Cryogenic Particle Detectors

Instrumentation Frontier Community Meeting (CPAD)
Argonne National Laboratory - Jan 9-11, 2013

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References:
LTD13 (2009) - SLAC http://ltd-13.stanford.edu
LTD14 (2011) - Heidelberg http://ltd-14.uni-hd.de
LTD15 (2013) - Caltech June 24-28, 2013

TES sensors invented by DOE HEP program

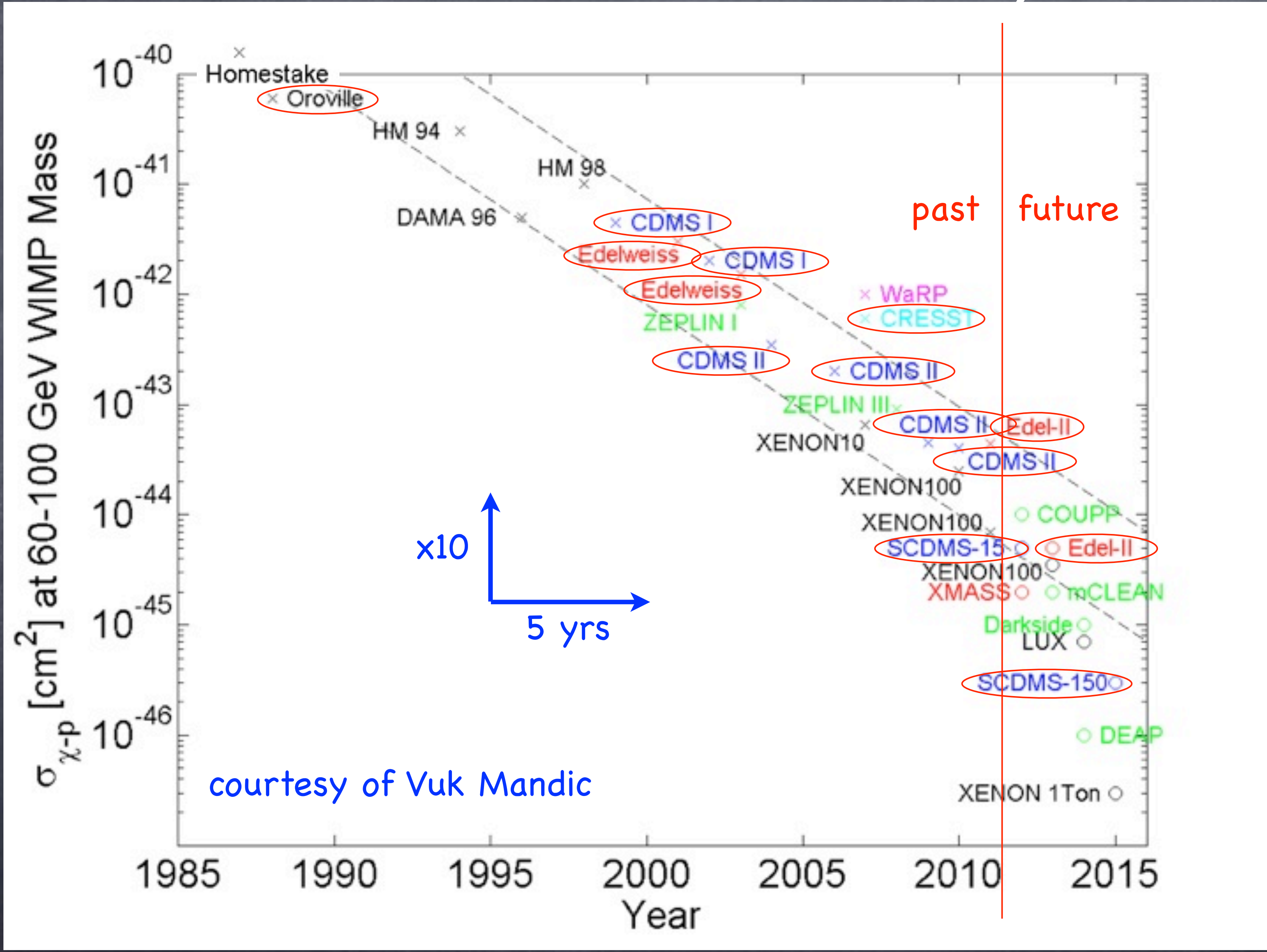
- Original motivation was search for Dark Matter funded by DOE HEP at Stanford + NIST SQUIDs
- Breakthourgh in 1995 when Kent Irwin suggested voltage bias negative feedback
- Rapidly implemented in CDMS Dark Matter
- Rapidly implemented in x-ray astrophysics and materials studies at NIST, Goddard and beyond
- Implemented in CMB by Adrian Lee in 1996
- Implemented in IR-optical-UV sensors in 1998
- DOE HEP should take credit for these spin offs

Original Motivation: Neutrinos & Dark Matter

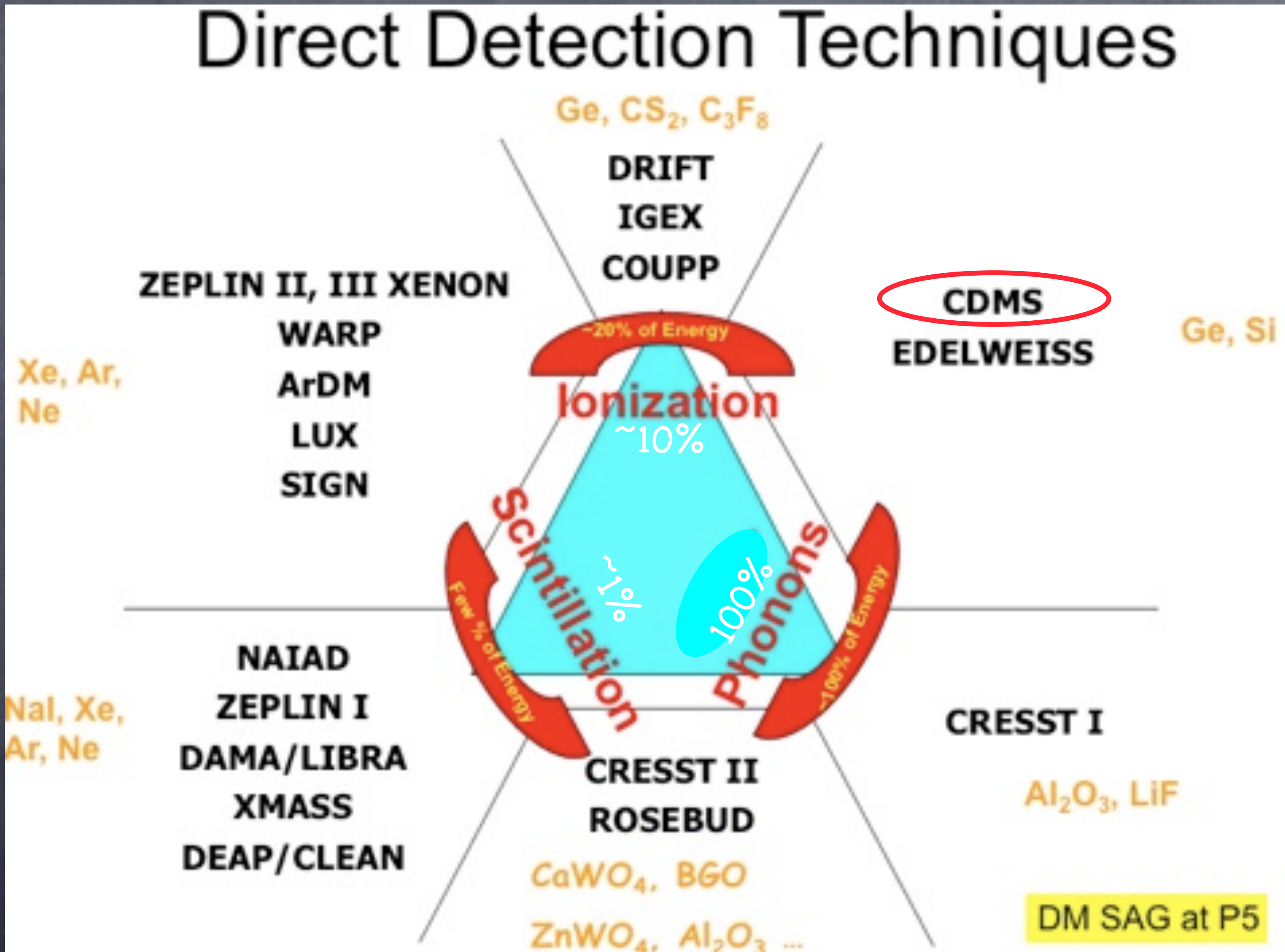
- wanted better resolution for large mass
- now for CMB & IR-Optical-Xray
- for Cosmic Frontier & Intensity Frontier

- Thermal detectors with NTD Ge sensors (T)
- Thermal sensors with doped semiconductors (T)
- Superconducting Tunnel Junctions (E)
- Superconducting Transition Edge Sensors (T)
- Superconducting Kinetic Inductance Devices (E)

WIMP Search Sensitivity



Discrimination strategies



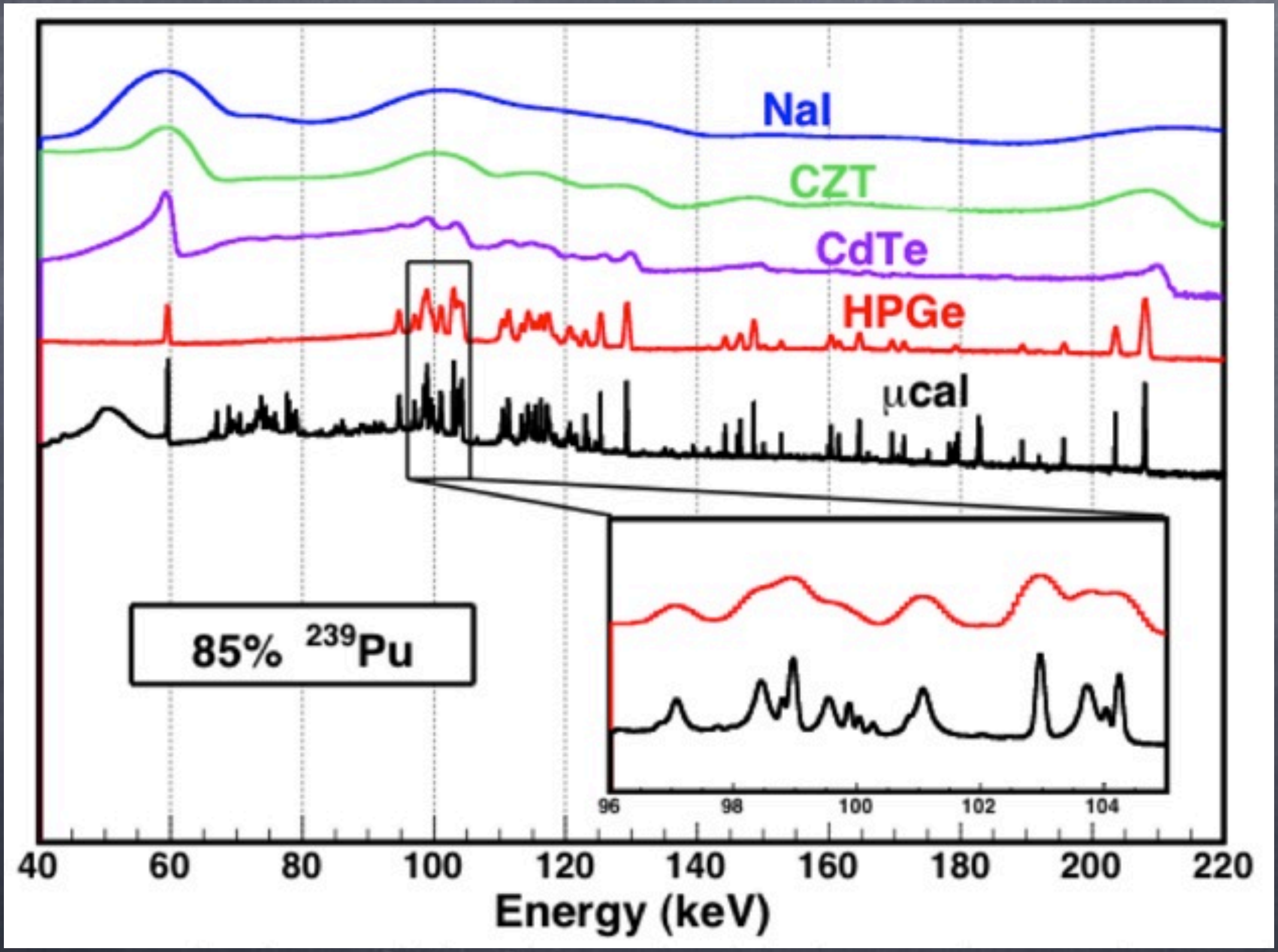
Intrinsic Resolution

- Phonon and Ions (CDMS, EDELWEISS)
- Scintillation and Ions/Phonons (XENON, CRESST)

Quanta	E_0 %	E_{quanta}	N_e/keV	N_N/keV	$Noise_{amp}$	$\Delta E_{e\text{-}FWHM}$	$\Delta E_{N\text{-}FWHM}$
Phonons	100%	1 meV	1000000	1000000	0.1 keV	0.1 keV	0.1 keV
Ions	10%	1 eV	300	100	1 keV	1 keV	3 keV
Photons	1%	10 eV	10	1	0.01 keV	1 keV	10 keV

