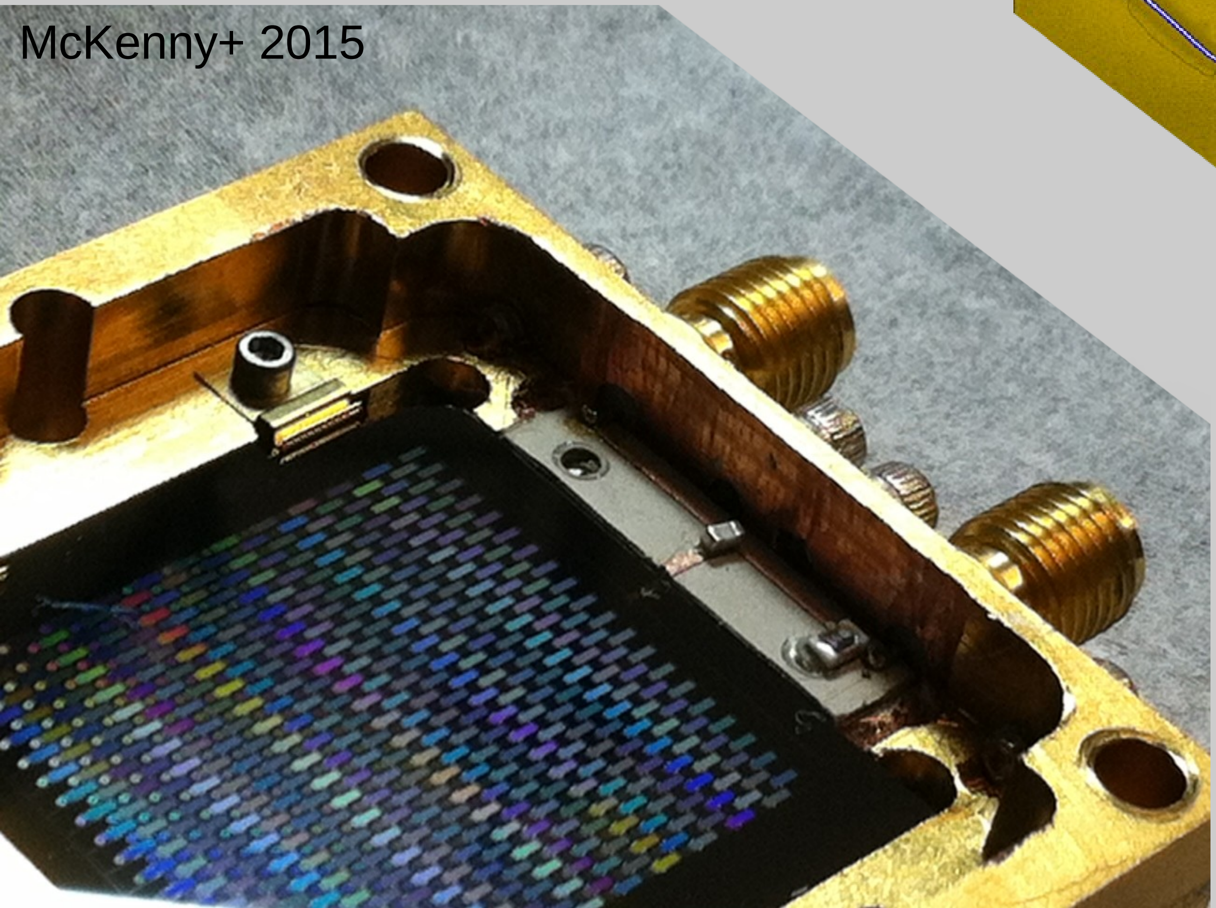
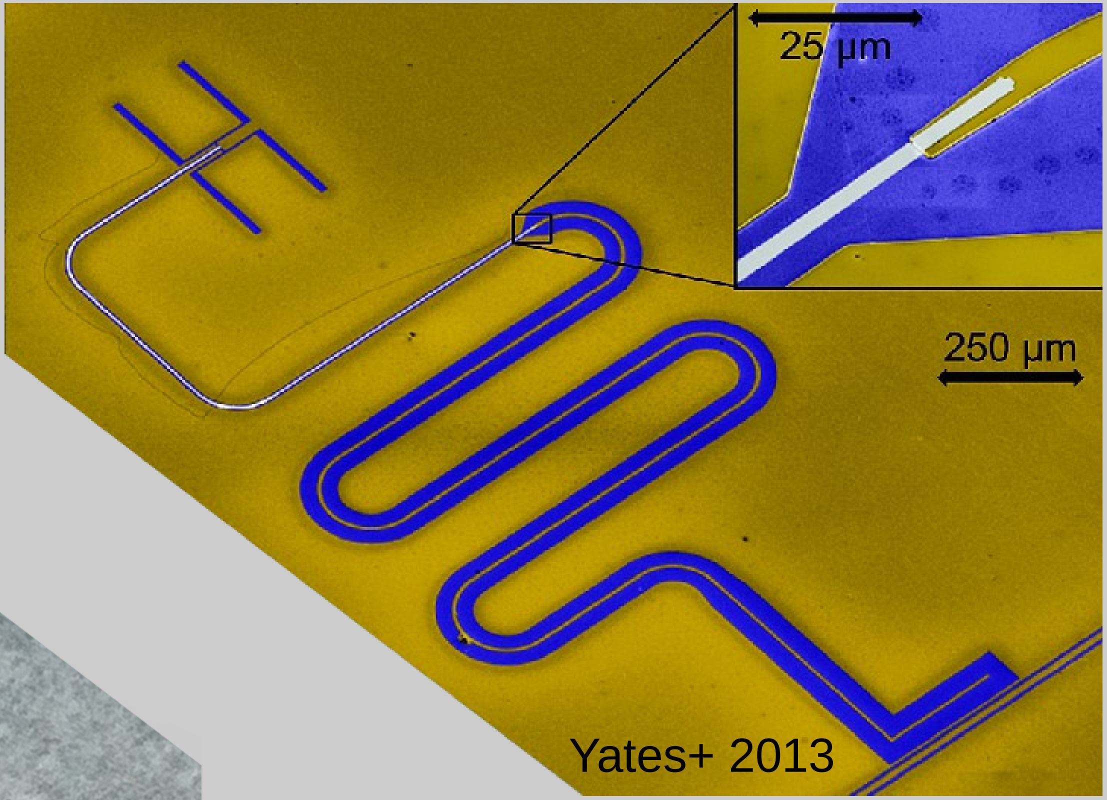
Kinetic Inductance Detectors for the CMB:

Erik Shirokoff

University of Chicago



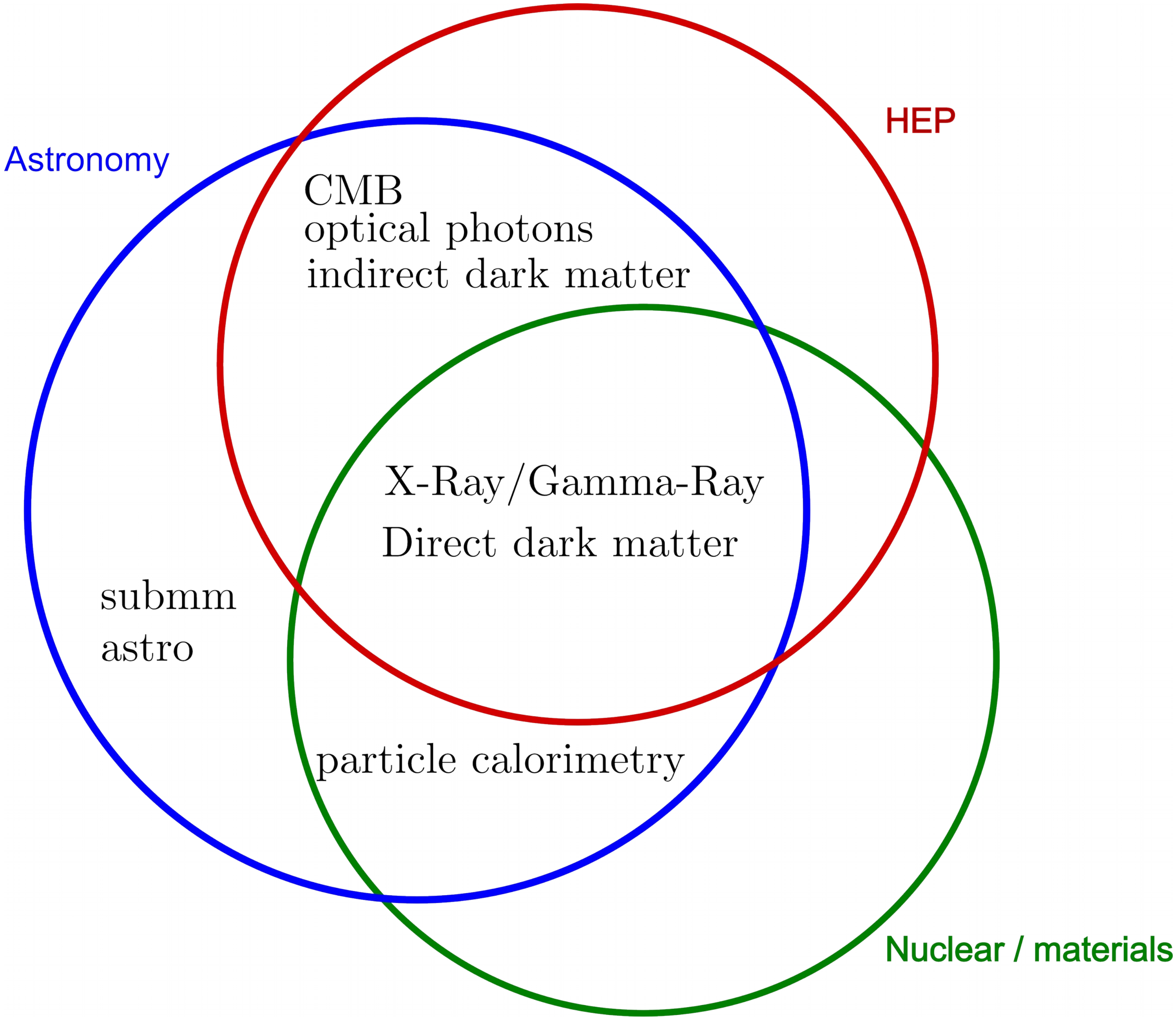


EDIT lecture

FNAL

March 08, 2018

Where are superconducting detectors used today?



Types of superconducing detectors

Today:

Transition edge sensor bolometers

Kinetic inductance detectors

Not covered, but important:

Metallic magnetic calorimeters

SIS mixers

SQUIDS

Why use superconducting detectors?

1. You need sub-Kelvin temperatures anyway.

   You're measuring sub-mm wavelength photons.

   You're looking for low energy phonon events.

Why use superconducting detectors?

1. You need sub-Kelvin temperatures anyway.

    You're measuring sub-mm wavelength photons.

    You're looking for low energy phonon events.

2. You want to create many pairs per event.

Why use superconducting detectors?

1. You need sub-Kelvin temperatures anyway.

    You're measuring sub-mm wavelength photons.

    You're looking for low energy phonon events.

2. You want to create many pairs per event.

3. You need a steep thermometer.

Why use superconducting detectors?

1. You need sub-Kelvin temperatures anyway.

    You're measuring sub-mm wavelength photons.

    You're looking for low energy phonon events.

2. You want to create many pairs per event.

3. You need a steep thermometer.

4. You need high-Q resonators.

Why use superconducting detectors?

1. You need sub-Kelvin temperatures anyway.

   You're measuring sub-mm wavelength photons.

   You're looking for low energy phonon events.

2. You want to create many pairs per event.

3. You need a steep thermometer.

4. You need high-Q resonators.

5. You want to use thin-film, wafer-fabrication techniques.

TES detectors

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

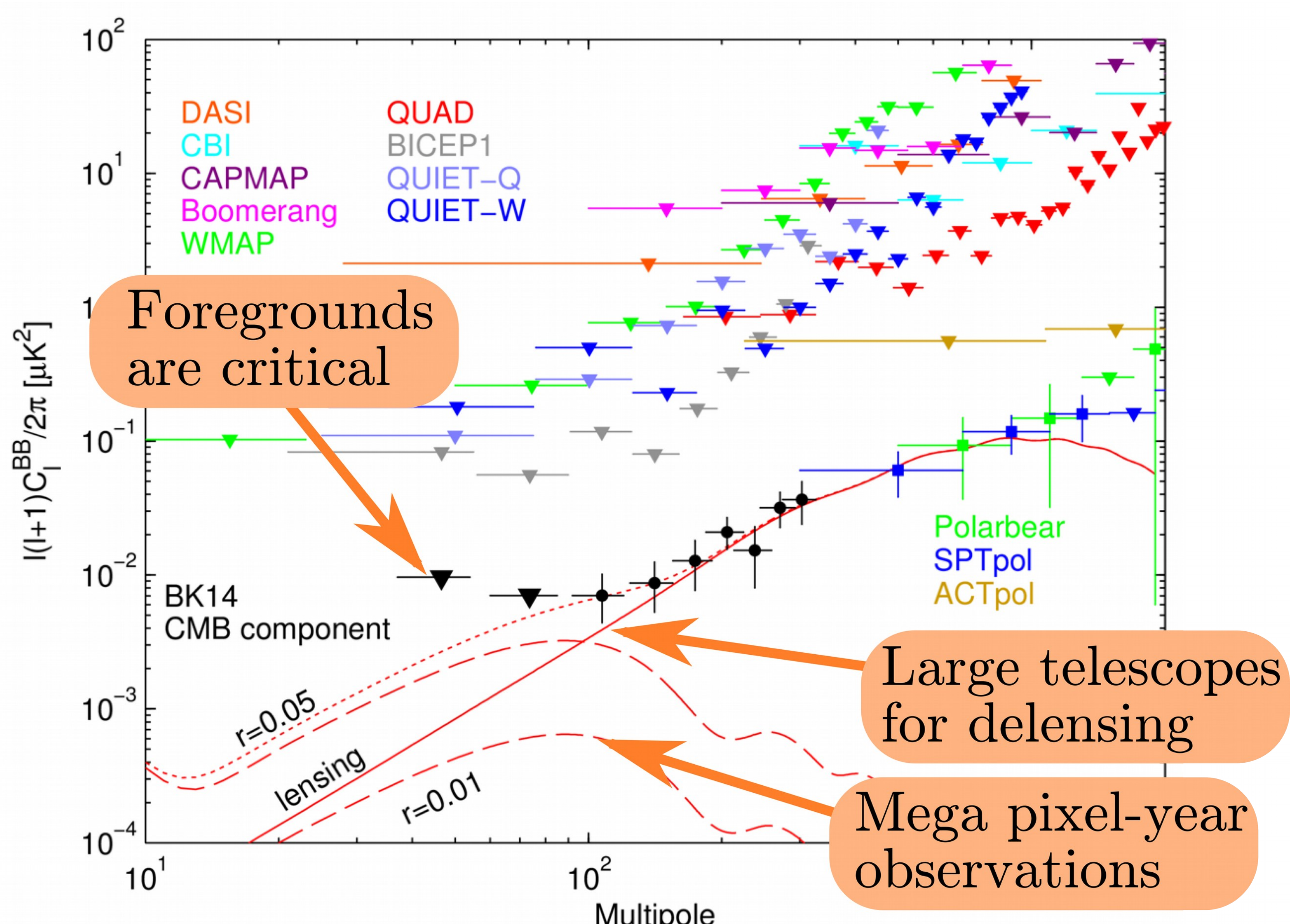
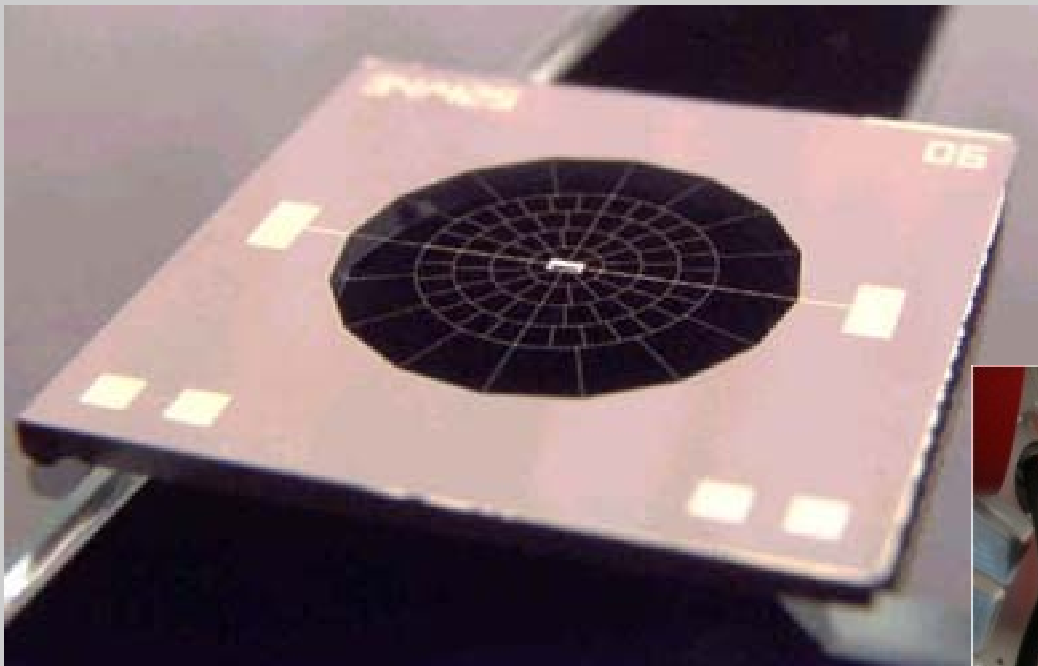
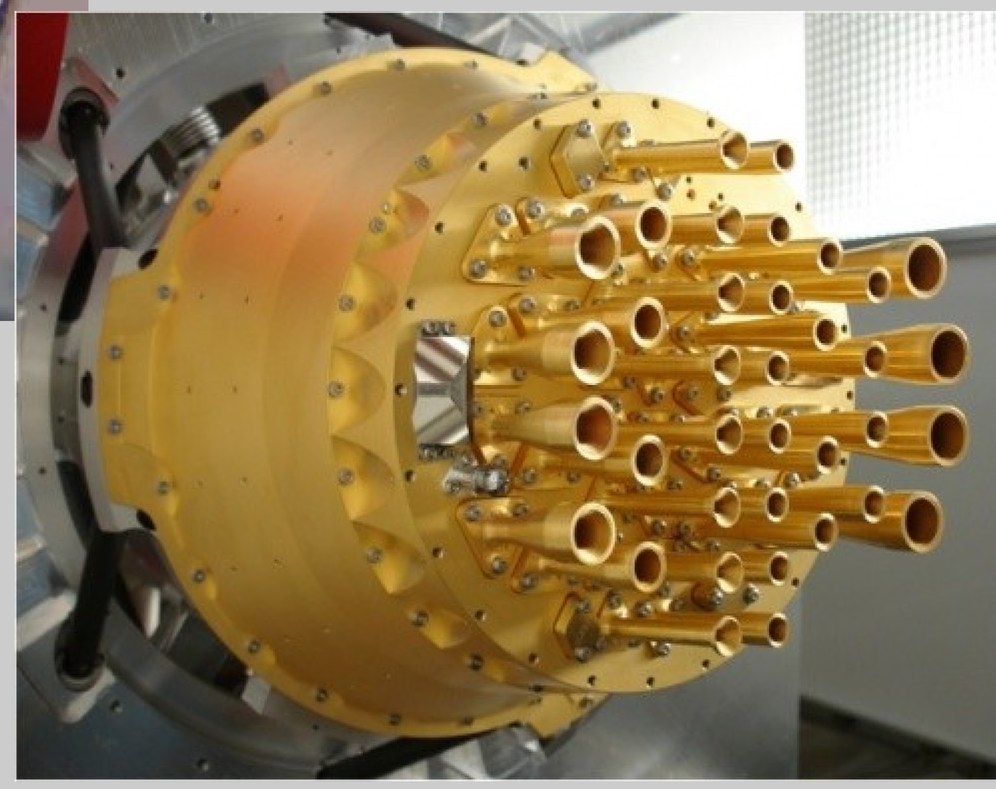


