MKIDS: Prospects for the far-IR

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- Colorado
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- UCSB
  - Sean McHugh, Ben Mazin & group
- NIST
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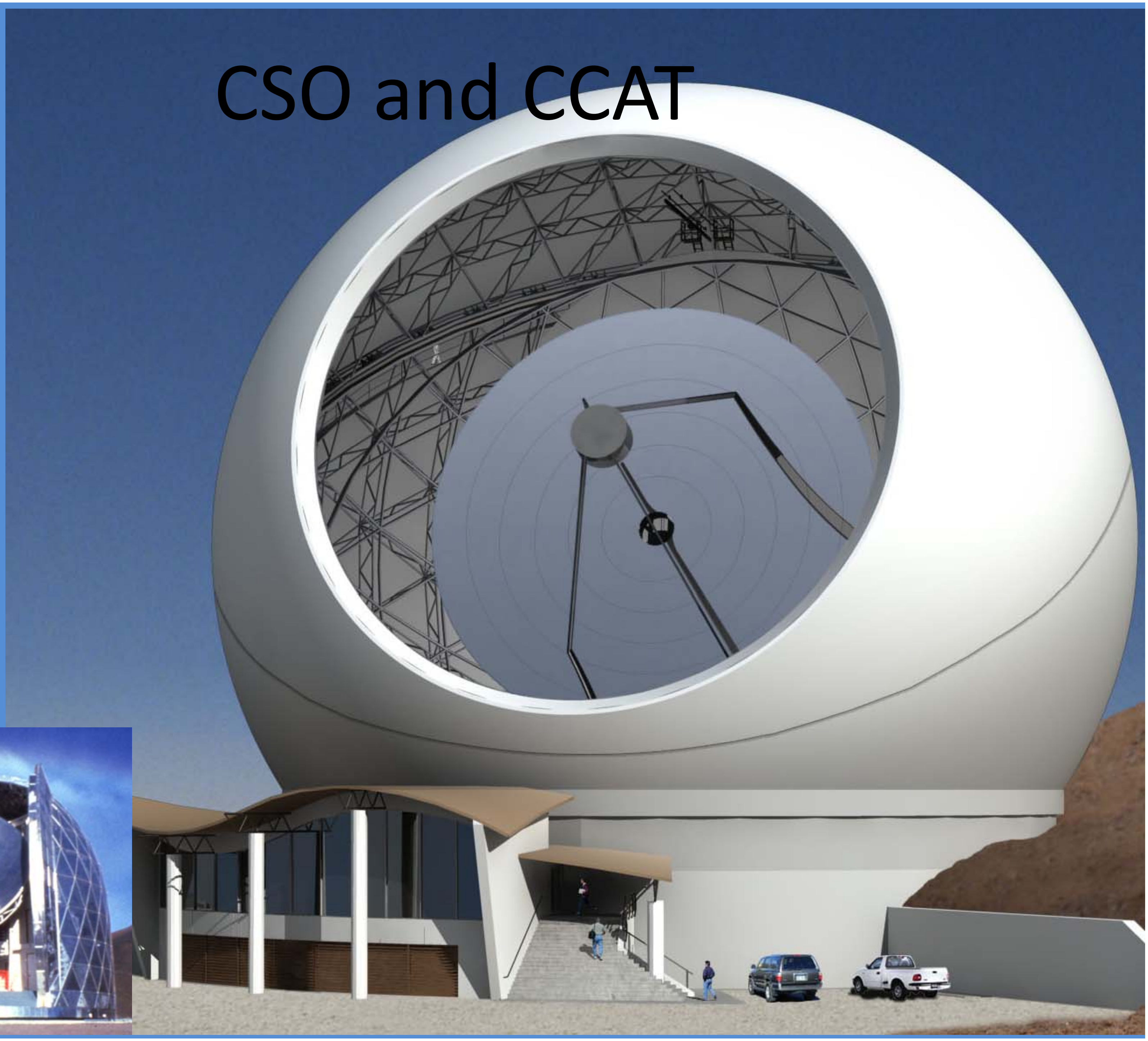
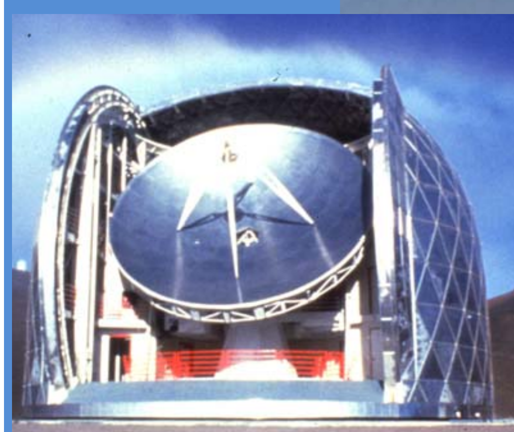
+ collaborators

CSO and CCAT





1961: STJ detector proposed

VOLUME 6, NUMBER 3 PHYSICAL REVIEW LETTERS FEBRUARY 1, 1961

SUPERCONDUCTORS AS QUANTUM DETECTORS FOR MICROWAVE AND SUB-MILLIMETER-WAVE RADIATION*

E. Burstein, D. N. Langenberg, and B. N. Taylor
University of Pennsylvania, Philadelphia, Pennsylvania
(Received January 6, 1961)

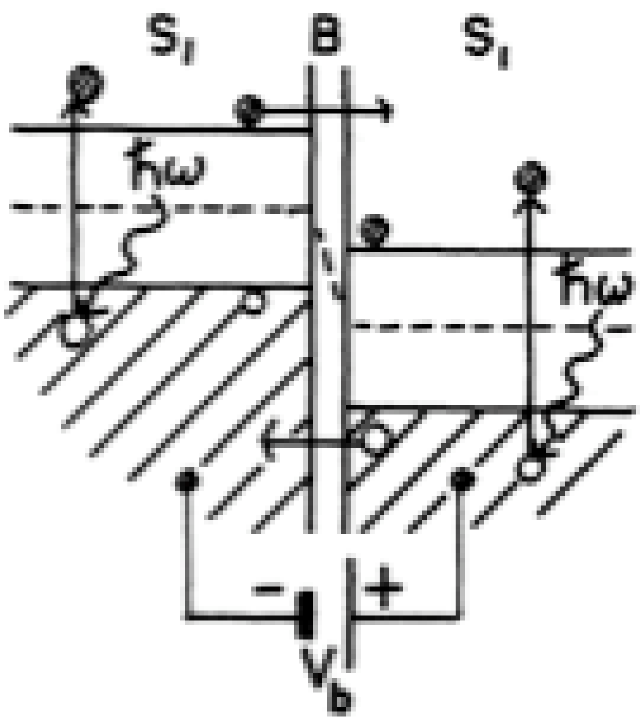


FIG. 1. (a) Quasi-particle energy band diagrams for an $M|B|S$ structure and an $S_1|B|S_2$ structure in which the two superconductors are the same. (b) Tunnelling of optically excited carriers in $M|B|S$ and $S_1|B|S_1$ structures under "low bias voltage" conditions.

1958: Mattis & Bardeen

PHYSICAL REVIEW VOLUME 111, NUMBER 2 JULY 15, 1958

Theory of the Anomalous Skin Effect in Normal and Superconducting Metals*

D. C. MATTIS† AND J. BARDEEN
Department of Physics, University of Illinois, Urbana, Illinois
(Received February 24, 1958)

Expressions for σ_1 and σ_2 are

$$\frac{\sigma_1}{\sigma_N}=\frac{2}{\hbar\omega}\int_{\epsilon_0}^{\infty}[f(E)-f(E+\hbar\omega)]g(E)dE$$

$$+\frac{1}{\hbar\omega}\int_{\epsilon_0-\hbar\omega}^{-\epsilon_0}[1-2f(E+\hbar\omega)]g(E)dE,$$

$$\frac{\sigma_2}{\sigma_N}=\frac{1}{\hbar\omega}\int_{\epsilon_0-\hbar\omega,\,-\epsilon_0}^{\epsilon_0}\frac{[1-2f(E+\hbar\omega)](E^2+\epsilon_0^2+\hbar\omega E)}{(\epsilon_0^2-E^2)^{\frac{1}{2}}[(E+\hbar\omega)^2-\epsilon_0^2]^{\frac{1}{2}}}$$

absorption

emission

Pair breaking

Kinetic inductance

$\epsilon_0 = \Delta$

$$\frac{\sigma_2}{\sigma_n}\approx\frac{\pi\Delta}{\hbar\omega}$$

$$g(E)=\frac{E^2+\Delta^2+\hbar\omega E}{\sqrt{E^2-\Delta^2}\sqrt{(E+\hbar\omega)^2-\Delta^2}}$$

$$\delta\sigma_1 - j\delta\sigma_2 \propto \delta f(E)$$

Implementation ?

Brief History

- 1987: McDonald (NIST; APL 50, 775)
  - kinetic inductance thermometer near T_c with a SQUID readout for bolometry
- 1992: Bluzer et al (Westinghouse; PRB 46, 1033)
  - electron relaxation in Nb (normal & superconducting) with laser pulses
- 1995: Bluzer proposes “QSKIP”
  - IR kinetic inductance detector, YBCO, with SQUID readout
  - Operating at $T \ll T_c$
- 1995: Gulian & Van Vechten (APL 67,2560)
  - microwave dissipation readout (see next slide)
- 1996: Sergeev & Reizer (IJMP B 10, 635)
  - “*Our calculations show that due to the exponentially small quasiparticle heat capacity and exponentially large recombination time, the low-temperature kinetic inductance response of ordinary superconductors is very promising for applications in sensitive detectors*.”

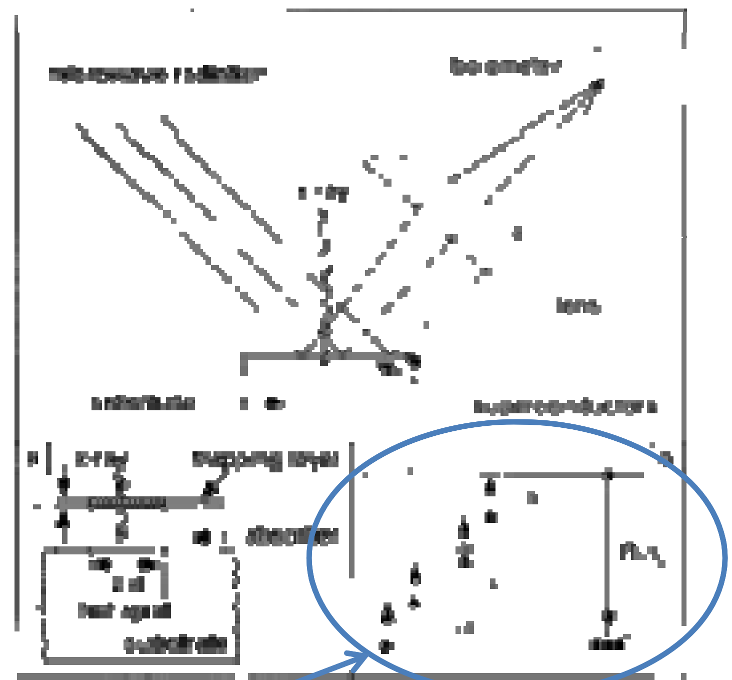
1995: Microwave dissipation readout

Nonequilibrium dynamic conductivity of superconductors: An exploitable basis for high-energy resolution x-ray detectors

A. M. Gulian

D. Van Vechten

[2]. Thus the response of the dynamic conductivity of a superconducting film to the passage of high-energy particles is basically the same as the response of the tunnel current in a nonequilibrium tunnel junction. Whether this response can be used as the basis of a detector is thus dependent on finding an experimental method of registration in which the change in the dynamic conductivity has sufficient accuracy.



