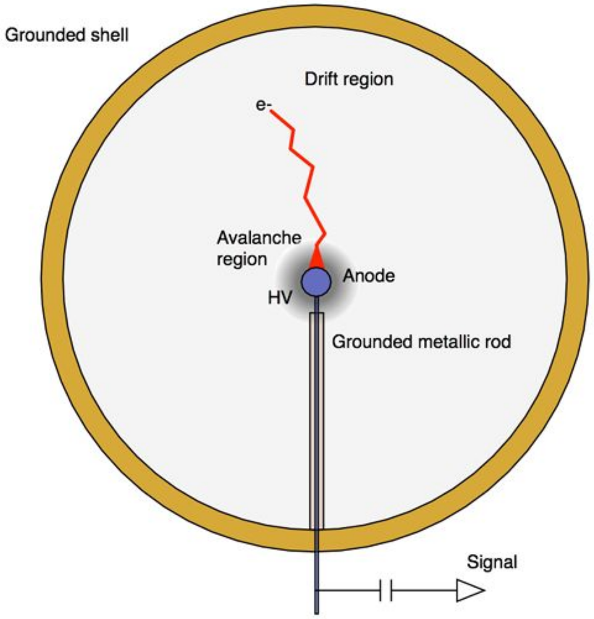
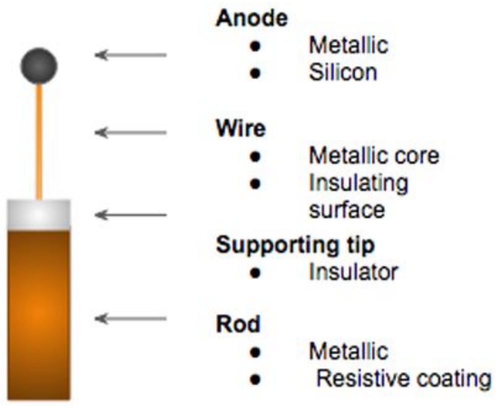
Non-collider Detectors

https://arxiv.org/pdf/1809.02485.pdf

NEWS-G -- continuing with gas chambers



(a)



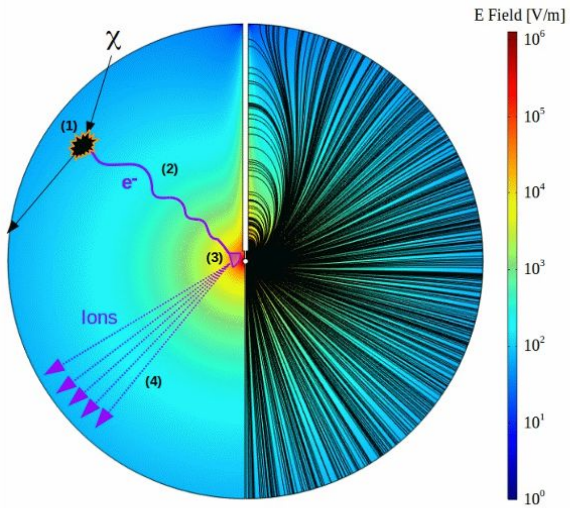
(b)

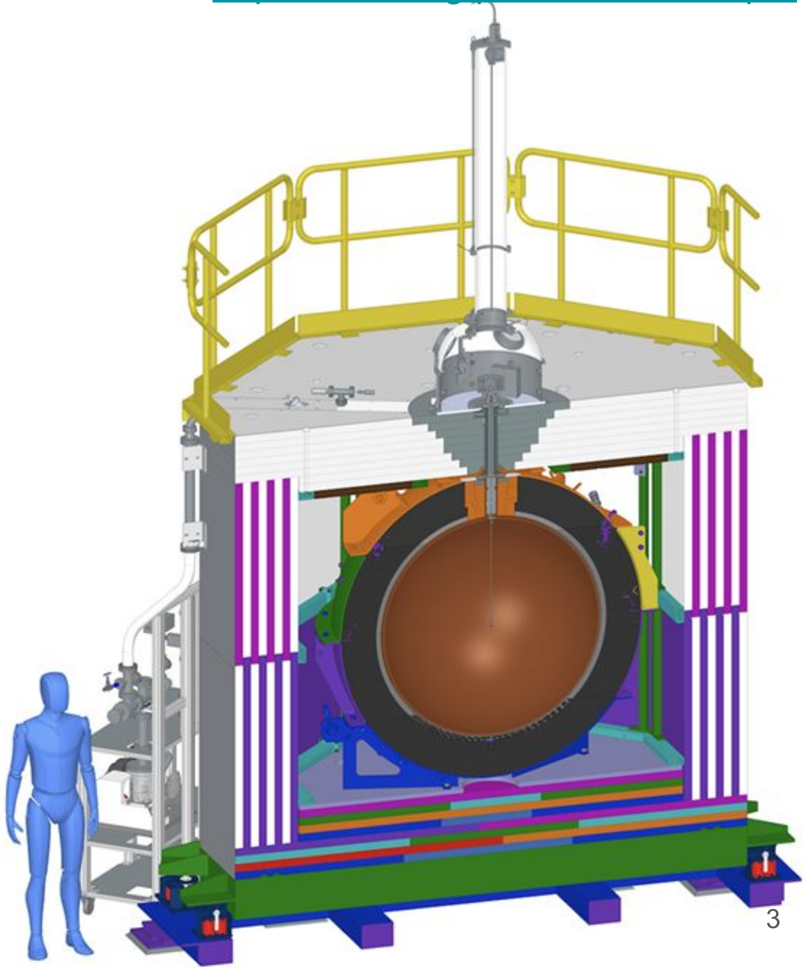
Figure 1: (a) SPC design and principle of operation and (b) illustration of the basic read out sensor[5].

https://arxiv.org/pdf/1809.02485.pdf
https://arxiv.org/pdf/2205.15433.pdf

NEWS-G

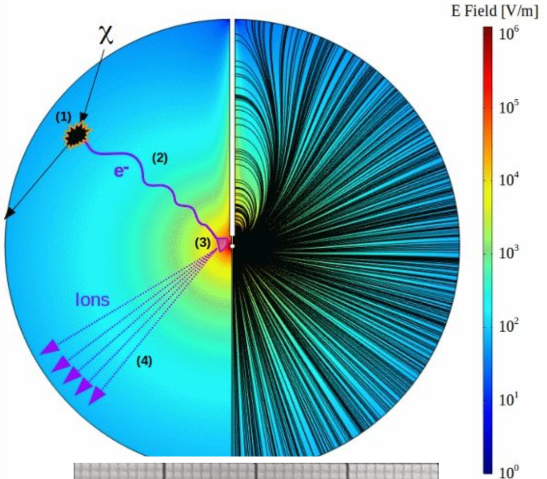
- New Experiments With Spheres-Gas
- Spherical Proportional Counter
- Noble gases as targets
- Search for light dark matter
  - Down to sub-GeV mass region





NEWS-G -- Electrode

- From last lecture:
  - Mostly measuring drifting ions
  - Most ions generated near surface of the anode
    - Large E-field $$E(r) \approx \frac{V}{r^2} r_A$$
    - Tend to make anodes small
    - → larger 2nd ionization
- For small r_A, E field at large r becomes small as well
- Attachment & recombination becomes a problem
- → "Achinos" sensor:
  - Large r E-field determined by overall sensor shape
  - Local E-field determined by individual anode



