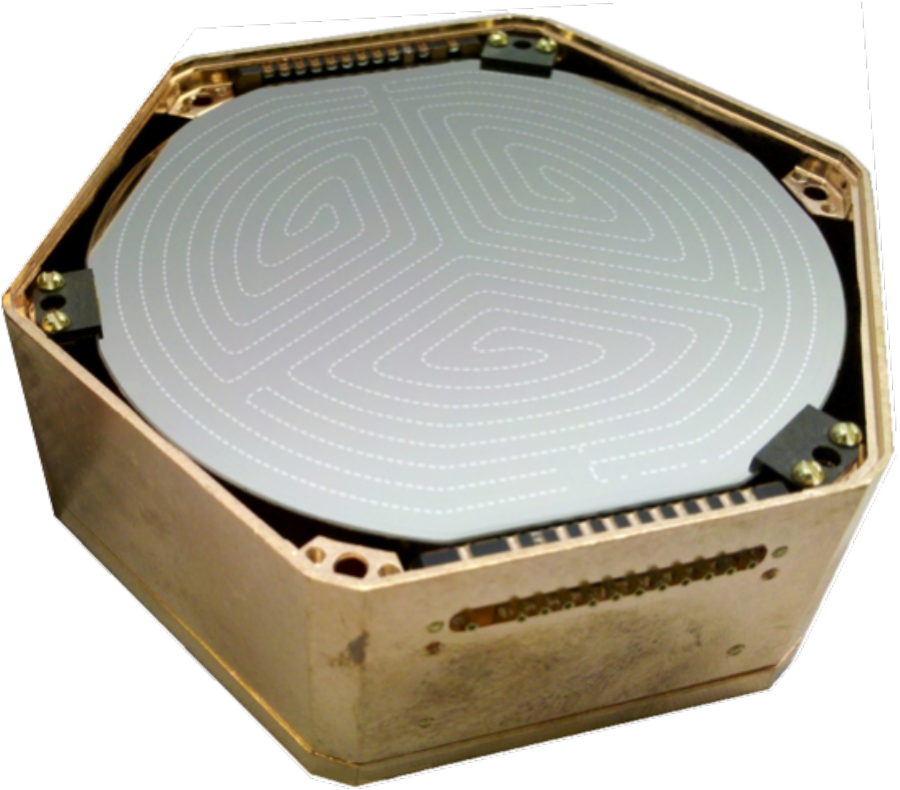
Cryogenic Large Area Photon Detectors For Use In Dark Matter Searches and Neutrinoless Double Beta Decay



Matt Pyle

For

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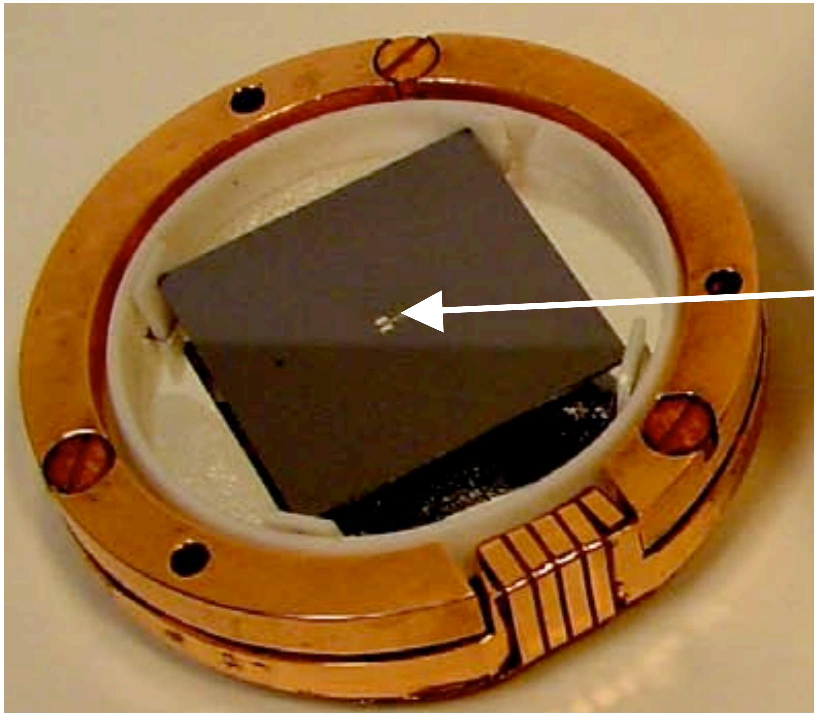
5/23/16

State of the Art: Photon Detectors



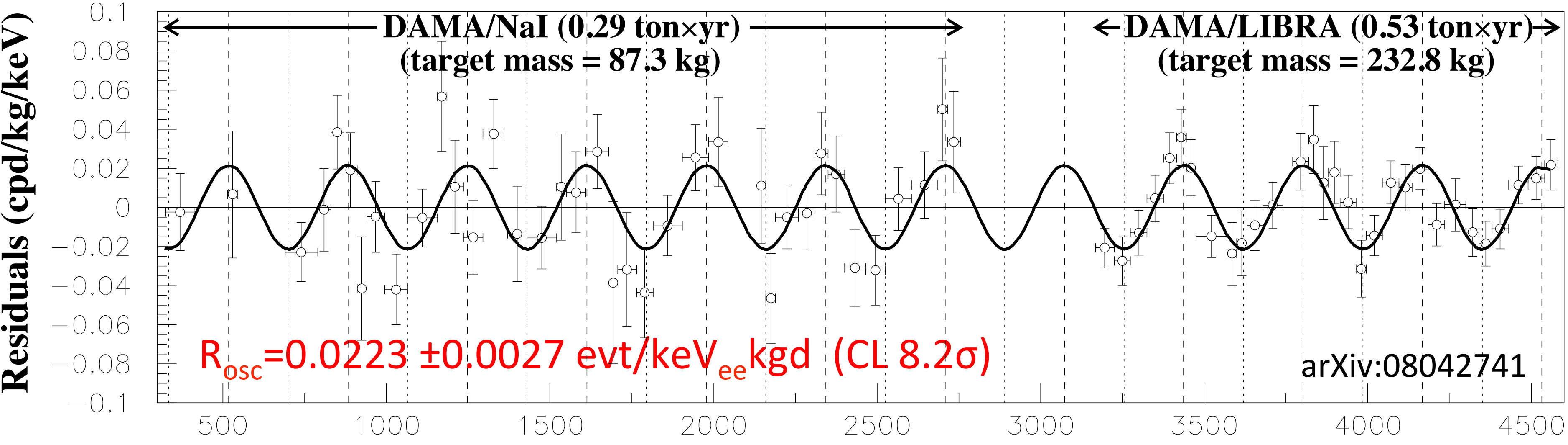
- CRESST Thermal Calorimeter Light Detector
  - (0809.1829)
  - 30mm x 30mm Si wafer
  - Single W TES (Tc ~10mK)
  - Sensitivity: 8.5 eV (σ baseline)

Is there a need for something better?