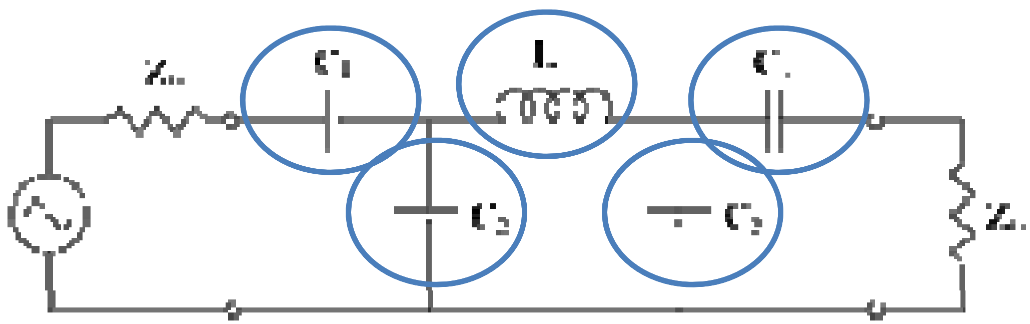
Quasiparticle generation by microwaves

1999: First MKID proposal

Proposal to JPL Director's Research and Development Fund - FY'00

A Novel Superconducting Detector and Multiplexed Readout Concept

September 16, 1999



Q_i - internal Q

Q_c - coupling Q

Q_r - resonator Q

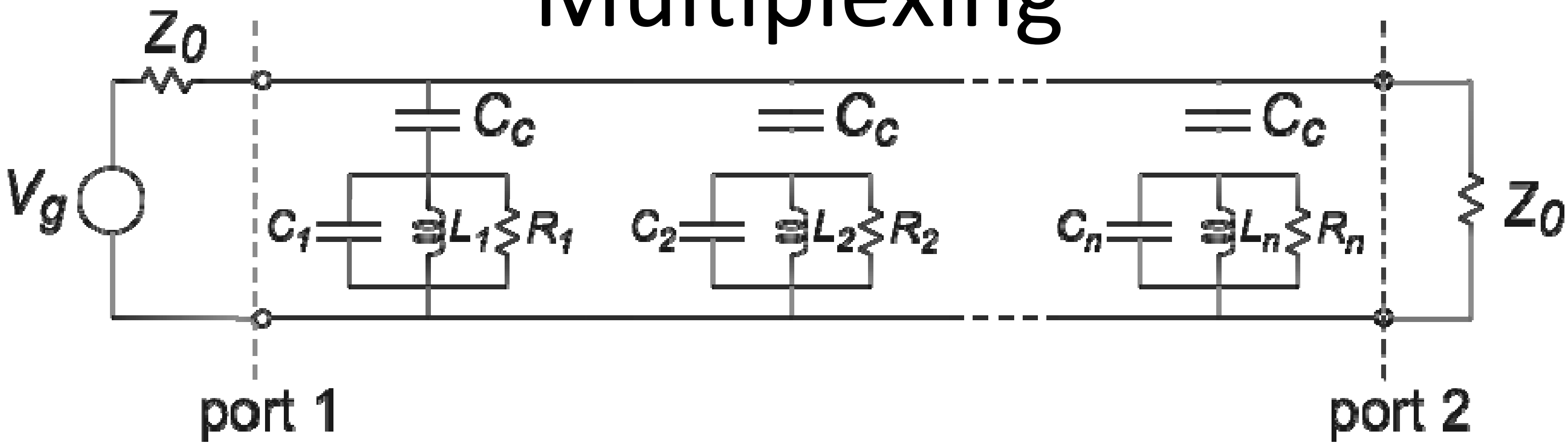
$$\frac{1}{Q_r} = \frac{1}{Q_i} - \frac{1}{Q_c}$$

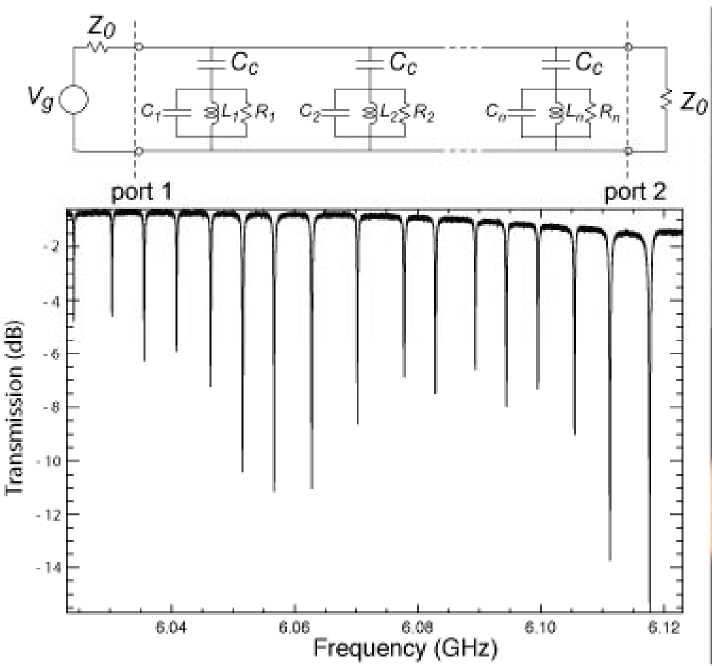
Figure 2: A possible circuit design of a microwave kinetic inductance detector. Here L represents the total inductance of the detector element, which is the sum of the magnetic and kinetic inductances $L = L_{mag} + L_{kin}$. The capacitors C_2 are chosen according to the desired resonant frequency $\omega_0 = 1/\sqrt{2LC_2}$. The coupling capacitors $C_1 = C_1$ determine the loading of the resonator by the source and load, and therefore the maximum possible quality factor Q. The source and load are the microwave generator and HEMT amplifier, respectively, and for simplicity are assumed to have a common impedance Z_0.

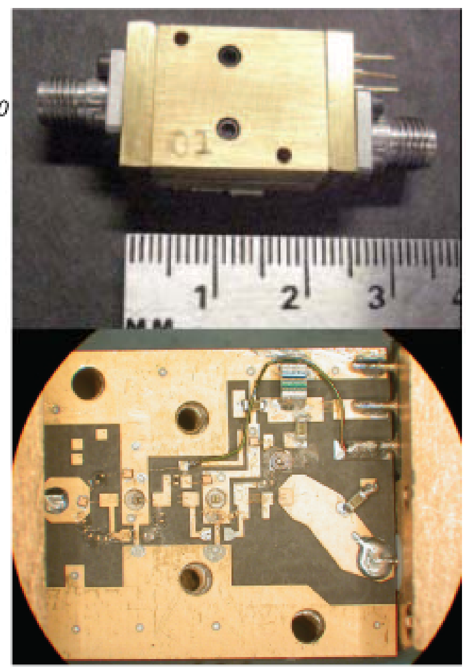
Issues considered in proposal

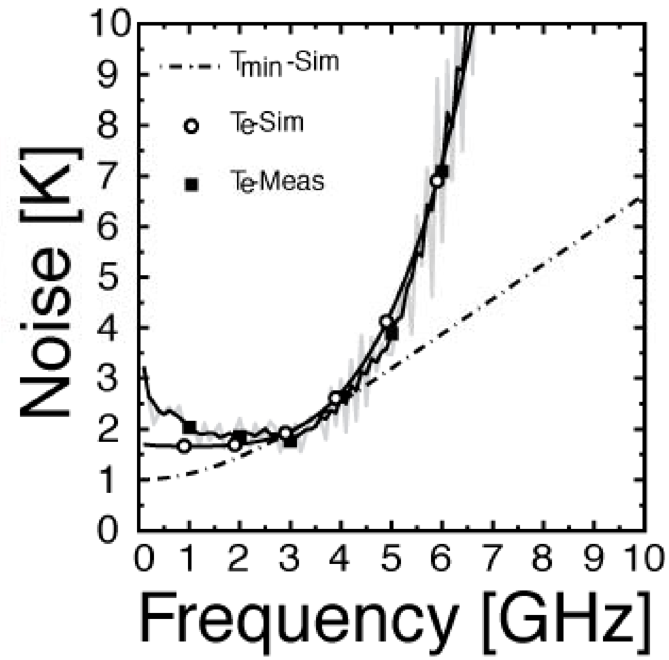
1. Responsivity (Mattis-Bardeen, expected Q)
2. Intrinsic detector noise
   – Random generation & recombination of quasiparticles
3. Microwave amplifier noise
4. Limitation on maximum microwave power
   – Absorbed microwave power < optical power
5. Phase noise of readout system
6. Expected NEP (below 10^{-18} W $Hz^{-1/2}$)
7. Multiplexing:
   – "Digital techniques are especially attractive since in principle multiple frequency components could be generated or analyzed simultaneously. However, the efficacy of digital techniques will depend on the frequency spacing (detector *Q)* and the available clock rates*"*

