Kinetic Inductance Detectors for the CMB:

Erik Shirokoff

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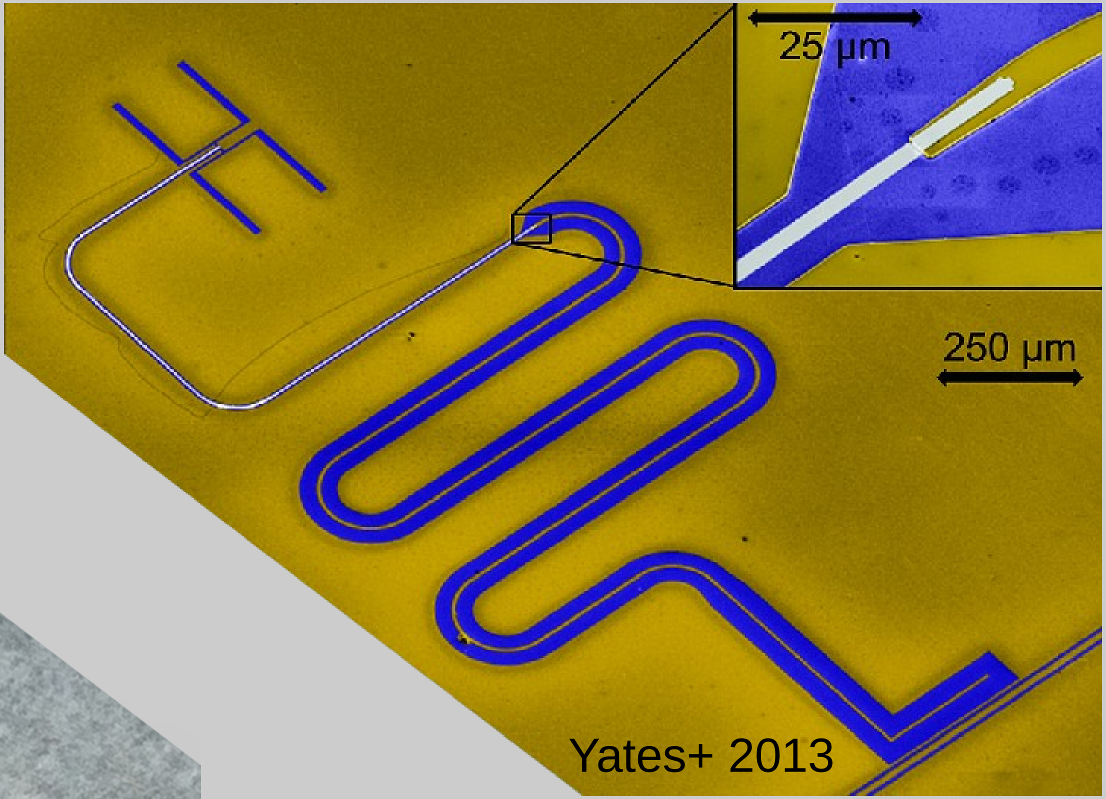
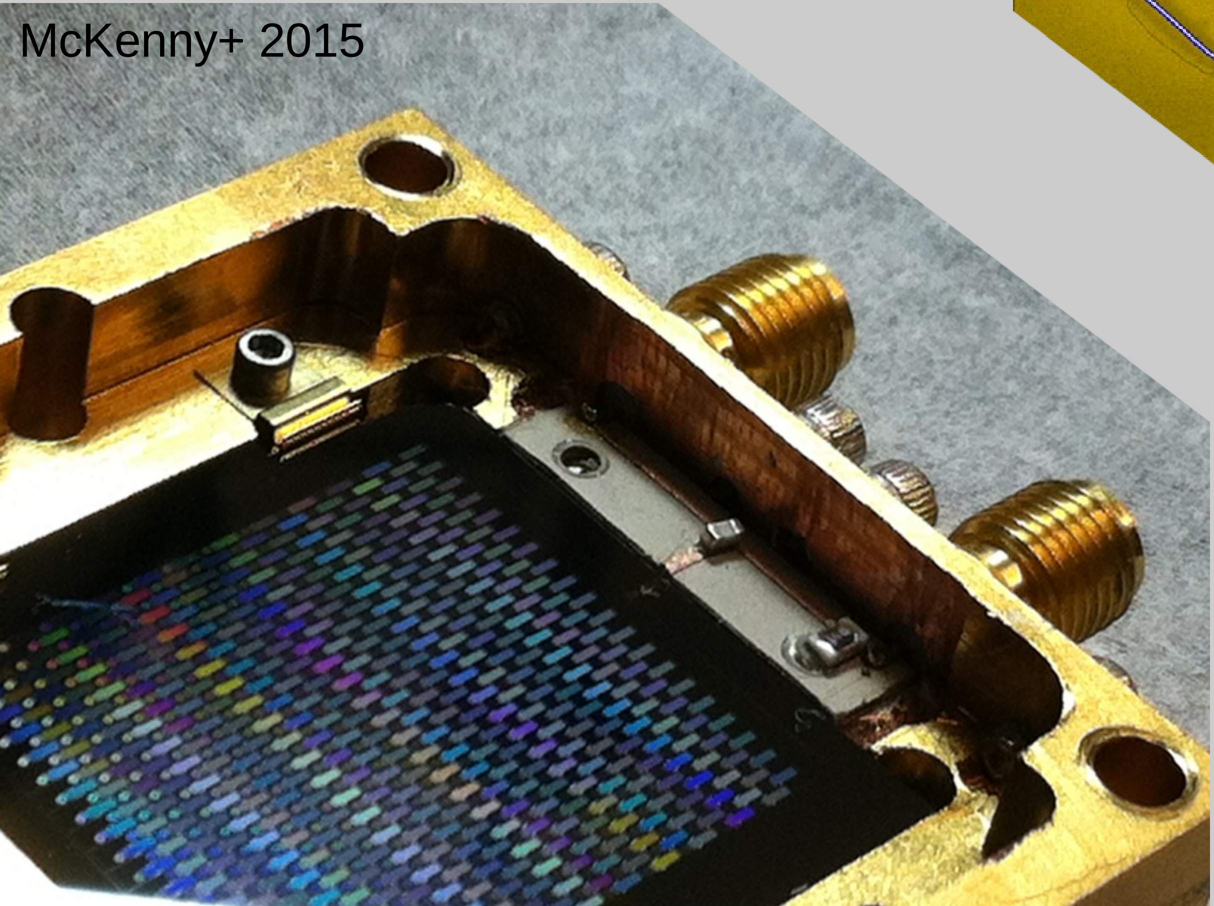


Yates+ 2013



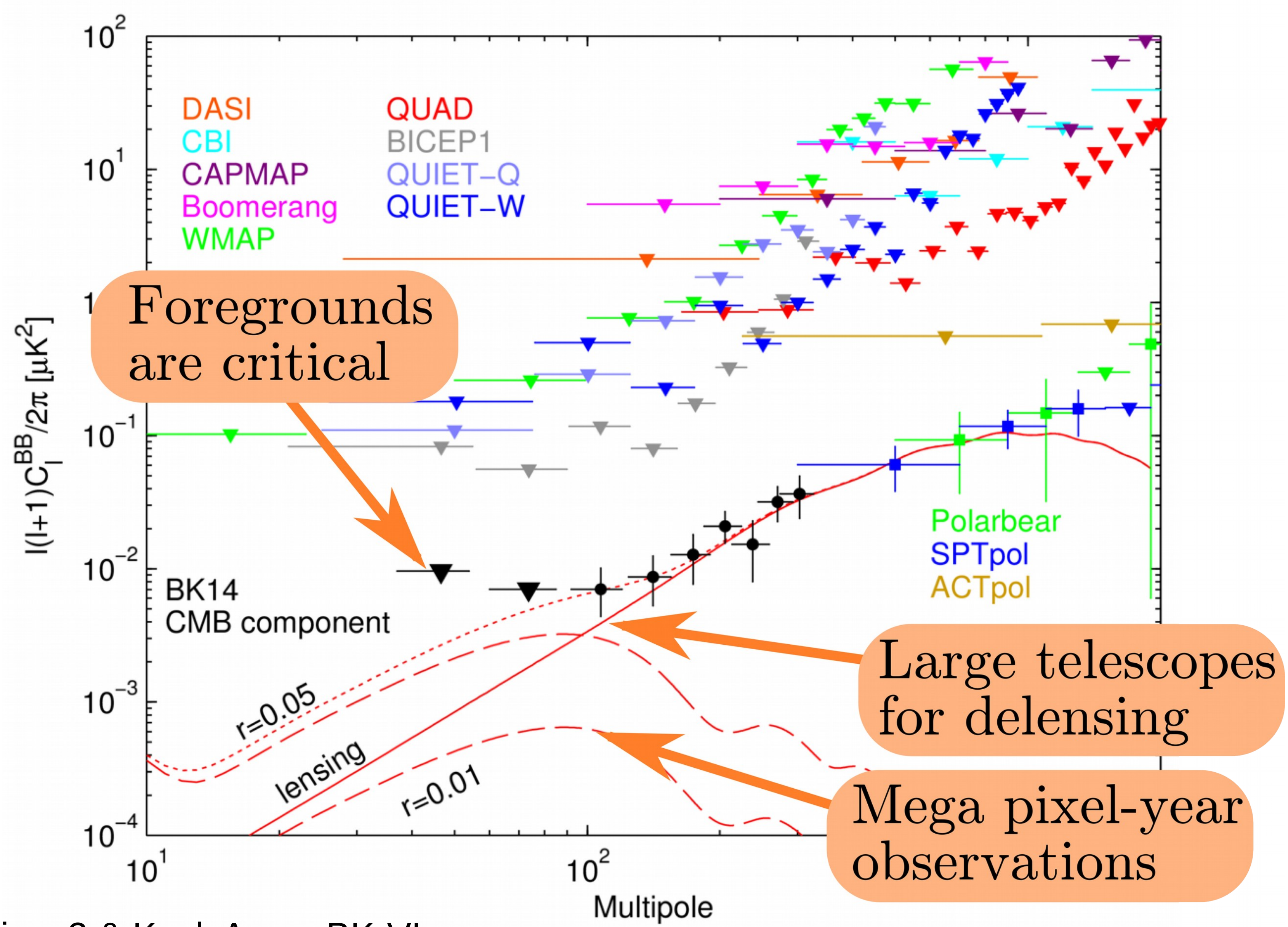
McKenny+ 2015

CPAD Instrumentation Frontier Meeting

Caltech

October 9, 2016

Further progress in CMB research requires hundreds of kilopixels and (at least some) large telescopes.



Foregrounds are critical

Large telescopes for delensing

Mega pixel-year observations

Image: Bicep2 & Keck Array, BK-VI

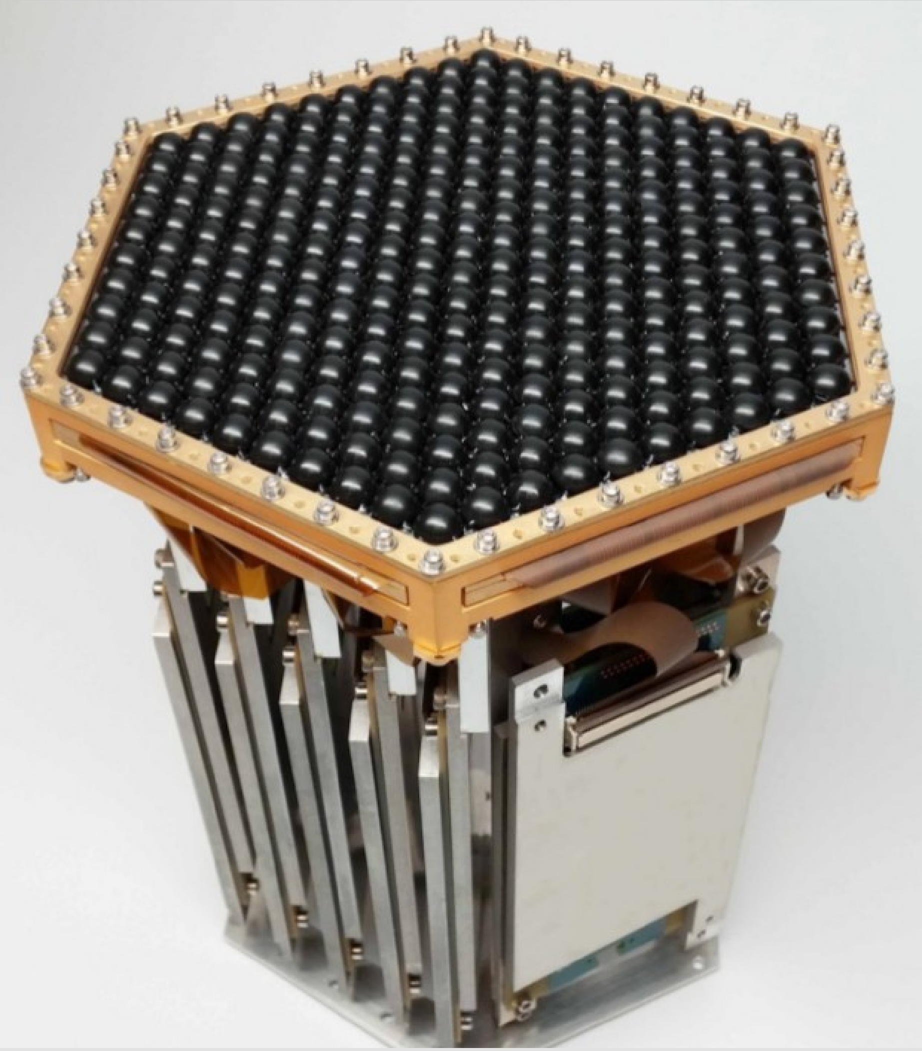
TES Bolometers: the good, the bad, and the hard to read-out.

