Applications of Microwave Kinetic Inductance Detectors for Cosmology

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FNAL Research Techniques Seminar

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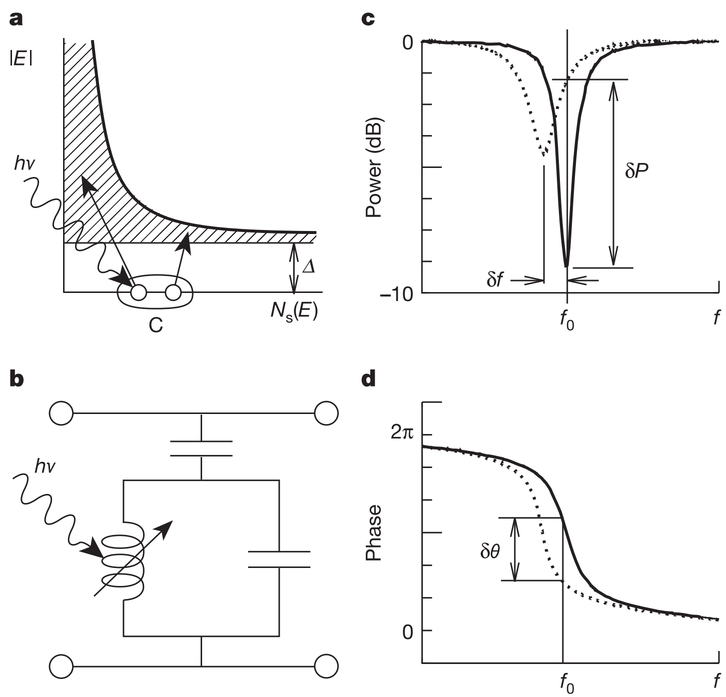
Overview

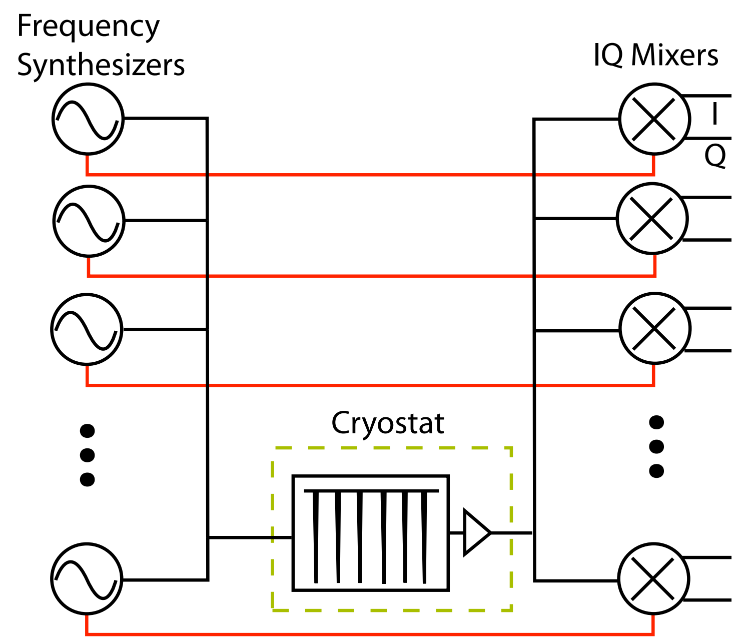
- Electrodynamics of superconductors
- Monitoring complex conductivity with resonators
- Multiplexing
- Optical coupling
- Noise sources and expected sensitivity
- Multiplexing electronics
- CMB and astrophysics applications
- Gamma-ray and dark matter applications

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
- Contact me for references; also, Mazin and Gao theses, Zmuidzinas Ann. Rev. Cond. Matt. Phys. (2011)

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:

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

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

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

  - Low frequency limit ($\hbar\omega$ << $k\,T$; 6 GHz = 300 mK):

$$\frac{\sigma_2}{\sigma_n} \approx \frac{\pi\Delta(T)}{\hbar\omega}\left[1-\exp(-\Delta(0)/k_B T)\right]$$ → constant as T → 0

$$\frac{\sigma_1}{\sigma_n} \approx \frac{2\Delta(T)}{k_B T}\exp(-\Delta(0)/k_B T)\left[\ln\left(\frac{2k_B T}{\hbar\omega}\right) - \gamma + \ln 2\right]$$ → 0 as T → 0

two-fluid model: imaginary (reactive, energy-conserving) part scales with supercurrent component, real (resistive, energy-dissipating) part scales with quasiparticle density

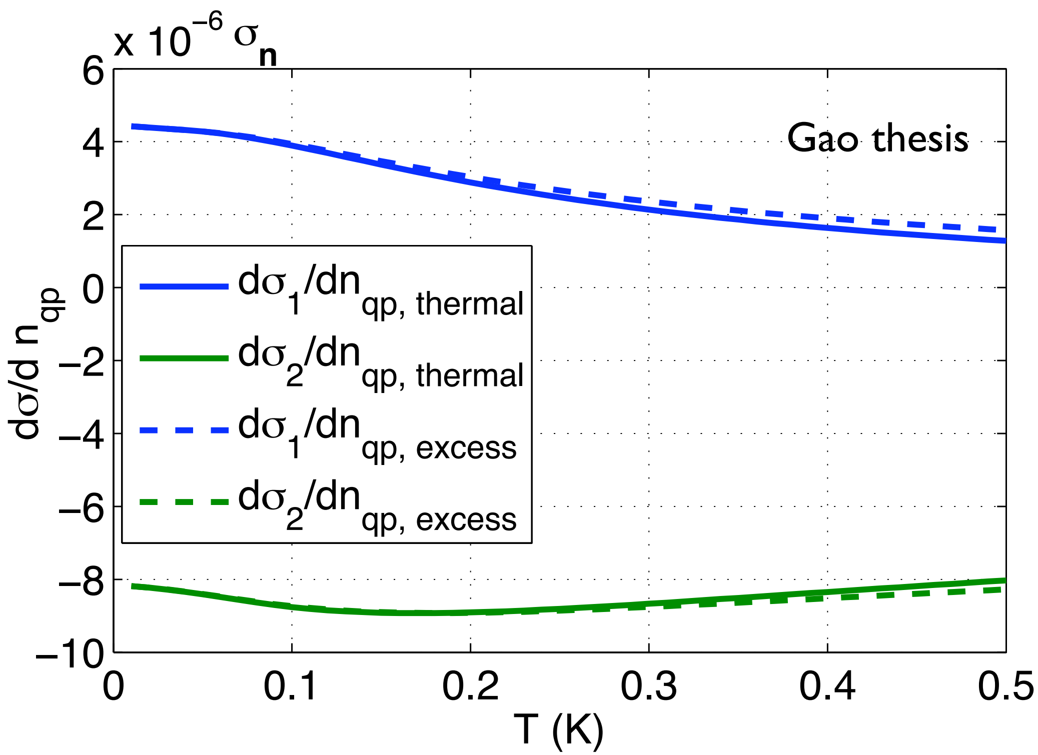
Electrodynamic Response of Superconductors

- 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 ~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

$$Z_s = R_s + i\,X_s \approx \frac{1}{(\sigma_1 - i\,\sigma_2)\,t} \qquad\qquad X_s = \omega\,L_s = \omega\,\mu_0\,\lambda_{eff}$$

    σ_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

$$\frac{\delta Z_s}{Z_s} = -\frac{\delta\sigma}{\sigma} \qquad \frac{\delta L_s}{L_s} = -\frac{\delta\sigma_2}{\sigma_2} > 0 \qquad \frac{\delta R_s}{\omega\,L_s} = \frac{\delta\sigma_1}{\sigma_2} > 0$$

  - Use relation between changes in real and imaginary parts:

$$\frac{\delta\sigma_1}{\sigma_2} \approx -\frac{1}{2}\,\frac{\delta\sigma_2}{\sigma_2} \Longrightarrow \frac{\delta R_s}{\omega\,\delta L_s} \approx \frac{1}{2}$$

  - 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 σ_2 goes to constant at low T while σ_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

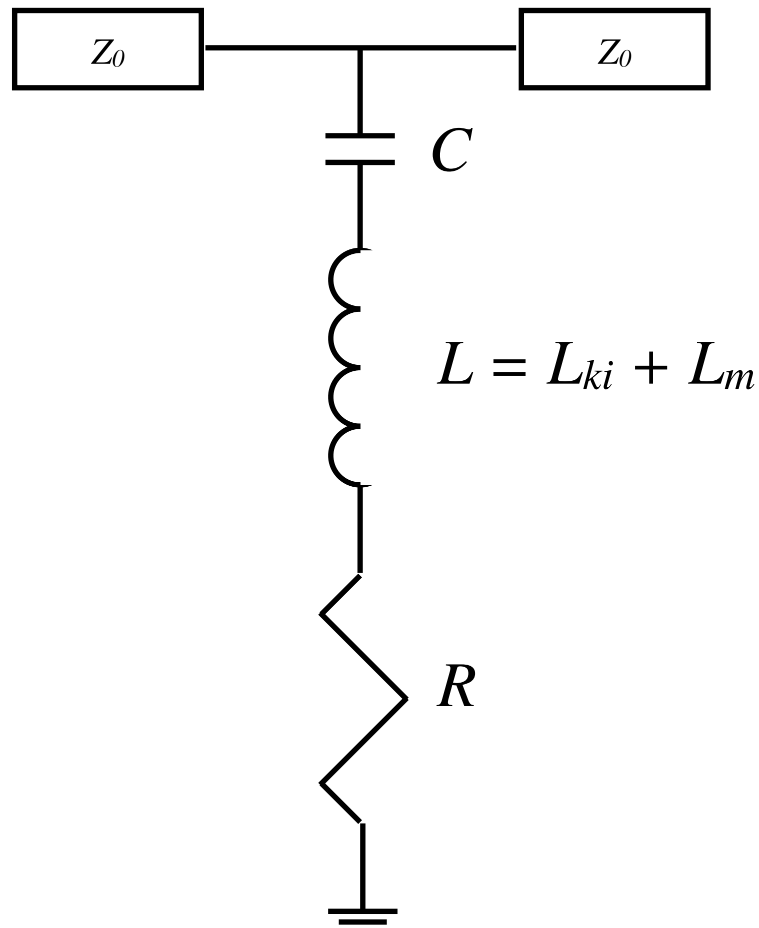
- RF resonator readout
  - Key driver: simple information considerations tell you that multiplexing capability increases with system bandwidth. RF is the way to go — that's why the telecom industry continually pushes to higher frequencies.
  - σ_2/σ_1 goes down as ω goes up, but still have lots of margin at RF frequencies:
    - e.g. use Al as detector. Δ_{Al} = 170 μeV, T = 0.1-0.3K provides reasonable operating temperature (well below T_c)
    - $\sigma_2/\sigma_1 = 1$ at [8x10^{18} Hz, 2.1x10^{13} 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 ($X_s = \omega L_{ki}$):

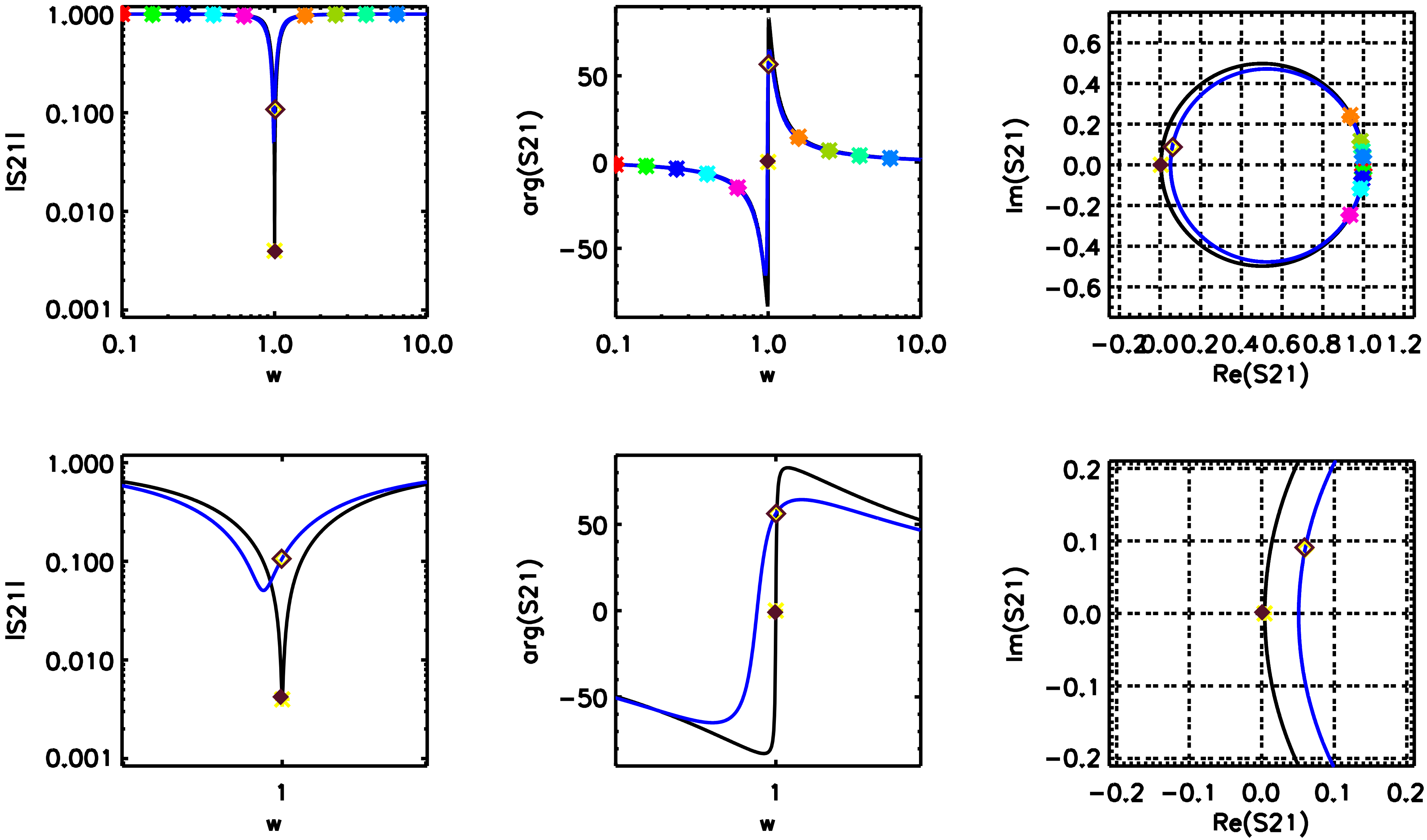
$$\frac{\delta f_r}{f_r} = -\frac{1}{2}\frac{\delta L}{L} = -\frac{\alpha}{2}\frac{\delta L_{ki}}{L_{ki}} = -\frac{\alpha}{2}\frac{\delta X_s}{X_s}$$

$$\delta\frac{1}{Q_i} = \frac{\delta R}{\omega_0 L} = \alpha\frac{\delta R_s}{X_s} \qquad \frac{dR}{dn_{qp}} \approx \frac{1}{2}\frac{dX_s}{dn_{qp}}$$



