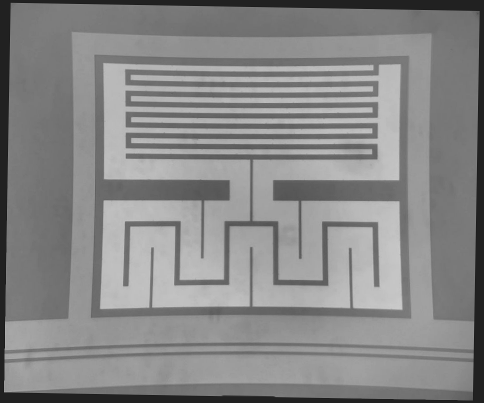
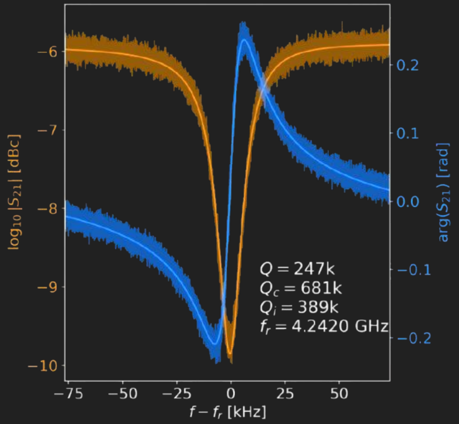
Kinetic inductance phonon-mediated (KIPM) detectors for low-mass dark matter

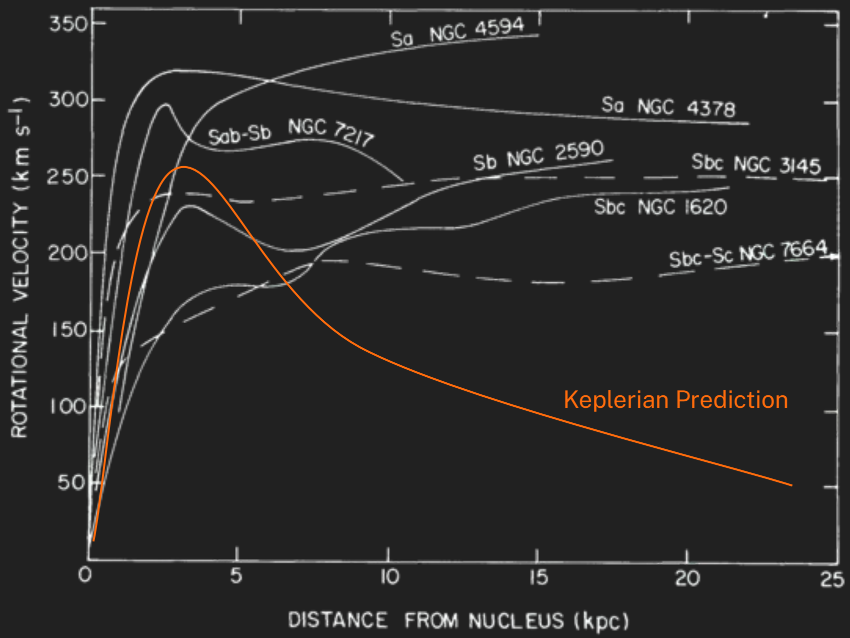




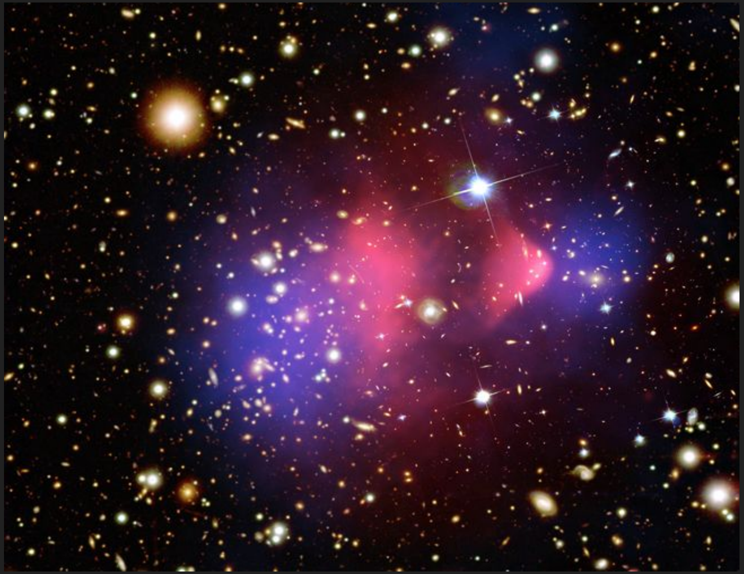
Brandon Sandoval, Advisor: Sunil Golwala

Caltech

Why does our universe point to dark matter?

