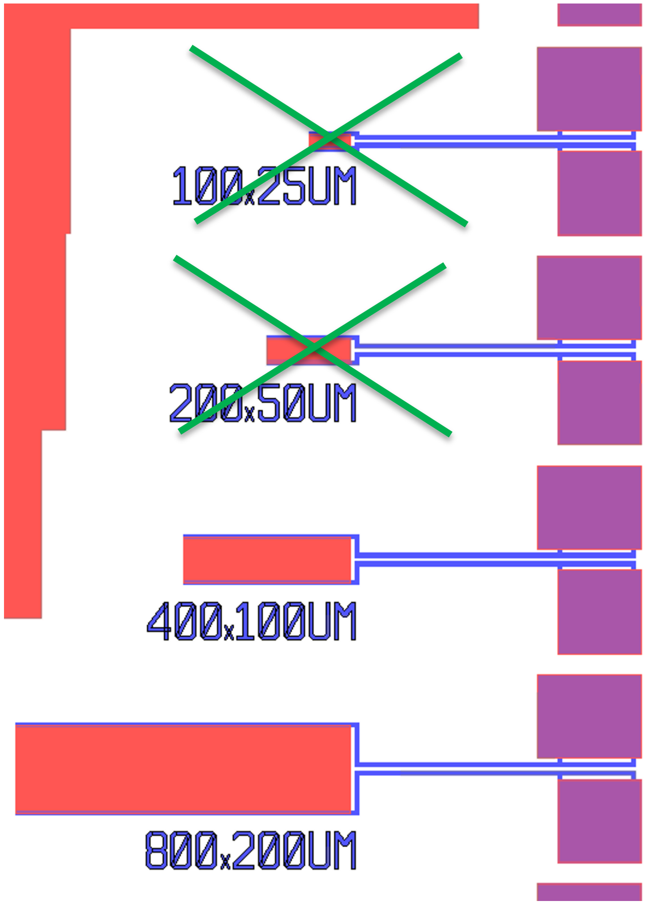

Various Phonon Traces

TES R&D

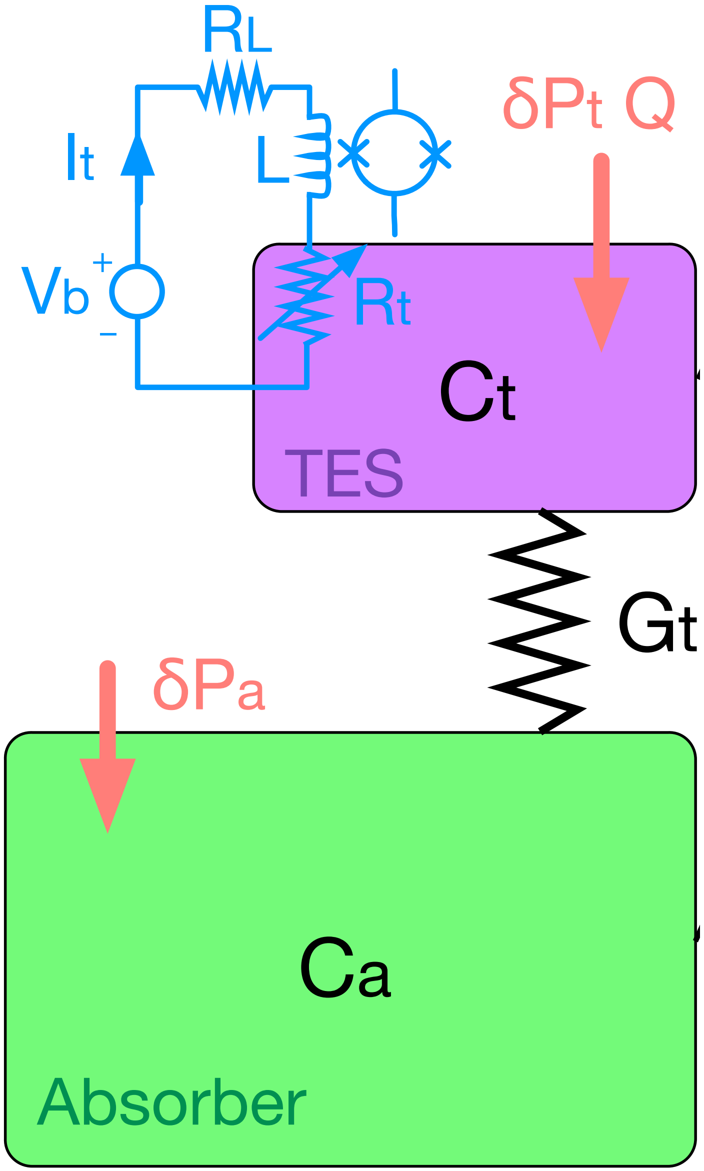
Energy Sensitivity: 40meV -> 1meV

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

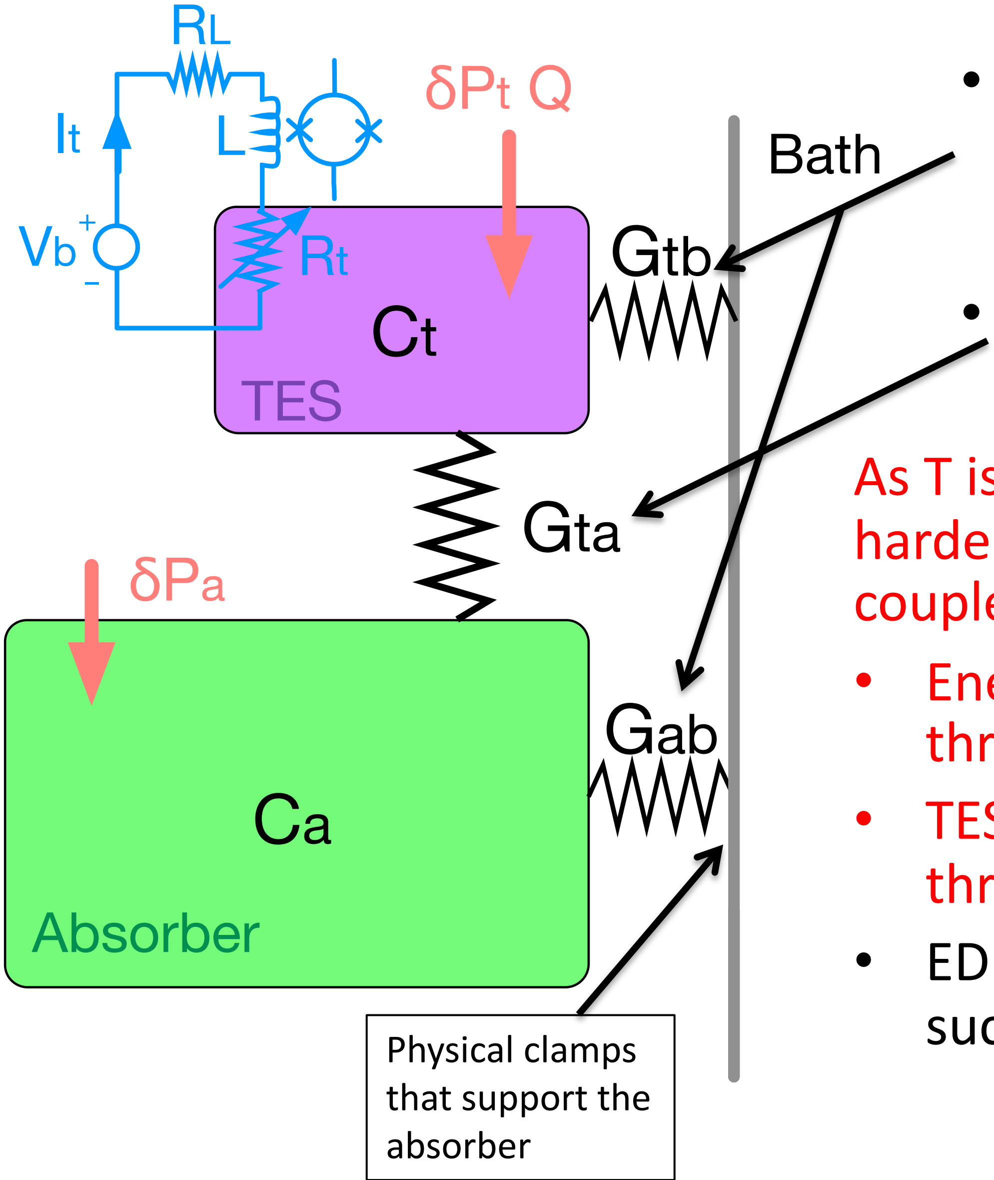


Increase Target Volume: Add Insulating Absorber



- Couple the sensor to a large volume insulator -> low heat capacity.
- Vibrational Energy in the Absorber is transported through Gt to the electronic system of the TES

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

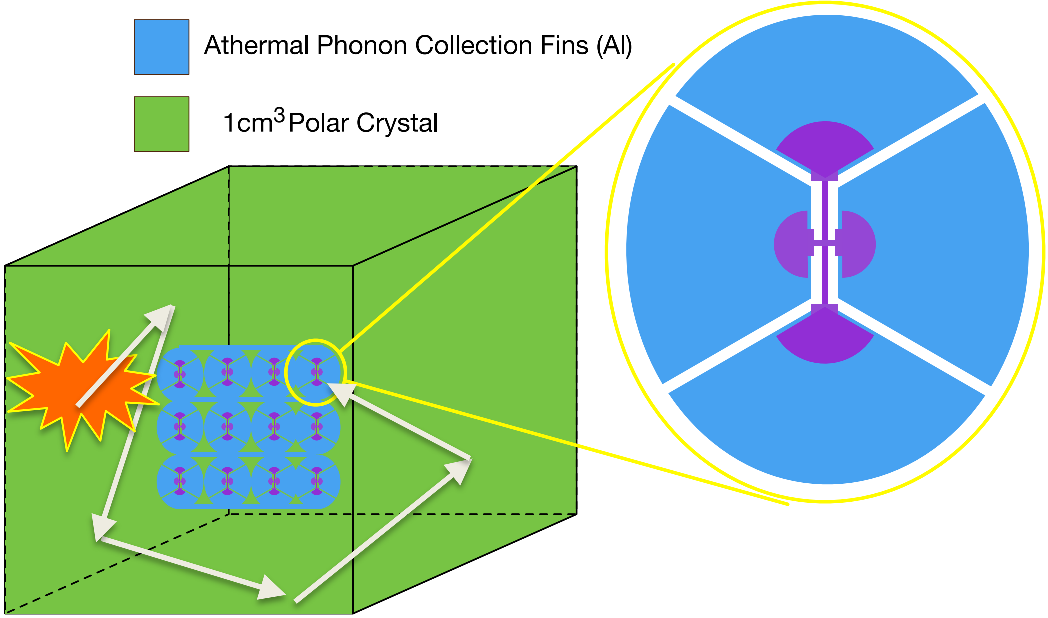
- Energy leaks out of the absorber through G_{ab} before its measured
- TES sensitive to power fluctuations through G_{tb}
- EDELWEISS has done this successfully

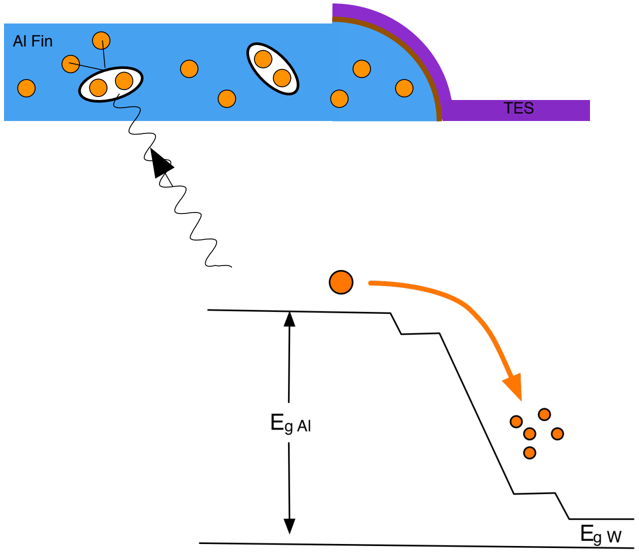
Athermal Phonon Sensor Technology

🟪 TES and QP collection antennas (W)

