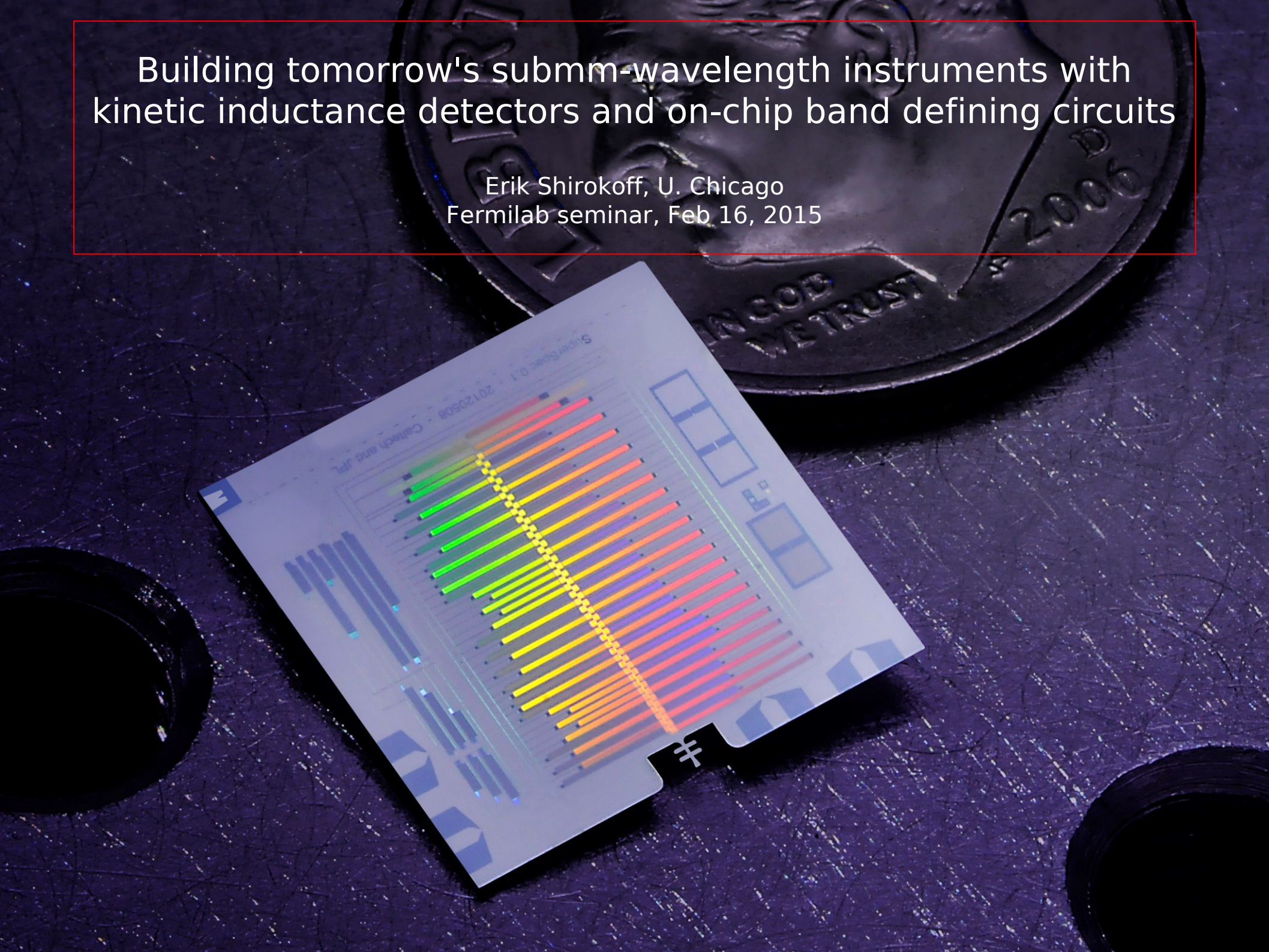
Building tomorrow's submm-wavelength instruments with kinetic inductance detectors and on-chip band defining circuits

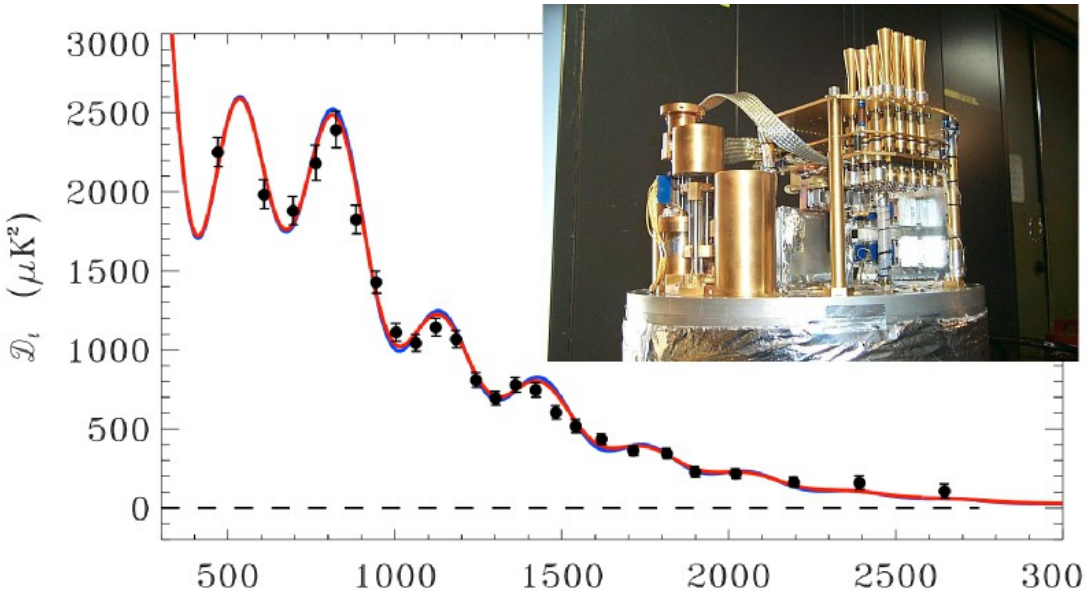
Erik Shirokoff, U. Chicago
Fermilab seminar, Feb 16, 2015



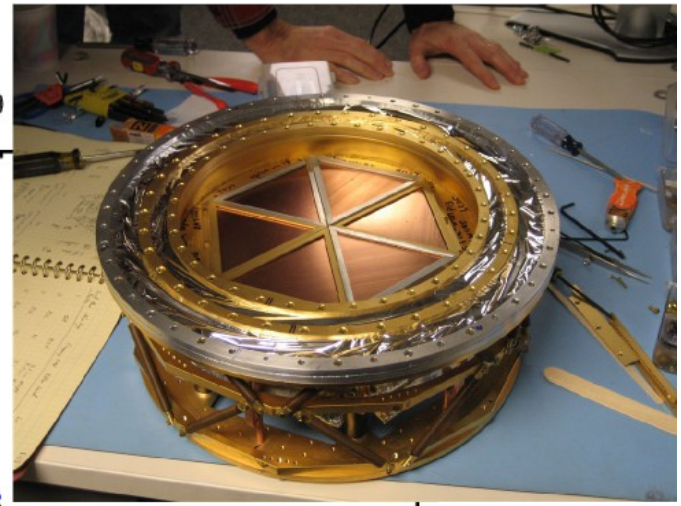
Outline

- Focal planes are growing!
- Astronomy at (sub)mm-wavelengths
- Introduction to Kinetic Inductance Detectors
- KID instruments at all wavelengths
- Superspec: an on-chip spectrometer
- Future directions

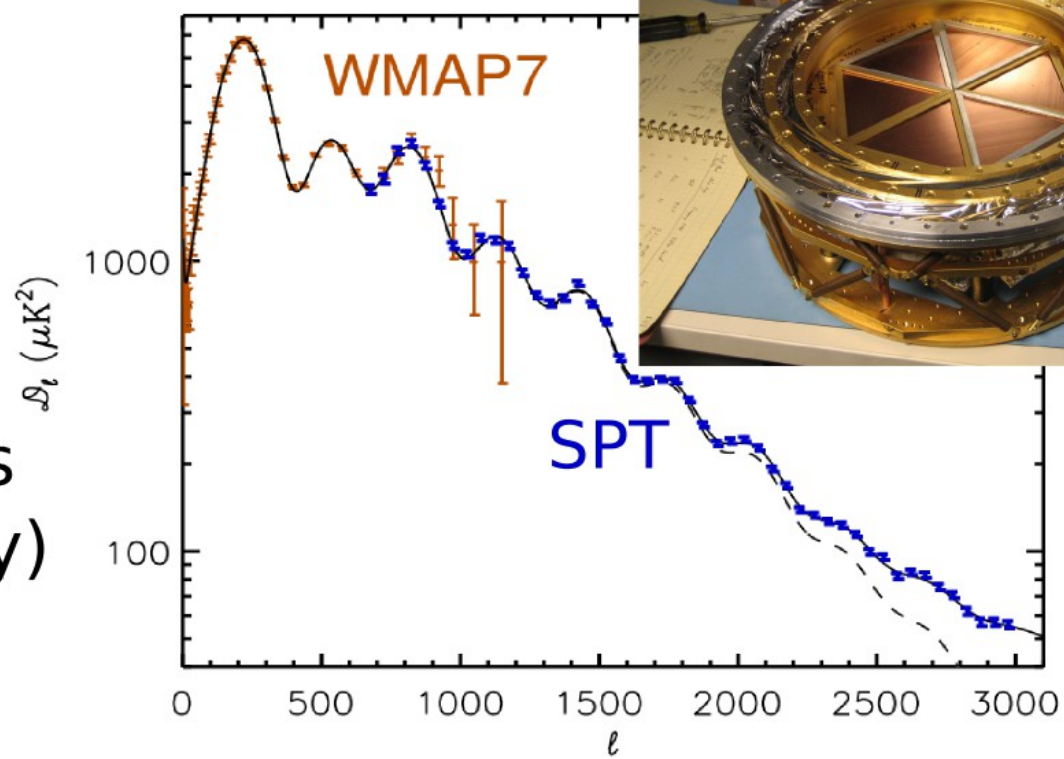
Ground based CMB detectors have been background limited for more than a decade. The only way to increase sensitivity is with more pixels.



