Applications of Microwave Kinetic Inductance Detectors for Cosmology

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FNAL Research Techniques Seminar
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Overview

• Electrodynamics of superconductors
• Monitoring complex conductivity with resonators
• Multiplexing
• Optical coupling
• Noise sources and expected sensitivity
• Multiplexing electronics
• CMB and astrophysics applications
• Gamma-ray and dark matter applications
Caltech/JPL MKID Group

• Caltech:
  • Jonas Zmuidzinas: inventor of the idea
  • Ben Mazin (UCSB), Jiansong Gao (NIST), Tasos Vayonakis, Shwetank Kumar (IBM), Omid Noroozian: students who developed the idea and understood the physics (esp. Gao on TLS, Noroozian on modified resonator designs to minimize TLS noise)
  • My group primarily involved in application for mm-wave imaging with MUSIC camera (esp. postdoc James Schlaerth, grad students Nicole Czakon and Seth Siegel, grad student Ran Duan and postdoc Tom Downes on readout, postdocs Matt Hollister and Jack Sayers on camera/dewar design)
  • new postdocs Chris McKenney and Loren Swenson
  • recently joined by Keith Schwab (APh) and Emma Wollman on understanding physics of TiN resonators

• JPL
  • Rick LeDuc: superconducting device fabrication expert. First suggested idea of using titanium nitride.
  • Peter Day: expert on superconductor/low-temperature physics. Has done most proof-of-principle tests of MKIDs (e.g., Nature 2003 paper).
  • Byeong Ho Eom: postdoc working with Day
  • Hien Nguyen: contributor of cryostats and lab setups

• Other collaborators
  • Jason Glenn (CU)
  • Teun Klapwijk and SRON/TU Delft group
  • Phil Mauskopf and Cardiff group

• See also work by Grenoble group (Benoit)

• Have been bad about crediting plots and ideas; in general, all the work has been done by the above people!

• Support: Caltech trustee Alex Lidow, Caltech President’s Fund, NASA APRA, NSF AST/ATI, Moore Foundation, JPL DRDF, Keck Institute for Space Studies

Microwave Kinetic Inductance Detector Overview

- Superconductors have an AC inductance due to inertia of Cooper pairs
  - alternately, due to magnetic energy stored in screening supercurrent
- Changes when Cooper pairs are broken by energy input
- 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
Electrodynamic Response of Superconductors

- Conductivity from microscopic BCS theory by Mattis and Bardeen
  - Use perturbation theory to calculate response to applied EM field
  - M&B assume extreme anomalous limit, but analysis can also be used for local limit with appropriate modification (see Gao thesis Ch 2).
  - Calculates complex conductivity explicitly:
    \[
    \frac{\sigma_1}{\sigma_n} = \frac{2}{\hbar \omega} \int_\Delta^\infty d\epsilon \frac{[f(\epsilon) - f(\epsilon + \hbar \omega)] (\epsilon^2 + \Delta^2 + \hbar \omega \epsilon)}{\sqrt{\epsilon^2 - \Delta^2} \sqrt{(\epsilon + \hbar \omega)^2 - \Delta^2}}
    \]
    \[
    f(\epsilon) = \frac{1}{[e^{\epsilon/k_BT} + 1]}
    \]
    \[
    \frac{\sigma_2}{\sigma_n} = \frac{1}{\hbar \omega} \int_{\Delta - \hbar \omega}^\Delta d\epsilon \frac{[1 - 2f(\epsilon + \hbar \omega)] (\epsilon^2 + \Delta^2 + \hbar \omega \epsilon)}{\sqrt{\Delta^2 - \epsilon^2} \sqrt{(\epsilon + \hbar \omega)^2 - \Delta^2}}
    \]
  - Low frequency limit (\(\hbar \omega \ll kT; 6 \text{ GHz} = 300 \text{ mK}\)):
    \[
    \frac{\sigma_2}{\sigma_n} \approx \frac{\pi \Delta(T)}{\hbar \omega} \left[1 - \exp(-\Delta(0)/k_BT)\right] \to \text{constant as } T \to 0
    \]
    \[
    \frac{\sigma_1}{\sigma_n} \approx \frac{2\Delta(T)}{k_B T} \exp(-\Delta(0)/k_BT) \left[\ln\left(\frac{2k_BT}{\hbar \omega}\right) - \gamma + \ln 2\right] \to 0 \text{ as } T \to 0
    \]
- two-fluid model: imaginary (reactive, energy-conserving) part scales with supercurrent component, real (resistive, energy-dissipating) part scales with quasiparticle density
Electrodynamic Response of Superconductors

