Low-Mass Dark Matter Searches Using Quantum Sensing and Readout with MKIDs and Paramps

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on behalf of Golwala-group

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New Directions in the Search for Light Dark Matter Particles

Fermilab

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Overview

- Detector requirements for various detection channels
- Kinetic inductance detector basics
- KID-based architectures for different science goals and expected energy resolutions
  - Small detectors focused on energy resolution for low-mass reach (< GeV, << GeV)
  - Large detectors focused on ER/NR rejection and position reconstruction for neutrino floor reach at 0.5-5 GeV
- Progress to date and plans

With thanks to:

- SuperCDMS
- Pyle, Zurek, Kurinsky, McKinsey et al

Rapid Introduction

Motivation for Small Sub-eV Resolution Detectors

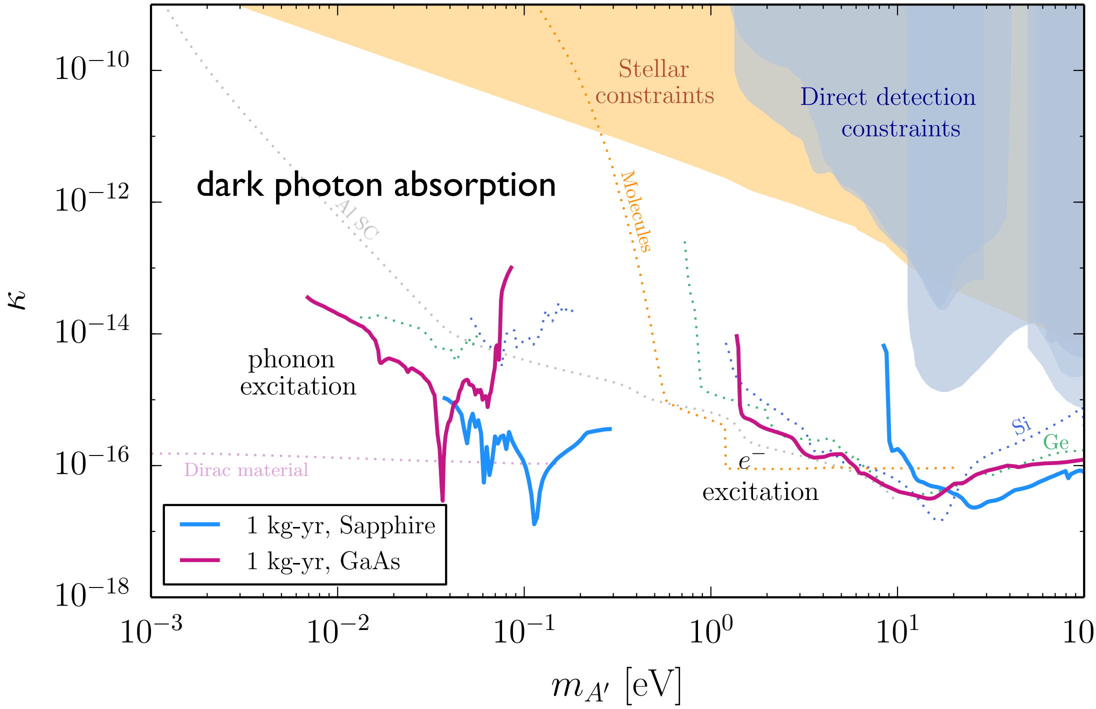
Current technologies ~1 eV threshold

- MeV thermal relics, eV dark photons

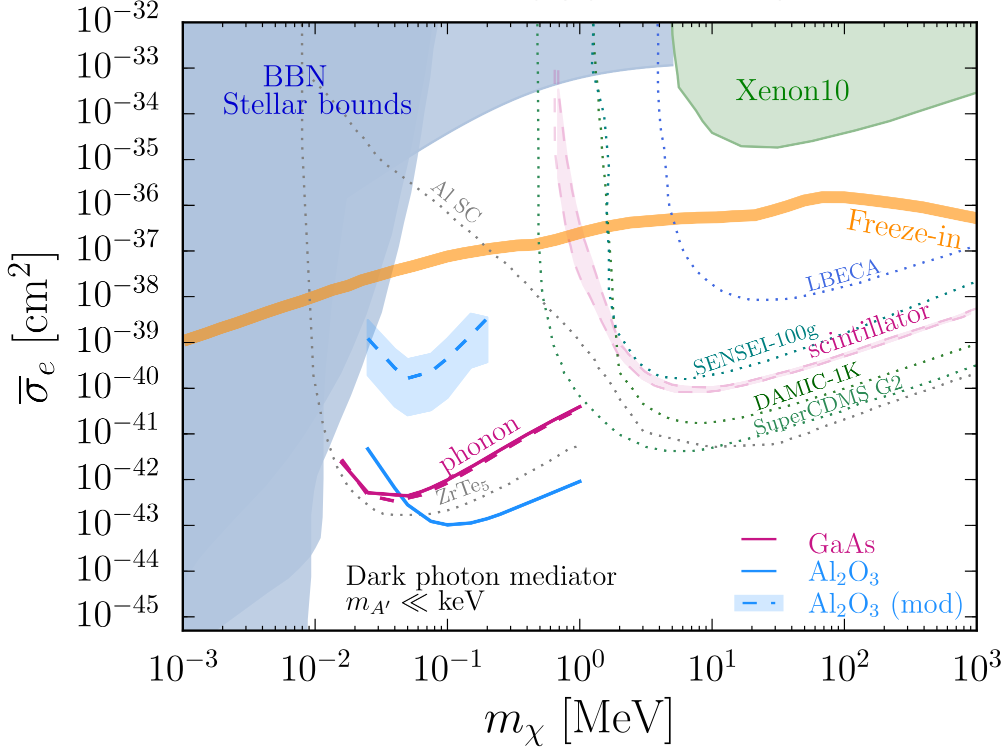
Need new technologies to access keV thermal relics, meV dark photons!

Sharp targets due to simplicity:

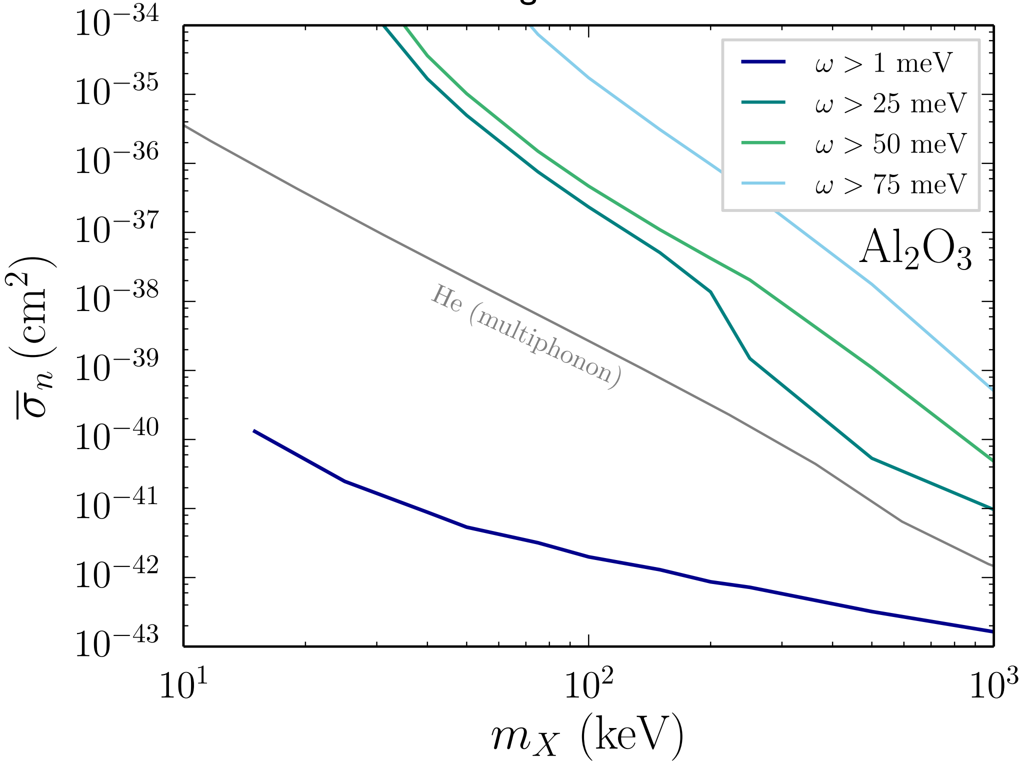
- same diagrams for annih. and scatt.
- no accidental cancellations



DM-electron scattering (light mediator)

