Very Low Threshold Scattering - an Experimentalist's Perspective

Low Threshold Detectors for Detection of Coherent Neutrino Scattering

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Livermore Valley Open Campus, Livermore, CA

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and
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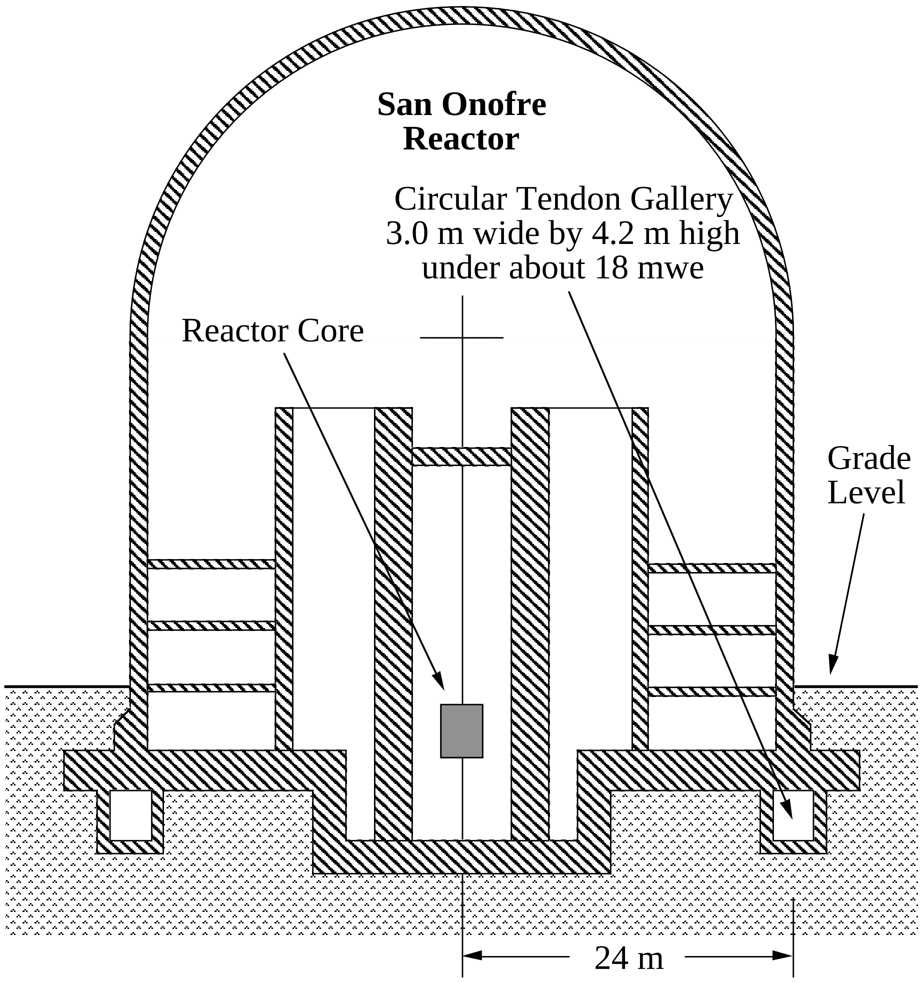
Outline

- Rates for coherent scattering off of nuclei
- Scattering off of electrons flavor dependent
- Sensitivity to magnetic dipole moment of neutrino
- Reactor experiment coherent scattering rates
- Experimentally need low threshold detectors and low backgrounds achieved at a shallow site
- Also see talks tomorrow:
  - Experimental Challenges and Sensitivity Reach with Phonon Detectors - E. Figueroa- Feliciano
  - Phonon Mediated Detection and Very Low Temperature Detectors - N. Mirabolfathi and M. Pyle
  - Solid State Dark Matter Detectors - B. Sadoulet

Nuclear Reactor Site

- Tendon gallery
- antineutrino flux 6×10^{12} per cm^2 per sec
- shielding from cosmic rays about 20 mwe
- Ge diode experiment
  - J. Collar
  - P. Barbeau



Model Reactor Neutrino Experiment

- A neutrino with incident energy E_ν will scatter off an electron $M = m_e$ or a nucleus M with recoil energy T with a cross section

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi}\left\{\left(C_V + C_A\right)^2 + \left(C_V - C_A\right)^2\left[1 - \frac{T}{E_\nu}\right]^2 - \left(C_V^2 - C_A^2\right)\frac{MT}{E_\nu^2}\right\}$$

for $\quad 0 \le T \le 2E_\nu^2 / \left(2E_\nu + M\right)$

- For neutrino scattering off electrons

$$\left.\begin{aligned} C_V &= 2\sin^2\theta_W + (-)\tfrac{1}{2} \\ C_A &= +(-)\tfrac{1}{2} \end{aligned}\right\} \text{ for } \nu_e\left(\nu_\mu \text{ or } \nu_\tau\right) \text{ and for } \bar{\nu}\text{'s } C_A \to -C_A$$

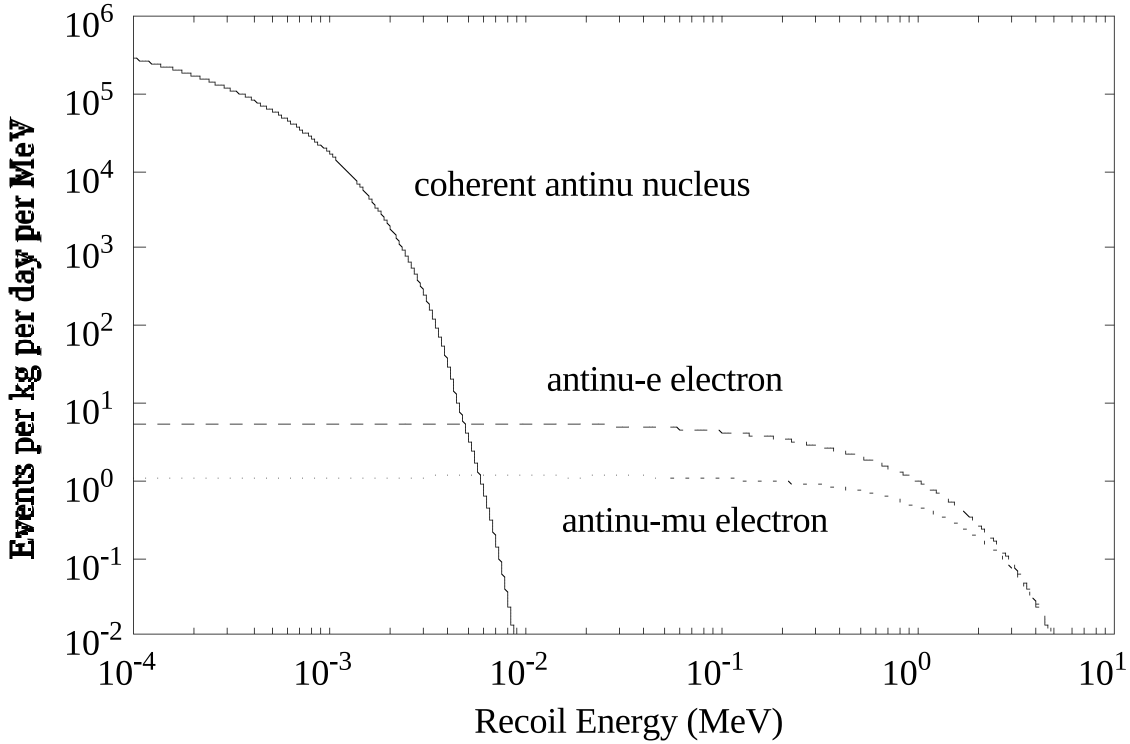
- For scattering off nuclei Z protons and N neutrons

$$C_V = \left(2\sin^2\theta_W - \tfrac{1}{2}\right)Z + \left(\tfrac{1}{2}\right)N \quad \text{and} \quad C_A = 0$$