- Responsivity in low-frequency limit:

\[
\frac{d(\sigma_2/\sigma_n)}{dn_{qp}} = \frac{1}{2 N_0 \hbar \omega} \sqrt{\frac{\pi \Delta(0)}{2kT}} = \left( \frac{\sigma_2}{\sigma_n} \right)_{T=0} \frac{1}{2 N_0 \sqrt{2\pi kT \Delta(0)}}
\]

  - Responsivity is stable with temperature. A possibly interesting detector of quasiparticles without extreme temperature dependent response.

- In practice, imaginary response is \(\sim 2X\) real response at low T, changes at higher T

\[
\frac{\delta \sigma_1}{\sigma_2} \approx -\frac{1}{2} \frac{\delta \sigma_2}{\sigma_2}
\]
Electrodynamic Response of Superconductors

• Observables
  
  • Assuming EM wave propagating in z direction normal to surface, surface impedance is $Z_s = \frac{E_x}{H_y}$ (e.g., impedance of free space, $Z = \sqrt{\mu_0/\epsilon_0} = 376.7 \ \Omega$)
  
  • One can show that for thin films (thickness $t$, therefore local limit), it holds
    
    $$Z_s = R_s + i X_s \approx \frac{1}{(\sigma_1 - i \sigma_2) t} \quad X_s = \omega L_s = \omega \mu_0 \lambda_{eff}$$
    
    $\sigma_2$ dominates for $T << T_c$, so $X_s$ dominates (factor of order unity for thick films)
  
  • Relate fractional changes in $Z_s$ to fractional changes in complex conductivity
    
    $$\frac{\delta Z_s}{Z_s} = -\frac{\delta \sigma}{\sigma} \quad \frac{\delta L_s}{L_s} = -\frac{\delta \sigma_2}{\sigma_2} > 0 \quad \frac{\delta R_s}{\omega L_s} = \frac{\delta \sigma_1}{\sigma_2} > 0$$
    
    • Use relation between changes in real and imaginary parts:
      
      $$\frac{\delta \sigma_1}{\sigma_2} \approx -\frac{1}{2} \frac{\delta \sigma_2}{\sigma_2} \quad \frac{\delta R_s}{\omega \delta L_s} \approx \frac{1}{2}$$
      
    • So, given a measurement of surface impedances in a thin film, we can infer changes in conductivity and thus qp density.
Monitoring Complex Conductivity with Resonators

• How to measure changes in $L_s$ and $R_s$?
  • bolometer: measure changes in dissipation ($R$) via monitoring $I$ or $V$ at constant current or voltage bias
  • here, want to measure changes in reactance ($L$) because $\sigma_2$ goes to constant at low $T$ while $\sigma_1$ vanishes
  • can’t measure $L$ at DC: no current goes into reactive mode, so forced into some sort of sinusoidal bias
  • Standard audio-frequency readout could work: want low-impedance current readout because source is low impedance; could plausibly do a TES-like SQUID readout using shunt inductor to bias instead of shunt resistor. Readout noise is unfavorable, though.
Monitoring Complex Conductivity with Resonators