Multiplexing



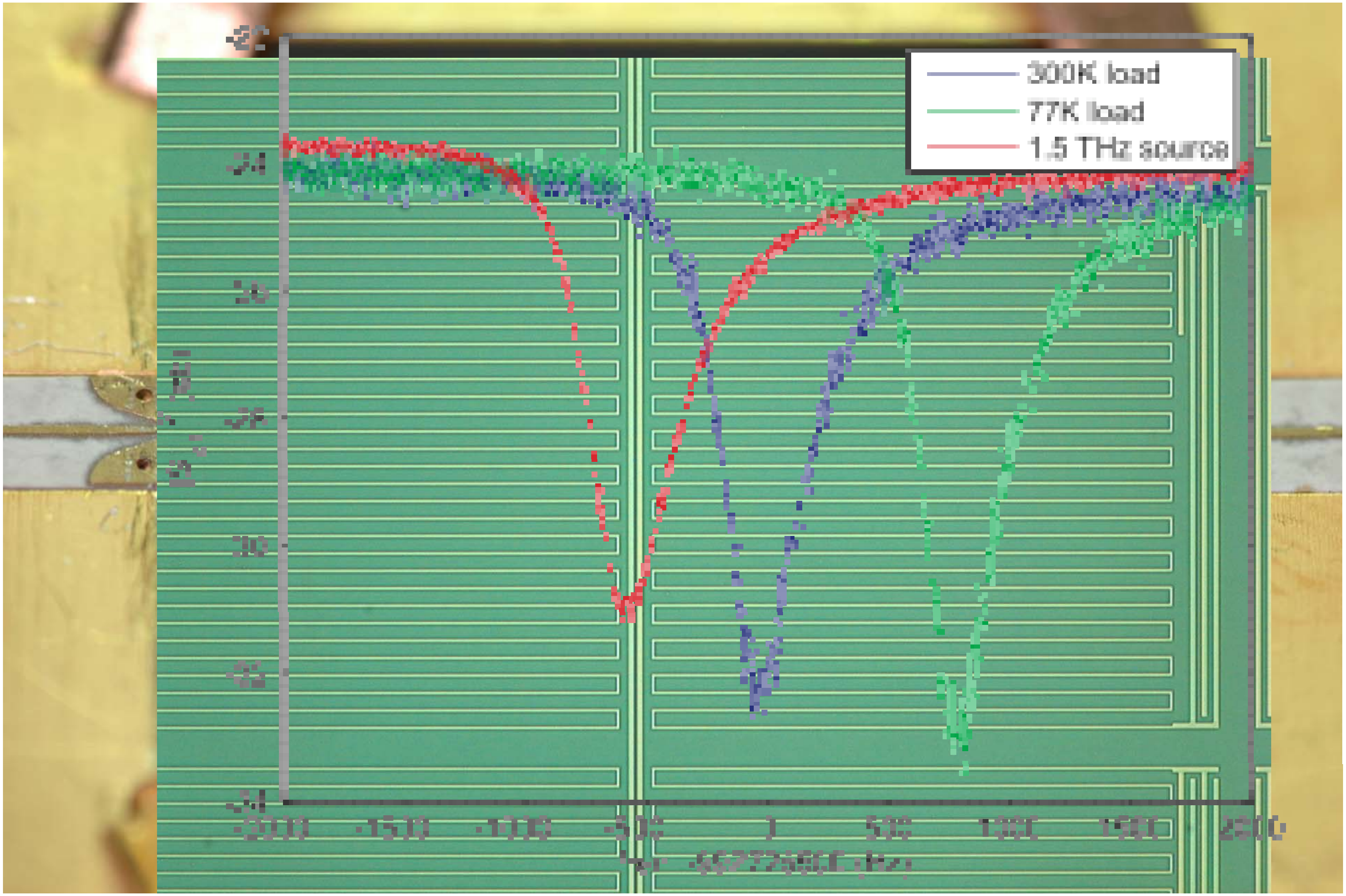




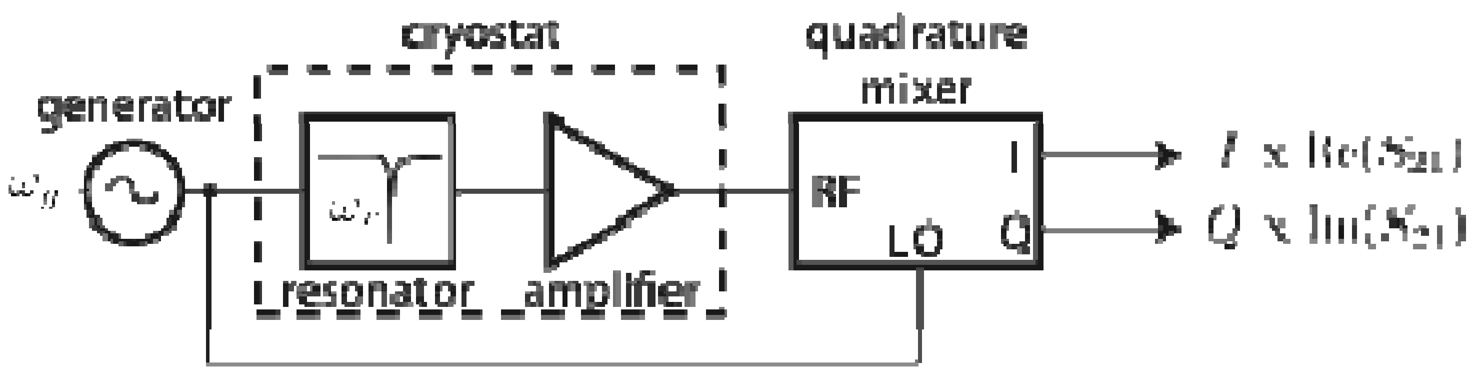


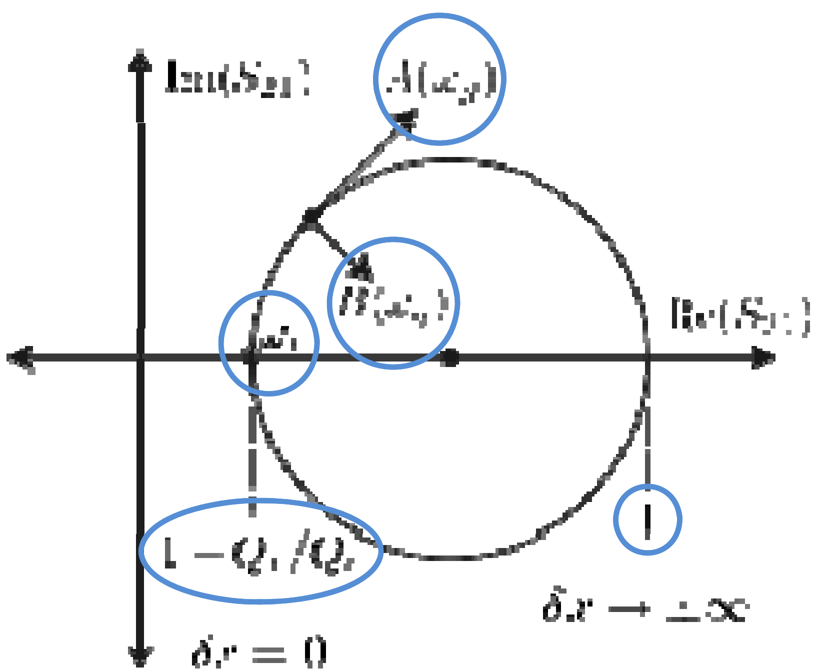
SiGe cyrogenic bipolar amp: Joe Bardin and Sandy Weinreb (Caltech)

Far-IR TiN MKID Array



Resonator Readout





$$S_{21}(\omega_g) = 1 - \frac{Q_r}{Q_c}\frac{1}{1 - 2jQ_r\delta x}$$

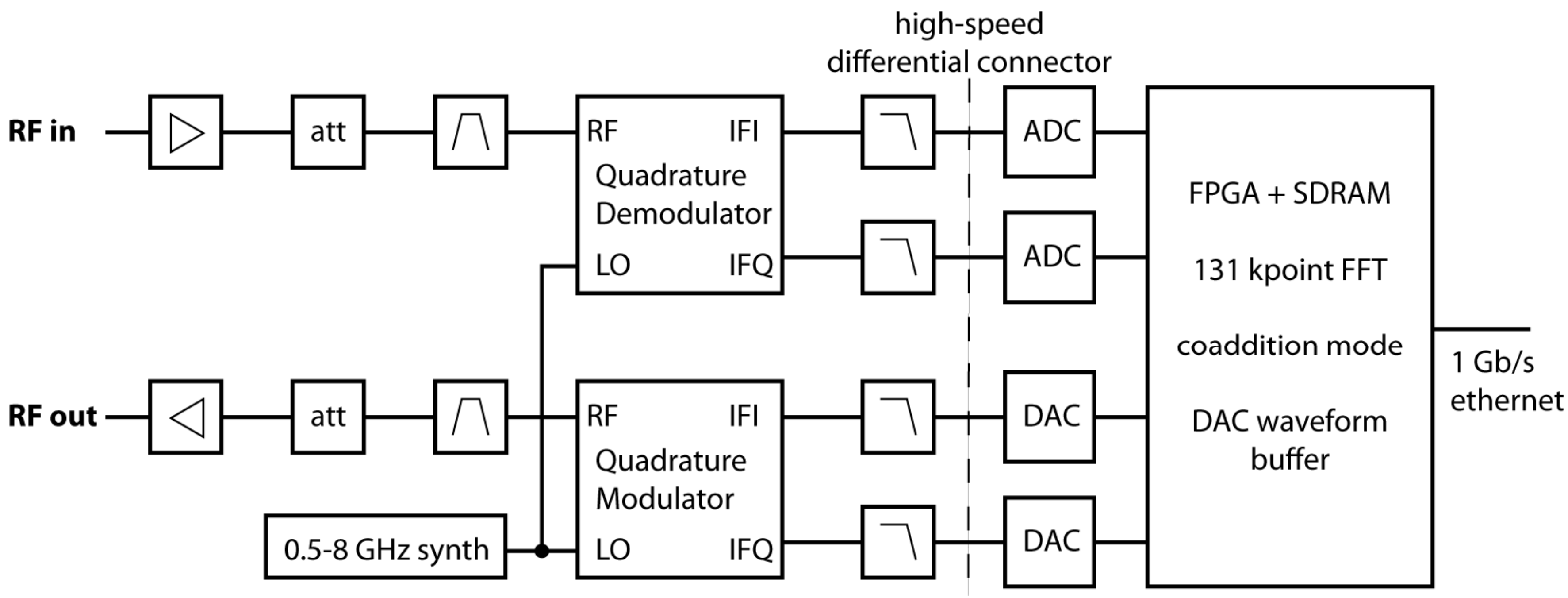
$$\delta x = \frac{\omega_g - \omega_r}{\omega_r}$$

$$A(\omega_g) = -\omega_r \frac{\partial S_{21}}{\partial \omega_r} = 2jQ_c\,|1 - S_{21}(\omega_g)|^2$$

$$B(\omega_g) = \frac{\partial S_{21}}{\partial Q_i^{-1}} = \frac{1}{2j}A(\omega_g)$$