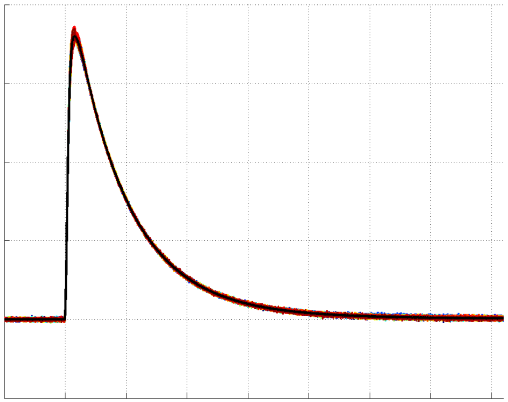
🟦 Athermal Phonon Collection Fins (Al)

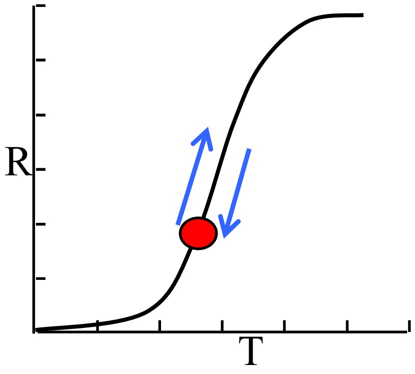
🟩 1cm^3 Polar Crystal



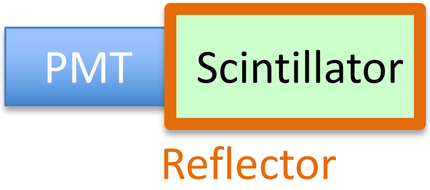


Collect and Concentrate Athermal Phonons (>4K) into Sensor before they thermalize





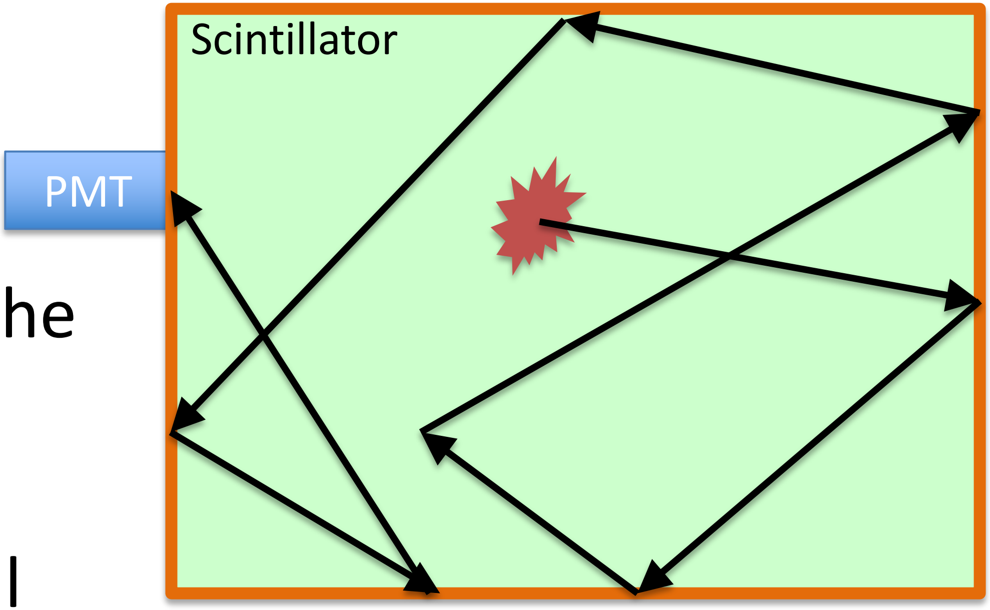
Excitation Detectors & Volume Scaling

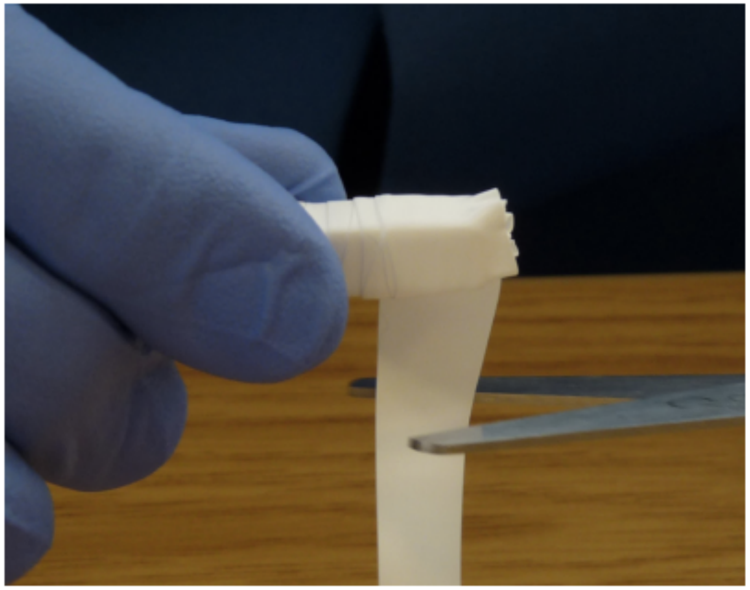


Will these detectors have the same energy sensitivity?

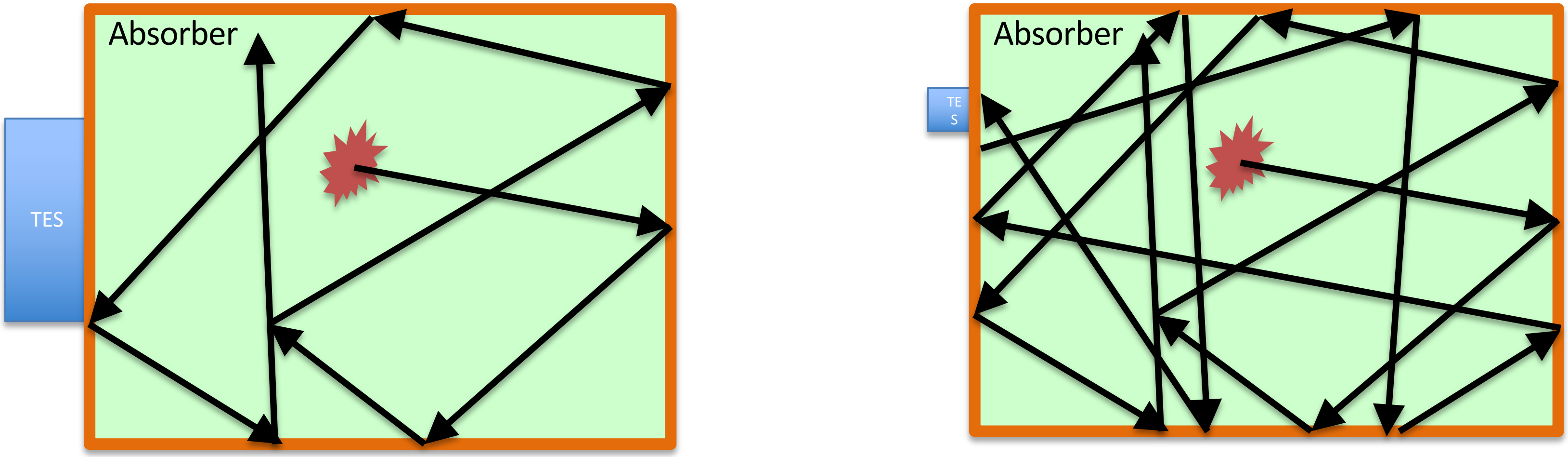
Yes, if:

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



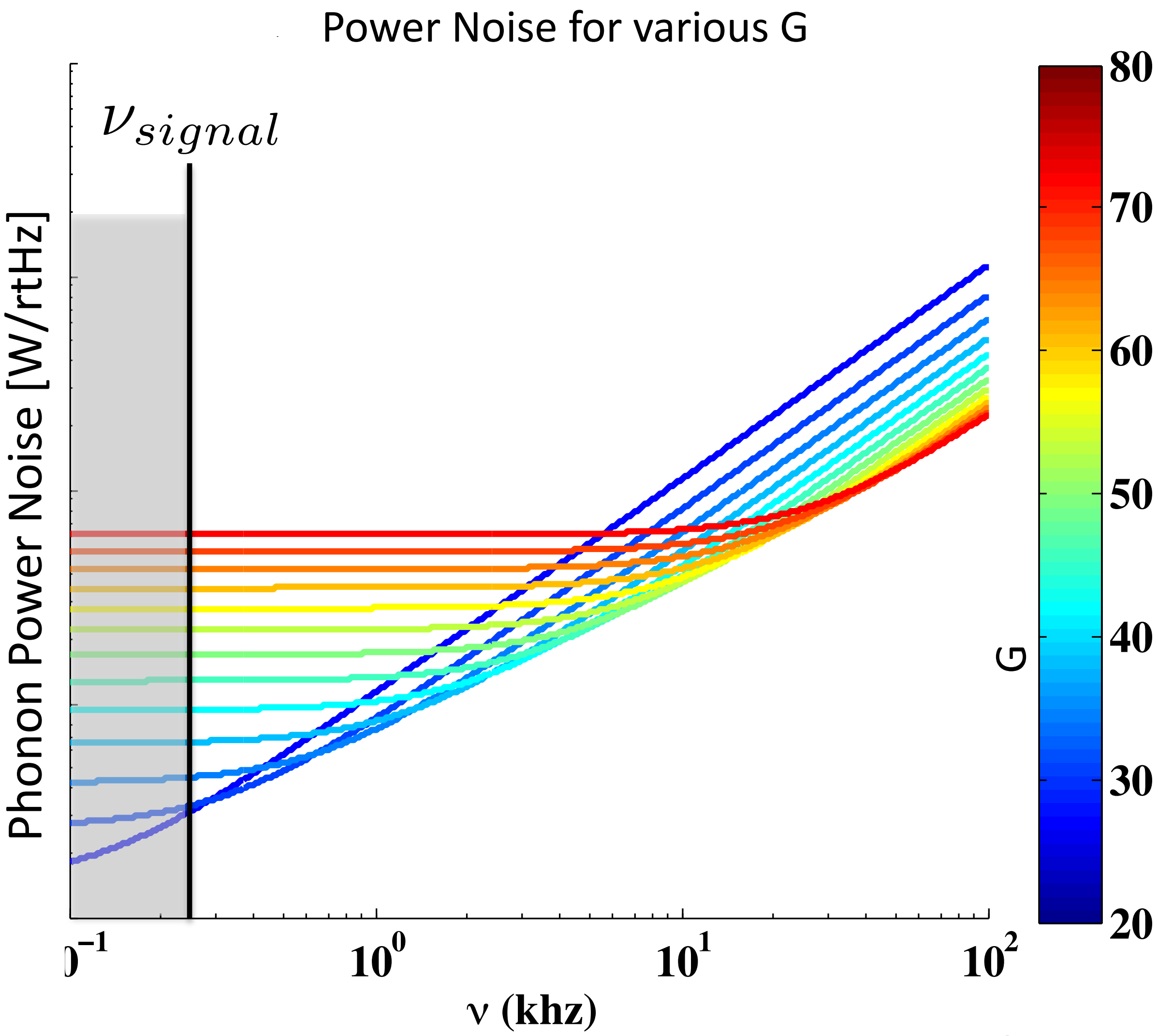


Optimizing the Athermal Phonon Excitation Detectors



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

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

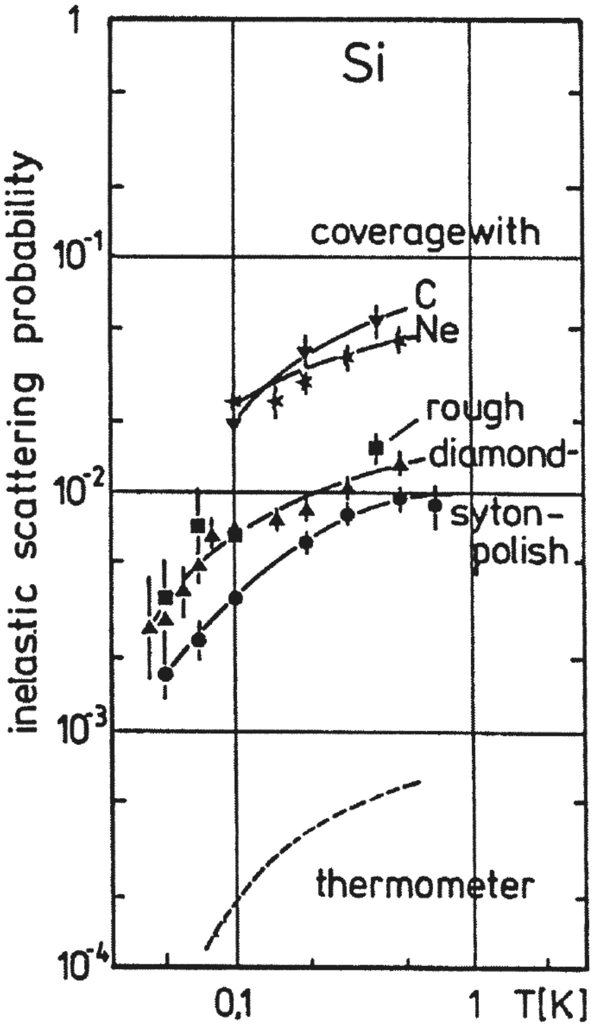
45mK-> 10mK: 2eV -> 20meV

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

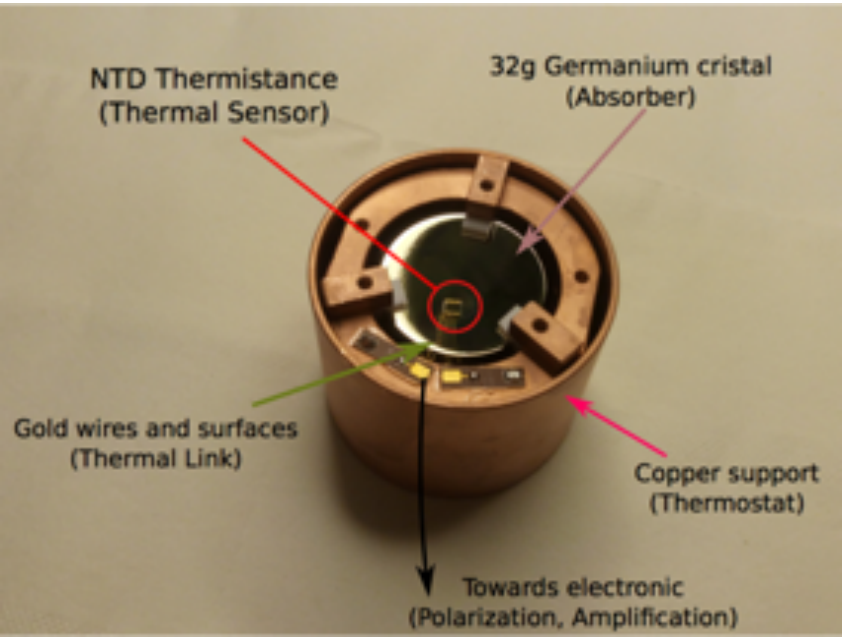


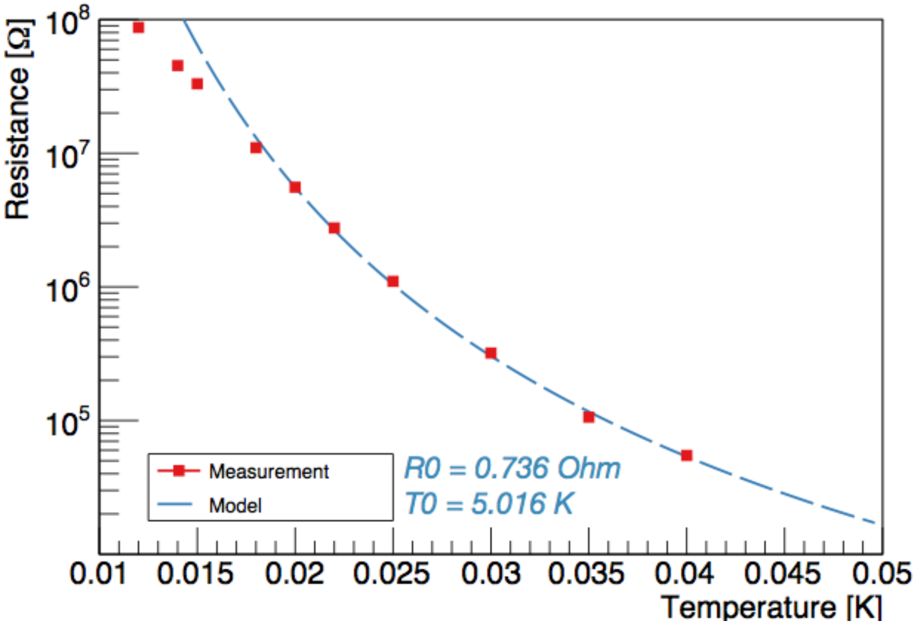
Large Area Photon Detectors

	Sensor	Area (cm2)	σ [eV]	σ/sqrt(A) [eV]
CRESST 2 LD Rothe et al JLTP 193,1160 (2018)	W TES	12.5	4-7	1.1-2.0
LAPD (CDMS tech)	W TES	45	3.9	0.58

NTD [Neutron Transmutation Doped Ge Thermistor]

NTD



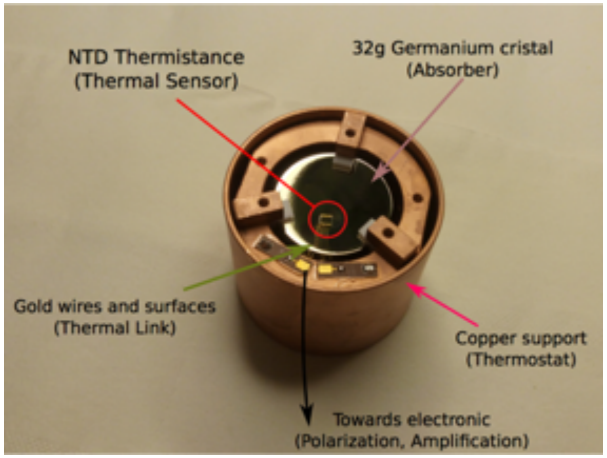


Thermal Calorimeter: $\sigma^2 \propto VT^3$

- Provided limited by TFN noise

Thermal/Athermal Phonon Detector

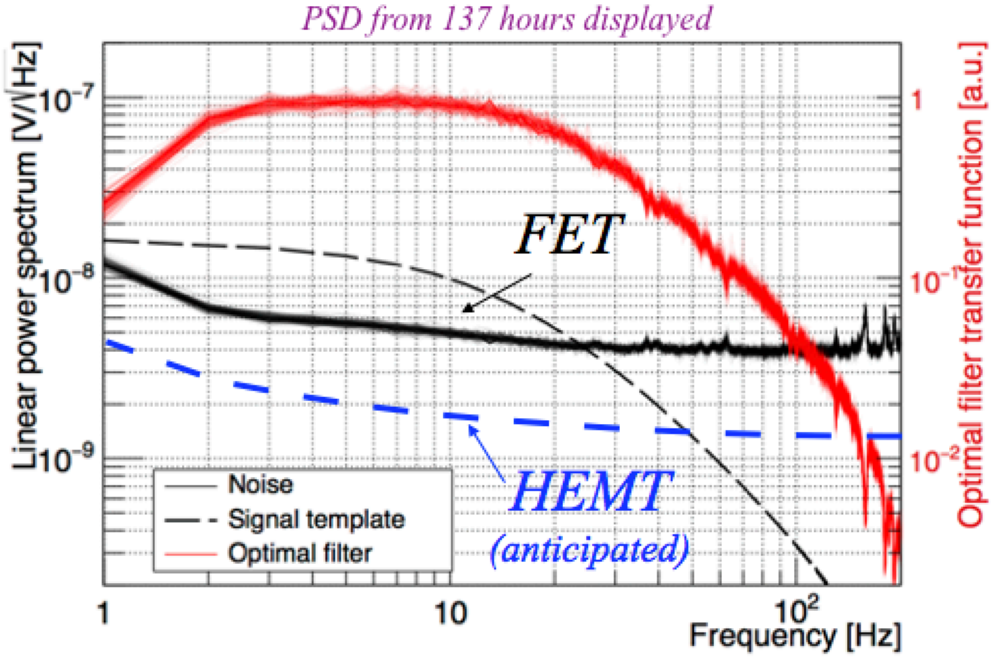
Ge Athermal/Phonon Detector



- 17.7eV on 33.4g Ge detector
- 50eV on 200g Ge detector

(x8 better than EDELWEISS 3 800g)

Hope to get to 10eV with improved electronics



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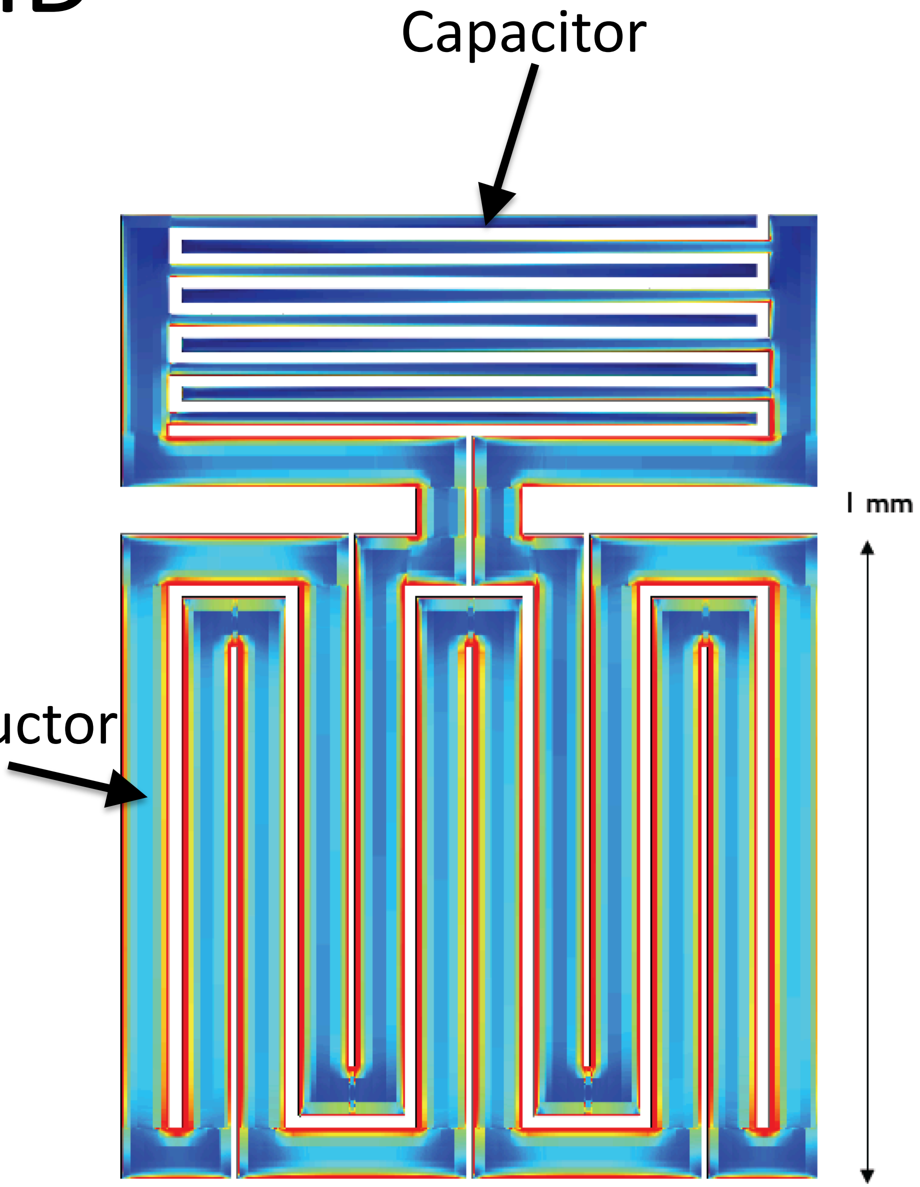
LMO-3 LD E. Armengaud et al, Eur. Phys. J. C (2017) 77 :785	NTD	5	7.7	3.4

