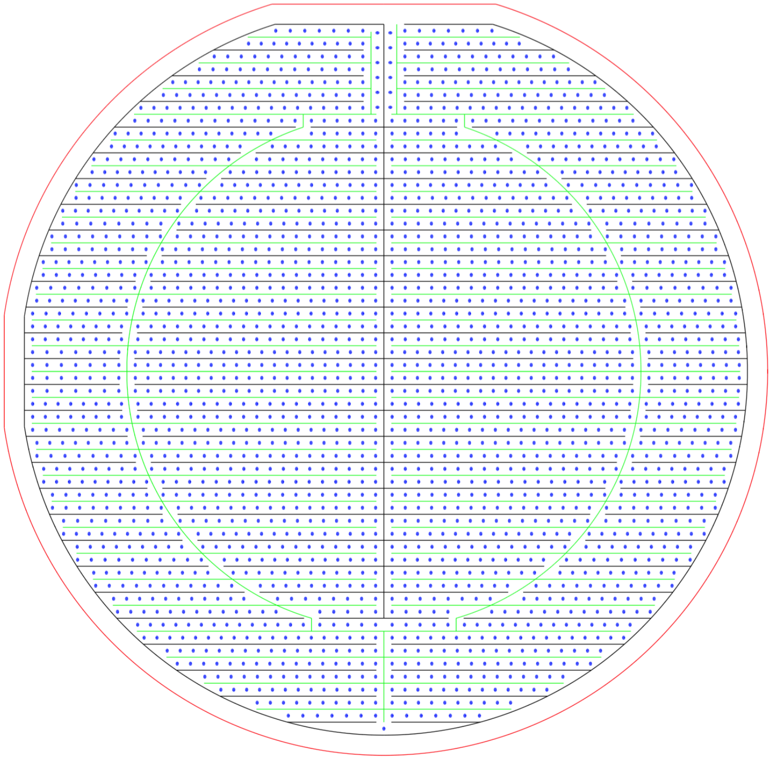
Calorimetric Detector Technology for Roton and Scintillation Photon (GaAs) Detection

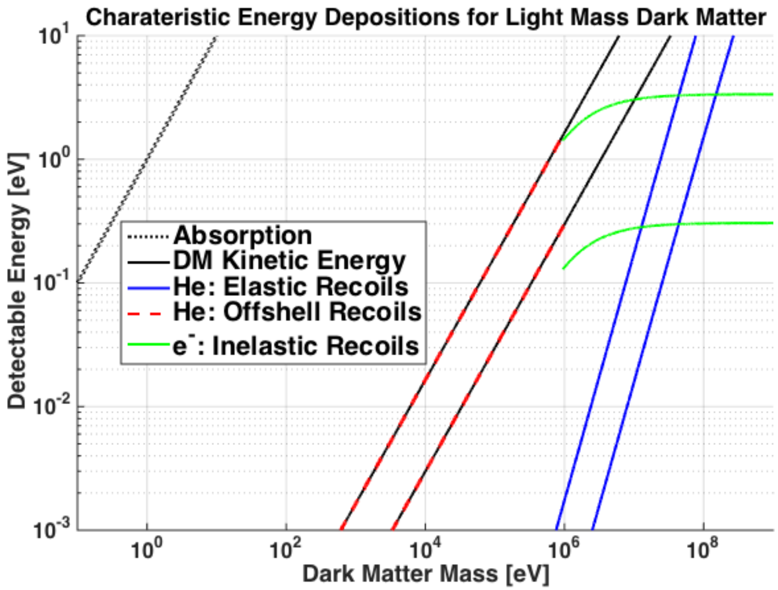


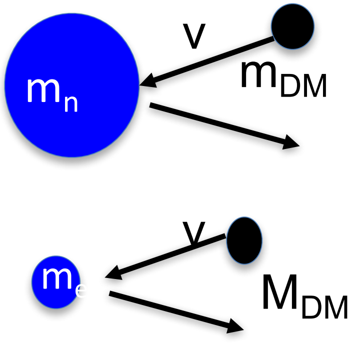
Matt Pyle
(for lots of People)
UC Berkeley

Cosmic Visions
03/23/17

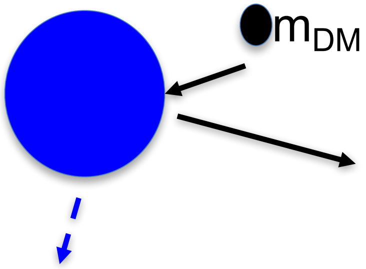
10meV-100MeV DM Detector Requirements:
1) Sensitivity to small energy recoils

- Dark matter is cold:
- $K = \frac{1}{2} M_{DM} V^2$ is tiny

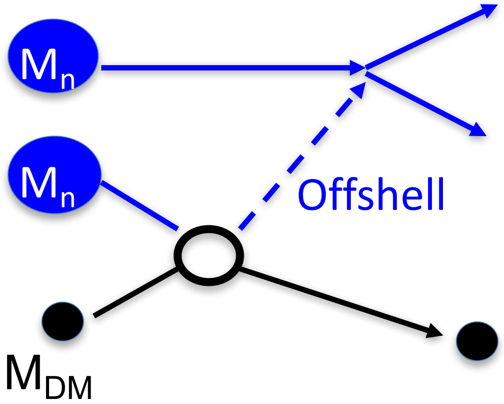




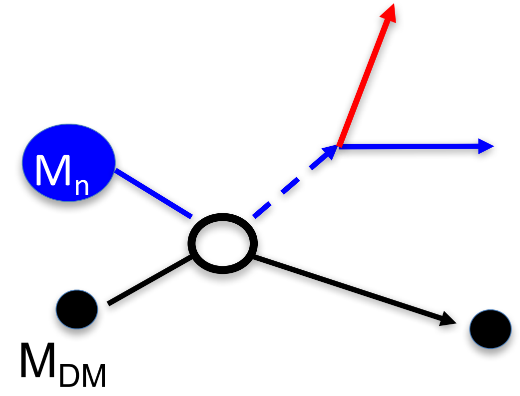
Elastic Nuclear and Electronic Recoils



Absorption

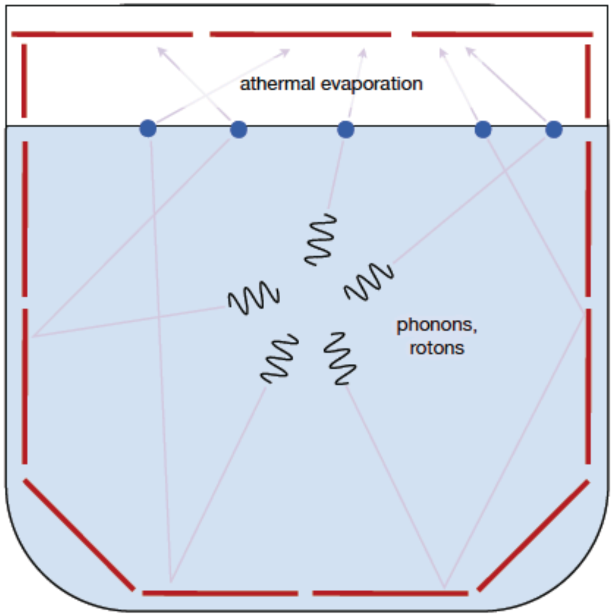


Offshell Nuclear Recoils

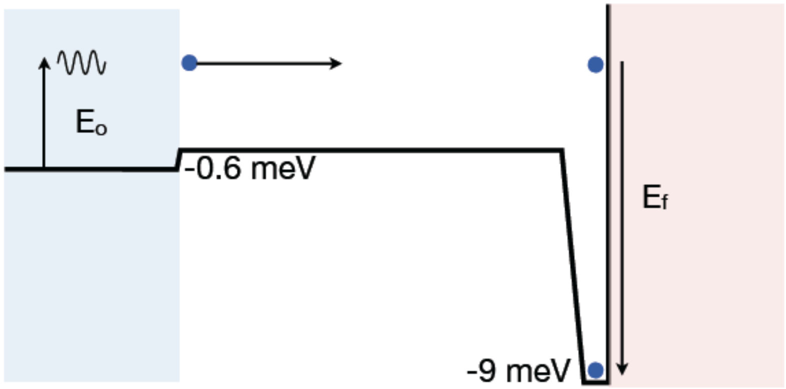


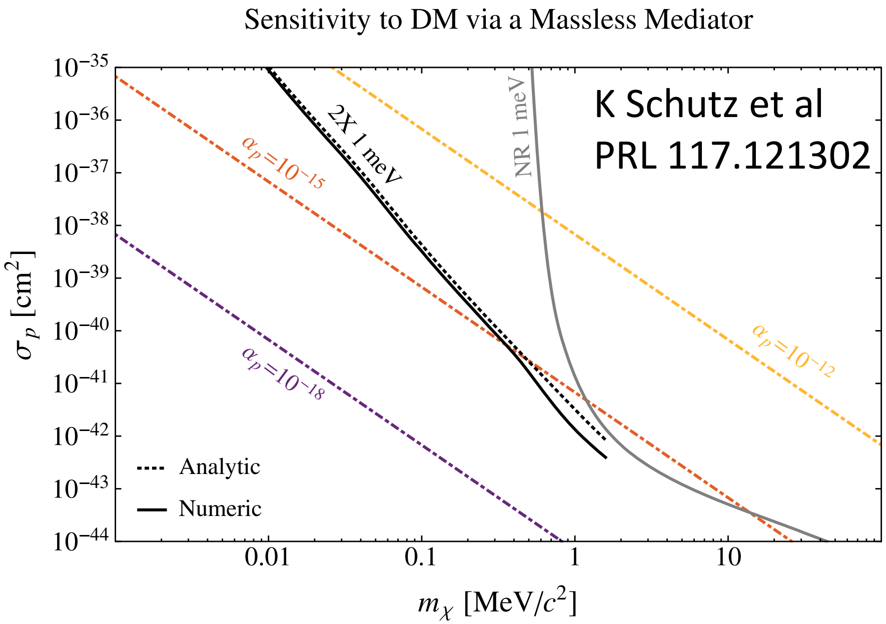
Offshell Photon Production

Experiment 1: Superfluid He



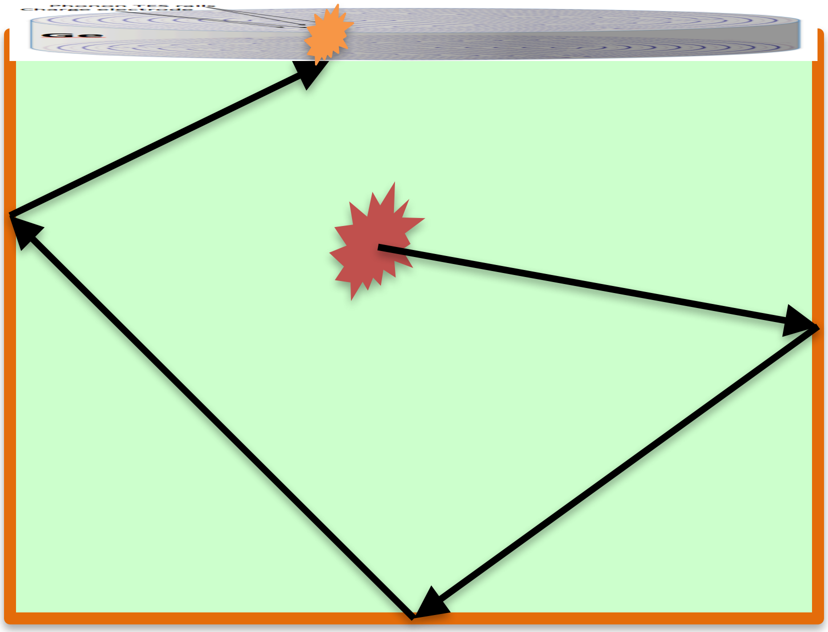
- Superfluid He: Many Long Lived Excitations
  - D. McKinsey, S. Hertel, HERON (G. Seidel, H. Maris, …), K. Zurek, T. Lin
  - Photons & Triplet Excimers: ~ 18 eV
  - Phonons & Rotons: 1 meV
  - x10 gain due to adsorption on bare surface




Sensitivity to DM via a Massless Mediator

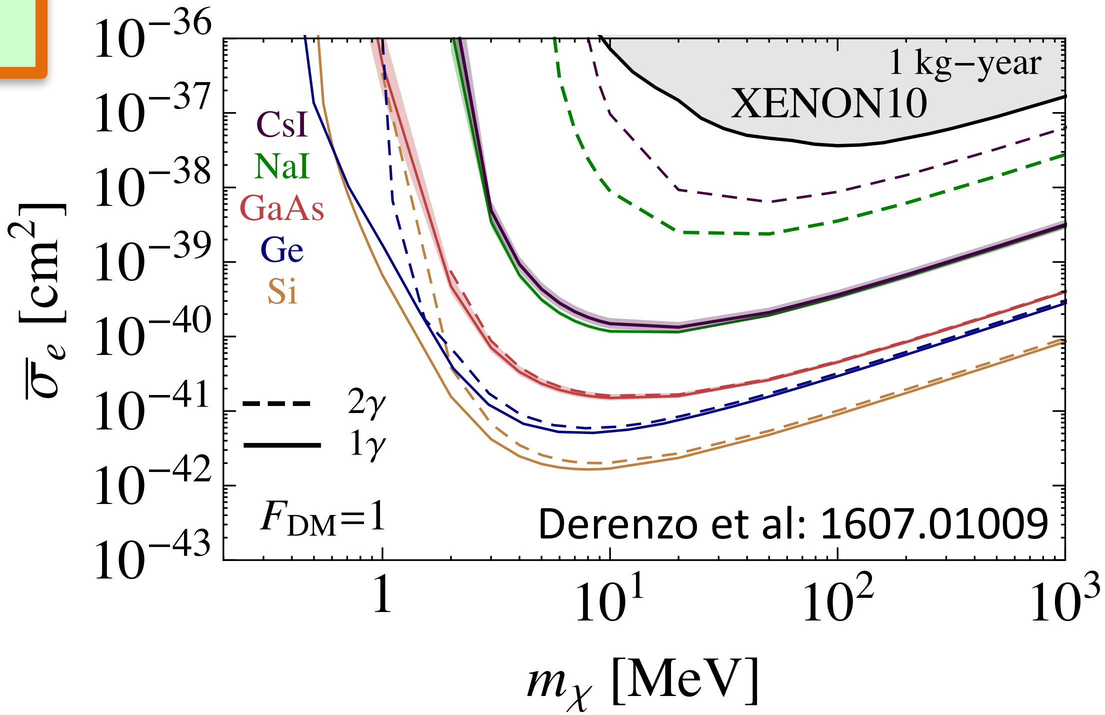
K Schutz et al PRL 117.121302

Experiment 2: Scintillating Crystals (GaAs)