• RF resonator readout
  • Key driver: simple information considerations tell you that multiplexing capability increases with system bandwidth. RF is the way to go — that’s why the telecom industry continually pushes to higher frequencies.
  • $\sigma_2/\sigma_1$ goes down as $\omega$ goes up, but still have lots of margin at RF frequencies:
    • e.g. use Al as detector: $\Delta_{Al} = 170$ µeV, $T = 0.1$-0.3K provides reasonable operating temperature (well below $T_c$)
    • $\sigma_2/\sigma_1 = 1$ at $[8\times10^{18} \text{ Hz}, 2.1\times10^{13} \text{ Hz}]$ for $T = [0.1, 0.3]$ K: $\sigma_2/\sigma_1 >> 1$ for $\omega < 2\Delta_{Al}$
  • Frequency-domain or time-domain multiplexing? Linear signal theory is inherently easier in frequency space, telecom industry invests primarily in FDM.
  • But, in addition:
    • Making the device a resonator makes the devices self-define its RF bands: no need for additional band-defining components; also, L and C needed are small, compatible with large-format arraying
    • Few GHz RF technology is well-developed, convenient, and approaches fundamental readout noise limits
Lumped Element Readout Model

- Simplest notch resonator model: $L$, $C$, and $R$ in series
  - $C$ couples resonator to feedline of impedance $Z_0$
  - Neglect any shunt $C$ for simplicity
  - Resonant frequency $\omega_0 = 1/\sqrt{LC}$
  - Quality factor $Q = \omega_0 / (L/R)$
- Kinetic inductance fraction
  - contribution of kinetic inductance to total inductance: $\alpha = L_{ki} / (L_{ki} + L_m)$
- Expected response ($X_s = \omega L_{ki}$):
  \[
  \frac{\delta f_r}{f_r} = -\frac{1}{2} \frac{\delta L}{L} = -\alpha \frac{\delta L_{ki}}{2 L_{ki}} = -\alpha \frac{\delta X_s}{2 X_s}
  \]
  \[
  \frac{\delta}{Q_i} = \frac{\delta R}{\omega_0 L} = \alpha \frac{\delta R_s}{X_s} \quad \frac{dR}{dn_{qp}} \approx \frac{1}{2} \frac{dX_s}{dn_{qp}}
  \]
Lumped Element Readout Model

- \( L = 1000 \ \Omega, \ R = 0.1 \ \Omega, \ C_c = 0.01 \ \text{F}, \ Z_0 = 50 \ \Omega, \ \omega_0 = 1, \ Q = 1000 \)
Transmission Line Resonators

- **Half-wave through resonator**
  - can be modeled as parallel *RLC* circuit with $R = Z_0/2$
  
  $$S_{21} = \frac{2}{2 + (1/j\omega L + j\omega C) Z_0}$$

  $$Z_l = \sqrt{\frac{L}{C}}$$

  $$\omega_0 = 1/\sqrt{LC}$$

  $$Q = \omega_0 Z_0 C/2$$

  $$\Delta \omega(\text{FWHM}) = \omega_0 / Q$$

  **near resonance**

  $$S_{21} = \frac{1}{1 + jQ(1 - \omega_0^2/\omega^2)}$$

  **coupled quality factor**

  $$Q_c = \omega_n \tau_1 / e = \frac{n\pi}{4Z_0 Z_l (\omega_n C)^2}$$

- **Open ends are voltage maxima, center is current maximum**

- **Looks like a classic mechanical resonator**
Transmission Line Resonators

- **Quarter-wave shunt resonator**
  - on-resonance, the transmission line inductance tunes out reactance of the coupler, leaving a resistive impedance
  - impedance looking into transmission line
  $$Z_{\text{in}} = Z_0 \tanh(\alpha + j\beta)l = Z_0 \frac{1 - j \tanh \alpha l \cot \beta l}{\tanh \alpha l - j \cot \beta l}$$
  - propagation constant
  $$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(j\omega C)}$$
  - coupled resonant frequency
  $$\omega_0 - \omega_{1/4} = \frac{-2Z_0\omega_{1/4}\omega_0 C}{\pi} \approx \frac{-2Z_0\omega_{1/4}^2 C}{\pi}$$
  - internal quality factor
  $$Q_i = \beta/2\alpha$$

