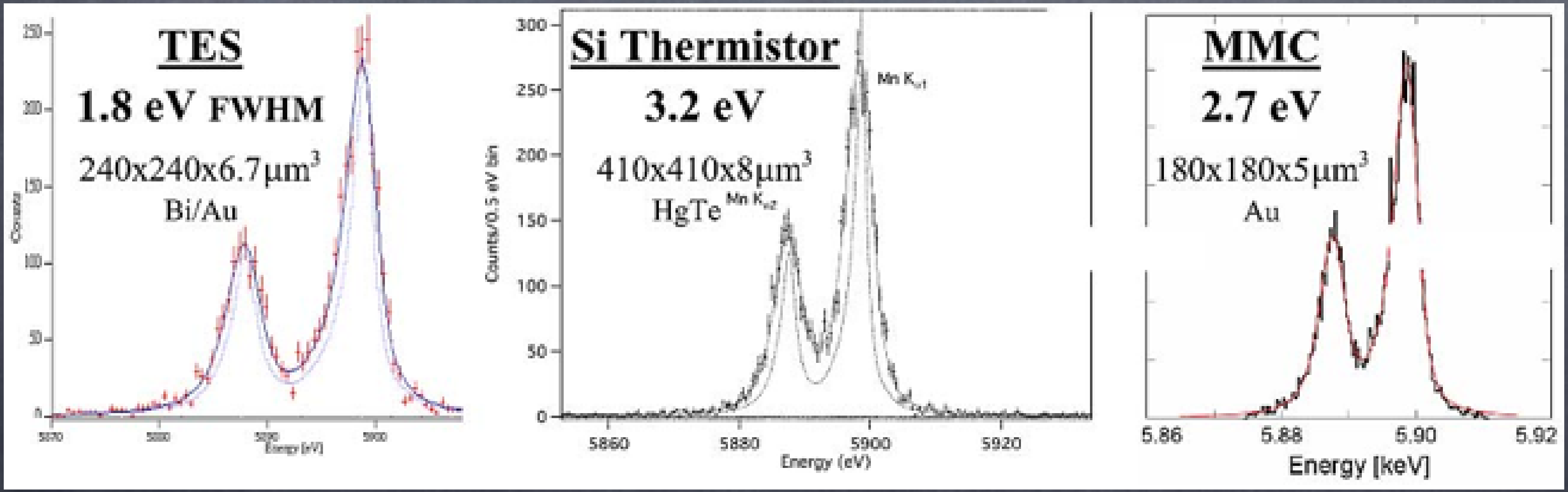
Many ways to measure temperature ($K\alpha 1$ / $K\alpha 2$ for ^{55}Fe at 6 keV)

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



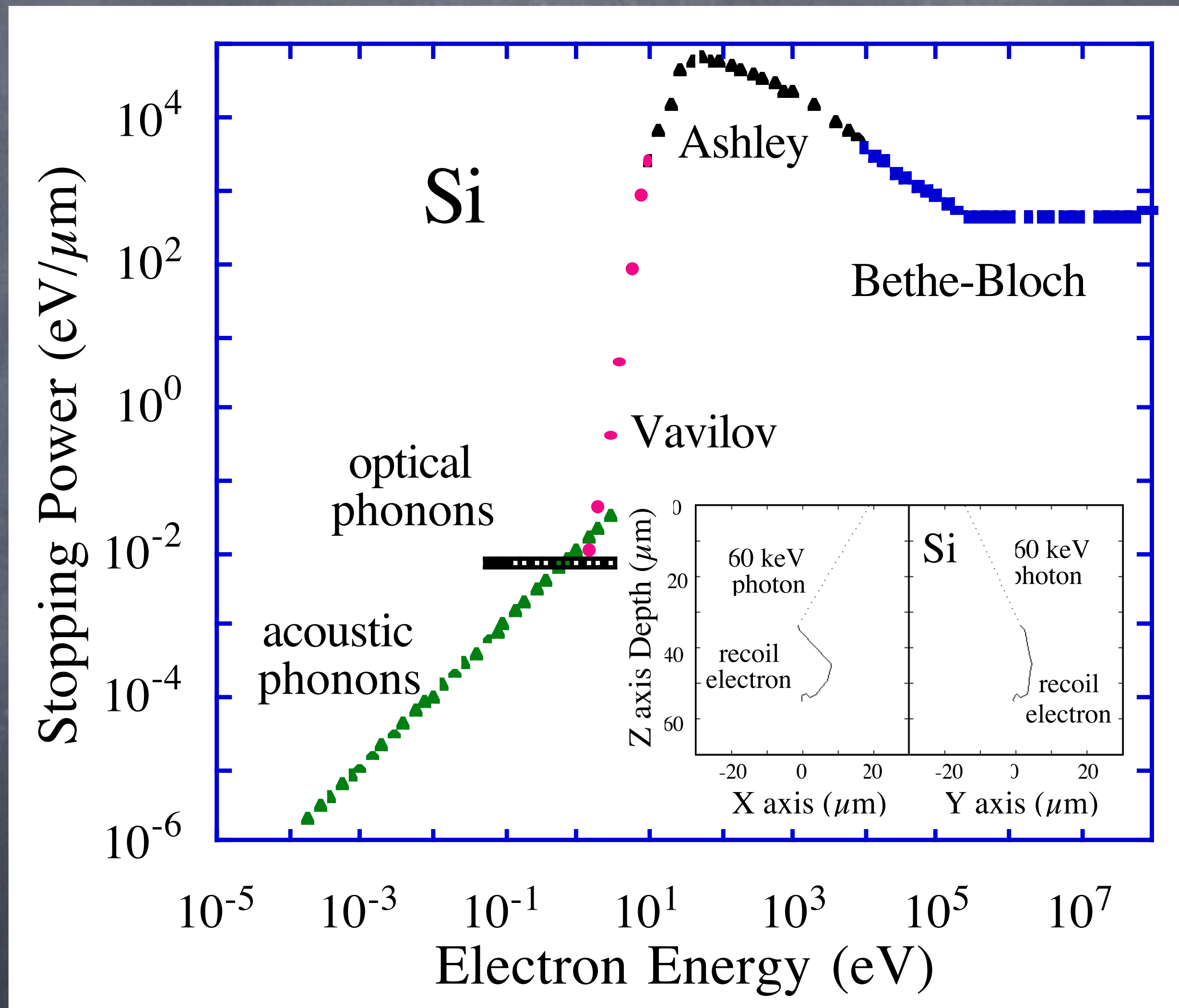
$$(\Delta E)_{rms} = \sqrt{k_B T^2 C}\,\frac{(40)^{1/4}}{\sqrt{\alpha}} \qquad (\Delta E)_{rms} = \sqrt{k_B T^2 C}\,\frac{4}{\sqrt{\alpha}} \qquad (\Delta E)_{rms} = \sqrt{k_B T^2 C}\,\sqrt{8}\left(\frac{\tau_0}{\tau_1}\right)^{1/4}$$