The good:

- Sensitivity is determined by two parameters:
  G(T), Tc.
- Heritage: ~10^6 person-hours already spent turning photons into CMB maps

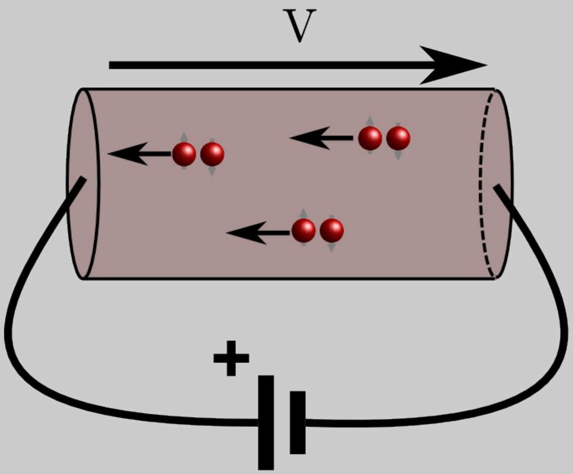
The bad:

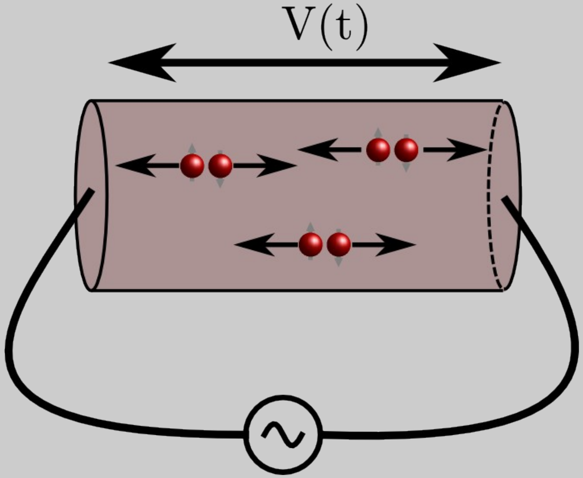
- Thin-film thermal prorties are hard to control.
- SQUID readout is complicated and expensive.
- Limited dynamic range.
- Integration and testing is already a bottleneck.



PolarBear-2 module

The kinetic inductance effect





The DC case:

- Cooper pairs carry charge without scattering.
- Internal E fields are canceled.

The AC case:

- Cooper pairs have momentum.
- Acceleration leads to a phase shift between I and V.
- This acts like an inductance!

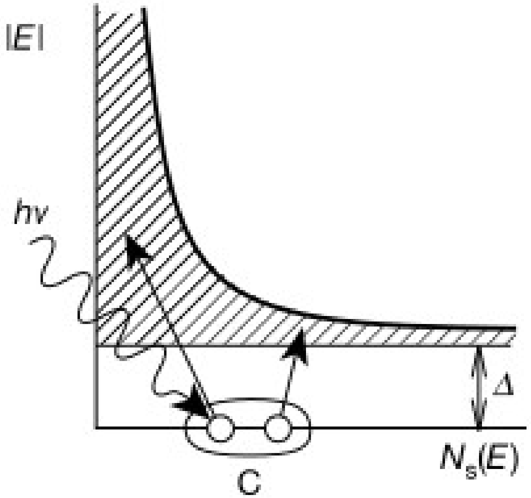
At low temperature:

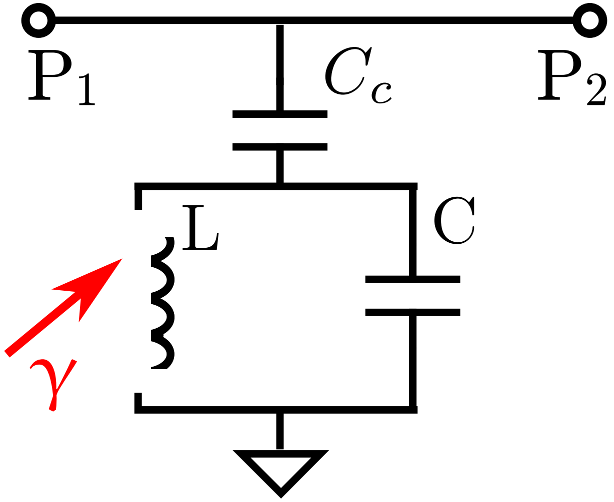
- To 1st order, L_k is constant.
- To 2nd order, L_k varies linearly with the number of pairs.

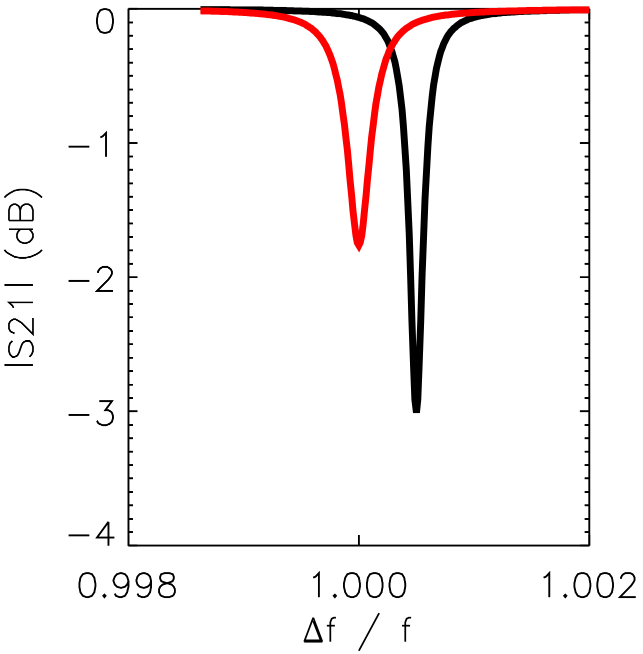
Phase shift leads to E field inside the conductor:

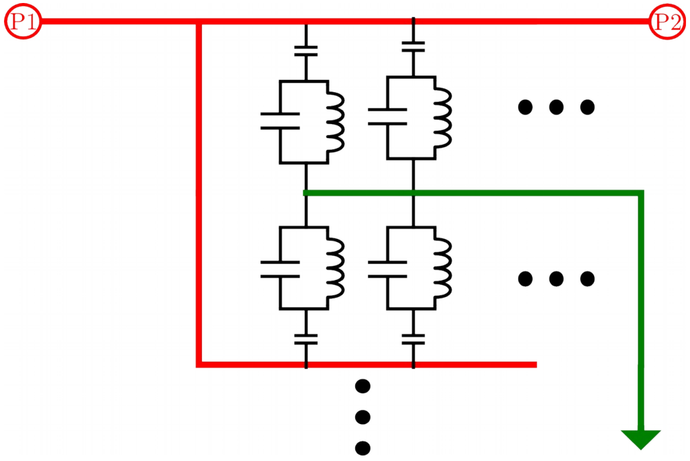
- Non-zero resistance from quasiparticle currents
- R also varies linearly with number of pairs

We can make a detector out of this.

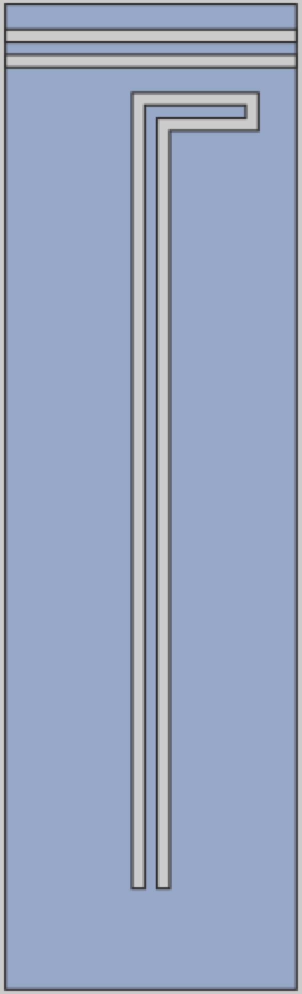


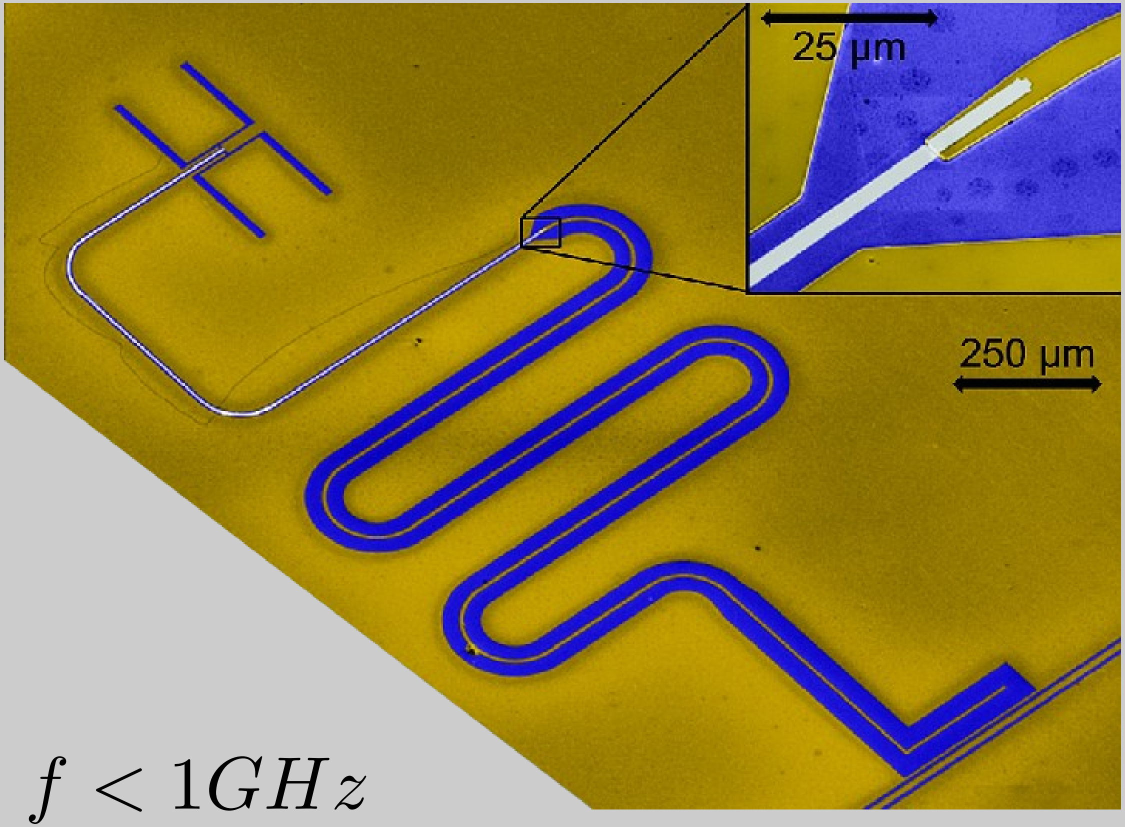






Transmission line MKID: ¼ or ½ wavelength antenna-coupled microwave line





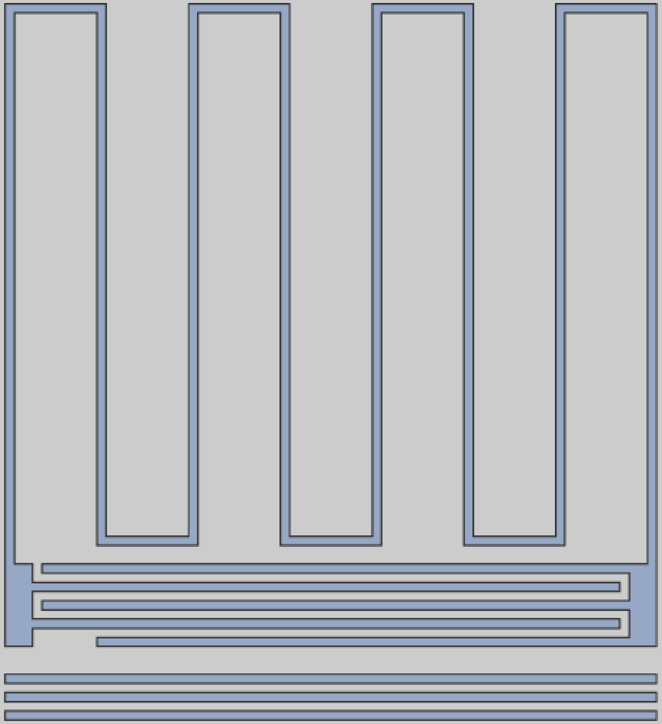
Hard to achieve $f < 1GHz$

L volumes are constrained (with caveats)

Allows on-chip filters, multi-band operation.

Image from Yates+13, A-MKID col.

Direct-absorbing lumped-element KID (LeKID): inductor is impedance matched absorber



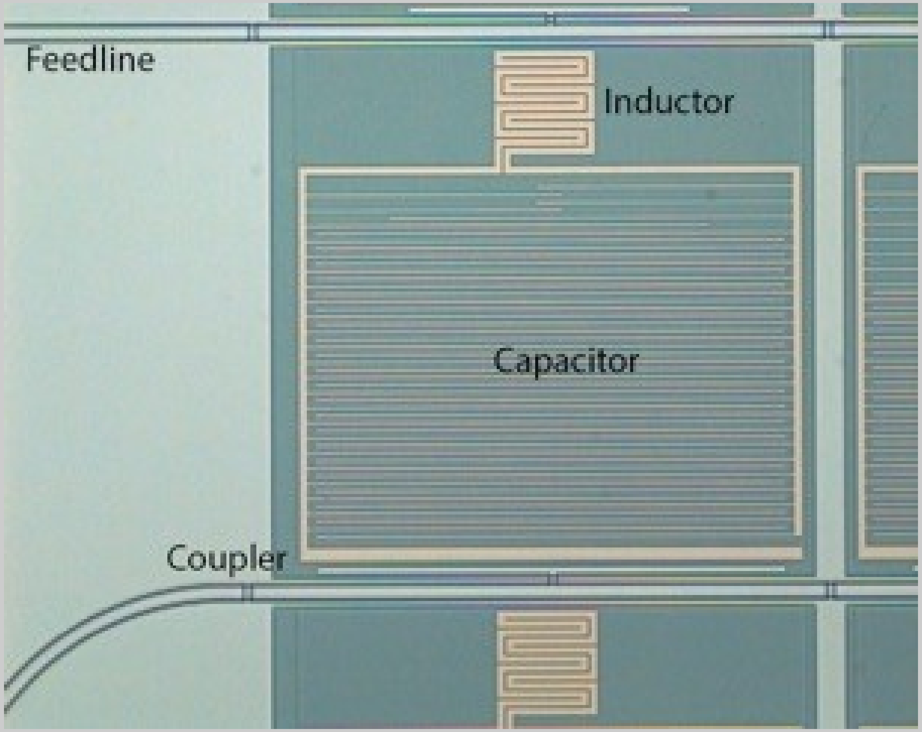


Image from Mazin group, UCSB

Decouple L and f.