NaI -> HPGe -> μcalorimeters

Cryogenic Sensors For High-precision Safeguards Measurements weblink



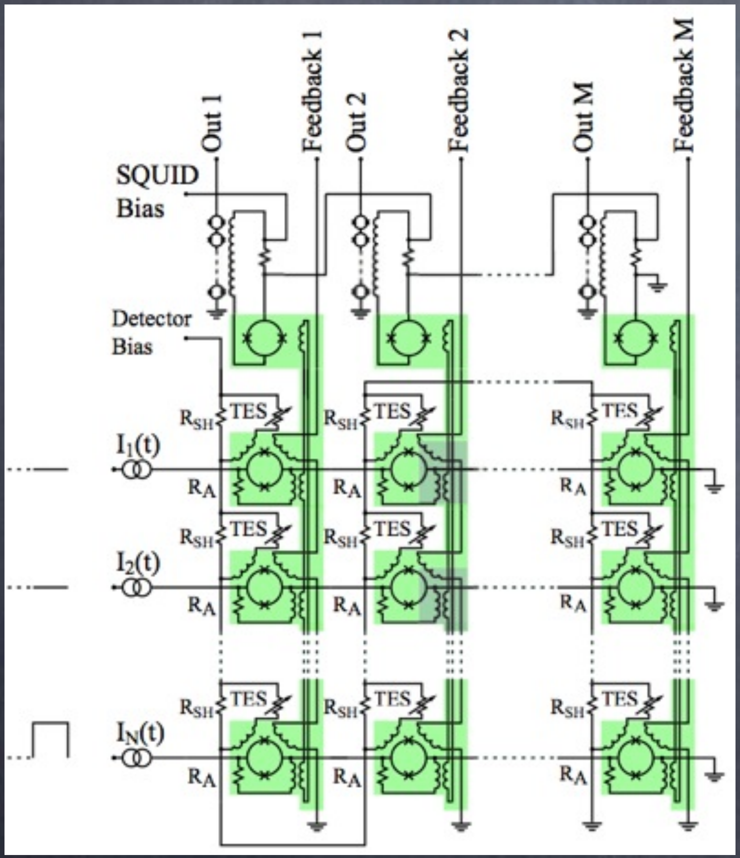
Scope of Cryogenic Detectors

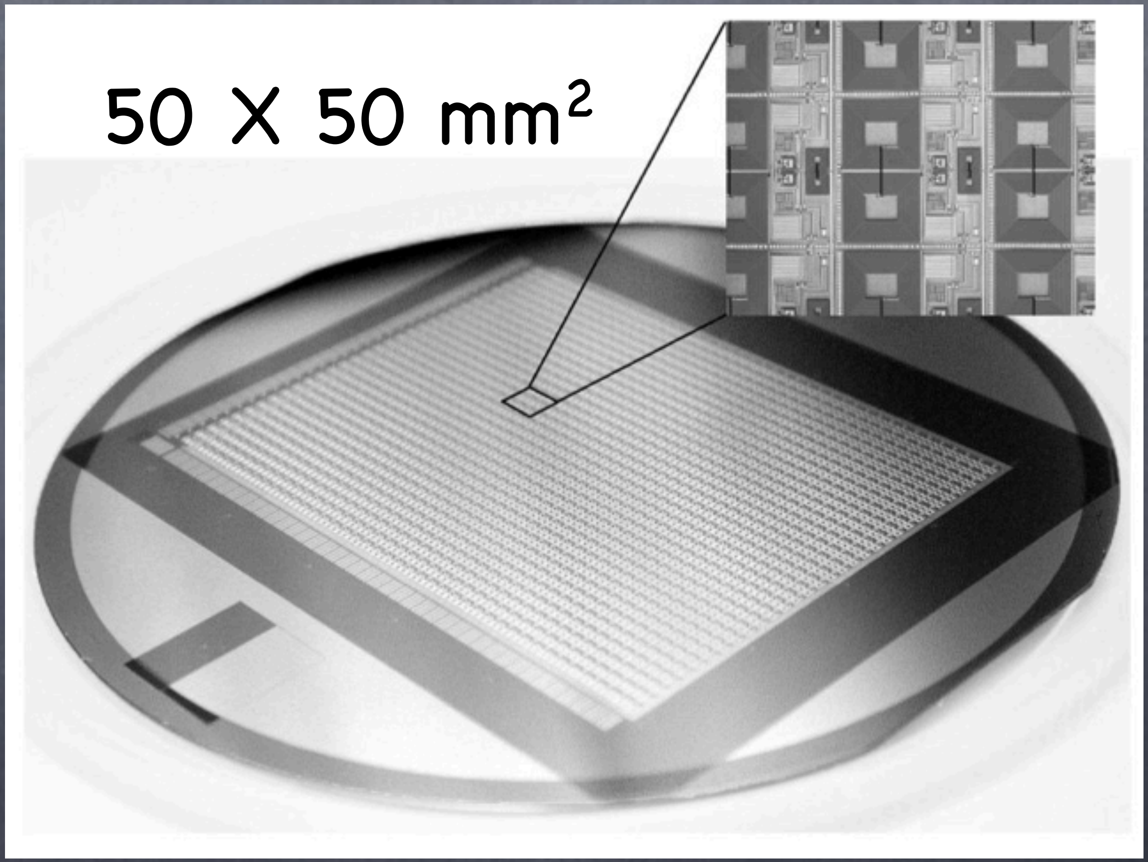
- Sub-Kelvin Sensor types
  - Transition Edge Sensors (T)
  - Kinetic Inductance Detectors (E)
  - Metallic Magnetic Calorimeters (T)
  - Novel detection techniques
- Technologies
  - Micro-fabrication with superconducting materials
  - Cryogenics using dilution refrigerators and ADRs
  - Multiplexing, SQUIDs, readout, & data analysis
  - Particle absorbers & antennas: physics & design considerations

Large TES arrays progressing

1,280-pixel SQUID TDM multiplexer for the SCUBA-2 weblink

- MUX chip has 32 columns each with 40 multiplexed SQUIDs

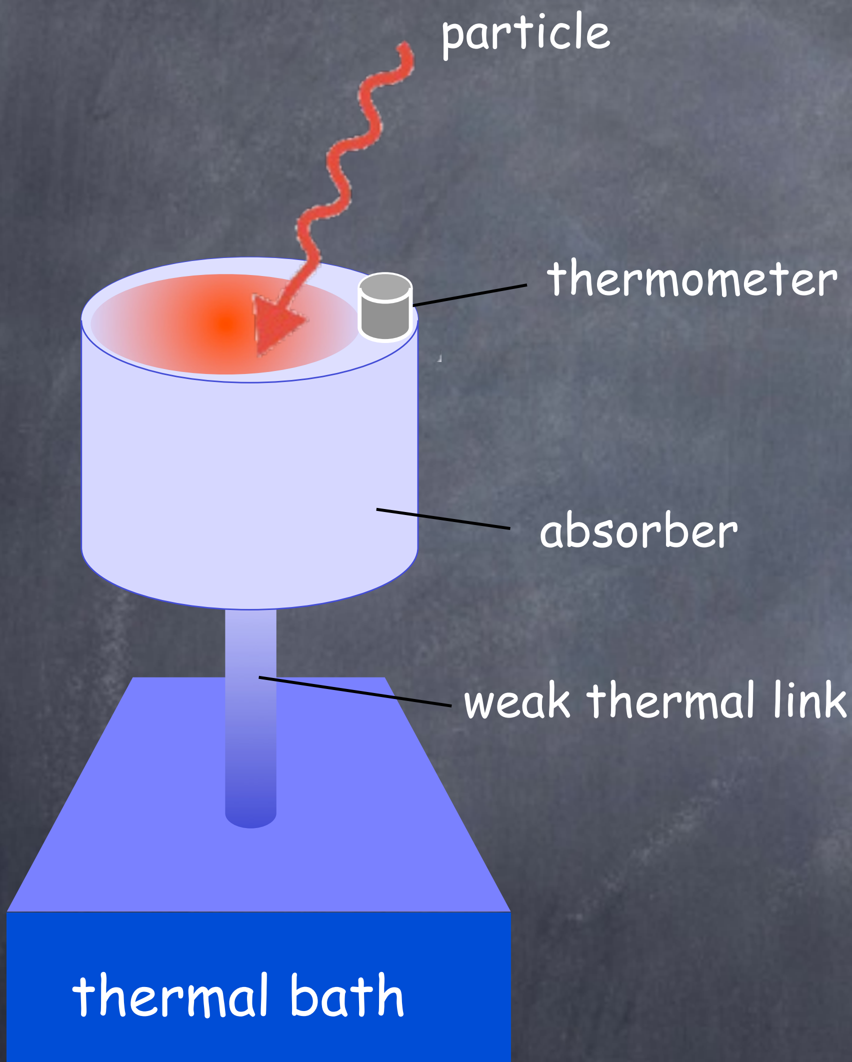


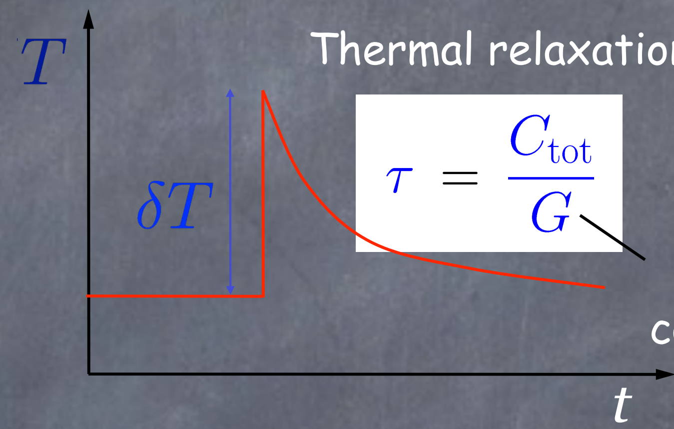


Detectors and Physics

- Detector Physics
  - Insulators - Debye heat capacity ~T^3 at low temperature
  - Conductors - Fermi liquid theory ~T at low temperature
  - Semiconductors - electrons & holes ~ 1eV excitation
  - Superconductors - quasiparticles ~ 1meV excitation
  - Magnetism - paramagnetism and diamagnetism
- Science applications
  - Neutrino mass experiments (IF)
  - Dark matter searches (CF)
  - Alpha & beta spectroscopy, mass spectroscopy, heavy ions, and neutrons
  - X-ray & gamma spectroscopy in atomic, nuclear, astrophysics & other fields
  - UV-optical-IR single photon detection
  - Bolometers in mm / sub-mm wave for astrophysics, THz applications (CF)

Calorimeter Principle





Thermal relaxation time:

$$\tau = \frac{C_{\rm tot}}{G}$$

Thermal conductance

$$\delta T = \frac{E}{C_{\rm tot}}$$

$C_{\rm tot}$: phonons

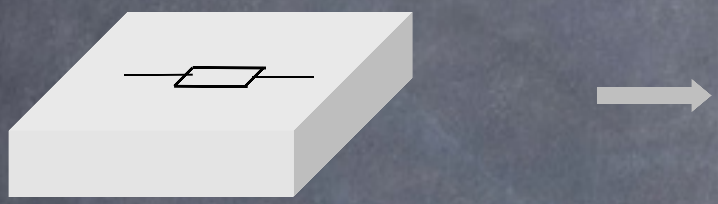
electrons

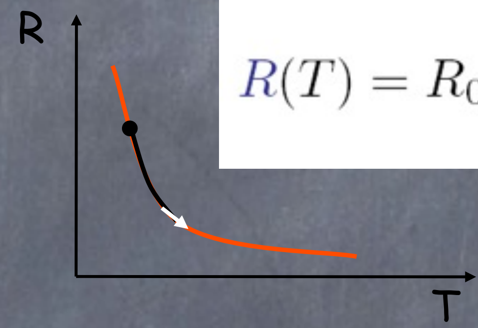
spins

tunneling states

quasi particles

Semiconducting Thermistors

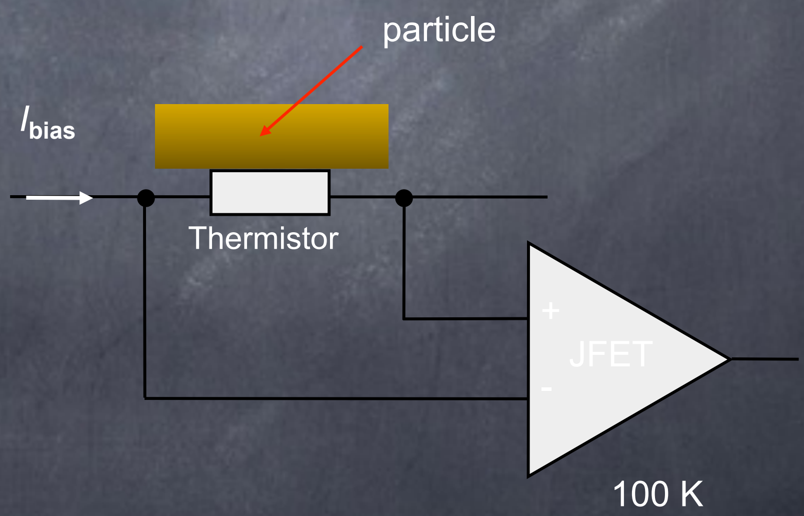




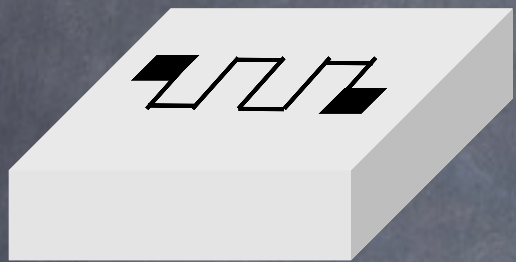
$$R(T) = R_0 \exp\left(\frac{T_0}{T}\right)^{1/2}$$

Si - ion-implanted (P,B)
Ge NTD (Neutron-Transmutation-Doped)

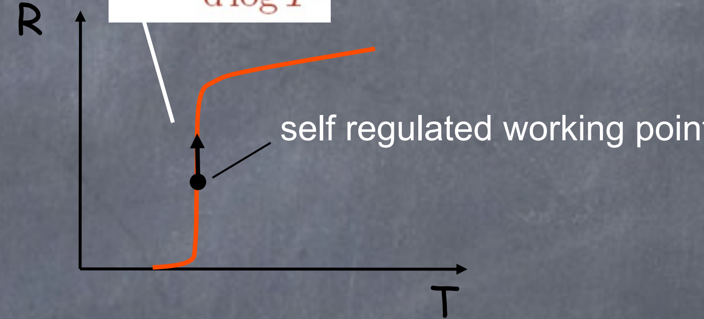
High impedance device



Superconducting Transition Edge Sensor (TES)



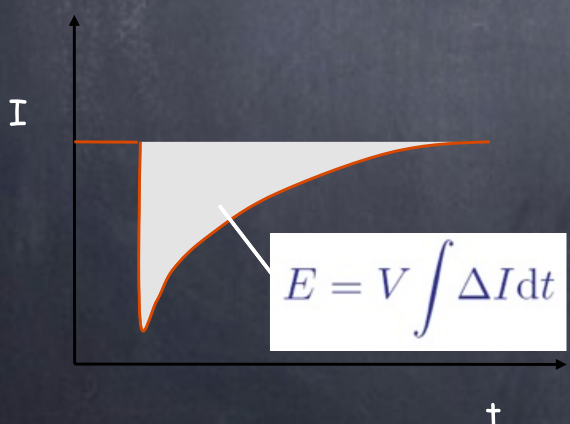
$$\alpha = \frac{\mathrm{d}\log R}{\mathrm{d}\log T}$$



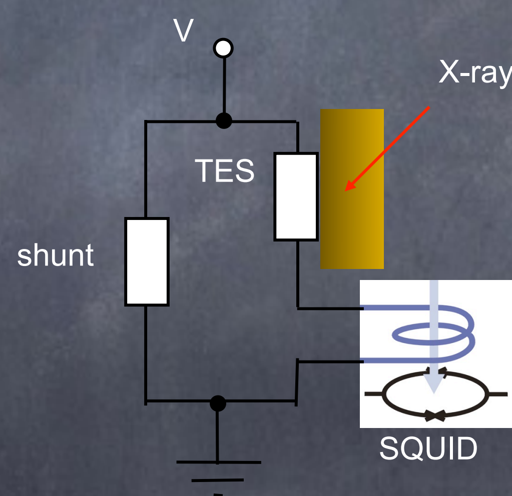
Materials Mo/Cu
Ir/Au
W

Electro-thermal feedback

K. D. Irwin, Appl. Phys. Lett. **66**, 1945 (1995)



$$E = V \int \Delta I \mathrm{d}t$$



heat input:

→ R_{TES} goes up

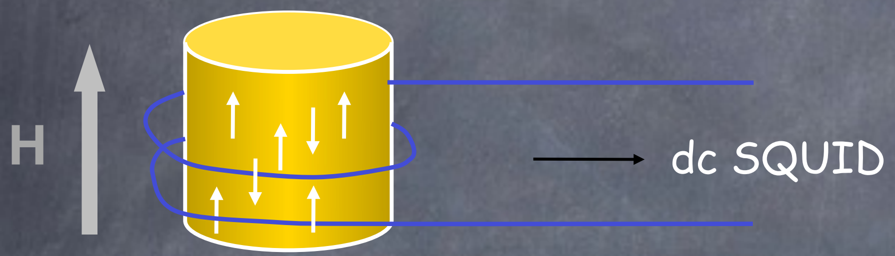
→ joule heating decreases

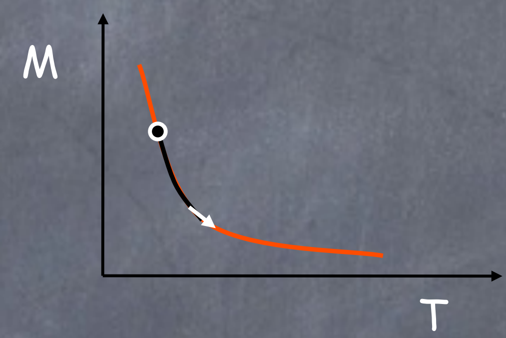
fast response time

$$\tau_{\mathrm{eff}} = \frac{\tau}{1 + \alpha/n}$$

$$G \propto T^n$$

Metallic Magnetic Calorimeter (MMC)





$$\delta M = \frac{\partial M}{\partial T}\delta T = \frac{\partial M}{\partial T}\frac{E_\gamma}{C_{\mathrm{tot}}}$$

Au:Er
Au:Yb
Ag:Er
Bi_2Te_3:Er
PbTe:Er
LaB_6:Er

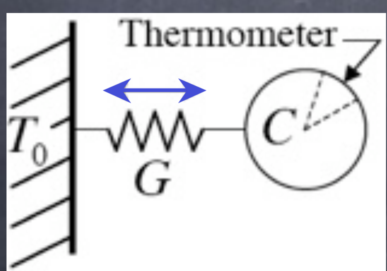
main differences to resistive calorimeters:

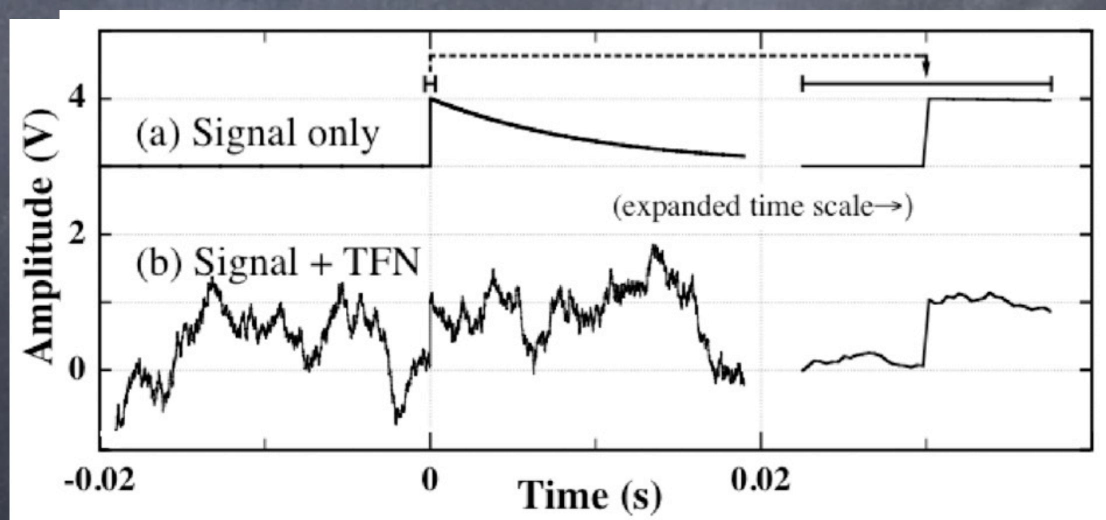
non-contact readout

no dissipation due to readout current

So what is intrinsic resolution for thermal detectors ?