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}

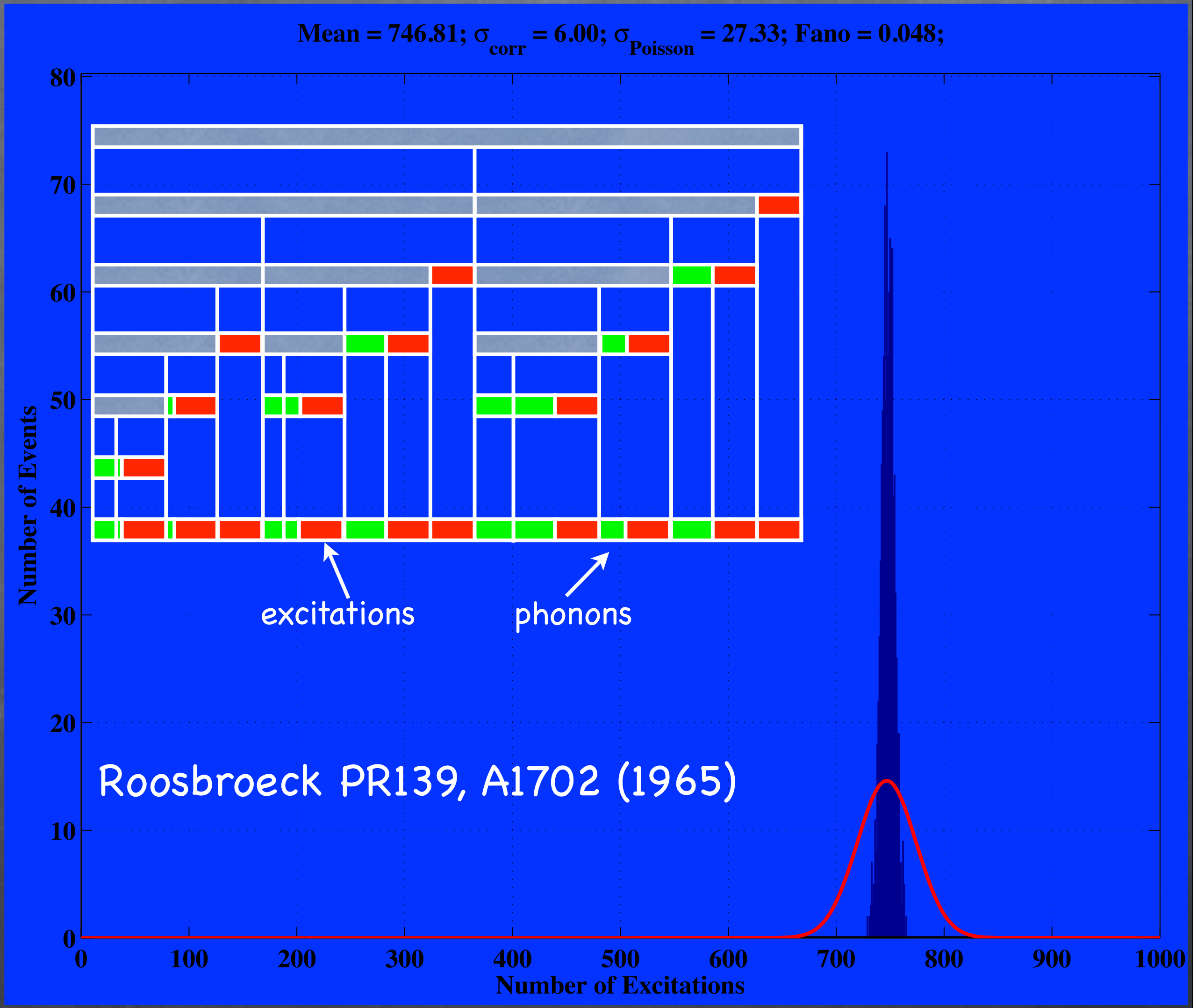


Semiconductor diodes

- 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

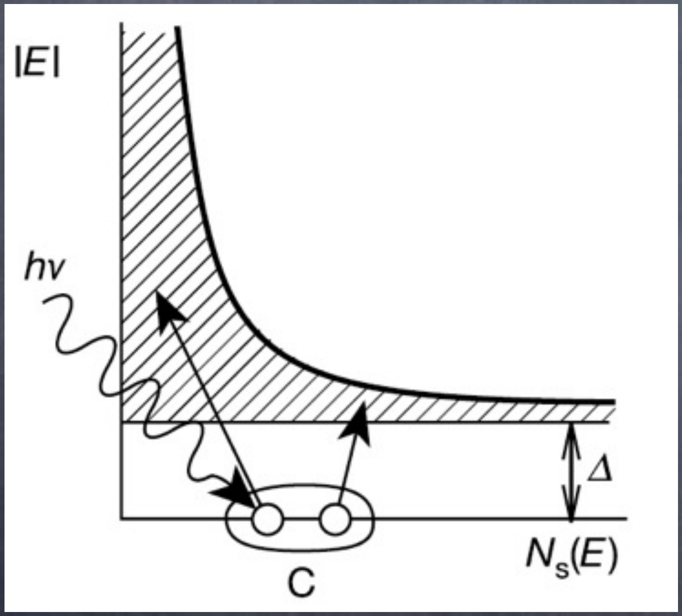
Fano factor 'crazy carpentry'

- $F = Var_{corr}/Var_{Poisson}$
- 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.



Quasiparticles

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

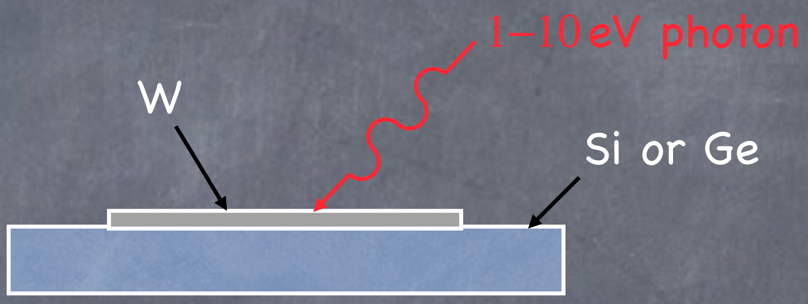


Day JPL

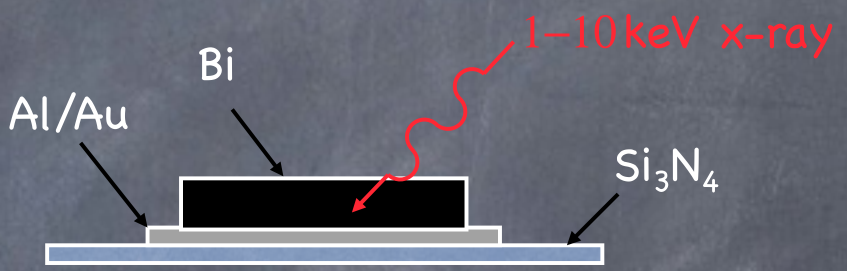
Element	T_c(K)	E_{gap}(meV)	$(E_{Si}/E_{gap})^{1/2}$
Nb	9.5	1.47	28
Ta	4.47	0.7	41
Al	1.14	0.17	84
Ti	0.39	0.06	140
Hf	0.13	0.02	245

Types of TES Detectors

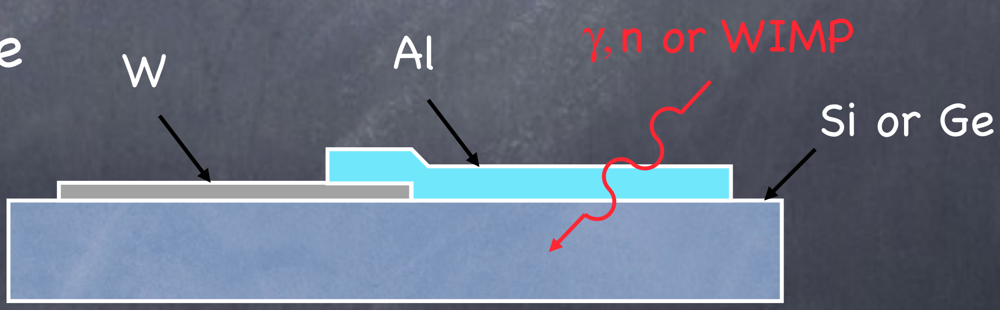
- Direct absorption of photon into TES
(e. g., optical photon detectors)



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



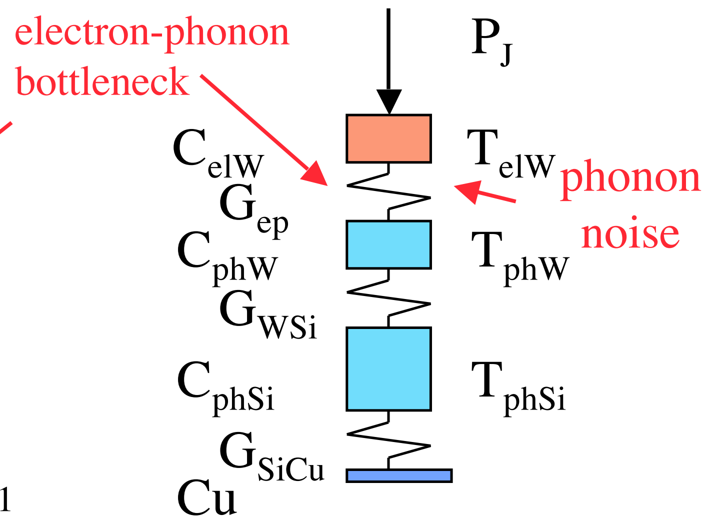
- Large mass absorbers generate phonons which are converted into quasiparticles which diffuse to the TES
(e. g., dark matter detectors)



TES Thermal Model

- Electrothermal Feedback
  - Voltage bias intrinsically stable

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



  - Fast response

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

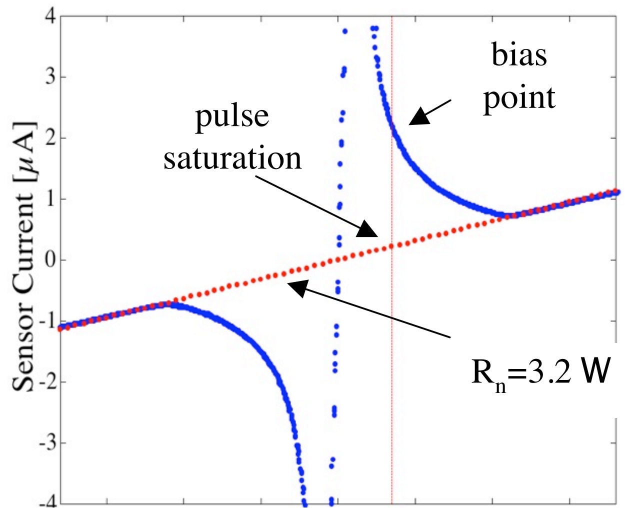
  - High Sensitivity

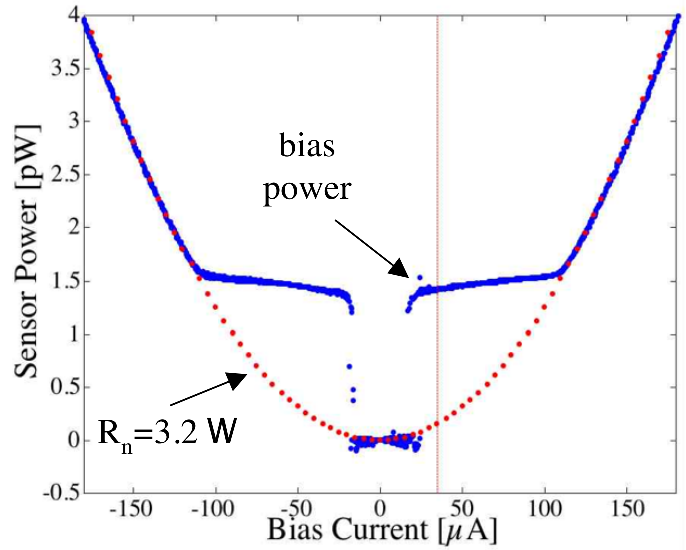
$$\Delta E_{FWHM} = 2.355\sqrt{4\,k_B\,T_e^2\,C\sqrt{\tfrac{n}{2}}\Big/\alpha} = 2.355\sqrt{4k_B\,T_e\,P_J\,\tau_{etf}\sqrt{\tfrac{n}{2}}}$$