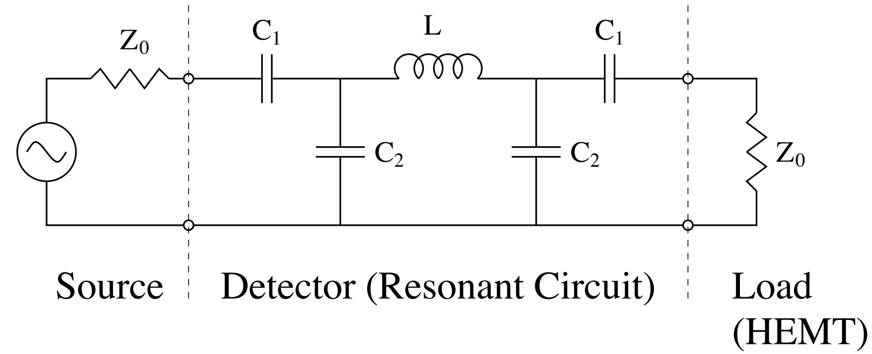
Lumped Element Readout Model

- $L = 1000\ \Omega$, $R = 0.1\ \Omega$, $C_c = 0.01$ 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 $R = Z_0/2$



$$S_{21} = \frac{2}{2 + (1/j\omega L + j\omega C)\, Z_0}$$

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

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

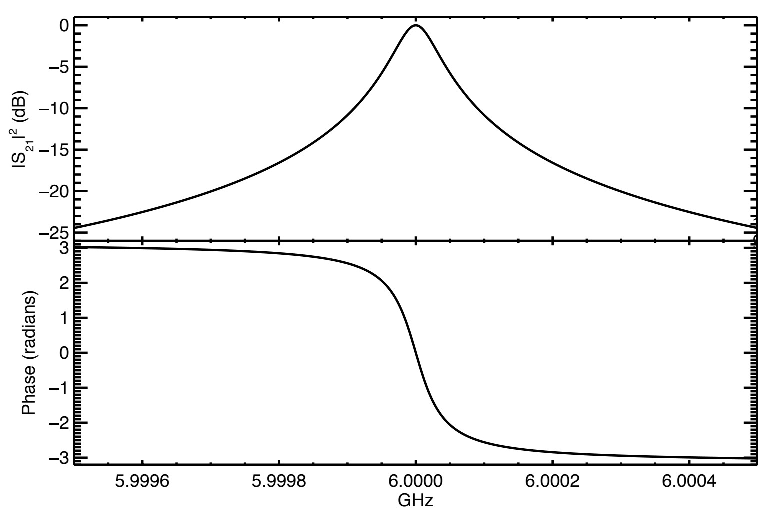
$$\omega_0 = 1/\sqrt{LC}$$

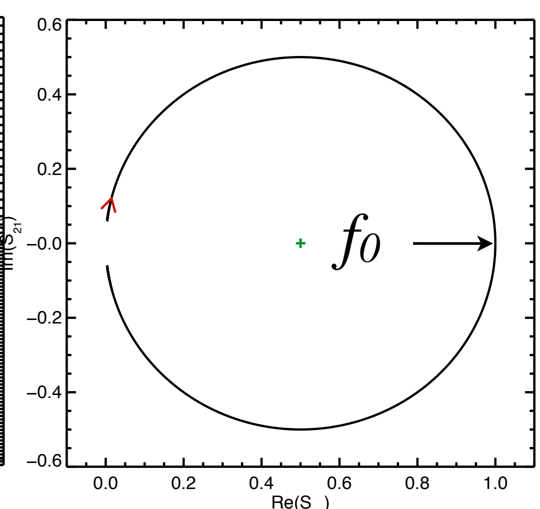
$$Q = \omega_0 Z_0 C/2$$

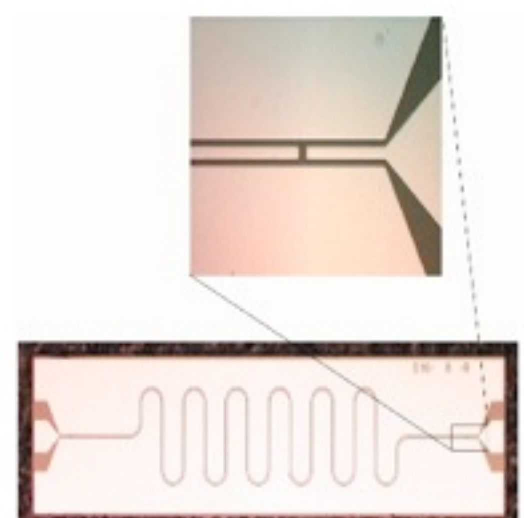
$$\Delta\omega(\mathrm{FWHM}) = \omega_0/Q$$

coupled quality factor $Q_c = \omega_n \tau_{1/e} = \dfrac{n\pi}{4 Z_0 Z_l (\omega_n C)^2}$

  - Open ends are voltage maxima, center is current maximum
  - Looks like a classic mechanical resonator



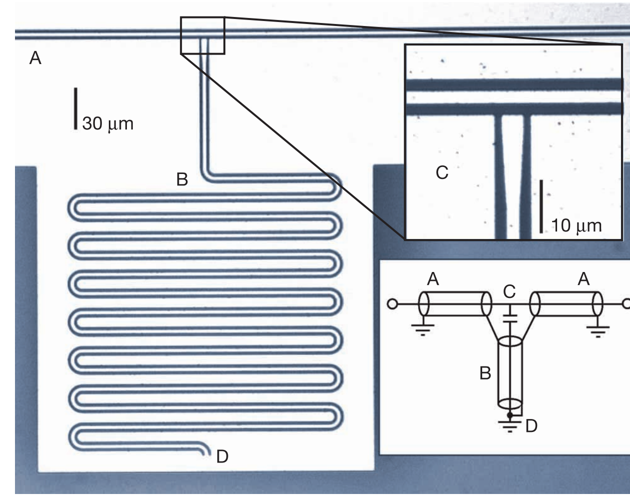




Transmission Line Resonators

- Quarter-wave shunt resonator

$$Z_0 = \sqrt{\frac{L}{C}}$$



  - on-resonance, the transmission line inductance tunes out reactance of the coupler, leaving a resistive impedance
  - impedance looking into transmission line

$$Z_{\rm in} = Z_0 \tanh(\alpha + j\beta)l = Z_0 \frac{1 - j\tanh\alpha l \cot\beta l}{\tanh\alpha l - j\cot\beta l}$$

    propagation constant $\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(j\omega C)}$

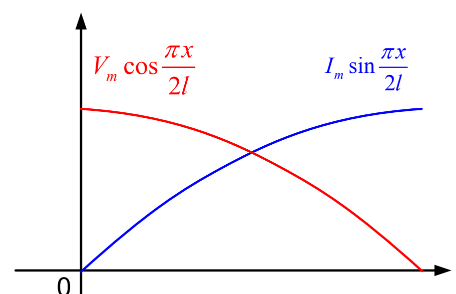
    coupled resonant frequency $\omega_0 - \omega_{1/4} = \dfrac{-2Z_0\omega_{1/4}\omega_0 C}{\pi} \approx \dfrac{-2Z_0\omega_{1/4}^2 C}{\pi}$

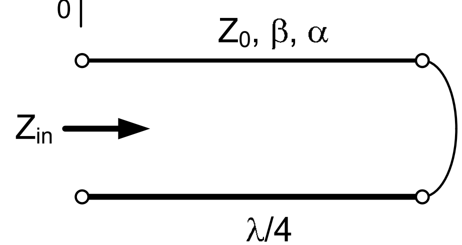
    internal quality factor $Q_i = \beta/2\alpha$

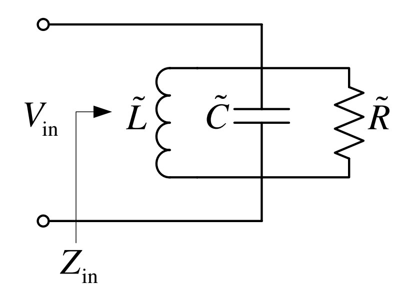
  - Can be modeled as a parallel *RLC* also

$$\tilde{R} = \frac{2}{l}\frac{L}{RC}, \quad \tilde{C} = \frac{l}{2}C, \quad \tilde{L} = \frac{8l}{\pi^2}L.$$

$$Q = \frac{\pi}{4\alpha l} = \omega_0 \frac{L}{R}$$



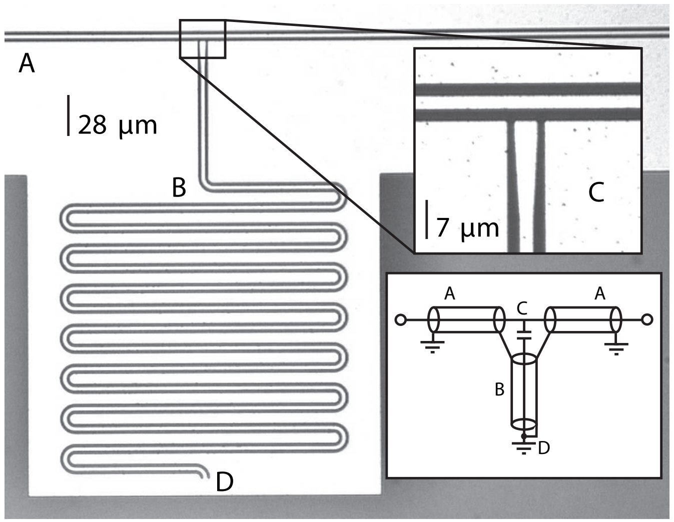


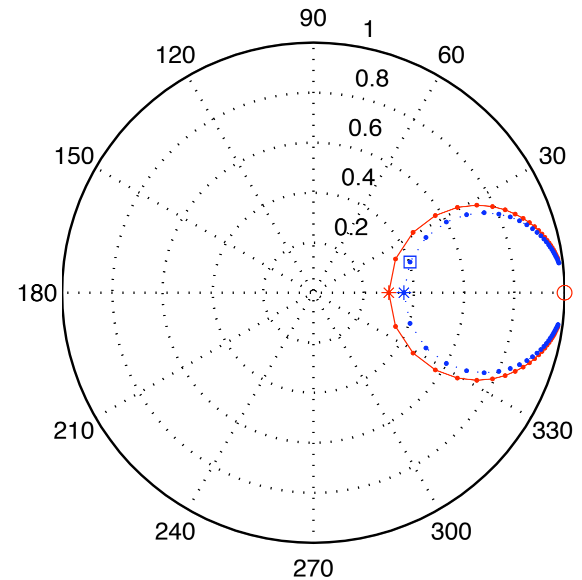


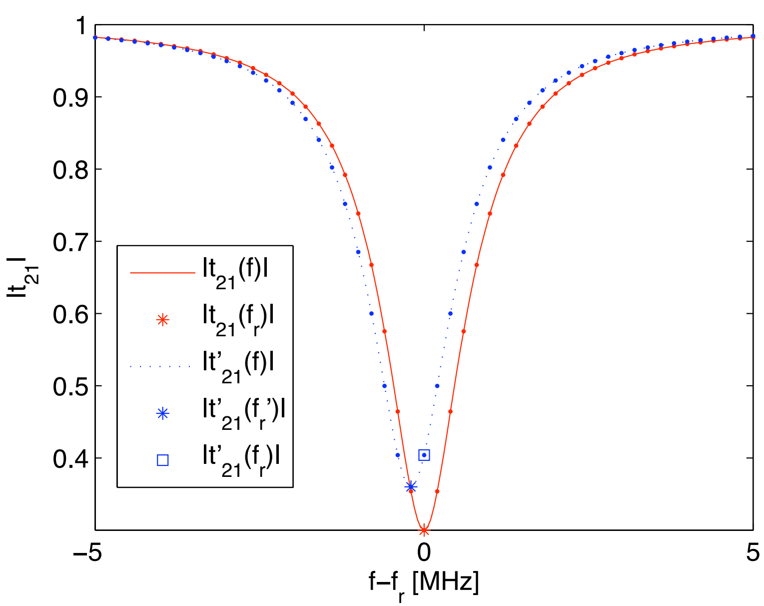
  - Voltage maximum at open end, current maximum at shorted end
  - Similar behavior for half-wave open-ended resonator

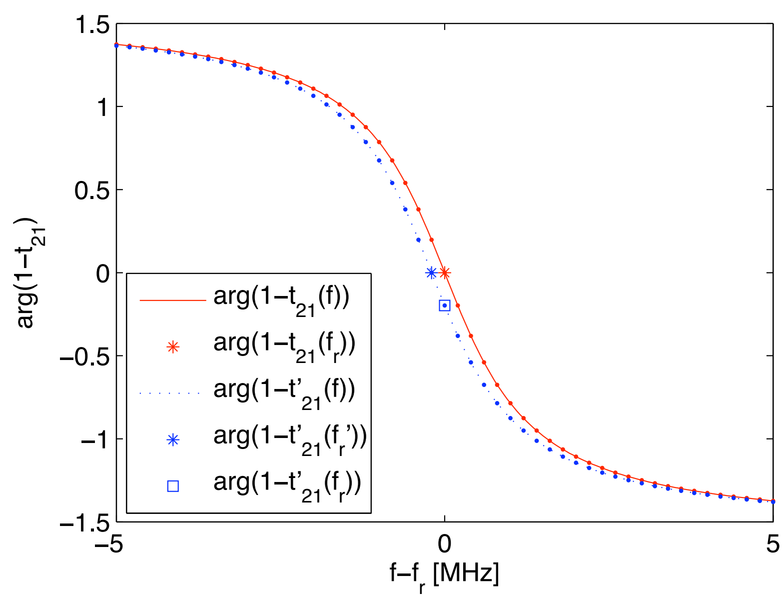
Transmission Line Resonators

- Quarter-wave shunt resonator

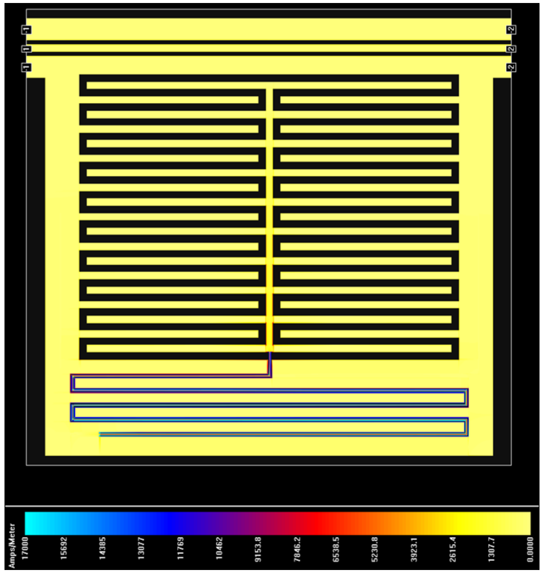








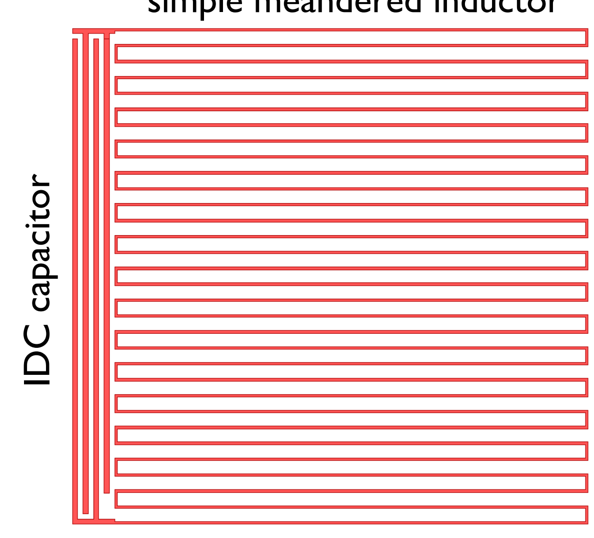
Lumped Element Resonators



current magnitude

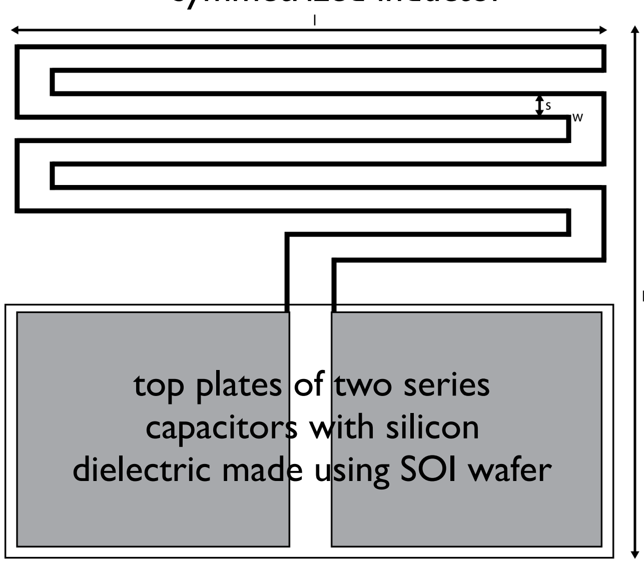
current is uniform in interdigitated capacitor (IDC):
acting as lumped element, not a transmission line, while inductive part is transmission-line-like

