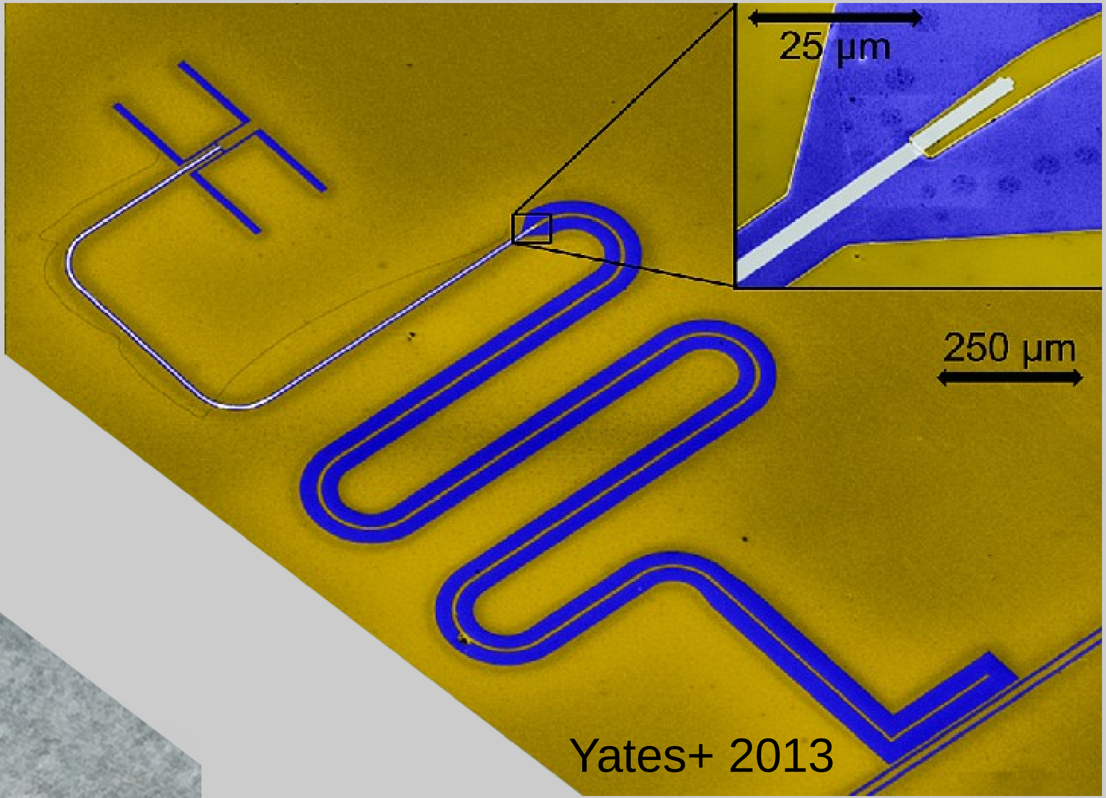
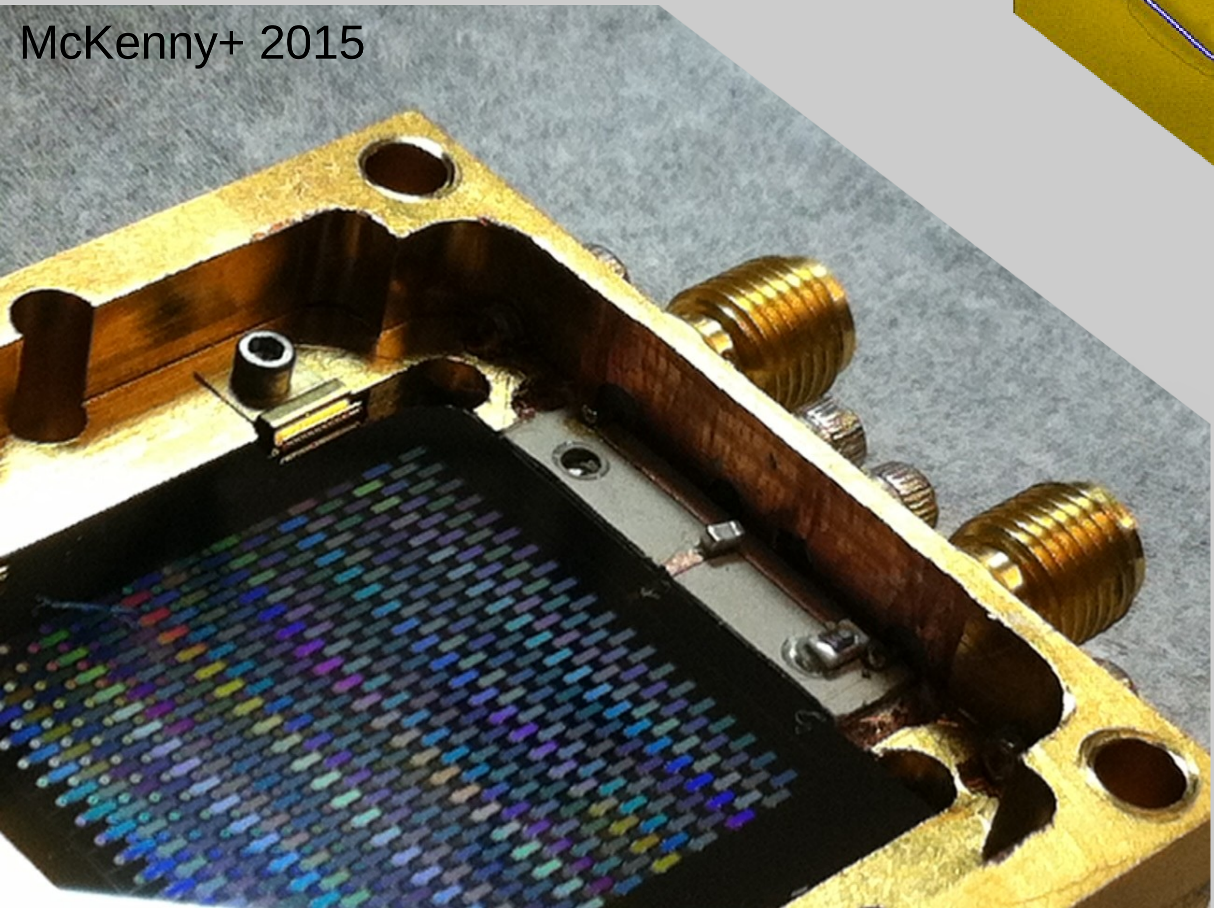
Kinetic Inductance Detectors for the CMB: faster, cheaper, just as good

Erik Shirokoff

University of Chicago





CPAD Instrumentation Frontier Meeting

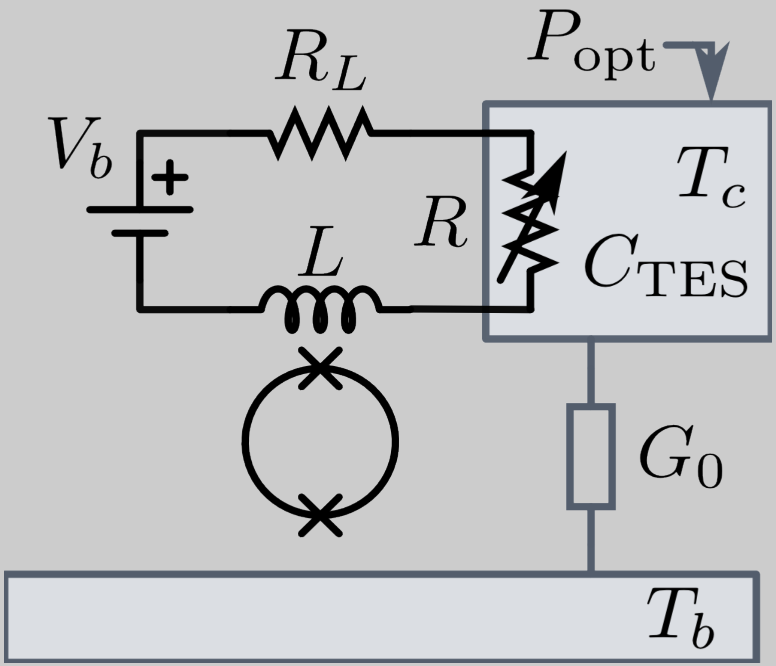
Arlington, TX

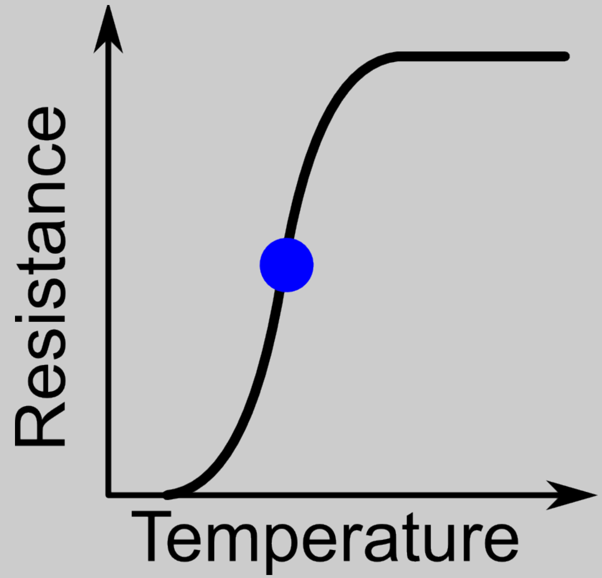
6 October 2015

Outline

- TES bolometers: the good, the bad, and the fabrication challenges
- Introduction to the kinetic inductance detector
- The state of the art: current and near-term experiments in the submm and mm-wave
- CMB KIDs
- Novel non-linear kinetic inductance devices
- Common myths
- Conclusions and questions

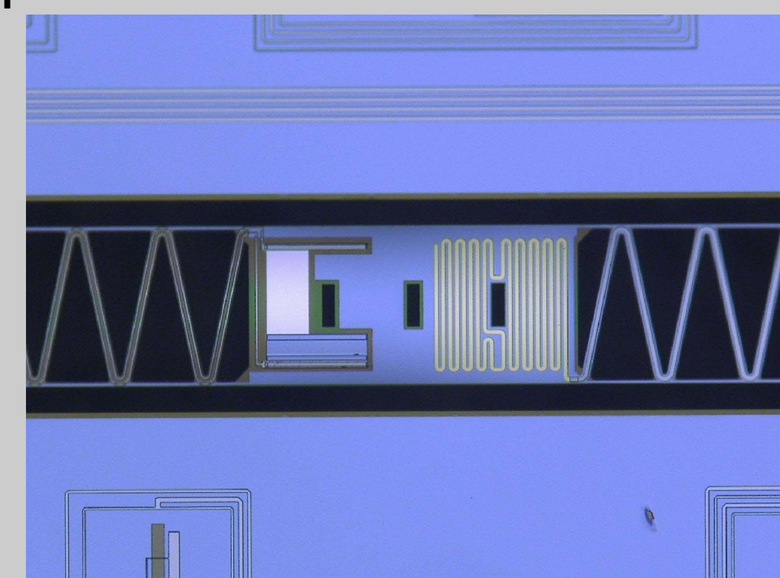
Features of TES bolometers





Sensitivity is *entirely* determined by two parameters:
G(T), Tc.