Easy to achieve low frequencies.

But, matching free space impedance constrains inductor.

Dual-pol & multi-band designs are challenging

Resonator-bolometer or thermal KID (tKID): measure thermal pair-breaking

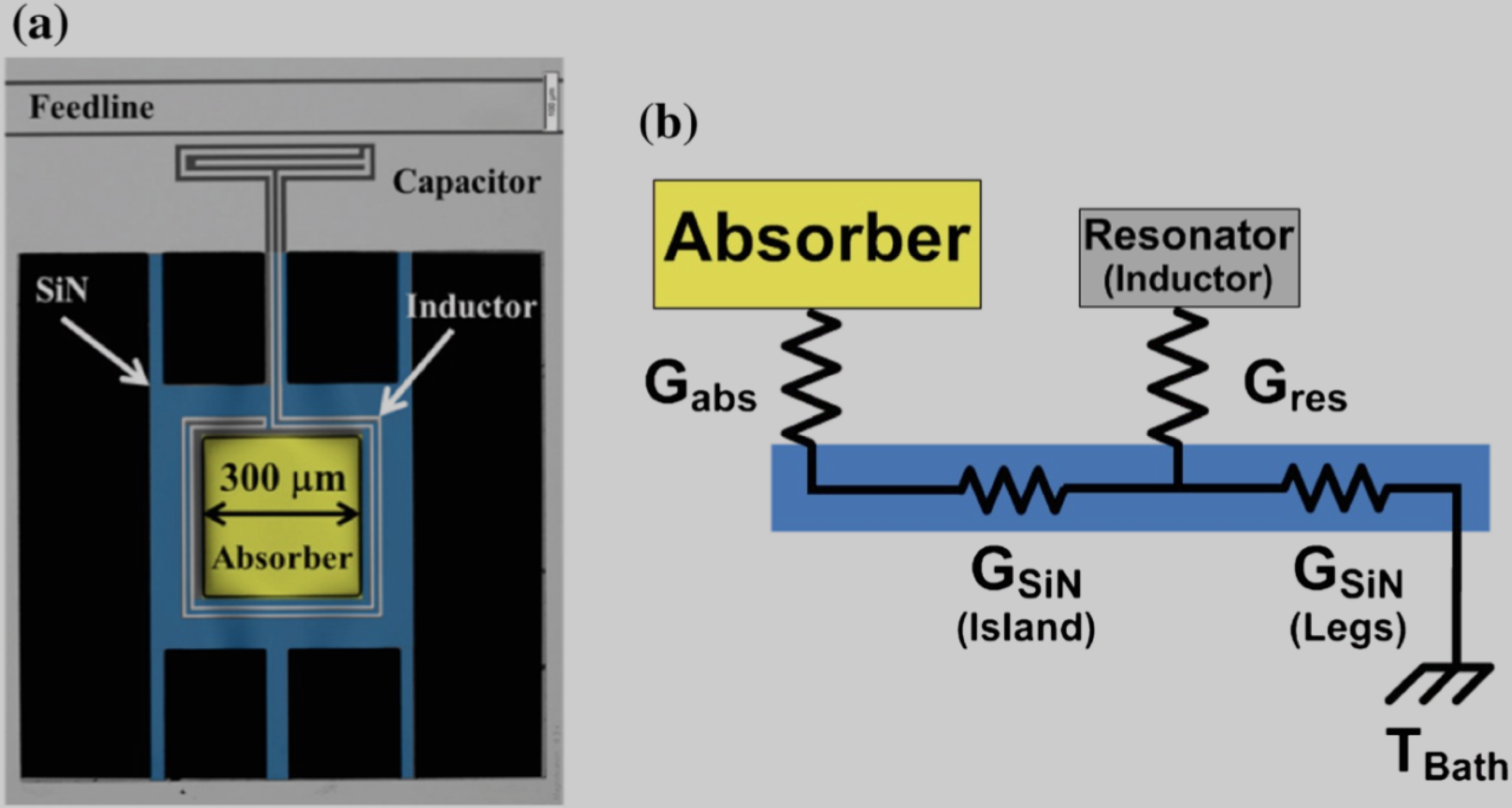


Image from Micelli group, ANL

Antenna or horn coupled LeKID: keeping the best features of each

Why an antenna or horn coupled LEKID?

Drop-in replacement for dual-pol, multi-band TESes.

Decouple absorber, inductor volume, frequency.

Can use either high-L_k or low-L_k materials (TiN, Al)

Materials: we're limited by nature, but there are several attractive choices

Optical cutoff: $\nu_{max} \lesssim 2\,\Delta \approx 73GHz \cdot T_c/1K$

Higher $R_{\text{normal}} \rightarrow$ higher $L_k \rightarrow$ higher response, lower freq.

Longer $\tau_{\text{recomb.}} \rightarrow$ higher response. Higher $Q_i \rightarrow$ denser mux.

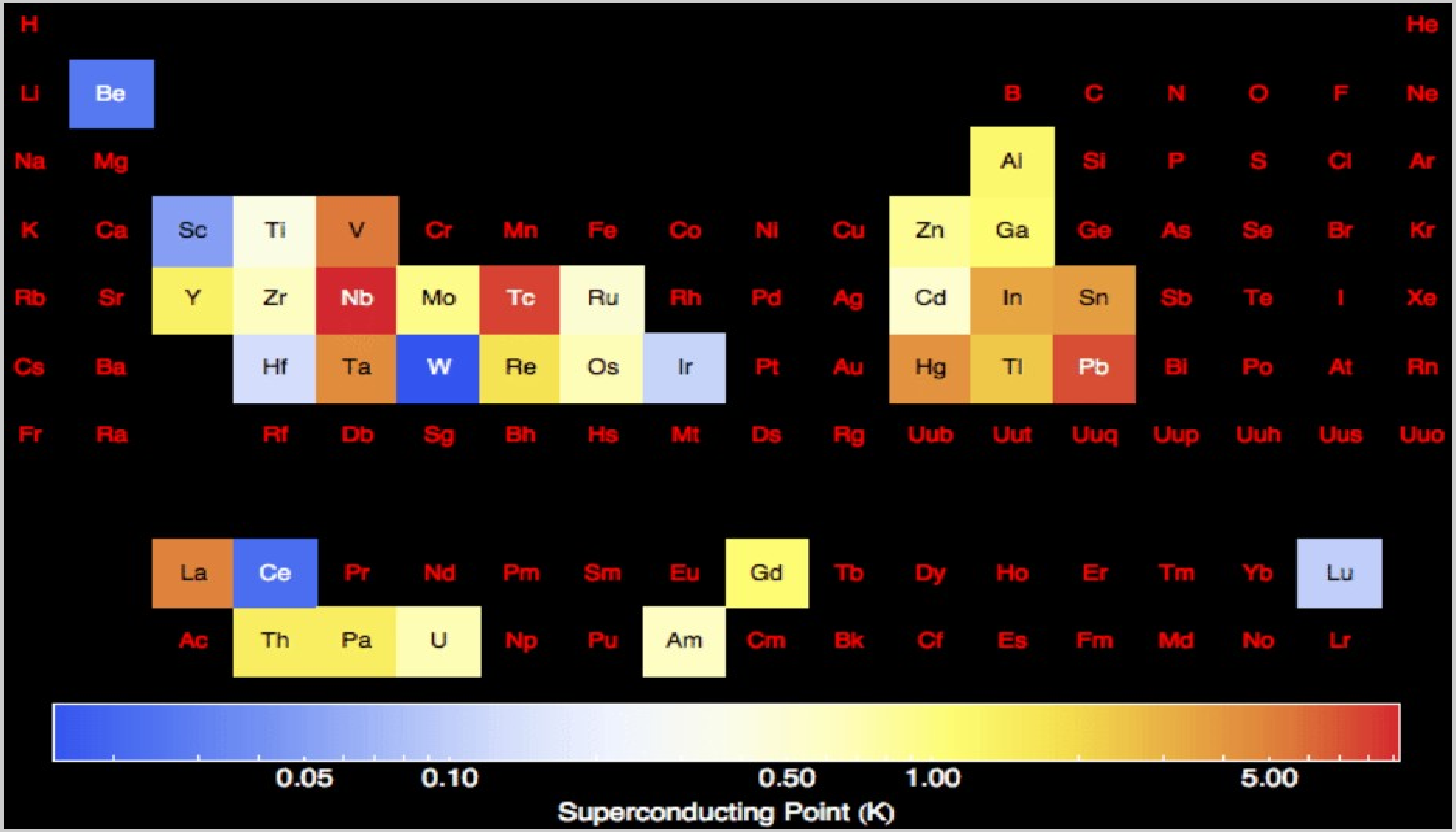


Image: periodictable.com

Aluminum: easy to make, well understood, and good enough for most applications.

Aluminum

Well described by theory (Mattis-Bardeen equations)

Easy to fabricate

Low L_k, but long τ

T_c $1.2\,\mathrm{K} \rightarrow 87\,\mathrm{GHz}$

Q_i few $\times\ 10^4$ limit multiplexing to ~ 500/octave.

Aluminum Manganese

Mn-doping of Al sputter target adjustably depresses Tc.

Well-explored as TES material.

Microwave properties are under study by several groups.

Titanium-Nitride: high Qs, low readout frequencies, demonstrated performance.

Sub-stoichiometric titanium nitride (TiN)

Nitrogen content determines $0.6\,\mathrm{K} \lesssim T_c 4.2K$

Very high $Q_i > 1 \times 10^6$ allows dense multiplexing.

Poorly fit by theory (Mattis-Bardeen equations)

Uniform sputtering is challenging.

High L_k, but moderate τ

Stoichiometric titanium nitride multi-layers

Adjust T_c using Ti or other normal metal in bi or tri-layer.

More uniform propeties when sputtered.

Compatible with atomic layer deposition.

Al multi-layers, novel materials.

Aluminum bi-layers

Use a multi-layer to lower Al Tc.

Al-Ti demonstrated with Al-like Qis.

Optical demonstrator in progress.

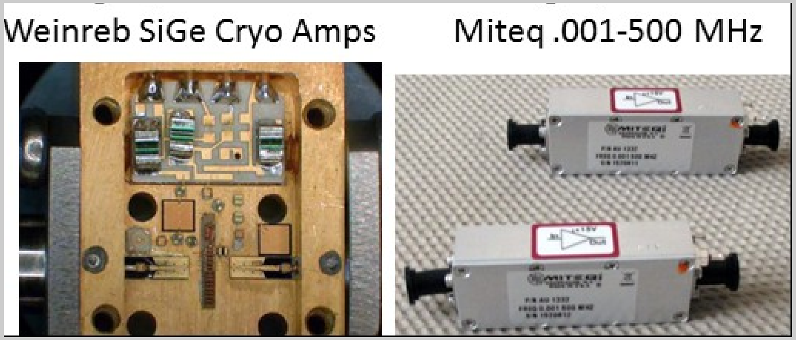
Short τ options

Tungsten-Silicide

Platinum-Silicide

CASPER-ROACH based FPGA systems: nearly off-the-shelf readout

CASPER-ROACH FPGA board:
Today: $10K, 500 Ch/octave X 1 octave



Cryogenic Low Noise Amplifiers
Today: $2-$4K per readout line

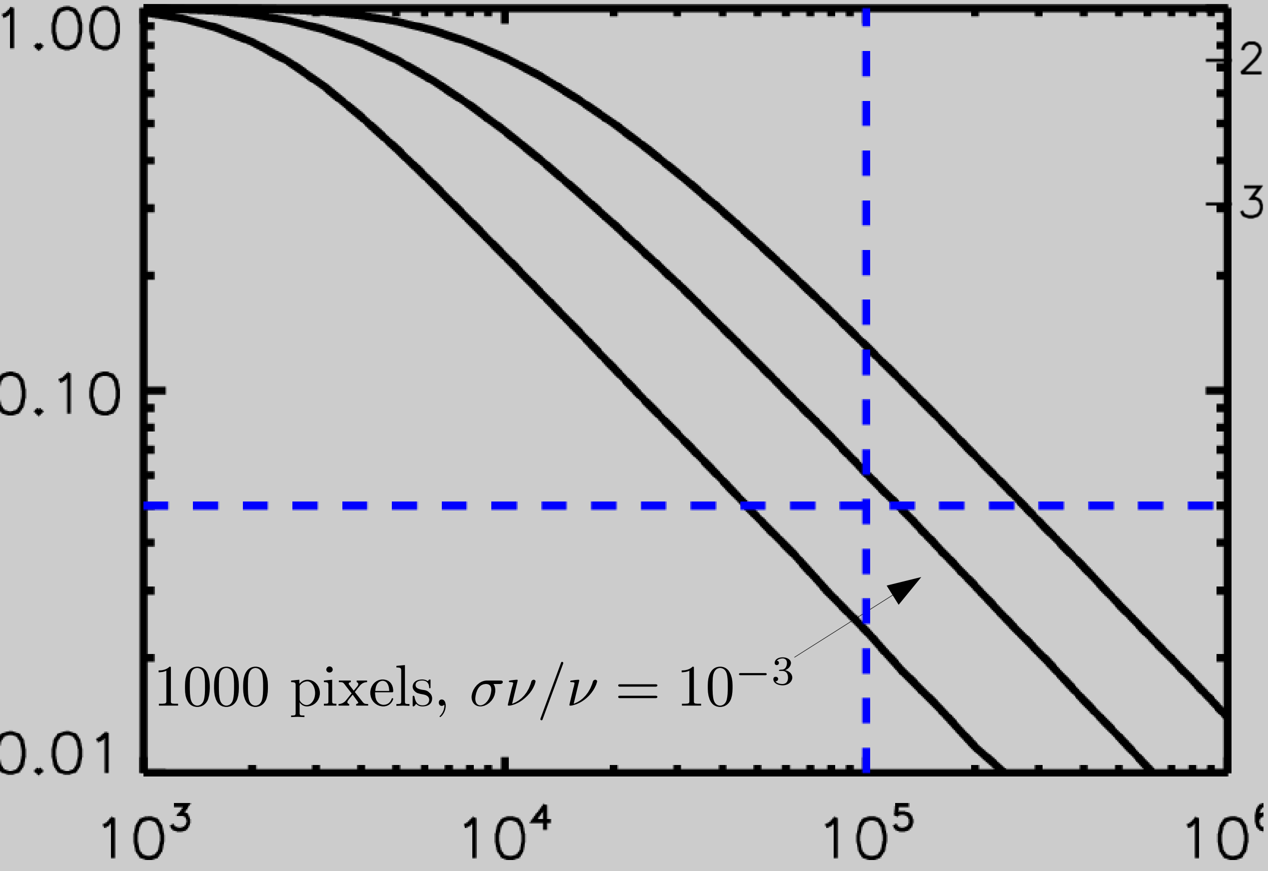
In Aug 2015, MAKO 500 pixel demo run cost $30/pixel for readout.