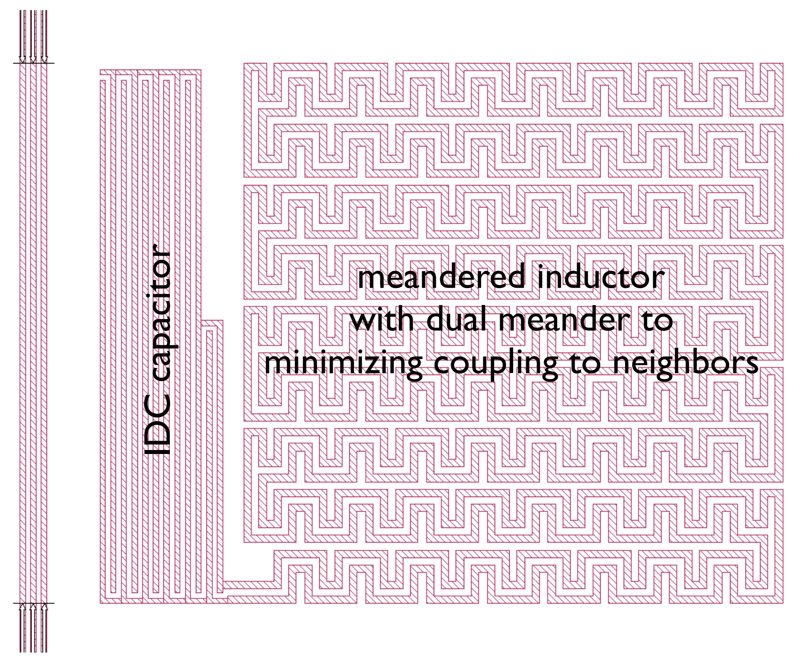
simple meandered inductor



true lumped element designs for direct FIR absorption

parallel-plate capacitors,
symmetrized inductor

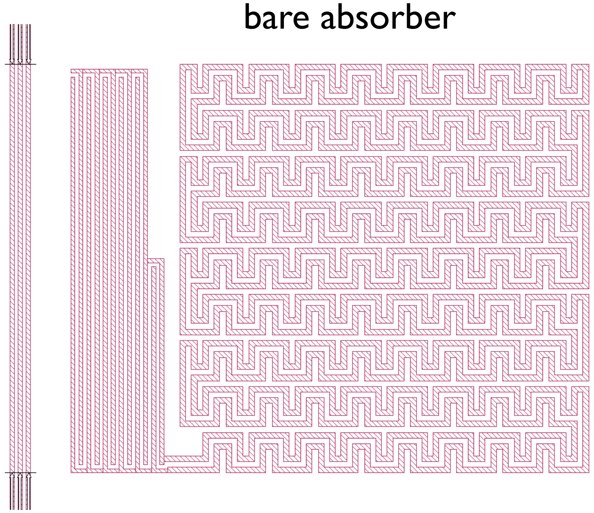




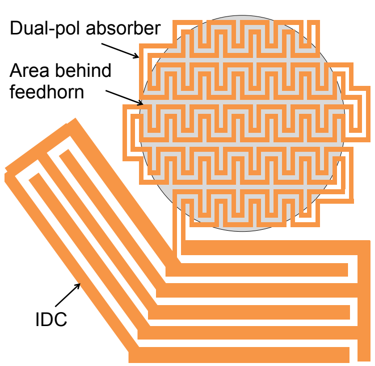
Optical Coupling Geometries

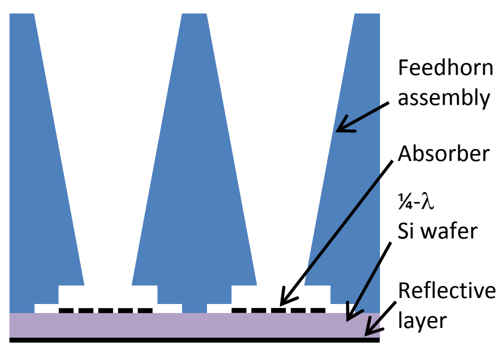
- Direct absorption (bare pixel or behind feedhorn)

bare absorber

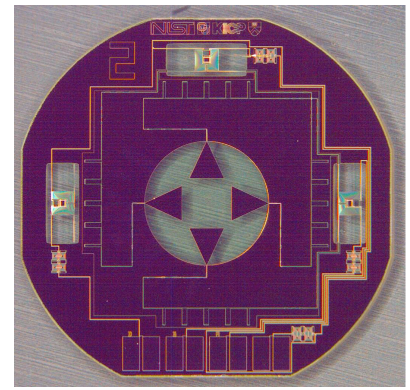


absorber behind feedhorn



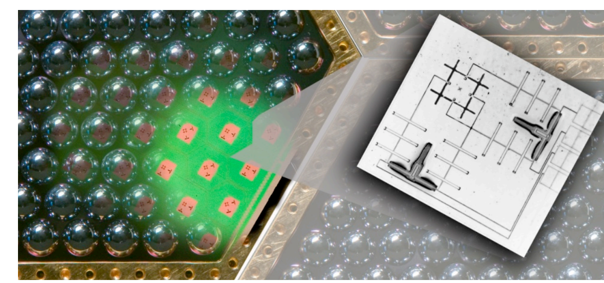


- Microstrip coupled

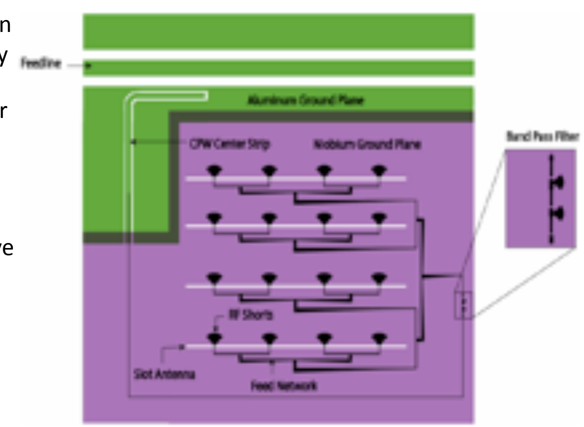


OMT probe into feedhorn waveguide

Twin-slot antenna + silicon lens



phased-array antennas



Noise and Sensitivity

- "Standard" noises

shot noise | Bose noise | generation-recombination noise ("G" noise) | amplifier noise

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

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

Noise and Sensitivity

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

$$\mathrm{NET}_{RJ} = \sqrt{\frac{2T_{load}\left(T_Q + \eta_{op}T_{load} + \frac{\Delta}{k}\frac{\eta_{op}}{\eta_{ph}} + \frac{16}{\xi\eta_{ph}r_\kappa^2}T_N\right)}{\eta_{op}\Delta\nu}}$$

$$\text{bolometer:}\ \mathrm{NET}_{RJ} = \sqrt{\frac{2T_{load}\left(T_Q + \eta_{op}T_{load} + \boxed{2\,\gamma\,f_S\,T_{bolo}\frac{T_{bolo}}{\Delta T_{bolo}}}\right)}{\eta_{op}\Delta\nu}}$$

"G" or phonon noise for bolometers

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

$$\begin{aligned}
\gamma &= \mathcal{O}(1)\ \text{factor describing thermal link to bath} \\
f_S &= 3\ \text{to}\ 5 = \text{safety factor to avoid TES saturation} \\
T_{bolo} &= \text{bolometer operating temperature} \\
\Delta T_{bolo} &= T_{bolo} - T_{bath} \\
T_{amp} &= \text{mm-wave noise temperature of coherent detector} \\
\chi &= \text{ratio of noise temperature of coherent detector to quantum limit at } \nu
\end{aligned}$$

n.b: T_{load} tends to be higher and η_{op} lower for MKIDs and TES bolometers due to need for thermal IR blocking

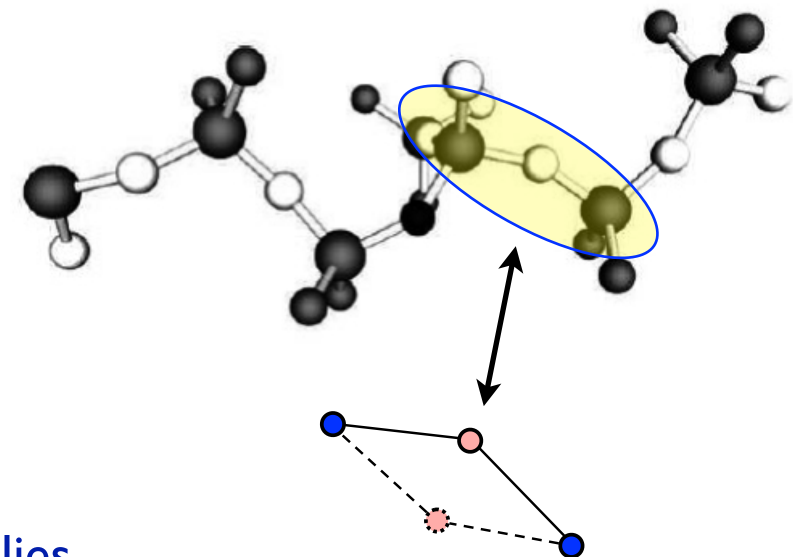
Test Case: 90 GHz Polarimeter at South Pole

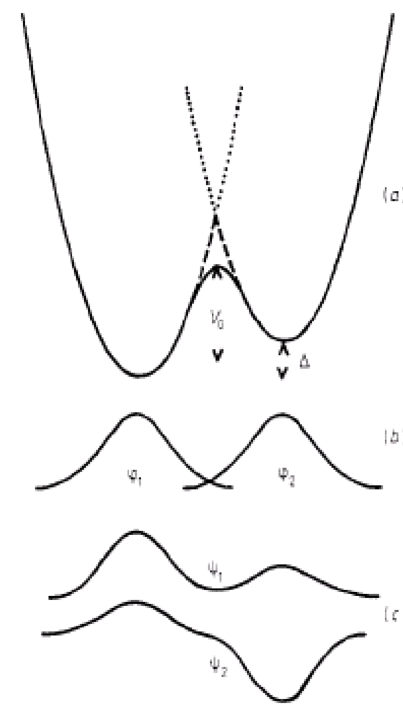
- Assume:
  - ν = 90 GHz → T_Q = 4.3K
  - T_{load} = 10K for coherent, 15K for MKID/bolometer
  - η_{op} = 0.8 for coherent,
    0.4 for MKID/bolometer (achieved w/ 2(*f*/#)λ dual-pol phased-array antennas)
  - T_N = 5K for MKID RF HEMT amplifier
  - χ = 5 achieved, 3 expected → T_{amp} = 22K for χ = 5, 13K for χ = 3
  - T_{bolo} = 0.5K, ΔT_{bolo} = 0.2K, γ = 0.5, safety factor f_S = 5
- Results:
  - *: $\sqrt{2}$ improvement included because Q and U measured with same module
  - technologies are all about the same

detector	NET_{RJ} [μK s$^{1/2}$] (single-pol)						
	shot	Bose	"G" or g-r	readout		**total**	
MKID	85	100	50	diss 260	freq 150	**150**	
TES	85	100	80	N/A		**150**	
coherent	N/A	70		χ=5 110	χ=3 180	**125***	**175***

Two-Level System Noise

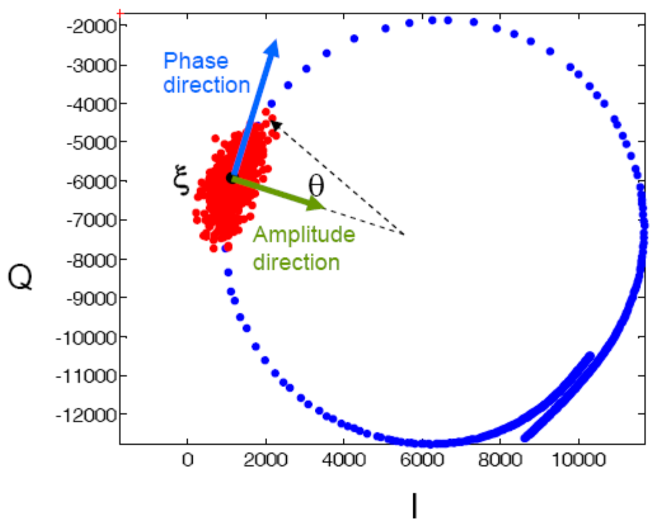
- Amorphous oxides on resonator metal film and bare substrate
- Amorphous materials have large population of "two-level systems"
  - Defect states in materials present opportunity for tunneling between two configurations
  - Theory of two-level systems in NMR applies
- TLS interacts with resonator via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

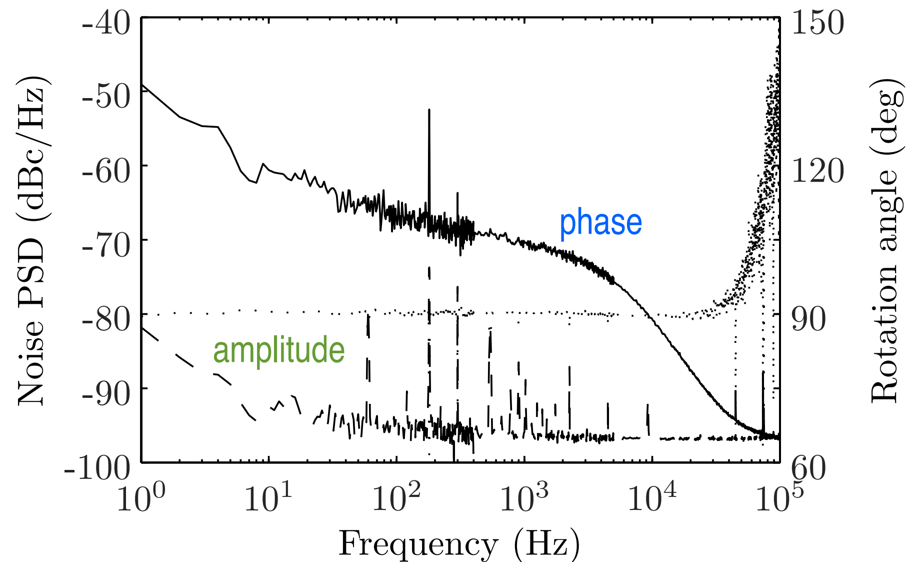




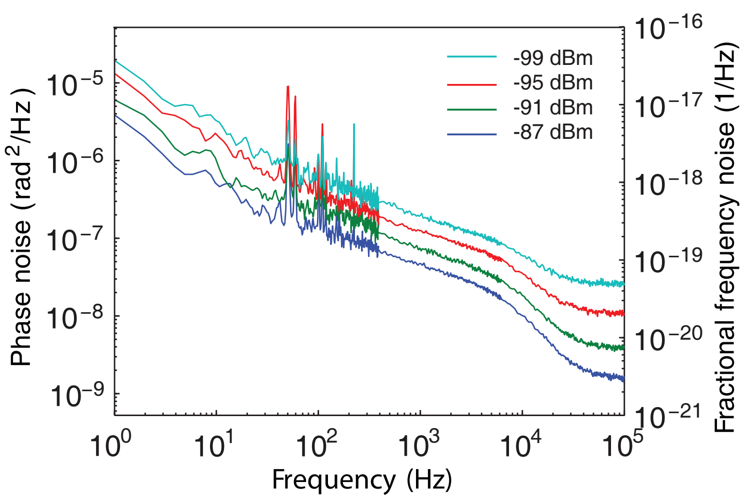
Two-Level System Noise Characteristics

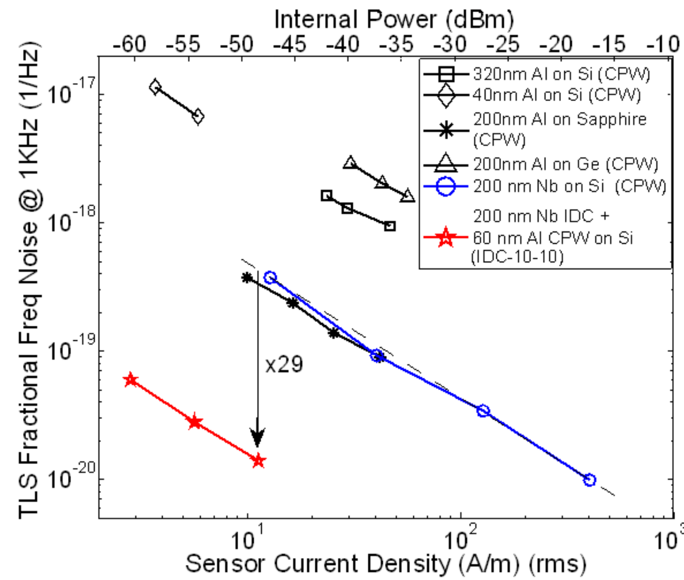
- Noise is only in phase (frequency shift) direction to high precision