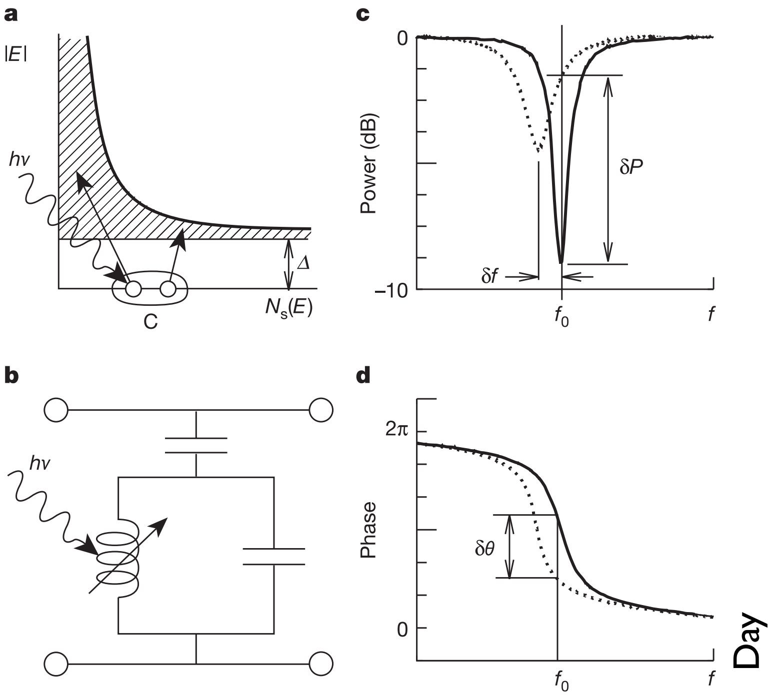


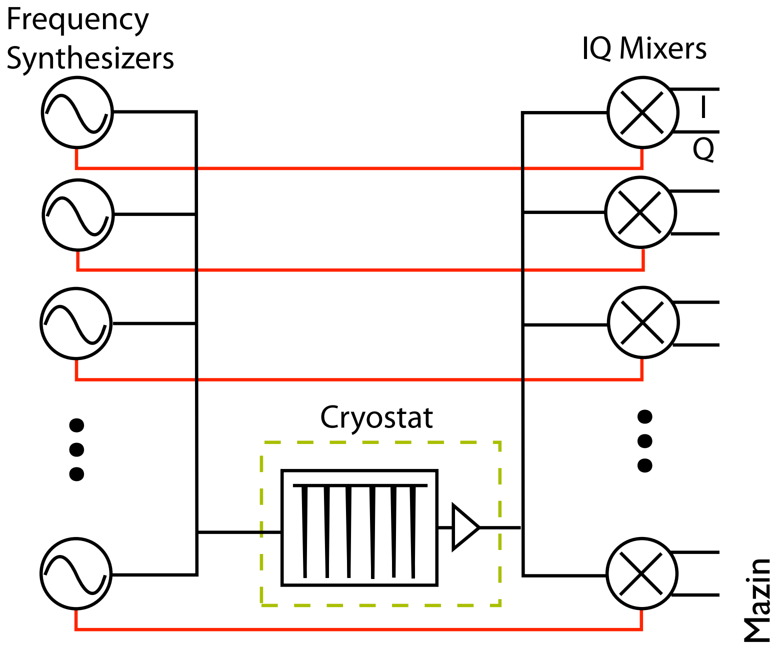
DM-nucleon scattering



Basics of Kinetic Inductance Detectors

sub-meV pair-breaking energy





Superconductors have an AC inductance due to inertia of Cooper pairs

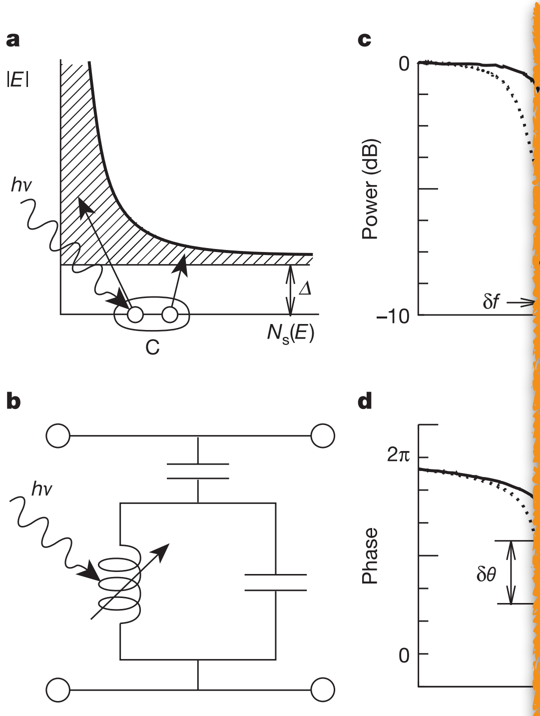
Changes when Cooper pairs broken by energy, creating quasiparticles (qps)

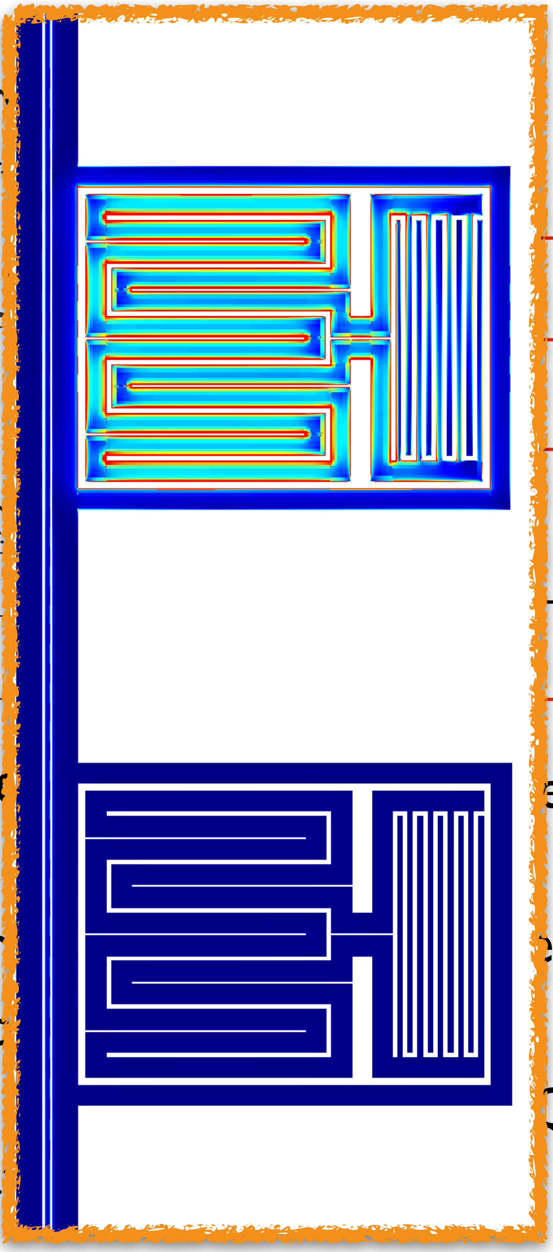
Sense the change by monitoring a resonant circuit

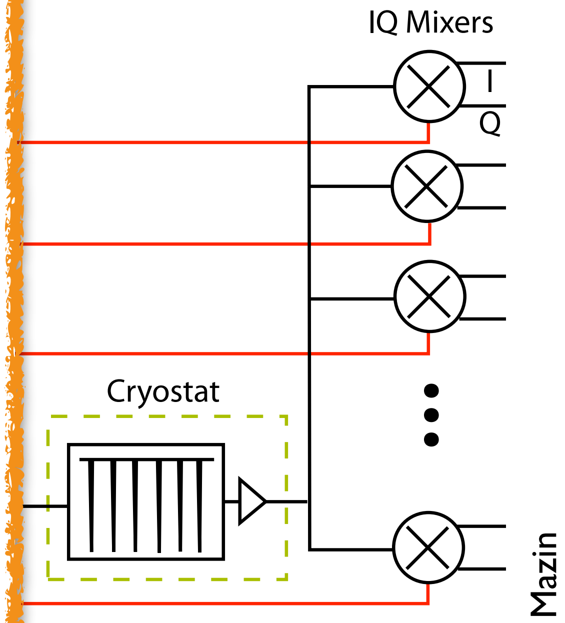
Key point: superconductors provide very high Q ($Q_i > 10^7$ achieved), so thousands of such resonators can be monitored with a single feedline

Basics of Kinetic Inductance Detectors

sub-meV pair-breaking energy







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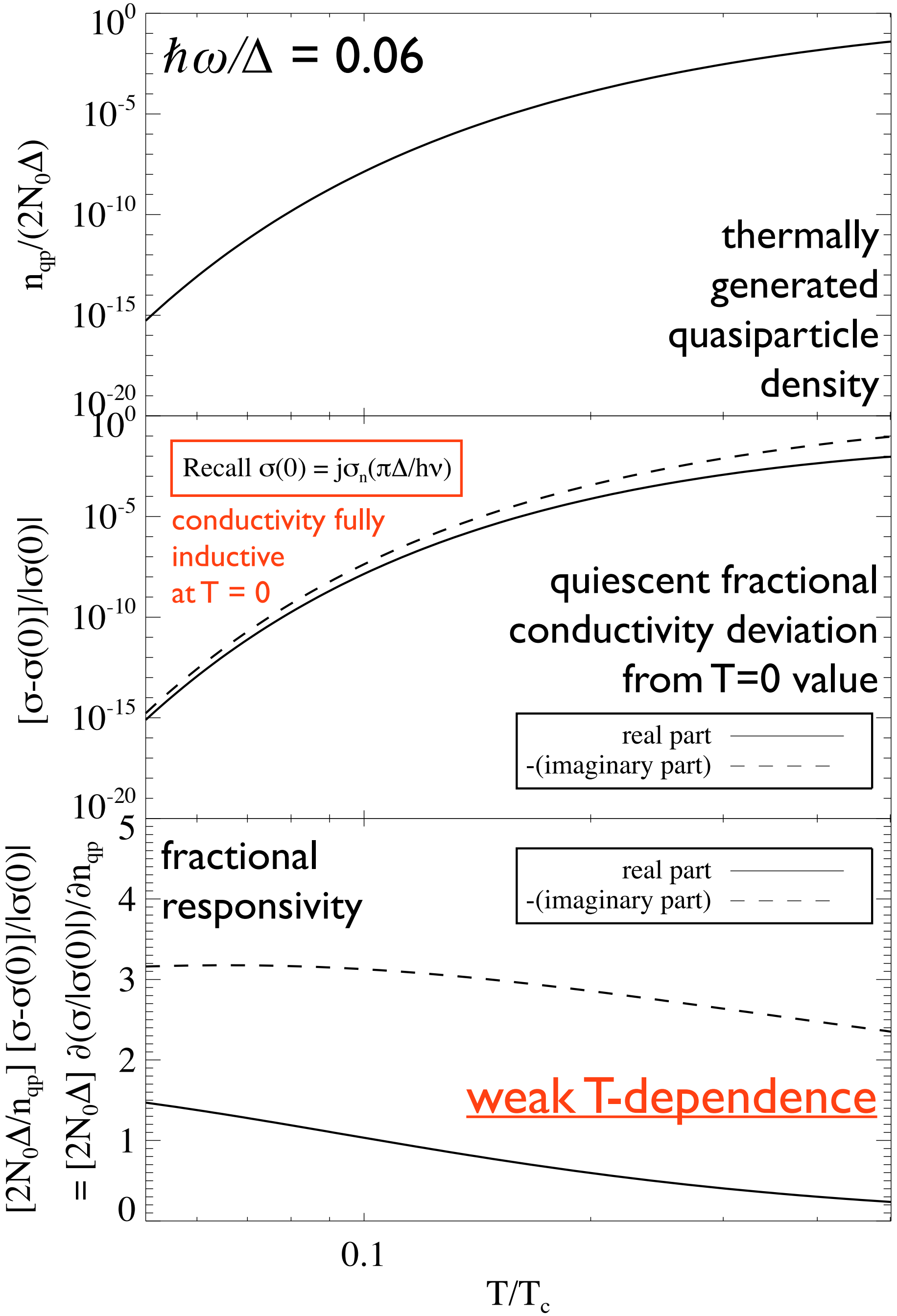
Detector physics

Quasiparticles to Conductivity



$\hbar\omega/\Delta$ = 0.06

thermally generated quasiparticle density

Recall $\sigma(0) = j\sigma_n(\pi\Delta/h\nu)$

conductivity fully inductive at T = 0

quiescent fractional conductivity deviation from T=0 value

fractional responsivity

weak T-dependence

MB gives characteristic T and $\hbar\omega/\Delta$ dependence

$$\frac{\sigma_1}{|\sigma(0)|} = \frac{4}{\pi}\frac{n_{qp}}{2N_0\Delta}\frac{1}{\sqrt{2\pi\frac{kT}{\Delta}}}\sinh\left(\frac{\hbar\omega}{2kT}\right)K_0\left(\frac{\hbar\omega}{2kT}\right)$$

$$\frac{\sigma_2}{|\sigma(0)|} = 1 - \frac{n_{qp}}{2N_0\Delta}\left[1+\sqrt{\frac{2\Delta}{\pi kT}}\exp\left(-\frac{\hbar\omega}{2kT}\right)I_0\left(\frac{\hbar\omega}{2kT}\right)\right]$$

$$2N_0\Delta\left.\frac{\partial(\sigma_1/|\sigma(0)|)}{\partial n_{qp}}\right|_T = \frac{2N_0\Delta}{n_{qp}}\frac{\sigma_1}{|\sigma(0)|}$$

$$2N_0\Delta\left.\frac{\partial(\sigma_2/|\sigma(0)|)}{\partial n_{qp}}\right|_T = \frac{2N_0\Delta}{n_{qp}}\frac{\sigma_2-\sigma_2(0)}{|\sigma(0)|}$$

Key features

- Quiescent n_{qp} exponentially suppressed as T decreases*
  - * as long as no anomalous qp recombination physics
  - * as long as no anomalous qp creation
- Responsivity only weakly T-dependent (not exponential!)

