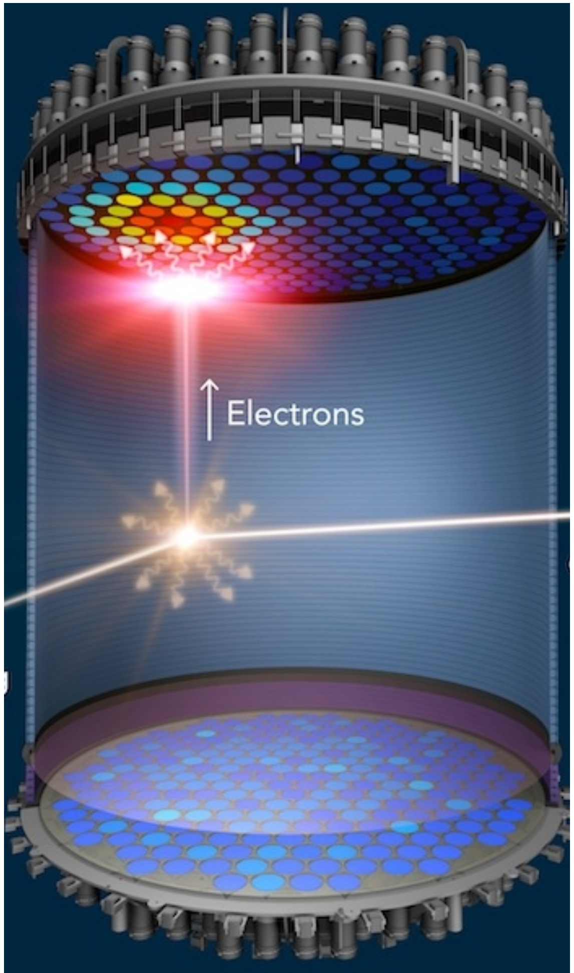
Design Drivers for Direct Detection Dark Matter Searches

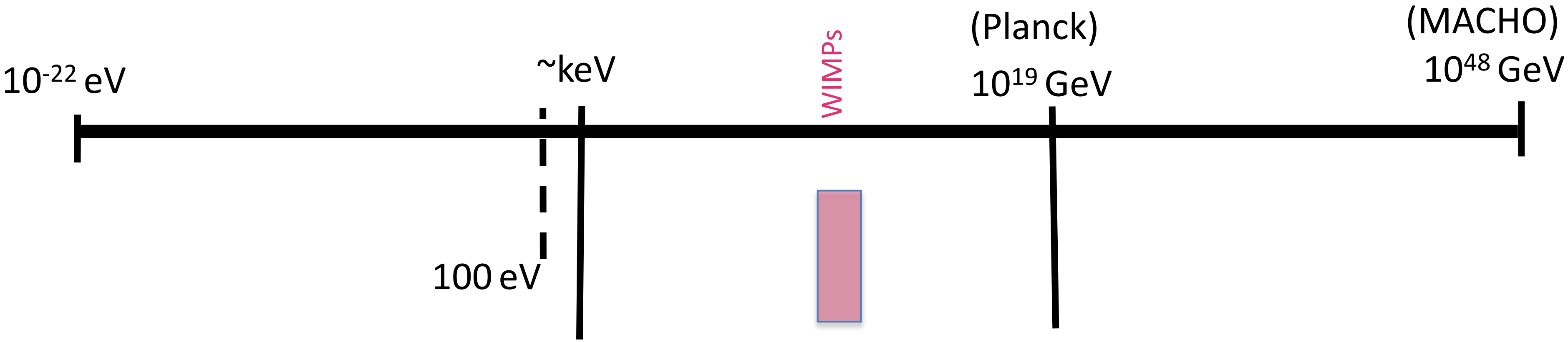


Matt Pyle
UC Berkeley
Physics 290e
9/17/19

Plan

- Briefest Theoretical Overview Ever!
- Interaction Processes and Experimental Design Drivers for Direct Detection
  - WIMPs: 6 GeV < M_{DM} < ~100 TeV
  - Light DM: 100 meV < M_{DM} < 6 GeV DM
  - ~~Ultralight DM: M_{DM} < 10 meV~~

10 Years Ago: WIMPs



10^{-22} eV

~keV

100 eV

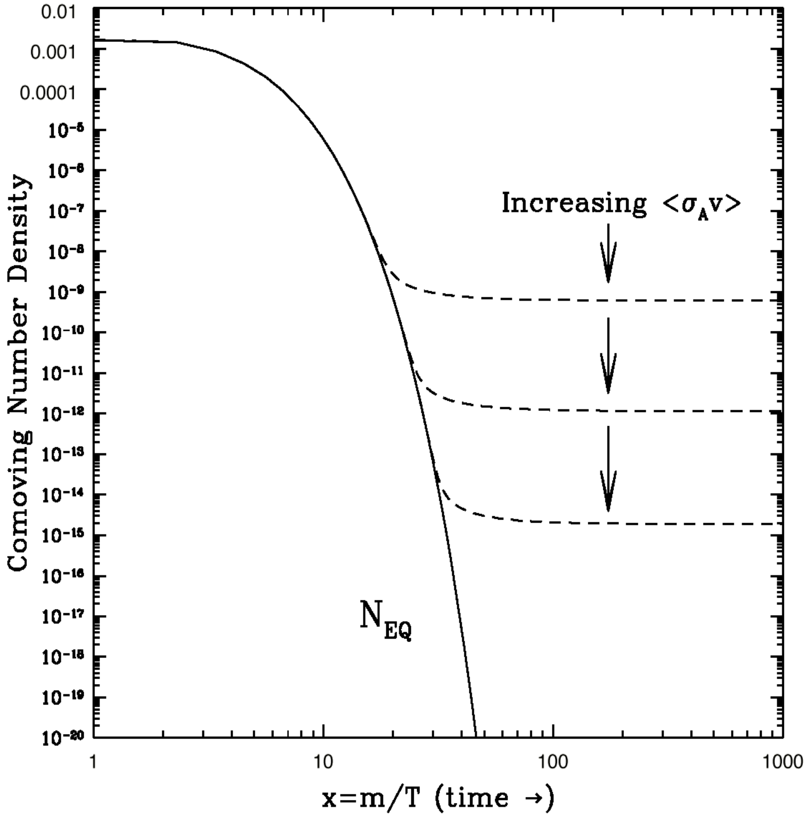
WIMPs

(Planck)

10^{19} GeV

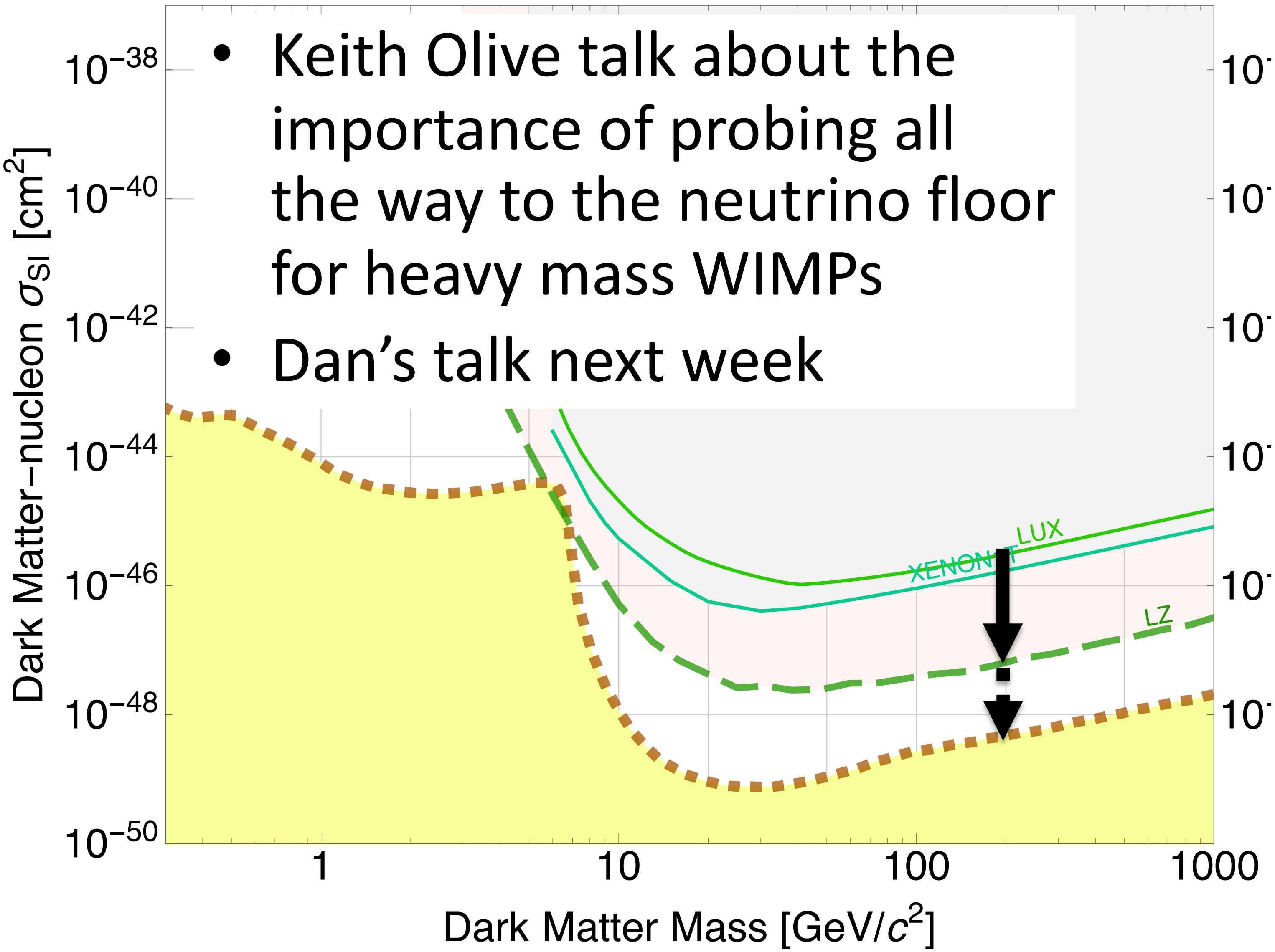
(MACHO)

10^{48} GeV



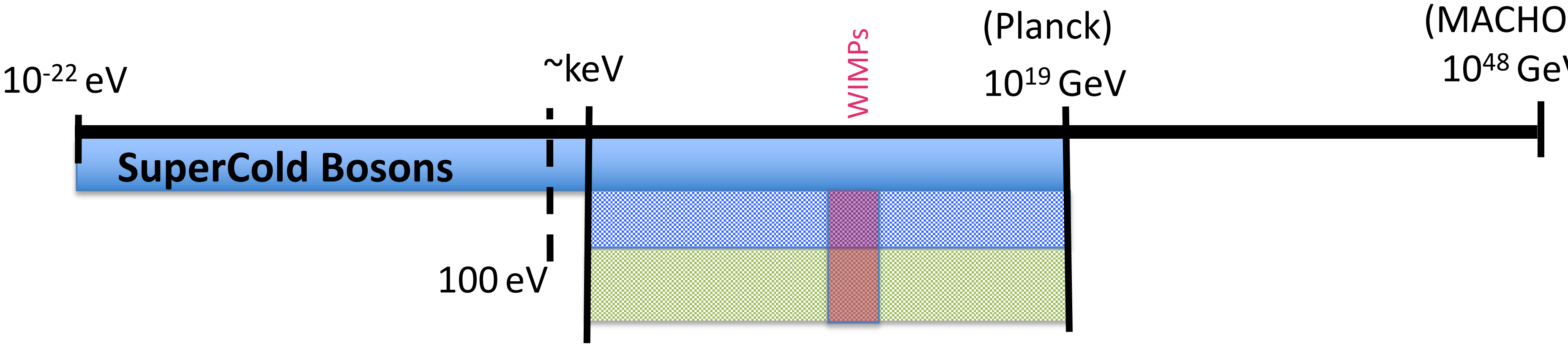
- Relic DM density suggest weak scale cross sections
- New physics (and particles) at the weak scale could solve the hierarchy problem

Today: Continue to Search for WIMPs



- Keith Olive talk about the importance of probing all the way to the neutrino floor for heavy mass WIMPs
- Dan’s talk next week

Today: Dark Matter Mass Parameter Space

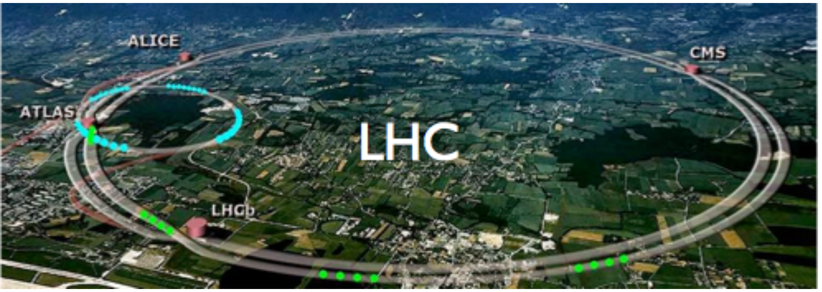


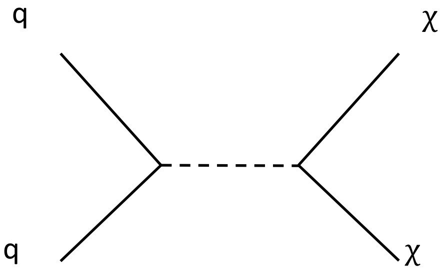
- M < 3 keV:
  - Axions, dark photons and other ultra-light bosons
- 3keV <M < 10 GeV
  - Assymetric Dark Matter Kaplan, Zurek et al: 0901.4117
  - Freeze In Hall, et al: 0911.1120
  - Dark Sectors

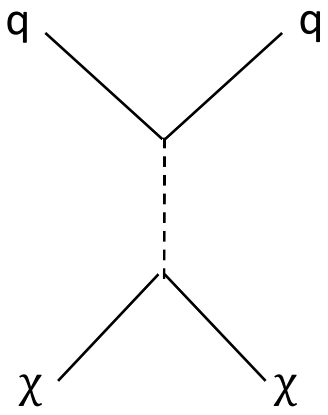
US Cosmic Visions: New Ideas in Dark Matter: 1707.04591

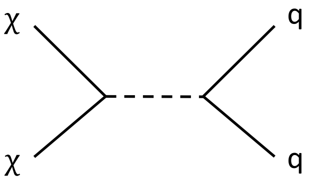
Dark Matter Detection

(not to scale)

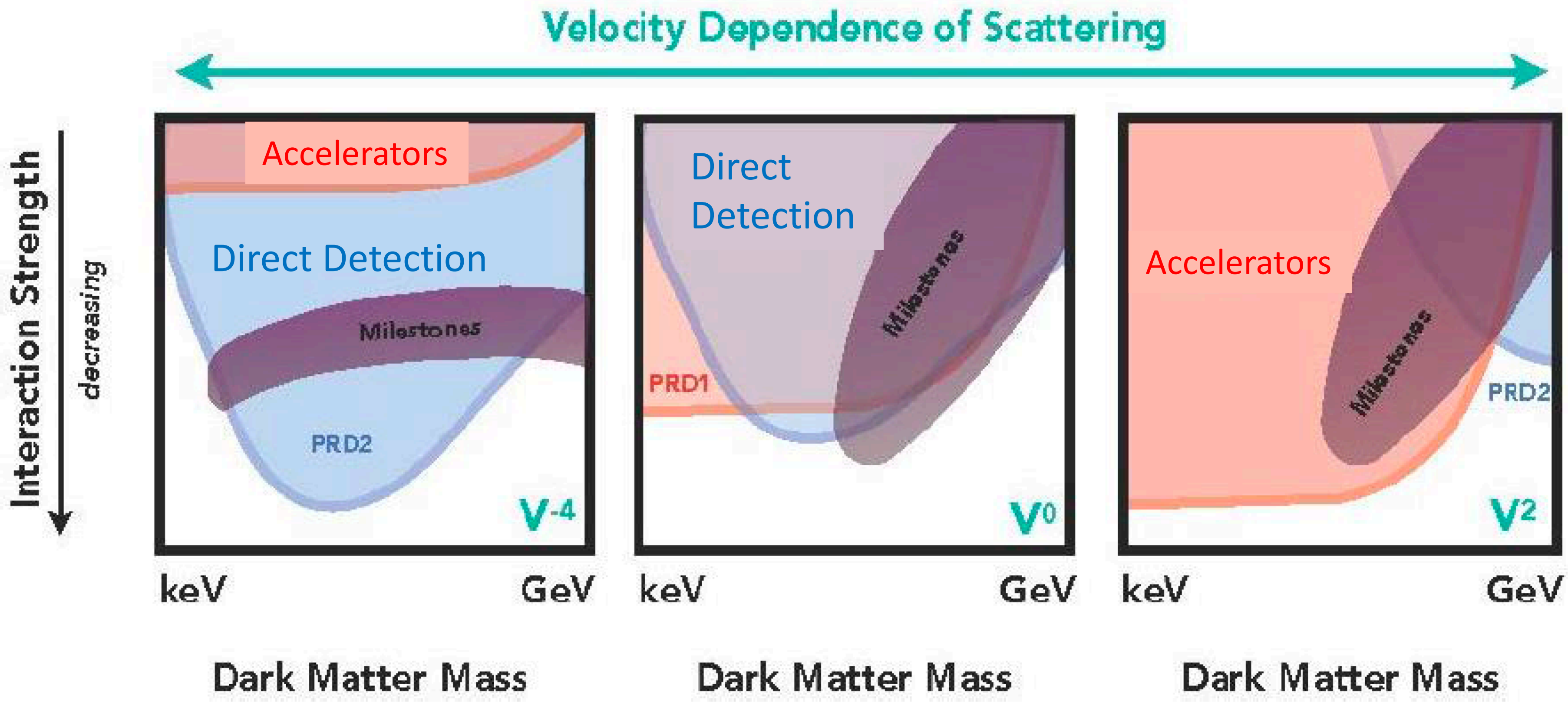






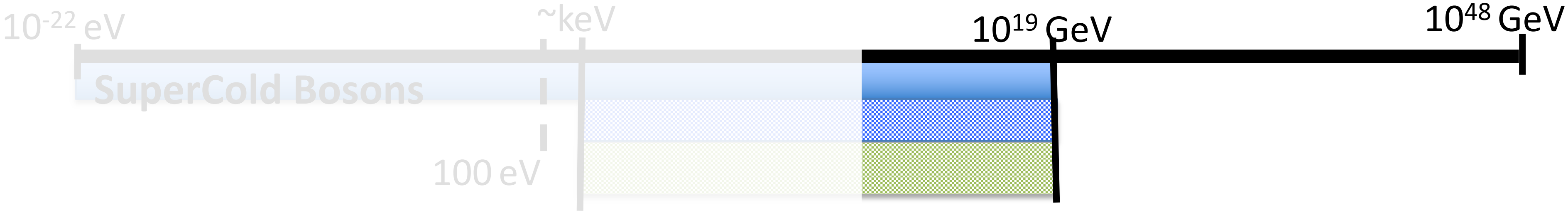


Complementarity with Accelerators



BRN: Dark Matter Small Projects New Initiatives

Experimental Design Drivers for Direct Detection

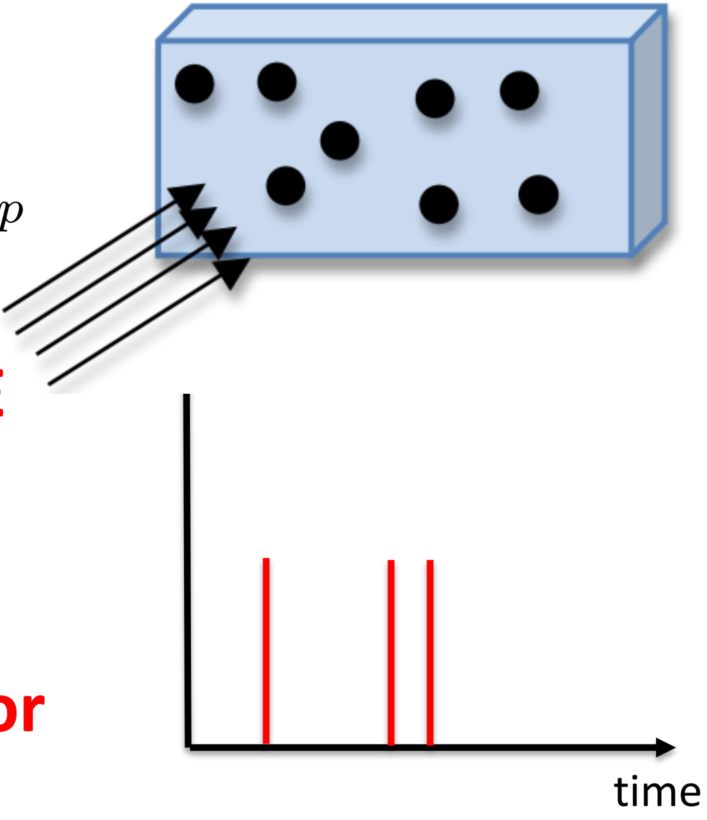


Design Drivers for M_{DM} >10 GeV

M_{DM} > 10 GeV: Tiny, Tiny Rates

- $n_{DM} = \rho_{DM}/M_{DM}$:
  As M_{DM} gets bigger, n_{DM} gets smaller

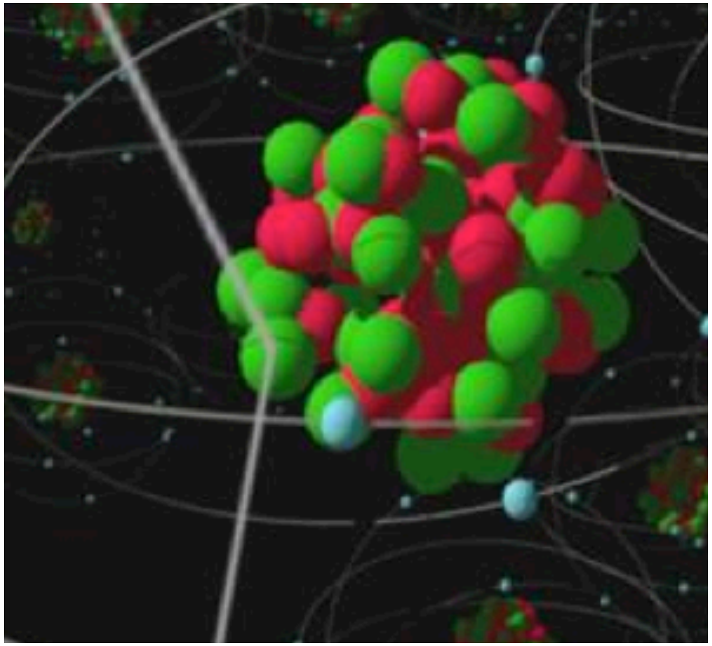
- Interaction Rate, $\underset{\nearrow\ \text{Really Small}}{R} = \underset{\uparrow\ \text{Small}}{\sigma n_{DM}} \underset{\uparrow\ \text{Small}}{v_{DM}} \underset{\uparrow\ \textbf{HUGE}}{N_{exp}}$



Design Driver #1: Big Exposure

You need a really big particle detector

M_{DM} > 10 GeV: Coherent Elastic Scattering

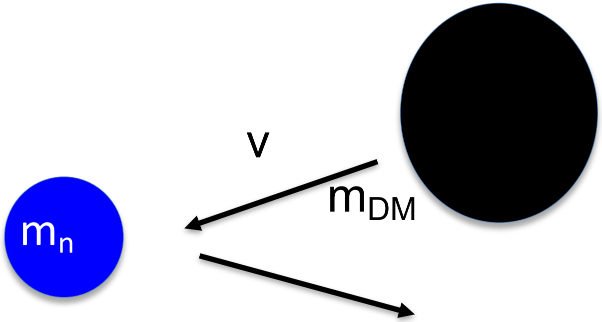


Scatter coherently off all the nucleons in a nucleus: $R \propto A^2$

Design Driver #2: Heavy Nuclei

Big Idea: For both very heavy and very light mass dark matter, we're going to take advantage of coherence

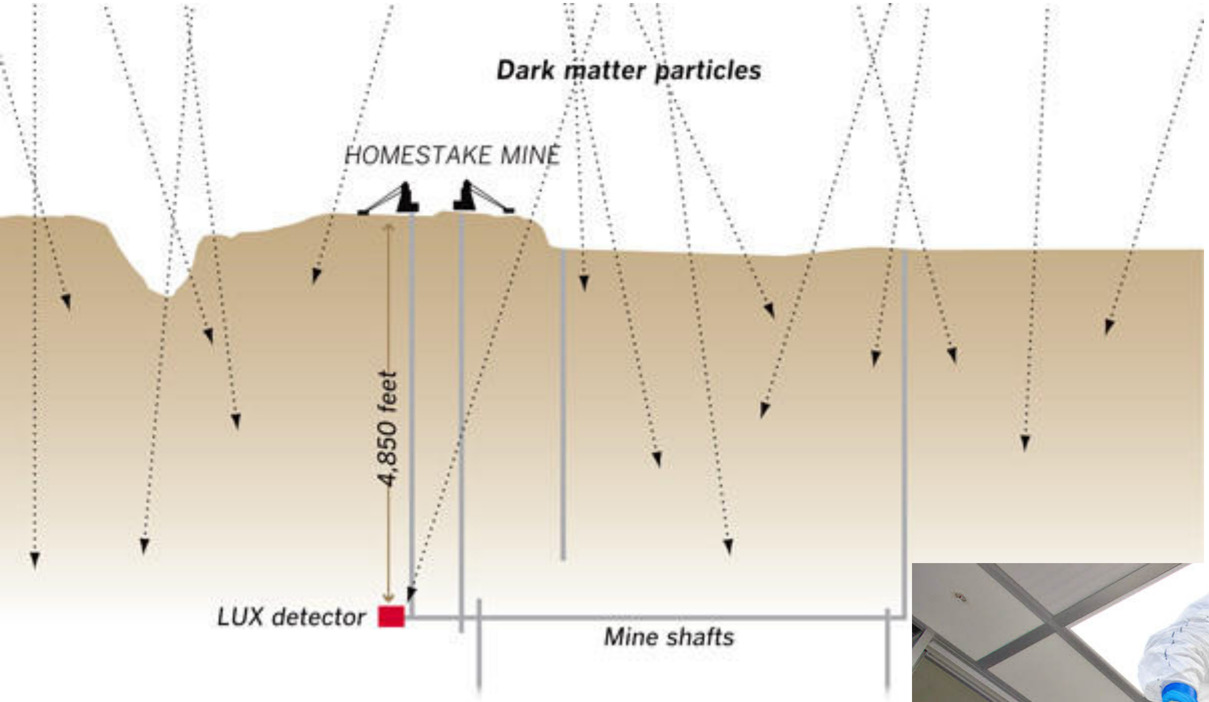
M_{DM} > 10 GeV: Backgrounds



- Characteristic Recoil Energy: O(10keV)
- Same recoil energy as radiogenic backgrounds

Design Driver #3: Minimal Radiogenic Backgrounds

Get rid of the Hay

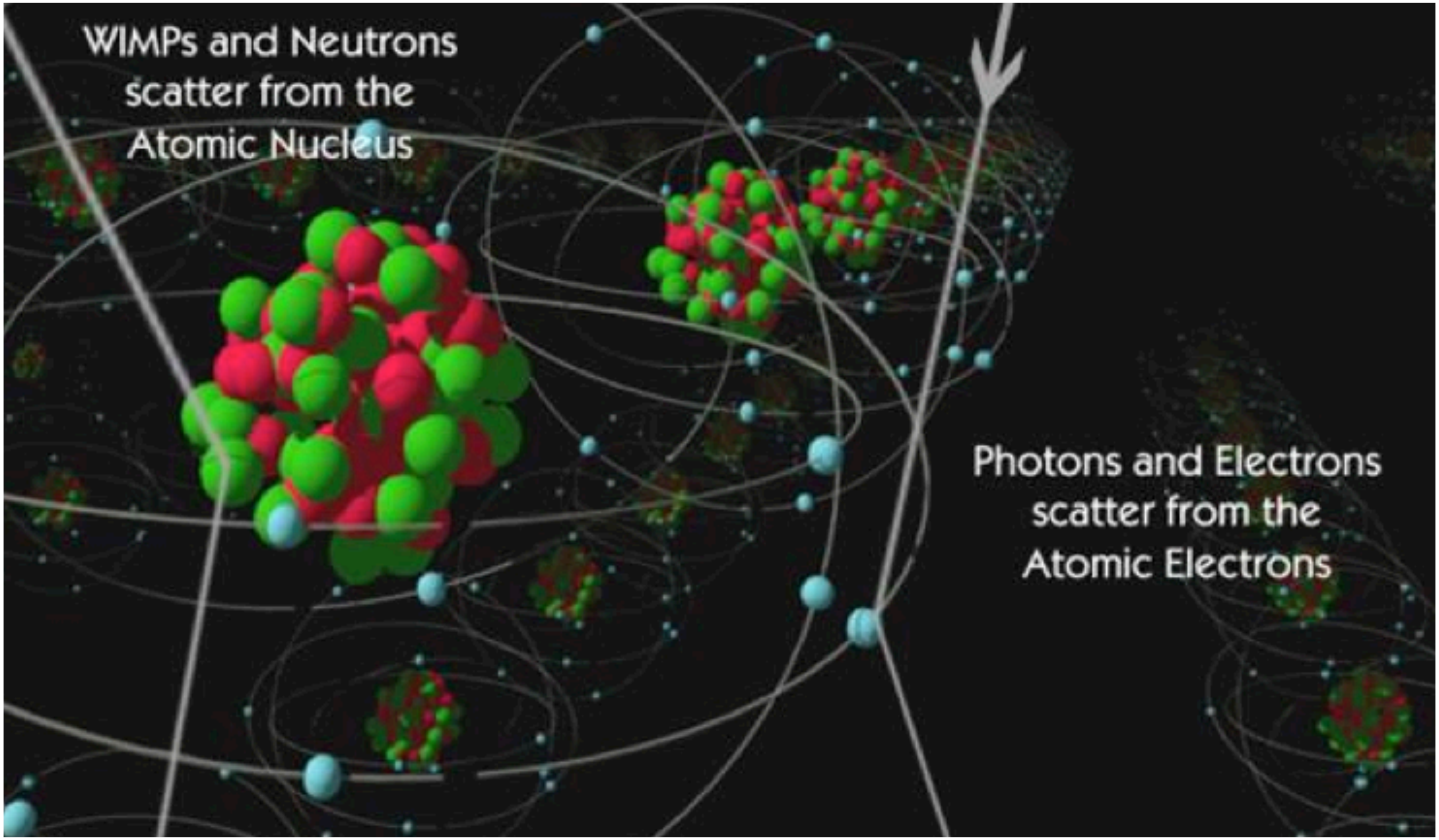


Go underground to shield detector from cosmic rays and their decay products

Use only radiopure materials and fabrication techniques

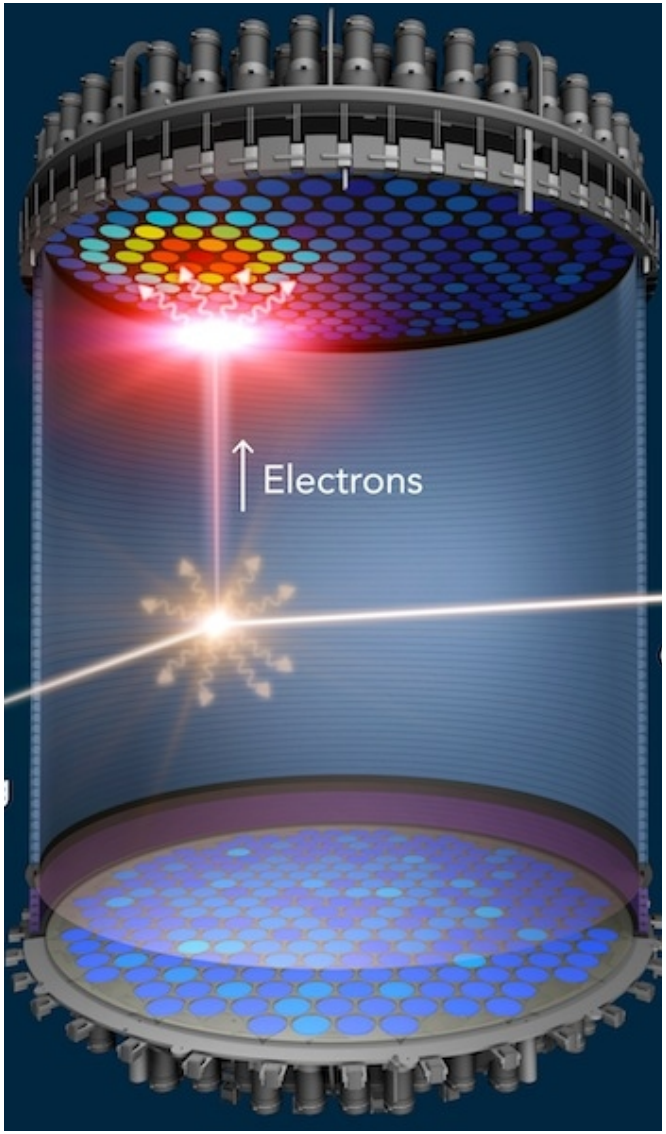
DEMO: Cloud Chamber

M_{DM} >10 GeV: Electronic Recoil / Nuclear Recoil Discrimination



Measure both scintillation light and ionization to distinguish nuclear recoils from electron recoils

