Dark Matter Detection using Phonons + Kinetic Inductance Detectors

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Caltech

New Probes for Physics Beyond the Standard Model

KITP

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Overview

Basics of kinetic inductance detectors

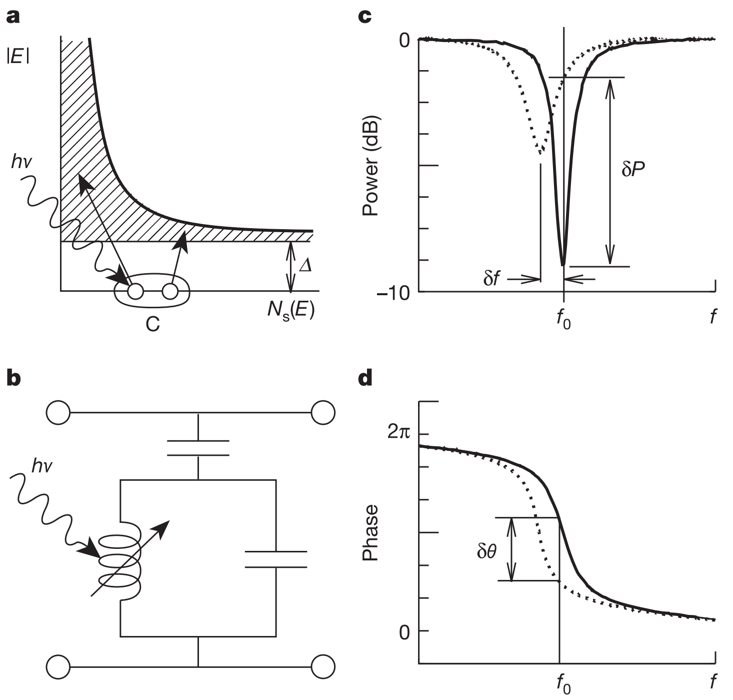
Expected energy resolution

Architectures for different science goals

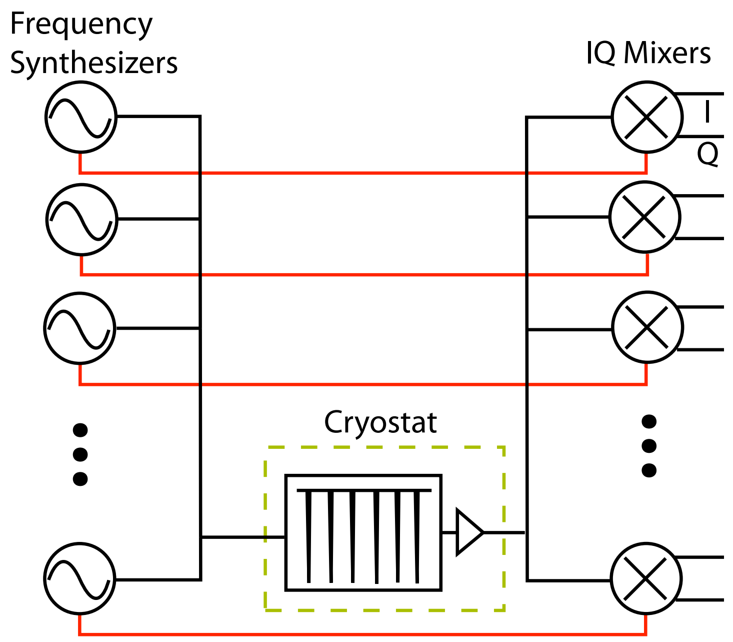
Progress to date and plans

Readout

Basics of Kinetic Inductance Detectors



Day



Mazin

- Superconductors have an AC inductance due to inertia of Cooper pairs
  - alternately, due to magnetic energy stored in screening supercurrent
- 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
  - enormous cryogenic multiplex technology relative to existing ones
  - very simple cryogenic readout components

Quasiparticles to Conductivity

Conductivity from microscopic BCS theory by Mattis and Bardeen

- Use perturbation theory to calculate response of BCS superconductor to EM field
- M&B assume extreme anomalous limit, but analysis can also be used for local limit with appropriate modification (see, e.g., Gao thesis Ch 2).
- Yields complex conductivity:

$$\frac{\sigma_1}{\sigma_n} = \frac{2}{\hbar\omega}\int_{\Delta}^{\infty} d\epsilon \frac{\left[f(\epsilon) - f(\epsilon + \hbar\omega)\right]\left(\epsilon^2 + \Delta^2 + \hbar\omega\epsilon\right)}{\sqrt{\epsilon^2 - \Delta^2}\sqrt{(\epsilon + \hbar\omega)^2 - \Delta^2}}$$

resistive

$$f(\epsilon) = 1/[e^{\epsilon/k_B T} + 1]$$

$$\frac{\sigma_2}{\sigma_n} = \frac{1}{\hbar\omega}\int_{\Delta-\hbar\omega}^{\Delta} d\epsilon \frac{\left[1 - 2f(\epsilon + \hbar\omega)\right]\left(\epsilon^2 + \Delta^2 + \hbar\omega\epsilon\right)}{\sqrt{\Delta^2 - \epsilon^2}\sqrt{(\epsilon + \hbar\omega)^2 - \Delta^2}}$$

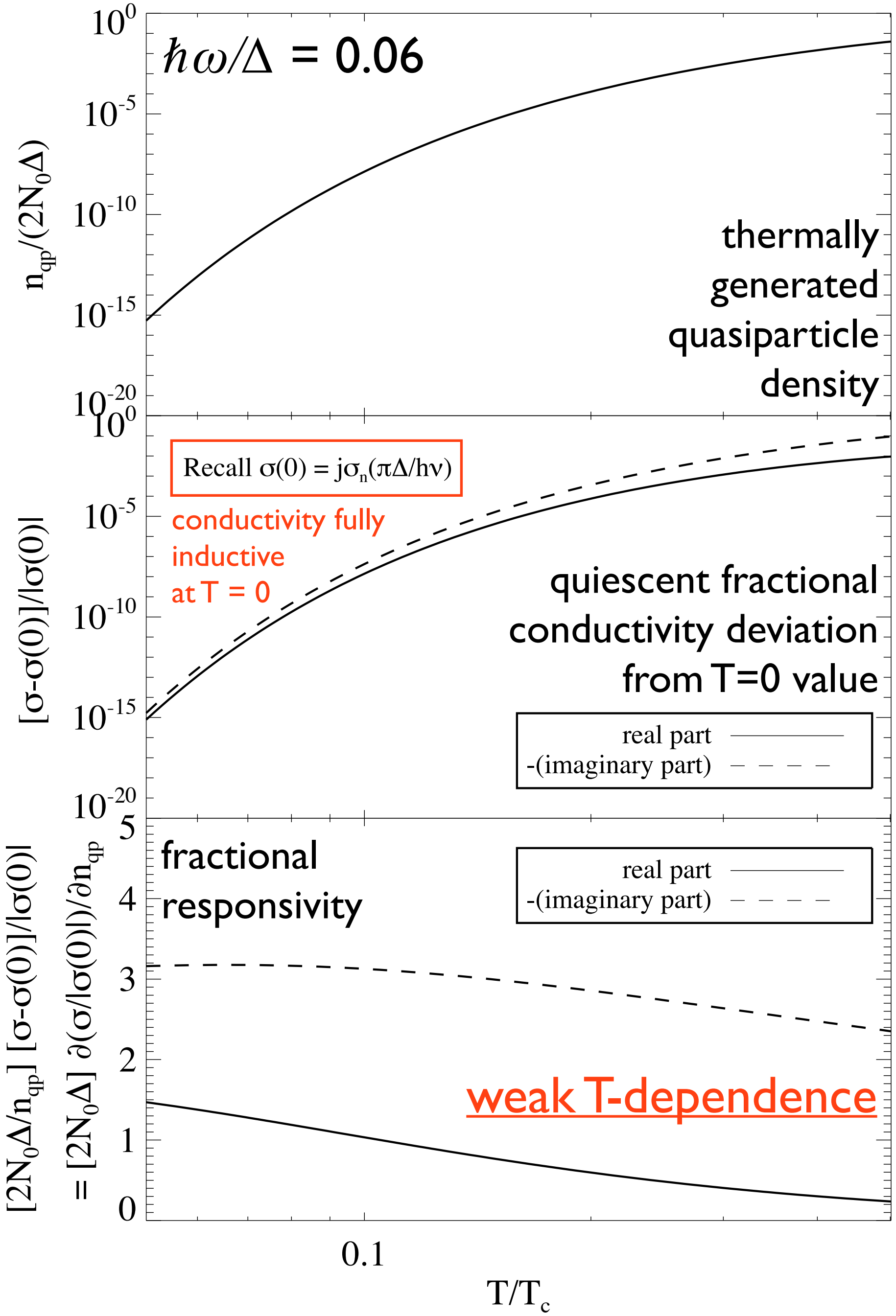
reactive

- Two-fluid model: imaginary (reactive) part scales with Cooper pair component, real (resistive) part scales with quasiparticle density
- Quasiparticle/Cooper pair population change ⇒ conductivity change

T. Klapwijk and others: "engineering" model insufficient due to non-BCS density of states, effects of readout power

For clarity here, stick with engineering model: changes in quasiparticle number completely characterize effect of energy input

Quasiparticles to Conductivity



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

conductivity fully inductive at T = 0

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!)