MKID

MKID

Superconductors have an AC inductance due to inertia of cooper pairs

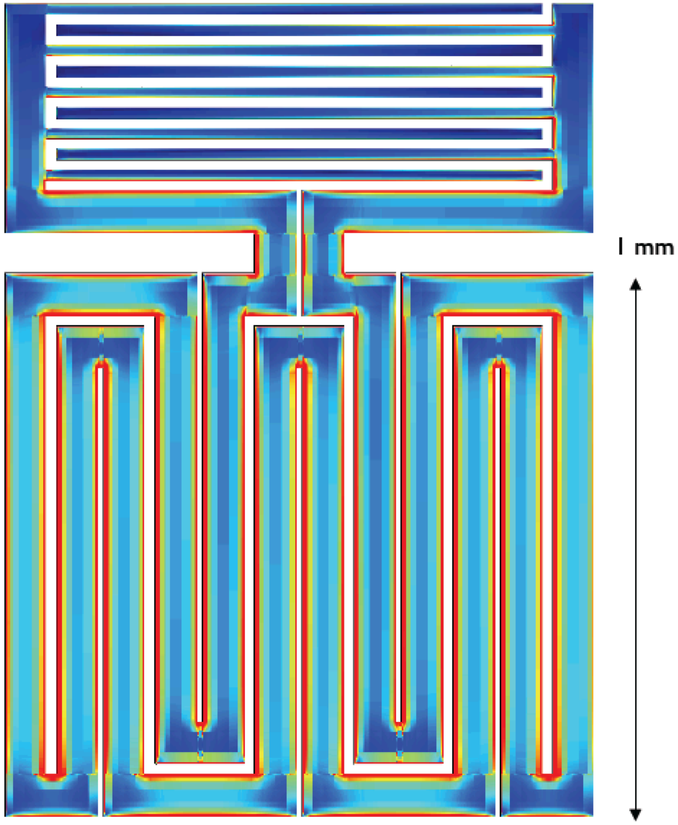
- fewer cooper pairs -> more inductance -> lower resonant frequency
- Easily Multiplexed
- 1mmx1mmx40nm active volume
- Frequency tuned by changing inductor length
- Capacitor: standard interdigitated capacitor to minimize TLS noise … can be made out of Nb to avoid phonon absorption



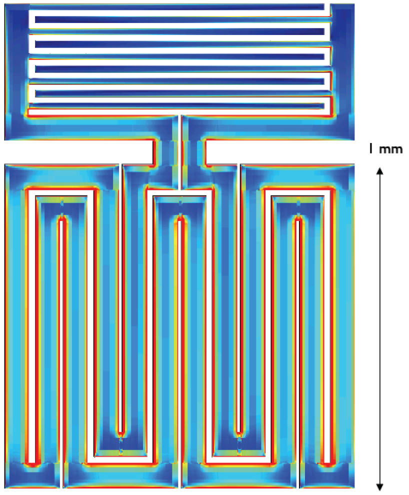
MKID Sensitivity

$$\sigma_E = 2\Delta\sqrt{\frac{\eta_a}{\chi_c\,\chi_{qp}}}\sqrt{\frac{k\,T_a\,N_0\,V_r}{\left[2N_0\Delta\,\frac{\partial(\sigma_1/|\sigma(0)|)}{\partial n_{qp}}\right]Q_s}}$$

- Scales with sensor volume
- Scales with amplifier noise temperature
  - 4K -> 70mK with parametric amplifier
- Scales with Tc / Δ
- Assumes no excess quasi-particle density
- Not sensitive to all frequencies of EMI

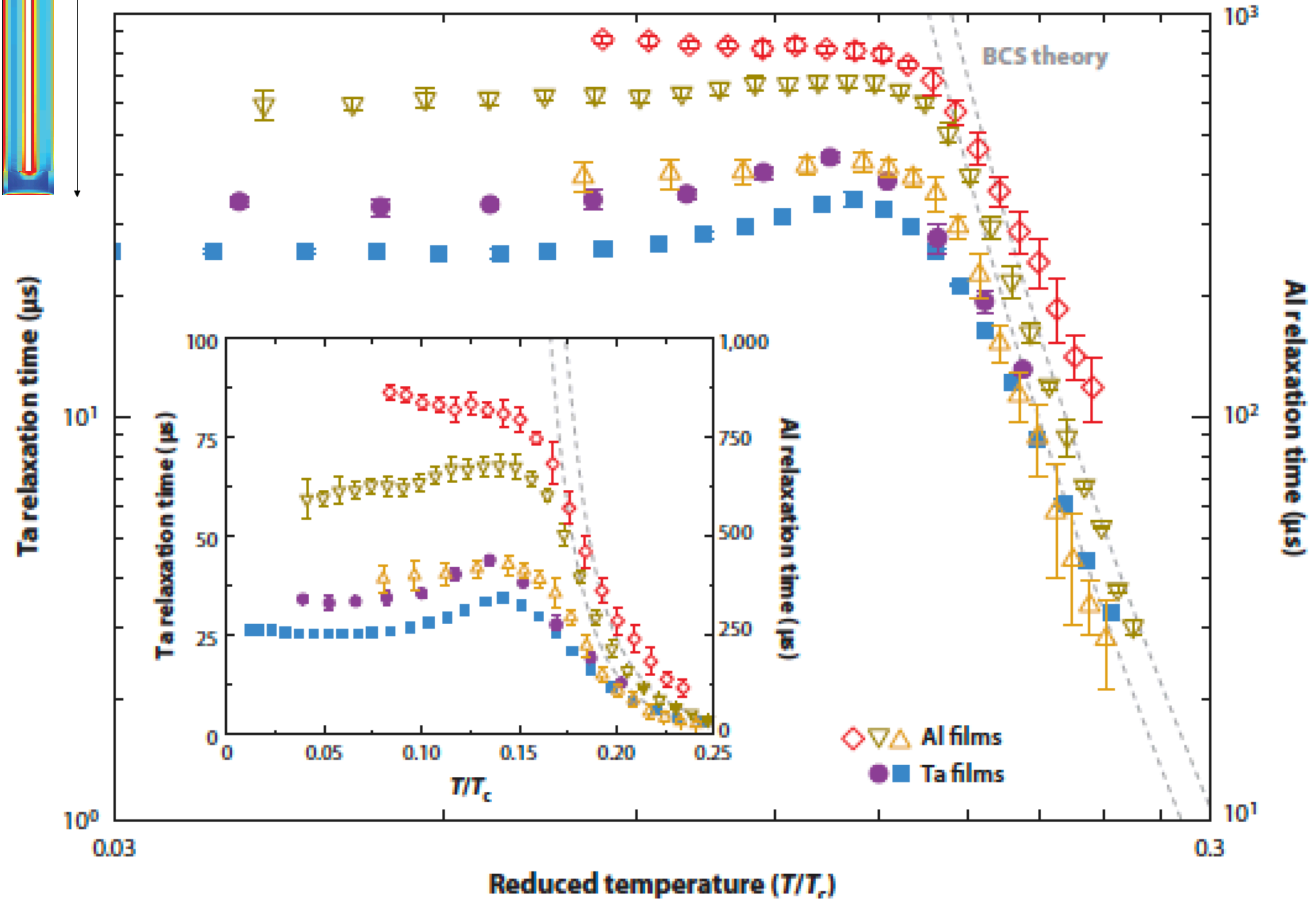


Excess Quasi-particle Density



asymptotic regime; limiting excess qp density n_*, or something else?

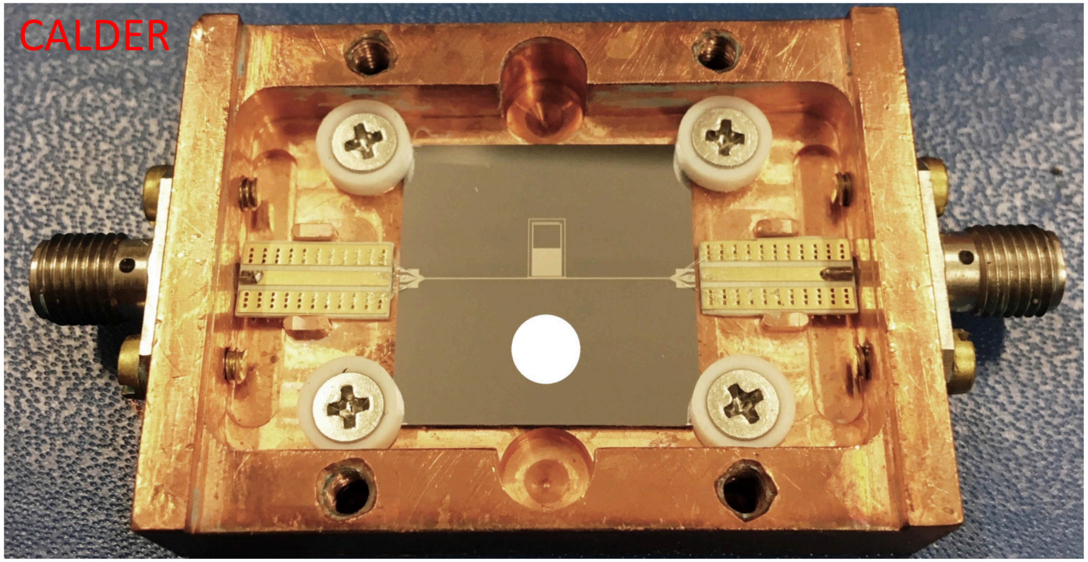
related to disorder? (Barends et al implantation experiment)

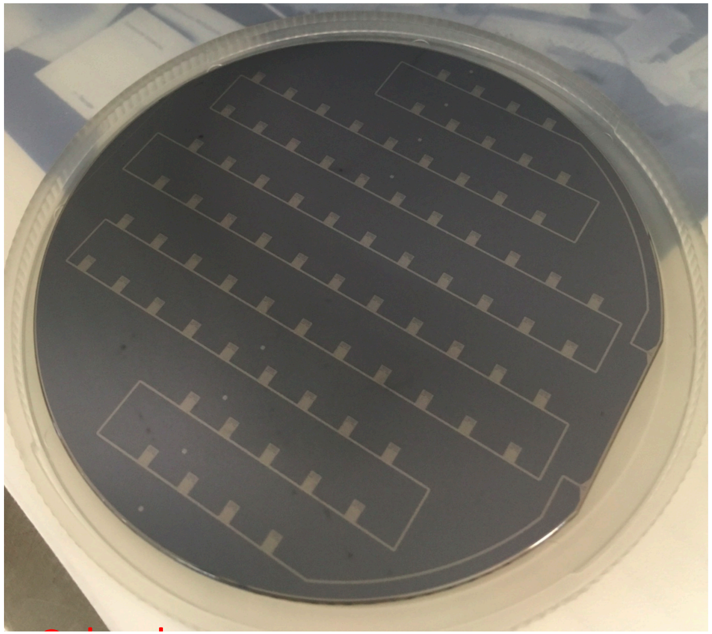


Barends et al PRL (2008)

as reproduced in Zmuidzinas,ARCMP (2012)

MKID: Athermal Phonon Sensor





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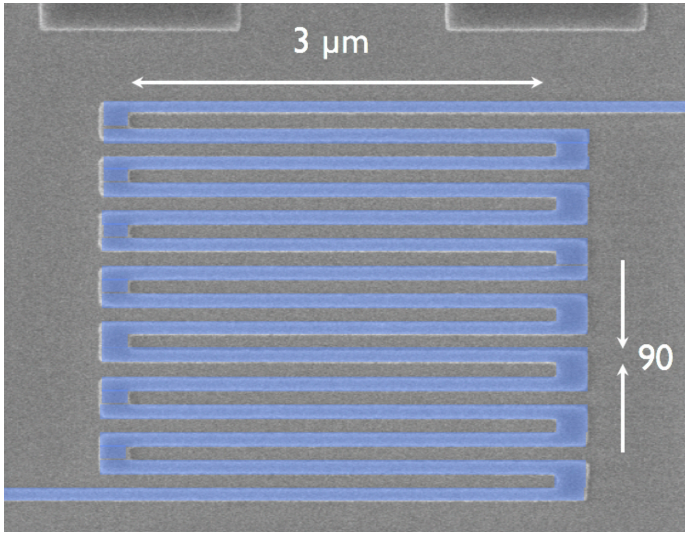
LAPD (CDMS tech)	W TES	45	3.9	0.58
LMO-3 LD E. Armengaud et al, Eur. Phys. J. C (2017) 77 :785	NTD	5	7.7	3.4
CALDER 1801.08403	Al/Ti/Al MKID	4	26	13

MKID R&D:

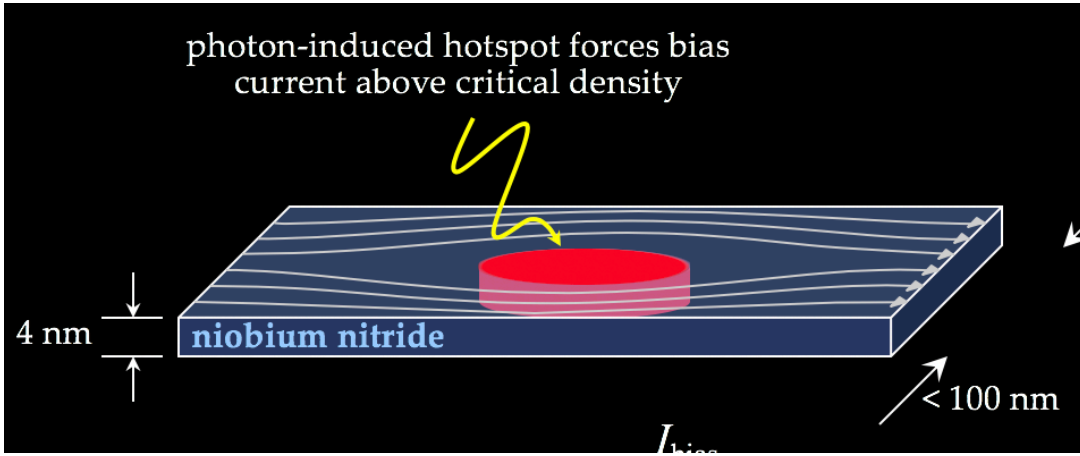
- Better Amplifiers (parametric amplifier at 70mK)
- Excess Quasi-particle density
- Two Level Systems

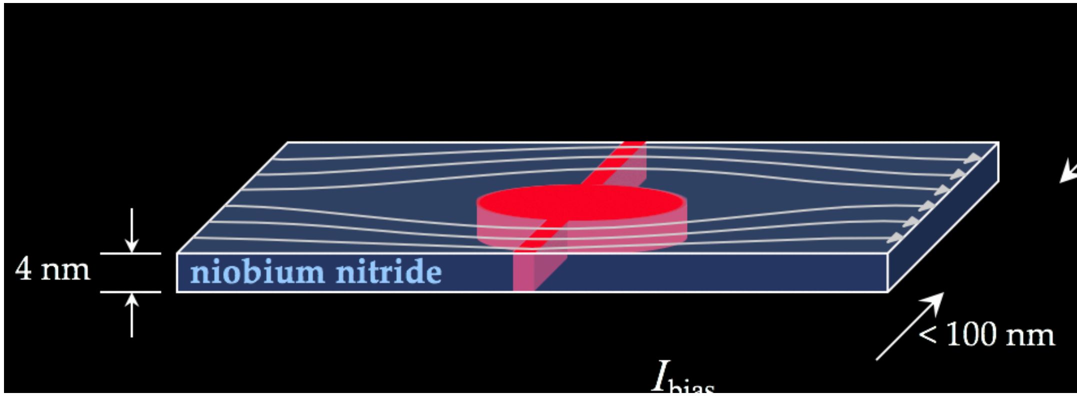
SNSPD
Superconducting Nanowire Single Photon Detector

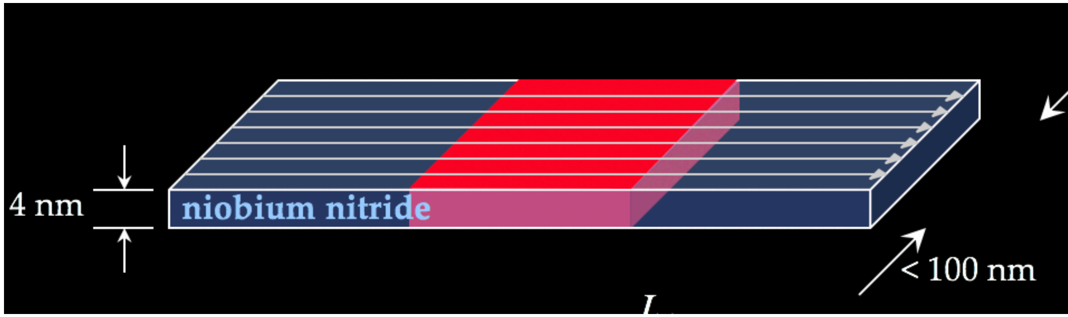
SNSPD: Operating principle



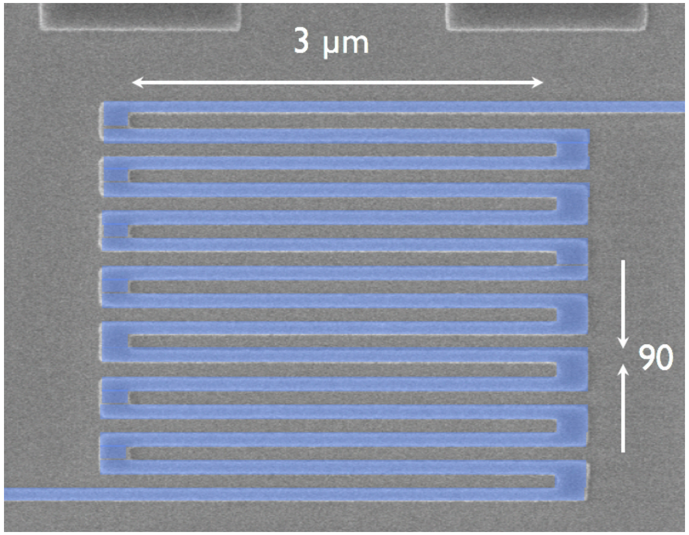
- SC wire biased very near critical current. Event causes nanowire to switch to normal state
- Natural Energy Amplification
- Event Measurement … doesn’t measure energy

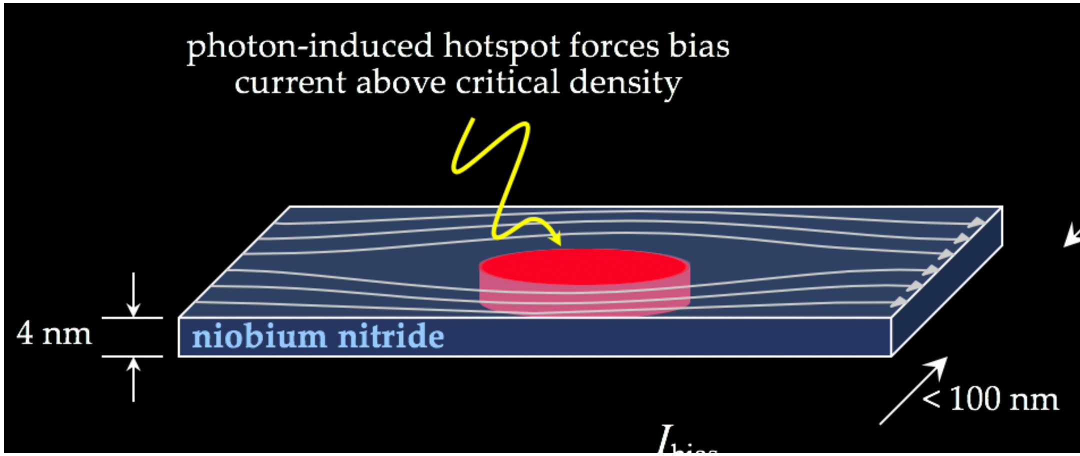

photon-induced hotspot forces bias current above critical density





SNSPD: Energy Threshold Scalings

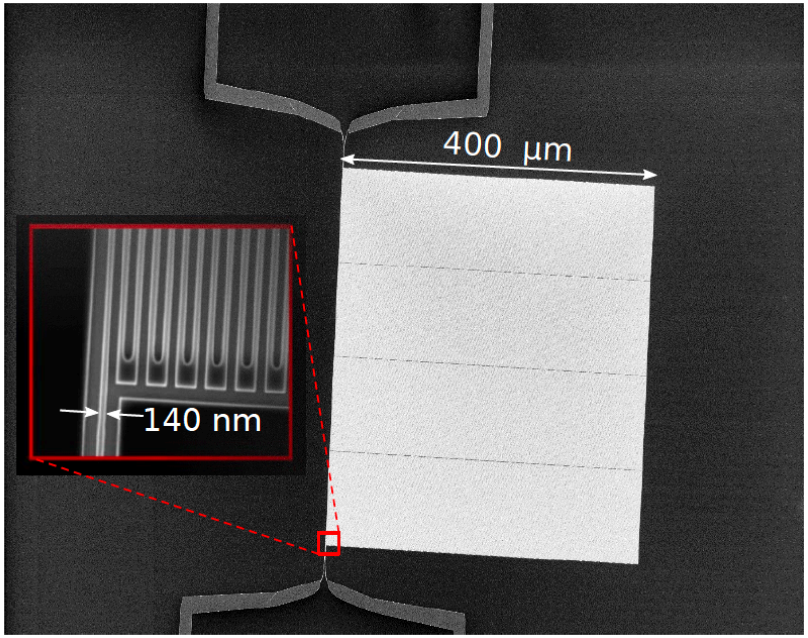



photon-induced hotspot forces bias current above critical density

Scales with cross sectional area, not volume.

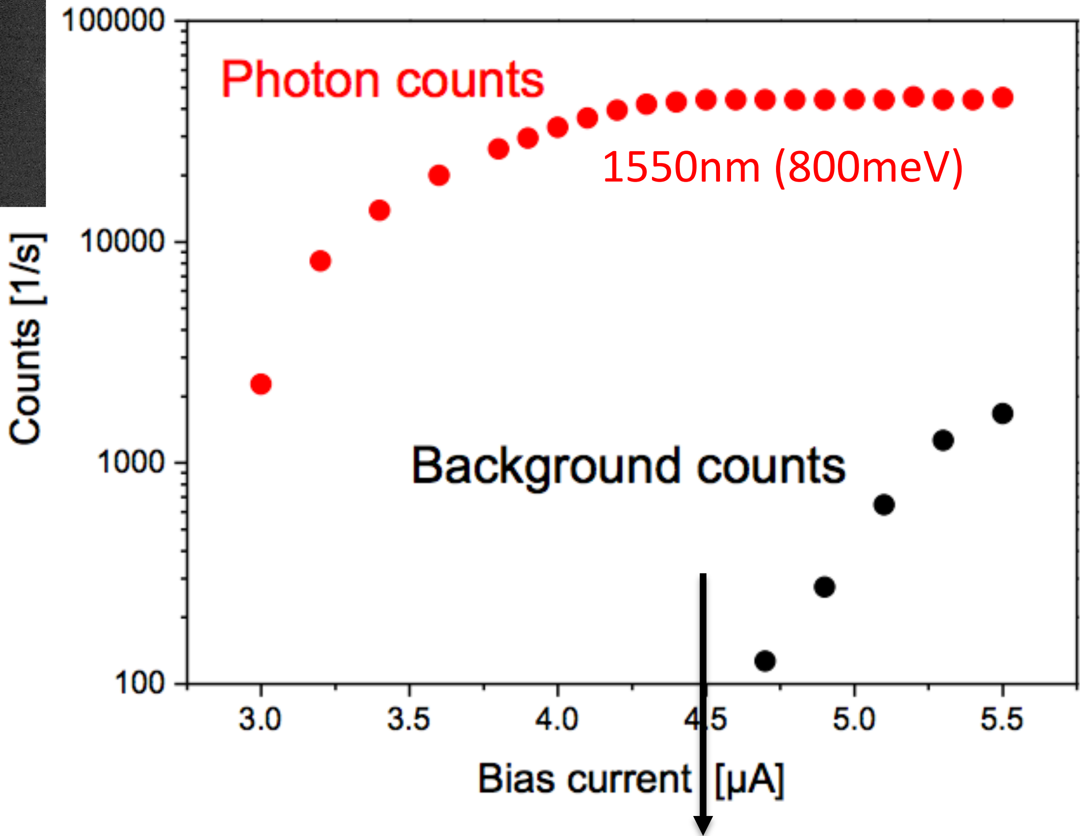
Can make the meander as long as you want