A decade of fielded kilopixel science instruments :
~10^6 person-hours already spent turning photons into CMB maps



SPIDER TES

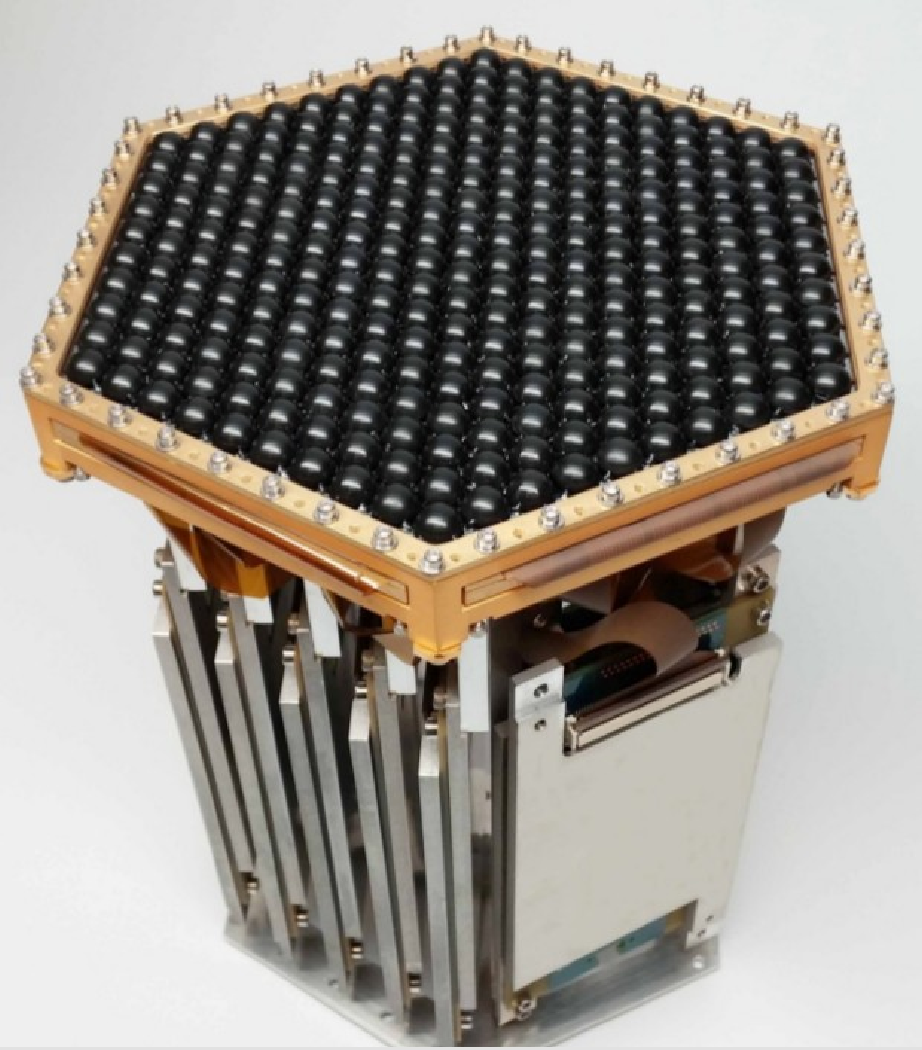
Failures of TES bolometers

Complicated fabrication:
 thermal properties hard to predict:
 10^{Th} good wafer as hard as 1^{st} good wafer
 (perhaps 100^{th} will be easier?)

SQUID readout is complicated and expensive
 No on-chip multiplexing yet
 Crosstalk and stability are a challenges

Limited dynamic range:
 You have to get G, Tc just right!

Integration and testing is hard!



PolarBear-2 module

The kinetic inductance effect

The DC case:

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

The AC case:

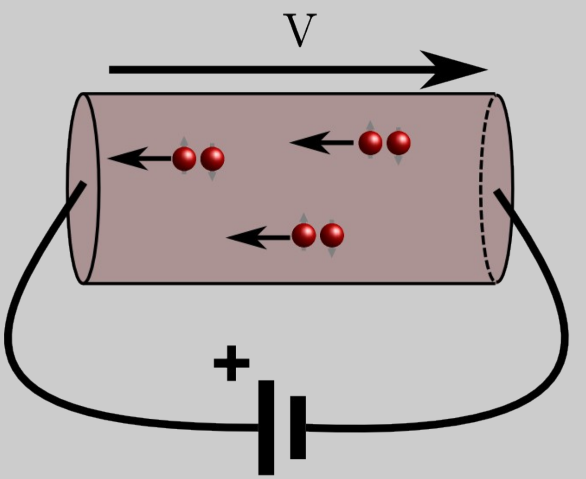
Cooper pairs have momentum.
Acceleration leads to a phase shift between I and V.
This acts like an inductance!

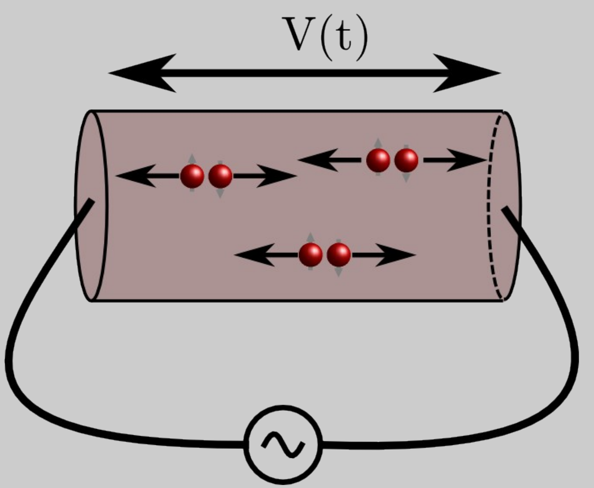
At low temperature:

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

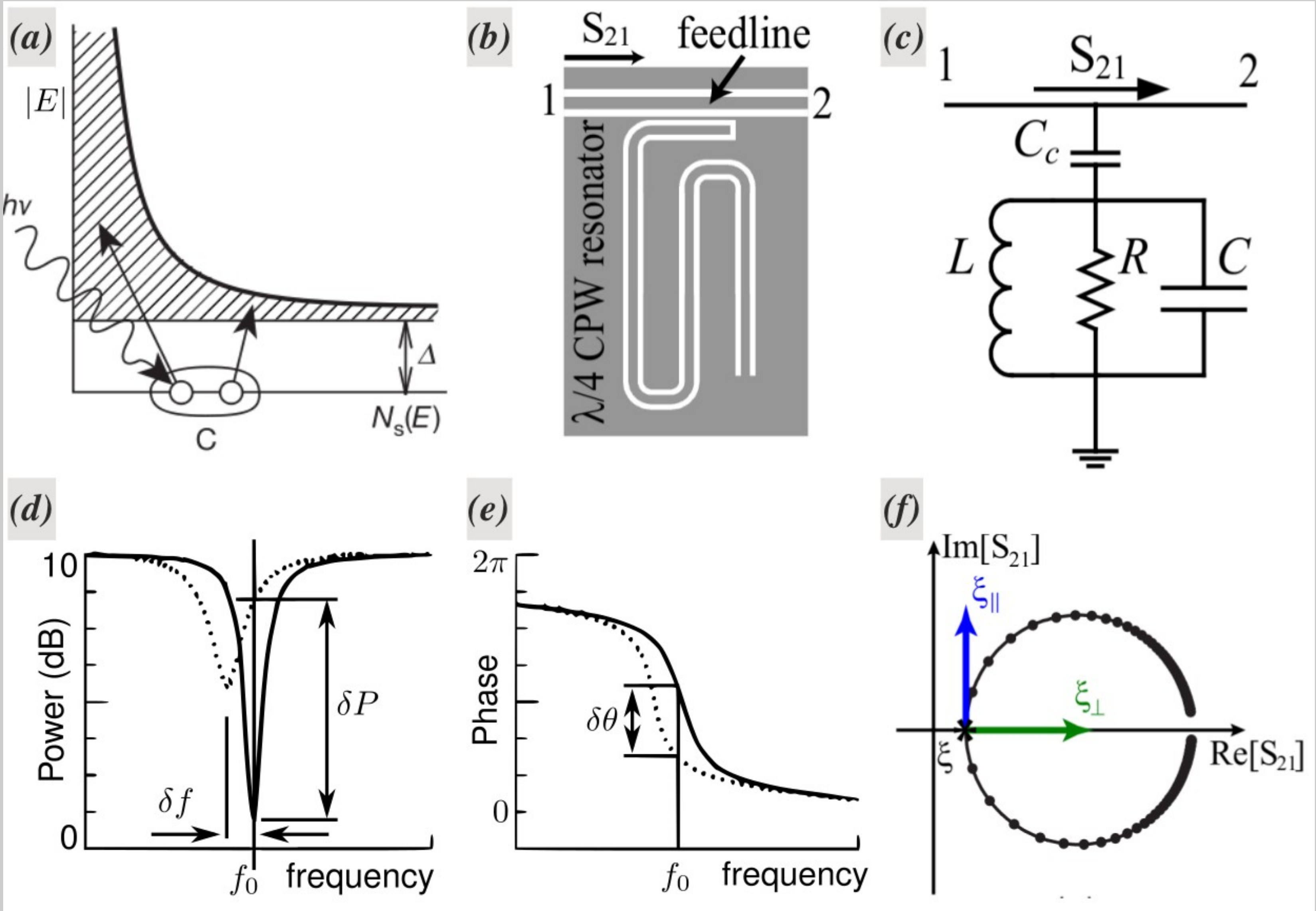
Phase shift leads to E field inside the conductor:

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



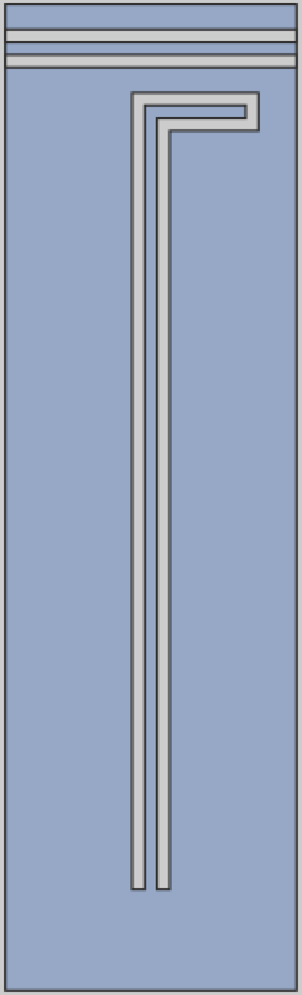


We can make a detector out of this



Figures from Mazin 2009 and Gao 2010

Alphabet soup:
transmission line mKID



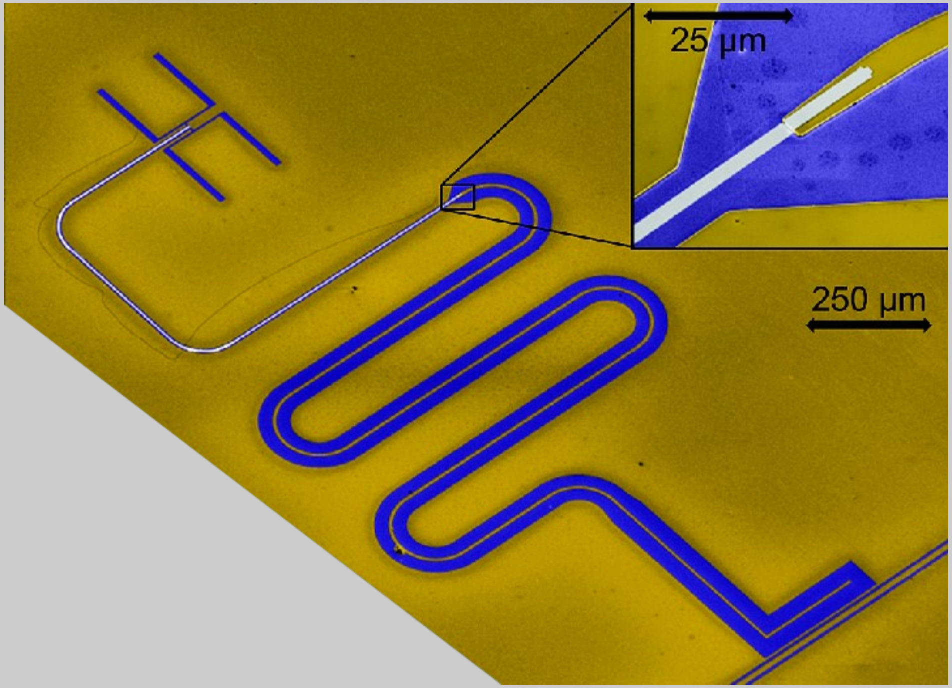
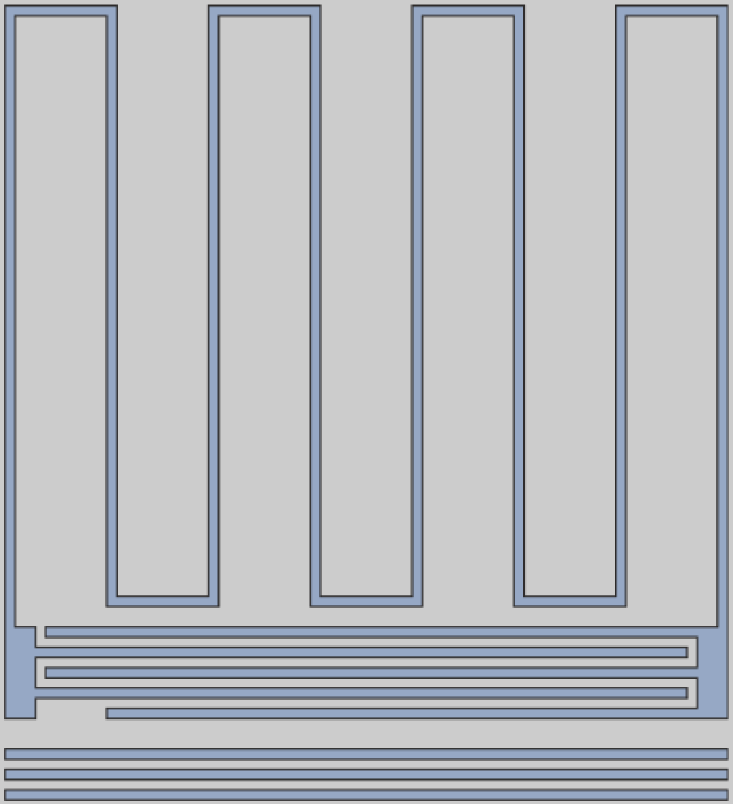


