Poisson photon variation example

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Based on work from: https://arxiv.org/abs/2510.01463

How To Calibrate the Energy Scale?

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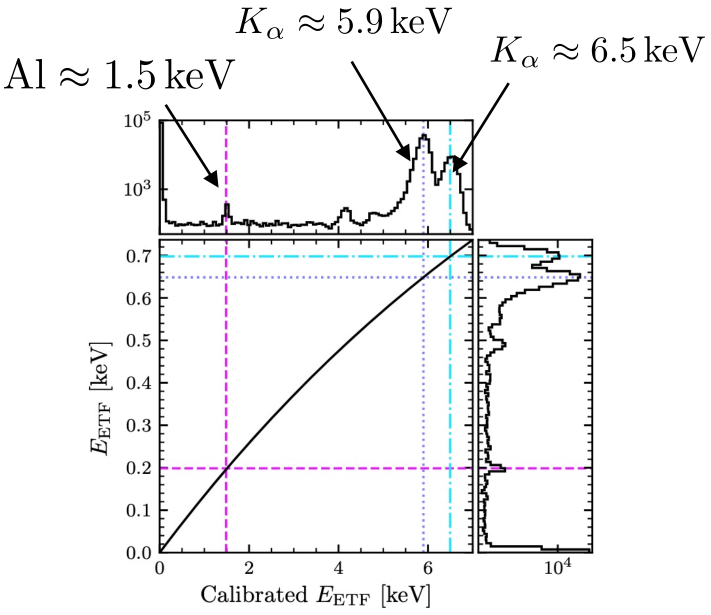
1. Gamma/X-ray source:
   - Pro: Decay energies are precisely known
   - Con: Energies of photons is very large
   - Good for large energy scales



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1. Gamma/X-ray source:
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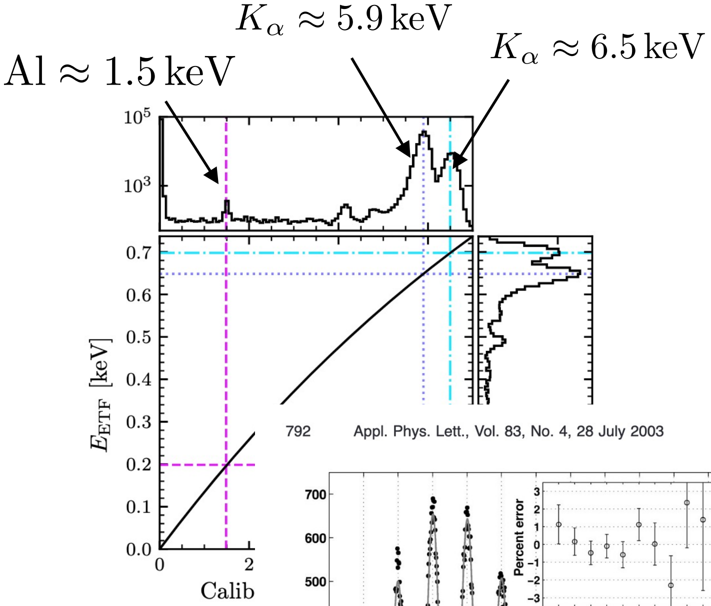
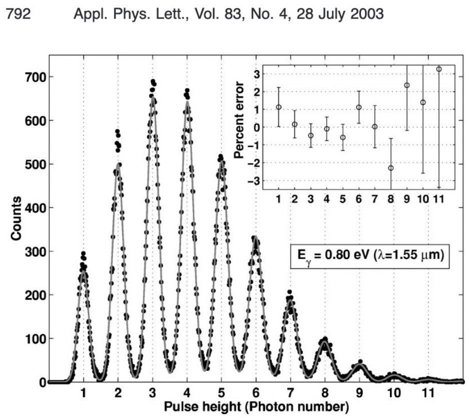
2. Single Optical/IR Photon:
   - Pro: Energy of single photon is precisely known
   - Con: Requires sensitivity to resolve single photons
   - Good for very small energy scales