- Heat capacity C at temperature T has energy CT
- The average energy per carrier ~kT
- So there are N ~ CT / kT carriers
- So statistical thermal noise $(\Delta E)_{rms} \sim kT\sqrt{N} = \sqrt{kT^2C}$
- But we can detect smaller signal as shown

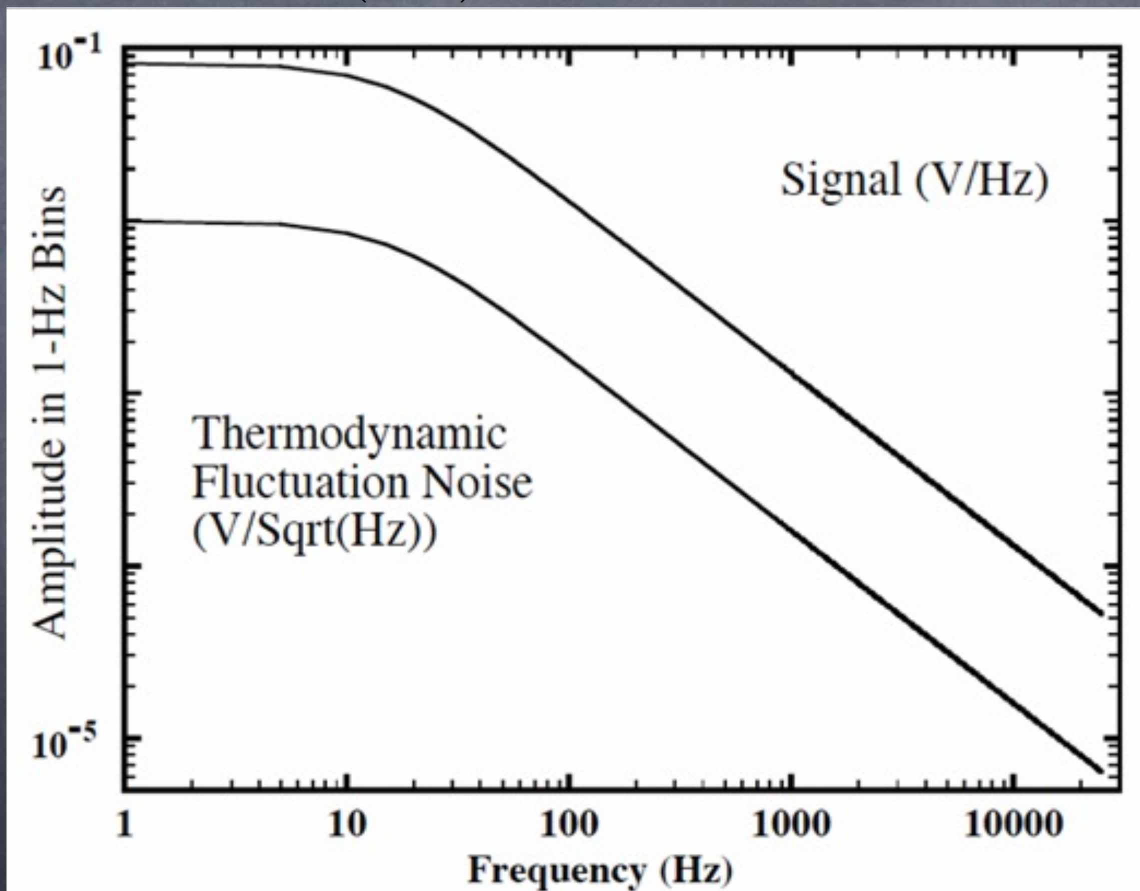




Signal and Noise

- Energy fluctuation is not energy resolution

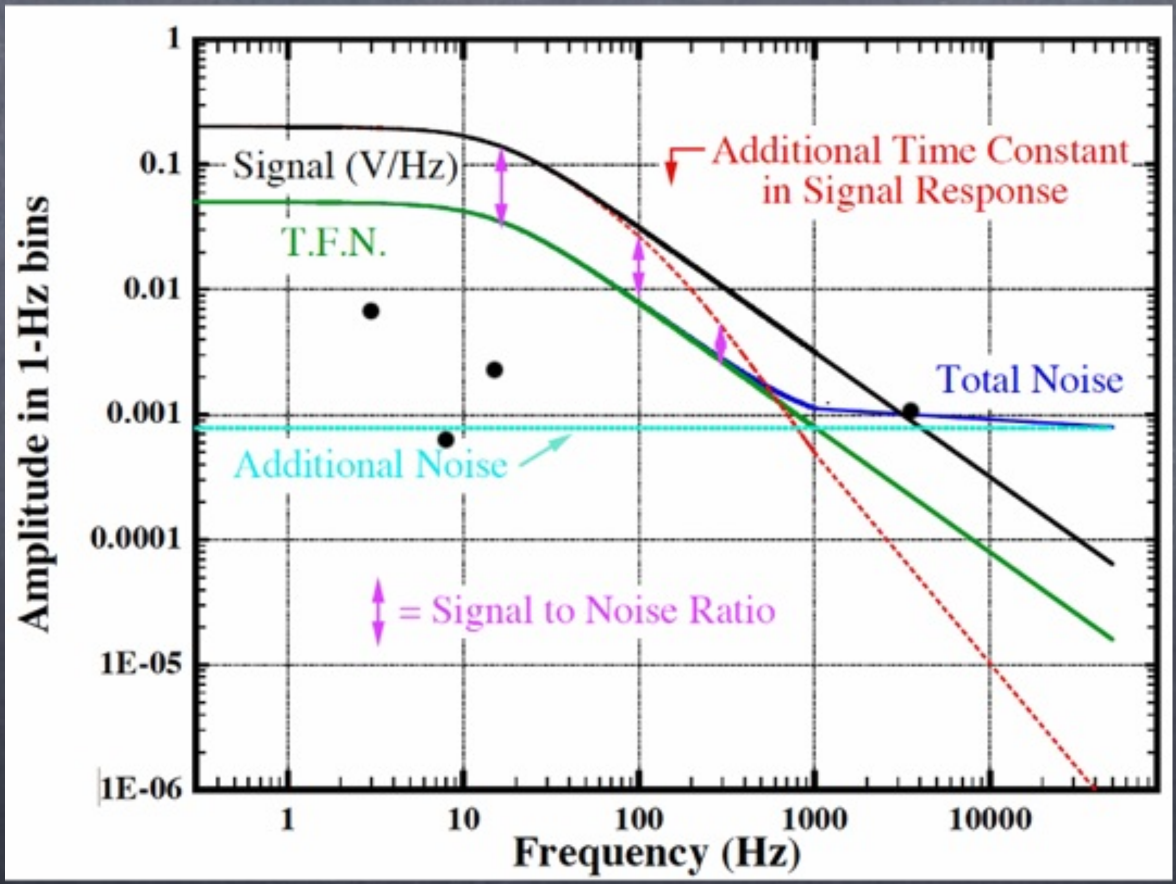
$$\Delta E = \left(\frac{2\pi f_c}{\Delta f}\right)^{1/2} \sqrt{k_B T^2 C}; \quad f_c = \frac{G}{2\pi C}$$



Signal & Noise

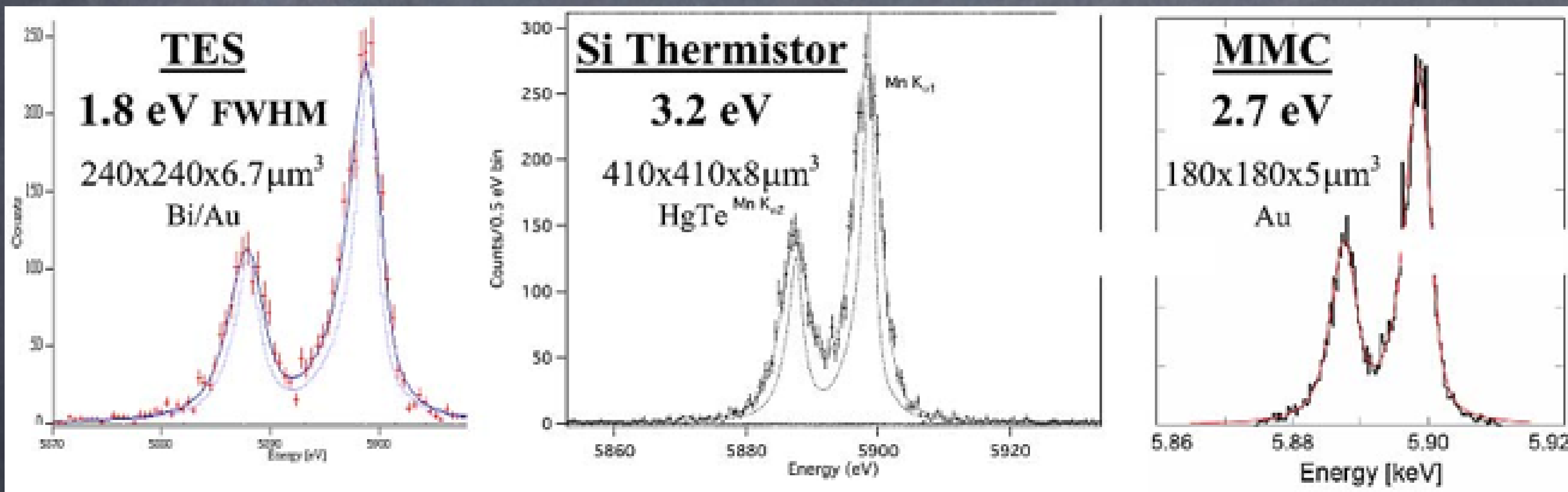
- But finite thermalization time and amp noise so Δf limited

$$\Delta E = \left(\frac{2\pi f_c}{\Delta f}\right)^{1/2} \sqrt{k_B T^2 C}; \quad f_c = \frac{G}{2\pi C}$$



Many ways to measure temperature ($K\alpha 1$ / $K\alpha 2$ for ^{55}Fe at 6 keV)

- Transition Edge Sensors (TES)
- Doped semiconductors - Si and NTD Ge
- Doped paramagnetism - MMC



$$(\Delta E)_{rms} = \sqrt{k_B T^2 C}\,\frac{(40)^{1/4}}{\sqrt{\alpha}}$$

$$(\Delta E)_{rms} = \sqrt{k_B T^2 C}\,\frac{4}{\sqrt{\alpha}}$$

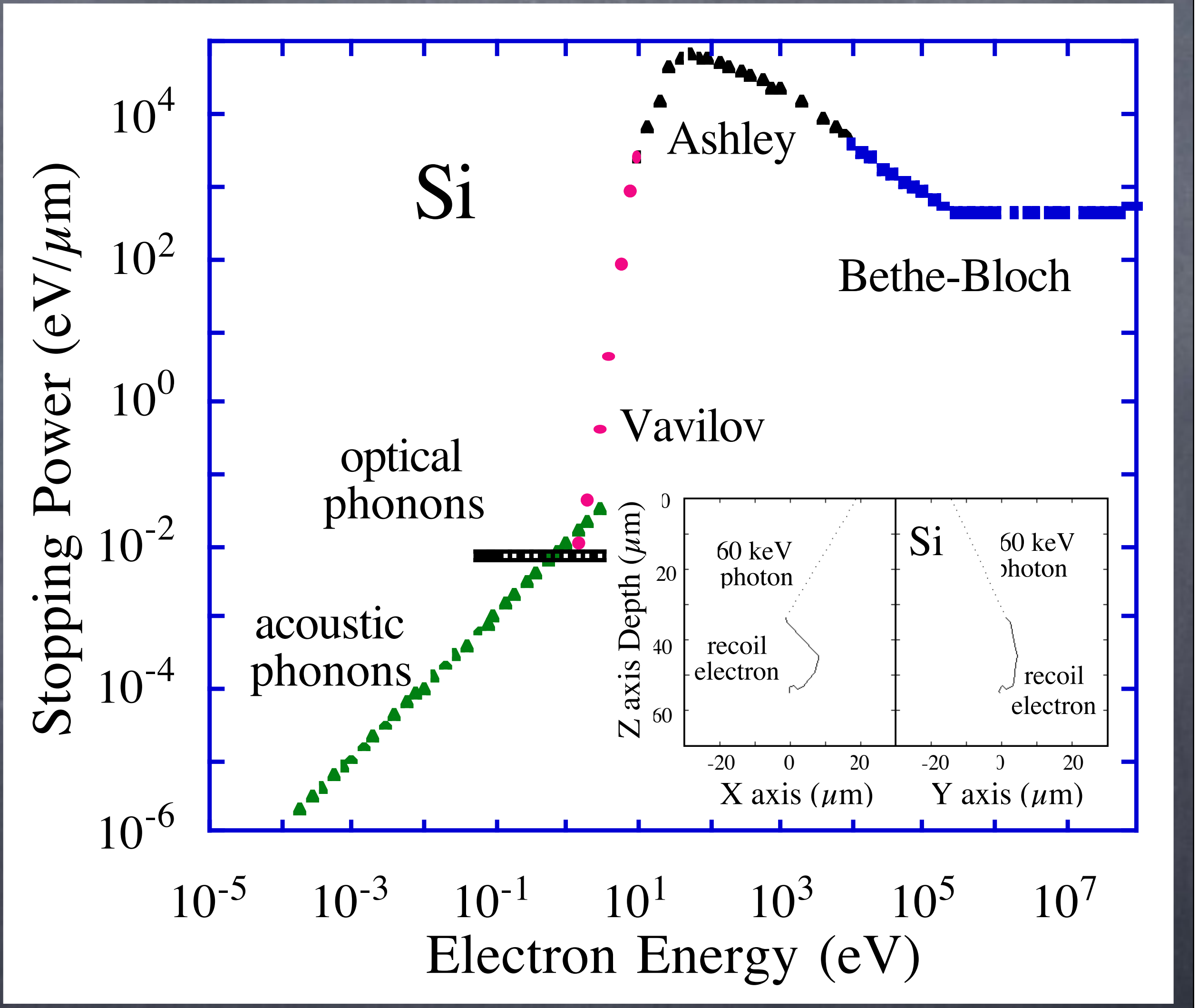
$$(\Delta E)_{rms} = \sqrt{k_B T^2 C}\,\sqrt{8}\left(\frac{\tau_0}{\tau_1}\right)^{1/4}$$

Non-equilibrium versus Equilibrium Detectors

- Non-equilibrium detectors have an energy gap which is much larger than kT and allows long-lived excitations which we count.
  - photons from scintillator (~2% E_{total}) - phototubes to count photons
  - e-h in a semiconductor (~30% E_{total}) - measure total charge
  - quasiparticle (e's) in superconductor (~40% E_{total}) - measure STJ, KID or TES
- Equilibrium detectors are weakly coupled to thermal bath so thermal equilibrium is reached
  - Insulators with Debye heat capacity $C_V \sim N\,k\left(12\pi^4/5\right)\left(T/T_D\right)^3$
  - Conductors with Fermi heat capacity $C_V = \underbrace{\gamma T}_{\text{electrons}} + \underbrace{\alpha T^3}_{\text{phonons}}$

Radiation interacting with Matter, e.g. Si

- Electron energy loss processes:
  - For $E_K > 10$ eV loss e-e collisions
  - For $E_{gap} < E_K < 10$ eV loss through e-h pair production
  - For $E_{opt} < E_K < E_{gap}$ optical phonon loss
  - For $E_s < E_K < E_{opt}$ acoustic phonon loss
  - For $E_K < E_s$ no loss, but in E-field continual acoustic phonon emission with v_{drift}