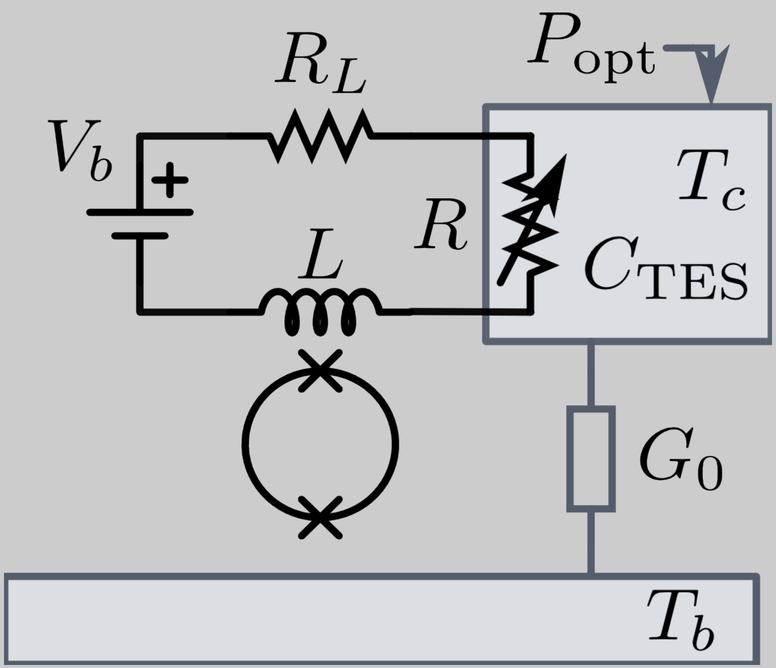
Image: Bicep2 & Keck Array, BK-VI

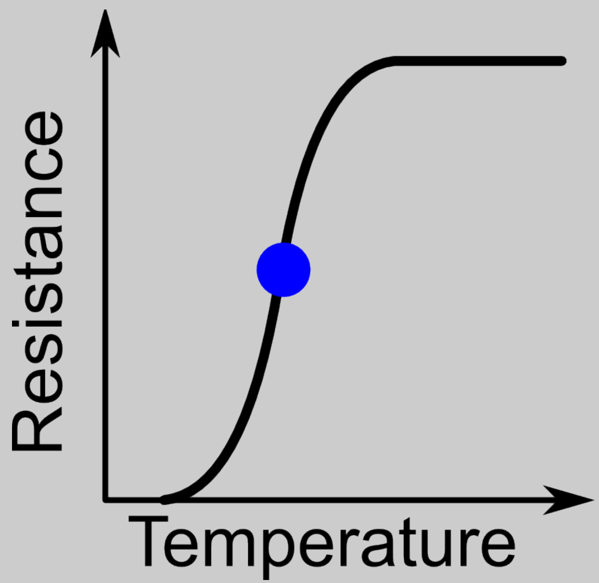
NTD bolometers in action: Planck HFI

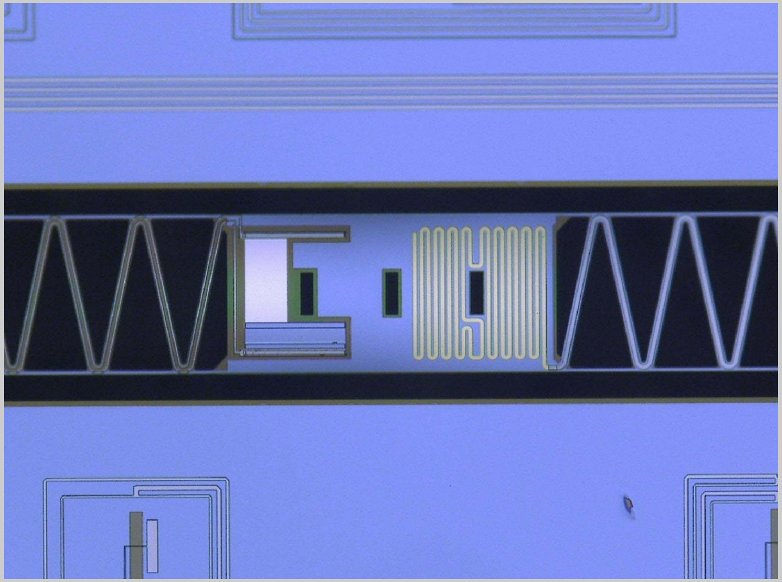




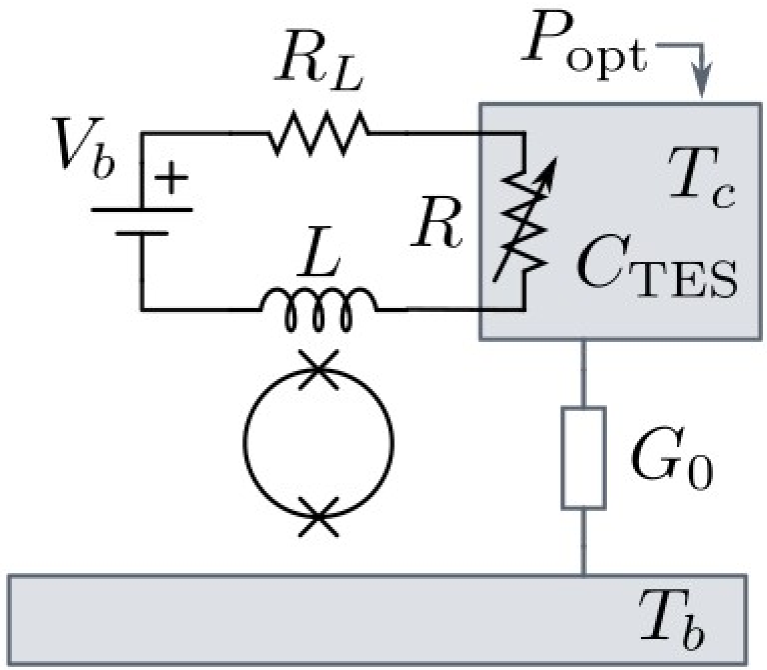
The Transition Edge Sensor Bolometer

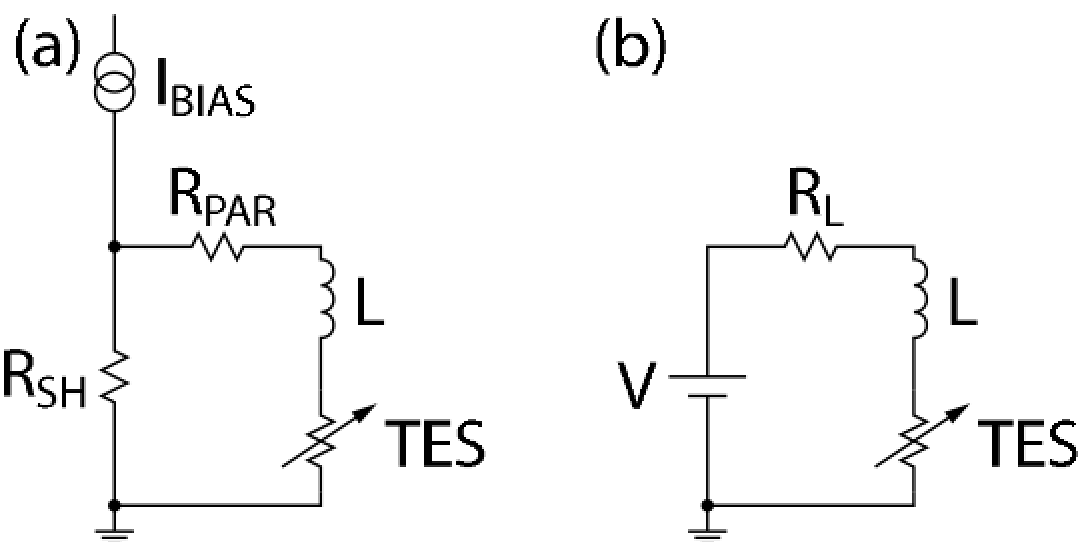






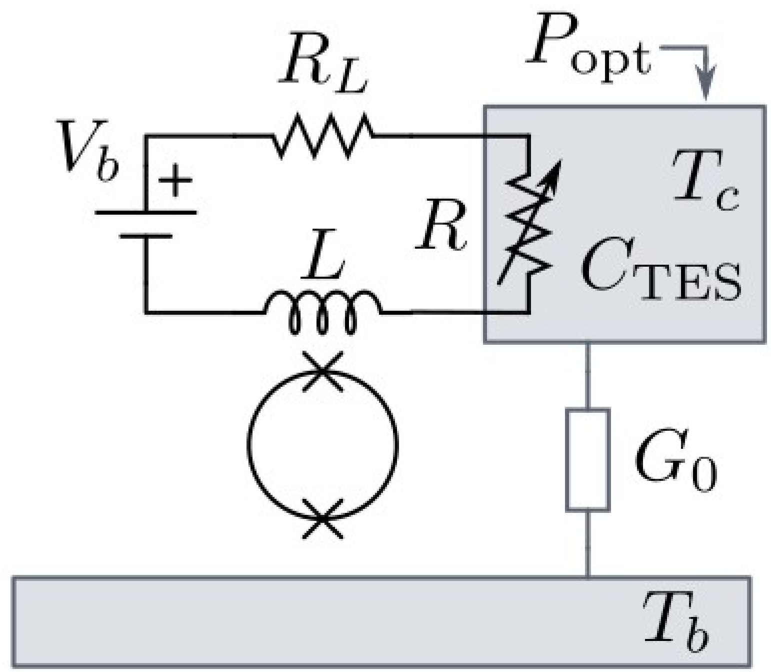
SPIDER TES





$$\tau_o = \frac{C}{G}$$

$$\tau_e = \frac{L}{R}$$



Thermal eqn:

$$C\frac{\mathrm{d}T}{\mathrm{d}t} = -P_{\mathrm{bath}} + P_{\mathrm{J}} + P$$

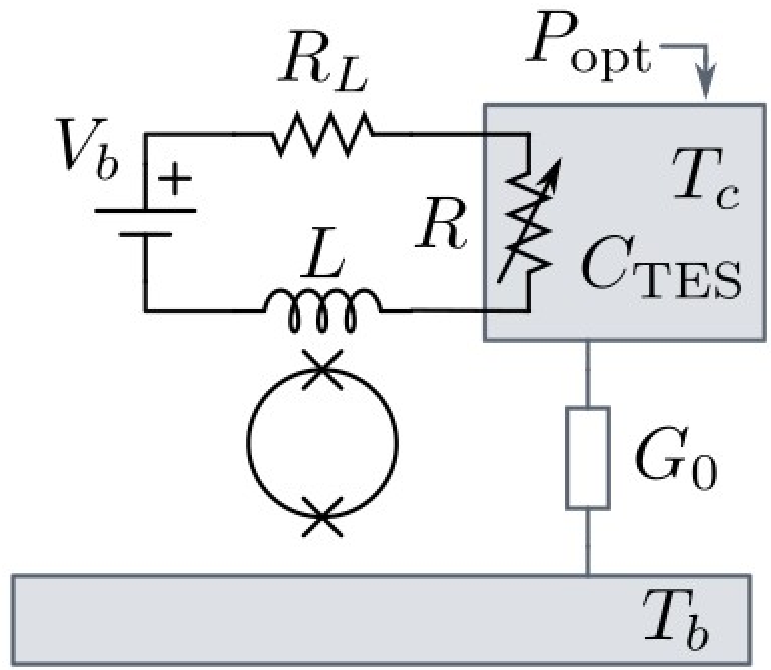
Typical assumptions:

$$P_{\mathrm{bath}} = K\left(T^n - T_{\mathrm{bath}}^n\right)$$

$$G \equiv \mathrm{d}P_{\mathrm{bath}}/\mathrm{d}T$$

$$G = nKT^{n-1}$$

$$P_{\mathrm{bath}} \approx P_{\mathrm{bath}_0} + G\delta T$$



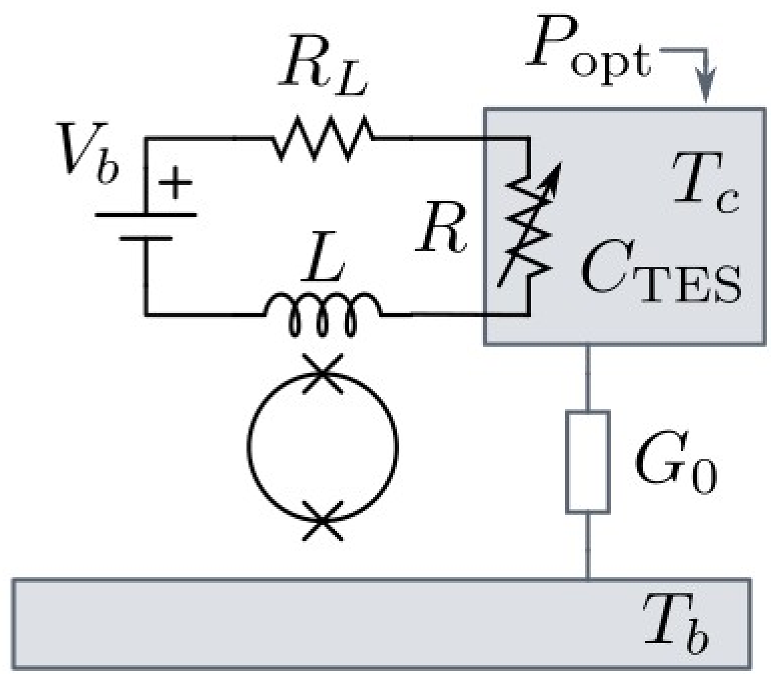
Electrical eqn: $$L\frac{\mathrm{d}I}{\mathrm{d}t} = V - IR_{\mathrm{L}} - IR(T,I)$$

$$R(T,I) \approx R_0 + \left.\frac{\partial R}{\partial T}\right|_{I_0} \delta T + \left.\frac{\partial R}{\partial I}\right|_{T_0} \delta I \; ;$$

$$\alpha_I \equiv \left.\frac{\partial \log R}{\partial \log T}\right|_{I_0} = \frac{T_0}{R_0}\left.\frac{\partial R}{\partial T}\right|_{I_0}$$

$$\beta_I \equiv \left.\frac{\partial \log R}{\partial \log I}\right|_{T_0} = \frac{I_0}{R_0}\left.\frac{\partial R}{\partial I}\right|_{T_0}$$

$$R(T,I) \approx R_0 + \alpha_I \frac{R_0}{T_0}\delta T + \beta_I \frac{R_0}{I_0}\delta I$$



$$\mathcal{L} \equiv \frac{\alpha P_{\text{bias}}}{GT_0} \tag{3.5}$$

Expanding the total power flowing through the thermal link, using the definitions of $\overline{G}$ and G as defined above and again keeping only first order terms,

$$\delta(\overline{G}(T - T_b)) = \overline{G}(T_0 - T_b) + G\delta T \tag{3.6}$$

$$\lim_{\mathcal{L}\to 0} \tau_+ = \tau_e = \frac{L}{R_0(1+\beta+\varepsilon)}$$

$$\lim_{\mathcal{L}\to 0} \tau_- = \tau_0 = \frac{C}{G}$$

Keeping lowest order terms with the two time constants are well separated:

$$\tau \approx \frac{\tau_0}{(2\zeta-1)\,\mathcal{L}+1} = \frac{\tau_0}{\left(\frac{1-\varepsilon}{1+\varepsilon+\beta}\right)\mathcal{L}+1}$$

Assuming beta->0 and perfect voltage bias, the term in parenthesis goes to 1:

$$\tau \approx \frac{\tau_0}{(L+1)}$$

$$L \equiv \frac{\alpha P_{\text{bias}}}{\bar{G}T_0}$$

$$\bar{G} = \frac{P_{total}}{\Delta T}$$

$$\tau_o = \frac{C}{G}$$

$$\alpha_I \equiv \left.\frac{\partial \log R}{\partial \log T}\right|_{I_0}$$

The differential equation also allows for unstable (growing) solutions. In general, we require:

$$\mathcal{L} \leq (3 - 2\sqrt{2})\frac{\tau_0}{\tau_e} \approx \frac{\tau_0}{5.8\tau_e} \qquad \tau_e \approx L/R$$

This is a critical factor in TES design: you need high enough bandwidth for your science, but long enough time constants for your readout.

We can do a similar calculation for noise, assuming thermal carriers move randomly back and forth in equilibrium along a thermal link.

Typically only two terms:

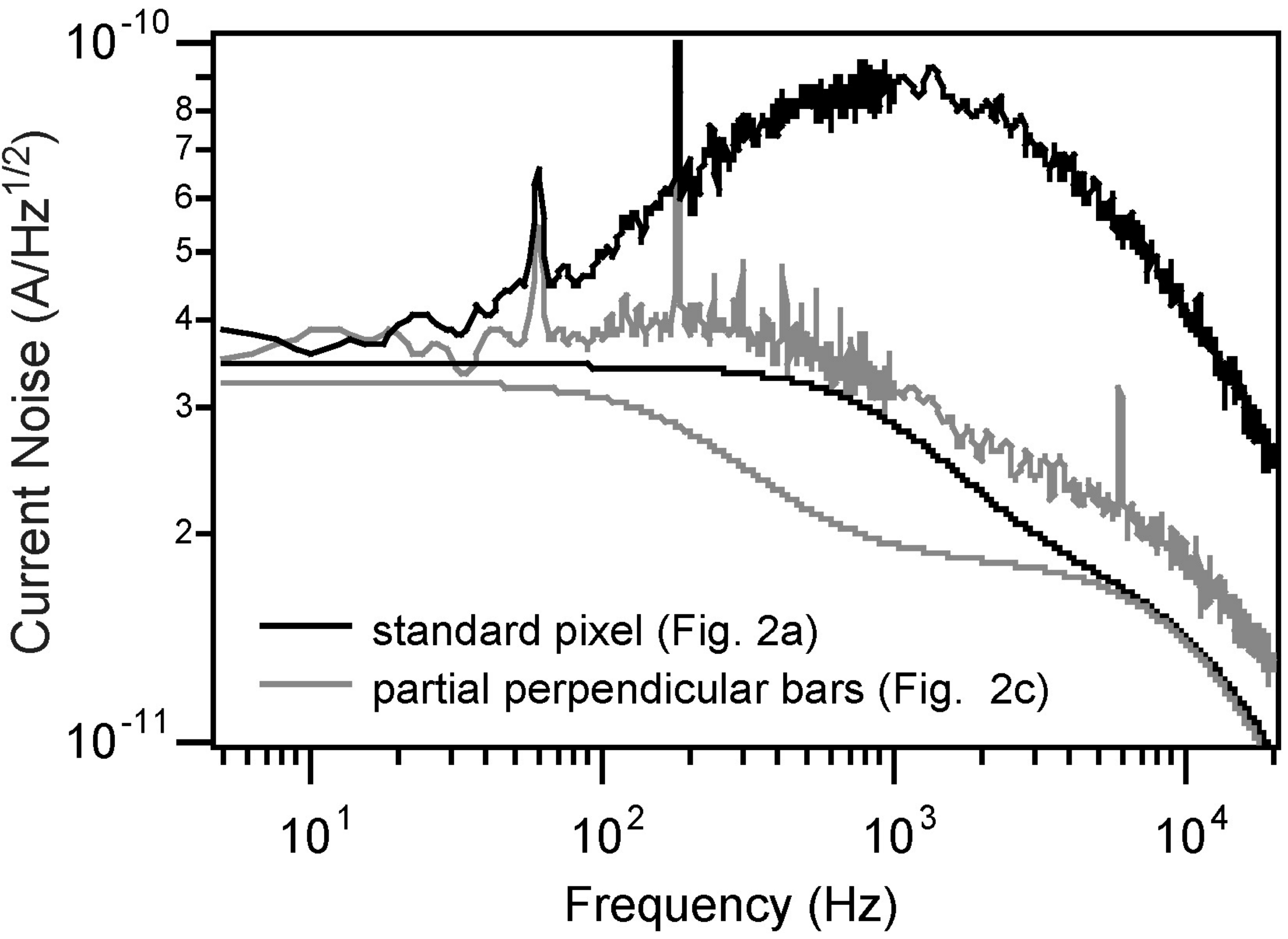
Photon noise:

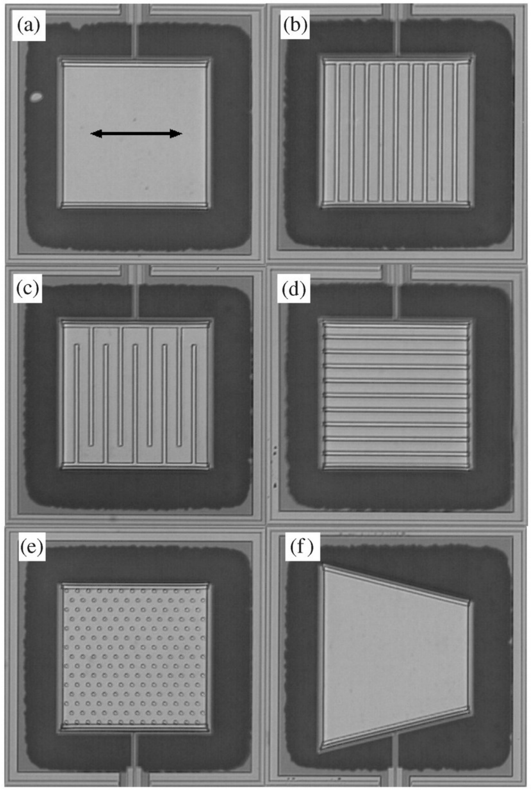
$$S_{\text{opt}} = 2h\nu P_{\text{opt}} + \frac{\xi P_{\text{opt}}^2}{\delta\nu}$$

Thermal carrier noise:

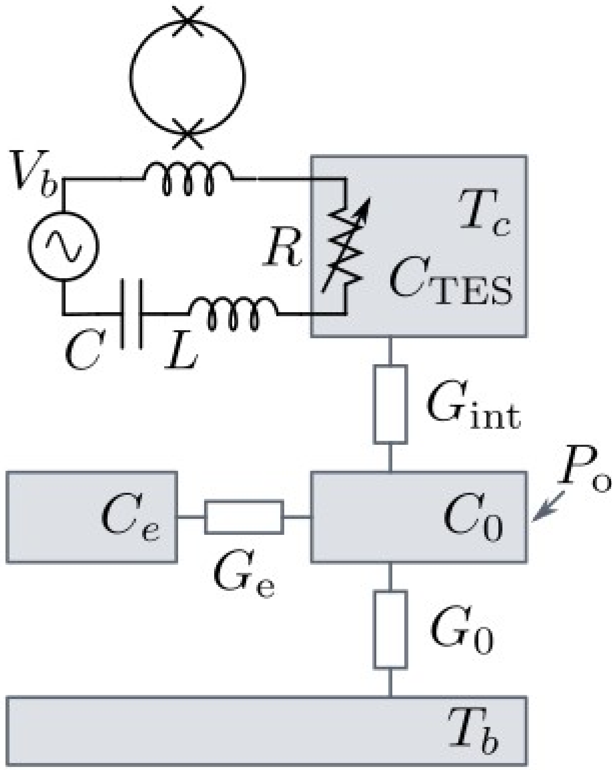
$$S_G = 4\gamma_{\text{NE}} k_B T_c^2 G$$

Excess noise





More complicated models are often required:

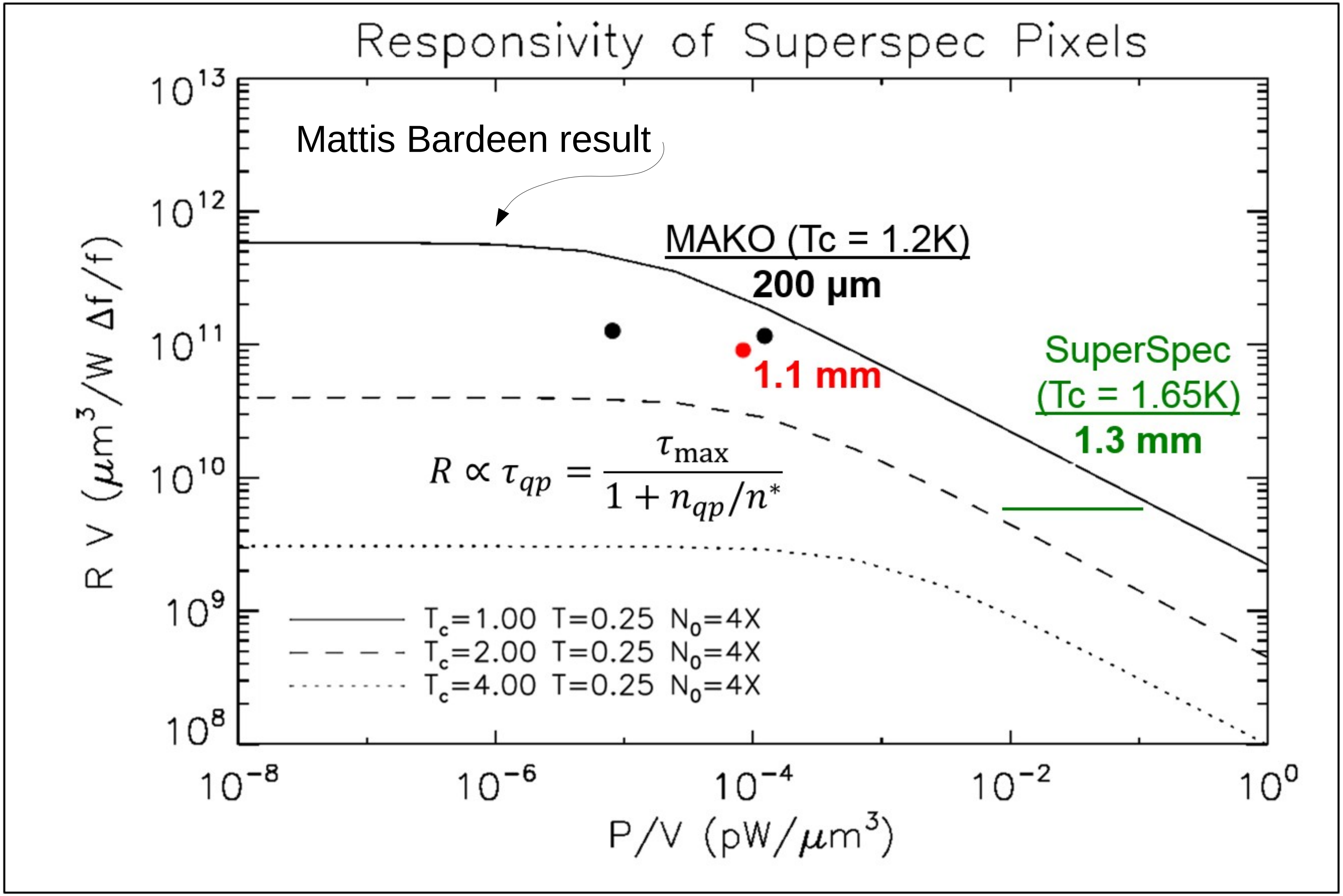


$$\frac{d}{dt}\mathbf{v} = \mathbf{A}\mathbf{v} + \mathbf{p}$$

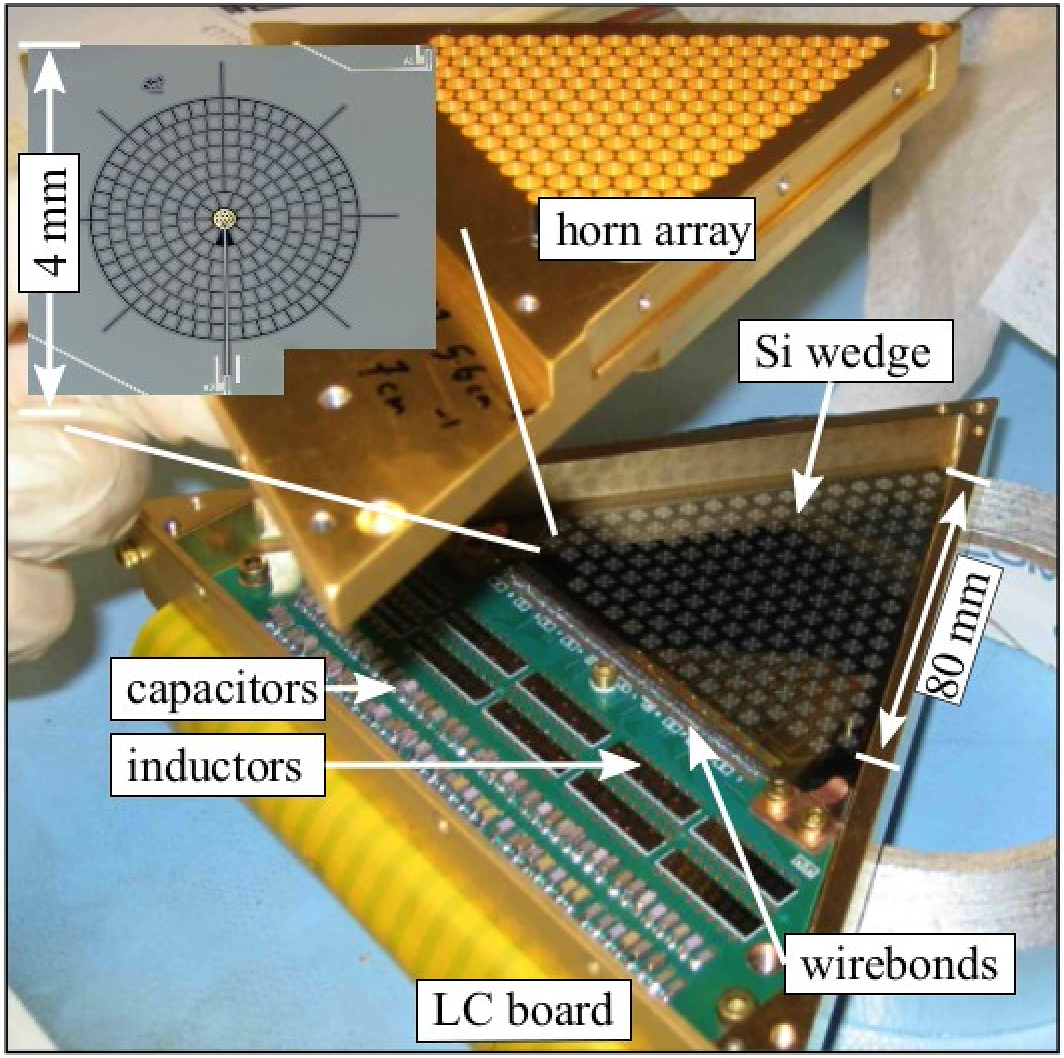
$$\mathbf{v} \equiv \begin{pmatrix} LI_0\delta I \\ \frac{C_0}{\eta}\delta T_{\mathrm{TES}} \\ C_0\delta T_0 \\ C_e\delta T_e \end{pmatrix}, \quad \mathbf{p} \equiv \begin{pmatrix} I_0\delta I \\ \delta P_{\mathrm{TES}} \\ \delta P_0 \\ \delta P_e \end{pmatrix}$$

$$\mathbf{A} \equiv \begin{pmatrix} -\tau_e^{-1} & -\eta\frac{\gamma}{\gamma+1}\mathcal{L}\tau_0^{-1} & 0 & 0 \\ 2\zeta\tau_e^{-1} & \left(\frac{\mathcal{L}G_{\mathrm{eff}}}{G_0} - \gamma G_0\right)\tau_0^{-1} & \gamma\tau_0^{-1} & 0 \\ 0 & \eta\gamma\tau_0^{-1} & -(\gamma+1)\tau_0^{-1} & \frac{\eta\gamma_e}{\eta_e}\tau_0^{-1} \\ 0 & 0 & \gamma_e\tau_0^{-1} & \frac{\eta\gamma_e}{\eta_e}\tau_0^{-1} \end{pmatrix}$$

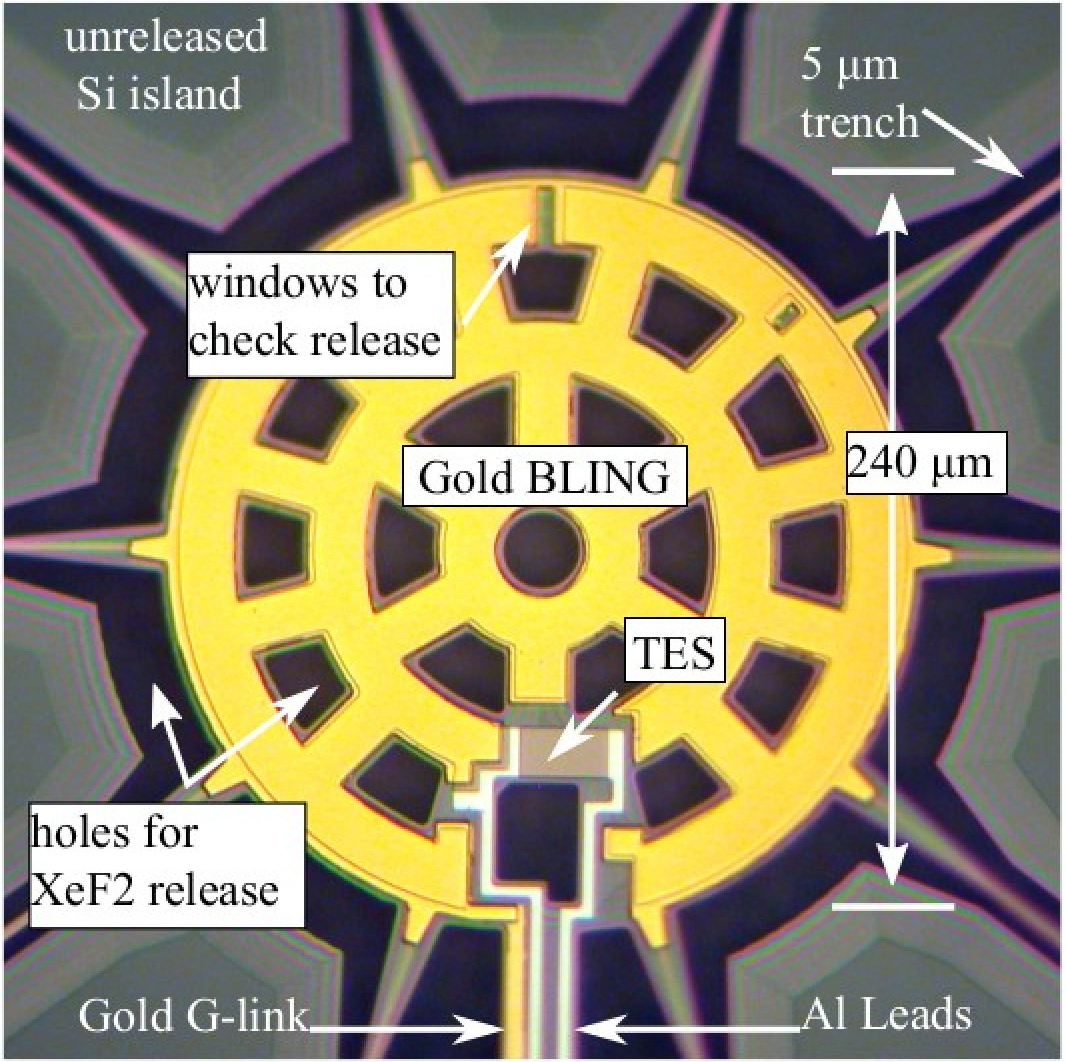
RV vs P/V plot

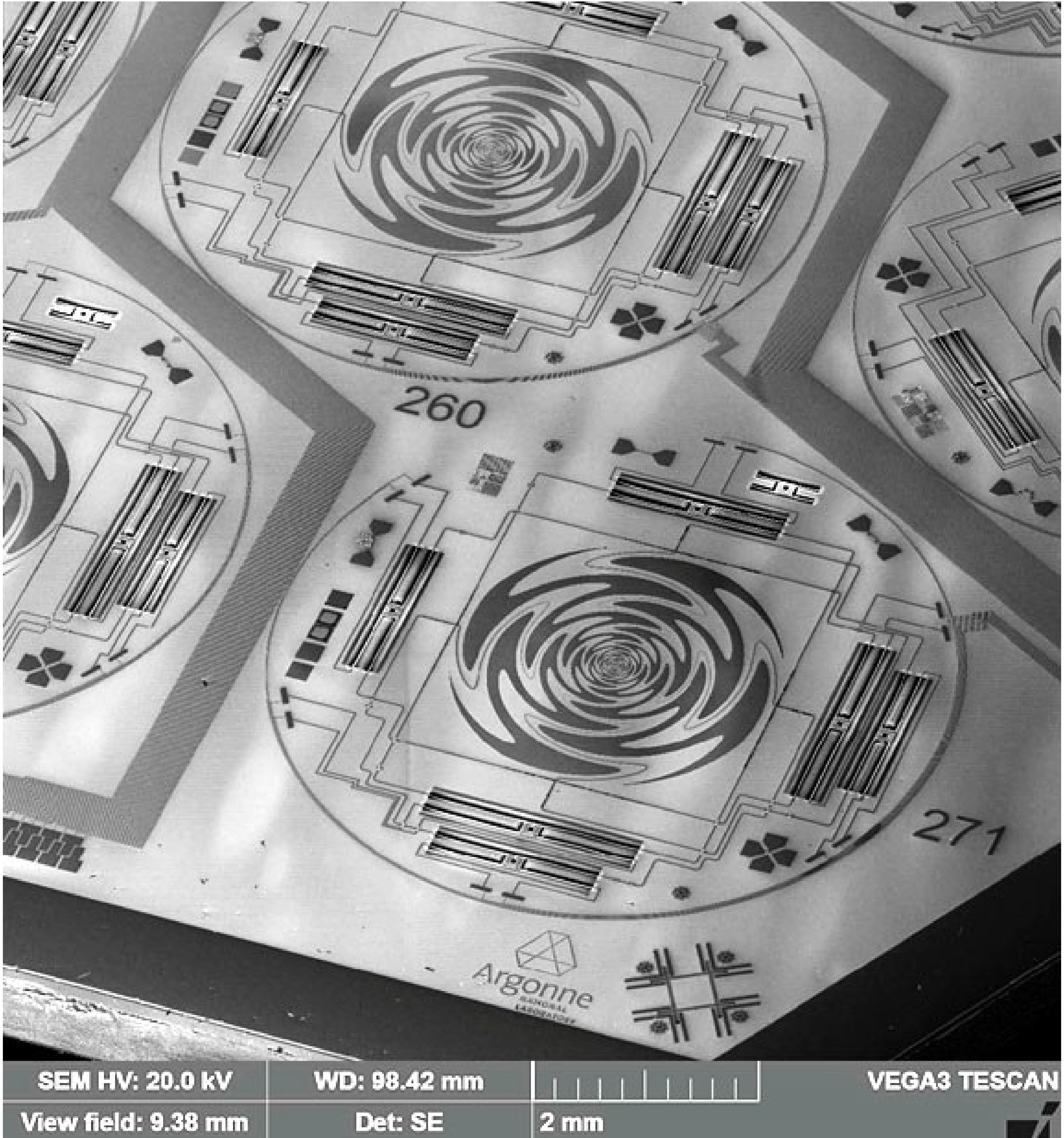


Responsivity of Superspec Pixels
Mattis Bardeen result
MAKO (Tc = 1.2K)
200 μm
1.1 mm
SuperSpec
(Tc = 1.65K)
1.3 mm
$R \propto \tau_{qp} = \frac{\tau_{max}}{1 + n_{qp}/n^*}$
T_c=1.00 T=0.25 N_0=4X
T_c=2.00 T=0.25 N_0=4X
T_c=4.00 T=0.25 N_0=4X
R V (μm^3/W Δf/f)
P/V (pW/μm^3)
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}

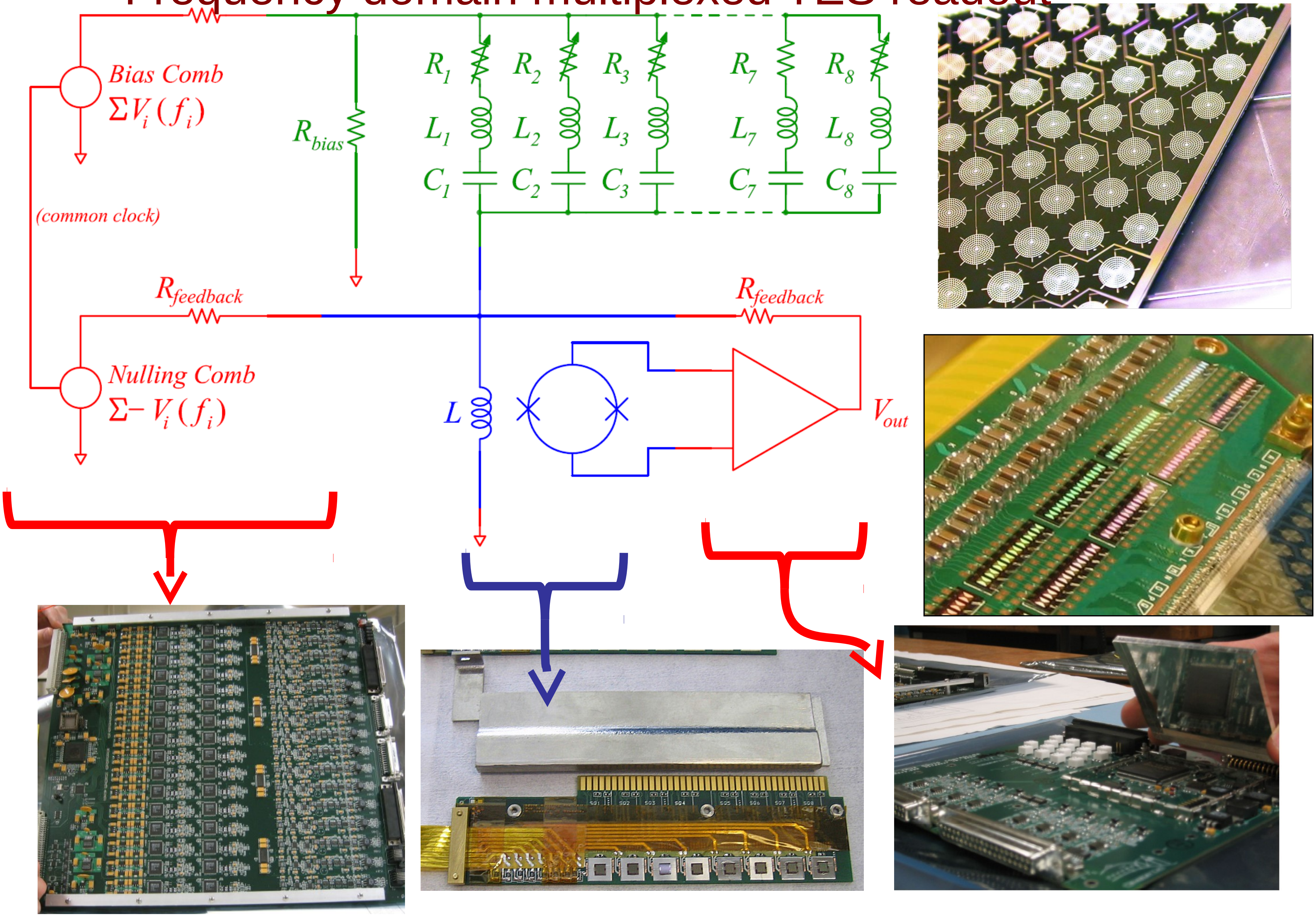


horn array
4 mm
Si wedge
80 mm
capacitors
inductors
wirebonds
LC board


unreleased
Si island
5 μm
trench
windows to
check release
240 μm
Gold BLING
TES
holes for
XeF2 release
Gold G-link
Al Leads


260
271
Argonne
SEM HV: 20.0 kV
WD: 98.42 mm
VEGA3 TESCAN
View field: 9.38 mm
Det: SE
2 mm

Frequency domain multiplexed TES readout



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

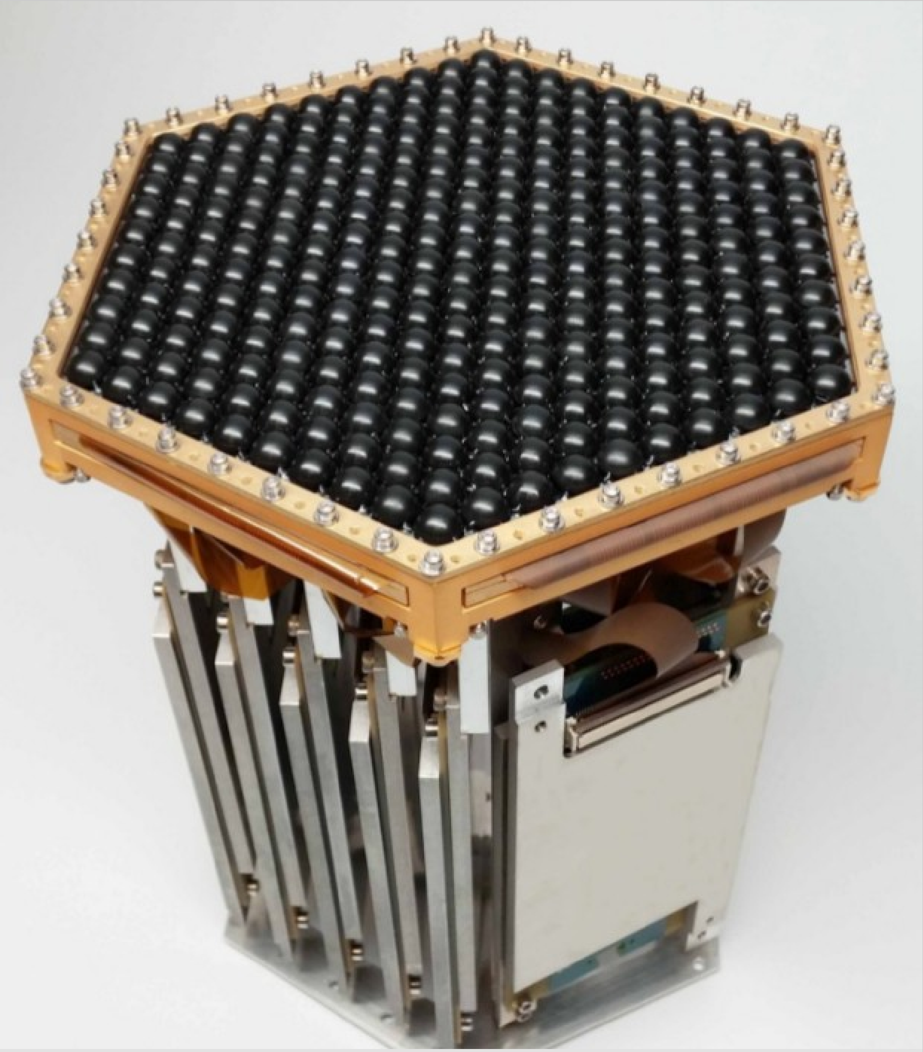
The bad:

- 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:

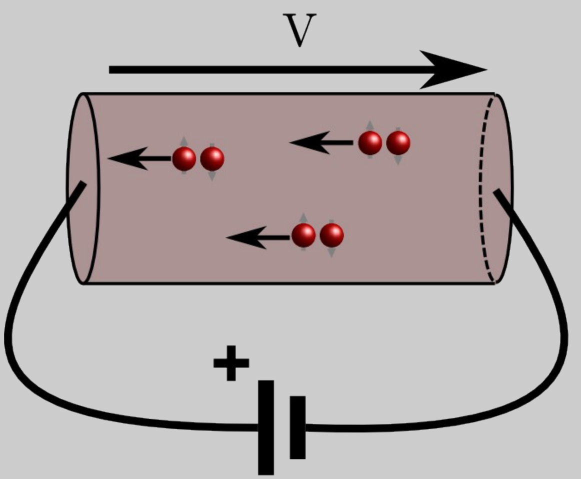
To 1st order, L_k is constant.