Conductivity to Observables

Observables

Surface impedance is $Z_s = E / H$ for EM wave propagating normal to surface

For thin films (thickness t, therefore local limit; $\gamma = -1$):

$$Z_s = R_s + i\,X_s \approx \frac{1}{(\sigma_1 - i\,\sigma_2)\,t}$$

$$\begin{aligned} Z_s \to i\,X_s(T=0) &= i\,\omega\,L_s(T=0) \\ &\propto -\left[\sigma(T=0)\right]^{-1} = i\left[\sigma_2(T=0)\right]^{-1} \end{aligned}$$

σ_2 dominates for $T << T_c$, so X_s dominates
$Q_s = X_s(T=0)/R_s = \sigma_2(T=0)/\sigma_1(T)$

Relate fractional changes in σ to fractional changes in Z_s (thin film limit)

$$\frac{\delta Z_s}{Z_s(T=0)} = \frac{\delta\sigma}{\sigma(T=0)} \qquad \frac{\delta L_s}{L_s} = \frac{\delta\sigma_2}{\sigma_2(T=0)} > 0 \qquad \frac{\delta R_s}{\omega L_s} = \frac{\delta\sigma_1}{\sigma_2(T=0)} > 0$$

"kinetic impedance" "kinetic inductance" "kinetic resistance"

Recall that the fractional conductivity change shows weak temperature dependence.

So, given a measurement of surface impedances in a thin film, we can infer changes in conductivity and thus qp density.

KID Readout and Multiplexing

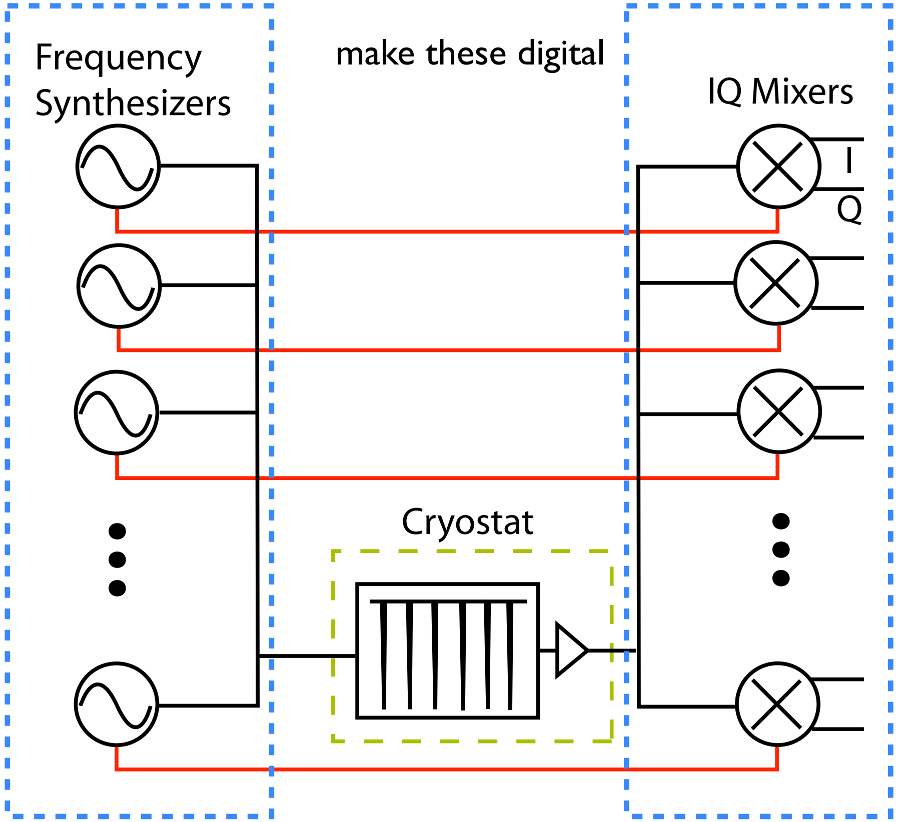
- KIDs response in both reactance and resistance
- High Q_s suggests KIDs can be incorporated into high-Q resonant circuits; yields frequency and Q response
- High-Q circuits lend themselves to frequency-domain multiplexing
  - Principle identical to AM/FM radio:
    - frequency → phase (FM),
    - Q → amplitude (AM)
  - Don't forget resonator bandwidth!
    - $f_{qp} < f_r / 2Q_r$
- Ever-growing capabilities in GHz digital electronics:
  - Fully digital generation, reception, and demodulation now possible

kinetic inductance fraction

$$\frac{1}{Q_{i,qp}} = \frac{R_s}{\omega\left(L_m + L_s(T=0)\right)} = \alpha\,\frac{R_s}{\omega L_s(T=0)}$$

$$\frac{f_r - f_r(T=0)}{f_r(T=0)} = -\frac{1}{2}\,\alpha\,\frac{L_s - L_s(T=0)}{L_s(T=0)}$$

$$\delta S_{21}\big|_{f=f_r} = \frac{Q_r^2}{Q_c}\left(\delta\frac{1}{Q_{i,qp}} - 2\,i\,\frac{\delta f_r}{f_r}\right)$$



Mazin (2004)

Quasiparticle Response to Energy Input

- 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

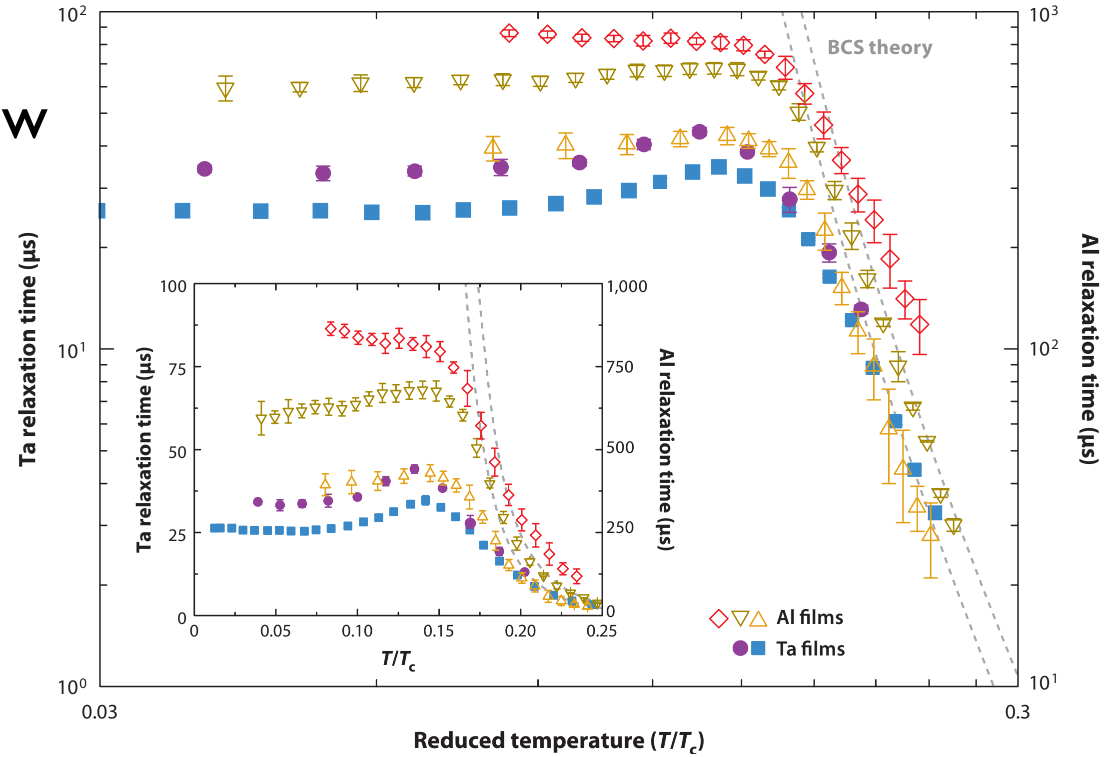
$$\frac{1}{\tau_{qp}} = 2\,R\,n_{qp} + \frac{1}{\tau_{max}}$$

with the recombination constant

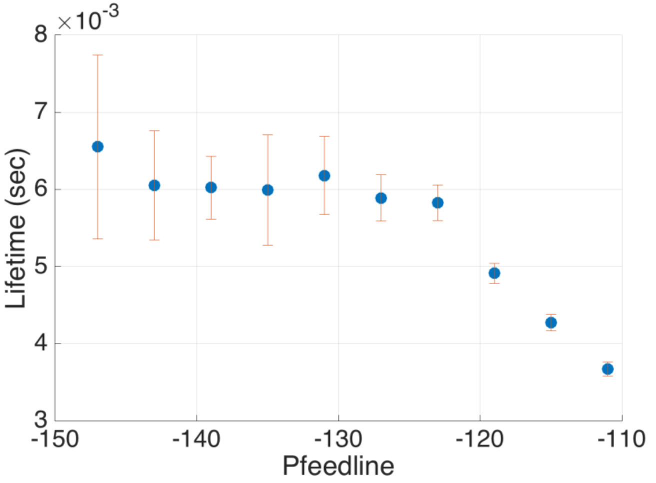
$$R = (2\,n_*\,\tau_{max})^{-1}$$

- Many ms lifetimes achievable but perhaps only at low readout powers!