ACBAR
2001-2005
36 pixel-years
(150 GHz only)



SPT-SZ
2007-2011
2 kpixel-years
(150 GHz only)



Focal planes keep growing

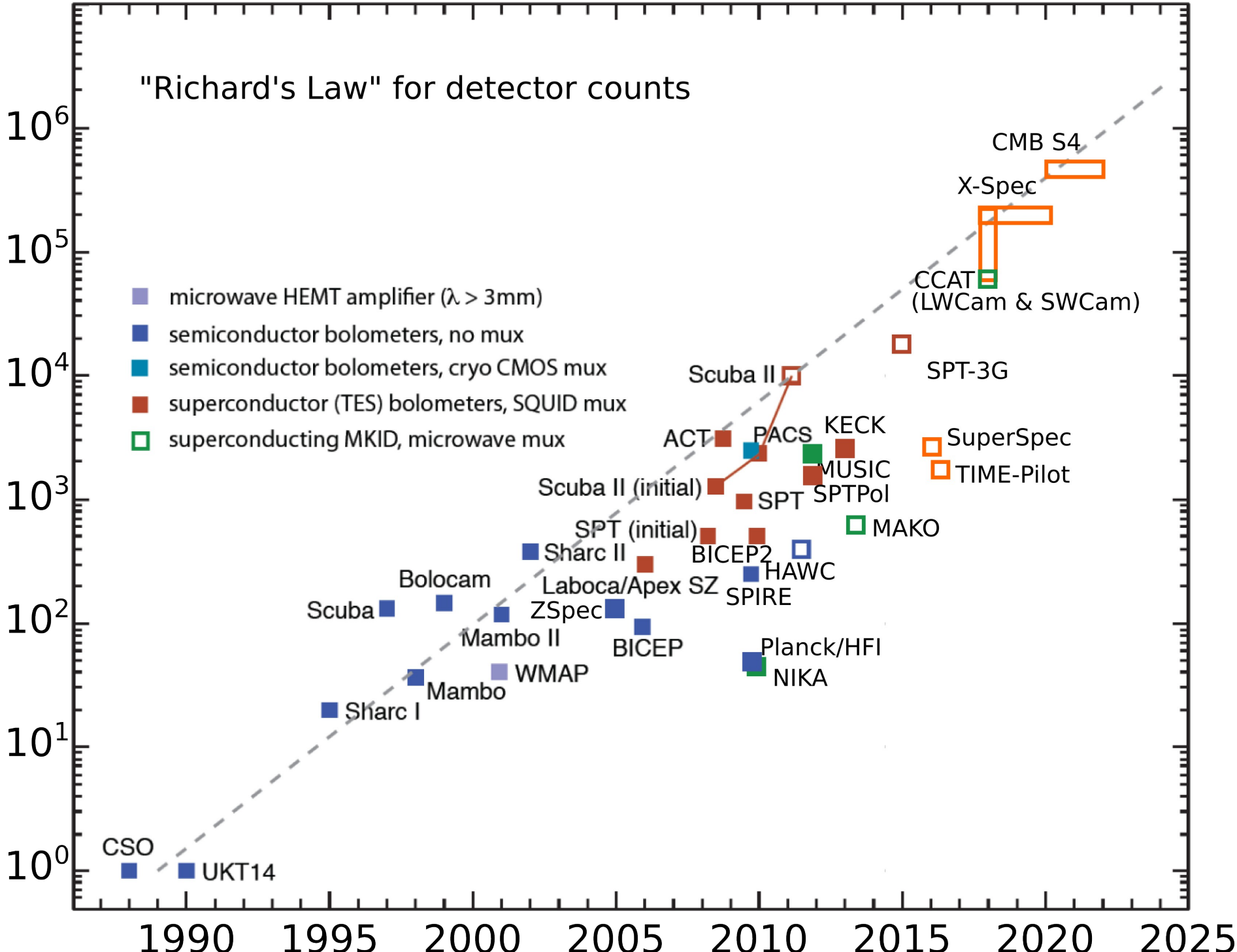
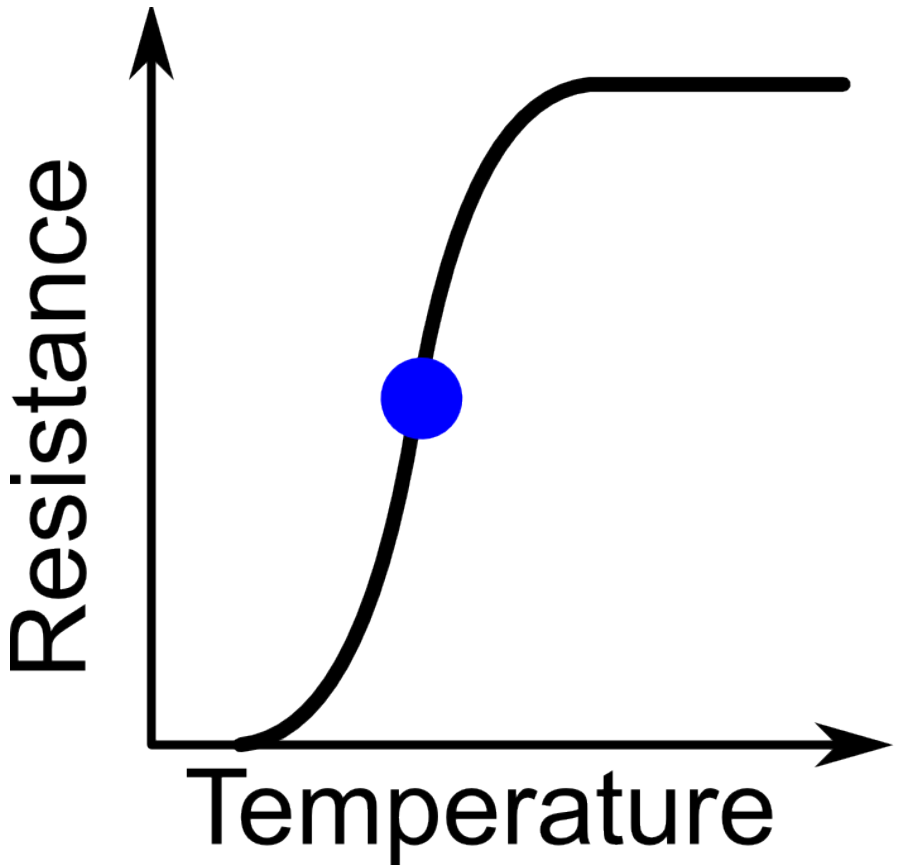
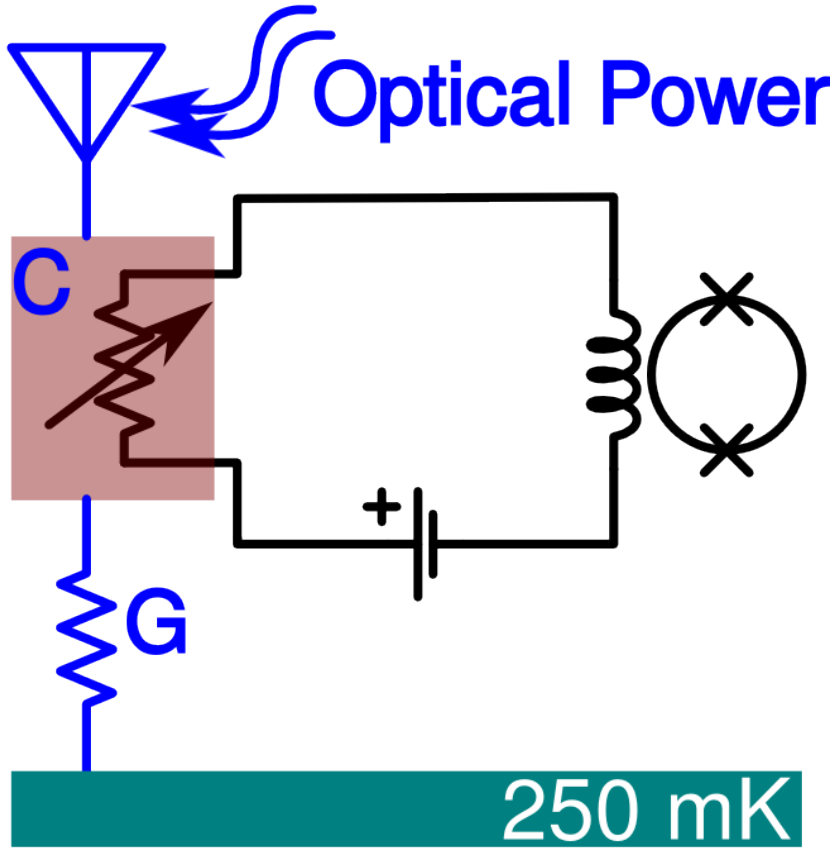