Nonidealities: Quasiparticle Density and Lifetime Limits

Quasiparticle response governed by quasiparticle lifetime, observed to follow

$$\tau_{qp} = \frac{\tau_{max}}{1 + n_{qp}/n_*}$$

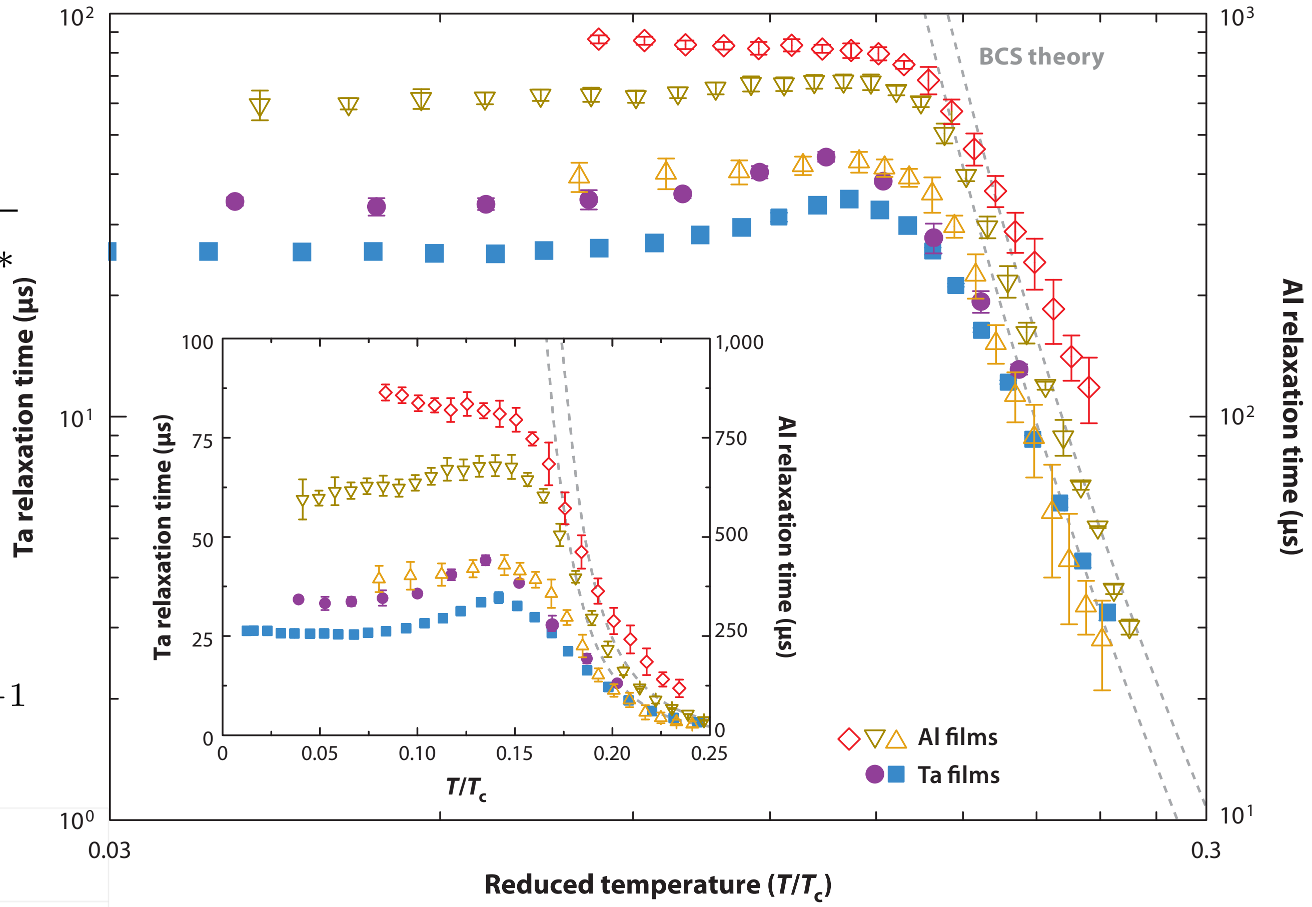
where n_* may be a limiting qp density

Frequently written as

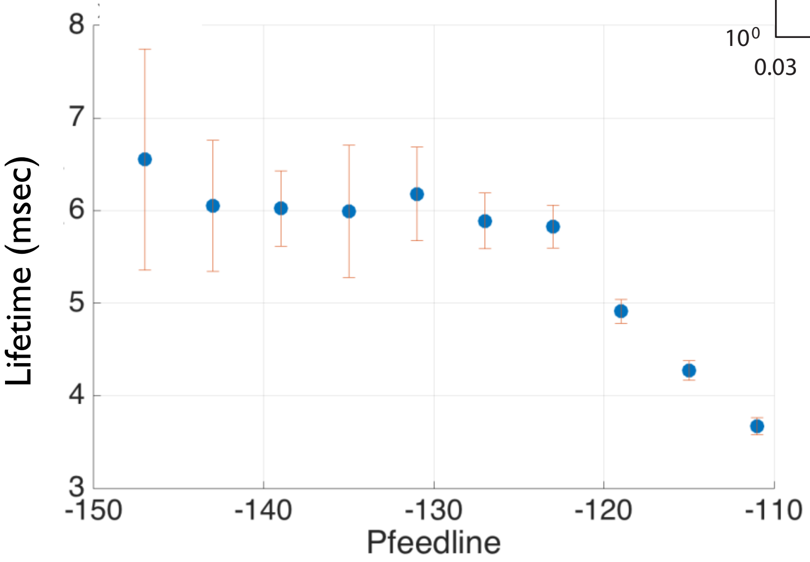
$$\frac{1}{\tau_{qp}} = 2\,R\,n_{qp} + \frac{1}{\tau_{max}}$$

with the recombination constant $R = (2\,n_*\,\tau_{max})^{-1}$

asymptotic regime; limiting excess qp density n_*, or something else? related to disorder? (Barends et al implantation experiment)



Barends et al PRL (2008)
as reproduced in Zmuidzinas, ARCMP (2012)



Noroozian

- Sets bandwidth over which noise integrated: larger τ_{qp} is better
- Many ms lifetimes achievable but perhaps only at low readout powers
- Need to make conservative assumptions about τ_{qp} to avoid optimistic predictions

Science: goals & prospects

Small-Detector (gram-scale) Architectures

Goal: detection of sub-eV energies from:

Dark phonon absorption, DM-e scattering, scalar-mediated nucleon scattering at very low recoil energies, directly producing phonons w/o e-h pairs

Methods:

Detection of qp creation in superconducting target via phonon or qp collection (Hochberg, Zhao, Zurek, arXiv:1504.07237)

Phonons appropriate when $2\Delta_{substrate} > h\nu_{phonon}$: phonons propagate quasi-ballistically with long decay times (100 μs - ms: SuperCDMS, Gaitskell thesis w/high RRR Nb)

Quasiparticles appropriate when $2\Delta_{substrate} < h\nu_{phonon}$: phonons cannot propagate, but qp's can, w/long decay times (e.g.: probably Al, other low T superconductors: untested!)

Detection of optical phonon production in polar materials:

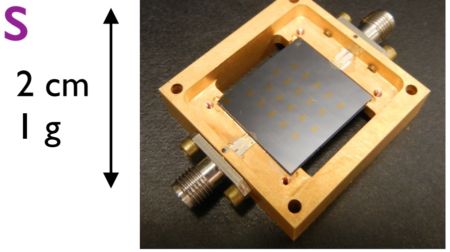
GaAs (Knapen, Lin, Pyle, Zurek, arXiv:1712.06598)

Al_2O_3 (Griffin, Knapen, Lin, Zurek, arXiv:1807.10291)

Architecture:

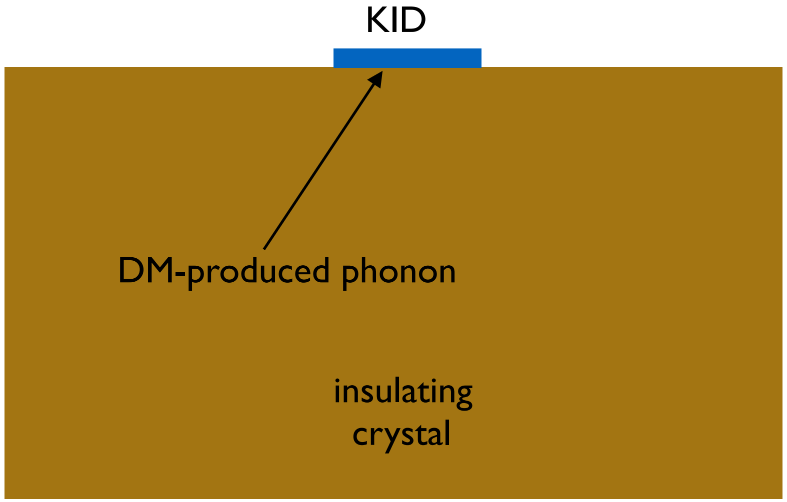
Single mm-scale KID on gm-scale, few-mm target substrate

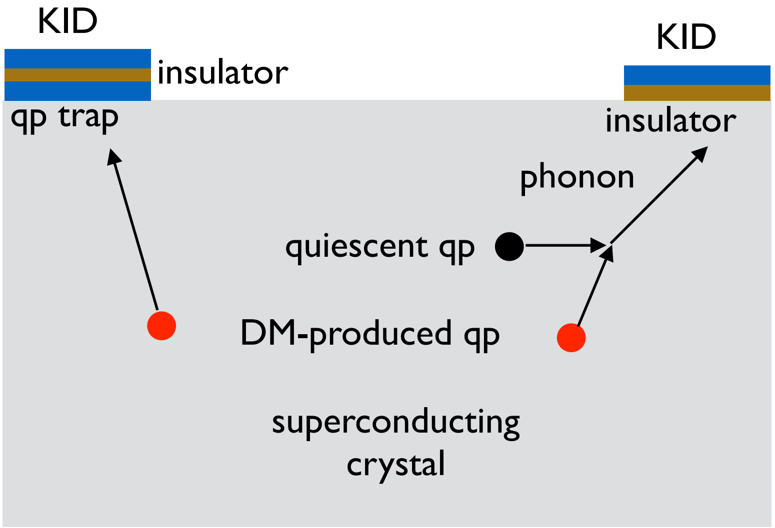
Lower-gap superconductor for KID (e.g., AlMn) and/or better amplifiers promise meV-scale resolution



no quasiparticle trapping!*

*of the conventional kind with collector >> KID





no quasiparticle trapping!