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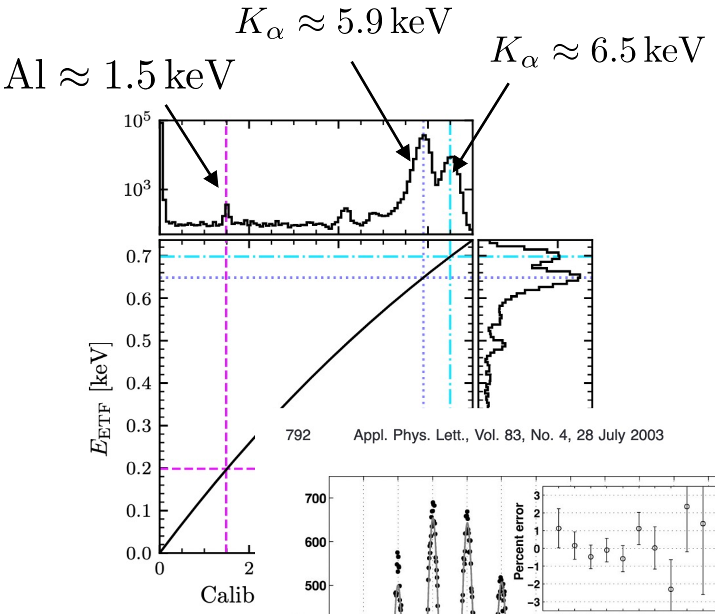
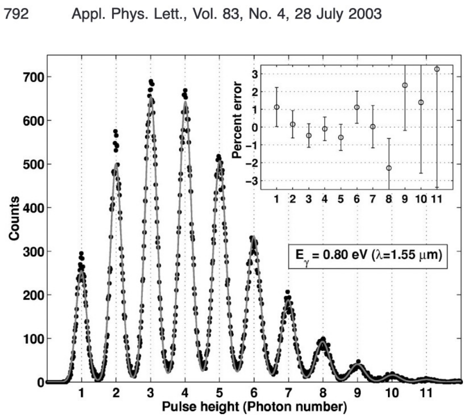




Problem: what about in-between these energy scales?

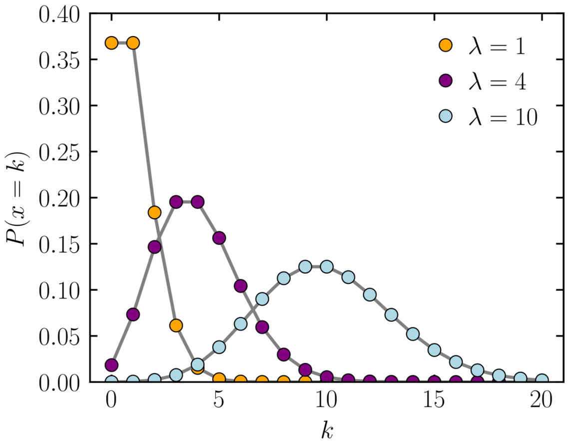
Solution

Use the Poissonian variation of a photon source to calibrate our detector

Aside: Poissonian Statistics

- For any counting experiment – driven by Poissonian process (e.g. number of photons in a light pulse)

$$\Pr(X=k) = \frac{\lambda^k e^{-\lambda}}{k!}$$



- Key point: Variance = mean

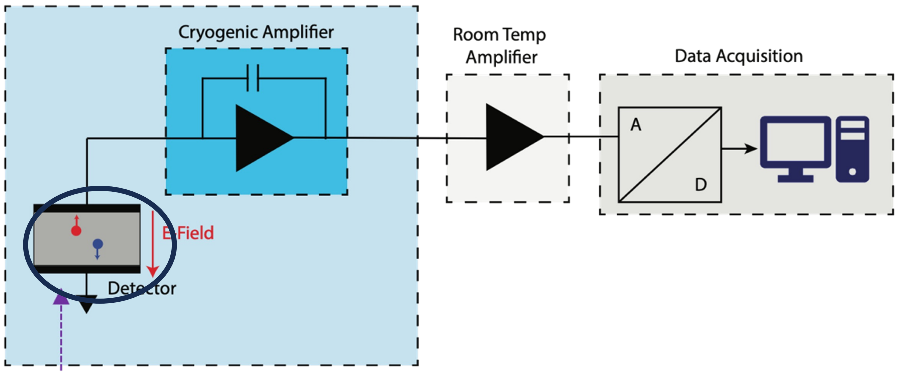
- Variance in photon number is equal to average photon number

- We can exploit this fact to calibrate the charge sensitivity of our detector!