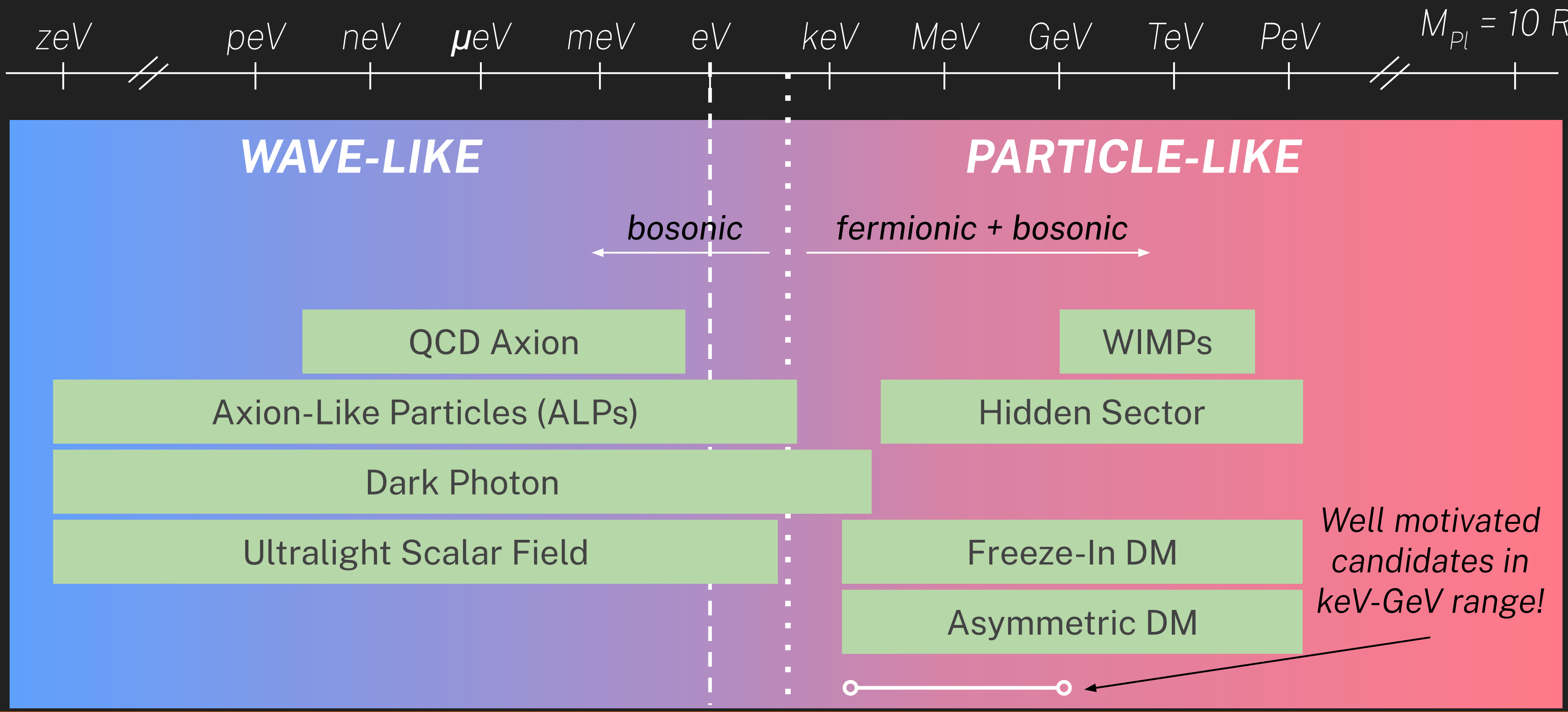


Rubin et al., 1978



Cluster G.L.: Majority of mass in galaxies is “collisionless”

Dark matter mass spectrum



Well motivated candidates in keV-GeV range!

Direct detection kinematics

NUCLEAR RECOIL

$$E_R^{\max} = \frac{2\mu_{\chi N}^2 \ v^2}{m_N}$$

$$E_R^{\max} = \frac{2m_\chi^2 v^2}{m_N}, \ m_\chi \lessapprox m_N$$

ELECTRON RECOIL

$$E_R \sim m_e v_e v_\chi, \ m_\chi \gtrapprox m_e$$

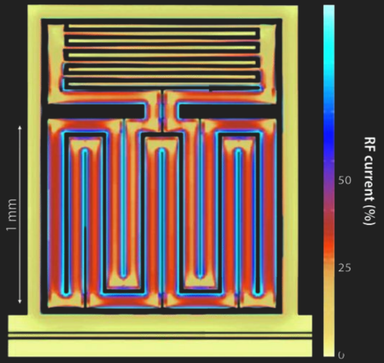
$$E_R \sim \frac{1}{2} m_\chi v_\chi^2, \ m_\chi \lessapprox m_e$$