- Cross section larger than electron scattering by N^2

100 day run with 3 kg of Si Detectors

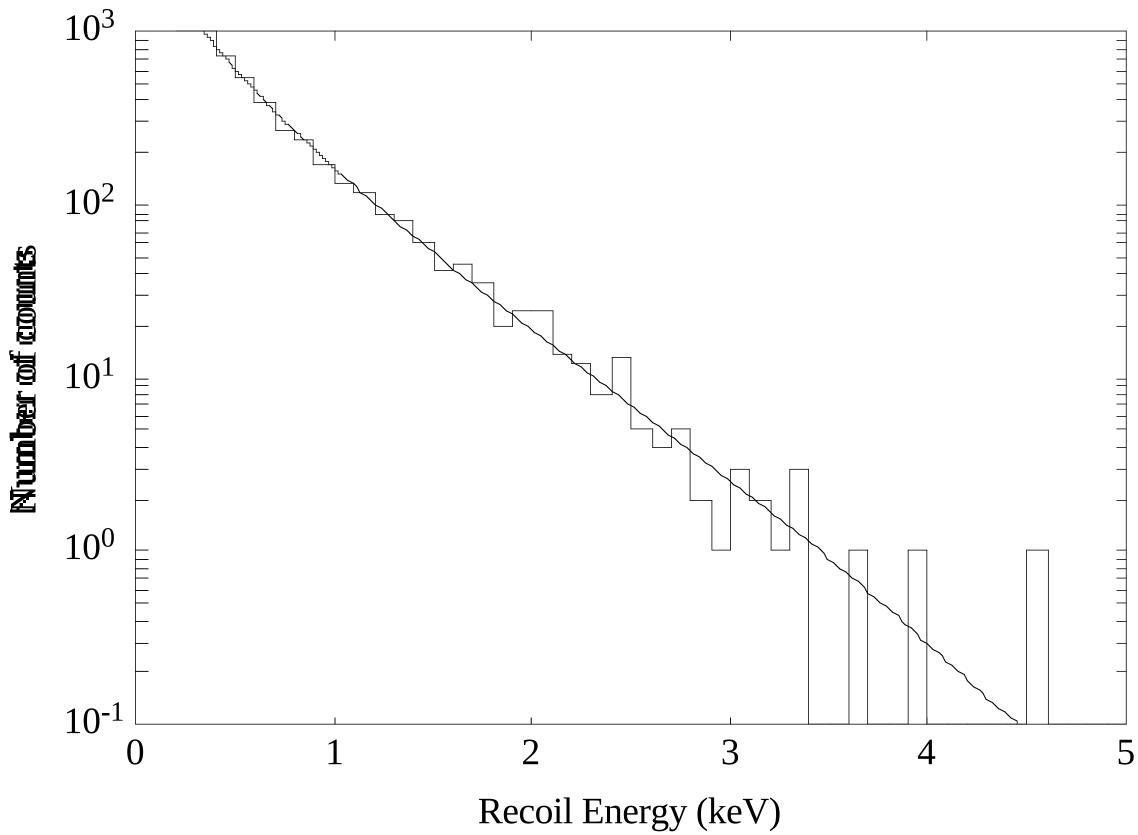
- In princple, we can measure total neutrino flux with nuclear scattering and electron neutrino flux with electron scattering
- But backgrounds are much more difficult for electron scattering



Nuclear recoils in 300 day run

- Coherent nuclear scattering, with 0.1 keV bins. A 0.5 keV threshold would yield hundreds of events per 0.1 keV at the lower energies. The spectrum could be fit with some accuracy up to about 3 keV.

divide by 30 to convert y-axis to events per keV per kg per day



Magnetic moment neutrino measurement

- Measure directly the magnetic moment of the neutrino through the coupling of magnetic moment to the electric charge of an electron or a nucleus.
- To model the effect of a neutrino magnetic moment on a reactor experiment, we use the additional neutrino-electron scattering cross section,

$$\frac{d\sigma}{dT} = \frac{\pi\alpha^2\mu_\nu^2}{m_e^2}\left[\frac{1}{T} - \frac{1}{E_\nu}\right]$$

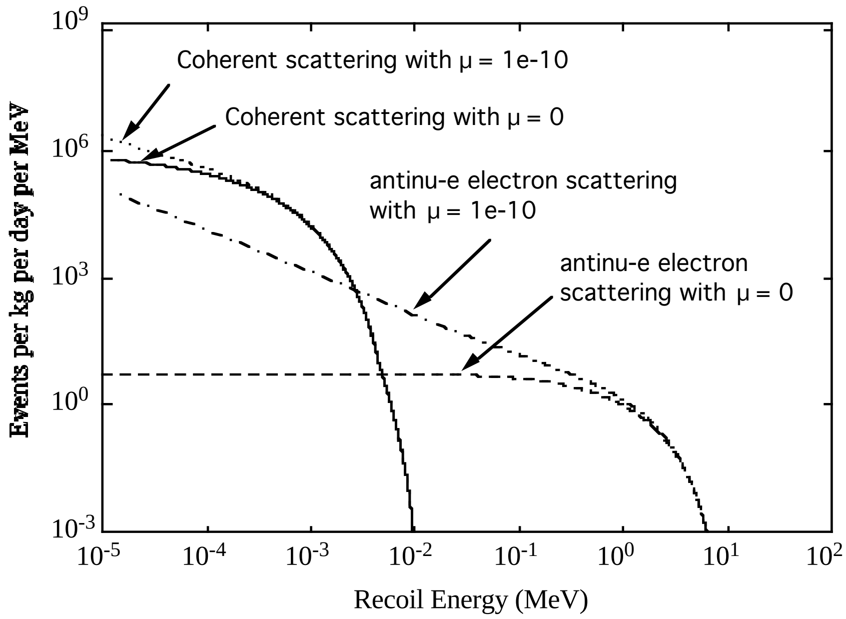
and for coherent nuclear scattering on a spin-zero nucleus,

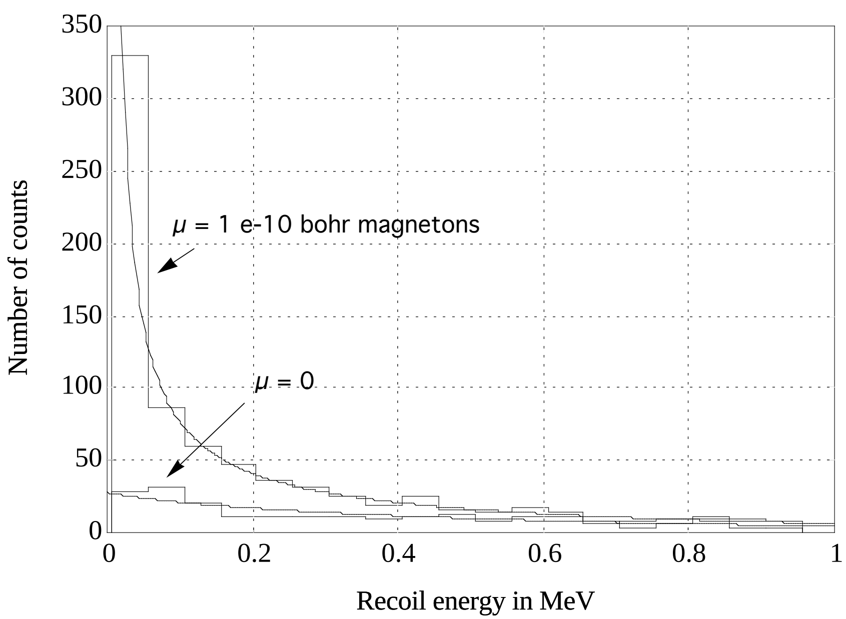
$$\frac{d\sigma}{dT} = \frac{\pi\alpha^2\mu_\nu^2}{m_e^2}\left[\frac{1}{T} - \frac{1}{E_\nu} + \frac{T}{4E_\nu}\right]Z^2$$

but there exists a $T_{\min}$ which is related to distance over which the electron or nuclear charge is screened.

For 300 kg-day reactor experiment

- The magnetic moment effects can be large particularly for electron scattering. Shown are the simulated results of a 100 day run with a 3 kg mass Si detector.
- Potentially such an experiment can set a direct upper limit approaching 10^{-11} Bohr magnetons or better.