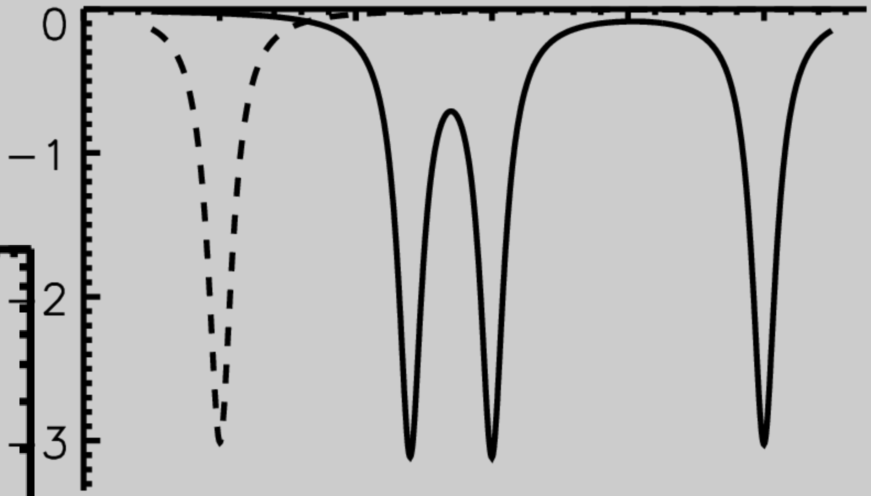
Reaching $10/pixel is straightforward. Reaching $1/pixel is possible. Other systems in development. (NIKA (NIKEL) FPGA, Stanford FPGA, Caltech GPU, Crimson commercial boards.)

Multiplexing density / yield trade off

MUX density dominated by resonator collisions

Higher Q, better uniformity → more channels





$$f_i = f_0 x^i + \delta_i \qquad \sigma = \sqrt{\langle \frac{\delta_i}{f_i} \rangle}$$

$$\text{Collision} \equiv f_i - f_j \leq 5 Q_i f_i$$

Figure based on Zmuidzinas internal memo

Fundamental sensitivity limits

$$\mathrm{NEP}^2 =$$

$$(\text{photon Poisson})^2 + (\text{photon Bose})^2$$

$$+(\text{recombination noise})^2$$

$$+1/R\cdot(\text{amplifier noise})^2$$

$$+1/R\cdot(\text{TLS Noise})^2$$

$$+\ (\text{small terms})$$

Background limit for all detectors

All pair breaking detectors.
For ground based CMB case:

$$\sim\ (\text{photon Poisson})^2$$

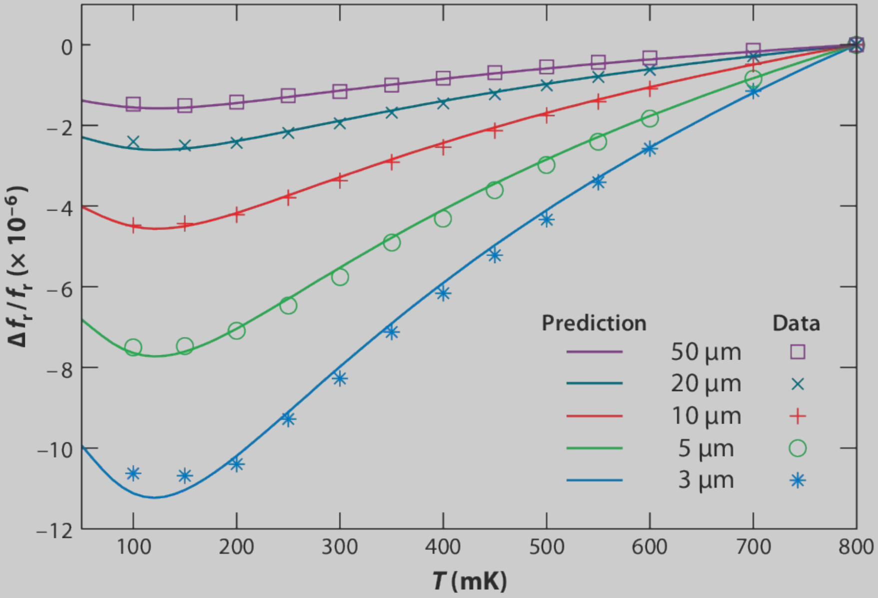
$$\sim f(\nu_{\text{readout}},\, Q,\, V_{\text{inductor}},\, T_{\text{c}})$$

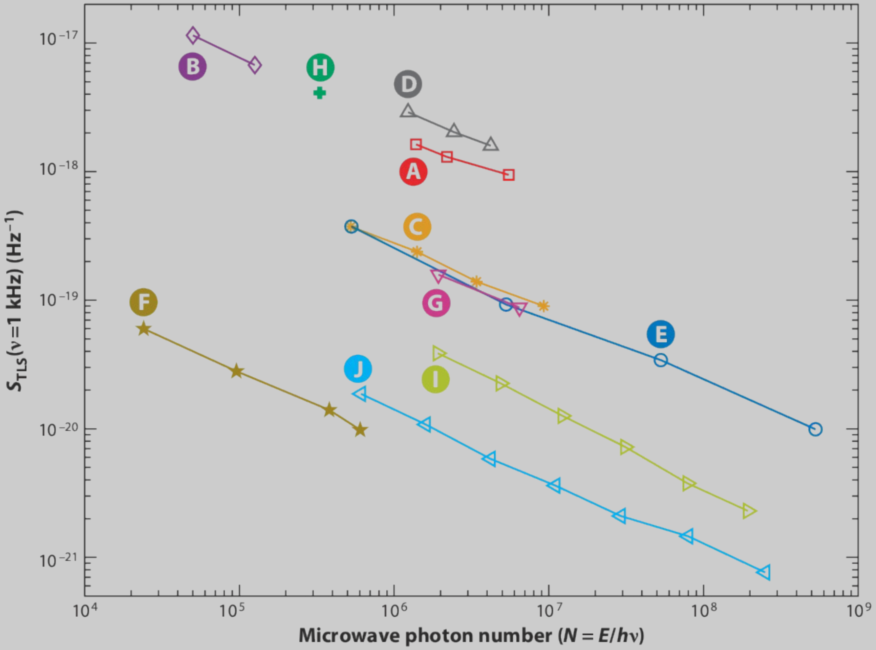
Two Level System Noise: hard to predict a priori, but follows known scaling laws

Attributed to tunneling states in amorphous dielectrics with broad microwave energy spectra.

Semi-emperical model of Gao et al. agrees with observations:

$$S_\nu \propto \nu^{-1/2} \qquad S_\nu \propto P_{\mathrm{ro}}^{-1/2} \qquad S_\nu \propto T^{-2} \qquad S_\nu \propto \frac{\int_{V_{\mathrm{tls}}} |\mathbf{E}|^3 d^3r}{\left(\int |\epsilon \mathbf{E}|^2 d^3r\right)^2}$$





Images: Zmuidzinas 12, J. Gao thesis

Sensitivity engineering: Thomas Edison science

In principle Mattis-Bardeen equations (and other BCS scalings) provide a full description of KID responsivity, G-R noise, and amplifier noise terms.

In practice, this works pretty well for aluminum, but poorly for other materials.

Solution: Iterate.
1. Make a KID, strive for clean surfaces.
2. Measure NEP.
3. Adjust design based on approximate scaling laws*:

$$\mathrm{NEP}_{\mathrm{TLS}} \propto Q_r^{1/4}\, T_c^3\, V_L^{0.75}\, T_{\mathrm{opp}}^{-0.35}$$

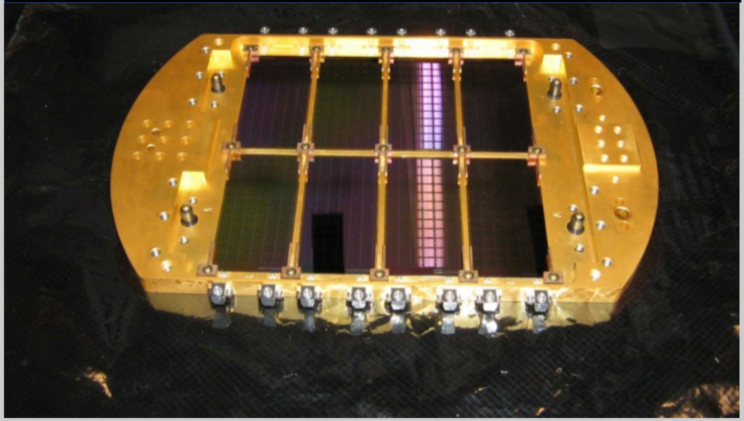
$$\mathrm{NEP}_{\mathrm{amp}} \propto T_{\mathrm{amp}}^{0.5} \left(Q_c/Q_r\right)^{0.5} T_c^{2.5}\, V_L^{0.5}\, T_{\mathrm{opp}}^{0.5}$$

4. GOTO 1.

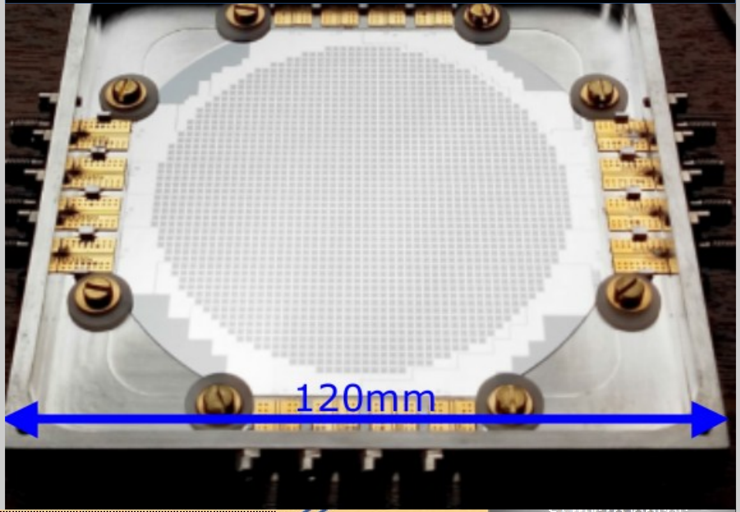
* In this case, for a resonator operating at a fixed fraction of bifurcation power in the linear-response regime.

On-sky cameras

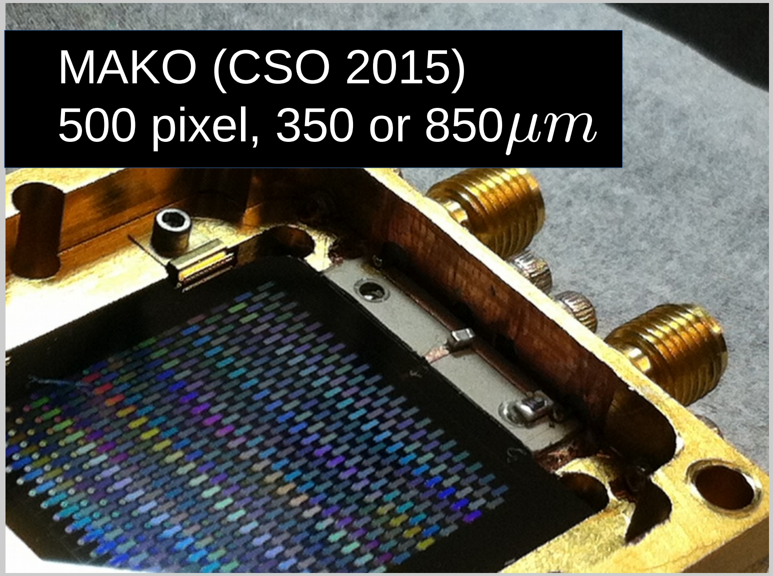
MUSIC: CSO 2012-2015
576 4-color pixels, 2mm-850μm