M_{DM} >~ 10 GeV: Liquid Noble TPCs

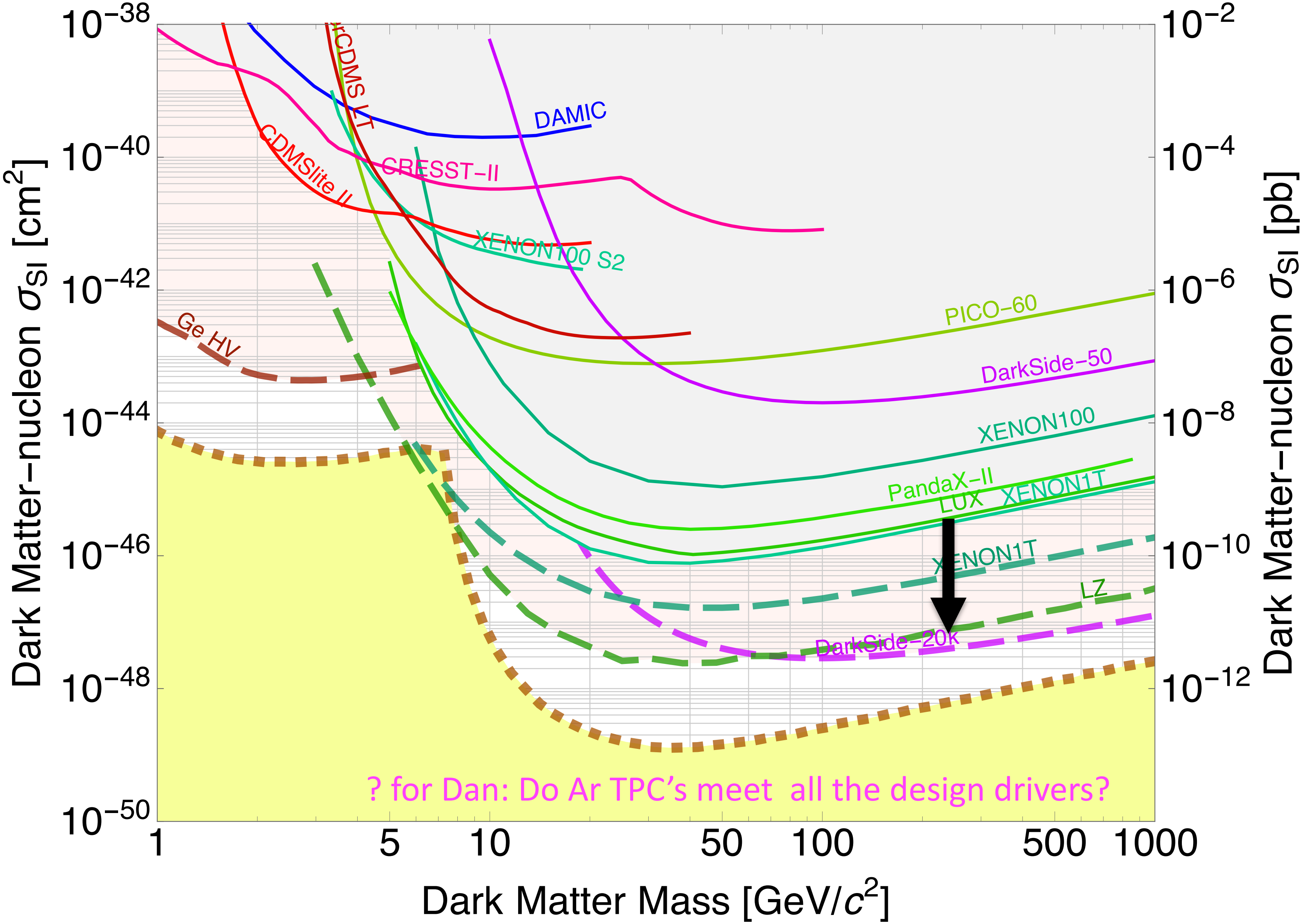


LZ (XENON 1T,PandaX)

- Exposure: (7 tons)
- High A: Xe
- Underground
- Radioclean: self shielding
- Electronic/Nuclear Recoil Discrimination

More: Dan’s talk next week

G2 High Mass Sensitivity Estimates



? for Dan: Do Ar TPC's meet all the design drivers?

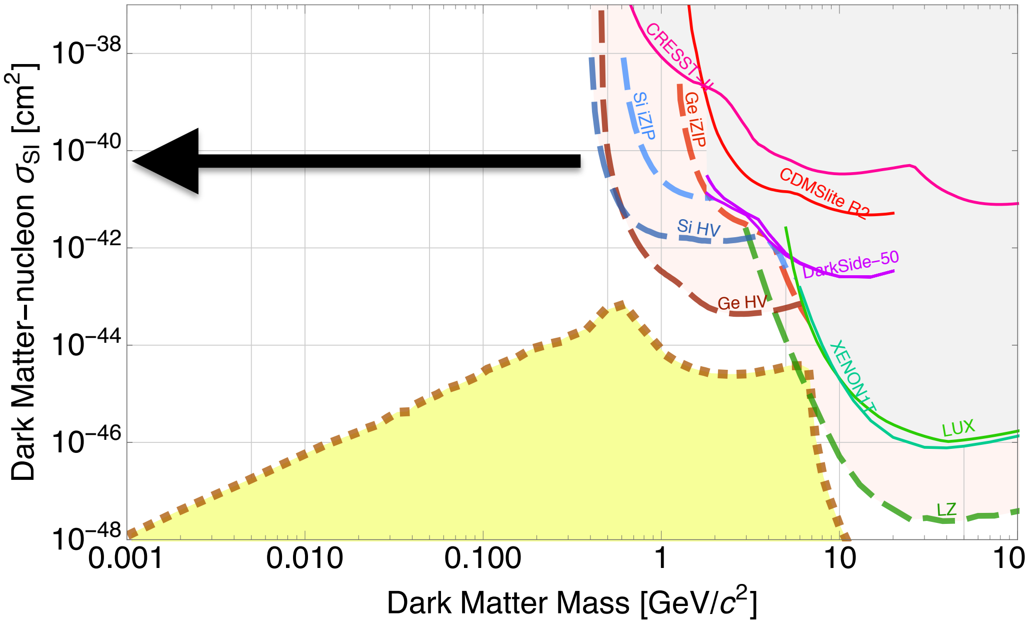
Design Drivers for 1 MeV < M_{DM} < ~6 GeV DM Scalar Interactions

Light Mass DM Design Drivers: ~~Exposure ?~~

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

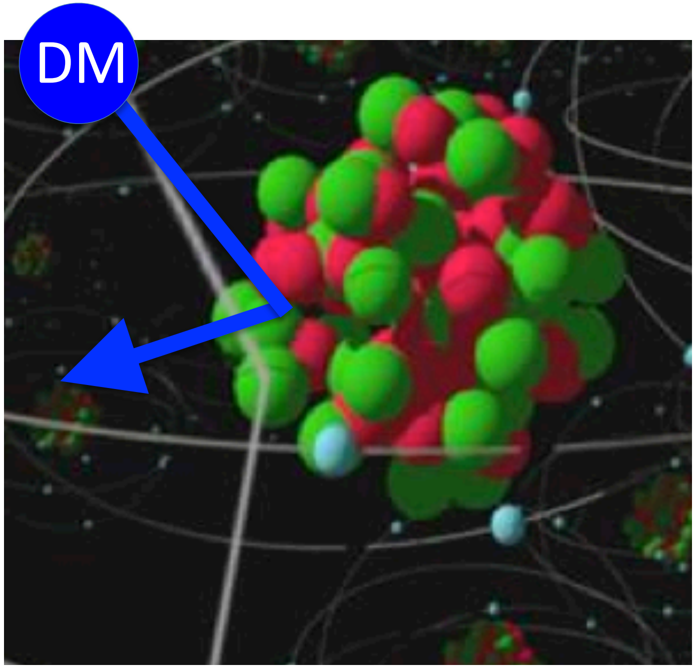
$$= \sigma \frac{\rho_{DM}}{M_{DM}} v_{esc} N_{exp}$$

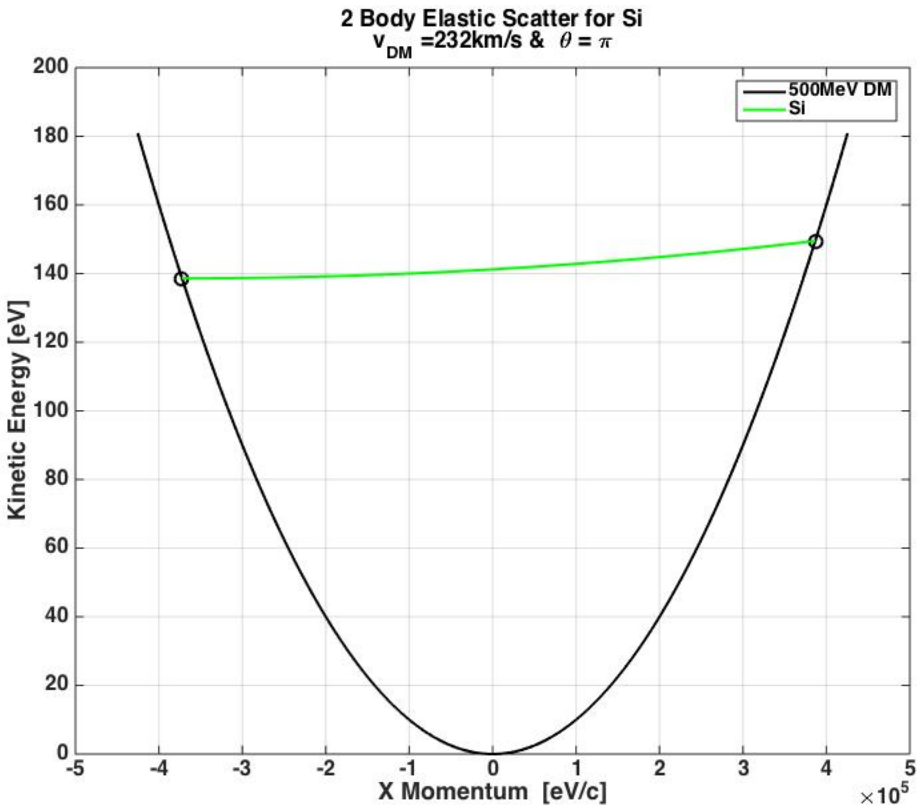
Interaction Rate scales with $1/M_{DM}$



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

Kinematics: 2 Body Elastic Nuclear Scattering





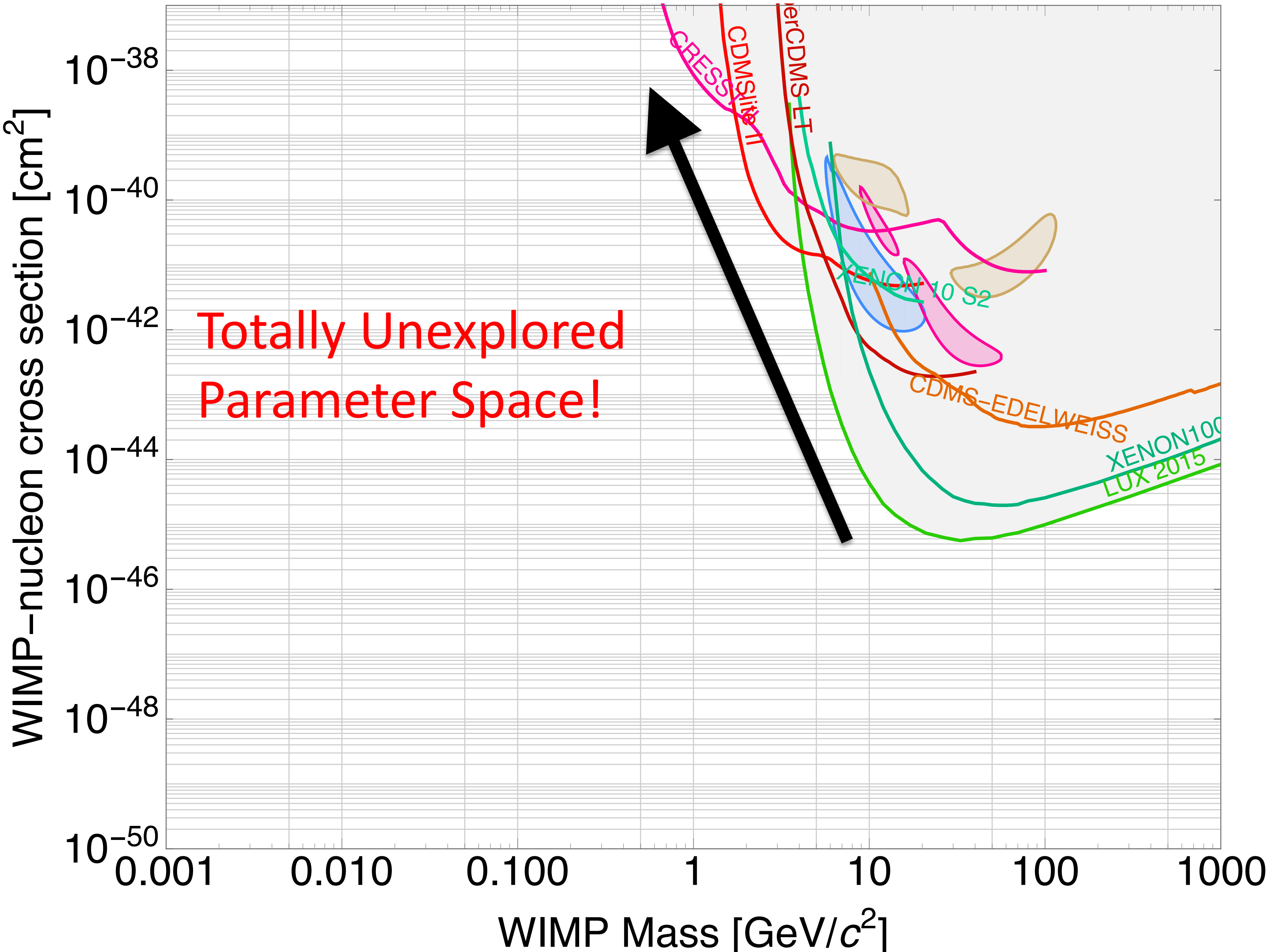
$$K_n = \frac{\mu^2 v_{DMo}^2}{M_n}\left(1 - \cos(\theta)\right)$$

When $M_n >> M_{DM}$

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

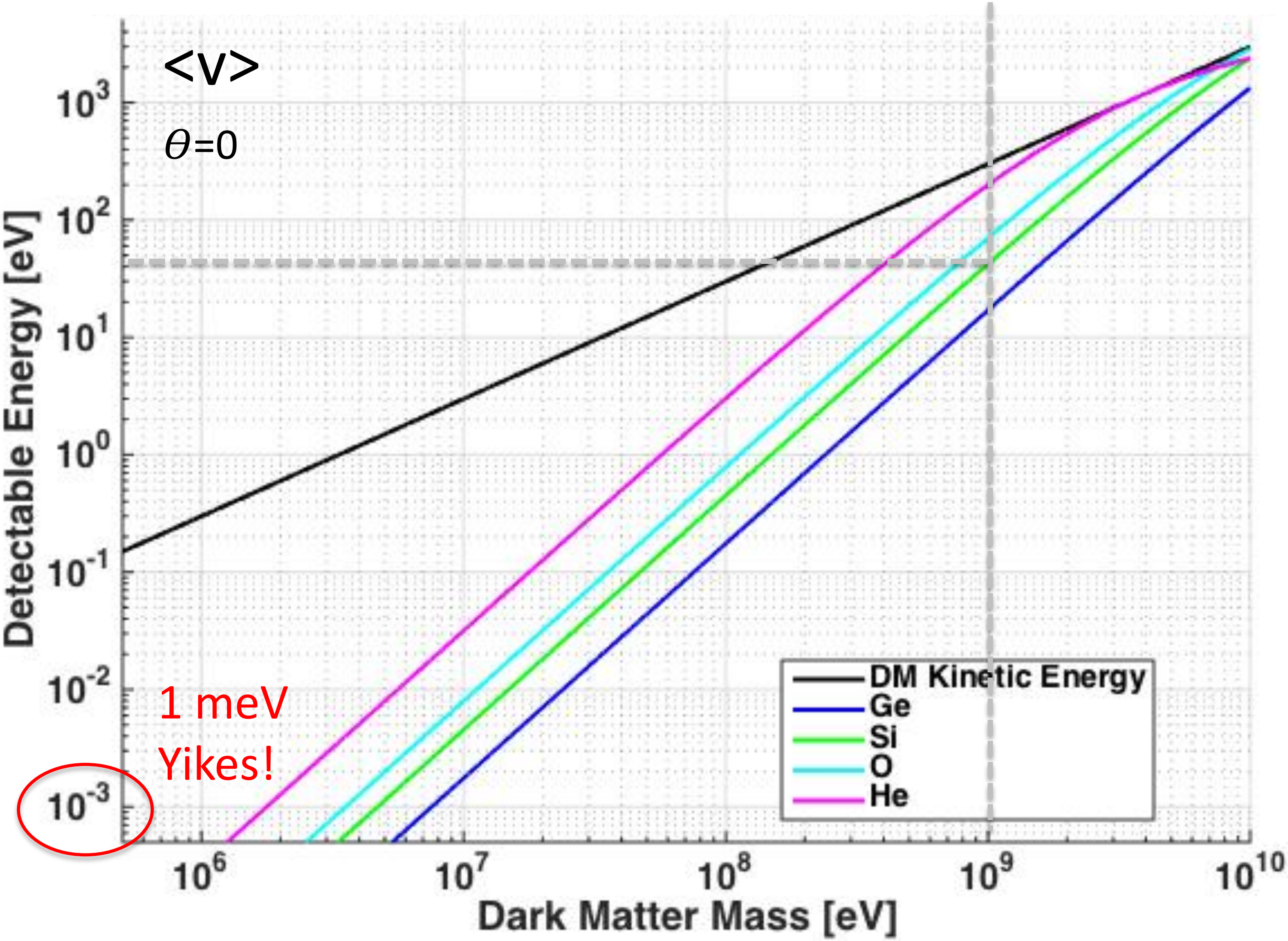
Recoil Energy Scales as M_{DM}^2. Transfer of DM kinetic energy is really inefficient for elastic 2 Body Scatters when $M_n >> M_{DM}$

Energy Sensitivity Is the Primary Design Driver



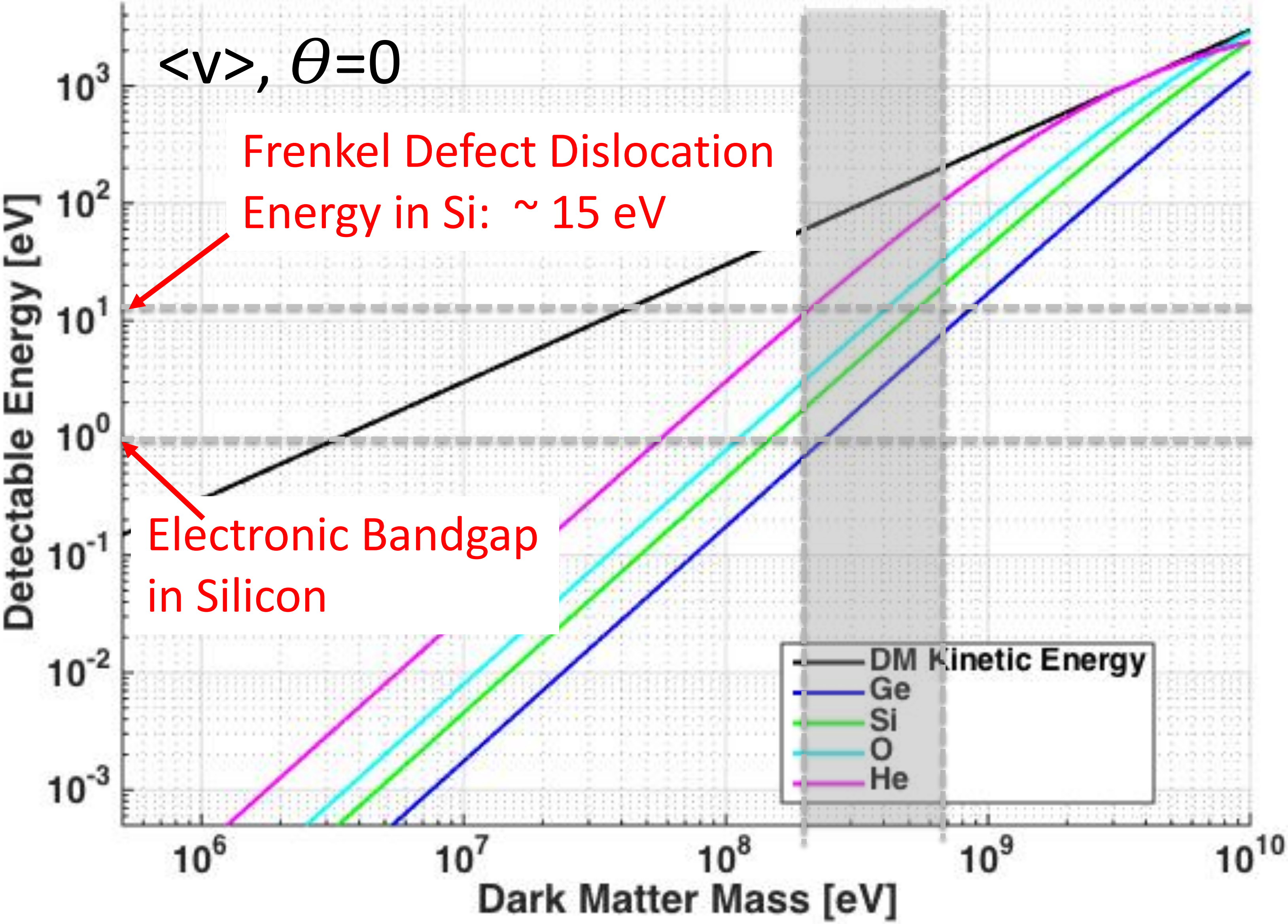
Totally Unexplored
Parameter Space!

Light Mass Dark Matter: Elastic Nuclear Scattering



Energy Sensitivity is Primary Design Driver

Ionization Production in eV Scale Nuclear Recoils

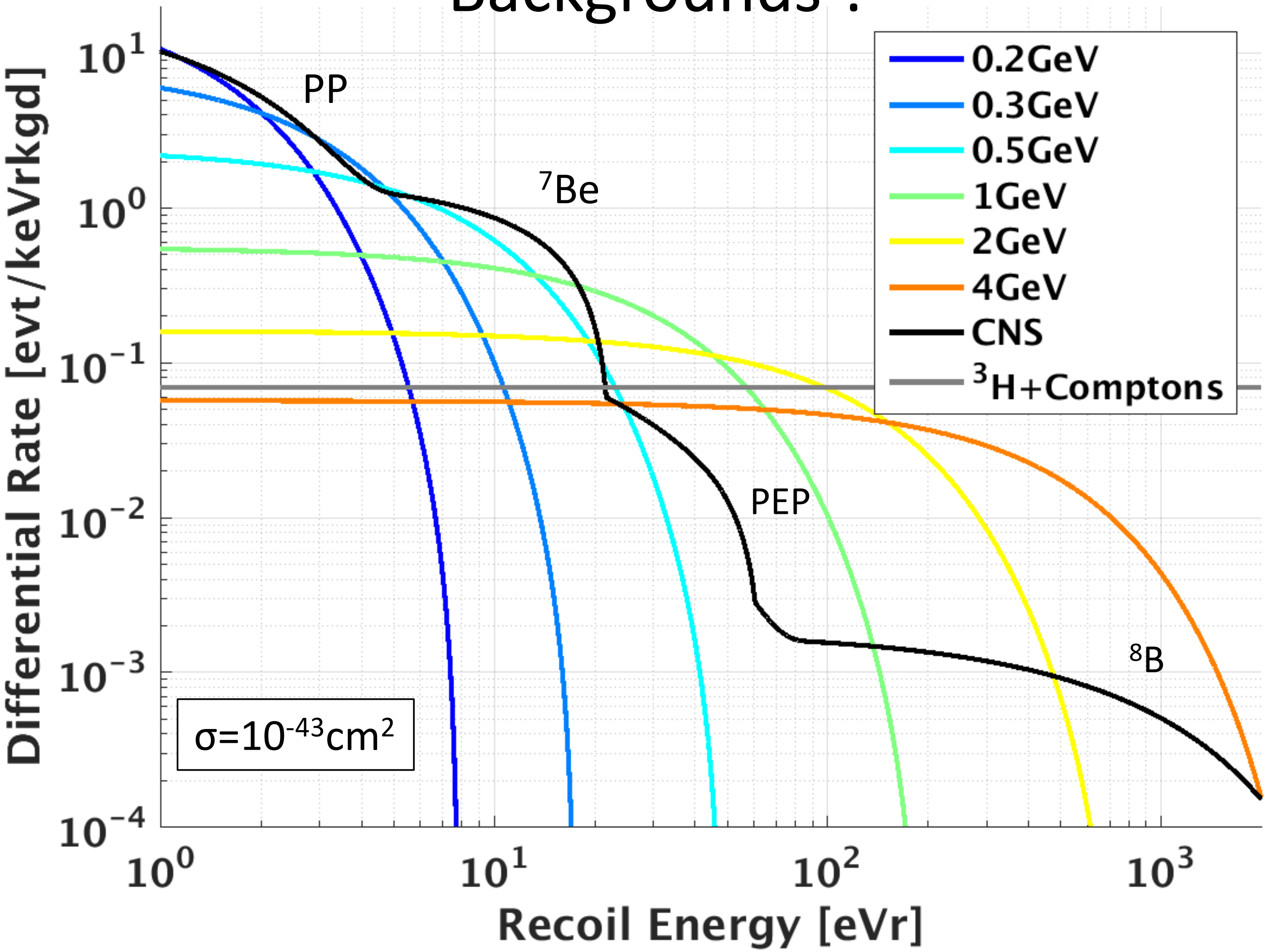


Frenkel Defect Dislocation Energy in Si: ~ 15 eV

Electronic Bandgap in Silicon

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

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

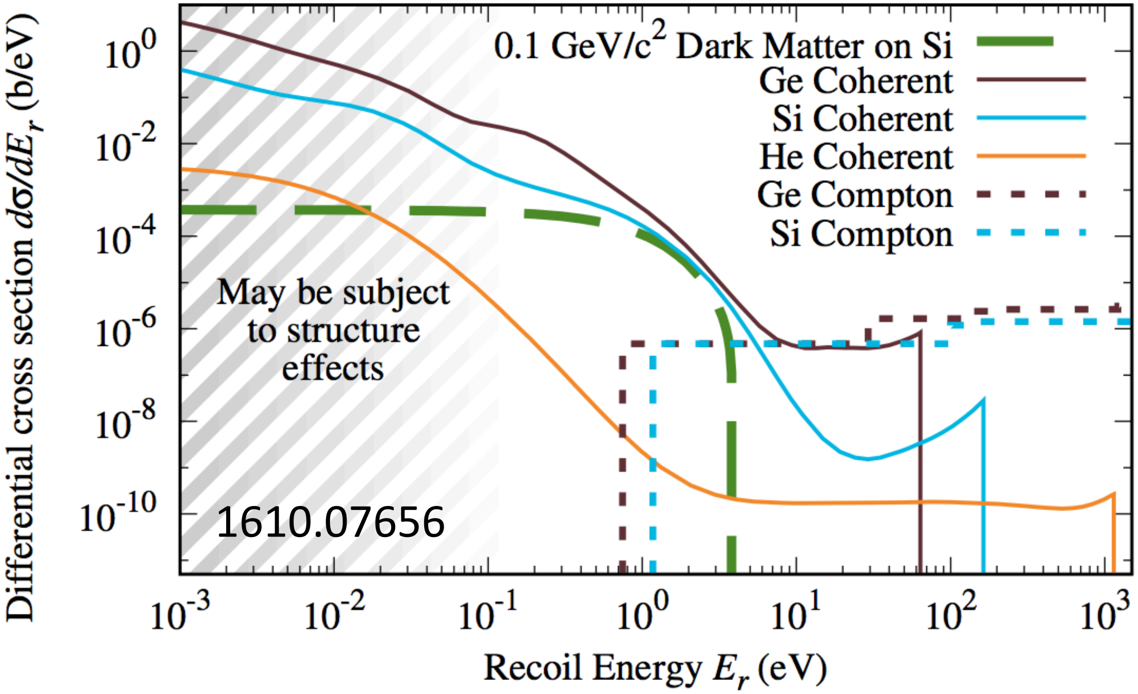


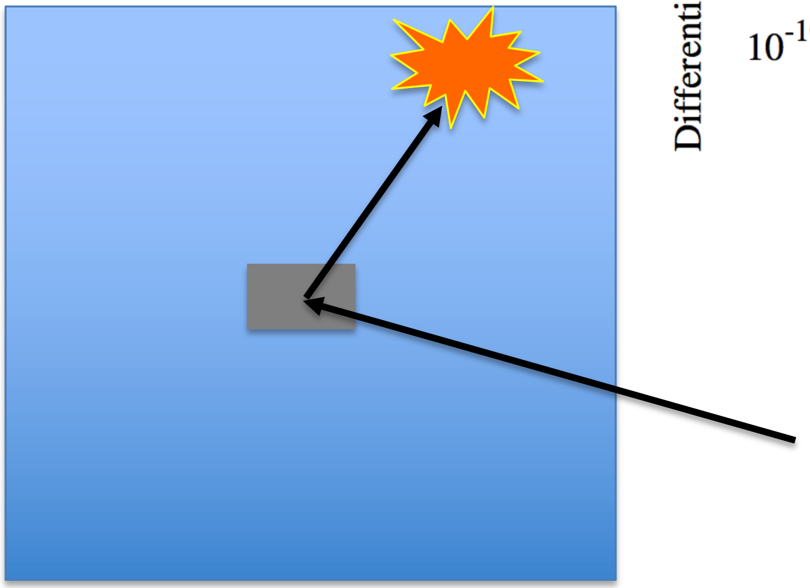
Smaller DM masses have less overlap with flat backgrounds!