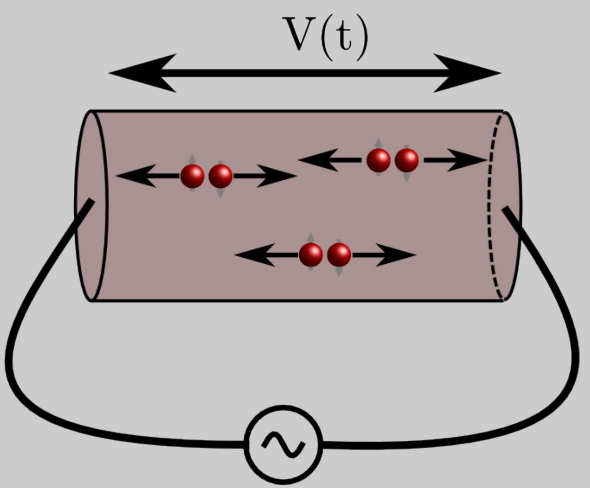
To 2nd order, L_k varies linearly with the number of pairs.

Phase shift leads to E field inside the conductor:

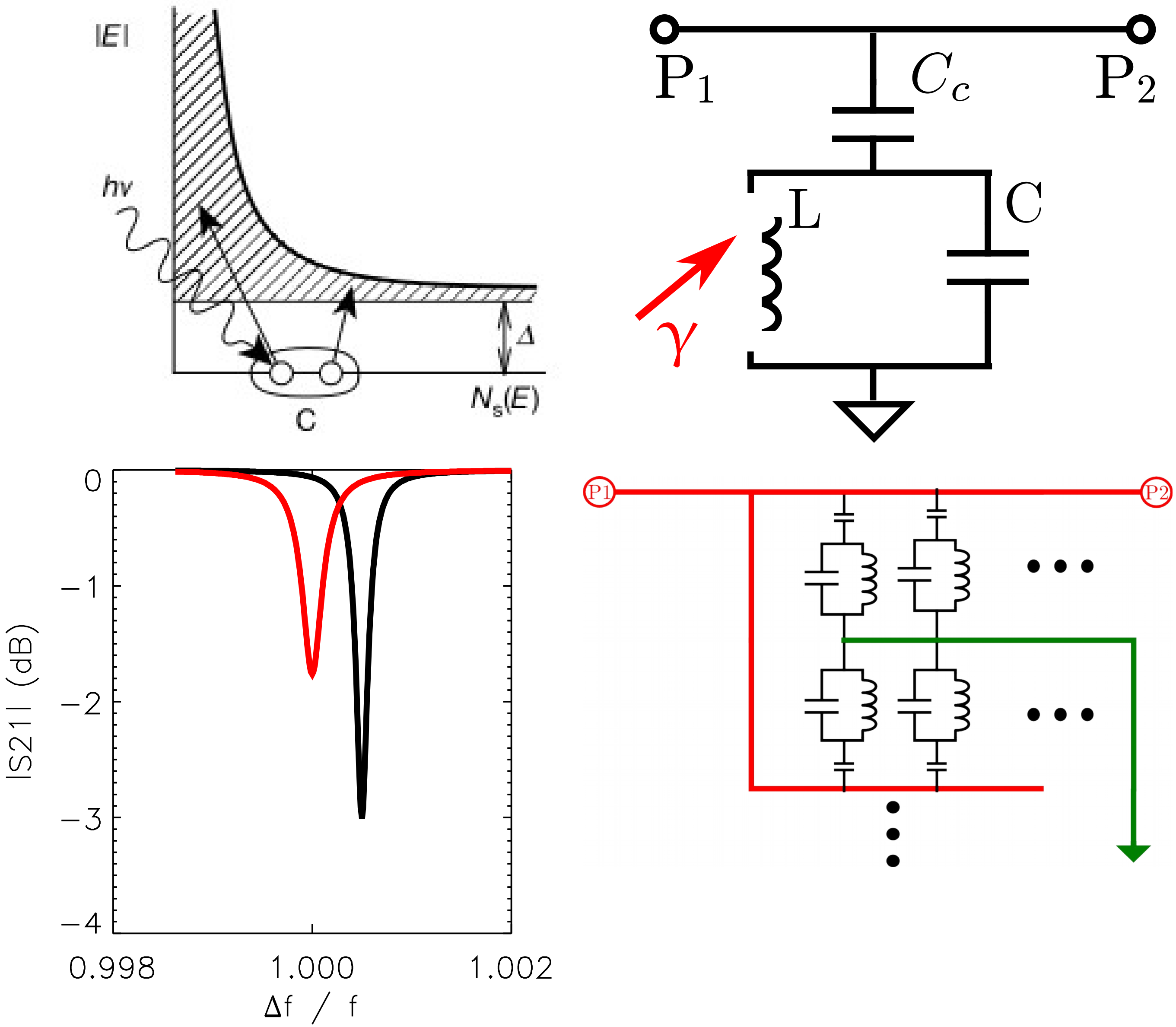
Non-zero resistance from quasiparticle currents

R also varies linearly with number of pairs

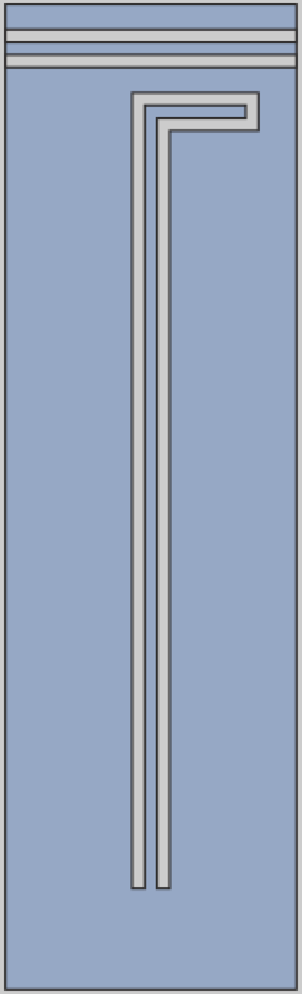


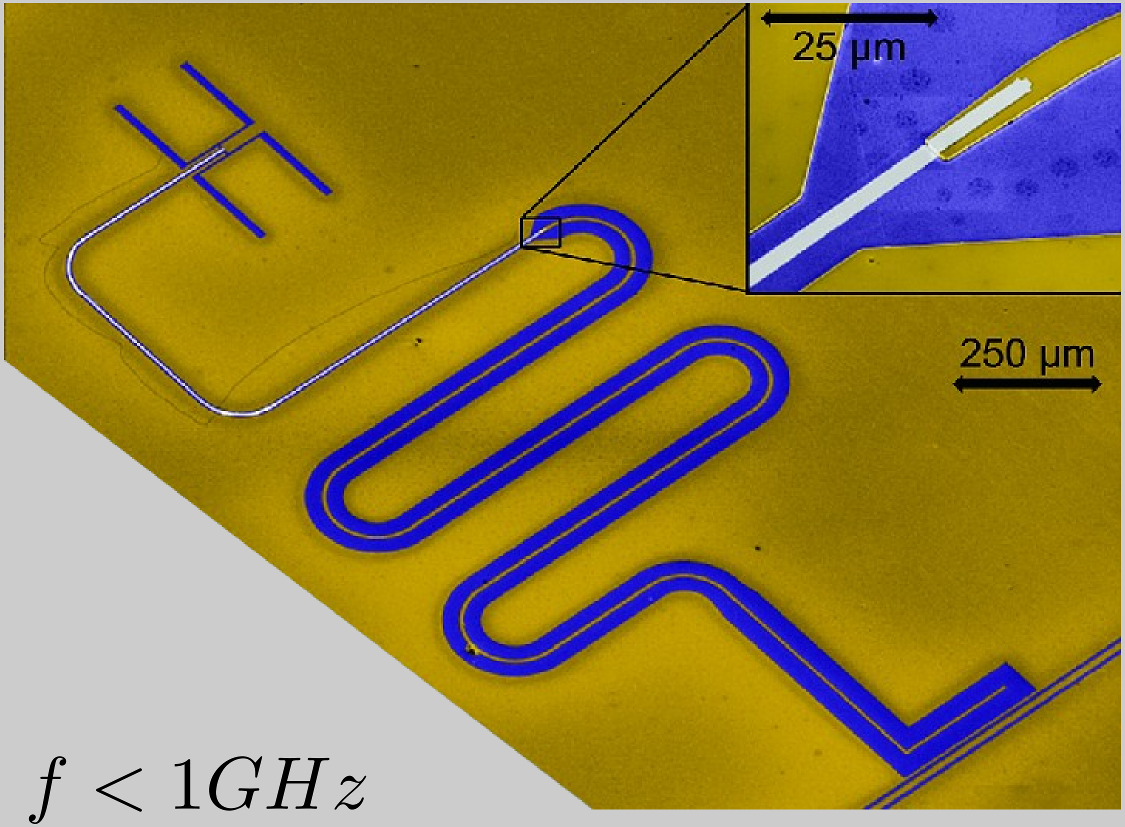


We can make a detector out of this.



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





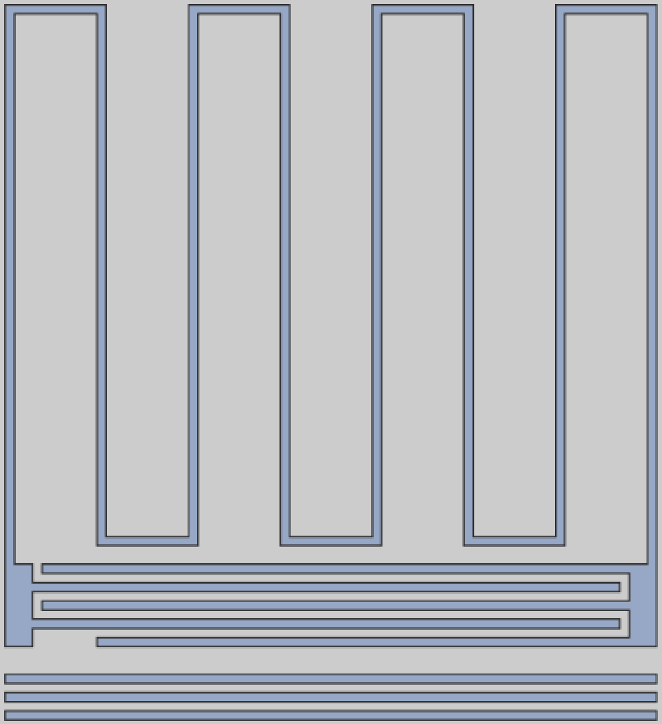
Hard to achieve $f < 1GHz$

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



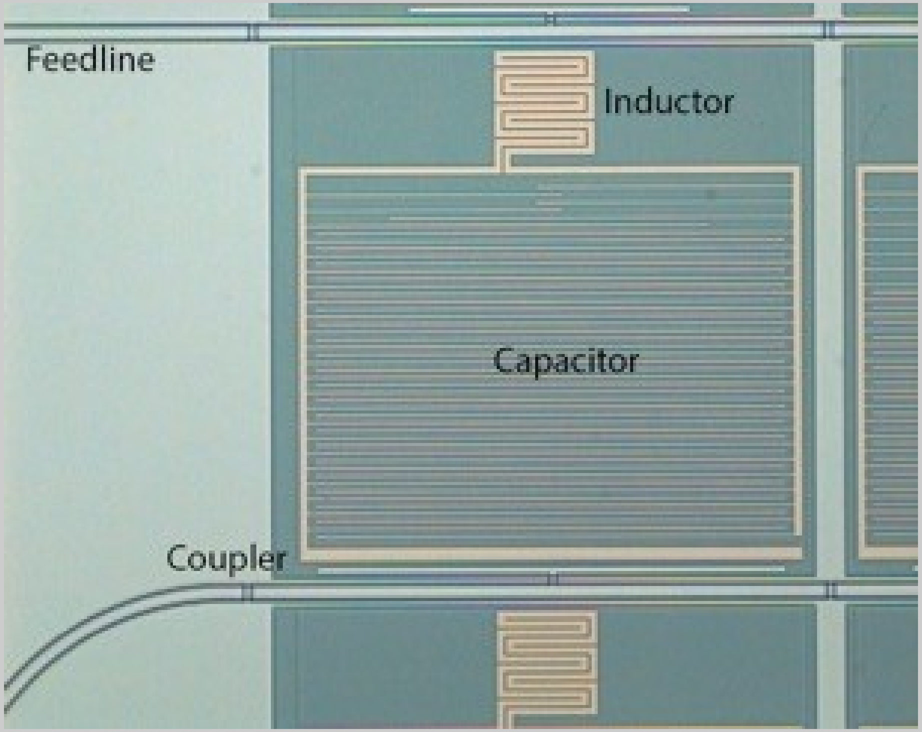


Image from Mazin group, UCSB

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

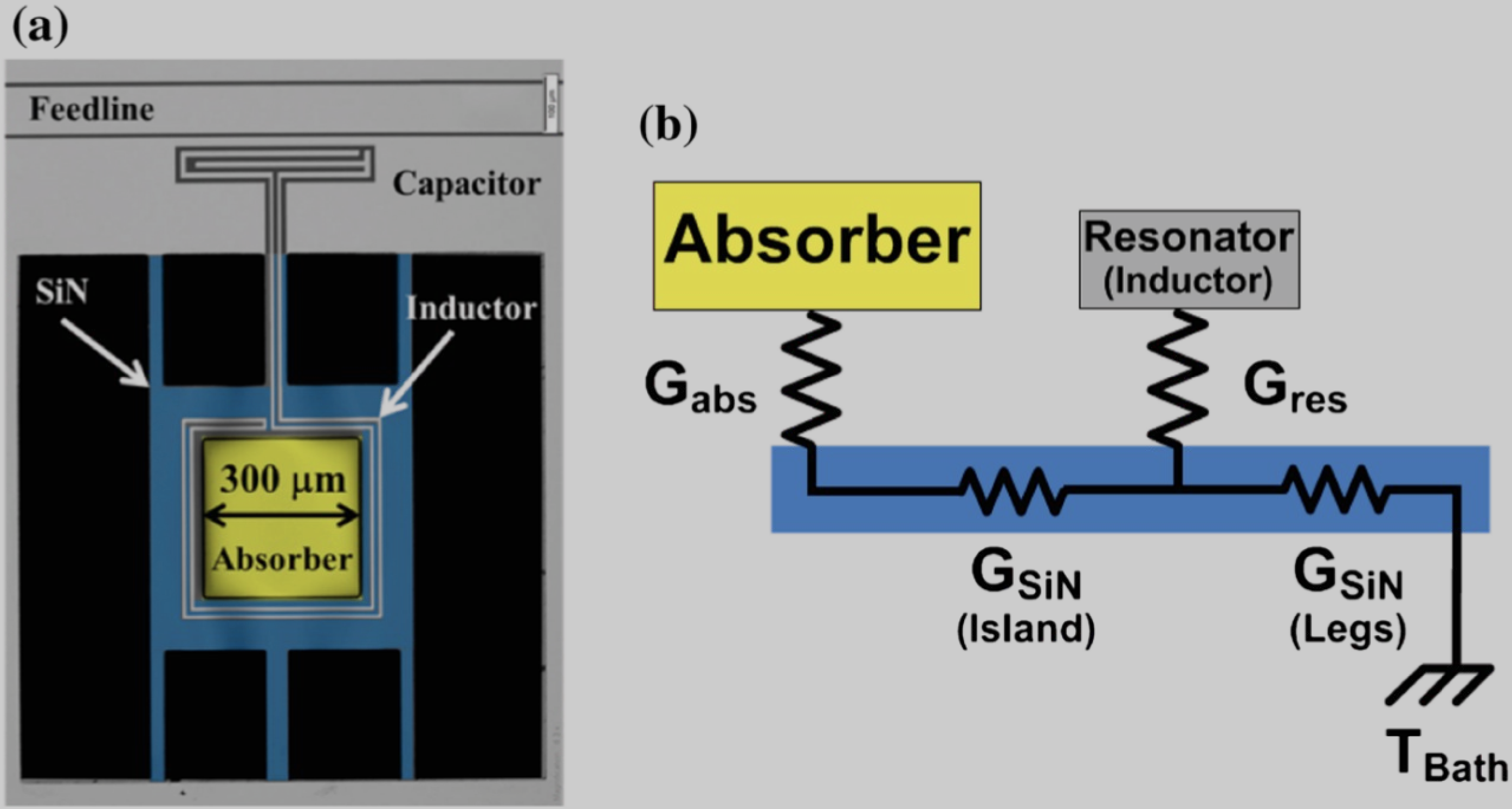
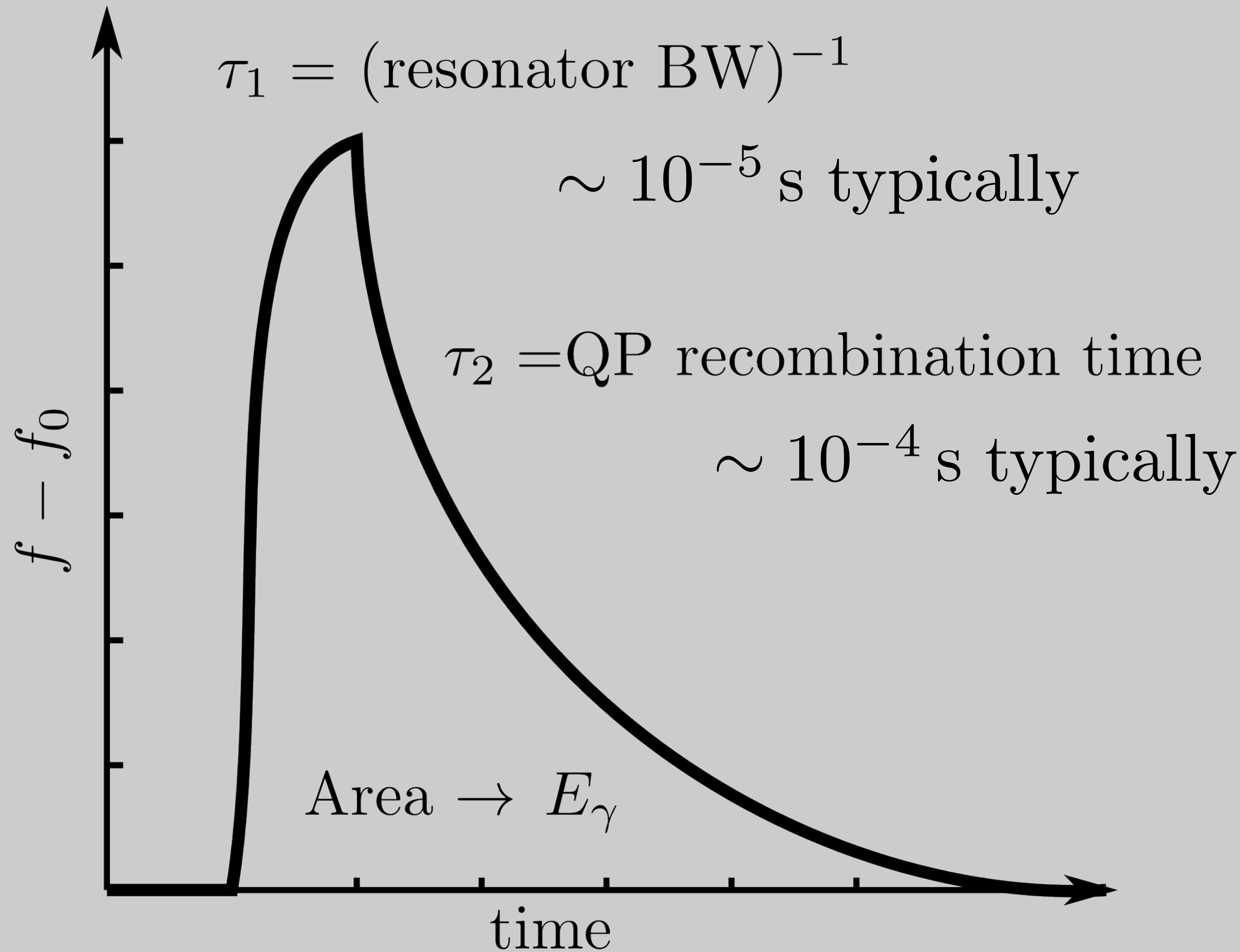