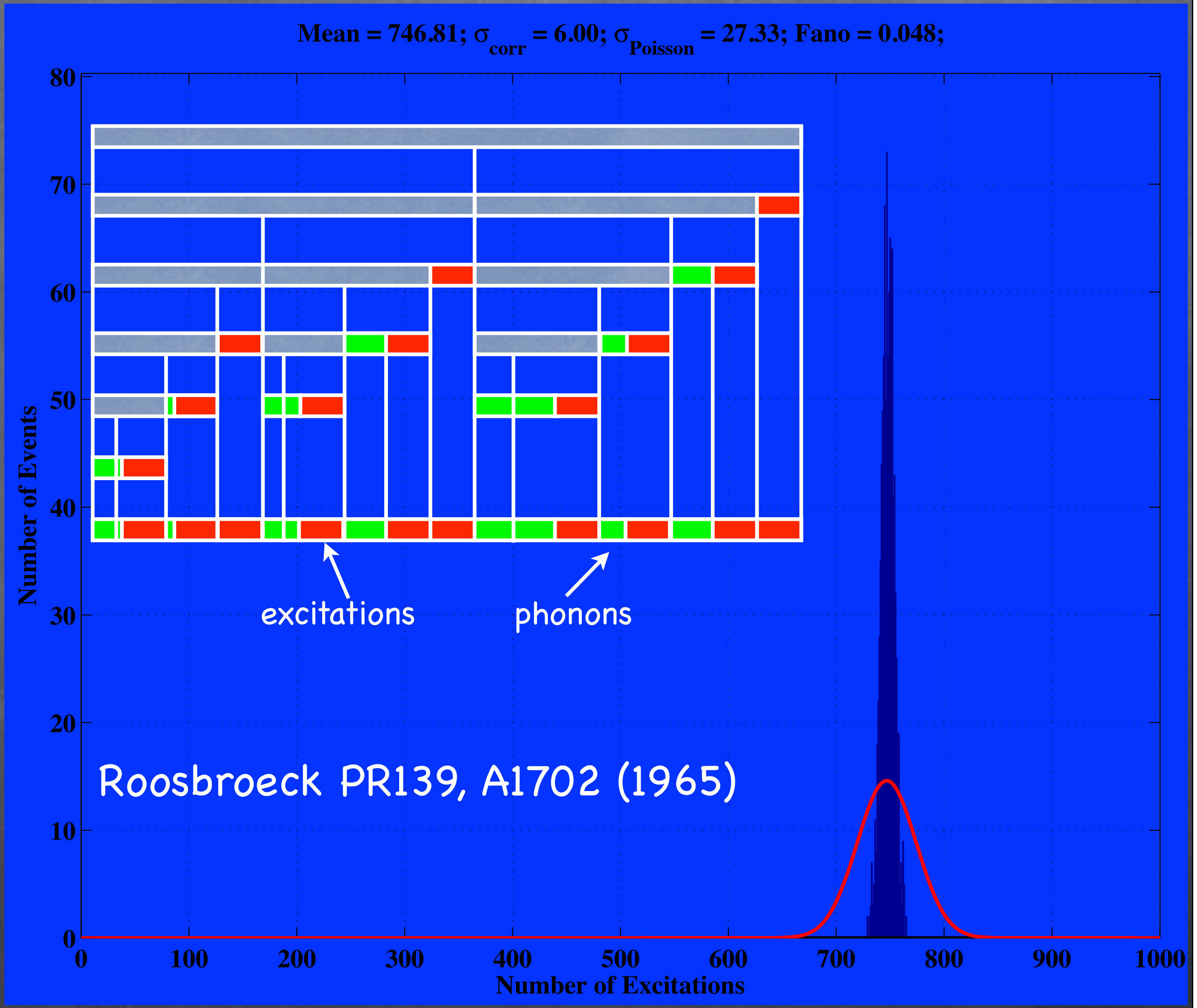


Semiconductor diodes

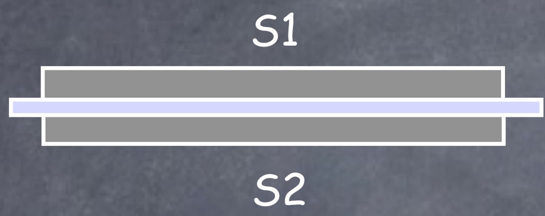
- Along track of primary electron cloud of e-h
  - some recombine close to track and are lost
  - the rest separate in the E-field and move to opposite electrodes
- Excellent x-ray and gamma spectrometers
  - Si diodes operate at 300K (gap 1.2 eV)
  - Ge diodes operate at 77K (gap 0.7 eV)
- Energy resolution given by counting statistics
  - Number of e-h pairs $N \neq E/E_{gap}$ but $N = E/\varepsilon$ where $\varepsilon_{Si} = 3.7\ \mathrm{eV}$ and $\varepsilon_{Ge} = 3.0\ \mathrm{eV}$
  - Also find $(\Delta E)_{rms} \neq \varepsilon\sqrt{N} = \sqrt{\varepsilon E}$ but better $(\Delta E)_{rms} = \sqrt{\varepsilon F E}$ where the Fano factor $F \approx 0.1$ thus $(\Delta E)_{rms} = \sqrt{\varepsilon F E} < \sqrt{E_{gap} E} < \sqrt{\varepsilon E}$
  - Obtain $(\Delta E)_{FWHM} = 120\ \mathrm{eV}\ @\ 6\ \mathrm{keV}$ for Si diodes

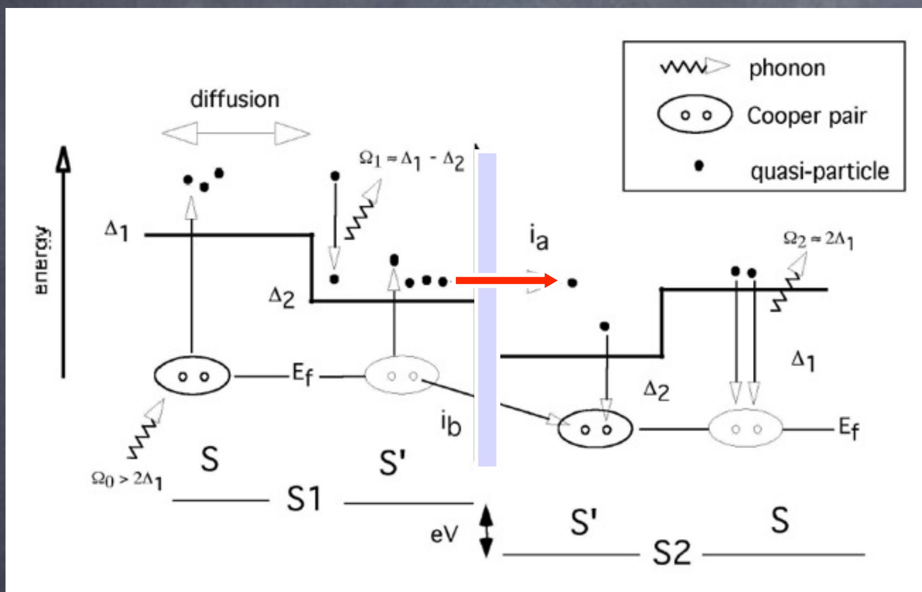
Fano factor 'crazy carpentry'

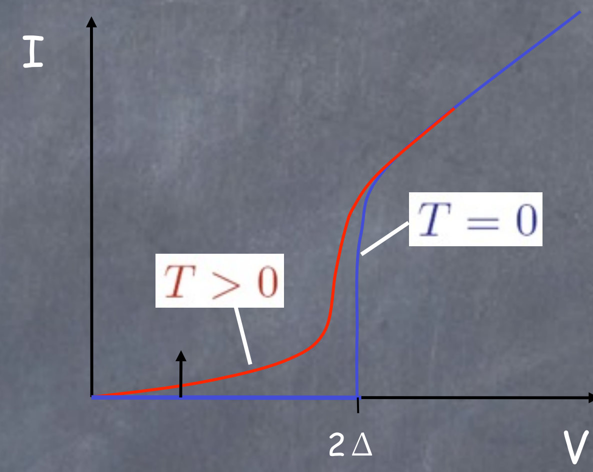
- $F = Var_{corr}/Var_{Poisson}$
- F always < 1 due to correlations forced by energy conservation.
- Simple example has one type of excitation and equal probability for any energy partition at each step in cascade.



Superconducting Tunnel Junction (STJ)







$$N_{\mathrm{excess}} = E_0/\Delta$$

thermal background $\Delta/k_{\mathrm{B}}T \ll 1$

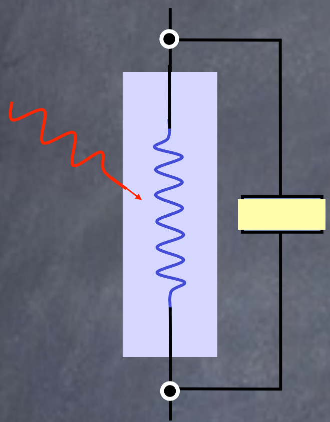
$$N_{\mathrm{therm}}(T) = 2N_0\sqrt{\frac{2\pi\,\Delta}{k_{\mathrm{B}}T_{\mathrm{c}}}}\mathrm{e}^{-\Delta/k_{\mathrm{B}}T}$$

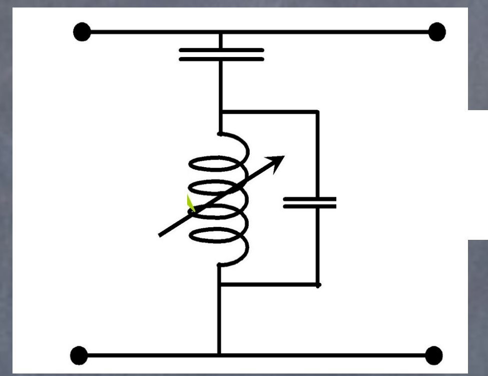
non-thermal - fast detector

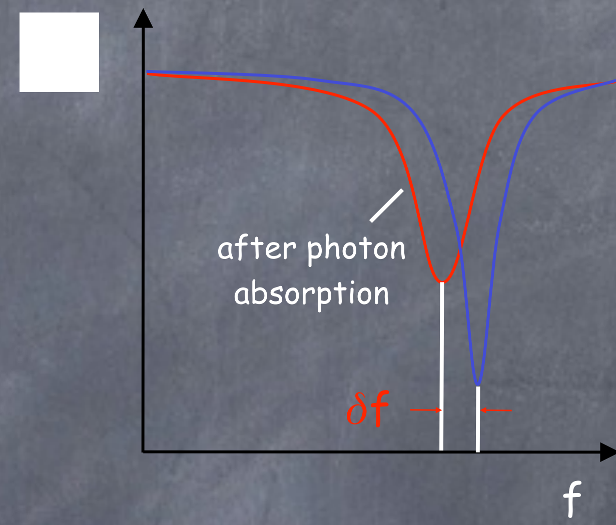
$\rightarrow$ $T < 0.1T_{\mathrm{c}}$

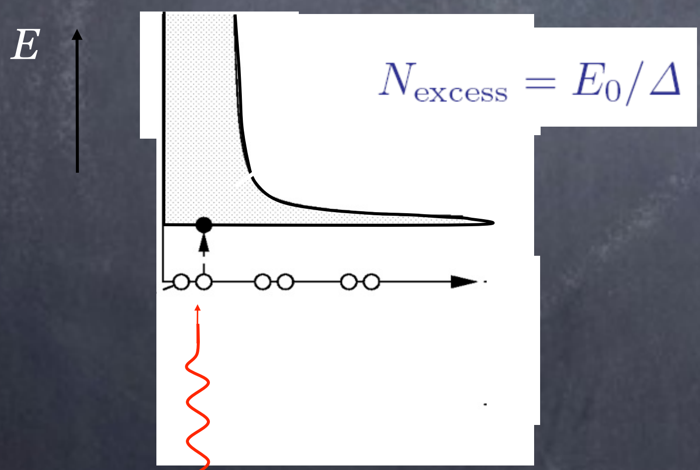
specially suited for low-energy photons

Kinetic Inductance Detectors: KID







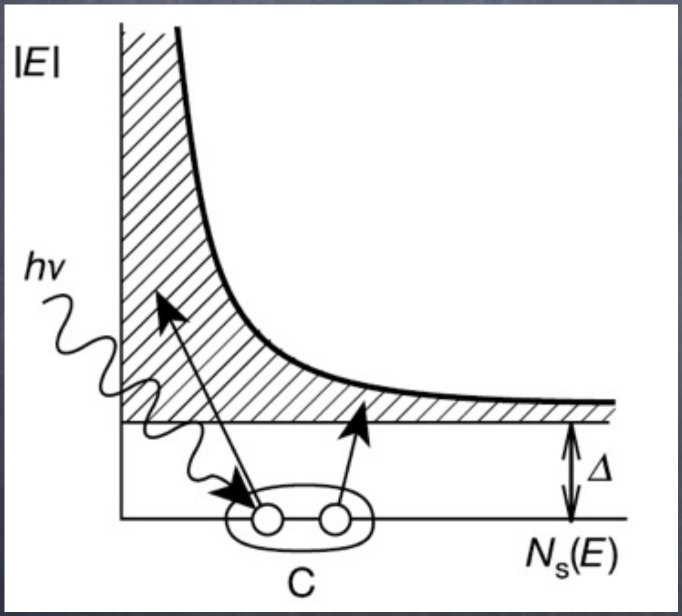


non-thermal fast detector

well suited for frequency domain multiplexing

Quasiparticles

- Quasiparticles are electron-like excitations in superconductors from breaking Cooper pairs



Day JPL

Element	T_c(K)	E_{gap}(meV)	$(E_{Si}/E_{gap})^{1/2}$
Nb	9.5	1.47	28
Ta	4.47	0.7	41
Al	1.14	0.17	84
Ti	0.39	0.06	140
Hf	0.13	0.02	245

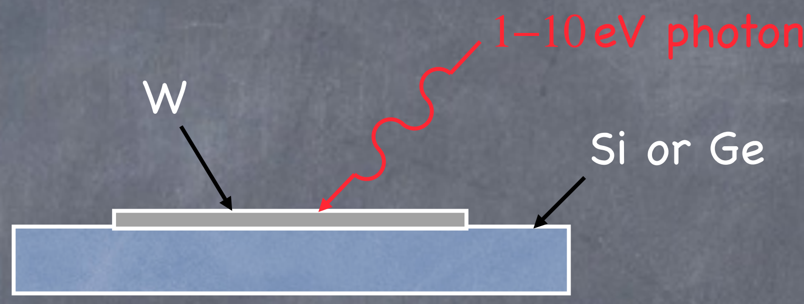
TES versus STJ or KID

- Intrinsic resolutions are similar because non-equilibrium detectors have excitations given by gap which is ~kT_c whereas thermal detectors have quanta with average ~kT_c

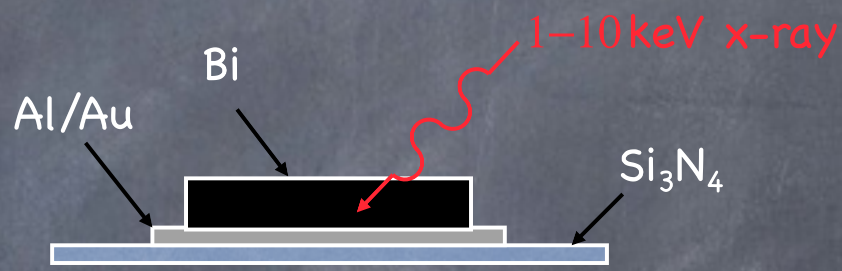
TES	STJ or L_K
$\Delta E_{FWHM} = 2.355\sqrt{4 k_B T_e^2 C \sqrt{\frac{n}{2}}/\alpha}$	$\Delta E_{FWHM} \approx 2.355\sqrt{E\,\varepsilon_0 (F+G)}$
$n=5$ electron - phonon coupling $T_e \approx T_c$ and $E_{sat} \approx T_c\, C/\alpha$	$\varepsilon_0 \approx 1.7\Delta \approx 1.7(1.76\,kT_c) = 3kT_c$ $F \approx 0.2$ is Fano; $G \approx 0-2$ (tunneling noise)
$\Delta E_{FWHM} = 2.355\sqrt{6.4\, k_B T_c E_{sat}}$	$\Delta E_{FWHM} \approx 2.355\sqrt{0.6kT_c E}$
$\Delta E_{FWHM} \approx 15\ \mathrm{meV}\left(\frac{E_{sat}}{1\ \mathrm{eV}}\right)^{1/2}\left(\frac{T_c}{70\ \mathrm{mK}}\right)^{1/2}$	$\Delta E_{FWHM} \approx 18\ \mathrm{meV}\left(\frac{E}{1\ \mathrm{eV}}\right)^{1/2}\left(\frac{T_c}{1\ \mathrm{K}}\right)^{1/2}$