Dark Matter

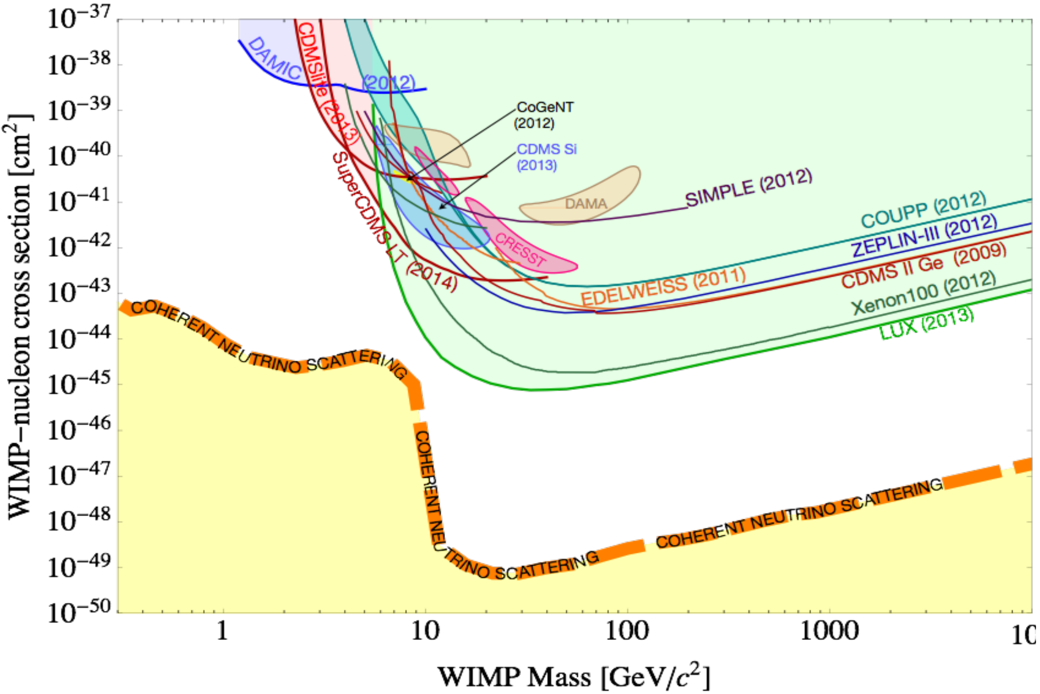
Dark Matter: Testing DAMA

Time Dependence of Residual Singles Rate in 2-4keVee bin



R_{osc}=0.0223 ±0.0027 evt/keV$_{ee}$kgd (CL 8.2σ)

arXiv:08042741

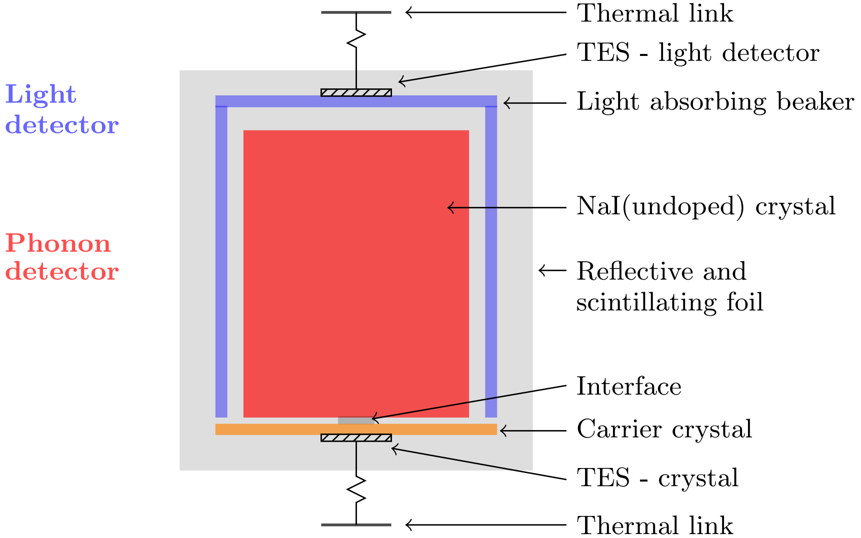


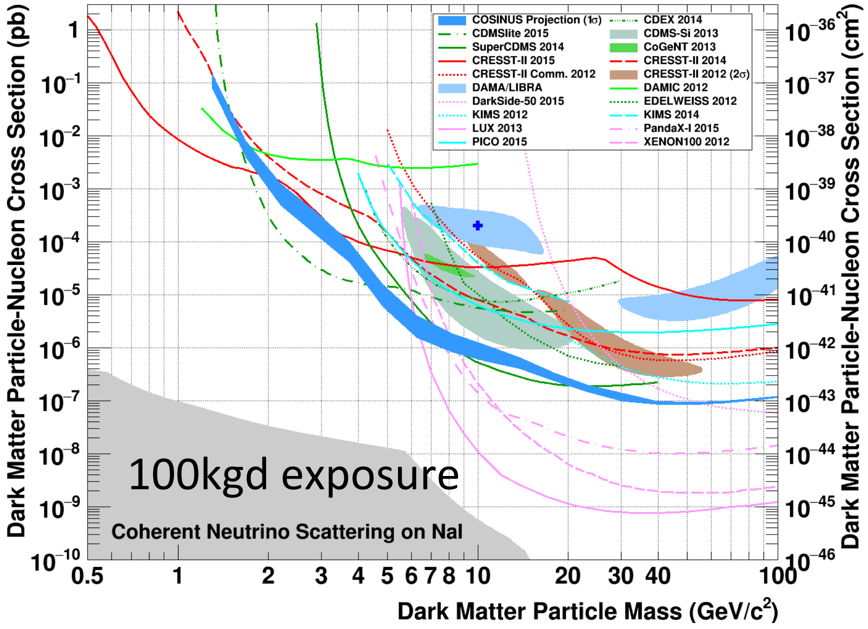
- Completely inconsistent with rest of the field
  - LUX 10^4 WIMP Scatters
- No smoking gun

Dark Matter: Testing DAMA

- Apples to Apples test: requires NaI
- Electron Recoil/ Nuclear Recoil Discrimination
- COSINUS
  - 1603.02214

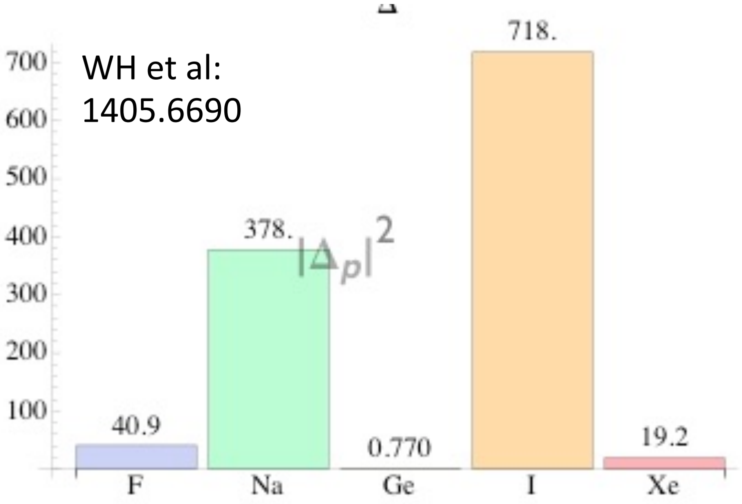
Requirements: Large area, high QE detector with single photon sensitivity