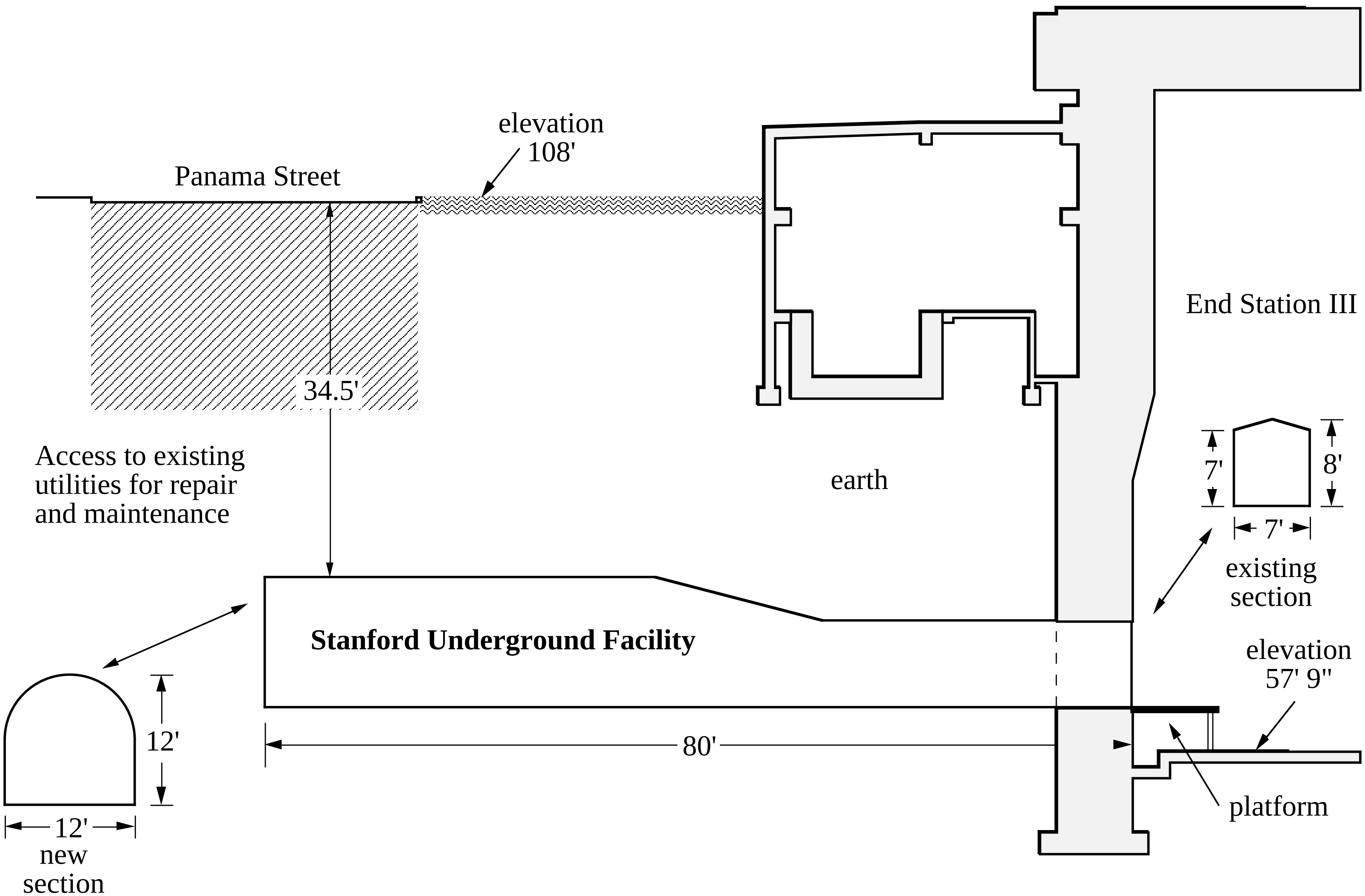




Background considerations

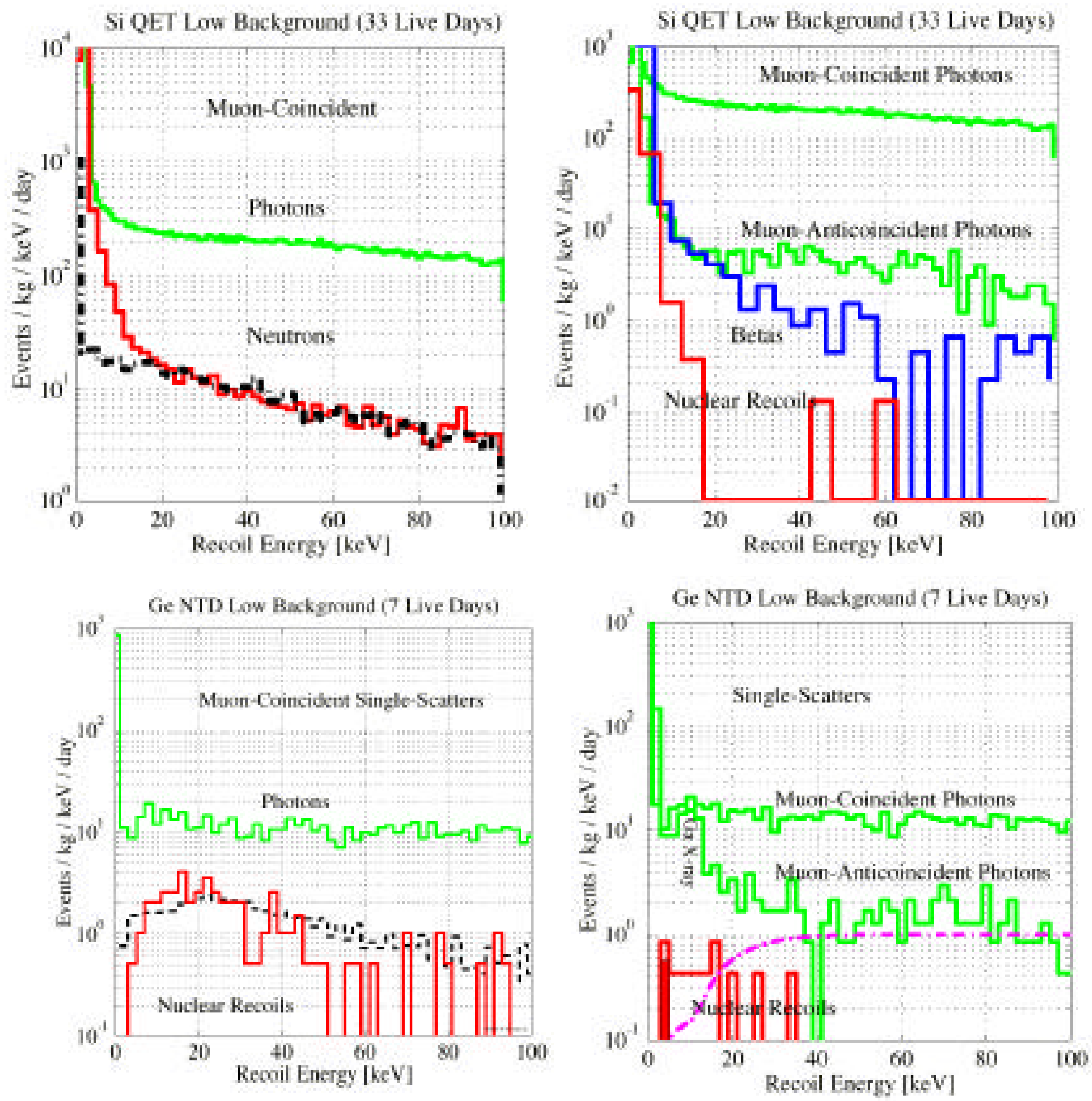
- Clearly, these event rates alone mean nothing until we compare them with backgrounds from radioactivity and neutrons.
- The CDMS experiment at SUF had nearly the same background considerations at 20 mwe overburden with a muon veto.
- Thus the background management strategy used for that experiment would be directly applicable for the reactor neutrino detector.
- These backgrounds are nearly all electron recoils from gammas and beta decays and would be largely removed by the discrimination of electron recoils versus nuclear recoils in our detectors.

Stanford Underground Facility (SUF)



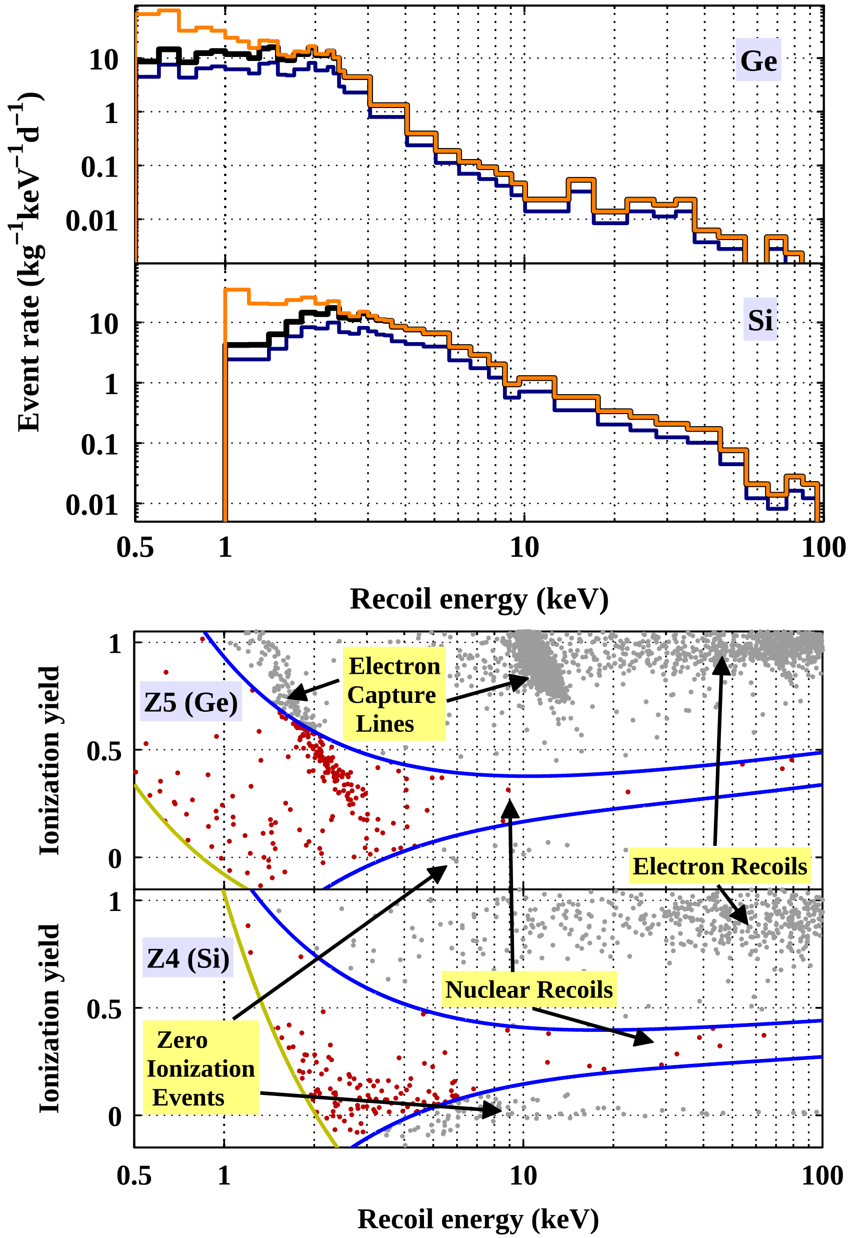
CDMS backgrounds at SUF

- Upper two plots for Si detectors
- Left muon coincident
- Right muon anti-coincident
- Lower two plots for Ge detectors
- Left muon coincident
- Right muon anti-coincident