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

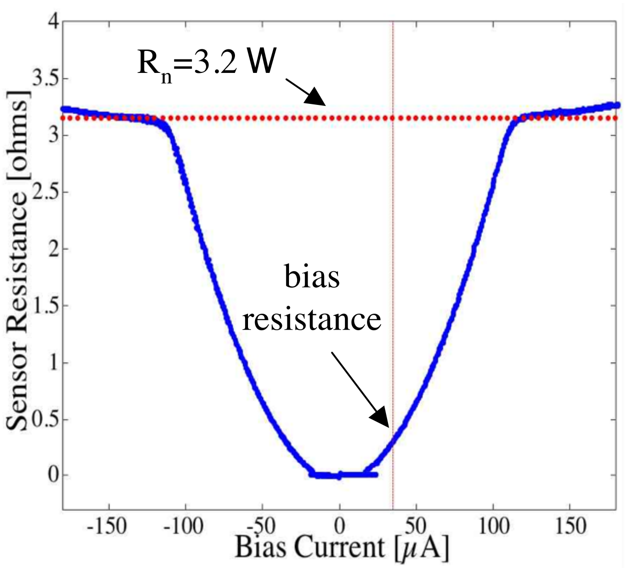
$$\text{For } E_{sat}\left(\sim C\,T_e/\alpha = P_J\,\tau_{etf}\right) = 1 \text{ eV then } \Delta E_{FWHM} = 11 \text{ meV}$$

Lower threshold for better resolution





But, must deal with pulse shape variation with energy

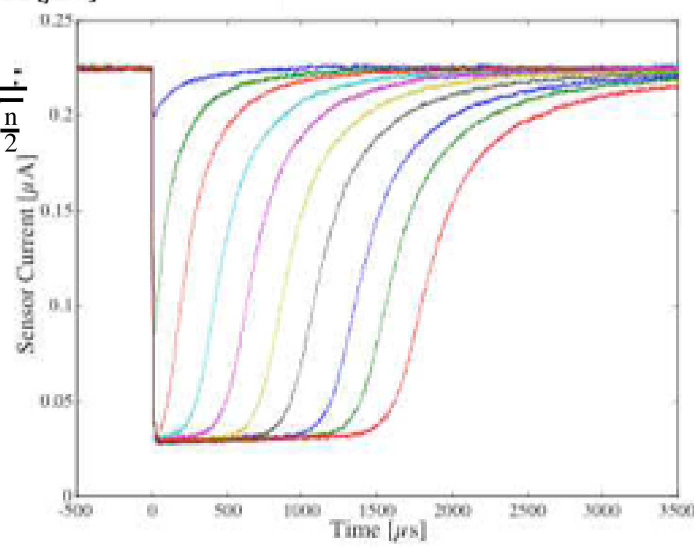


$$\Delta E_{FWHM} = 2.355\sqrt{4\, k_B\, T_e\, P_0\, \tau_{etf}\, \sqrt{\tfrac{n}{2}}}$$

for $E < E_{sat} = P_0\, \tau_{etf}$

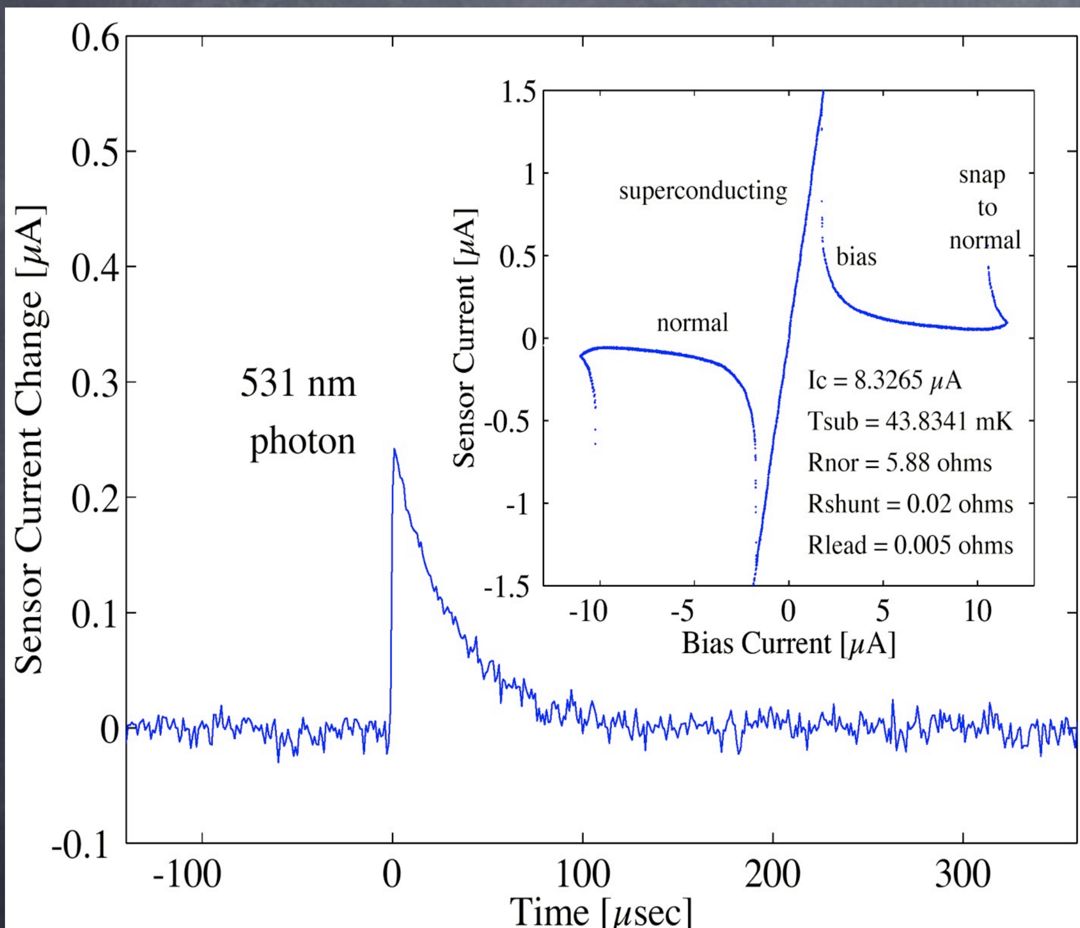
$$\Delta E_{FWHM} \approx 2.355\sqrt{4\, k_B\, T_e\, E\sqrt{\tfrac{n}{2}}}$$