Image from Micelli group, ANL

KIDs as single photon detectors



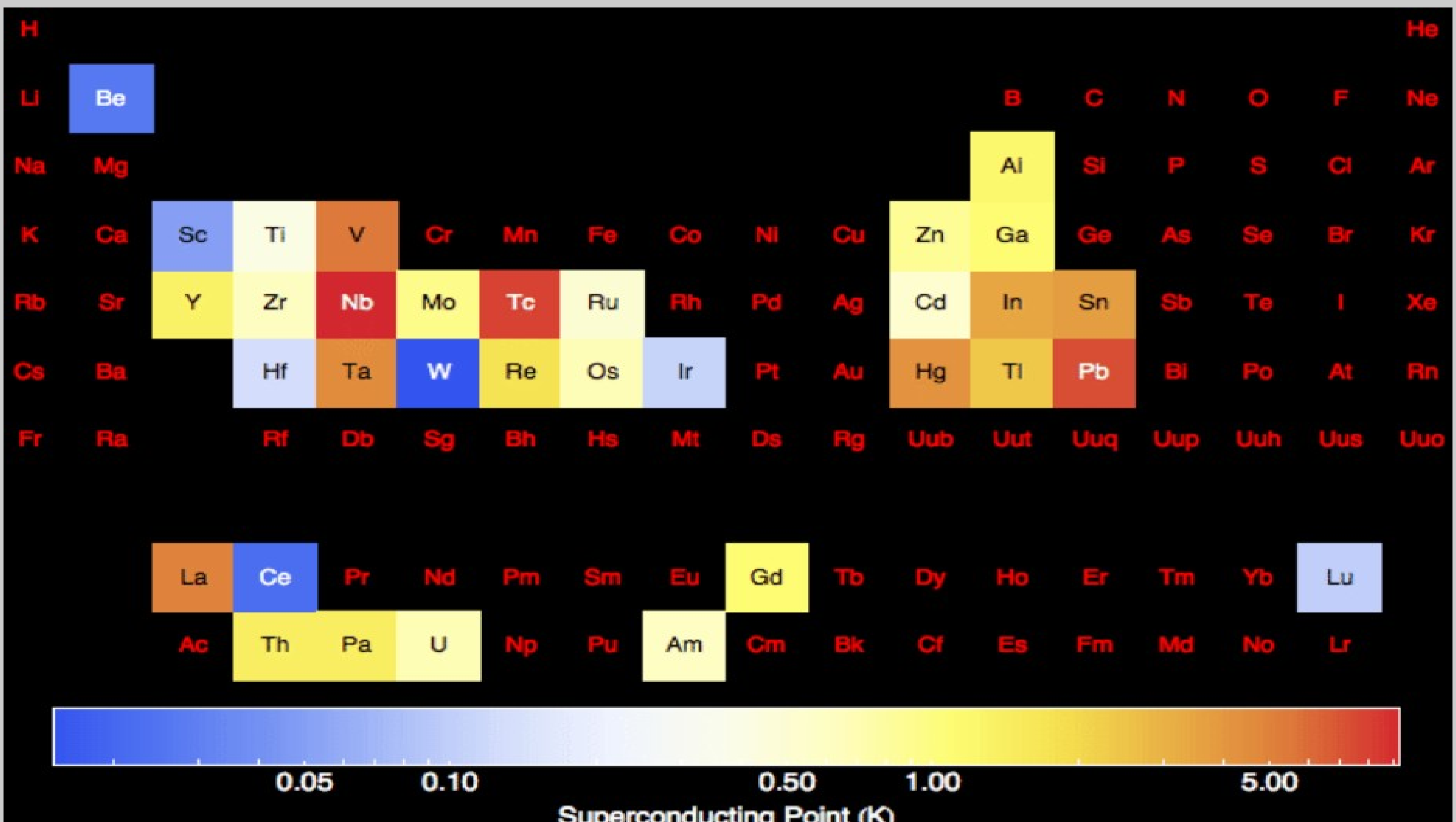
Materials: we're limited by nature, but there are several attractive choices

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 K $\rightarrow$ 87 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

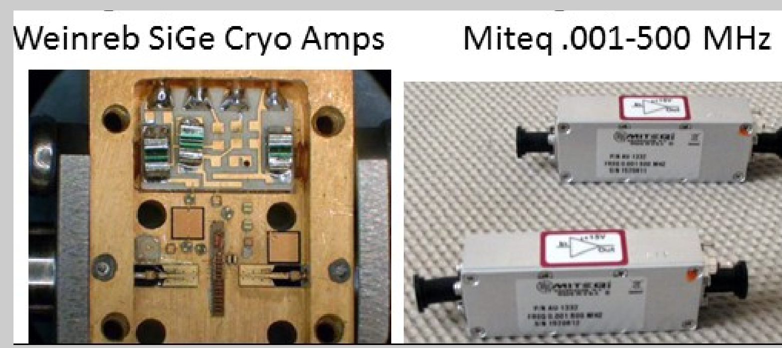
Platinum-Silicide

A complete system:

CASPER-ROACH
open-source
FPGA board

Low noise cryogenic
amplifiers

Sub-K fridge with
microwave coax

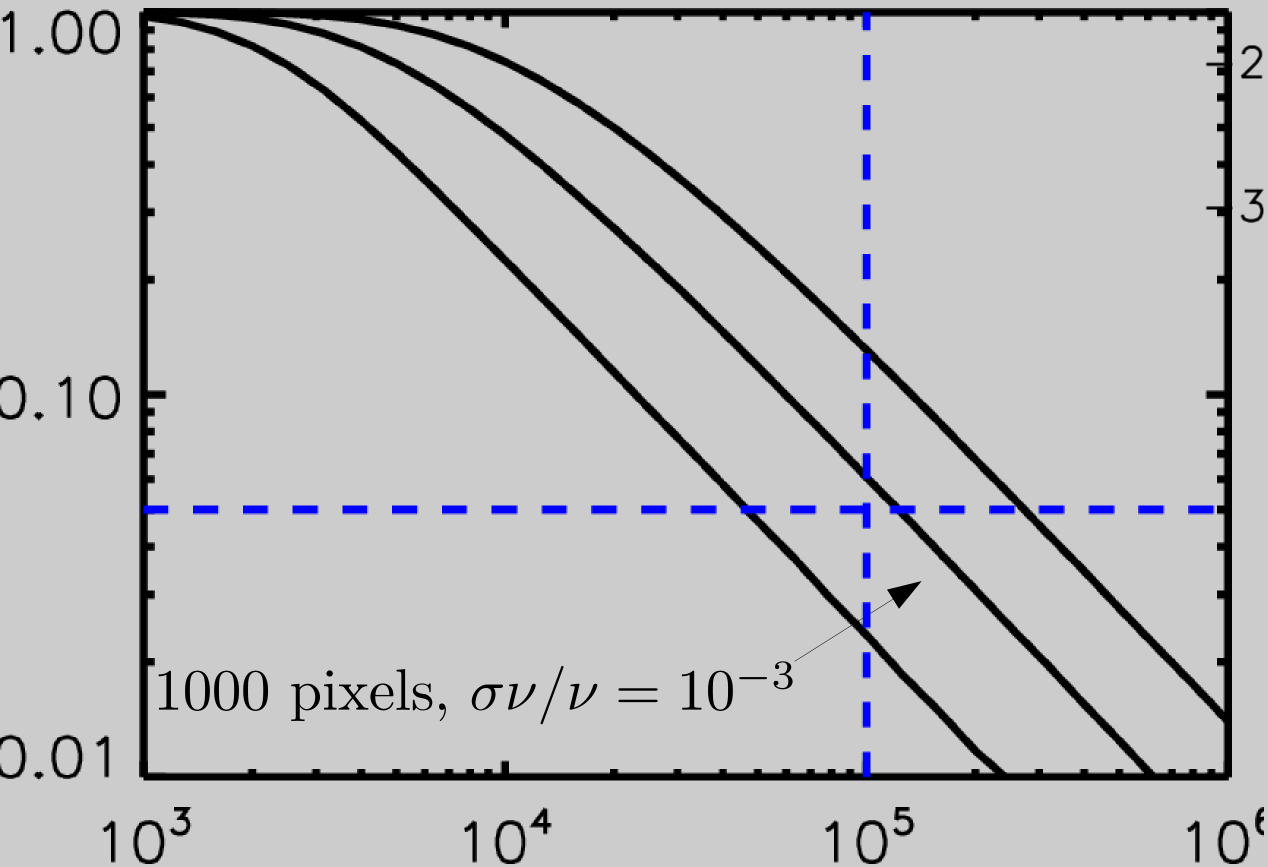


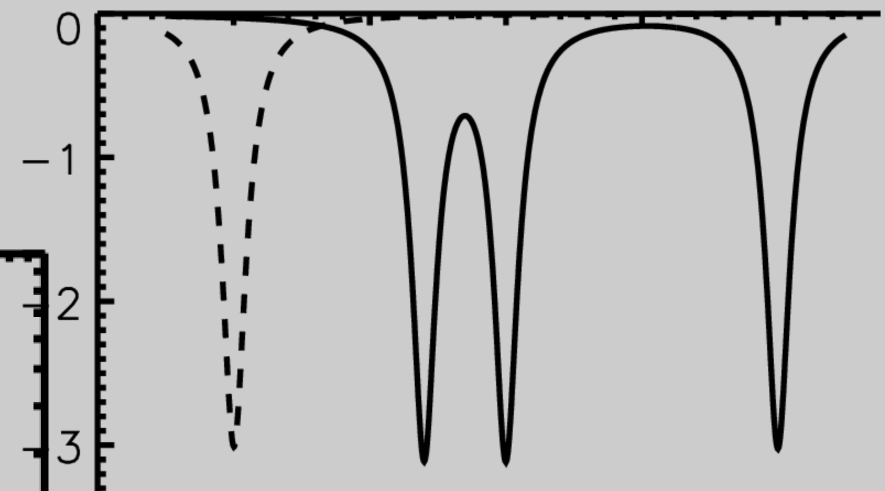
<u>Readout:</u> Today, \$10/pixel with off-the-shelf hardware
→ \$1/pixel with custom boards and large orders

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:

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

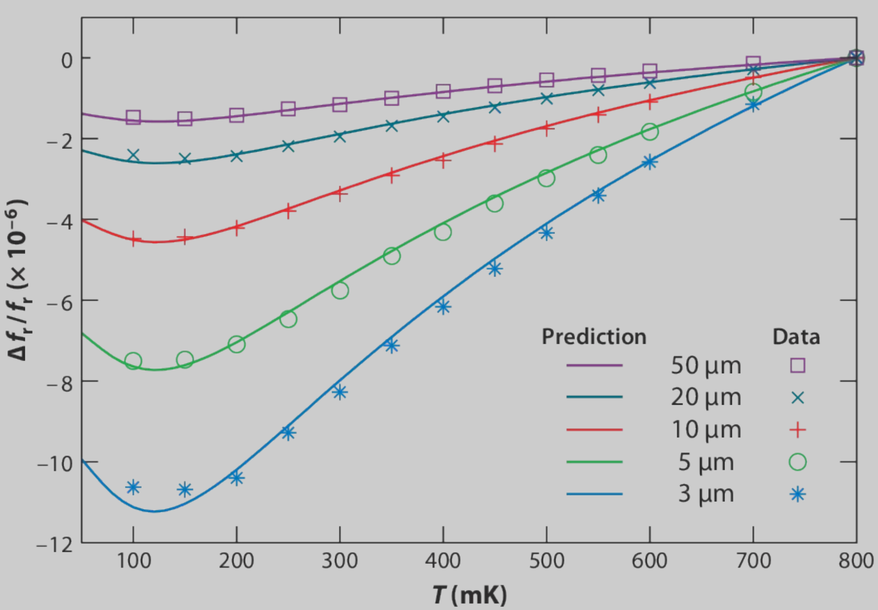
$$\sim f(\nu_{\text{readout}}, Q, V_{\text{inductor}}, T_{\text{c}})$$

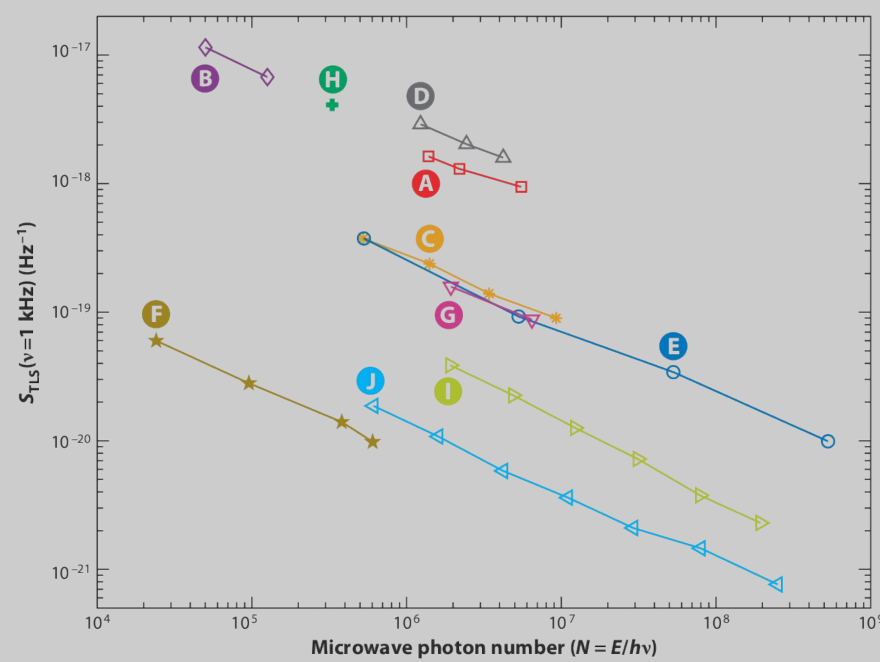
Two Level System Noise: hard to predict a priori, but follows known scaling laws

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

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

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





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*:

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

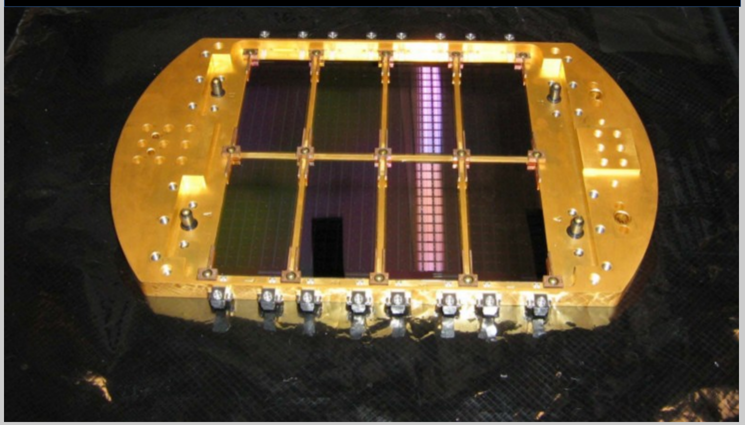
$$\mathrm{NEP}_{\mathrm{amp}} \propto T_{\mathrm{amp}}^{0.5} \left(Q_c/Q_r\right)^{0.5} T_c^{2.5}\, V_L^{0.5}\, T_{\mathrm{opp}}^{0.5}$$

4. GOTO 1.

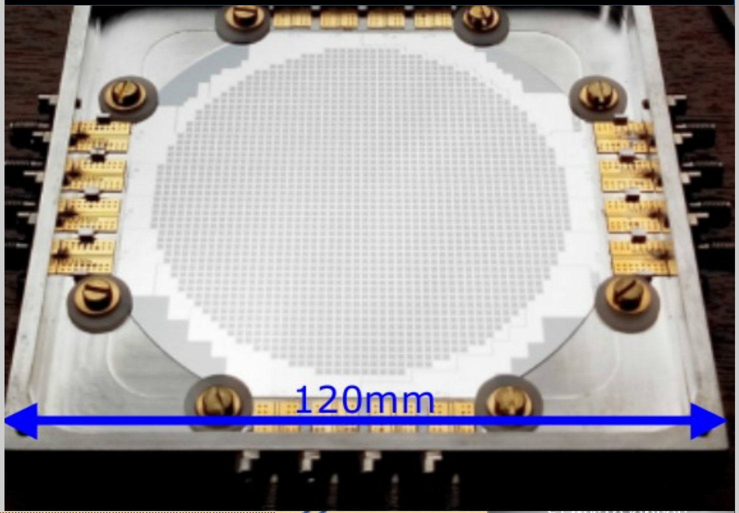
* In this case, for a resonator operating at a fixed fraction of bifurcation power in the linear-response regime.

On-sky cameras

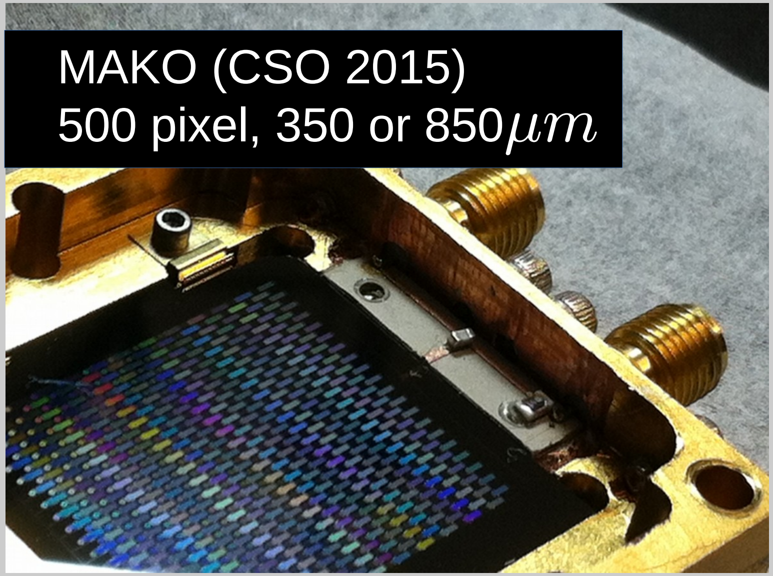
MUSIC: CSO 2012-2015
576 4-color pixels, 2mm-850μm