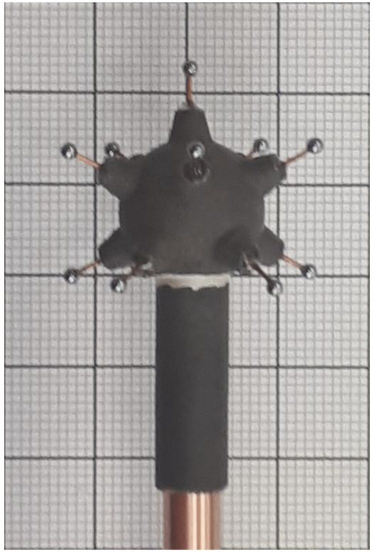


Figure 2. An 11-anode ACHINOS sensor.

https://en.wikipedia.org/wiki/Shockley%E2%80%93Ramo_theorem

Shockley–Ramo theorem

The Shockley–Ramo theorem states that the instantaneous current i induced on a given electrode due to the motion of a charge is given by:

$$i = E_v q v$$

where

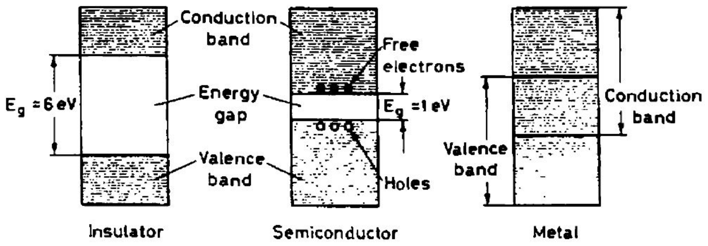
- q is the charge of the particle;
- v is its instantaneous velocity; and
- E_v is the component of the electric field in the direction of v at the charge's instantaneous position, under the following conditions: charge removed, given electrode raised to unit potential, and all other conductors grounded.

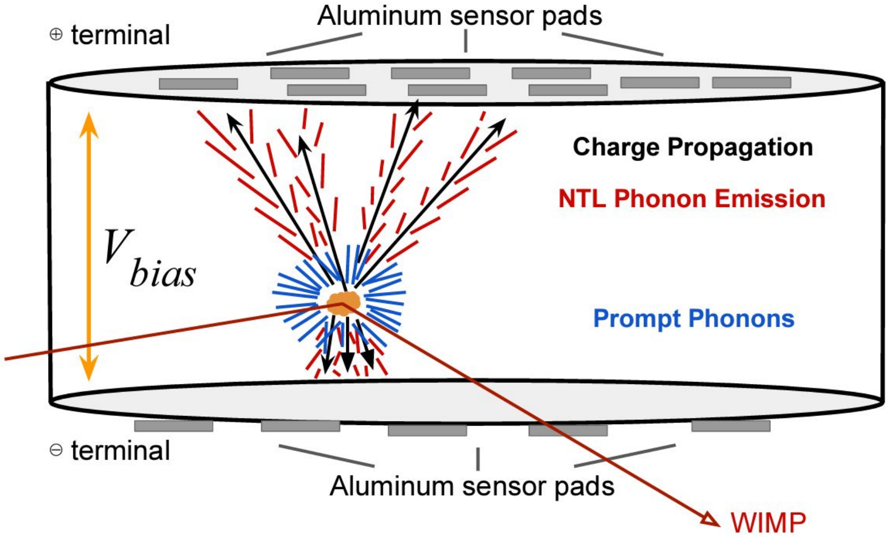
Can verify expression in last lecture

INDUCED SIGNAL $dv = \frac{Q}{C \ell V_0} \frac{dV}{dr} dr.$

Take away: The signal measured is charge-drifting induced signal…

Semiconductor detectors: Charge and phonon readouts

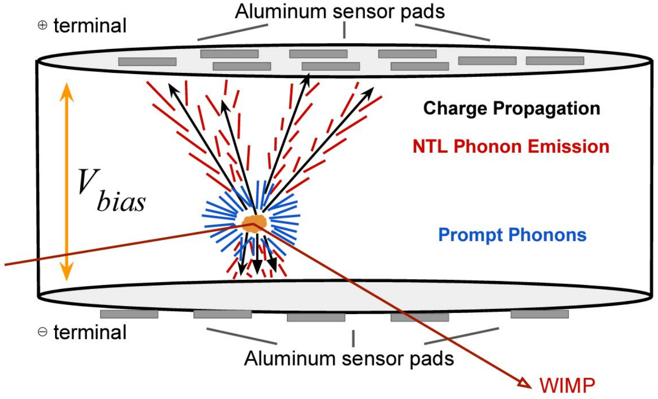




$$\text{Phonon energy} = E_{recoil} + E_{Luke}$$

$$= E_{recoil} + n_{eh}\, e^{-}\, \Delta V$$

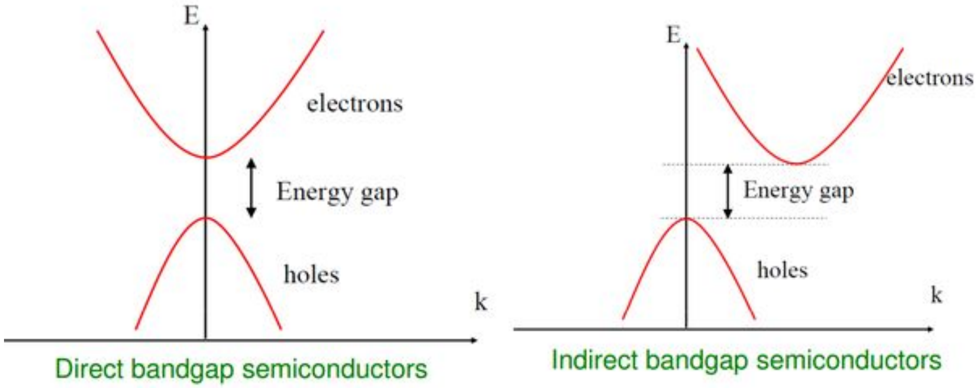
Semiconductor detectors
Microscopic interactions



- Detector crystal is voltage biased
- Initial recoil generates electron-hole pairs
- Electrons and holes gain initial kinetic energy
  - Immediately emit as phonons -- NTL effect
- Electrons and holes drift across semiconductor
  - Drift speed depends on E-field and temperature
    - ~5000 cm/s at low temperature, ~ 1 V/cm
  - Notice electrons don't follow electric field
    - Tensor mass of electron in semiconductor
  - All ionization happens at ~ initial recoil
    - Tend not to induce avalanche (except Avalanche PhotoDiodes/SiPM)
  - Emit phonons as they go
- Charge measured by Shockley–Ramo theorem, $E_{Phonon}=E_{recoil} + n_{eh}\, e^{-}\, \Delta V$

Direct band-gap vs indirect band-gap

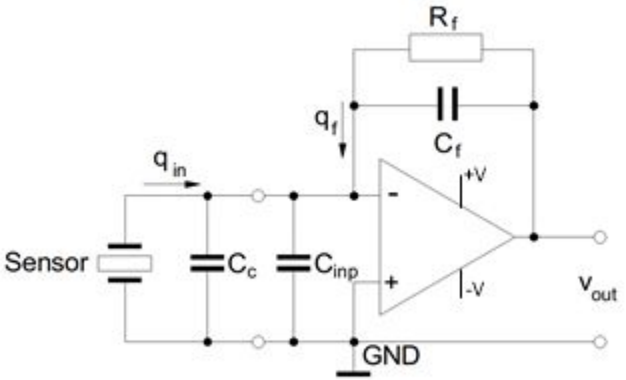
- Energy and momentum both need to be conserved in a transition
- During absorption, momentum compensation can be via phonon absorption (room temp.) or phonon emission (low temp.)