Small-Detector Architecture
Characteristic Energy Resolution: Optimistic Prediction

Assume

- delta-function-like energy deposition
- qp population dominated by readout power generation
- dissipation readout (no TLS noise)
- amplifier noise dominant over g-r noise (T ~ 0.1 T_c required)
- quasiparticle lifetime >> phonon absorption time, $\tau_{qp} >> \tau_{ph,abs} \sim 100\ \mu s$
  - optimistic, requires increasing τ_{qp} from ~100 μs
- Reduce Δ, T_N to get well below eV resolution

"efficiency factors" all assumed to be unity by design (optimistic)

$$\chi_c = \frac{4\,Q_r^2}{Q_i\,Q_c} \leq 1$$

$$\chi_{qp} = \frac{Q_i}{Q_{i,qp}} \leq 1$$

$$\chi_{BW} = \frac{\tau_{qp}}{\tau_{abs} + \tau_{qp}} \leq 1$$

superconducting gap energy

efficiency of qp creation by readout power

normal state single-spin density of states

resonator effective volume (weighted by current²)

amplifier noise temperature

$$\sigma_E = \frac{2\,\Delta}{\eta_{ph}} \sqrt{\frac{\eta_{read}}{\alpha \chi_c \chi_{qp}}} \sqrt{\frac{N_0 V_r}{\gamma_s S_1(f_r, T_{qp}, \Delta)\, Q_{i,qp}}} \sqrt{\frac{k_B T_N}{\chi_{BW}}}$$

$$= (0.9\ \mathrm{eV}) \left(\frac{0.3}{\eta_{ph}} \sqrt{\frac{\eta_{read}}{p_t}} \frac{0.1}{\alpha}\right) \left(\frac{\Delta}{200\ \mu\mathrm{eV}}\right) \sqrt{\frac{10^6}{Q_{i,qp}}} \sqrt{\frac{V_r}{10^4\ (\mu\mathrm{m})^3} \frac{T_N}{5\ \mathrm{K}} \frac{1.6}{S_1(f_r, T_{qp}, \Delta)}}$$

efficiency for converting phonons to qps

probability for phonon to enter KID per try

fraction of inductance due to KI

~ aluminum gap

quality factor due to quasiparticles

1 mm² x 10 nm

superconductivity factor

Small-Detector Architecture
Characteristic Energy Resolution: Conservative Prediction

no quasiparticle trapping!

Assume (conservatively):

- qp population dominated by readout power generation
- dissipation readout (no TLS noise)
- amplifier noise dominant over g-r noise (T ~ 0.1 T_c required)
- quasiparticle lifetime in KID << phonon absorption timescale ($\tau_{qp} << \tau_{ph,abs}$ ~ 100 μs; conservative)
- Reduce Δ, T_N, increase τ_{qp} to get well below eV resolution

“efficiency factors” χ_c, χ_{qp} assumed to be unity by design, $\chi_{BW} << 1$ (conservative)

$$\chi_c = \frac{4\,Q_r^2}{Q_i\,Q_c} \leq 1$$

$$\chi_{qp} = \frac{Q_i}{Q_{i,qp}} \leq 1$$

$$\chi_{BW} = \frac{\tau_{qp}}{\tau_{abs} + \tau_{qp}} \leq 1$$

superconducting gap energy

efficiency of qp creation by readout power

normal state single-spin density of states

amplifier noise temperature

substrate volume

pair-breaking length in KID film

$$\sigma_E = \frac{2\,\Delta}{\eta_{ph}}\sqrt{\frac{\eta_{read}}{\alpha p_t}}\sqrt{\frac{1}{\chi_c\chi_{qp}}}\sqrt{\frac{N_0}{\gamma_s S_1(f_r, T_{qp}, \Delta)}}\sqrt{\frac{1}{Q_{i,qp}}}\sqrt{\frac{k_B T_N}{\tau_{qp}}}\sqrt{\frac{V_{abs}\lambda_{pb}}{c_s}}$$

$$= (7\text{ eV})\left(\frac{0.3}{\eta_{ph}}\sqrt{\frac{\eta_{read}}{p_t}\,\frac{0.1}{\alpha}}\right)\left(\frac{\Delta}{200\ \mu\text{eV}}\right)\sqrt{\frac{10^6}{Q_{i,qp}}}\sqrt{\frac{M_{sub}}{1\text{ gm}}\,\frac{\lambda_{pb}}{1\ \mu\text{m}}\,\frac{7\text{ km/s}}{c_s}\,\frac{100\ \mu\text{s}}{\tau_{qp}}\,\frac{T_N}{5\text{ K}}\,\frac{1.6}{S_1(f_r, T_{qp}, \Delta)}}$$

efficiency for converting phonons to qps

probability for phonon to enter KID per try

fraction of inductance due to KI

~ aluminum gap

quality factor due to quasiparticles

substrate mass (assuming silicon)

sound speed

quasiparticle lifetime

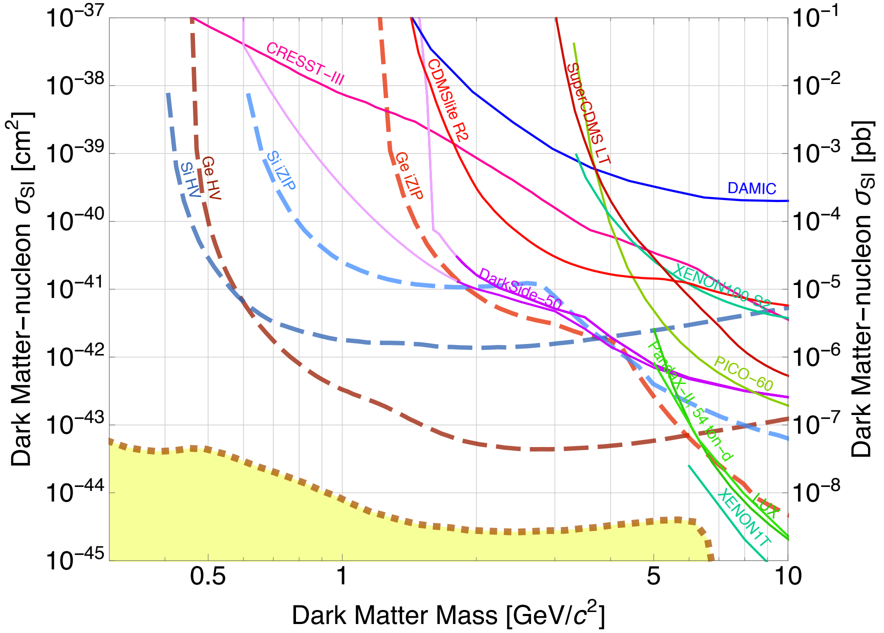
superconductivity factor

Large-Detector (kg-scale) Architectures

SuperCDMS 0.5-5 GeV search limited by:

Bulk cosmogenics producing electron recoils

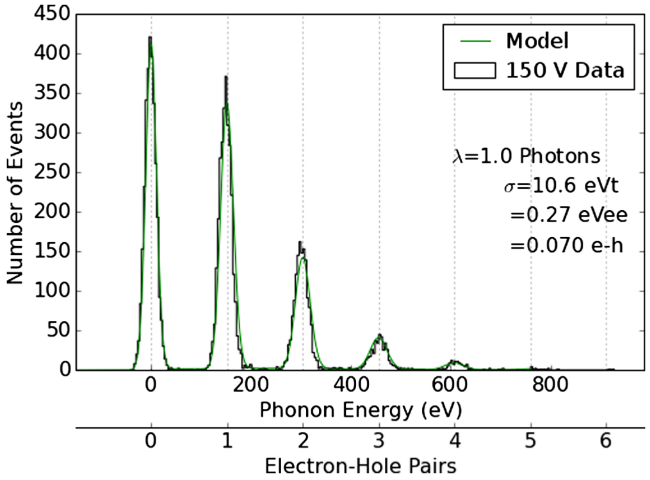
Surface background rejection



Requirements:

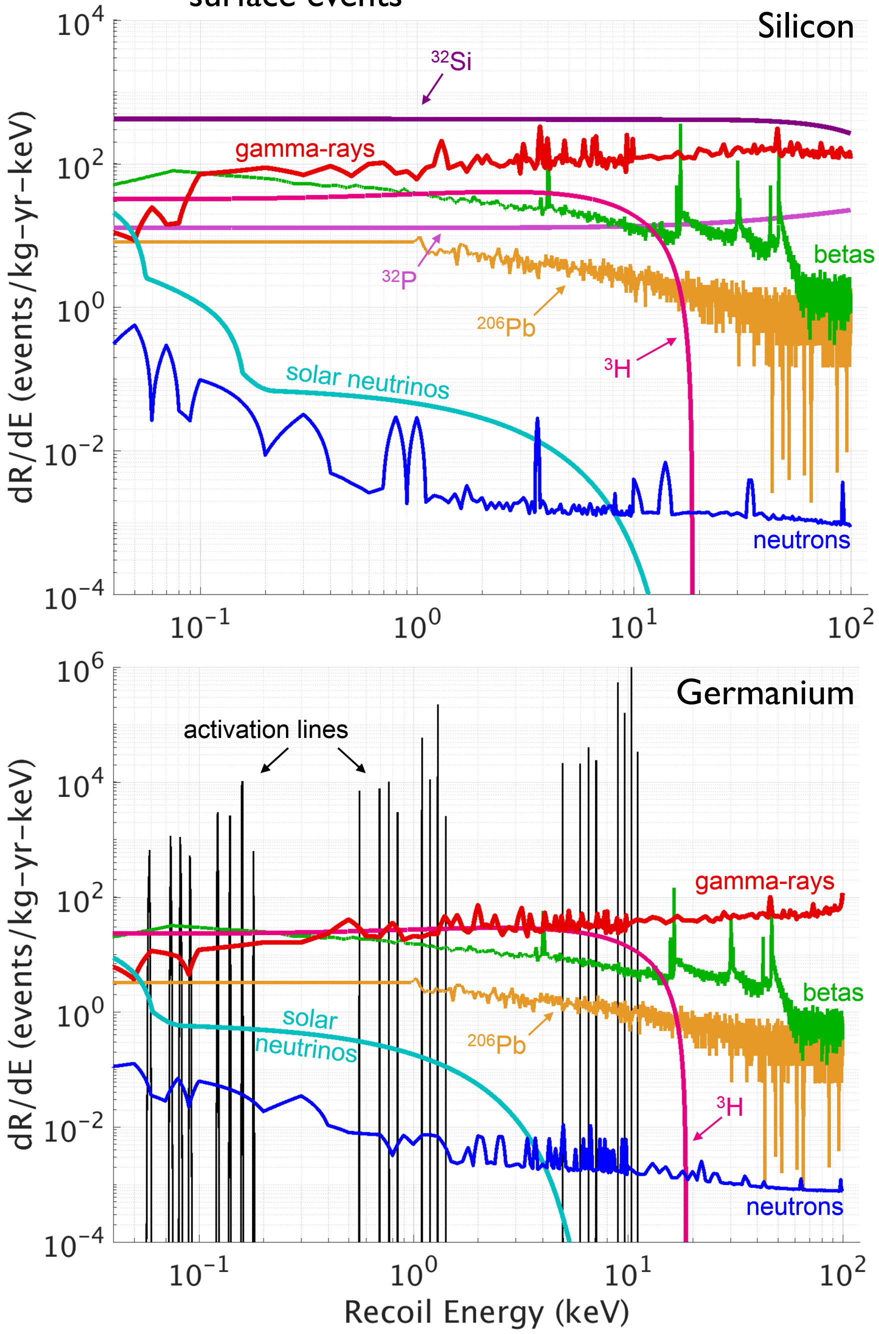
ER/NR rejection
using spectral
information and
e/h quantization