Types of TES Detectors

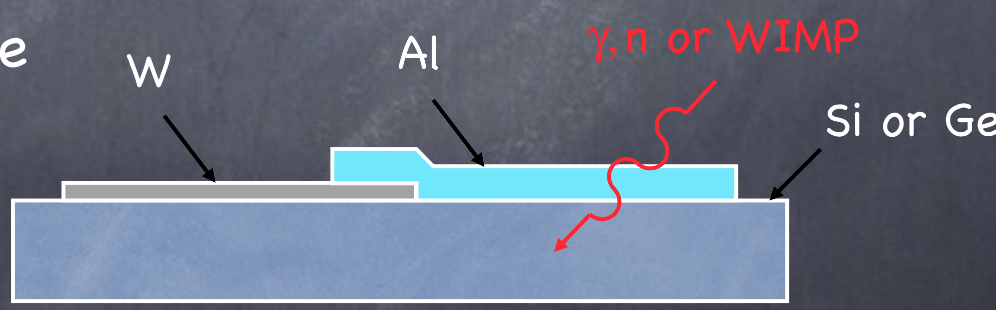
- Direct absorption of photon into TES
(e. g., optical photon detectors)



- Photon absorber in electrical contact with TES
(e. g., x-ray detectors)



- Large mass absorbers generate phonons which are converted into quasiparticles which diffuse to the TES
(e. g., dark matter detectors)

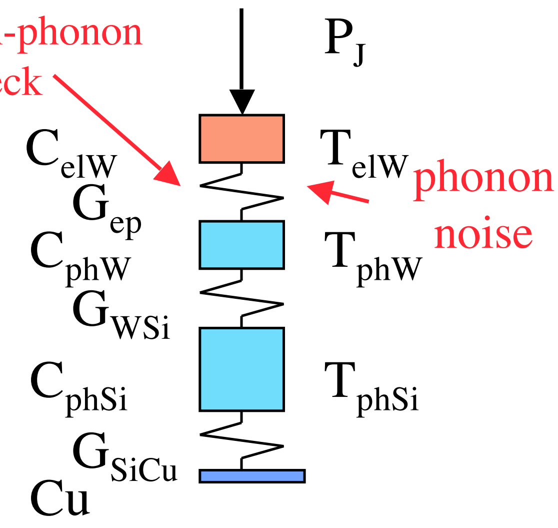


TES Thermal Model

- Electrothermal Feedback
  - Voltage bias intrinsically stable

$$C\frac{dT}{dt} = \frac{V_B^2}{R} - \Sigma\left(T_e^n - T_{ph}^n\right), \quad n = 5$$

electron-phonon
bottleneck



  - Fast response

$$\tau_{etf} = \frac{\tau_0}{1 + \alpha/n}, \quad \tau_0 = \frac{C}{g}, \quad g = n\Sigma T_e^{n-1}$$

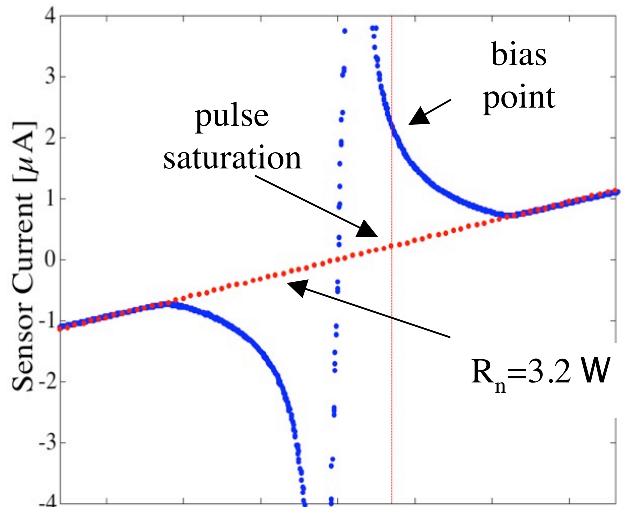
  - High Sensitivity

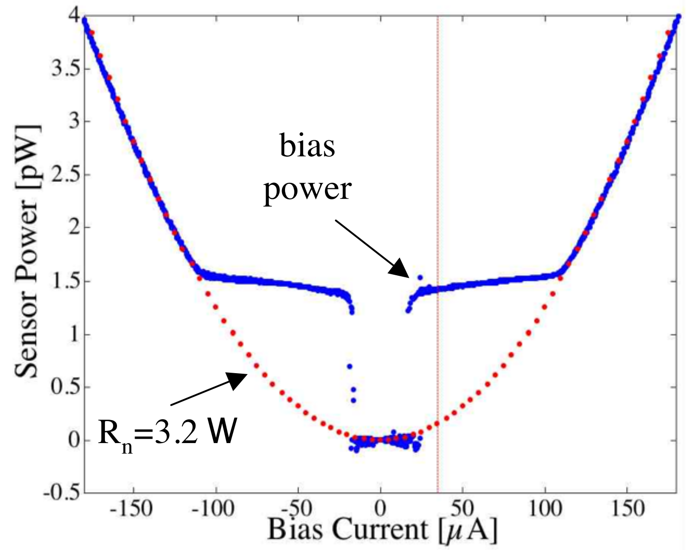
$$\Delta E_{FWHM} = 2.355\sqrt{4\,k_B\,T_e^2\,C\sqrt{\tfrac{n}{2}}/\alpha} = 2.355\sqrt{4k_B T_e P_J \tau_{etf}\sqrt{\tfrac{n}{2}}}$$

For $E_{sat}\left(\sim C\,T_e/\alpha = P_J\tau_{etf}\right) = 10$ keV then $\Delta E_{FWHM} = 1.1$ eV

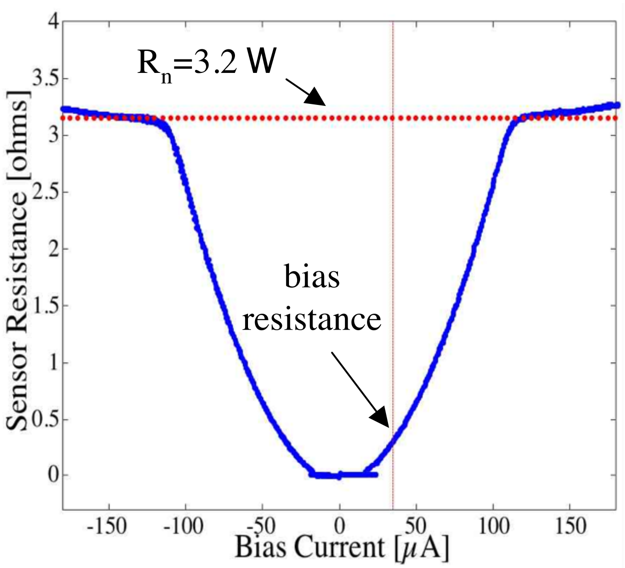
For $E_{sat}\left(\sim C\,T_e/\alpha = P_J\tau_{etf}\right) = 1$ eV then $\Delta E_{FWHM} = 11$ meV

Lower threshold for better resolution

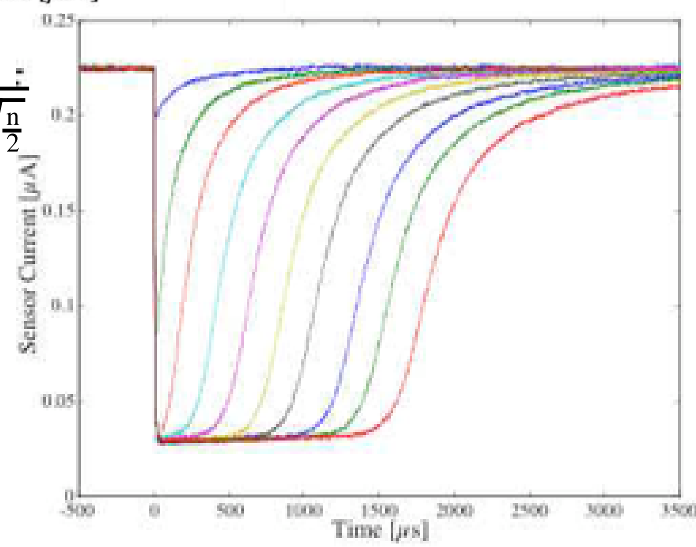




But, must deal with pulse shape variation with energy

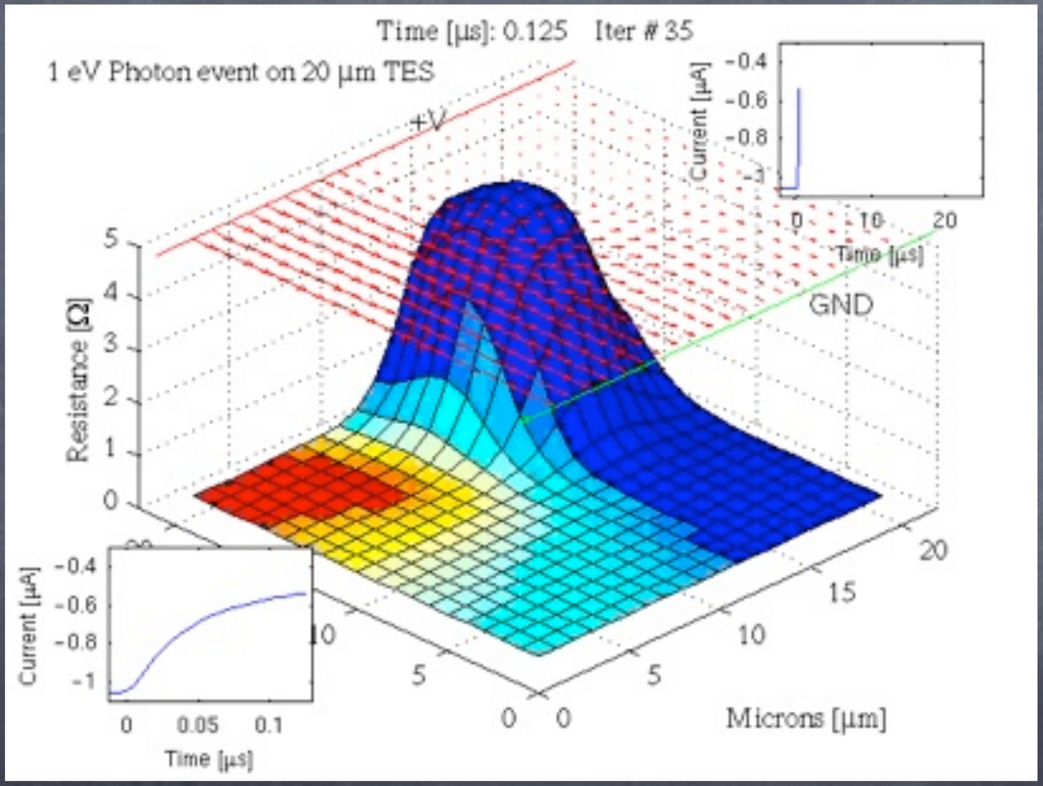


$$\Delta E_{FWHM} =$$
$$2.355\sqrt{4\,k_B\,T_e\,P_0\,\tau_{etf}\,\sqrt{\tfrac{n}{2}}}$$
$$\text{for } E < E_{sat} = P_0\,\tau_{etf}$$
$$\Delta E_{FWHM} \approx$$
$$2.355\sqrt{4\,k_B\,T_e\,E\sqrt{\tfrac{n}{2}}}$$
$$\text{for } E > E_{sat}$$



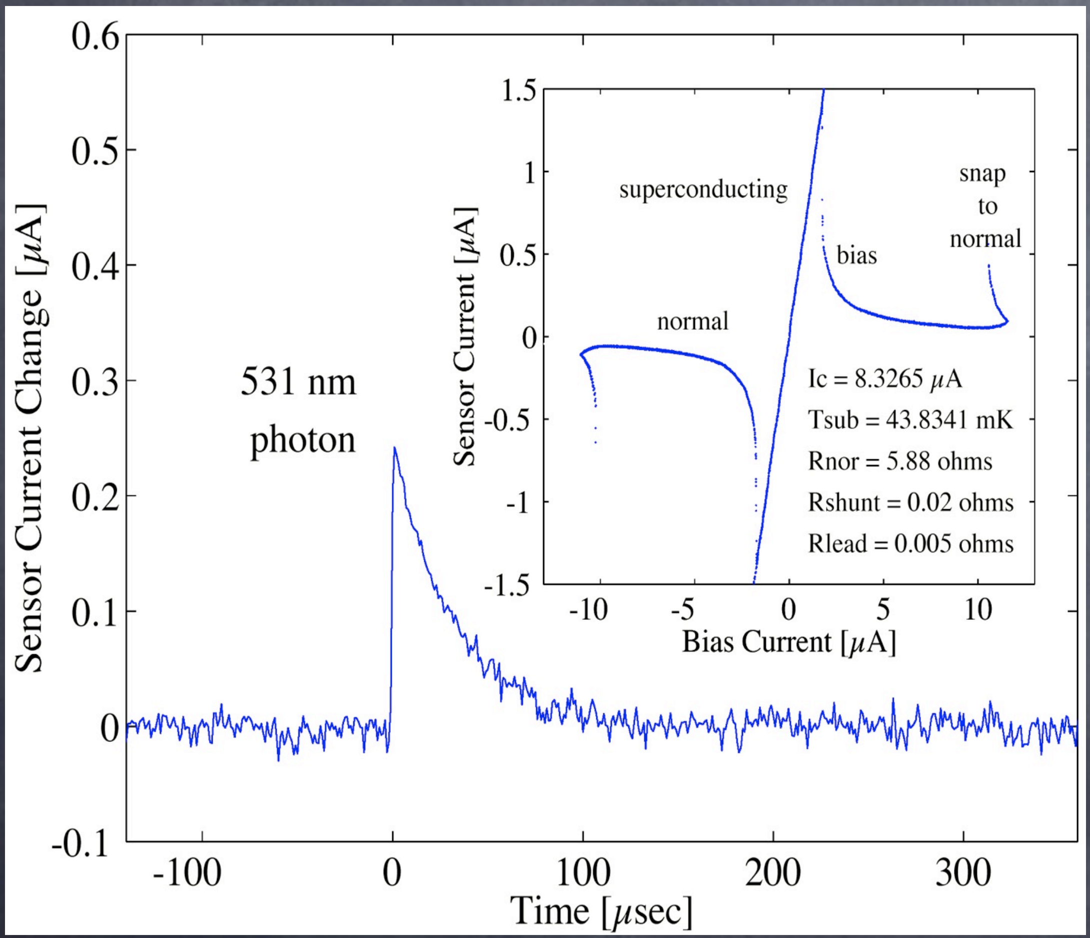
TES Simulation

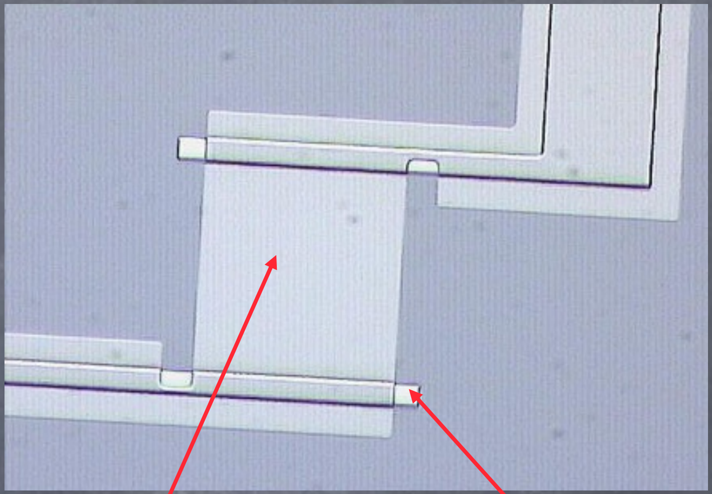
- Optical photon absorbed in TES (Tali Figueroa)