Current Performance

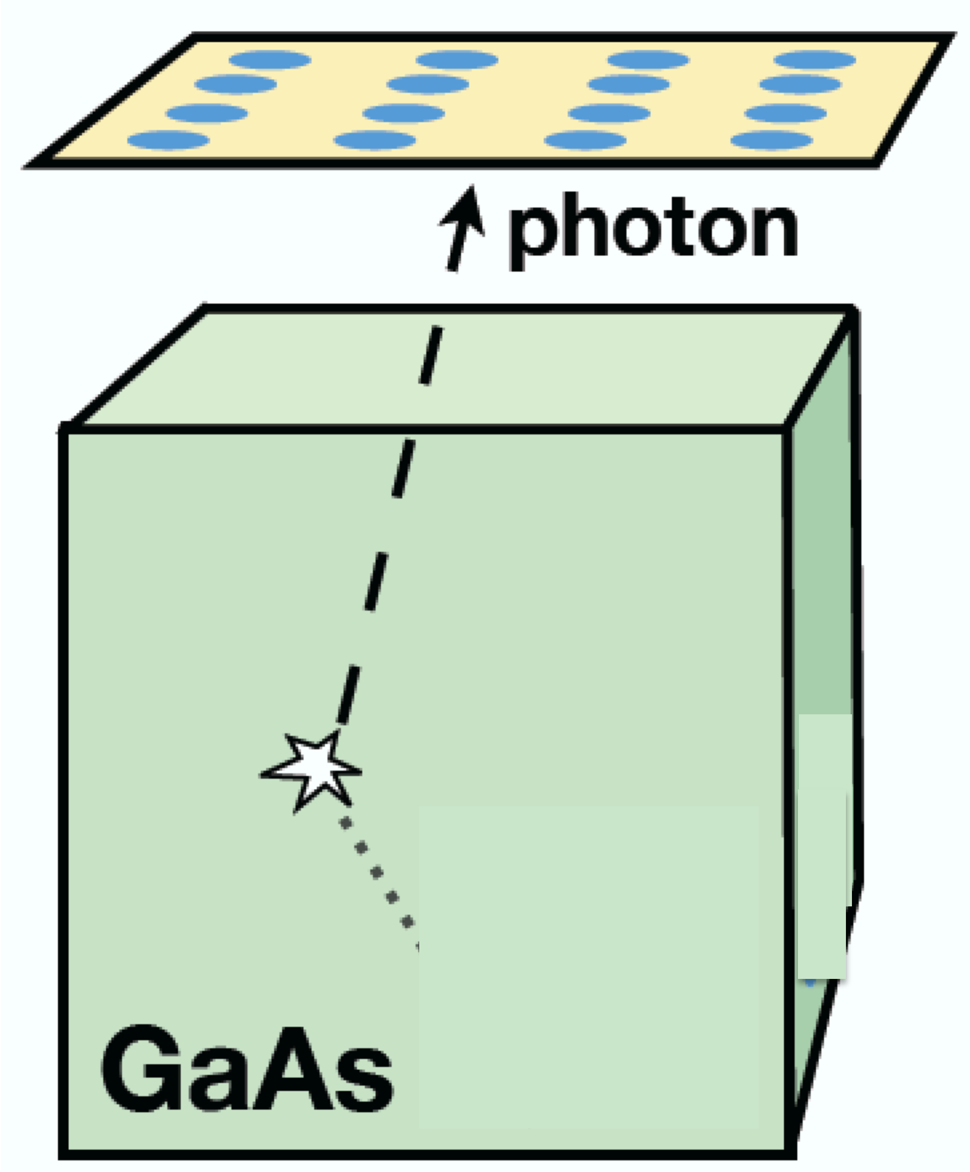


- 1903.05101
- WSi 400umx400umx7nm Meander

< 10^{-4} Hz dark count rate @ 4.5uA



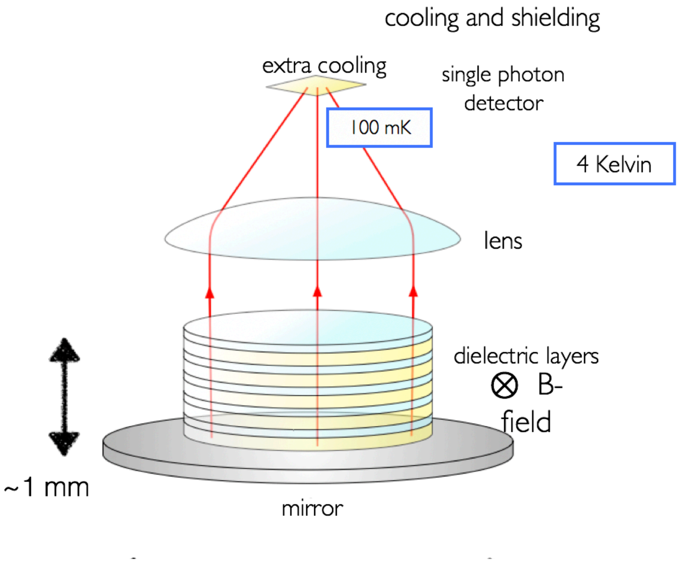
Measuring Energy With Multipixel SNSPD Arrays



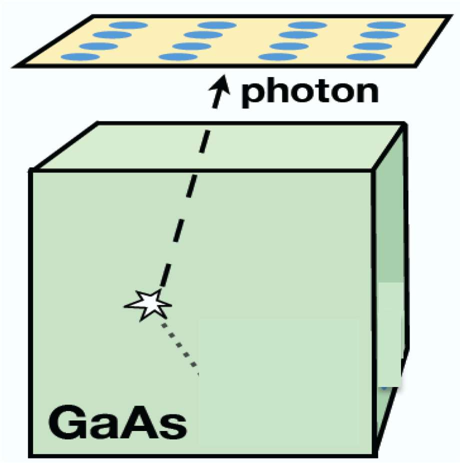
In the limit of large pixel number,
the probability of 2 photons hitting the same pixel is small (and can be corrected)
… it’s the same probability distribution as the shared birthday problem

SNSPD Applications

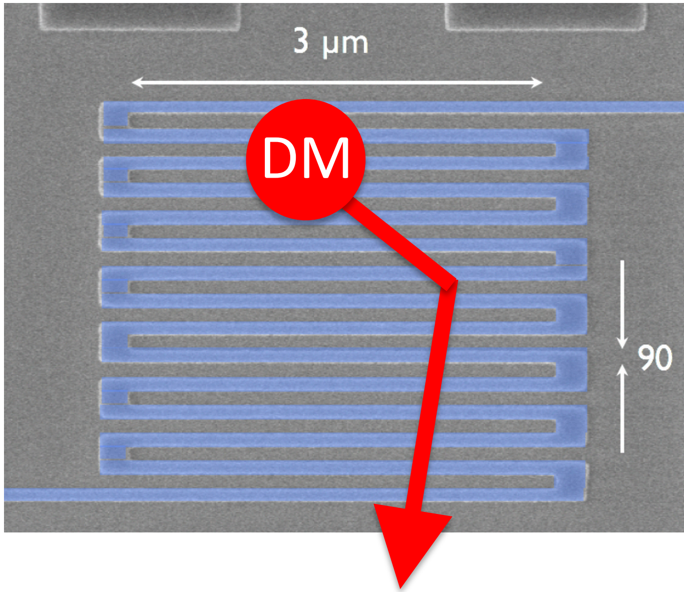
Optical/IR Haloscopes



Inelastic Electronic Recoil DM Search with Scintillator



Bulk DM search

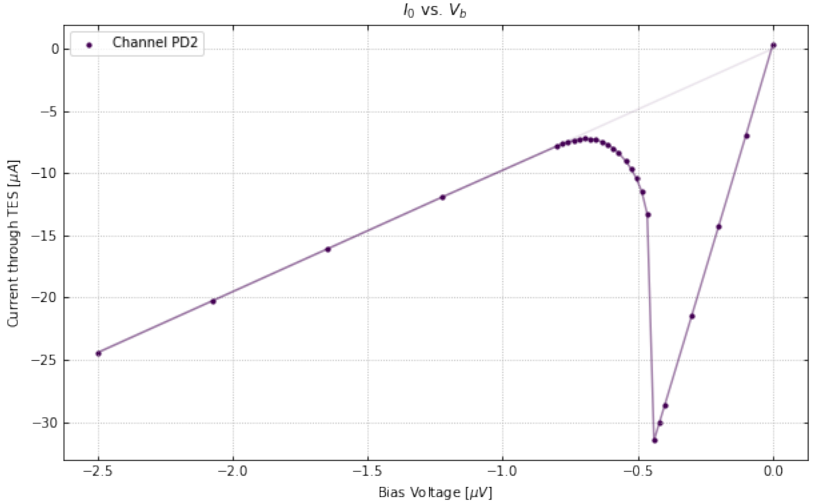


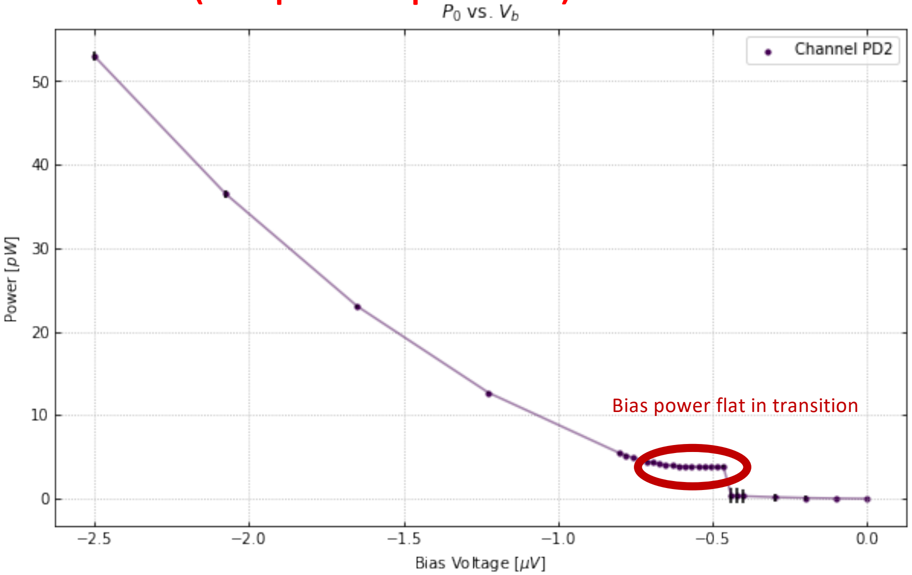
- 1903.05101
- 4.3ng per pixel
- $2.3\text{x}10^8$ channels for 1g

Backup

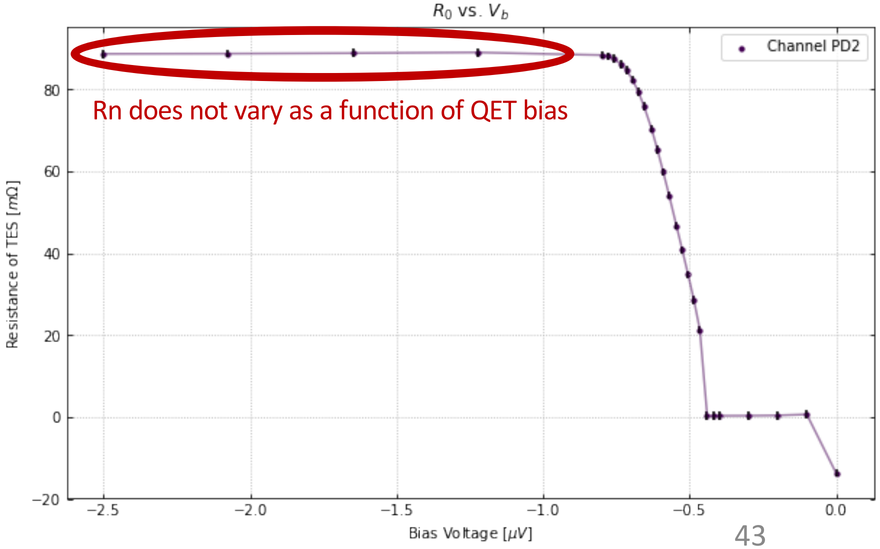
Measured Performance: Tc & IV

- 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)