Figure from J. Zmuidzinas (extended)

Transition Edge Sensor Bolometer

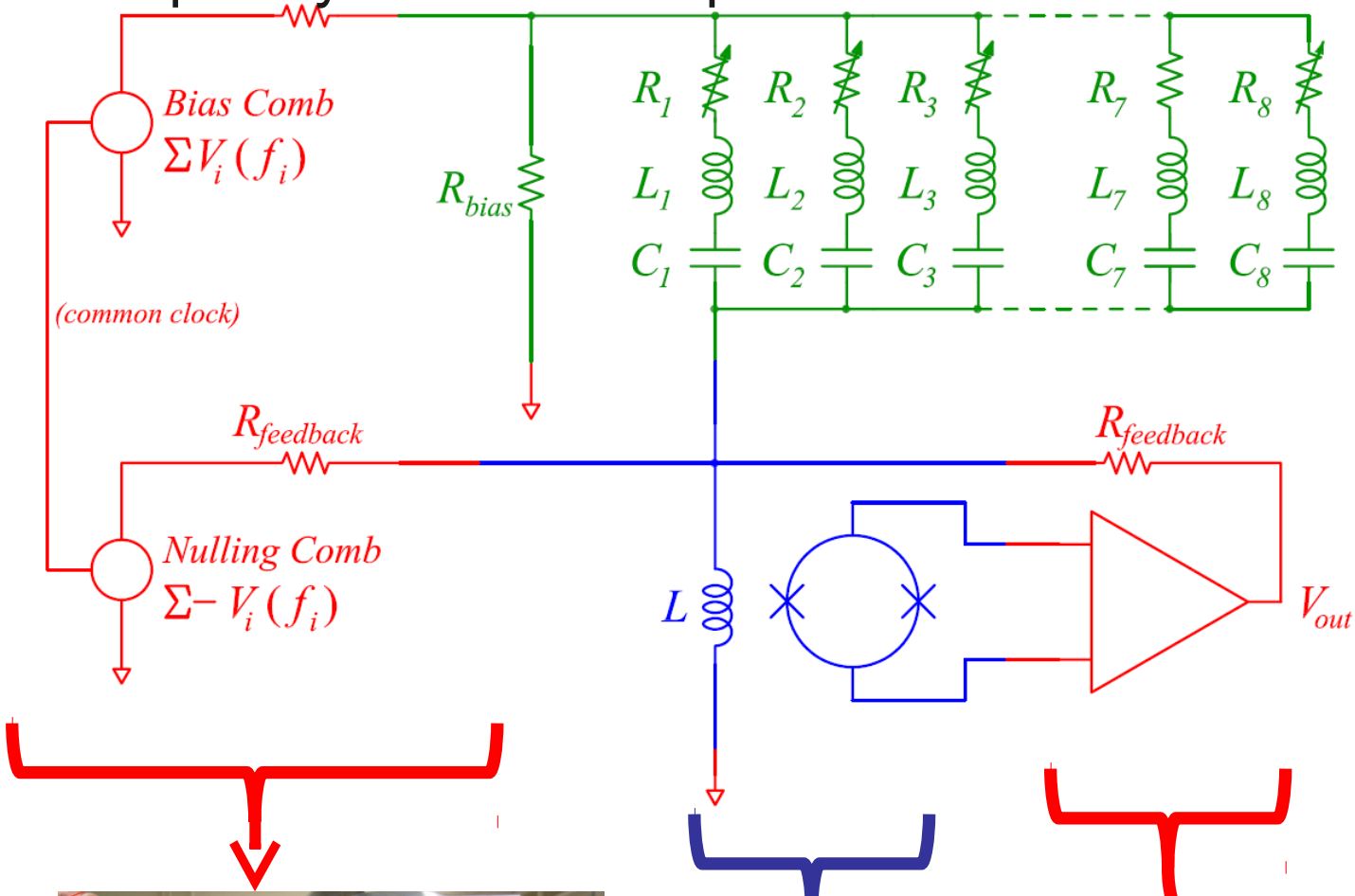


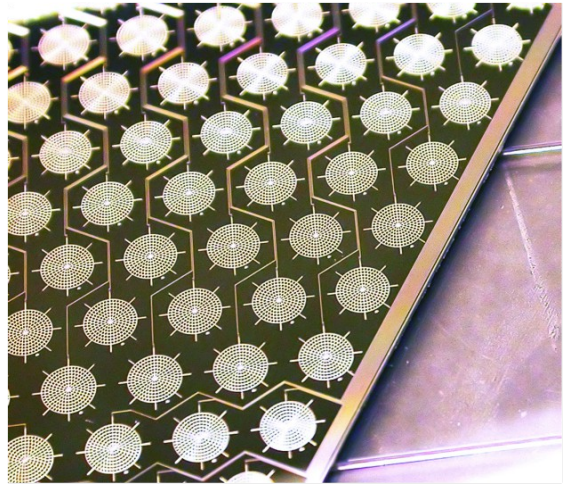


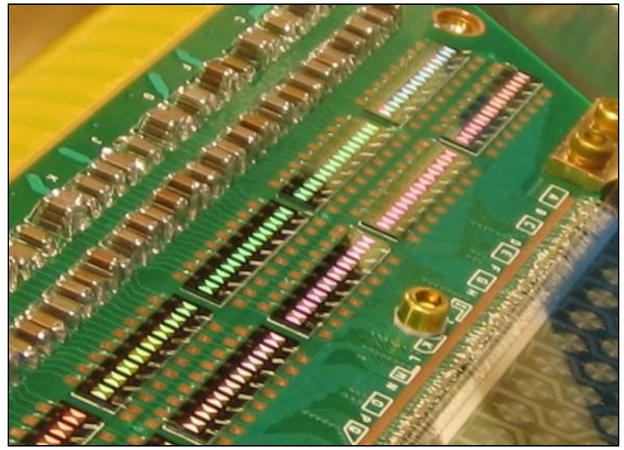
$$P_{electrical} + P_{optical} \approx \text{Constant}$$

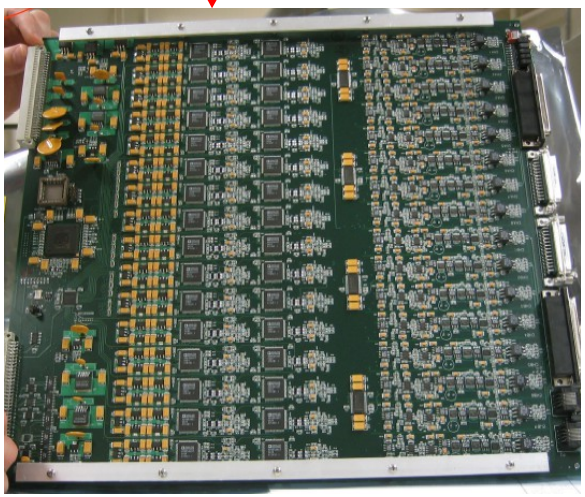
$$S_i \equiv \frac{dI}{dP_{optical}} \rightarrow \frac{-1}{V_{bias}}$$

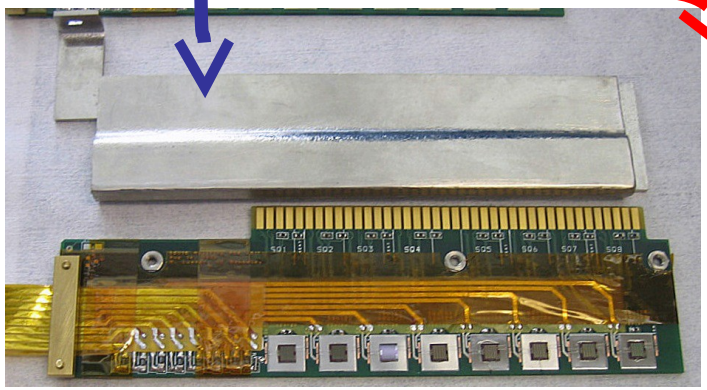
Frequency domain multiplexed TES readout

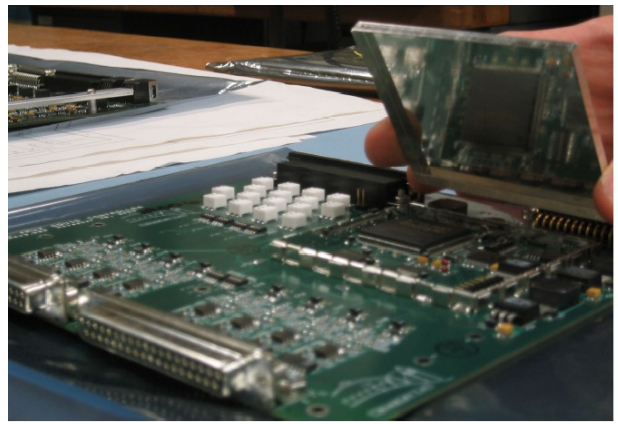












SQUID readout works great. But, it's bulky, expensive, a dominant heat load, and sensitive to RF & magnetic fields.

Do we need a new detector technology?