Are Backgrounds Really Flat?: Coherent Photon Scattering

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

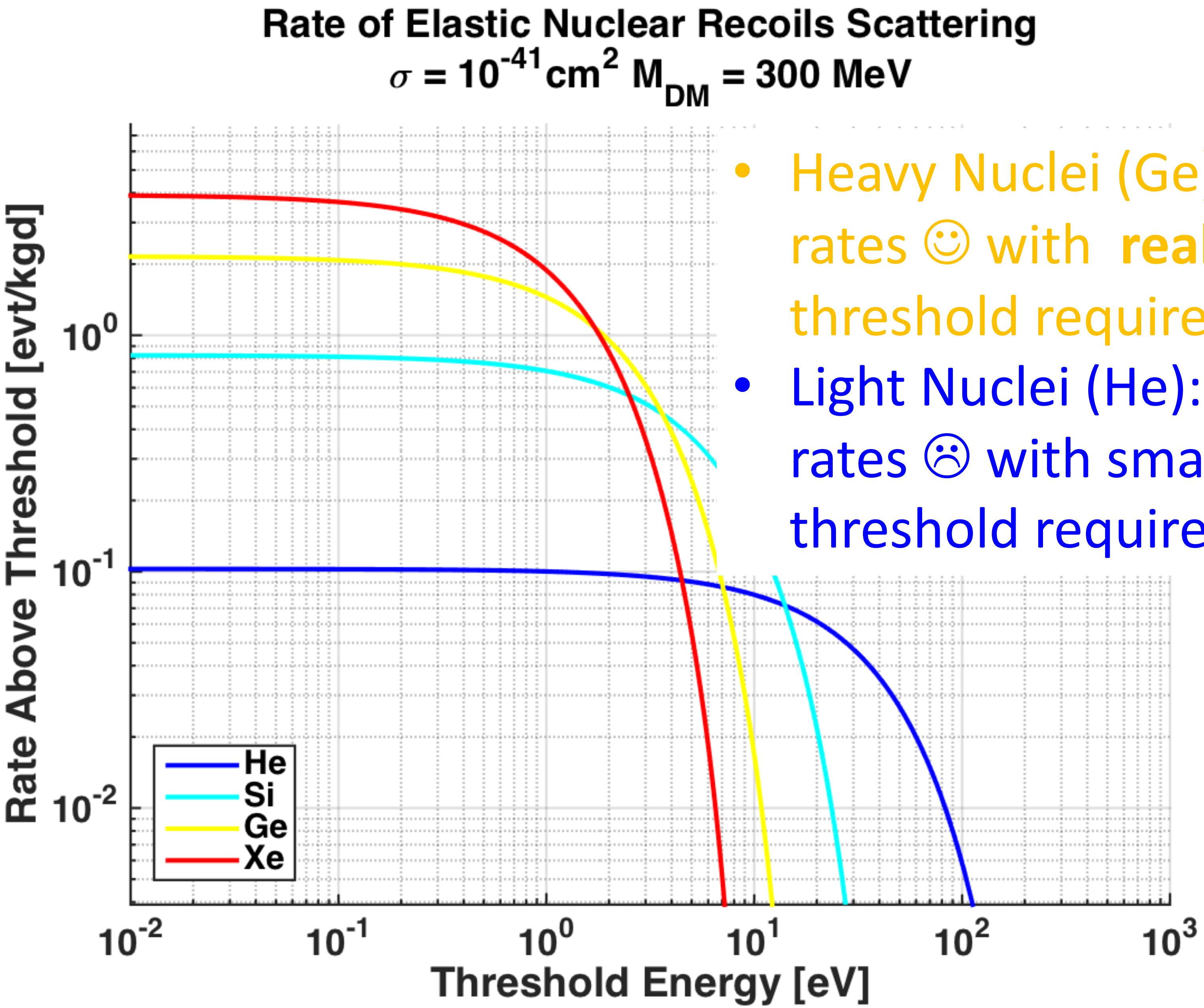
1461keV Photon from ^{40}K





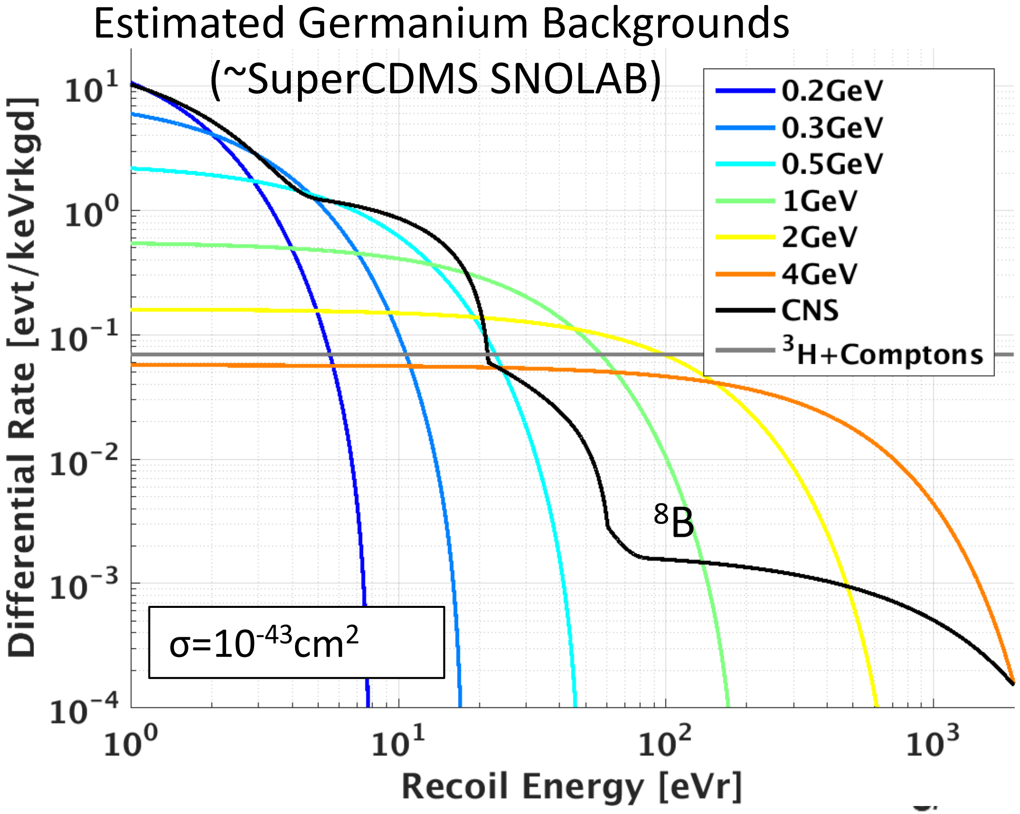
Build a Active Photon Veto

Aside: Heavy vs Light Nuclei: Rates



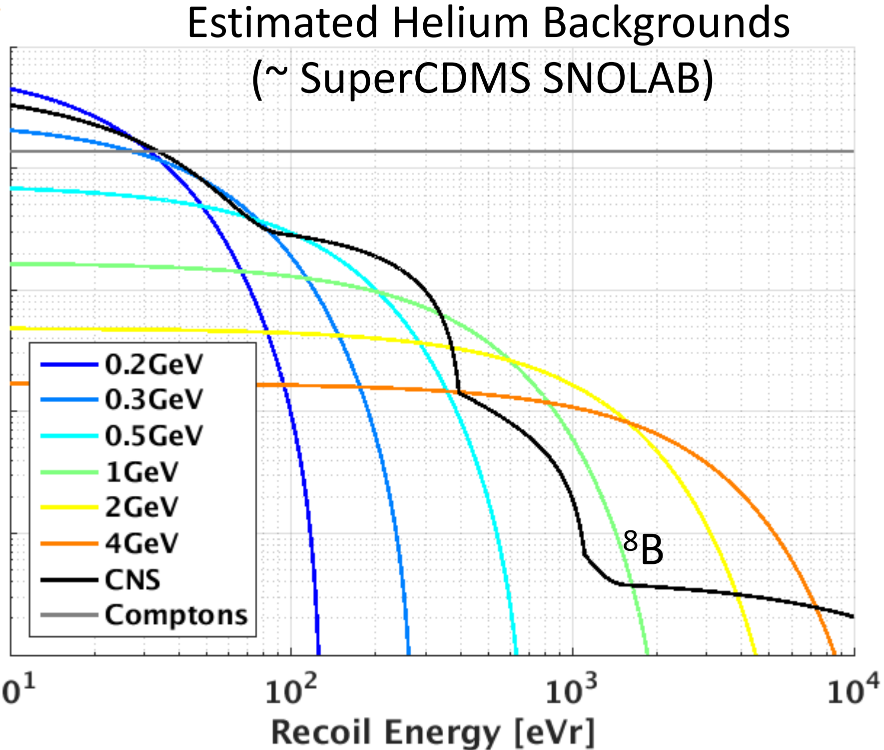
- Heavy Nuclei (Ge): larger rates ☺ with **really** small threshold requirements ☹.
- Light Nuclei (He): smaller rates ☹ with small threshold requirements ☺

Heavy vs Light Nuclei: Susceptibility to Electronic Recoil Backgrounds

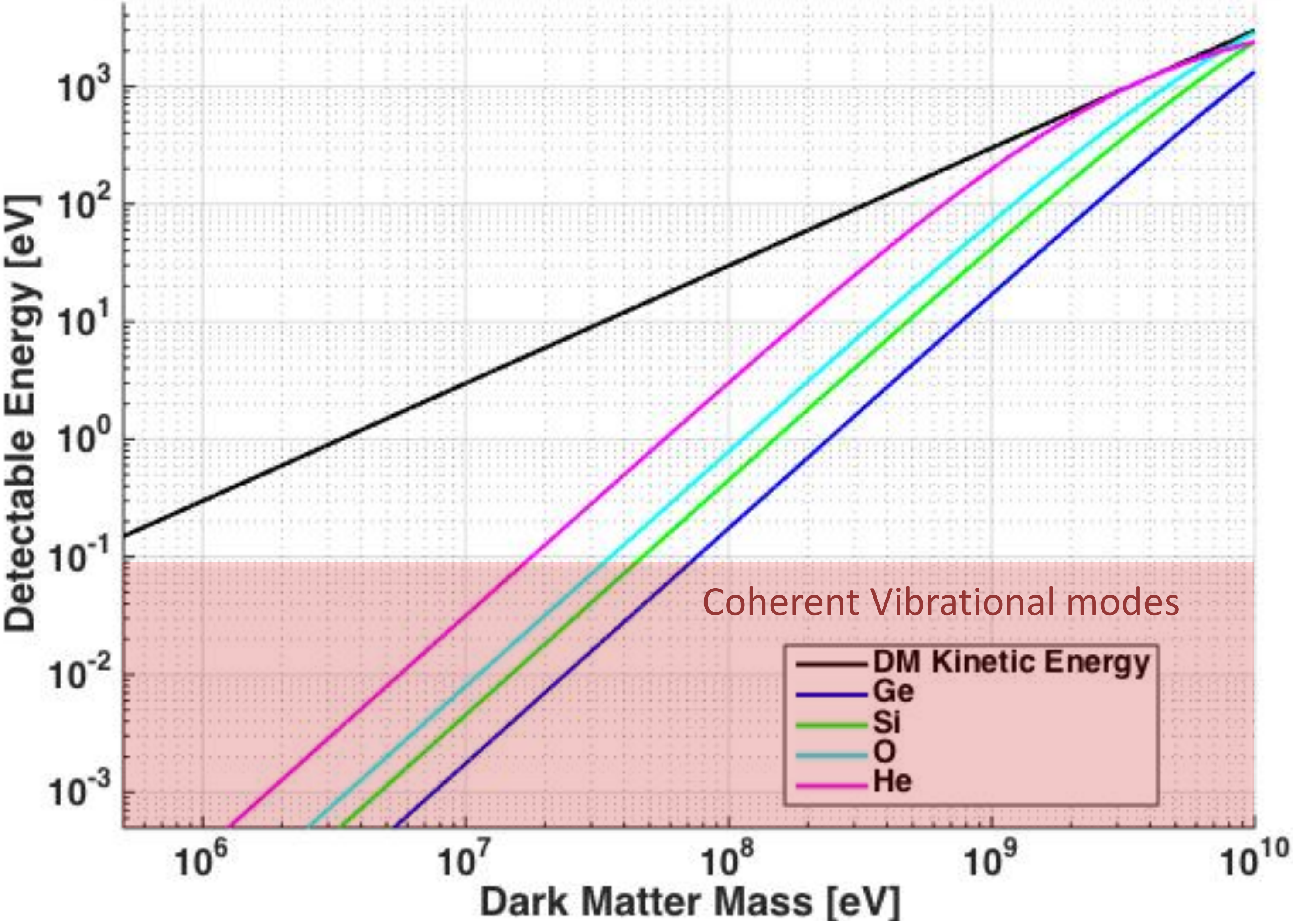

Estimated Germanium Backgrounds (~SuperCDMS SNOLAB)

Heavy Nuclei less sensitive to electronic recoil backgrounds

See 2nd half of Dan's talk next week on superfluid He detectors

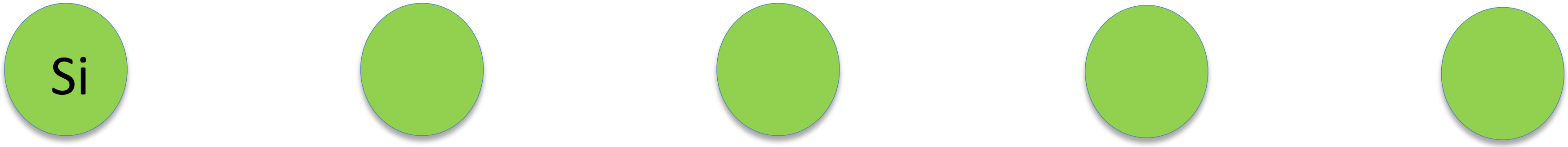

Estimated Helium Backgrounds (~ SuperCDMS SNOLAB)

Coherent Vibrational Excitation Regime



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

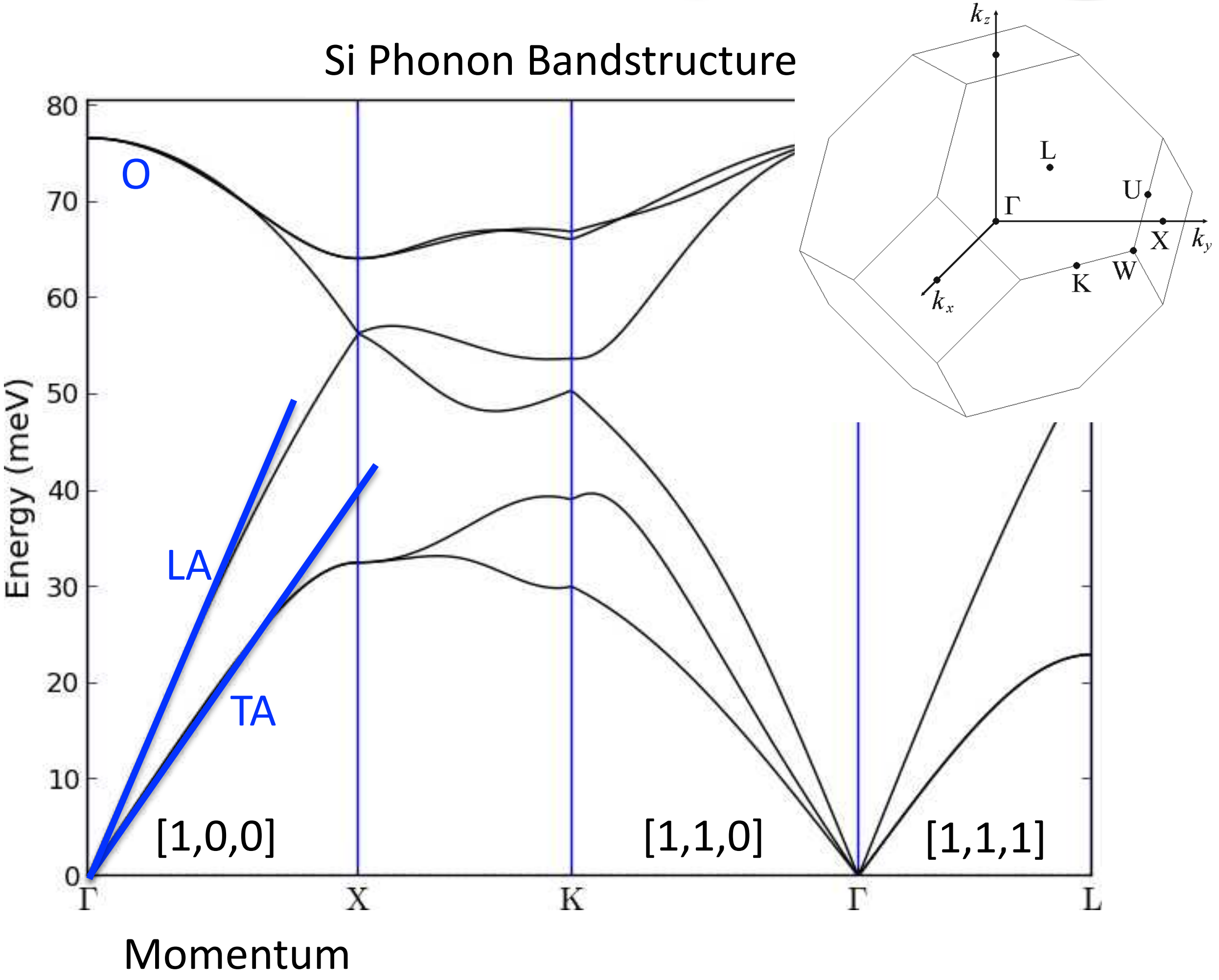
Acoustic Phonons



← $5.4\text{x}10^{-10}$ m →

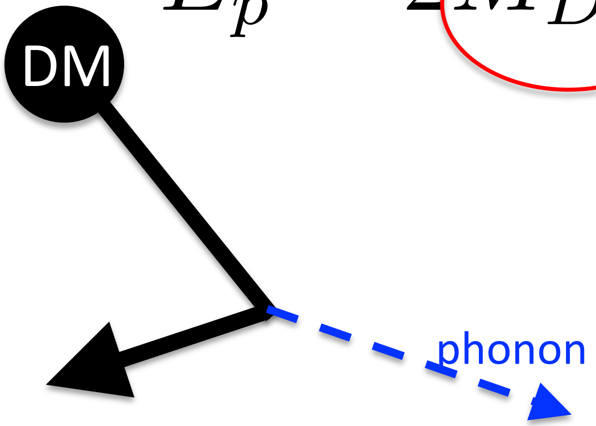
P = h/a = 2.3 keV/c

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

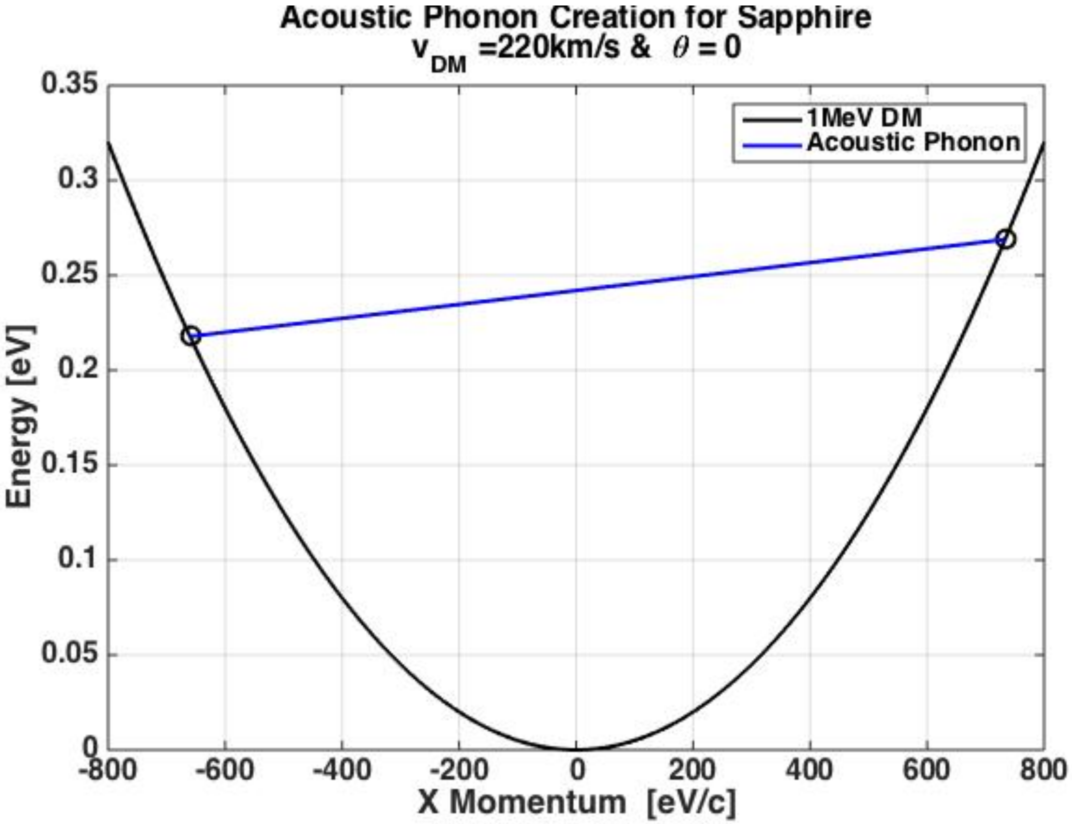


Kinematics: Acoustic Phonon Production

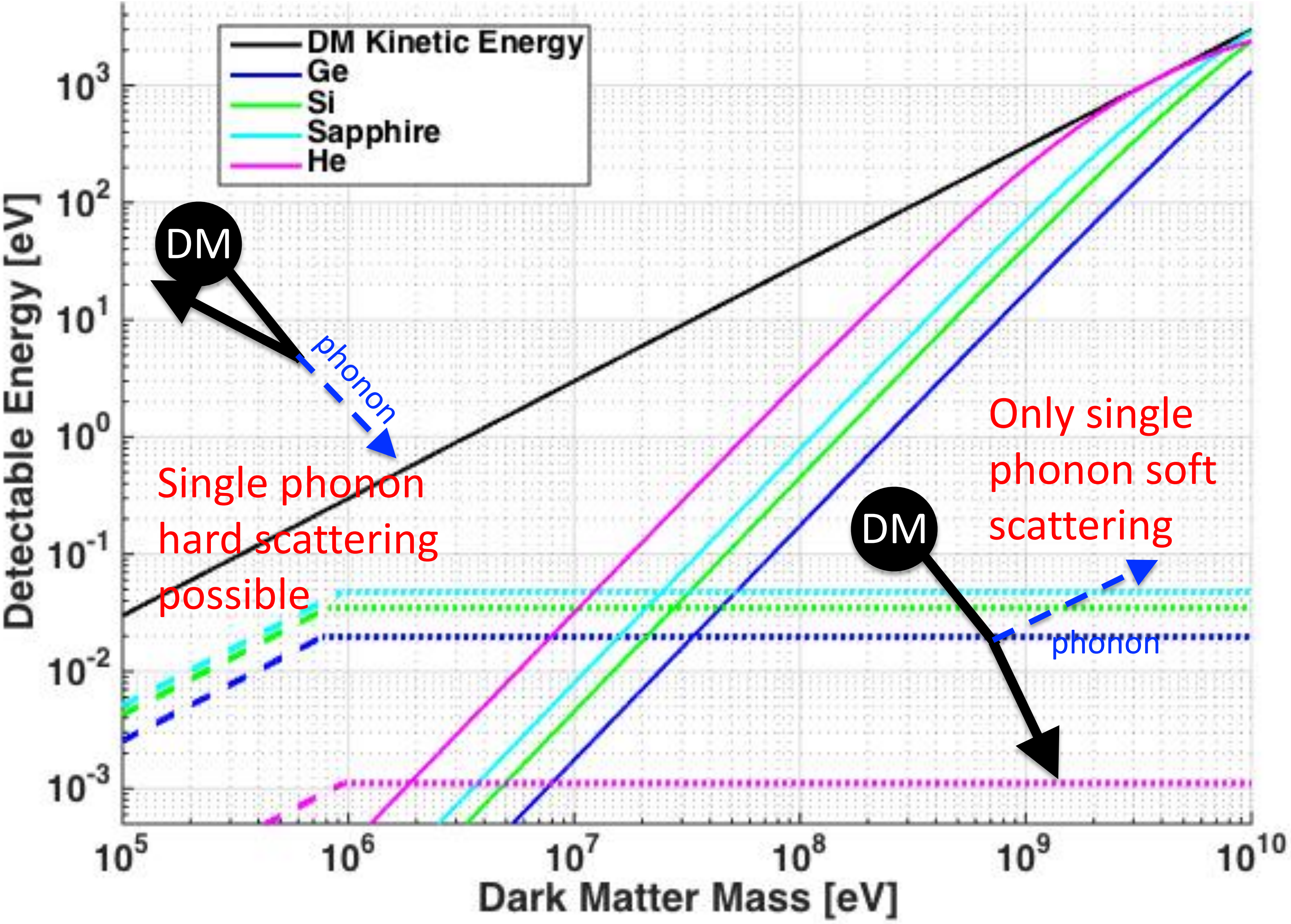
$$E_p = 2M_{DM} v_a \left(v_{DM\,0} \cos(\theta) - v_a\right)$$



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



Acoustic Phonon Production from DM



Single phonon hard scattering possible

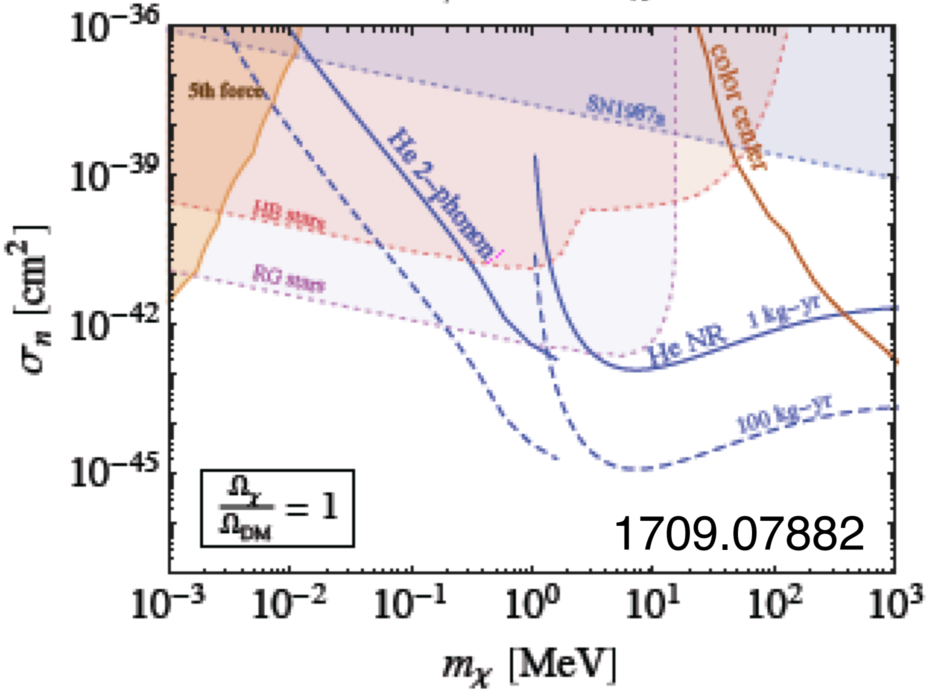
Only single phonon soft scattering

Acoustic Phonon Sensitivity Curves

Work In Progress by Griffin, Knapen, Lin, Zurek

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

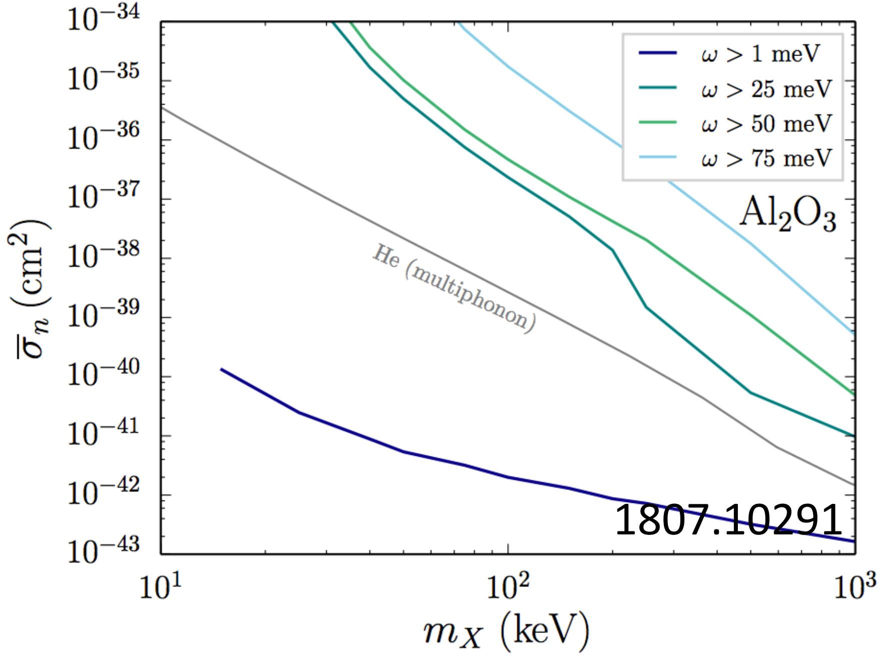
$m_\phi = 10^{-3}\, m_\chi$ (light mediator)