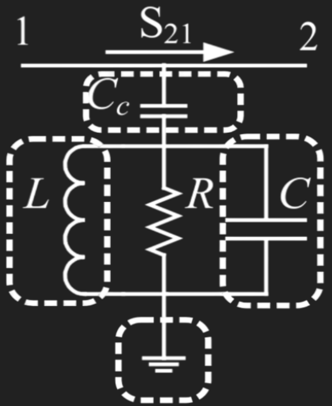
$$v_\chi \sim 300 \ \mathrm{km/s}$$

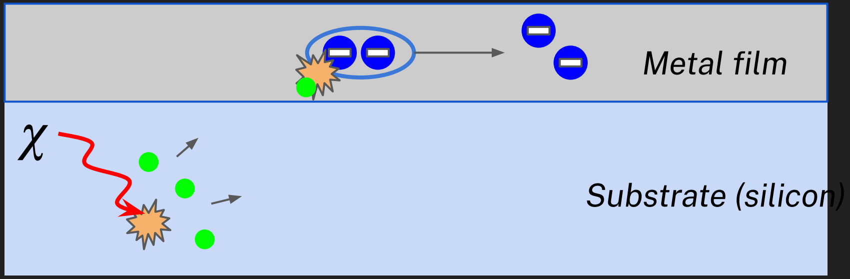
*Dark matter with mass between 1 MeV to 1 GeV results in **0.1 meV to 100 eV** deposited energy. Dominant energy excitation in this regime is **phonons**.*

Kinetic Inductance Phonon-Mediated (KIPM) Detectors

- Cooper pairs in superconducting film "lag" behind the field due to their inertia: kinetic inductance
- Energy deposition in substrate generates phonons, which travel to break cooper pairs, which increases the kinetic inductance
- By measuring the ratio of power sent into the LC resonator to the power on the output (S21), we can calculate the change in inductance, and hence the change in quasiparticle density and resulting energy deposited.