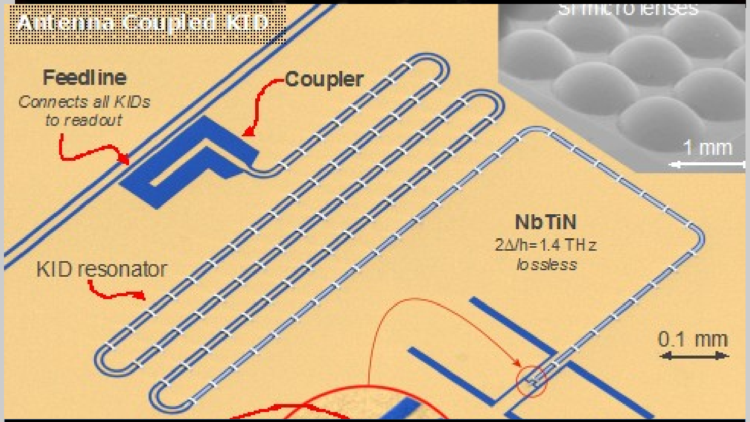


NIKA / NIKA2 (IRAM 2011-pres.)
300/5000 1.25 and 2mm pixel



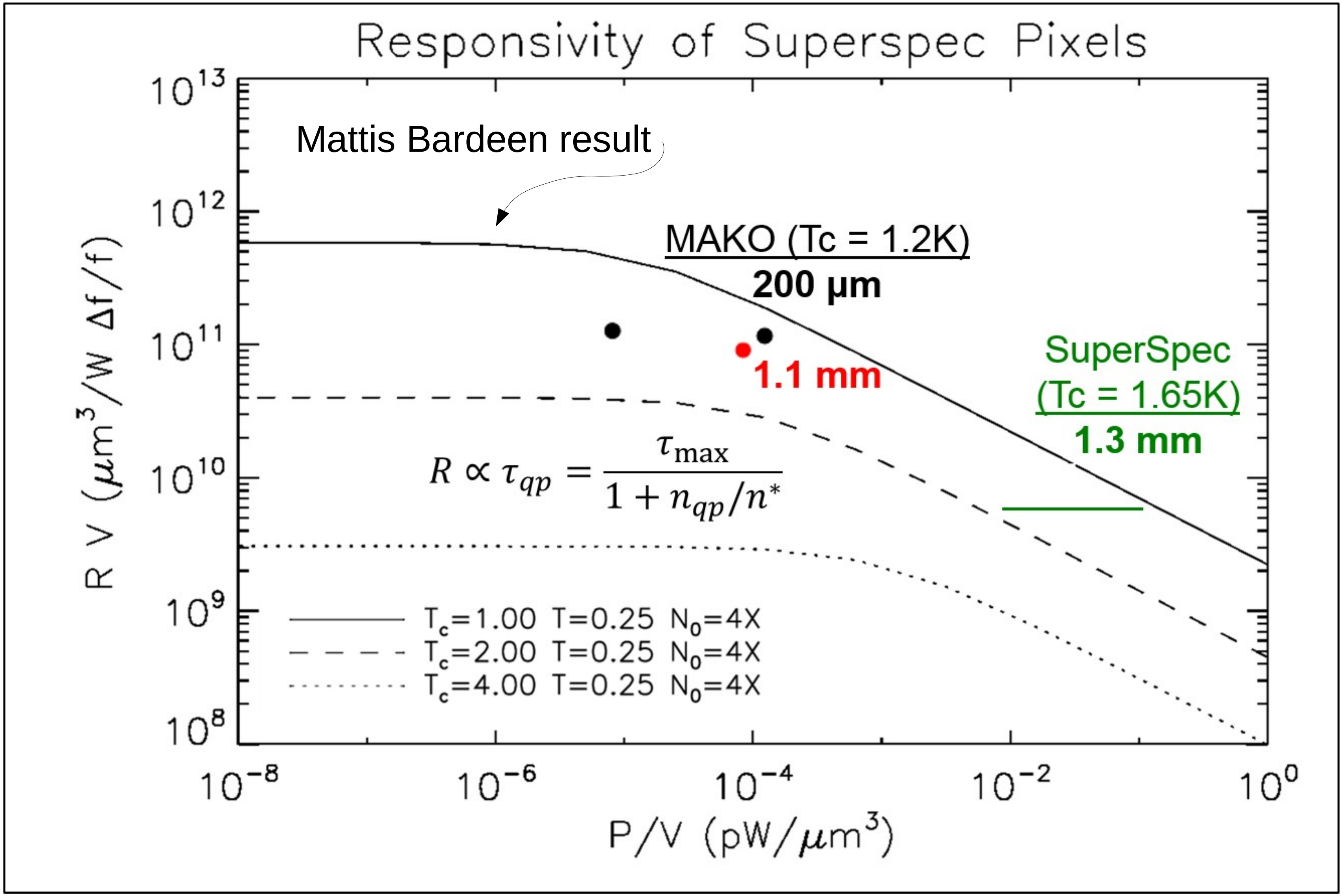
MAKO (CSO 2015)
500 pixel, 350 or 850μm





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

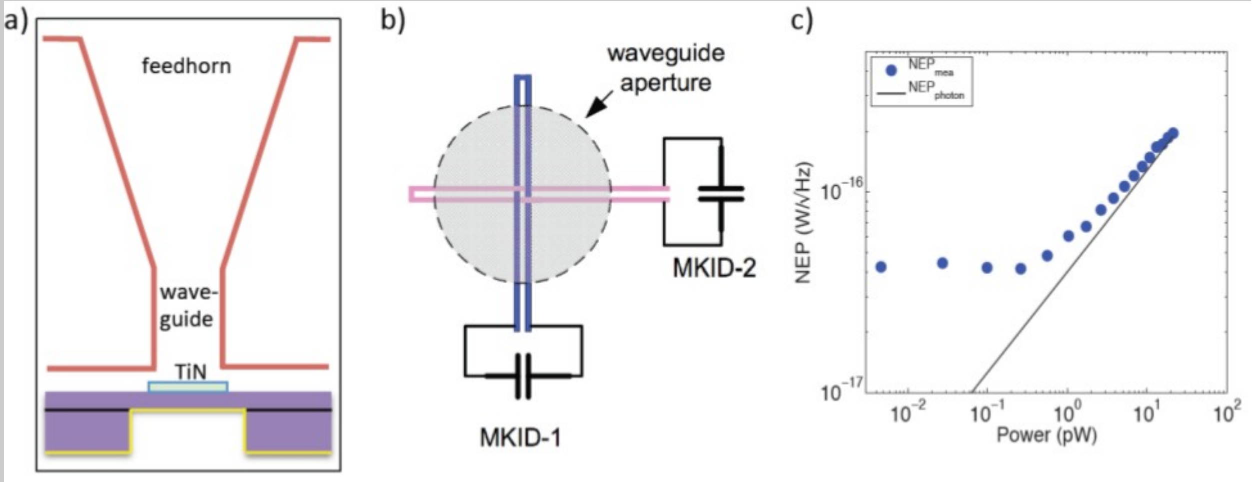
RV vs P/V plot



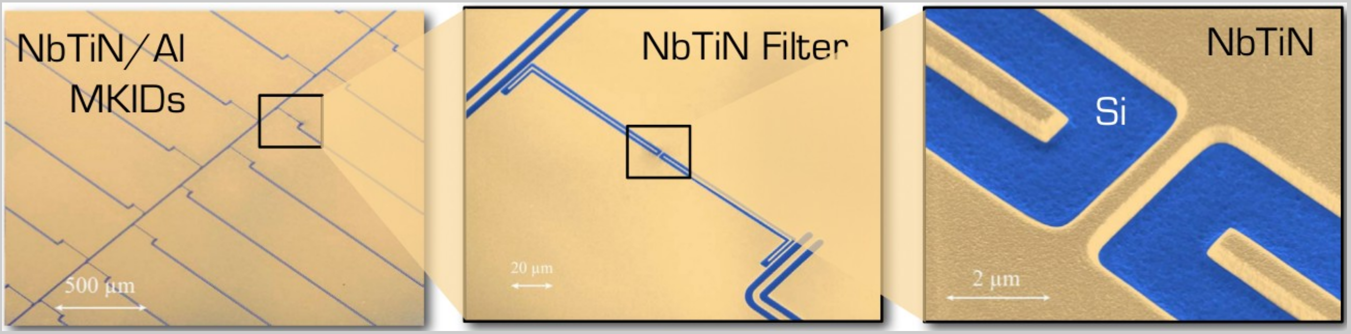
Responsivity of Superspec Pixels
Mattis Bardeen result
MAKO (Tc = 1.2K)
200 µm
1.1 mm
SuperSpec
(Tc = 1.65K)
1.3 mm
$R \propto \tau_{qp} = \frac{\tau_{max}}{1 + n_{qp}/n^*}$
T_c=1.00 T=0.25 N_0=4X
T_c=2.00 T=0.25 N_0=4X
T_c=4.00 T=0.25 N_0=4X
R V (μm^3/W Δf/f)
P/V (pW/μm^3)
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}

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

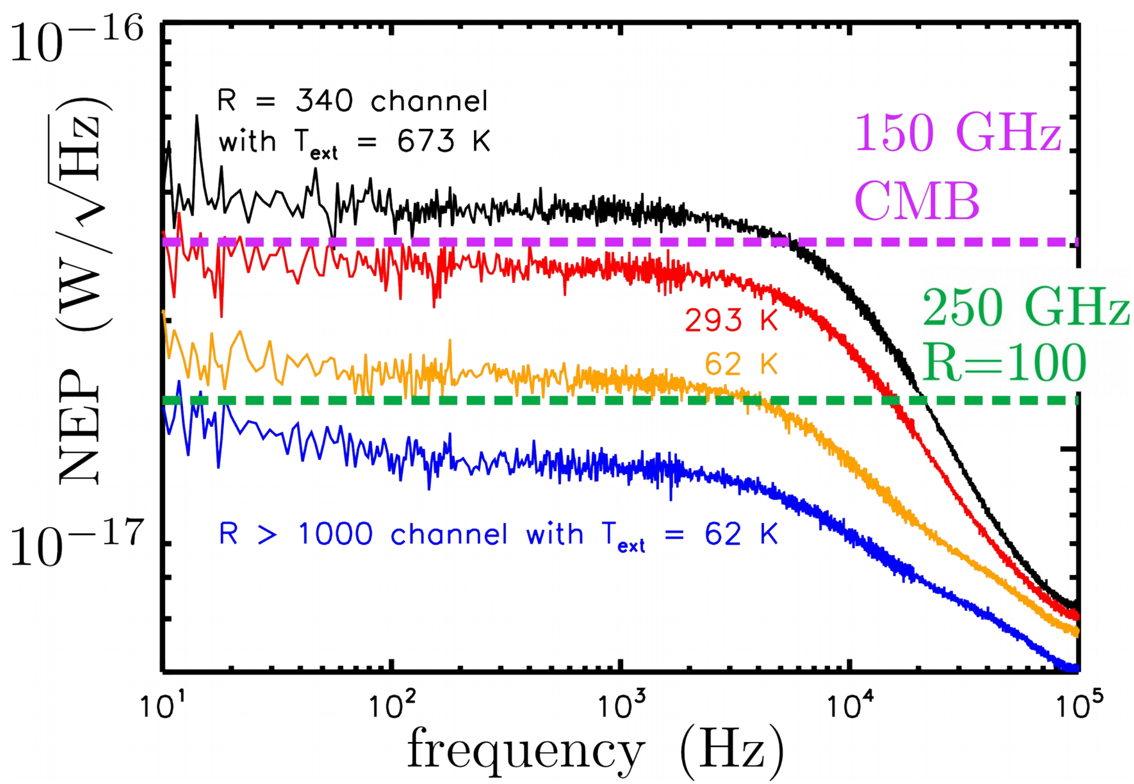


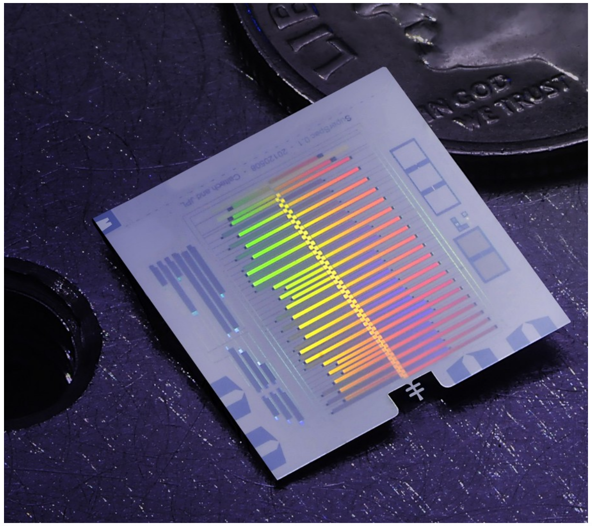
BLAST TNG prototype, from Galitzki+14

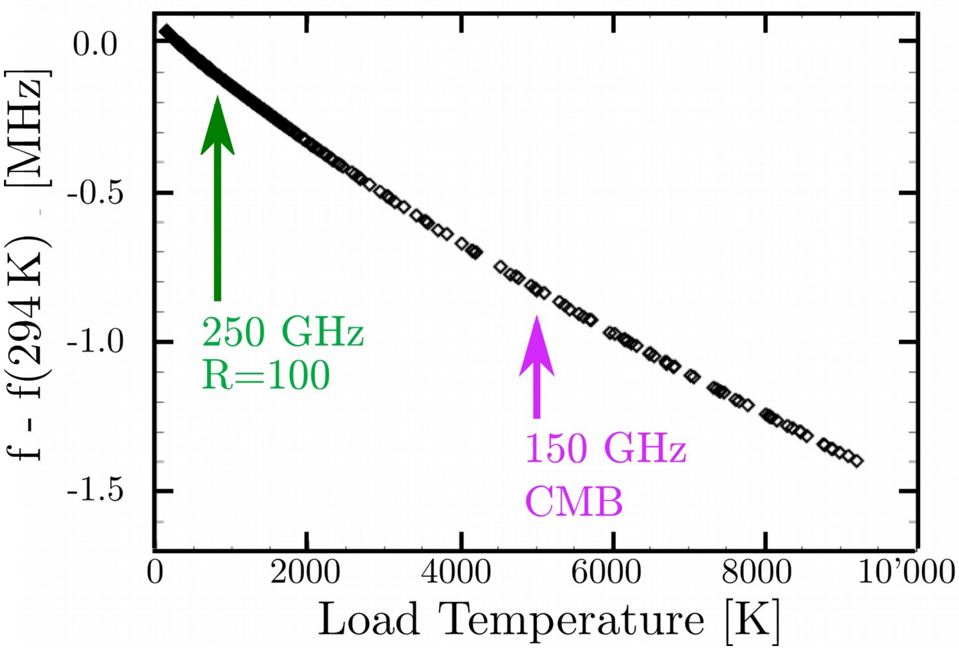


DESHIMA devices, image from A. Endo

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







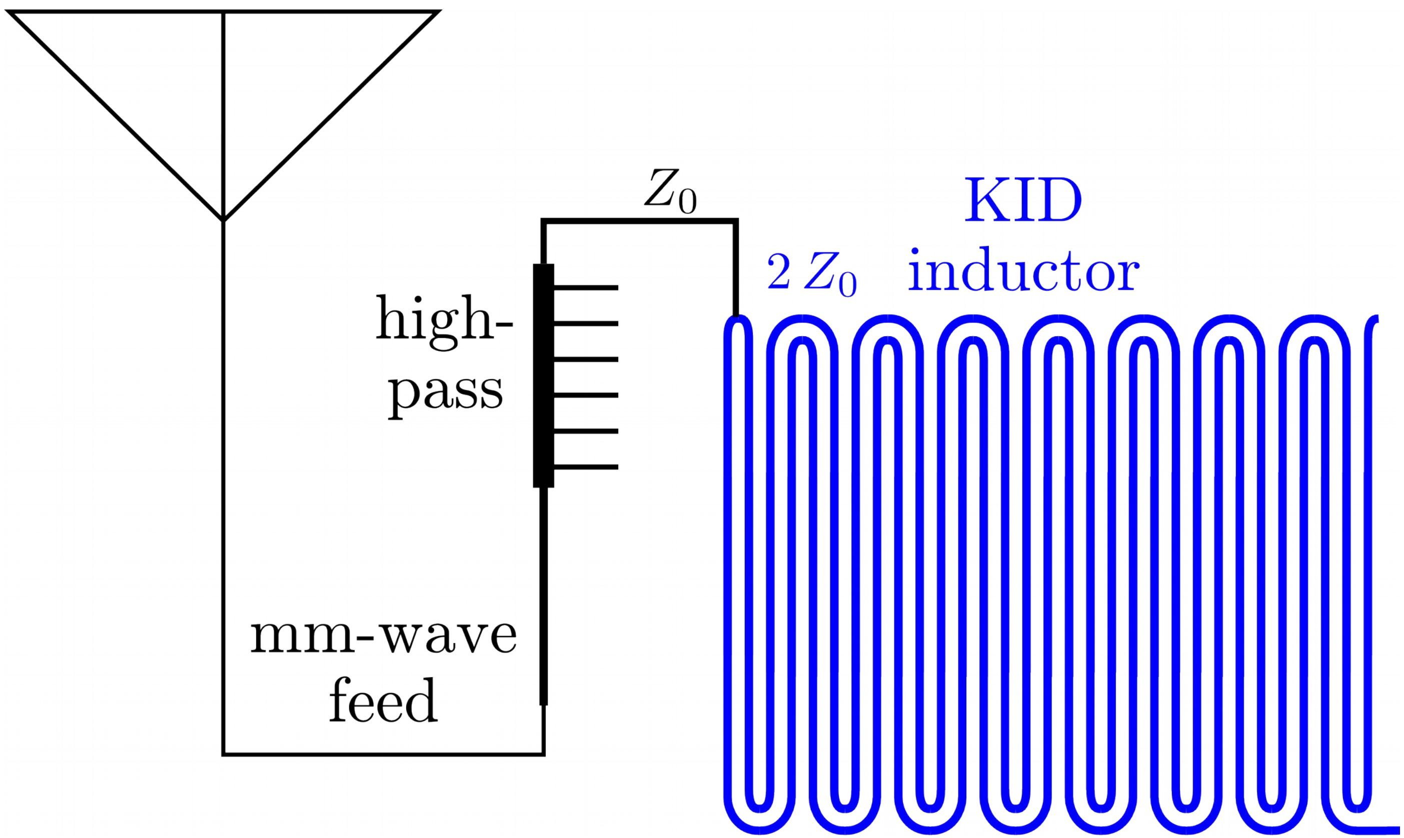
Conservative, P/V conserving estimates:

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

6× below background limit

Fig by S. Hailey-Dunsheath

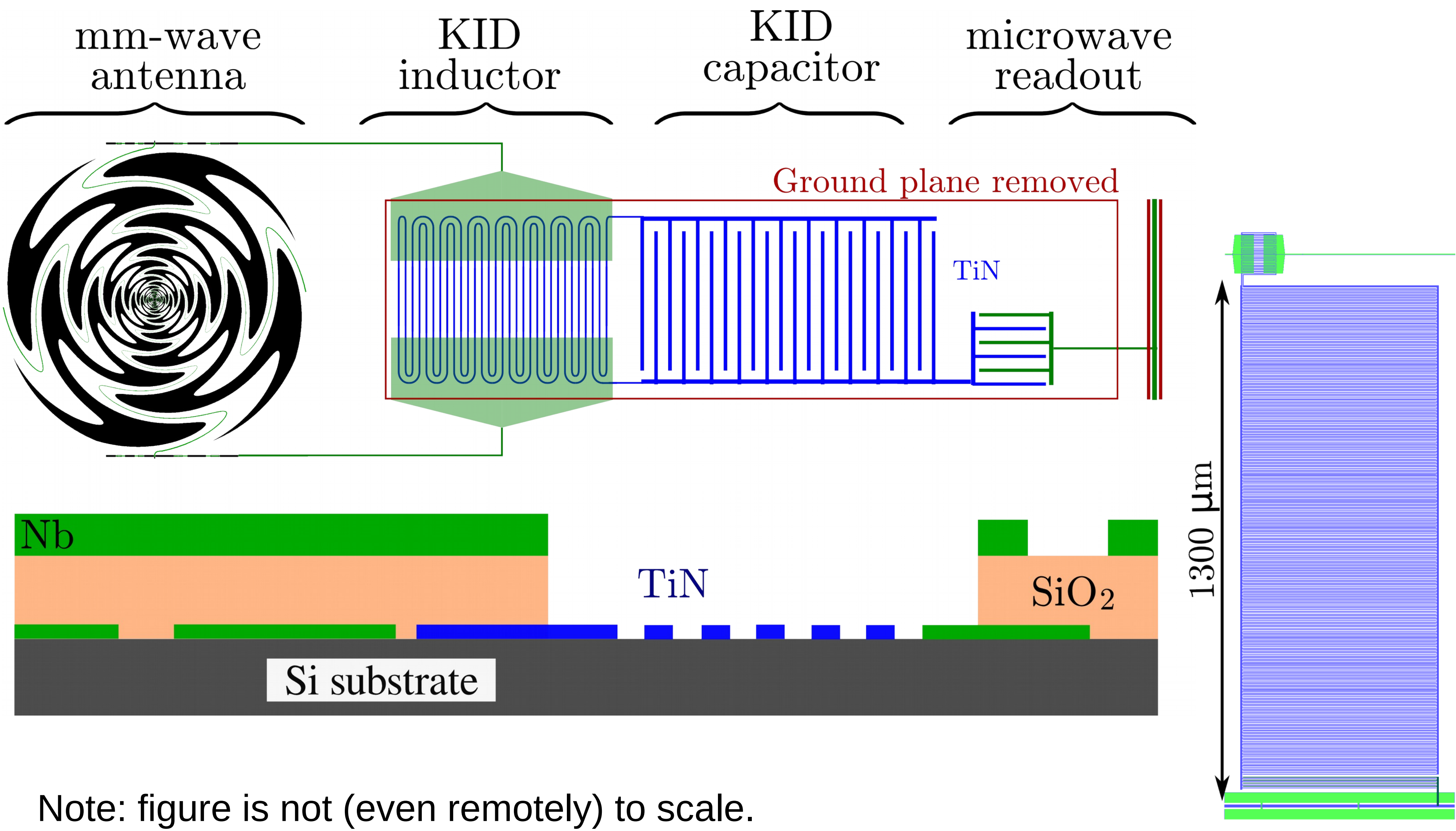
Impedance matched microstrip works for low-impedance materials (Al)



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

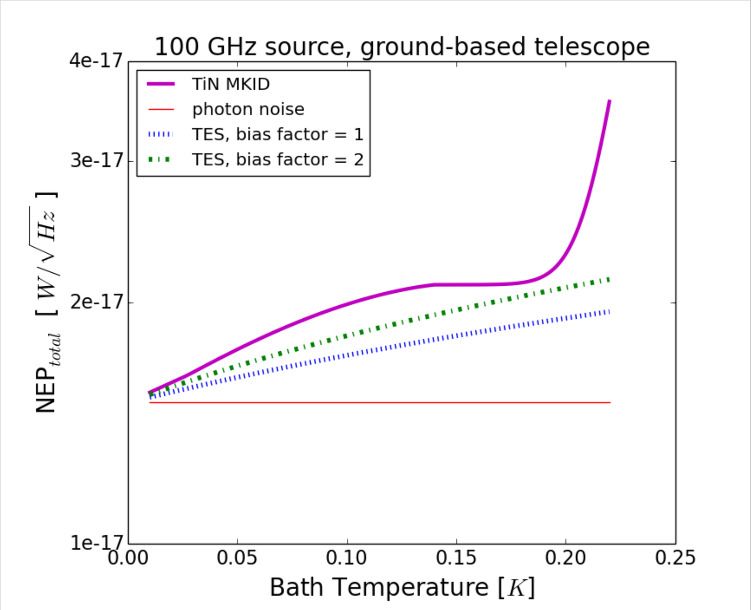
We're building an Al demonstration now. Goddard's mu-Spec uses this approach already.