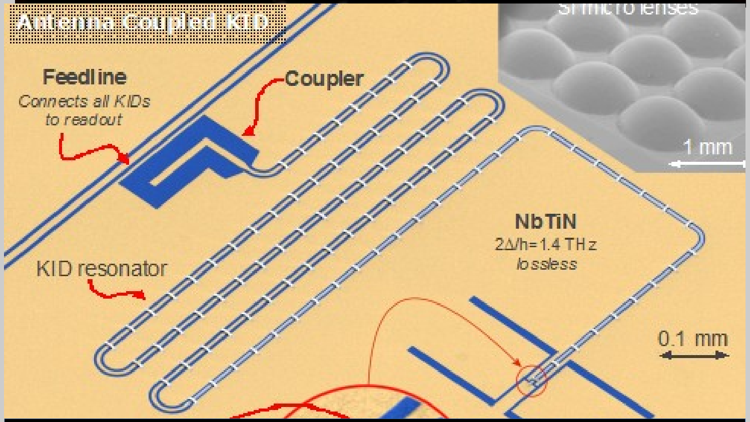


NIKA / NIKA2 (IRAM 2011-pres.)
300/5000 1.25 and 2mm pixel



MAKO (CSO 2015)
500 pixel, 350 or 850μm

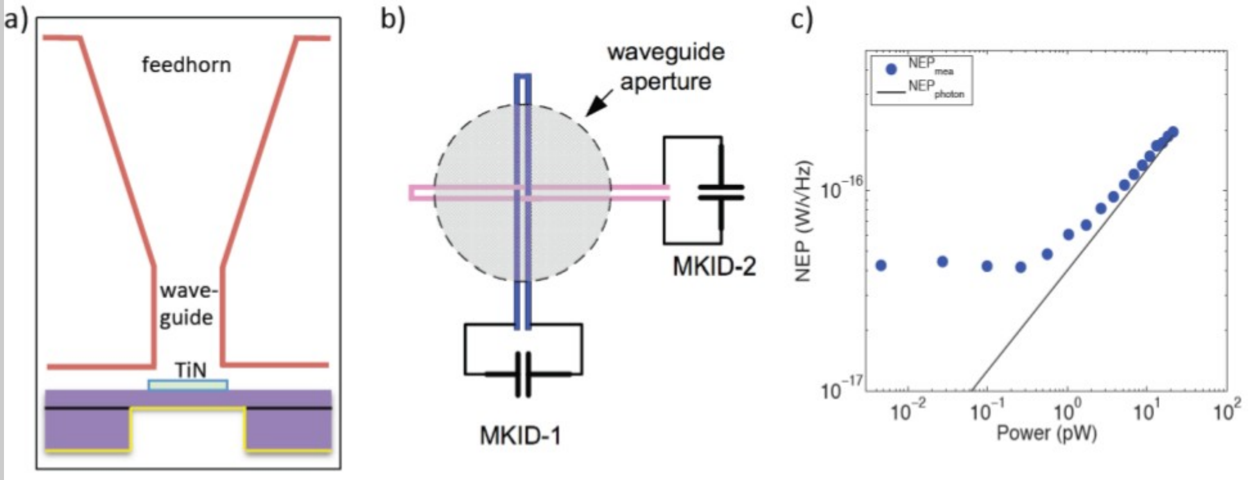




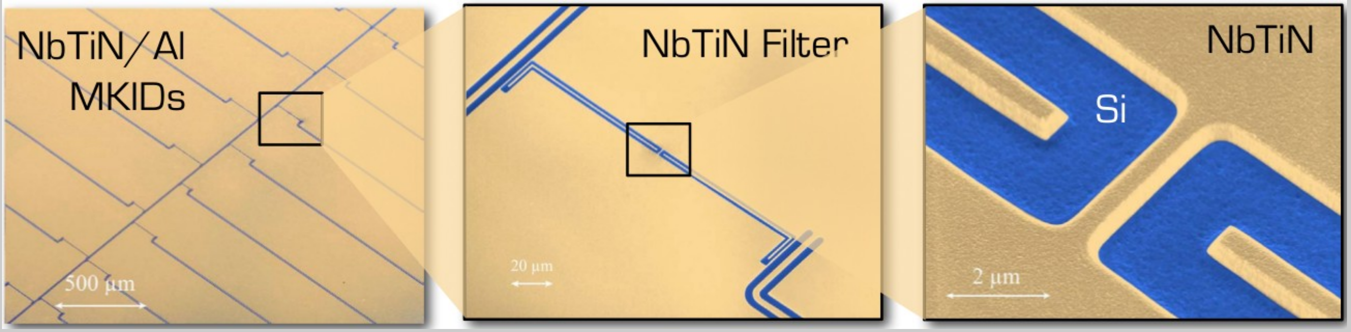
A-MKID (APEX 2015-pres.);
~20kpixel, 350 & 850μm

Many near term projects and demonstrators. (Some are even funded.)

Golwala BB TiN
JPL TKIDs
BLAST TNG
E.U. SPACE-KIDs
GroundBird
LITEBird KIDs
uSpec
DESHIMA
X-Ray groups

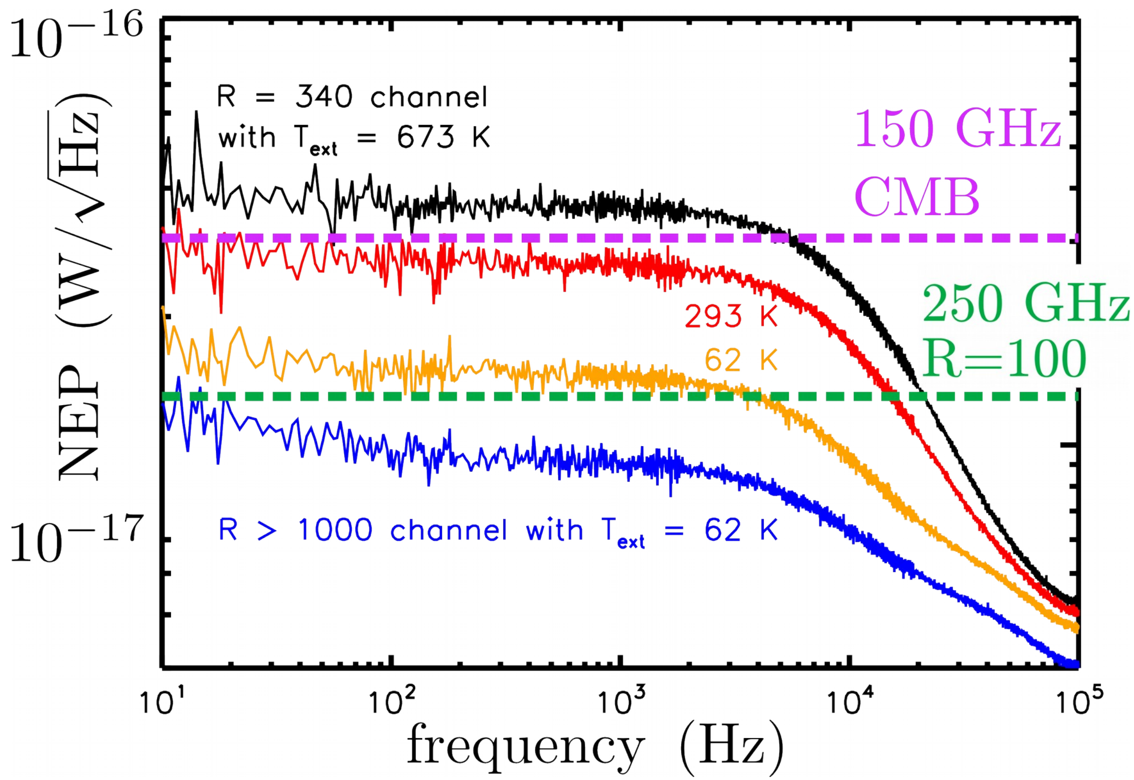


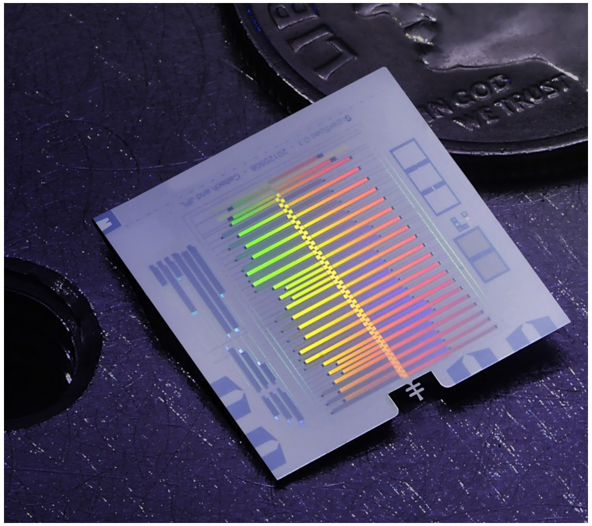
BLAST TNG prototype, from Galitzki+14

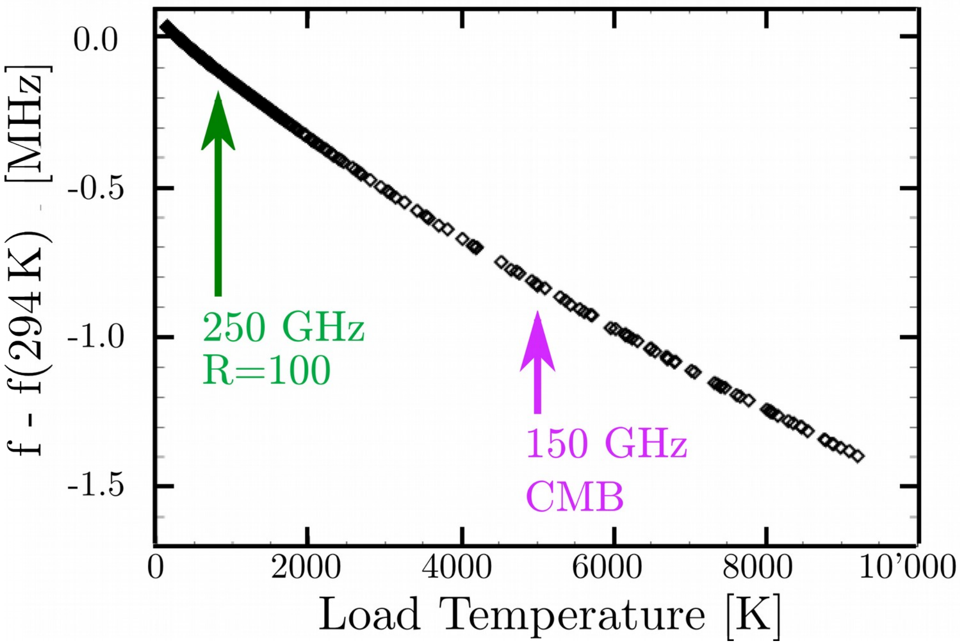


DESHIMA devices, image from A. Endo

Existing KIDs already meet requirement for a broad-band CMB pixel.







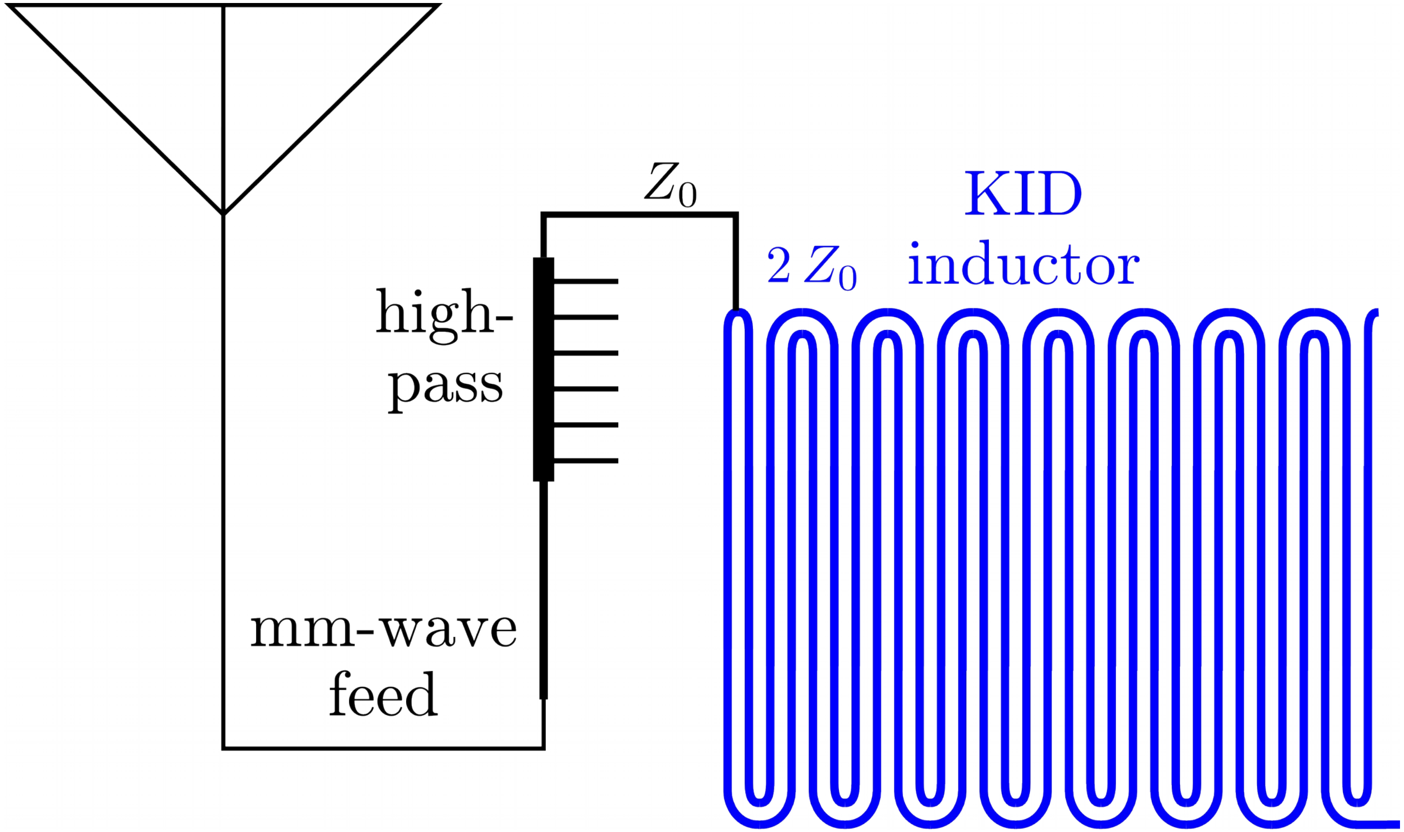
Conservative, P/V conserving estimates:

$90GHz : 5pW/\sqrt{Hz}$

6× below background limit

Fig by S. Hailey-Dunsheath

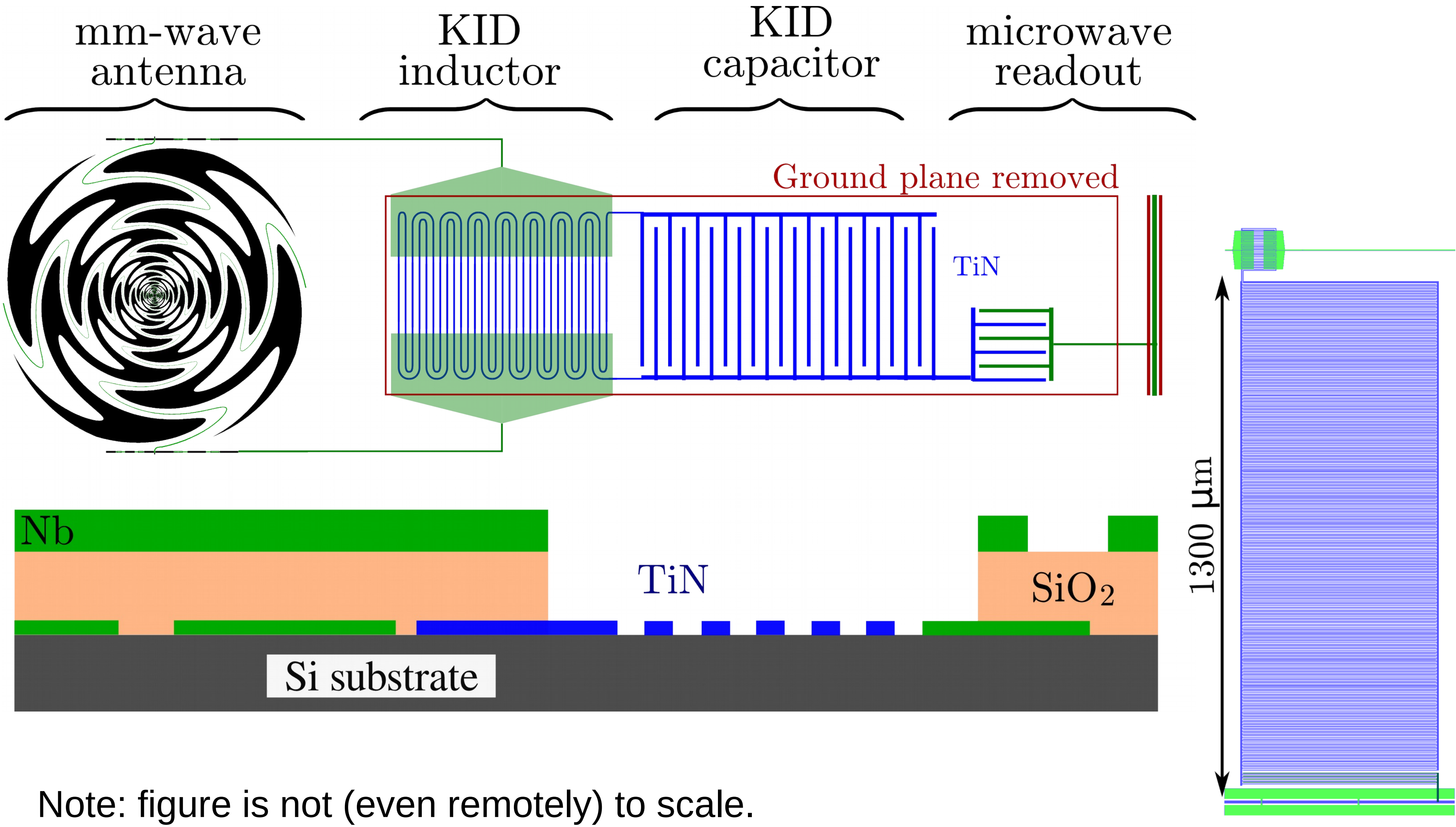
Impedance matched microstrip works for low-impedance materials (Al)



For materials with R_{normal} few $\Omega/\square$, either transmission-line KID or LeKID can work as dissipative mm-wave microstrip.

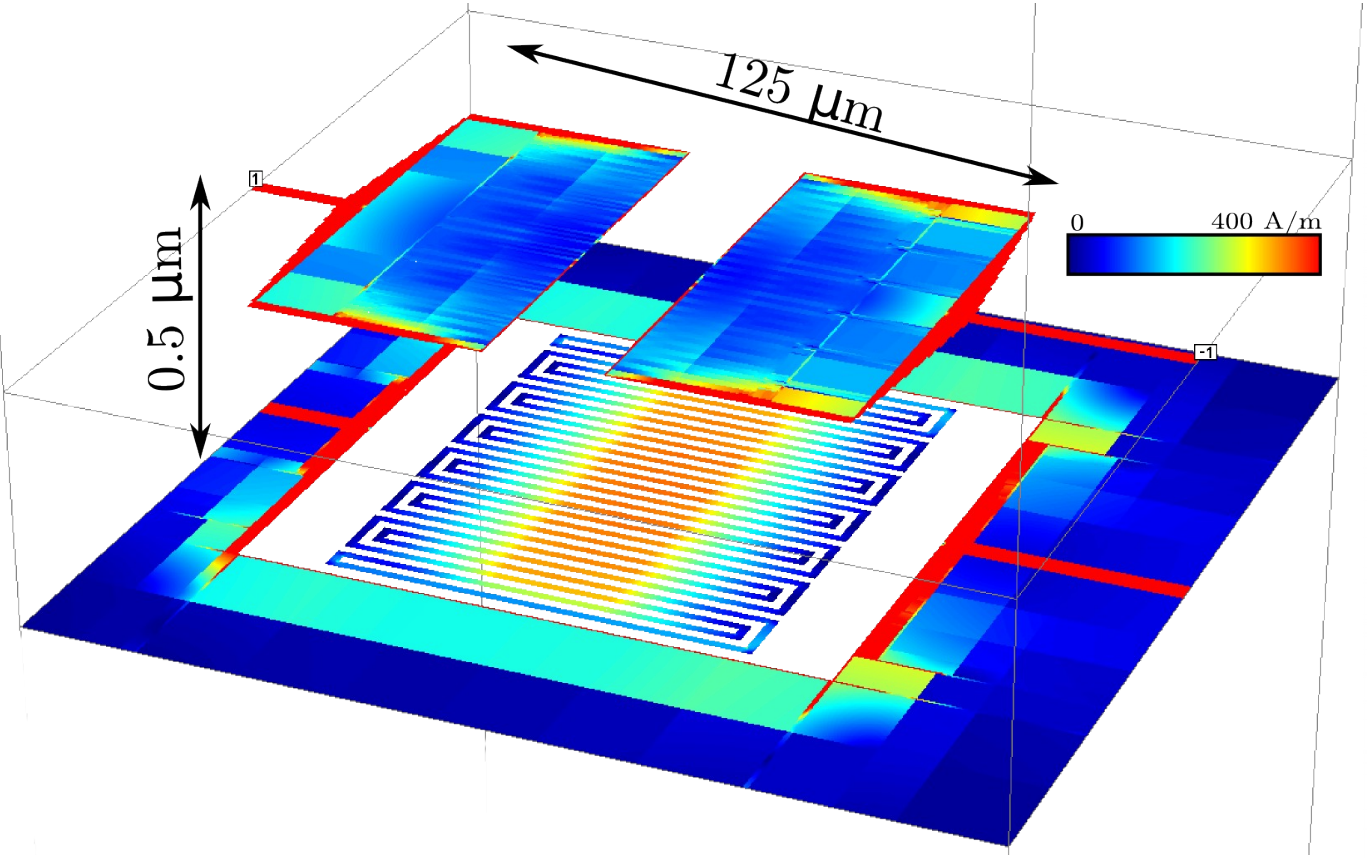
We're building an Al demonstration now. Goddard's mu-Spec uses this approach already.

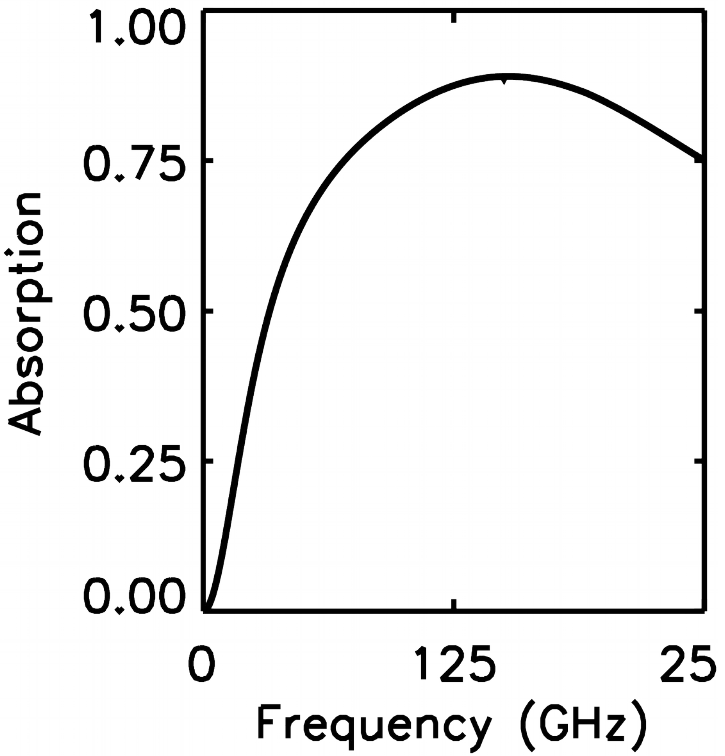
Chicago's CMB-KIDs program: Antenna-coupled, multi-band CMB pixels



Note: figure is not (even remotely) to scale.

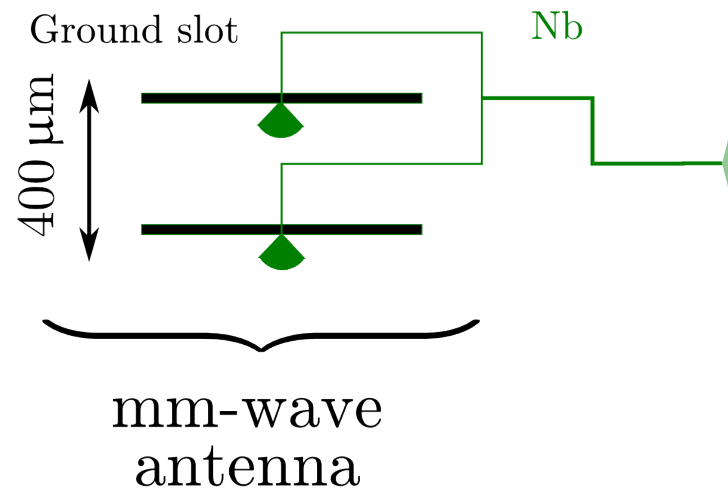
Broad-band mm-wave feed line to detector coupling is a new challenge.

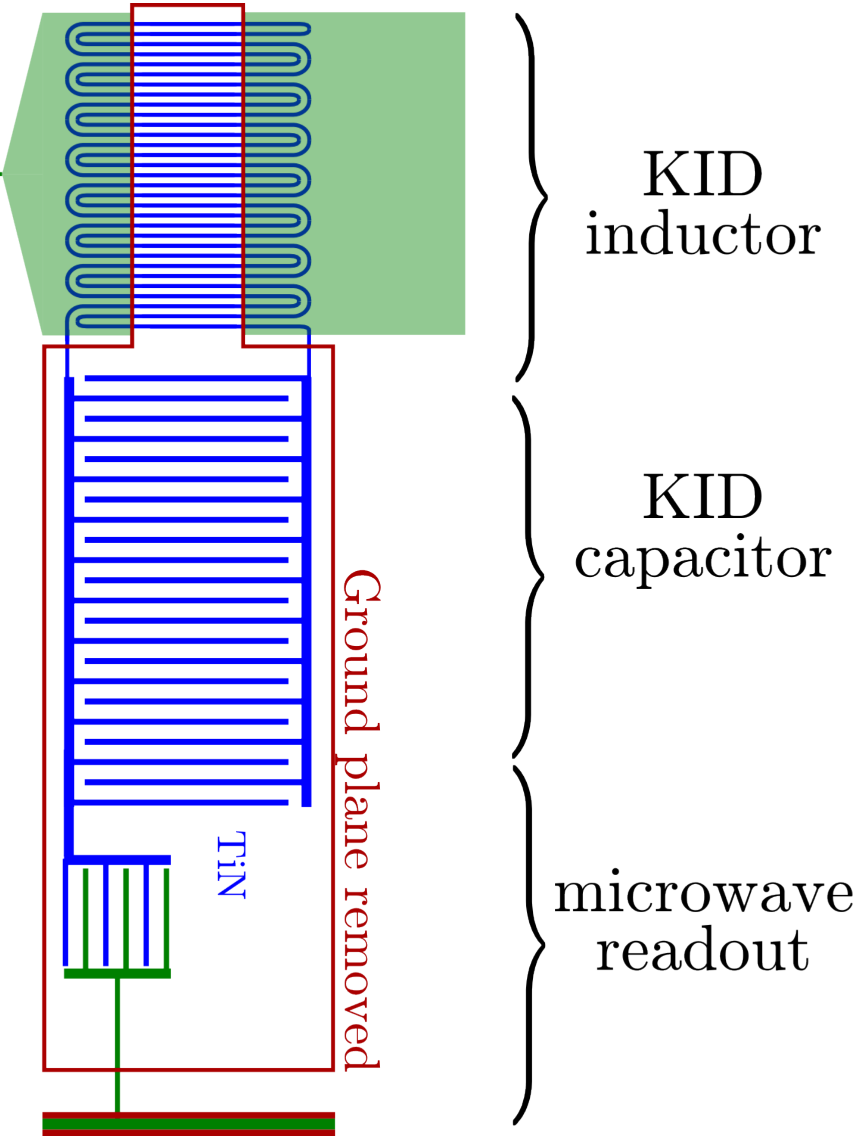




With very little optimization, this approach achieves >90% over any single CMB band. Further optimization seems likely to yield universal, multi-band coupling designs.