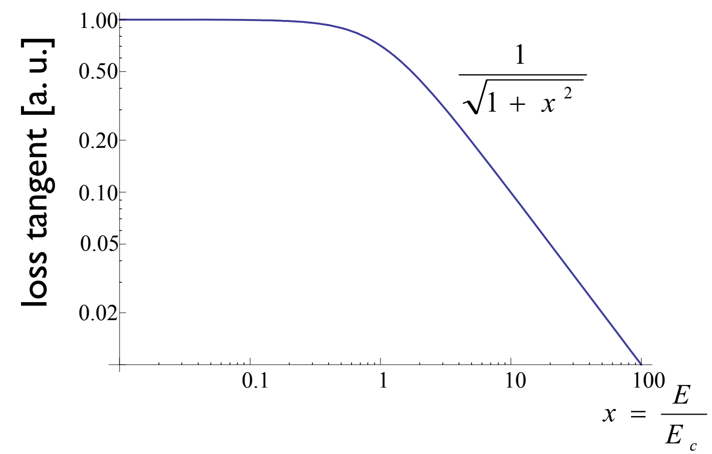
- Noise varies as $f_{audio}^{-1/2}$ and $P_{readout}^{-1/2}$





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 ~ $(1 + |E|/|E_c|)^{-1/2}$
  - Expected behavior of phase noise converted to frequency (it is effectively the f_0 of resonator that is fluctuating)



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

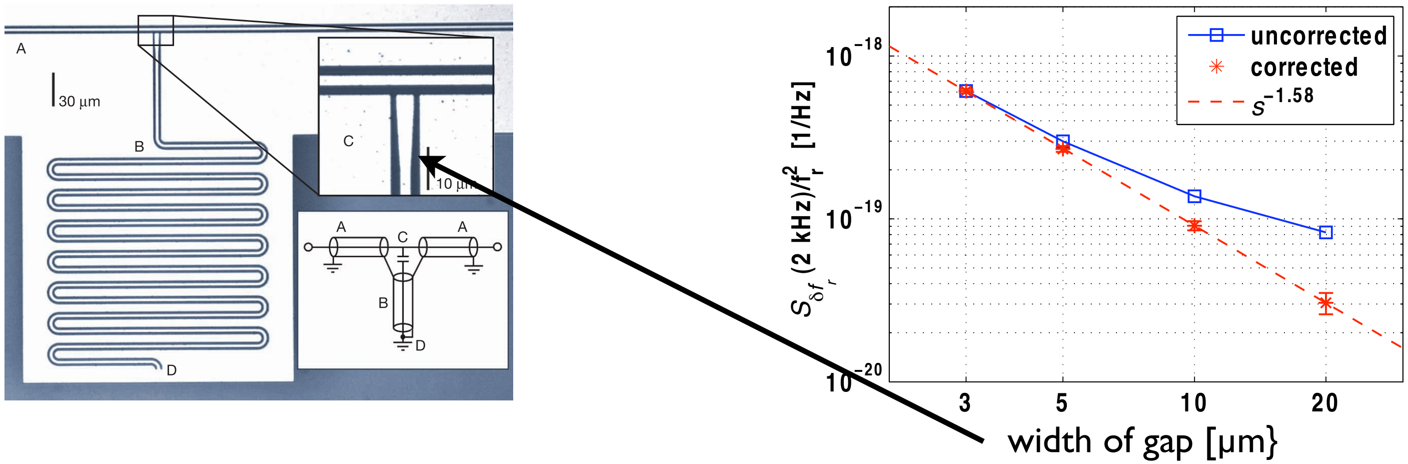
  - Yields

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

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

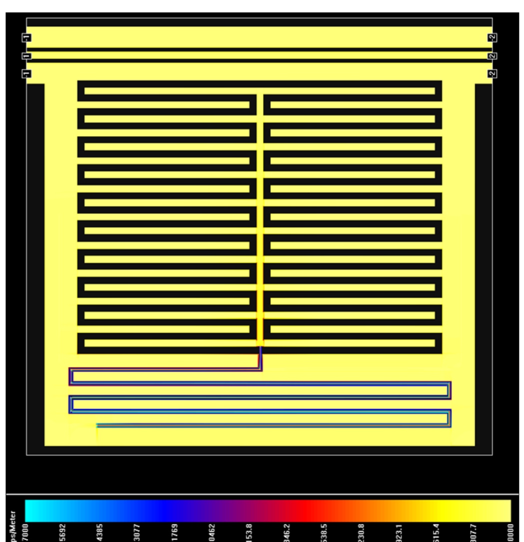
Two-Level System Noise Reduction

- Showed expected behavior with width of resonator



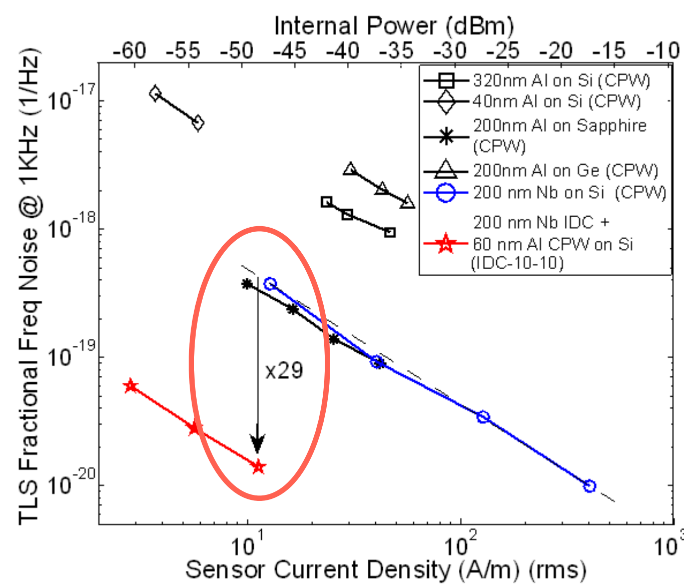
- Change design to make wide capacitive (high |E|) section, keep inductive (high |B|) section

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



current magnitude

remarkable reduction in noise from change in C geometry

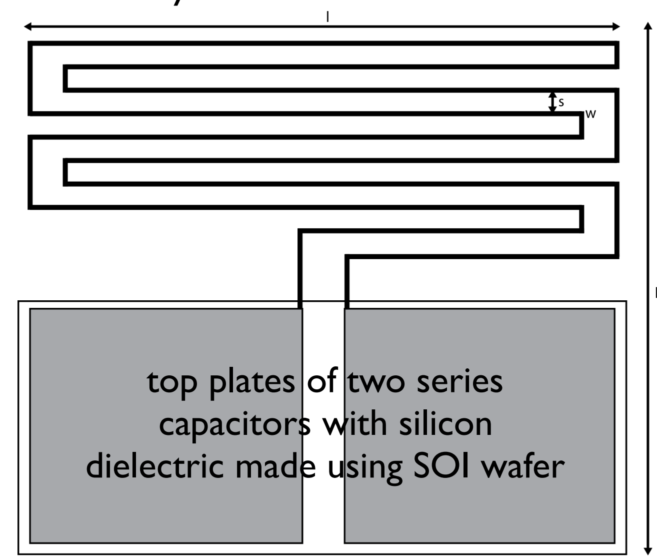


Expectations for Two-Level System Noise

$$\mathrm{NET}_{TLS} = \sqrt{16\,T_{load}^2 S_{\delta f/f}\,\frac{Q_i^2}{r_\kappa^2}} = \sqrt{\frac{2T_{load}\left(8\eta_{op}T_{load}S_{\delta f/f}\Delta\nu\,\frac{Q_i^2}{r_\kappa^2}\right)}{\eta_{op}\Delta\nu}}$$

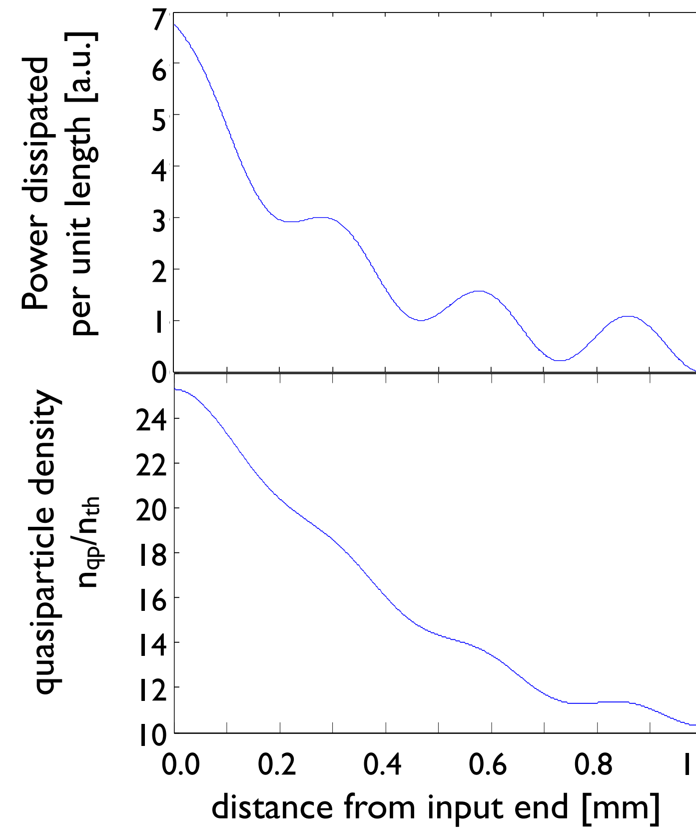
- $S_{\delta f/f} = 3 \times 10^{-19}\ \mathrm{Hz}^{-1}$, $Q_i = 10^4 \rightarrow \mathrm{NET}_{TLS} = 60\ \mu\mathrm{K\ s}^{1/2}$
- In principle, TLS noise has already been reduced to acceptable level!
- And expect continued gains:
  - Have physical theory of TLS noise
  - Expect substantial improvement 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 = 2K)
    - increases r_κ (Mattis-Bardeen)

parallel-plate capacitors,
symmetrized inductor



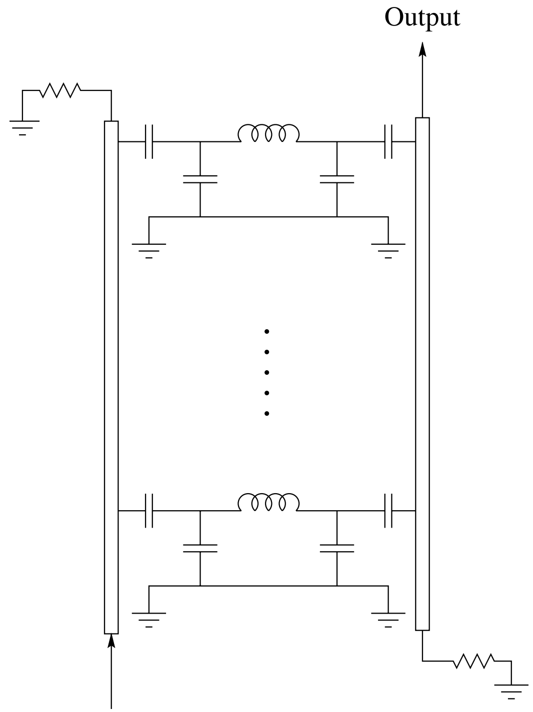
Challenges

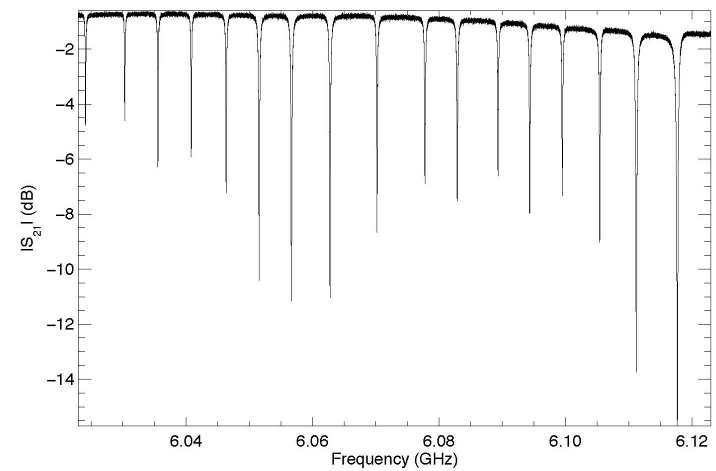
- η_{ph} = 0.57 is an undesirable hit to take
- amplifier noise nonnegligible
- amplifier noise aggravated by nonuniform absorption
  - exponential power profile $\rightarrow$ n_{qp} artificially increased at input end, reduces reponsivity
  - can't reduce length (volume) to compensate, would lose efficiency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