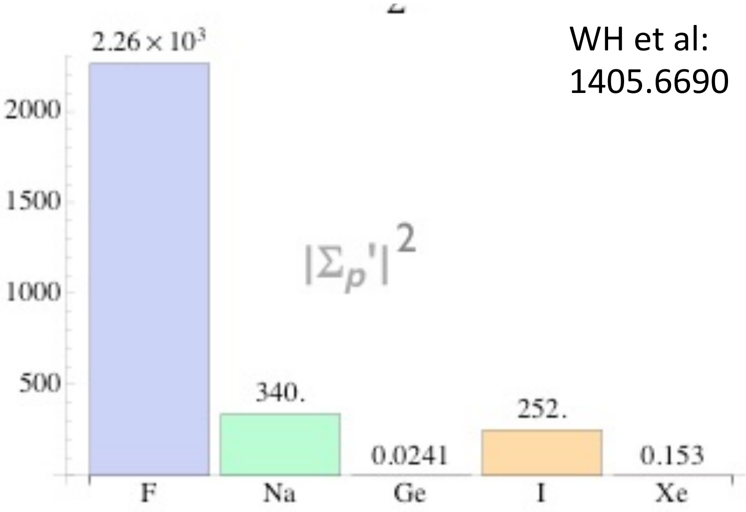


Dark Matter: Exotic Coupling Dark Matter

Orbital Angular Momentum Coupling


WH et al: 1405.6690

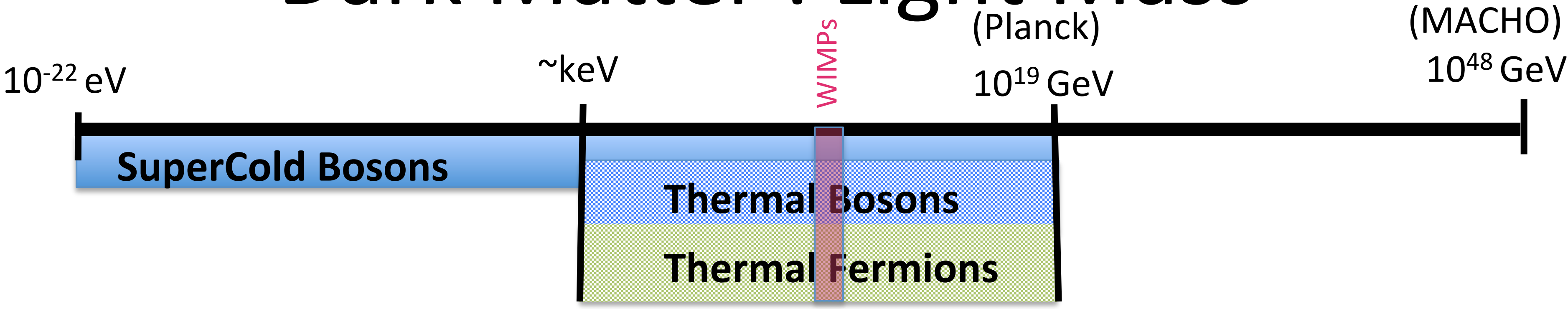
Vector (Transverse) Proton Spin Coupling


WH et al: 1405.6690

- Traditional ER/NR DM targets all [even, even] low angular momentum nuclei: Xe, Ar, Ge, Si
- What if DM couples via spin? What if DM coupling has strong velocity dependence? (1405.6690)
- ~10kg of CRESST like Scintillation + Phonon Detectors for ER/NR rejection made from NaI and CaF_2 could compete with much larger experiments

Requirements: Large area, high QE detector

Dark Matter : Light Mass



10^{-22} eV

~keV

WIMPs

(Planck)

10^{19} GeV

(MACHO)

10^{48} GeV

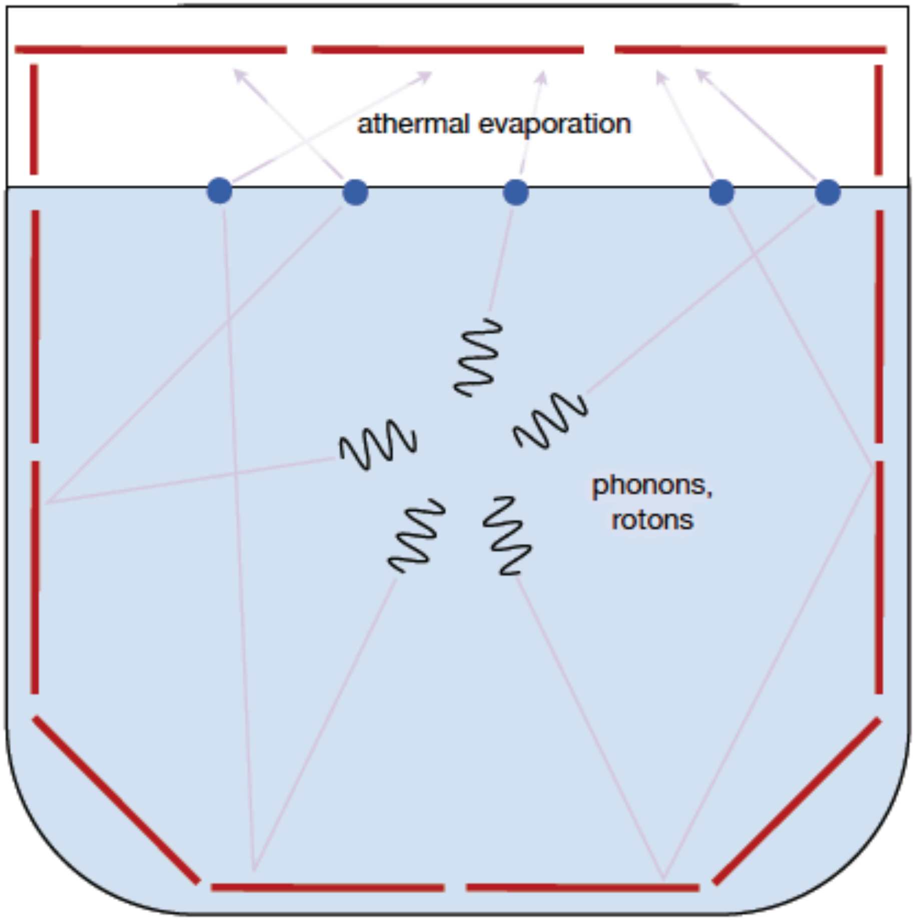
SuperCold Bosons

Thermal Bosons

Thermal Fermions

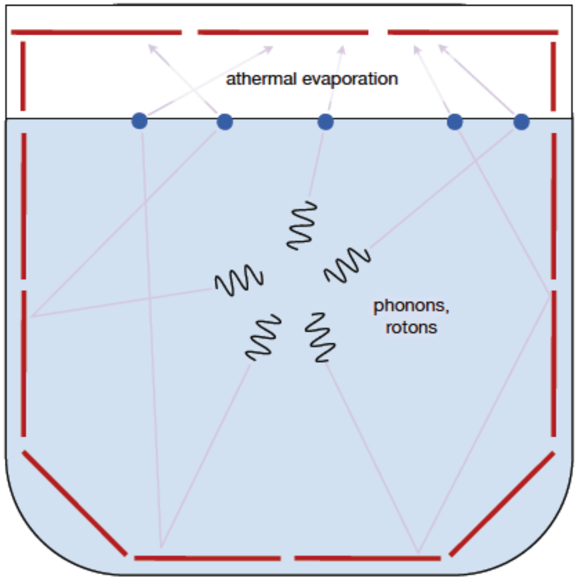
- Historical focus on WIMP DM
- Well Motivated DM Models with $1\text{keV} < M_{DM} < 10\text{GeV}$
- (KZ, MP et al, 1512.04533)