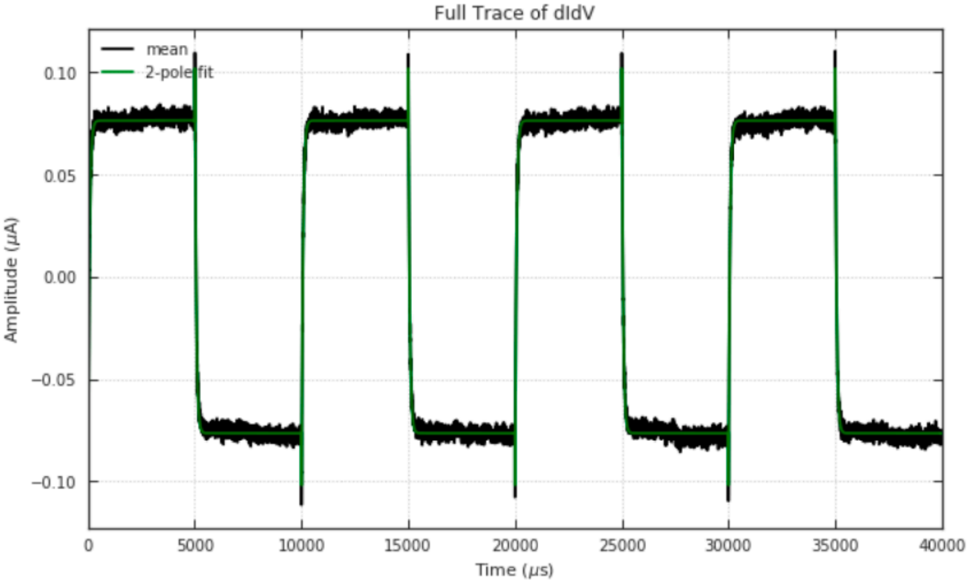


Bias power flat in transition



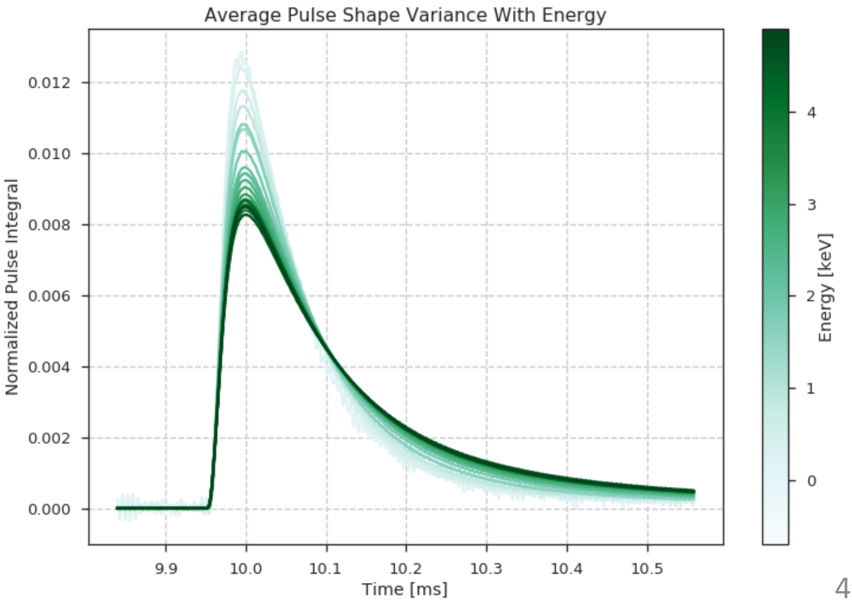
Rn does not vary as a function of QET bias

Measured Performance: dIdV

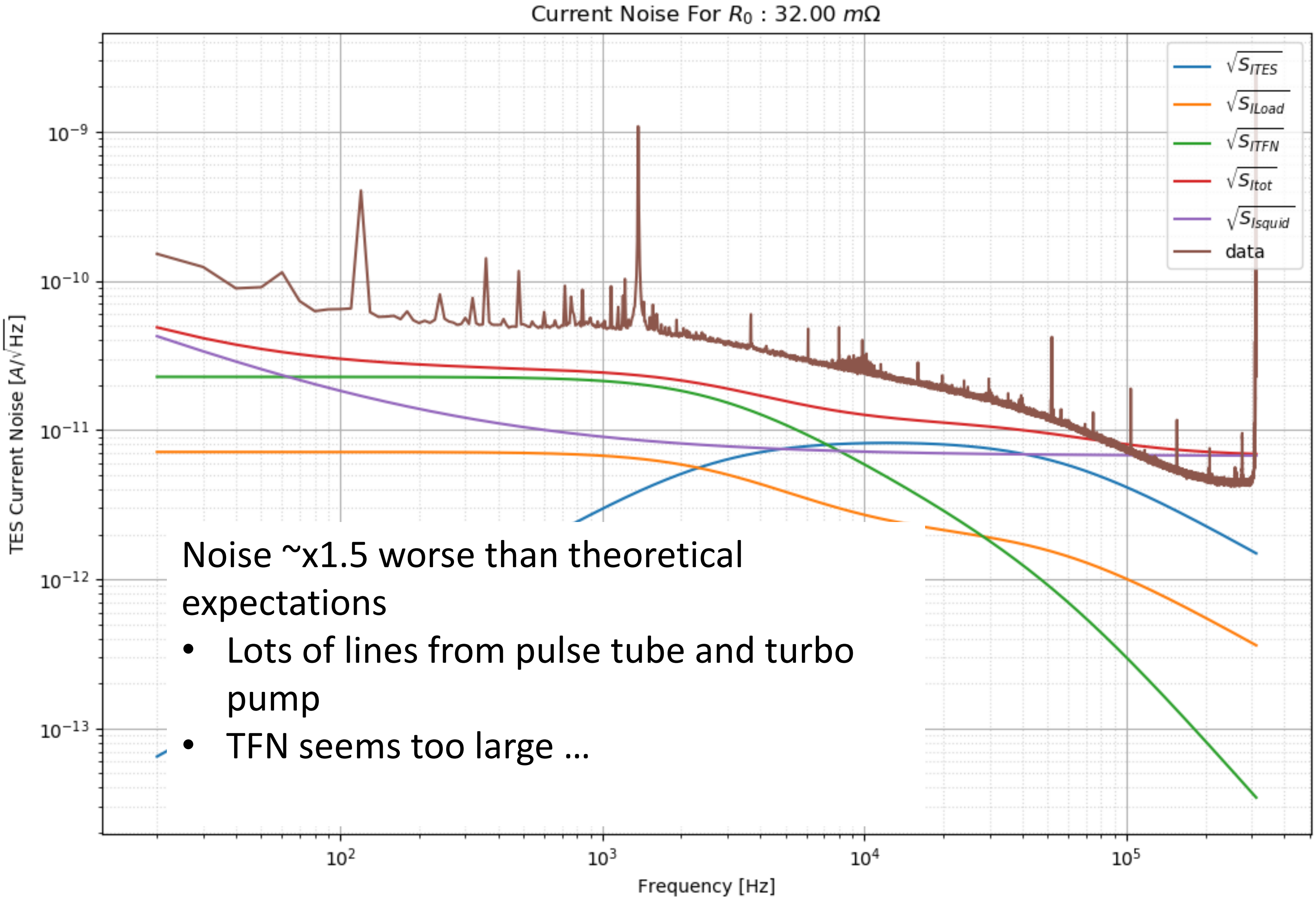


- TES sensor pretty fast @ 60us. However, it's not as fast as the estimated athermal phonon collection (20us)