- For direct band-gap materials, excited electron can recombine by **photon** emission
  - → Materials for scintillator detectors / LED (InAs, GaAs)
- Indirect band-gap materials don’t emit photons
  - → Charge detectors (Si, Ge)

https://en.wikipedia.org/wiki/Charge_amplifier

Charge amplifier



- Detector design is often integrated with readouts
- Charge detector:
  - Collecting charge on its capacitance
  - Amplifying via "charge amplifier"
  - Discharge via feedback resistor

$$q_{in} = q_f$$

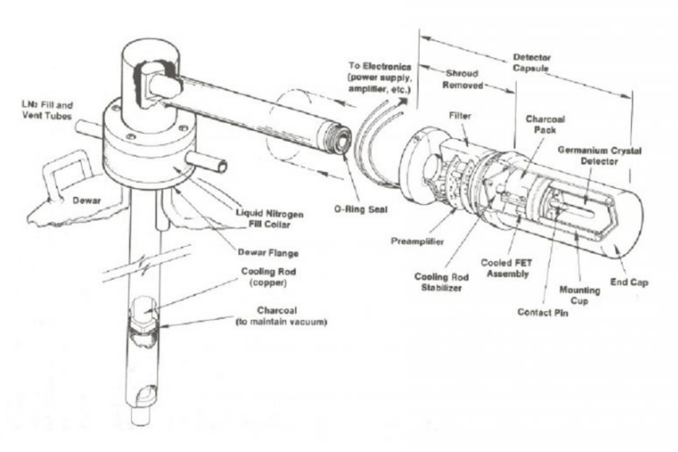
$$V_{out} = q_f / C_f = q_{in} / C_f$$

Decay time: R_f*C_f

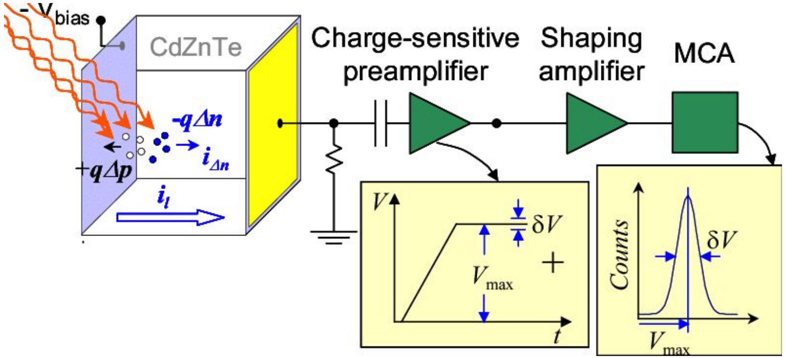
- Detector capacitance critical for noise
  - Voltage noise (v_n) amplified by C_{in}/C_f

Semiconductor charge detector examples

- High purity germanium (HPGe)
  - Work at liquid Nitrogen temperature
  - Can cool down electronics
  - Resolution ~keV

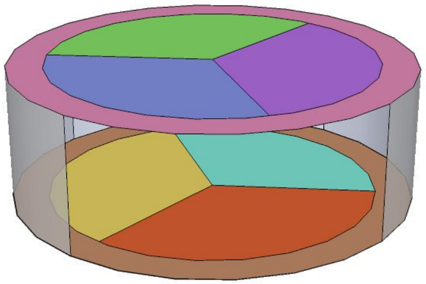


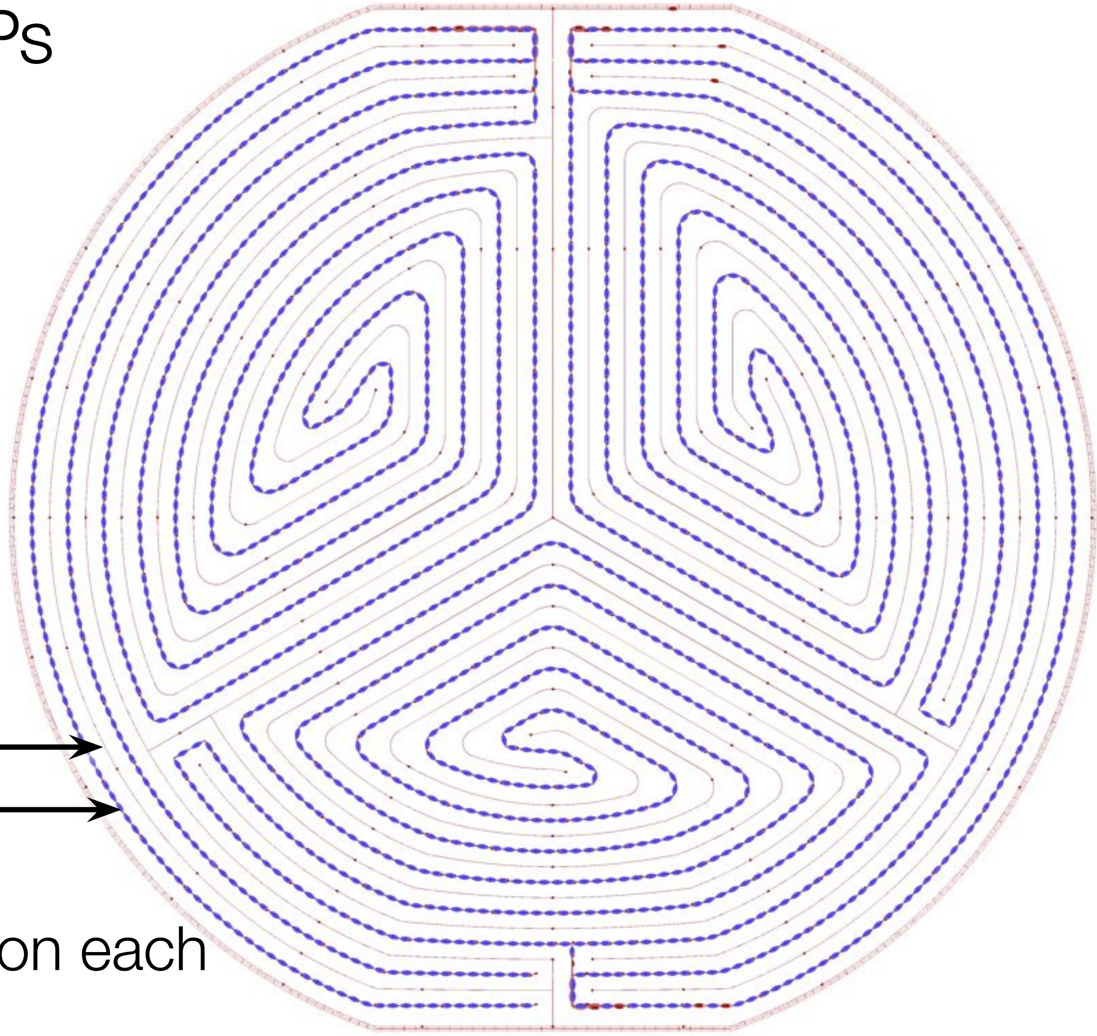
- CdTe/CdZnTe
  - Work at room temperature
  - Resolution ~ a few keV



SuperCDMS Soudan iZIPs

8 phonon channels +
4 charge sensors =
Lots of information per event!