- 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
- Advantages: surface vs volume

G. Bizarri, E. Bourret-Courchesne, S. Derenzo, R. Essig, MP, T. Yu

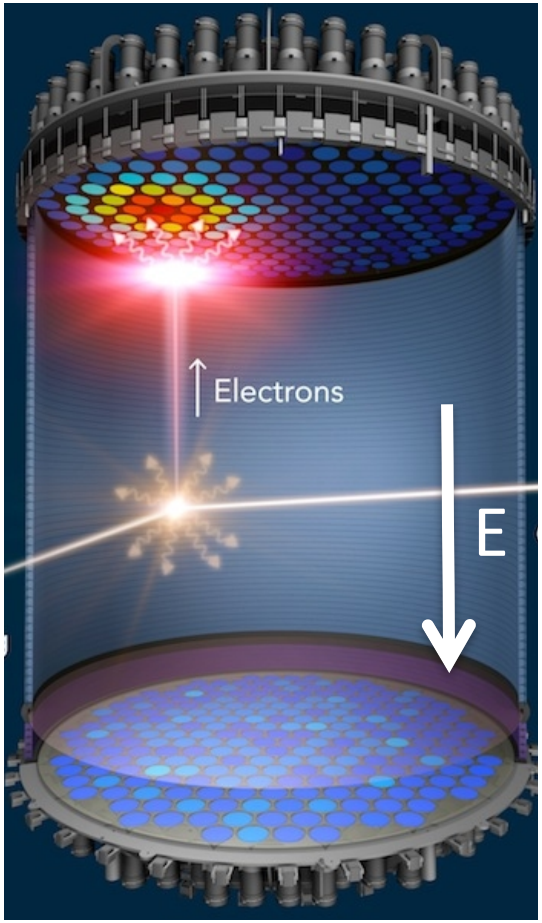


Derenzo et al: 1607.01009

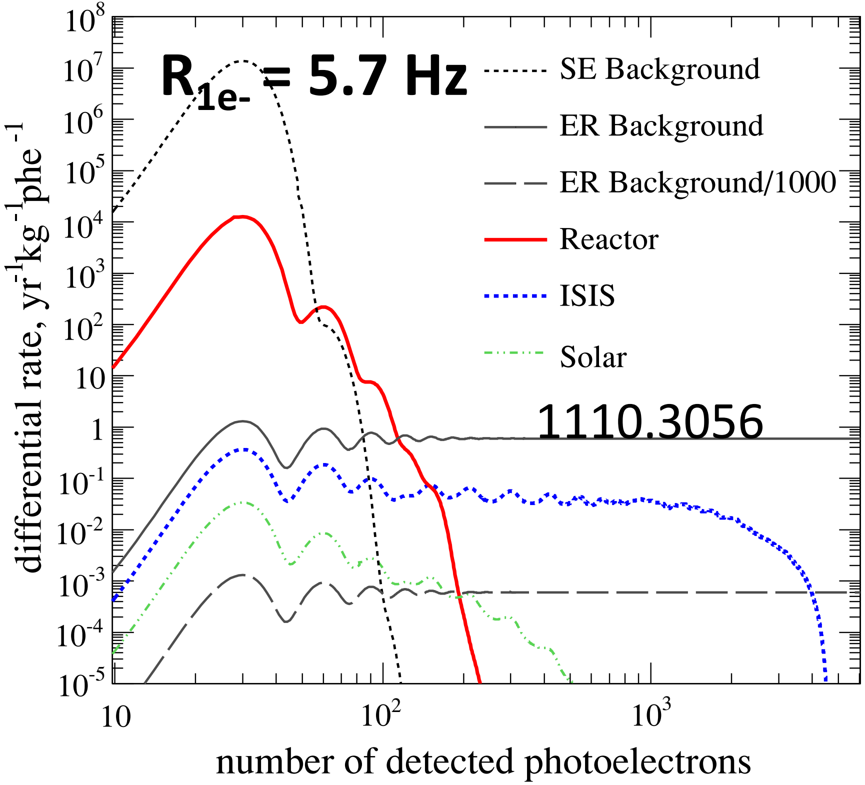
Science Requirement Summary: Photon/Roton Detector Sensitivity

	Sensitivity	
0νDBD	50 eV	
He Scintillation	14 eV	
GaAs Scintillation	1.5 eV	
Xe subgap Optical	1.0 eV	
He Roton	20 meV	

Light Mass DM Detector Requirements:
2) No Dark Counts



e^- (S2) Background Rate in Zeplin III



R_{1e-} = 5.7 Hz

1110.3056

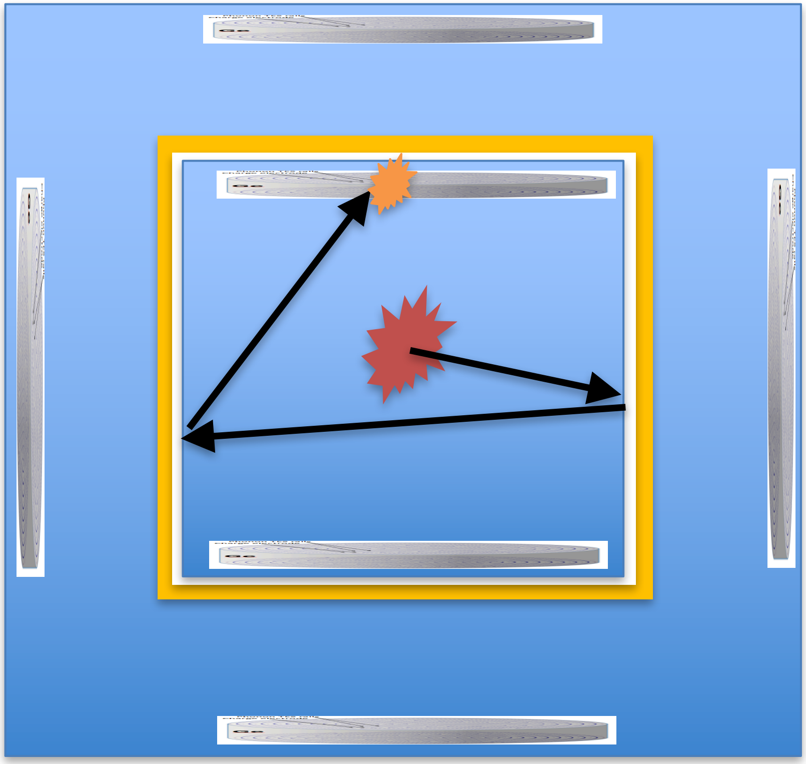
No E-Fields:

- ~~PMTs~~
- ~~TPCs~~
- CCDs

Science Requirement Summary: Photon/Roton Detector Sensitivity

	Sensitivity	Dark Counts
0νDBD	50 eV	Yes
He Scintillation	14 eV	None
GaAs Scintillation	1.5 eV	None
Xe subgap Optical	1.0 eV	None
He Roton	20 meV	None

Experiment 3: Xe S1 Only



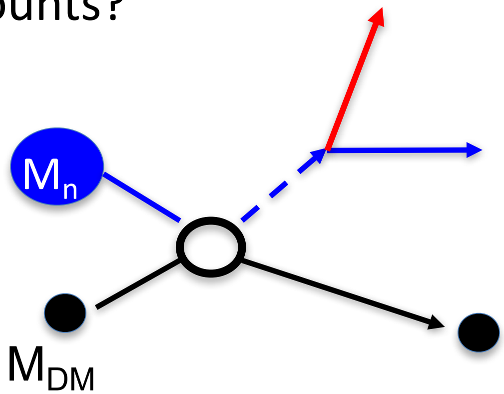
Xe

- High A: Coherent Rate Enhancement
- High Z and Radiopure = Active Compton Shield
- Liquid which is easily distillable underground: No ^3H, ^{32}Si

No E-Field:

No Dark Counts?

Afterglow?

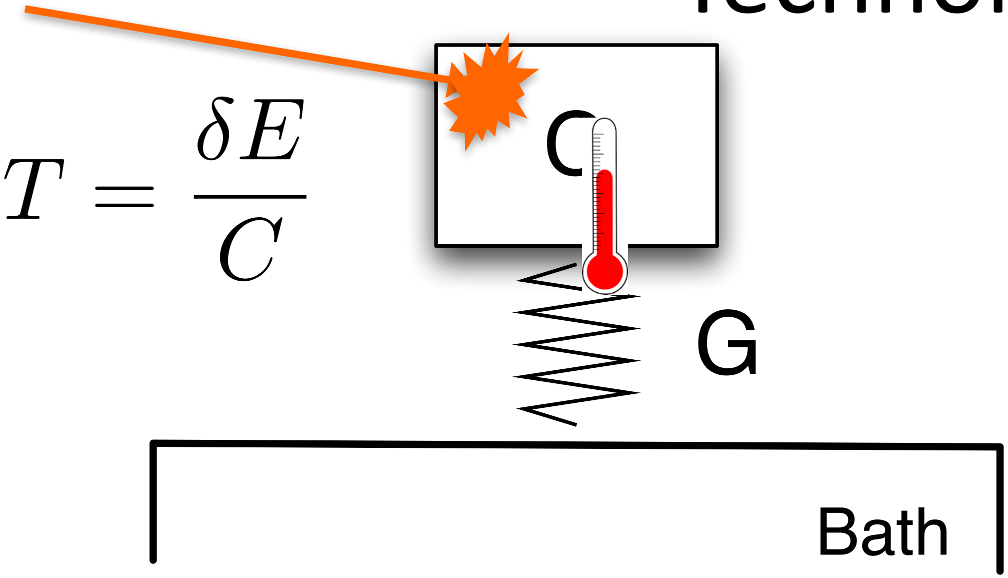


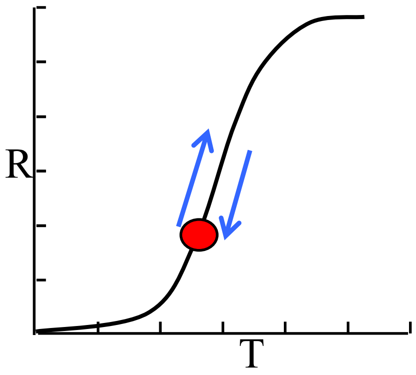
Can a 30kg Xe S1 only experiment that only looks for events with 1-14eV photon energy hit the neutrino floor from 100 MeV-6 GeV?

Single Photon / 2 Roton Detector with no dark count rate

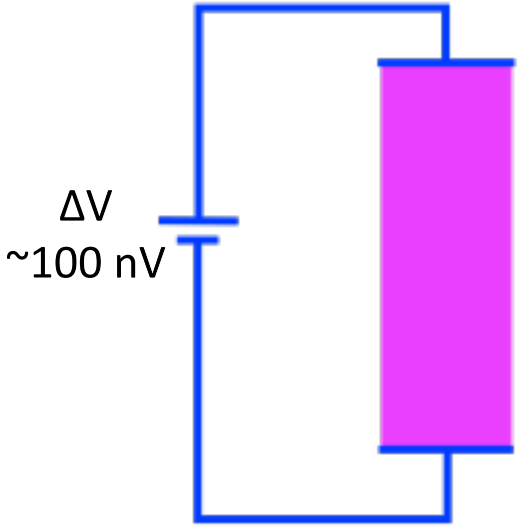
Low Temperature TES Calorimeter Technology

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





- Transition Edge Sensor (TES): A superconducting metal film (W) that is externally biased so as to be within its superconducting/normal transition
- **“Near Equilibrium Sensor”: No Dark Count Rate**