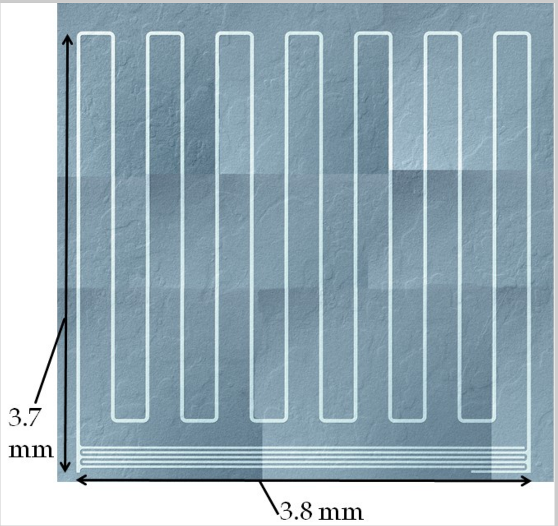
Chicago's CMB-KIDs program: Antenna-coupled, multi-band CMB pixels

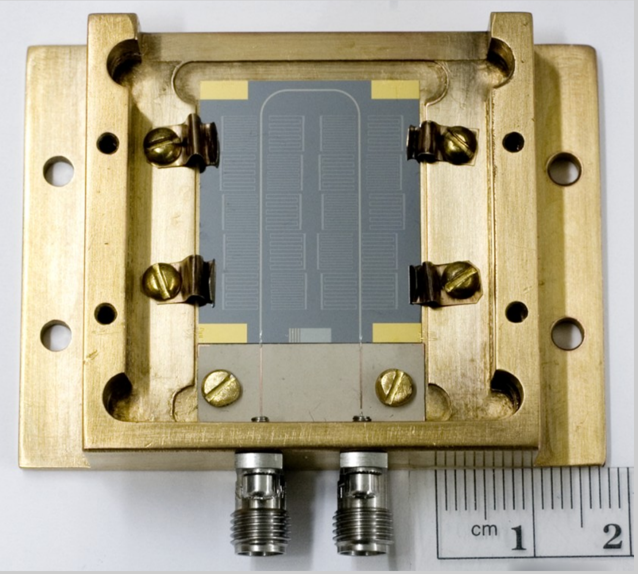


Note: figure is not (even remotely) to scale.

Wisconsin & Goddard CMB KIDs: TiN direct absorber for QUBIC



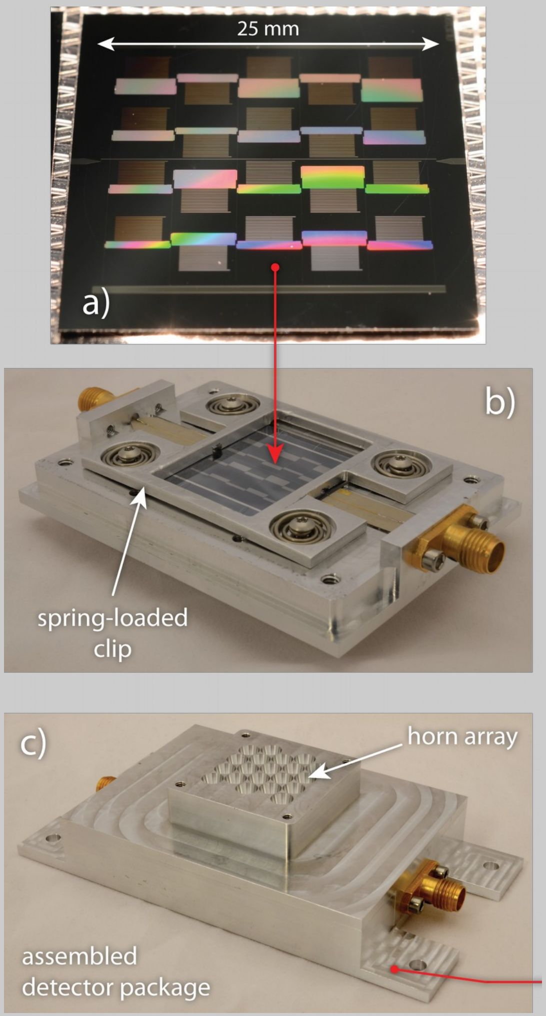


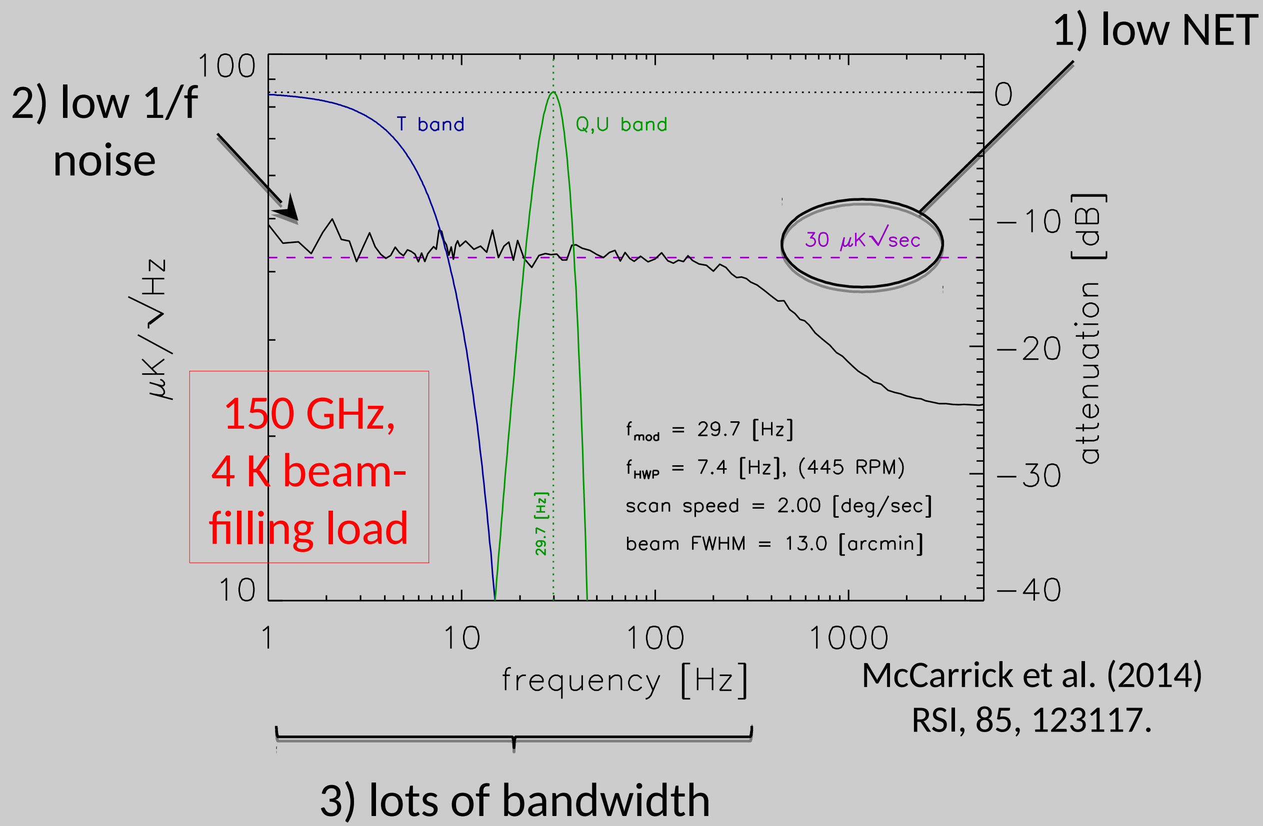


- At 100 mK, a 100 GHz KID pays a 10% penalty in NEP compared to a TES with a readout bias factor of 2.

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





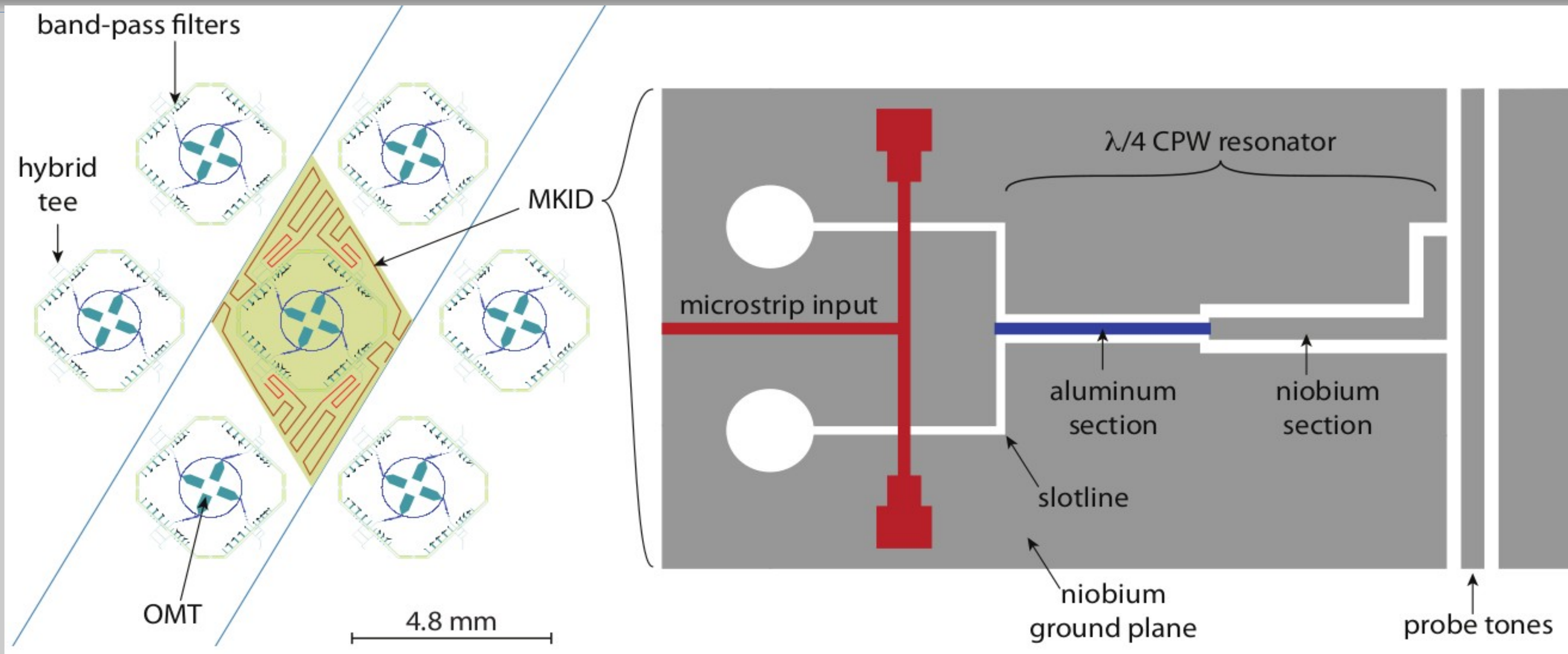
McCarrick et al. (2014) RSI, 85, 123117.

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

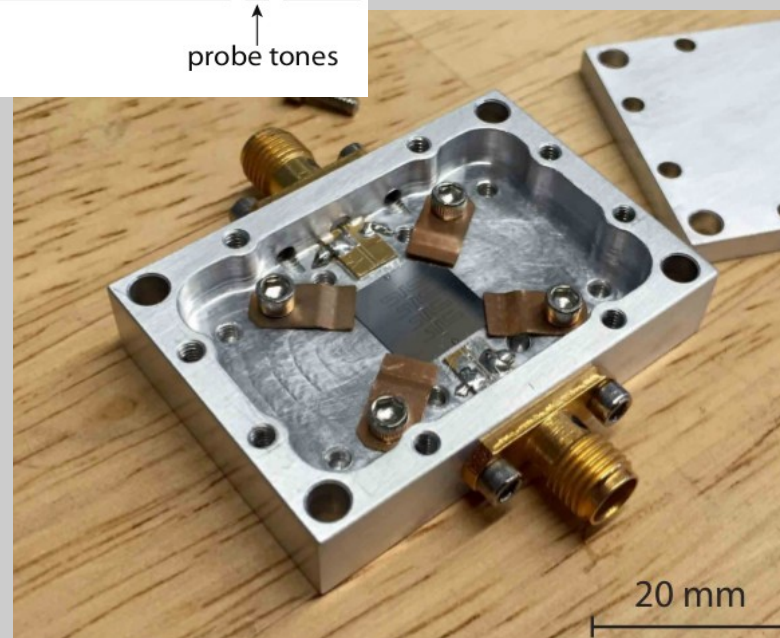
Dual-pol prototype now being tested. Multichroic horn+OMT pixels in design.

All figures: B. Johnson

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



Figures from Johnson+ 2016



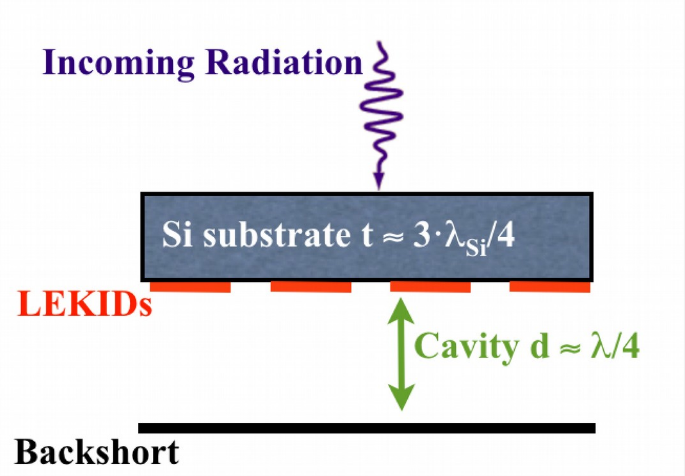
Dual-pol horn-coupled KIDs.

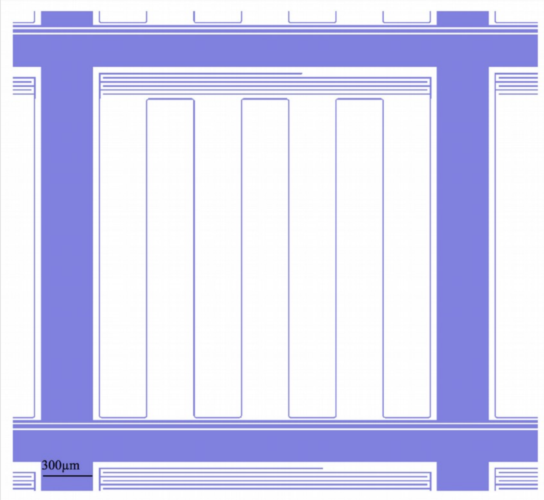
OMT and band-defining filters.

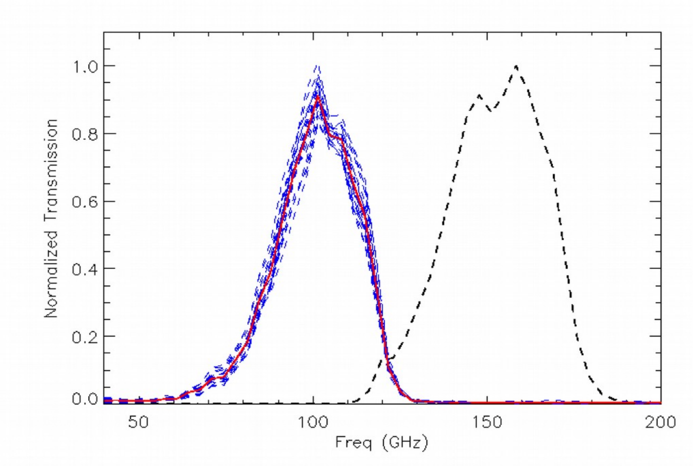
Al CPW KIDs.

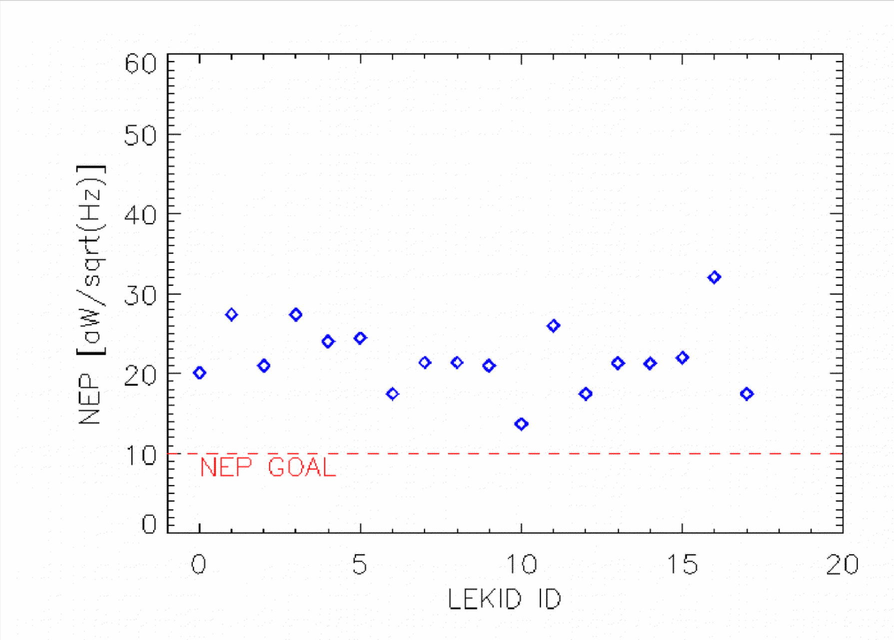
Al-Ti bilayer 100 MHz kids from Grenoble

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



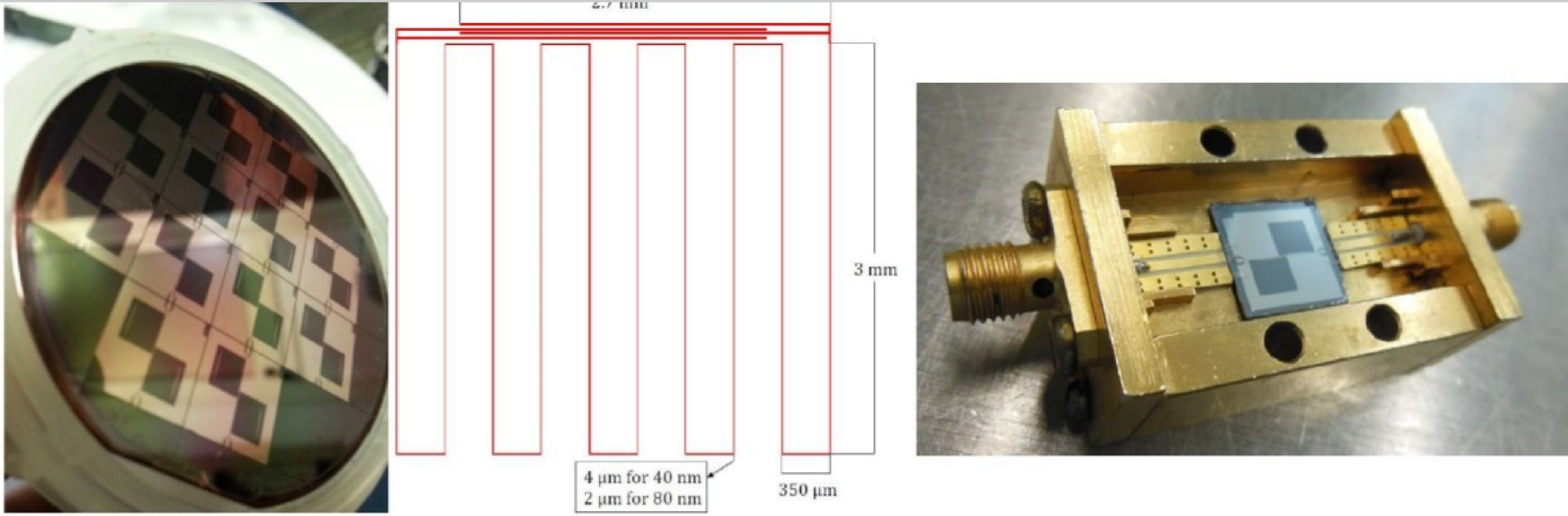






All figures from Catalano+15

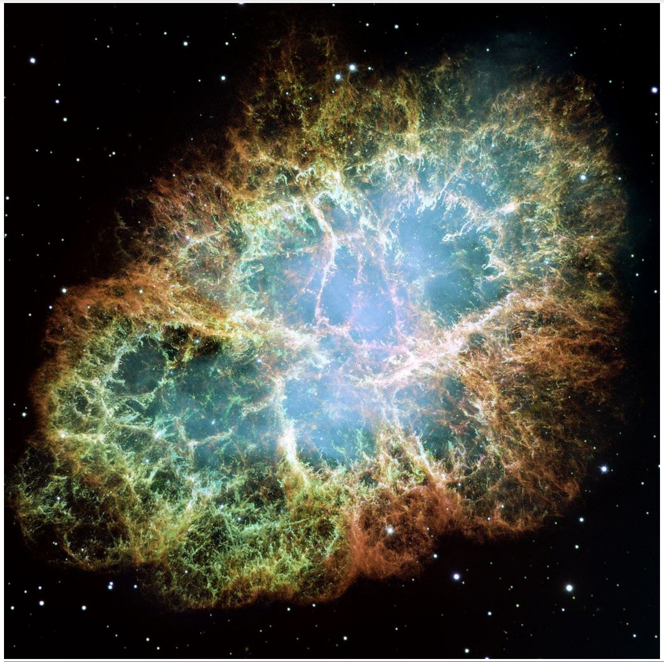
90 GHz Al-Ti bilayer horn-coupled LEKIDs from Rome

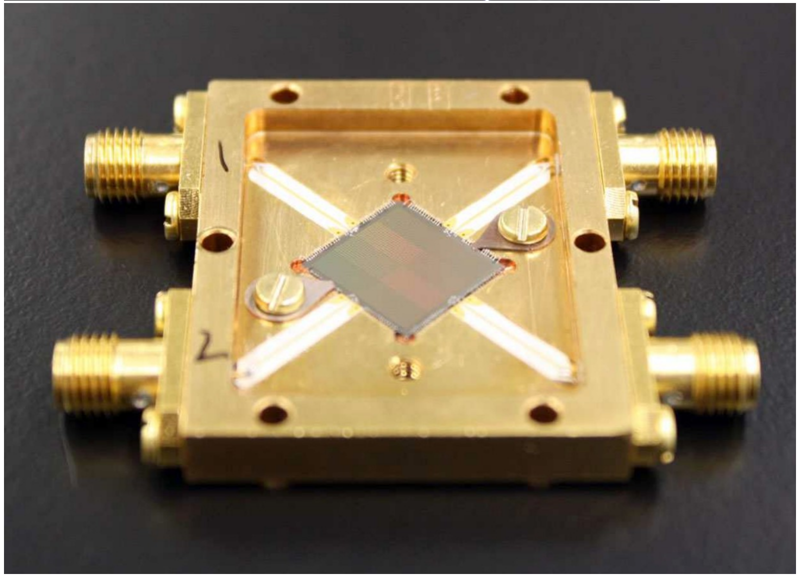


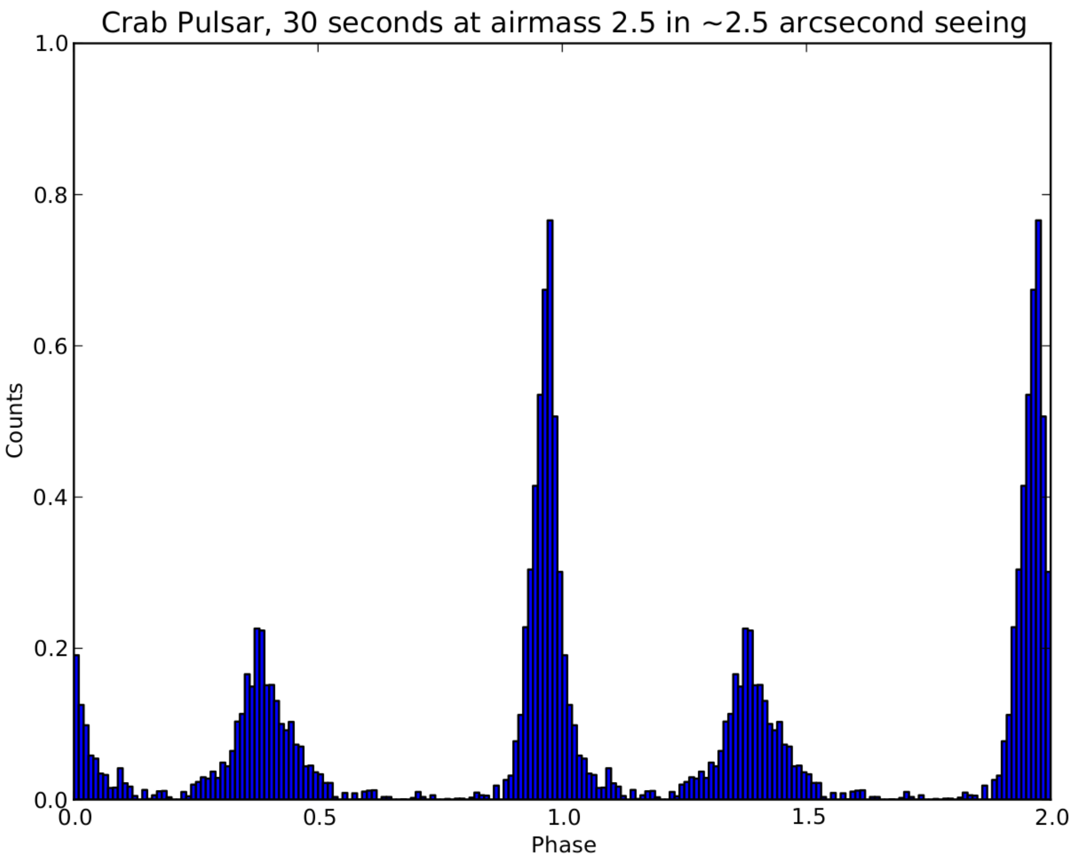
Goal: 90 GHz horn-coupled demonstrator for the SMT.
Currently have optical tests of Al pixels, plans to test Al-Ti bi-layers.