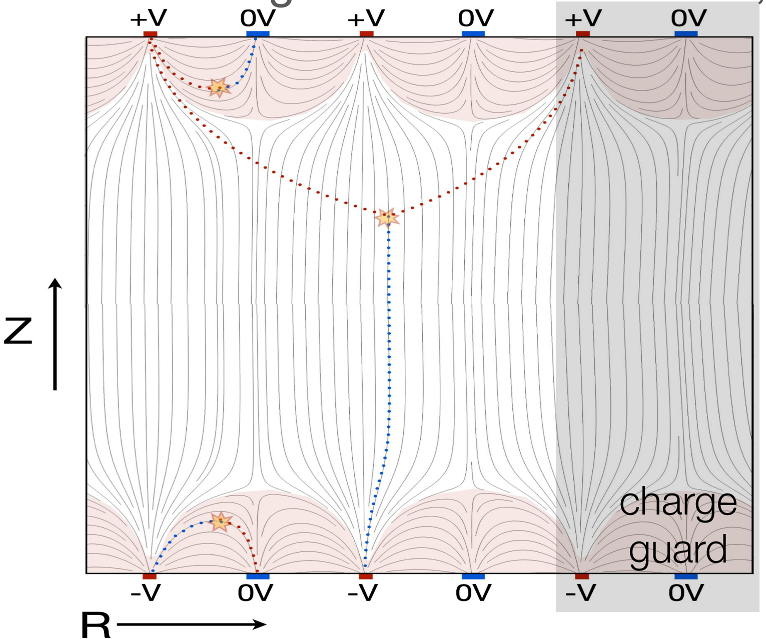


"interwoven"
phonon *and* charge on each side!

https://doi.org/10.1016/j.nima.2008.03.103

SuperCDMS Soudan iZIP

- Minimize C_D and C_P
- Cool down first stage amplifier (JFET)
  - Next generation uses HEMT, operating at 1 Kelvin



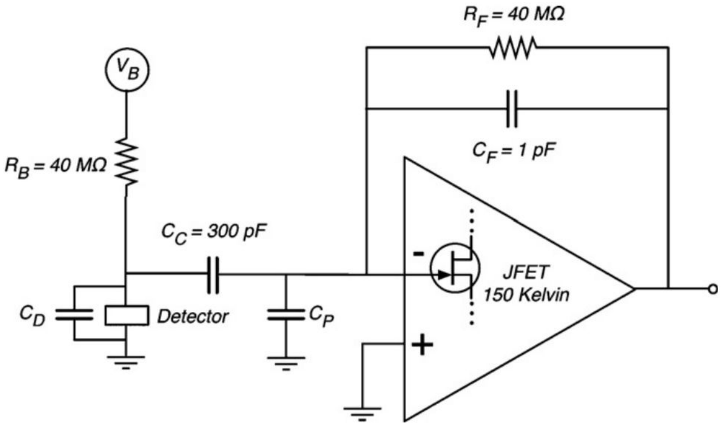
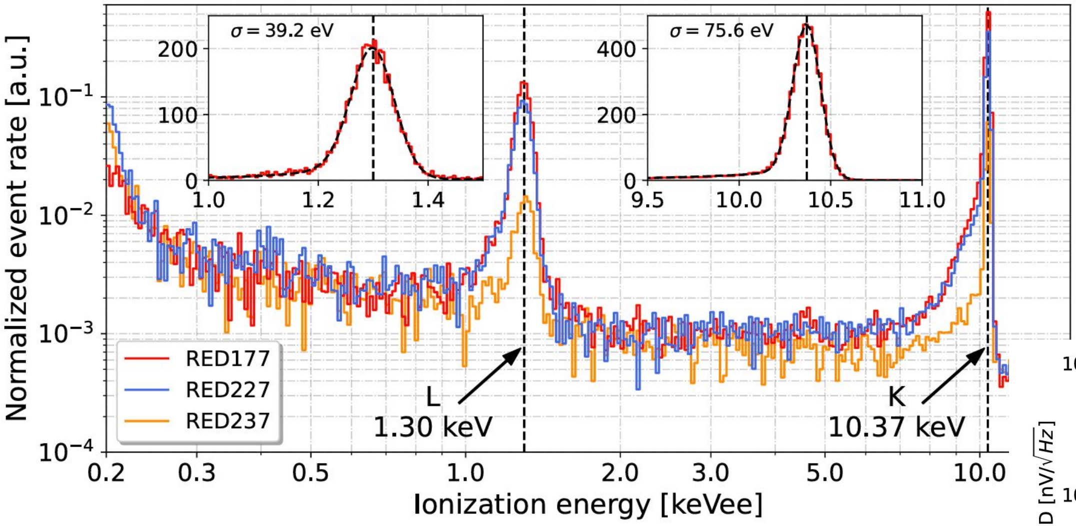
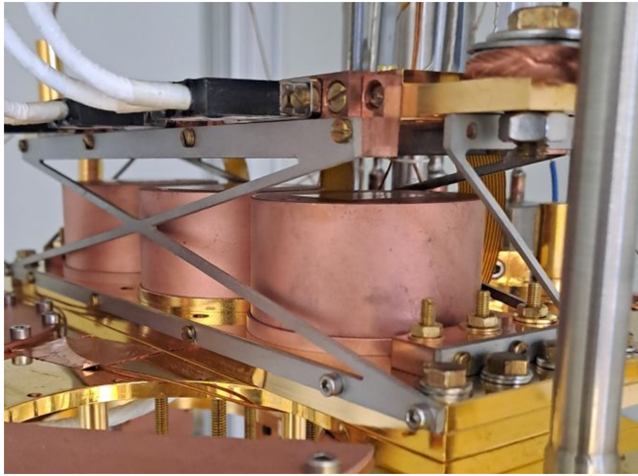


Fig. 5. Charge readout circuit. The heart of the amplifier is a JFET. The parasitic capacitance has been measured to be $C_p = 100\,pF$ and the detector capacitance is typically $C_D = 50\,pF$. G denotes the gate of the JFET.

https://arxiv.org/pdf/2306.00166.pdf

Ricochet HEMT readout





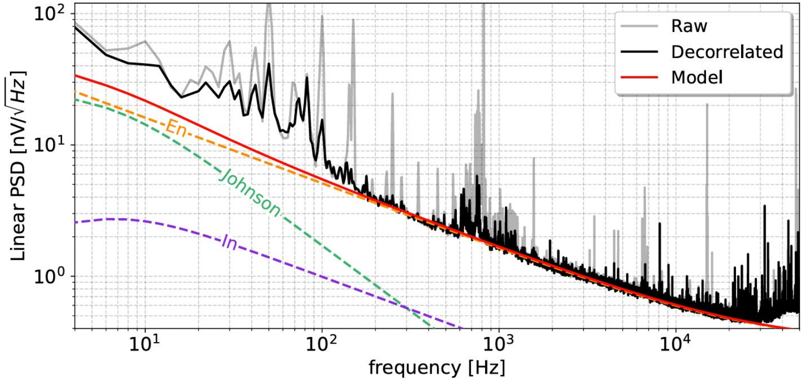
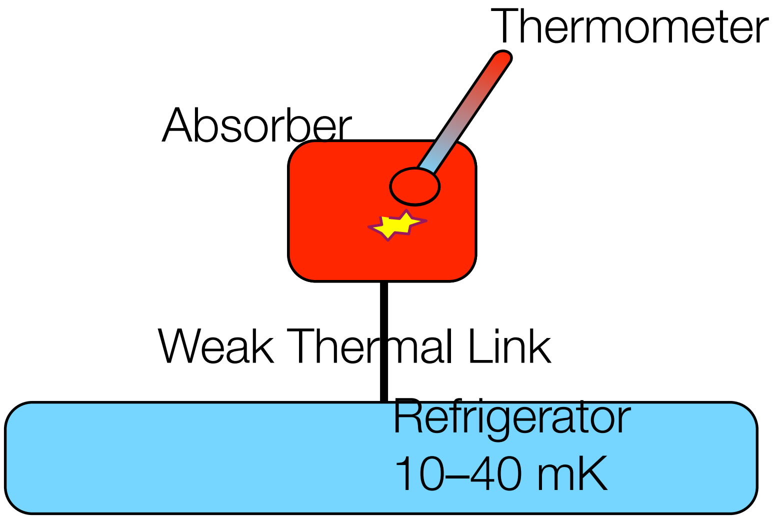
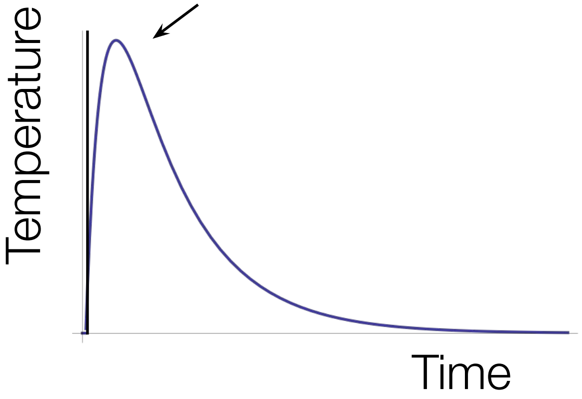