- Can be modeled as a parallel $RLC$ also
  $$\tilde{R} = \frac{2L}{lRC}, \quad \tilde{C} = \frac{l}{2}C, \quad \tilde{L} = \frac{8l}{\pi^2}L.$$
  $$Q = \frac{\pi}{4\alpha l} = \omega_0 \frac{L}{\tilde{R}}$$

- Voltage maximum at open end, current maximum at shorted end

- Similar behavior for half-wave open-ended resonator
Transmission Line Resonators

- Quarter-wave shunt resonator
Lumped Element Resonators

Current is uniform in interdigitated capacitor (IDC): acting as lumped element, not a transmission line, while inductive part is transmission-line-like.

Current magnitude

True lumped element designs for direct FIR absorption

Parallel-plate capacitors, symmetrized inductor

Top plates of two series capacitors with silicon dielectric made using SOI wafer

Simple meandered inductor

Meandered inductor with dual meander to minimizing coupling to neighbors.
Optical Coupling Geometries

- Direct absorption (bare pixel or behind feedhorn)
- Microstrip coupled

![Diagram of optical coupling geometries]

- Direct absorption (bare pixel or behind feedhorn)
- Microstrip coupled

- Twin-slot antenna + silicon lens
- phased-array antennas

1.3 Perceived Impact to State of Knowledge

The successful completion of the goals of this project will bring the TRL of a promising detector technology, originally developed under APRA funding, to near the level where it can be credibly proposed for flight missions. MKID arrays have been tested in the field by the MUSIC collaboration and by the NIKA collaboration, although not yet in the submm–FIR wavebands or in science-grade instruments. Laboratory testing of submm–FIR band MKIDs has demonstrated the critical functions of high optical efficiency and near background limited noise, so we consider the current TRL to be low. Under this program, we will both rigorously test a small array in MUSTANG and demonstrate larger arrays in optical test beds, paving the way to large focal plane formats of several tens of thousands needed for the next generation of mm–submm–FIR imagers. The successful completion of the goals of this project will bring this technology to a high-fidelity laboratory testing of integrated components.
Noise and Sensitivity

- “Standard” noises

\[
\text{single-polarization } \text{NET}_{RJ} = \sqrt{2T_{load} \left( T_Q + \eta_{op} T_{load} + \frac{\Delta}{k} \frac{\eta_{op}}{\eta_{ph}} + \frac{16}{\xi \eta_{ph} r_{\kappa}^2} T_N \right) \eta_{op} \Delta \nu}
\]

- \( T_{load} \): optical load incident on receiver, equivalent Rayleigh-Jeans temperature
- \( T_Q \): \( h\nu/k \) = “quantum” noise temperature
- \( T_N \): RF amplifier noise temperature
- \( \eta_{op} \): receiver optical efficiency (window to MKID)
- \( \eta_{ph} \): \( \approx 0.57 \) = phonon loss efficiency (fraction of incoming photon energy converted to broken Cooper pairs)
- \( \Delta \): superconducting gap energy
- \( \Delta/(k\eta_{ph}) \): \( 3.1T_c \) for BCS superconductors
- \( \Delta \nu \): mm-wave bandwidth
- \( \xi \): readout power / optical power received \( \geq 1 \)
- \( r_{\kappa} \): 1 for amplitude (dissipation) readout, 3-4 for phase (frequency) readout
Noise and Sensitivity