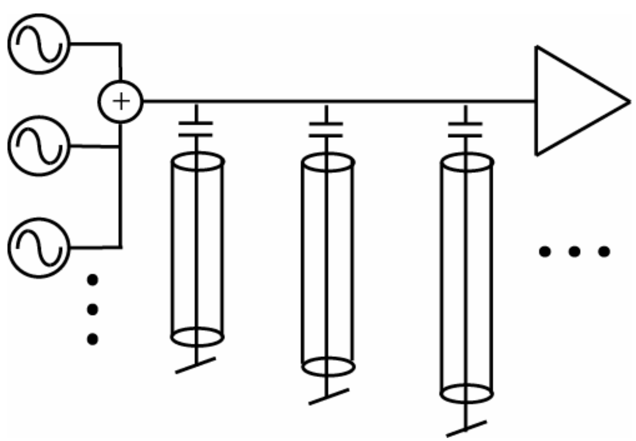
Multiplexing

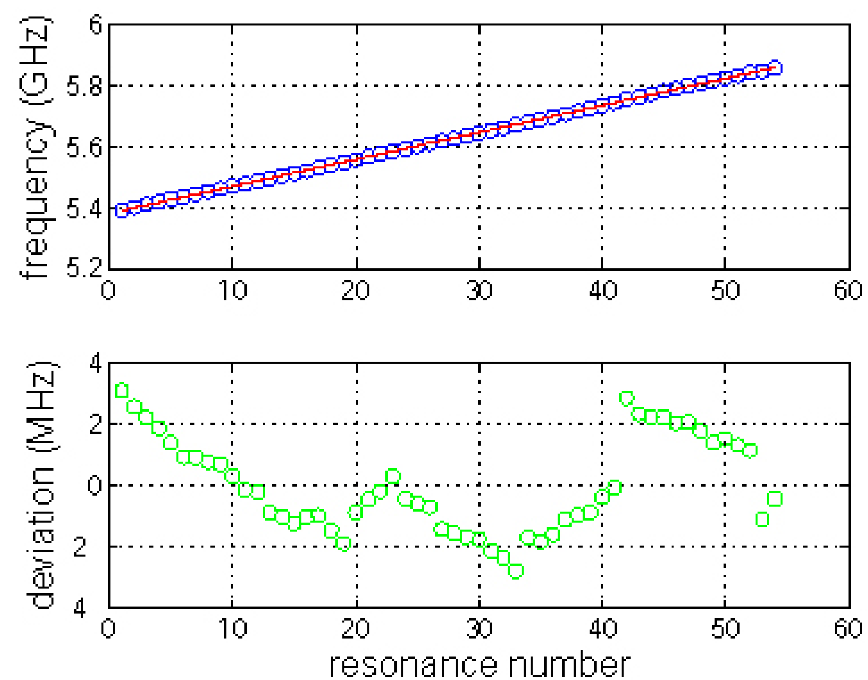
Half-wave through



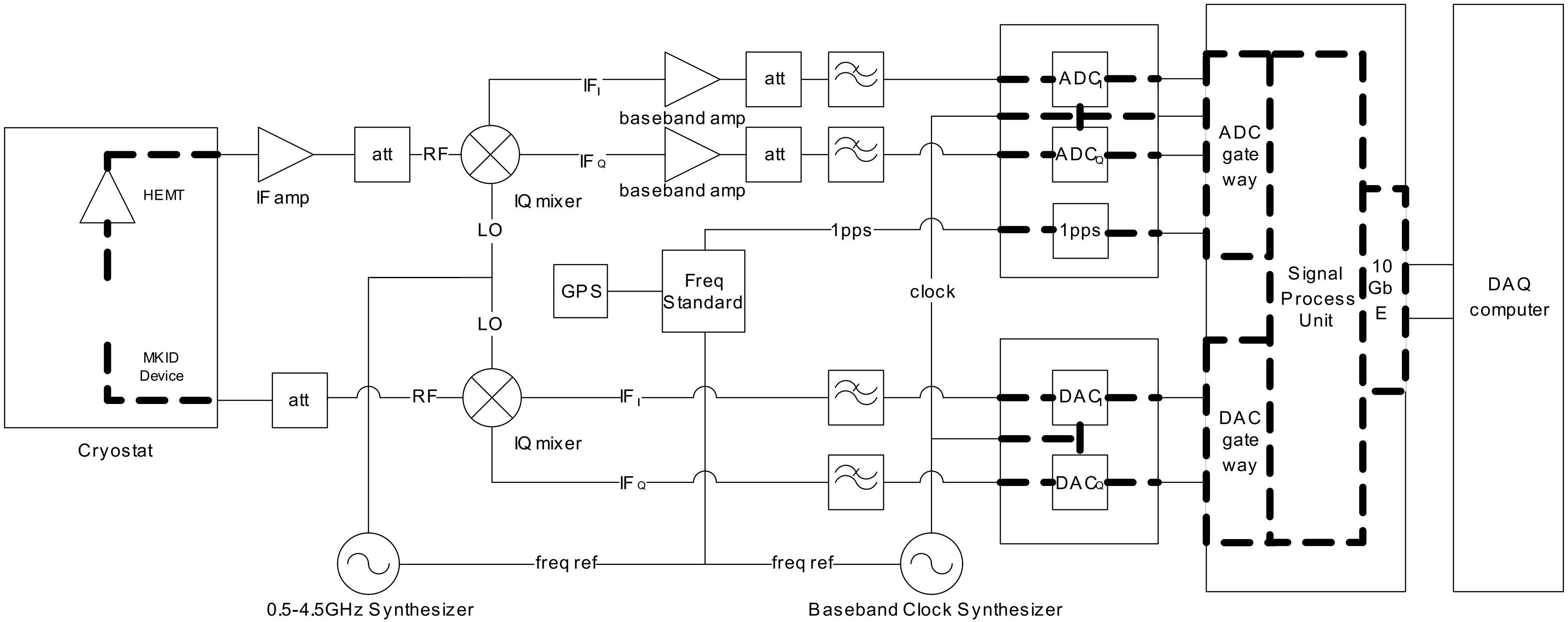


Quarter-wave shunt, lumped-element shunt



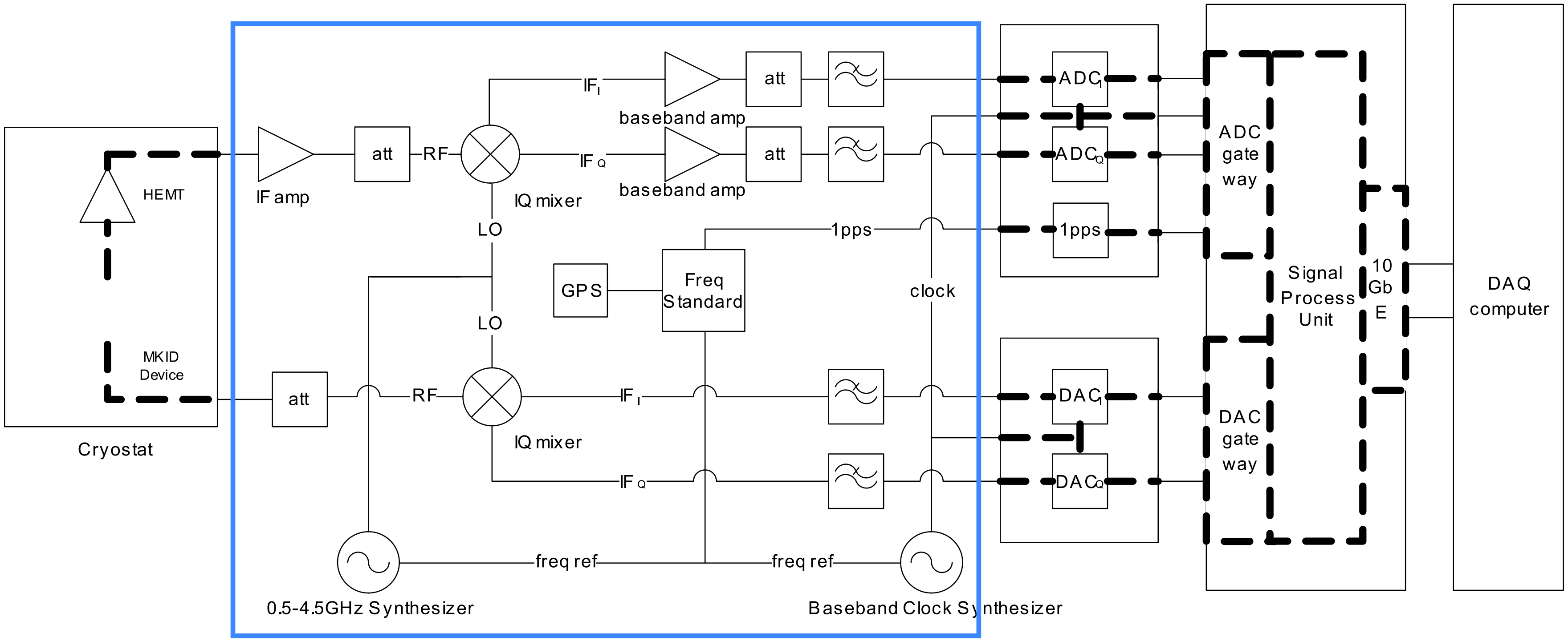


Multiplexed Readout

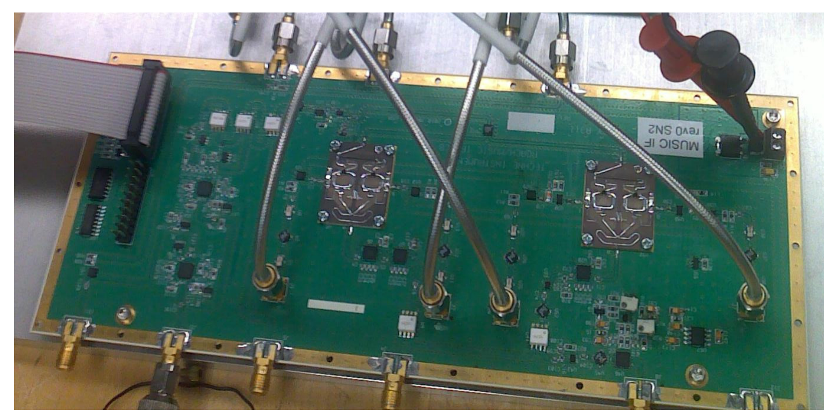


- UCSB/Caltech/JPL have developed digital readout
- Signal generation and demodulation done digitally
- IF system block upconverts from DAC/ADC baseband (0-500 MHz) to resonator RF band (3 GHz)
- Critical issues:
  - ADC SNR: need 12 bits @ 500 MHz to ensure readout does not add noise
  - 1/f performance: for bolometric instruments, need stability down to 0.01-0.1 Hz

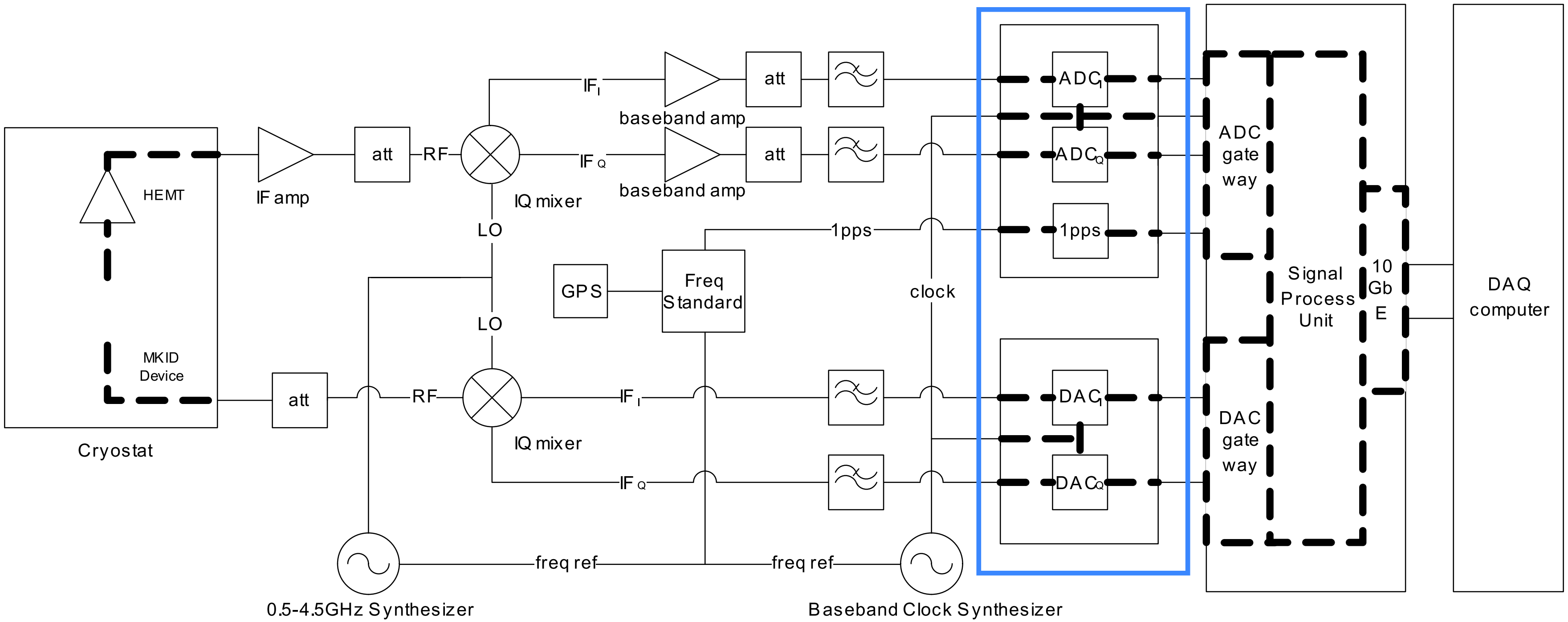
Multiplexed Readout



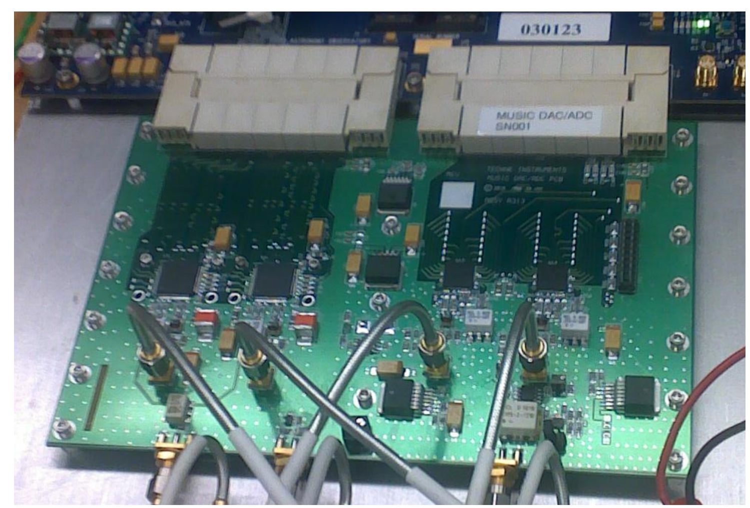
- IF (intermediate frequency) board:
  - Freq synth to generate local osc. locked to GPS-referenced 10 MHz Rb freq standard
  - Analog IQ mixers to upconvert and downconvert w/ double-sideband recovery
  - Anti-alias filtering
  - Gain/atten. to match to DAC/ADC ranges
  - Great care taken with heatsinking for 1/f



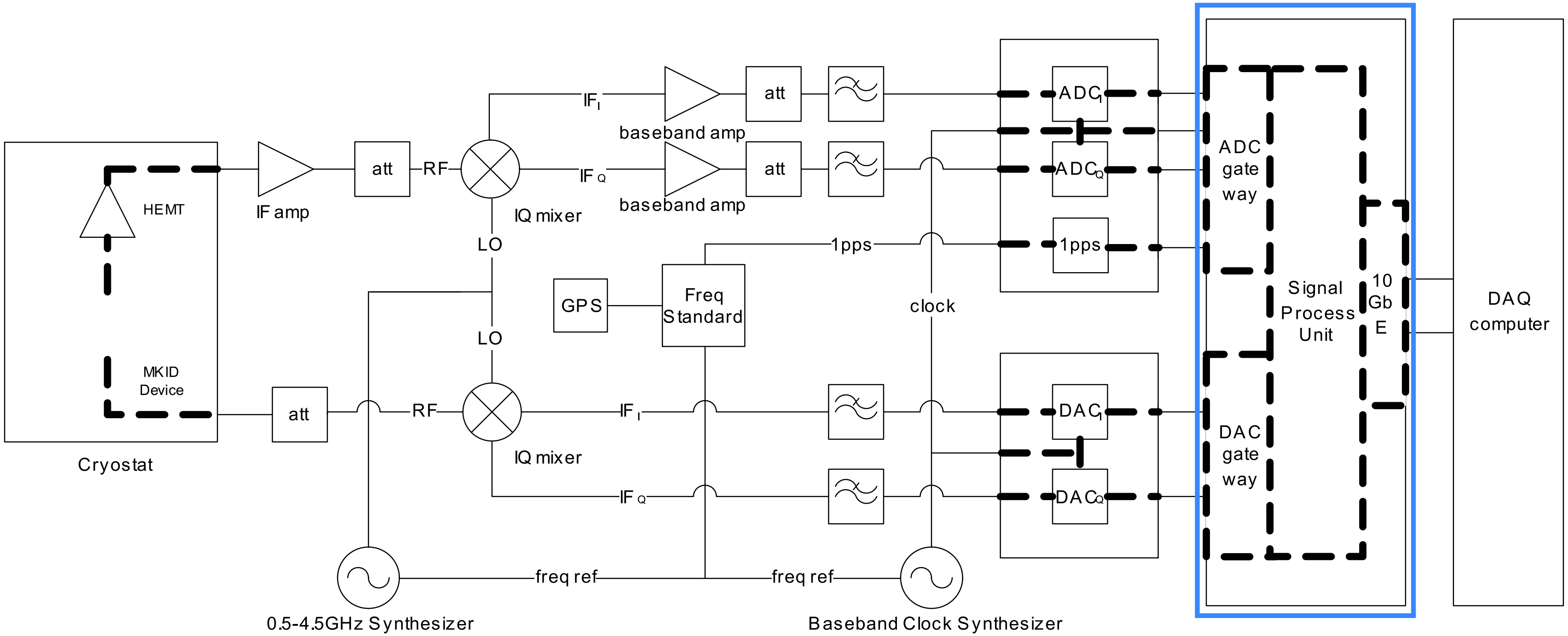
Multiplexed Readout

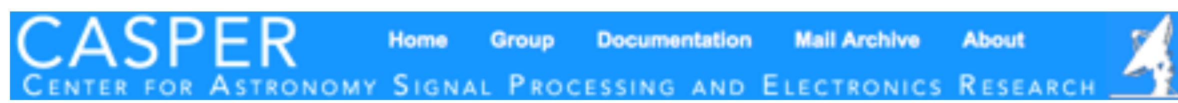


- ADC/DAC board:
  - 12-bit 550 MHz ADC (TI ADS5463)
  - 16-bit 1000 MHz DAC (TI DAC5681)
  - Common voltage reference, extensive heat-sinking to minimize 1/f
  - Mates to ROACH FPGA/PowerPC platform