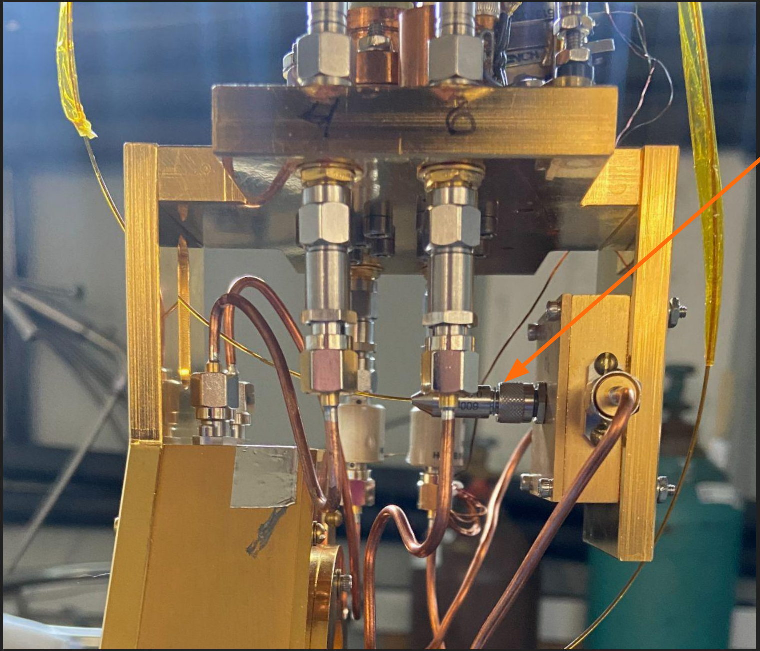




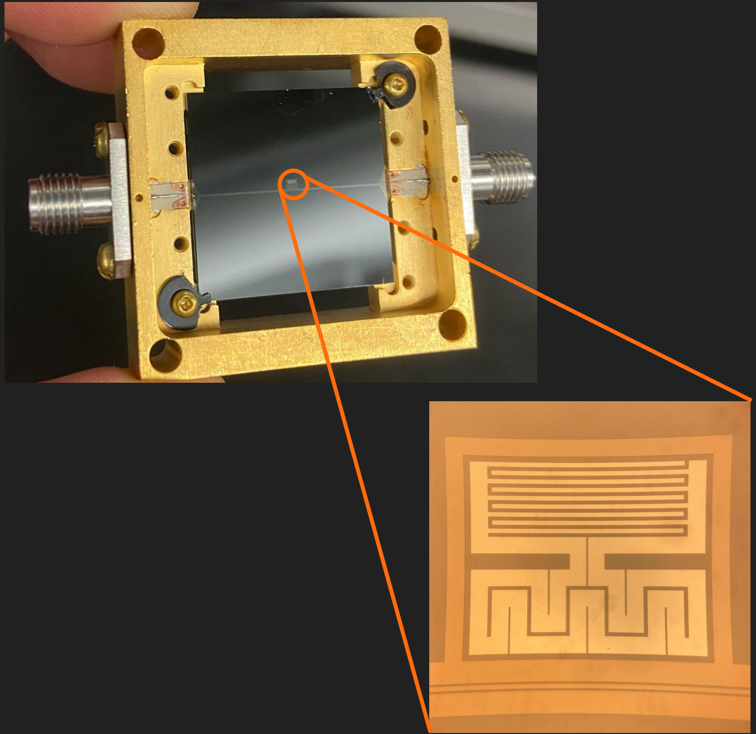


$$L_k \sim \frac{m_e}{2e^2 n_{cp}}$$

KID Deposited Energy Resolution Measurement



470 nm LED flashing the ***back*** of the silicon chip



Energy resolution measurements: FNAL

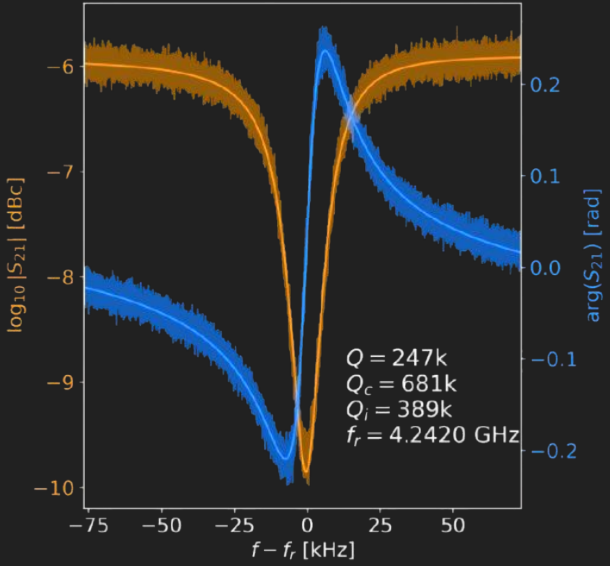
FNAL, 2023

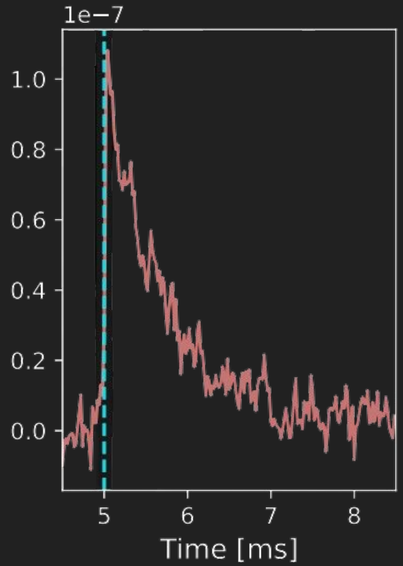
$$\sigma_E^{\text{Device}} = 2.1 \pm 0.2 \text{ eV}$$

$$\sigma_E^{\text{Deposited}} = 318 \pm 28 \text{ eV}$$

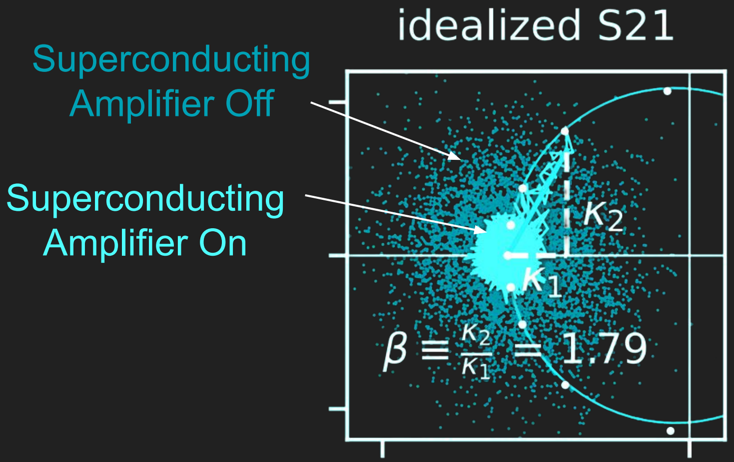
$$\eta_{ph} = \frac{\sigma_E^{\text{Dev}}}{\sigma_E^{\text{Dep}}} = 0.0066 \pm 0.001$$

<1% of generated phonons making it to the KID!

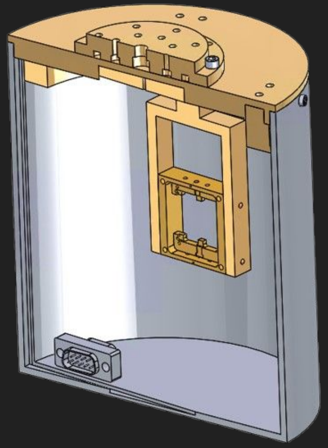




KIPM current work: increase σ^{Device}



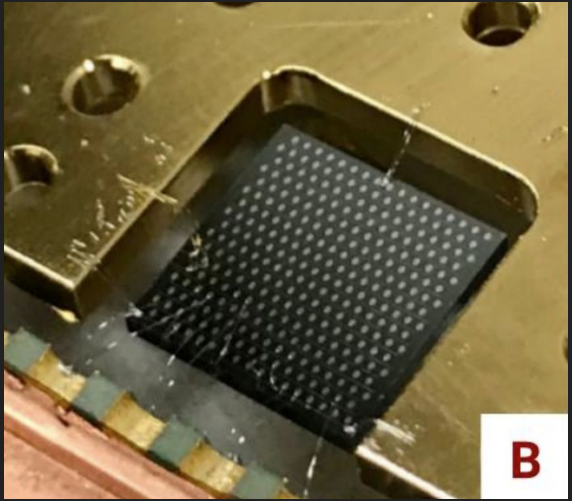
- Replacing semiconductor amplifier (HEMT) with superconducting amplifier
- Tests at JPL have shown a ~5x improvement in energy resolution