Fig. 2 Differential ($V_B - V_A$) noise power spectrum of RED227 with $V_{ds} = 100$ mV and $I_{ds} = 300$ μA and the mixing chamber at 17 mK. The black, grey and red solid lines show the decorrelated and raw data, and our noise model considering a parasitic capacitance of 20 pF, respectively. The total contributions from the two ionization channels A and B of the current (I_n), voltage (E_n), and Johnson noise sources are also shown as dashed purple, orange, and green lines, respectively.

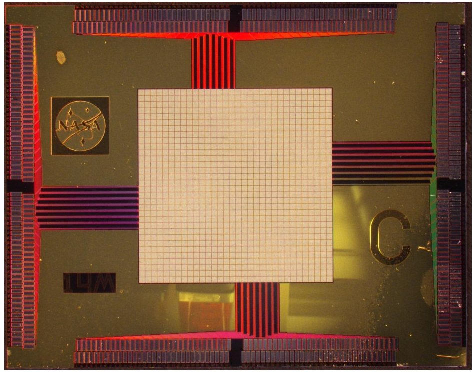
Measuring phonons: Cryogenic Crystal Detectors

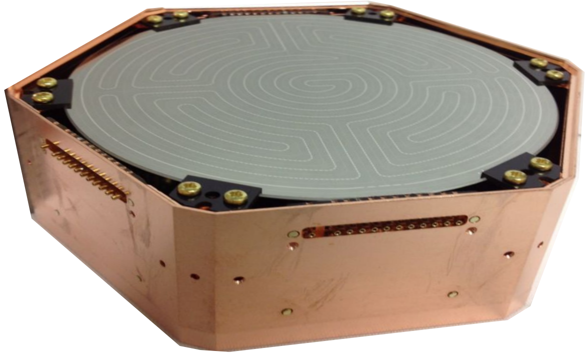




Cryogenic Crystal Detectors are used in…

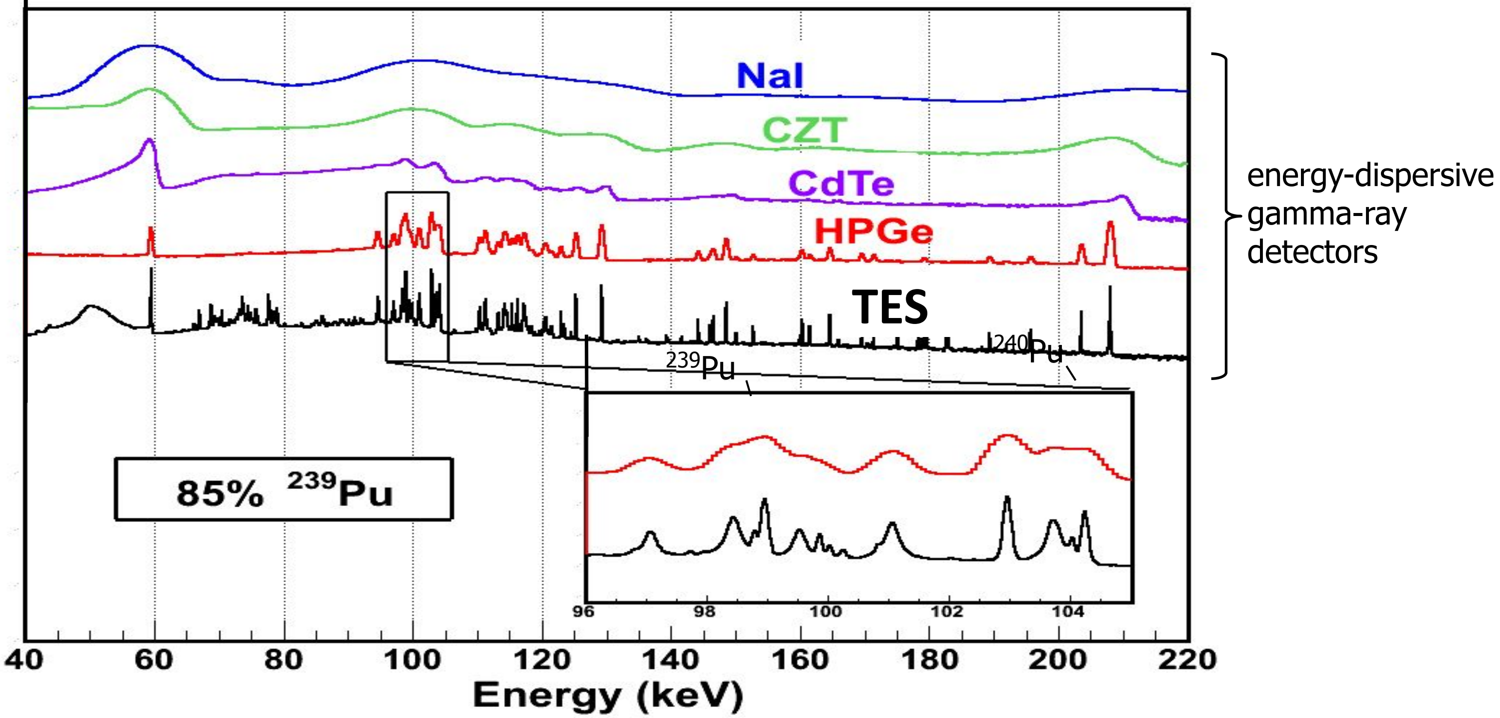
- Astrophysics
  - mm to gamma-ray energies
- Particle Physics
  - Dark Matter Detectors
  - Neutrino Physics
- Materials-analysis
- Others!



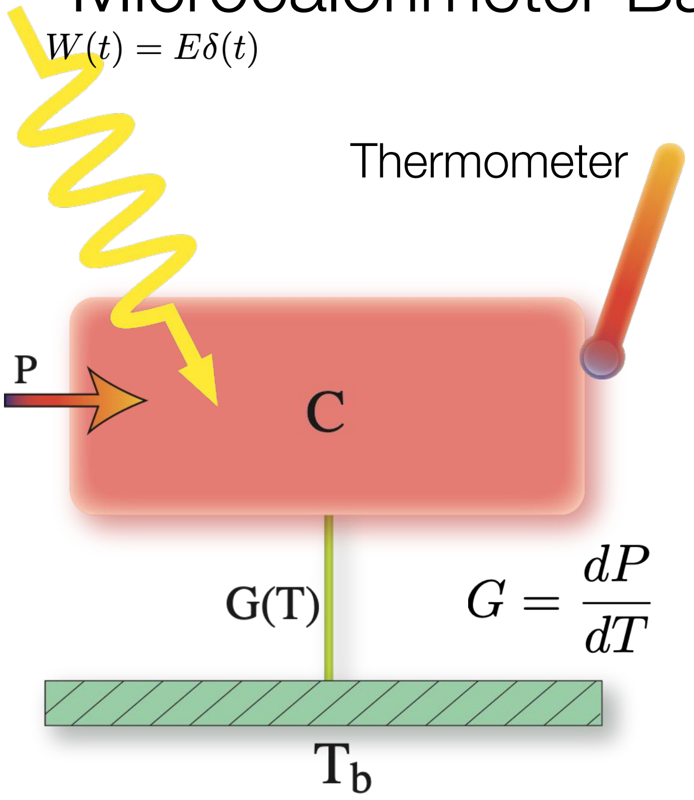


Why Use Cryogenic Detectors?