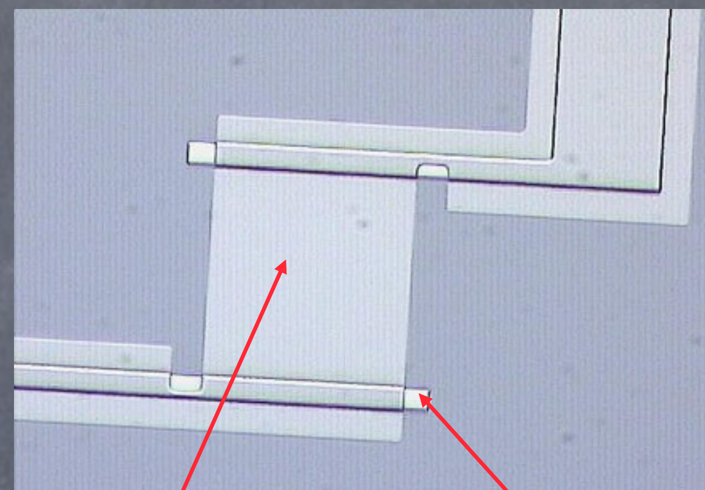
for $E > E_{sat}$



Optical Photon Detectors

- **Demonstration of W TES sensitivity**





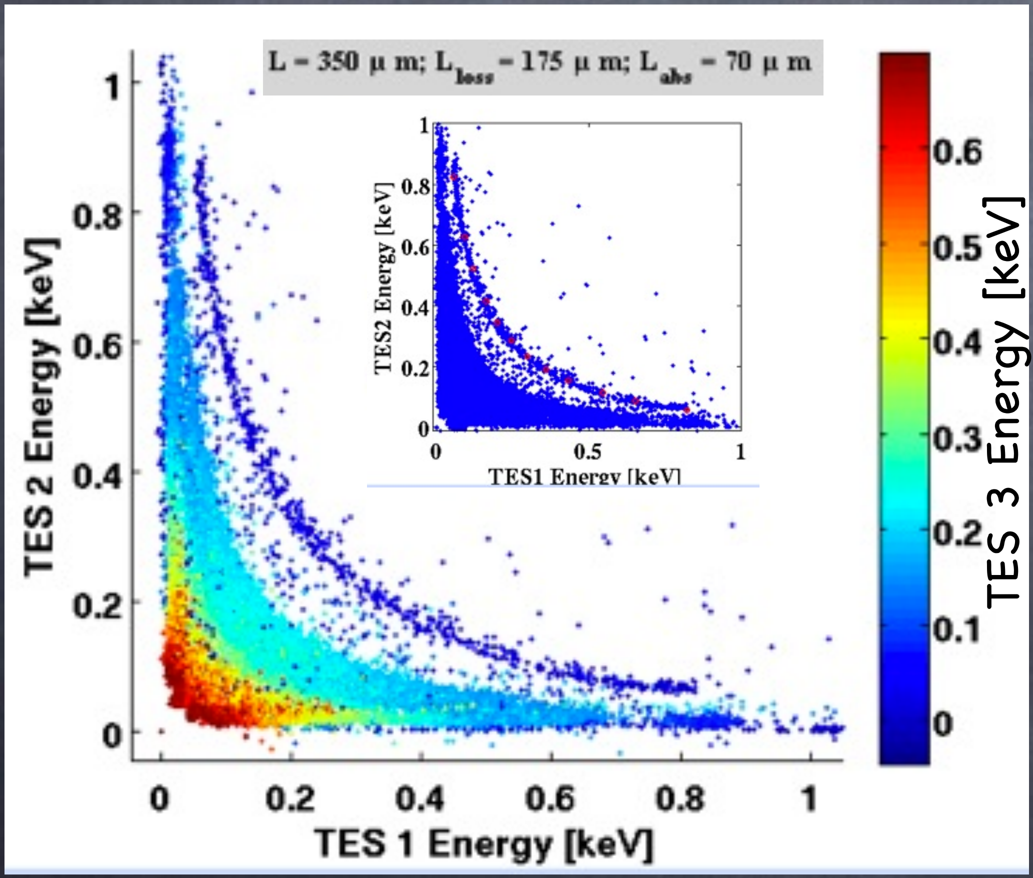
active
W sensor

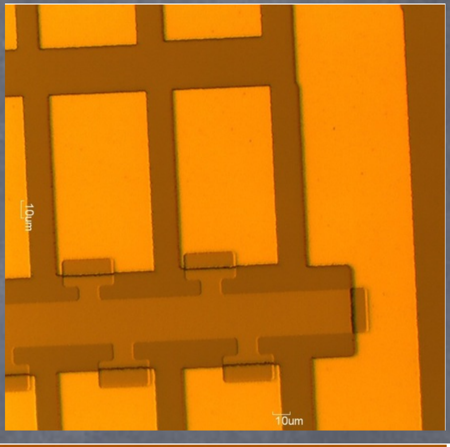
Al
voltage
rails

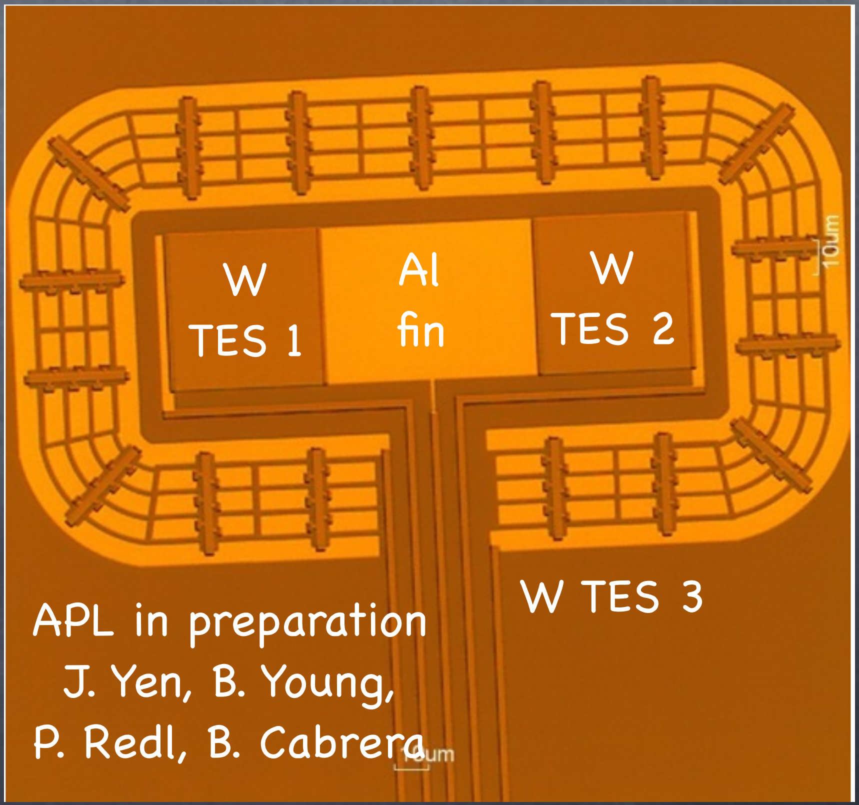
Appl. Phys. Lett. 73, 735 (1998)
B. Cabrera, R. Romani, A. J. Miller
E. Figueroa-Feliciano, S. W. Nam