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

Quasiparticle Response to Energy Input

queiscent point (τ_{qp} and n_{qp}) set using g-r equation to balance qp generation by power (readout and stray) and qp decay:

$$\frac{\eta P}{\Delta} = N_{qp}\left(\frac{1}{\tau_{max}} + R\,\frac{N_{qp}}{V}\right) \qquad N_{qp} = n_{qp}\,V \qquad N_* = n_*\,V$$

$$\Longrightarrow \quad \tau_{qp} = \frac{\tau_{max}}{\sqrt{1+2\,(\eta\,P/\Delta)\;\tau_{max}/N_*}} \qquad \frac{N_{qp}}{N_*} = \sqrt{1+2\,(\eta\,P/\Delta)\,\tau_{max}/N_*} - 1$$

In absence of known power, $\tau_{qp} \rightarrow \tau_{max}$, $N_{qp} \rightarrow N_*$, and $\eta P \rightarrow N_*\Delta/\tau_{max}$

Dynamic response: use dynamic g-r equation to obtain

$$\frac{\delta N_{qp}(f)}{N_{qp}} \propto \frac{1}{1+2\,\pi\,i\,f\,\tau_{qp}}\,\frac{\delta P(f)}{P}\,\frac{1+N_{qp}/N_*}{1+N_{qp}/2\,N_*}$$

Calorimetric mode: $\delta P(f) = \delta E$: exponentially decaying pulse response with pulse height $\delta n_{qp} = \eta\delta E/\Delta$ and decay time τ_{qp}

Use relations between δn_{qp} and observables to obtain expected signal

Don't forget resonator bandwidth! $f_{qp} < f_r\,/\,2Q_r$

Noise

generation-recombination noise

amplifier noise temperature

$$\mathrm{NEP}^2_{\mathrm{diss}} = \boxed{\frac{4\eta_a \chi_{qp} \Delta_0}{\eta_o^2} P_a + \frac{2N_{qp}\Delta_0^2}{\eta_o^2}\left(\tau_{\max}^{-1} + \tau_{qp}^{-1}\right)} + \boxed{\frac{8N_{qp}^2\Delta_0^2}{\eta_o^2 \chi_c \chi_{qp}^2 \tau_{qp}^2}\,\frac{kT_a}{P_a}}$$

$P_a = (\chi_c/2)\, P_g$

$$\mathrm{NEP}^2_{\mathrm{freq}} = \boxed{\mathrm{NEP}^2_{\mathrm{g-r}}} + \boxed{\frac{8N_{qp}^2\Delta_0^2}{\beta^2 \eta_o^2 \chi_c \chi_{qp}^2 \tau_{qp}^2}\,\frac{kT_a}{P_a}} + \frac{8N_{qp}^2\Delta_0^2 Q_i^2}{\beta^2 \eta_o^2 \chi_{qp}^2 \tau_{qp}^2} S_{\mathrm{TLS}}$$

readout power stored in resonator

feedline readout power

amplifier noise

two-level system noise

$\beta = \dfrac{\delta\sigma_2}{\delta\sigma_1}$ ratio of imaginary (frequency) to real (dissipation) response

η_o efficiency for creation of qps from energy in target

$\eta_a = (\Delta_0/\chi_{qp})\partial\Gamma/\partial P_a$ differential efficiency for creation of qps from readout power

total internal quality factor

qp internal quality factor

$\chi_{qp} = Q_i/Q_{qp} \leq 1$

quasiparticle quality factor efficiency

$\chi_c = \dfrac{4Q_cQ_i}{(Q_c+Q_i)^2} \leq 1$ resonator-feedline coupling efficiency

Generation and recombination noise for qps created by readout

Amplifier noise reduced by factor β in frequency direction

TLS noise only in frequency direction

no quasiparticle trapping!

Characteristic Energy Resolution

Assume

- delta-function-like energy deposition
- qp population determine by readout power generation
- dissipation readout (no TLS noise)
- amplifier noise dominant over g-r noise (T ~ 0.1 T$_c$ required)

$$\sigma_E = 2\Delta \sqrt{\frac{\eta_a}{\chi_c\,\chi_{qp}}}\,\sqrt{\frac{k\,T_a\,N_0\,V_r}{\left[2N_0\Delta\,\frac{\partial(\sigma_1/|\sigma(0)|)}{\partial n_{qp}}\right] Q_s}}$$

normal state single-spin density of states

resonator effective volume (weighted by current^2)

= $X_s(T=0)/R_s$
intrinsic surface quality factor of film (generally lower than qp-limited value, 10^5-10^7 achievable)

dissipation fractional responsivity; approaches unity for T << T$_c$

$$\sigma_E \approx 100\ \mathrm{meV}\left(\frac{2\Delta}{363\ \mu\mathrm{eV}}\right)\sqrt{\frac{\eta_a}{\chi_c\,\chi_{qp}}}\,\sqrt{\frac{T_a}{5\ \mathrm{K}}\,\frac{V_r}{10^4\ (\mu\mathrm{m})^3}\,\frac{10^6}{Q_s}}$$

BCS aluminum

typical amplifier noise temperature

1 mm^2 x 10 nm

no quasiparticle trapping!

Architectures

Small detectors (gram-scale)

Goal: detection of sub-eV energies from:

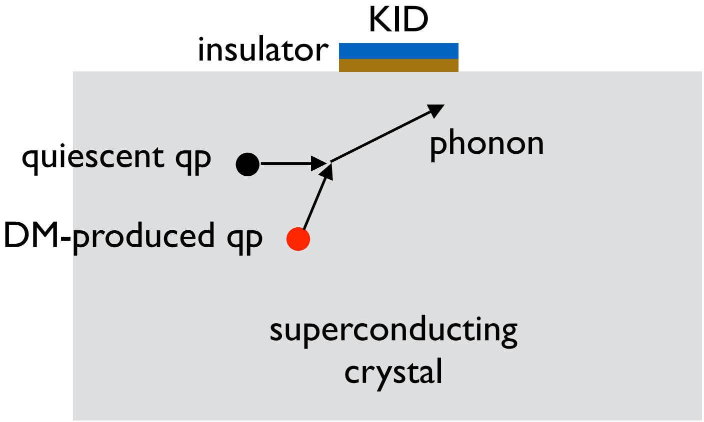
- Dark photon absorption
- DM-e scattering
- Scalar-mediated nucleon scattering at very low recoil energies producing phonons

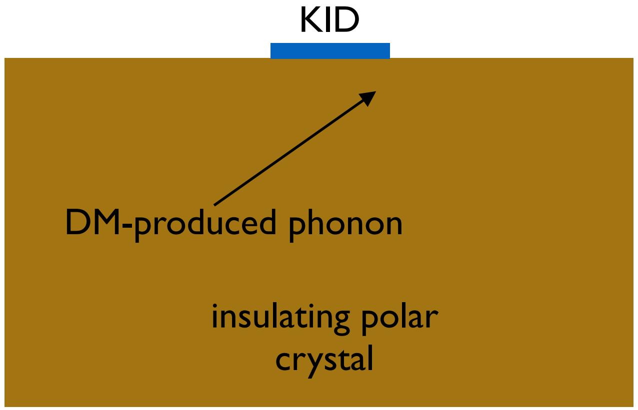
Methods:

- Detection of qp creation in superconducting target *via phonons* (Hochberg, Zhao, Zurek, arXiv:1504.07237)
  - qp propagation diffusive, subject to pair recomb.
  - phonons quasiballistic, long decay times
- Detection of optical phonon production in polar materials:
  - GaAs (Knapen, Lin, Pyle, Zurek, arXiv:1712.06598)
  - Al_2O_3 (Knapen talk (Tues))

Architecture:

- single mm-scale KID on few-mm target substrate
- previous slide energy estimate ~ valid

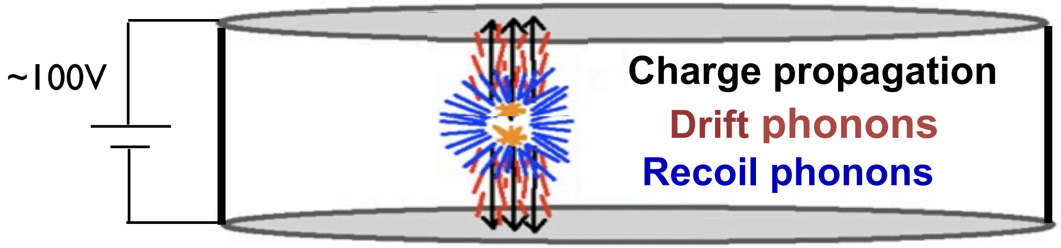




Need lower-gap superconductor for KID (e.g., AlMn) or better amplifiers (kinetic inductance parametric amplifier recently demo'd T_a ~ 70 mK at 3 GHz)

no quasiparticle trapping!