Optical Photon Detectors

- **Demonstration of W TES sensitivity**





active
W sensor

Al
voltage
rails

Appl. Phys. Lett. 73, 735 (1998)
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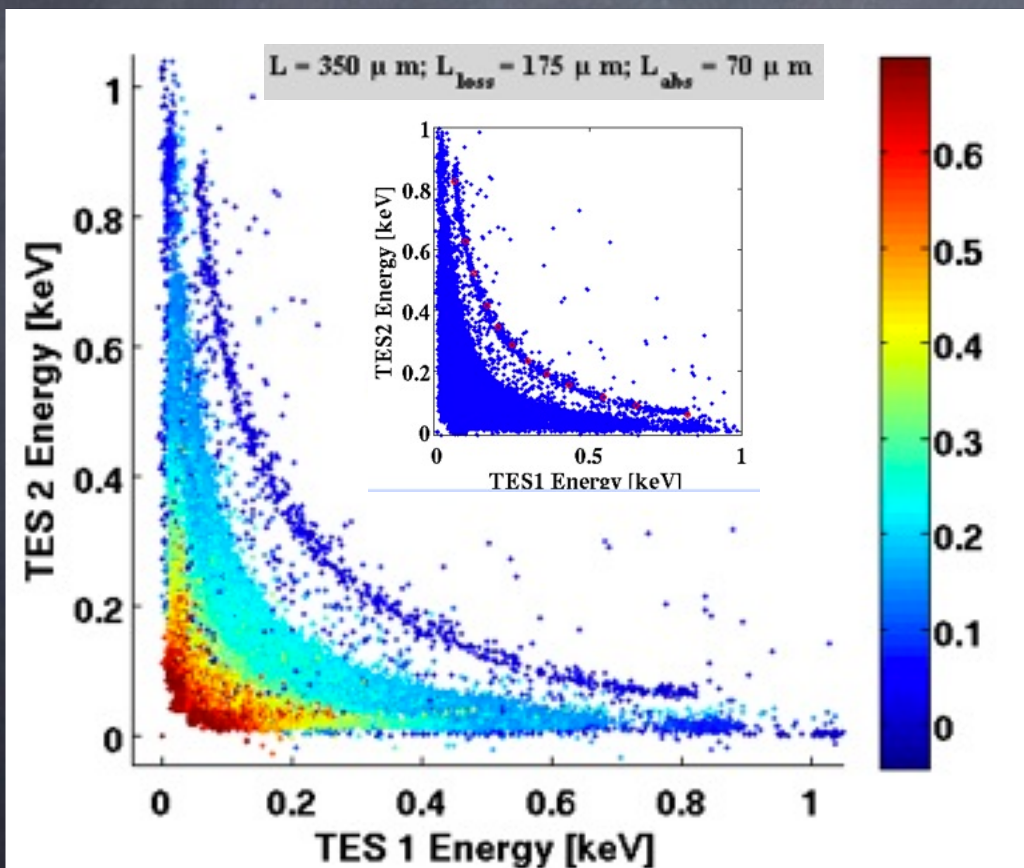
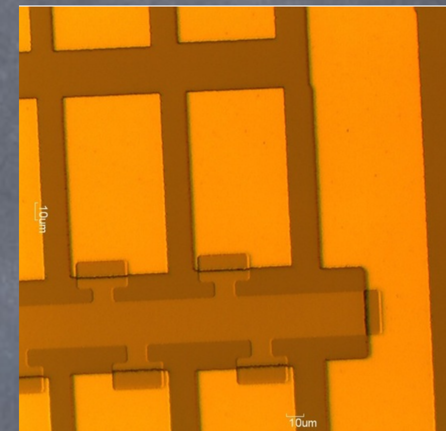
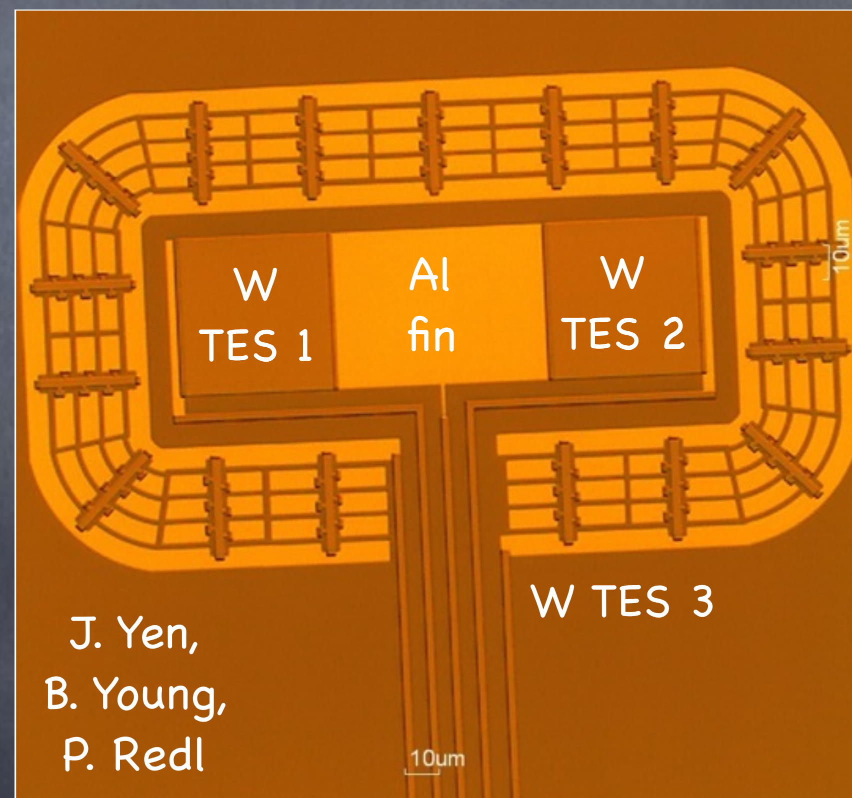
Optimize QET design

- Detailed testing of fabrication techniques using 2.6 keV x-rays allow us to measure the quasiparticle trapping length and the transmission from Al fins to W TESs

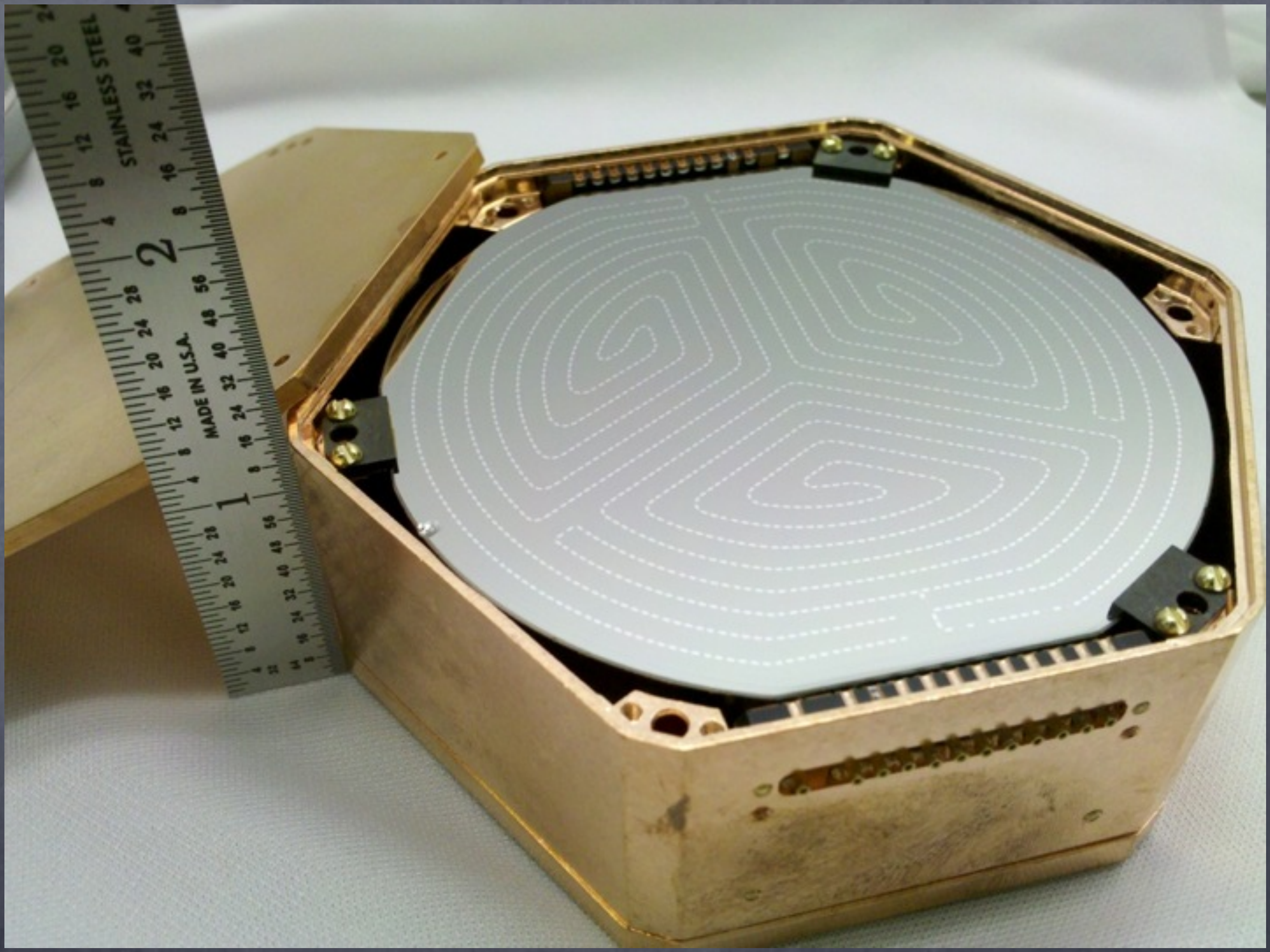






iZIP interleaved charge & phonon design

- Interleaved electrodes and phonon sensors on both sides of the detector.
- Alternating +2V/ground on one side and -2V/ground on the opposite side with phonon sensors at ground potential on both sides.



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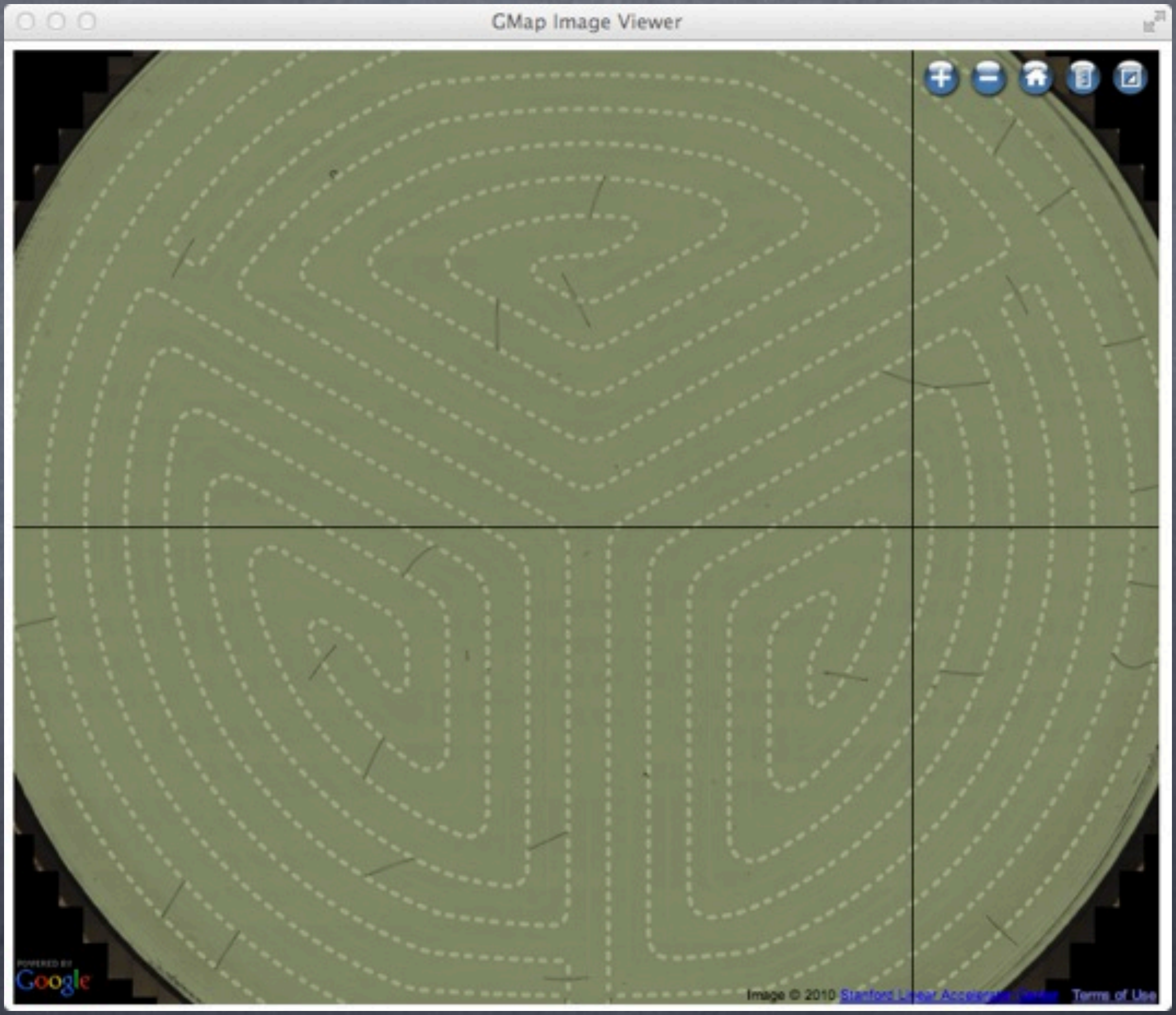

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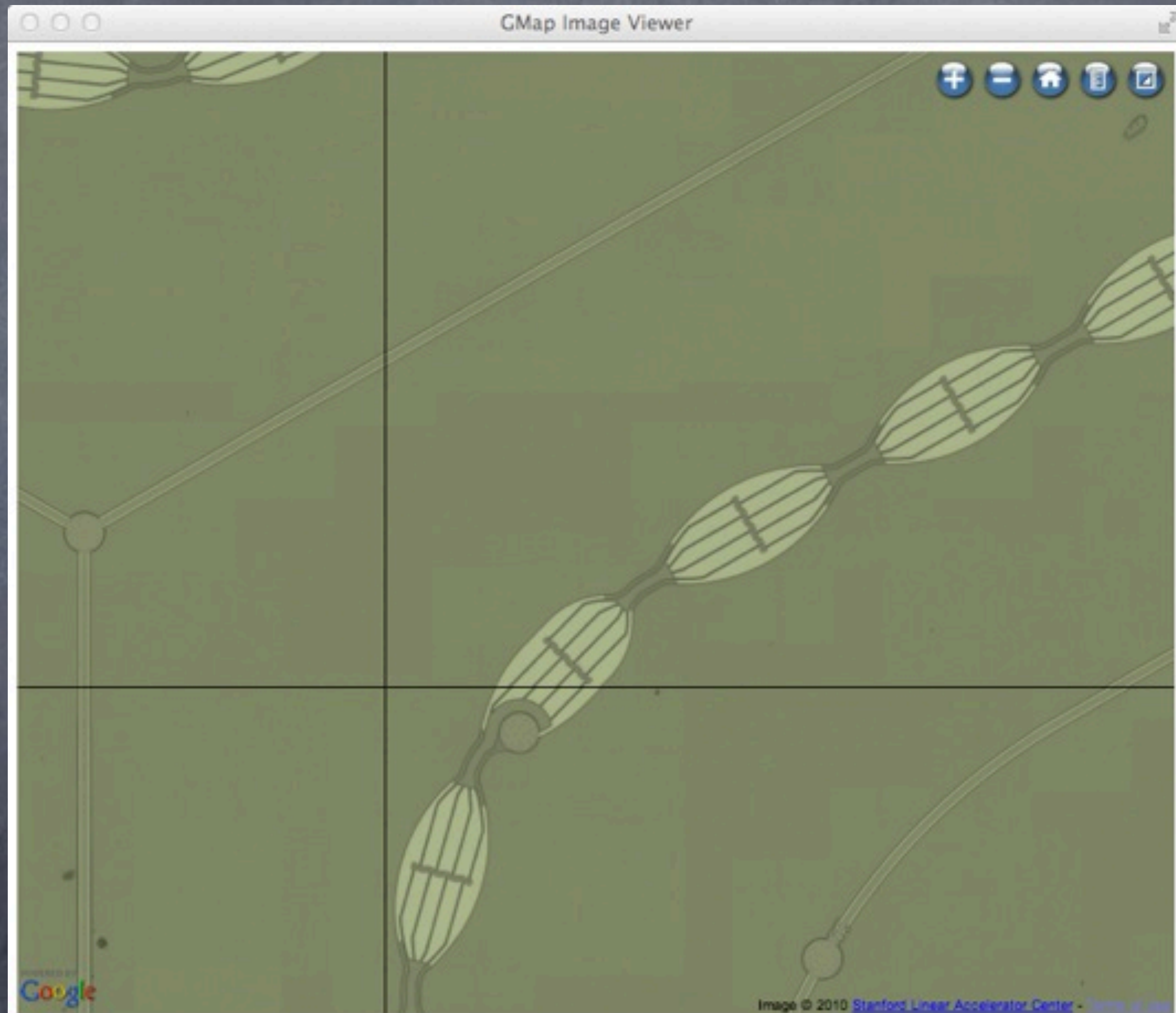