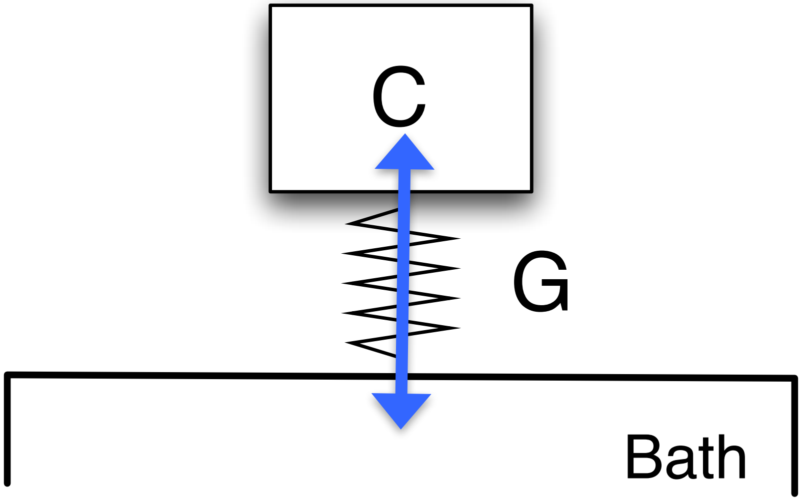


Calorimeter Sensitivity

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

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

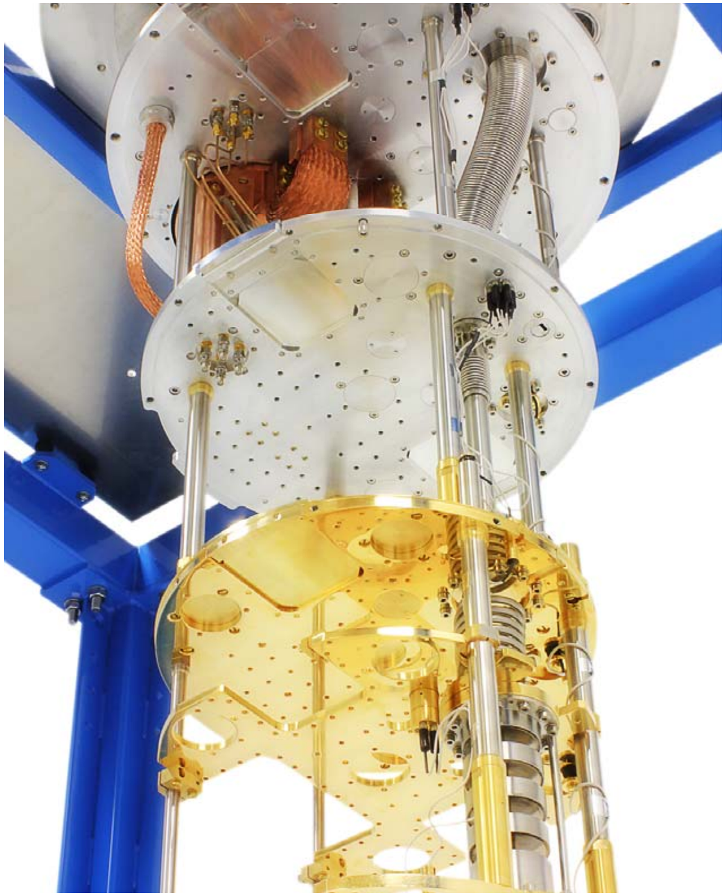
$$= -\frac{\partial <E>}{\partial \beta} = \frac{\partial <E>}{\partial T} k_b T^2 = C k_b T^2$$



~ Intrinsic Thermal Noise of Calorimeters

Calorimeter Optimization

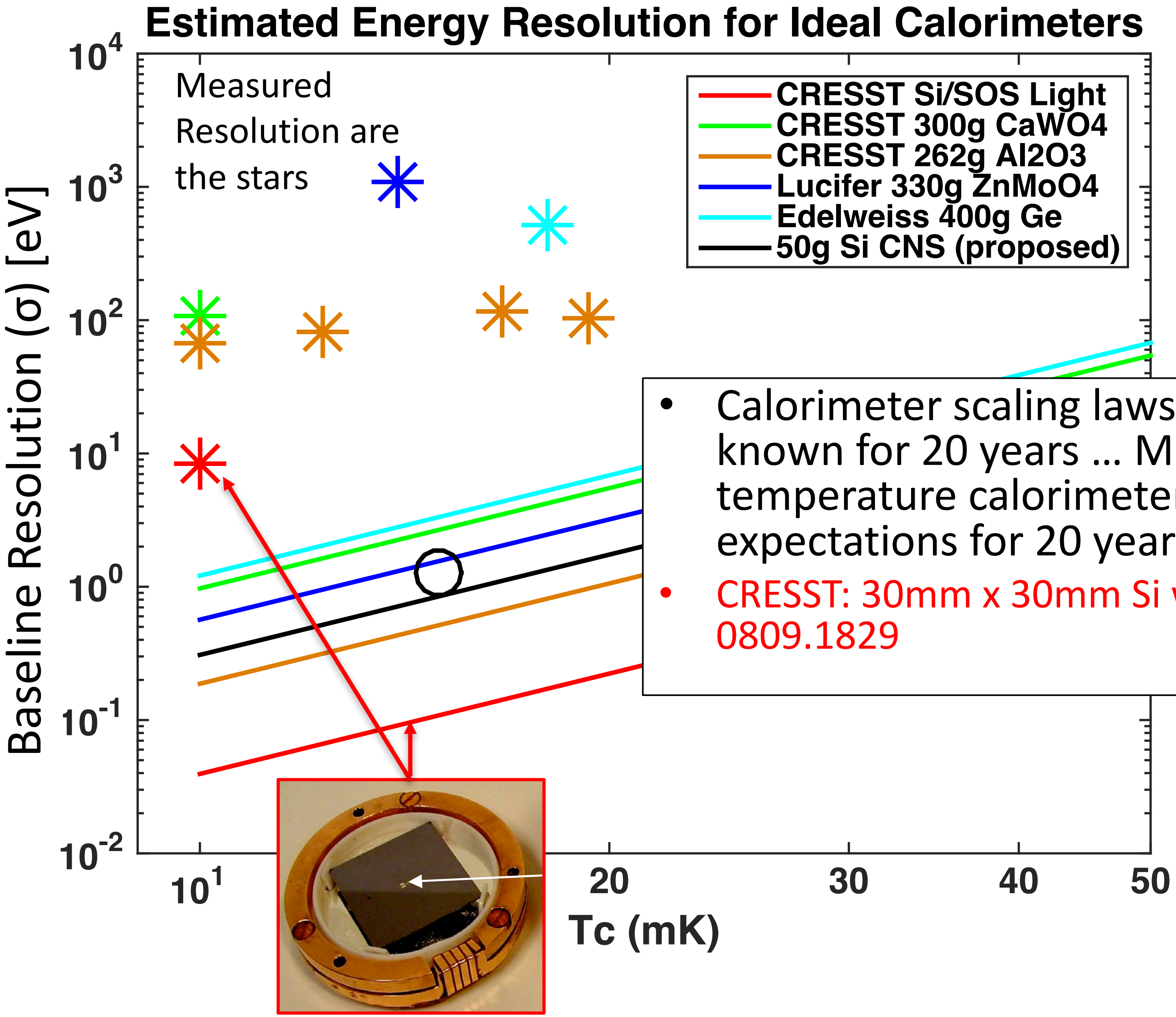
$$\sigma^2_{<E>} = C k_b T^2$$



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

} Freeze out

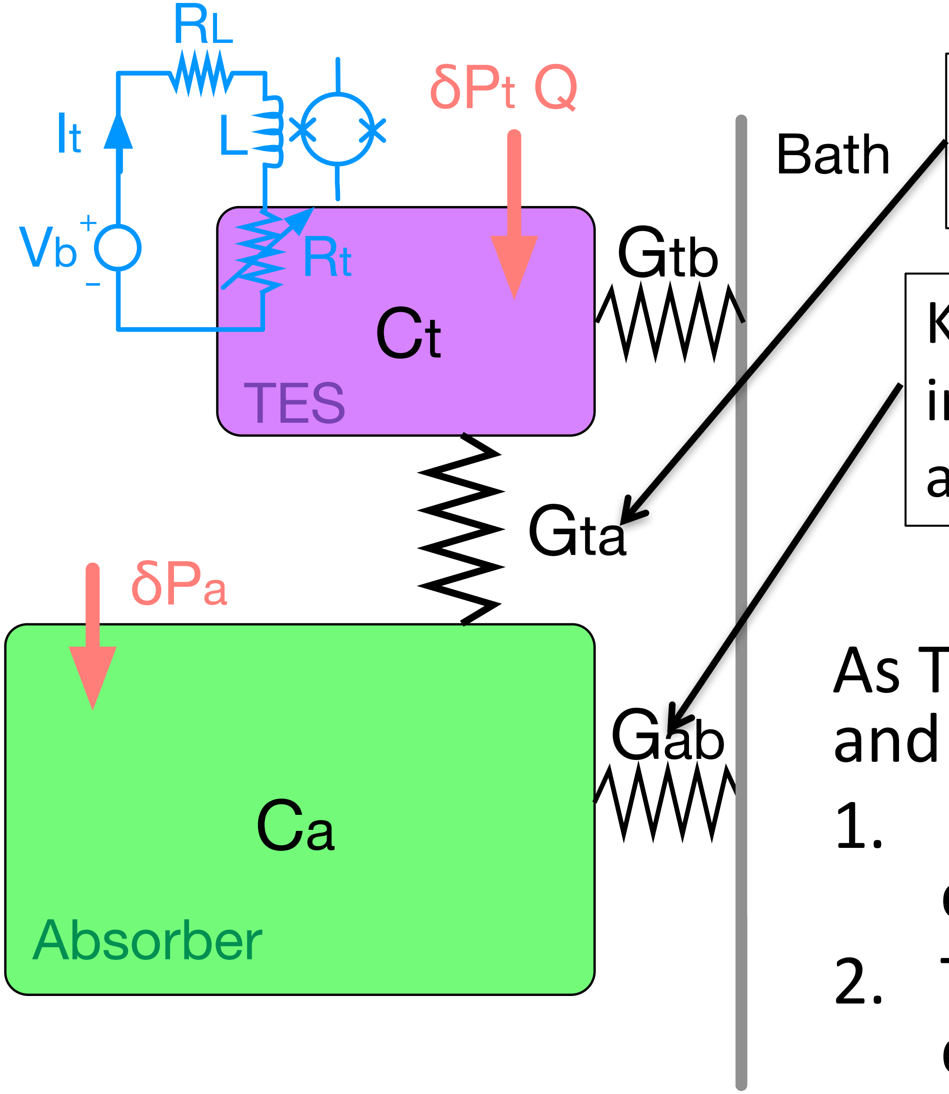
Shouldn’t this be a solved problem?



Estimated Energy Resolution for Ideal Calorimeters

- Calorimeter scaling laws have been known for 20 years … Massive low temperature calorimeters haven’t met expectations for 20 years
- CRESST: 30mm x 30mm Si wafer: σ = 8.5 eV 0809.1829

Culprit: Decoupling between the Sensor and Absorber at Low Temperature



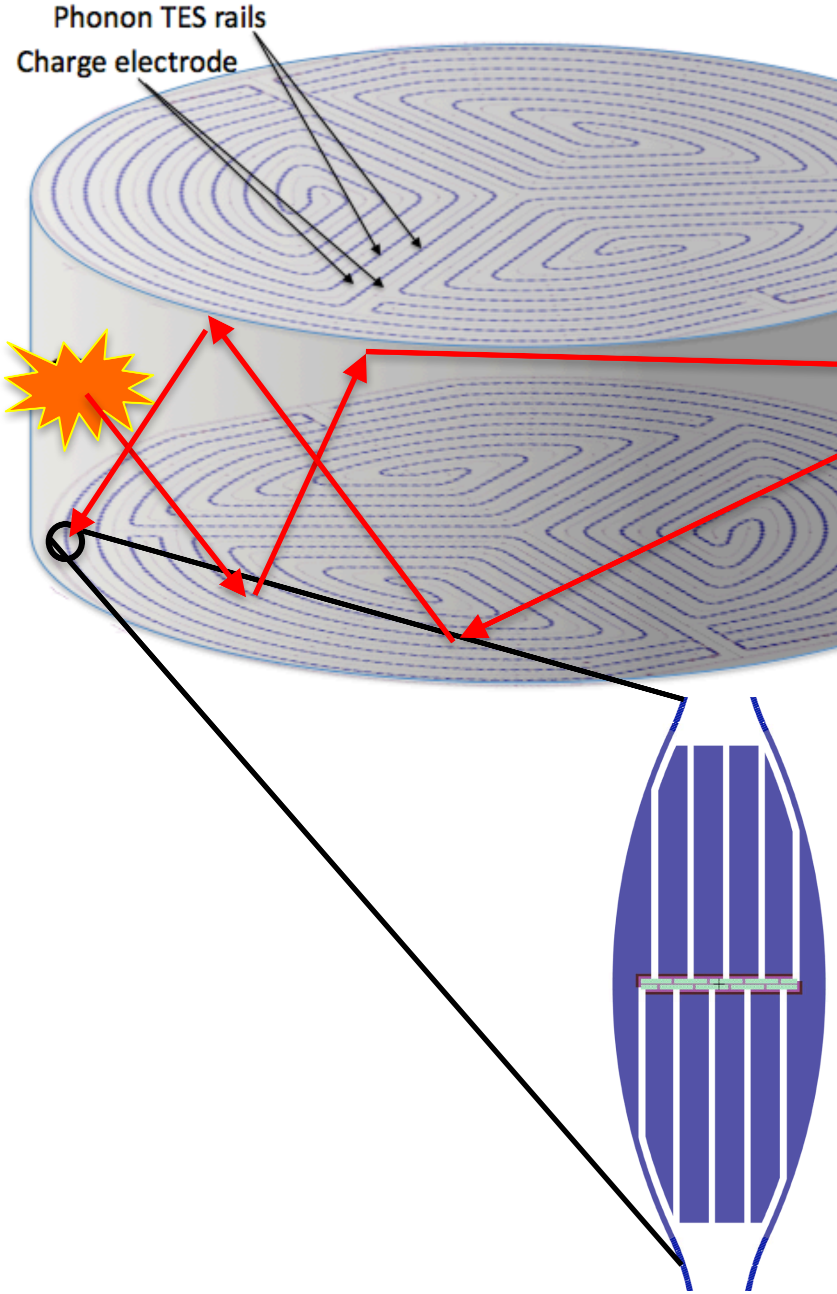
e^-/phonon thermal conductance scales as T^4