Architectures



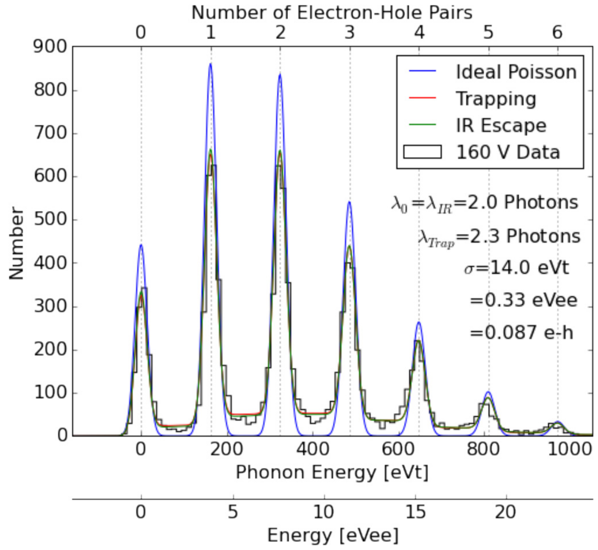
Large detectors (kg-scale)

Goal:

- traditional nuclear recoil search at very low recoil energies (10 eV_r)
- DM-e scattering at eV scales

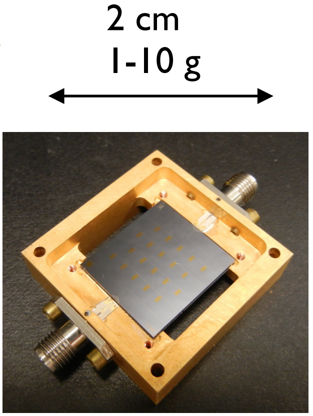
Method:

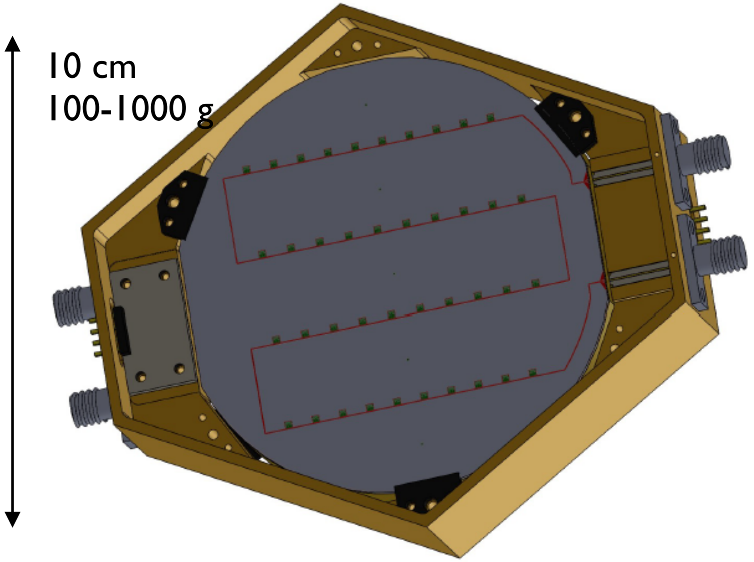
- Neganov-Luke-Trofimov phonon production by drifting e-h pairs in large electric field (Romani et al APL 112, 043501 (2018)) providing single e-h pair detection



Architecture:

- few KIDs on cm-scale substrate
- ~100 KIDs on 10-cm-scale substrate
  - Fine pixellization intended to provide fiducialization away from detector surfaces (most low-energy bg)
  - Also provide pos’n correction for energy





no quasiparticle trapping!

Large Detector Energy Resolution

Assume:

- readout noise dominates (T << T$_c$ ensures g-r noise subdominant)
- qp density determined by readout power generation
- resonator is coupling dominated (Q$_c$ << Q$_i$)
- quasiparticle lifetime in KID << phonon absorption timescale ($\tau_{qp} << \tau_{abs}$)

superconducting gap energy

efficiency of qp creation by readout power (assume = 1 to be conservative)

area of substrate (including sidewalls)

pair-breaking length in KID film

amplifier noise temperature

density of states

superconductivity factors, ~1

$$\sigma_E = \frac{\Delta}{\eta_{ph}}\sqrt{\frac{\eta_{read}}{2\pi\alpha p_t}}\sqrt{\frac{A_{sub}\lambda_{pb}}{f_r\tau_{qp}}}\sqrt{\frac{kT_N N_0}{2N_0\Delta\,\frac{\partial(\sigma_1/|\sigma(0)|)}{\partial n_{qp}}}}$$

$$\sigma_E = (22\ \mathrm{eV})\left(\frac{1}{\eta_{ph}}\sqrt{\frac{1}{\alpha p_t}}\right)\left(\frac{\Delta}{200\ \mu\mathrm{eV}}\right)\sqrt{\frac{A_{sub}}{100\ \mathrm{cm}^2}\,\frac{\lambda_{pb}}{1\ \mu\mathrm{m}}\,\frac{5\ \mathrm{GHz}}{f_r}\,\frac{100\ \mu\mathrm{s}}{\tau_{qp}}\,\frac{T_N}{3\ \mathrm{K}}\,\frac{1.18}{2N_0\Delta\,\frac{\partial(\sigma_1/|\sigma(0)|)}{\partial n_{qp}}}}$$

efficiency for converting phonons to qps

fraction of inductance due to KI (~1)

probability for phonon to enter KID per try

KID resonant frequency

quasiparticle lifetime

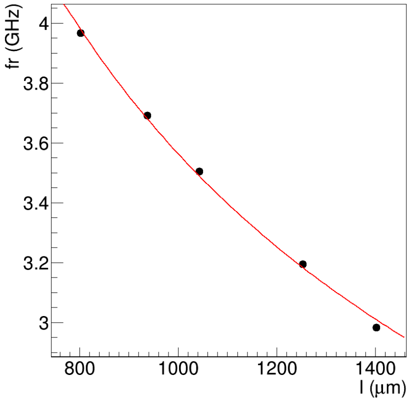
no quasiparticle trapping!

KID Design

10-30 nm thick film

Inductor

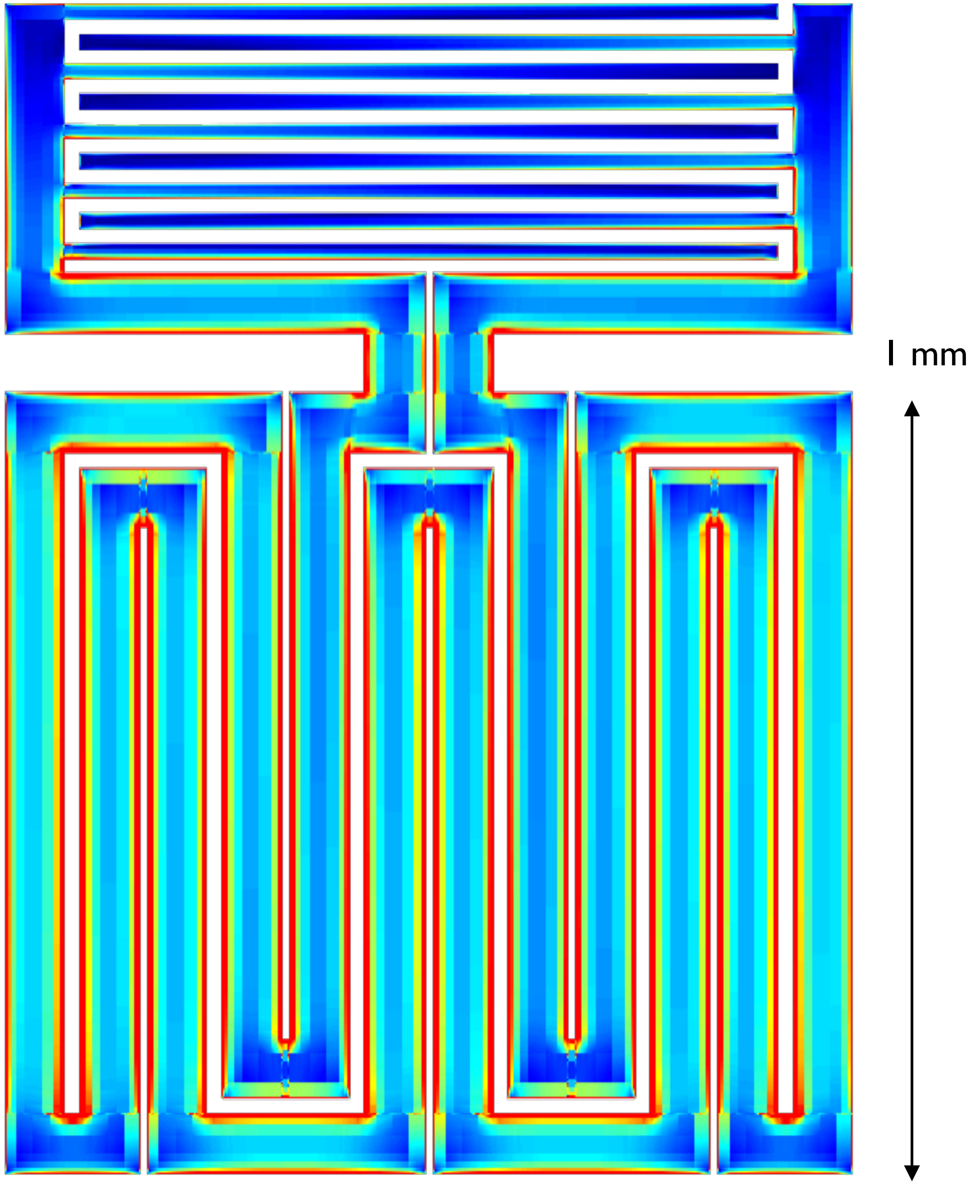
- Symmetric coplanar strip design minimizes dipole crosstalk while maintaining >95% current density uniformity
- Frequency tuning is done by adjusting inductor length