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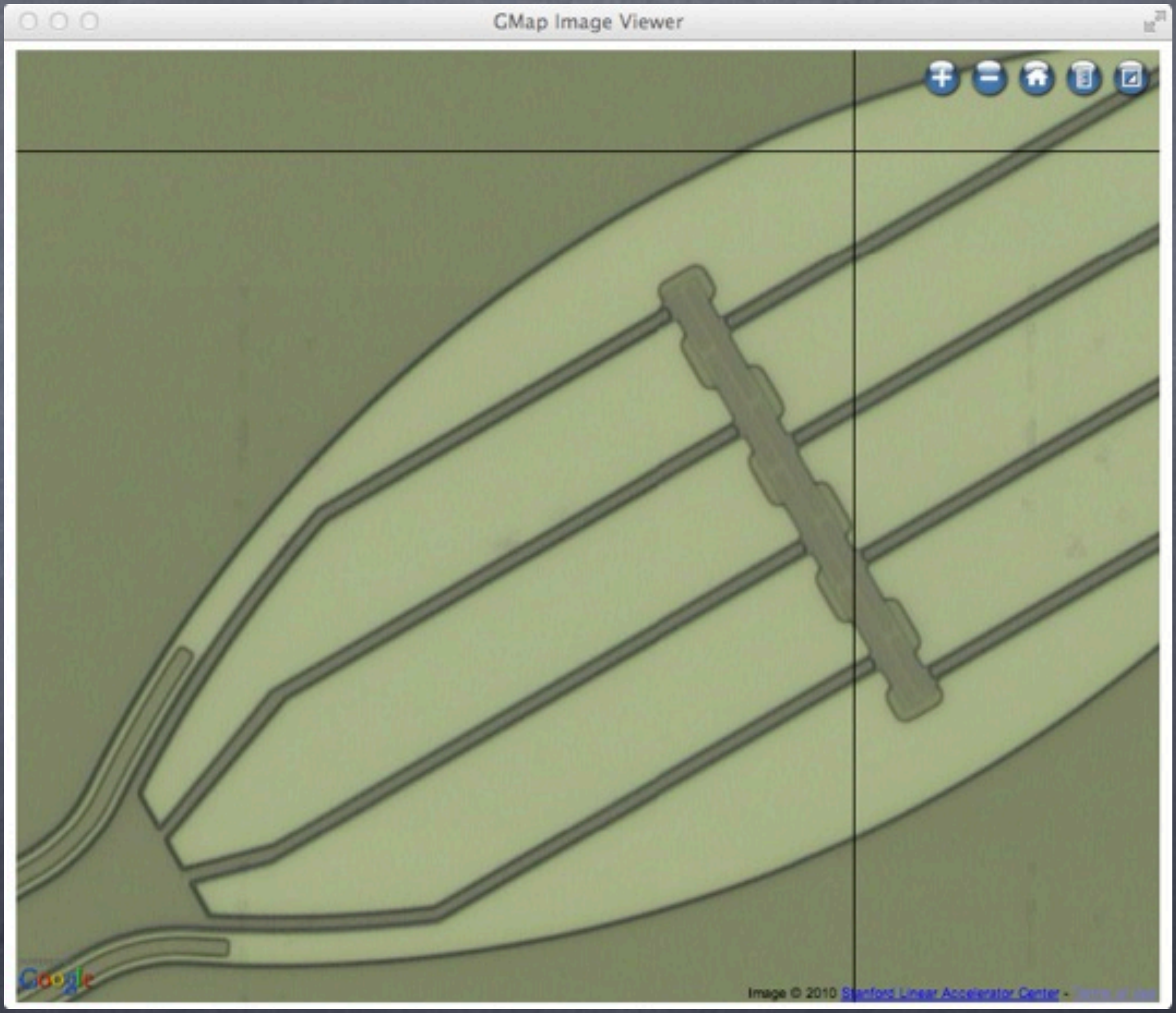
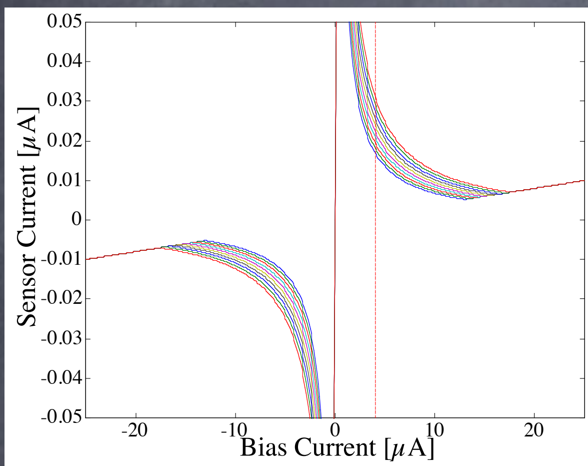
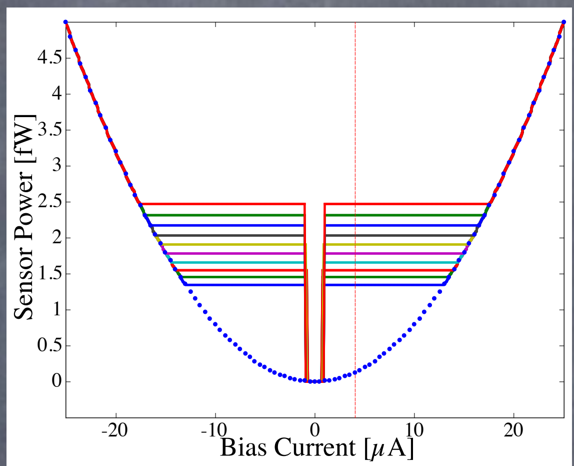
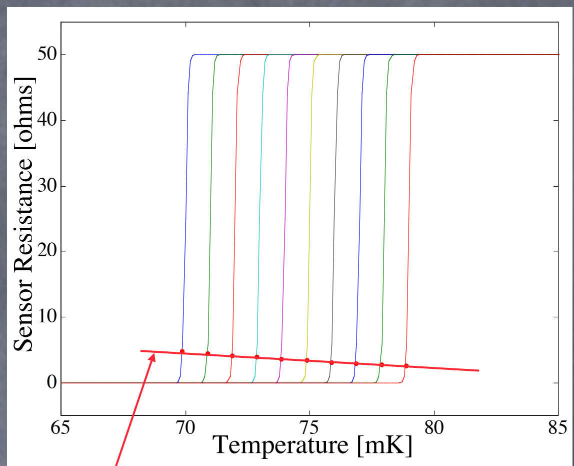


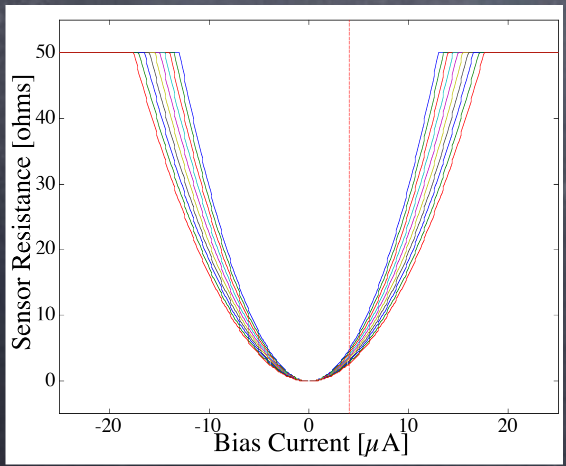
CDMS Tc Gradient Problem

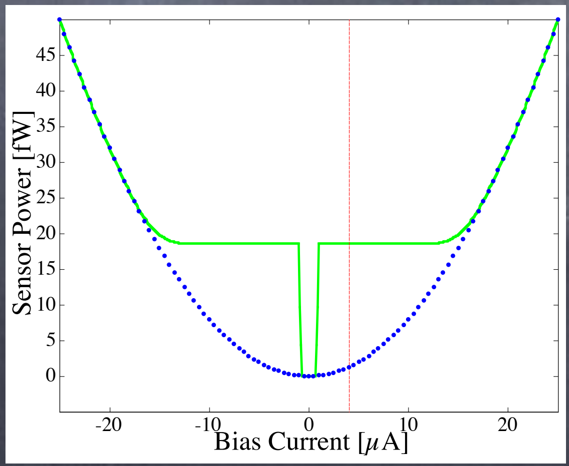
- Voltage biased TES sensors where invented to solve the Tc gradient problem for large area sensors





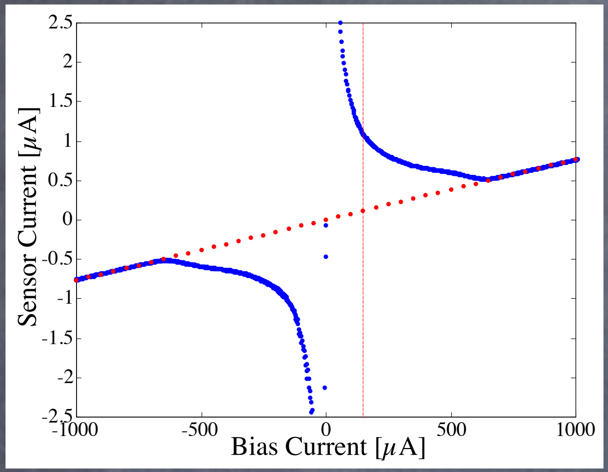


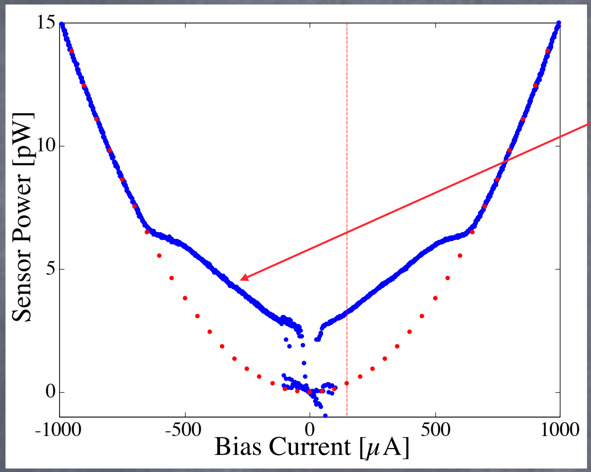




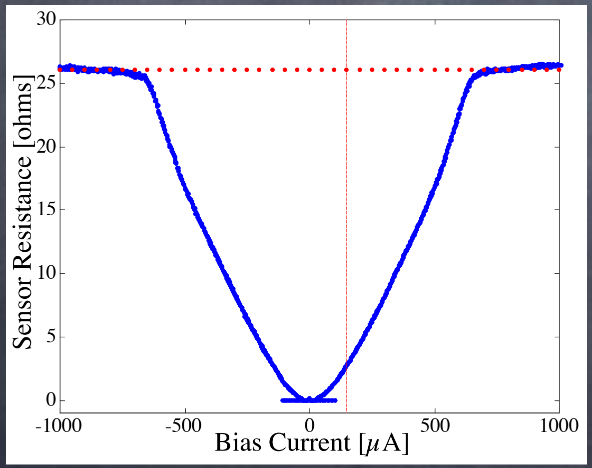
With current bias, there did not exist a bias temperature for all, but with self voltage biasing all at high sensitivity.

N/S Phase Separation along TES

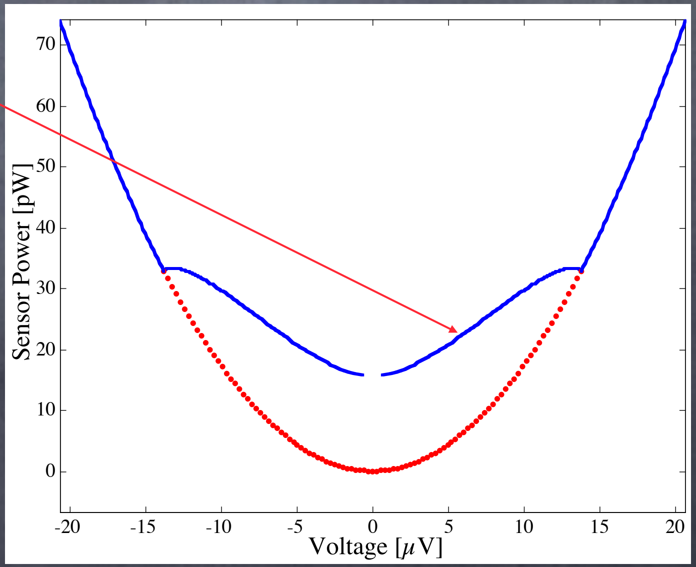




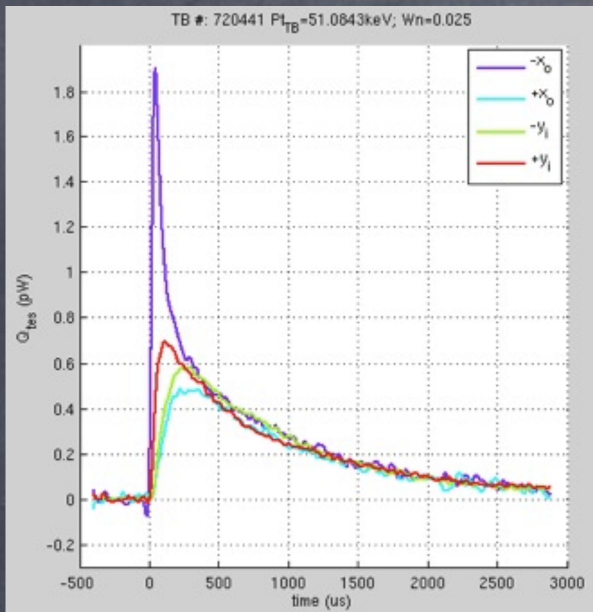
See linear downward slope instead of flat power region.