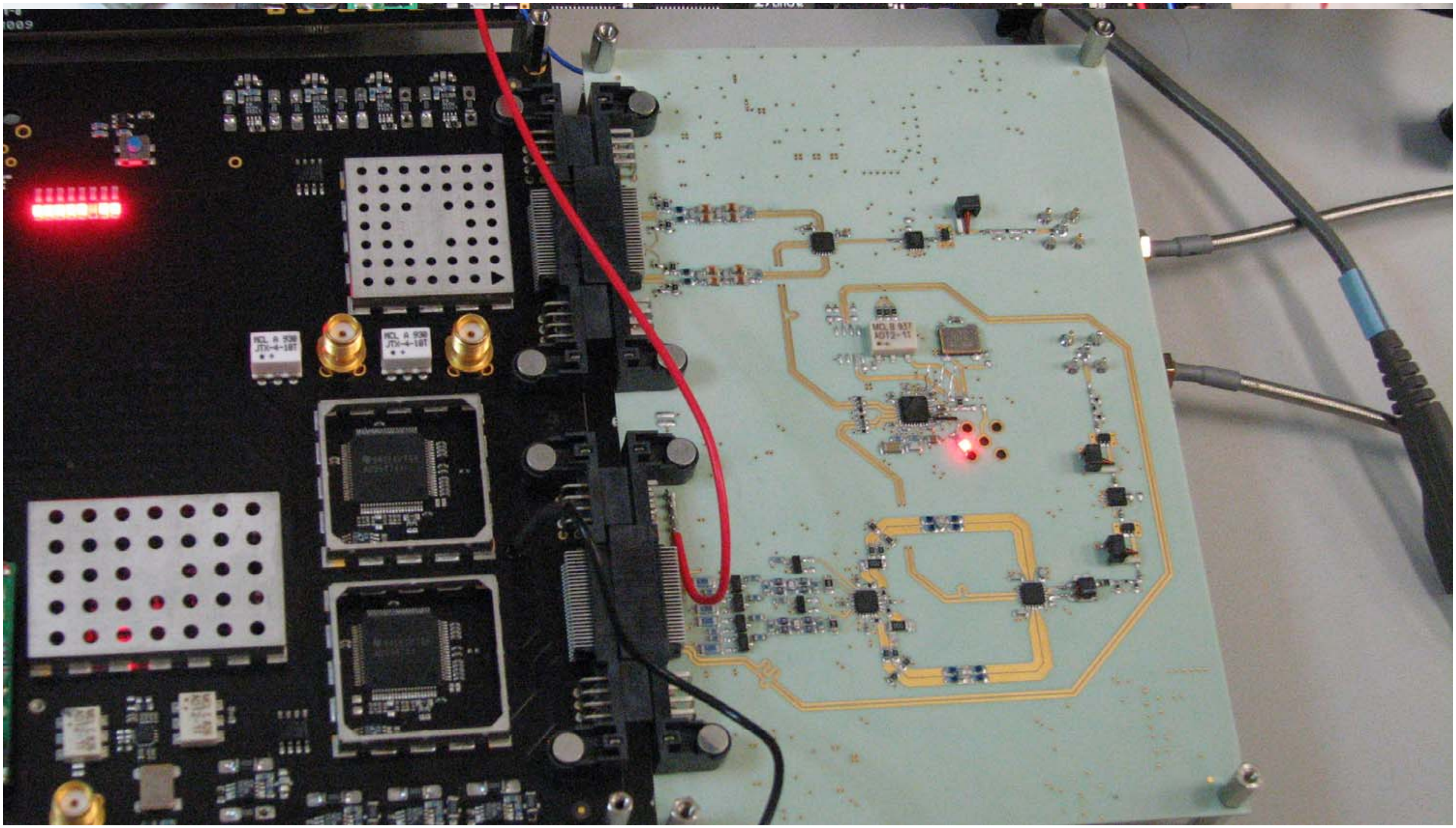
Vector measurement of S_{21} provides information on both frequency (σ_2) and dissipation (σ_1)

Multichannel Readout Electronics



MUSIC readout at Omnisys AB

Johan Riesbeck, Martin Kores, Anders Emrich



Conductivity Perturbations

Start at T=0 and turn on thermal, optical, and microwave excitation:

$$\sigma(T=0) \rightarrow \sigma(T) \rightarrow \sigma(T, P_{\rm opt}, P_{\rm read})$$

Then analyze effect of small perturbations $dP_{\rm opt}, dP_{\rm read}$

$$\delta Z_s = \omega L_s \left(\frac{\delta\sigma_1}{\sigma_2(0)} + j \frac{\delta\sigma_2}{\sigma_2(0)} \right) \qquad \delta\sigma = \sigma(T, P_{\rm opt}, P_{\rm read}) - \sigma(0)$$

$$\delta x = -\frac{\delta f_r}{f_r} = +\frac{\delta L}{2L} = \frac{\alpha}{2} \frac{\delta\sigma_2}{\sigma_2(0)} \qquad \alpha = \frac{L_{\rm kinetic}}{L_{\rm total}}$$

$$Q_{\rm i,qp}^{-1} = \alpha \frac{\delta\sigma_1}{\sigma_2(0)}$$

Response to Quasiparticles

$$\frac{\delta\sigma_1}{\sigma_2(0)} \qquad \frac{2}{\pi\Delta}\int_\Delta^\infty dE\,K_1(E,\omega)f(E)$$

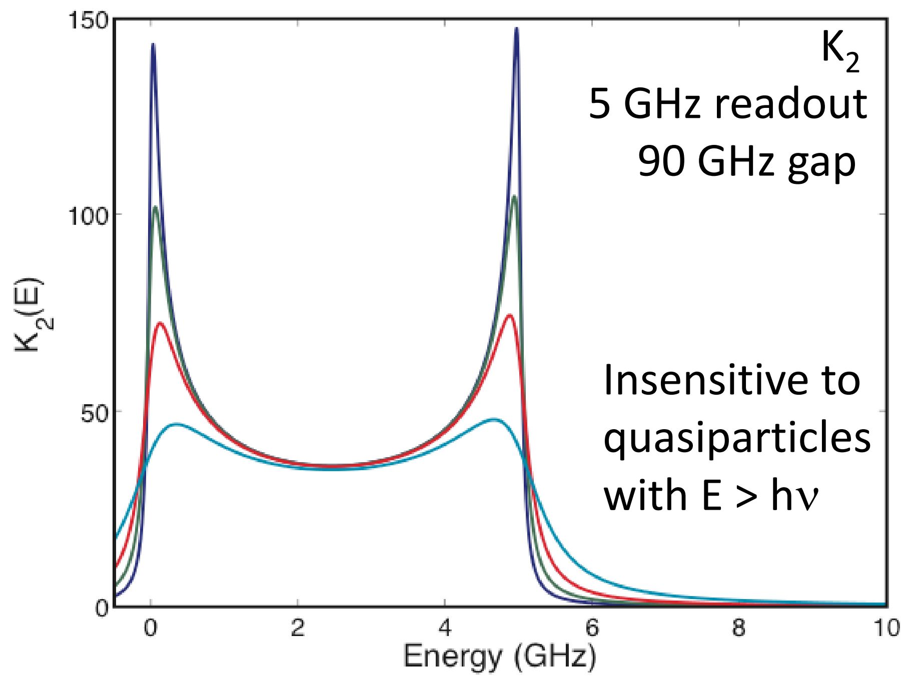
K_1 = dissipation kernel

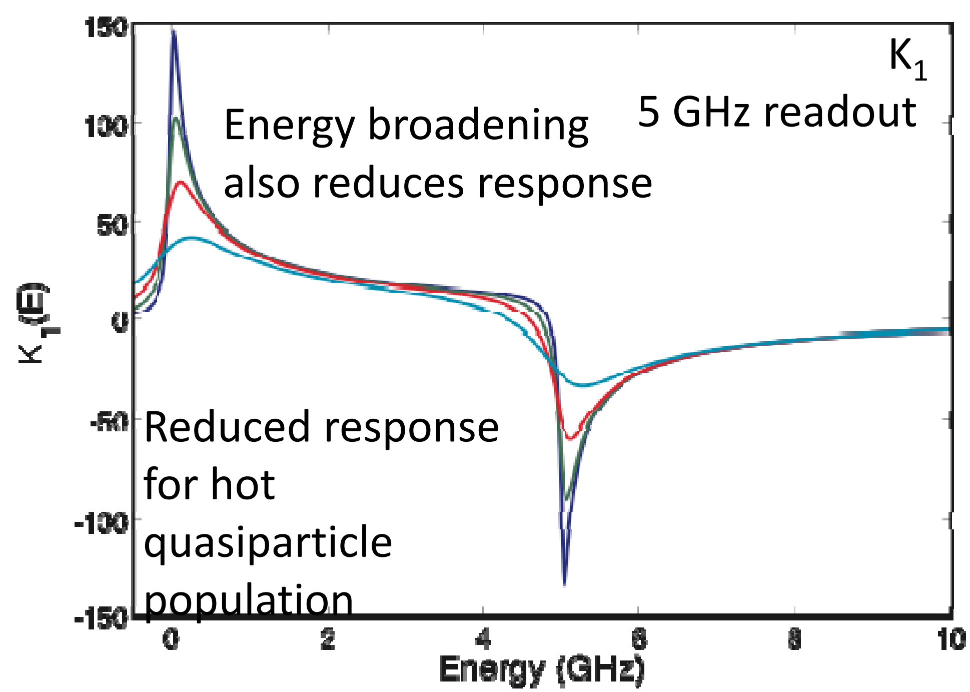
$$\frac{\delta\sigma_2}{\sigma_2(0)} \qquad \frac{2}{\pi\Delta}\int_\Delta^\infty dE\,K_2(E,\omega)f(E)$$

K_2 = "inductance" kernel

$$n_{qp} \qquad 4N_0\int_\Delta^\infty dE\,\frac{E}{\sqrt{E^2\quad\Delta^2}}f(E)$$

$$f(E,T) \qquad \frac{1}{e^{E/kT}+1} \approx e^{-E/kT}$$ in thermal equilibrium





A (too?) simple model

- Ignore microwave heating of quasiparticles
  - Follow Owen-Scalapino: $f(E) \propto e^{-E/kT}$
  - Reduce problem to one variable: N_{qp}

$$
\begin{aligned}
\frac{\delta\sigma}{\sigma(0)} &= -\left[S_2(\omega,T) - jS_1(\omega,T)\right]\frac{N_{qp}}{2N_0\Delta V} \\
S_1(\omega,T) &= \frac{2}{\pi}\sqrt{\frac{2\Delta}{\pi kT}}\sinh(\hbar\omega/2kT)K_0(\hbar\omega/2kT) \\
S_2(\omega,T) &= 1+\sqrt{\frac{2\Delta}{\pi kT}}\exp(-\hbar\omega/2kT)I_0(\hbar\omega/2kT) \\
\beta(\omega,T) &= S_2/S_1 \sim 3
\end{aligned}
$$

Quasiparticle Generation

- Allow microwave generation of quasiparticles:

$$
\begin{aligned}
\frac{dN_{\rm qp}}{dt} &= \Gamma_{\rm gen} - \Gamma_{\rm rec} \\
\Gamma_{\rm gen} &= \Gamma_{\rm th} + \Gamma_{\rm opt} + \Gamma_{\rm read} \\
\Gamma_{\rm opt} &= \eta_{\rm opt} P_{\rm opt} / \Delta \\
\Gamma_{\rm read} &= \eta_{\rm read} P_{\rm read} / \Delta
\end{aligned}
$$

(should add g-r noise term)