- ~10^4 (μm)^3 active volume

Capacitor

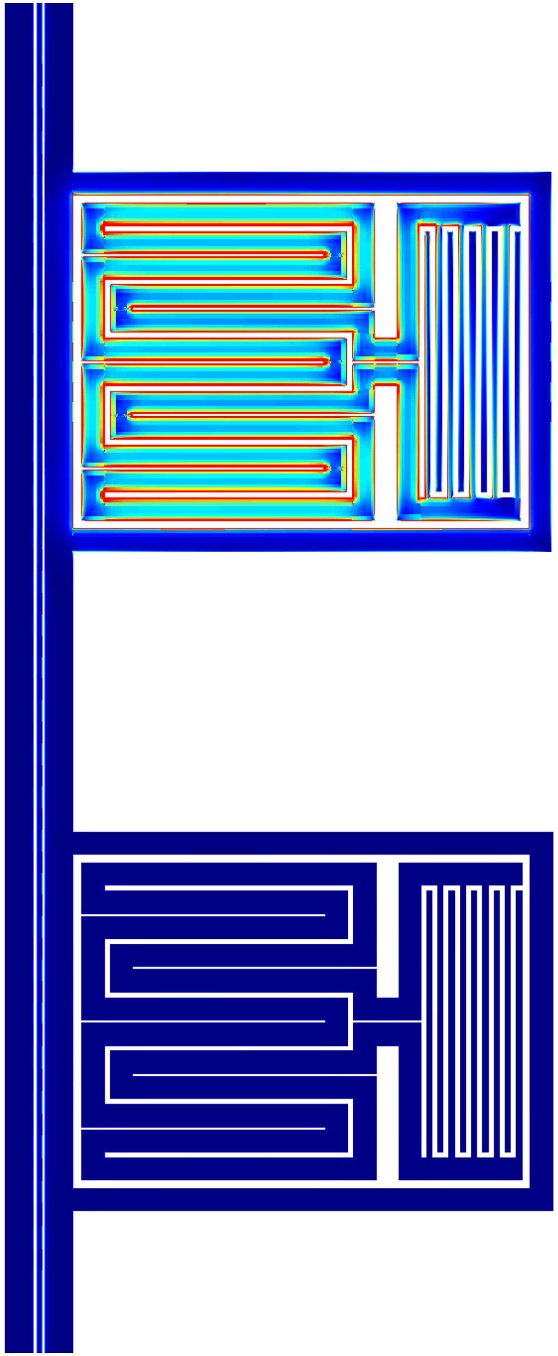
- Standard interdigitated capacitor to minimize TLS noise
- Can be made out of Nb in long run to avoid absorbing phonons

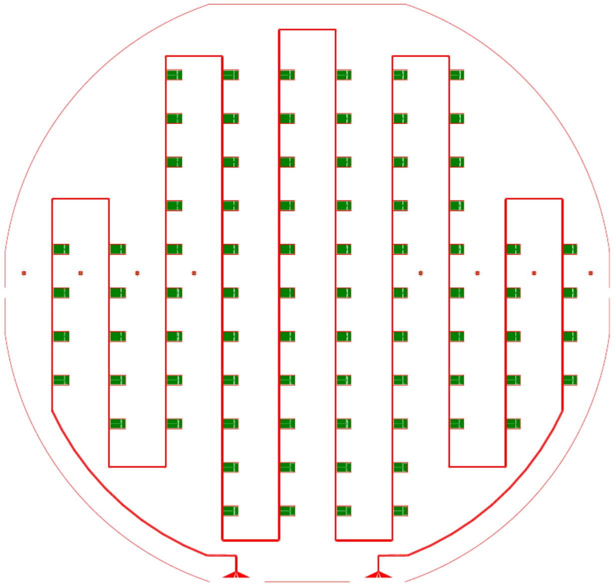


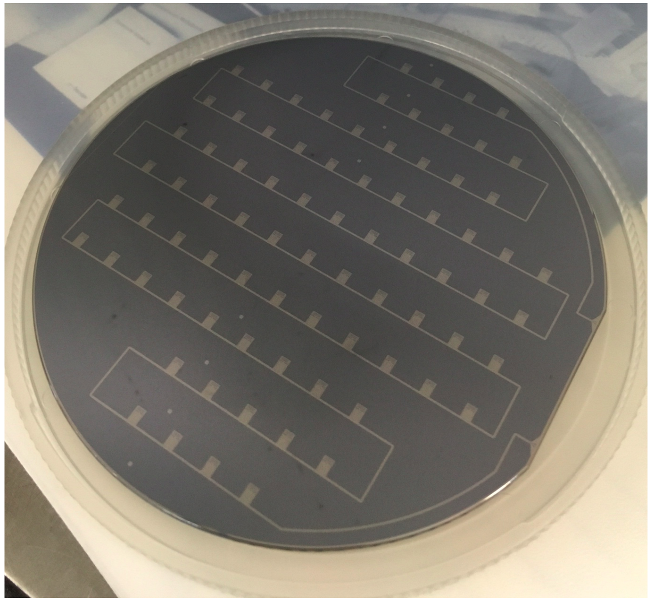
no quasiparticle trapping!

Full Wafer Design

- Feedline: 300 nm Nb coplanar waveguide
  - Thick feedline ensures reliable fab, good transmission
- Crosstalk minimized
  - Using the specialized inductor design with ground shield (a la CALDER) see negligible crosstalk in simulation
  - Critical for ensure frequency predictability
- Full wafer fab via contact mask
  - Large features (10 μm)