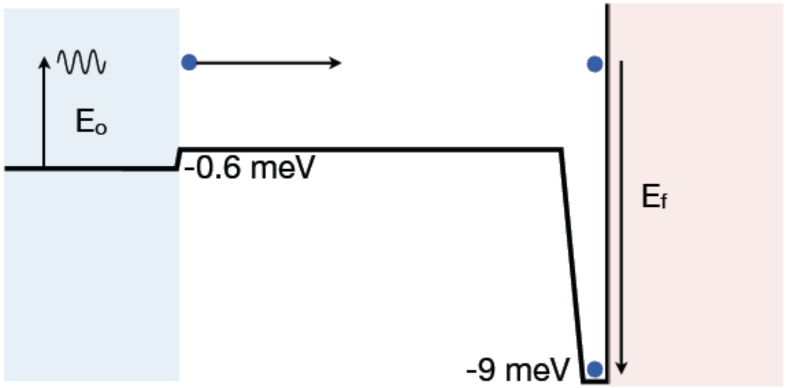
Superfluid He Detector



- 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

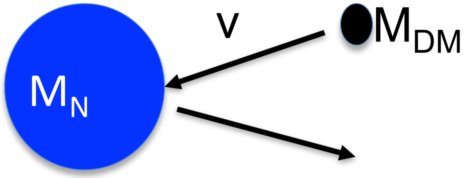
Superfluid He: Natural Roton Amplification



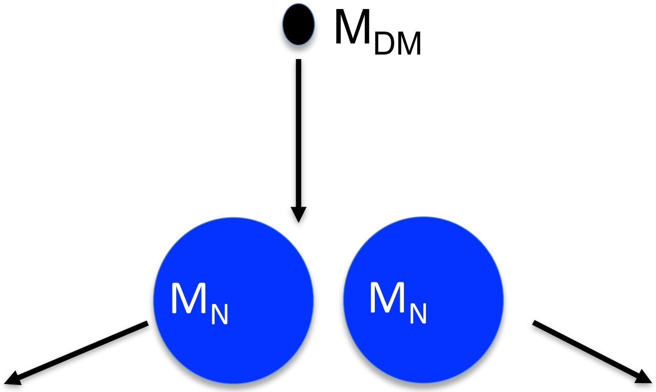


- Intrinsic amplification of rotons: x10 via helium atom quantum evaporation, then adsorption on bare Si mounted in vacuum above liquid surface (HERON)
- Roton Detector Requirements: Large area, high QE, Ideally Single Roton Sensitivity

Superfluid He: 1keV-10MeV Dark Matter



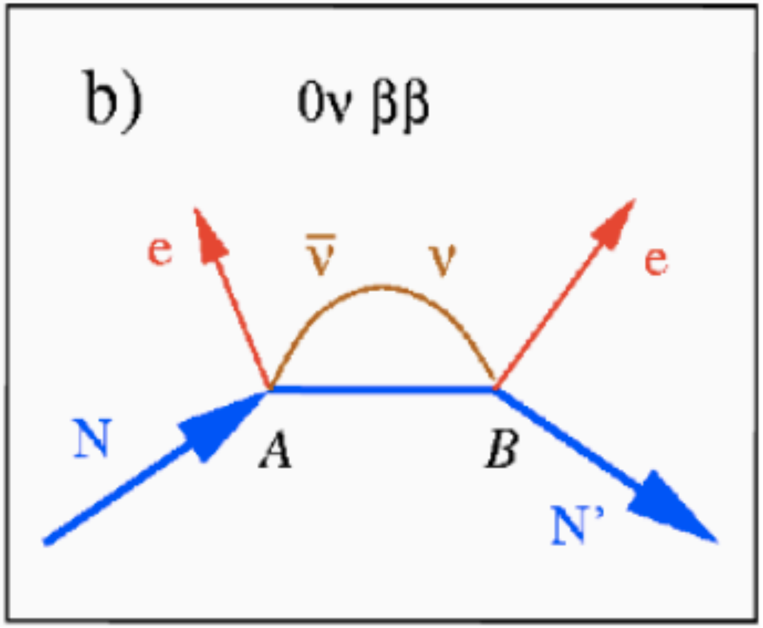
$$\Delta E = \frac{\Delta P^2}{2M_N} \sim \frac{2M_{DM}^2 v^2}{M_N}$$

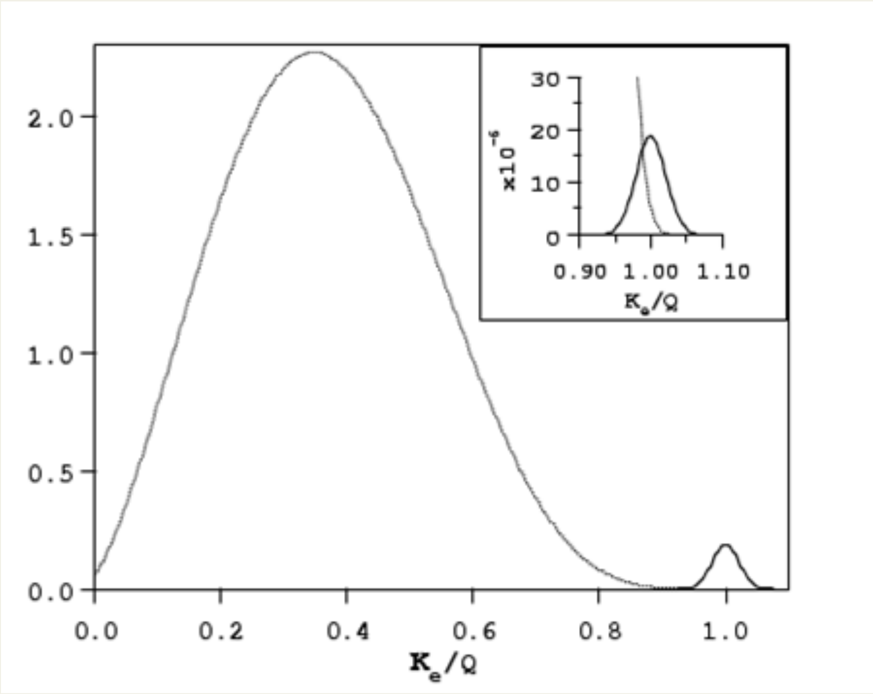


- Off shell roton production(Kathryn Zurek)
- Electronic recoils always produce at least 1 photon
  - Potentially no electronic recoil background below 14 eV
- Detector Backgrounds: ?
  - Equilibrium Detector: No dead counts

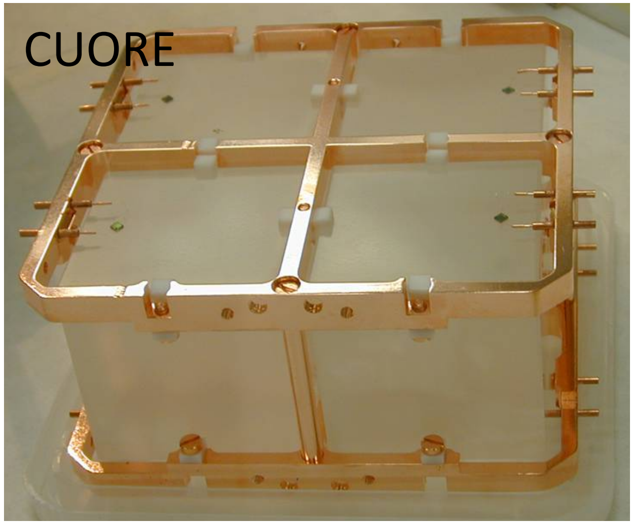
Neutrinoless Double Beta Decay

- Most sensitive test of
  - lepton number conservation
  - Majorana/Dirac nature of ν
- Central to most theories of Leptogenesis
- Potentially measures ν mass