Detailed analysis of SUF data

- Top plot is combined Ge (upper panel) and Si (bottom panel) WIMP candidate event rates as a function of recoil energy.
- Bottom plot is ionization yield vs recoil energy for unvetoed single scatters for Ge (top panel, Z5 6 V) and Si (bottom panel, Z4 3 V) WIMP searches
- From PHYSICAL REVIEW D 82, 122004 (2010)

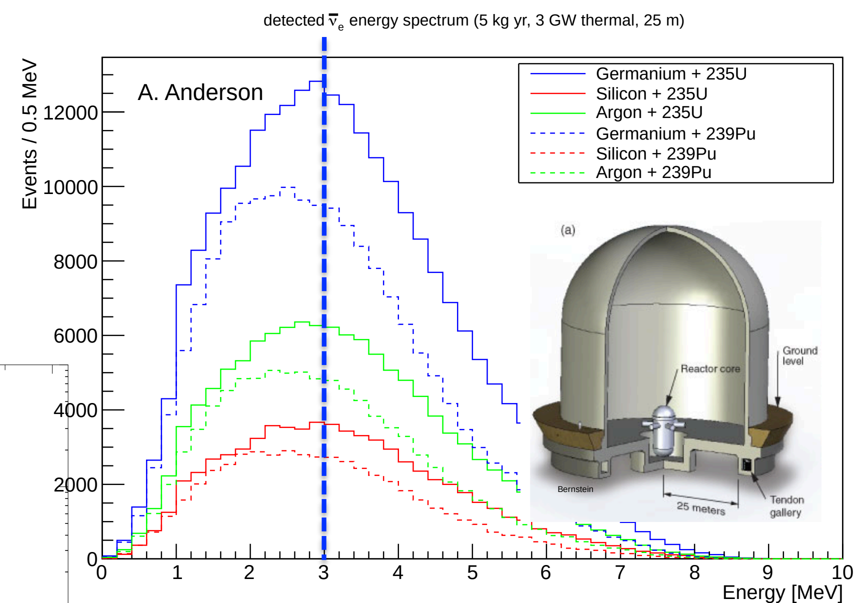


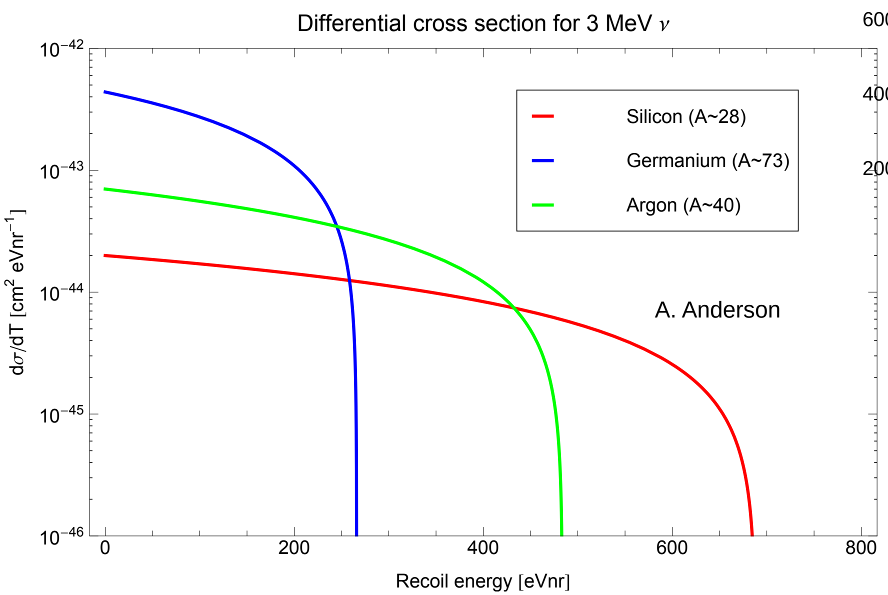
CNS - Recoil Energy Scale is lower

- Never Been Measured!
- $M_N >> E_\nu$ & 4 momentum conservation dictates:

$$\Delta P \lesssim 2P_\nu$$

$$\Delta E \lesssim \frac{\Delta P^2}{2M_n} = \frac{2E_\nu^2}{M_n c^2}$$





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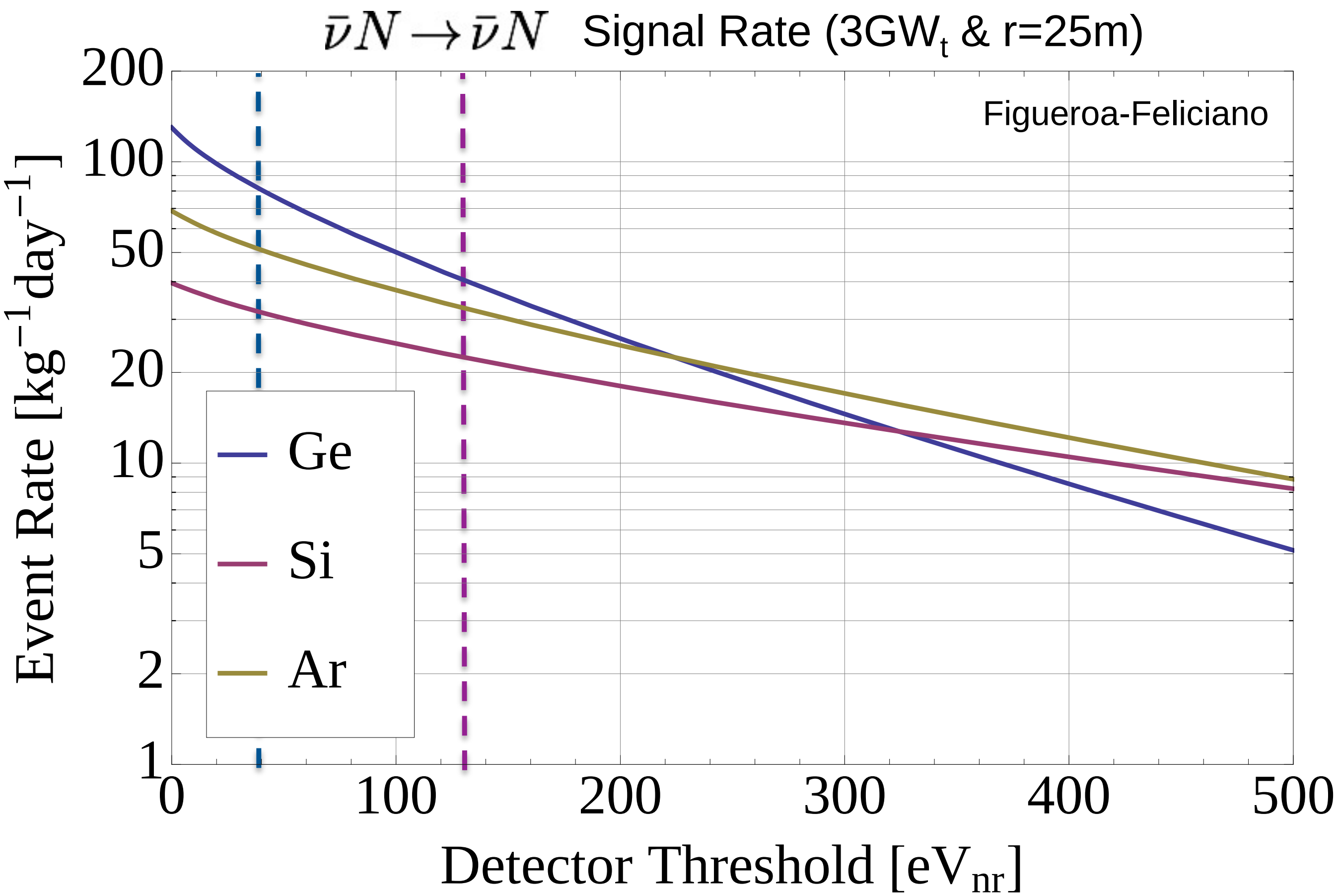
CNS - Reactor Trigger Thresholds