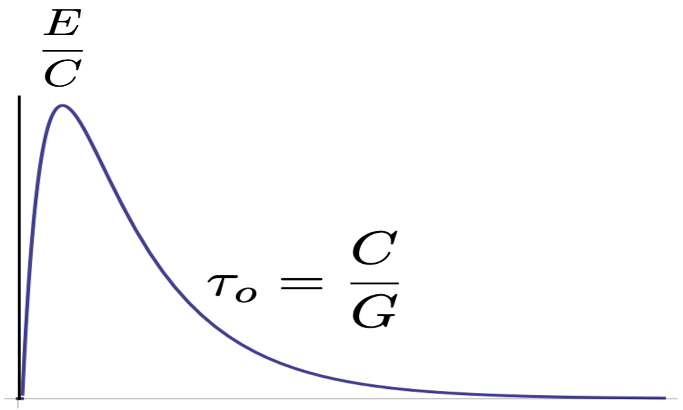
Cryogenic microcalorimeters can provide a unique combination of energy sensitivity and efficiency



Microcalorimeter Basics



$$C\frac{dT}{dt} = P - G(T - T_b) + W(t)$$



$$T(t) = \frac{E}{C}e^{t/t_o} + \left(\frac{P}{G} + T_b\right)$$

Some types of thermometers:

- resistive
- capacitive
- inductive
- paramagnetic
- thermoelectric

Thermometer #1

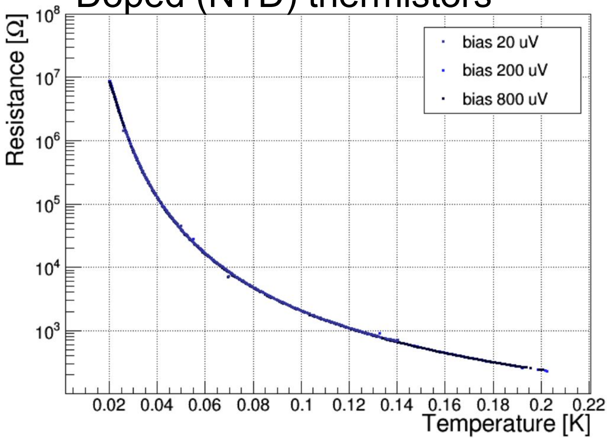
Neutron Transmutation Doped (NTD) thermistors

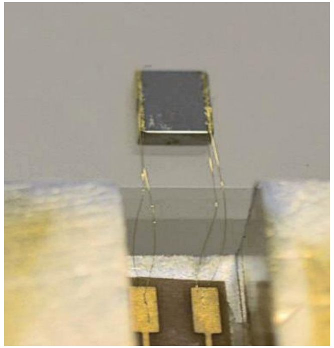
- Doped germanium/silicon chips
- Resistance follows Efros-Shklovskii law:

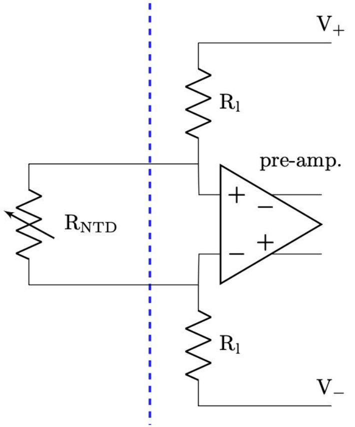
$$R = R_0 e^{\sqrt{T_0/T}}$$

- Taking advantage of the steep slope at low temperature
- Also comes with high dynamic range
- Readout with FETs, operating at room temperature or in cold

Neutron Transmutation Doped (NTD) thermistors





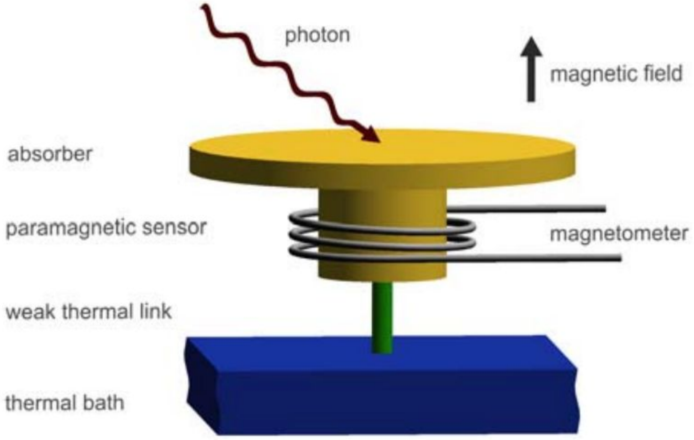


Figures from V. Novati

Metallic magnetic calorimeter (MMC)

- Paramagnetic sensor positioned in weak magnetic field
- Heat changes its induced magnetic field
- Readout by SQUIDs as magnetometer

Metallic magnetic calorimeter (MMC)

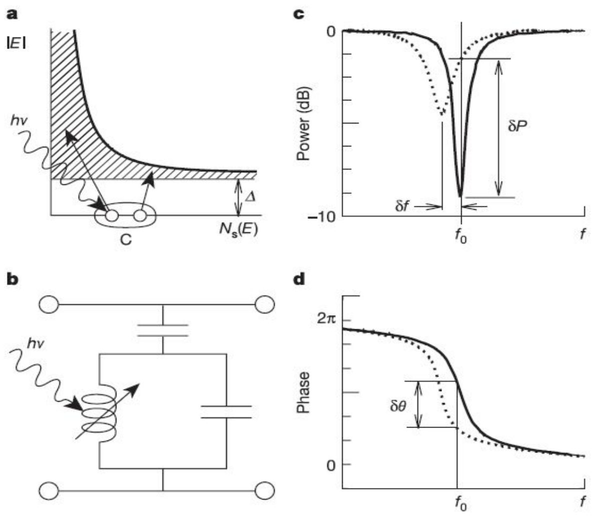


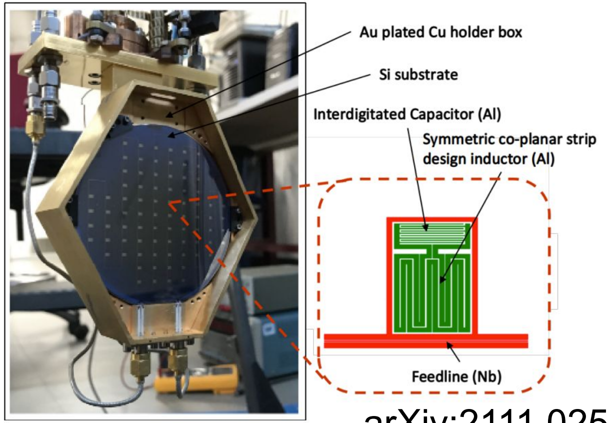
TASC.2009.2012724

Thermometer #3

Microwave Kinetic Inductance Detectors (MKIDs)

- Resonators made of superconducting metal films
- Resonance frequency and phase response depending on its temperature
- Radio-Frequency (RF) Readout system
- Intrinsic capability for multiplexing