Short-term optical test #2: twin-slot coupled single-band, single-pol, KIDs





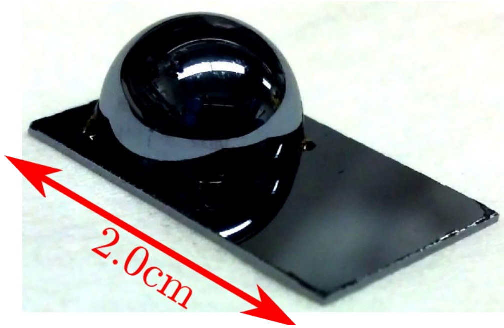
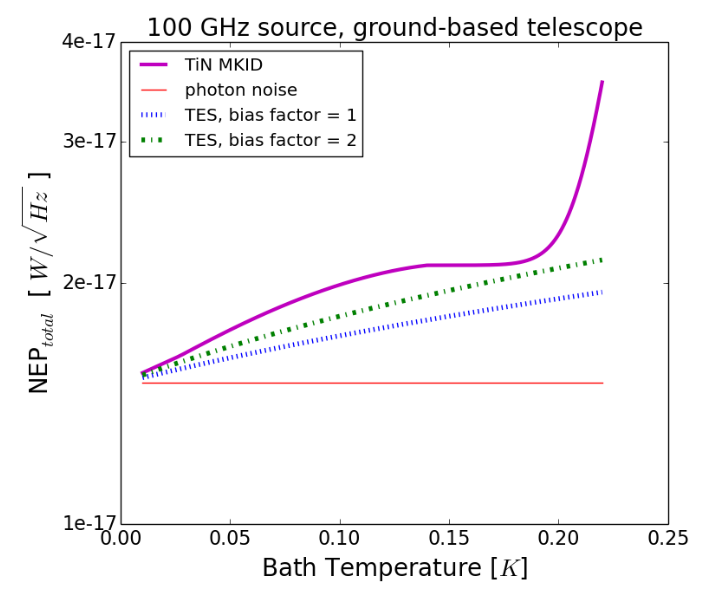
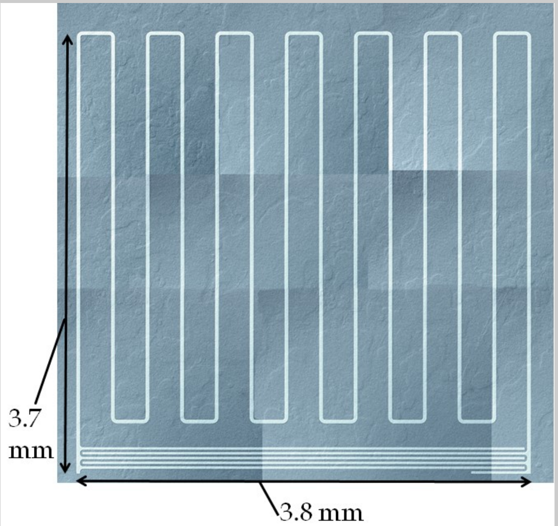


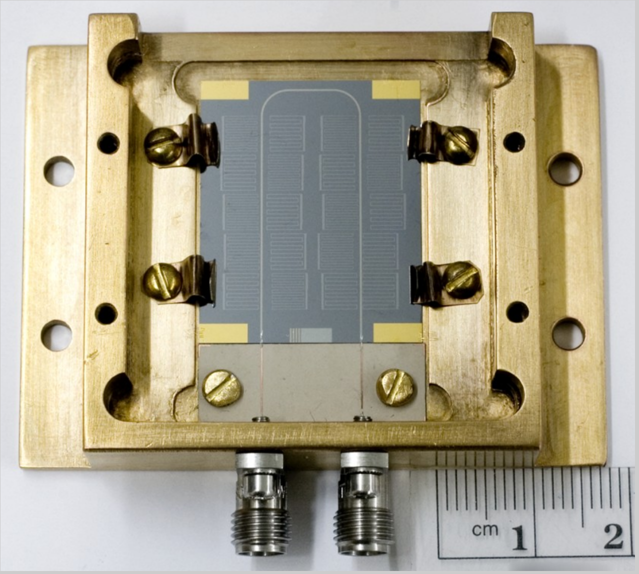
Image: SuperSpec test pixel

Note: figure is not (even remotely) to scale.

Wisconsin & Goddard CMB KIDs: TiN direct absorber for QUBIC



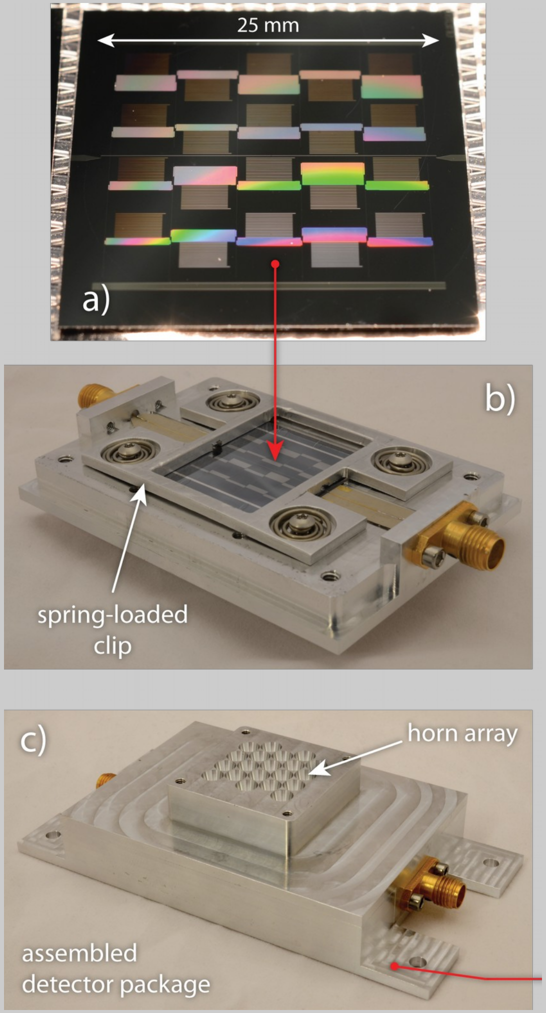




- At 100 mK, a 100 GHz KID pays a 10% penalty in NEP compared to a TES with a readout bias factor of 2.

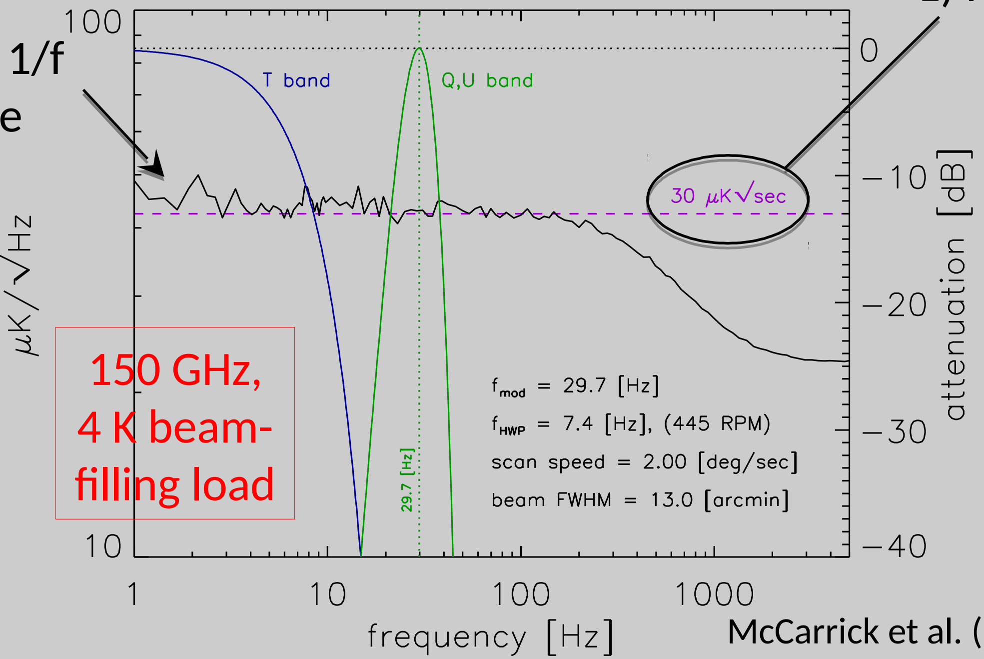
Courtesy of A. Lowitz, A. Brown, V. Mikula, T. Stevenson, P. Timbie, and E. Wollack

Columbia CMB KIDs: thin Al LeKIDs from a commercial vendor for ground based CMB



1) low NET

2) low 1/f noise



150 GHz, 4 K beam-filling load

McCarrick et al. (2014) RSI, 85, 123117.

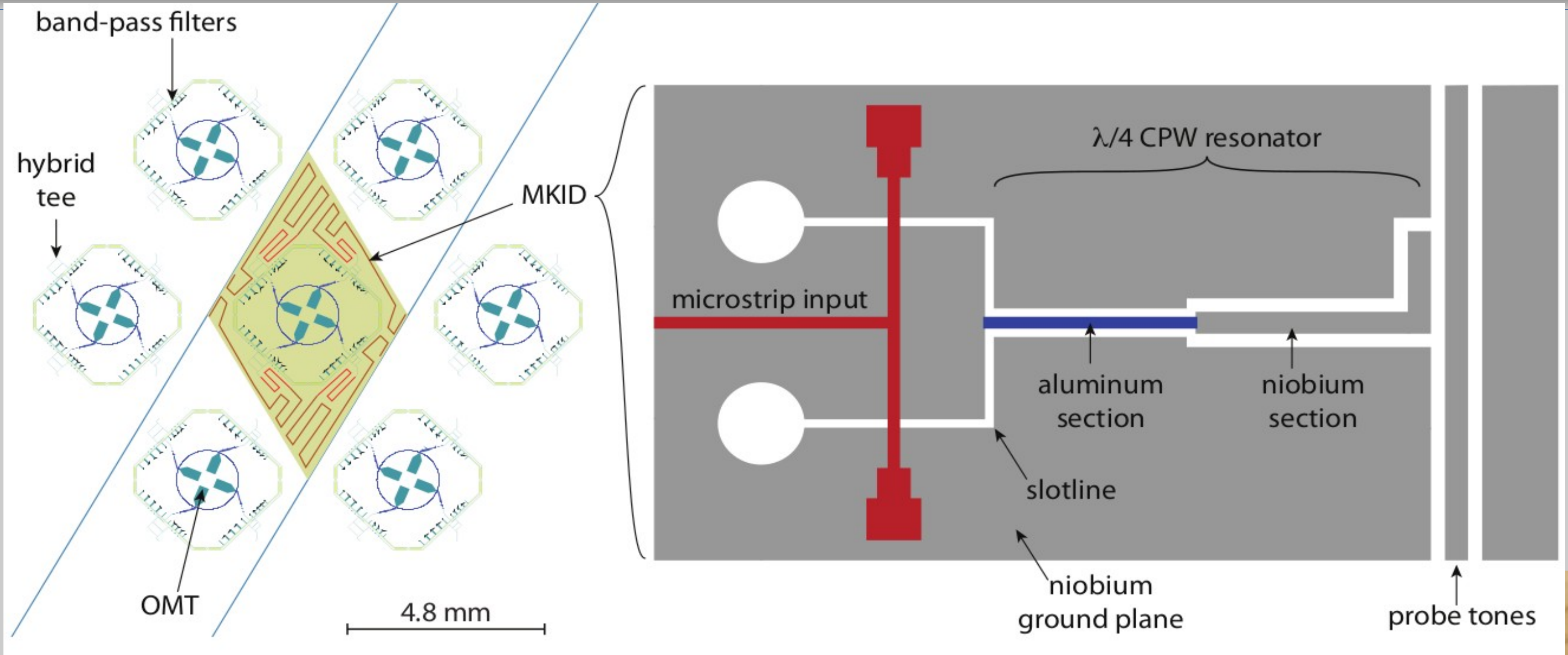
3) lots of bandwidth

Measured photon noise for single layer direct absorber leKIDs from a commercial fabrication house.

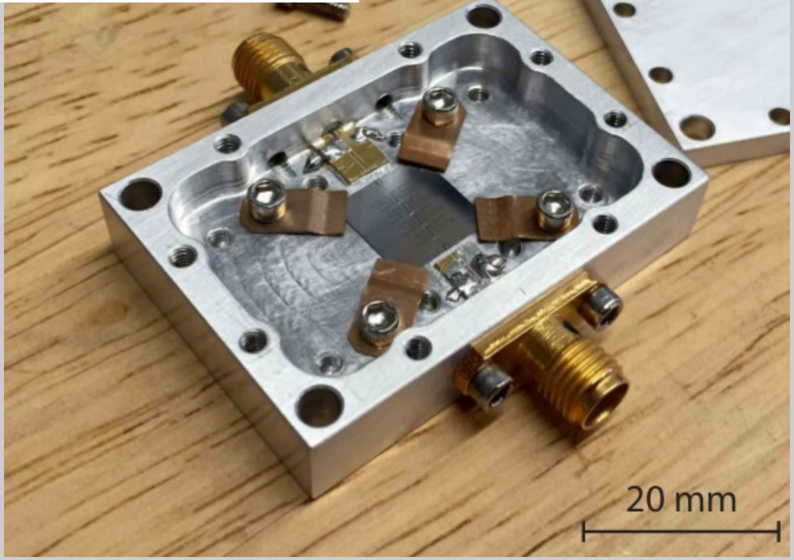
Dual-pol prototype now being tested. Multichroic horn+OMT pixels in design.

All figures: B. Johnson

Columbia/SLAC multi-band, horn-coupled CMB MKIDs.



Figures from Johnson+ 2016



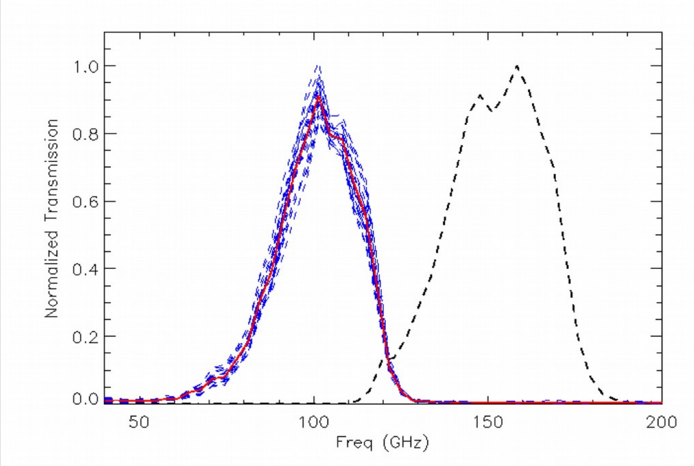
Dual-pol horn-coupled KIDs.