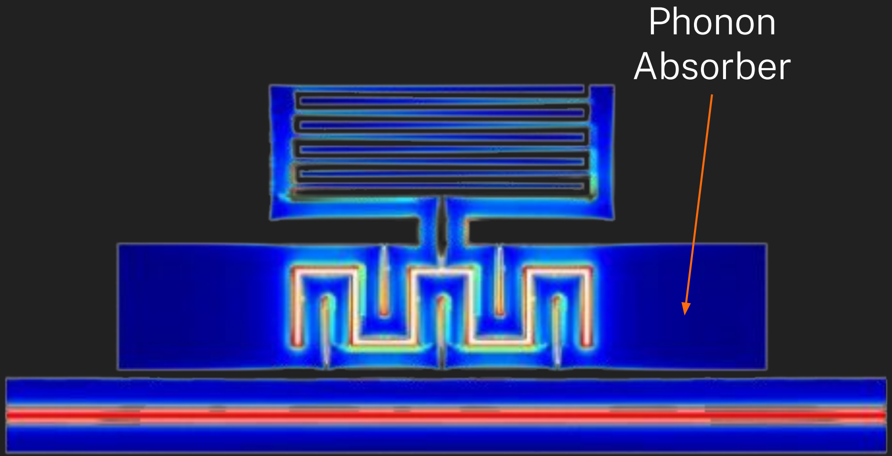
- Enhanced blackbody shielding – has been shown in partner facility in Fermilab to increase QP lifetime

KIPM current work: increasing η_{phonon}

Anthony-Petersen et al., 2022



- Designing new mounting scheme for wirebond-suspended chips



- Designing quasiparticle trapping KIDs with phonon absorbers

KIPM detector energy resolution projection

Literature value

	σ(E,dev) (freq.)	***σ(E,dev) (diss.)***	***σ(E,dep)*** $\eta_{ph} = 30\%$
current performance	2.1 eV	7.5 eV	6.4 eV*
optimal RF resp.	TLS-limited	580 meV*	1.9 eV*
SQL amplifier		140 meV*	460 meV*

GR Noise?

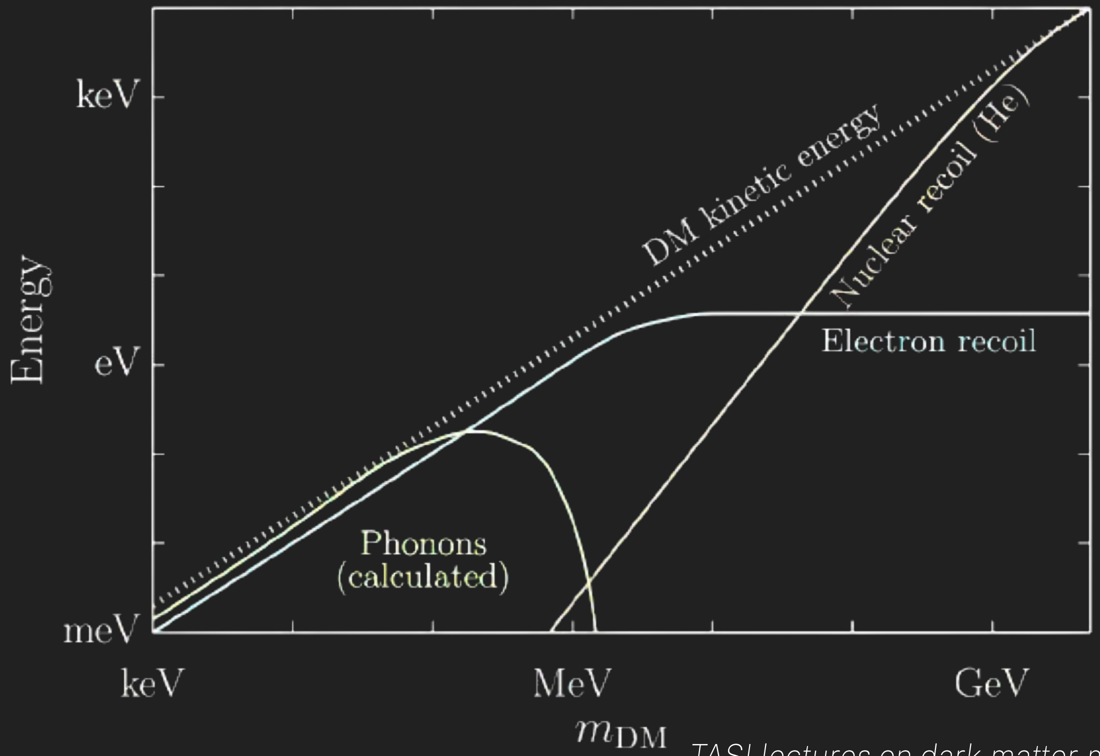
*Projection

Thank You!