Image from Yates+13, A-MID collaboration

Alphabet soup:
Lumped Element KID (leKID)



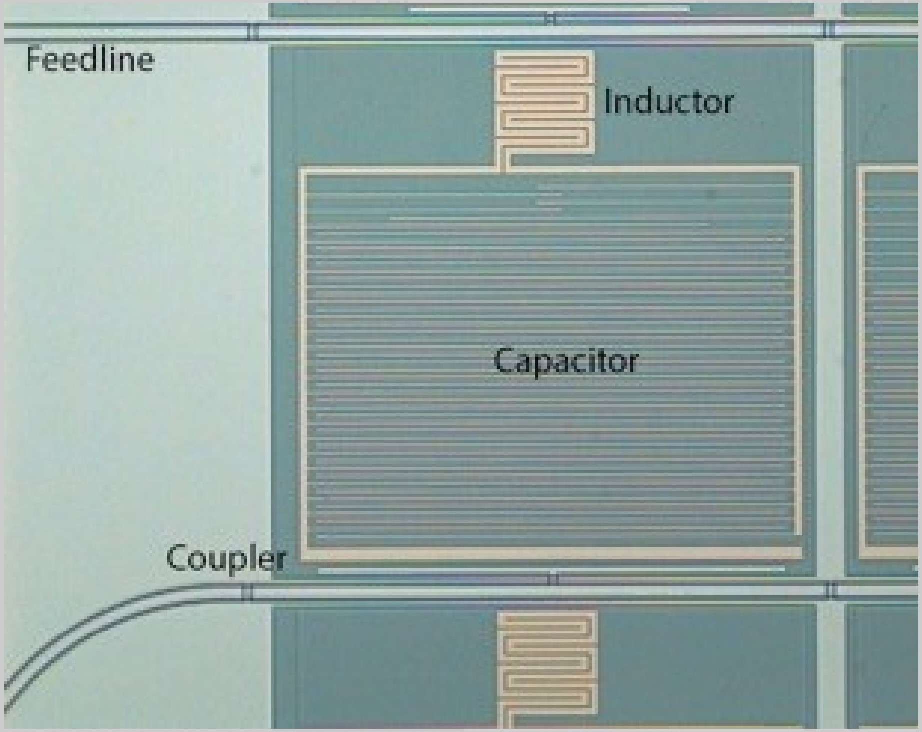
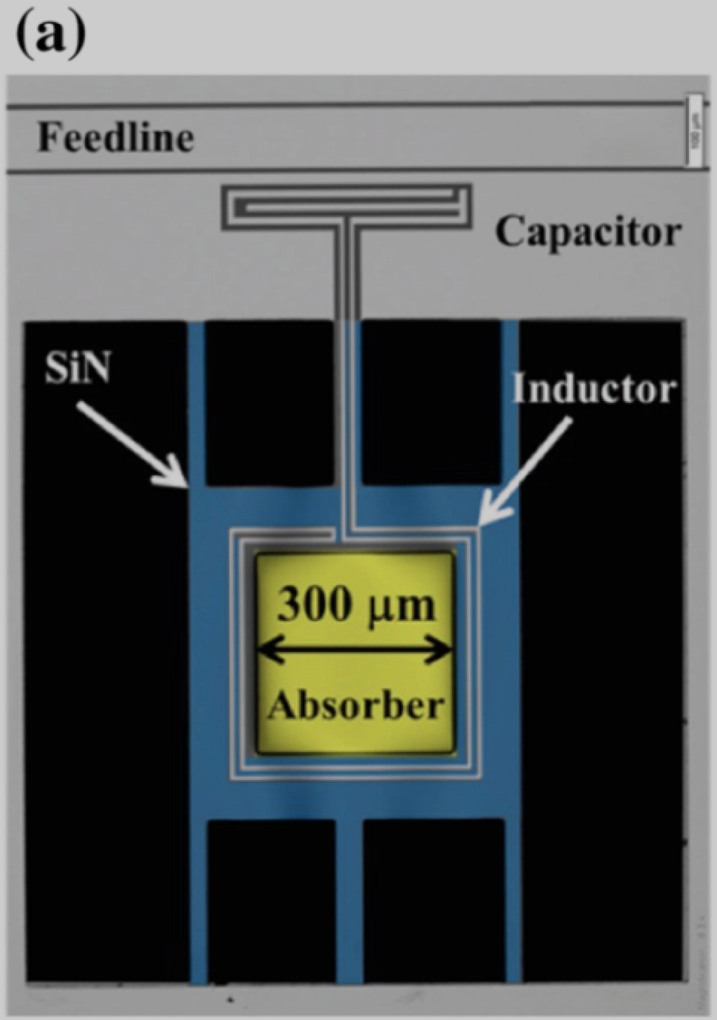


Image from Mazin group, UCSB

Alphabet soup:
thermal KID (tKID)



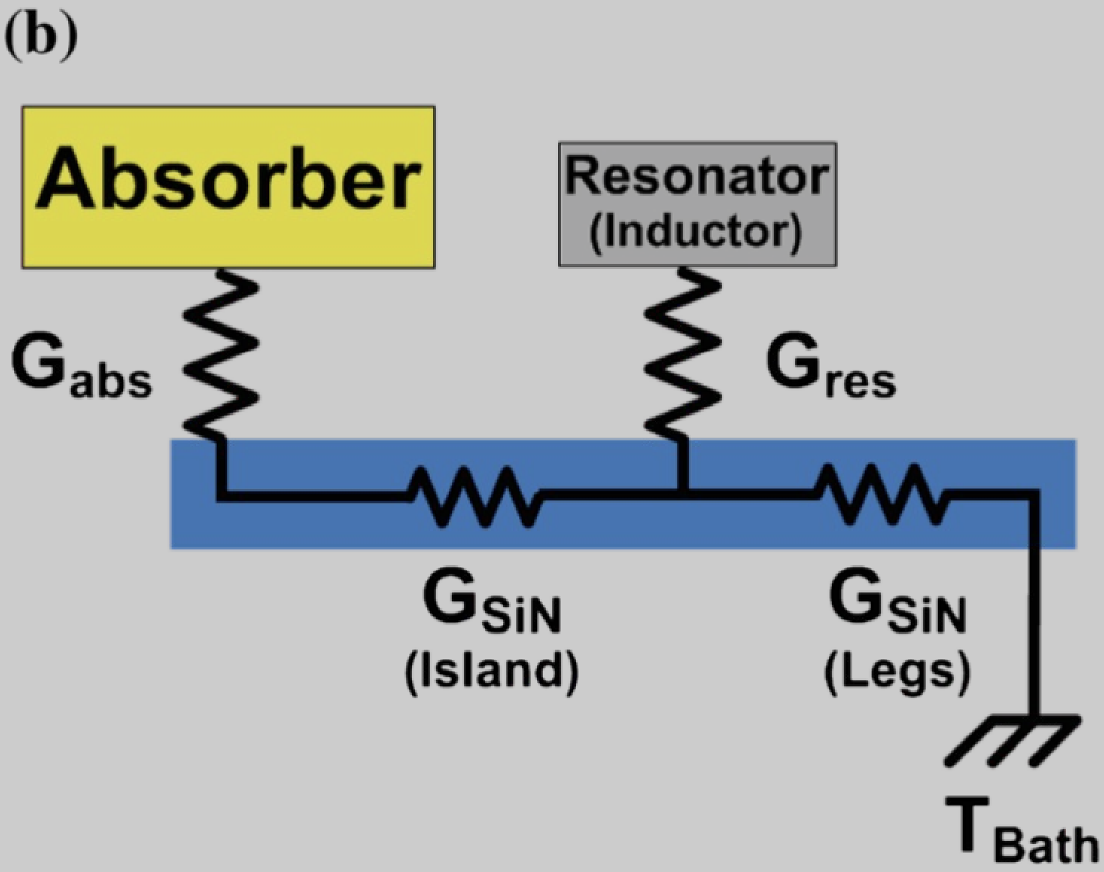
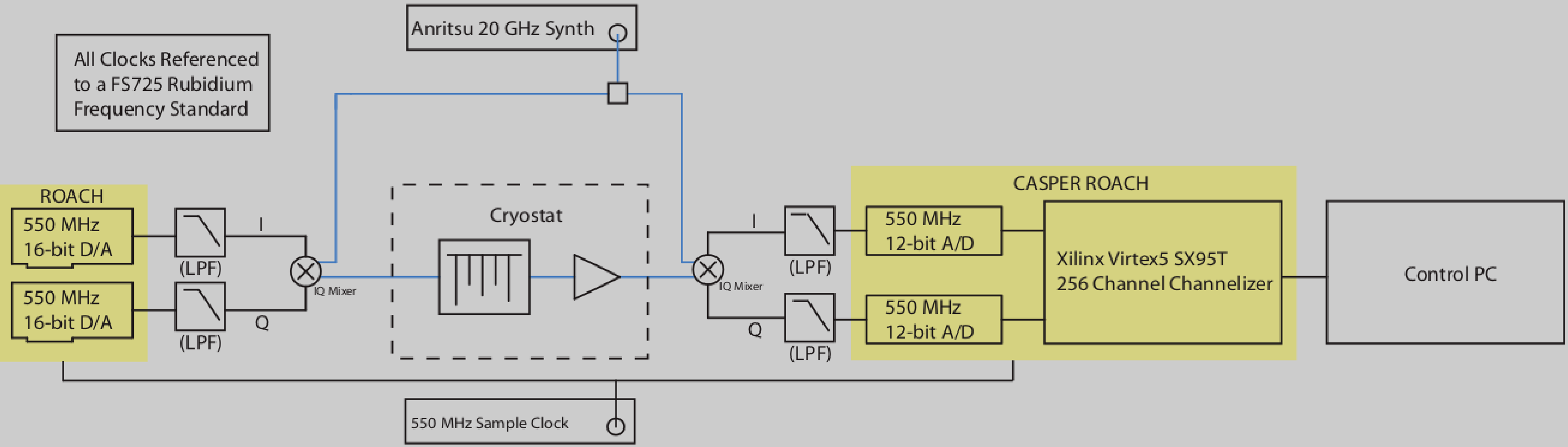
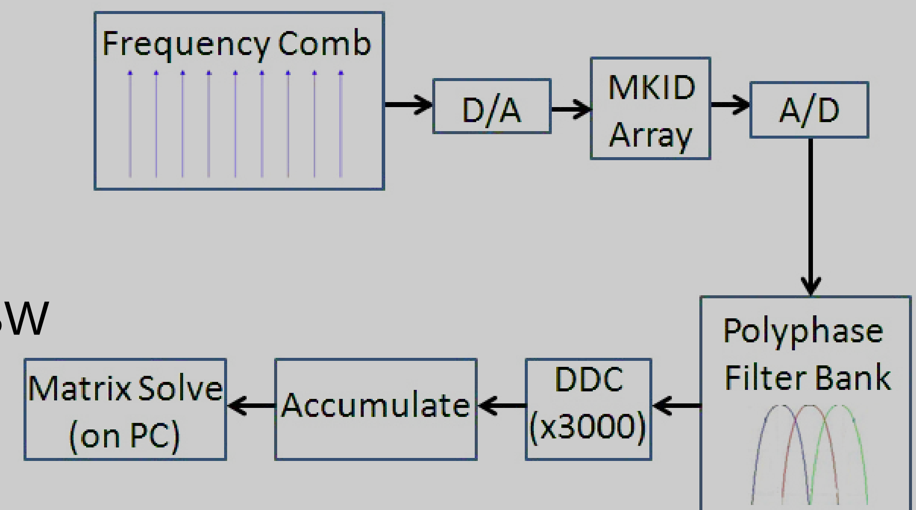