$0 \leq \eta_{\rm opt} \leq 1$

$0 \leq \eta_{\rm read} \leq 1$

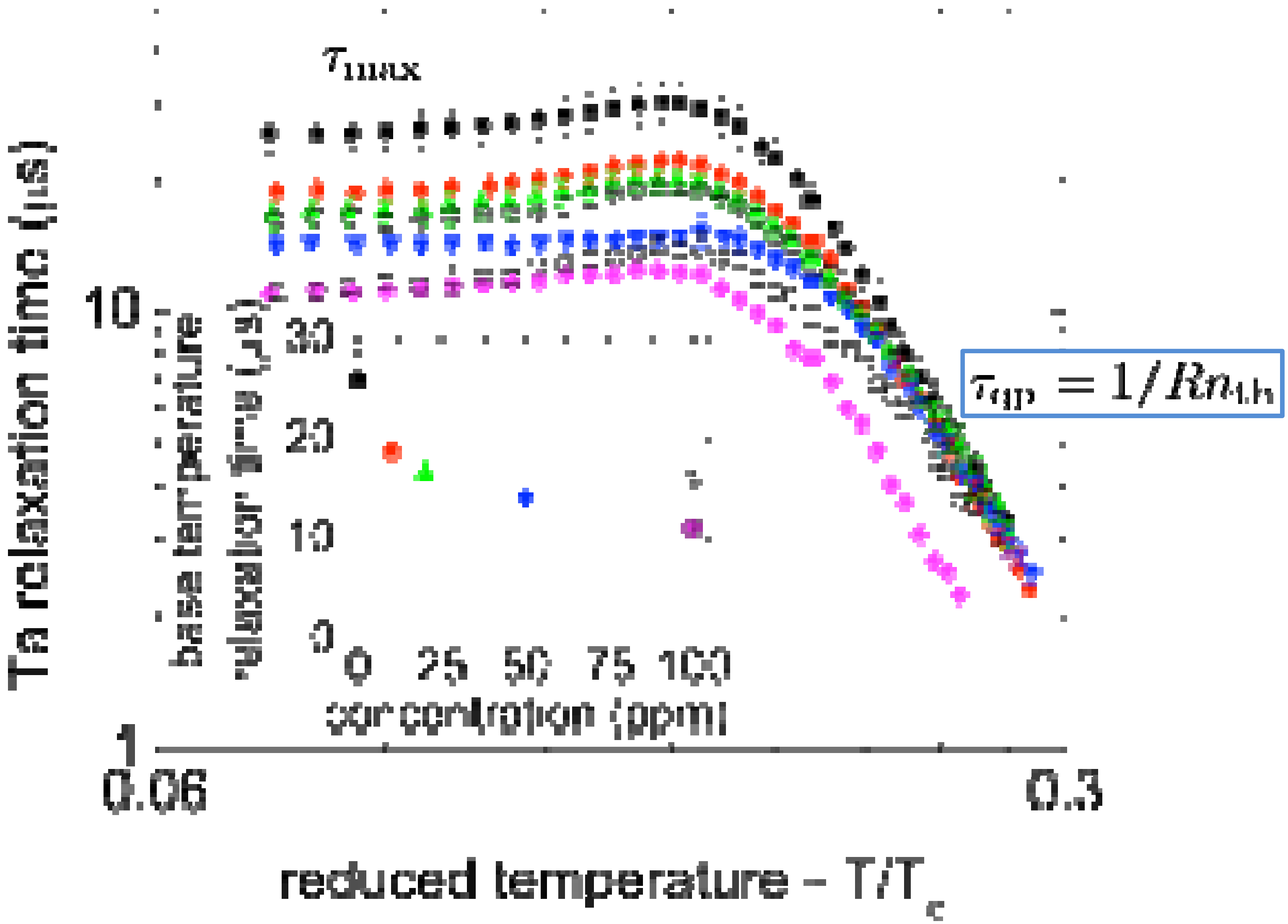
Quasiparticle Recombination

$$\begin{aligned}
\Gamma_{\rm rec} &= N_{\rm qp}\left({\tau_{\rm max}}^{-1} + \frac{1}{2V} R N_{\rm qp}\right) \\
\tau_{\rm qp}^{-1} &= {\tau_{\rm max}}^{-1} + R N_{\rm qp}/V \\
R^{-1} &= \tau_0 (2N_0 kT_c)(2\Delta/kT_c)^2 \propto T_c^{-2} \\
\tau_0 &= \frac{\hbar(1+\lambda)}{2\pi b (kT_c)^3} \quad \alpha^2 F(\Omega) = b\Omega^2
\end{aligned}$$

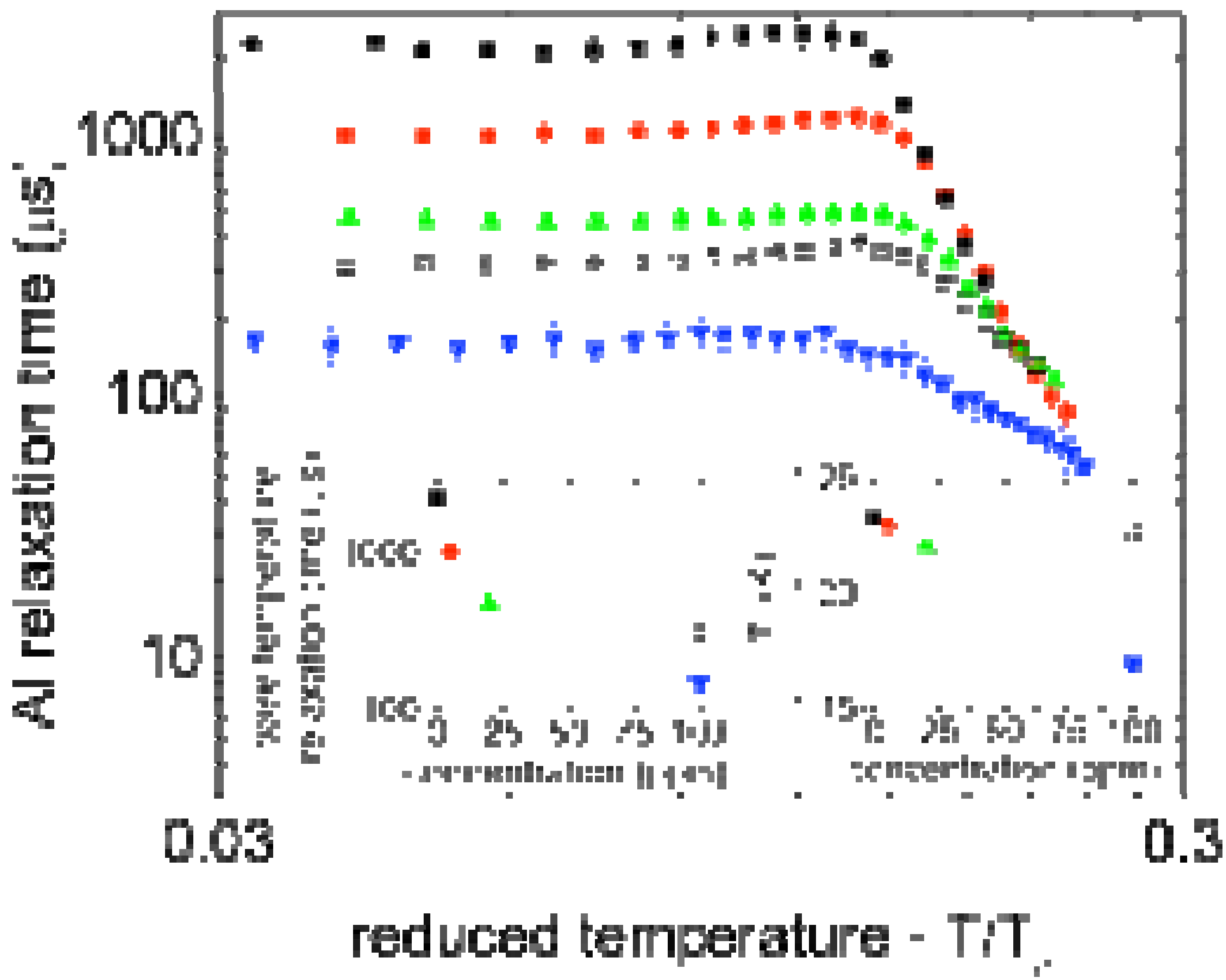
See Kaplan et al, PRB 14, 4854, 1977

Quasiparticle Recombination

Barends et al PRB 79, 020509 (2009)



Quasiparticle Recombination

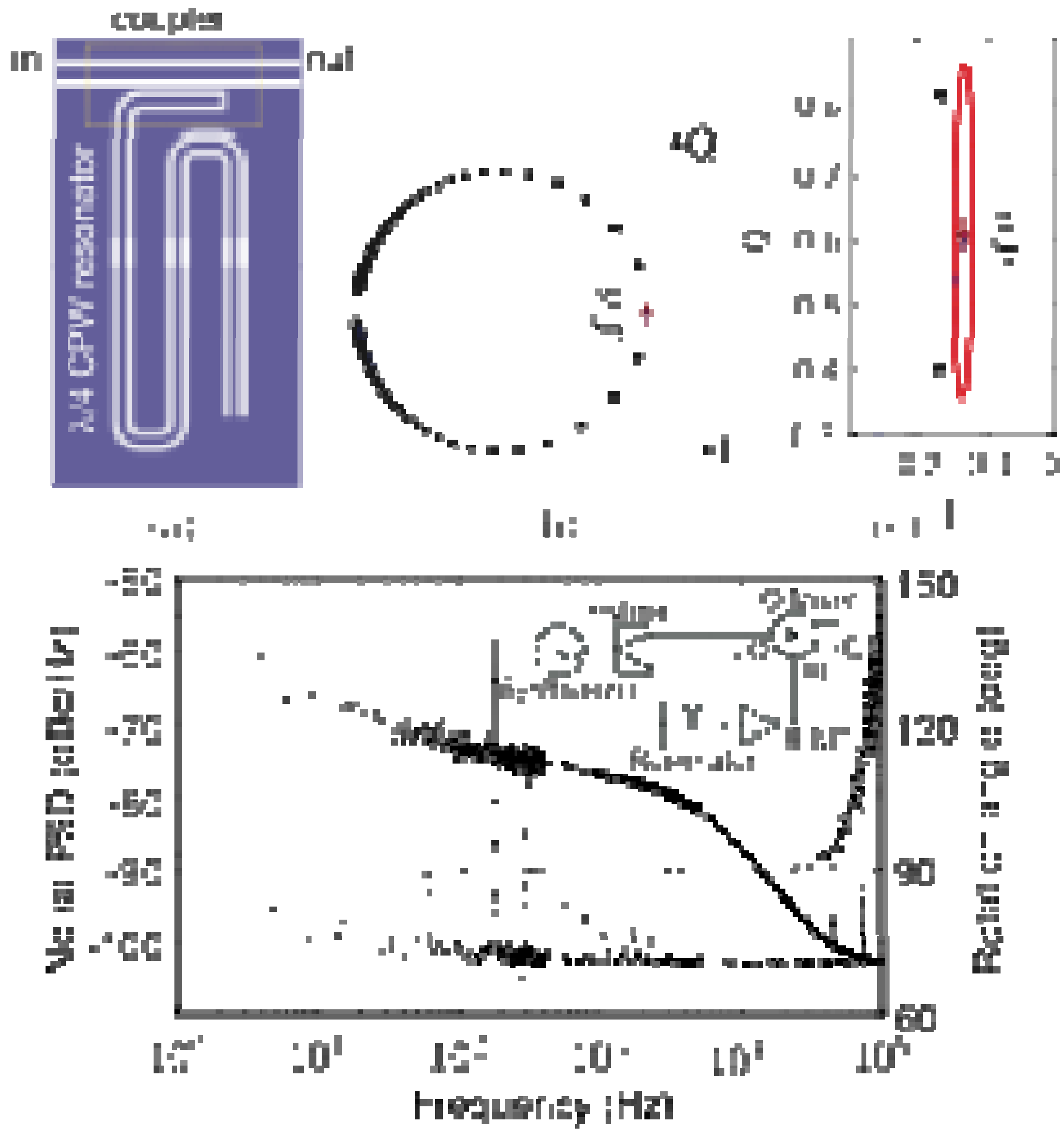


Calculating MKID Responsivity

- Set generation = recombination
  – Calculate $N_{qp}(T, P_{opt}, P_{read})$
- Analyze small perturbations
  – Could include frequency roll-off due to resonator bandwidth & quasiparticle lifetime, nonzero generator-resonator detuning, microwave power feedback, etc.
  – Keep it simple here: $dN_{qp} = \frac{\eta_{opt}\tau_{qp}}{\Delta} dP_{opt}$