1709.07882

- Nominal meV Threshold
- No Backgrounds

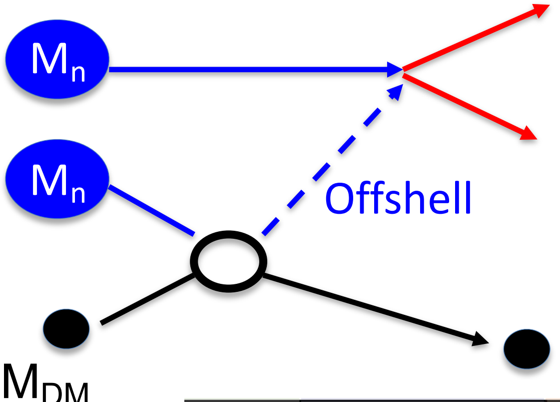
Acoustic Phonons in Sapphire



1807.10291

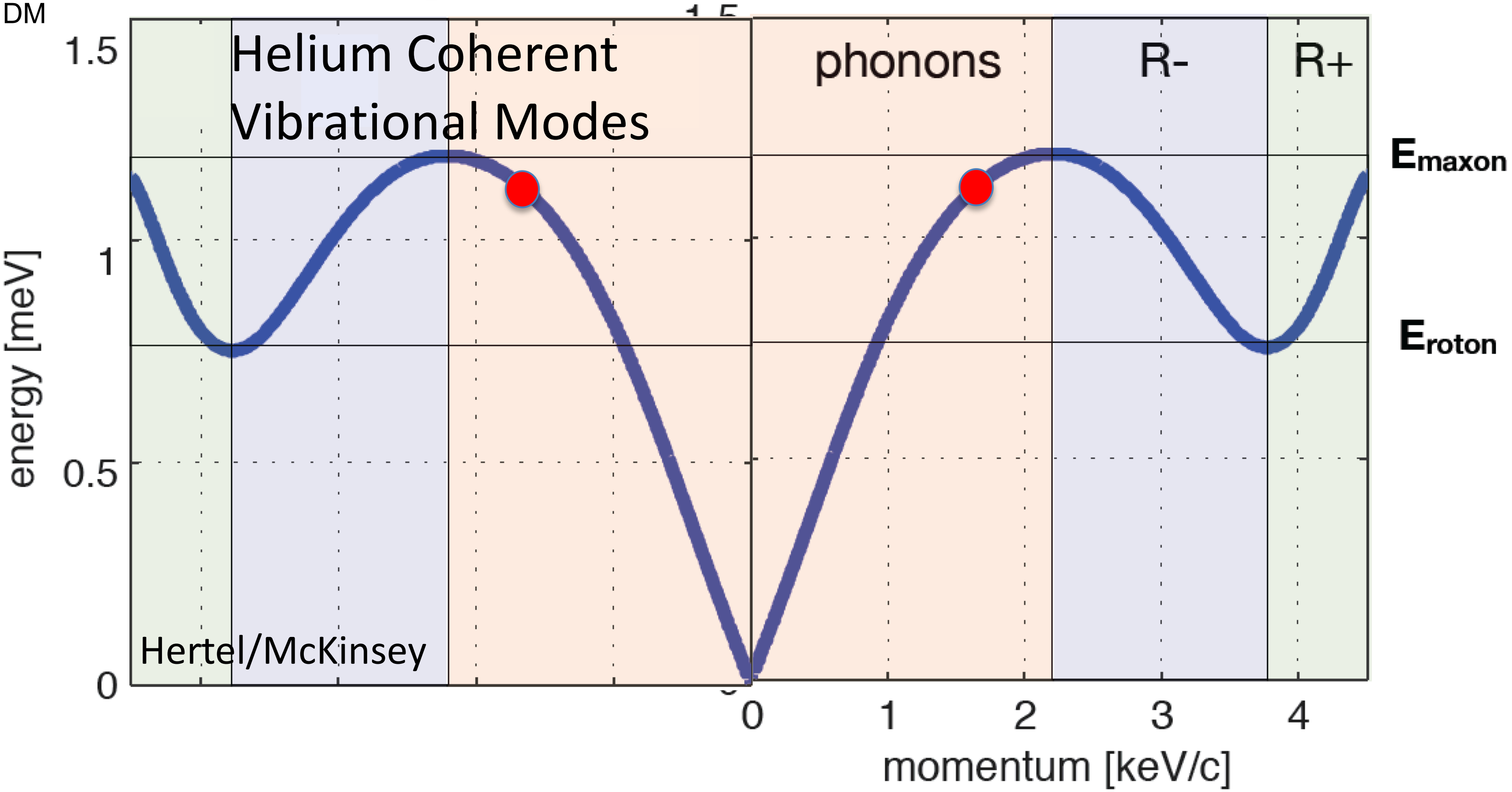
- Various Phonon Energy Thresholds
- 1kgyr
- No Backgrounds

Multiphonon Processes: Offshell 3 body scatters

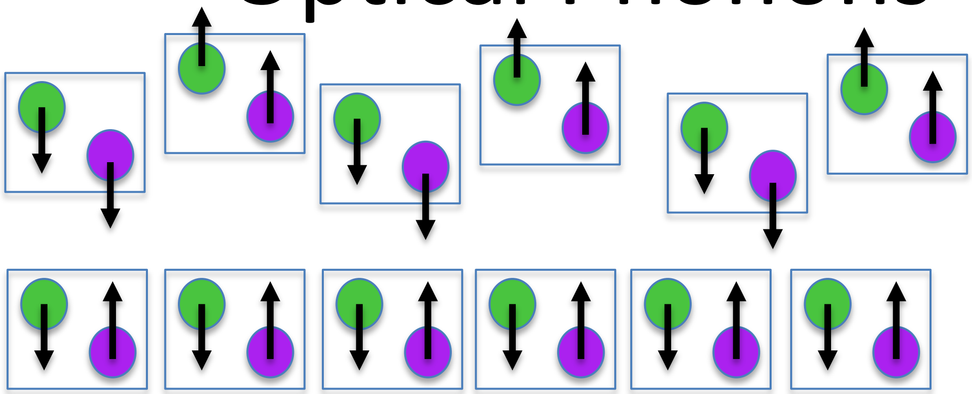


DM can scatter via production of 2 nearly back to back excitations

- 1604.08206: Schutz and Zurek
- rate somewhat suppressed since offshell
- Calculated for superfluid He only so far …
- See 2nd half of Dan's talk

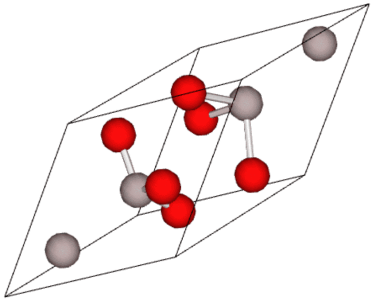


Optical Phonons

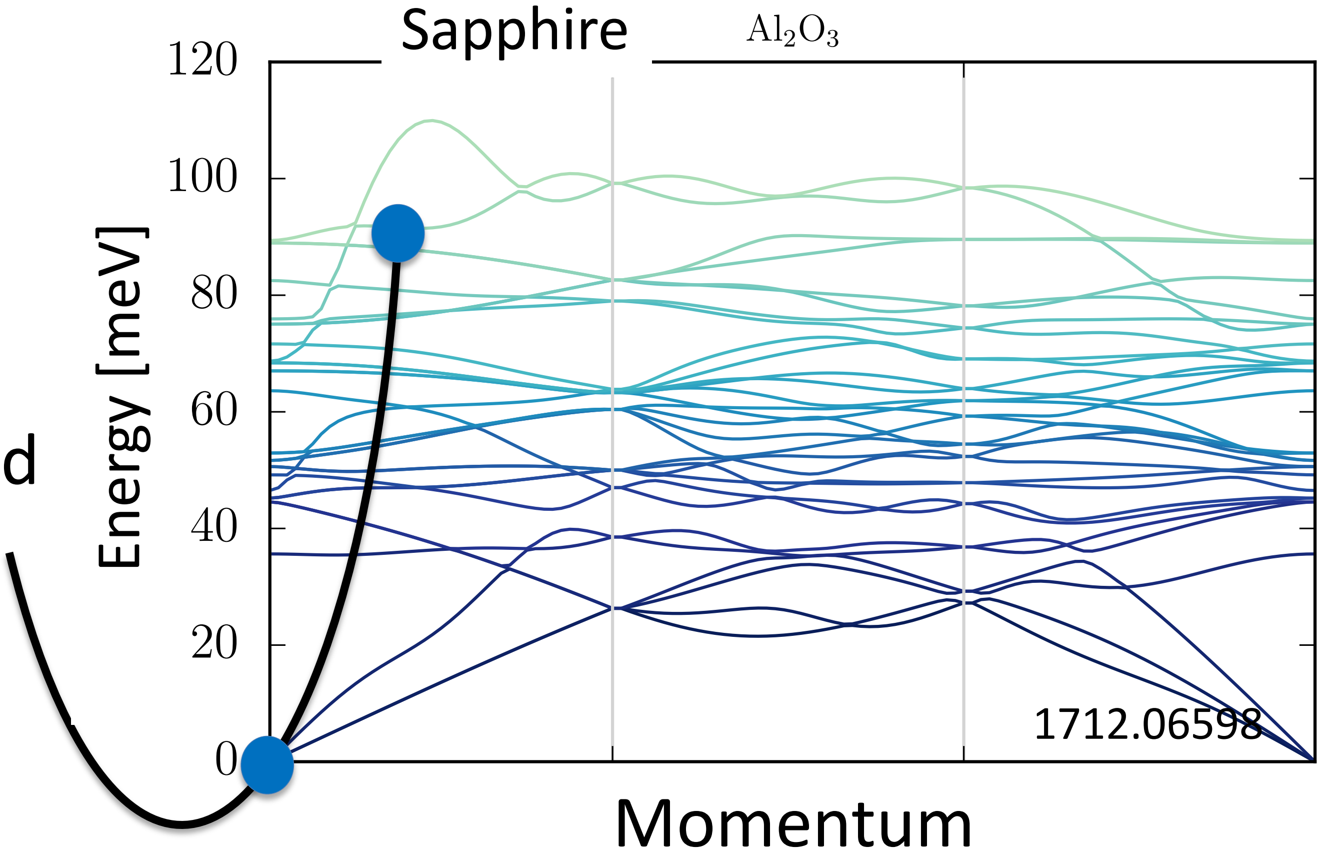


Acoustic:

Optical:

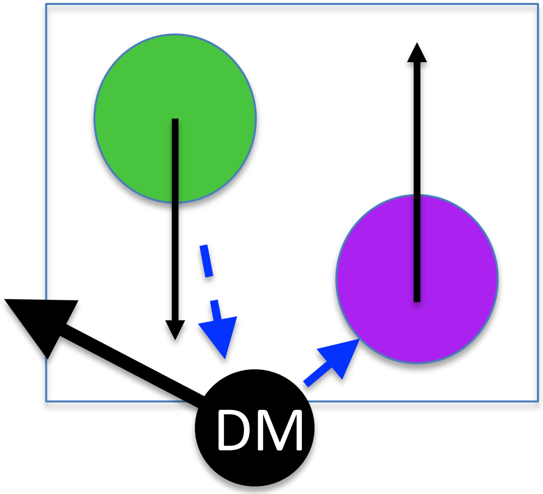


Due to their gapped nature, optical phonons are kinematically matched to IR and light mass DM!



Knapen, Lin, Pyle, & Zurek: 1712.06598

Optical Phonons: Sensitivity to Scalar Interactions?



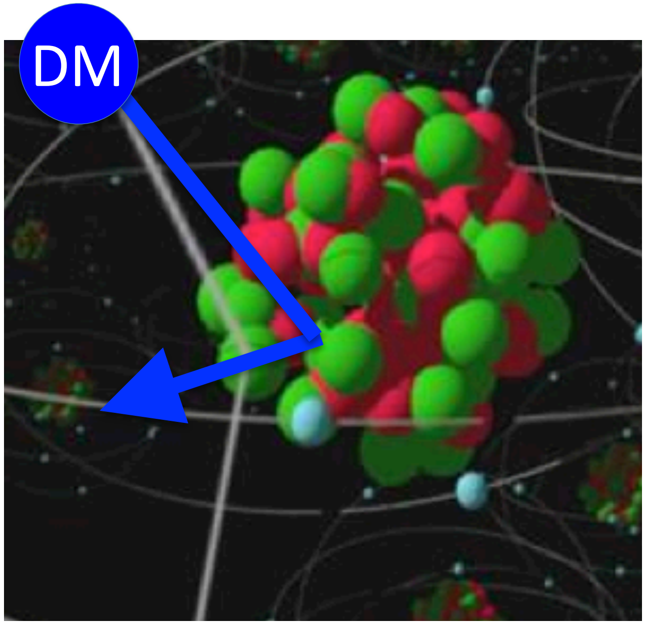
- To create an optical phonon, DM needs to push one atom and pull the other … simple scalar interactions tend to want to pull or push both atoms in the same direction -> sizeable rate suppression ☹
- Knapen,Lin,Pyle& Zurek: 1712.06598
- Rajendran et al: 1905.05575

But … there are an enormous number of crystals with all sorts of optical phonons with different properties.

- High Z and low Z atoms ?
- Optical/Acoustic phonon mixing ?

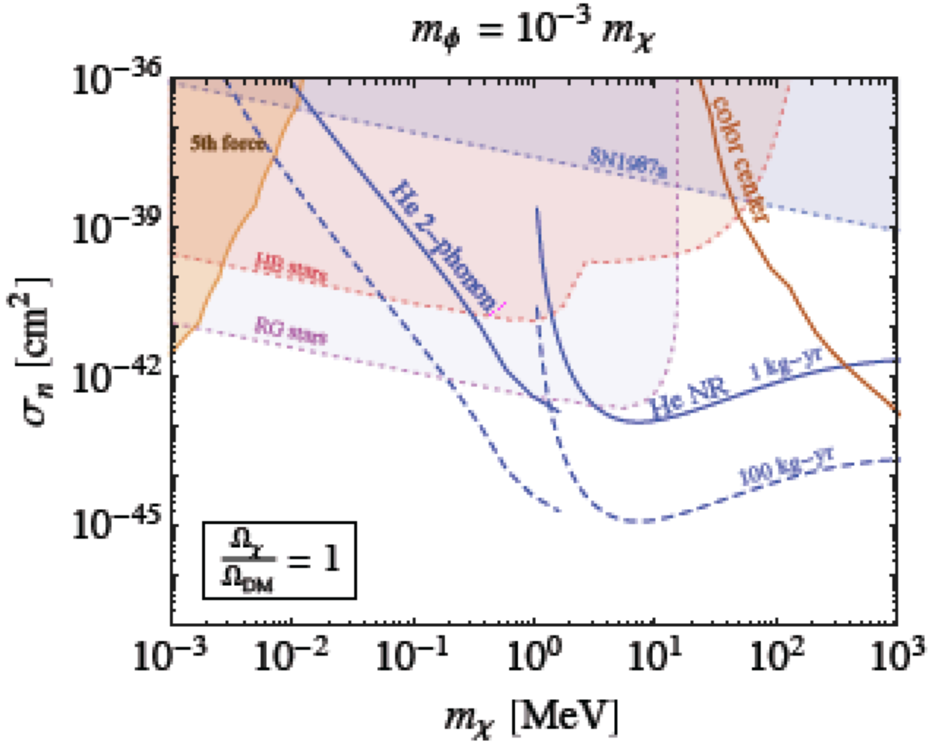
Work in Progress: Griffin, Knapen, Lin, Zurek

Other DM Interactions?

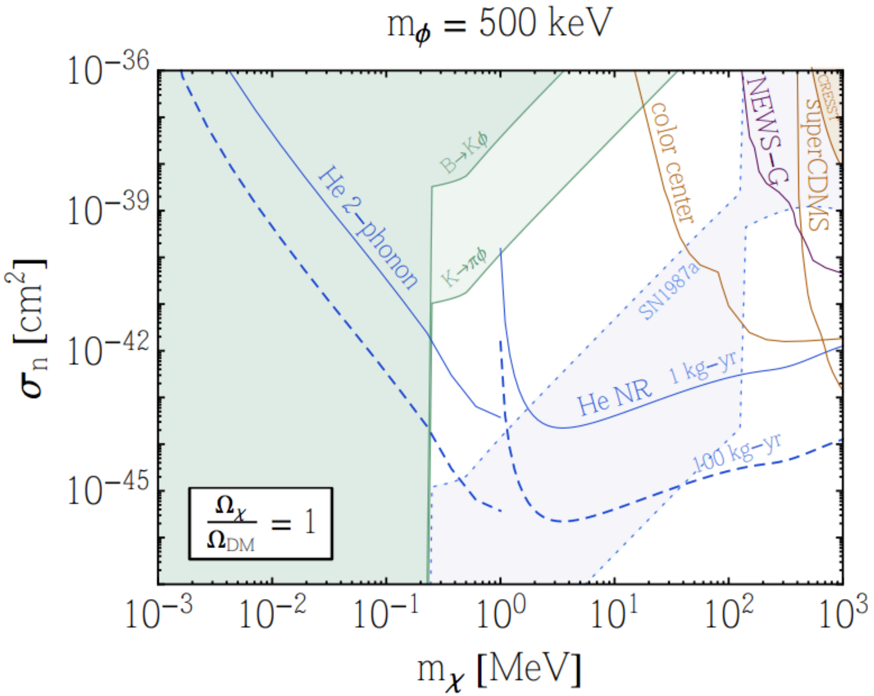


- Focused on scalar DM interaction so far …
  - Coherent rate enhancement
  - For supersymmetry and lots of models particularly at high mass, this usually dominates (you need a bit to a lot of fine tuning to have spin or orbital interactions dominate)

For light DM, not so clear …



Light Mediator



Heavier Mediator

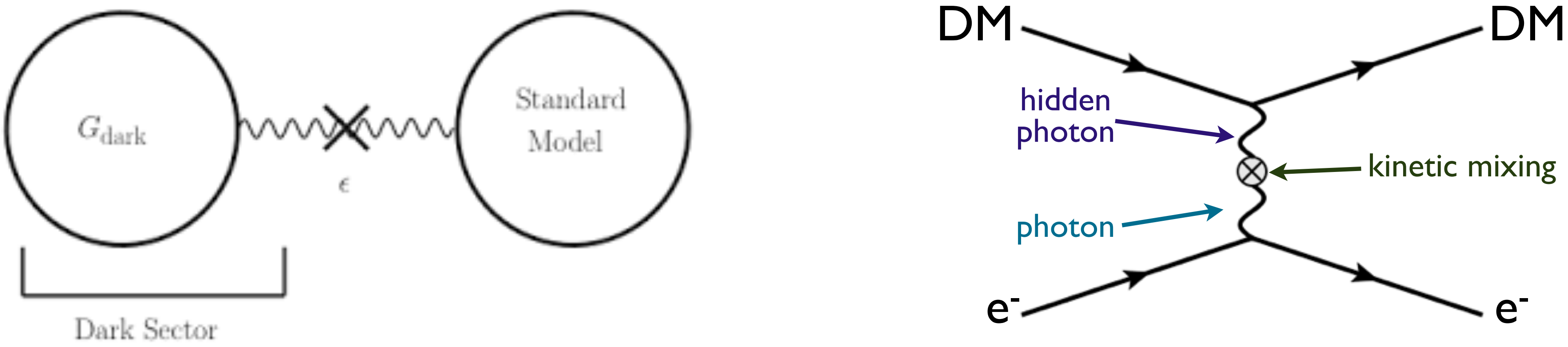
- M>1 MeV: Lots of empty parameter space for kg-yr scale experiments!
- M <1 MeV: Lot's of parameter space for simple scalar interacting DM already ruled out by astrophysics and colliders below

Summary: Scalar DM Interactions
1MeV< MeV < 10 GeV

- Design Drivers
  - ~~Exposure~~
  - ~~Radiogenic backgrounds~~
  - Energy Threshold
- 2 Body Elastic Scattering -> Coherent Excitations

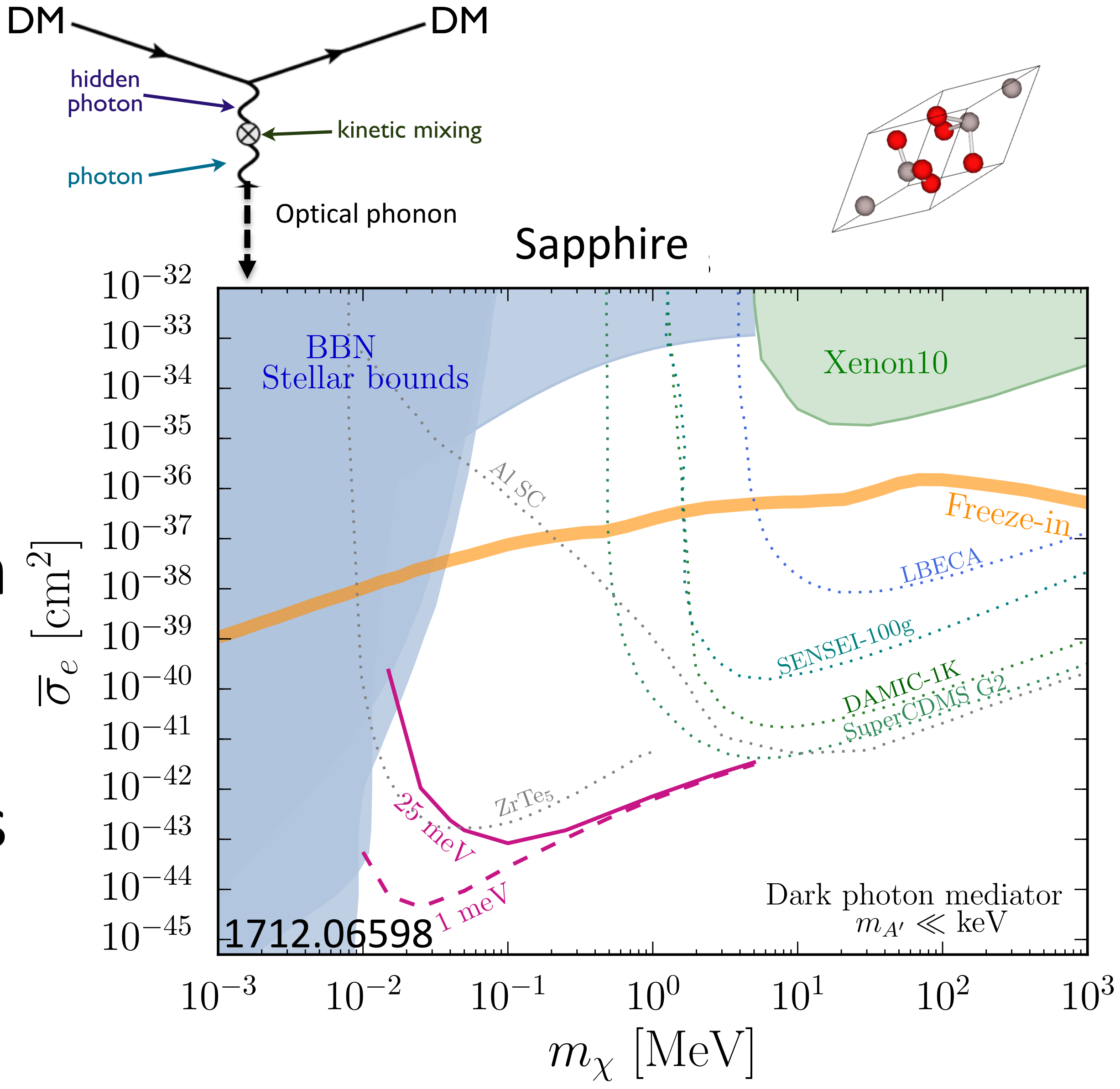
Dark Sectors and Dark Photons

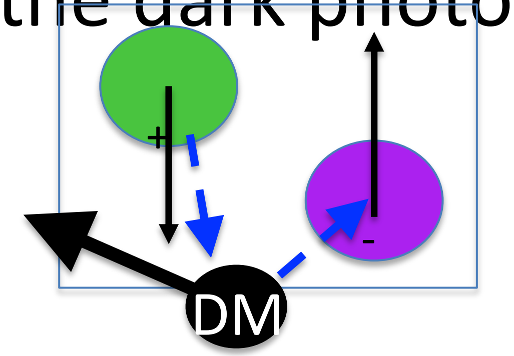
- Cosmic Visions 1707.04591
- Dark Photon coupling via kinetic mixing is one of the standard well motivated models



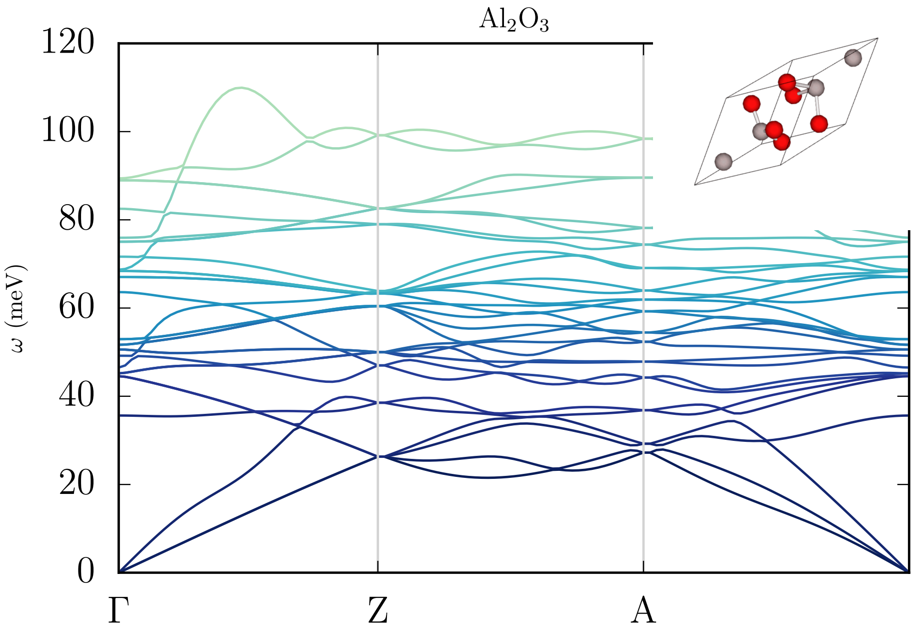
Dark Photon Couplings: Polar Crystals

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



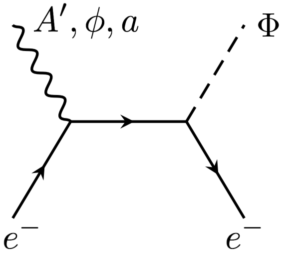


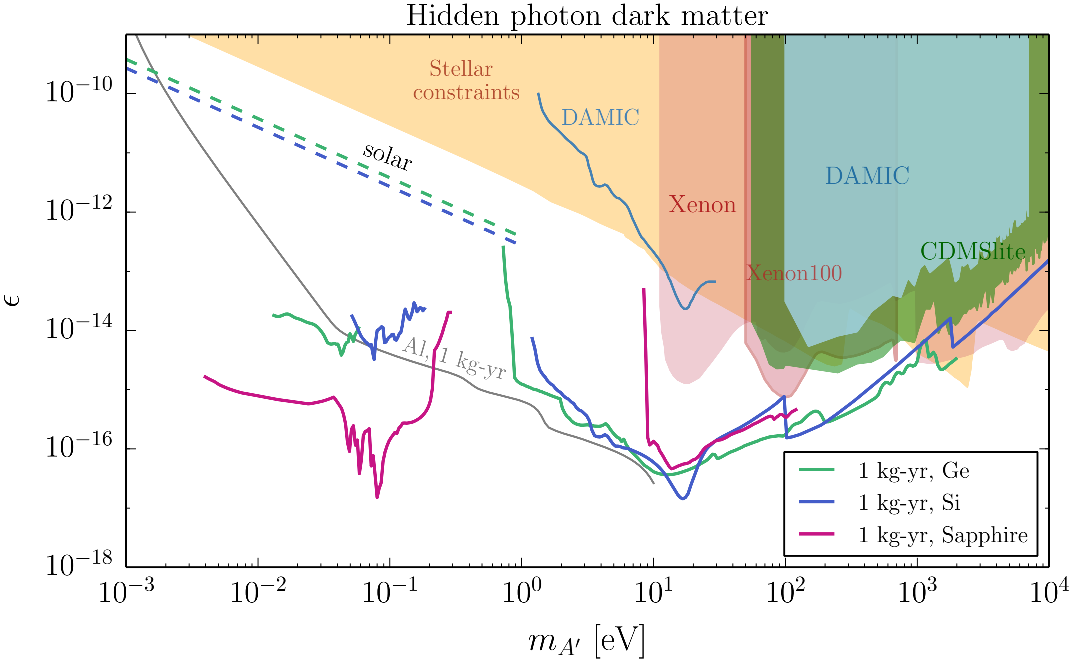
Sapphire: Lot's of Optical Phonon Bands



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

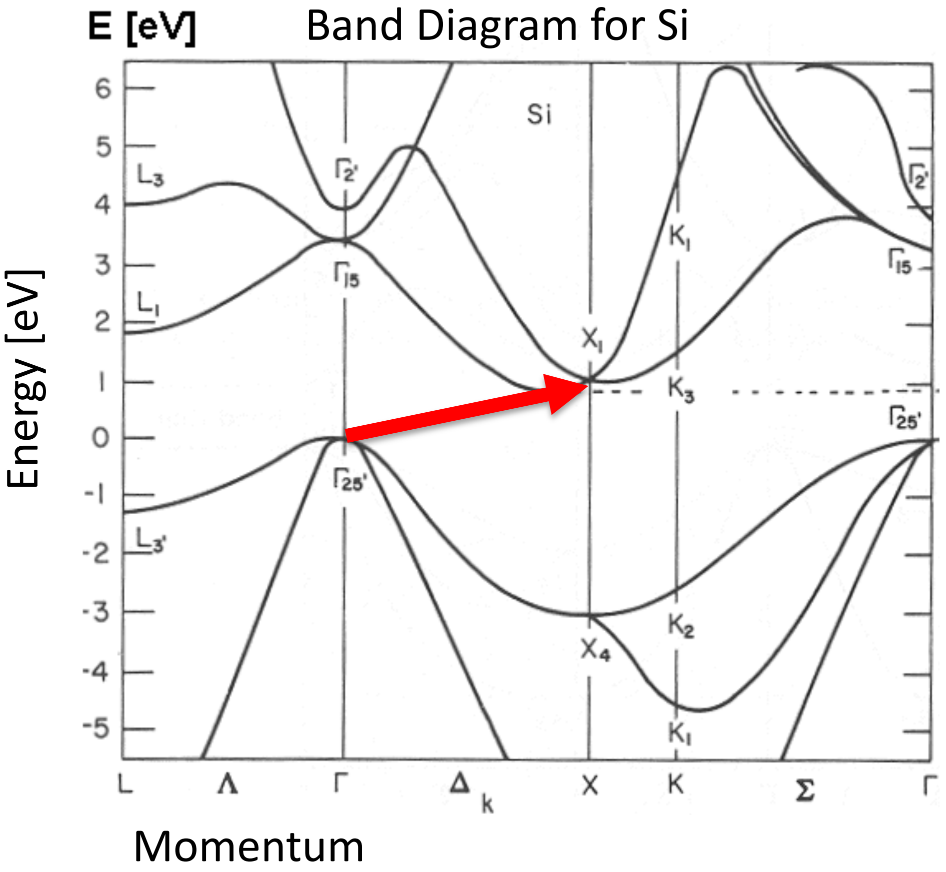
To search for thermal DM down to keV masses via scattering and ultracold bosonic DM to 30 meV, we need a detector sensitive to a single optical phonon