Kapitza boundary conductance in the mechanical support scale as as T^3

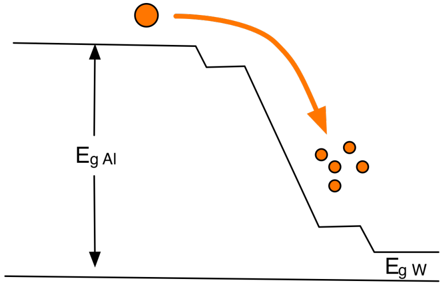
As T is decreased, it’s harder and harder to keep the sensor:

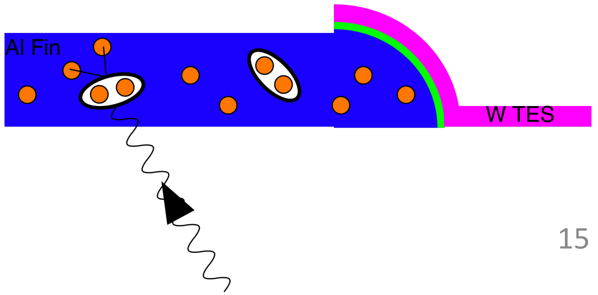
1. the sensor thermally coupled to the absorber
2. The absorber and sensor decoupled from the bath

Solution: Athermal Phonon Sensors

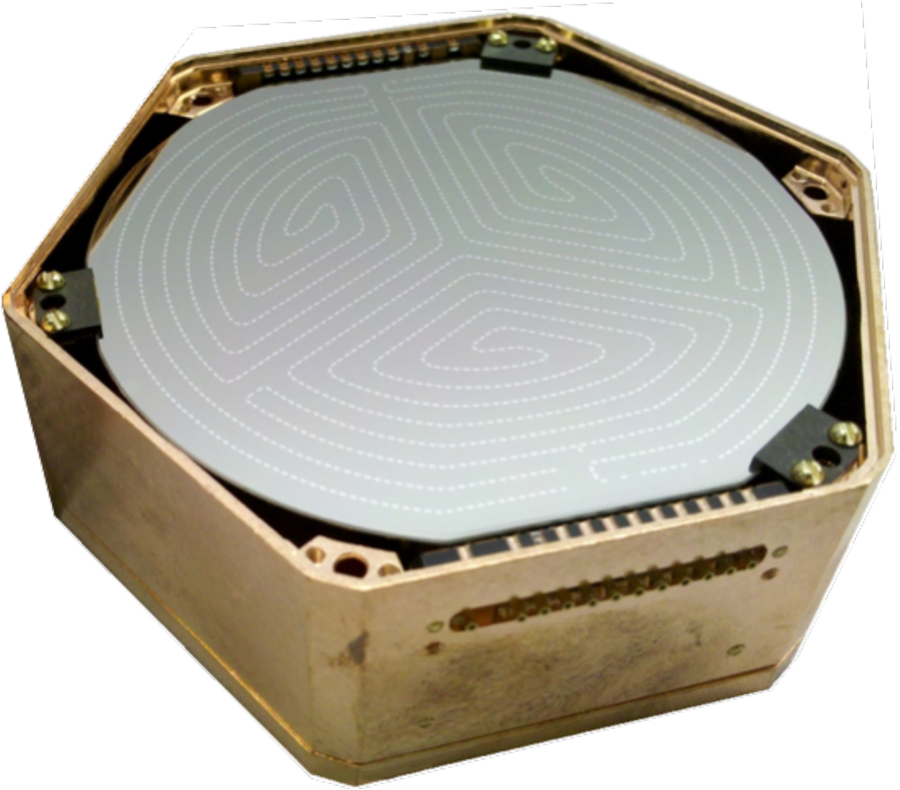


Collect and concentrate athermal phonon energy into TES via Al QP collection fins, completely bypassing the G_{ep} bottleneck



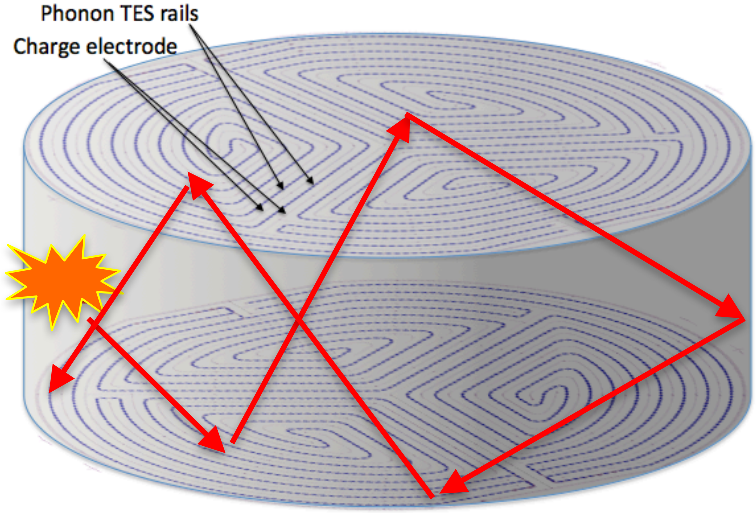


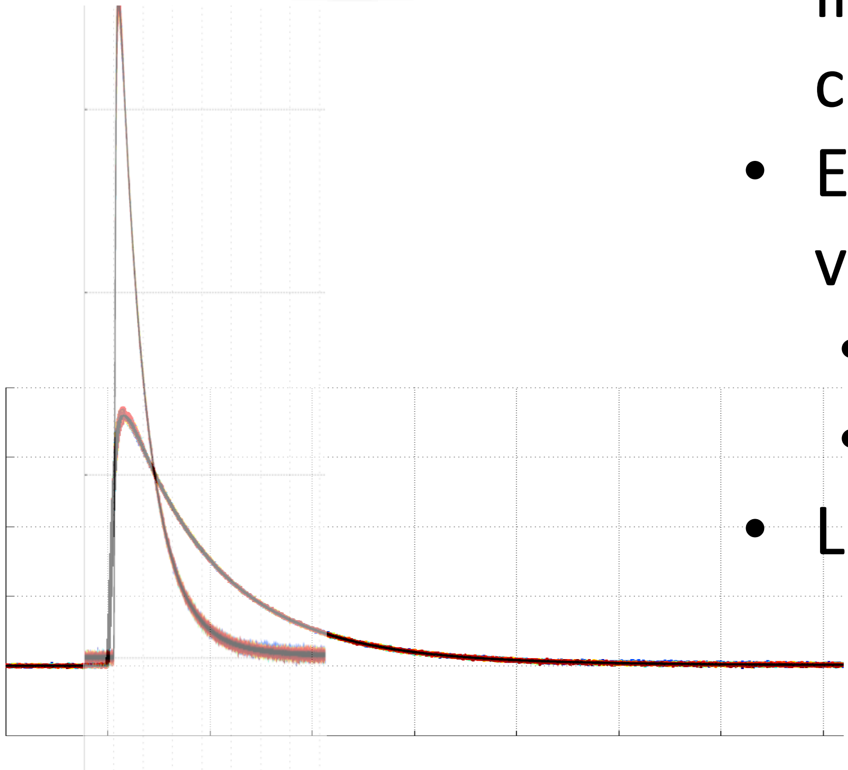
The Ultimate Cryogenic Photon and Roton Detector: thin / pixelized SuperCDMS Detector



STEAL FROM SUPERCDMS!

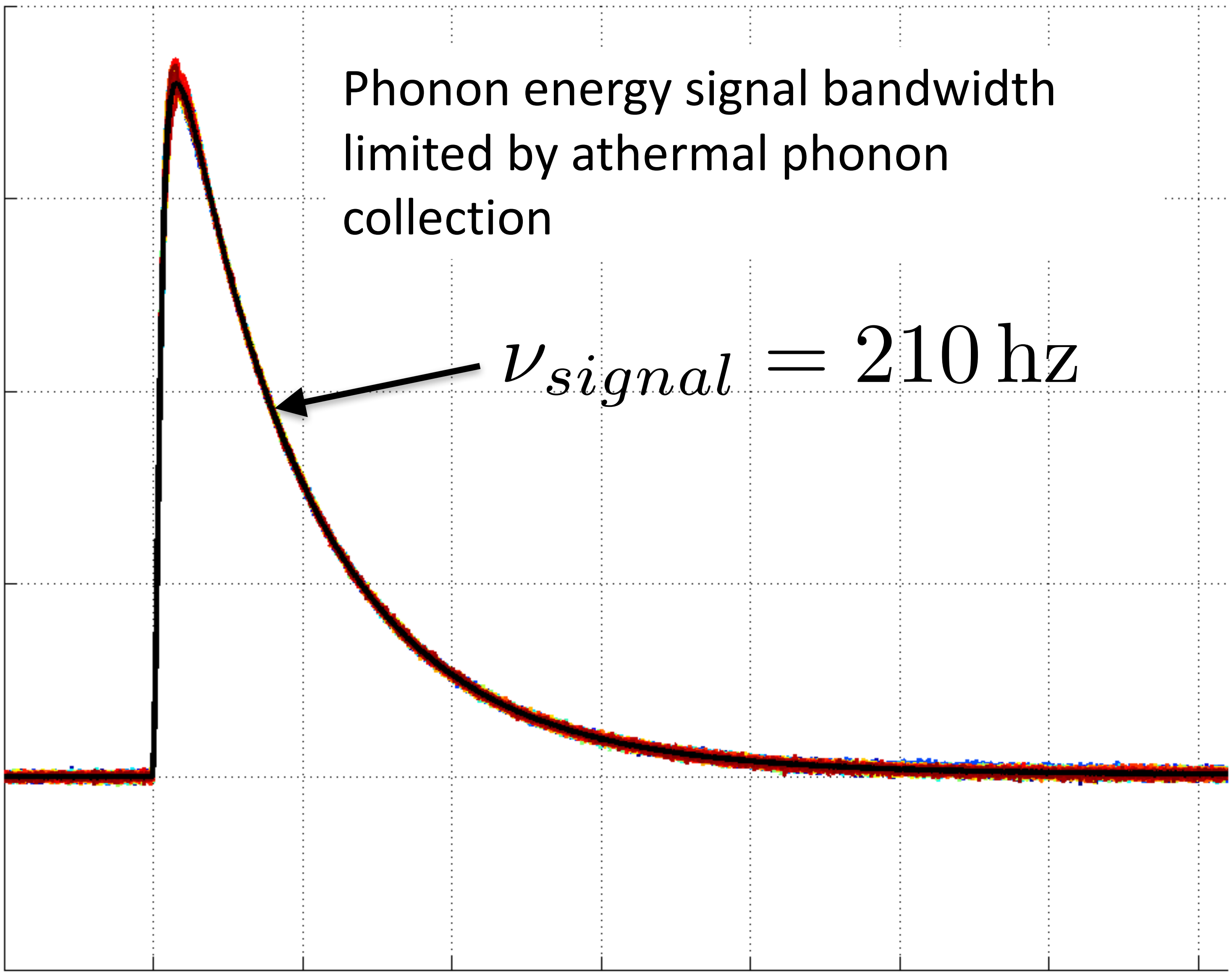
What happens when we shrink





- Pulse fall time varies inversely with thickness!
- Phonon energy signal bandwidth limited by athermal phonon collection
- Energy Resolution scales as volume$^{-1/2}$:
  - 33mm -> 1mm
  - 5 eV (Si HV Goal) -> 1 eV
- Lower Tc 50mK ->10mK: 20 meV