Questions?

BACKUP SLIDES

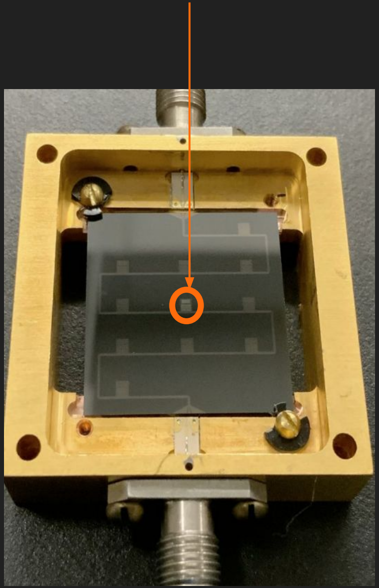
Energy deposition channels

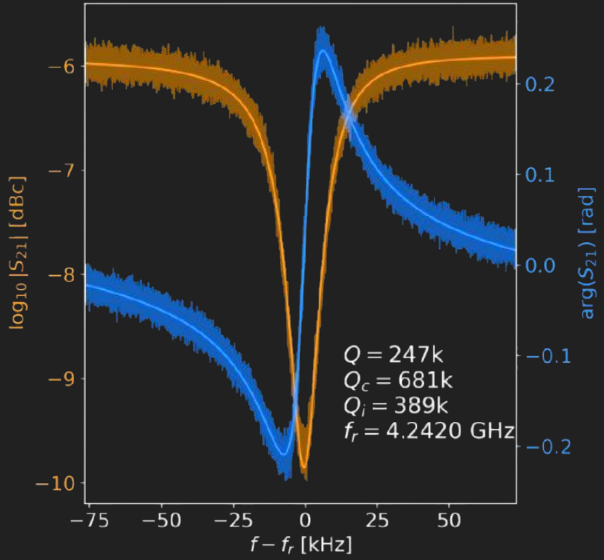


TASI lectures on dark matter models and direct detection, 2019

Energy resolution measurement: FNAL

Phonon sensitive central KID





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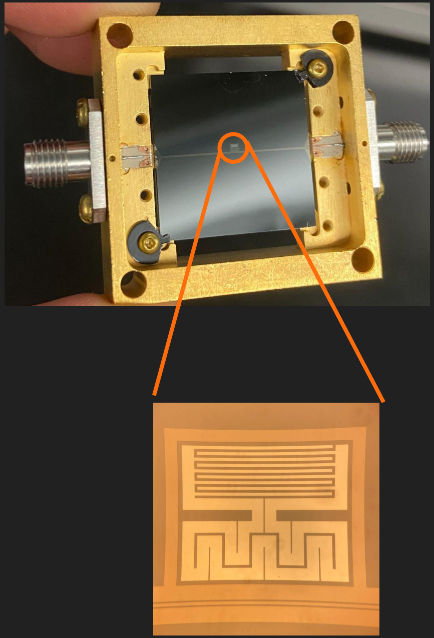
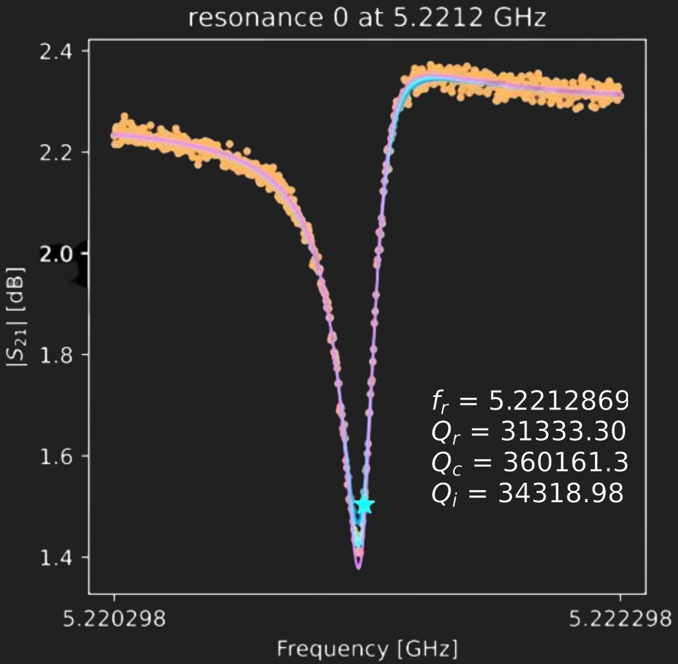
Energy resolution measurement: Caltech