Electronic Excitations

Inelastic e$^-$ Recoils in Semiconductors

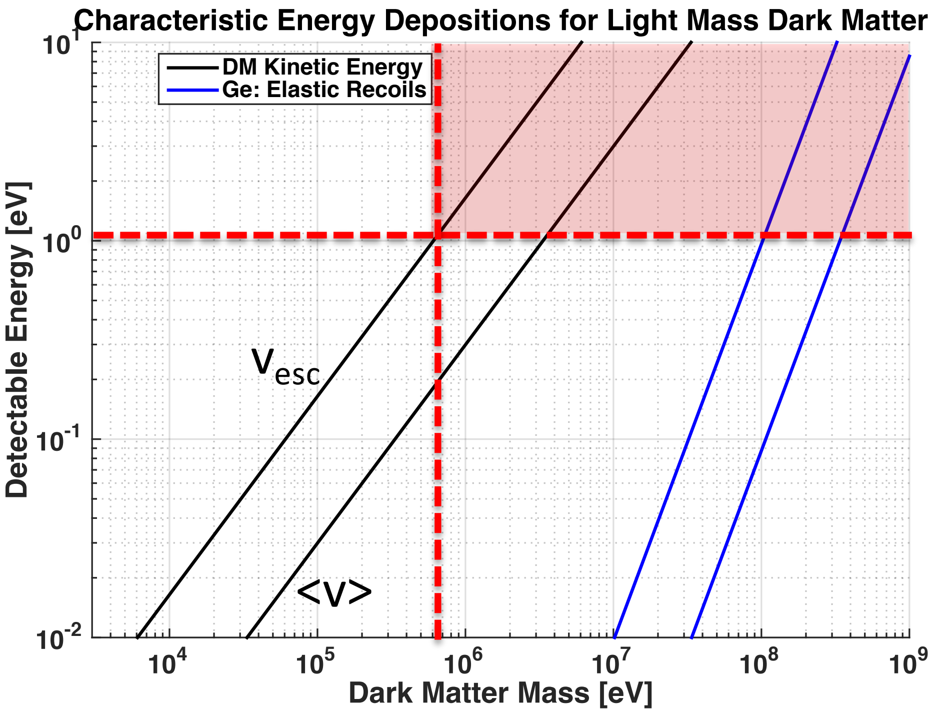

E [eV]

Band Diagram for Si

Energy [eV]

Momentum

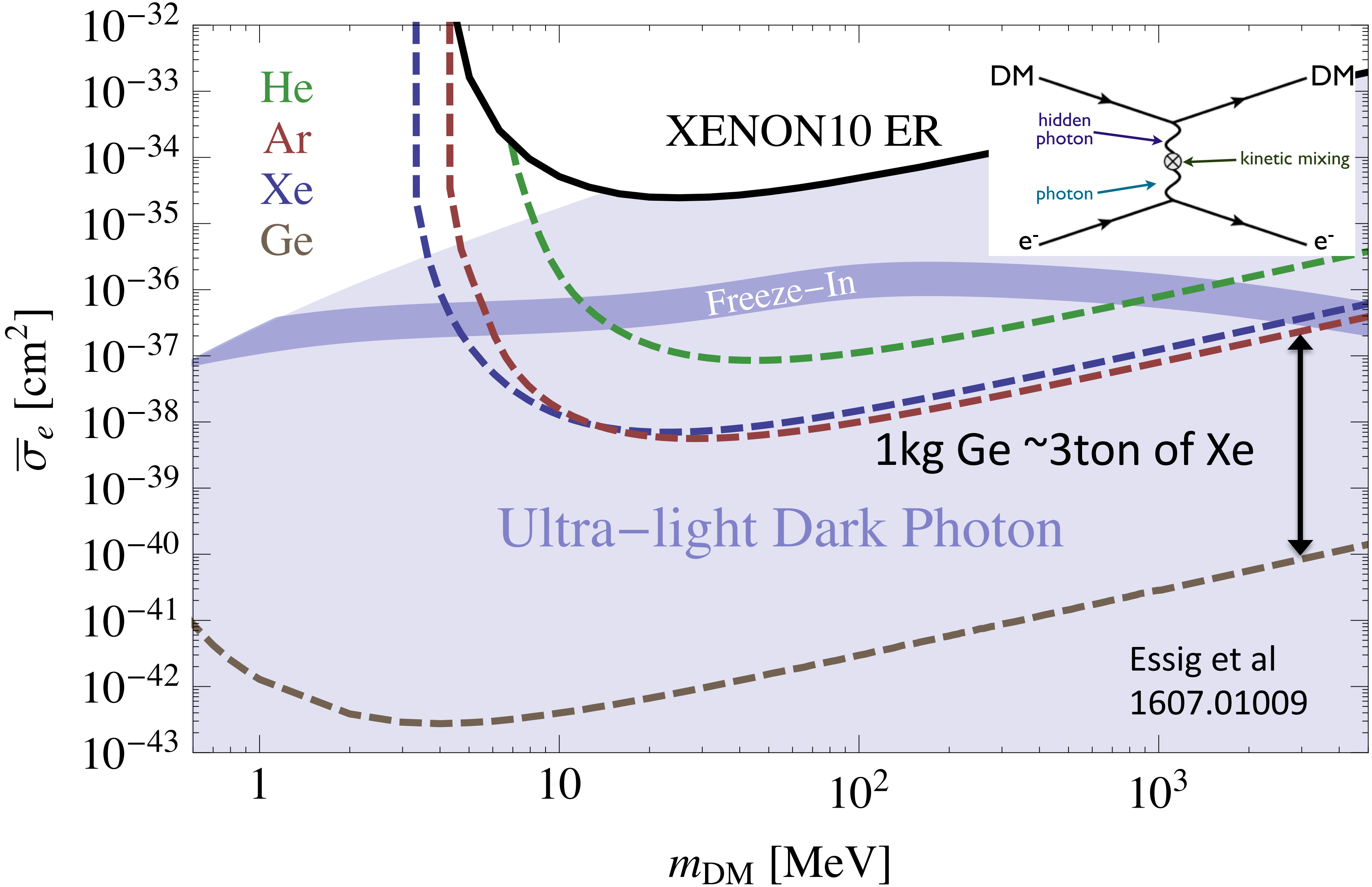
- e- excitation momentum and energy scales in semiconductors well matched to 1 MeV-100MeV DM
- Essig et al: 1108.5383



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

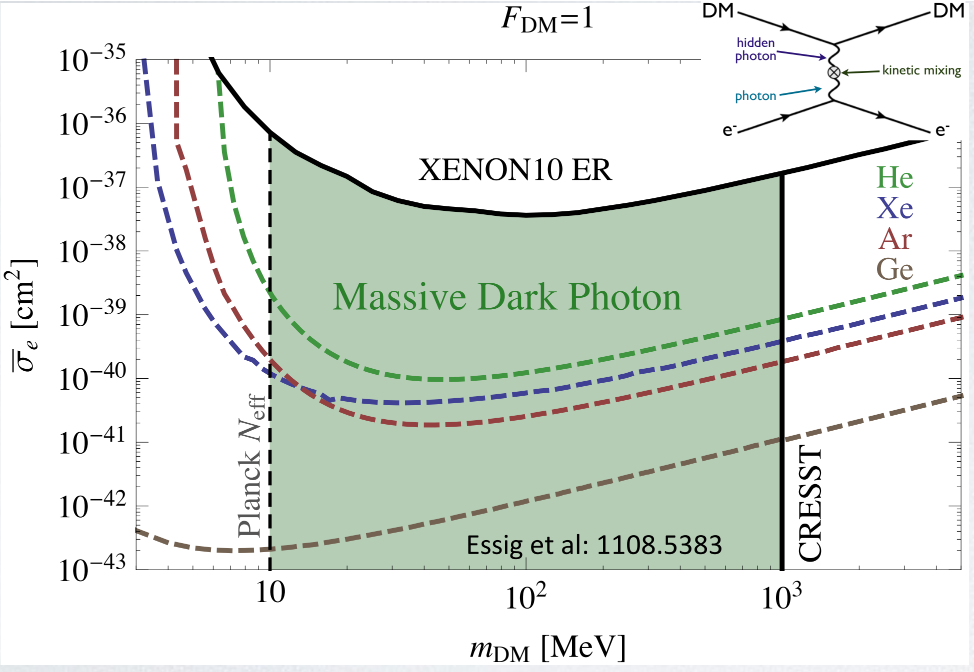
Smaller Bandgaps are Better

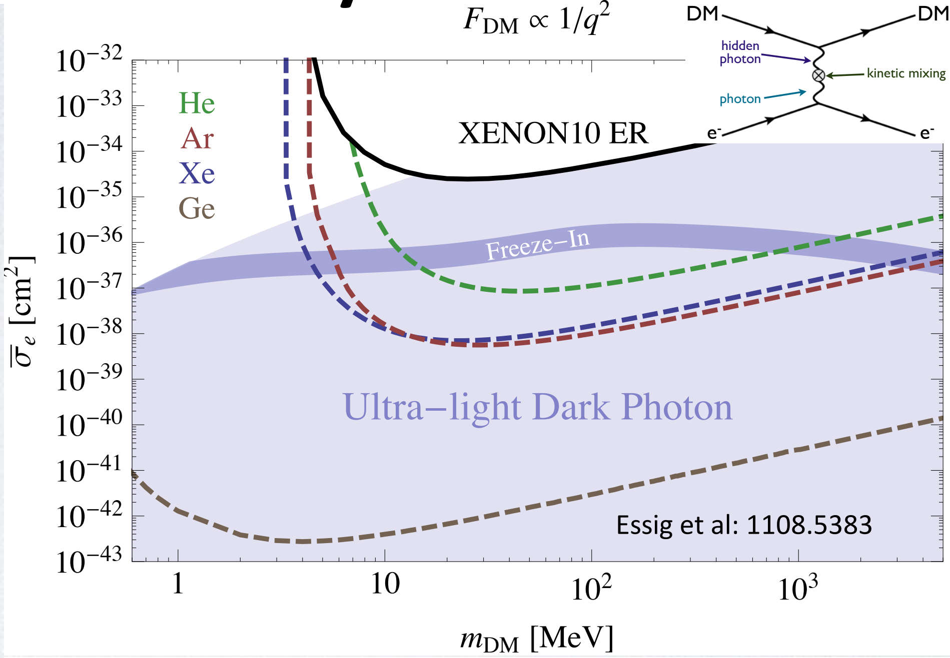
$F_{\mathrm{DM}} \propto 1/q^2$ (Ultra-light Mediator)

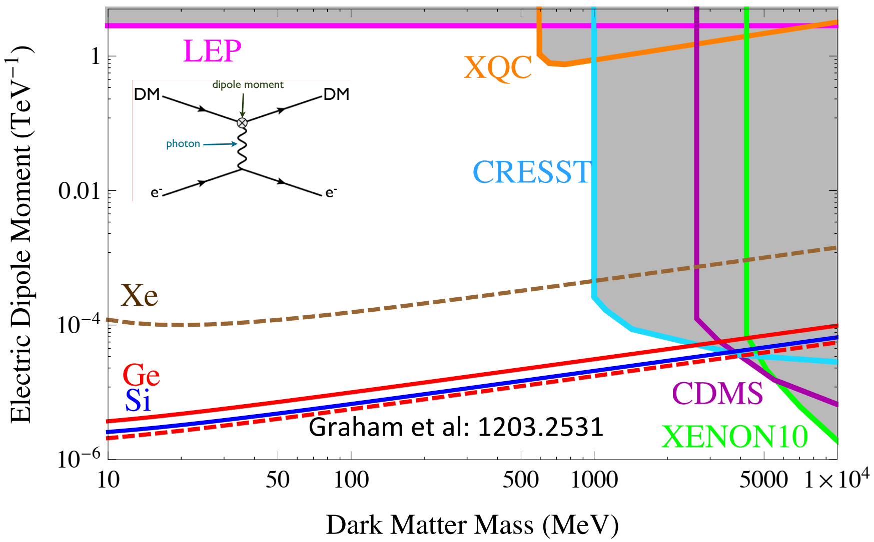


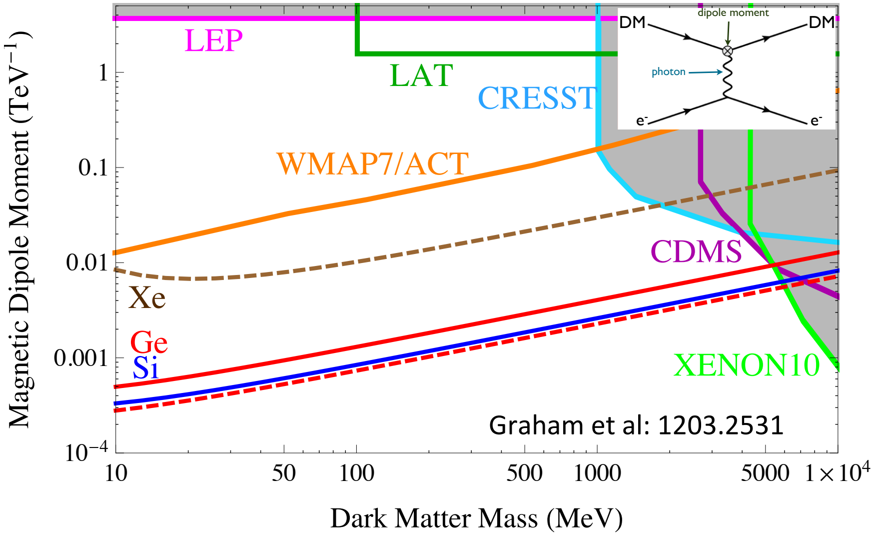
Essig et al
1607.01009

Potential ER Sensitivity Limits

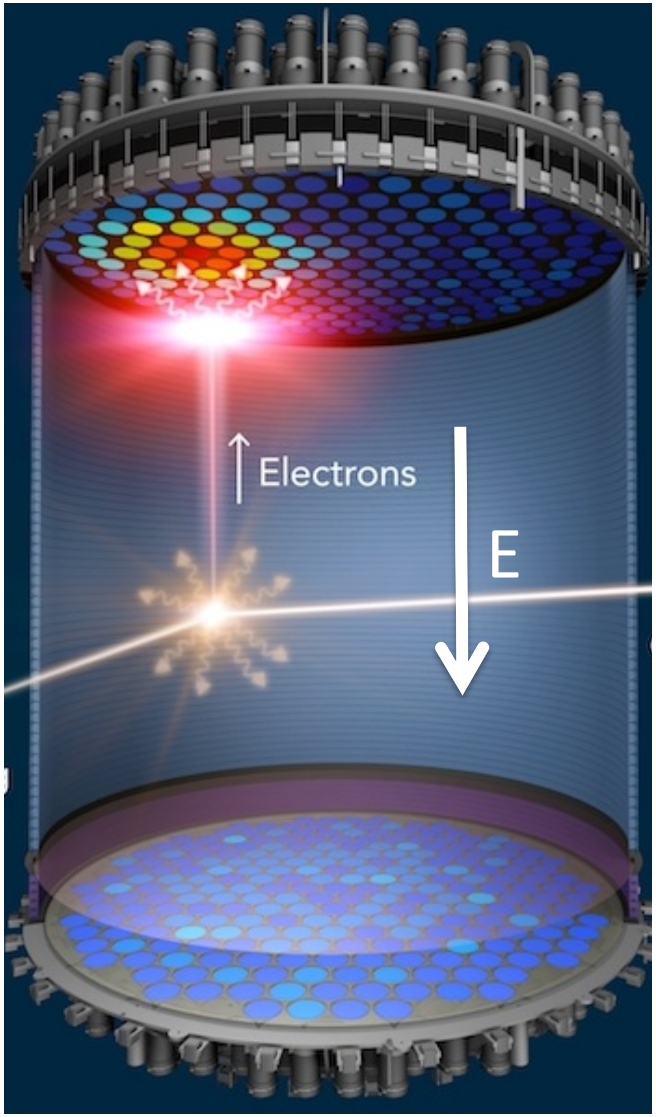

Essig et al: 1108.5383

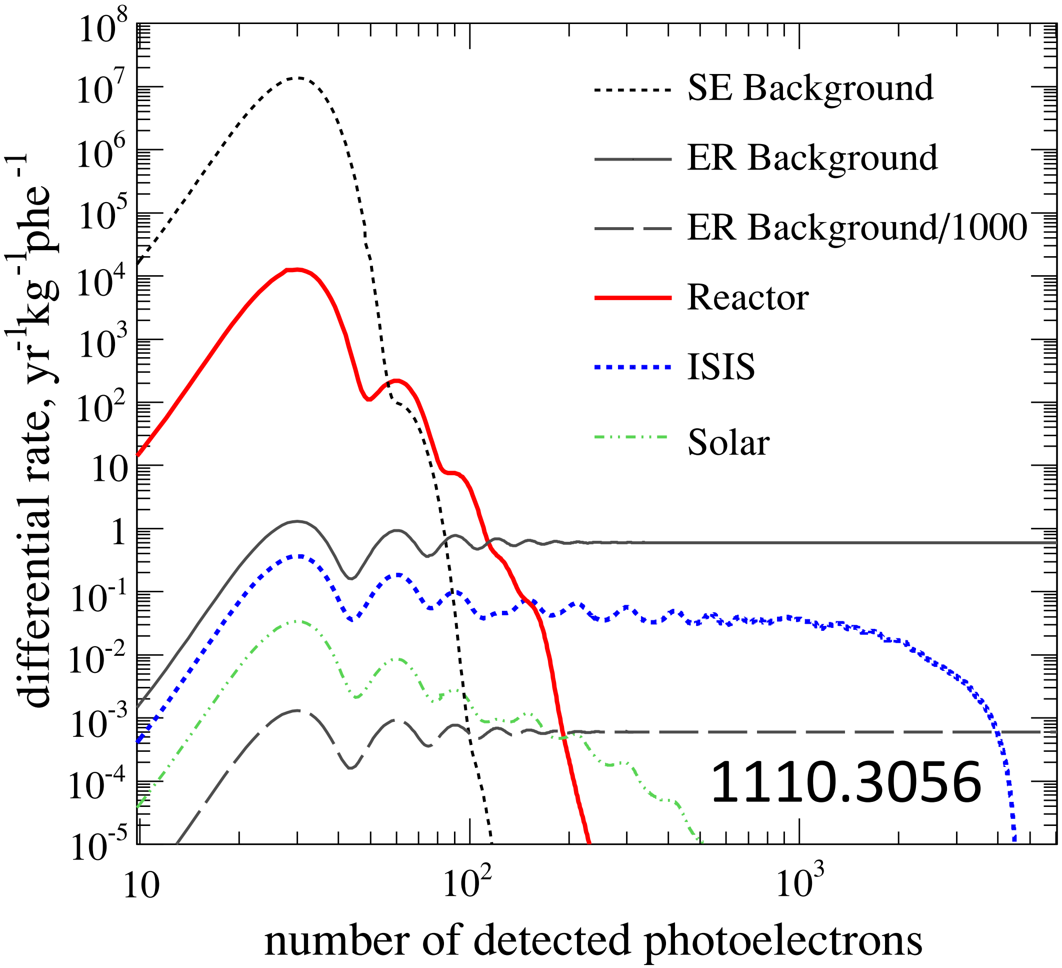

Essig et al: 1108.5383


Graham et al: 1203.2531


Graham et al: 1203.2531

Problem: Detector Backgrounds in TPCs



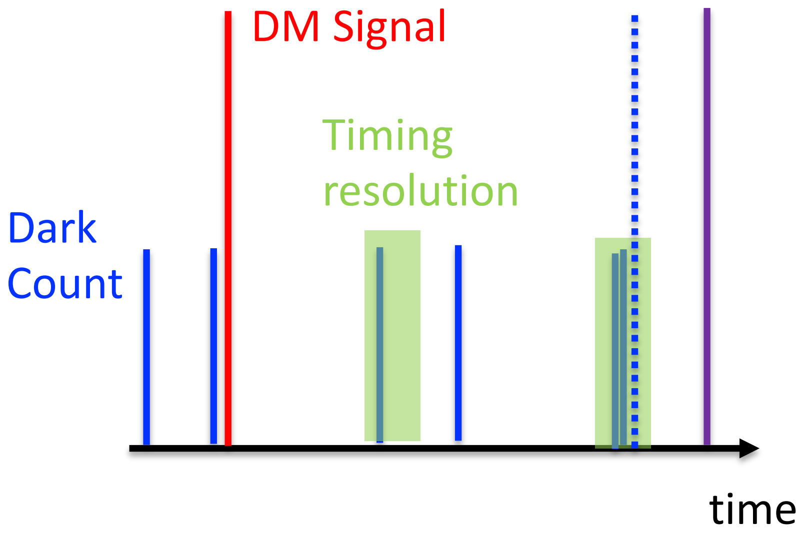


e^- (S2) Background Rate in Zeplin III

R_{1e-} = 5.7 Hz -> YIKES!

Leakage is Non-Poissonian

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)

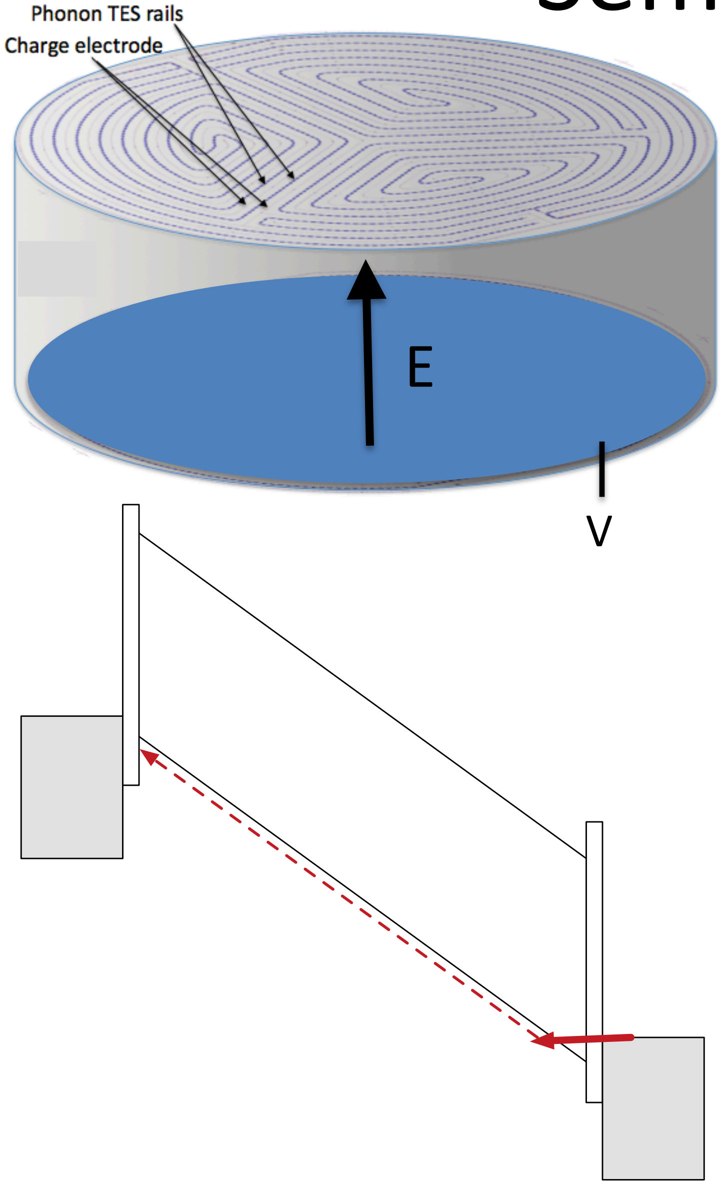
Xenon TPCs:

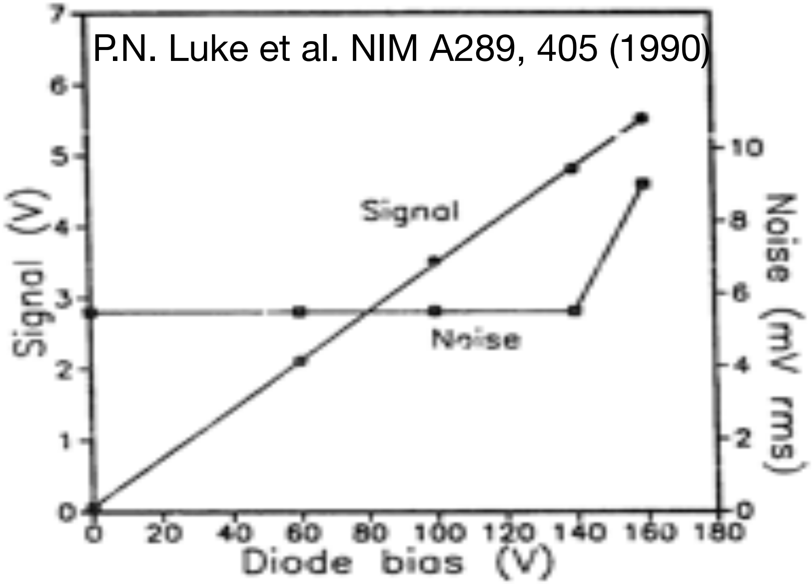
- R_{1e-} =10Hz
- Δt =100ns
- R_{2e-}(Poissonian) =10^{-5}Hz

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

(Sorensen: R&D into Xe TPC leakage)

Dark Leakage Rate in Biased Semiconductors

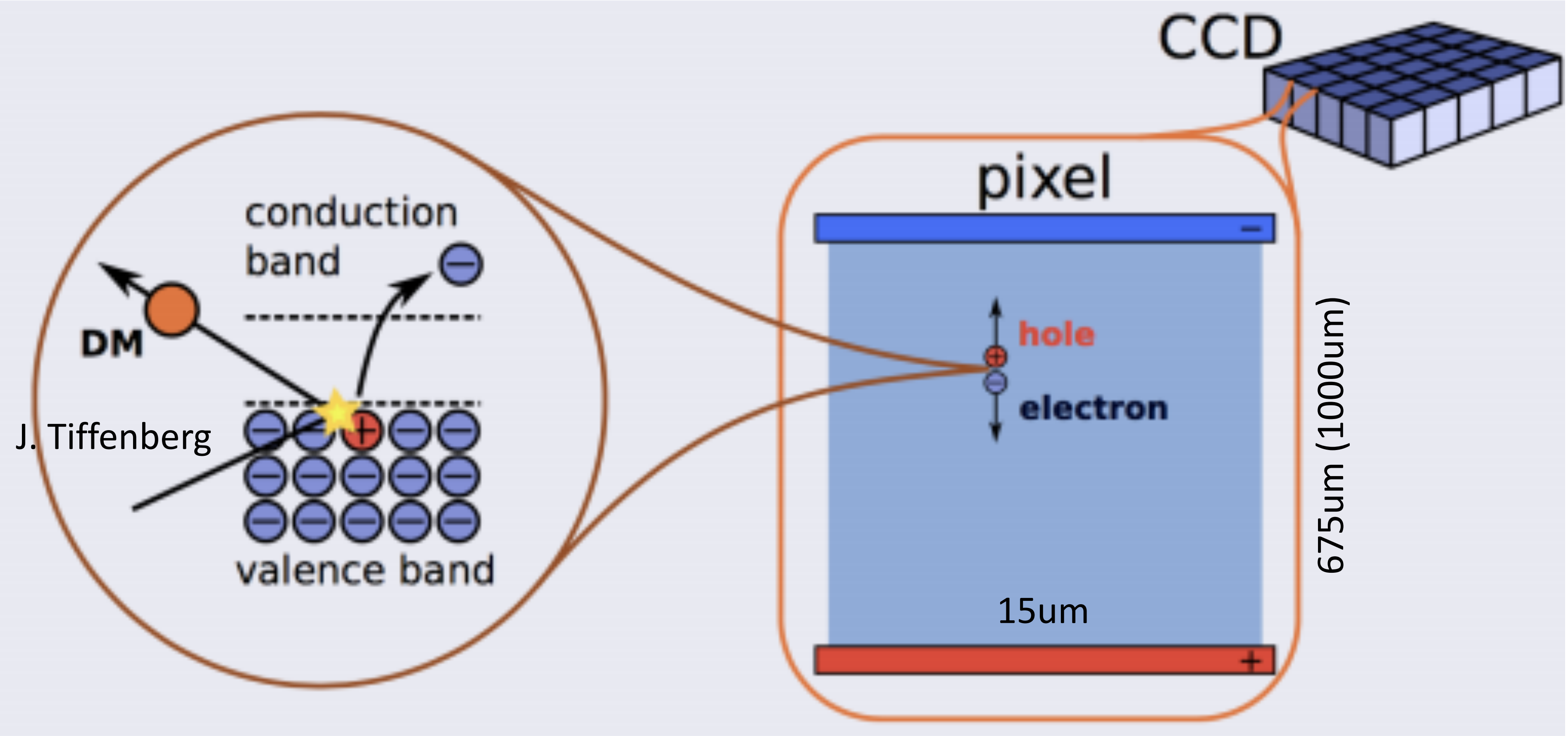



P.N. Luke et al. NIM A289, 405 (1990)