Multiplexed Readout

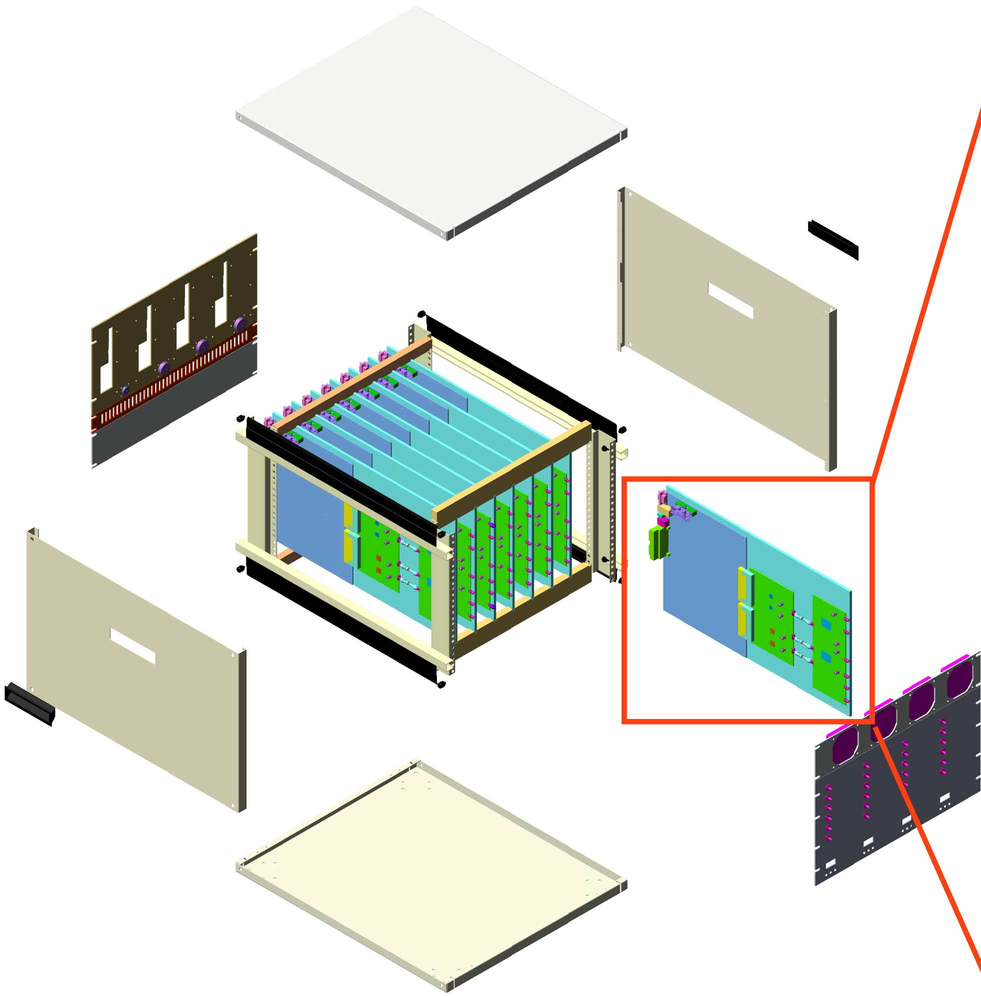


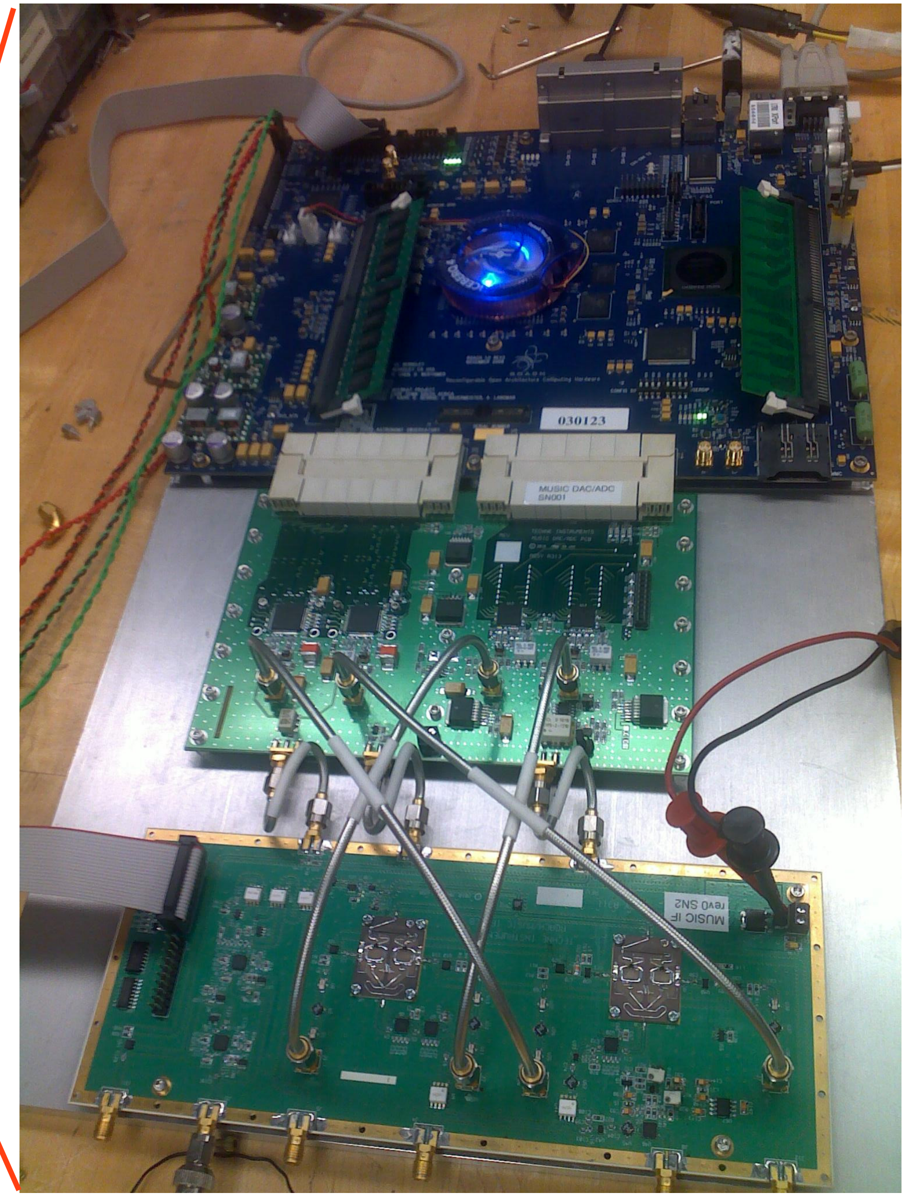


- ROACH board
  - Reconfigurable Open Architecture Computer Hardware (dev'd by CASPER)
  - Xilinx Virtex5 FPGA, Power PC CPU, 1 DDR DRAM + 2 QDR SRAM, 2 Zdok connectors, 10 Gb, 1 Gb, and 100 Mb interfaces
  - Simulink FPGA programming
  - Dev'd 1-stage FFT + FIR filter decimator

Multiplexed Readout

- 8-block crate being developed



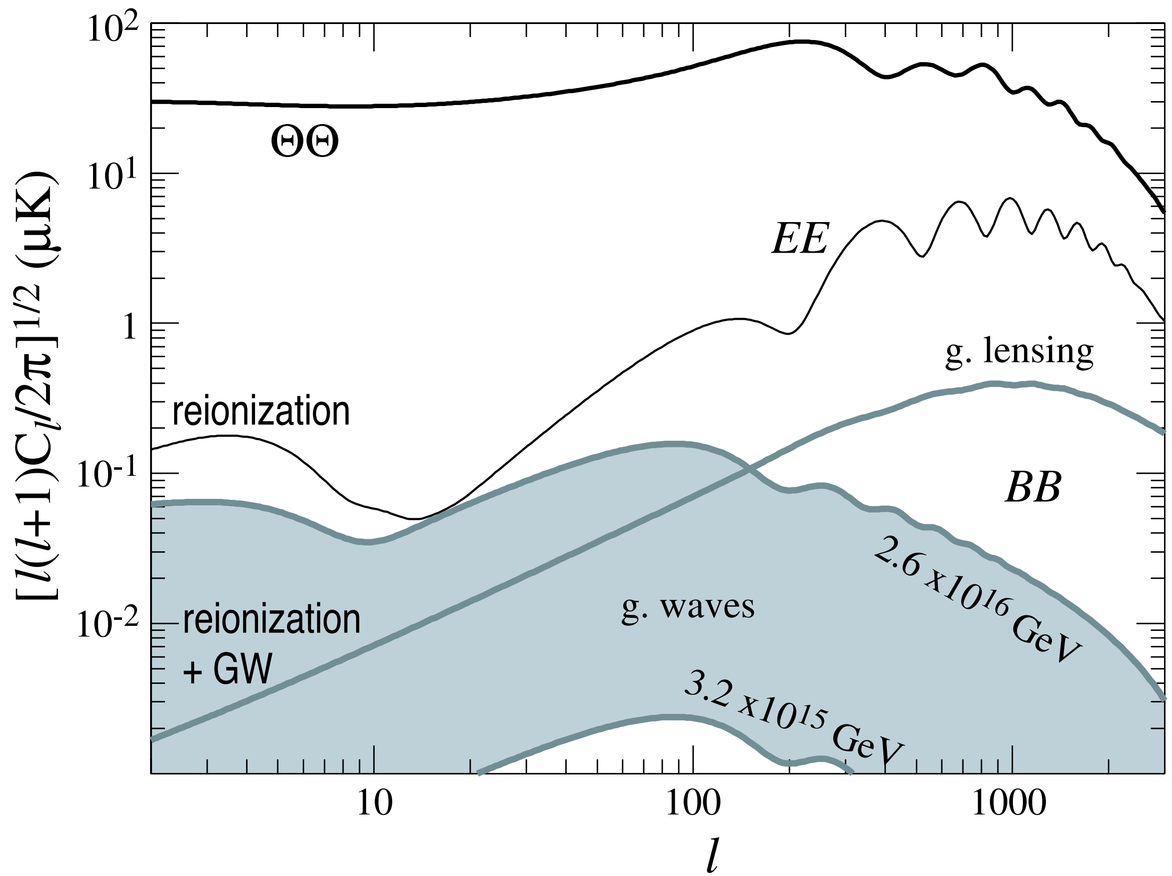


- High-stability PSU for IF, ADC/DAC

Applications

CMB Polarization: Now

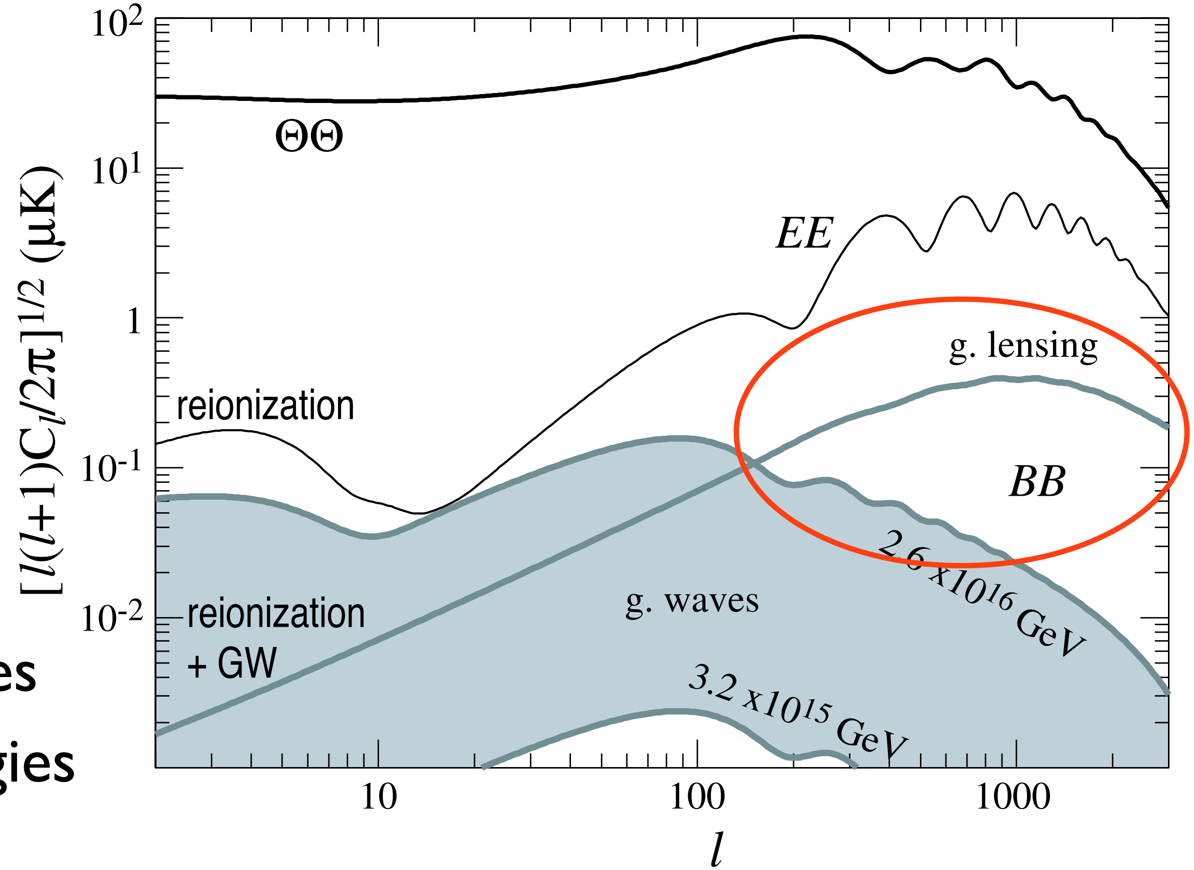
- BICEP2, Keck Array, SPIDER demonstrating very sensitive CMB polarization mapping with antenna-coupled TES arrays
  - PIs: Bock, Kovac, Pryke, Kuo, Jones, Netterfield, Ruhl
  - 256 pixels, 512 TES detectors per cryostat
  - Uses time-domain NIST SQUID mux: 32-channel unit
  - BICEP2: in the field 18 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-1'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



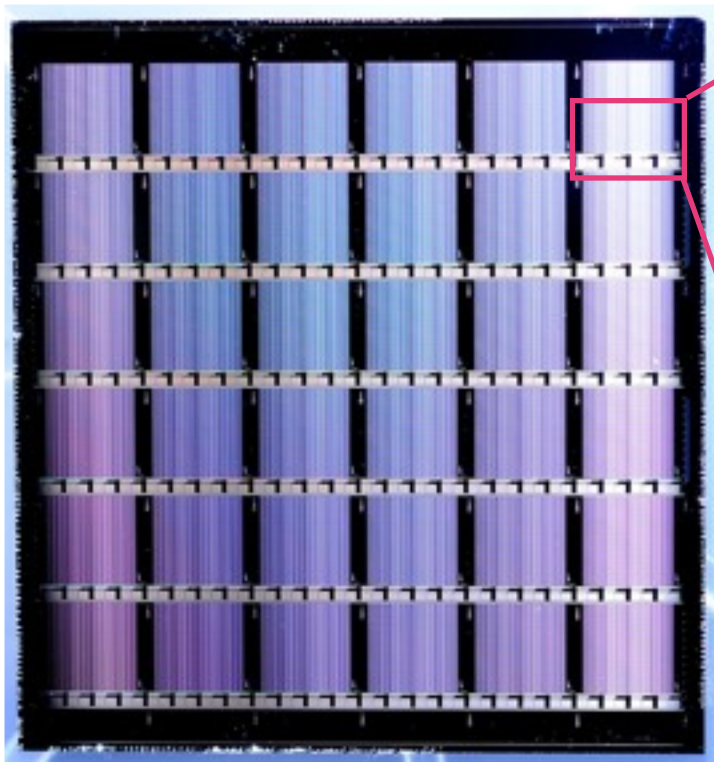
- Can the existing technologies meet the challenge?
  - Standard multiplexing of TES arrays seems challenging, though perhaps brute-force doable: O(50-100) crates, O(1000) multiplex units
  - New TES multiplexing schemes being developed based on RF multiplexing a la MKIDs, though more complicated
  - MKIDs present a viable alternative that already meets the multiplexing challenge and can in principle provide requisite sensitivity.