- Comparison to “perfect” transition-edge sensor (TES) bolometer (no readout noise) and coherent detector

\[
NET_{RJ} = \sqrt{\frac{2T_{\text{load}} \left( T_Q + \eta_{\text{op}} T_{\text{load}} + \frac{\Delta}{k} \frac{\eta_{\text{op}}}{\eta_{\text{ph}}} + \frac{16}{\xi \eta_{\text{ph}} \kappa^2} T_N \right)}{\eta_{\text{op}} \Delta \nu}}
\]

bolometer: \(NET_{RJ} = \sqrt{\frac{2T_{\text{load}} \left( T_Q + \eta_{\text{op}} T_{\text{load}} + 2\gamma f_S T_{\text{bolo}} \frac{T_{\text{bolo}}}{\Delta T_{\text{bolo}}} \right)}{\eta_{\text{op}} \Delta \nu}}\)

coherent: \(NET_{RJ} = \sqrt{\frac{2}{\Delta \nu} \left( \frac{T_{\text{amp}}}{\eta_{\text{op}}} + T_{\text{load}} \right)} = \sqrt{\frac{2}{\Delta \nu} \left( \frac{\chi T_Q}{\eta_{\text{op}}} + T_{\text{load}} \right)}\)

\(\gamma = \mathcal{O}(1)\) factor describing thermal link to bath

\(f_S = 3\) to 5 = safety factor to avoid TES saturation

\(T_{\text{bolo}} = \) bolometer operating temperature

\(\Delta T_{\text{bolo}} = T_{\text{bolo}} - T_{\text{bath}}\)

\(T_{\text{amp}} = \) mm-wave noise temperature of coherent detector

\(\chi = \) ratio of noise temperature of coherent detector to quantum limit at \(\nu\)

n.b: \(T_{\text{load}}\) tends to be higher and \(\eta_{\text{op}}\) lower for MKIDs and TES bolometers due to need for thermal IR blocking
Test Case: 90 GHz Polarimeter at South Pole

• Assume:
  • $\nu = 90 \text{ GHz} \rightarrow T_Q = 4.3K$
  • $T_{\text{load}} = 10K$ for coherent, $15K$ for MKID/bolometer
  • $\eta_{\text{op}} = 0.8$ for coherent,
    $0.4$ for MKID/bolometer (achieved w/ $2(f/\#)\lambda$ dual-pol phased-array antennas)
  • $T_N = 5K$ for MKID RF HEMT amplifier
  • $\chi = 5$ achieved, $3$ expected $\rightarrow T_{\text{amp}} = 22K$ for $\chi = 5$, $13K$ for $\chi = 3$
  • $T_{\text{bolo}} = 0.5K$, $\Delta T_{\text{bolo}} = 0.2K$, $\gamma = 0.5$, safety factor $f_s = 5$

• Results:
  • $\ast$: $\sqrt{2}$ improvement included because $Q$ and $U$ measured with same module
  • technologies are all about the same

<table>
<thead>
<tr>
<th>detector</th>
<th>NET$_{\text{RJ}}$ [$\mu\text{K s}^{1/2}$] (single-pol)</th>
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<tr>
<td></td>
<td>shot</td>
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<tr>
<td>MKID</td>
<td>85</td>
</tr>
<tr>
<td>TES</td>
<td>85</td>
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<tr>
<td>coherent</td>
<td>N/A</td>
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<td></td>
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MKIDs for Cosmology
Two-Level System Noise

- Amorphous oxides on resonator metal film and bare substrate
- Amorphous materials have large population of “two-level systems”
  - Defect states in materials present opportunity for tunneling between two configurations
  - Theory of two-level systems in NMR applies
- TLS interacts with resonator via electric dipole moment
  - Trades energy with resonator’s RF EM field.
  - But can also emit to substrate via phonons.
  - Loss (dissipation) $\rightarrow$ noise in the coupling.
- Coupling to dipole moments in substrate
  = dielectric constant
  Fluctuations in TLSs
  = dielectric constant fluctuations
Two-Level System Noise Characteristics

- Noise is only in phase (frequency shift) direction to high precision

- Noise varies as \( f_{\text{audio}}^{-1/2} \) and \( P_{\text{readout}}^{-1/2} \)
Two-Level System Noise Model for Resonators