Image from Micelli group, ANL

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





Multiple demonstrated flavors in use:

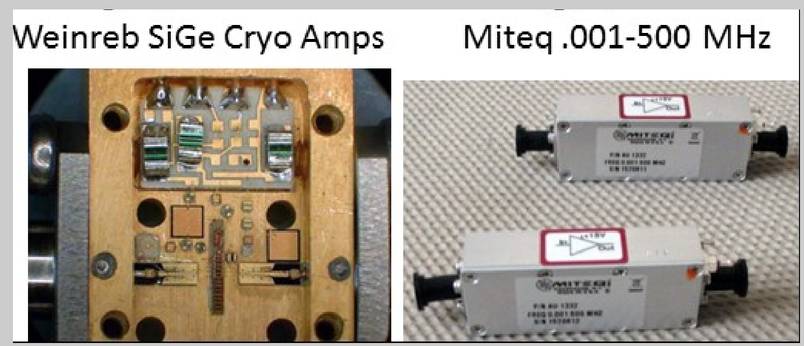
- MUSIC – 256 resonators at 3-6 GHz
- SRON – 4096 resonators at 6 GHz
- MAKO – 500 resonators at 100 MHz
- ARCHONS/FNAL – 256 resonators, high BW
- NIKMOS – custom HW for NIKA/NIKA2
- More coming soon. . .

Images: B. Mazin and R. Monroe

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

CASPER-ROACH FPGA board:
Today: $10K, 500 Ch/octave X 1 octave
→ increase MUX factor
→ use more octaves
→ custom FPGA solution (multiple ADCs)

Cryogenic Low Noise Amplifiers
Today: $4K per readout line
But note: >90% of cost is engineering & testing
→ increase MUX factor
→ use more octaves
→ custom design and fabrication



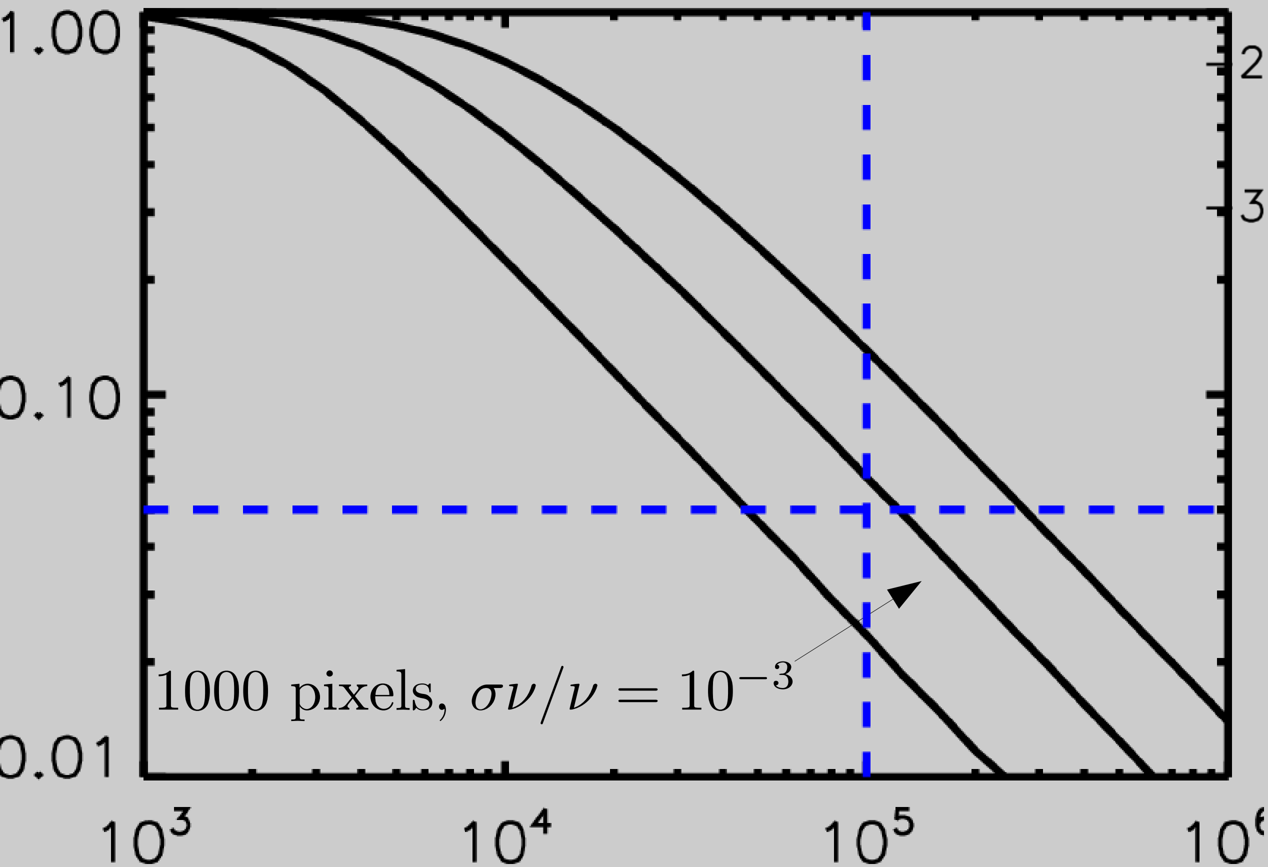
In Aug 2015, MAKO 500 pixel demo run cost $30/pixel for readout.

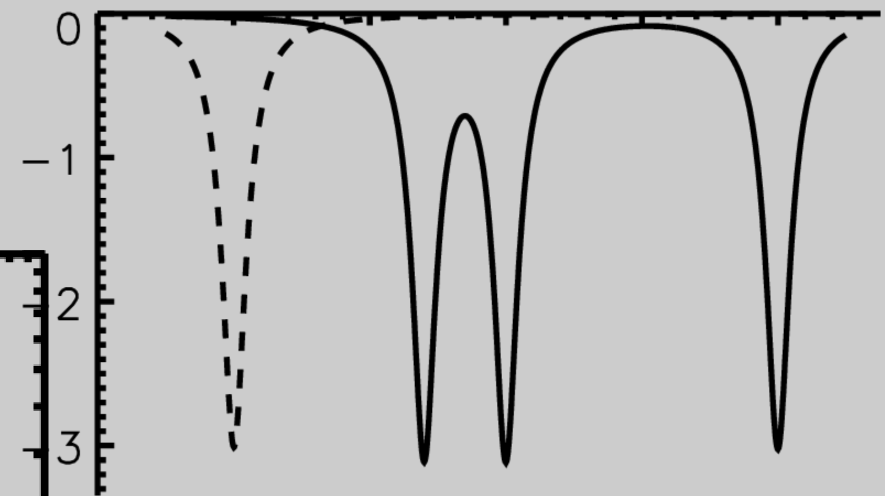
Reaching $10/pixel is straightforward. Reaching $1/pixel is possible.

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:

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

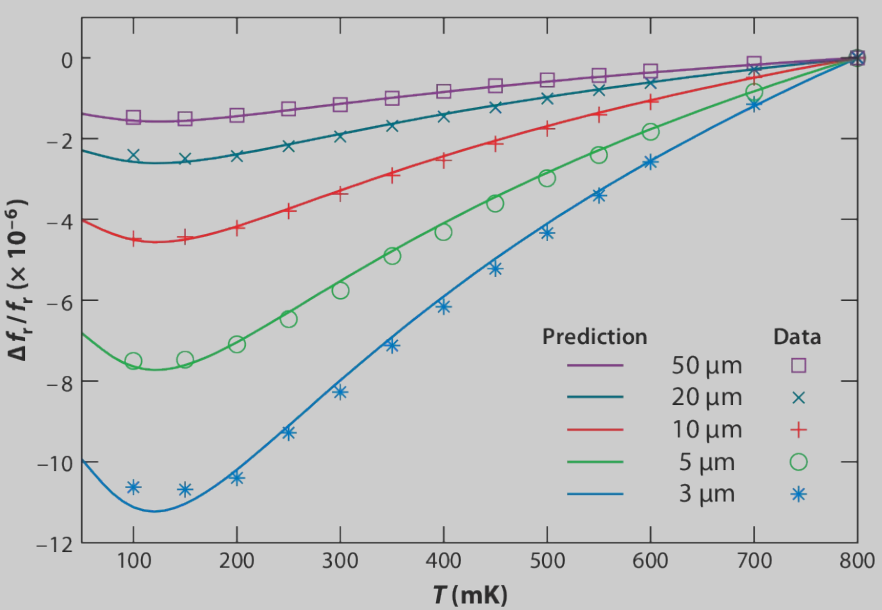
$$\sim f(\nu_{\text{readout}},\, Q,\, V_{\text{inductor}},\, T_{\text{c}})$$

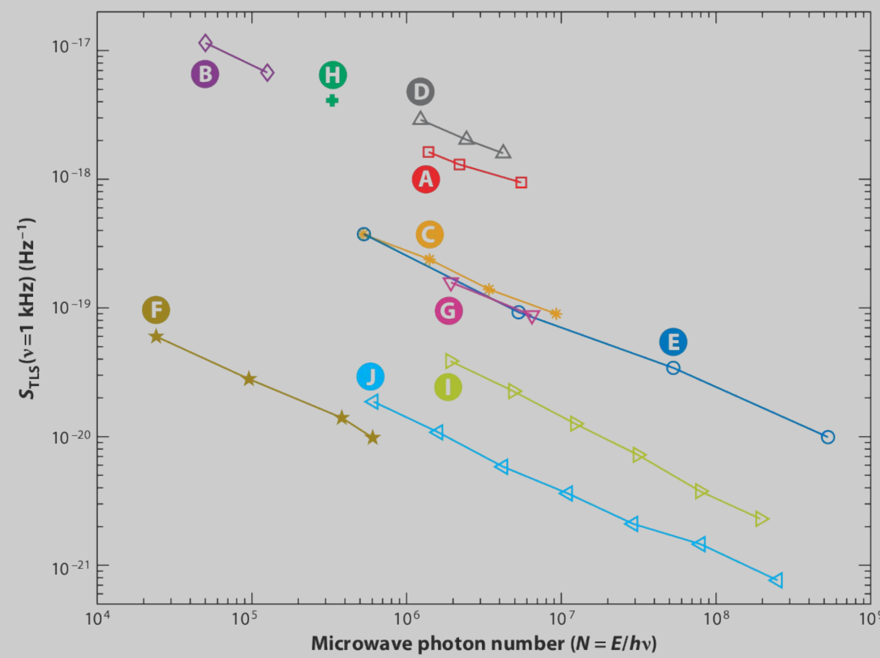
Two Level System Noise: hard to predict a priori, but follows known scaling laws

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

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

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





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*:

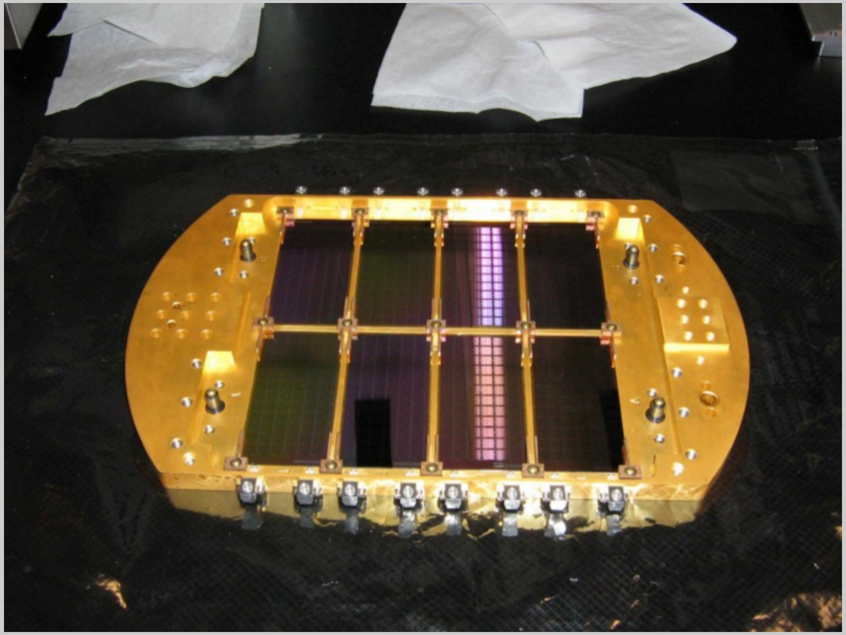
$$\mathrm{NEP}_{\mathrm{TLS}} \propto Q_r^{1/4}\, T_c^3\, V_L^{0.75}\, T_{\mathrm{opp}}^{-0.35}$$

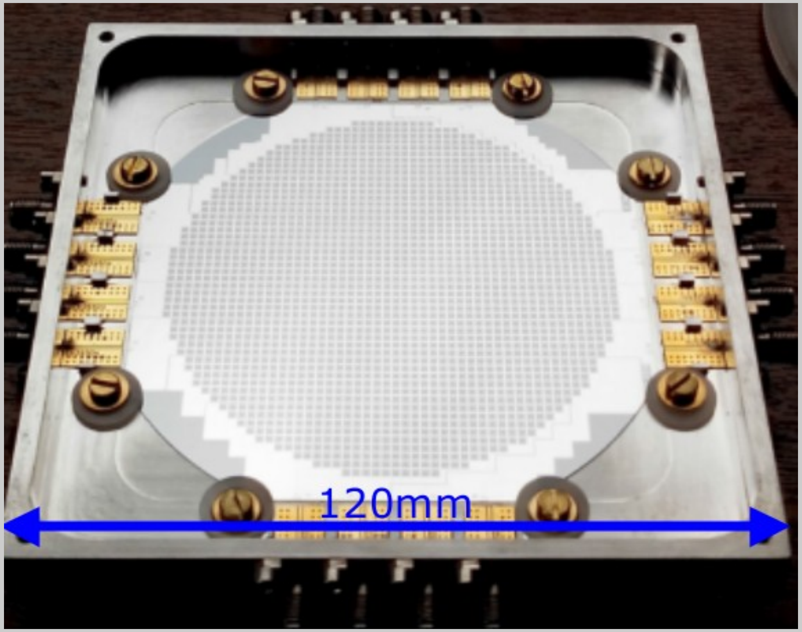
$$\mathrm{NEP}_{\mathrm{amp}} \propto T_{\mathrm{amp}}^{0.5} \left(Q_c/Q_r\right)^{0.5} T_c^{2.5}\, V_L^{0.5}\, T_{\mathrm{opp}}^{0.5}$$

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 I



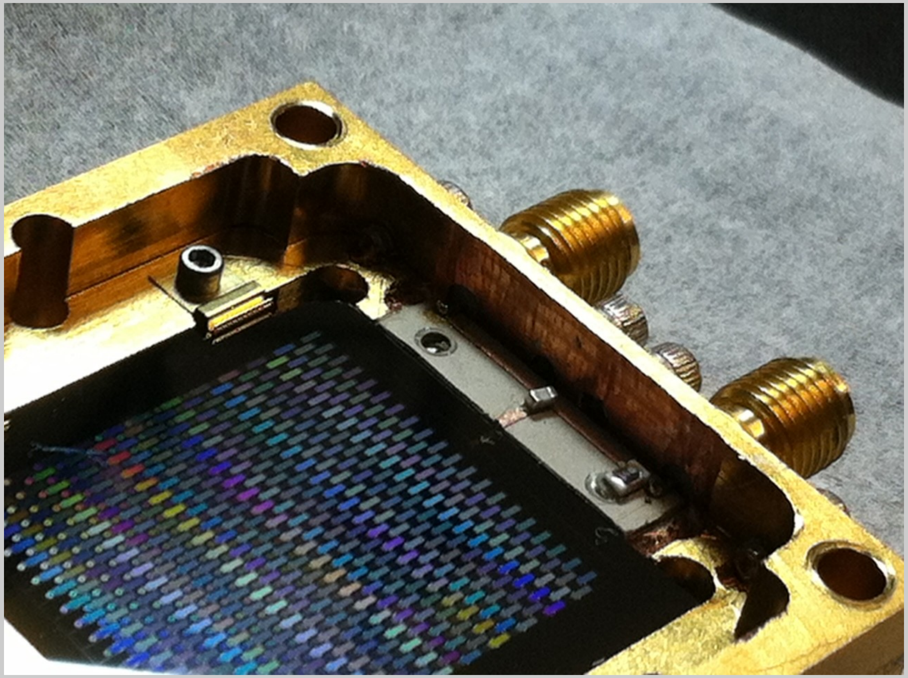


MUSIC; Caltech, JPL,
CU Boulder, NIST, UCSB
576 4-color pixels, 2mm-850μm
CSO 2012-2015
Science papers; user facility

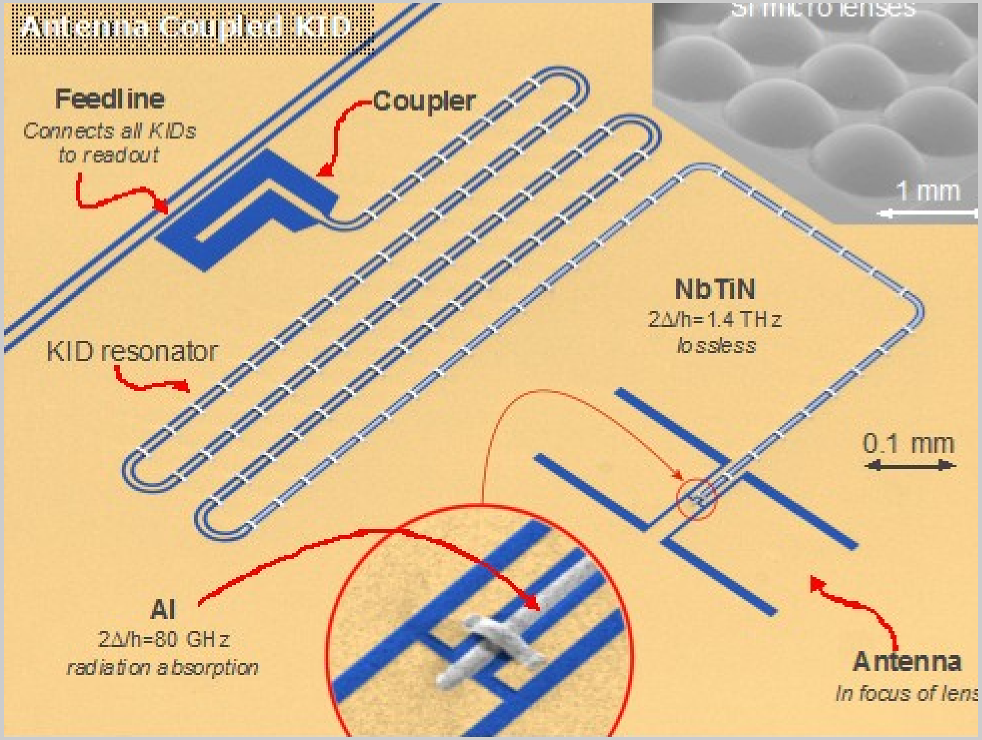
NIKA; Grenoble, SRON, Cardiff, MPFIR, etc. ;
300pixel, 1.25 or 2 mm
IRAM telescope 2011
Science papers, user facility

NIKA2; 5000 pixel, 1.25 & 2mm
Engineering run 2015

On-sky cameras II



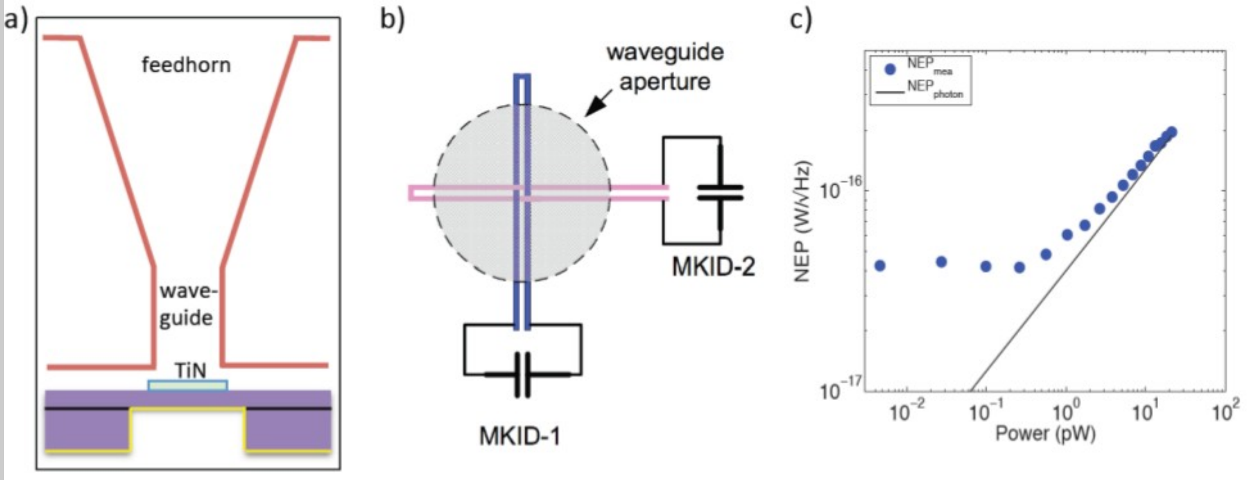
MAKO; Caltech & JPL
500 pixel, 350 or 850μm
CSO 2015



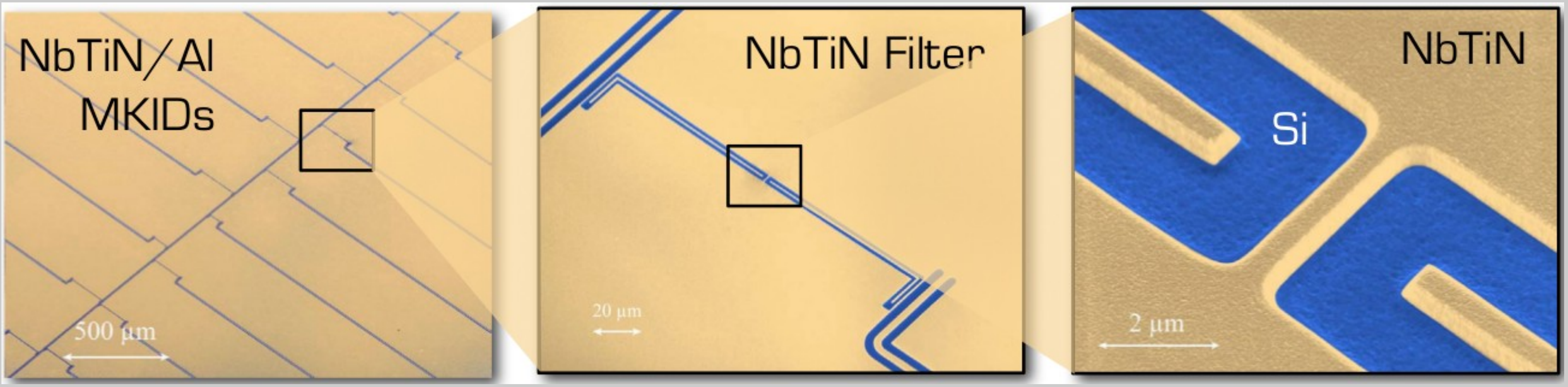
A-MKID; Delft, SRON, MPFIR;
~20kpixel, 350 & 850μm
APEX telescope 2015

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

BLAST TNG
SPACE-KIDs
GroundBird
uSpec
DESHIMA
. . .