Position-based rejection
of surface bgnds



Raw background spectra expected for SuperCDMS SNOLAB dominated by :

- ERs from cosmogenics (^{32}Si, ^{3}H)
- continuum gammas
- surface events



Large-Detector (kg-scale) Architectures

no quasiparticle trapping!

Goal:

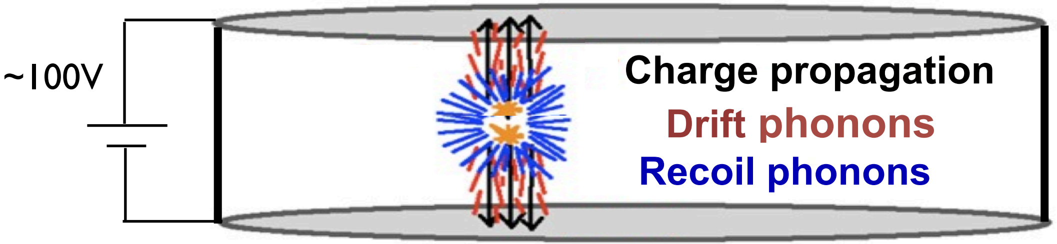
- traditional nuclear recoil search at very low recoil energies (10 eVr)

Method:

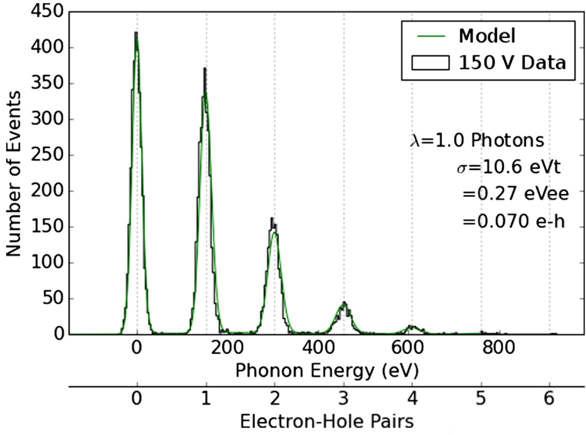
- 10 eV resolution + Neganov-Trofimov-Luke phonon production by drifting e-h pairs in large electric field for single e-h pair detection
- Or, 0.25-eV resolution and no NTL

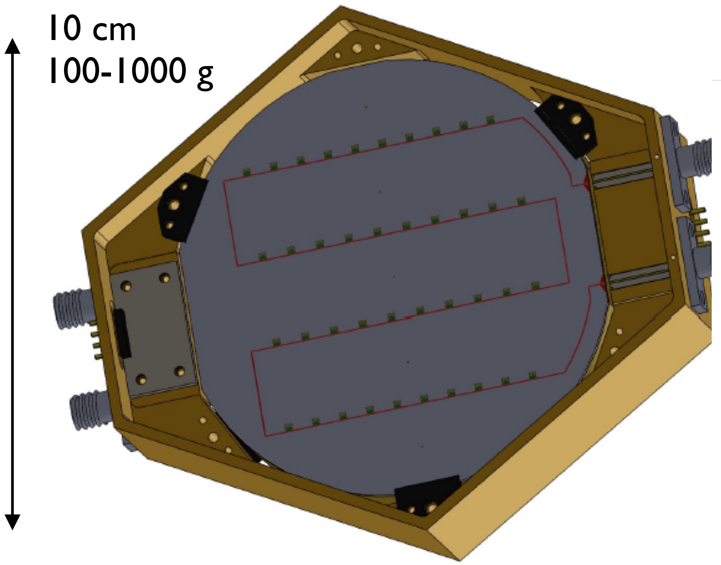
Architecture:

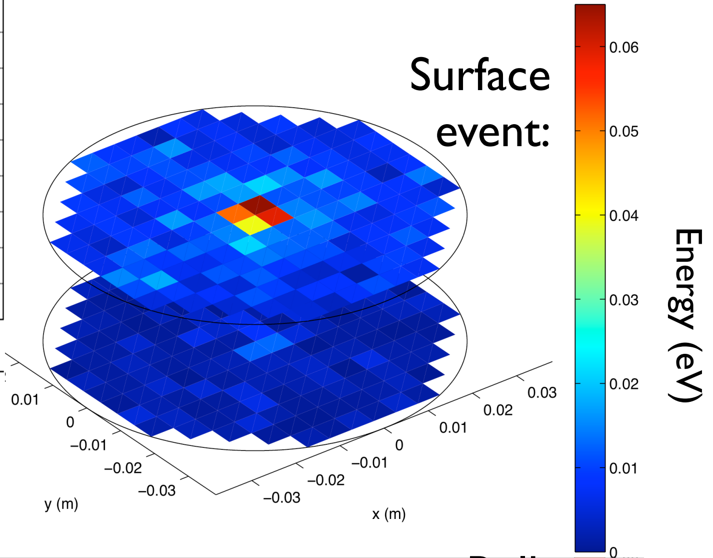
- ~100 KIDs on 10-cm-scale substrate
- Energy resolution provides ER/NR discrimination
- Fine pixelation yields surface bgnd rejection via fiducialization
- Also provides pos'n correction for energy

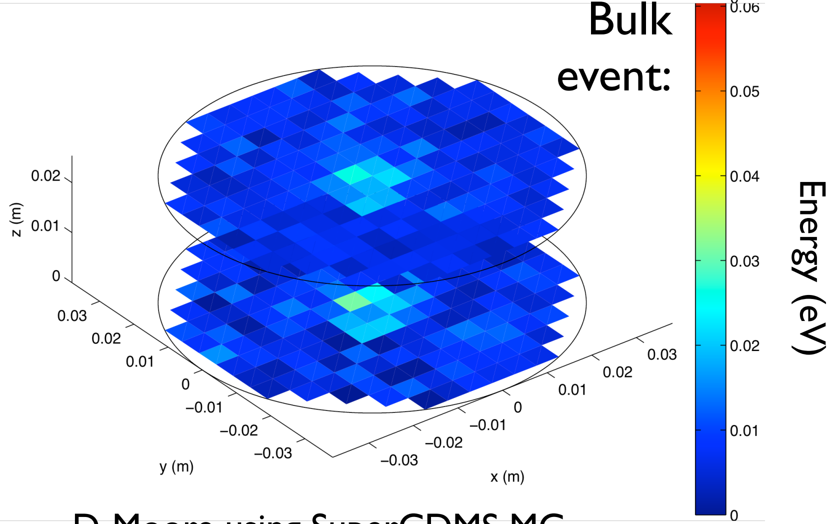


SuperCDMS
PRL **121**: 051301 (2018)









D. Moore using SuperCDMS MC

no quasiparticle trapping!

Large-Detector Architecture
Characteristic Energy Resolution: Conservative Prediction

Assume (conservatively):

- qp population dominated by readout power generation
- dissipation readout (no TLS noise)
- amplifier noise dominant over g-r noise (T ~ 0.1 T_c required)
- resonator is coupling dominated (Q_i >> Q_c = 10k-50k) so $\tau_r < \tau_{ph,r}$
- quasiparticle lifetime in KID << phonon absorption timescale ($\tau_{qp} << \tau_{ph,abs}$ ~ ms; conservative)
- Reduce Δ, T_N, increase τ_{qp} to reach eV resolution

superconducting gap energy

efficiency of qp creation by readout power

area of substrate (including sidewalls)

pair-breaking length in KID film

normal state single-spin density of states

amplifier noise temperature

$$\sigma_E = \frac{\Delta}{\eta_{ph}}\sqrt{\frac{\eta_{read}}{\alpha p_t}}\sqrt{\frac{A_{sub}\lambda_{pb}N_0}{\gamma_s S_1(f_r,T_{qp},\Delta)}}\sqrt{\frac{k_B T_N}{2\pi f_r \tau_{qp}}}$$

$$= (330\ \mathrm{eV})\left(\frac{0.3}{\eta_{ph}}\sqrt{\frac{\eta_{read}}{p_t}}\frac{0.1}{\alpha}\right)\left(\frac{\Delta}{200\ \mu\mathrm{eV}}\right)\sqrt{\frac{A_{sub}}{100\ \mathrm{cm}^2}\frac{\lambda_{pb}}{1\ \mu\mathrm{m}}\frac{3\ \mathrm{GHz}}{f_r}\frac{100\ \mu\mathrm{s}}{\tau_{qp}}\frac{T_N}{5\ \mathrm{K}}\frac{1.6}{S_1(f_r,T_{qp},\Delta)}}$$