- Reactor Experiment Trigger Threshold Requirements
  - Si: 130eV$_{nr}$
  - Ge: 40eV$_{nr}$

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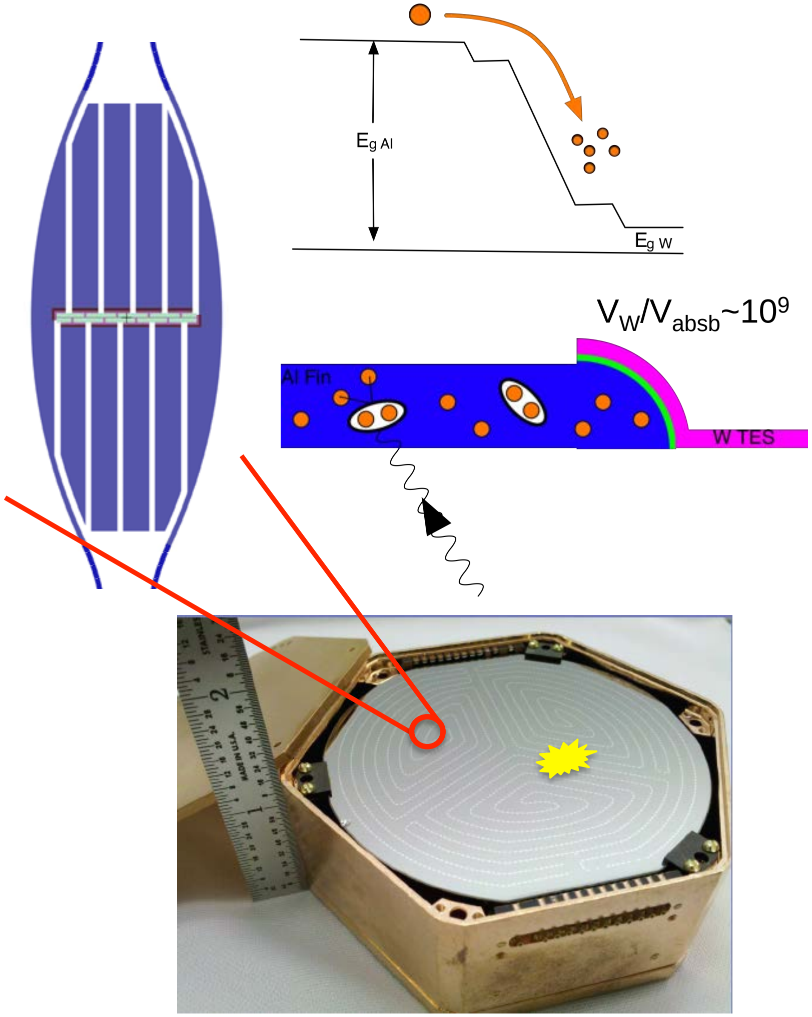
Athermal Phonon Detection Principles

QET (quasiparticle trap assisted electrothermal feedback transition edge sensor)



- Become insensitive to $C_{absorber}$ by collection and concentration of Phonons
- More Complex
- Collection efficiencies (ε)
  - Theoretical Max: ~40%
  - Best Measured: 20±4%
  - CDMS II: 1-4%
  - SuperCDMS <ε>: ~12±3%
  - Active Research Area for Stanford SuperCDMS
- Not New -> CDMS technology (10+ yrs)

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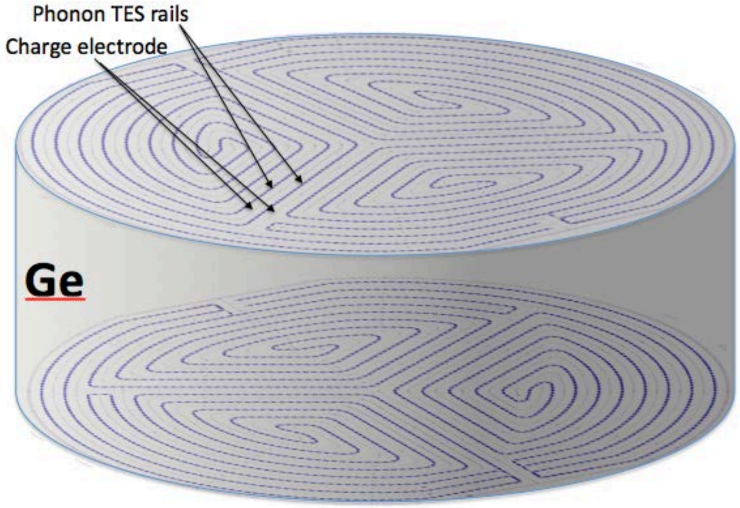
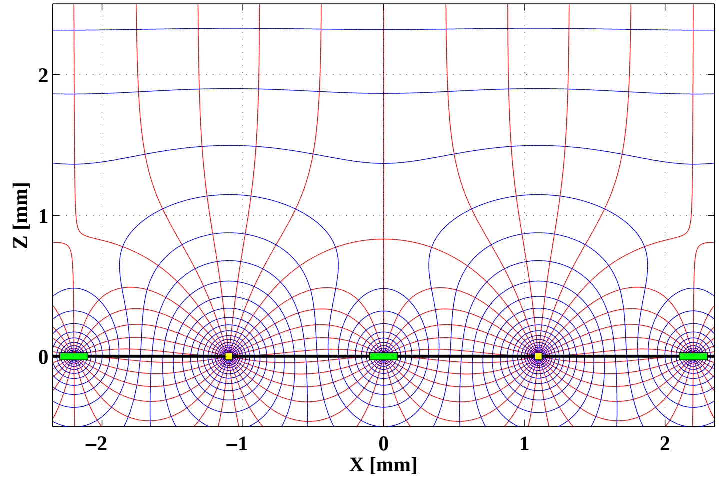
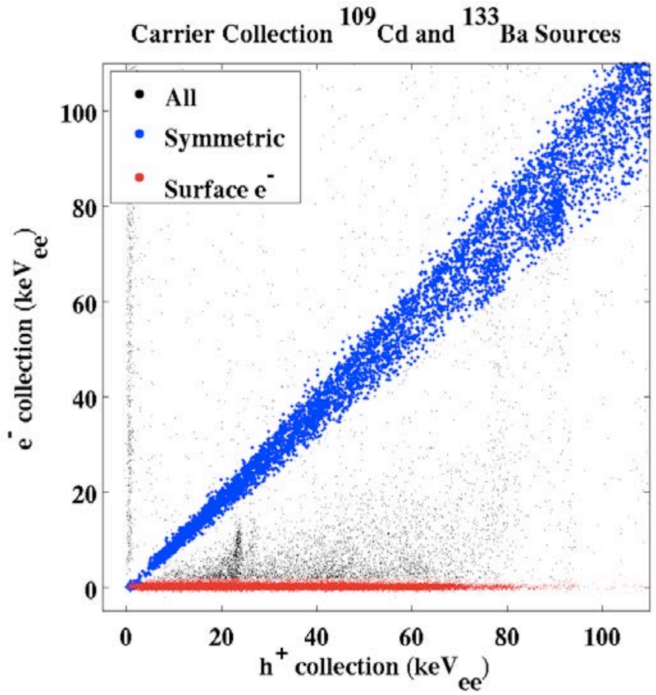
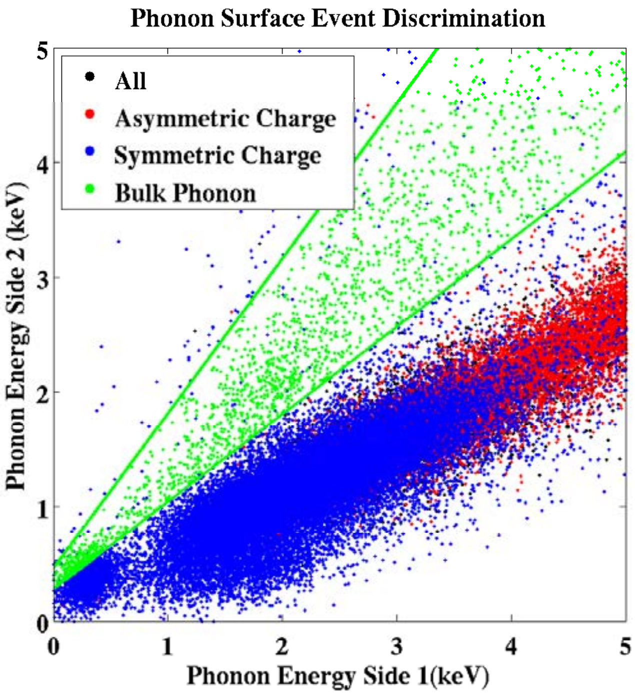
Advanced IZIP Detectors