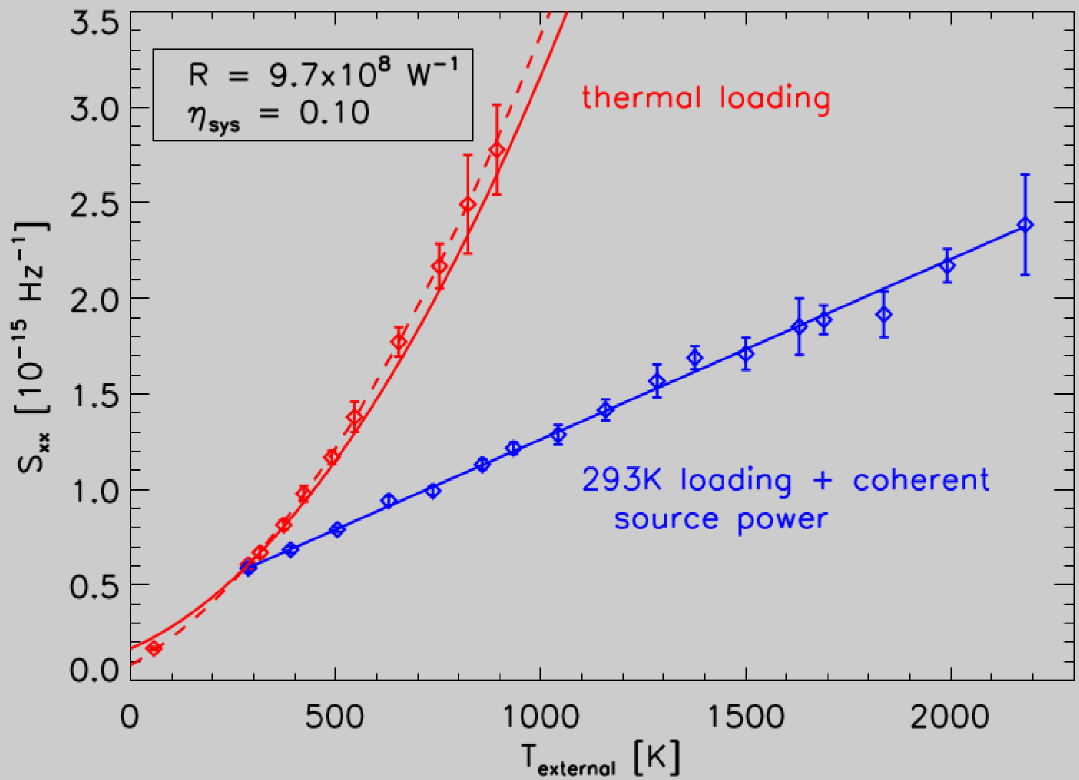


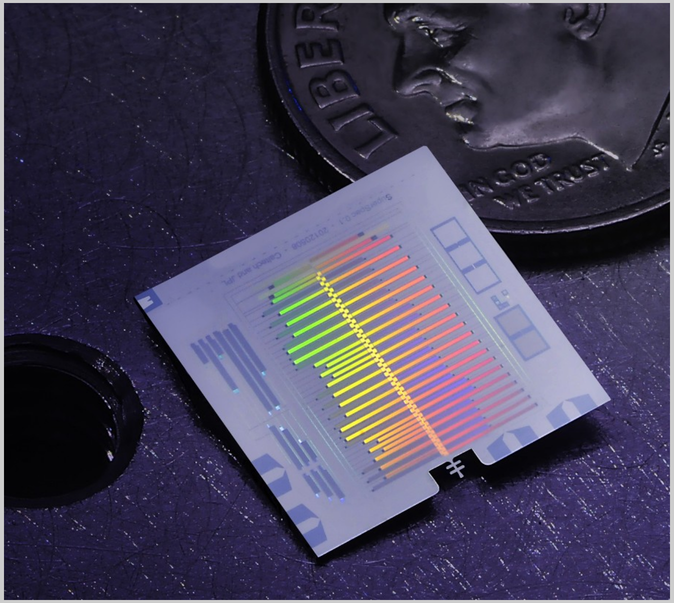
BLAST TNG prototype, from Galitzki+14

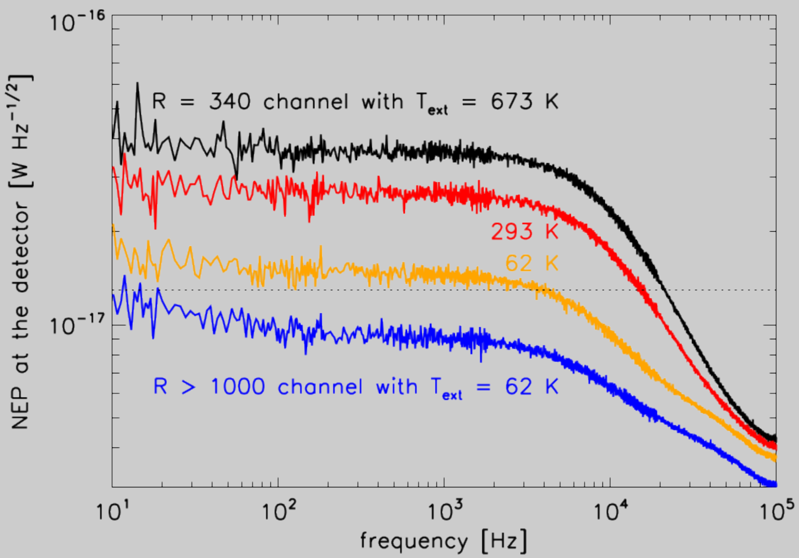


DESHIMA devices, image from A. Endo

SuperSpec: a mm-wave on-chip spectrometer for high-redshift astronomy







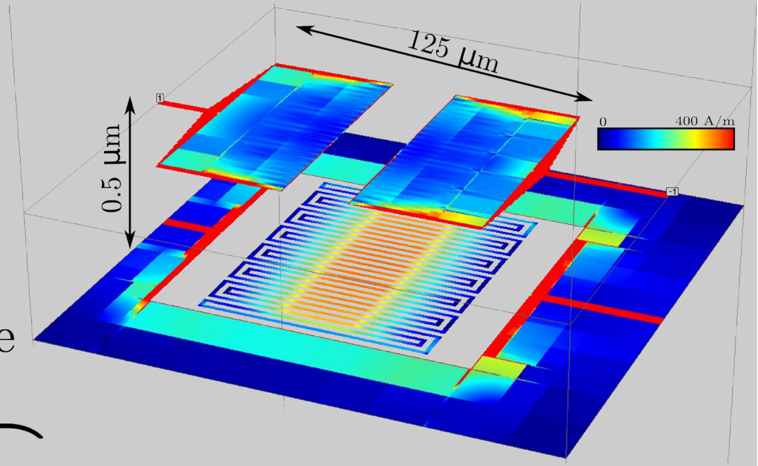
Photon noise vs. loading → power and NEP calibration.

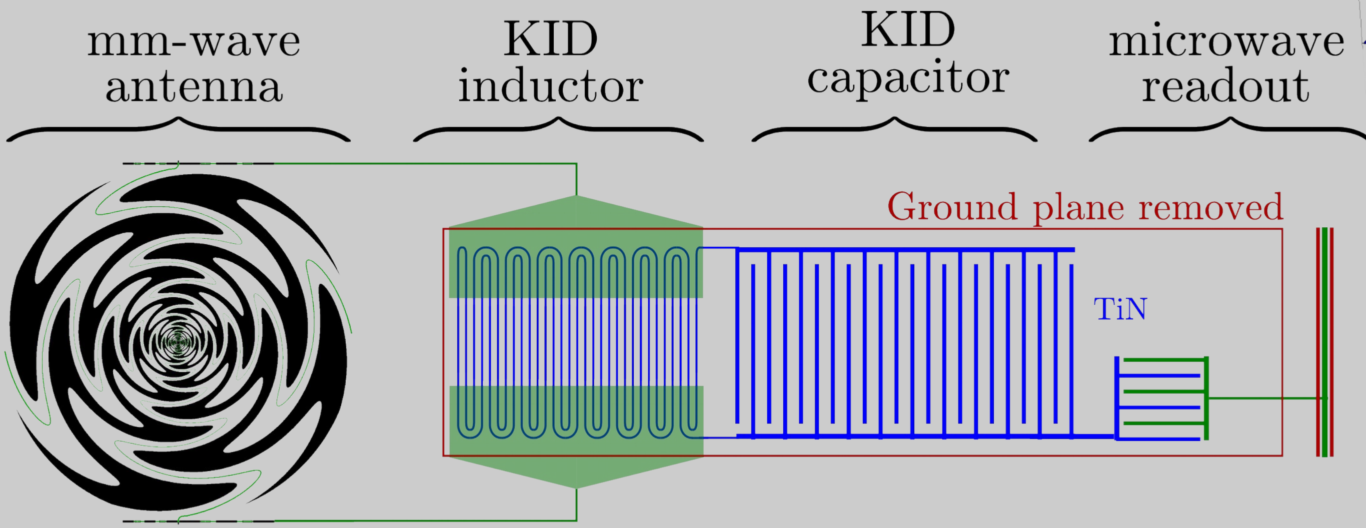
$\mathrm{NEP} < 10^{-17}\,\mathrm{W}\sqrt{\mathrm{Hz}}$

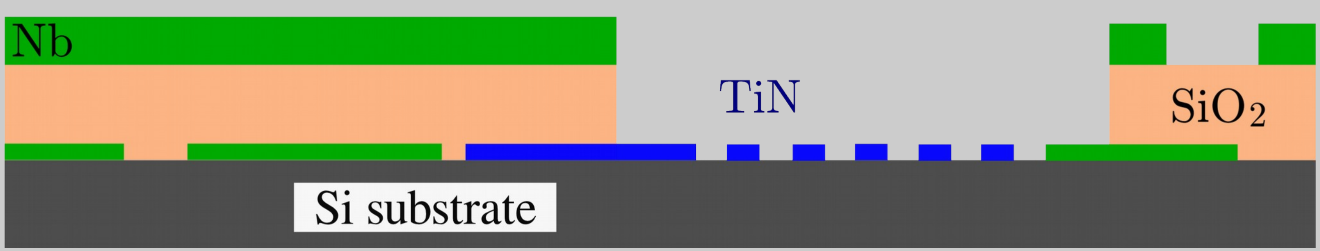
Take this working design and adapt it to make an antenna coupled CMB pixel.

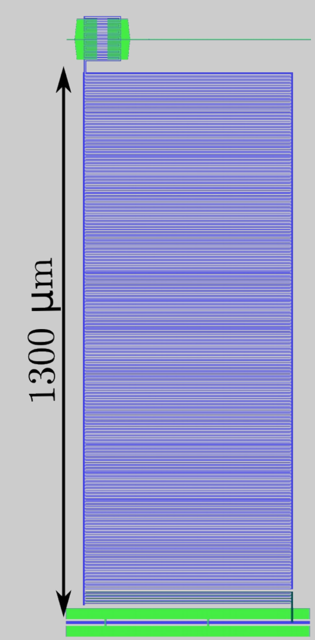
$T_c \to 0.8\,\mathrm{K}$ $\quad T \to 100\,\mathrm{mK}$

New mm-wave coupling scheme.