Signal Flow

- Start with charge inside detector

$$V_{\text{out}} = \frac{q_{\text{in}}}{C} \varepsilon G$$



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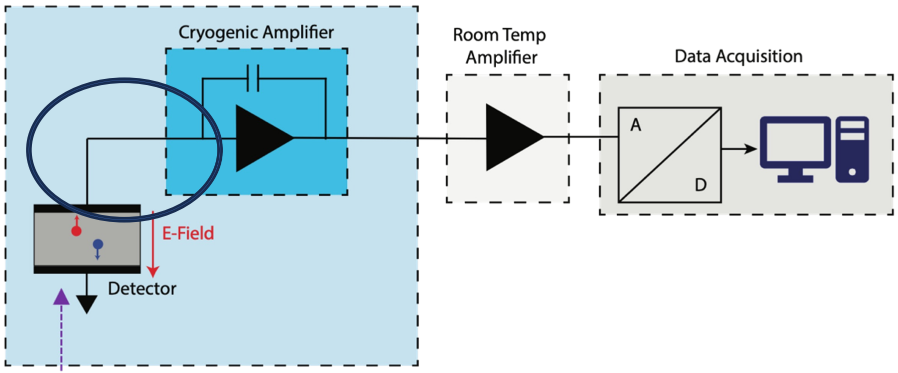

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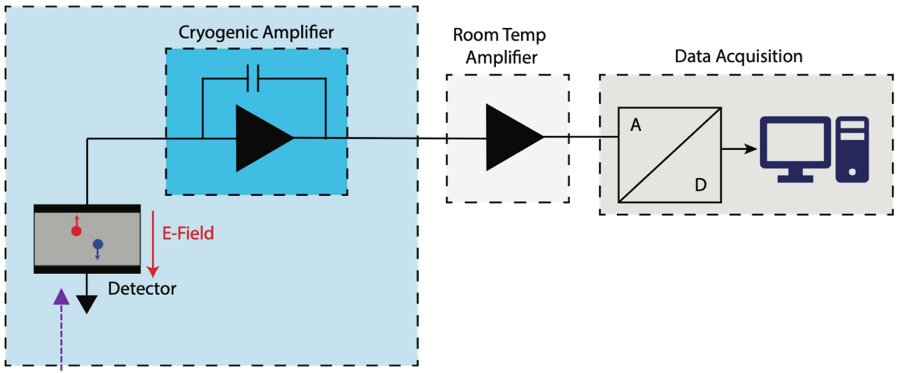

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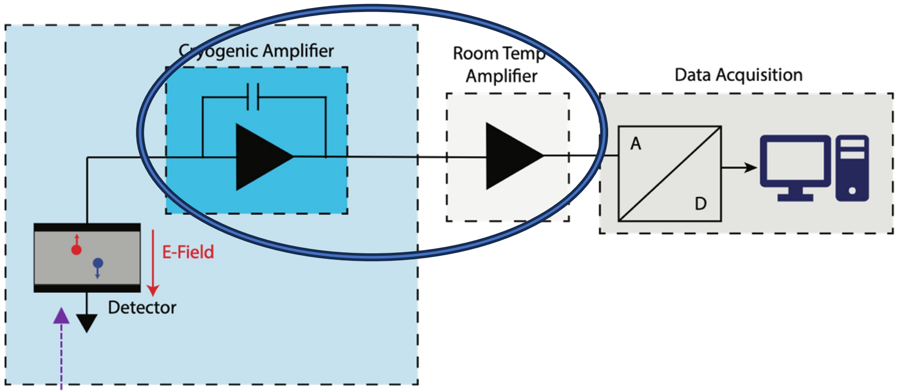