Figure from Paiella+ 2016

Application #1: time resolved astronomy

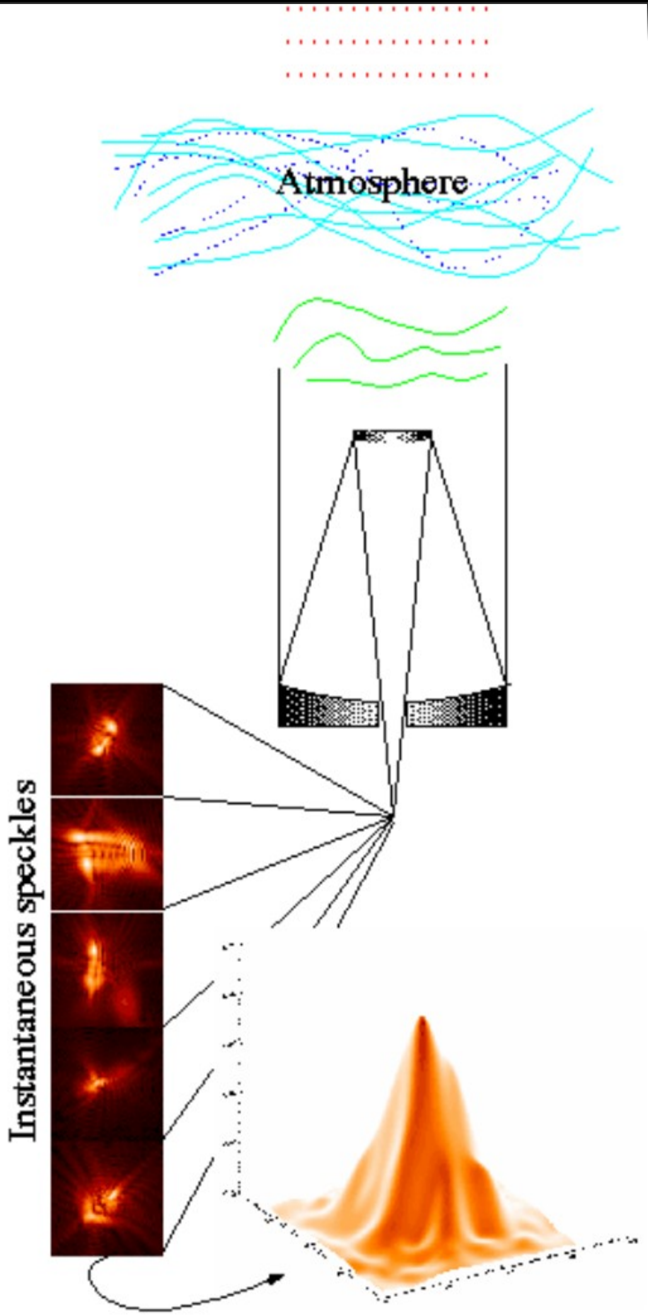


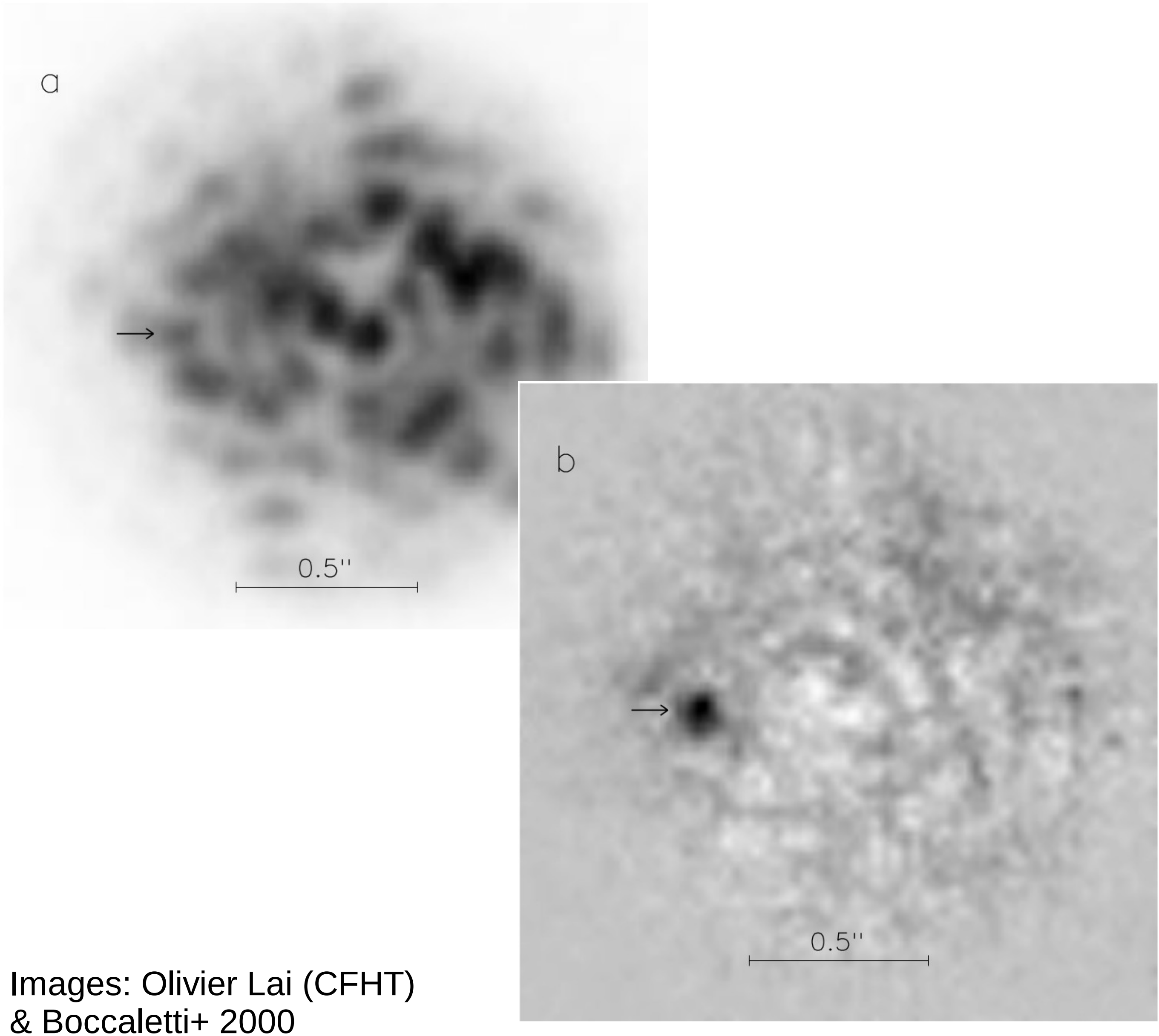




Optical enhancement of the Crab Nebula.
ARCONS MKID camera
Mazin Group, 2011

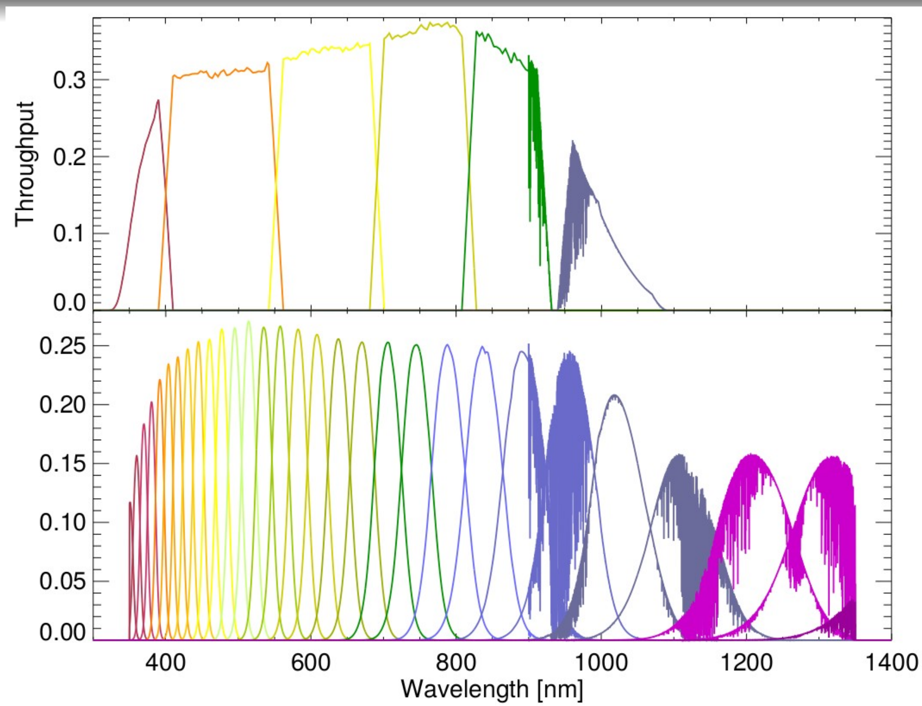
Application #2: speckle techniques

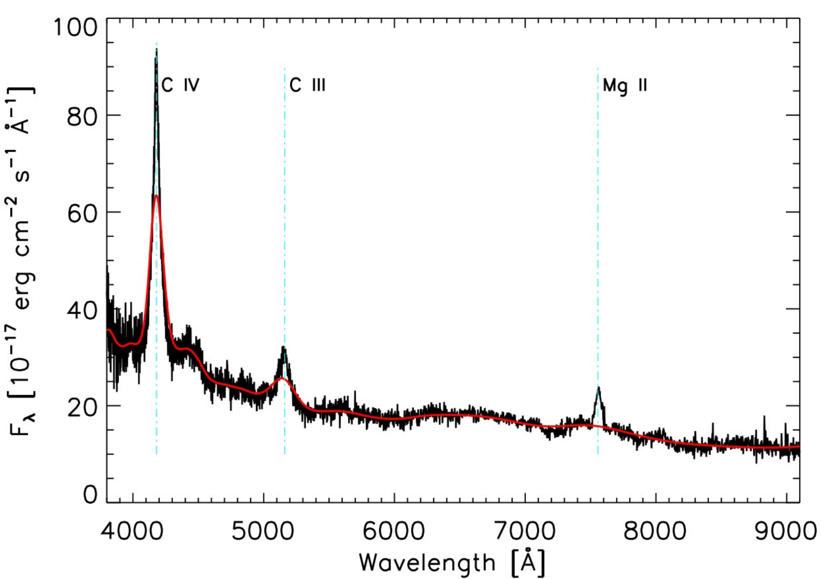


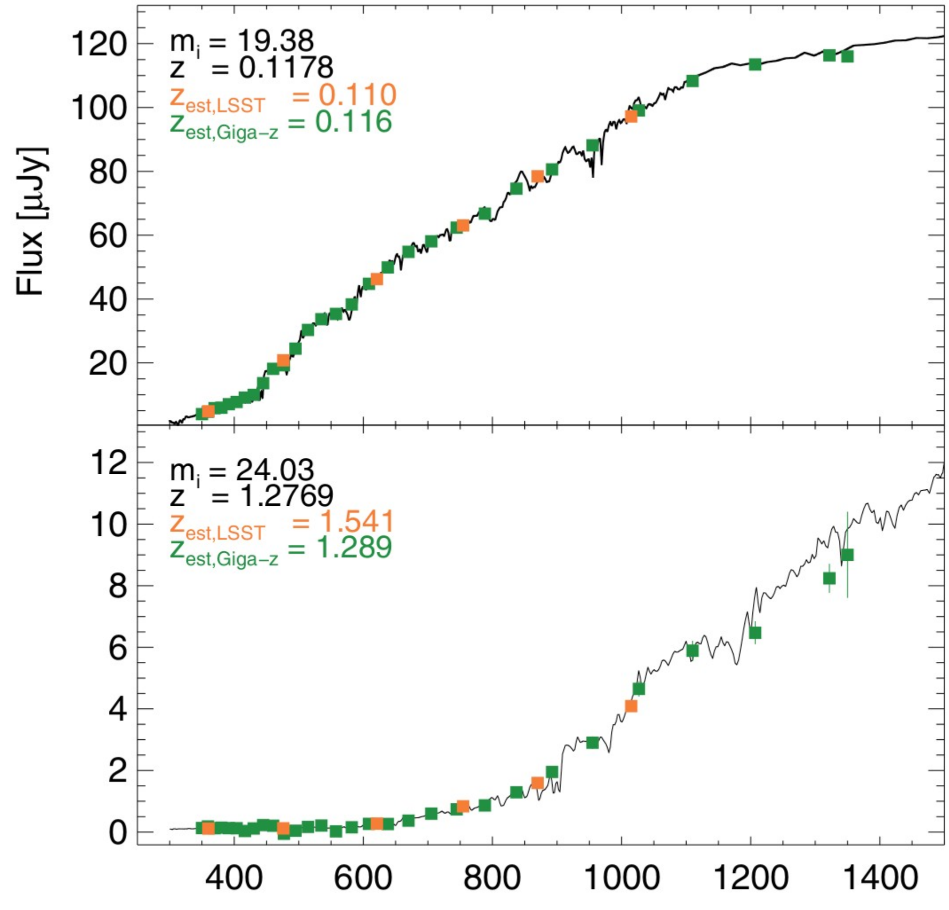


Images: Olivier Lai (CFHT)
& Boccaletti+ 2000

Application #3: low resolution spectroscopy for large scale optical surveys and followup



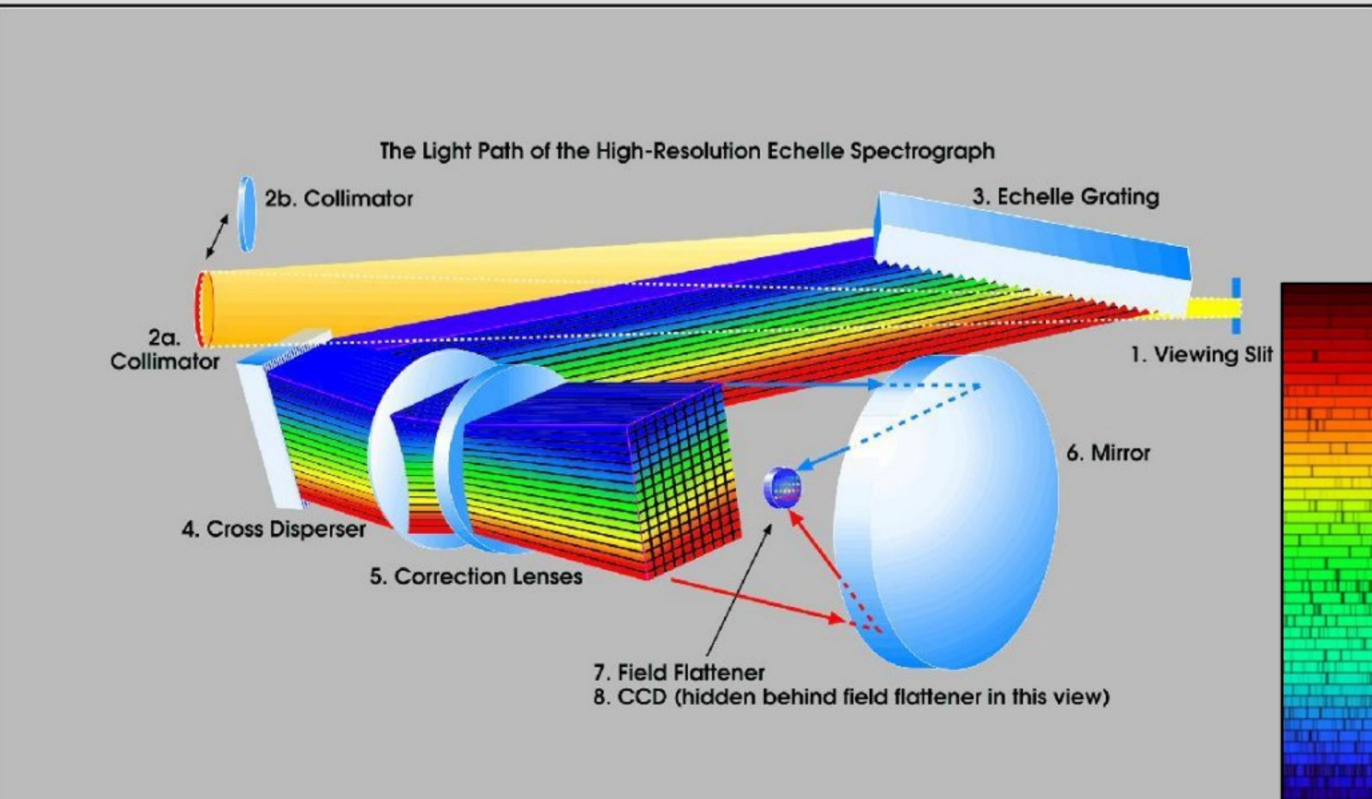


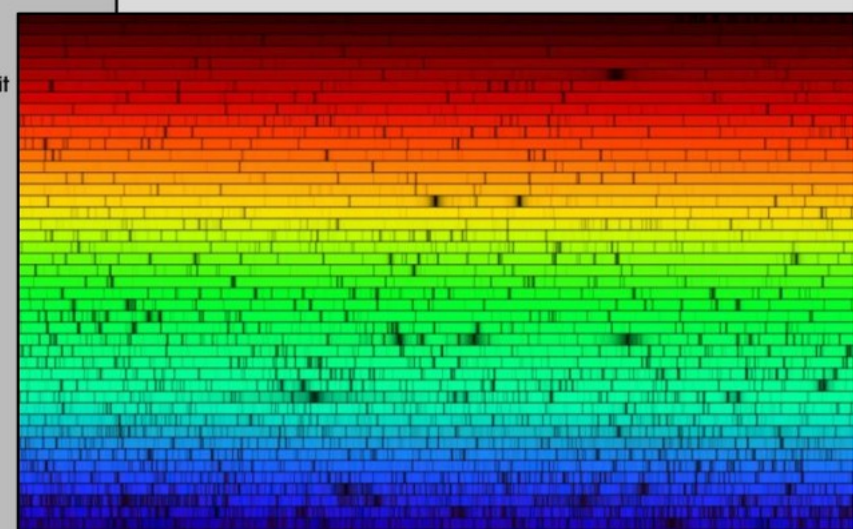


Figures from Marsden+ 2013

Application #4: order sorting following high-resolution dispersive spectroscopy

- Grating disperses incident light into diffraction orders
- A Cross disperser separates orders spatially
- CCD imager





HIRES at Keck Telescope - http://www2.keck.hawaii.edu/inst/hires

http://www.vikdhillon.staff.shef.ac.uk/teaching/phy217/instruments/phy217_inst_echelle.html

Slide from Sumedh Mahashabde, Oxford, KIDSpec

Conclusions

- Superconducting detectors provide:
  - Very low NEP for continuum measurements
  - Very high energy resolution for single-events
- Superconducting detectors require:
  - Sub-Kelvin systems
  - Thin-film fabrication