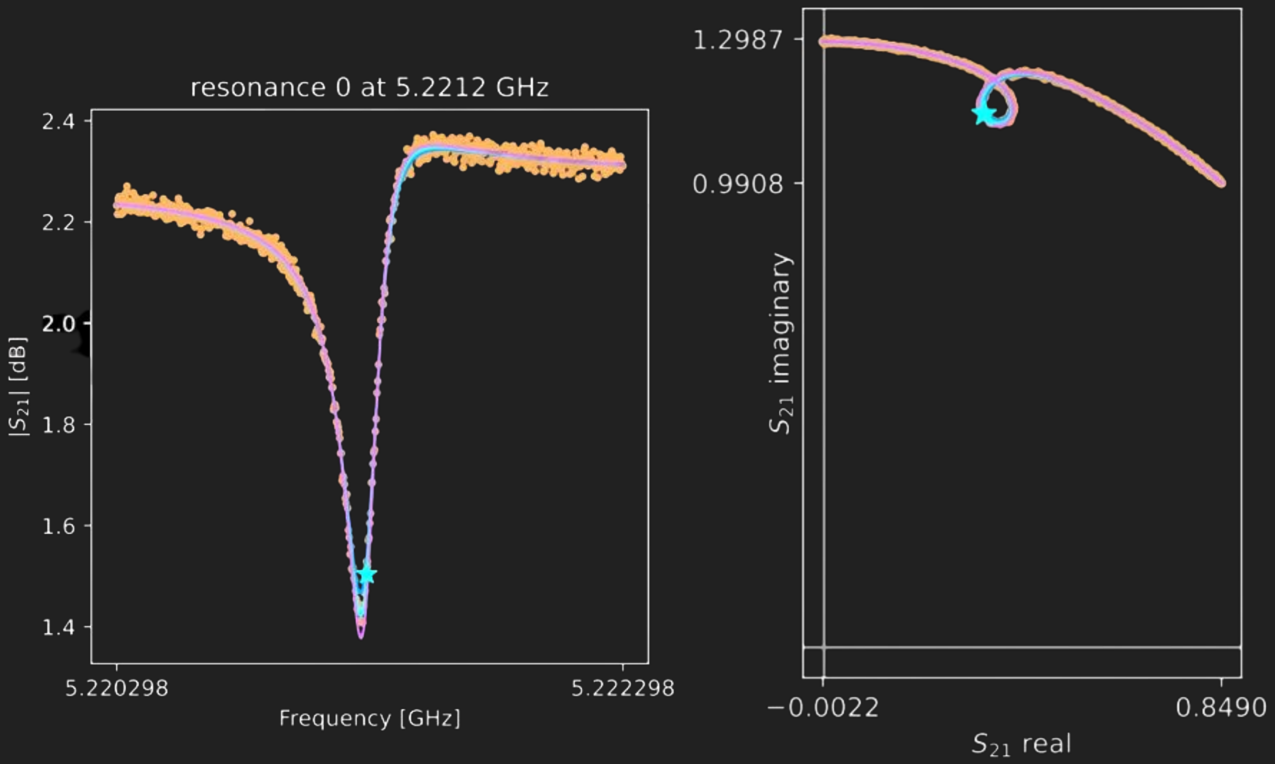


$$\sigma_E^{\text{Device}} \sim 15\ \text{eV}$$

$$\sigma_E^{\text{Deposited}} \sim 1.5\ \text{keV}$$

$$\eta_{ph} = \frac{\sigma_E^{\text{Dev}}}{\sigma_E^{\text{Dep}}} \sim 0.01$$

Aluminum KID Phonon Collection Efficiency Measurement



$f_r = 5.2212869$

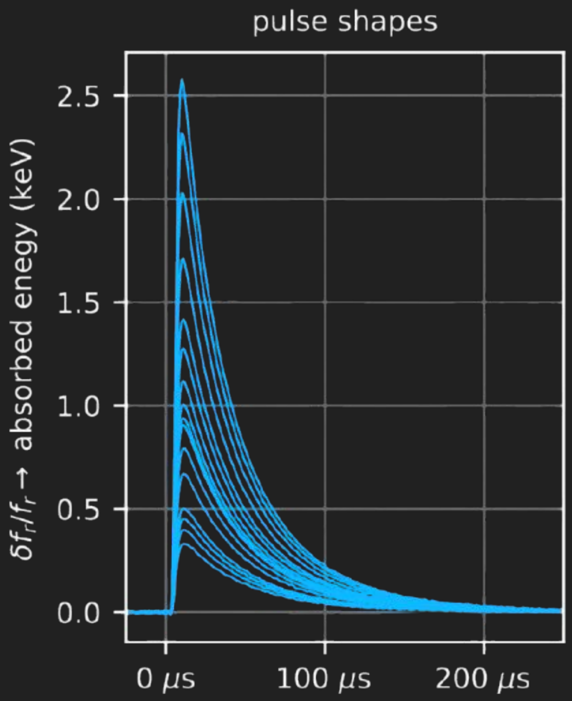
$Q_r = 31333.30$

$Q_c = 360161.3$

$Q_i = 34318.98$

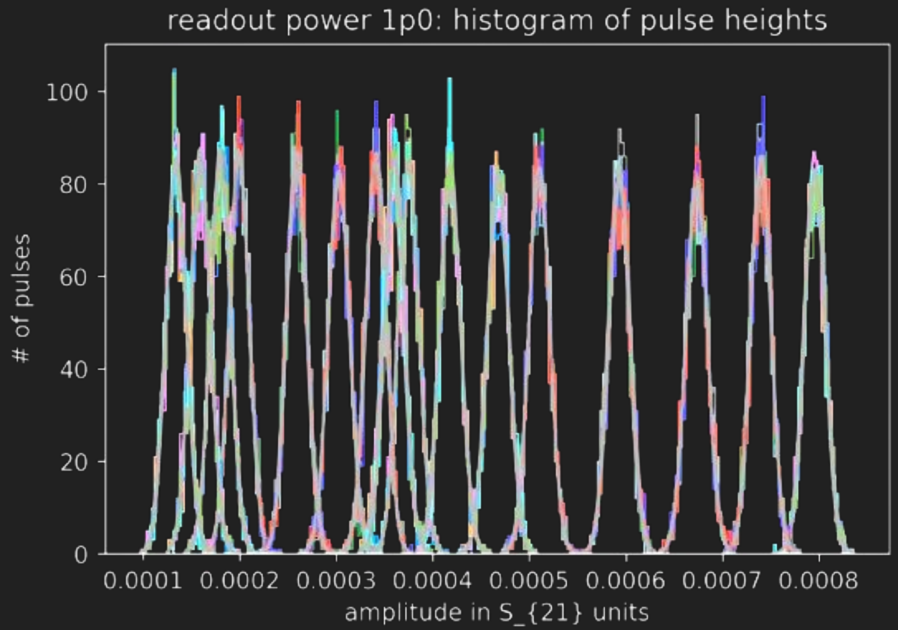
Aluminum KID Phonon Collection Efficiency Measurement

Average Pulses for Each LED Power



Aluminum KID Phonon Collection Efficiency Measurement

Histograms of Pulse Heights



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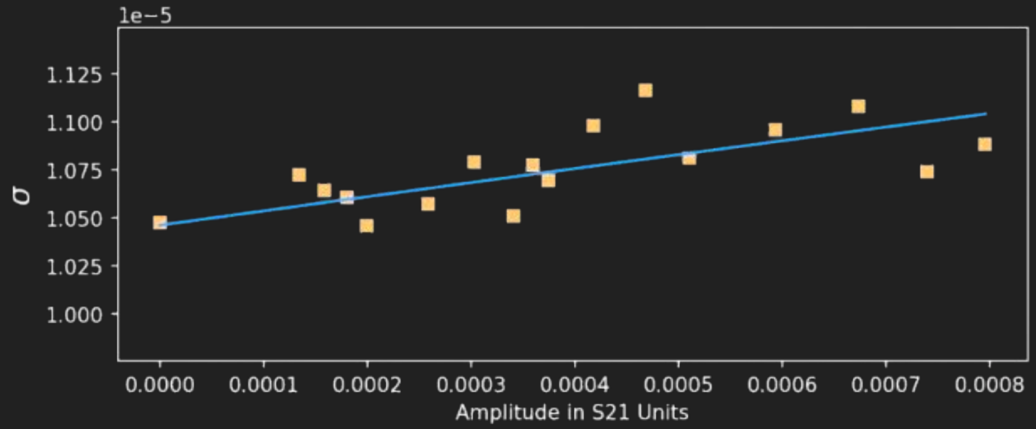

$$\sigma^2 = \sigma_0^2 + r \cdot \mu$$

r is the responsivity per photon – exact expression depends on readout quadrature. Typical form is:

$$r = \alpha \frac{\kappa_i}{V} \frac{h\nu}{2\Delta} \eta_{ph}$$

$$\sigma_E^{\text{Deposited}} \sim 1.5 \text{ keV} \qquad \sigma_E^{\text{Device}} \sim 15 \text{ eV}$$

$$\eta_{ph} = \frac{\sigma_E^{\text{Dev}}}{\sigma_E^{\text{Dep}}} \sim 0.01$$

Kinetic Inductance Traveling Wave Parametric Amplifier (KI-TWPA)

$$\frac{\partial^2 I}{\partial z^2} - \frac{\partial}{\partial t}\left(LC\frac{\partial I}{\partial t}\right) = 0 \longrightarrow L(I) = L_0\left(1+\frac{I^2}{I_*^2}+\frac{I^4}{I_*^4}+\dots\right)$$