MUSIC: MUlticolor Sub/millimeter Inductance Camera

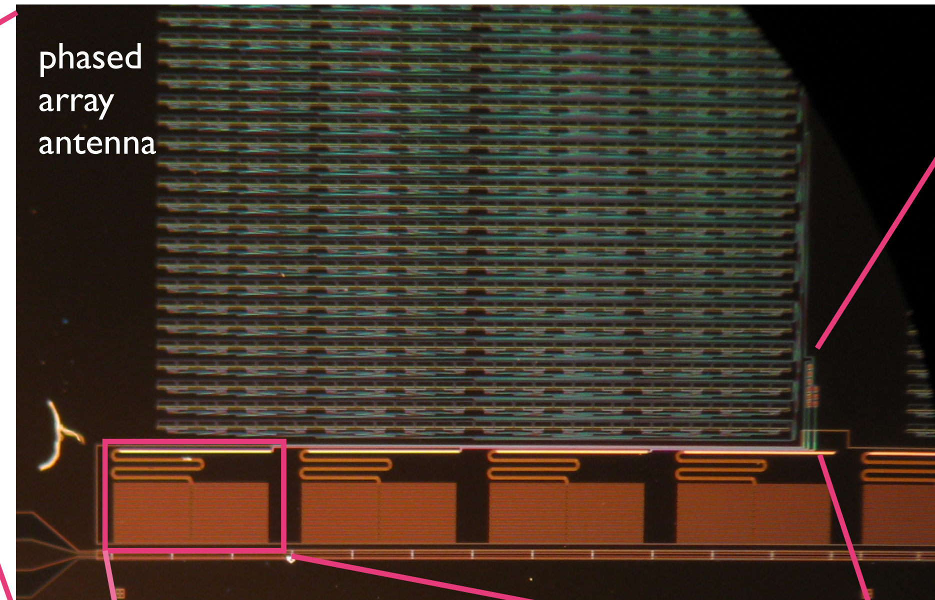
- New technologies enable ~background-limited, multi-color camera (850 μm - 2 mm) with wide FOV (14', 600 spatial pixels)
  - Planar photolithographic phased-array antennas: large-format arrays on a single wafer, ~octave instantaneous bandwidth
  - Planar photolithographic bandpass filters: many colors 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

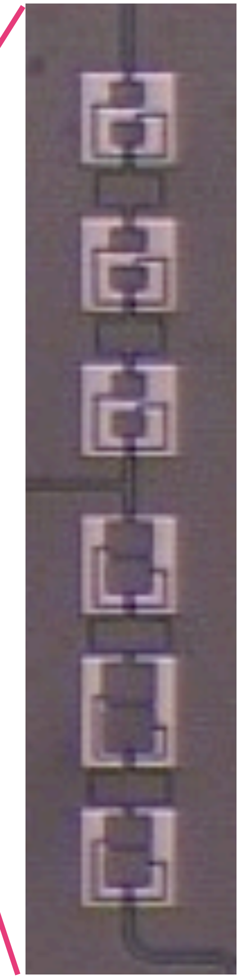
Multicolor Antenna-Coupled MKIDs

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

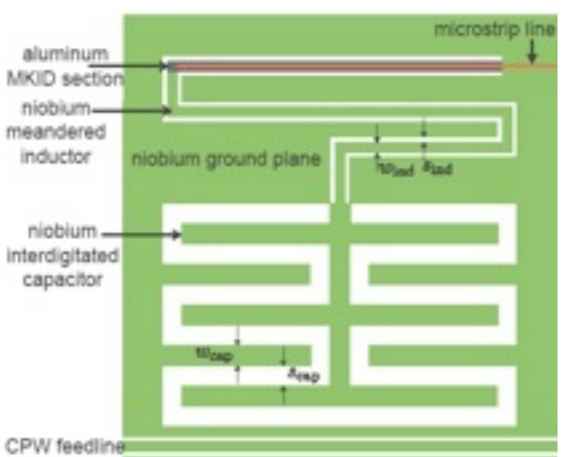


single pixel

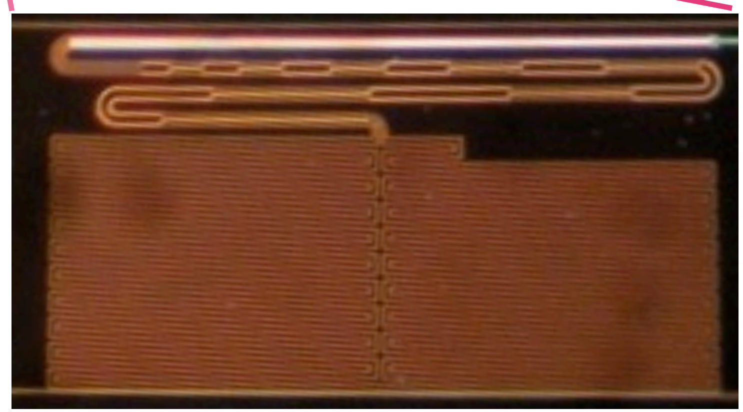




bandpass filters
(2 colors)



MKIDs
(four,
one per color)

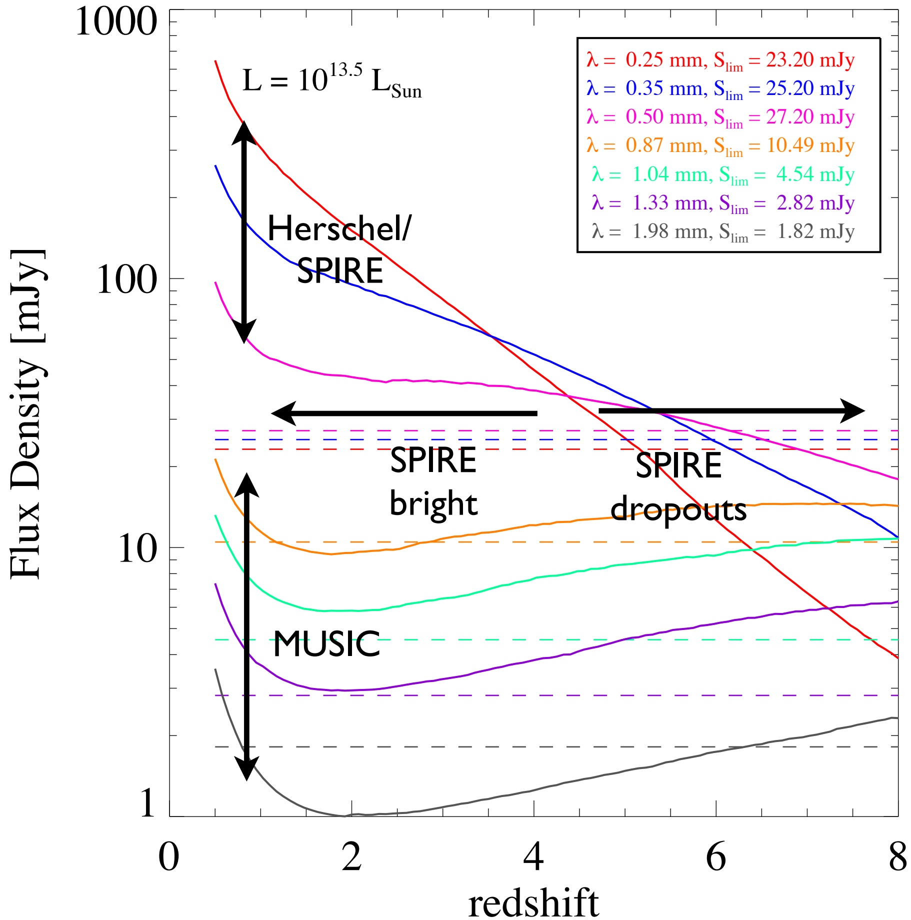


Detector development funded by JPL RTD,
NASA APRA, Moore Foundation

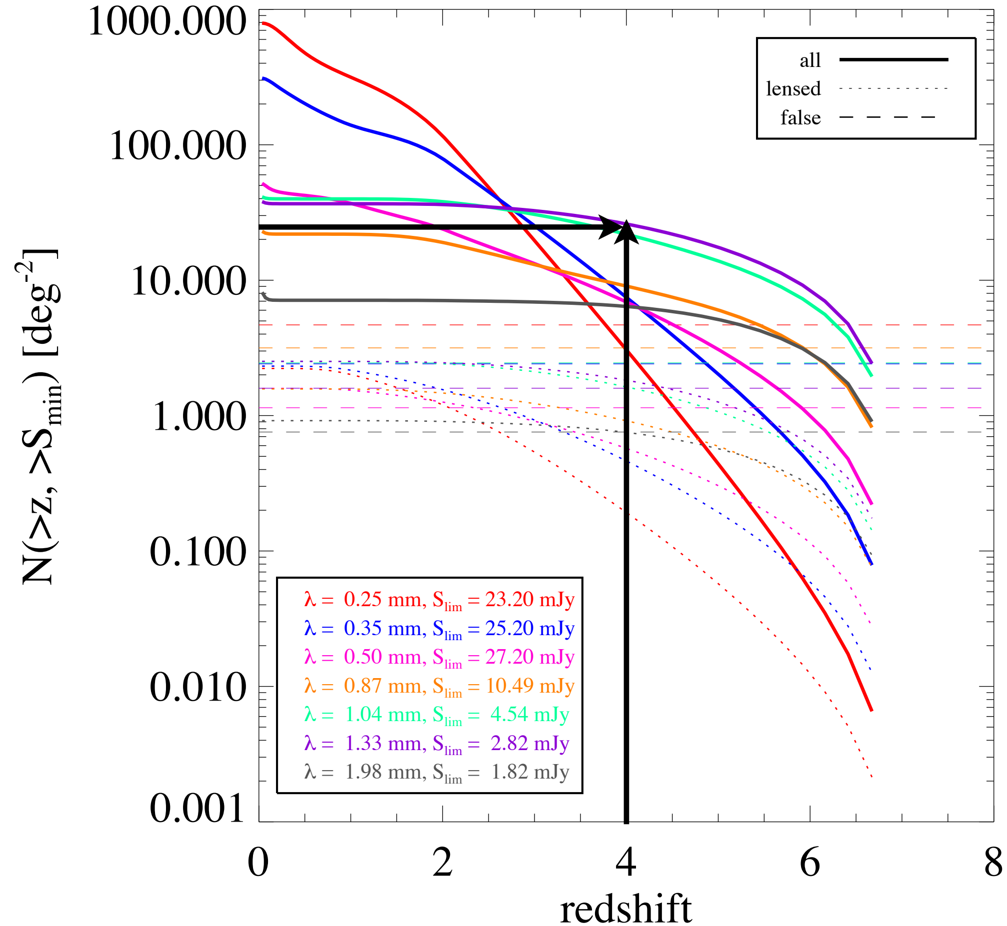
MUSIC 15 deg² Wide-Field Survey

- 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_{Sun} SMG



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

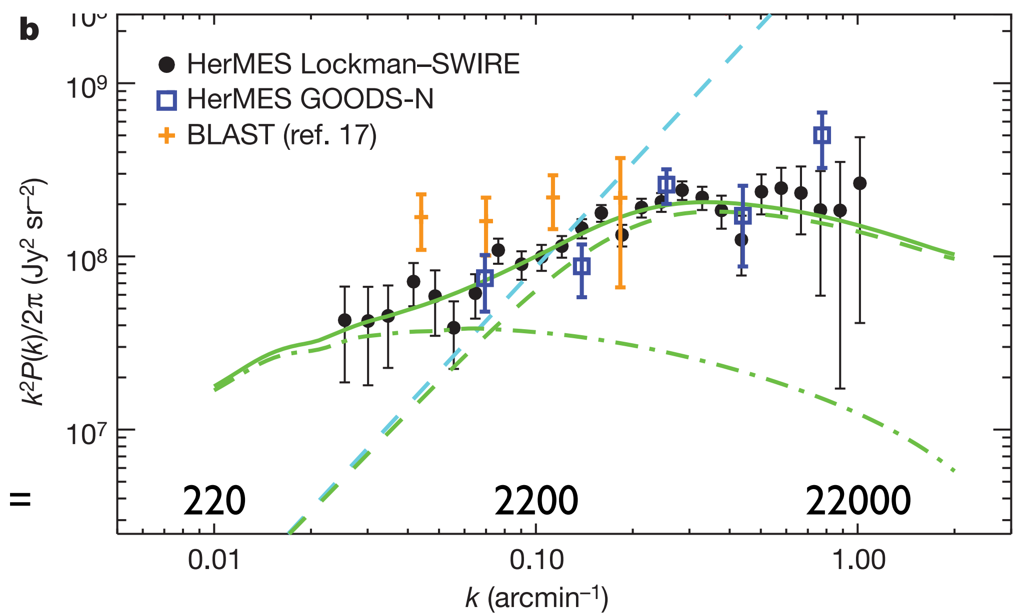


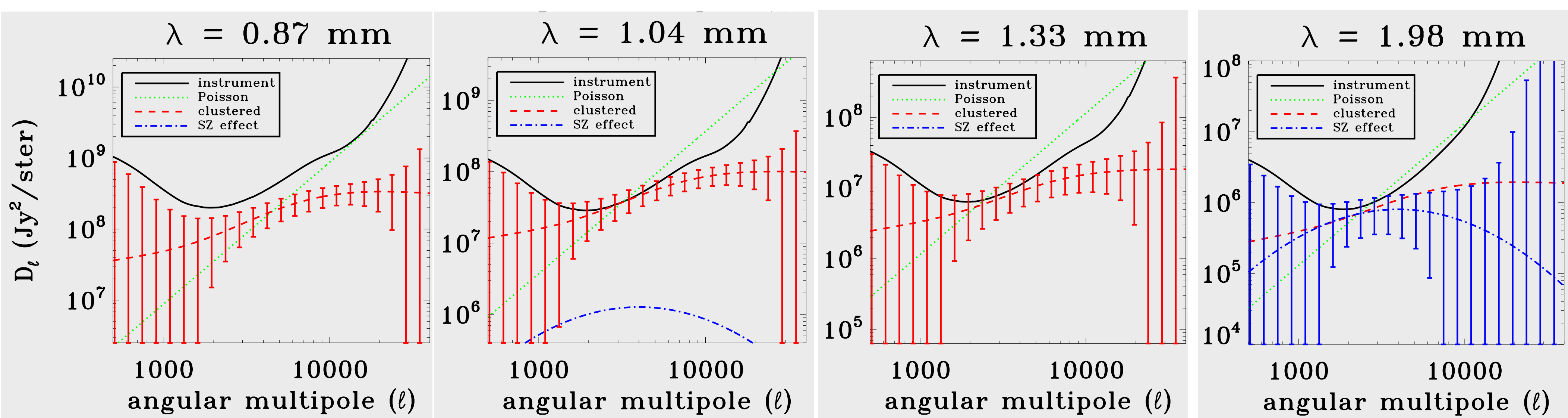
Calculations based on Bethermin et al 2010 models