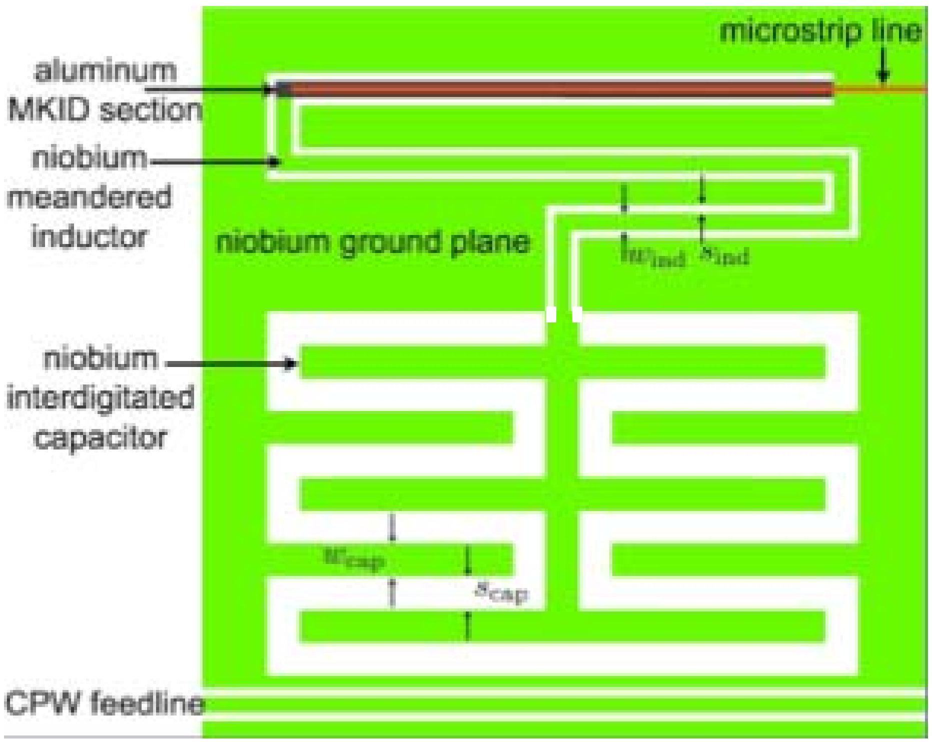
$$dS_{21} = \frac{\chi_c \chi_i}{4} \left[1 + j\beta(\omega, T)\right] \frac{dN_{qp}}{N_{qp}} \qquad \begin{aligned} \chi_c &= 4Q_r^2/Q_c Q_i \leq 1 \\ \chi_i &= Q_i/Q_{i,qp} \leq 1 \end{aligned}$$

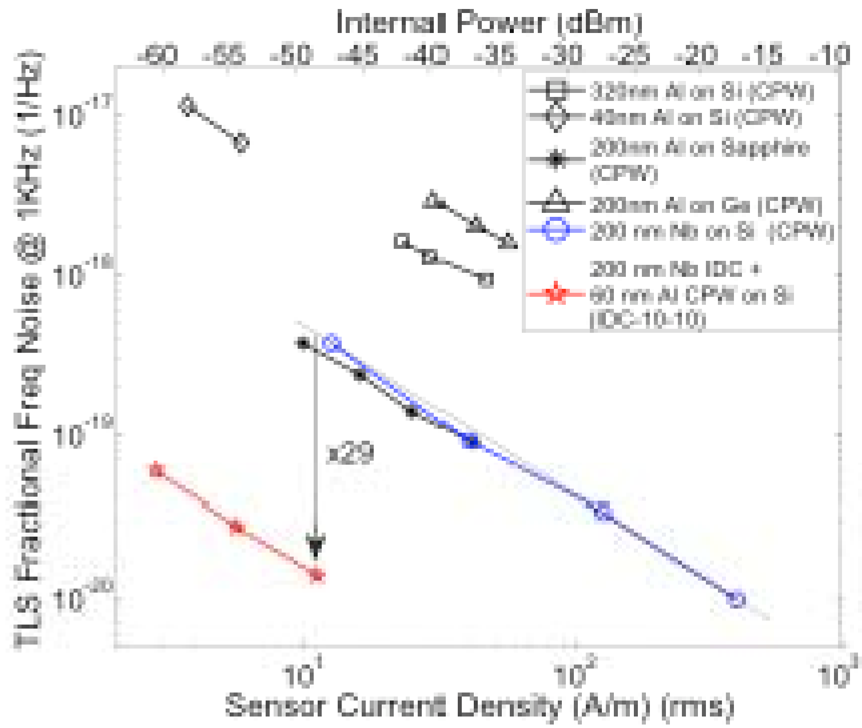
Noise: Gao et al. 2007
(APL 90, 102507)



Surface TLS noise reduction with IDC

Noroozian et al. LTD 2009 (AIP Conf. Series vol. 1185)





- Demonstrates that noise source is “capacitive” rather than “inductive”
- Consistent with surface distribution of TLS fluctuators (Gao et al 2008 a,b)
- **Conclusion: develop better (TLS-free) capacitors** !

Dissipation Readout

- No TLS noise for dissipation readout
  - Baselmans et al. approach for NEP < 10^{-18} W $Hz^{-1/2}$
- Amplifier noise NEP:

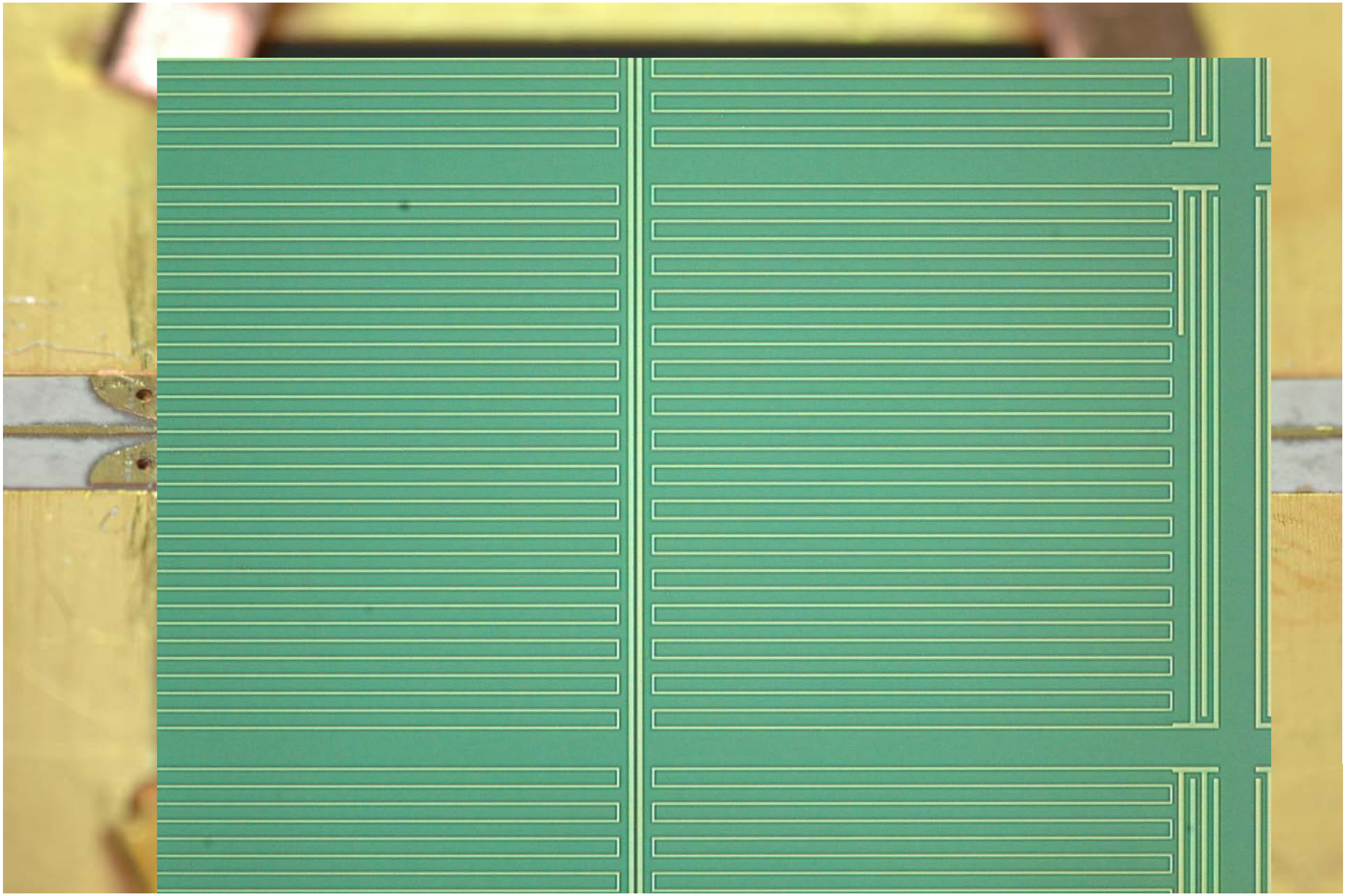
$$\mathrm{NEP}_{\mathrm{amp}} = 4\sqrt{\eta_{\mathrm{read}} k T_{\mathrm{amp}} P_{\mathrm{opt}} / \chi_c \chi_i \eta_{\mathrm{opt}}}$$

- Achieved when:

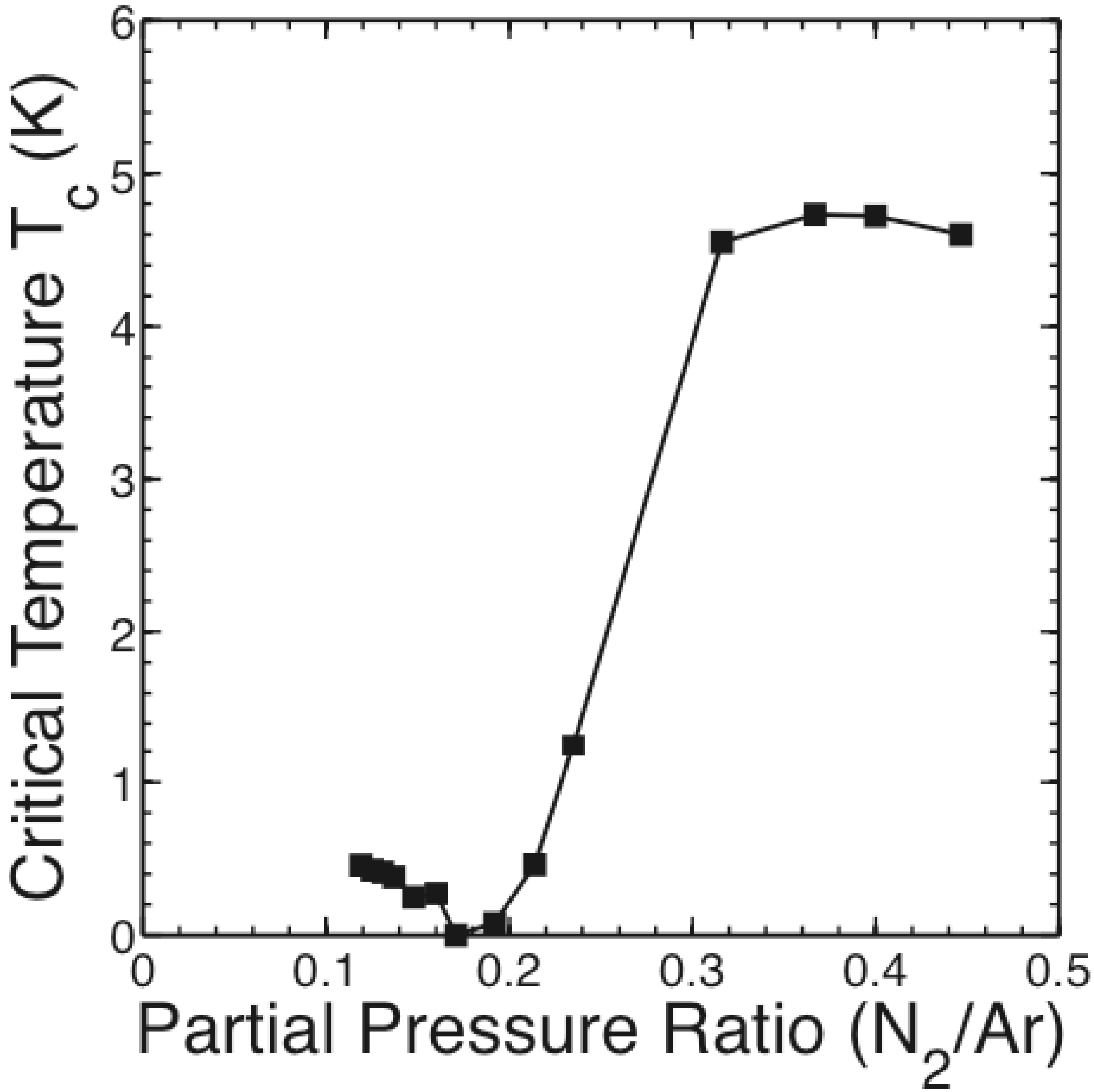
$$\eta_{\mathrm{read}} P_{\mathrm{read}} = \eta_{\mathrm{opt}} P_{\mathrm{opt}}$$

- Compare to photon NEP:
  - T_{amp} ~ 2 K should reach BLIP in submm/far-IR
  - Achievable with SiGe bipolar amps (Bardin/Weinreb)

Far-IR TiN MKID Array

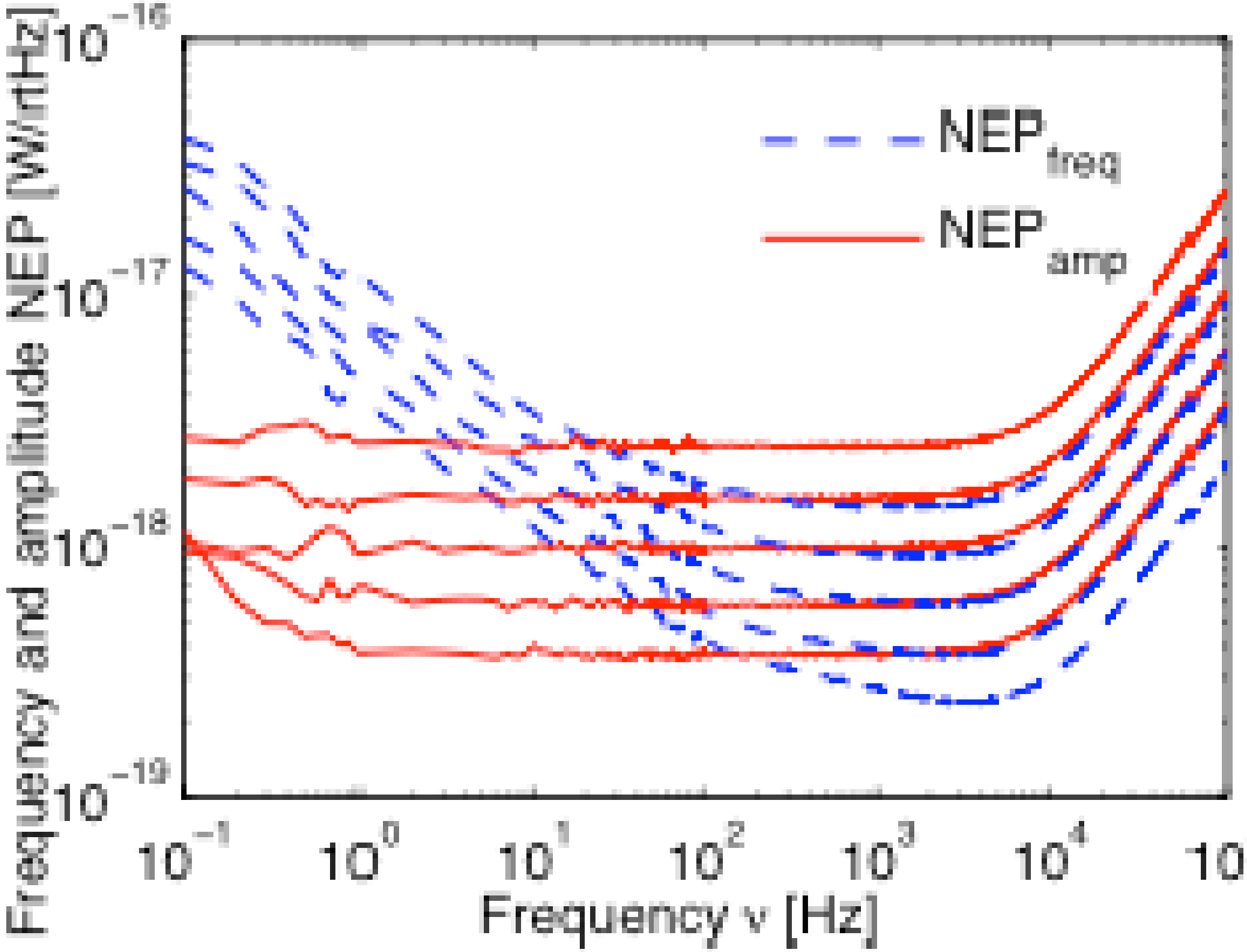


Titanium Nitride



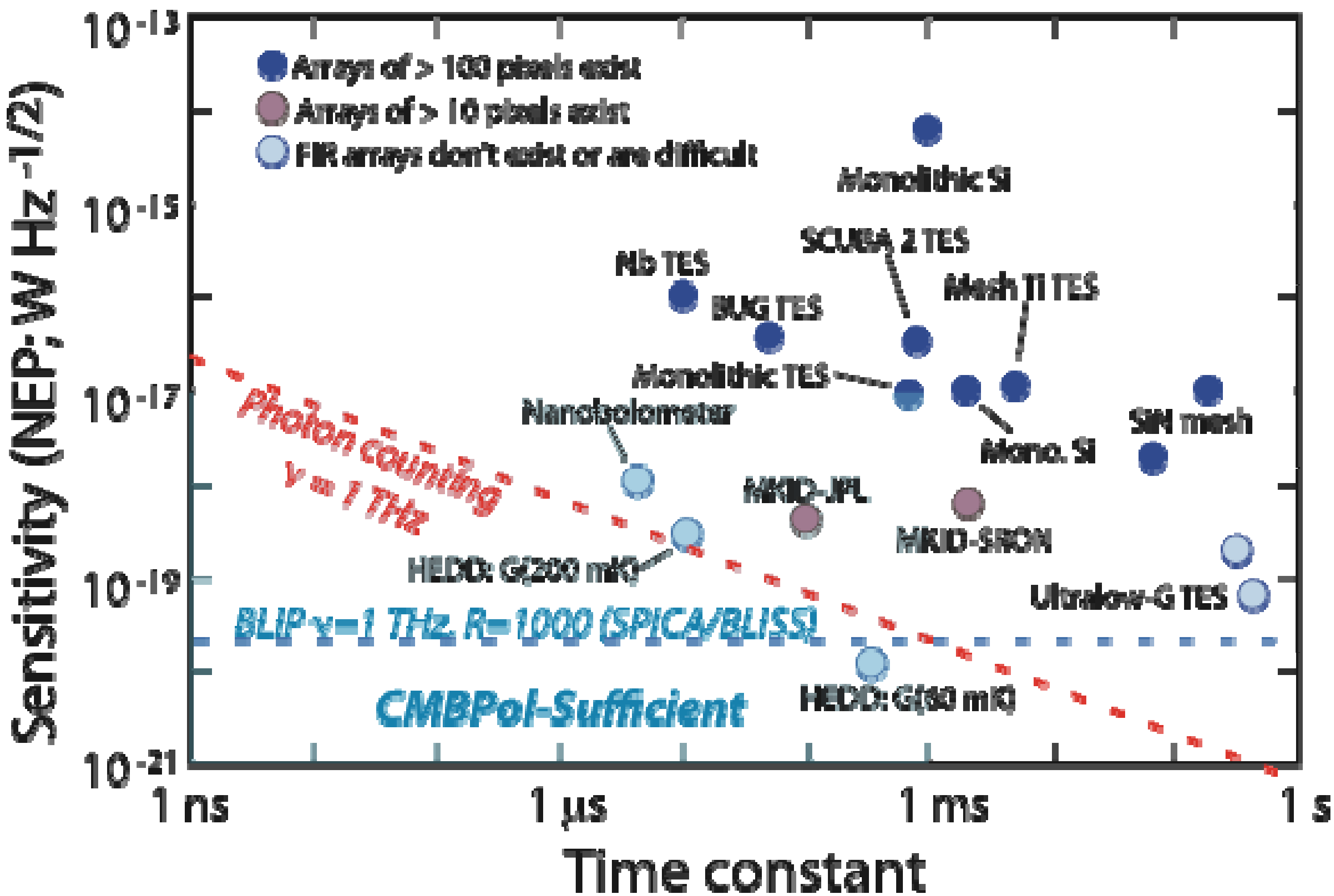
- Reactive sputtering in Ar/N_2 mixture
- ρ=100 $\mu\Omega$ cm
- RRR ~ 1
- R_s=20 Ω/sq for t=20 nm
- FCC structure