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

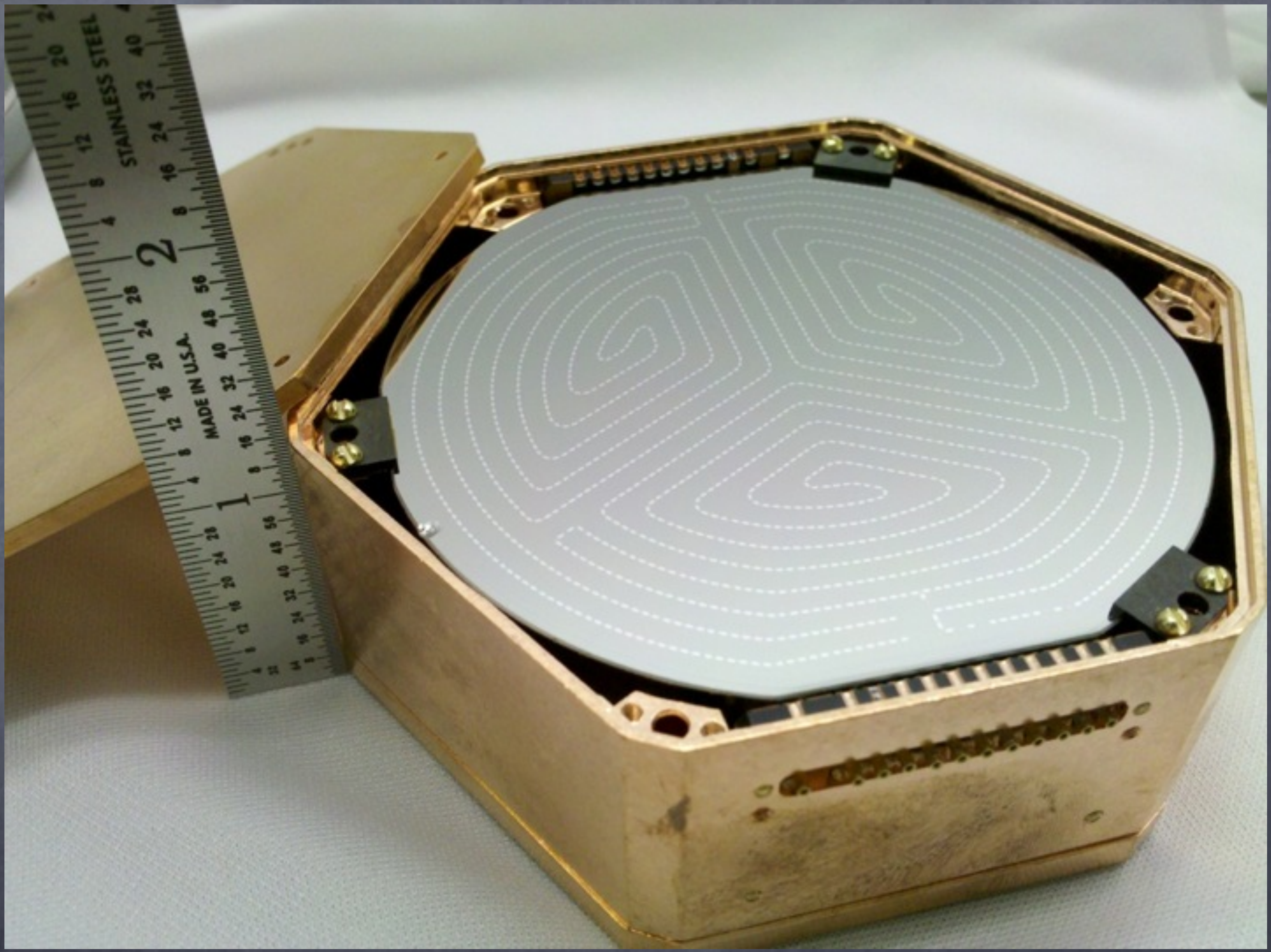






iZIP interleaved charge & phonon design

- 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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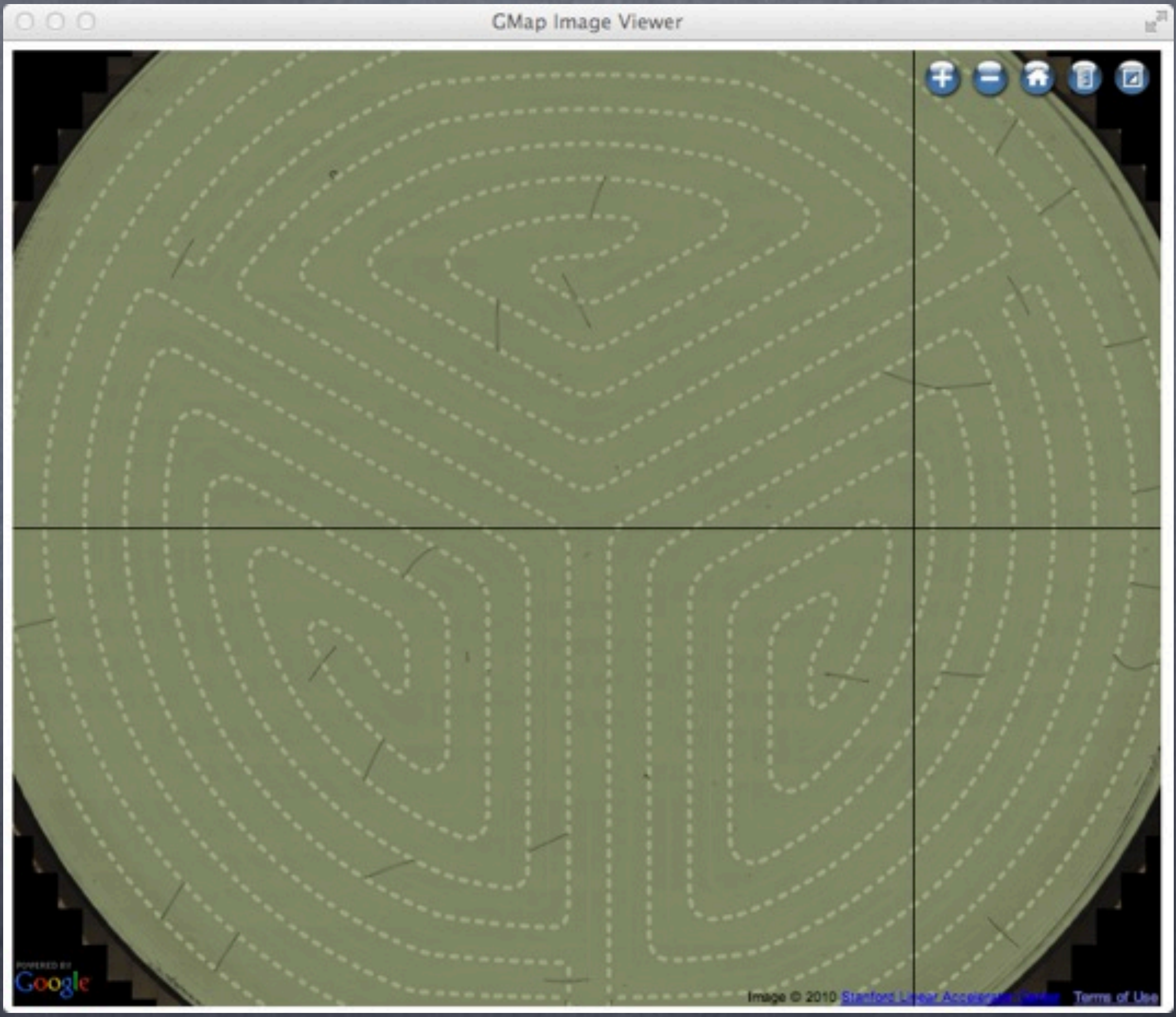

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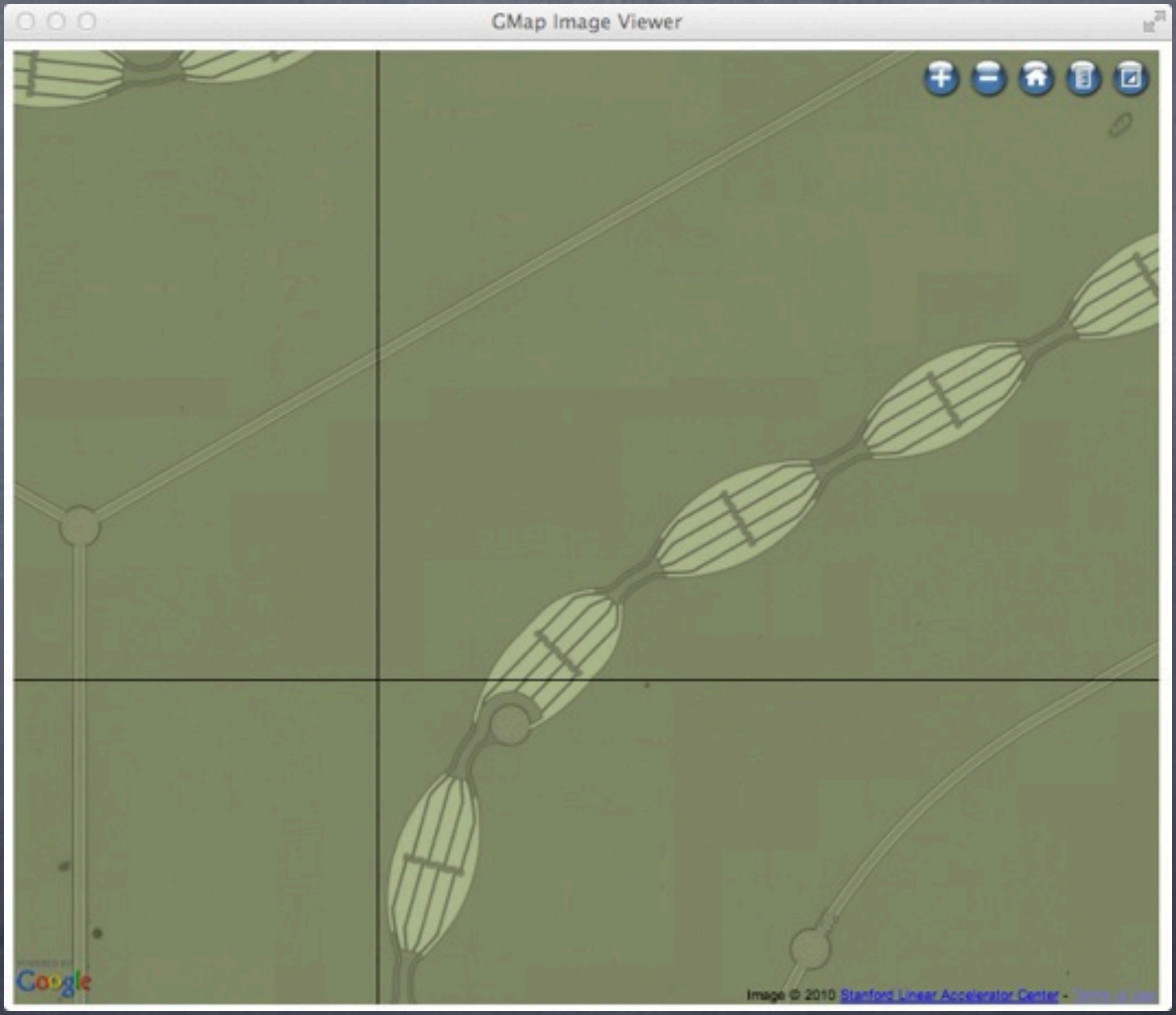