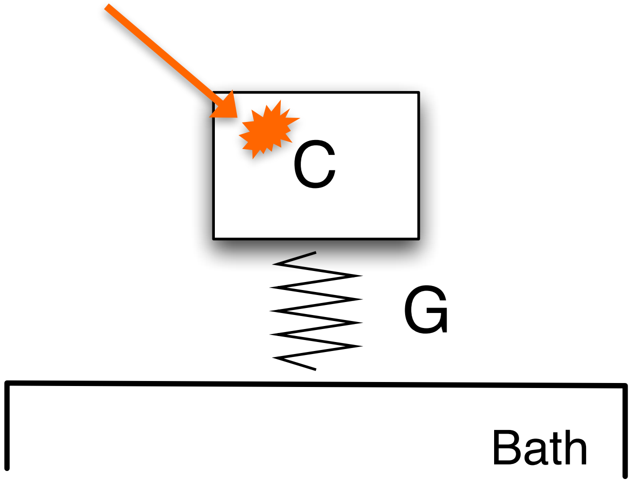
Lowering T_c: Phonon Signal Bandwidth

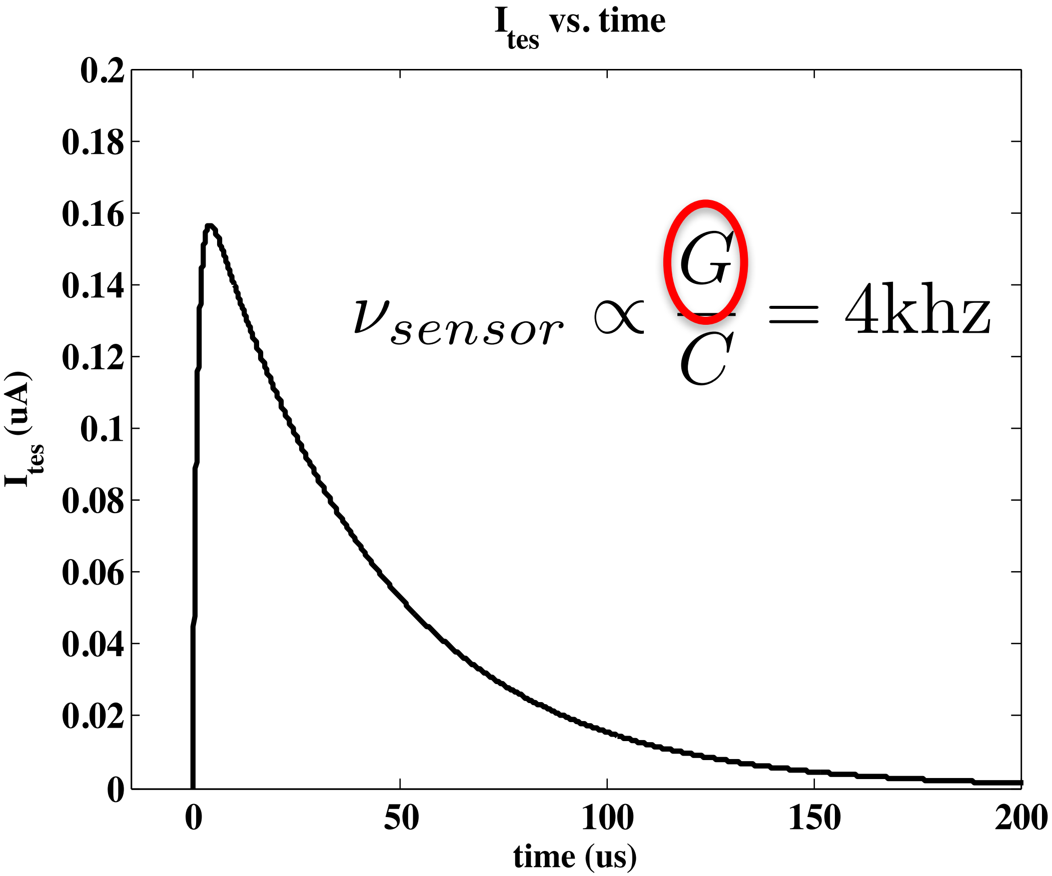


Phonon energy signal bandwidth limited by athermal phonon collection

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

Lowering T_c: TES Dynamics

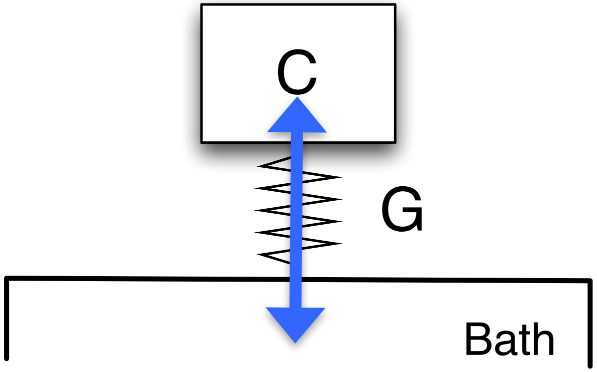




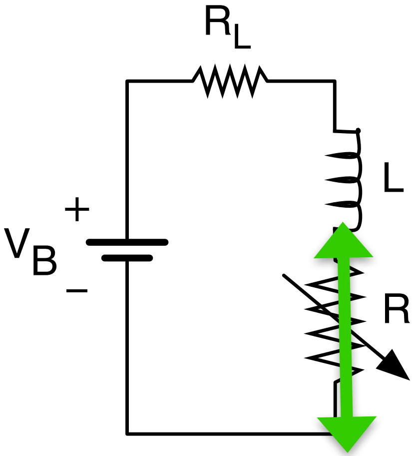
$$\nu_{sensor} \propto \frac{G}{C} = 4\text{khz}$$

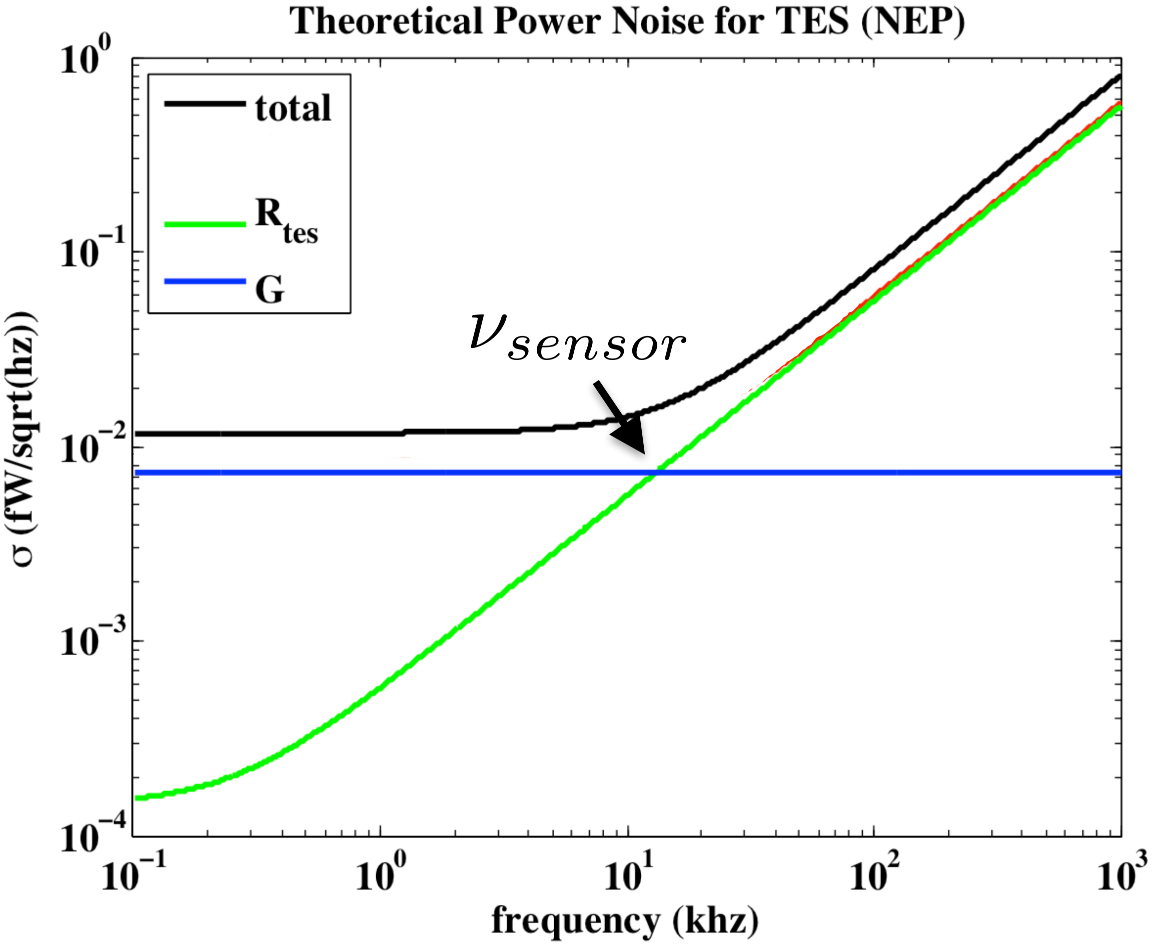
$$\nu_{signal} << \nu_{sensor}$$

Lowering T_c: TES Noise



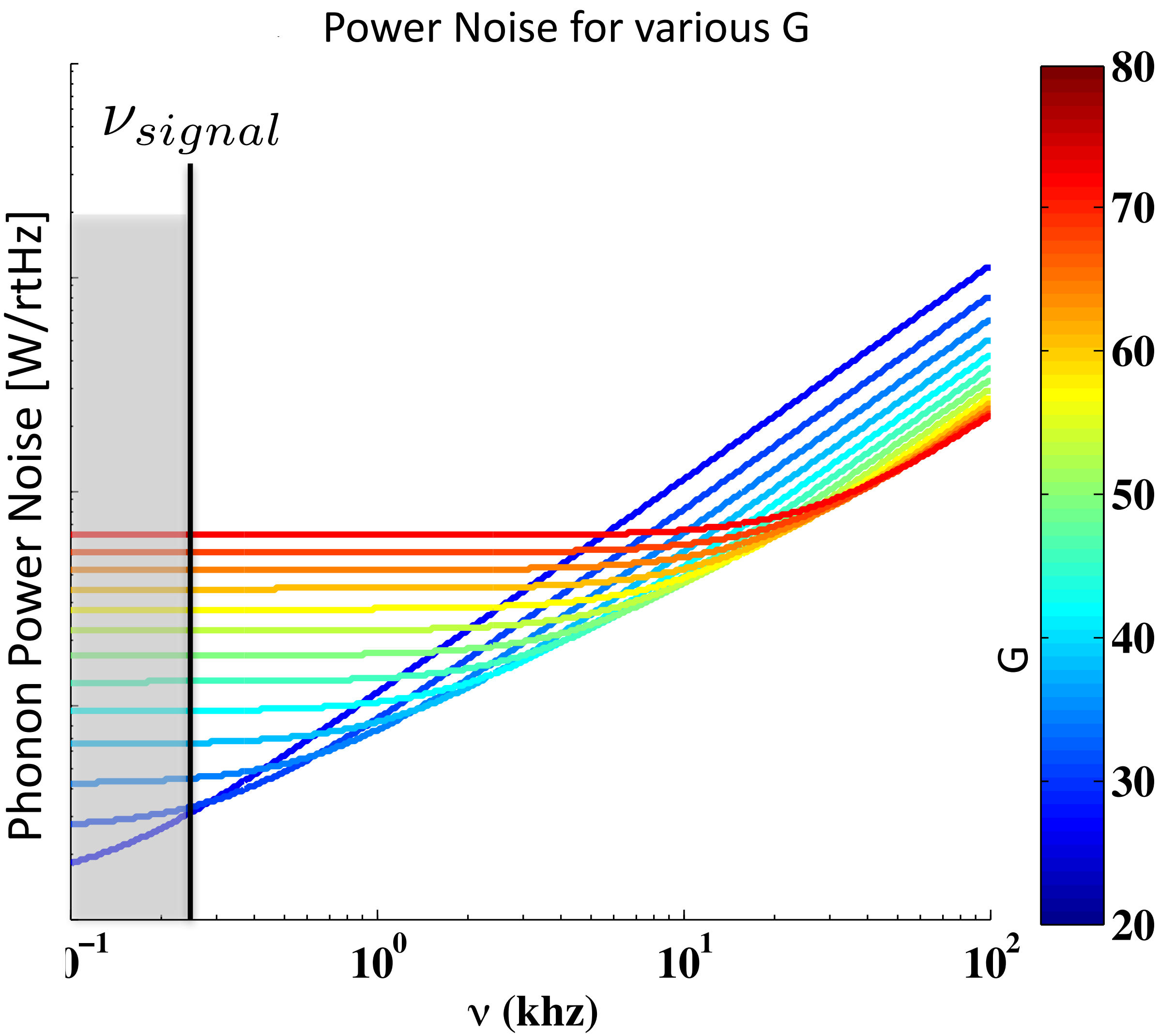
$S_{pG} = 4k_bT^2\mathbf{G}$





DC noise scales with G

Lowering T_c: Bandwidth Optimization Rule



$$G \propto T_c^4$$

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

$$\propto T_c^6$$

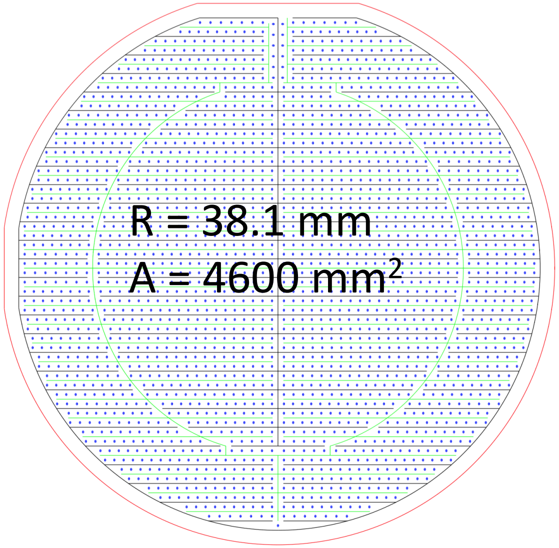
$$\sigma_E \propto T_c^3$$

- 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 T_c^3 scaling (in principle)

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

What happens when we pixelize for rotons?