efficiency for converting phonons to qps

probability for phonon to enter KID per try

fraction of inductance due to KI

~ aluminum gap

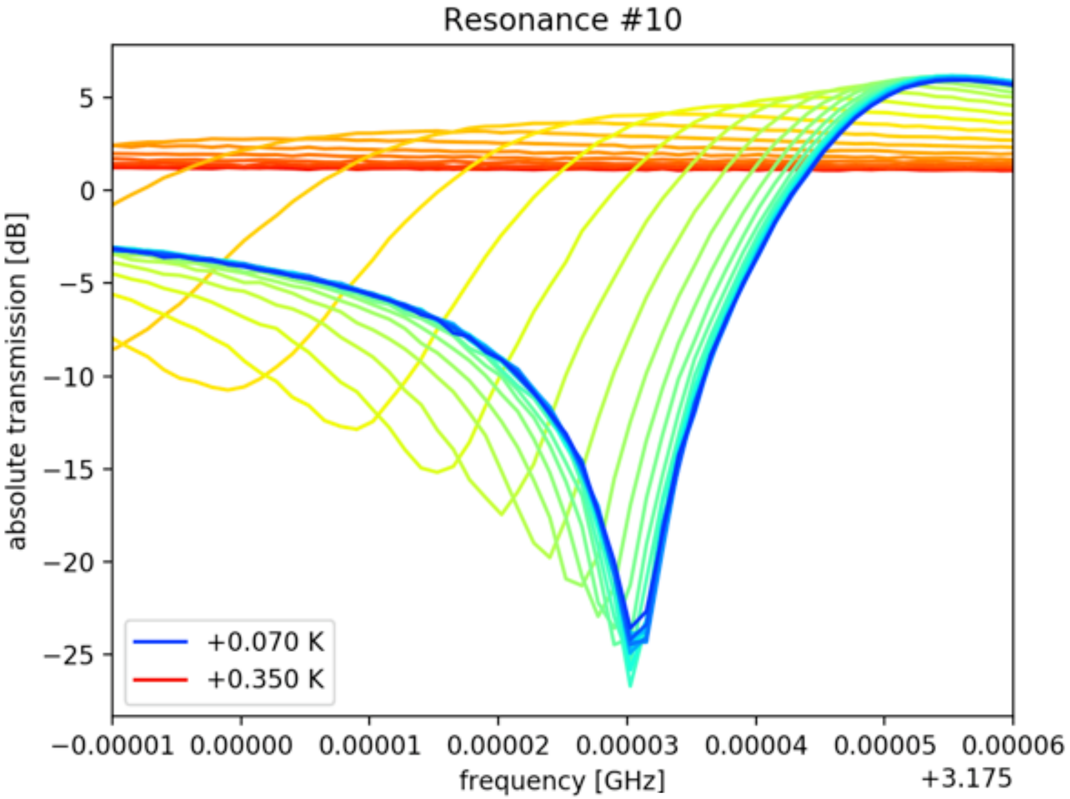
KID resonant frequency

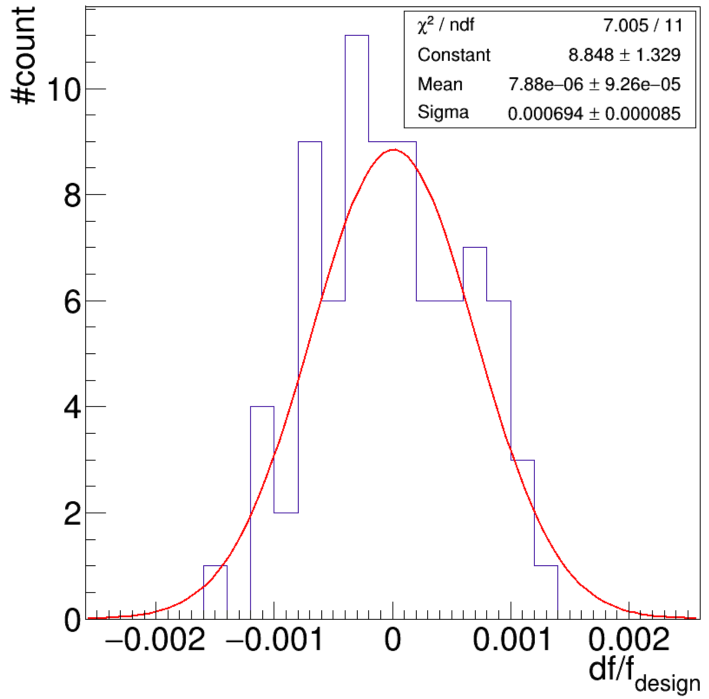
quasiparticle lifetime

superconductivity factor

Laboratory performance

KID Performance





Reasonable yield

Qi's spread from 10^4 - few 10^6

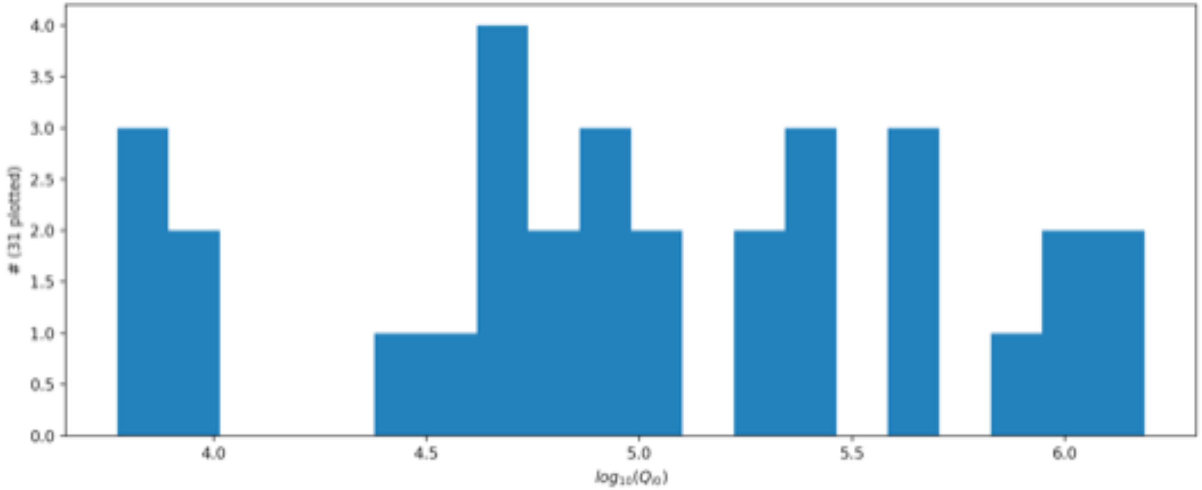
Fab goal is a cluster > 10^5

Formal noise limit being studied:

GR or TLS, no evidence of TLS yet

Proper responsibly calibrations

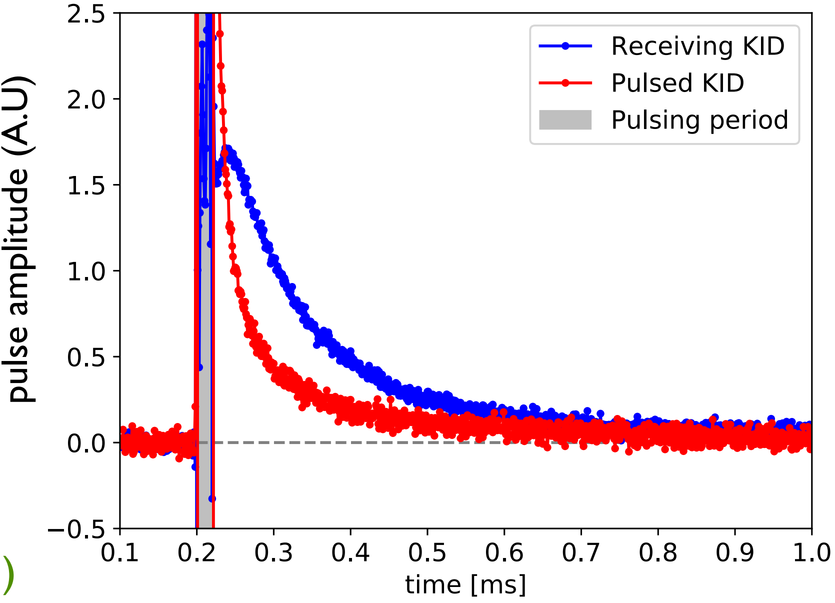
Sub-mm community has standard techniques



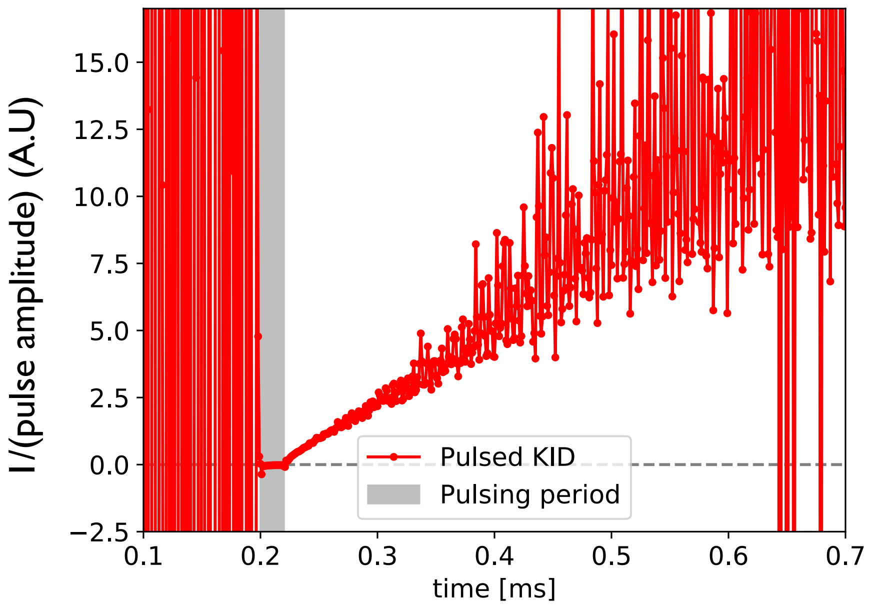
KID Power Pulsing

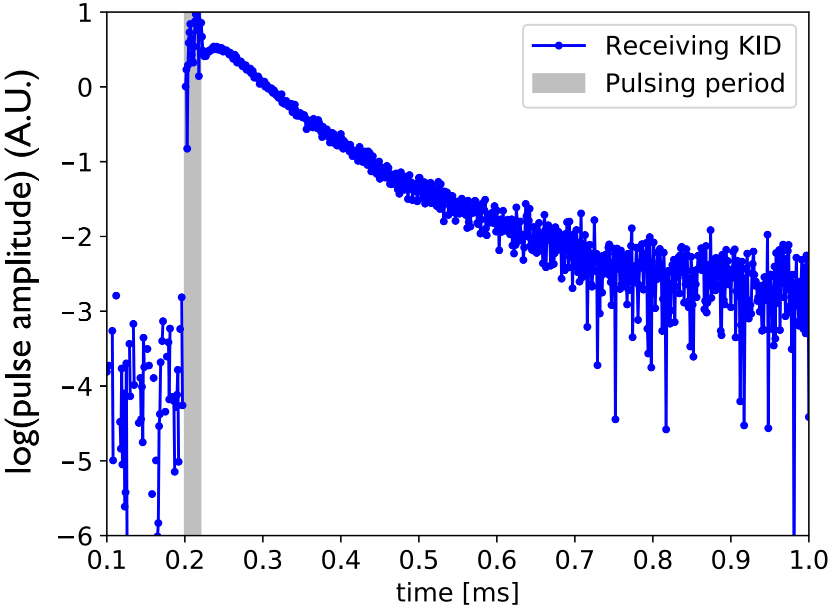
Calibration of KID response with readout power pulsing

- Apply a 10 μs readout power pulse to one KID (red), off-resonance, while reading out it + another (blue)
- Quasiparticle recombination visible in pulsed KID
  - 1/(pulse amplitude) shows linear relationship with time as expected for pair recombination
- Phonon-mediated signal seen in other KIDs (blue)
  - Quasiparticle decay creates phonons
  - Phonons propagate in substrate to other KID and create quasiparticles there (with rise time)
  - Those quasiparticles decay (exp. decay because $\delta n_{qp}/n_{qp}$ small)



Calibrate position information with many localized sources!