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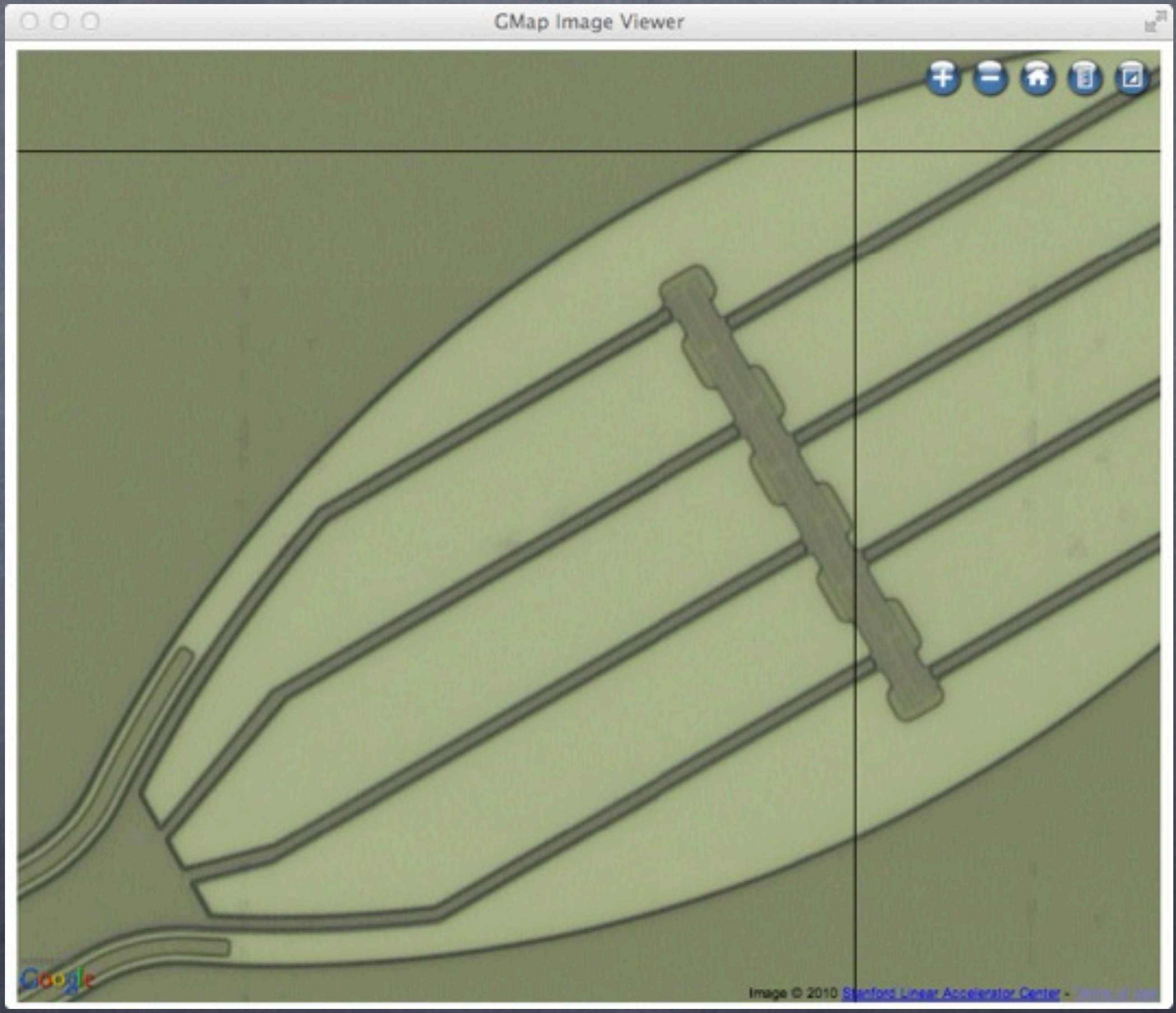
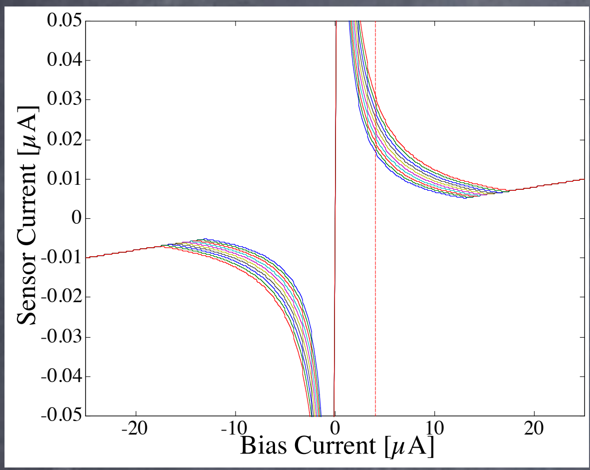
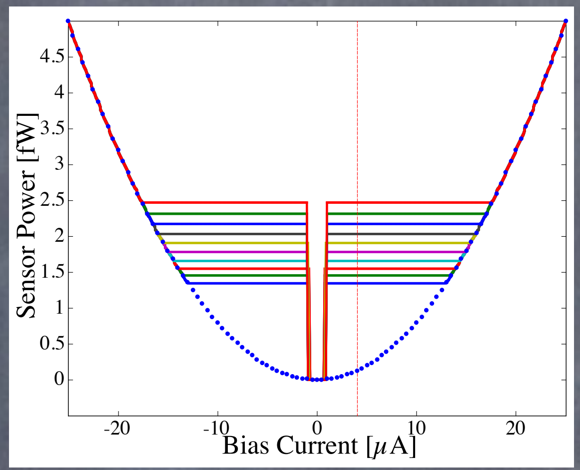
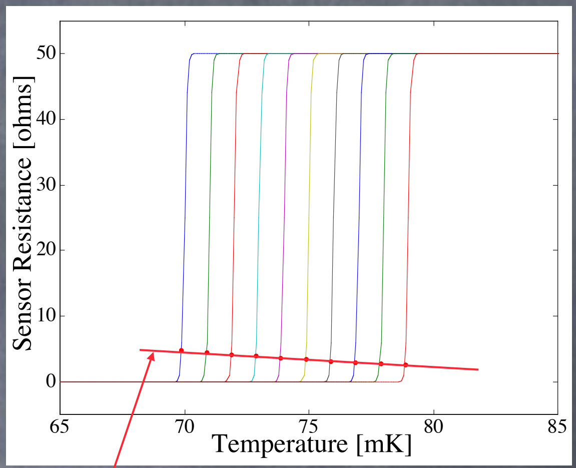


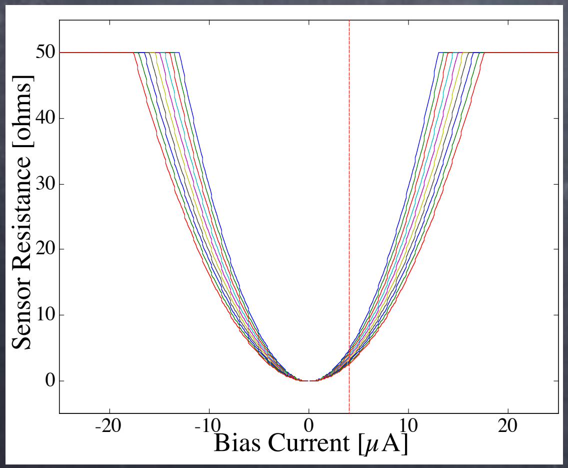
CDMS Tc Gradient Problem

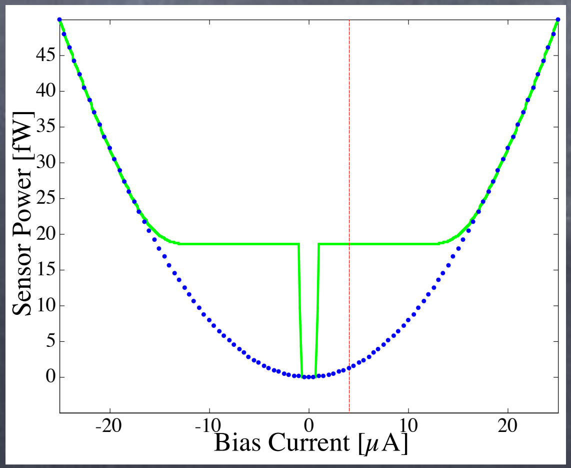
- Voltage biased TES sensors where invented to solve the Tc gradient problem for large area sensors





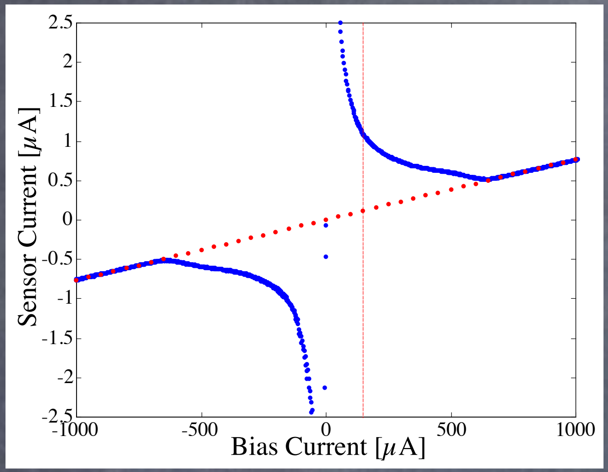


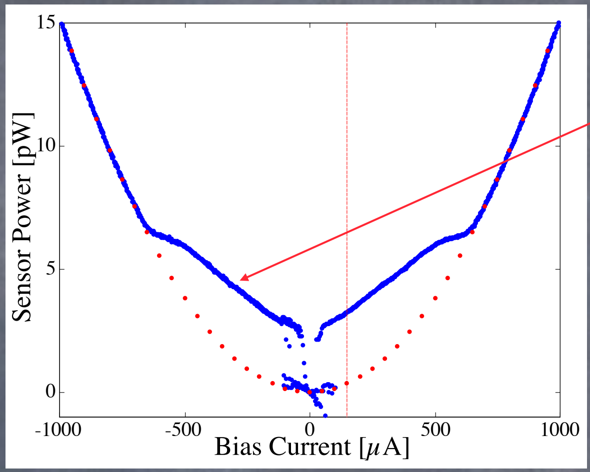




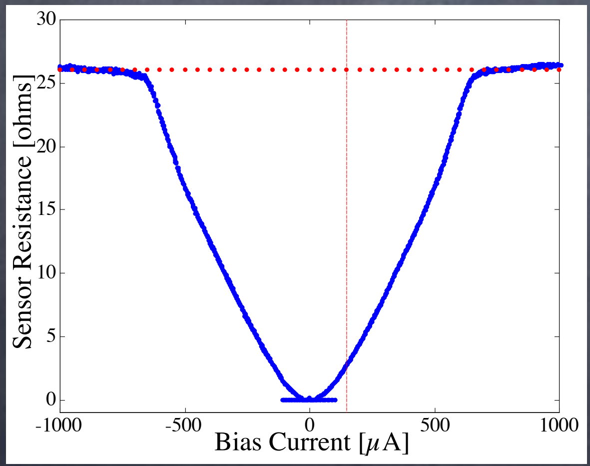
With current bias, there did not exist a bias temperature for all, but with self voltage biasing all at high sensitivity.