A realistic focal plane must satisfy:

$$\frac{\text{focal plane area}}{\text{wavelength}^2} \times \frac{\text{detectors}}{\text{pixel}} \times \frac{\text{dollars}}{\text{detector}} \ll \text{instrument budget}$$

For CMB cameras and TESes:

$$\begin{aligned}
&\text{SQUIDs} \sim \$100/\text{pixel} \\
&\text{Warm readout} \sim \$100/\text{pixel} \\
&\text{Detectors} \sim \text{few } \ \$100/\text{pixel} \\
&\text{Npixels} \sim \text{1-10k / focal plane} \\
&\quad \Rightarrow \text{few million dollars / instrument}
\end{aligned}$$

For submm (350μm) cameras and TESes:

$$\begin{aligned}
&\text{Npixels} \sim \text{100k / focal plane} \\
&\quad \Rightarrow \text{few} * 10^7 \text{ dollars / instrument}
\end{aligned}$$

For 100 pixel R$\sim$500 mm-wavelength MOS and TESes:

$$\begin{aligned}
&\text{Ndetectors} \sim \text{100k} \\
&\quad \Rightarrow \text{few} * 10^7 \text{ dollars / instrument}
\end{aligned}$$

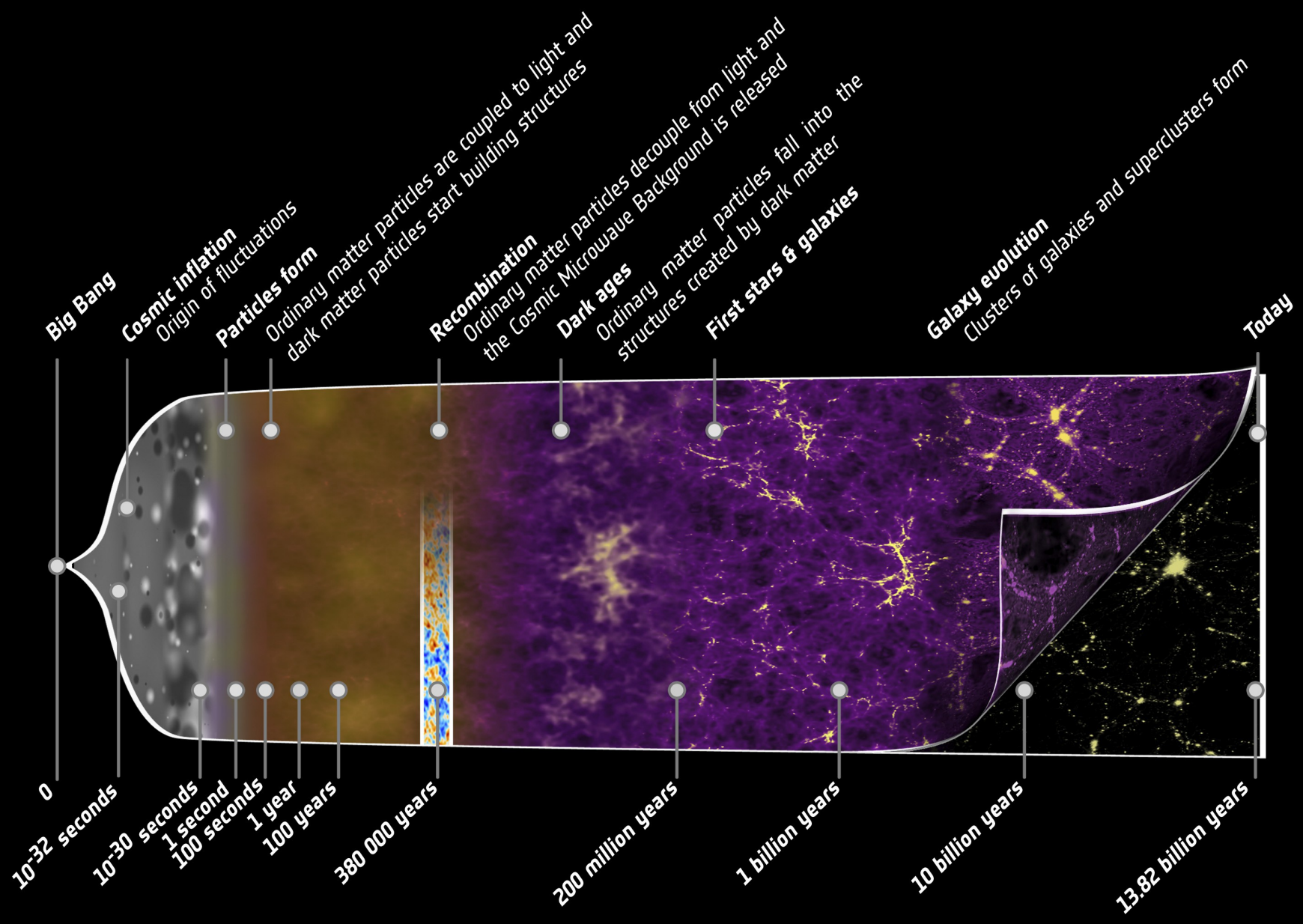
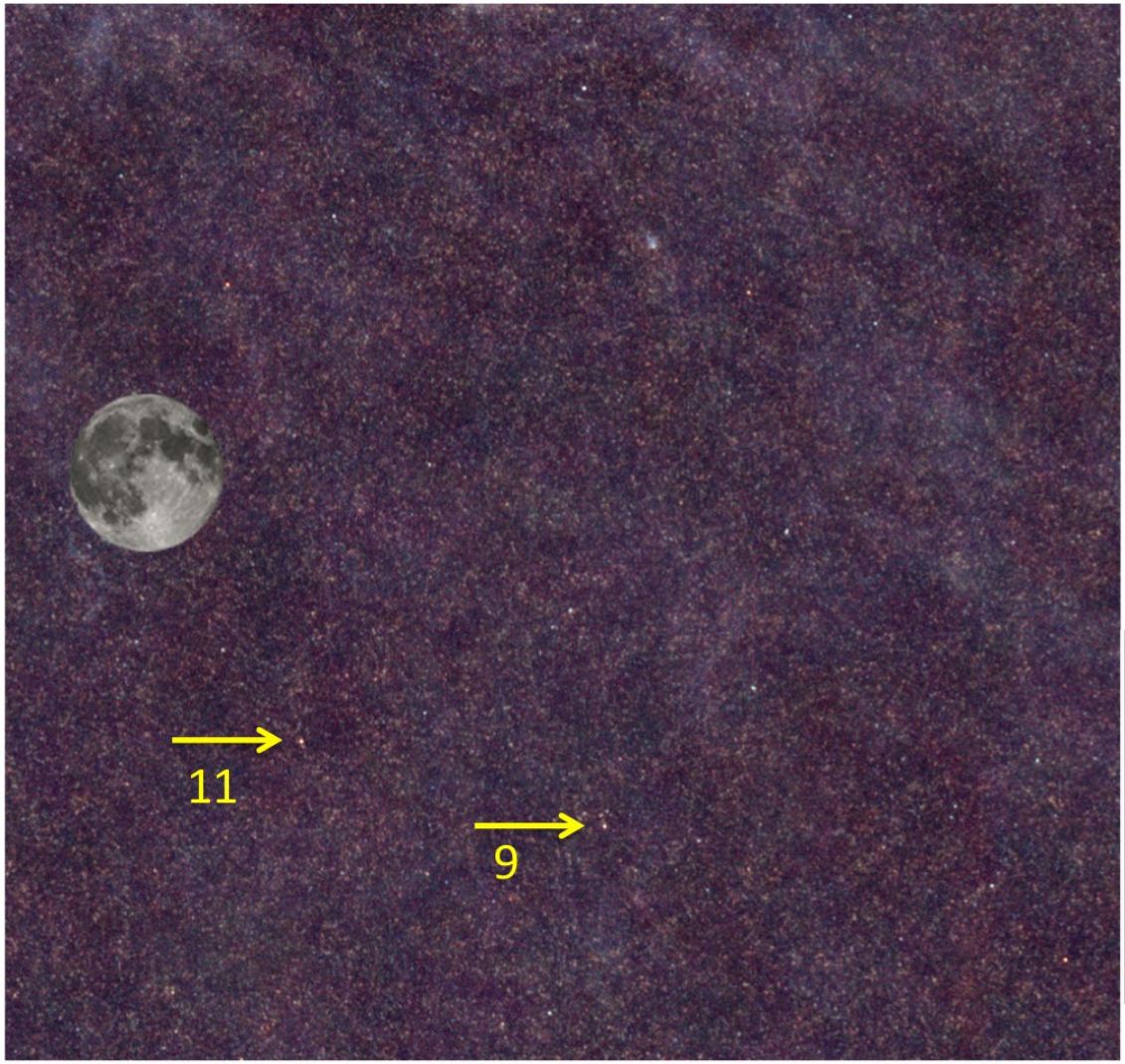
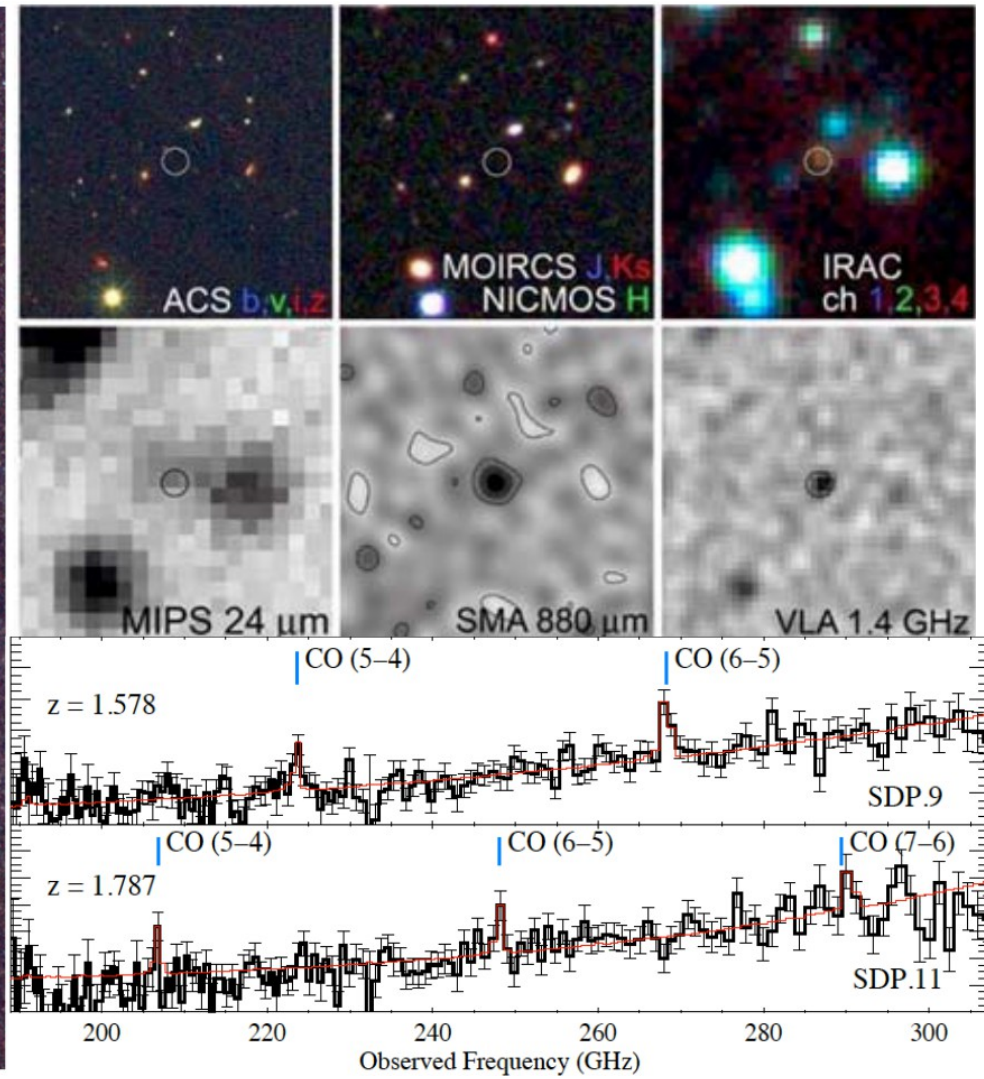