Imminent improvements

$$\sigma_E \propto \Delta \sqrt{\frac{T_N}{5K} \frac{100\mu s}{\tau_{qp}} \ldots}$$

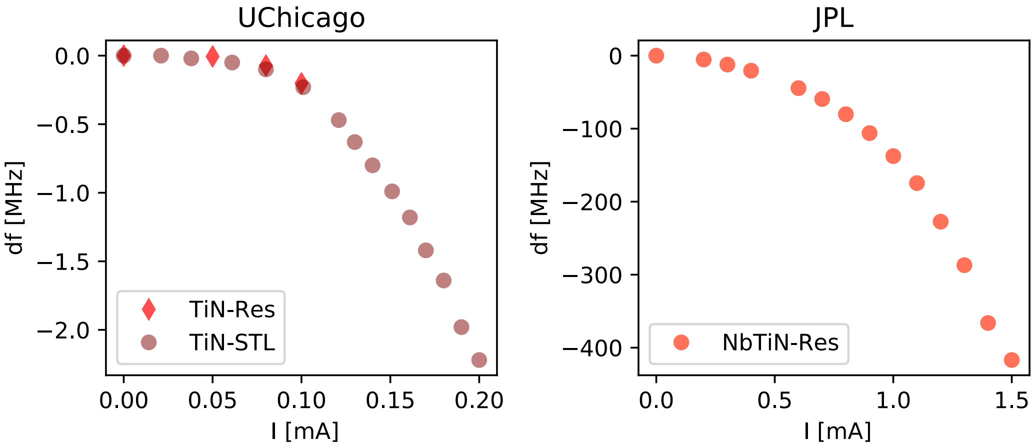
Broadband Kinetic Inductance Parametric Amplifier

Colleagues at JPL (P. Day et al) are developing a quantum-limited amplifier based on:

Nonlinearity due to kinetic inductance

3-wave mixing (DC + pump)

Broadband gain and quantum-limited performance demonstrated



Transmission line: df ∝du ∝**dθ (phase)**

$$u(I) = 1/\sqrt{\mathcal{C}\left(\mathcal{L}_g + \mathcal{L}_{k,0}\left(1 + (I/I_*)^2\right)\right)}$$

Sum of currents: pump, weak-signal, idler

$$I = \frac{1}{2}\left(\sum_n A_n(z)e^{i(k_n z - \omega_n t)} + \text{c.c.}\right)$$

Transmission line traveling wave eq.

$$\frac{\partial^2 I}{\partial z^2} - \frac{\partial}{\partial t}\left[\mathcal{L}(I)\mathcal{C}\,\frac{\partial I}{\partial t}\right] = 0$$

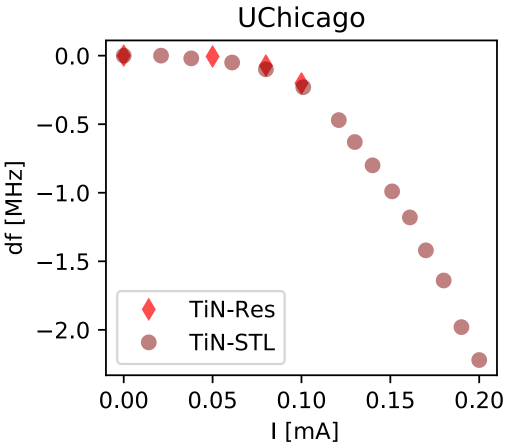
3-current (nonlinear) mixing

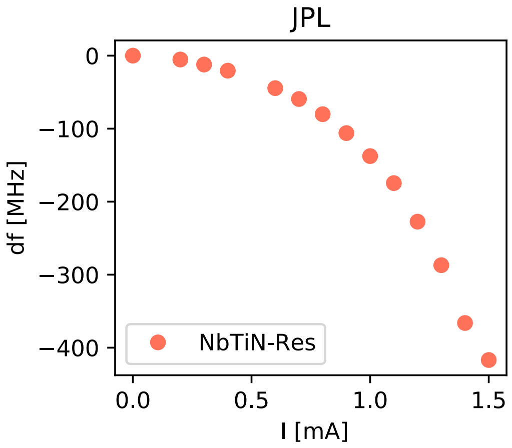
Broadband Kinetic Inductance Parametric Amplifier

Colleagues at JPL (P. Day et al) are developing a quantum-limited amplifier based on:

- Nonlinearity due to kinetic inductance
- 3-wave mixing (DC + pump) (really 4 wave, but pumps are degenerate)

Broadband gain and quantum-limited performance demonstrated





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Transmission line traveling wave eq.

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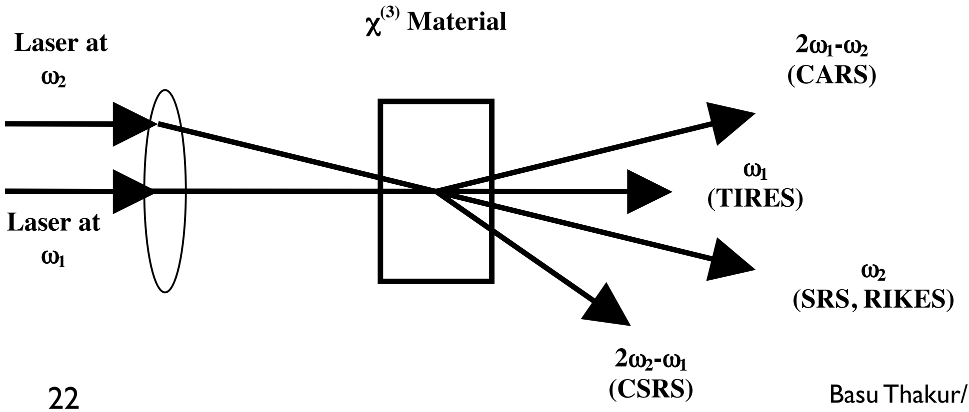
3-current (nonlinear) mixing

4-wave mixing (any nonlinear optics text book)

In order to understand the four-wave mixing process, a closer examination of the third order nonlinear polarization must be made. The general form of the polarization may be written as shown in (3).

$$P_i(\omega_4,\vec{r}) = \tfrac{1}{2}\chi^{(3)}_{ijkl}(-\omega_4,\omega_1,-\omega_2,\omega_3)E_j(\omega_1)E^*_k(\omega_2)E_l(\omega_3)\exp[i(\vec{k}_1-\vec{k}_2+\vec{k}_3)\cdot\vec{r}-i\omega_4 t] + \text{c.c.} \qquad (3)$$



Broadband Kinetic Inductance Parametric Amplifier

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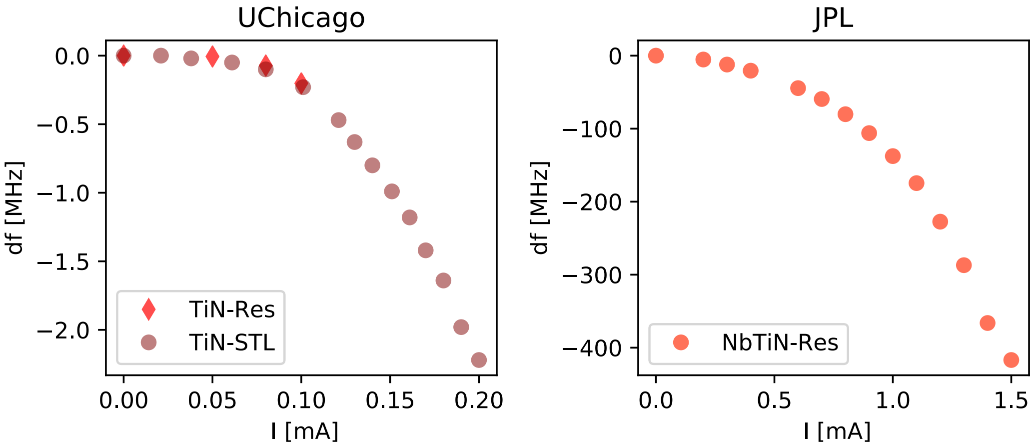
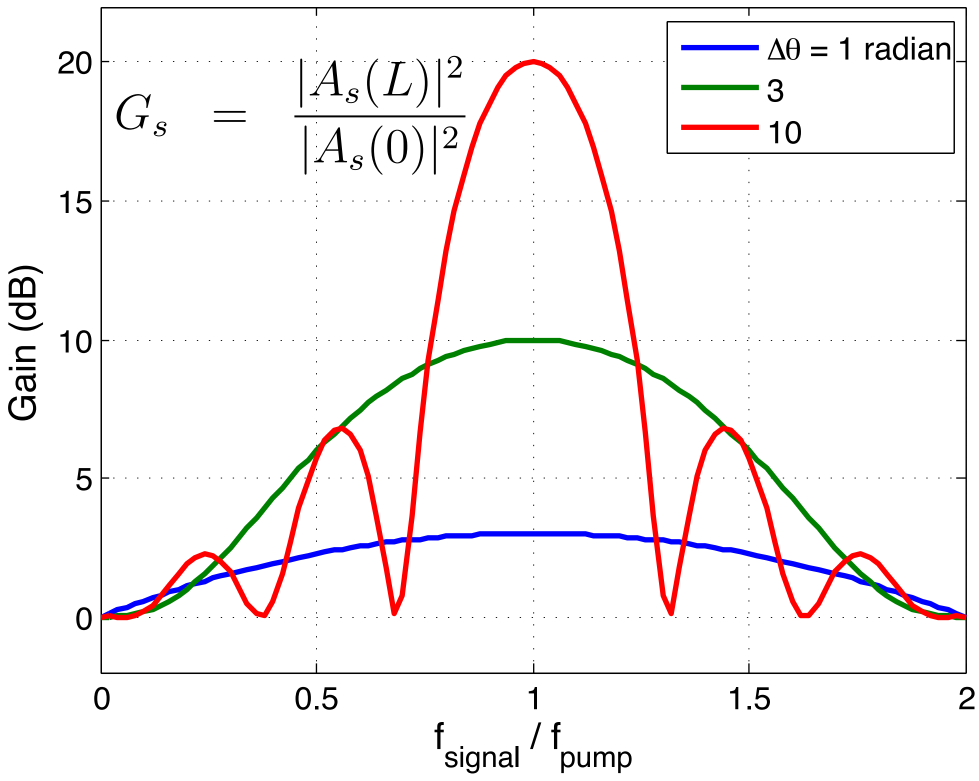
- 3-wave mixing (DC + pump)