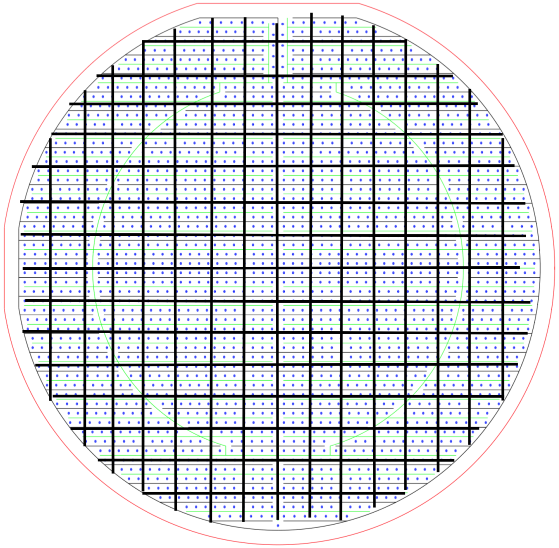
R = 38.1 mm

A = 4600 mm^2

A_{pixel} = 25mm^2

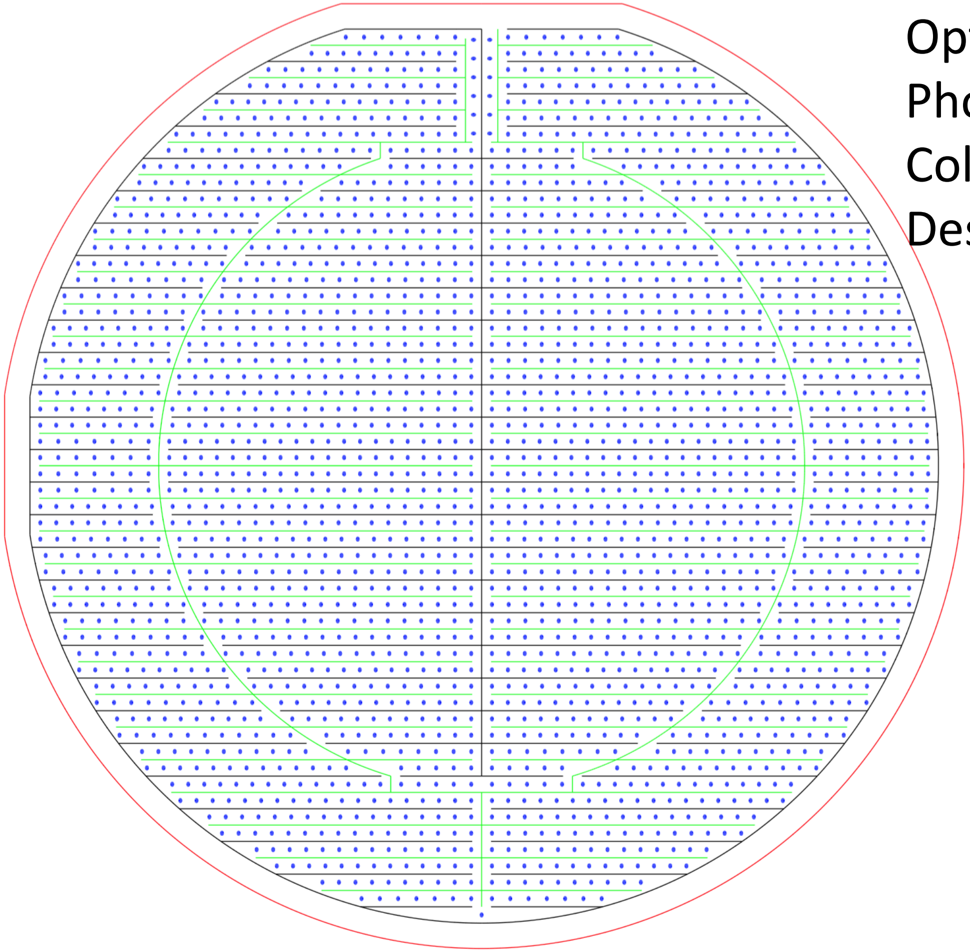
N_{pixel} = 184

→

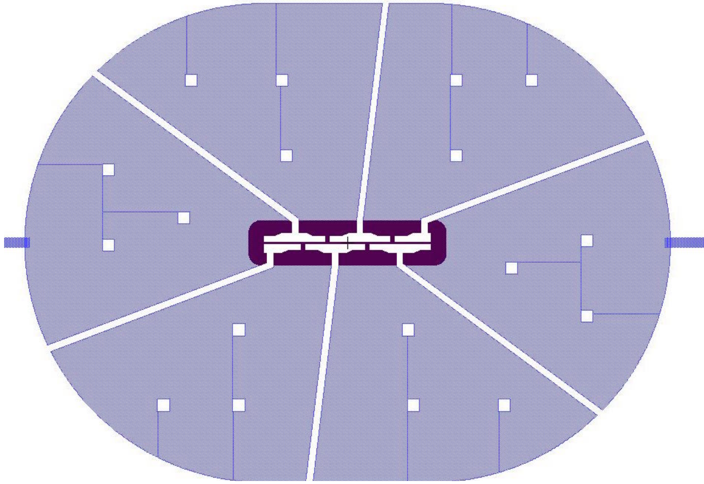


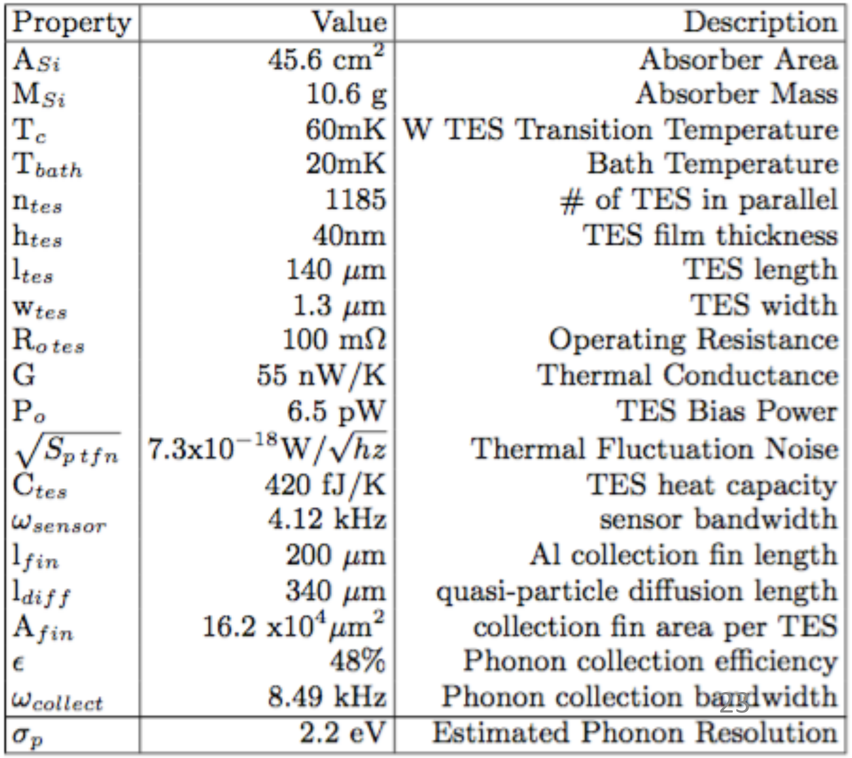
- Naively, TES Noise sums in quadrature (Big Assumption!)
- 20 meV -> 1.5 meV

First Prototype Design



Optimized Phonon Collection Fin Design



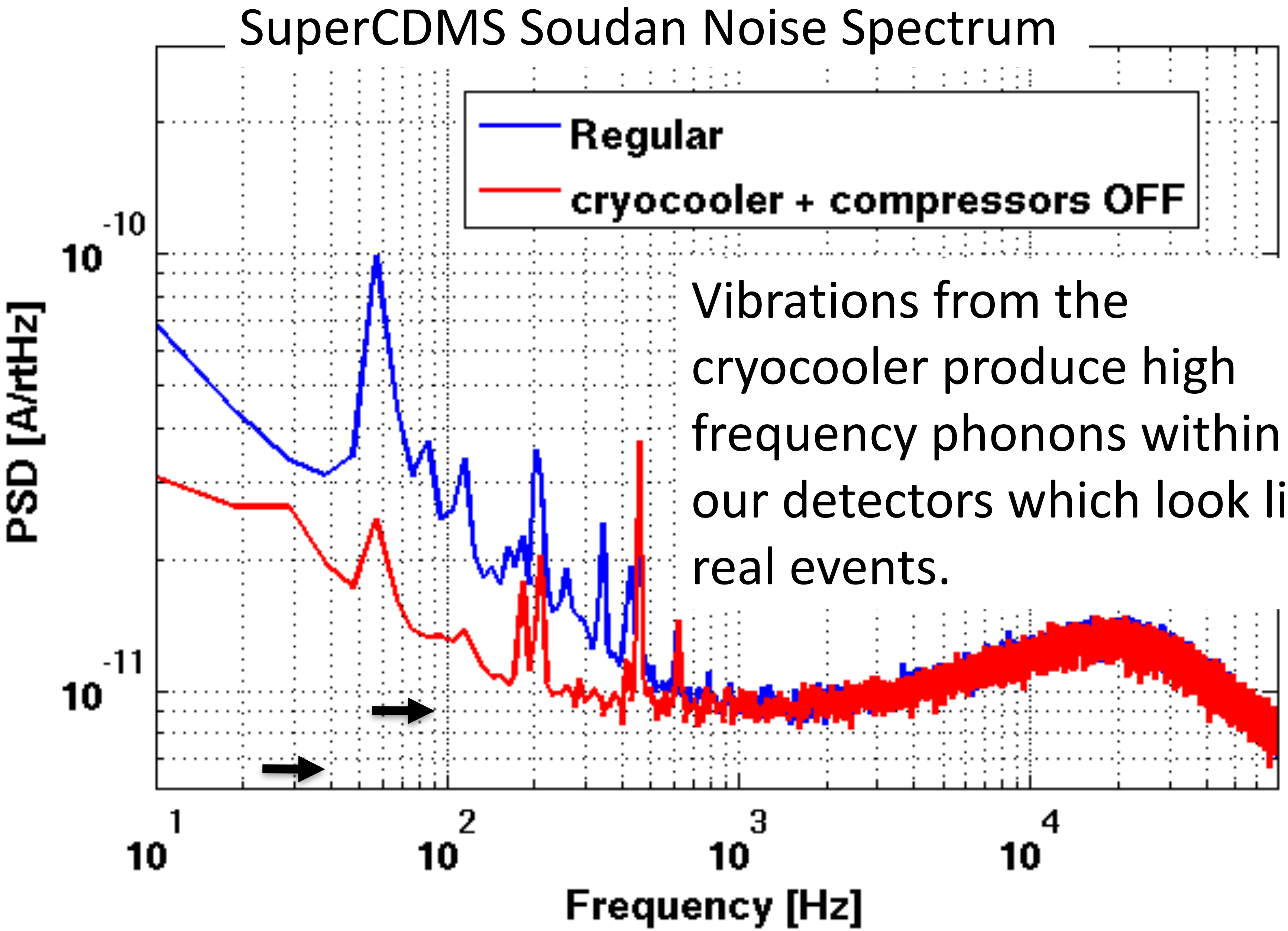


Property	Value	Description
A_{Si}	45.6 cm^2	Absorber Area
M_{Si}	10.6 g	Absorber Mass
T_c	60mK	W TES Transition Temperature
T_{bath}	20mK	Bath Temperature
n_{tes}	1185	# of TES in parallel
h_{tes}	40nm	TES film thickness
l_{tes}	140 μm	TES length
w_{tes}	1.3 μm	TES width
$R_{o\,tes}$	100 mΩ	Operating Resistance
G	55 nW/K	Thermal Conductance
P_o	6.5 pW	TES Bias Power
$\sqrt{S_{p\,tfn}}$	$7.3\text{x}10^{-18}\text{W}/\sqrt{hz}$	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

- Cold with ^{55}Fe Source
- In transition: Tc= 41mK, T_{MC}=40mK

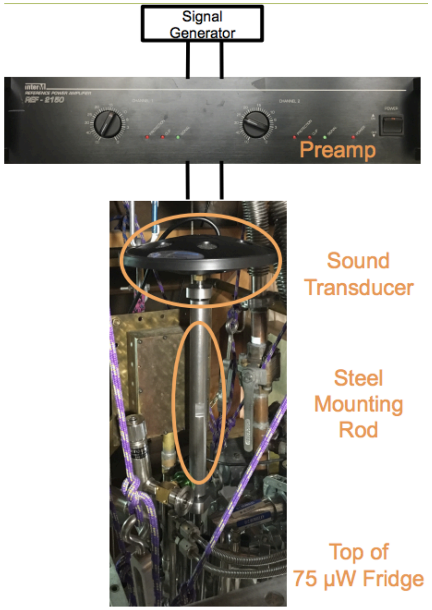
THE PROBLEMS

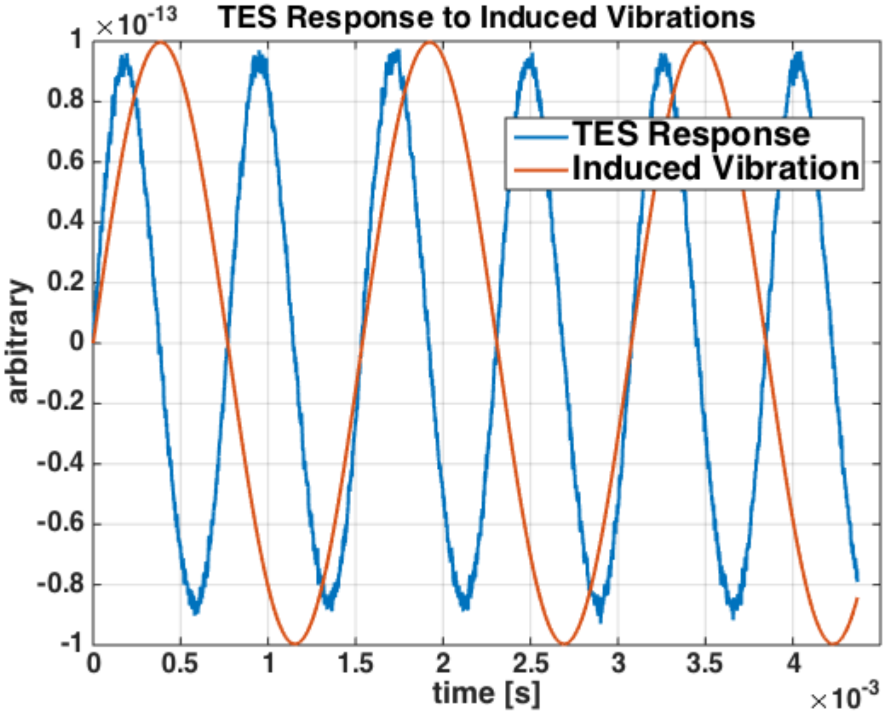
Problem #1: Vibrational Parasitic Power

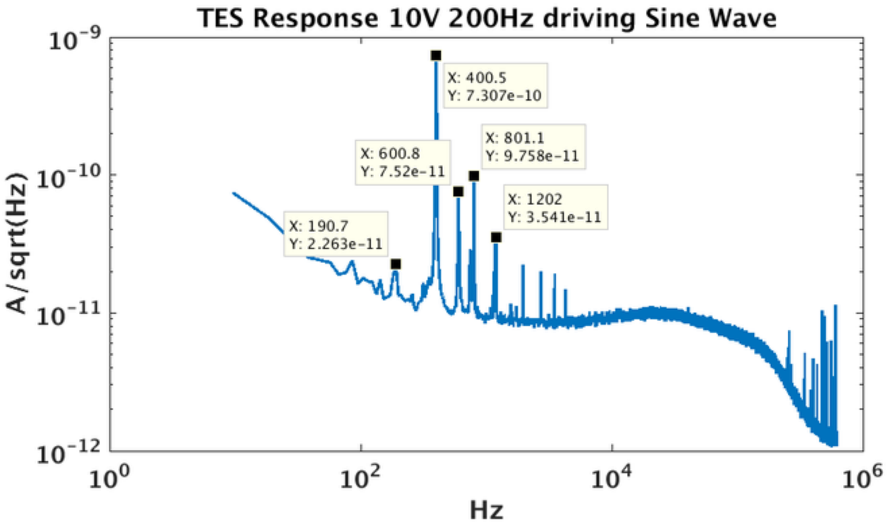

SuperCDMS Soudan Noise Spectrum

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

SuperCDMS Vibration ~~R~~&D:

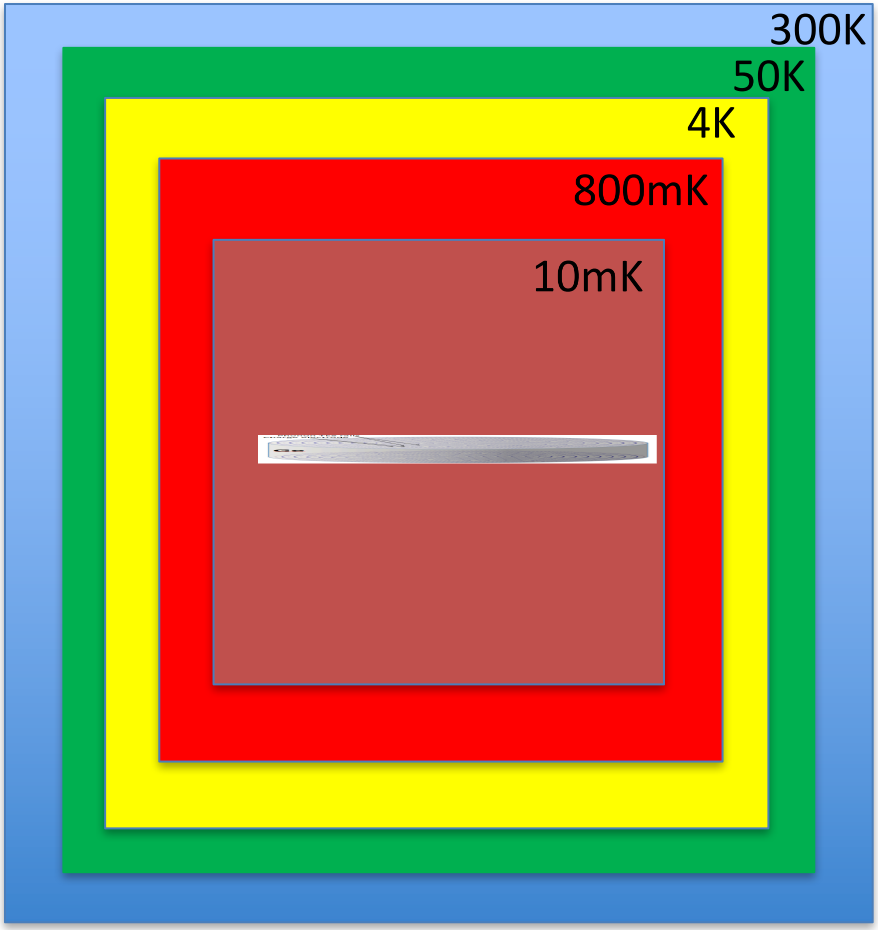






- A 200 Hz Vibration Signal Gives rise to a primarily 400 Hz Phonon Pulse Signal
- Phonon Signal scales as Vibration^2 => Vibrations coupling by friction!
- **Studies mostly complete. Cryostat design work ongoing**

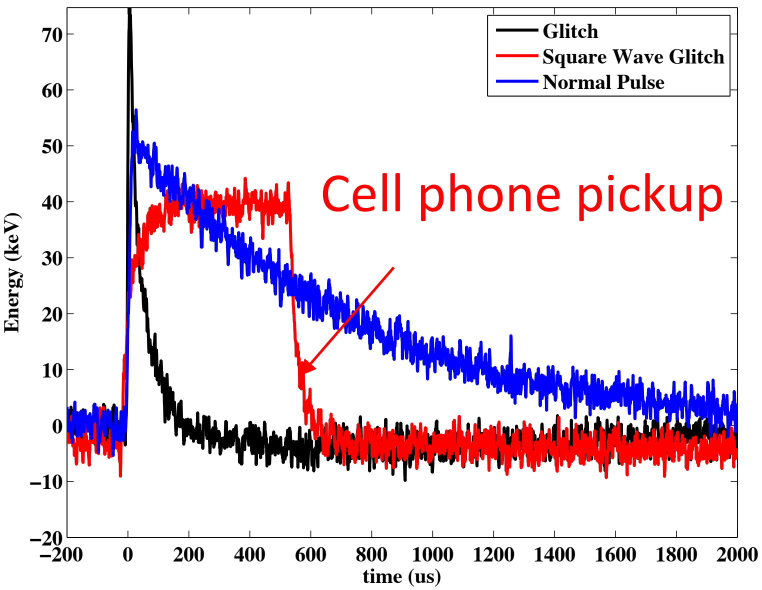
Problem #2: IR Parasitic Power



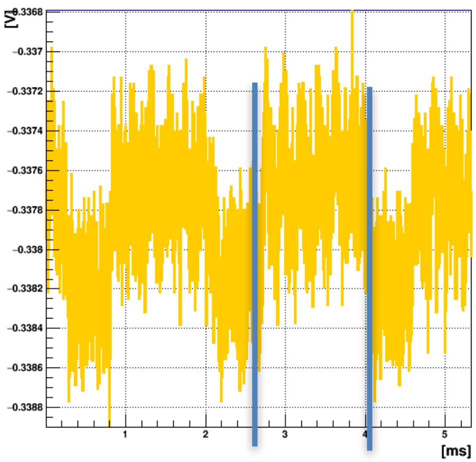
Blackbody Radiation Can Heat the TES until it’s always normal

- SuperCDMS HV Studies show this is a subdominant term
- IR shielding is important in detector housing design

Problem #3: RF


Various Phonon Traces

Width of RF heat pulse depends on trace length readout

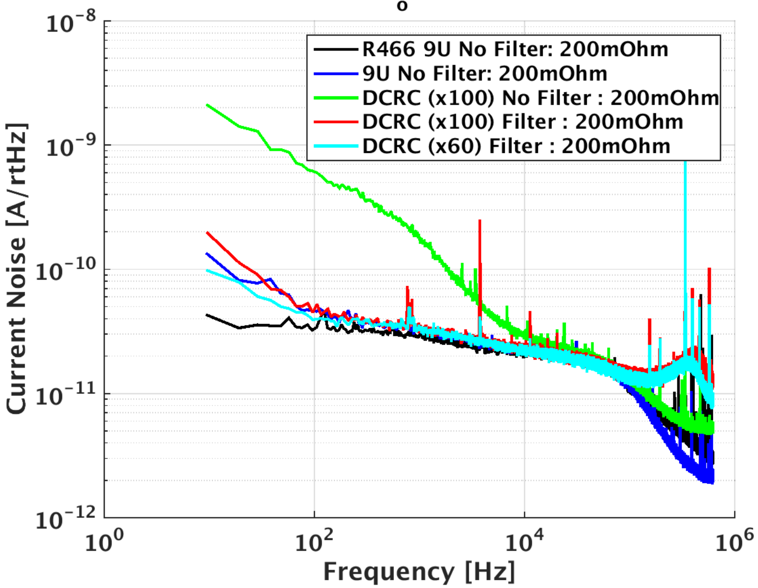

Digital Telegraph Noise

~1.2ms

DC Parasitic Power

RevD PA	**Ibias [uA]**	**Pbias [pW]**
Pi Filter	**100**	**21.7**
No Pi Filter	**88**	**16.8**
Δ	**12**	**4.9**

$$P_{bias} = P_{cool} - P_{parasitic}$$


DCRC vs 9U: R_o=200mOhm: Cd2

Significant Improvement solved with improved filtering at the cryostat feedthrough

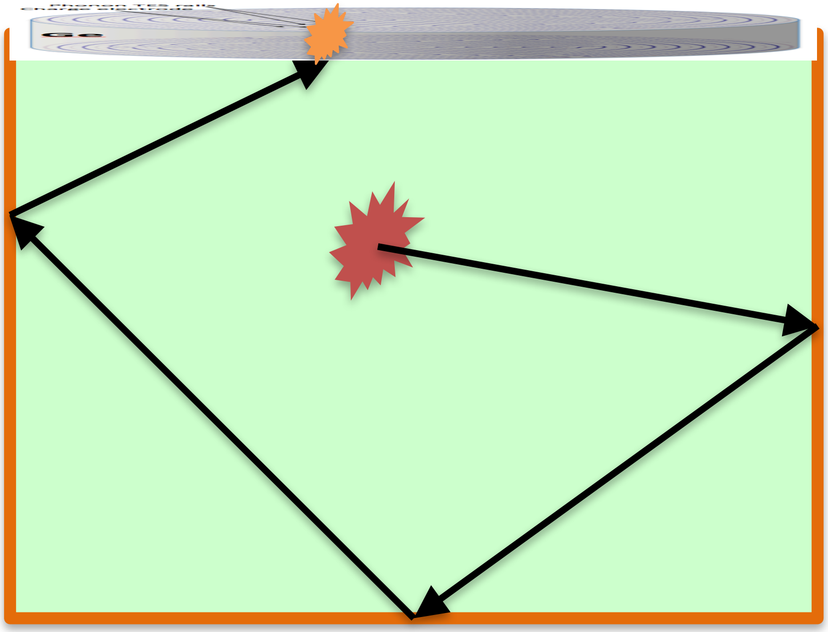
Problem #4?

?

DM Searches with GaAs(Si)

Gregory Bizarri, Edith Bourret, Stephen Derenzo, Rouven Essig, and MP

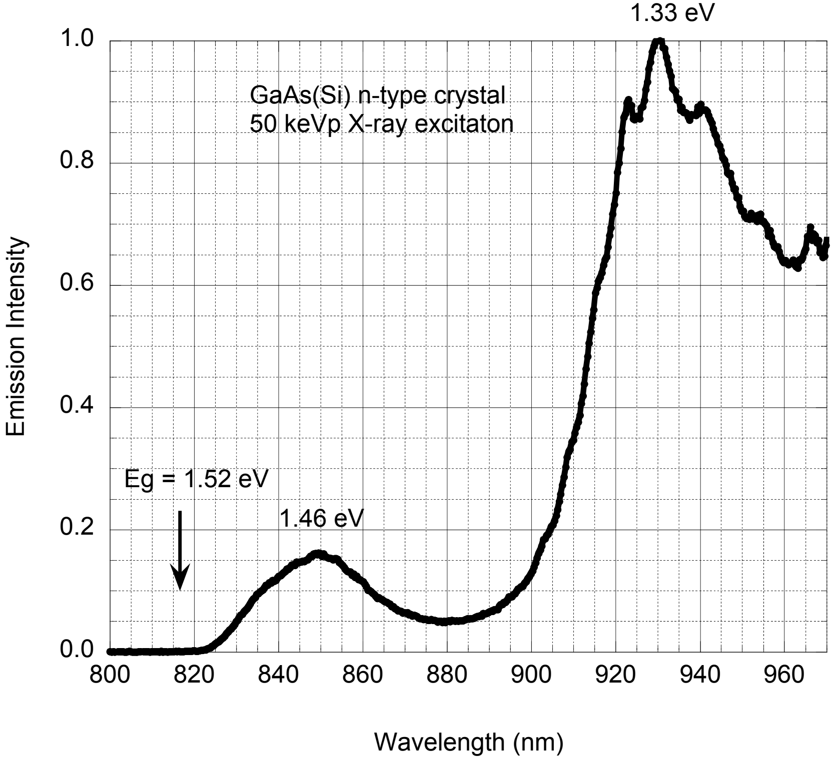
Why use a Scintillator?