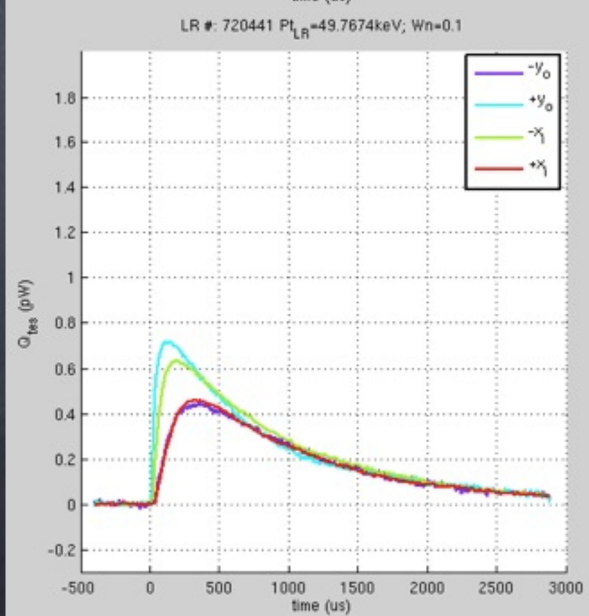


Analytic solution assuming sharp transition and constant conductivity

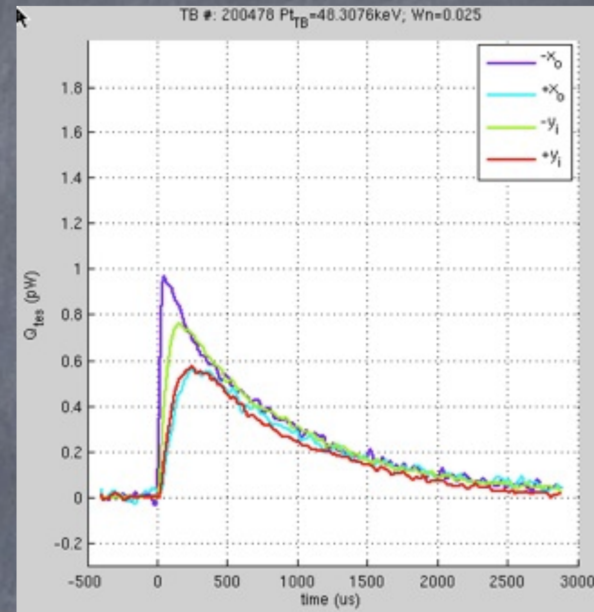


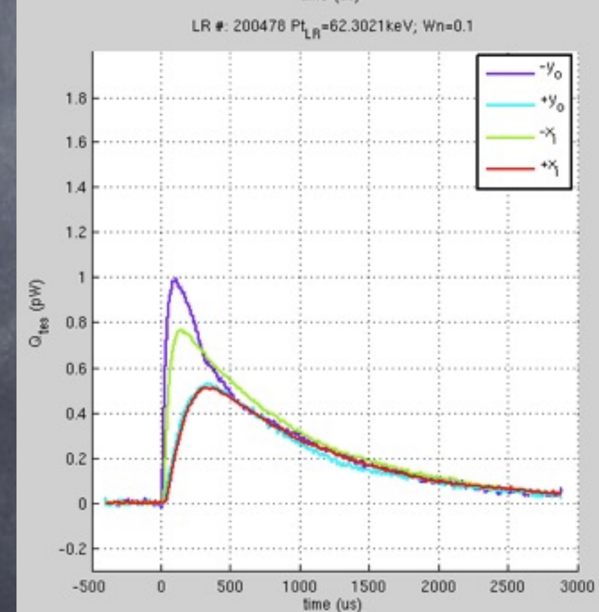
Phonon thermalization process



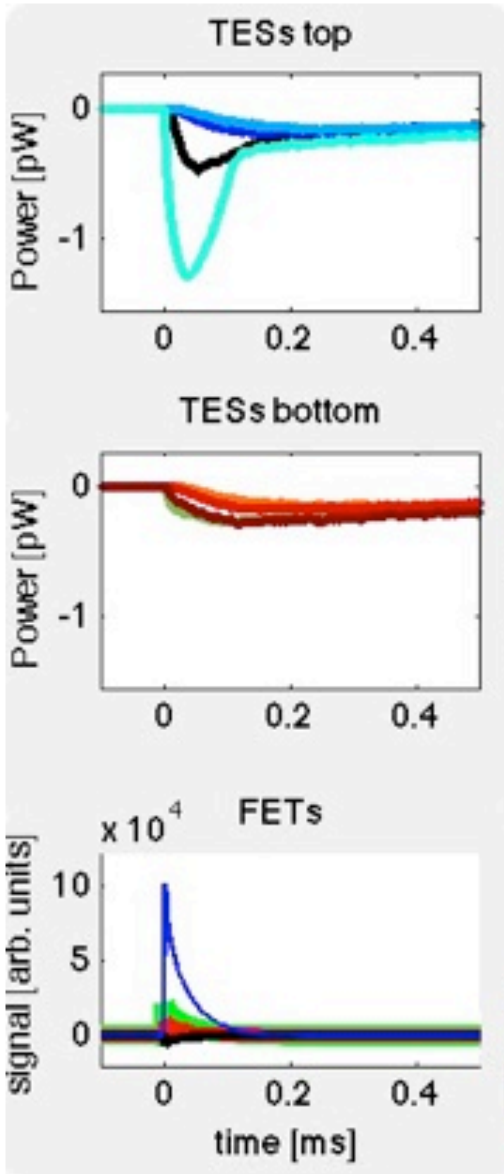


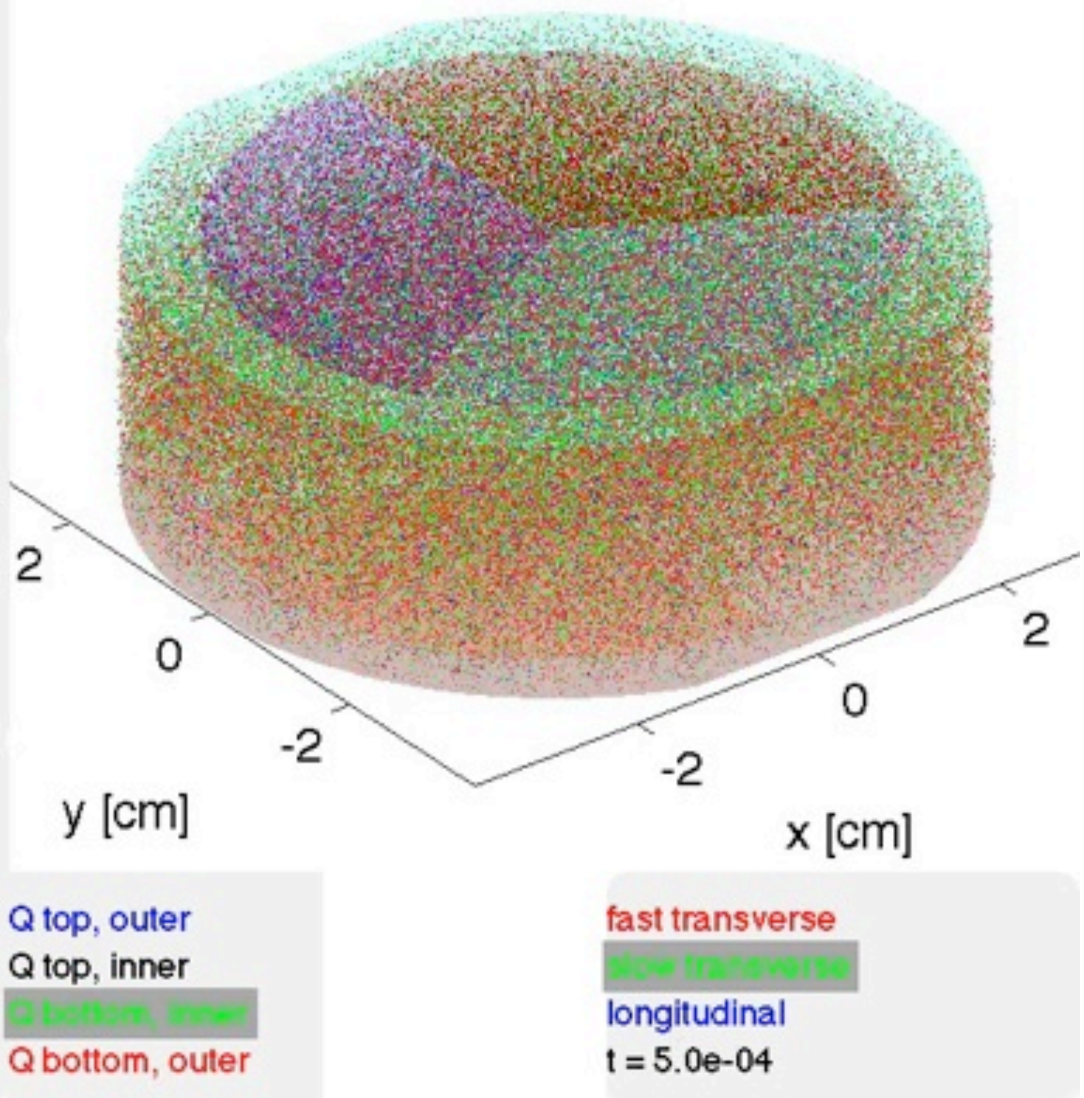
- diffusive phonons are localized -> ballistic phonons distribute uniformly
- two separate events on left and right hand side
- top is top side and bottom is the bottom side
- note that after 500 μs all channels identical
- position information in leading part



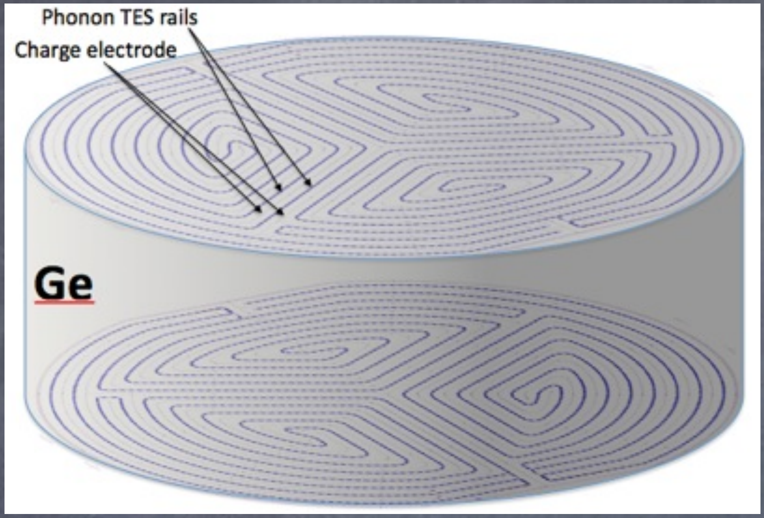


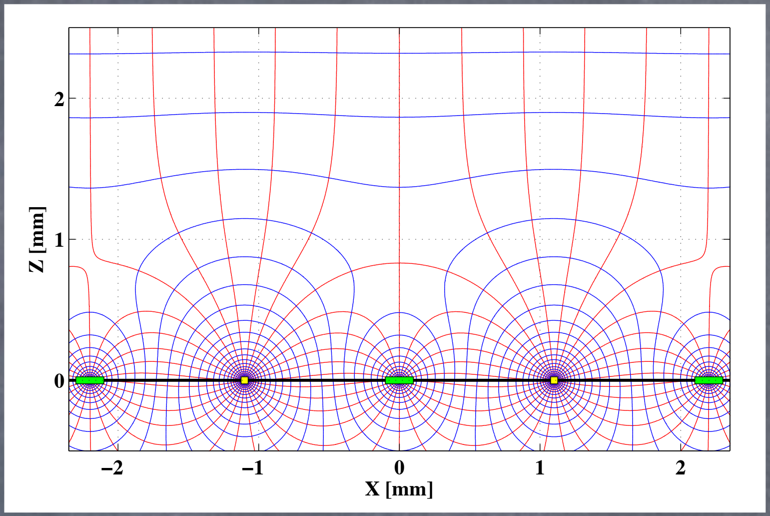
soon GEANT4 framework

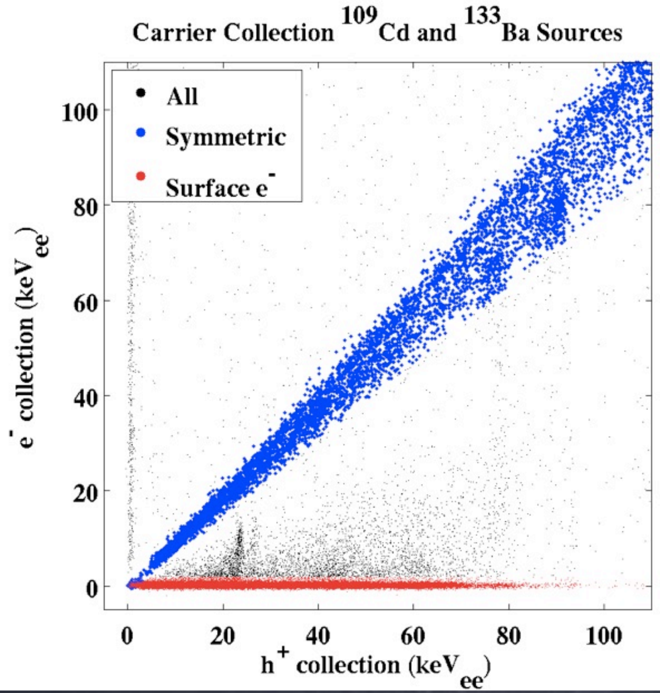


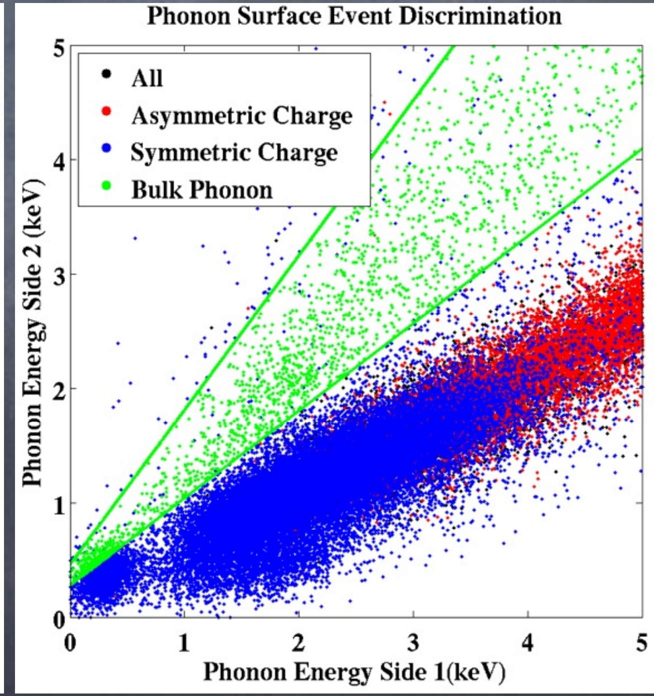


Advanced iZIP Detectors



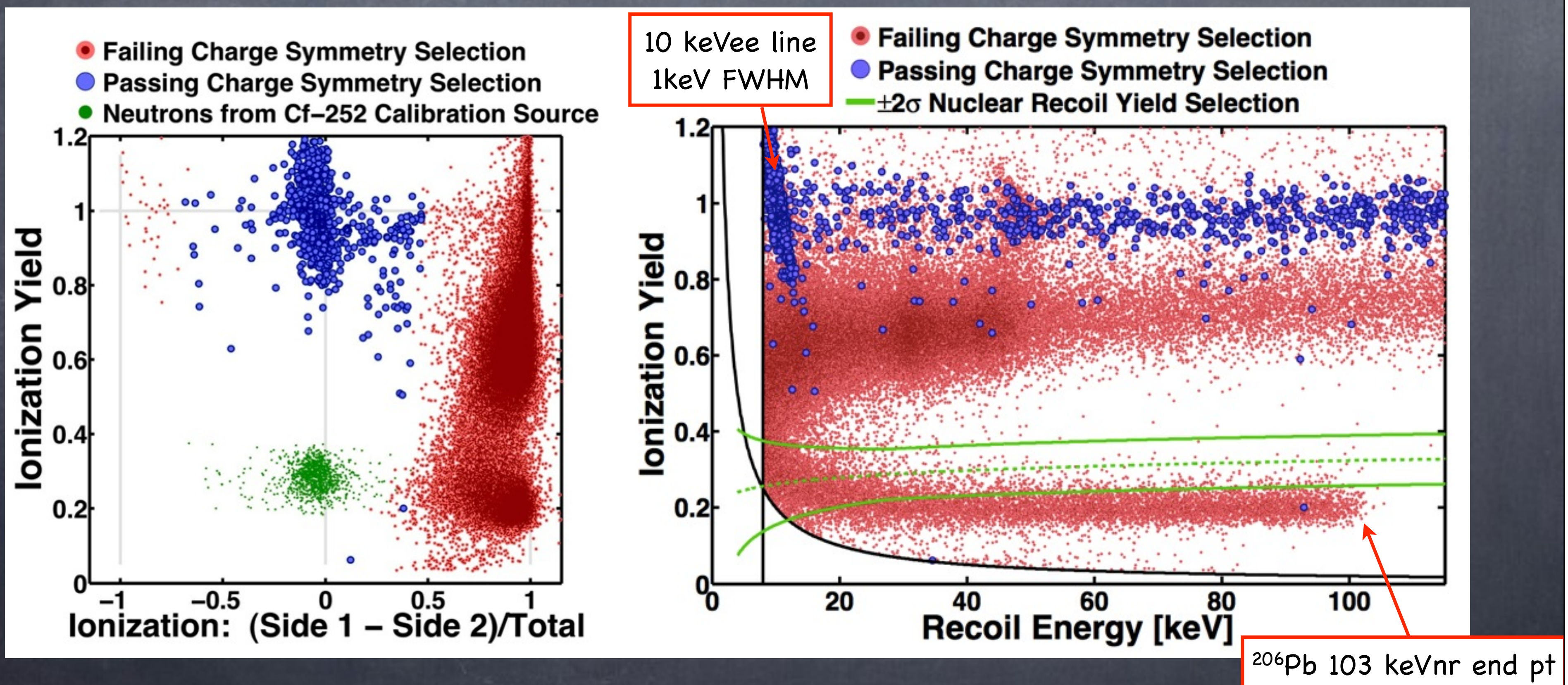






^{210}Pb Surce Data from SuperCDMS Soudan

- Two detectors with one ^{210}Pb decay every min operated for 20 live days corresponds to more than total ^{210}Pb events for SuperCDMS Soudan and even for future 200 kg SuperCDMS SNOLAB



Summary

- Original science motivations for cryogenic detectors were neutrinos and dark matter, but great success in many other areas continuing to the present day.
- Many recent advances in single sensor performance and more importantly in large array performance.
- Continued improvements in our fundamental understanding of these devices including non-equilibrium nature of TESs
- Encourage those interested to attend LTD15