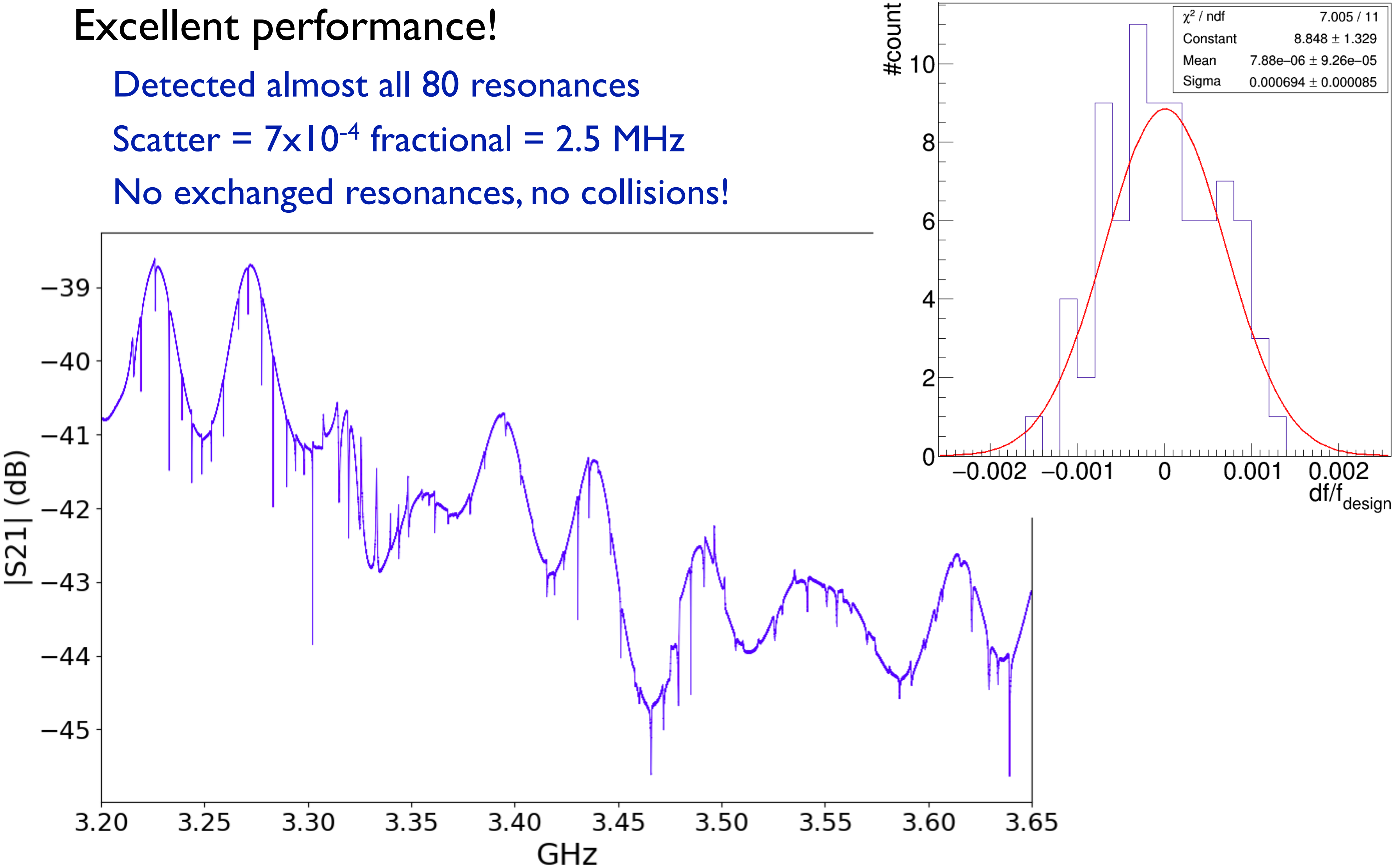


RF Performance

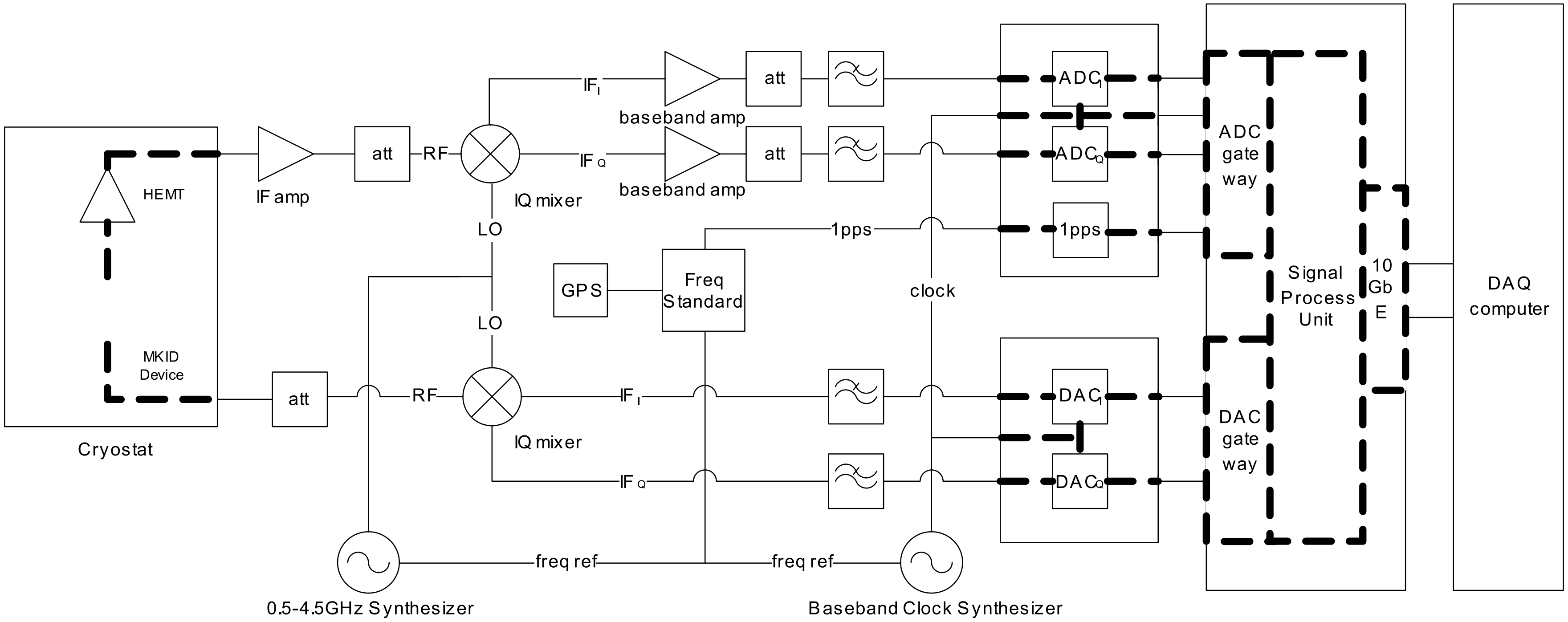
Fabricate a Nb-only device to test RF simulations

Excellent performance!

- Detected almost all 80 resonances
- Scatter = 7×10^{-4} fractional = 2.5 MHz
- No exchanged resonances, no collisions!



Multiplexed Readout



UCSB/Caltech/JPL + partners have developed digital readout

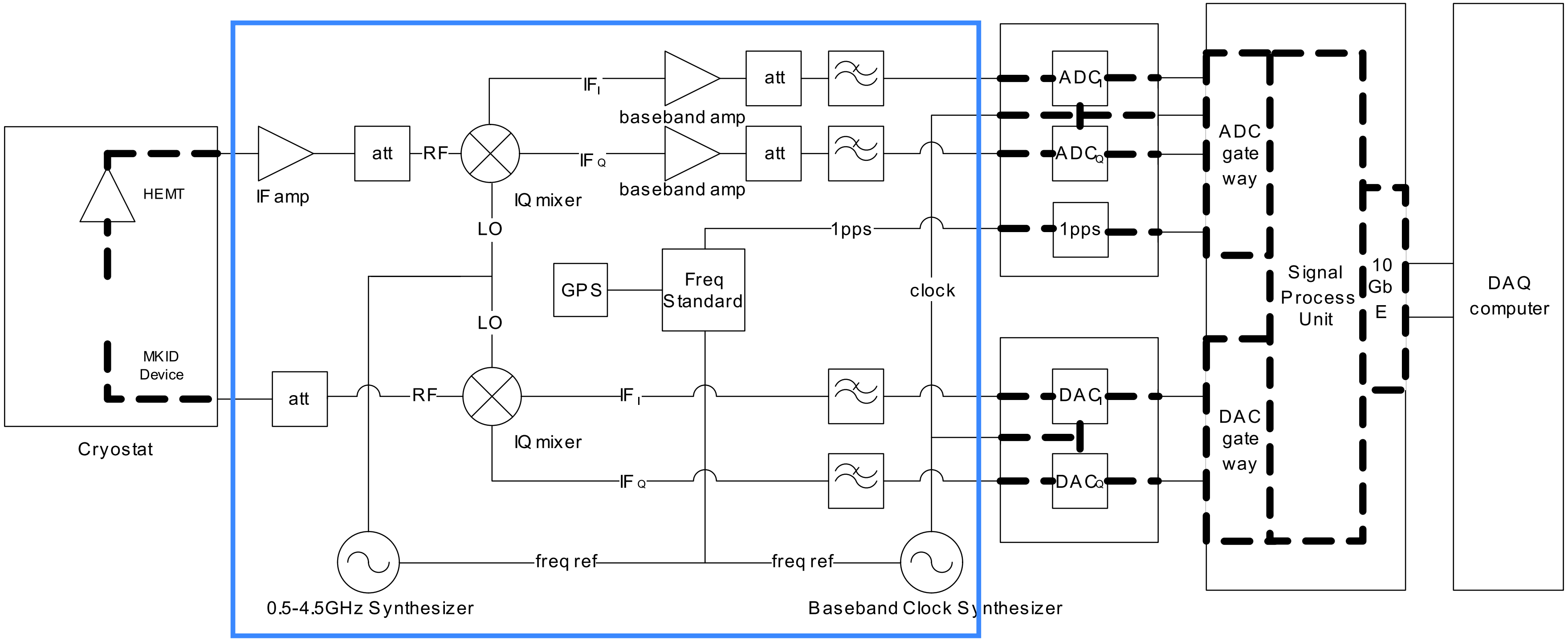
Signal generation and demodulation done digitally

IF system block upconverts from DAC/ADC baseband (0-500 MHz) to resonator RF band (3 GHz)

Critical issues:

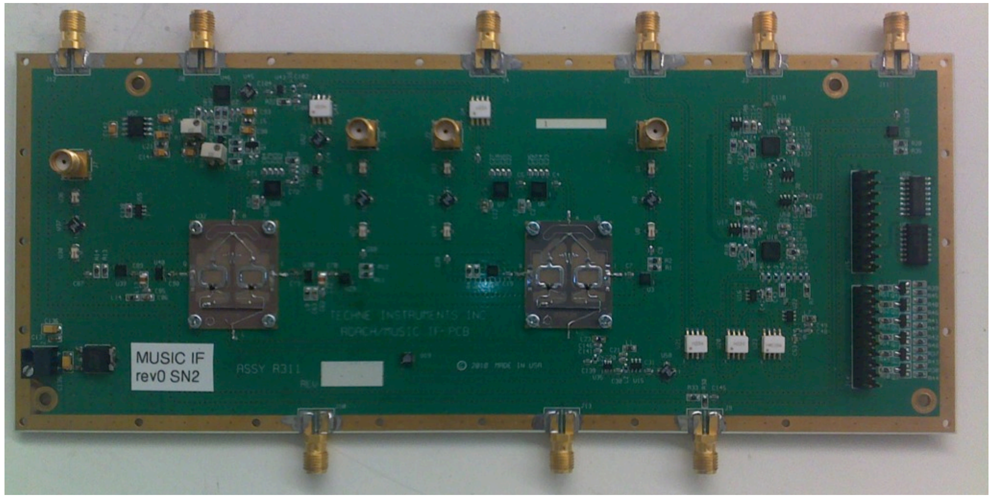
- ADC SNR: need 12 bits @ 500 MHz to ensure readout white noise ok
- 1/f: for bolometric instruments, need stability down to 0.01-0.1 Hz