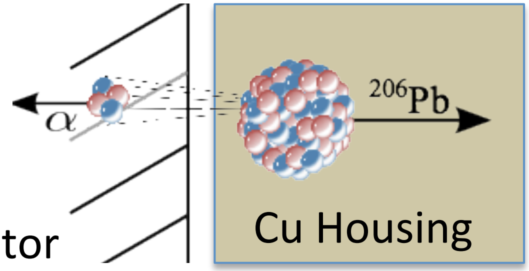


DBD: Cryogenic Calorimeters

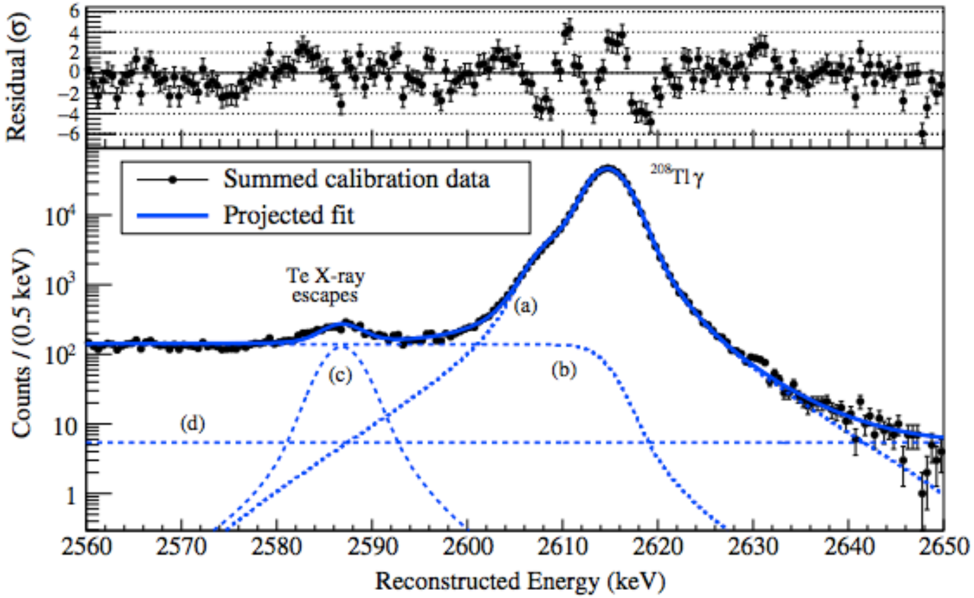


- Advantages:
  - Excellent energy resolution
  - Variety of target isotopes

- Disadvantage: Backgrounds, in particular degraded alphas from Cu support structure



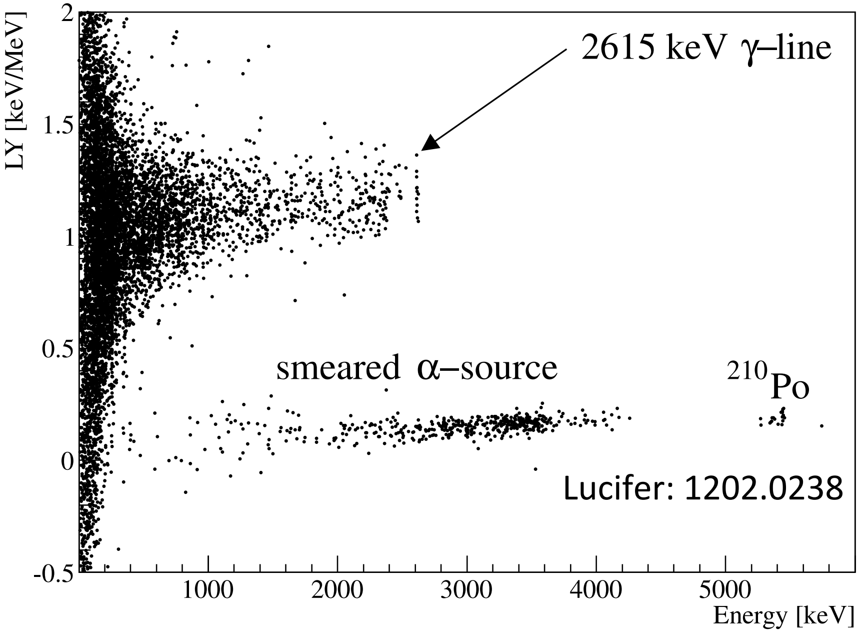
CUORE-0: PRL 115, 102502 (2015)