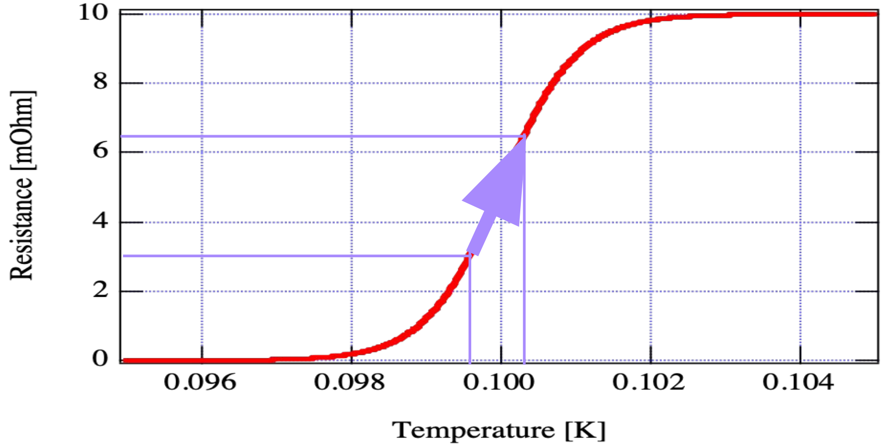


arXiv:2111.02587

Thermometer #4

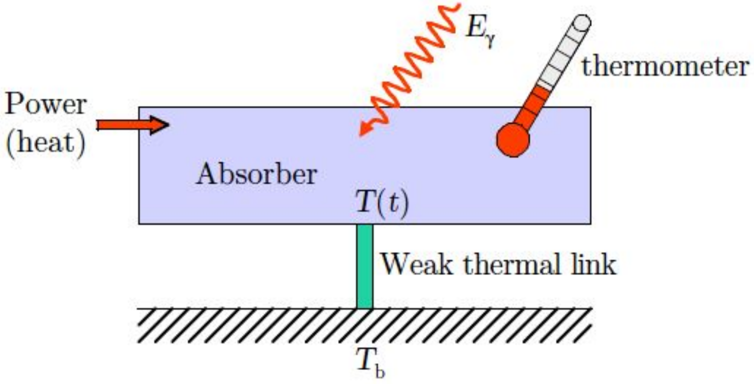
Transition-Edge Sensors

- Superconductor biased in its transition
- Several metal systems are used:
  - Elemental: W, Al, Re, Pb, etc.
  - Paramagnetic impurity doped: Al/Fe, Al/Mn, etc.
  - Bi-layers: Mo/Au, Mo/Cu, Ti/Al, etc.
- $50 < \alpha < 1000$
- Low resistance allows read out with SQUIDs



$$\alpha = \frac{T}{R}\frac{dR}{dT}$$

Balance the heat



- Sensor heat capacity C
- P is heat flowing into the sensor
  - For now assume as a constant
- Energy deposition E_γ at t_γ

$$C\frac{dT(t)}{dt} = P - P_{\text{link}}\big(T(t), T_{\text{b}}\big) + E_\gamma \delta(t - t_\gamma)$$

- $$P_{\text{link}}\big(T(t), T_{\text{b}}\big) = G\big(T(t) - T_{\text{b}}\big)$$

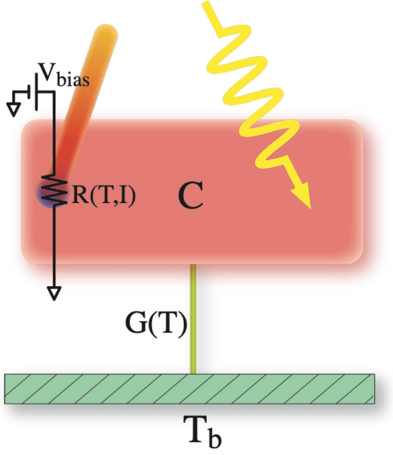
$$T(t) = \frac{E_\gamma}{C} e^{-t/\tau_o} + \left(\frac{P}{G} + T_{\text{b}}\right) \qquad \tau_o \equiv C/G$$

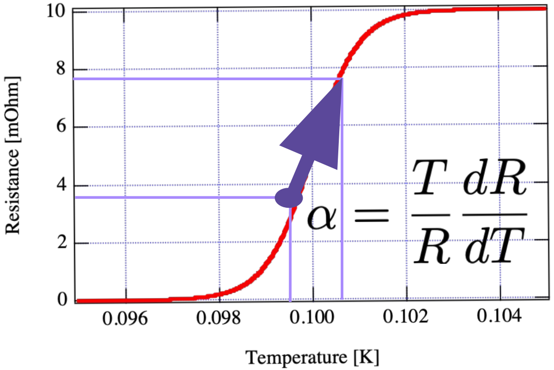
Electro-thermal Feedback (ETF)

$$P = \frac{V_{\text{bias}}^2}{R(T)}$$

$$C\frac{dT(t)}{dt} = P - P_{\text{link}}\left(T(t), T_{\text{b}}\right) + E_\gamma \delta(t - t_\gamma)$$

$$P_{\text{link}}\left(T(t), T_{\text{b}}\right) = K\left(T(t)^n - T_{\text{b}}^n\right)$$



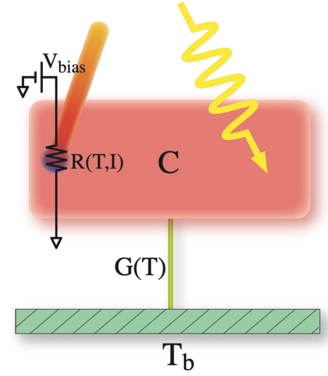


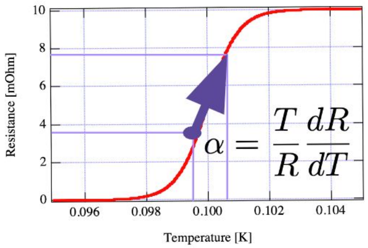
$$\alpha = \frac{T}{R}\frac{dR}{dT}$$

Electro-thermal Feedback (ETF)

$$P = \frac{V_{\mathrm{bias}}^2}{R(T)}$$

$$C\frac{dT(t)}{dt} = \frac{V^2}{R(T)} - K\left(T(t)^n - T_{\mathrm{b}}^n\right) + E_\gamma \delta(t - t_\gamma)$$





- In quiescence:

$$P = \frac{V^2}{R} = K(T^n - T_{\mathrm{b}}^n)$$

- Note, in quiescence $T \sim T_c$. Thus P is roughly constant
- Taylor expand with ΔT, note R_0, T_0 are the quiescent values

$$R = R_0 + \alpha \frac{R_0}{T_0}\Delta T$$

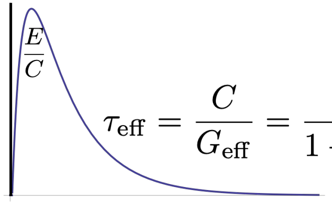
$$C\frac{d\Delta T}{dt} = \frac{V^2}{R_0} - K(T_0^n - T_b^n) - \frac{V^2}{R_0^2}\frac{dR}{dT}\Delta T - nKT_0^{n-1}\Delta T + E_\gamma \delta(t - t_\gamma)$$