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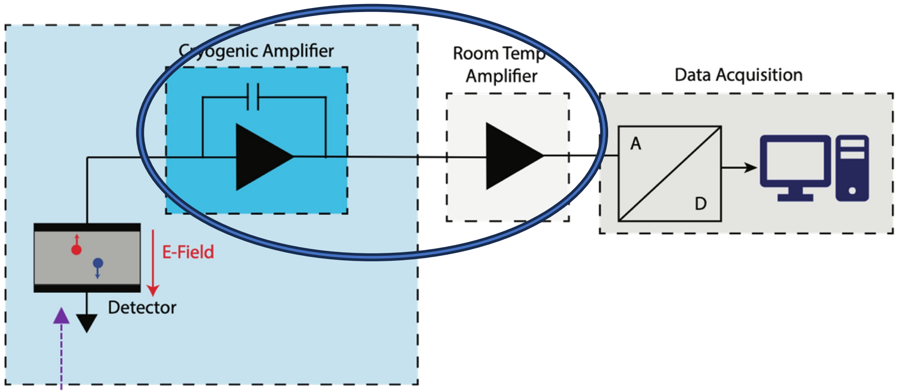
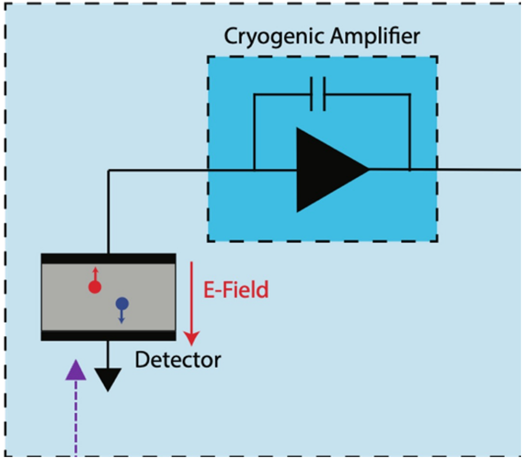


None of these factors are known well

Where is our signal coming from?



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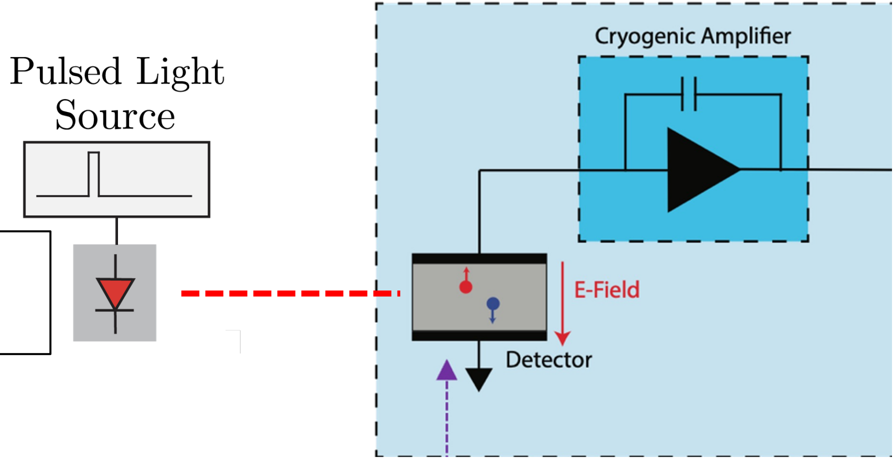
1. Photons from LED source:

$$q_\gamma = n_\gamma \eta$$

Number of photons absorbed by detector

Number of charge carriers per photon



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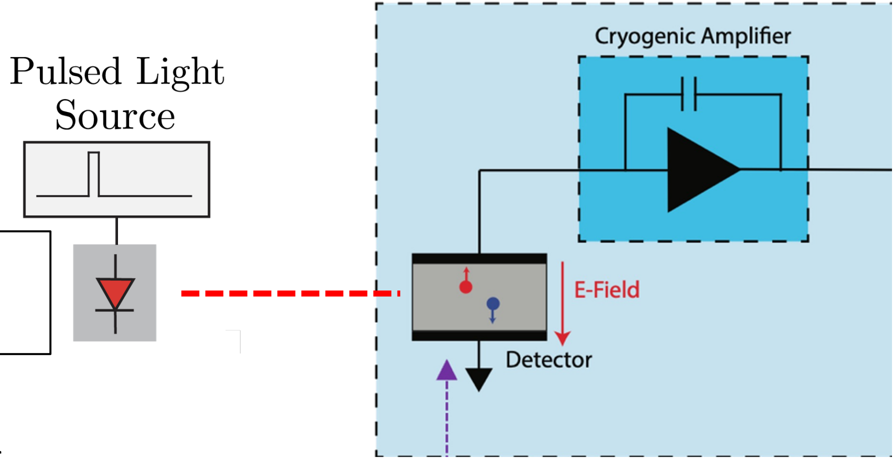

2. Intrinsic free charge carriers in detector (e.g. thermally generated):

$$q_{\mathrm{Free}} = \delta_q$$

Full input signal

- We can calculate the mean and variance of this signal:

$$V_{\text{out}} = \frac{G}{C}\varepsilon\left[n_\gamma\eta + \delta_q\right]$$

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Mean is zero since NRV

- Mean: $$\langle V_{\text{out}} \rangle = \frac{G}{C}\eta\varepsilon\langle n_\gamma \rangle$$

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Photon number is Poissonian!

- Variance: $$\sigma^2_{V\mathrm{out}} = \left(\frac{G}{C}\varepsilon\right)^2 \left[\eta^2 \langle n_\gamma \rangle + \sigma_q^2\right]$$

Variances add in quadrature since independent random gaussian (approximated) variables

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This is what we want to measure

Why does this matter?

- We can rearrange these expressions in terms of measurable quantities

$$\sigma^2_{V\mathrm{out}} = \frac{G}{C}\varepsilon\eta\left\langle V_{\mathrm{out}}\right\rangle + \left(\frac{G}{C}\varepsilon\right)^2 \sigma_q^2$$

Why does this matter?

- Simple linear equation!

Constants

$$\sigma_{V\mathrm{out}}^2 = \frac{G}{C}\varepsilon\eta\langle V_{\mathrm{out}}\rangle + \left(\frac{G}{C}\varepsilon\right)^2 \sigma_q^2$$

Measurable

Why does this matter?

$$\sigma^2_{V\text{out}} = m \left\langle V_{\text{out}} \right\rangle + b$$

$$m = \frac{G}{C}\eta\varepsilon \qquad b = \left(\frac{G}{C}\varepsilon\right)^2 \sigma_q^2$$

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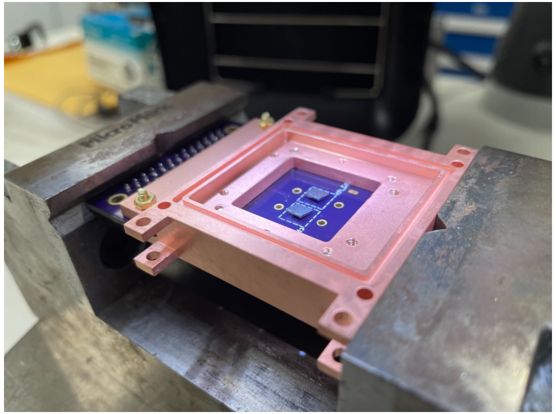
Unknown?

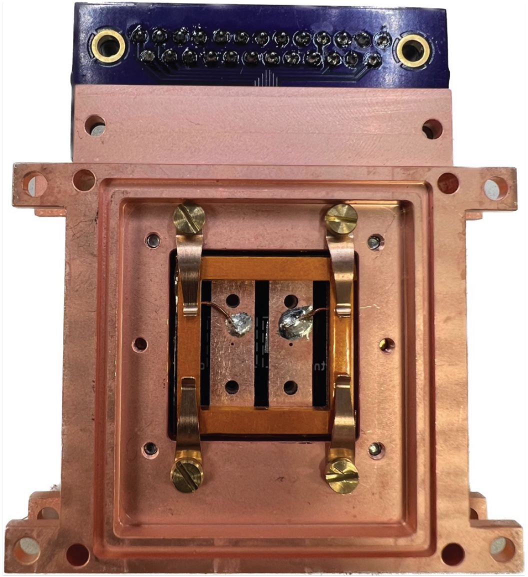
Can rearrange to almost get the quantity we want.....