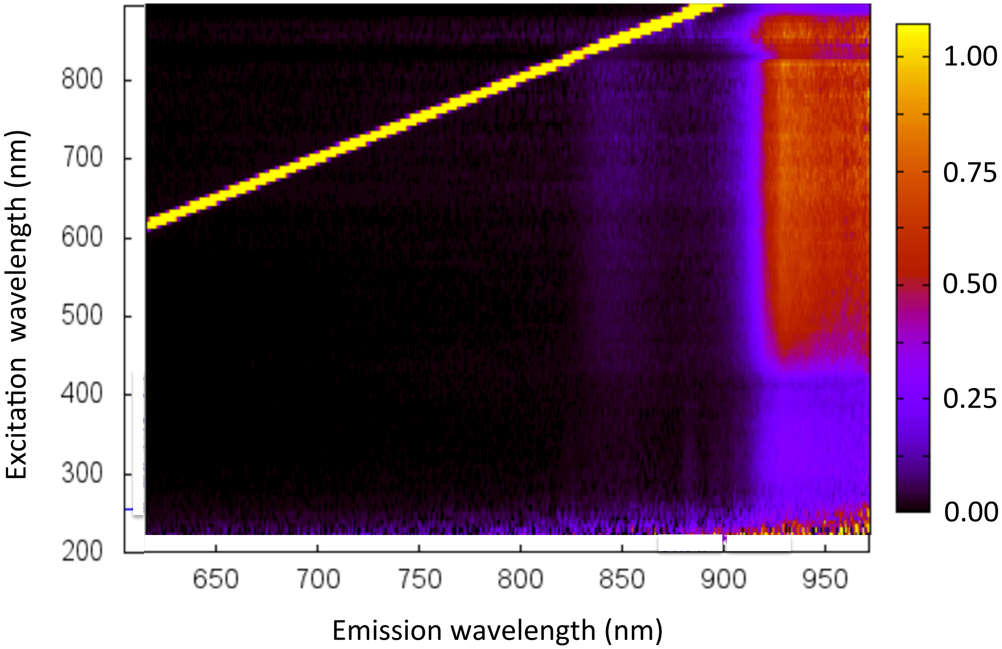
No E-field = No Dark Current

GaAs(Si) Scintillation Spectrum

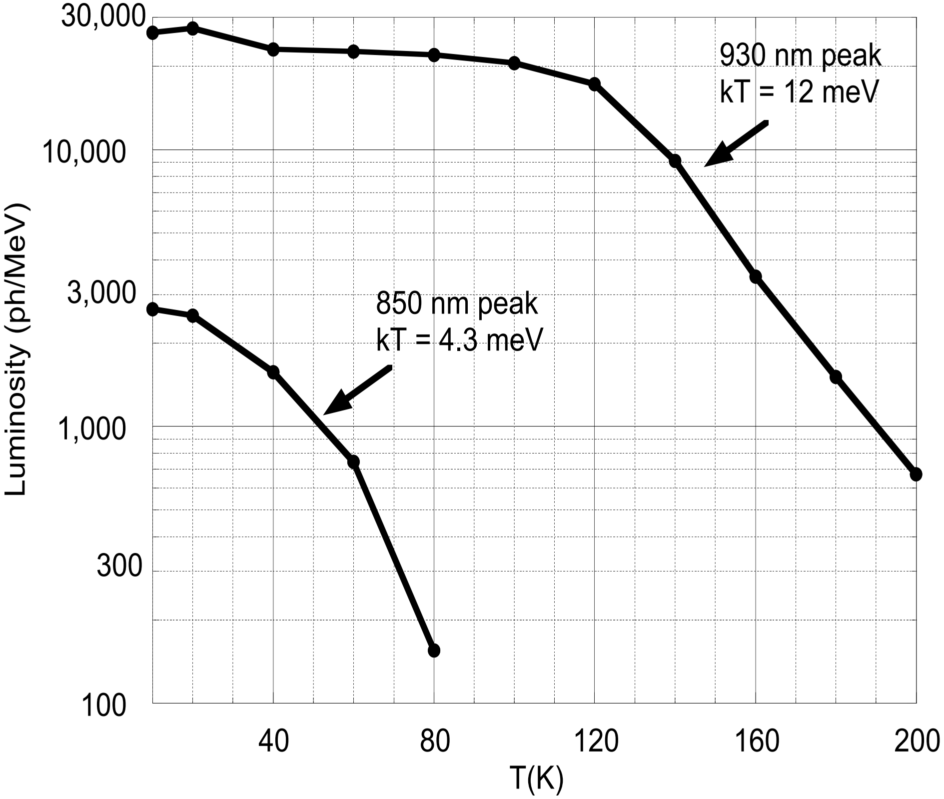
50 keV x-ray Excitation



Optical Photon Excitation



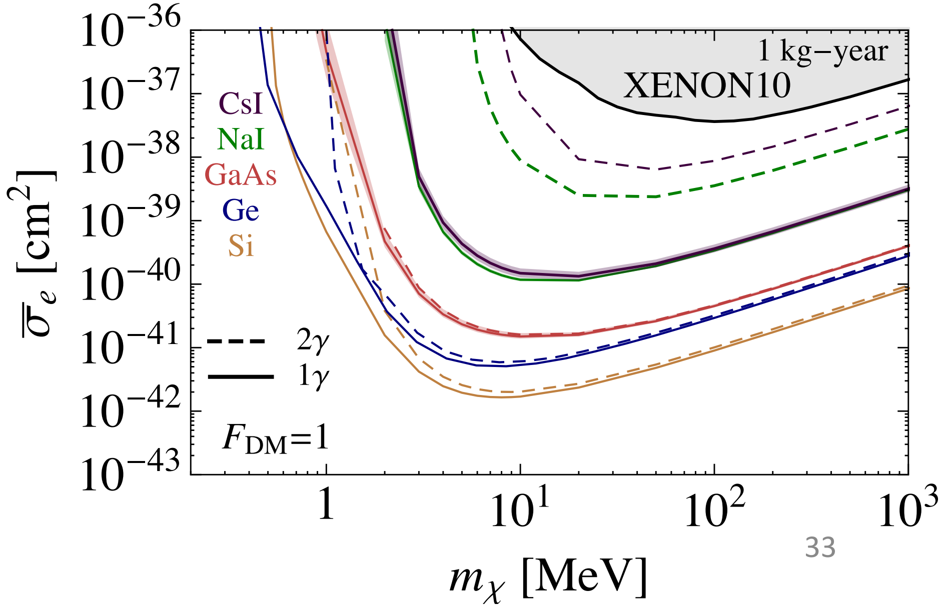
GaAs(Si) Brightness


50keV x-ray @ Berkeley

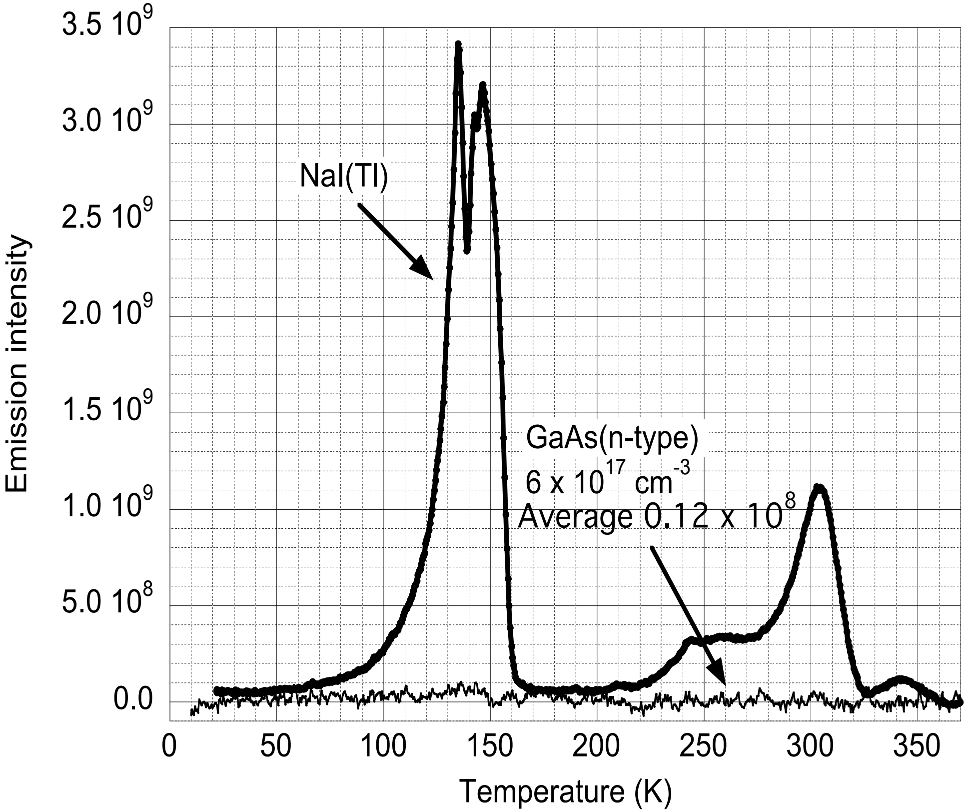
- Pretty Bright … potentially even better?
- 60% QE reported in GaAs(Si): 7.5eV/γ

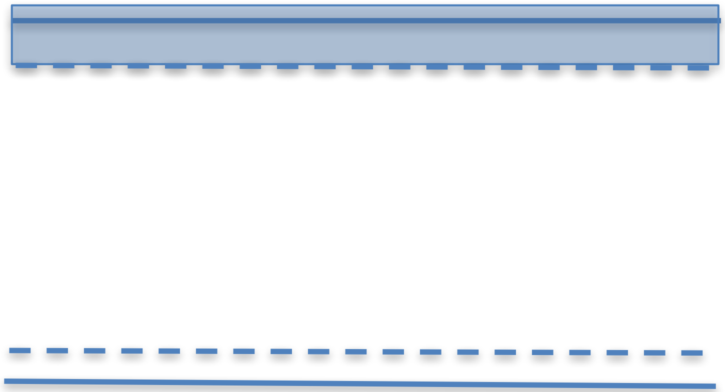
Cusano, Solid State Communications, 2:353-358, 1964

Sensitivity Curves assume 100% QE



No Evidence of Afterglow in GaAs(Si)





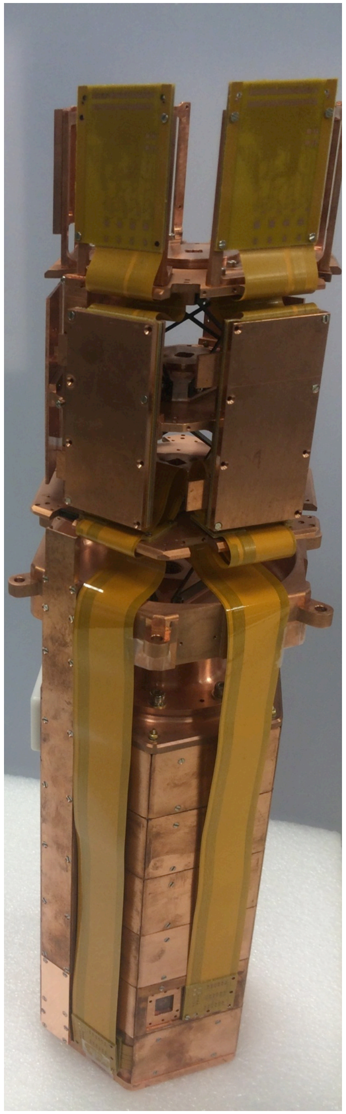
GaAs: Direct Gap

$n_{Si} = 6\mathrm{x}10^{17}\ 1/\mathrm{cm}^3$ is above the Mott transition.

- Lot’s of overlap between between D and A states … fast decay!
- Scintillator self absorption? R&D: decrease n_{Si}

GaAs: Rough Cost Estimates

- R&D to 1eV threshold:
  - 2 x 2 FTE Postdoc
  - ½ FTE RF Engineer
  - 2 FTE Gradstudent
  - 100k
- Crystal R&D
  - 2 x ½ FTE Postdoc
  - 100k
- Project
  - Just another tower in SuperCDMS SNOLAB
  - ~600k



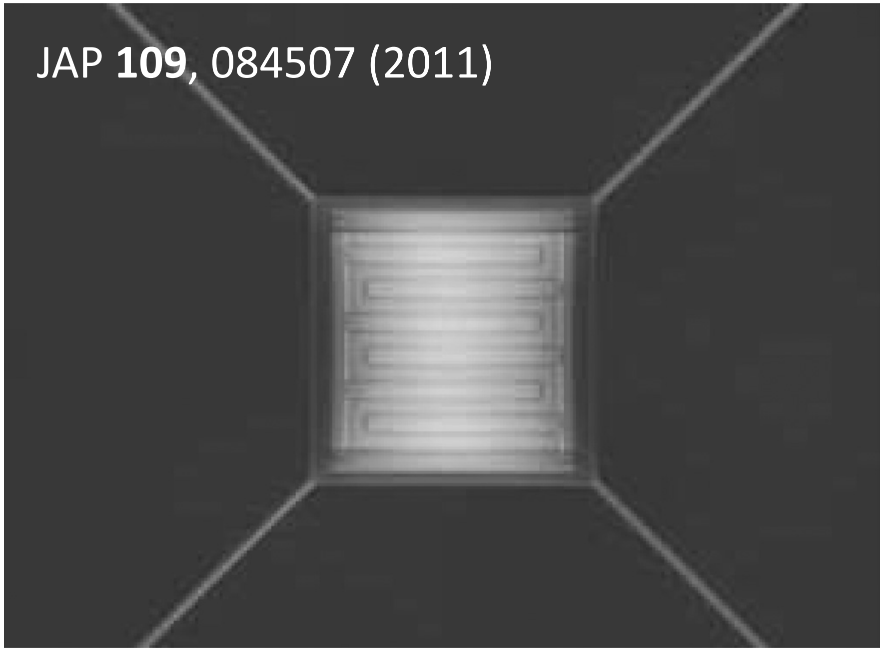
Summary

- Light Mass Dark Matter Detector:
  - Energy Sensitivity
  - No Dark Counts
- Photon/Roton Detector based on athermal phonon calorimeters
  - Intrinsic energy resolution scales as T_c^3
  - Challenges: Isolating from environmental noise
  - Phased Development Program with interesting science at every stage
- GaAs(Si): 1MeV < M_{DM} < 300 MeV
- Superfluid He: 10meV < M_{DM} < 300MeV

Backup

Resolution Limits: Parasitic Power

SAFARI has created devices with x75 smaller G & x9 smaller P_{bias} than we require



JAP **109**, 084507 (2011)

	SuperCDMS (modeled)	SAFARI (measured)
Tc	30 mK	111 mK
G	12800 fW/K	170 fW/K
P_{bias}	76 fW	8.9 fW
S_{NEP}	$6x10^{-19}$ W/rthz	$4.2x10^{-19}$ W/rthz

We're far from the fundamental limits on phonon resolution due to parasitic power