Multiplexed Readout

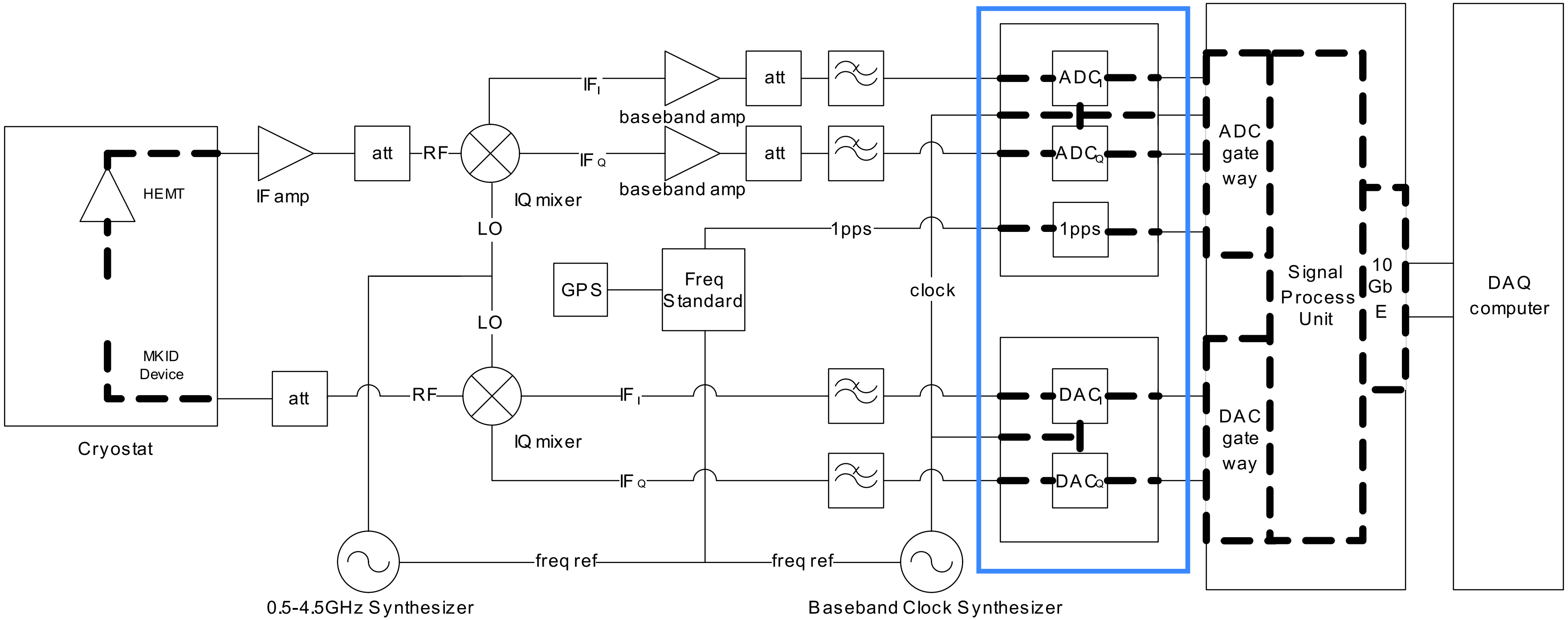


IF (intermediate frequency) board:

- Freq synth to generate local osc. locked to GPS-referenced 10 MHz Rb freq std
- Analog IQ mixers to up- and down-convert w/double-sideband recovery
- Anti-alias filtering
- Gain/atten. to match to DAC/ADC ranges
- Great care taken with heatsinking for 1/f

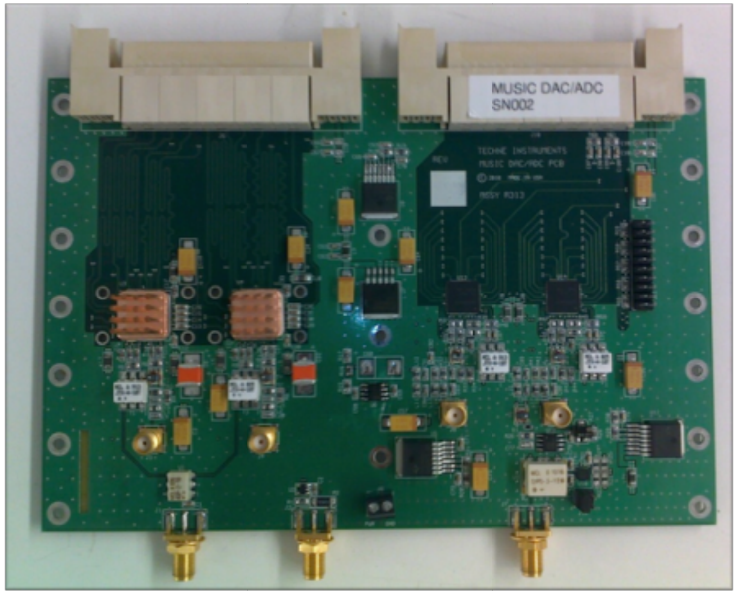


Multiplexed Readout



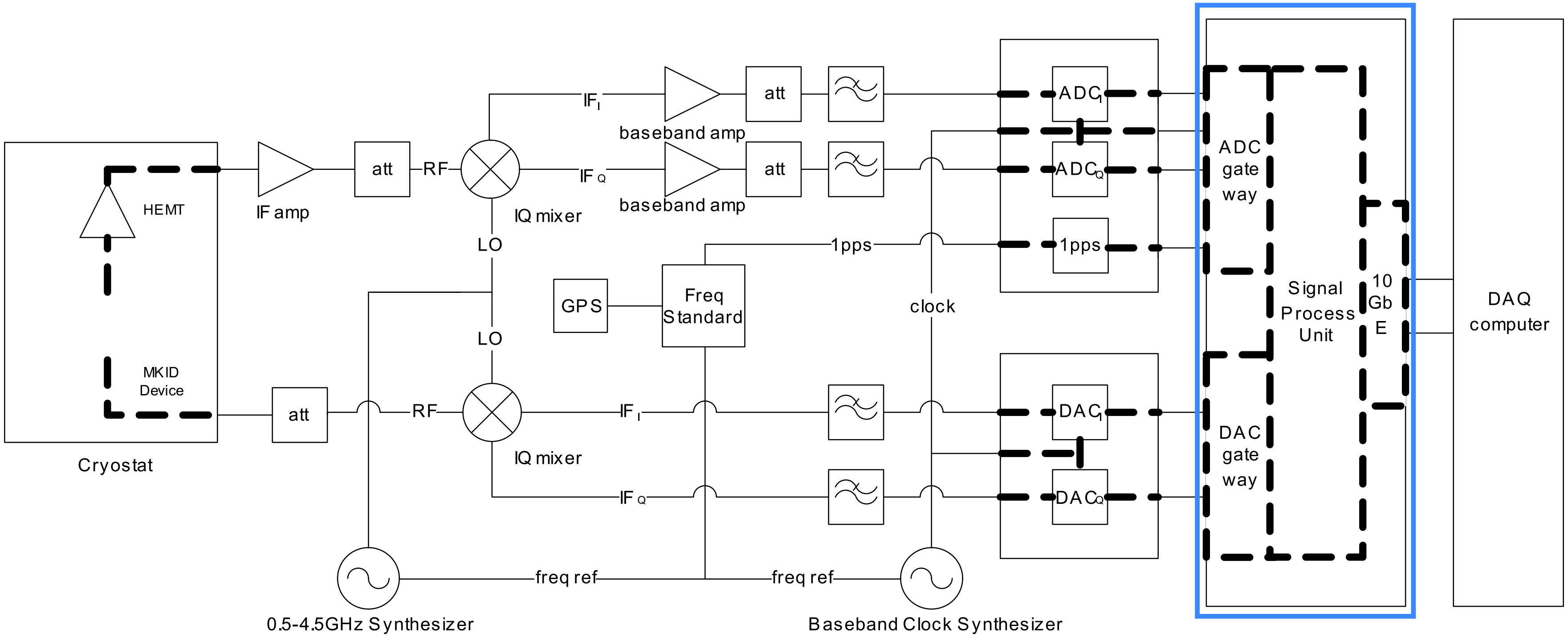
ADC/DAC board:

- 12-bit 550 MHz ADC (TI ADS5463)
- 16-bit 1000 MHz DAC (TI DAC5681)
- Common voltage reference, extensive heat-sinking to minimize 1/f
- Mates to ROACH FPGA/PowerPC platform