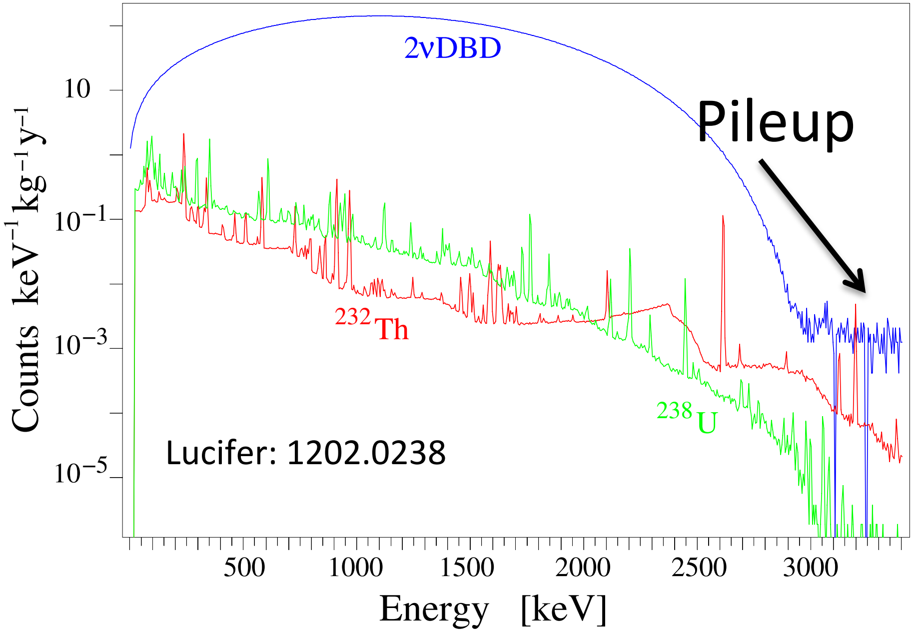


Requirements: Neutrinoless Double Beta Decay

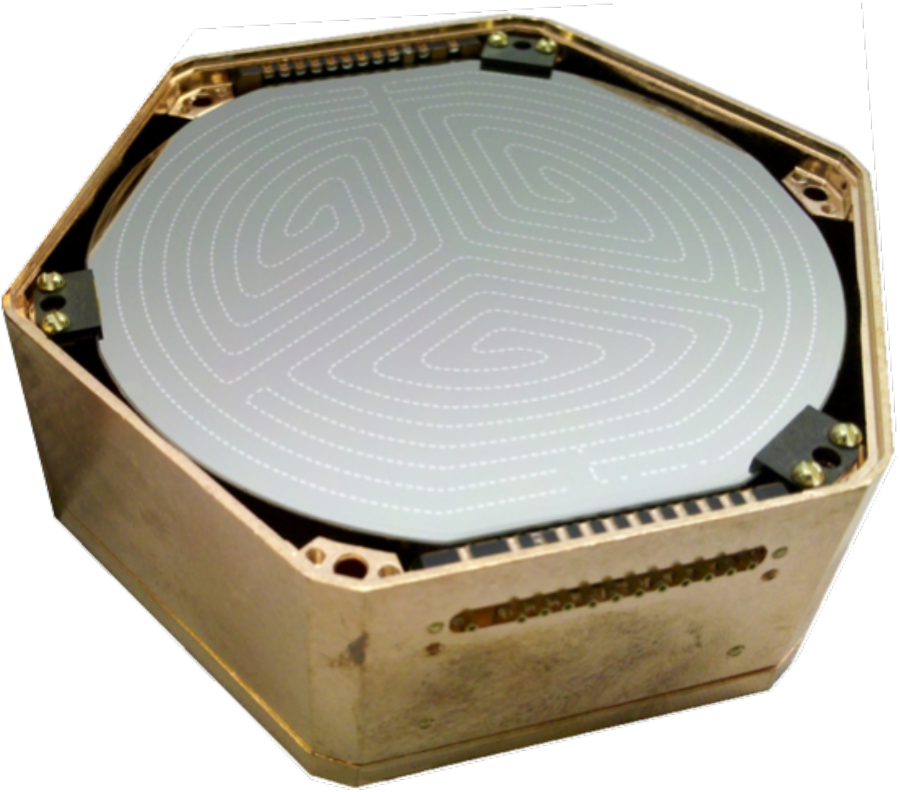
Large area, High QE Photon Detector:

- TeO_2:
  - 100 eV Cherenkov light for ββ events
  - 10 eV Sensitivity
- $ZnMoO_4$
  - 3 keV Scintillation light for ββ events
  - Fast sensor response to minimize pileup
    - ~1us





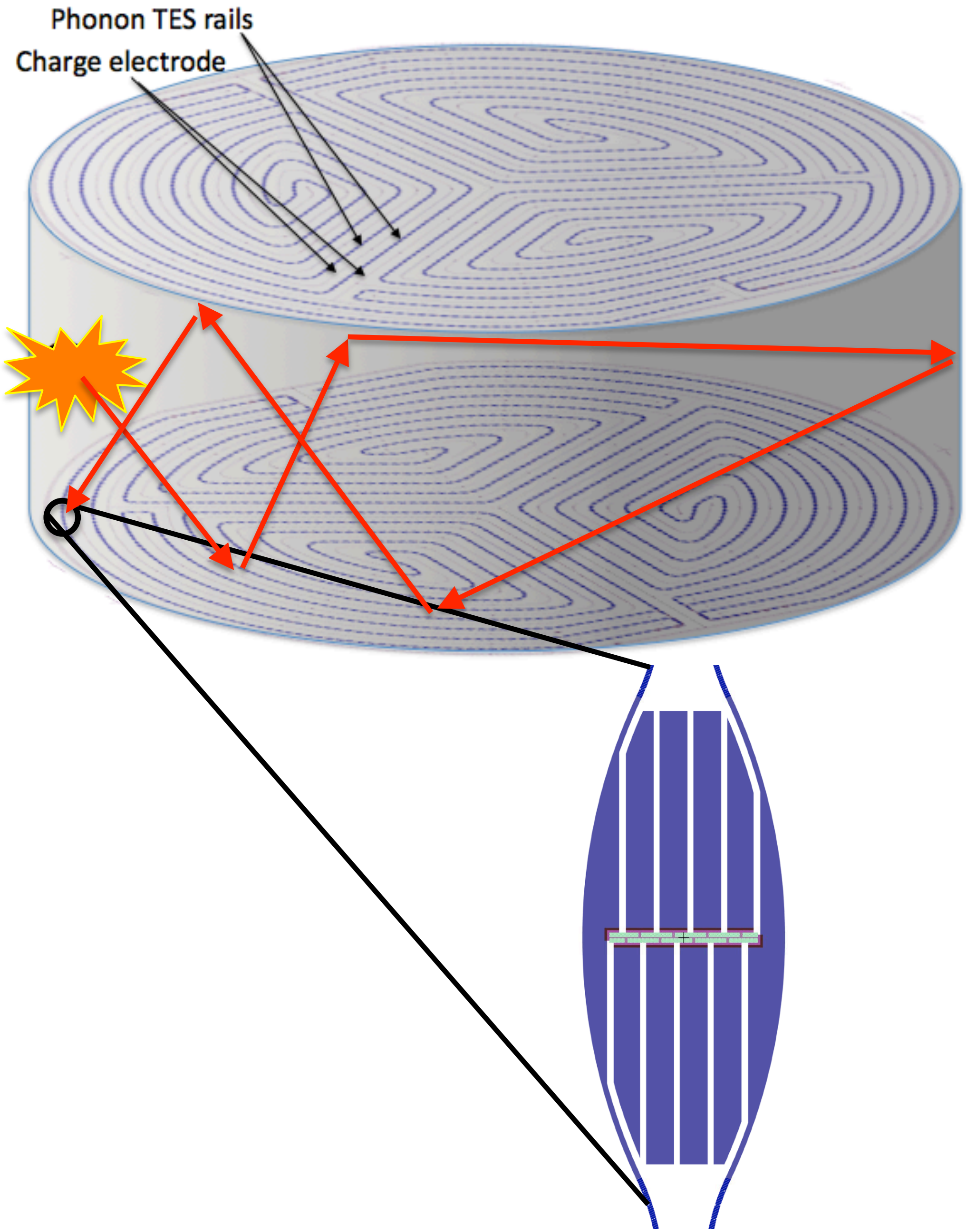
Building a Cryogenic Large Area Photon Detector



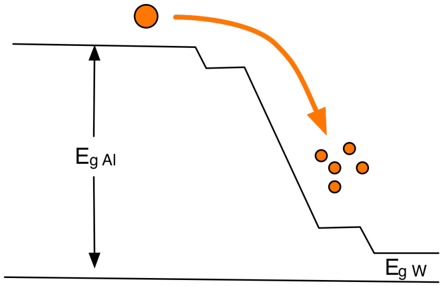
- x5 Larger!
- Much Faster!
- Single Photon Sensitivity
- (Single Roton Sensitivity)

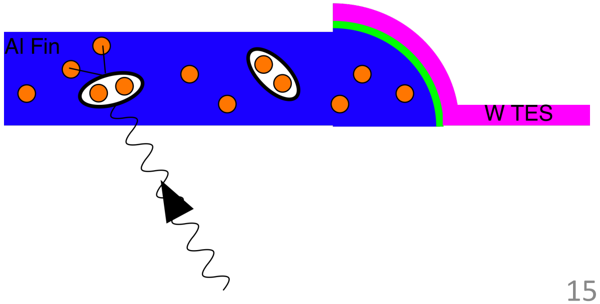
STEAL FROM SUPERCDMS!