MUSIC 15 deg^2 Wide-Field Survey

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)

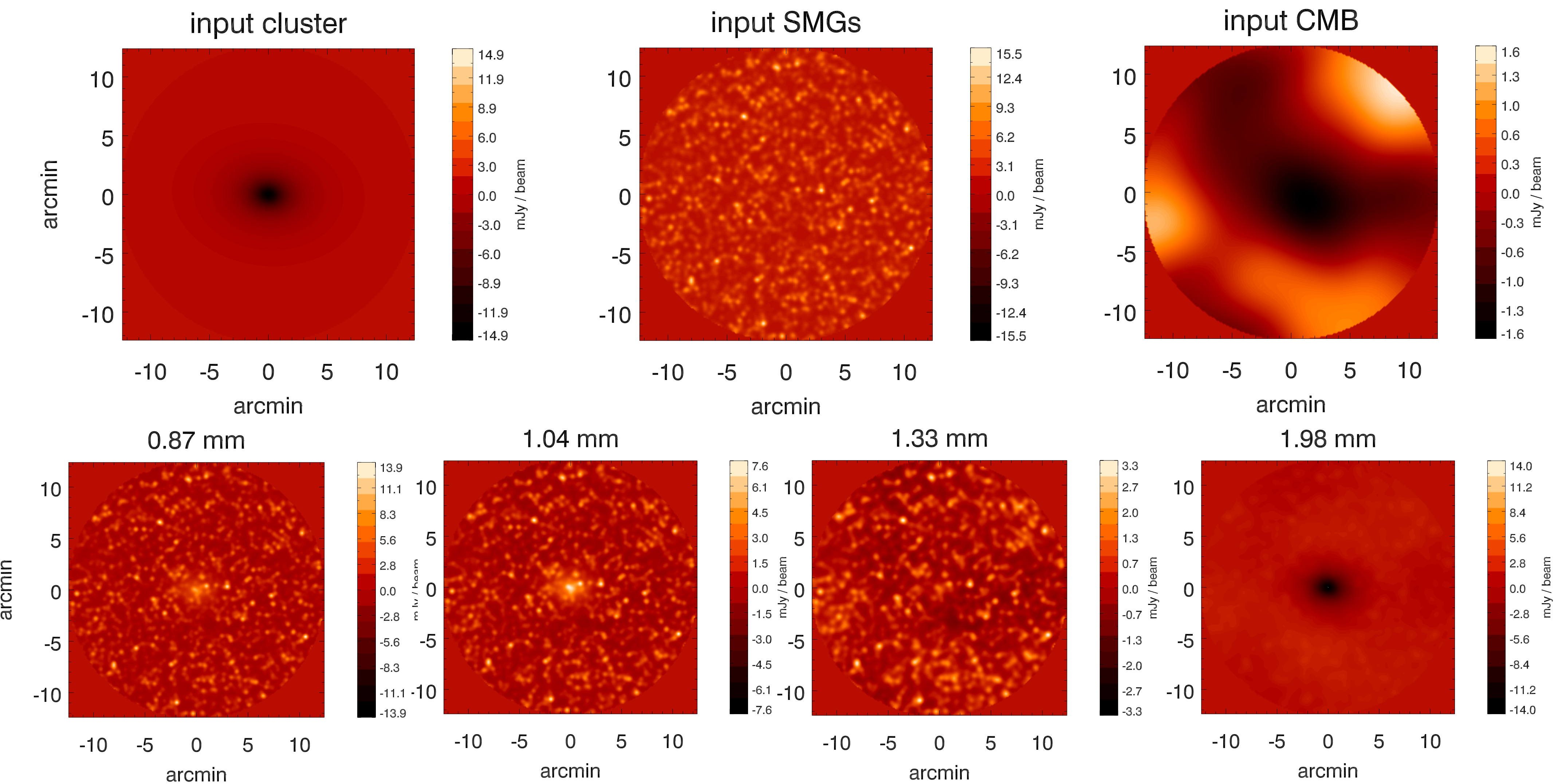
- Goal 2: Study clustering as a function of wavelength
  - Clustering at different wavelengths provides (coarse) way to study evolution of clustering with z.
  - Clustering well-studied at 250, 350, 500 μm w/SPIRE, can push to z > 4 with MUSIC.
  - MUSIC primarily sensitive to 1-halo term, may be able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





MUSIC Galaxy Cluster Studies

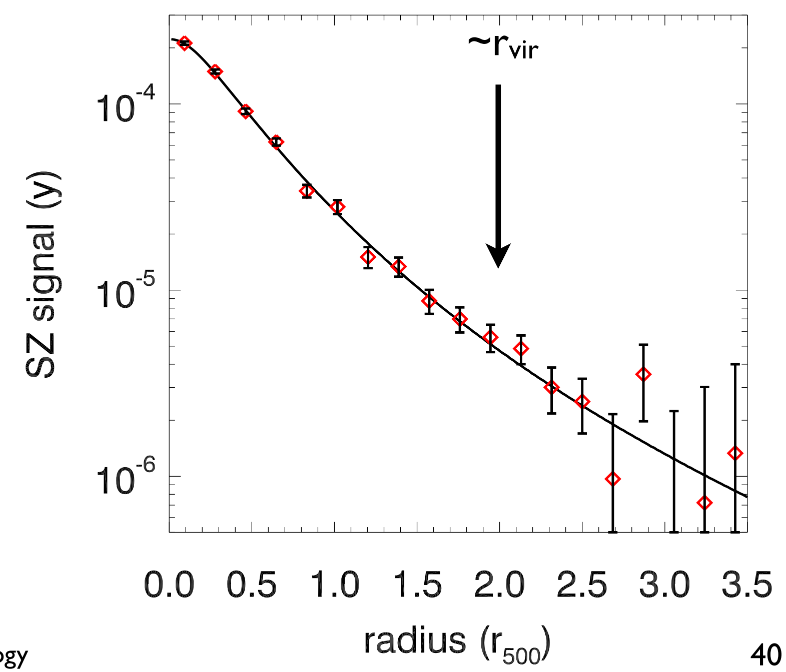
- Study galaxy clusters across wavelength regime where SZ gives way to DSFGs; separate SZ, CMB, and DSFGs using multi-wavelength information.



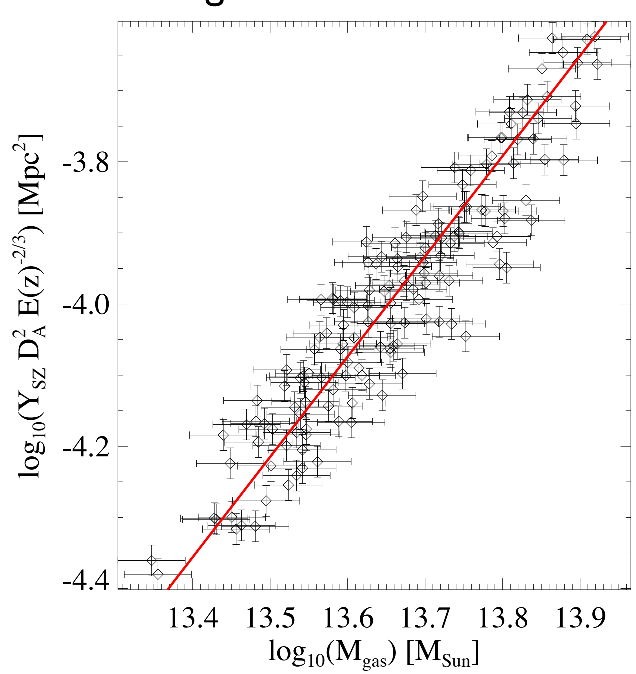
MUSIC Galaxy Cluster Studies

- 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

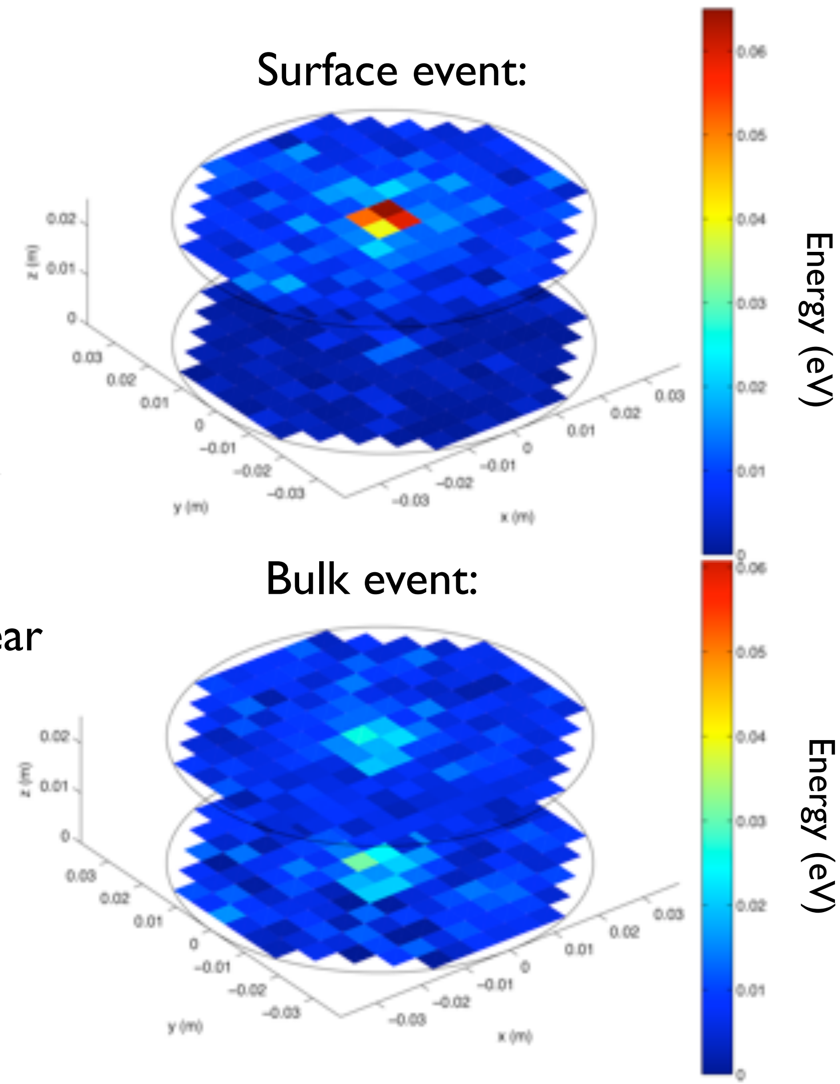


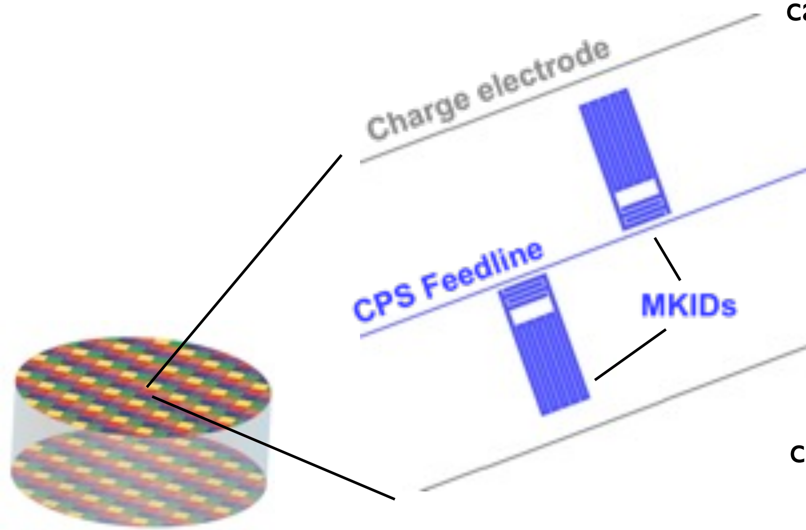
scaling relation determination

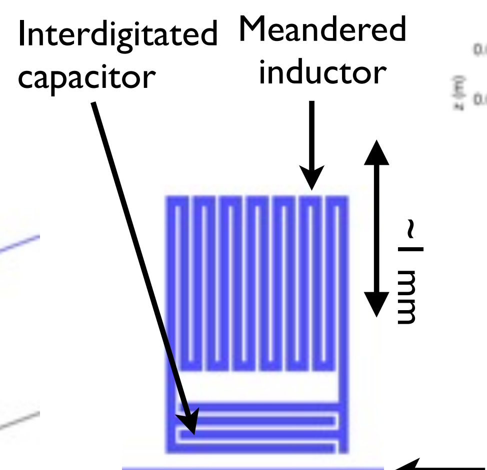


Phonon Detection Using MKIDs

- 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





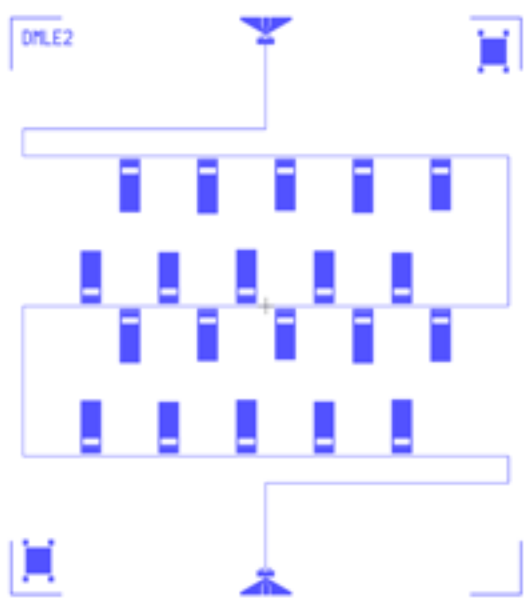


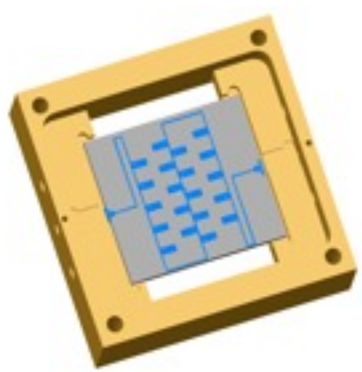
coplanar stripline (CPS) feedline to excite/probe resonator

Figures by D. Moore

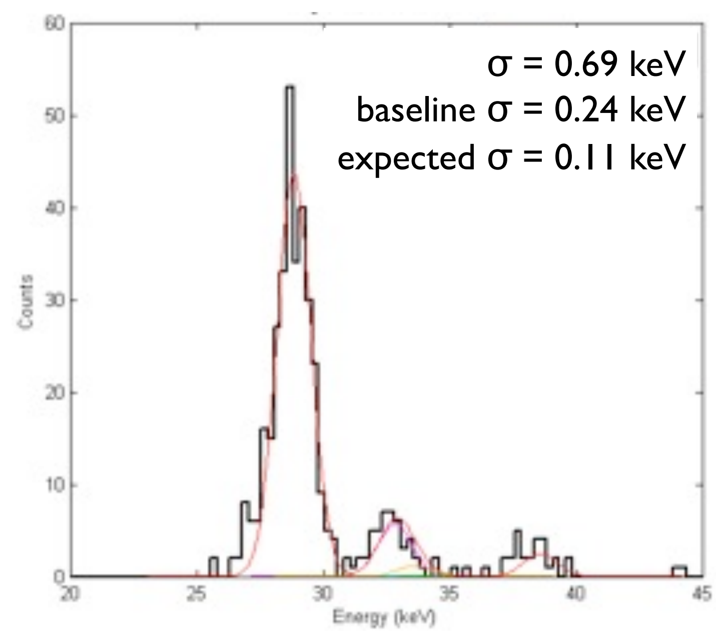
Progress to Date

- 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 Tc = 0.5-1K devices
- Need to better control phonon losses to box highly variable decay times observed (10 μs to 100 μs)





collimated source incident on bottom side of silicon wafer



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