- Define

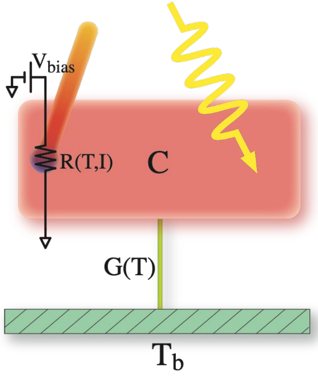
$$G \equiv \frac{dP}{dT} = nKT^{n-1}$$

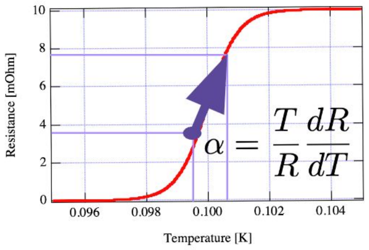
$$\Delta\dot{T}(t) = -\left(\frac{\alpha P}{TC} + \frac{G}{C}\right)\Delta T + \frac{E_\gamma}{C}\delta(t - t_\gamma)$$

Electro-thermal Feedback (ETF)



$$P = \frac{V_{\text{bias}}^2}{R(T)}$$





$$\Delta\dot{T}(t) = -\left(\frac{\alpha P}{TC} + \frac{G}{C}\right)\Delta T + \frac{E_\gamma}{C}\delta(t - t_\gamma)$$

- Solution is a simple exponential, with

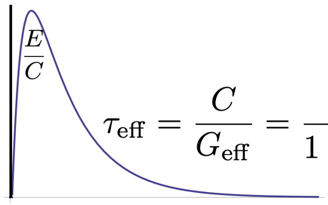
$$\tau_{\text{eff}} = \frac{\tau_0}{1+\frac{\alpha P_0}{T_0 G}} = \frac{\tau_0}{1+\frac{\alpha}{n}\left(1-\left(\frac{T_b}{T_0}\right)^n\right)}$$

- Define $\phi = 1 - \left(\frac{T_b}{T_0}\right)^n$ $\quad \tau_{\text{eff}} = \frac{\tau_0}{1+\frac{\alpha\phi}{n}}$
- In "extreme electrothermal feedback regime"
  - Cold fridge → $T_0^n << T_b^n$
  - Excellent detector → $\alpha/n >> 1$

$$\tau_{\text{eff}} = \frac{n\tau_o}{\alpha}$$

- Higher α → Faster detector
  - Will see later that higher α also leads to better detector

ETF as virtual conductance

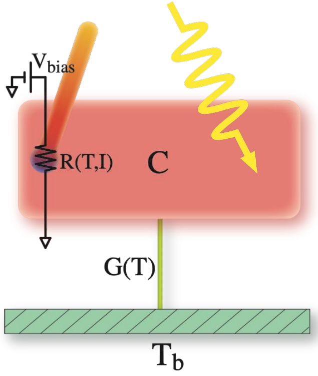


$$\tau_{\text{eff}} = \frac{C}{G_{\text{eff}}} = \frac{\tau_o}{1 + \frac{\alpha P}{GT}}$$

$$P = \frac{V_{\text{bias}}^2}{R(T)}$$

$$G_{\text{ETF}} \equiv \frac{\alpha P}{T} \qquad \tau_{\text{ETF}} \equiv \frac{C}{G_{\text{ETF}}} = \frac{C}{\frac{\alpha P}{T}} = \frac{\alpha P}{TG}\tau_o$$

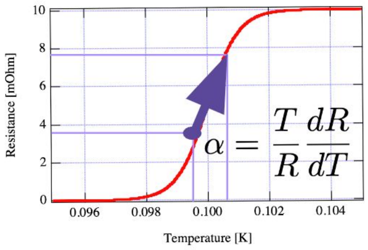
$$\tau_{\text{eff}} = \frac{C}{G_{\text{eff}}} = \frac{C}{G + G_{\text{ETF}}} = \frac{C/G}{1 + \frac{\alpha P}{TG}} = \frac{1}{\frac{1}{\tau_o} + \frac{1}{\tau_{\text{ETF}}}}$$



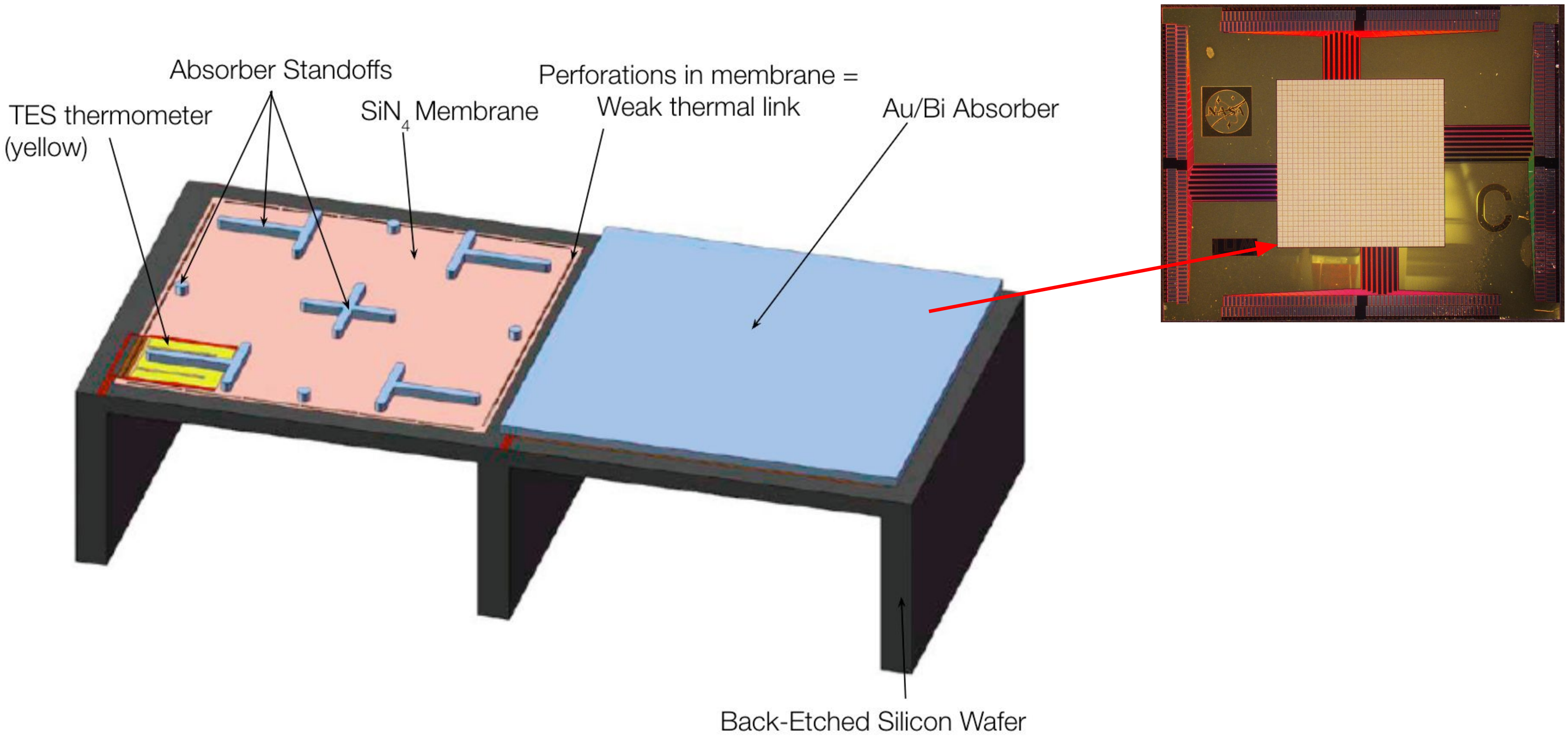
- ETF acts like another conductance, in parallel with the natural thermal conductance
- For ETF to be stable $\frac{\alpha P}{TG} > -1$

  Naturally satisfied for TES, flipped for NTD
- → TES needs to be “Voltage biased”

  NTD needs to be “current biased”



Example microcalorimeter -- MicroX



Example microcalorimeter -- MicroX