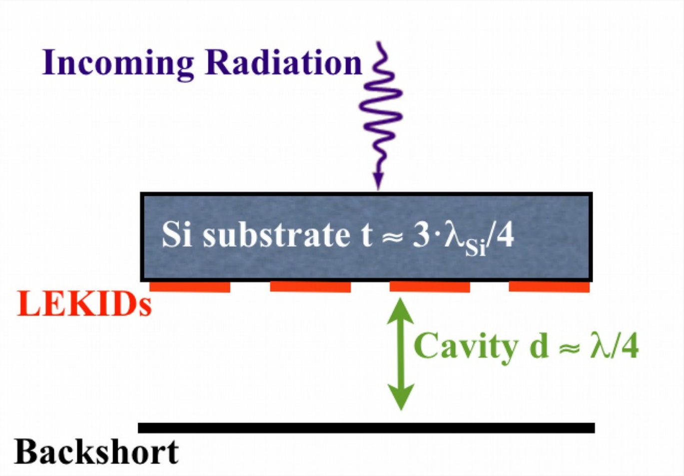
OMT and band-defining filters.

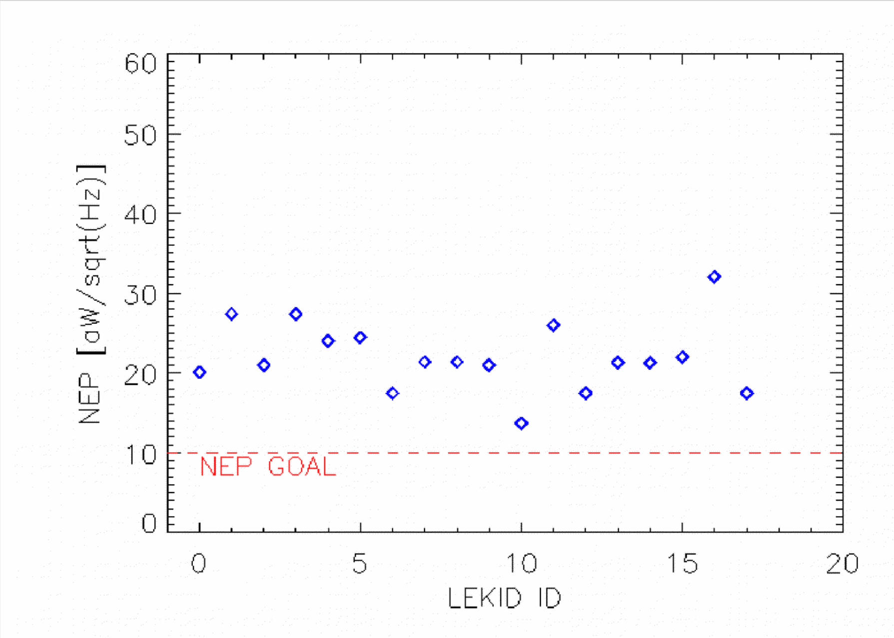
Al CPW KIDs.

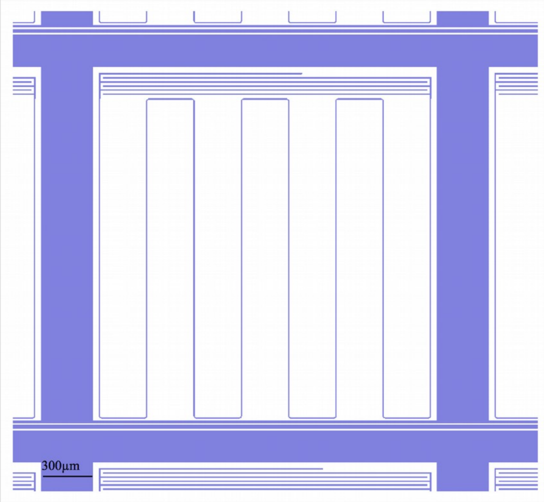
Al-Ti bilayer 100 MHz kids from Grenoble

Tc~900 mK, F0~ 1.5 GHz, Qi~8*10^4



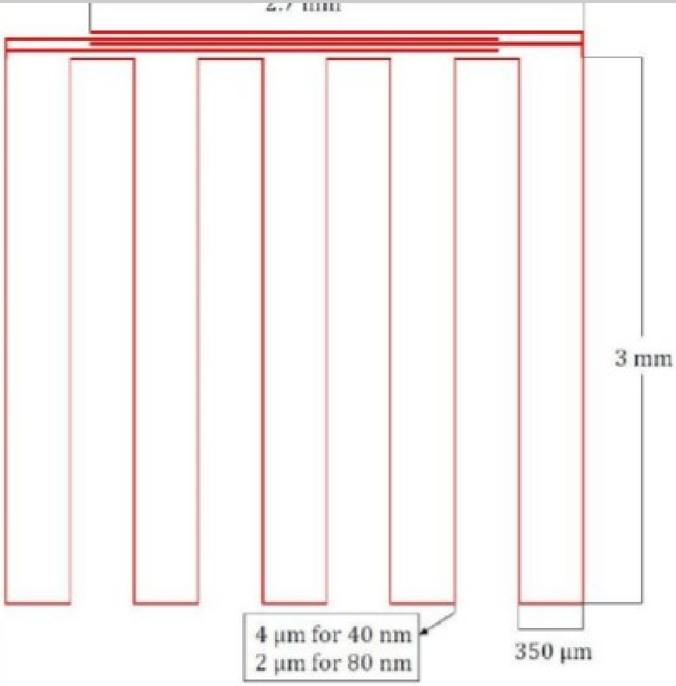


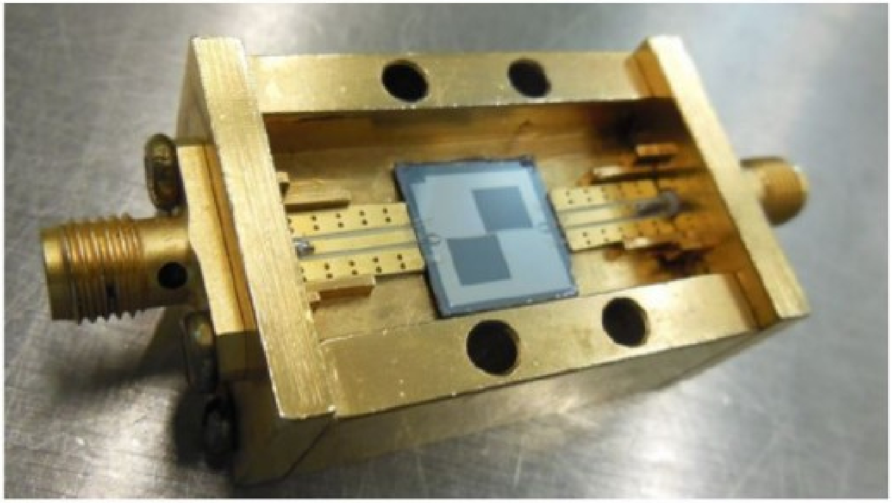




All figures from Catalano+15

90 GHz Al-Ti bilayer horn-coupled LEKIDs from Rome





Goal: 90 GHz horn-coupled demonstrator for the SMT.
Currently have optical tests of Al pixels, plans to test Al-Ti bi-layers.

Figure from Paiella+ 2016

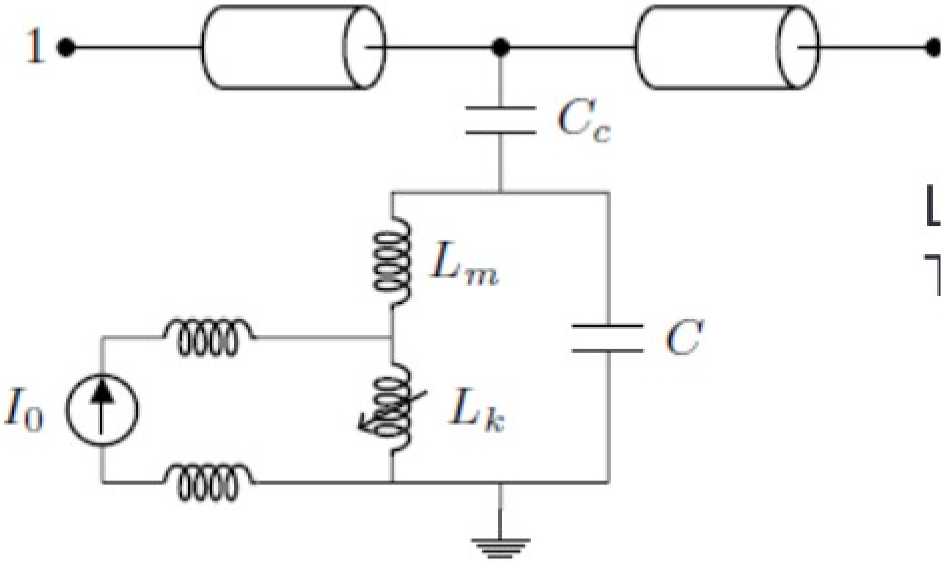
Novel non-linear kinetic inductance devices: the KPUP as a SQUID replacement

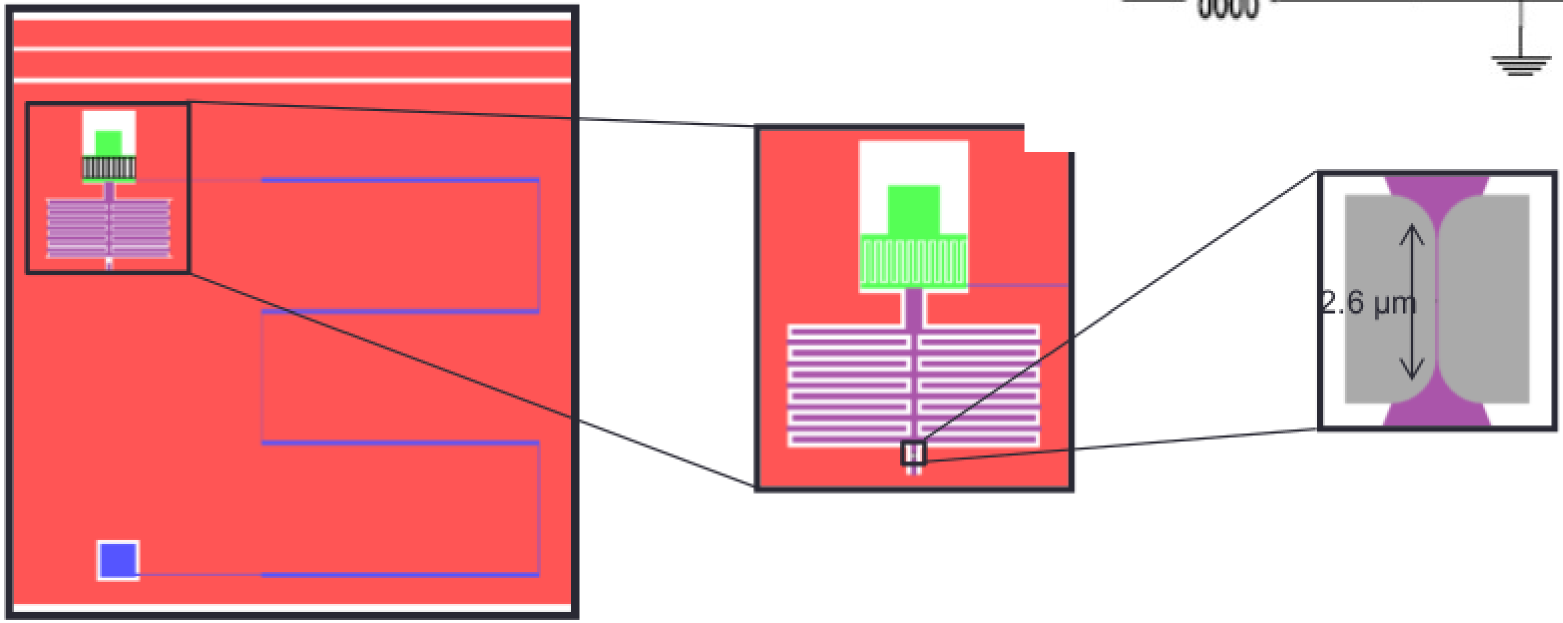
Use a KID to read out TES currents.

Demonstrated $8\,\mathrm{pA}/\sqrt{\mathrm{Hz}}$ with resistors

Tests with TESes under way.

Needs $\sim 10\,\mathrm{nm}$ features (for now).





Images from P. Day group (JPL)

Conclusions and subjective opinions I

KIDs today are more mature than TESes were in early 2006, 1 year before SPT, ACT, APEX-SZ deployment.

KIDs have demonstrated:

- Operation in CMB bands.
- NEP for BL at a good CMB site
- High photon-QP conversion efficiency
- On-sky science publications

What's left to do?

- Demonstrate all of these at the same time.
- Yield & NET uniformity for large arrays.
- 1/f noise under realistic conditions.
- On-sky, dual-pol NETs.

KIDs *will* play a role in near-term submm-science, CMB-S5, future space telescopes.
What about CMB-S4?

Conclusion and subjective opinions II

Consensus from the last CMB-S4 meeting (as interpreted by me):

KIDs are promising and we should consider them for S4.

An on-sky demo of dual-pol KIDs for CMB bands from a good site, with published NET and 1/f in the next 2-3 years is vital to convince the community to try KIDs.

Current US funding $\lesssim$ $1M/yr, through NSF and NASA PI grants, fellowships, institutional seed grants. Combined EU and Japan funding is similar.

CMB KIDs are an important moderate-risk / high-reward component of a diversified future CMB science portoflio. A small investment soon could have significant benefits.