• Gao et al developed semi-empirical theory
  • TLS theory implies that dielectric constant fluctuates due to variations in whether energy is returned to RF field or not (fluctuation-dissipation theorem).
  • TLSs can saturate: if field is strong enough, they no longer may fluctuate. Expected dependence of loss tangent $\sim (1 + |E|/|E_c|)^{-1/2}$
  • Expected behavior of phase noise converted to frequency (it is effectively the $f_0$ of resonator that is fluctuating)

$$
\frac{S_{\delta f_{RF}}(f)}{f_0^2} = \kappa \left( f, \frac{hf_0}{kT} \right) \frac{\int_V |\vec{E}|^3 d^3r}{4 \left( \int_V \epsilon |\vec{E}|^2 d^3r \right)}
$$

• Yields

$$
\frac{S_{\delta f_{RF}}(f)}{f_0^2} \propto |\vec{E}|^3
\quad S_{\delta f_{RF}}(f) \propto P_{\text{readout}}^{-1/2}
\quad S_{\delta f_{RF}}(f) \propto f^{-1/2}
\quad S_{\delta f_{RF}}(f) \propto T^{-0.14} \tanh^2 \left( \frac{hf_0}{2kT} \right)
$$

• Implications:
  • Reduce $|E|$ while holding quasiparticle responsivity (current, B field) fixed
  • In a fixed configuration for $|E|$, maximize $P_{\text{readout}}$
  • Be careful as $f$ decreases.
  • Decrease $f_0$.
  • Serious physics model, verified by experiment.
Two-Level System Noise Reduction

- Showed expected behavior with width of resonator

- Change design to make wide capacitive (high |E|) section, keep inductive (high |B|) section

remarkable reduction in noise from change in C geometry

current is uniform in interdigitated capacitor (IDC): acting as lumped element, not a transmission line

current magnitude
Expectations for Two-Level System Noise

\[
\text{NET}_{TLS} = \sqrt{16 T_{load}^2 S_{\delta f/f} Q_i^2 r_0^2} = \sqrt{\frac{2 T_{load} (8 \eta_{op} T_{load} S_{\delta f/f} \Delta \nu \frac{Q_i^2}{r_0^2})}{\eta_{op} \Delta \nu}}
\]

- \( S_{\delta f/f} = 3 \times 10^{-19} \text{ Hz}^{-1} \), \( Q_i = 10^4 \) \( \rightarrow \) \( \text{NET}_{TLS} = 60 \mu \text{K s}^{1/2} \)
- In principle, TLS noise has already been reduced to acceptable level!
- And expect continued gains:
  - Have physical theory of TLS noise
  - Expect substantial improvement in TLS with parallel-plate capacitor design (much reduced amorphous materials)
  - Design could be used to sense temperature rise of a leg-isolated island and move to lower \( f_0 \)
    - increase overall signal so can beat amplifier noise in dissipation direction
    - lower amplifier noise (\( T_N = 2 \text{K} \))
    - increases \( r_\kappa \) (Mattis-Bardeen)

parallel-plate capacitors, symmetrized inductor

top plates of two series capacitors with silicon dielectric made using SOI wafer
Challenges

- $\eta_{ph} = 0.57$ is an undesirable hit to take
- amplifier noise nonnegligible
- amplifier noise aggravated by nonuniform absorption
  - exponential power profile
    $\rightarrow n_{qp}$ artificially increased at input end, reduces reponsivity
  - can’t reduce length (volume) to compensate, would lose efficiency due to power reflection
- current IDC + meandered inductor suffers broadband direct absorption
  - not sure whether in IDC or in meandered inductor; have a blocking filtered between IDC and inductor
  - Adds 1-2 pW absorbed load; comparable to expected 150 GHz load at S. Pole
Multiplexing