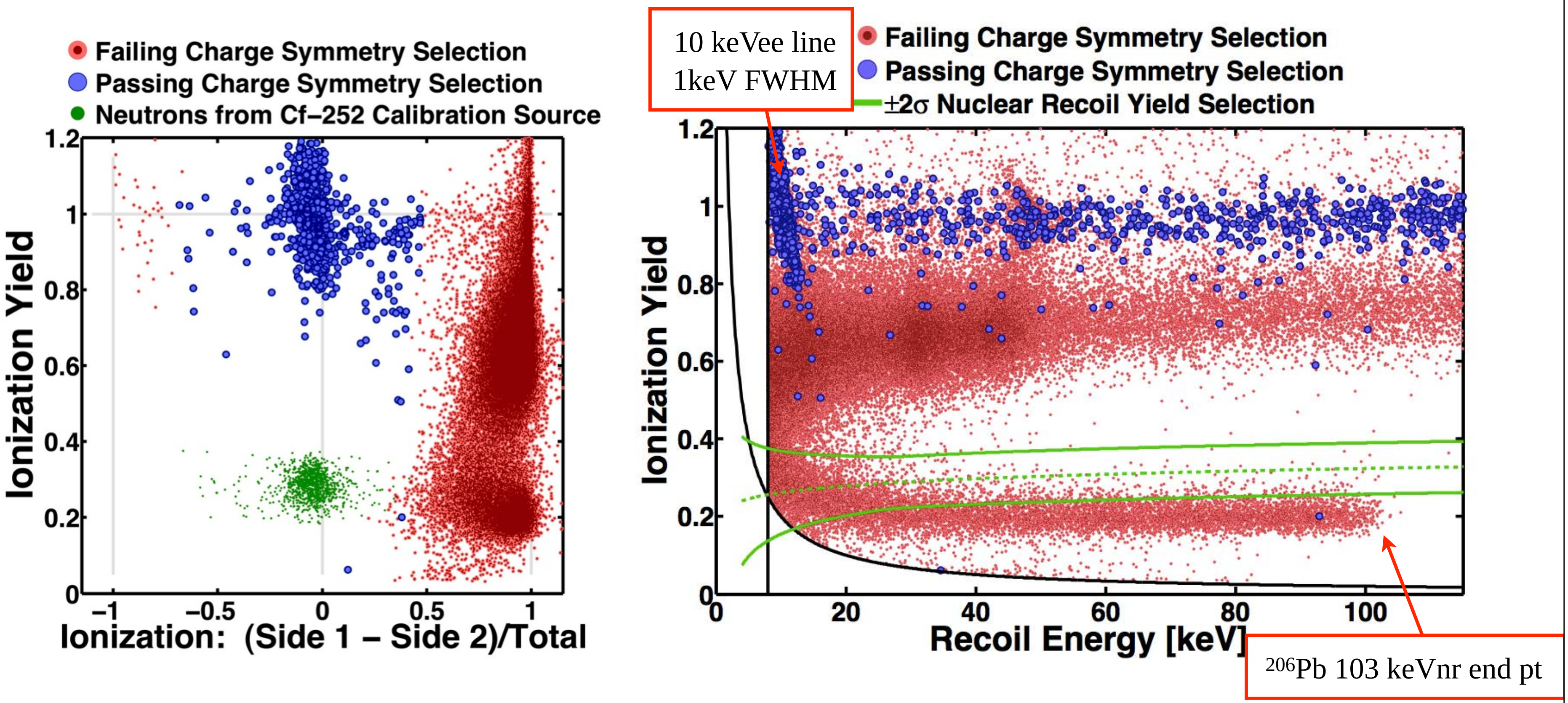






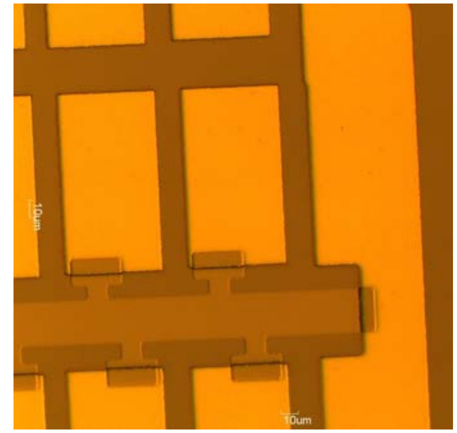
Pb210 Source Data from SuperCDMS Soudan

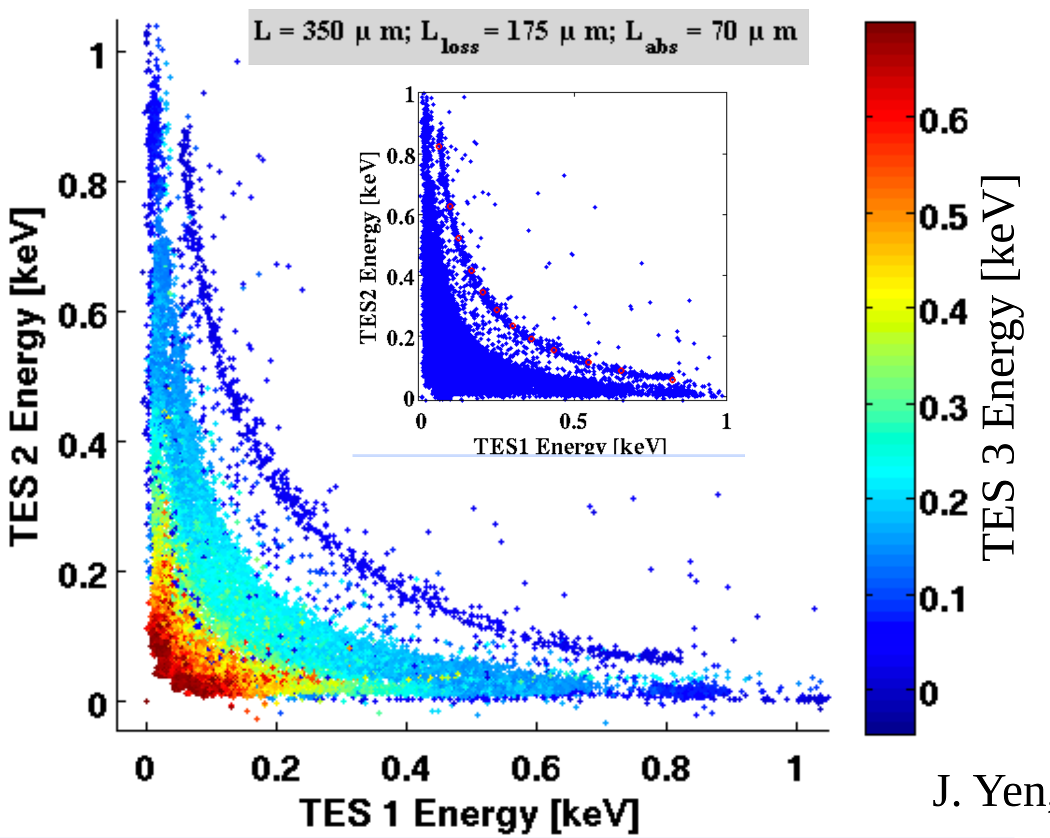
- Two detectors with one Pb210 decay every min operated for 20 live days corresponds to more than total Pb210 events for SuperCDMS Soudan and even for future 200 kg SuperCDMS SNOLAB