Man vs Nature

- Precision engineering required to have large E-fields and no leakage
- Often nature wins ☹

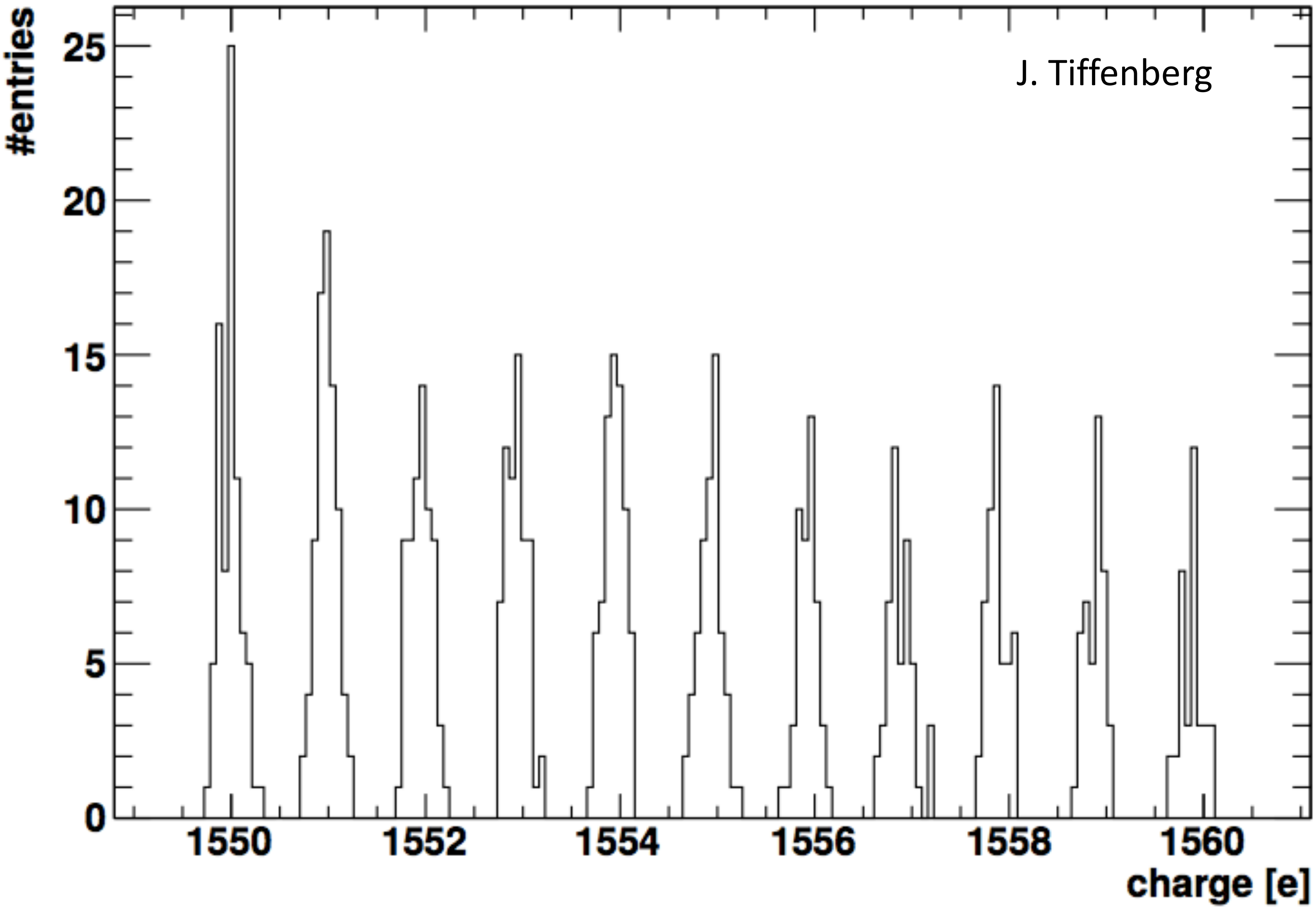
Si CCDs: Really Good Engineering



J. Tiffenberg

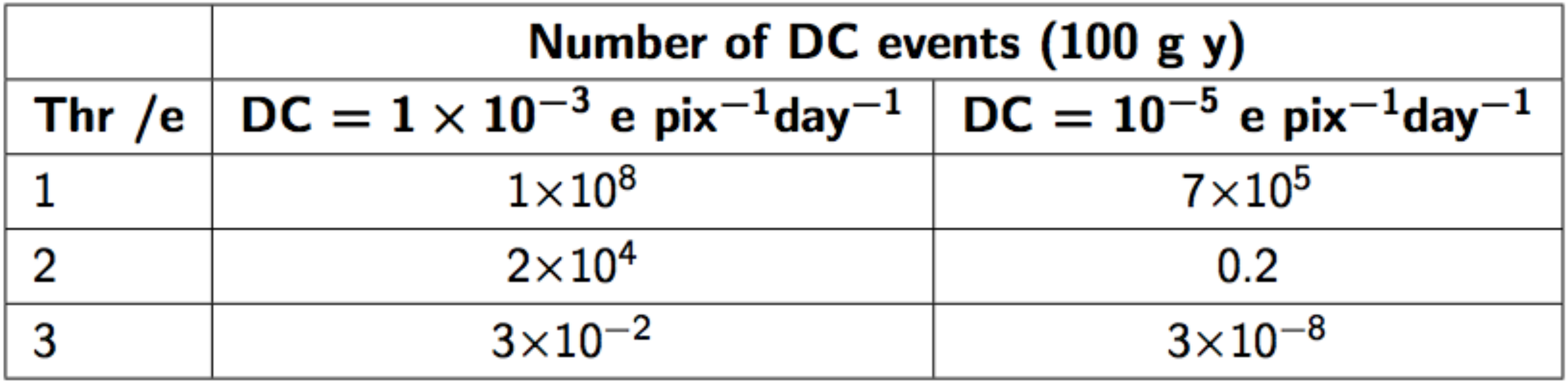
DAMIC &SINSEI:

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



SINSEI/DAMIC: Dark Current

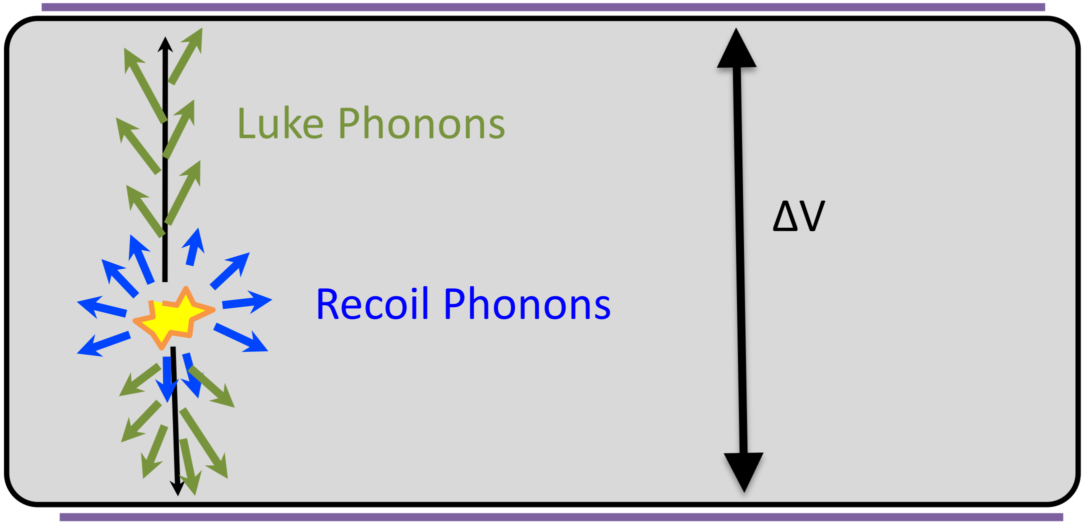
Dark Current: < 10-3 e/d/pixel
(arXiv:1611.03066)



	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}

Luke-Neganov (LN) Phonon Amplification

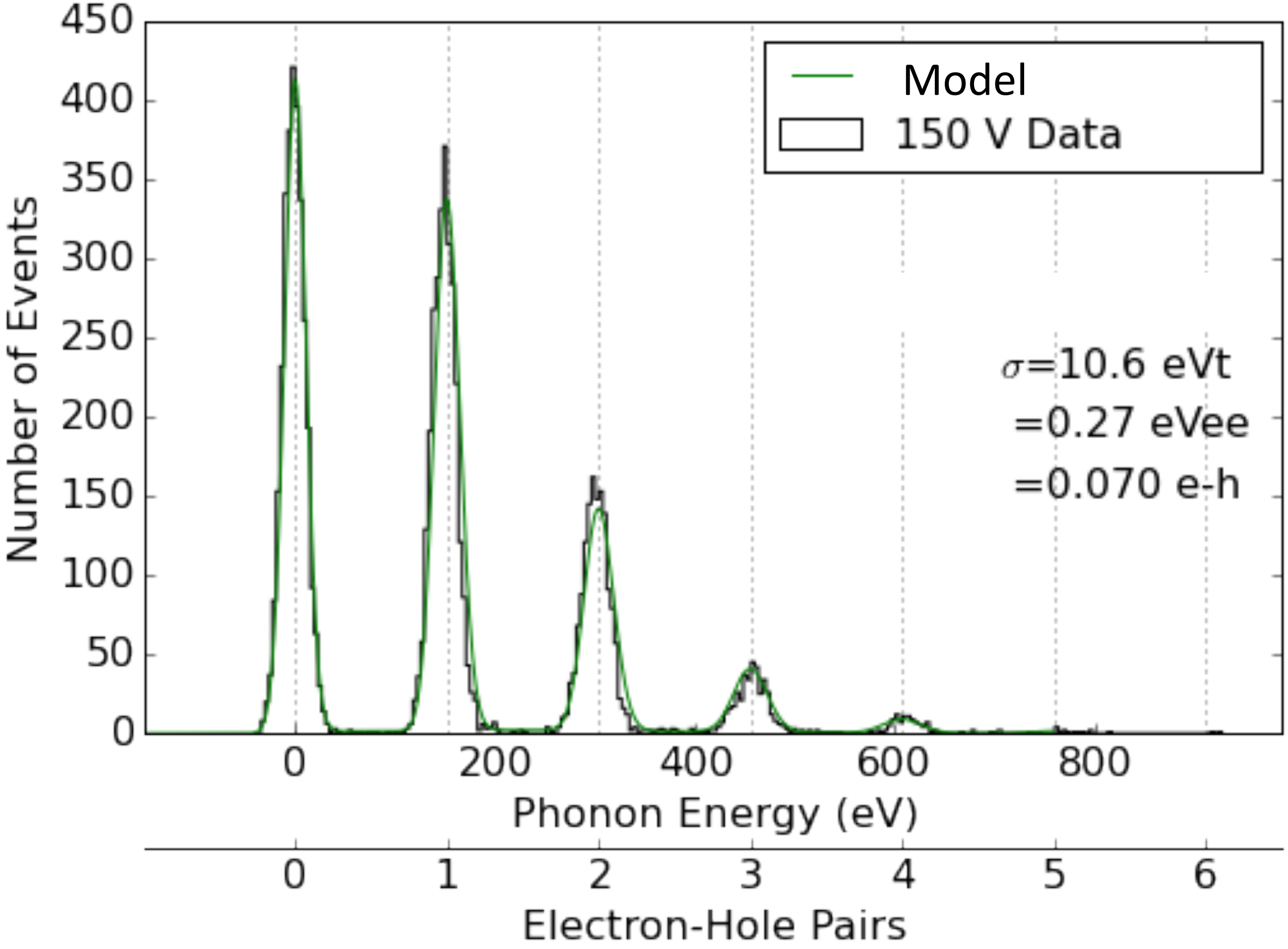
- Drifting charges release kinetic energy via NTL Phonon Production
- $$\begin{aligned} E_{total} &= E_{recoil} + E_{NTL} \\ &= E_{recoil} + n_{eh} e \Delta V \end{aligned}$$
- $$\lim_{\Delta V \to \infty} E_{total} \propto Q$$



PHYSICAL REVIEW LETTERS **121,** 051301 (2018)

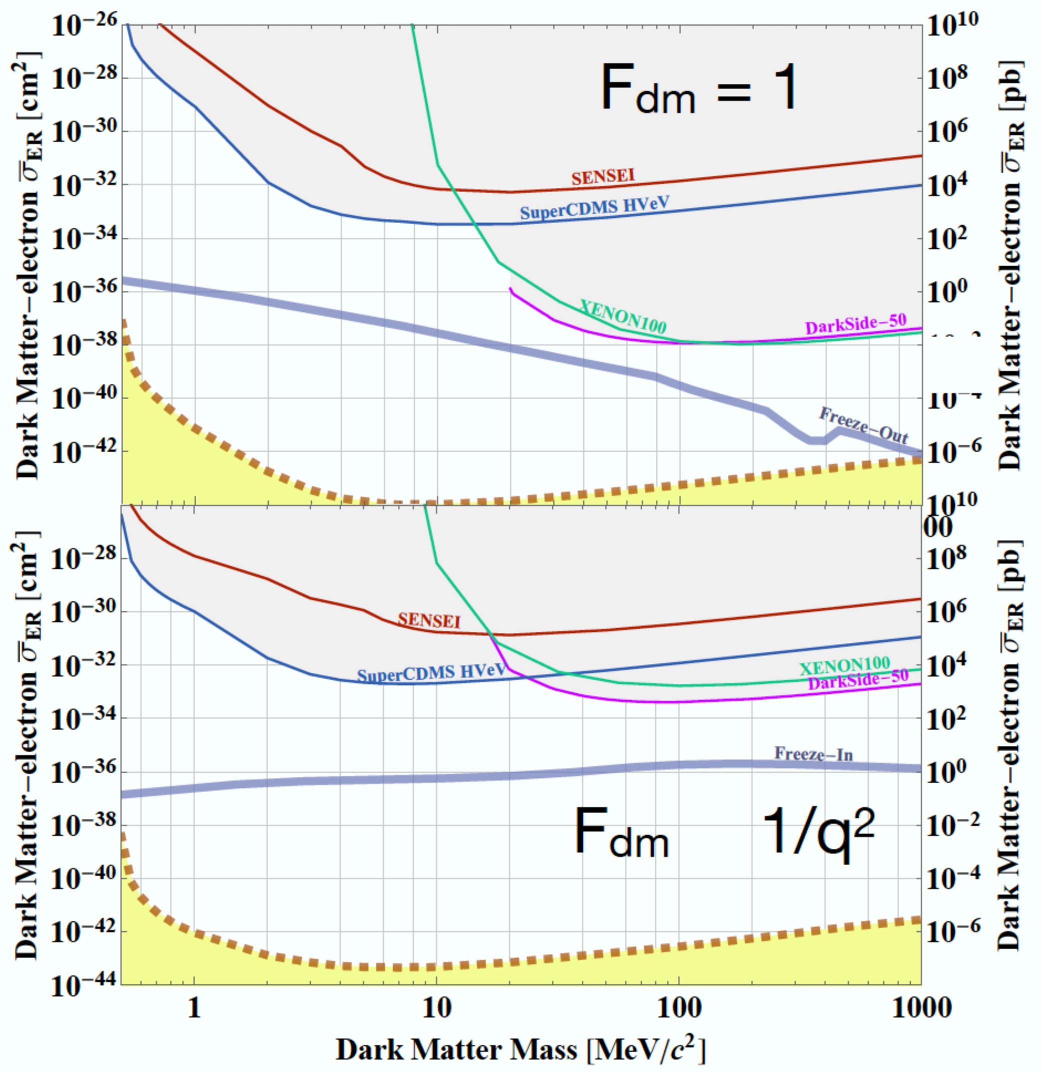
First Dark Matter Constraints from a SuperCDMS Single-Charge Sensitive Detector

Laser Calibration Data



- Average performance during DM search slightly worse due to dilution fridge base temperature variation (this is R&D!)
- Average Baseline Energy Resolution for DM search, <**σ**> = 14 eV = 0.10 e^-h^+

Current ER DM Search Sensitivities



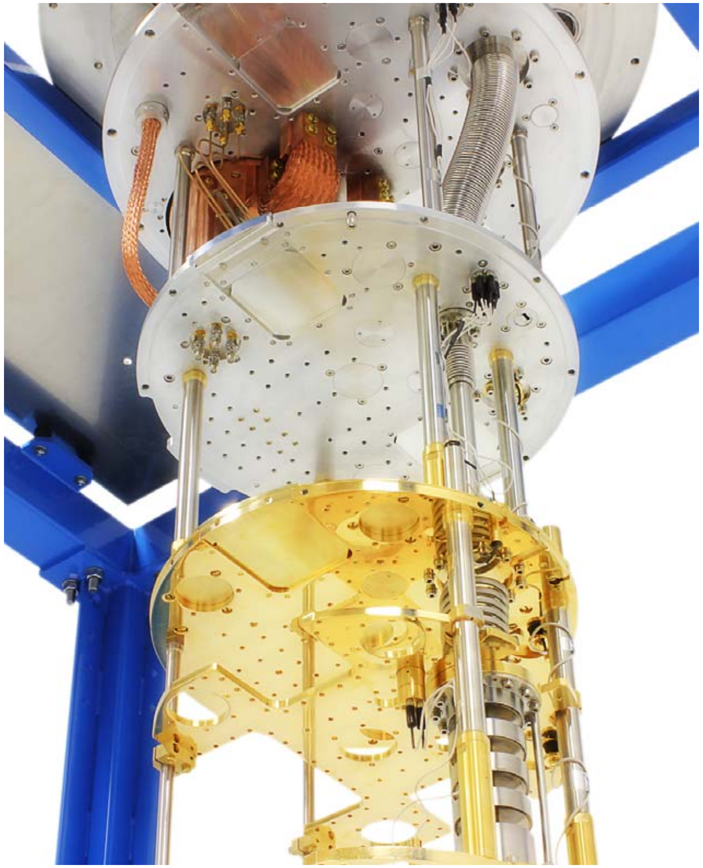
You can do world leading DM searches:

- At the surface
- ½ gd exposure
- SuperCDMS (MP): 1804.10697
- SENSEI: 1901.10478

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

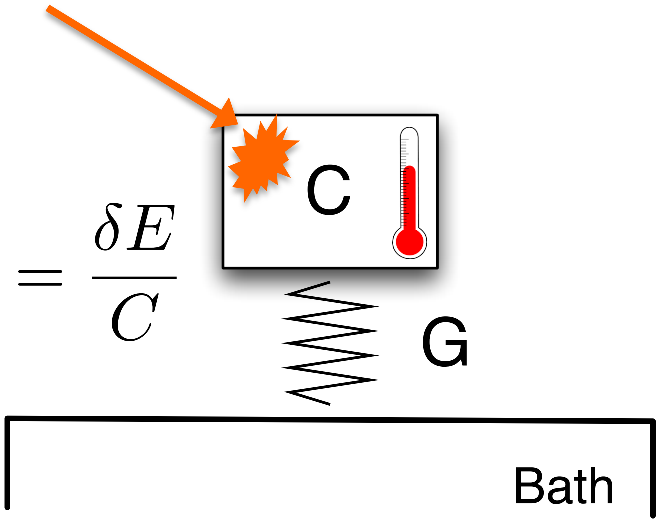
Optical Phonon Sensitivity -> Low Temperature Detectors

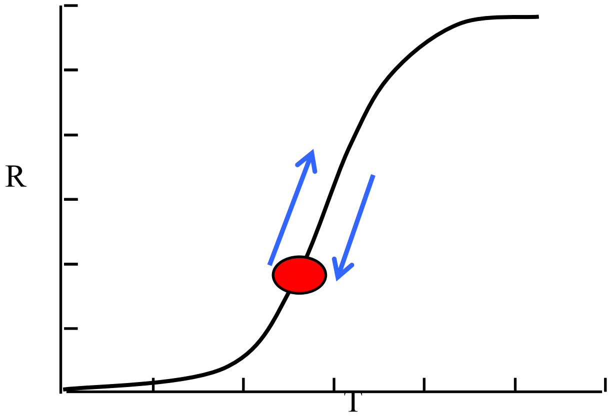
- 300K = 26meV
- To sense single optical phonons we’ll need to cool the detector down to near absolute zero
- Use superconducting detector technology
  - MKIDs
  - **Transition edge sensors**



~~The Simplest Thermal Calorimeter~~

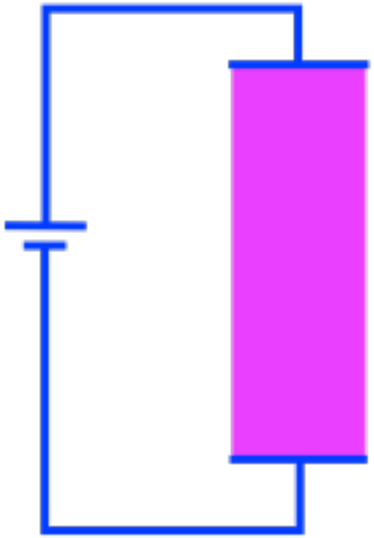
$$\delta T = \frac{\delta E}{C}$$



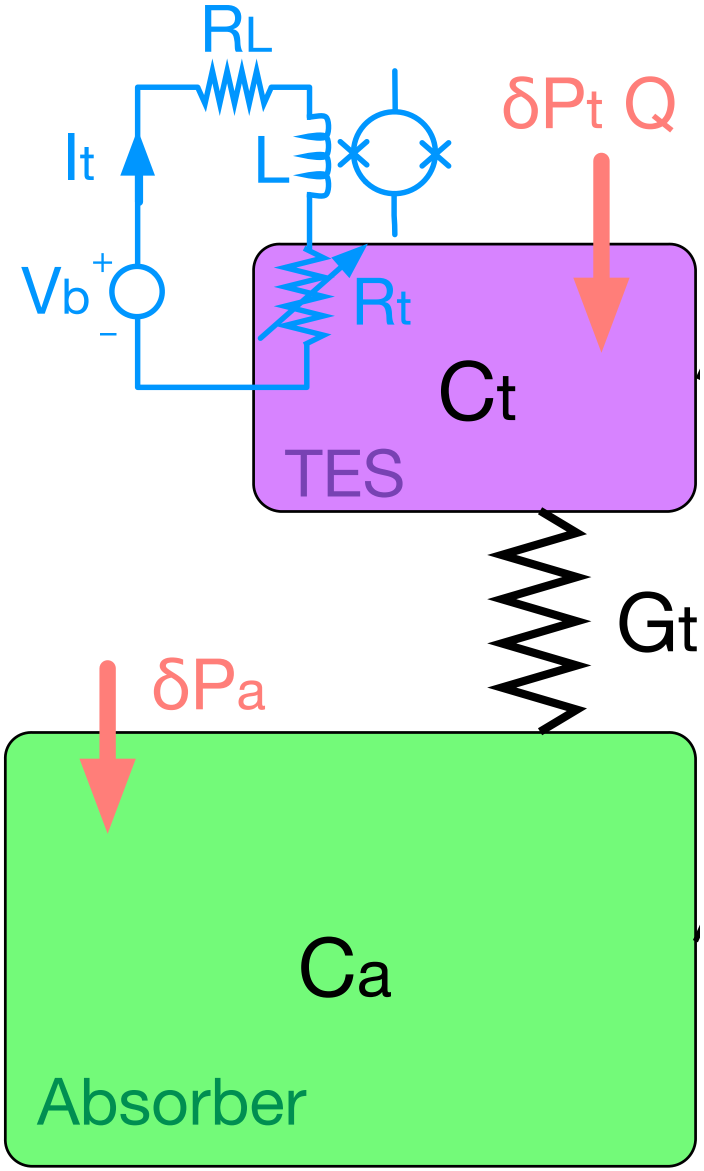


Transition Edge Sensor (TES):

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

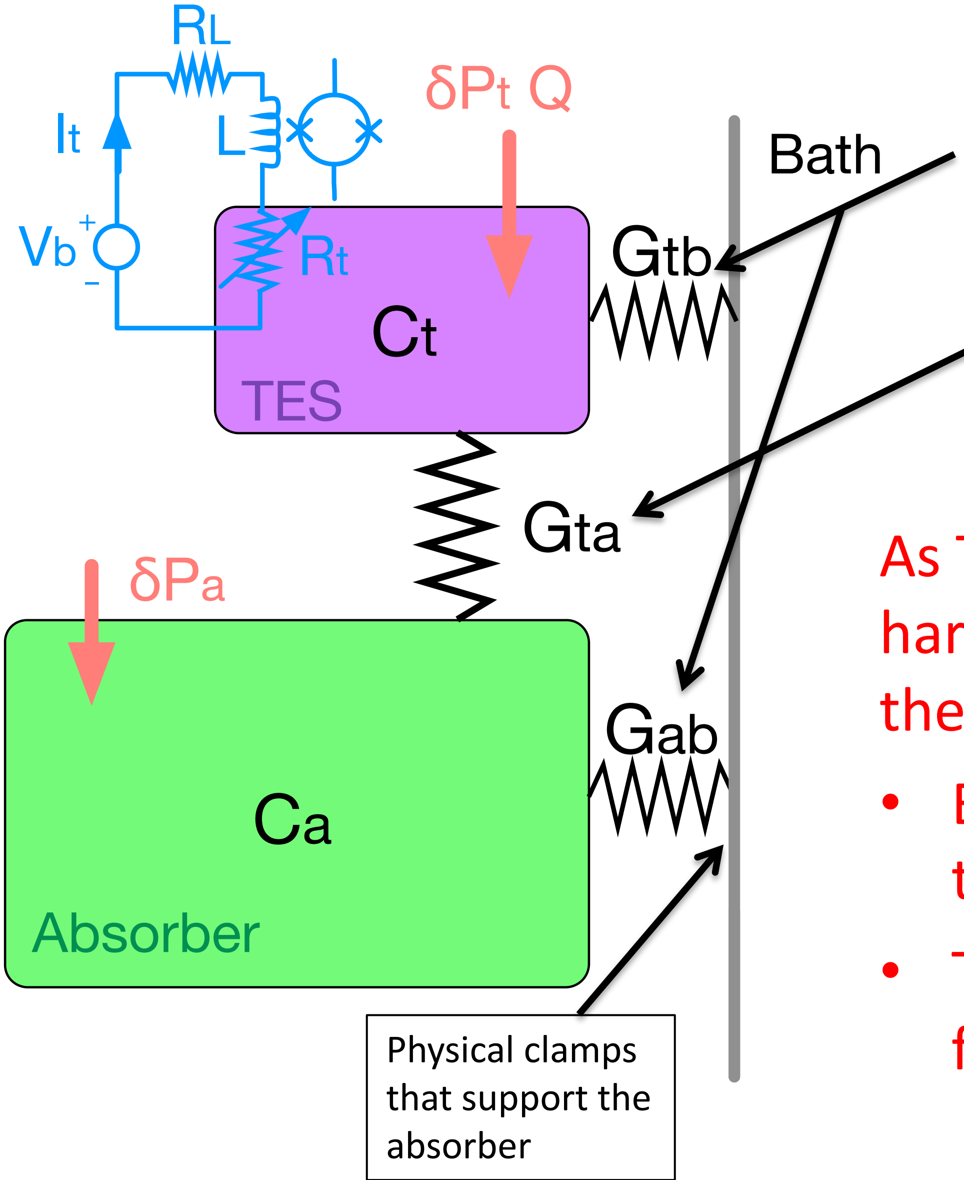


~~2nd most simple thermal calorimeter~~



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

Problem: Decoupling between the Sensor and Absorber



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

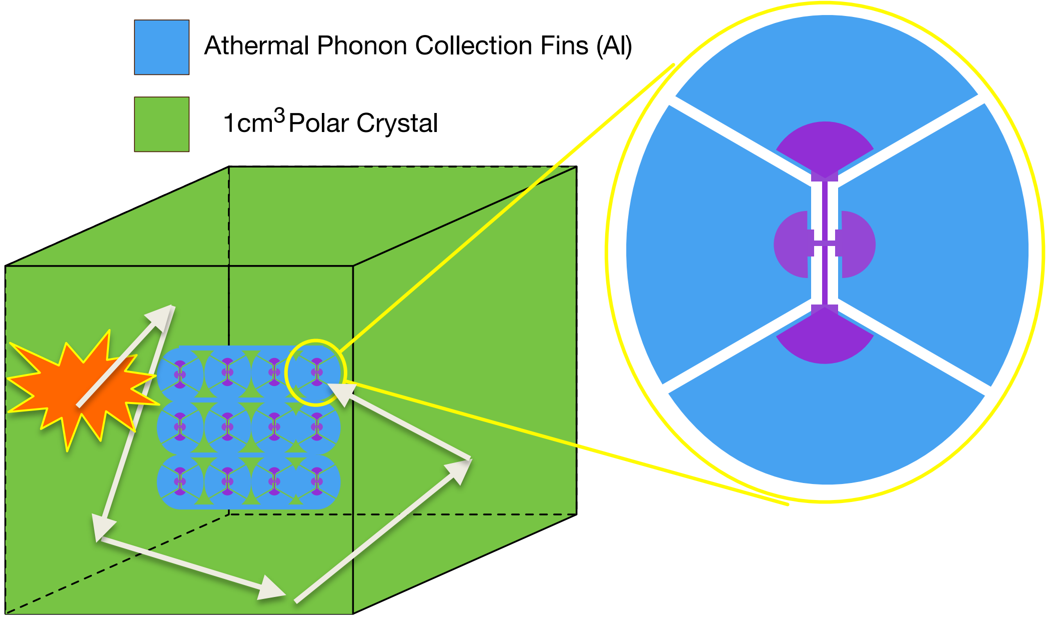
- Energy leaks out of the absorber through G_{ab} before its measured
- TES sensitive to power fluctuations through G_{tb}