Broadband gain and quantum-limited performance demonstrated



Transmission line: df ∝du ∝**d**θ **(phase)**

$$u(I) = 1/\sqrt{\mathcal{C}\left(\mathcal{L}_g + \mathcal{L}_{k,0}\left(1 + (I/I_*)^2\right)\right)}$$



Sum of currents: pump, weak-signal, idler

$$I = \frac{1}{2}\left(\sum_n A_n(z)e^{i(k_n z - \omega_n t)} + \text{c.c.}\right)$$

Transmission line traveling wave eq.

$$\frac{\partial^2 I}{\partial z^2} - \frac{\partial}{\partial t}\left[\mathcal{L}(I)\mathcal{C}\,\frac{\partial I}{\partial t}\right] = 0$$

3-current (nonlinear) mixing

Broadband Kinetic Inductance Parametric Amplifier

Colleagues at JPL (P. Day et al) are developing a quantum-limited amplifier based on:

- Nonlinearity due to kinetic inductance
- 3-wave mixing (DC + pump)

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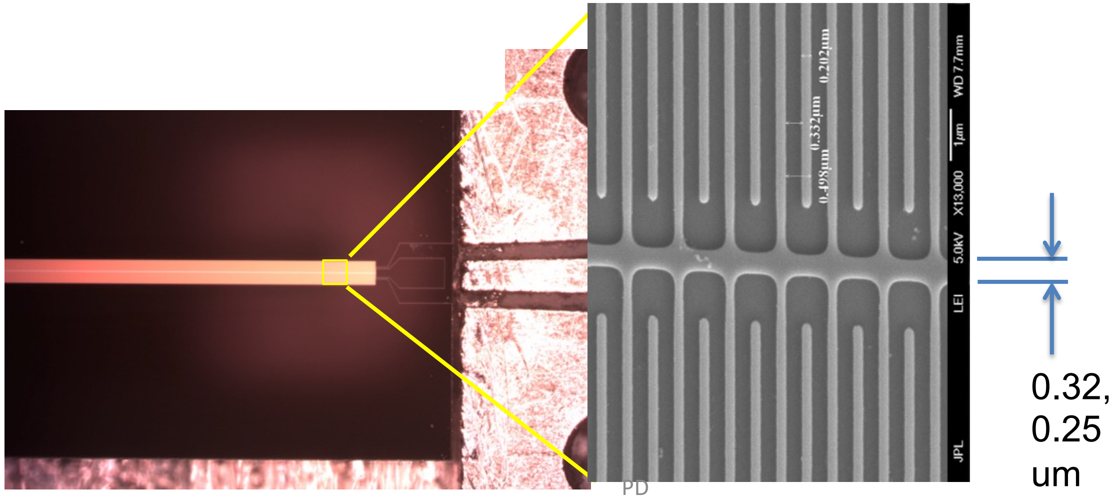

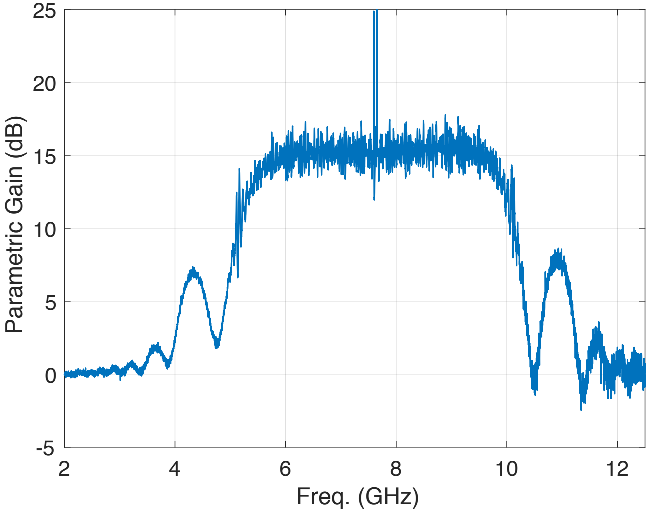

Applied to UV/O/IR MKIDs
to obtain 10x lower T_N

High kinetic inductance thin films requires carful engineering of transmission lines

- High Lk materials for higher gains
- Phase mismatch for varying frequencies for large BW
- Transmission / reflection optimized for large BW

Jet Propulsion Laboratory
California Institute of Technology

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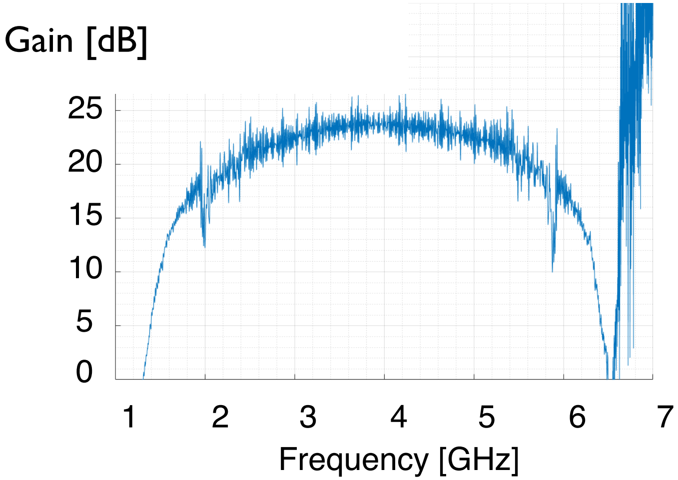

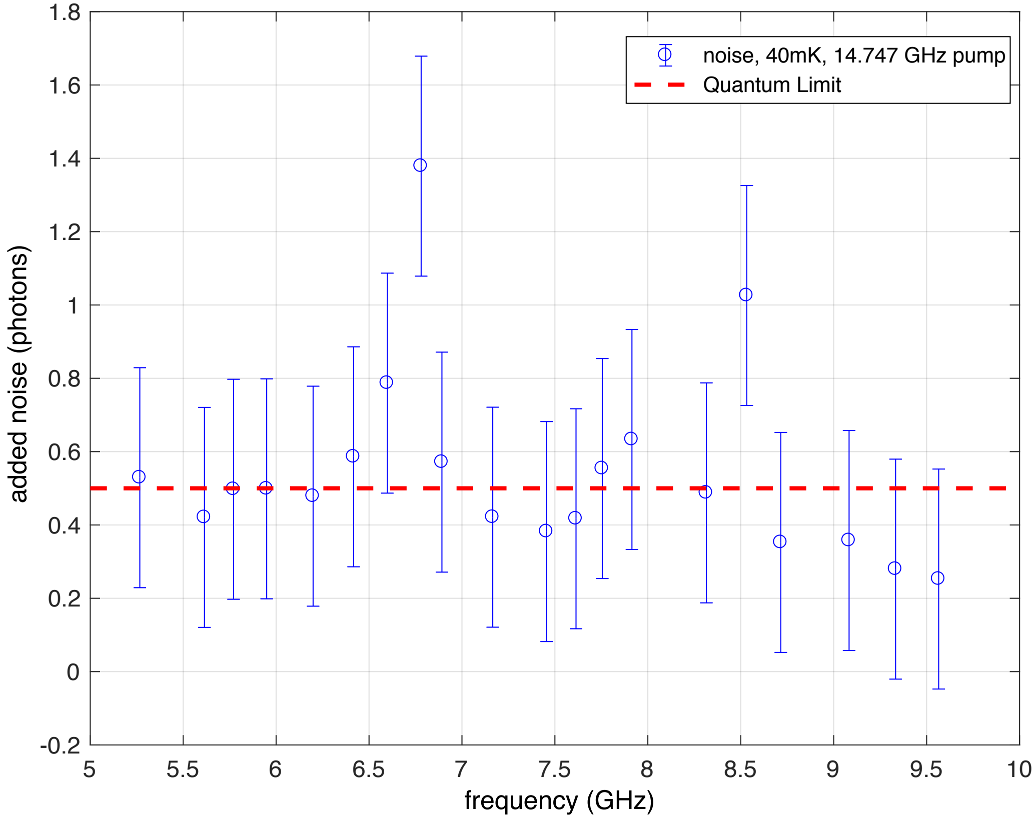

New version made showing higher Gain!

Y-factor noise measurement done!

New low-loss a-Si:H
dielectric enables
higher-yield version:
gain demonstrated,
T_N = 4 x QL at 3 GHz, likely to improve to QL

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Plans and Context

Near-term

- Using KID pulsing scheme and ^{55}Fe/^{129}I x-rays to measure baseline σ_E; position-correct also

Mid-term

- Provide position reconstruction and NR discrimination to reach neutrino floor > 1 GeV
  - Provide NR discrimination via e-h spectral peaks to reject dominant tritium and 32Si backgrounds
  - Provide position reconstruction to reject non-cosmogenic surface bgnds (^{210}Pb betas and ^{206}Pb nuclei)
  - Large-detector track 1: σ ~ 5-10 eV + HV: QL paramp + 1 ms qp lifetime
  - Large-detector track 2: σ ~ 0.25 eV at 0V: QL paramp + 1 ms qp lifetime + lower Δ + higher KI fraction
- Small-detector track
  - Reoptimize design purely for energy resolution and small target size; σ ~ 0.15 eV possible with Al
    - Threshold, not position information
  - Continue using phonon absorption on semiconducting substrates. but begin to consider polar substrates
    - Start with Al_2O_3, try out GaAs for better mass reach.

Long-term

- Revisit design for superconducting substrates, σ ~ 1 meV
  - Use quasiparticles or phonons? Phonon propagation challenging in superconductors (check Gaitskell).
  - Find a configuration that works. Hybrid CPW-lumped element? Microstripline?

Other efforts? Not many!

- CALDER = effort to deploy KIDs for photodetection in CUORE follow-on $0\nu\beta\beta$ expt CUPID
  - No scintillation in TeO_2, but betas Cherenkov radiate. Separate dominant alpha background from betas by requiring Cherenkov signal. Need σ ~ 20 eV to see 100 eV signal → simpler needs.

Conclusions

KIDs coupled to insulating and superconducting substrates promise to extend reach in dark matter mass and cross section

- Small-detector architectures have potential to reach thermal relic mass limit via DM-e scattering and to probe boson DM in the meV - keV mass range inaccessible to coherent techniques
- Large-detector architectures have potential for background rejection needed to reach neutrino floor

Quantum-limited readout is critical to achieving these goals

Ideas for evading standard quantum limit may provide additional gains

There is a lot of work to do!