Athermal Phonon Sensors

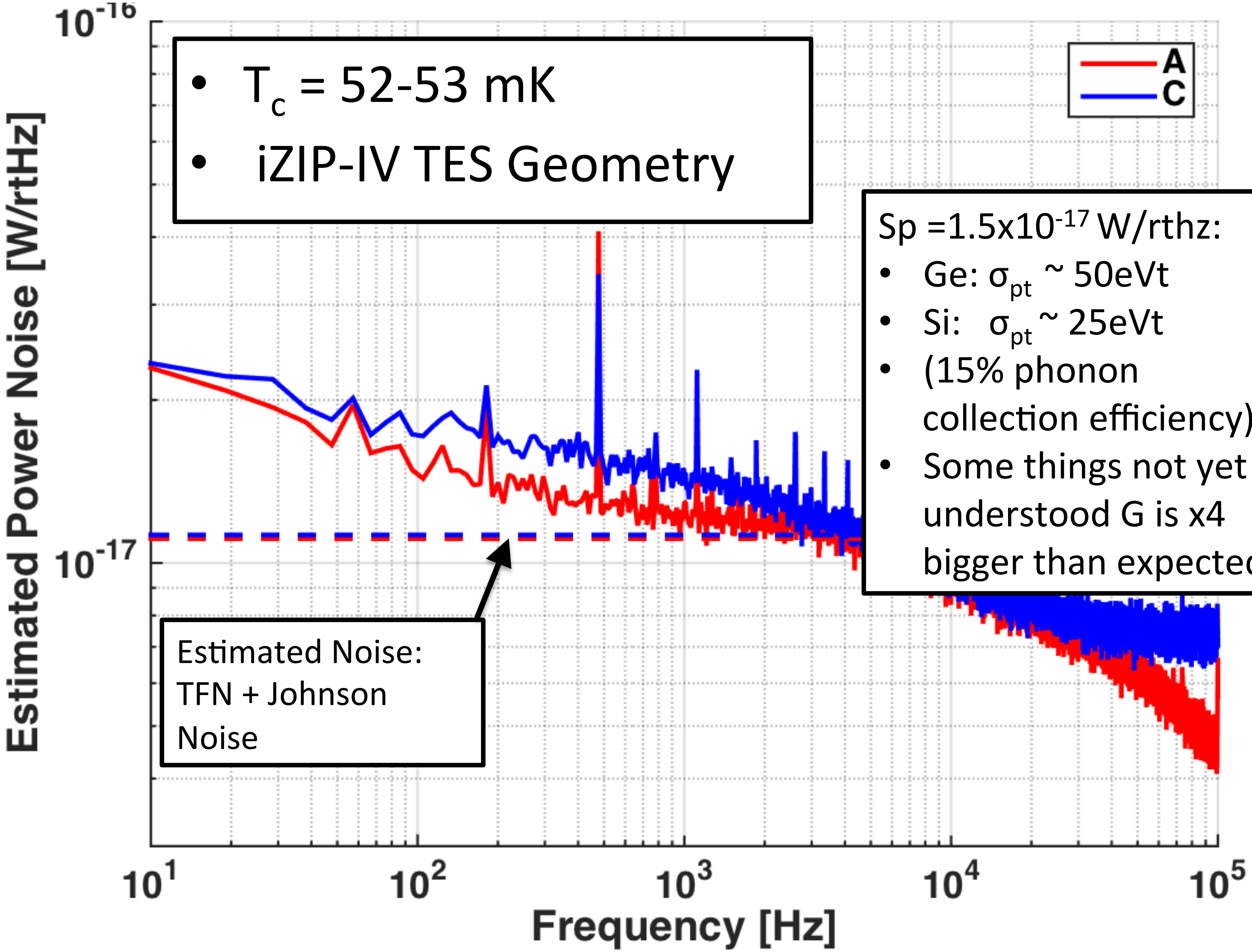


Collect and Concentrate Phonon Energy into W TES (Transition Edge Sensor)





Noise of G23R Test Device



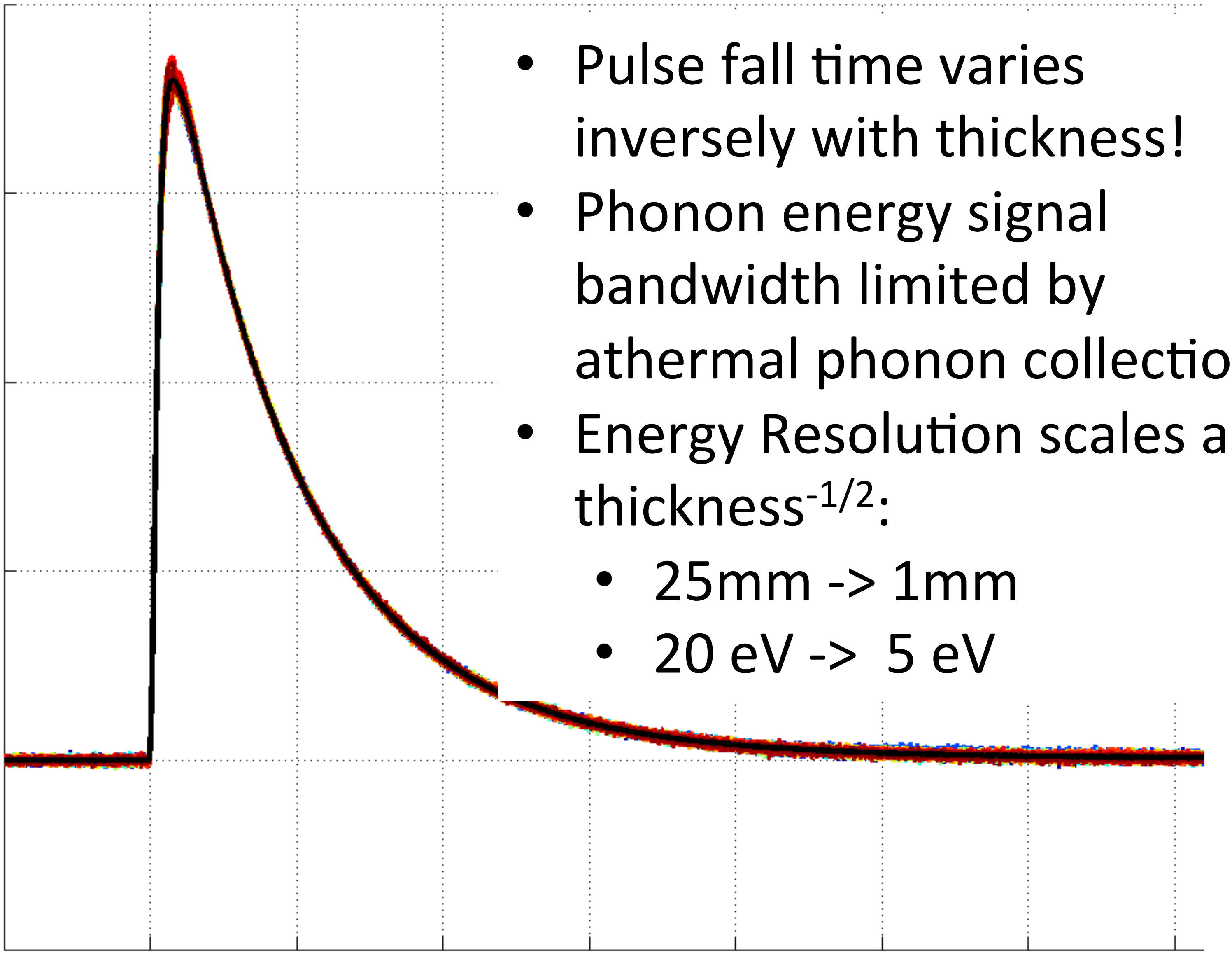
- T_c = 52-53 mK
- iZIP-IV TES Geometry

Sp =1.5x10^{-17} W/rthz:

- Ge: σ_{pt} ~ 50eVt
- Si: σ_{pt} ~ 25eVt
- (15% phonon collection efficiency)
- Some things not yet understood G is x4 bigger than expected

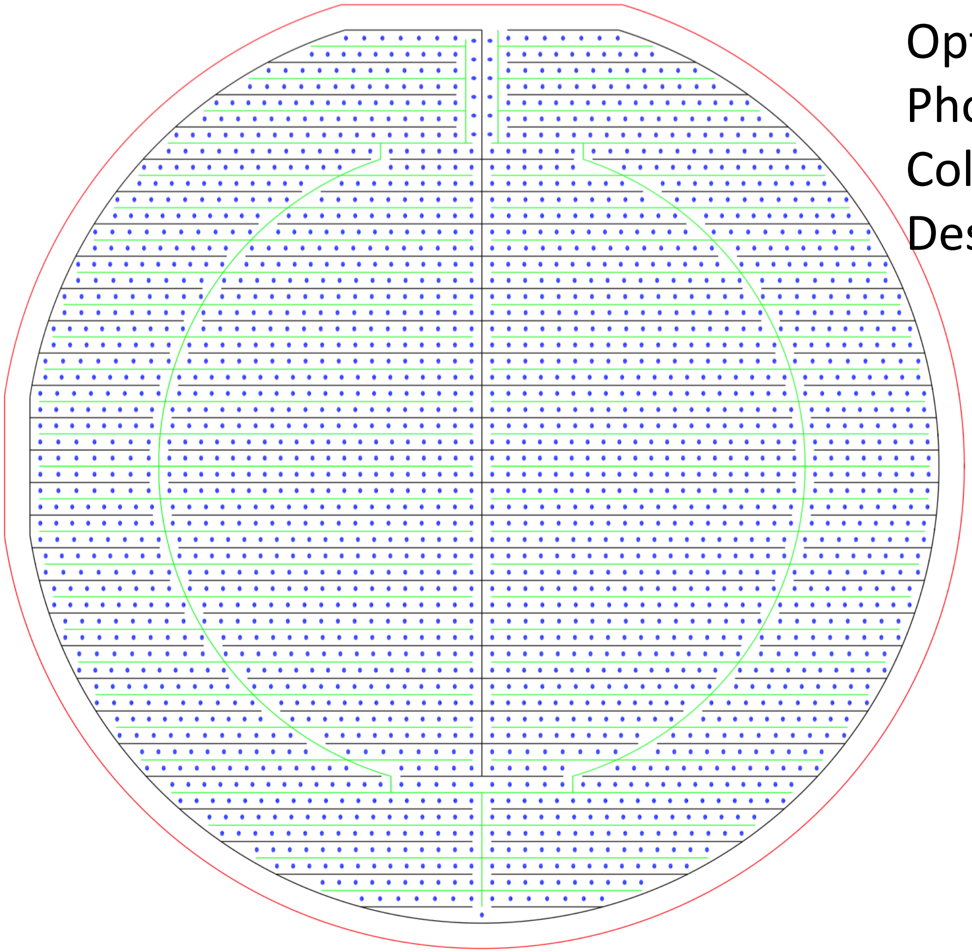
Estimated Noise:
TFN + Johnson
Noise

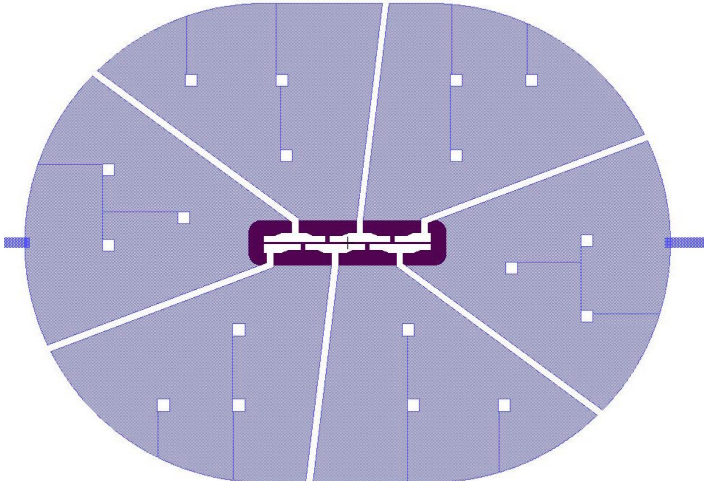
What happens when we shrink the detector?



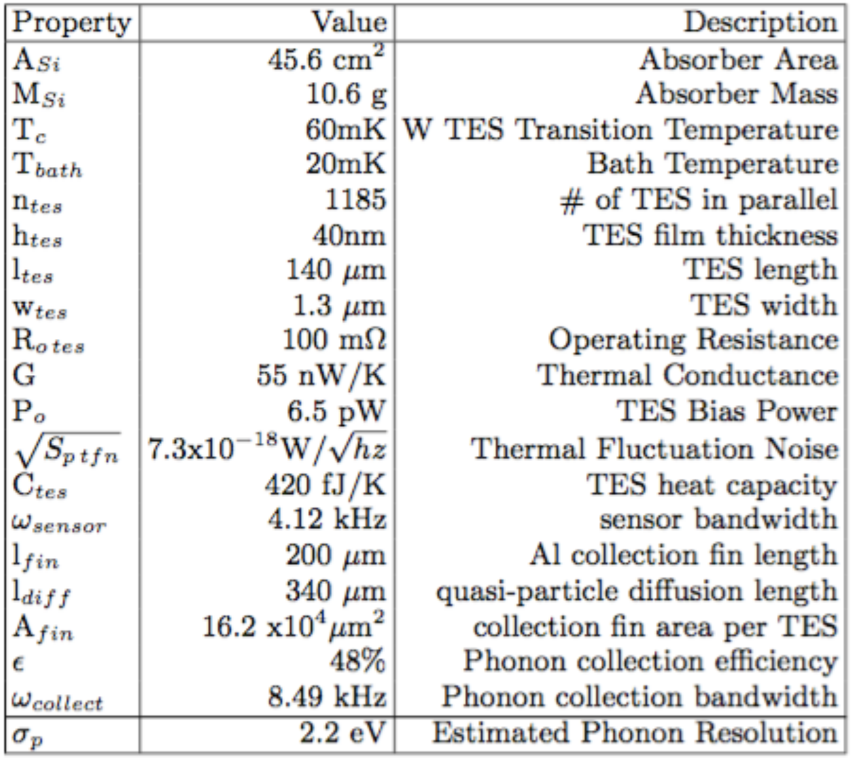
- Pulse fall time varies inversely with thickness!
- Phonon energy signal bandwidth limited by athermal phonon collection
- Energy Resolution scales as thickness$^{-1/2}$:
  - 25mm -> 1mm
  - 20 eV -> 5 eV

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
$\sqrt{S_{ptfn}}$	$7.3\text{x}10^{-18} W/\sqrt{hz}$	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

Lower T_c

- Improve sensitivity
- Smaller bandwidth

Conclusion

- Multiple uses for large area photon/roton detector in Dark Matter and Neutrino Physics
- Stealing should be easy!