N/S Phase Separation along TES

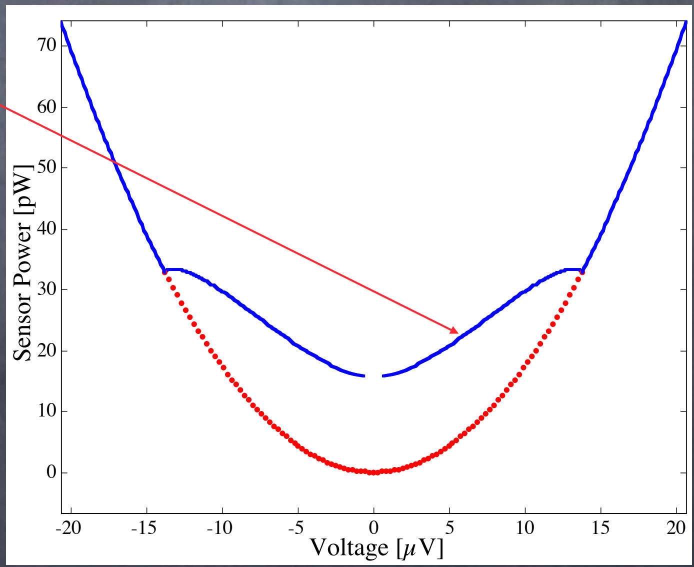




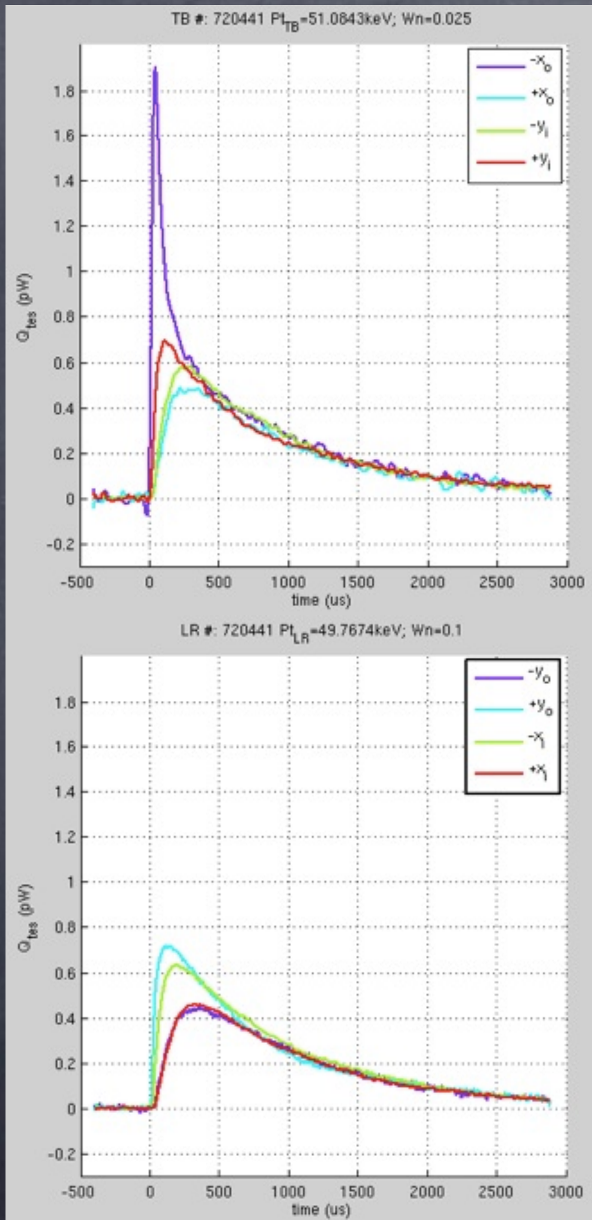
See linear downward slope instead of flat power region.



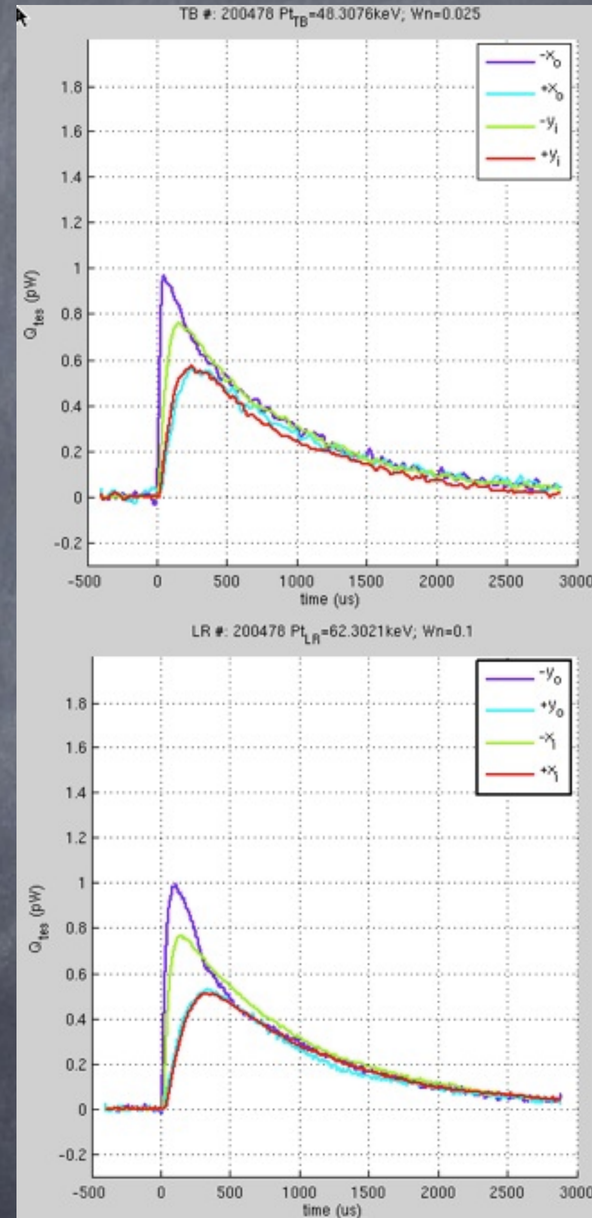
Analytic solution assuming sharp transition and constant conductivity



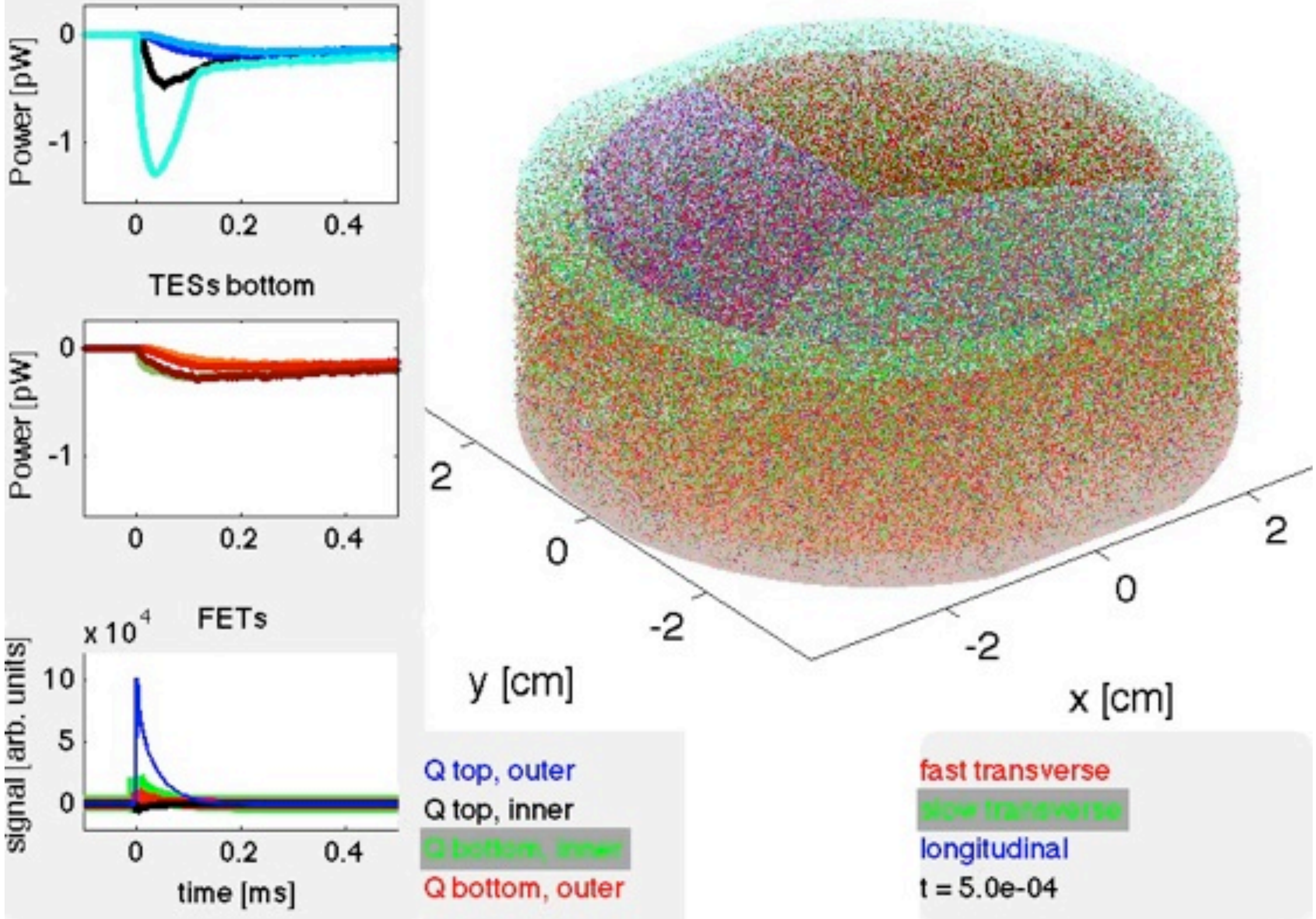
Phonon thermalization process



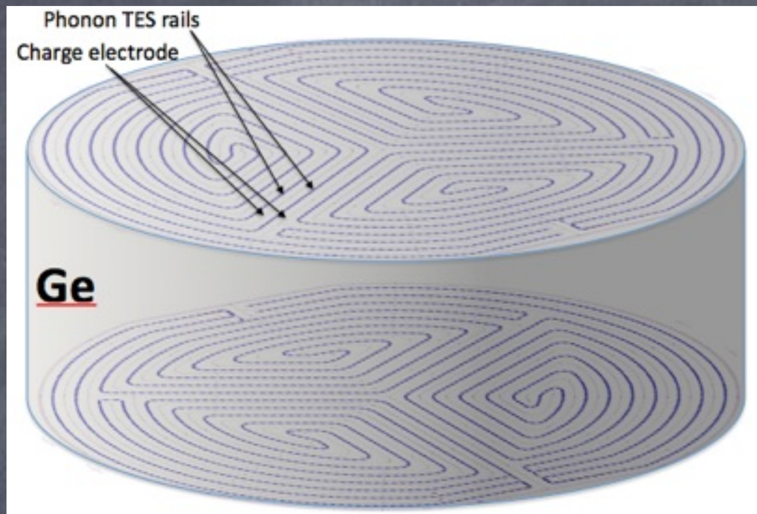
- diffusive phonons are localized -> ballistic phonons distribute uniformly
- two separate events on left and right hand side
- top is top side and bottom is the bottom side
- note that after 500 μs all channels identical
- position information in leading part