Image: ESA & Planck collaboration

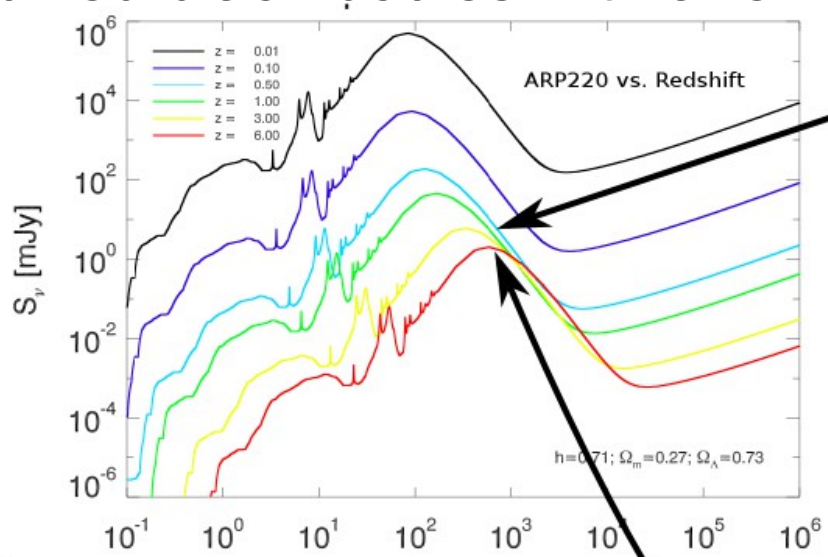
Cameras at mm and submm wavelengths will soon find thousands of sources per degree, with hundreds at z>4.