Half-wave through

Quarter-wave shunt, lumped-element shunt

Input

Output

Quarter-wave shunt, lumped-element shunt

Frequency (GHz)

deviation (MHz)

resonance number

MKIDs for Cosmology

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Multiplexed Readout

- UCSB/Caltech/JPL 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 does not add noise
  - 1/f performance: 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 standard
  - Analog IQ mixers to upconvert and downconvert 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 board
  - Reconfigurable Open Architecture Computer Hardware (dev’d by CASPER)
  - Xilinx Virtex5 FPGA, Power PC CPU, 1 DDR DRAM + 2 QDR SRAM, 2 Zdok connectors, 10 Gb, 1 Gb, and 100 Mb interfaces
  - Simulink FPGA programming
  - Dev’d 1-stage FFT + FIR filter decimator
Multiplexed Readout

- 8-block crate being developed

- High-stability PSU for IF, ADC/DAC
Applications
CMB Polarization: Now

- **BICEP2, Keck Array, SPIDER** demonstrating very sensitive CMB polarization mapping with antenna-coupled TES arrays
  - Pls: Bock, Kovac, Pryke, Kuo, Jones, Netterfield, Ruhl
  - 256 pixels, 512 TES detectors per cryostat
  - Uses time-domain NIST SQUID mux: 32-channel unit
  - BICEP2: in the field 18 mo, many times deeper than BICEP1 at degree scales
    - Keck Array has 3 similar receivers in the field (and planning 90 GHz for late 2011)
    - SPIDER planning to fly 4 to 6 receivers late 2012 (incl. 90 GHz and 275 GHz)
- **POLAR-1** developing larger arrays and optimizing for few-arcmin scales to focus on lensing signal
  - (Kuo, Bock, Kovac, Pryke)
  - Tapered phased-array antennas to reduce sidelobes, tighter packing, ~4000 detectors/receiver
  - Also using 32-channel unit of NIST mux: 5-8 crates required
CMB Polarization: Future

- There is interest in an array of POLAR-I’s to measure the lensing signal to much higher precision, enabling 50 meV neutrino mass measurement, early dark energy test, and large-scale structure studies.
- Can the existing technologies meet the challenge?
  - Standard multiplexing of TES arrays seems challenging, though perhaps brute-force doable: O(50-100) crates, O(1000) multiplex units.
  - New TES multiplexing schemes being developed based on RF multiplexing a la MKIDs, though more complicated.
  - MKIDs present a viable alternative that already meets the multiplexing challenge and can in principle provide requisite sensitivity.
MUSIC: MUlticolor Sub/millimeter Inductance Camera

• New technologies enable ~background-limited, multi-color camera (850 µm - 2 mm) with wide FOV (14’, 600 spatial pixels)
  • Planar photolithographic phased-array antennas: large-format arrays on a single wafer, ~octave instantaneous bandwidth
  • Planar photolithographic bandpass filters: many colors from a single antenna
  • Microwave Kinetic Inductance Detectors (MKIDs): a new, highly multiplexable detector

• Science goals
  • Dusty star-forming galaxies (DSFGs)
    • Wide-area surveys with multicolor information: find the high-z objects
    • Follow-up of Herschel DSFGs: measure spectral energy distributions, select high-z
    • Study DSFGs in lensed galaxy cluster fields
  • Galaxy clusters
    • Multicolor Sunyaev-Zeldovich effect observations of known clusters to study ICM, measure cosmological parameters in coordination with X-ray, optical/IR
    • e.g., followup of Planck catalog, HST CLASH program, etc.