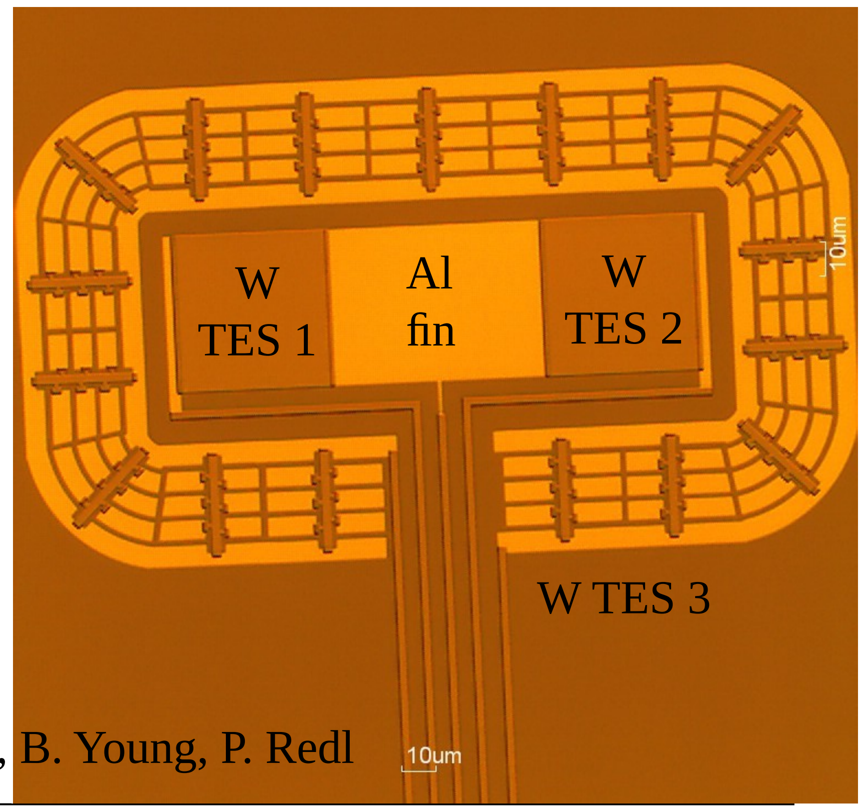


Optimize QET design

- 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



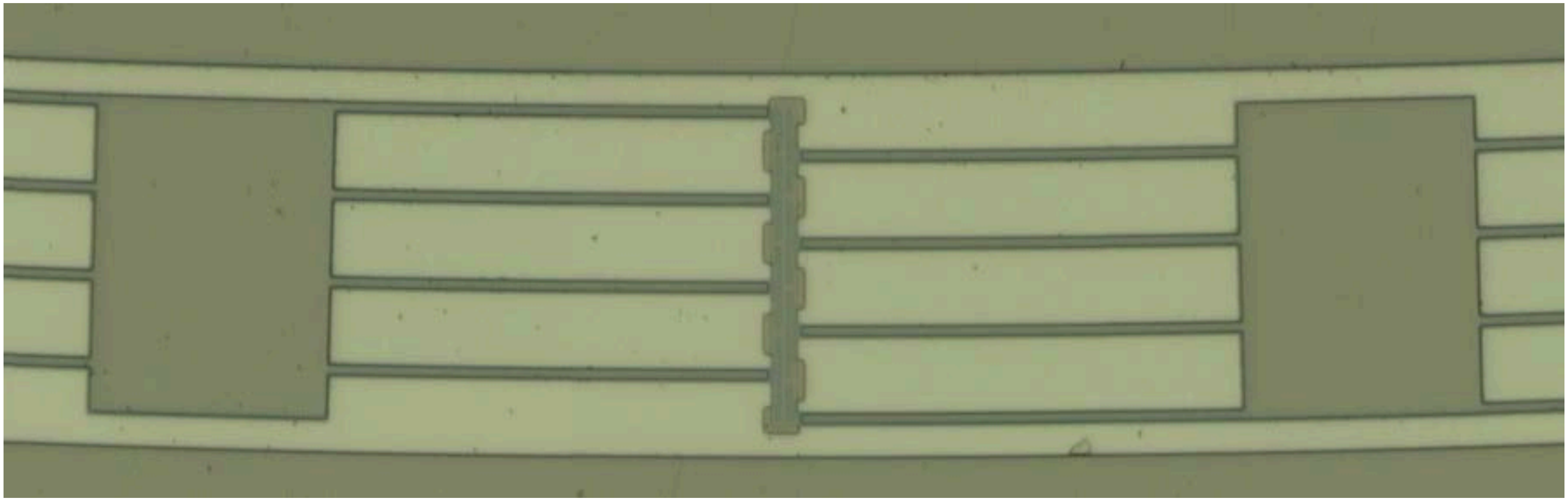




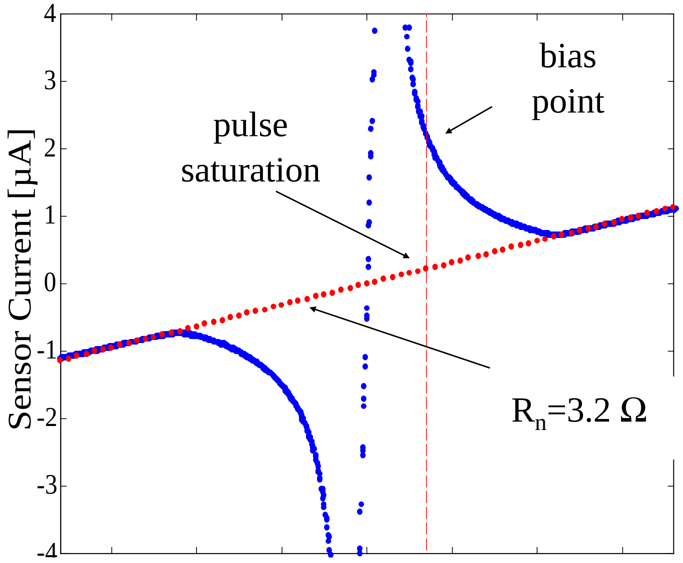
J. Yen, B. Young, P. Redl

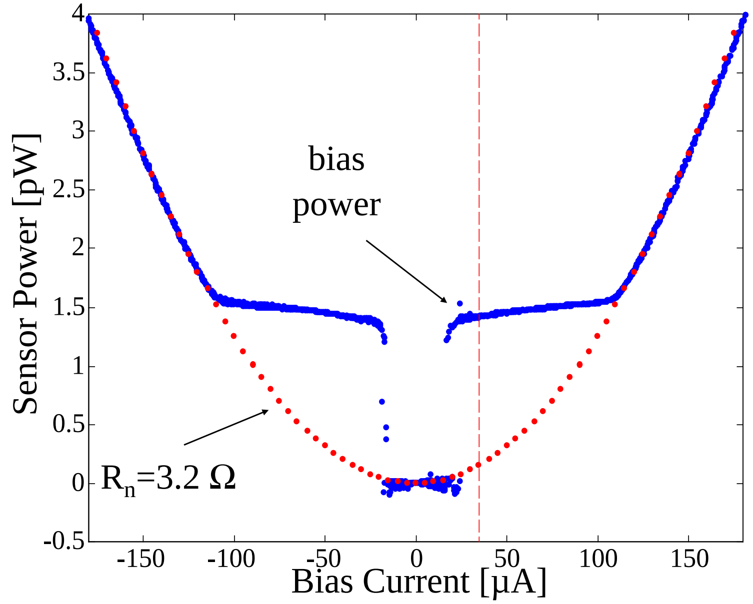
Further Optimization of Al Fins

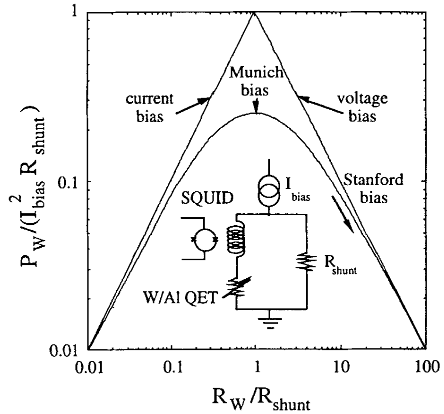
- Adjust length of Al fins to optimize quasiparticle collection into TES lines
- Adjust length of W lines to avoid phase separation along each line
- Adjust W transition temperature to optimize energy resolution