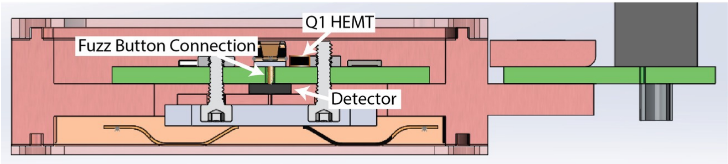
$$\sigma_q = \eta\sqrt{\frac{b}{m^2}}$$

Experimental Setup

- We have two channels in our amplifier:
    1. $Eu_5In_2Sb_6$
    2. Si







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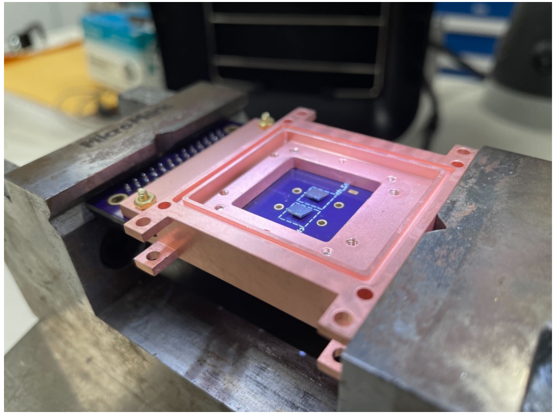
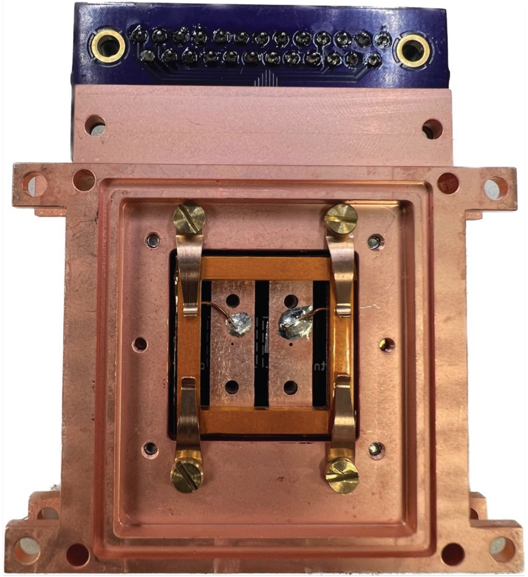
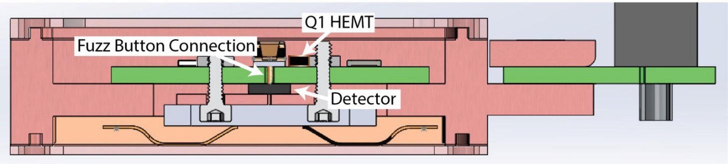
- We have two channels in our amplifier:
  1. **$Eu_5In_2Sb_6$** - bandgap: ~50meV (somewhat unknown…)
  2. **Si** – bandgap: 1.12 eV







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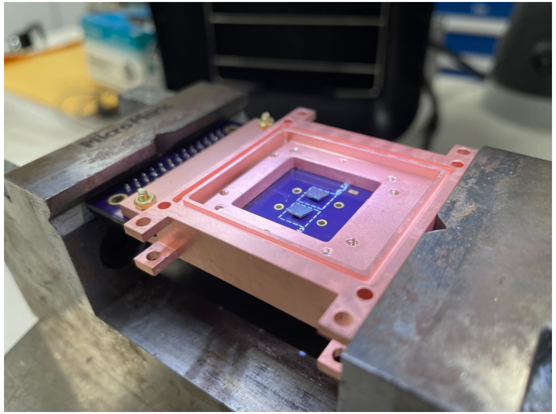


Use LED with wavelength less that twice Si bandgap

$$\sigma_q = \cancel{m}\sqrt{\frac{b}{m^2}}$$

We can now calibrate charge precision of amplifier precisely!