NEP of TiN CPW Resonator

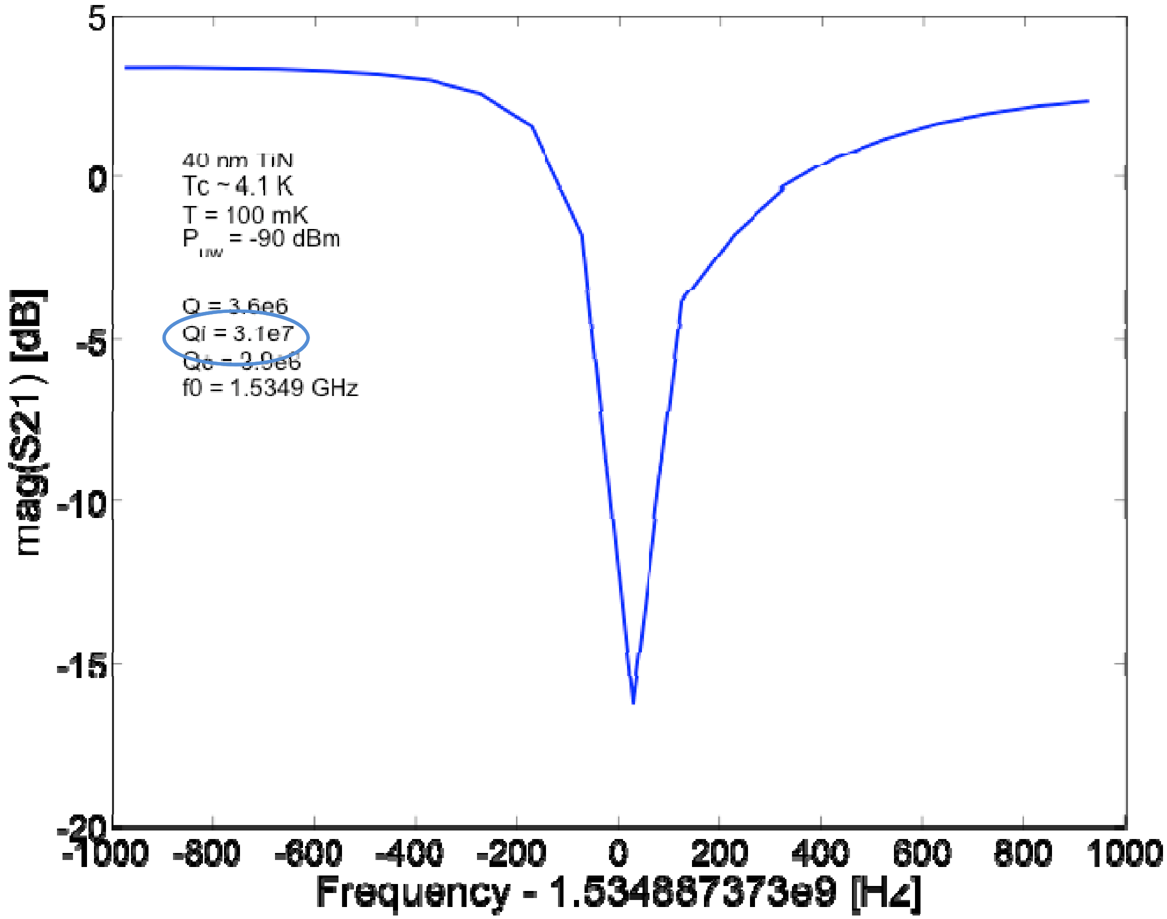


Q_r=40,000, 3f_r=5.4 GHz, t=20 nm, T_c=1.1 K, w=3 μm, g=2 μm, α=0.95, P_{gen}=5 fW to 200 fW

Cleland-Benford Plot

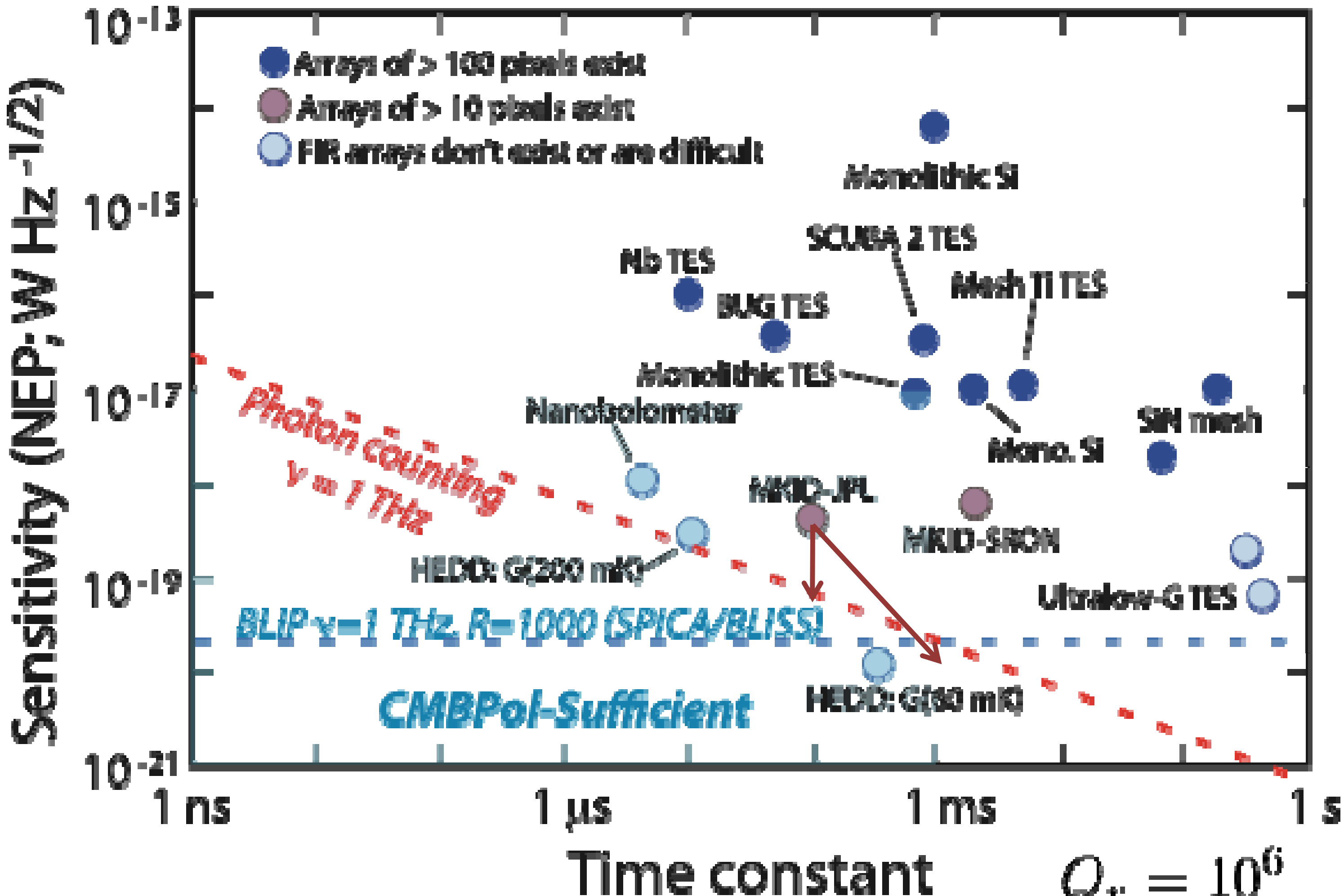


Much higher Q is possible



$$\mathrm{NEP_{amp}} \geq 4\sqrt{\frac{\eta_{\mathrm{read}} k T_{\mathrm{amp}} N_0 \Delta^2 V}{\eta_{\mathrm{opt}} \alpha S_1 \tau_{\max} Q_{i,\max}}}\,.$$

Cleland-Benford Plot



$Q_r = 10^6$

$Q_r = 1.5 \times 10^7$

Conclusions

- Good progress in our fundamental understanding
  - Key issues remain, e.g. quasiparticle recombination, effect of microwaves
- Major progress toward system demonstrations
  - Readout electronics rapidly approaching reality
- New materials offer very exciting prospects
  - Combination of high resistivity and very high Q

$$\mathrm{NEP}_{\mathrm{amp}} \geq 4\sqrt{\frac{\eta_{\mathrm{read}} k T_{\mathrm{amp}} N_0 \Delta^2 V}{\eta_{\mathrm{opt}} \alpha S_1 \tau_{\mathrm{max}} Q_{i,\mathrm{max}}}} \; .$$

  - NEP below 10^{-19} W $Hz^{-1/2}$ now looks quite feasible

Prospects

- Far-IR absorber-coupled pixels
  - Cardiff Lekid design looks very simple & attractive
  - GSFC has alternate concept
  - Pixel-pixel microwave coupling is a critical issue, but appears to be solvable
- Antenna-coupled detectors:
  - Will be deployed in MUSIC (24x24 x 4 color)
  - Conceptual design for uSpec (Moseley)
  - Offers considerable volume reduction
- The full potential of TiN should be explored !

Calculating f(E)*

PHYSICAL REVIEW B VOLUME 15, NUMBER 5 1 MARCH 1977

Kinetic-equation approach to nonequilibrium superconductivity*†

Jhy-Jiun Chang and D. J. Scalapino
Department of Physics, University of California, Santa Barbara, California 93106

(Received 26 July 1976)

The population of states with energy E changes because:

Quasiparticle injection

Phonon absorption

Phonon emission

$$\frac{df(E)}{dt} = I_{qp}(E) - \frac{2\pi}{\hbar}\int_0^\infty d\Omega\, \alpha^2(\Omega)F(\Omega)\rho(E+\Omega)\left(1-\frac{\Delta^2}{E(E+\Omega)}\right)\{f(E)[1-f(E+\Omega)]n(\Omega) - f(E+\Omega)[1-f(E)][n(\Omega)+1]\}$$
$$-\frac{2\pi}{\hbar}\int_0^{E-\Delta} d\Omega\, \alpha^2(\Omega)F(\Omega)\rho(E-\Omega)\left(1-\frac{\Delta^2}{E(E-\Omega)}\right)\{f(E)[1-f(E-\Omega)][n(\Omega)+1] - [1-f(E)]f(E-\Omega)n(\Omega)\}$$
$$-\frac{2\pi}{\hbar}\int_{E+\Delta}^\infty d\Omega\, \alpha^2(\Omega)F(\Omega)\rho(\Omega-E)\left(1+\frac{\Delta^2}{E(\Omega-E)}\right)\{f(E)f(\Omega-E)[n(\Omega)+1] - [1-f(E)][1-f(\Omega-E)]n(\Omega)\} \quad (1a)$$

Recombination

Pair breaking

and

$$\frac{dn(\Omega)}{dt} = I_{ph}(\Omega) - \frac{8\pi}{\hbar}\frac{N(0)}{N}\int_\Delta^\infty dE\int_\Delta^\infty dE'\, \alpha^2(\Omega)\rho(E)\rho(E')$$
$$\times\left((1-\Delta^2/EE')\{f(E)[1-f(E')]n(\Omega) - f(E')[1-f(E)][n(\Omega)+1]\}\,\delta(E+\Omega-E')\right.$$
$$\left.-\tfrac{1}{2}(1+\Delta^2/EE')\{[1-f(E)][1-f(E')]n(\Omega) - f(E)f(E')[n(\Omega)+1]\}\delta(E+E'-\Omega)\right). \quad (1b)$$

Phonon equation

*A. Vayonakis PhD Thesis, Caltech, 2010