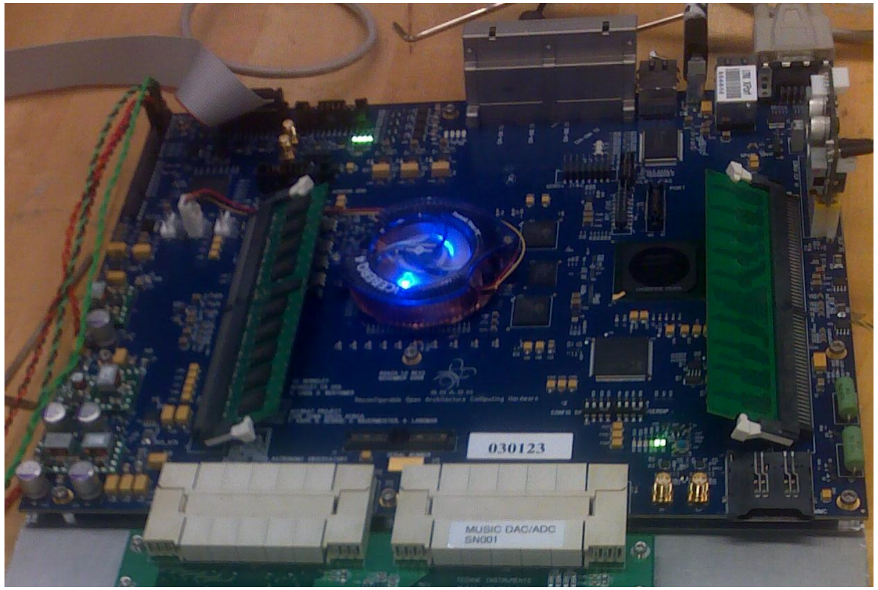
Multiplexed Readout

ROACH
Reconfigurable Open Architecture Computing Hardware



ROACH board

- FPGA + CPU + memory
- Simulink FPGA programming
- System built on ROACH1/Virtex5
- UCSB has developed 256-ch digital downconverter (multiplier) firmware
- ROACH2 based on Virtex6 now standard (firmware ported by UCSB)



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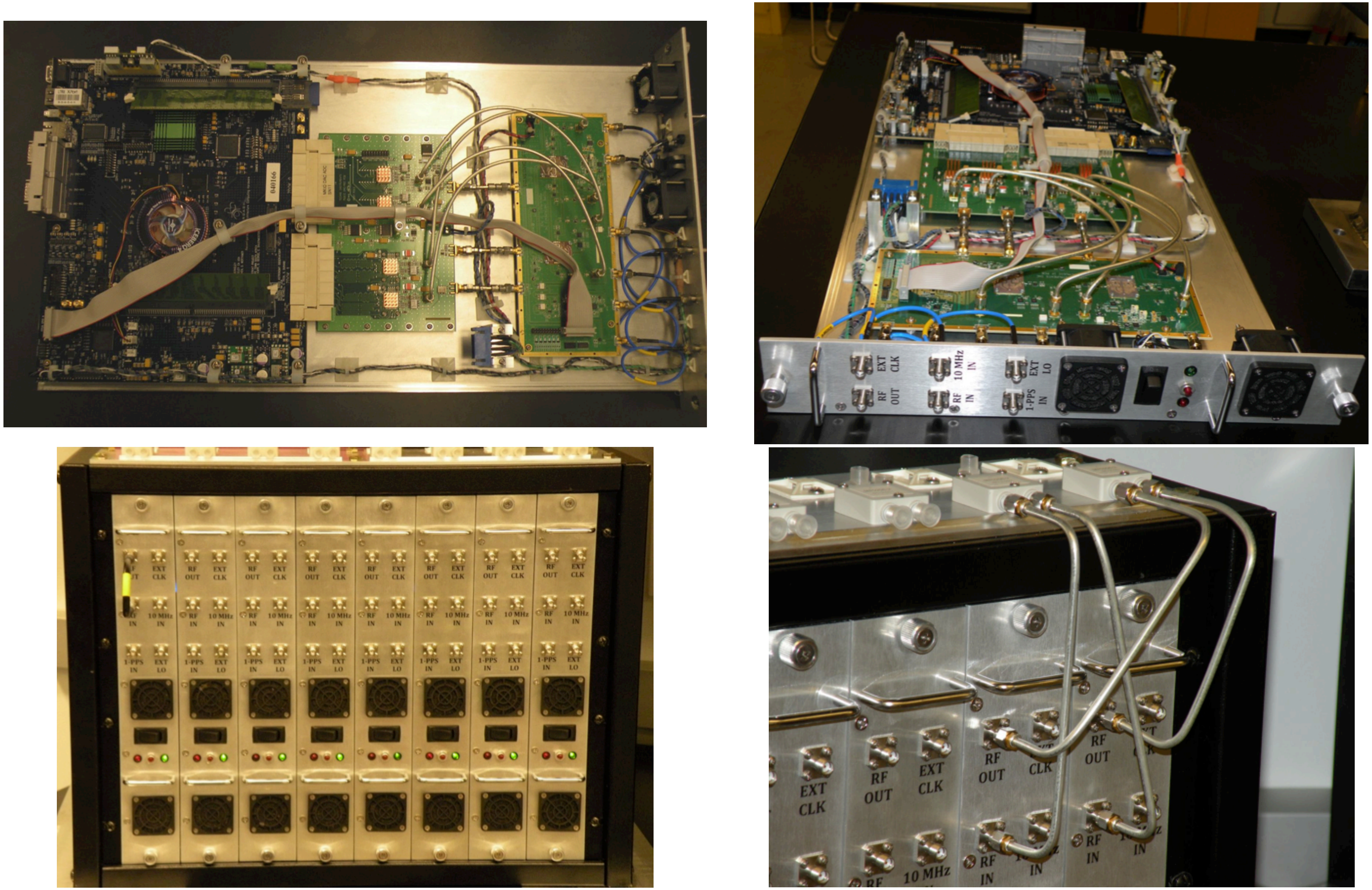
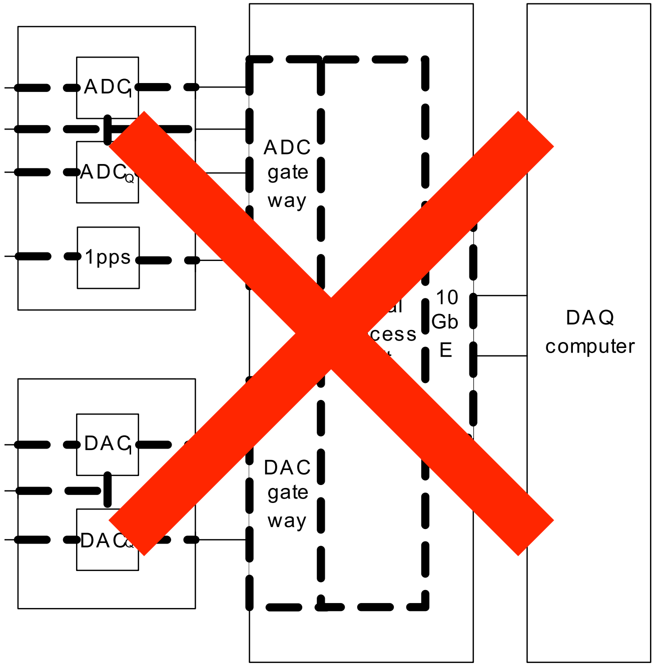
Multiplexed Readout

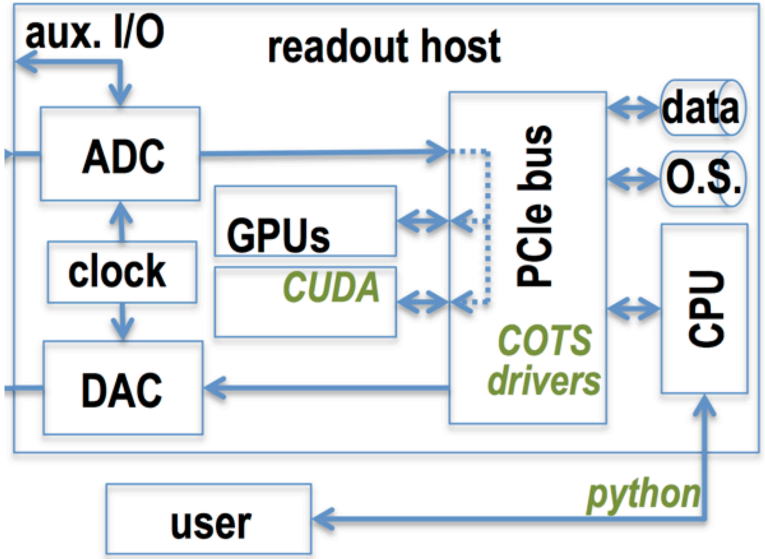
8-block crate developed; high-stability PSU for IF, ADC/DAC



New Readout Option

- ROACH system good for mid-scale instrument deployment
  - Optimized firmware and data transport → max channel count, min cost/channel
- ROACH system not good for lab development
  - Special-purpose hardware (even ROACH)
  - Changes to multiplexing algorithm require firmware changes
  - Multiple layers of software/firmware
    - Firmware for FPGA
    - Linux system for PowerPC
    - Linux system for DAQ computer
- JPL developing GPU-based system programmable in C++ and Python
  - Commercial off-the-shelf hardware
  - Flexible multiplexing algorithms
  - Easier user interface





O'Brient/Dowell/Steinbach

Plans

Near-term

- Have device with Al KID films in hand
- Characterize at sub-Kelvin temperatures
  - RF performance, kinetic inductance fraction
  - expose to ^{55}Fe and ^{129}I x-rays to measure energy resolution, do position reconstruction and energy correction

Mid-term

- Refine design
- Scale up to thick (100 g Si) substrates

Long-term

- Revisit design with focus on single-resonator energy resolution for sub-eV depositions