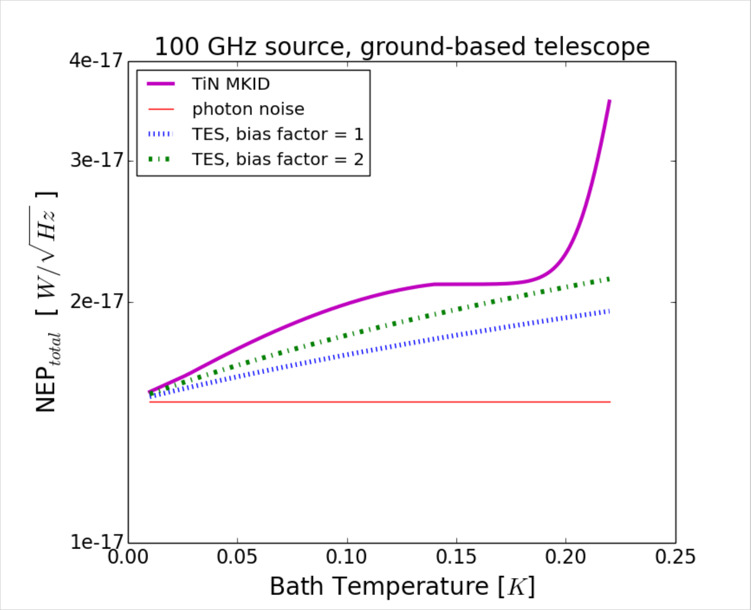


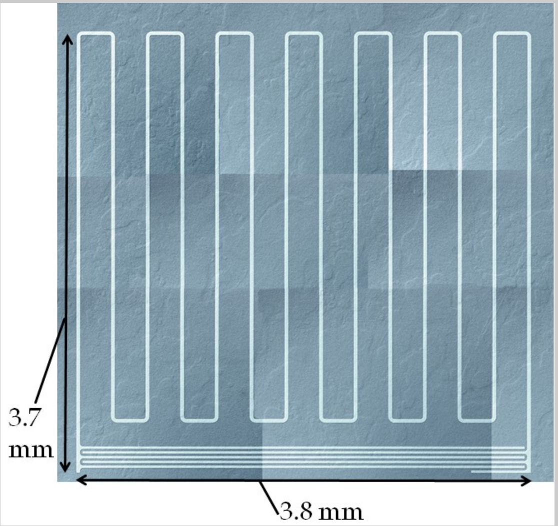


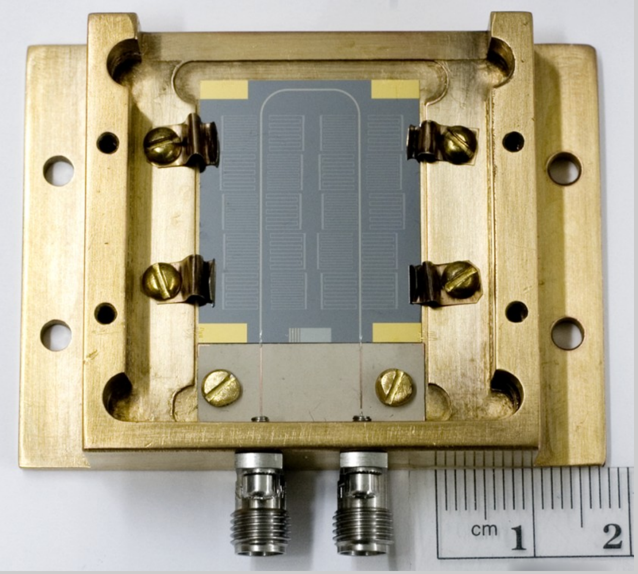




Wisconsin & Goddard CMB KIDs: TiN direct absorber for QUBIC



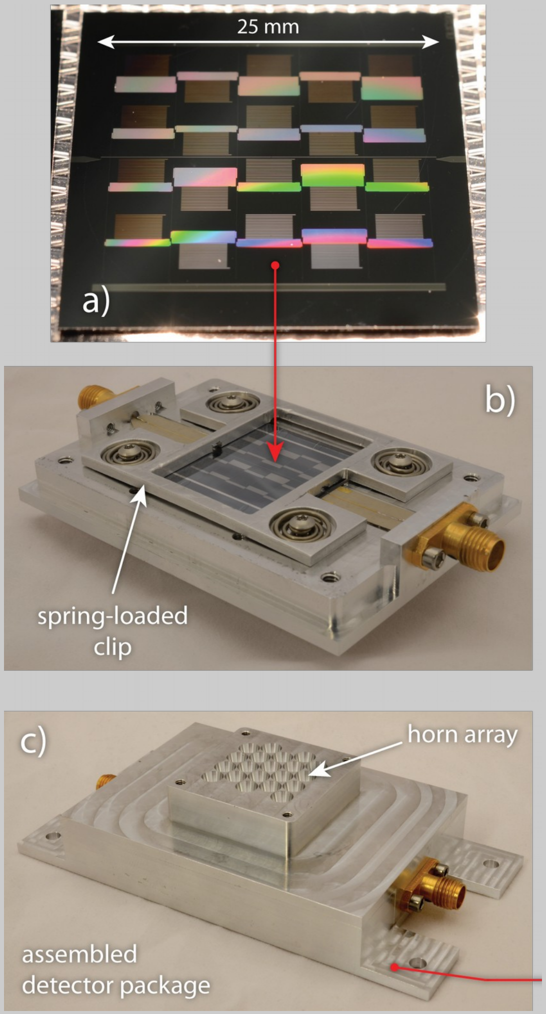




- At 100 mK, a 100 GHz KID pays a 10% penalty in NEP compared to a TES with a readout bias factor of 2.

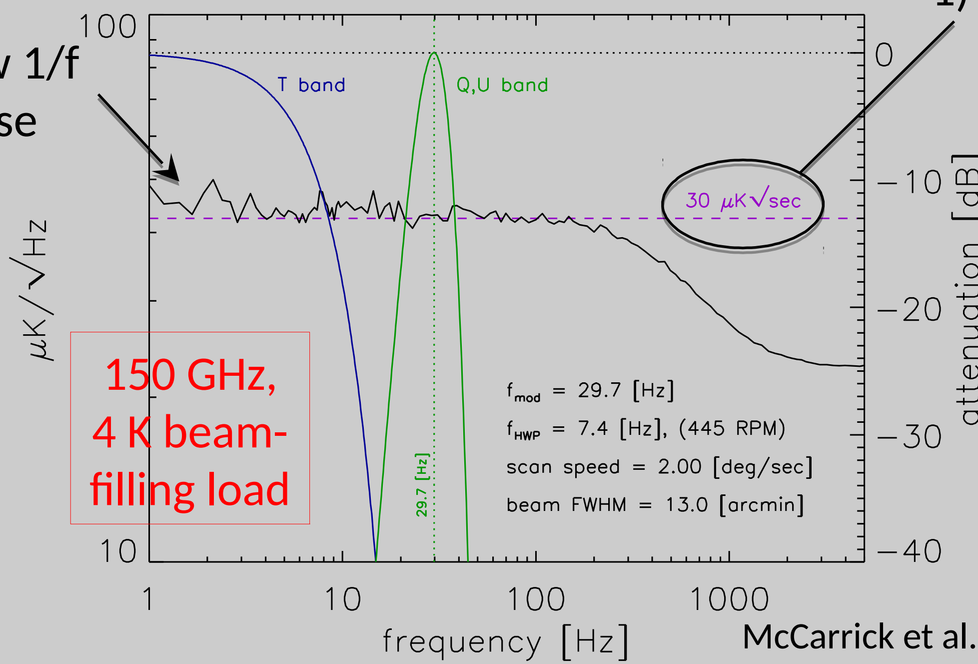
Courtesy of A. Lowitz, A. Brown, V. Mikula, T. Stevenson, P. Timbie, and E. Wollack

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



2) low 1/f noise

1) low NET



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

3) lots of bandwidth

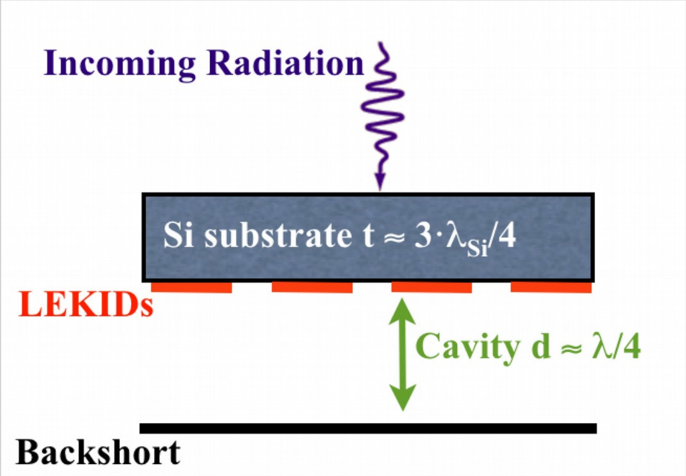
Measured photon noise for single layer direct absorber leKIDs from a commercial fabrication house.

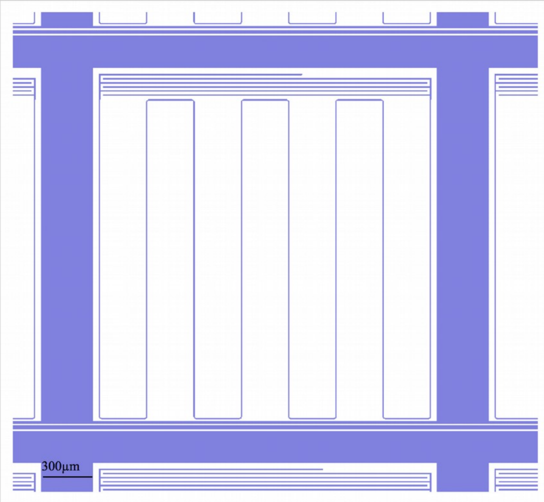
Dual-pol prototype now being tested. Multichroic horn+OMT pixels in design.

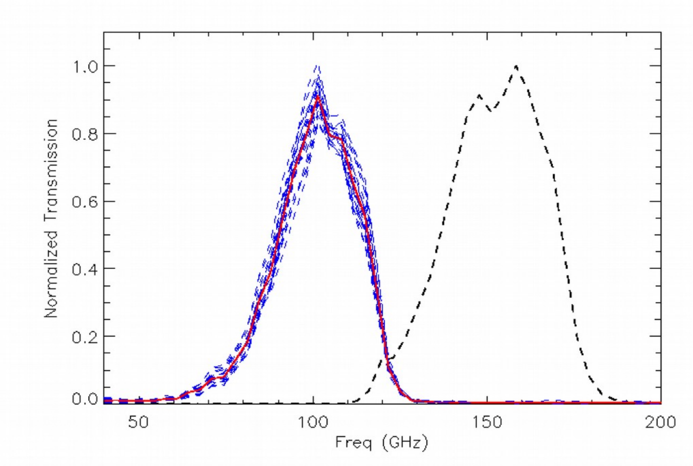
All figures: B. Johnson

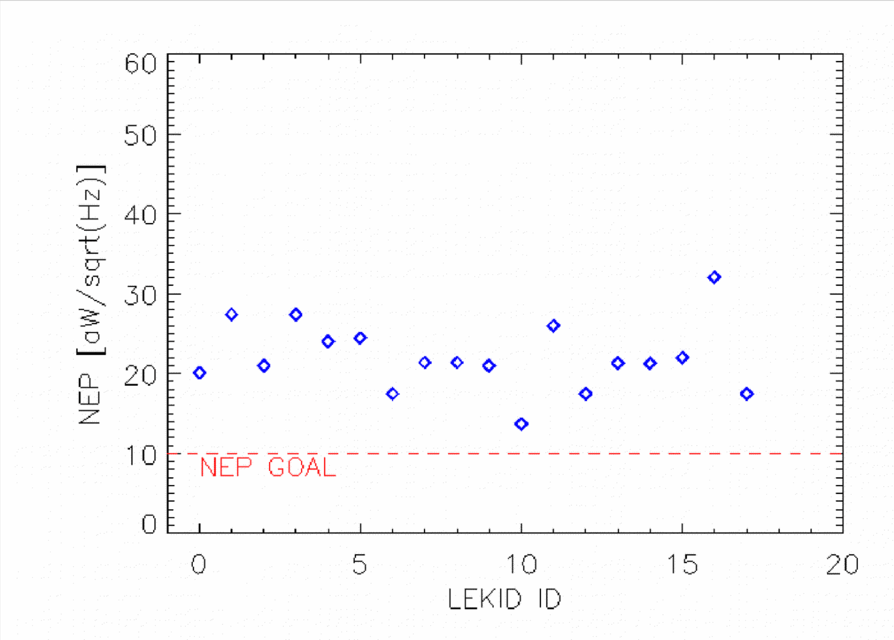
Al-Ti bilayer 100 MHz kids from Grenoble