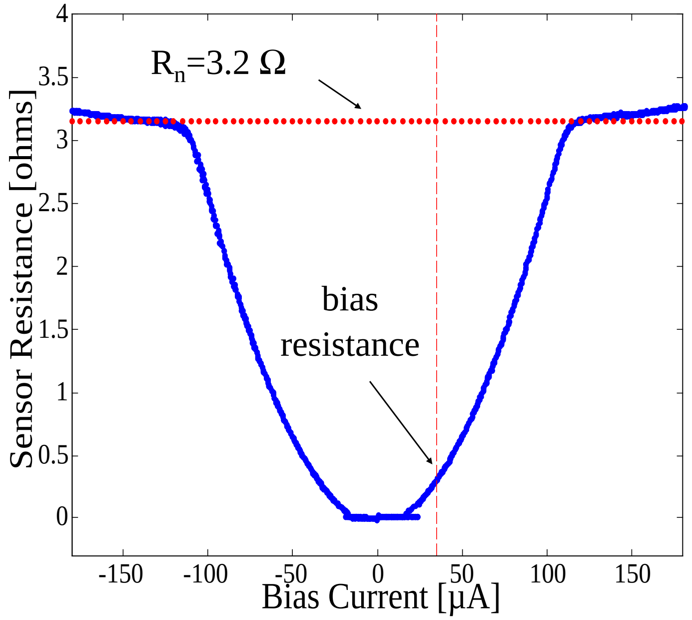


Characterize Performance of TES



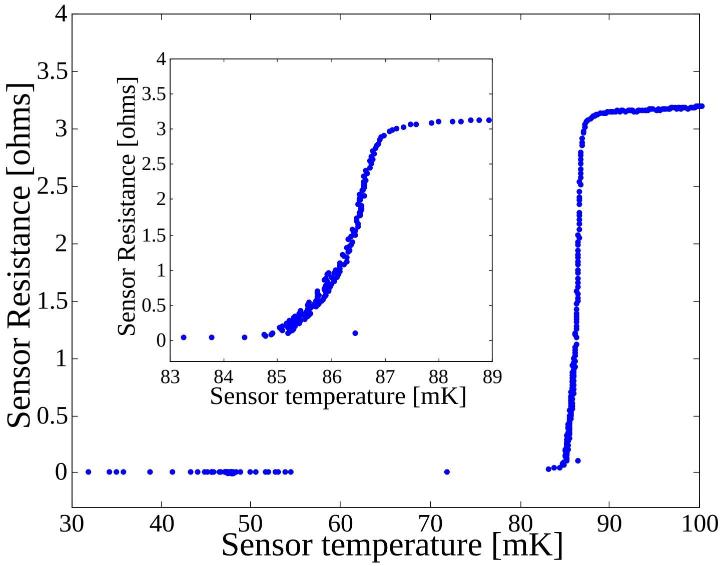






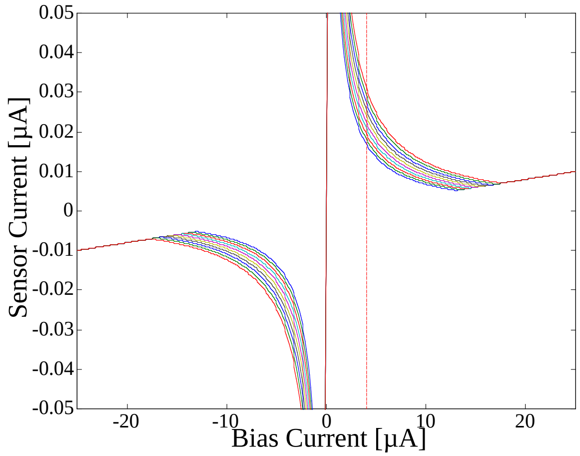
We calculate transition width from power curve using

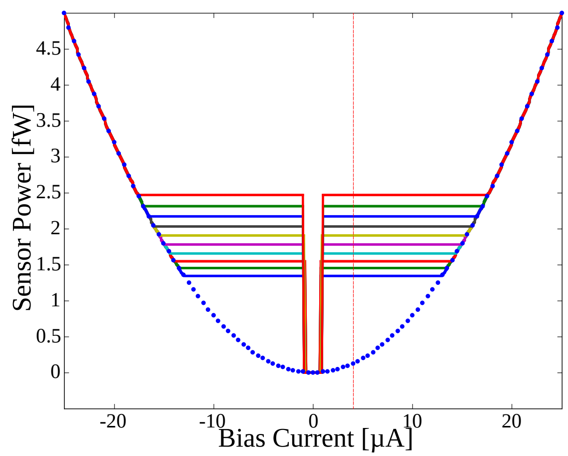
$$P_J = \Sigma\left(T_e^5 - T_{ph}^5\right)$$

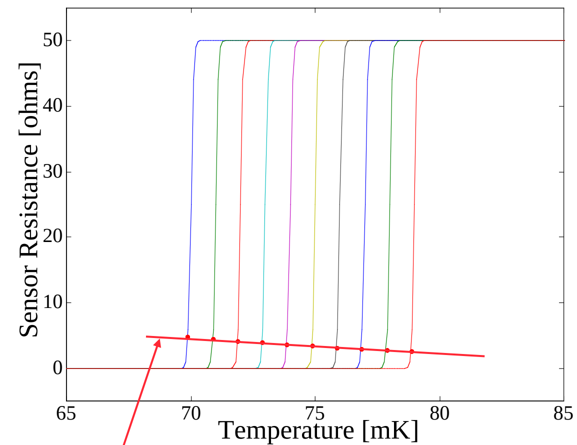


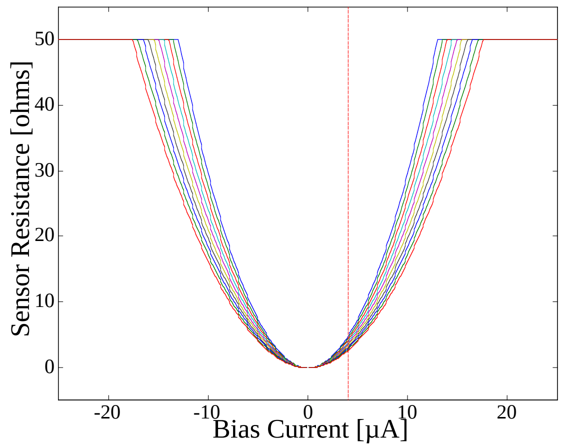
Transition Temperature Gradient Problem

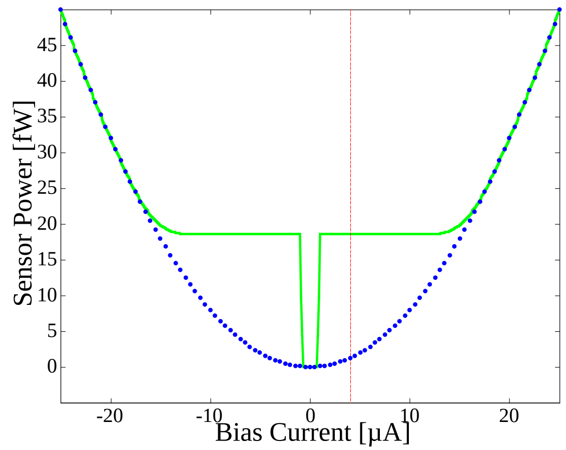
- Voltage biased TES sensors where invented to solve the Tc gradient problem for large area sensors





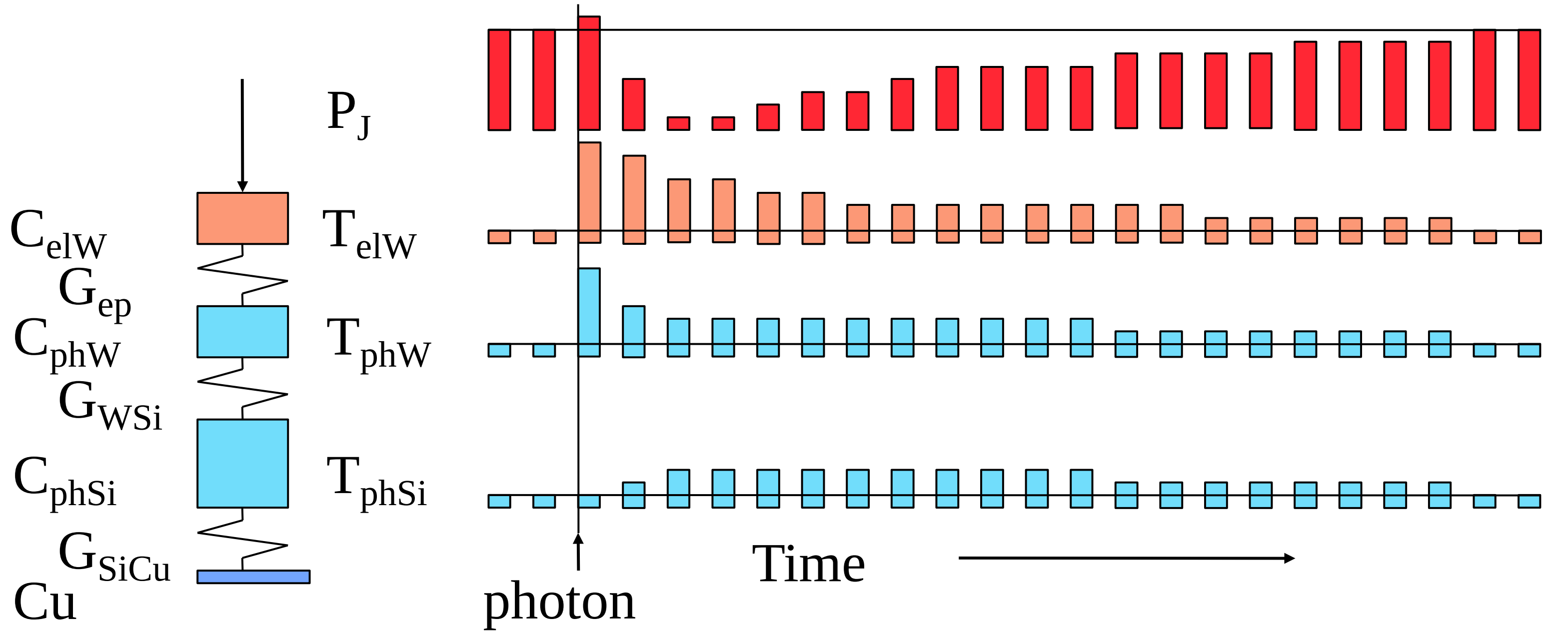






With current bias, there did not exist a bias temperature for all, but with self voltage biasing all at high sensitivity.

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 interaction limits conductance at low temperature

  - 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

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

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

Summary

- Interesting science applications at low energy
  - neutrino-nucleus coherent scattering
  - searches of sterile neutrinos
  - limits on neutrino magnetic dipole moment
  - ultra-light dark matter candidates (~MeV)
- iZIP advanced detectors reject surface electrons
  - interleaved design allows identification of surface events
  - preserves timing discrimination
  - demonstrated nuclear recoil discrimination with phonons
- Sub - 100 eV thresholds seem technically possible
  - Tc^3 scaling for athermal phonon detectors shown
  - Optimize detector design to maximize phonon collection