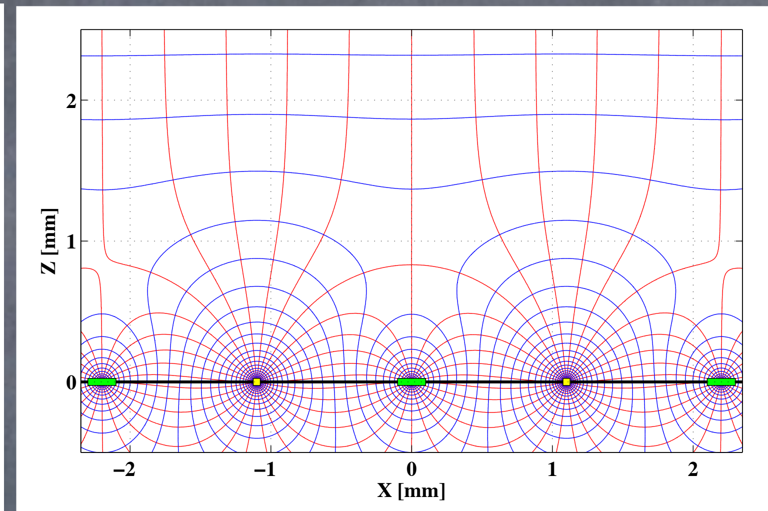


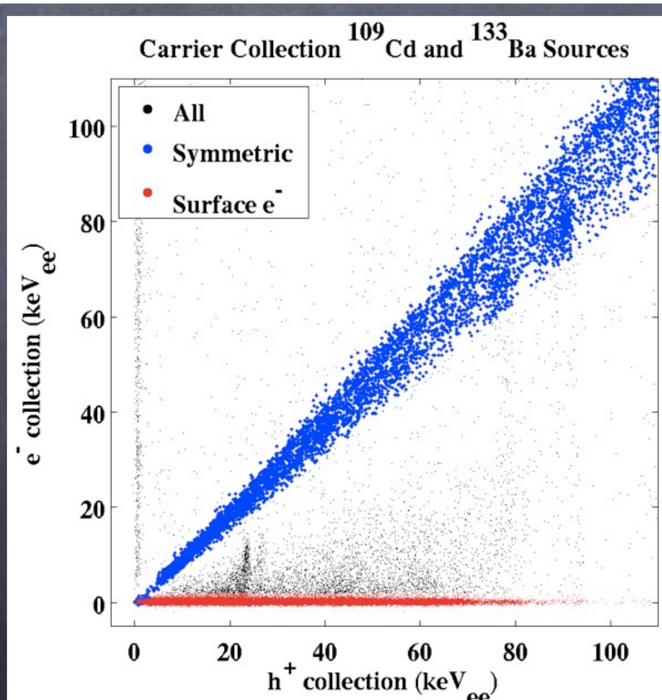
soon GEANT4 framework

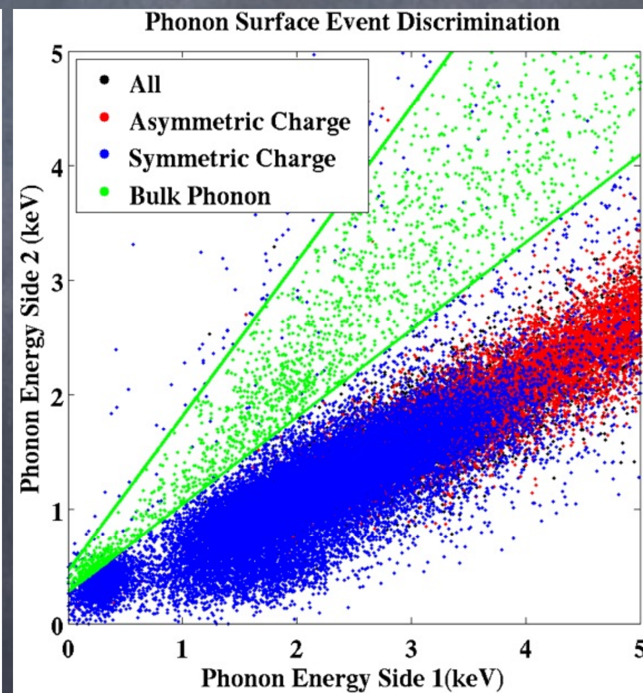


Advanced iZIP Detectors



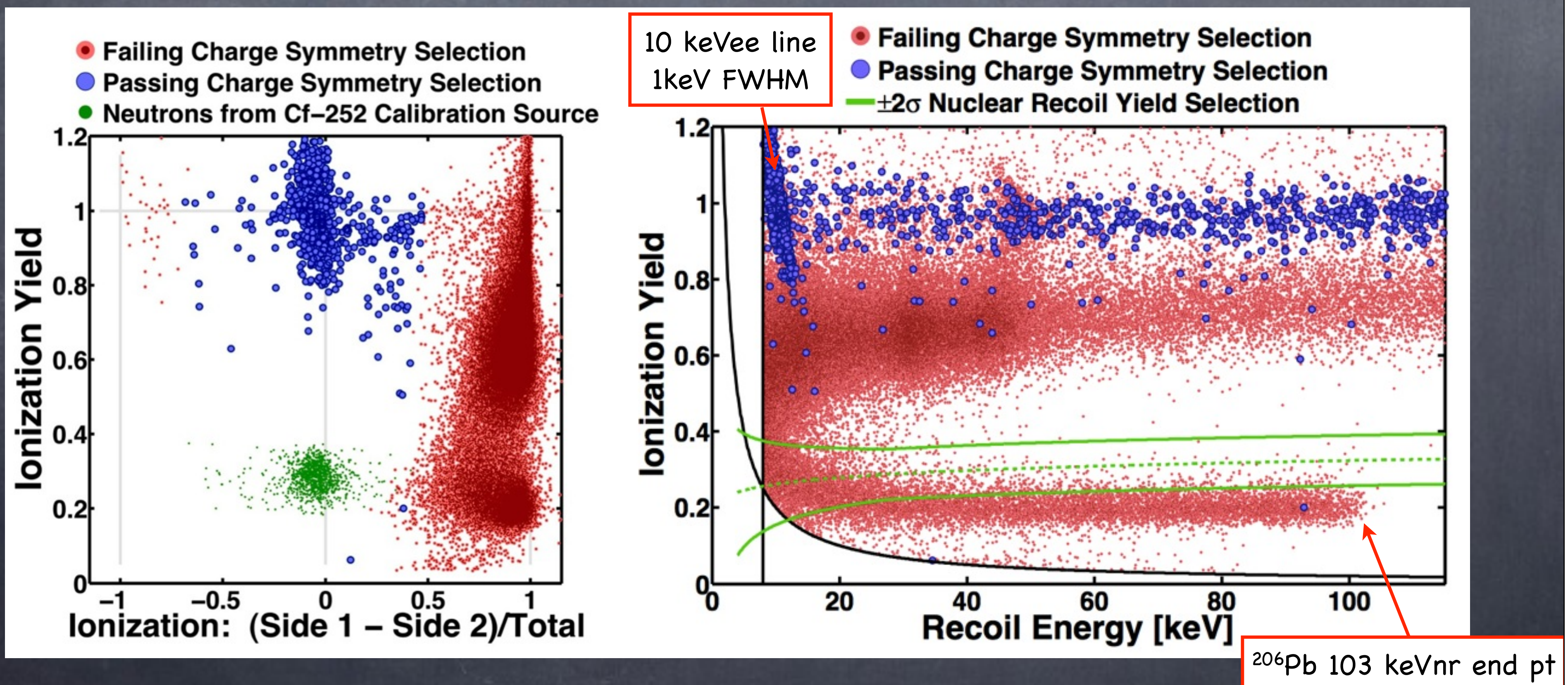






^{210}Pb Source Data from SuperCDMS Soudan

- 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



Conclusion

- Experiments now in most exciting region for neutralino as dark matter in many models of supersymmetry (mSUGRA)
- XENON100 now leads field by x3 at high mass with 3 events in signal region. Plans progressing for XENON1T.
- LUX, Darkside, DEEP, CLEAN and COUP progressing as well.
- SuperCDMS Soudan is now operating 9 kg of Ge and will run for two years improving sensitivity by x5. SuperCDMS SNOLAB with iZIP detectors totaling 200 kg is in R&D phase with plans to start operations in SNOLAB by 2016 will improve sensitivity by an additional x20.
- We have a great horse race for discovering WIMPs. Strong science case for ton scale direct detection major projects, as endorsed by Dark Matter SAG , P5 and PASAG.