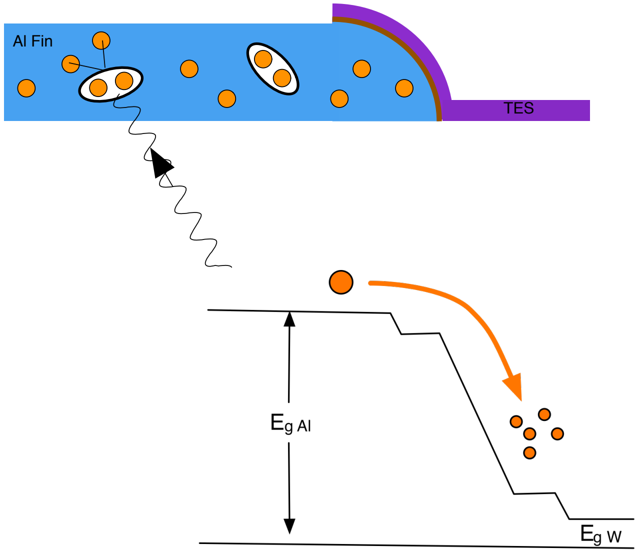
Athermal Phonon Sensor Technology

🟪 TES and QP collection antennas (W)

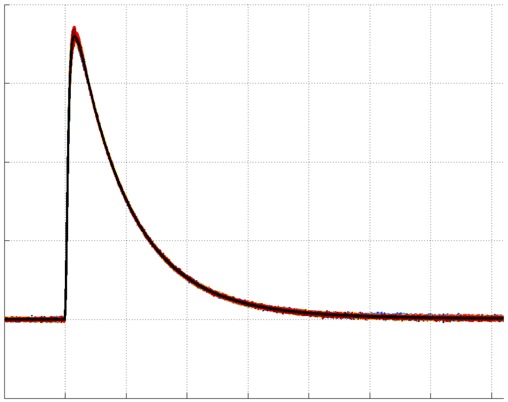
🟦 Athermal Phonon Collection Fins (Al)

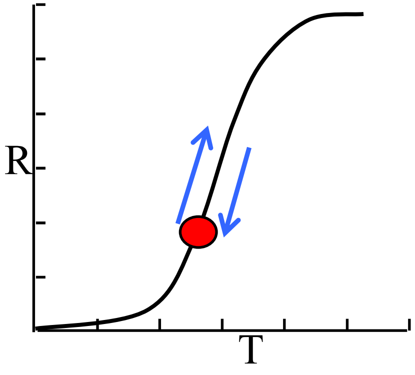
🟩 1cm^3 Polar Crystal



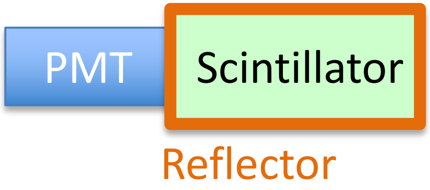


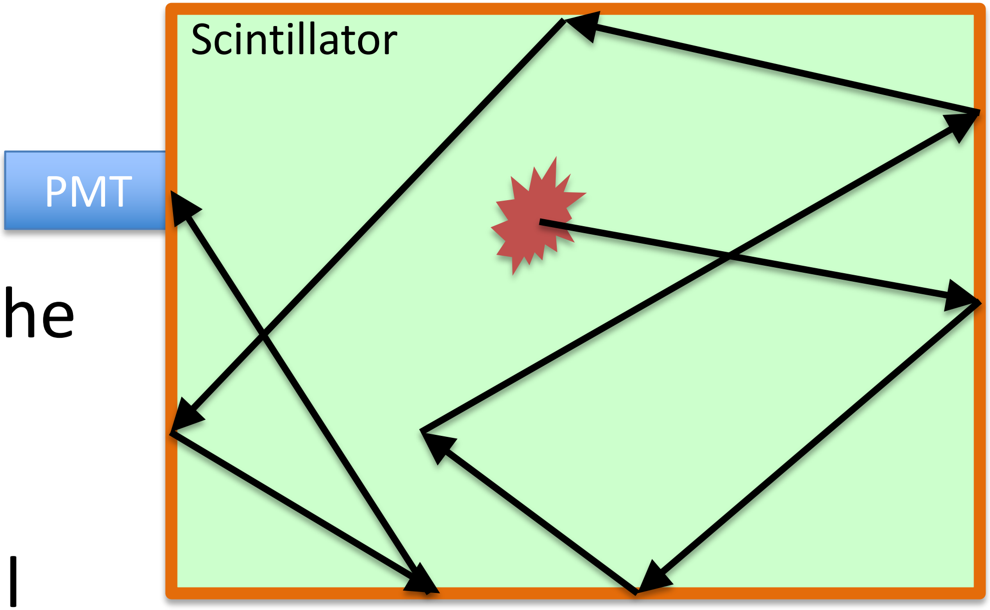
Collect and Concentrate Athermal Phonon Energy into Sensor





Excitation Detectors & Volume Scaling

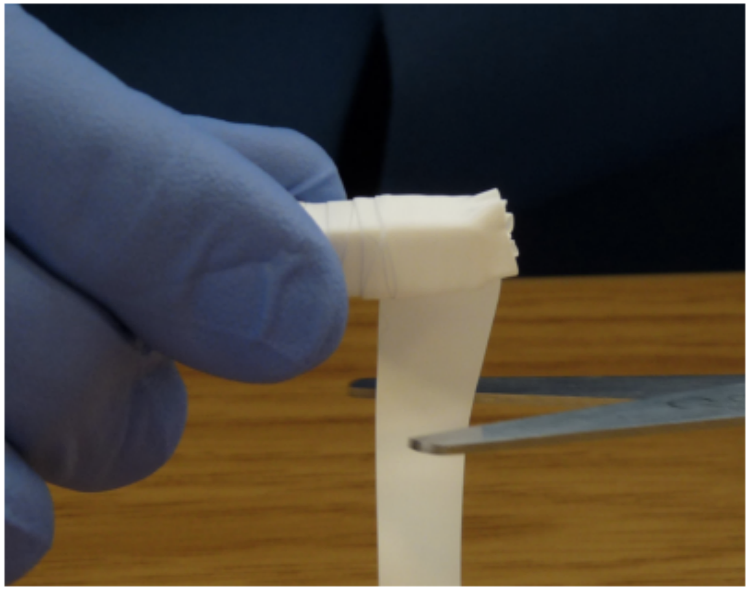




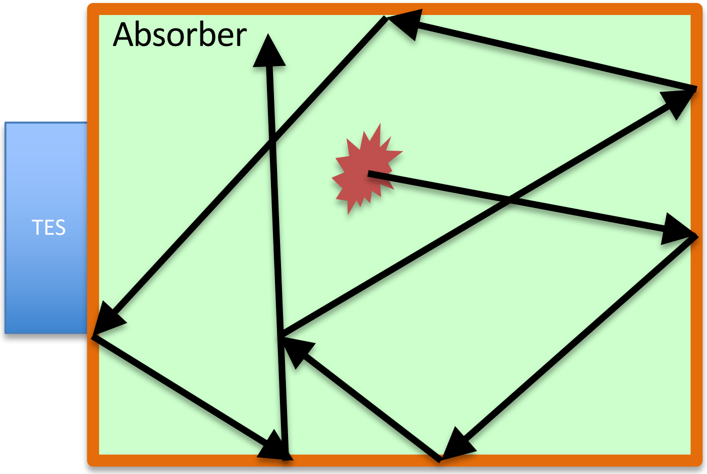
Will these detectors have the same energy sensitivity?

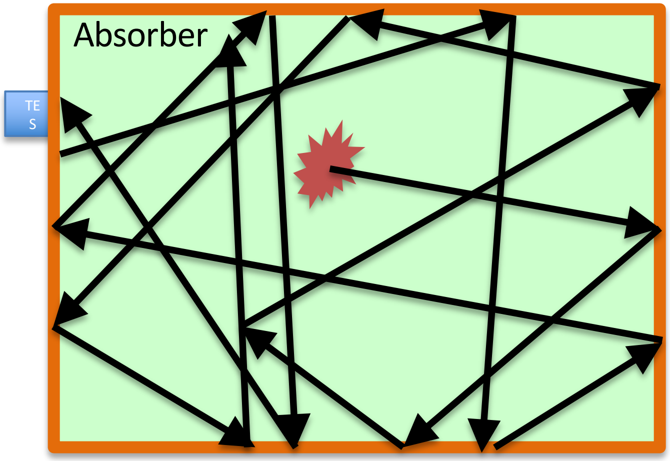
Yes, if:

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



Optimizing the Athermal Phonon Excitation Detectors





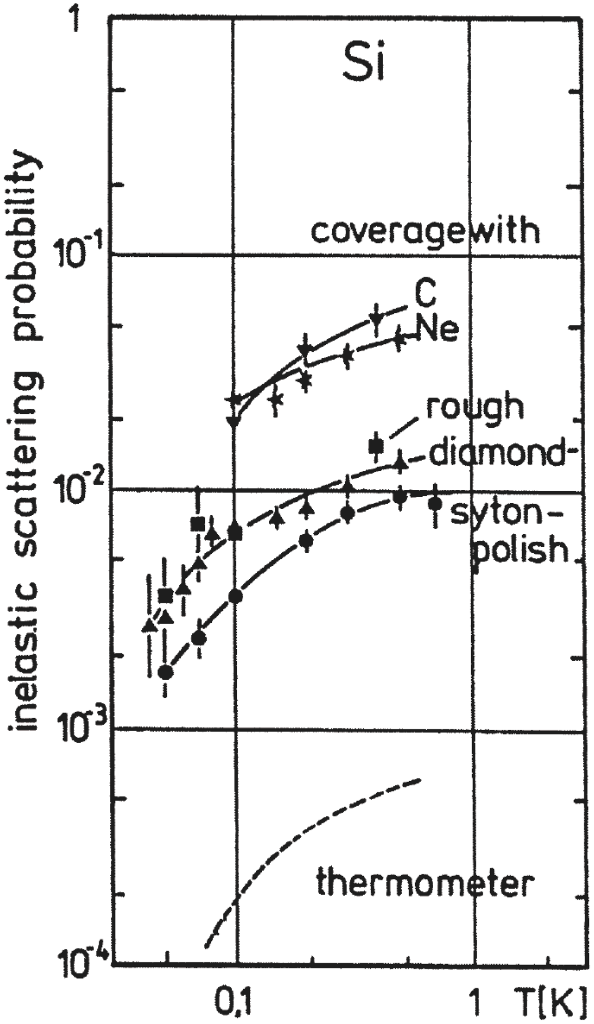
Minimize the number/volume of the TES sensors instrumented on the surface to the point that you begin to see the bare surface thermalization rate

Athermal Phonon Thermalization at Surfaces

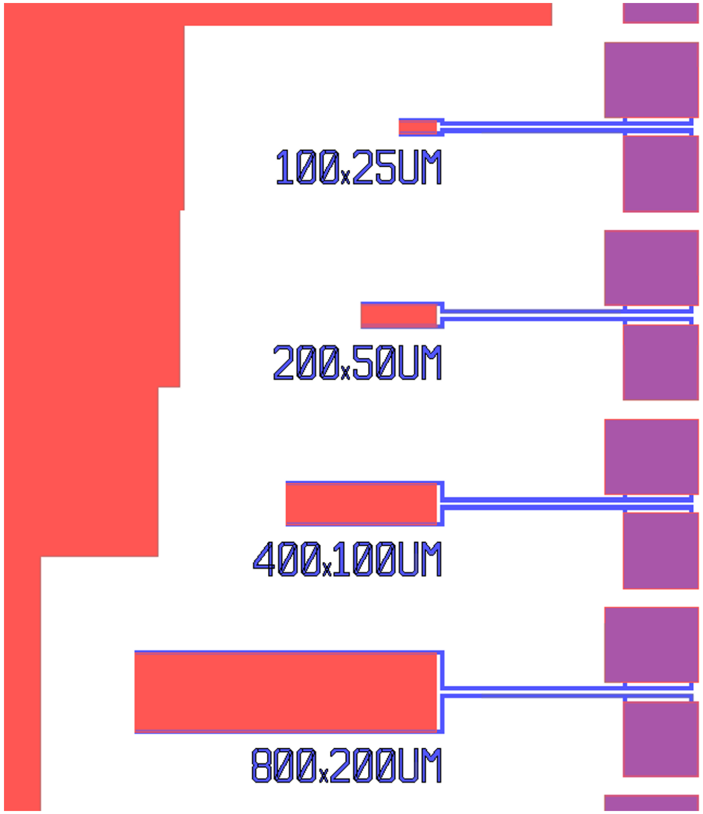
- Athermal phonon surface thermalization probability found to depend upon
  - Crystal
  - Surface roughness
  - Surface cleanliness

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

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



Making Ultra-Sensitive TES

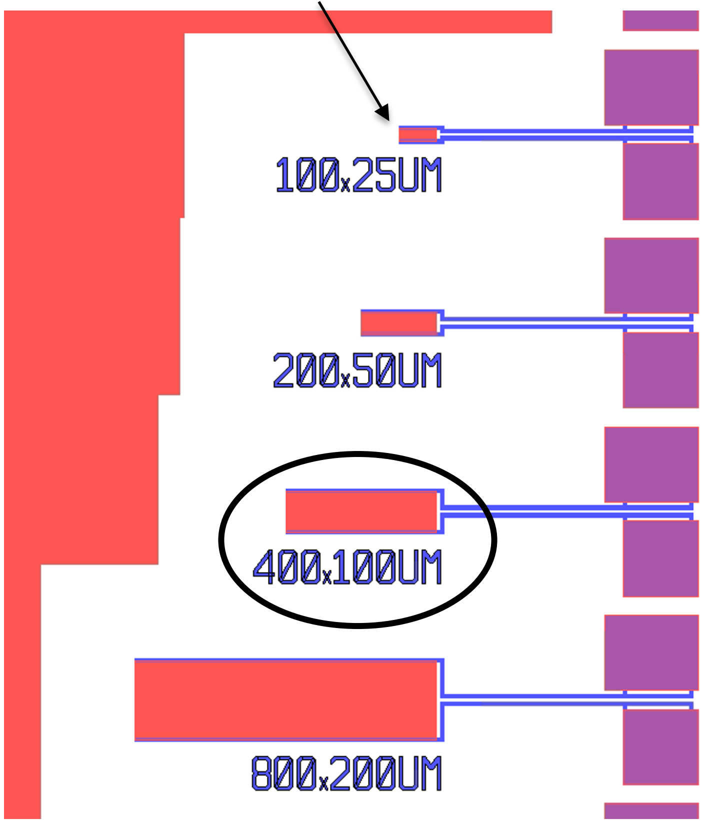


Matt Pyle

For

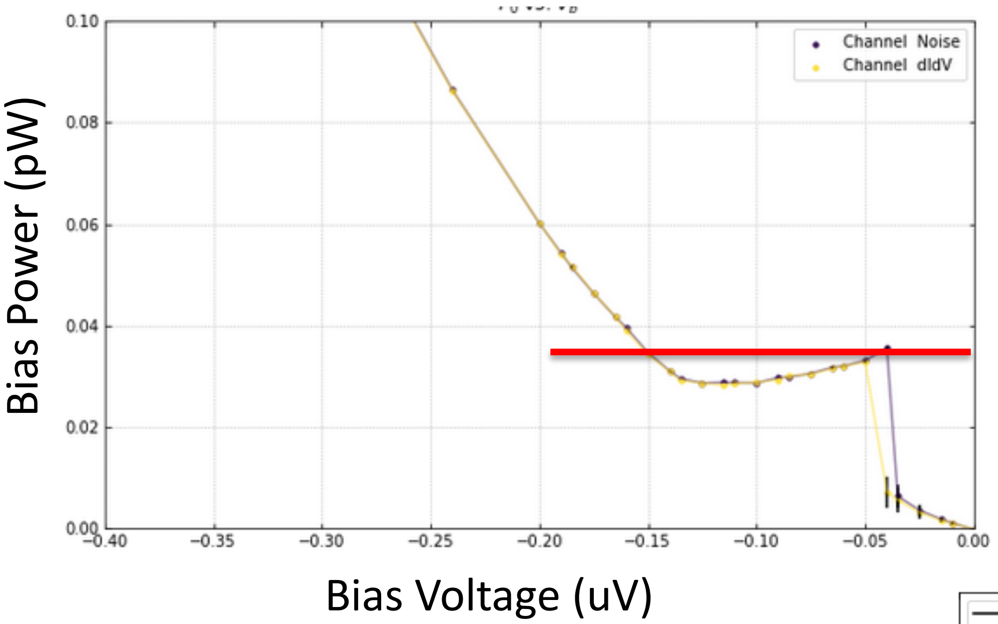
T. Aramaki, P. Brink, C. Fink, R. Harris, Y. Kolomensky, R. Mahapatra, N. Mirabolfathi, **R.Partridge**, M. Platt, B. Sadoulet, B. Serfass, S. Watkins

Step 1)Make An Ultra-Sensitive TES


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

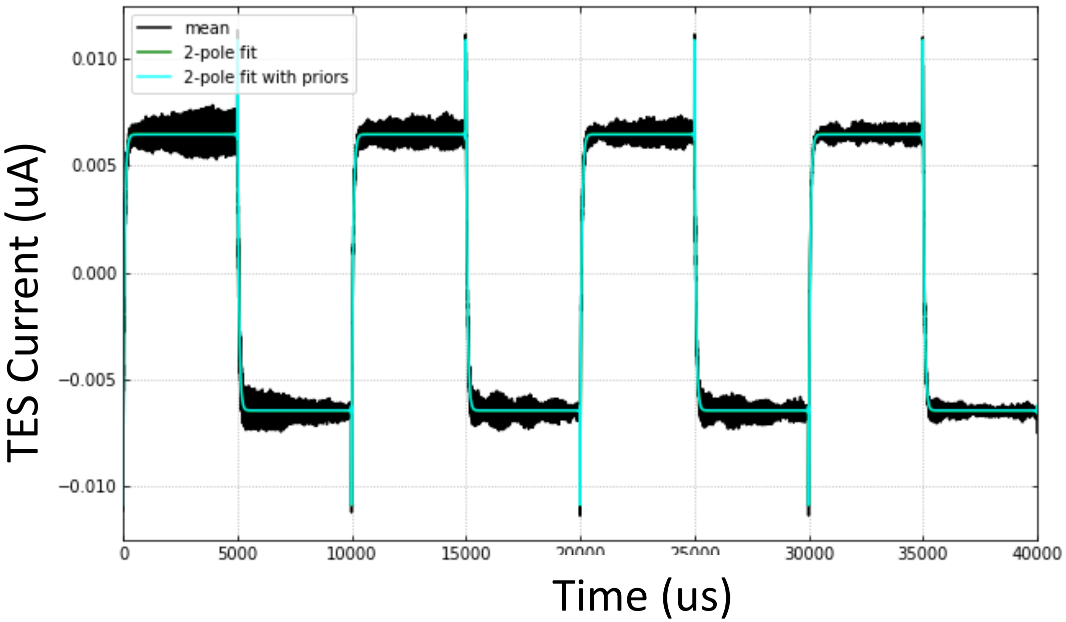
- Build and test simple TES test structures for noise is performance
- $\sigma^2_{<E>} = C k_b T^2$
  - small volume TES(40nm thick) more sensitive to both DM and environmental backgrounds (RF and vibrations)
- Tc =41 mK

100um x400um TES Characterization


TES Power vs TES Bias Voltage

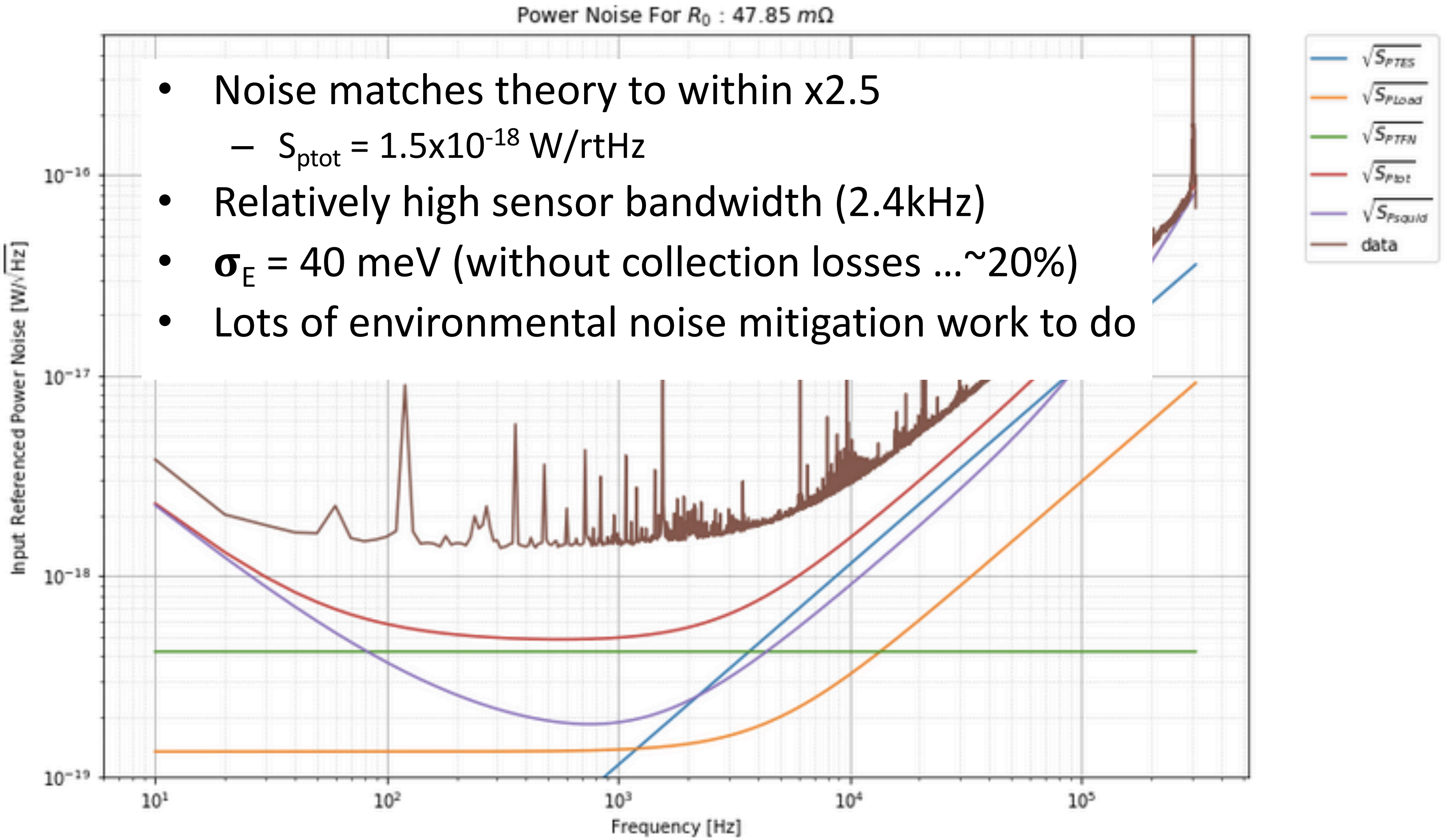
- Complex Impedance
  - Simple 2 pole TES dynamical model perfectly fits response
- TES falltime: ~66us (2.4kHz)
  - Relatively fast
  - Long term -> 1ms and allow athermal phonons to ballistically bounce

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


TES Response to Square Wave Jitter

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 (without collection losses …~20%)
- Lots of environmental noise mitigation work to do

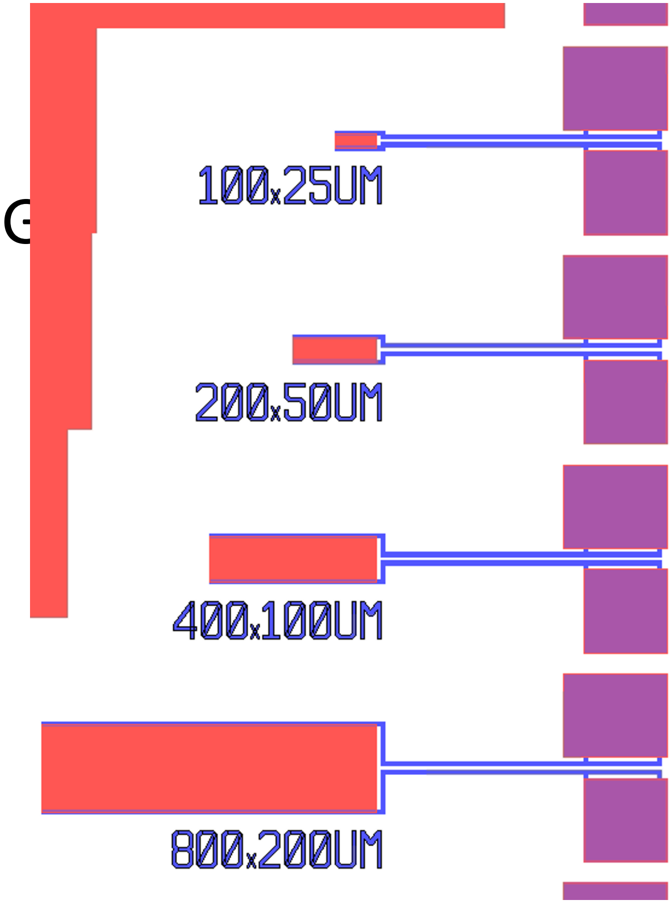


TES R&D

Energy Sensitivity: 50meV -> 1meV

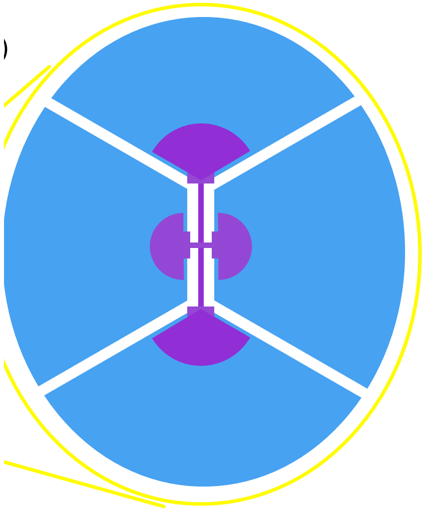
R&D Work Plan

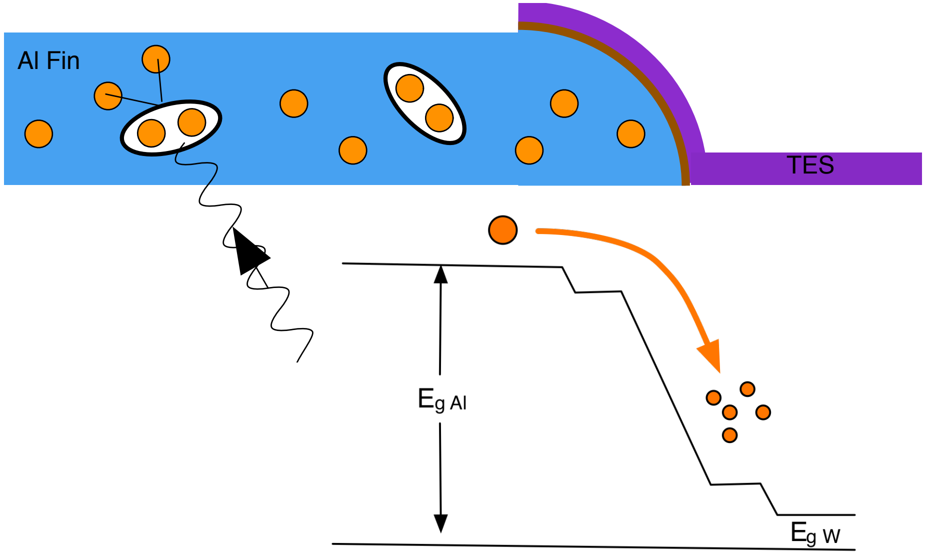
- Lower Tc from 40mK -> 10mK. Since intrinsic theoretical noise, $S_p = 4k_bT^2G \propto T^6$, energy sensitivity should improve by $x4^3 = x64$
- Lower volume by x16, should mean x4 improvement in sensitivity (provided
- Decrease environmental noise susceptibility