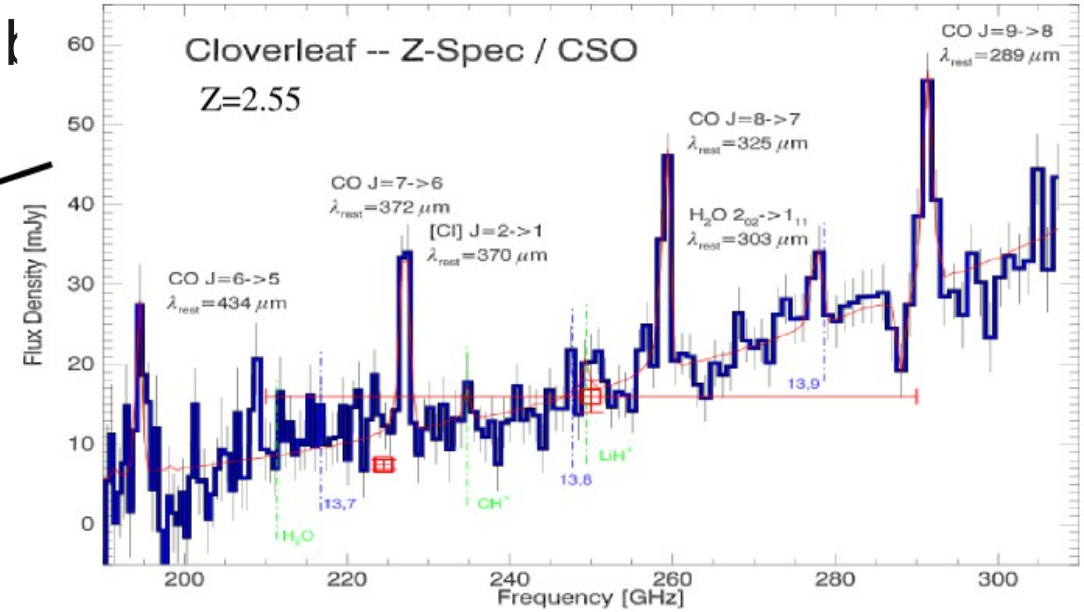


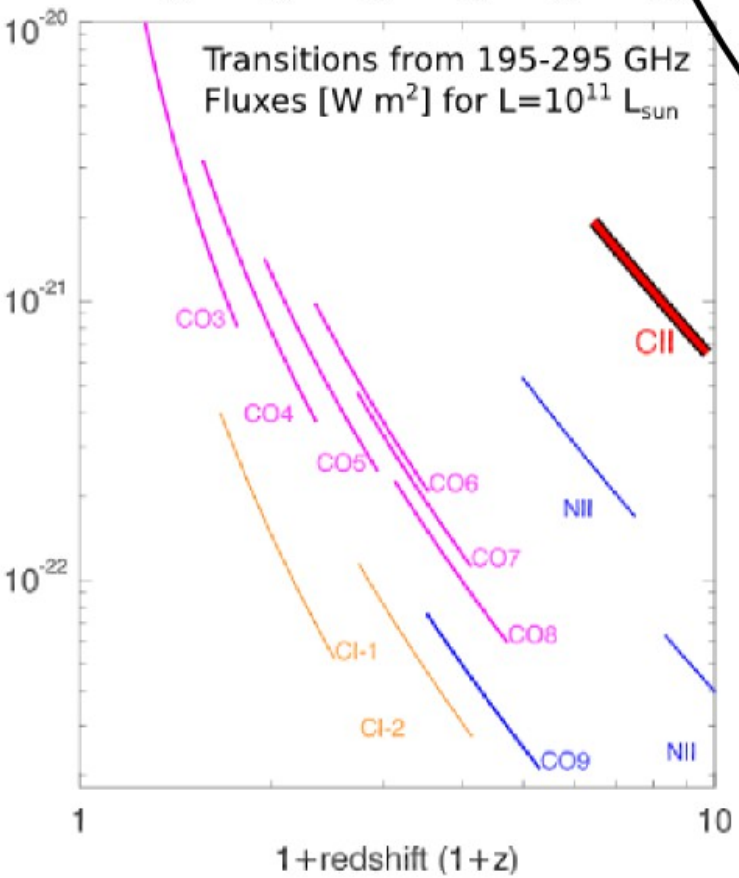


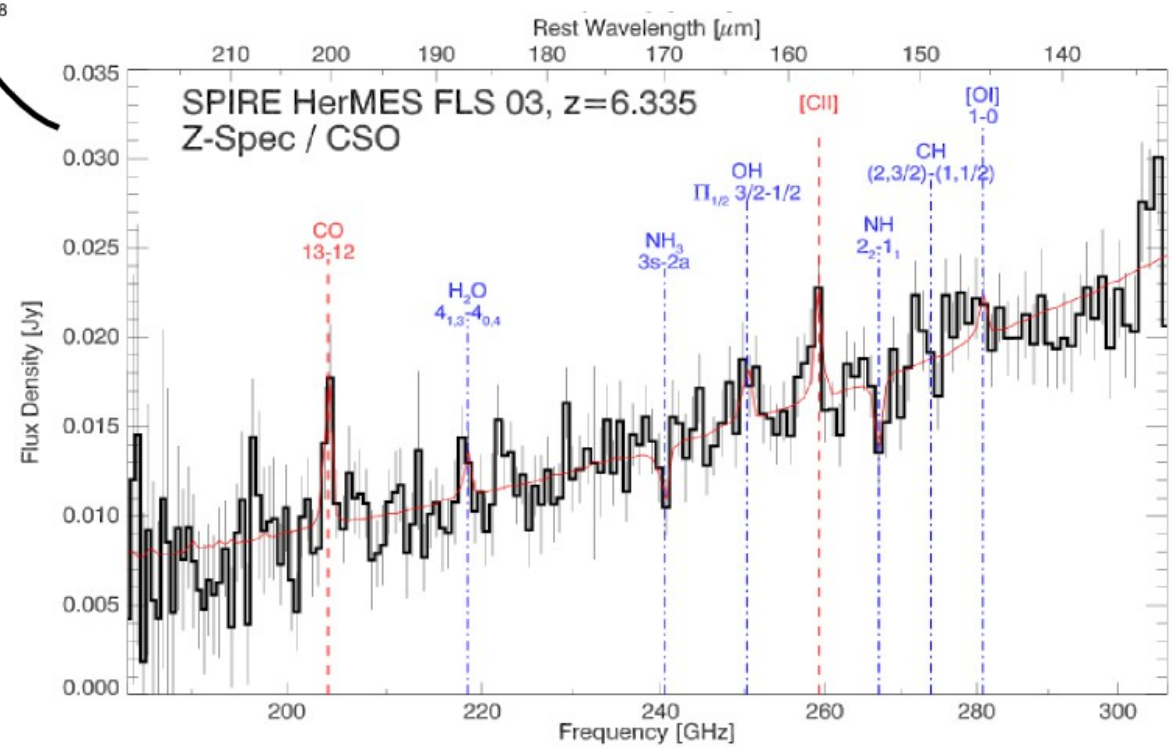
Even today, spectroscopic followup remains a major bottleneck.

At mm-wavelength, dusty star forming galaxies are modified black bodies with a few l



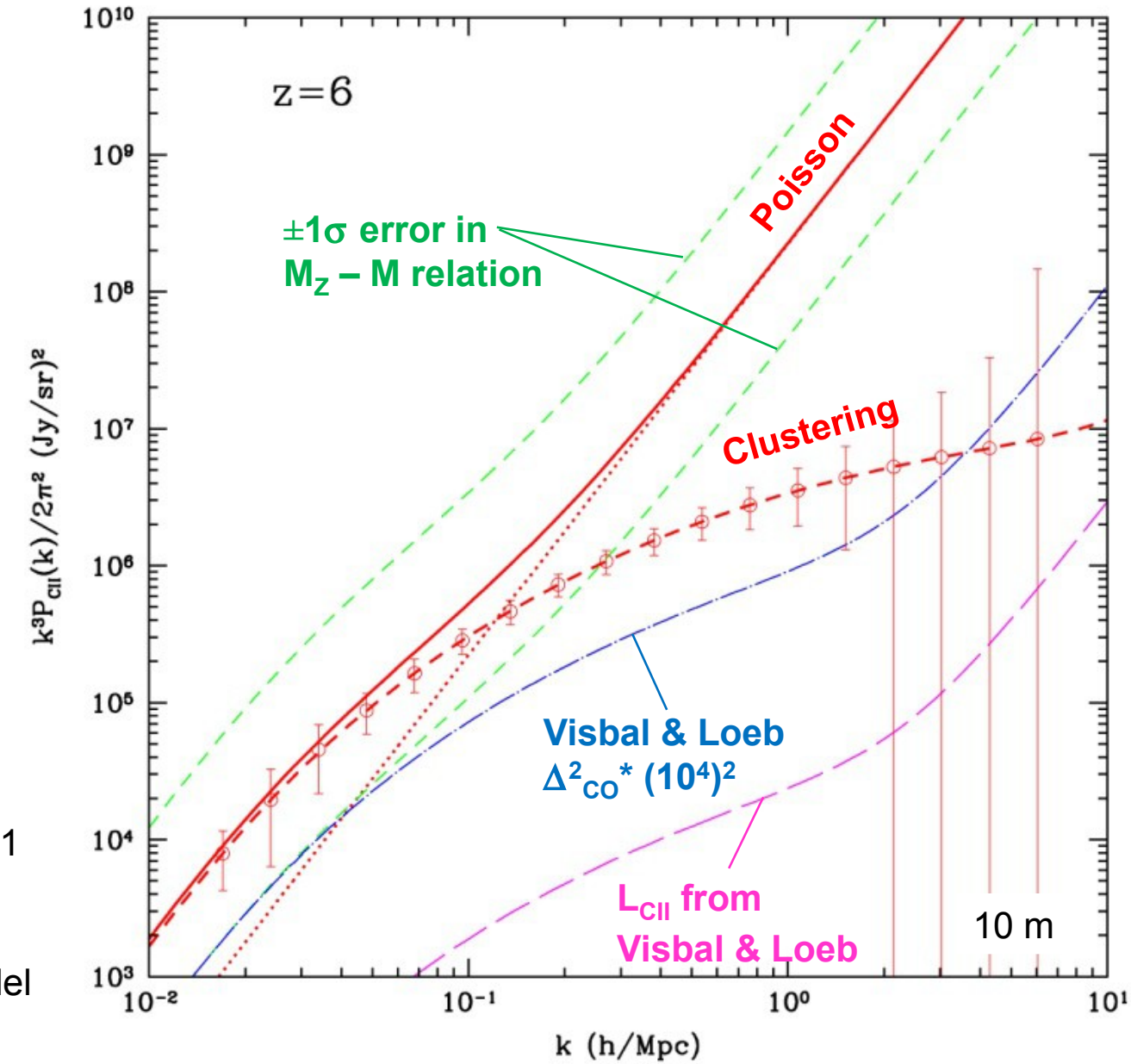






Images: J. Veiera; Blein 2002, A. Cooray (TIME-Pilot proposal) Reichers et al. (in press)

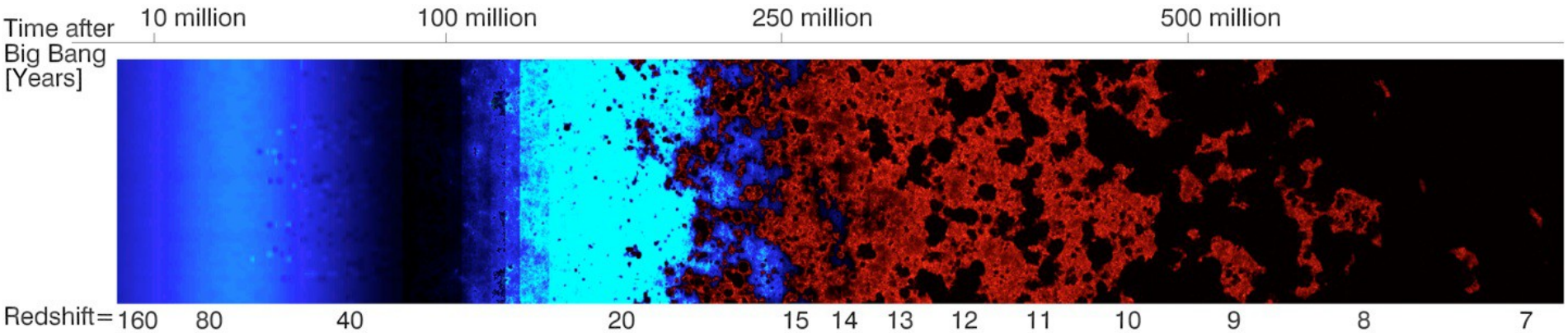
C+ tomographic mapping of unresolved sources