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





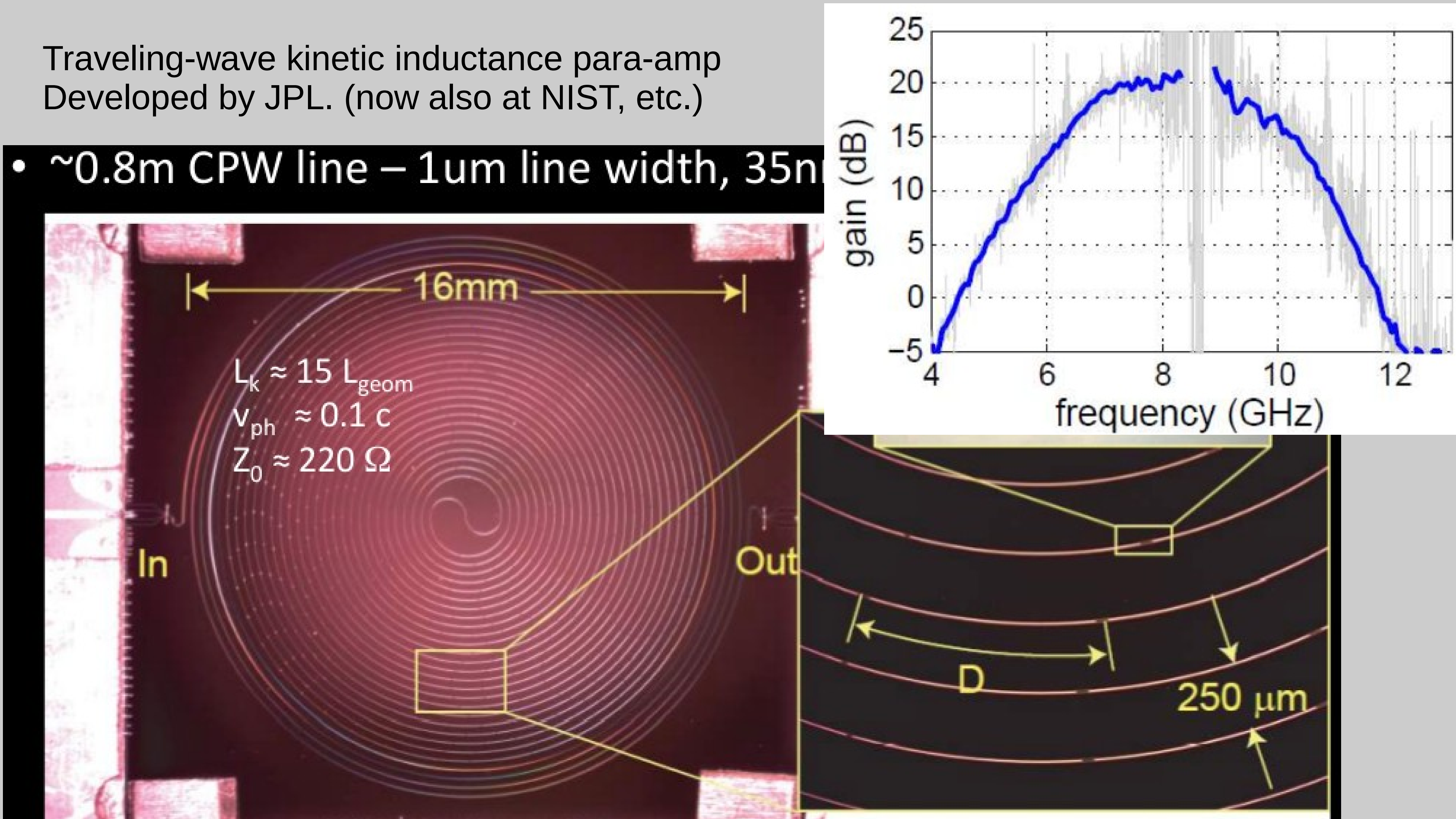




All figures from Catalano+15

Novel non-linear kinetic inductance devices: parametric amplifiers

Traveling-wave kinetic inductance para-amp
Developed by JPL. (now also at NIST, etc.)



Figures: R. Obrient

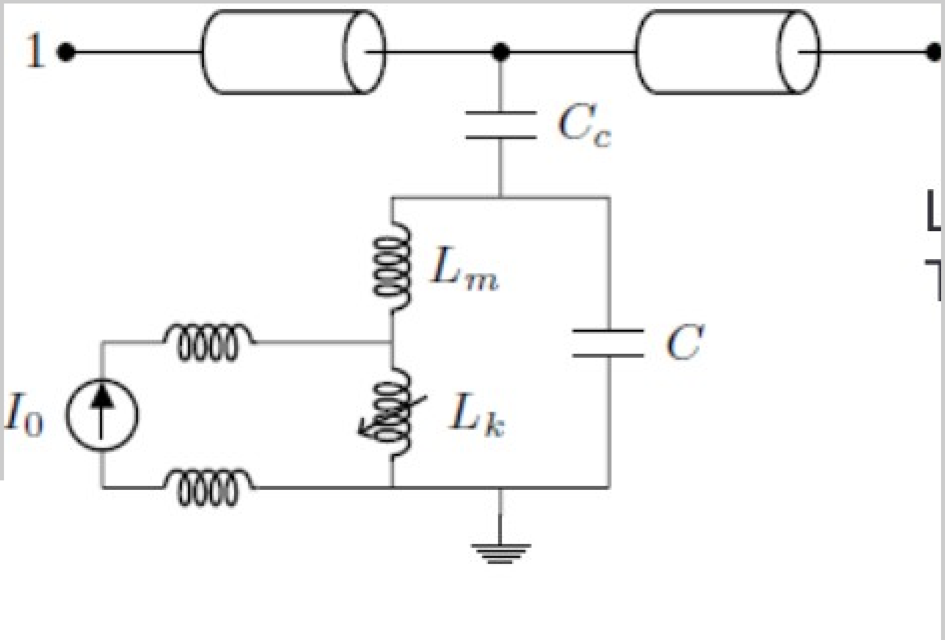
Novel non-linear kinetic inductance devices: the KPUP as a SQUID replacement

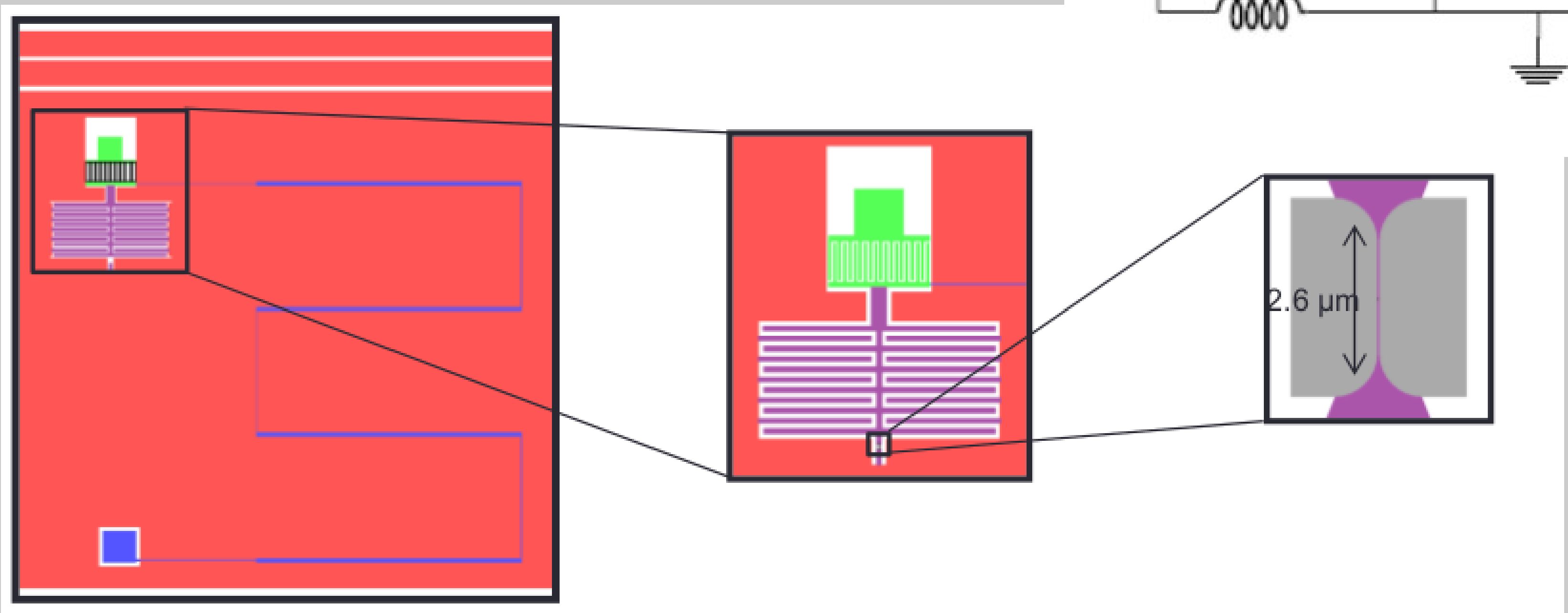
Use a KID to read out TES currents.

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

Tests with TESes under way.

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





The KIDs are alright: Debunking common myths I

1. KIDs are only good at submm frequencies

Dense focal plane packing makes KID multiplexing more important at high frequencies.
Background limited operation is easier at higher frequencies.
Operating at <100 GHz places constraints on Tc, and thus Tstage and materials.

But, there's no fundamental reason KIDs can't compete with TESes in all CMB bands.
A robust demonstration is just around the corner.

2. KIDs are inherently noisier than TESes.

All pair-breaking detectors suffer a recombination noise penalty.
But, this is at most $\sqrt{2}$ times the photon limit.

Also, this is comparable to any real world TES with a viable safety margin in G

The KIDs are alright: Debunking common myths II.

3. Superconducting nitrides were a mistake.

Superconducting nitrides are complicated and poorly described by BCS equations. The most robust and sensitive KIDs demonstrated to date have been transmission line resonators made from aluminum. (Or hybrids.)

BUT, titanium-nitride KIDs have demonstrated BL sensitivity in the lab.
High resistivity is a good match for direct-absorption leKIDs.
High-Qs and low-frequencies enable cheaper readout.
Also, extremely thin Al films aren't exactly simple either.

4. You don't need KIDs to do the near-term science we want to do with the CMB instruments.

Okay – actually this one is probably true. But, is “need” the right question?

If fabricating, reading out, and **testing** half a million good TESes were easy, then the answer would be obvious. But, is it really easier than investing in KID development?

Conclusions and questions

KIDs today are as mature as TESes were in 2006.

KIDs have demonstrated:

- Operation in CMB bands.
- NEP for BL for 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.

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

Qustions:

1. Can we really build half a million TESes within a realistic S4 budget?
2. What sort of KID demonstration would be compelling, and is it a realistic possibility?
3. We've got lots of options. How should we spend resources among:
   - Brute force approaches– more wafers, more wires, more SQUIDs
   - Low-risk extensions – microwave MUX, on-chip FDMUX, etc.
   - Less mature but promising technology – KIDs
   - Blue-sky, high-risk technology – KPUPs.