- 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

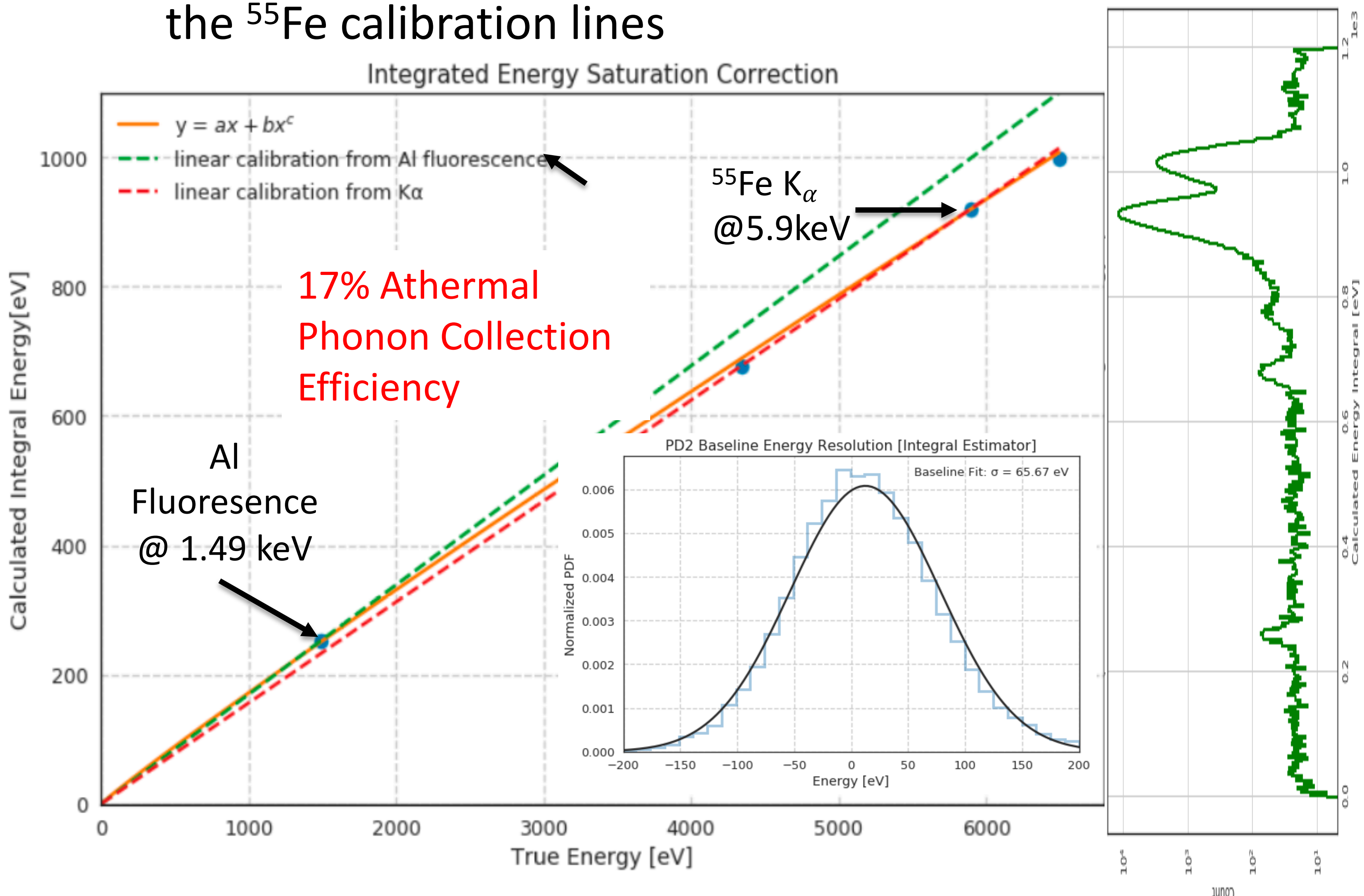


Noise ~x1.5 worse than theoretical expectations

- 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

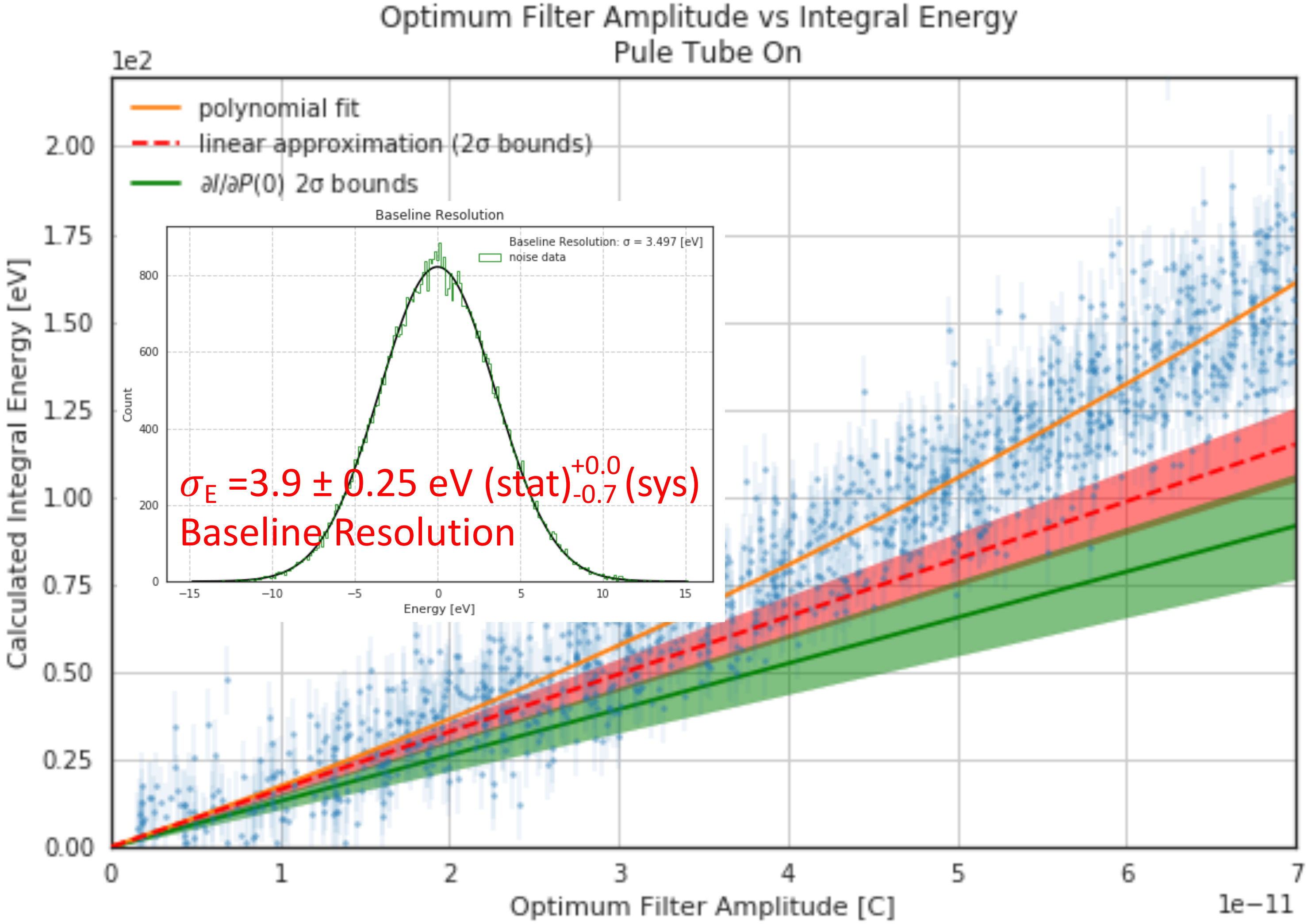


^{55}Fe K_α
@5.9keV

17% Athermal Phonon Collection Efficiency

Al Fluoresence
@ 1.49 keV

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

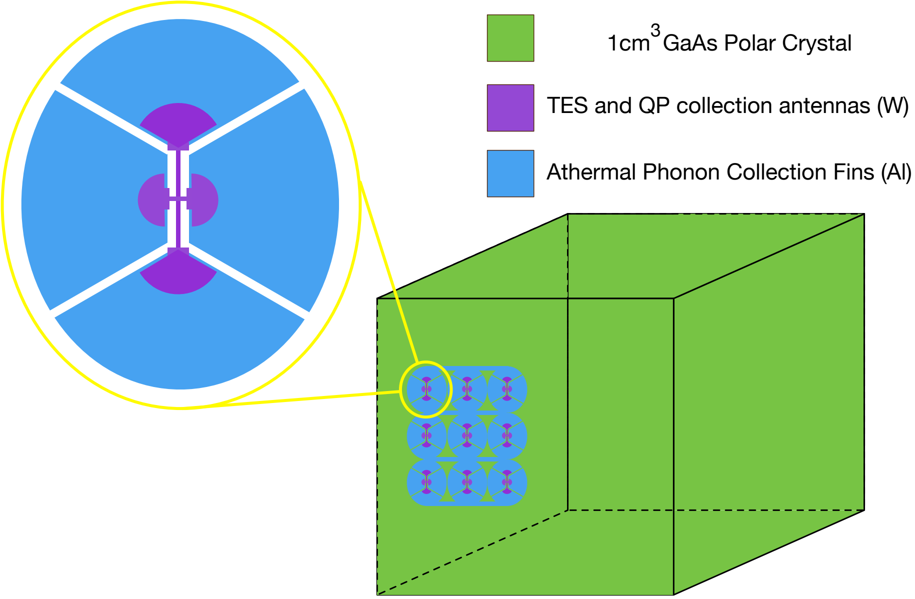


$\sigma_E = 3.9 \pm 0.25$ eV (stat)$^{+0.0}_{-0.7}$(sys)

Baseline Resolution

Surface Dark Matter Search Completed at SLAC

Prototype Design Estimated Sensitivities

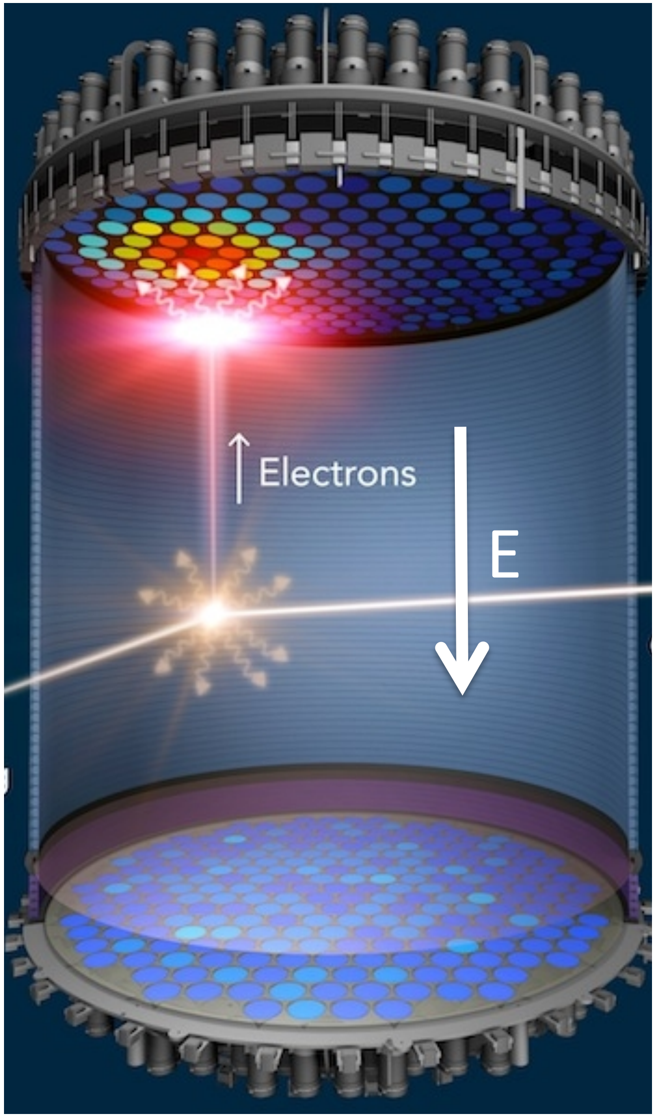


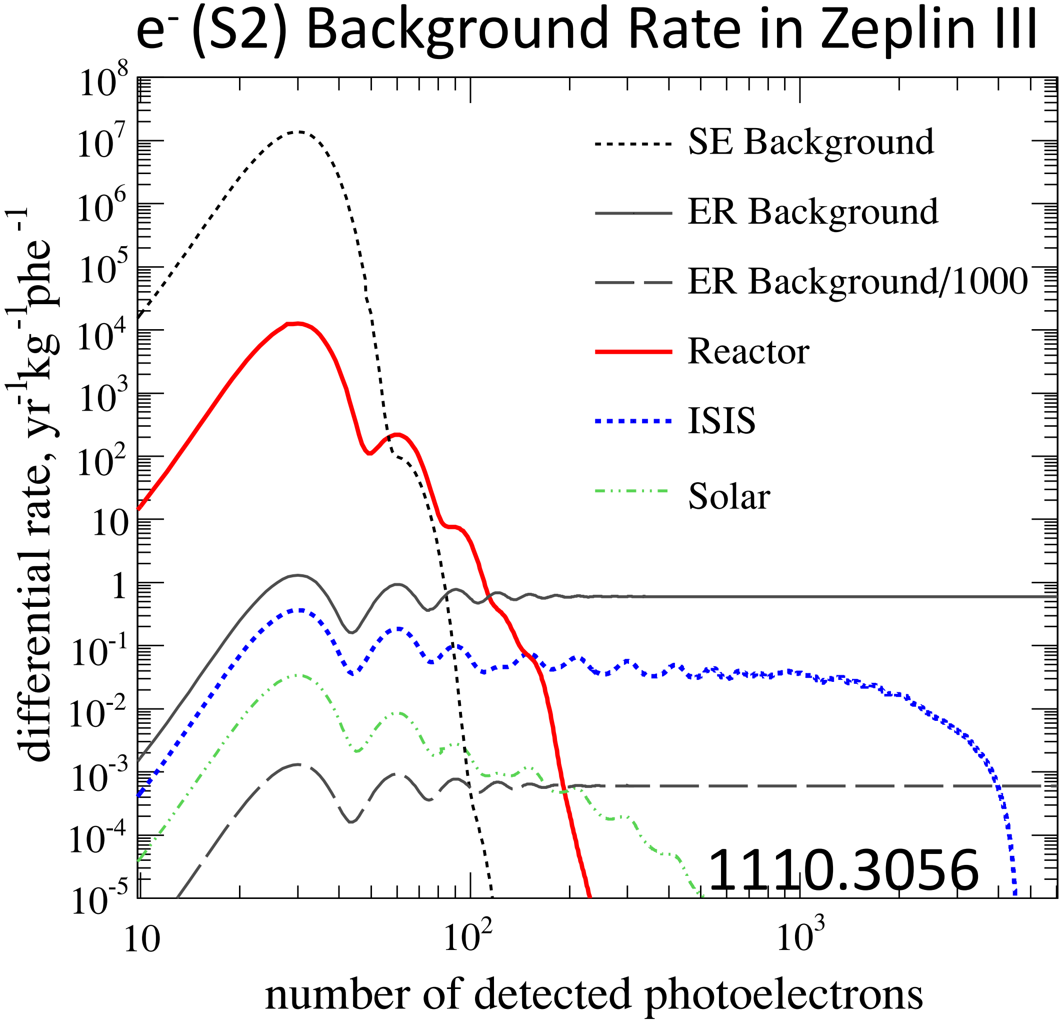
New 1cm^3 Prototype Test Design

# 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**

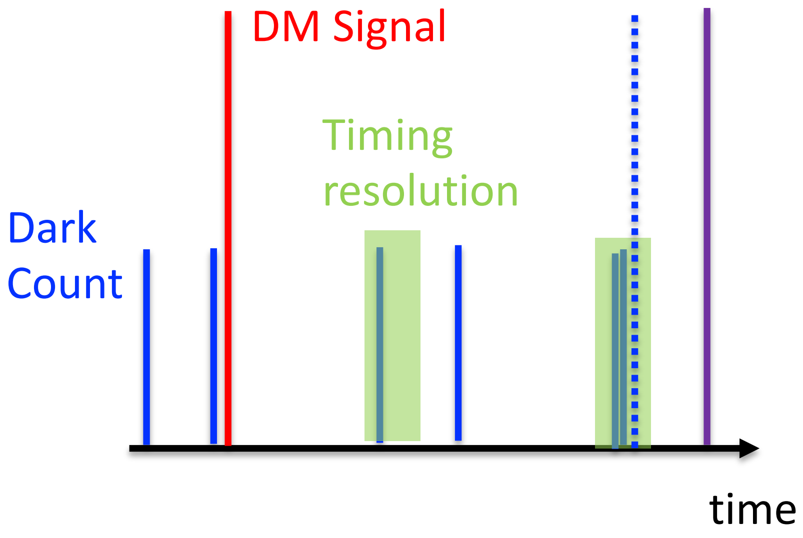
- With a Si Absorber: single e/h sensitivity without Luke-Neganov gain. Can be used for inelastic electronic recoil DM
- World Leading Elastic Nuclear Recoil DM search potential

Problem: Detector Backgrounds in TPCs





Dark Leakage Needs to be Poissonian



N e^- background

- N $1e^-$ events occur within detector timing resolution (Poissonian Leakage)
- N e^- leakage event (Non-Poissonian Leakage)

Xenon TPCs:

- R_{1e-} =10Hz
- Δt =100ns
- R_{2e-}(Poissonian) =10^{-5}Hz

Due to fast timing Xe TPCs can handle a relatively high $1e^-$ rate and still have $2e^-$ bin free. Unfortunately, leakage is non-poissonian (R&D needed)