• Instrument Team
  • CU: Jason Glenn, Phil Maloney, James Schlaerth; JPL: Peter Day, Rick LeDuc, Hien Nguyen; Caltech: Nicole Czakon, Tom Downes, Ran Duan, Sunil Golwala, Matt Hollister, Dave Miller, Omid Noroozian, Jack Sayers, Seth Siegel, Tasos Vayonakis, Jonas Zmuidzinas; UCSB: Ben Mazin, Sean McHugh
Multicolor Antenna-Coupled MKIDs

6 x 6 spatial pixel array
x16 to make full focal plane

6 x 6 spatial pixel array
x16 to make full focal plane

single pixel

phased array antenna

MKIDs (four, one per color)

Detector development funded by JPL RTD, NASA APRA, Moore Foundation
Goal 1: Find high-z DSFGs by using MUSIC/SPIRE colors. Expect ~600 DSFGs at 4 sigma, most at z > 4. Color-select objects for z-search and follow-up w/ALMA, Z-SPEC, ZEUS. Add substantial value to SPIRE.

mm-wave bands provide ~z-independent ability to detect $L = 10^{13.5} L_{\text{Sun}}$ SMG

More than half of the 1.04/1.33mm detected sources will be at z > 4

Calculations based on Bethermin et al 2010 models
MUSIC 15 deg² Wide-Field Survey

- **Goal 2:** Study clustering as a function of wavelength
  - Clustering at different wavelengths provides (coarse) way to study evolution of clustering with z.
  - Clustering well-studied at 250, 350, 500 µm w/ SPIRE, can push to z > 4 with MUSIC.
  - MUSIC primarily sensitive to 1-halo term, may be able to detect 2-halo term depending on sky-noise removal transfer f’n.

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**Figure 1**
- green dashed-dot: 2-halo term (galaxies in different DM halos)
- green dashed: 1-halo term (galaxies in the same halo)
- cyan dashed: shot noise level (subtracted)
MUSIC Galaxy Cluster Studies

- Study galaxy clusters across wavelength regime where SZ gives way to DSFGs; separate SZ, CMB, and DSFGs using multi-wavelength information.
MUSIC Galaxy Cluster Studies

- Sample: comparable to ACT/SPT SZ surveys in size
  - ~25 individual CLASH clusters with deep integrations
  - shallow integrations on ~250 clusters selected from WISE, Planck, and/or eROSITA
- Cluster astrophysics and cosmology
  - Goal 3: What is the ICM doing in the infall region at the virial radius?
  - Goal 4: Measure scaling relations to high statistical precision
    - Constrain dark energy via measurement of mass function of clusters as fn of z.

**Azimuthally averaged radial profile expected for deep integration on MS0451-like cluster**

**Scaling relation determination**
Recent development of lumped-element designs having low susceptibility to dielectric constant fluctuation noise and using large penetration depth materials enables large-area resonators for phonon sensing (Day, Gao, LeDuc, Noroozian, Zmuidzinas).

- Single film, 5 µm features would simplify GEODM detector fab.
- Finer pixellization of phonon sensor provides additional surface event rejection.
- Also very promising for 10-80 keV gamma-ray detection: would provide 0.1% ΔE/E needed to measure velocity near mass cut in SNR from $^{44}$Ti line.

Phonon Detection Using MKIDs

Figures by D. Moore
Progress to Date

• 12 mm x 16 mm arrays of 20 TiN resonators on 1-mm silicon substrates show promising performance
  • 0.11 keV expected baseline energy resolution, 0.24 keV obtained
  • 0.69 keV obtained at 29 keV; residual position resolution likely

• Need to improve robustness of fab:
  • $T_c$ not well controlled at 0.5-1K, expected better at 1K-2K
  • aging seen in $T_c = 0.5$-1K devices

• Need to better control phonon losses to box highly variable decay times observed (10 µs to 100 µs)
Conclusions

• Microwave Kinetic Inductance Detectors are a highly multiplexable and sensitive technology for astrophysical and cosmological applications, competitive in sensitivity with current technologies

• Many aspects of MKIDs under development
  • Optimization of device design to maximize sensitivity and minimize TLS noise
  • Optical coupling architectures
  • Readout systems

• A possibility for a large CMB polarization lensing B-modes array

• Being deployed in MUSIC submm/mm camera

• Also under development for phonon-mediated detection for dark matter and gamma-rays