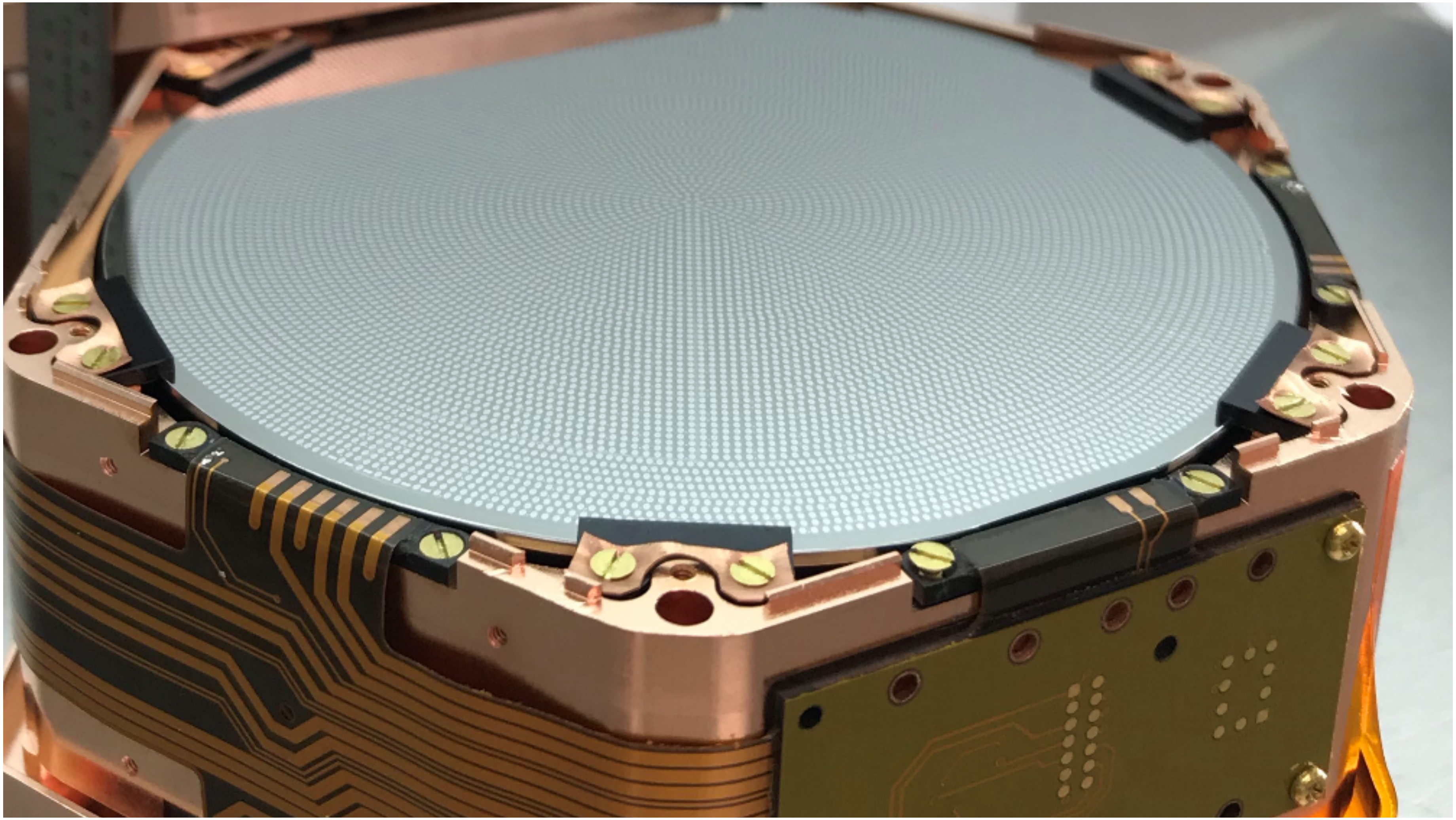
Step 2: Make the Athermal Phonon Sensor

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

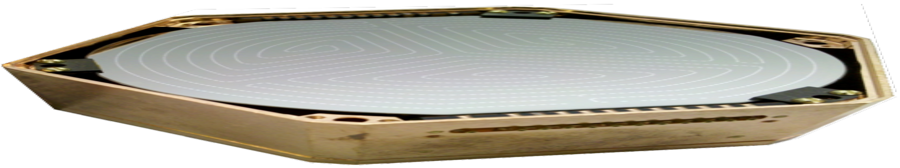




Step 3: Fabricate Sensors on Crystal



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



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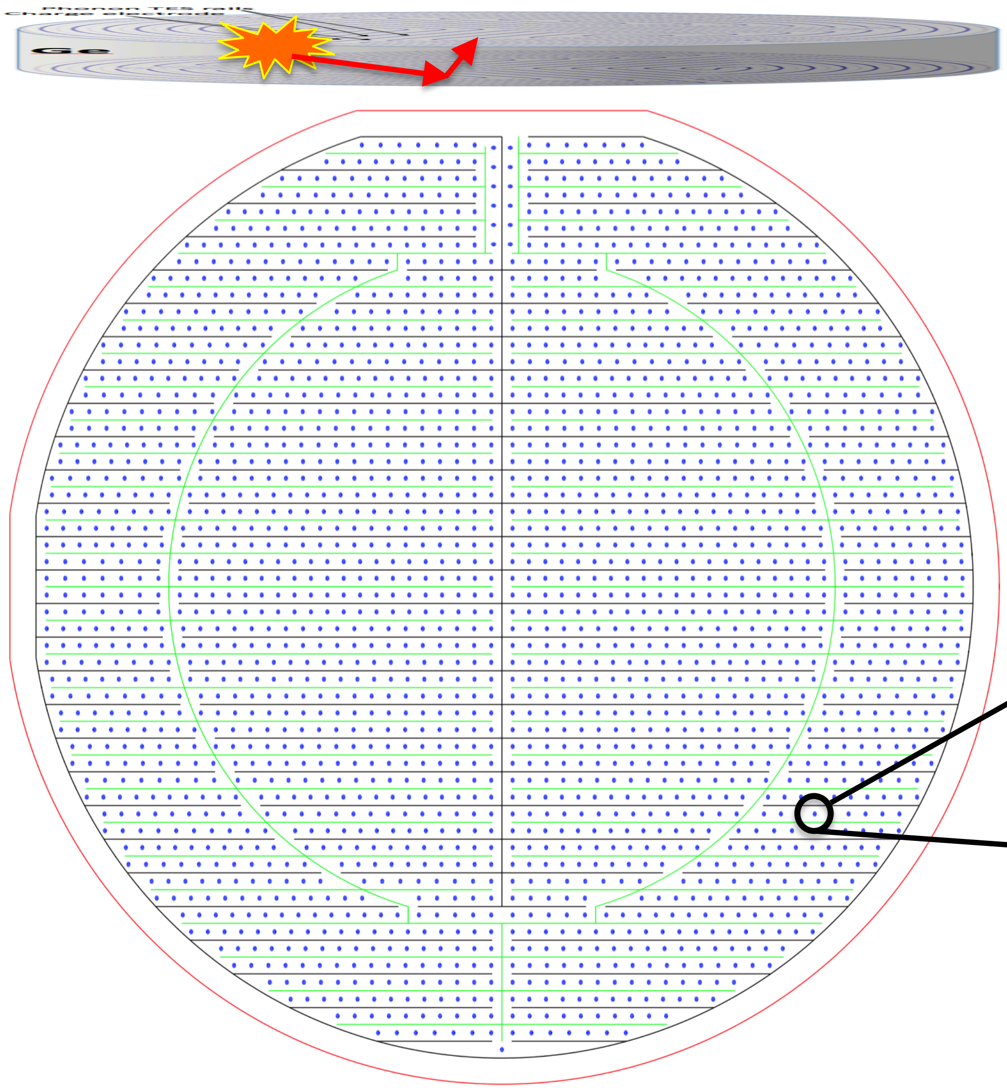
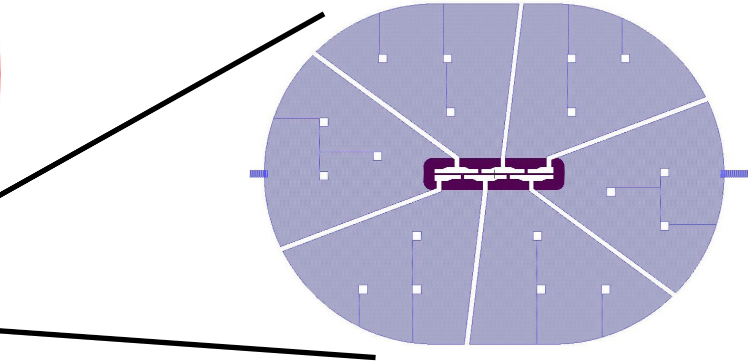
T. Aramaki, P. Brink, J. Camilleri, C. Fink, R. Harris, Y. Kolomensky, R. Mahapatra, N. Mirabolfathi, R.Partridge, M. Platt, B. Sadoulet, B. Serfass, S. Watkins, T. Yu

Current Progress: Large Area Photon Detector

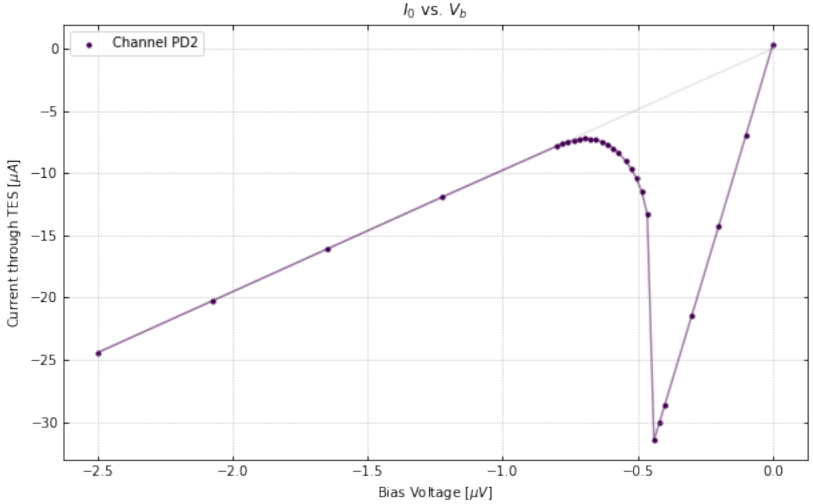


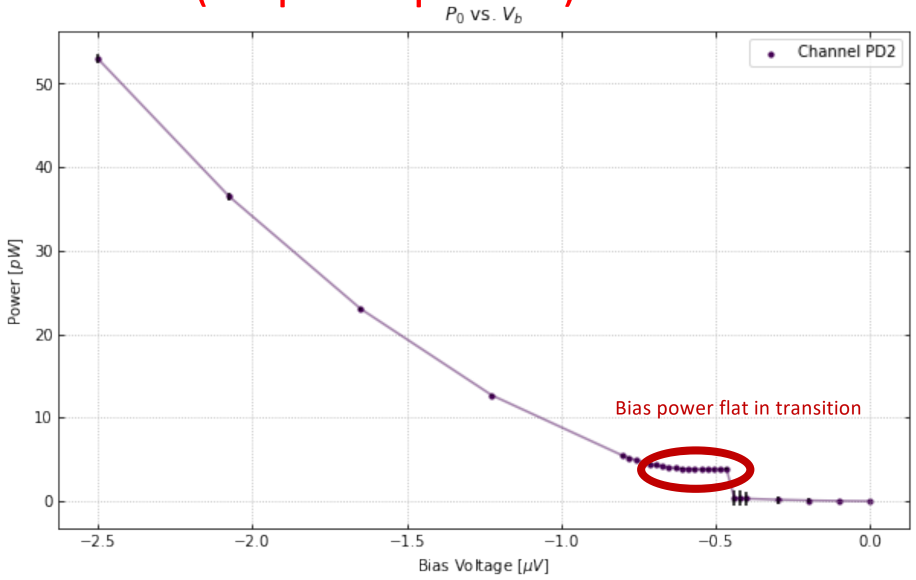


- 3” diameter Si wafer (45.6 cm^2)
- 1mm thick
- Distributed athermal phonon sensors minimize phonon collection time (as fast as it can be for its size)
  - Athermal Phonon collection time estimated to be ~20us
  - 2.5% sensor coverage

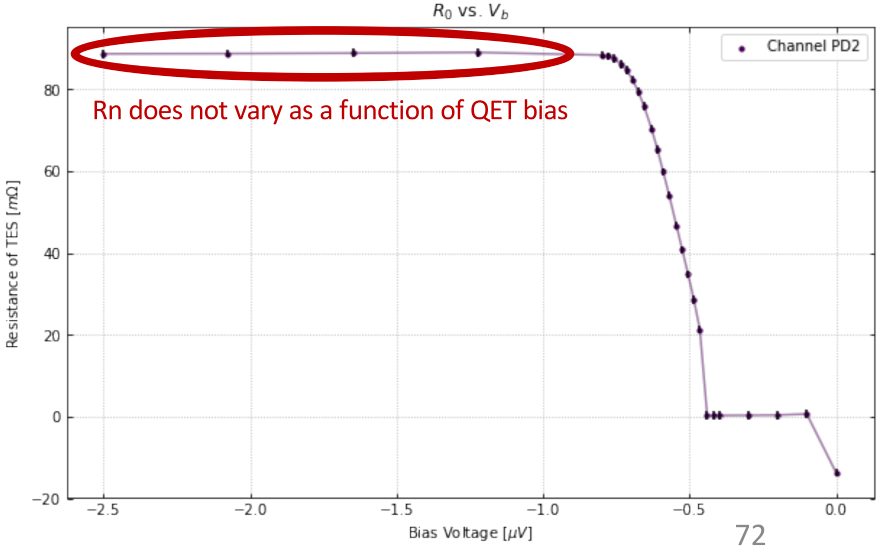
Measured Performance: Tc & IV

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



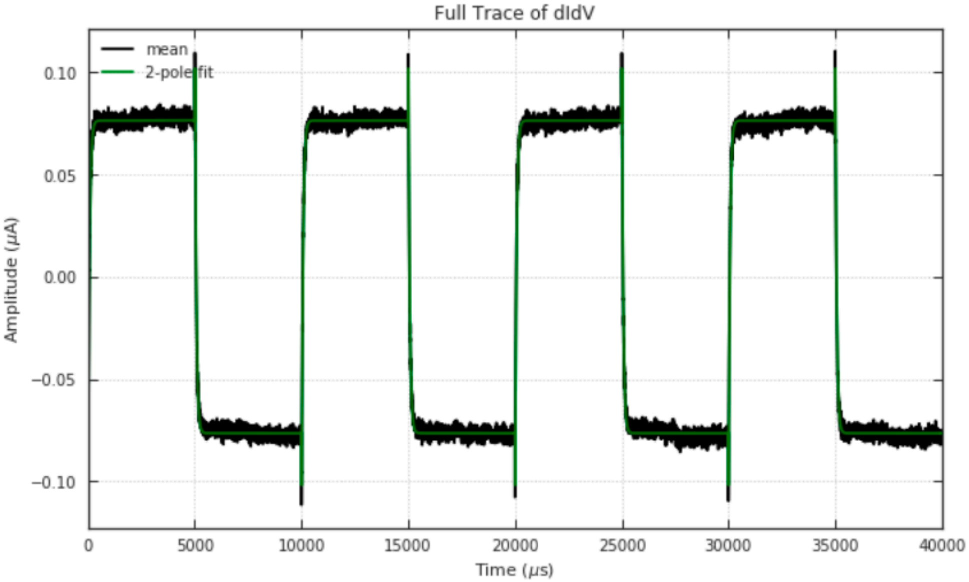


Bias power flat in transition



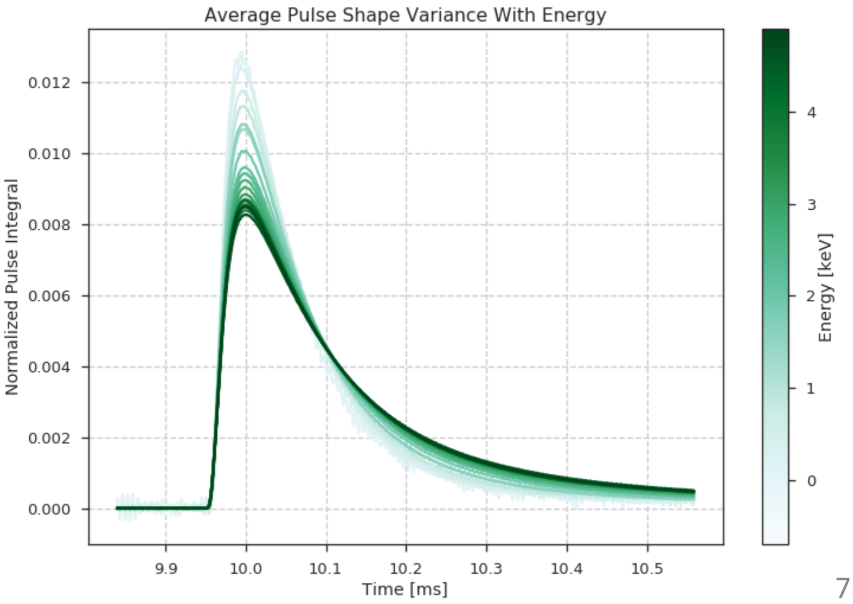
Rn does not vary as a function of QET bias

Measured Performance: dIdV

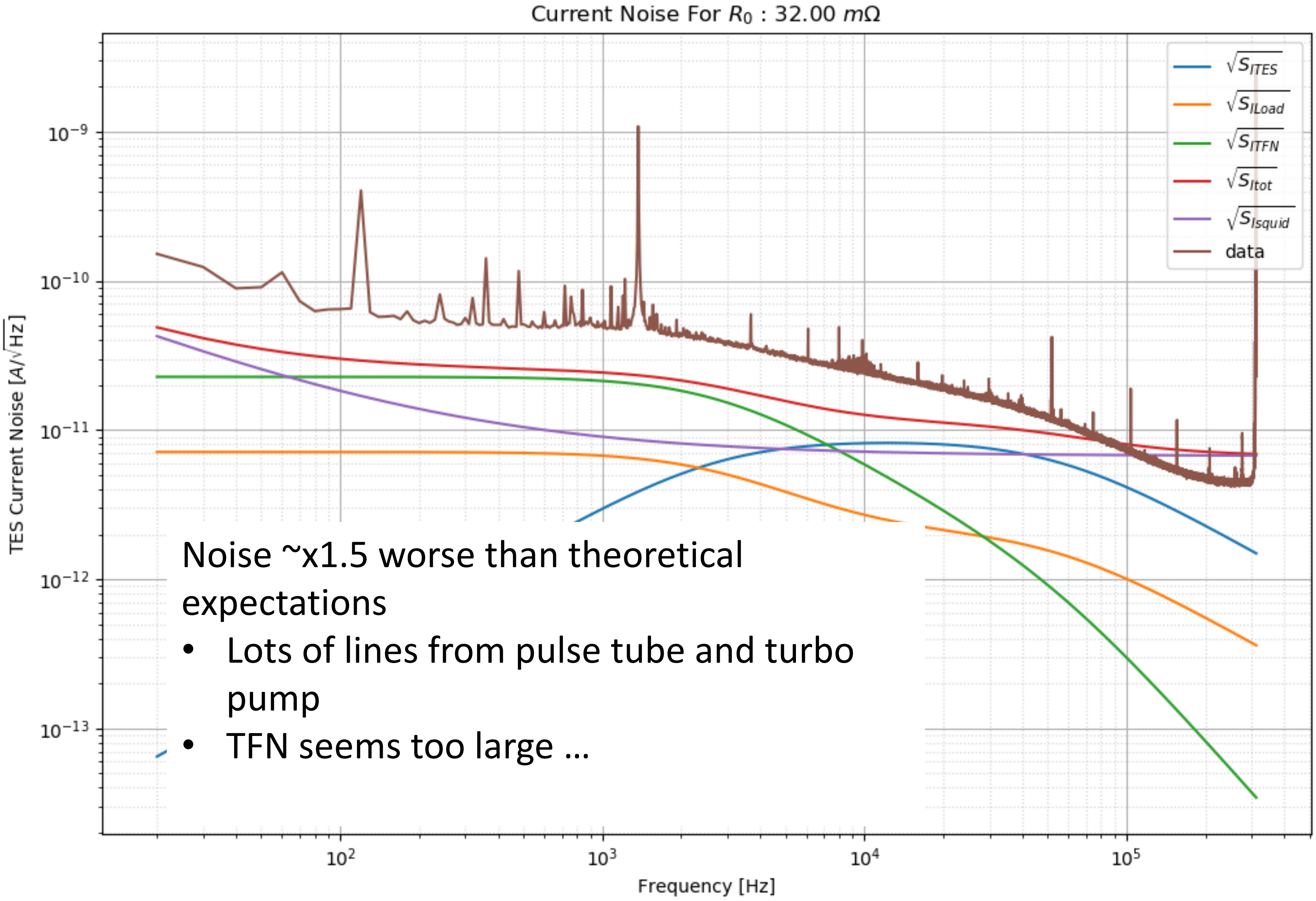


- TES sensor pretty fast @ 60us. However, it's not as fast as the estimated athermal phonon collection (20us)

- 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

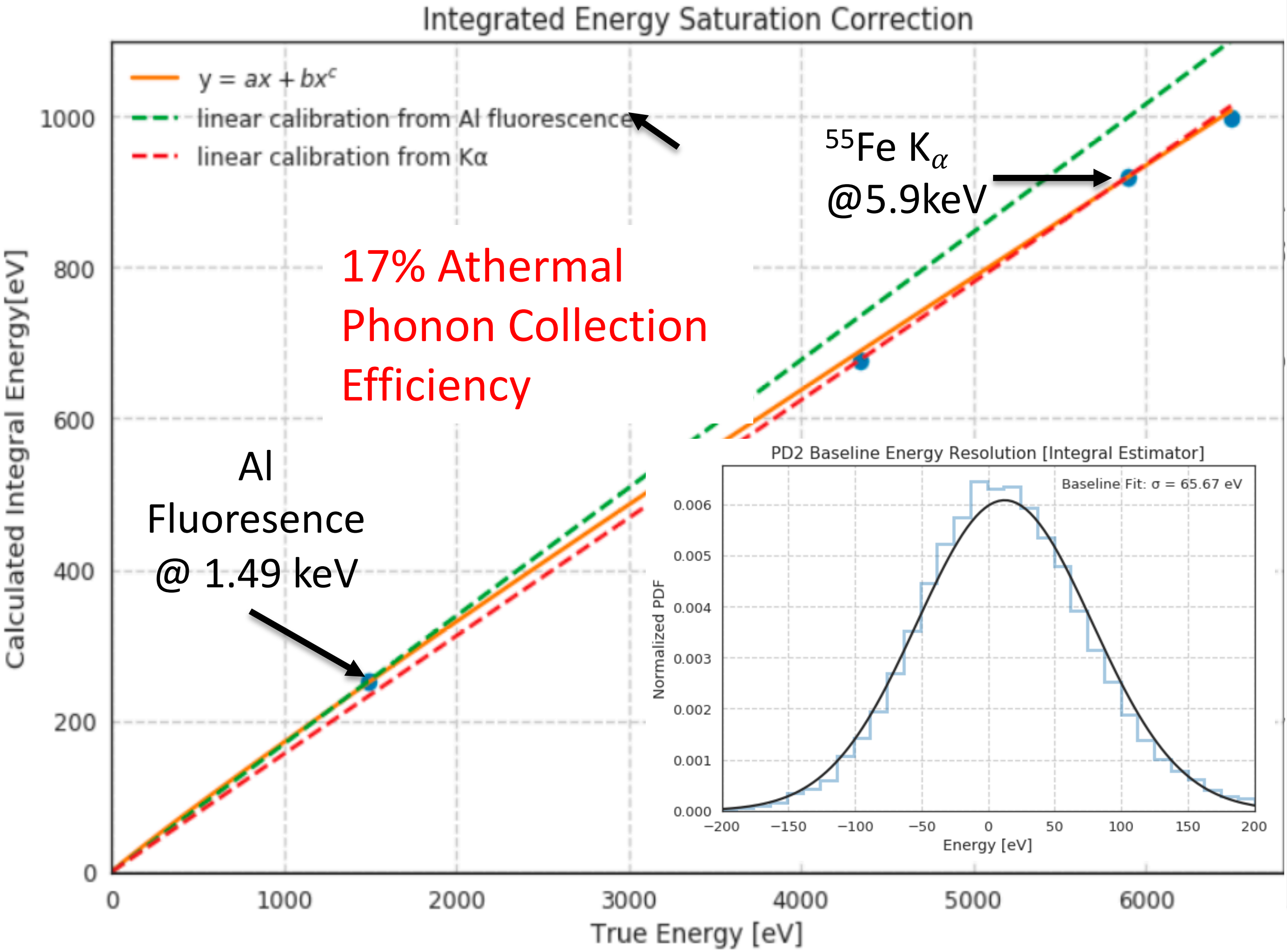


Noise ~x1.5 worse than theoretical expectations

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

Integral Estimators for relative ^{55}Fe calibration

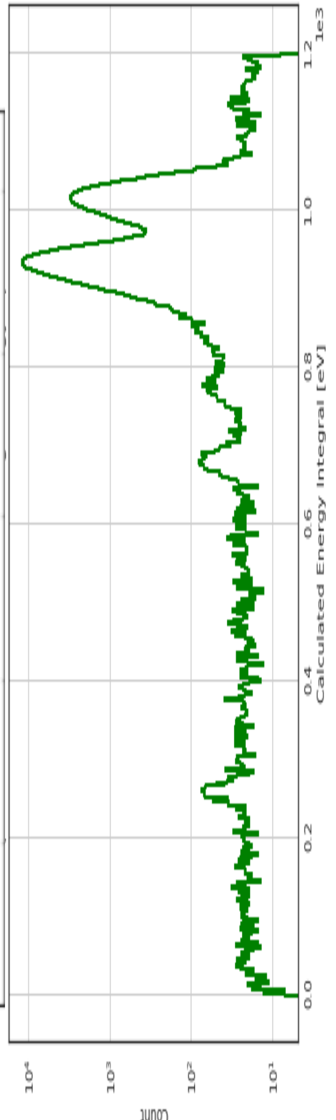
- Since pulse shape has significant variation with energy, we must use noisy but minimally biased DC estimators to fit the ^{55}Fe calibration lines



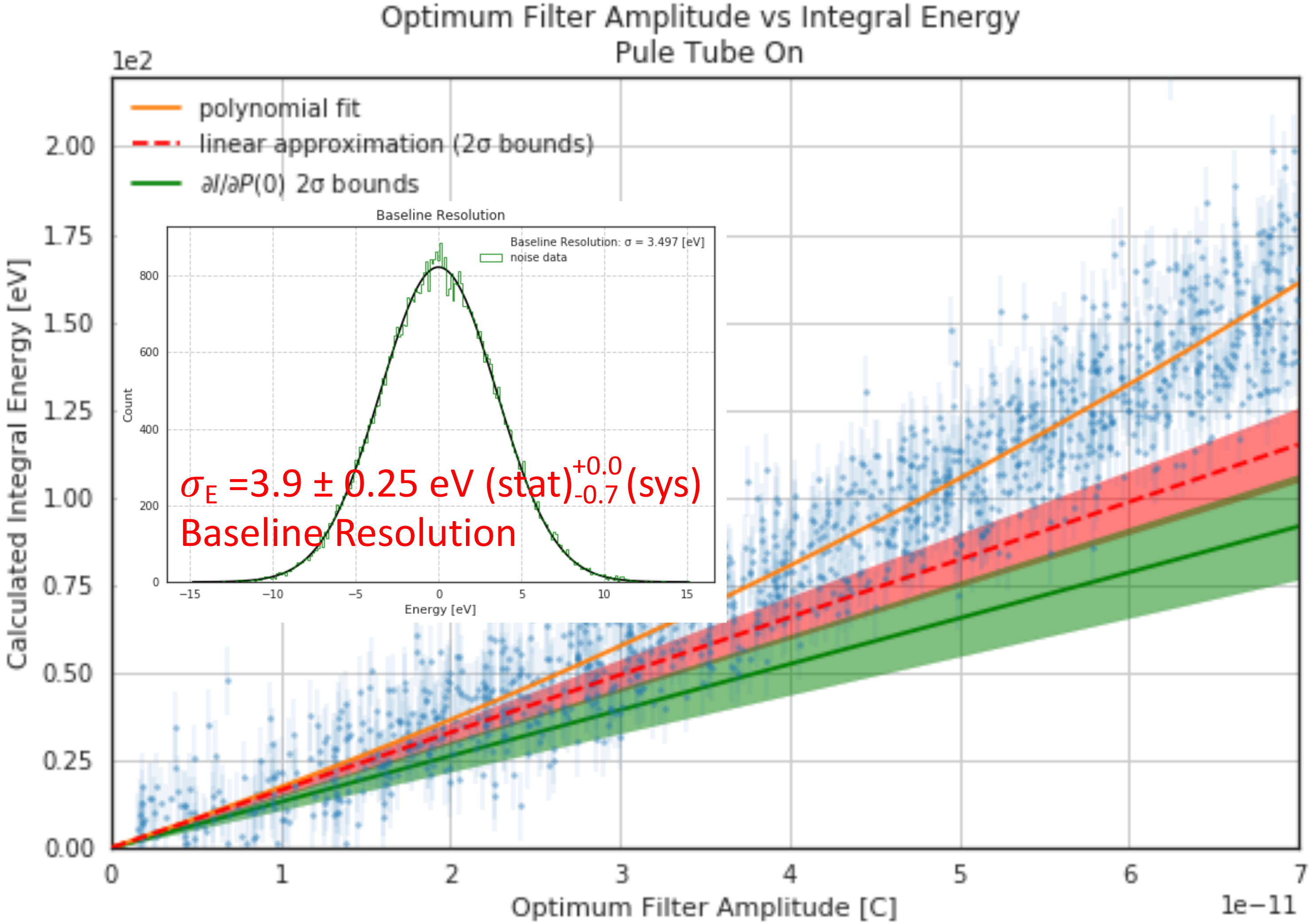
^{55}Fe K_α
@5.9keV

17% Athermal Phonon Collection Efficiency

Al Fluoresence
@ 1.49 keV



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

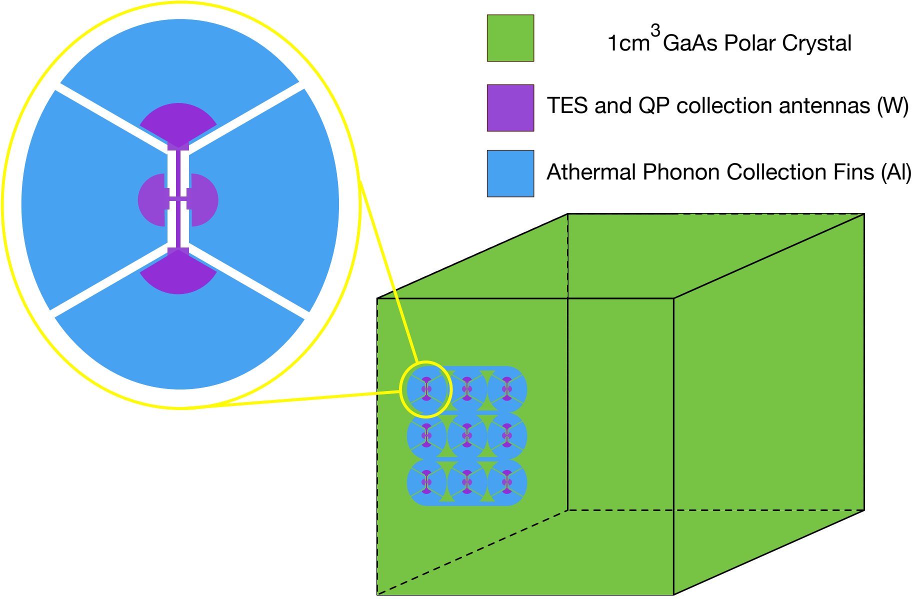


σ_E =3.9 ± 0.25 eV (stat)$^{+0.0}_{-0.7}$(sys)

Baseline Resolution

20gd 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

Summary:

- Design Drivers for 10meV-1GeV DM: Energy Sensitivity
- Athermal Phonon Detectors are a promising technique to search for 10meV-1GeV Dark Matter
- Current Progress:
  - 3” large are photon detector 3.5eV resolution
  - 100x400um TES test chip: 50meV resolution
- R&D Plan: Towards the single quantum regime
  - Increase TES sensitivity: lower Tc
  - Improve Collection efficiency: optimize W/Al interface
  - Fabricate on a variety of crystal substrates
  - Study how phonon surface themalization depends on surface roughness.