Lidz *et al*. 2011
Δ^2_{CO}*4000^2
agrees with
Gong C+ model
at z = 7

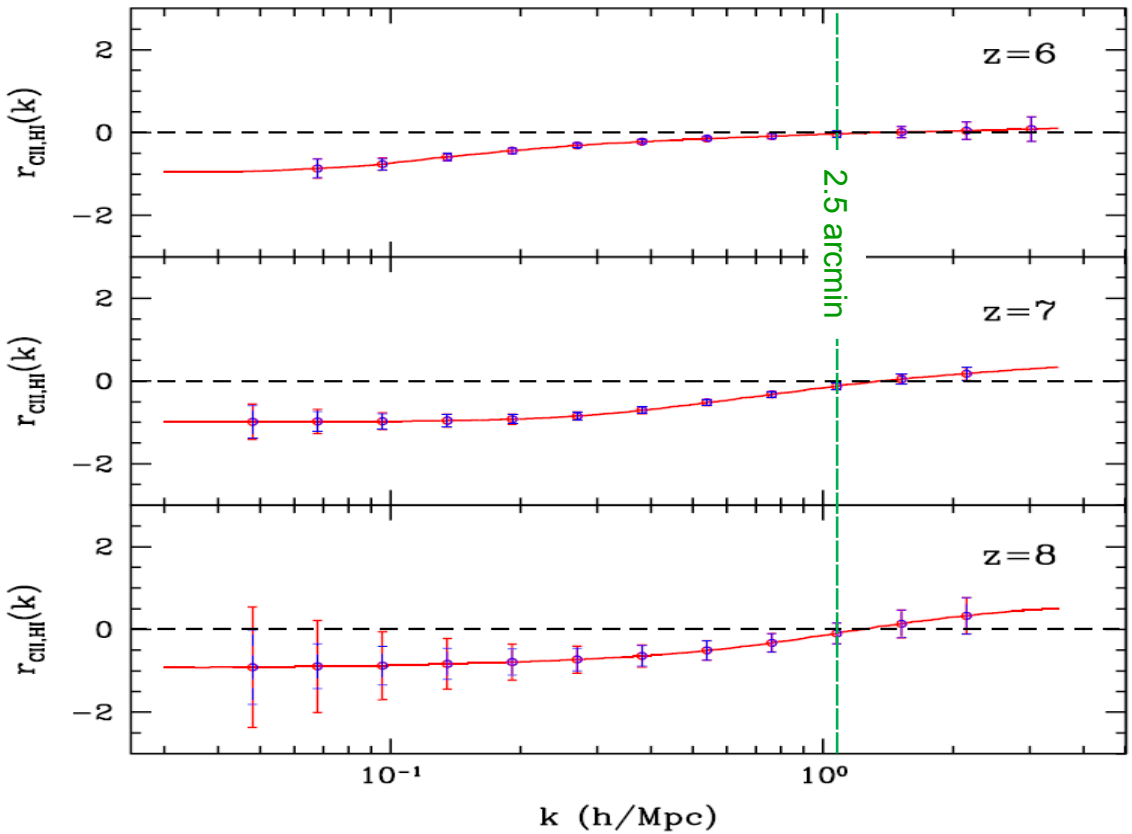
Figures from Gong et al. 2012, ApJ 745, 49G; Slide from J. Bock

Using 21 cm & C+ Together



- Star formation rate vs. z
- Ionization state vs. z
- Bubble size

C+ and 21 cm Cross-Correlation

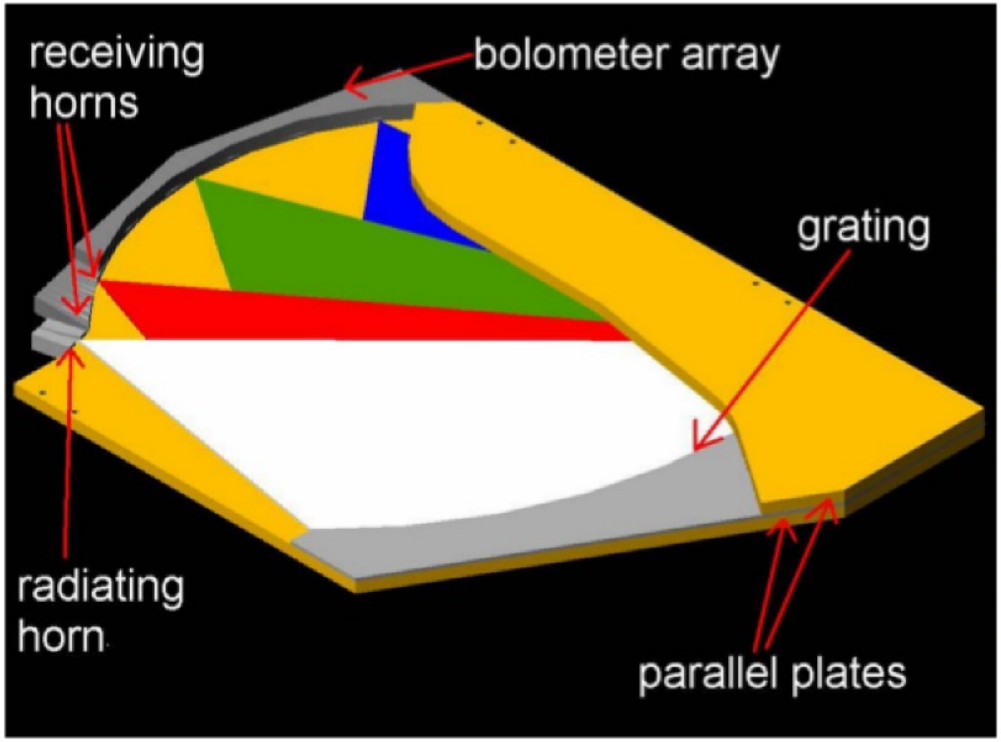


Figures from Gong et al. 2012, ApJ 745, 49G; Slide from J. Bock

Z-Spec: a pioneering mm-wavelength spectrometer

120 channels from 190-305 GHz $R = \frac{\nu_{\rm obs}}{\Delta\nu} =\sim 250$

First light in 2005, and still in the field producing science results.



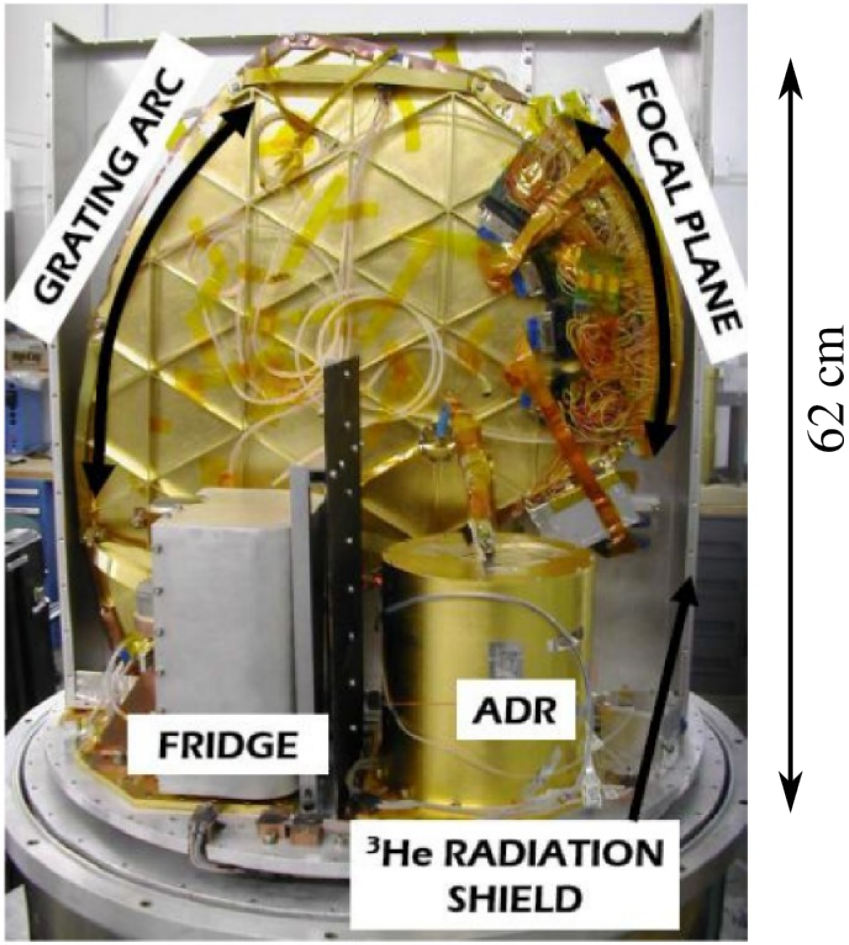


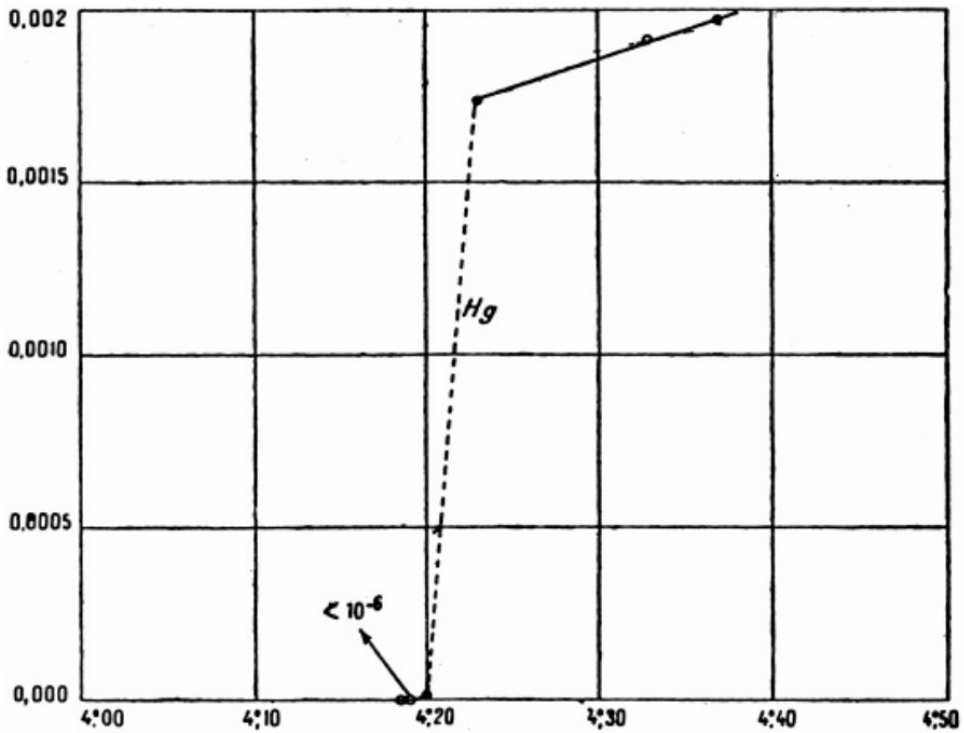
Image: Earle 2006

Superconductors aren't perfect conductors.