Calibration Procedure

1. Fiber couple LED into cryostat

2. Gate LED with external trigger

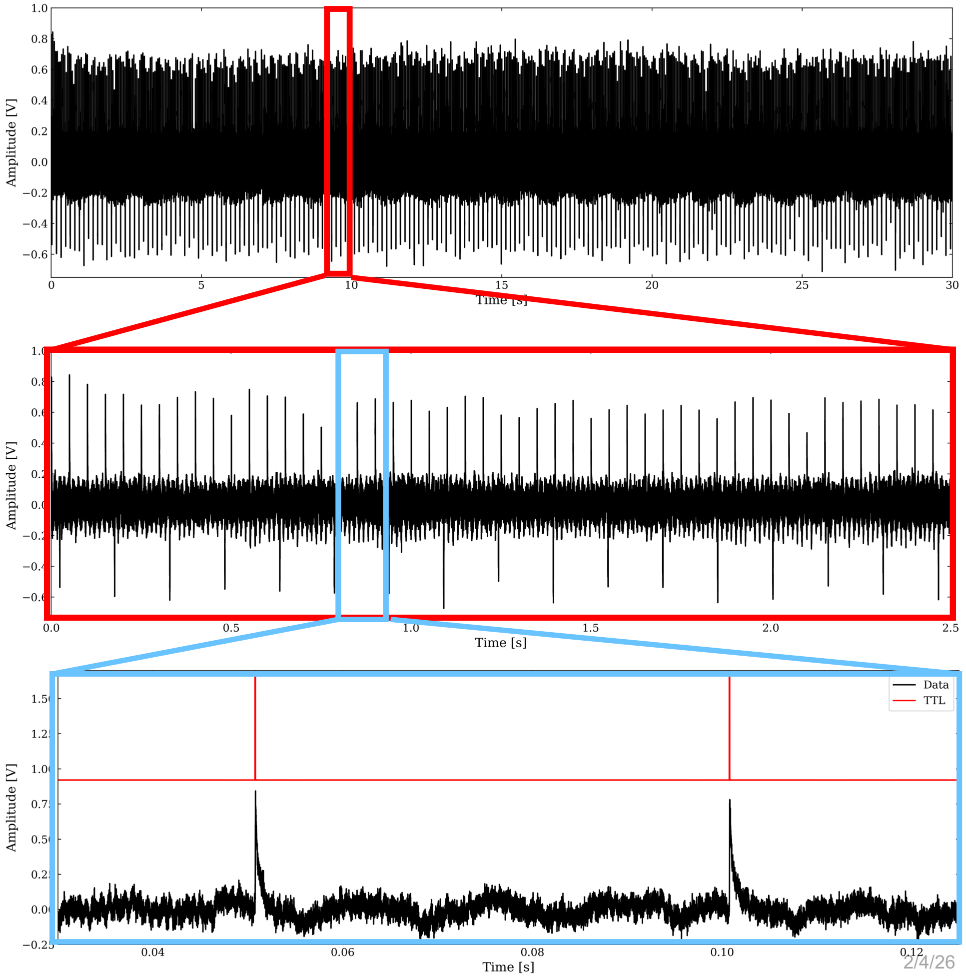
3. Measure LED pulses as a function of LED Power
   - 600 pulses per LED power
   - 10 different LED powers

4. Fit average and variance of pulse amplitude for each LED power pulse distribution

5. Fit variance vs average to extract gain and charge resolution parameters

Raw Data

- LED pulsed at 20Hz for 30 seconds per LED power
- LED trigger (TTL) also recorded
- TTL used to 'chunk' data into individual traces:
  1. Pulse data
  2. Noise (no pulses)



Calibration