Above the gap energy (Δ),
photons break pairs

$$h\nu = 2\Delta(T=0) = 3.53\,T_c$$

$$74\,\mathrm{GHz} \rightarrow 0.3\,\mathrm{meV} \rightarrow 1.0\,\mathrm{K}$$



For T>0, there are significant
numbers of residual quasiparticles

Cooper-pairs don't scatter,
But they do posses momentum!

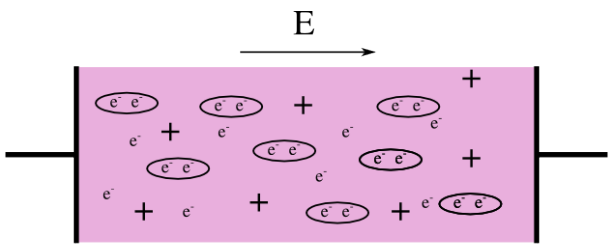
At microwave frequencies, this leads to a complex impedance.

Figure: Onnes 1912 (via Goodstein & Goodstein 2000)

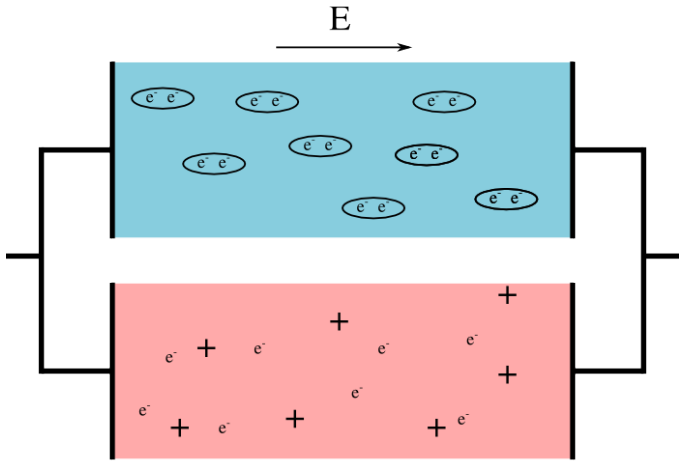
At microwave frequencies, superconductors present a complex impedance.

Momentum and residual quasiparticles give rise to a complex conductivity:

$$\sigma(\omega) = \sigma_1(\omega) - i\sigma_2(\omega)$$



Solving the Mattis-Bardeen equations for 0 < T << T_c:



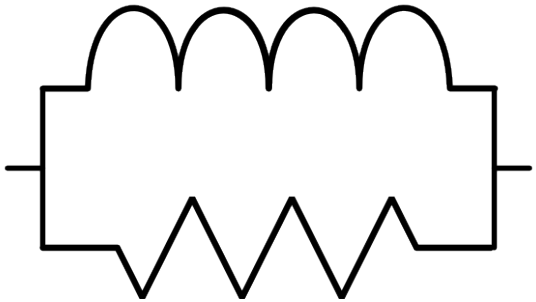
First order:

$$\sigma_1(\omega) \sim \sigma_n \, n_{\mathrm{qp}}$$

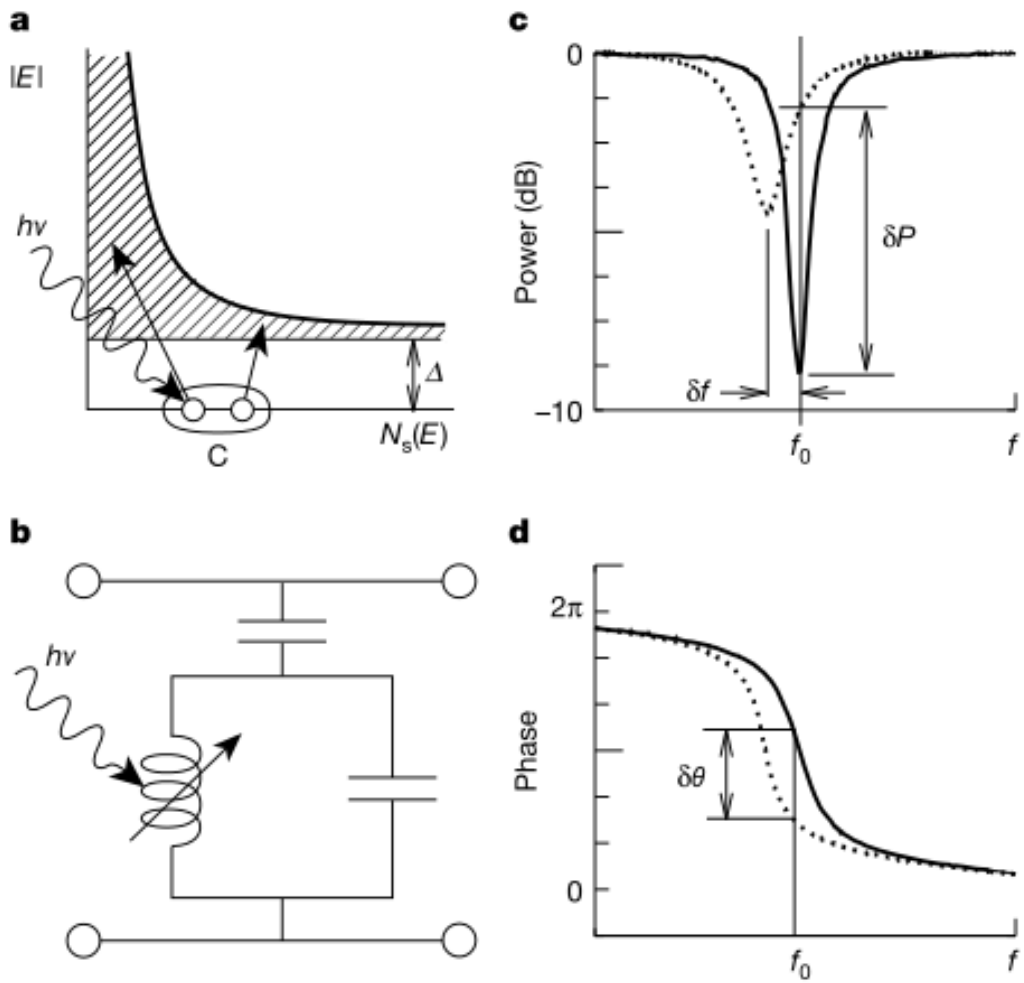
$$\sigma_2(\omega) \sim \sigma_n \, \Delta_0$$

Second order:

$$\sigma_2(\omega) - \sigma_2(\omega)|_{n_{\mathrm{qp}}=0} \sim \sigma_n \, n_{\mathrm{qp}}$$



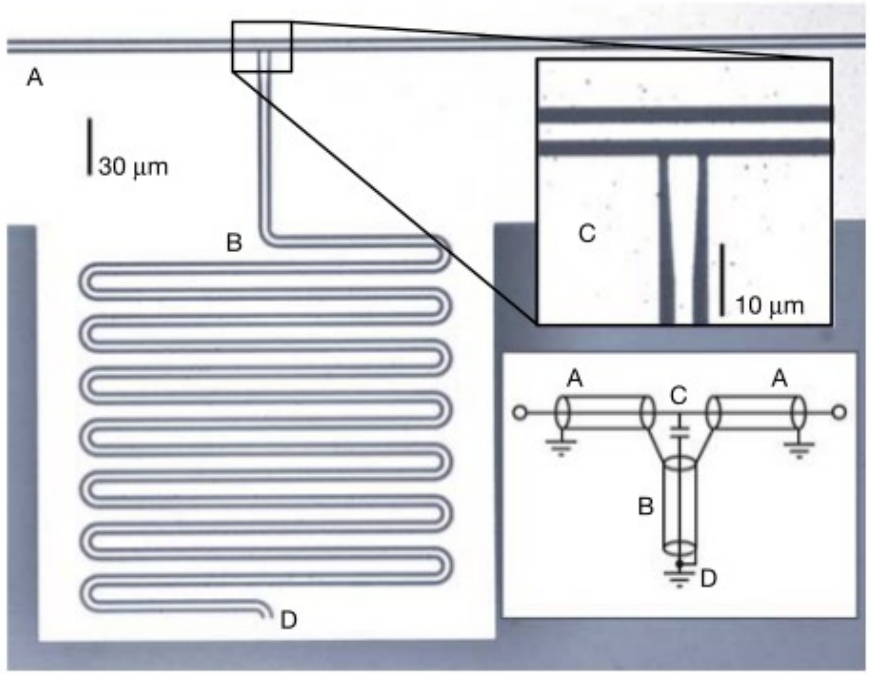
QP density dependence can be used as a power detector.



A broadband superconducting detector suitable for use in large arrays

Peter K. Day[1], Henry G. LeDuc[1], Benjamin A. Mazin[2], Anastasios Vayonakis[2] & Jonas Zmuidzinas[2]

[1]*Jet Propulsion Laboratory, Pasadena, California 91107, USA*
[2]*California Institute of Technology, 320-47, Pasadena, California 91125, USA*



All images: Day, 003

Microwave shunt readout leads to natural multiplexing:

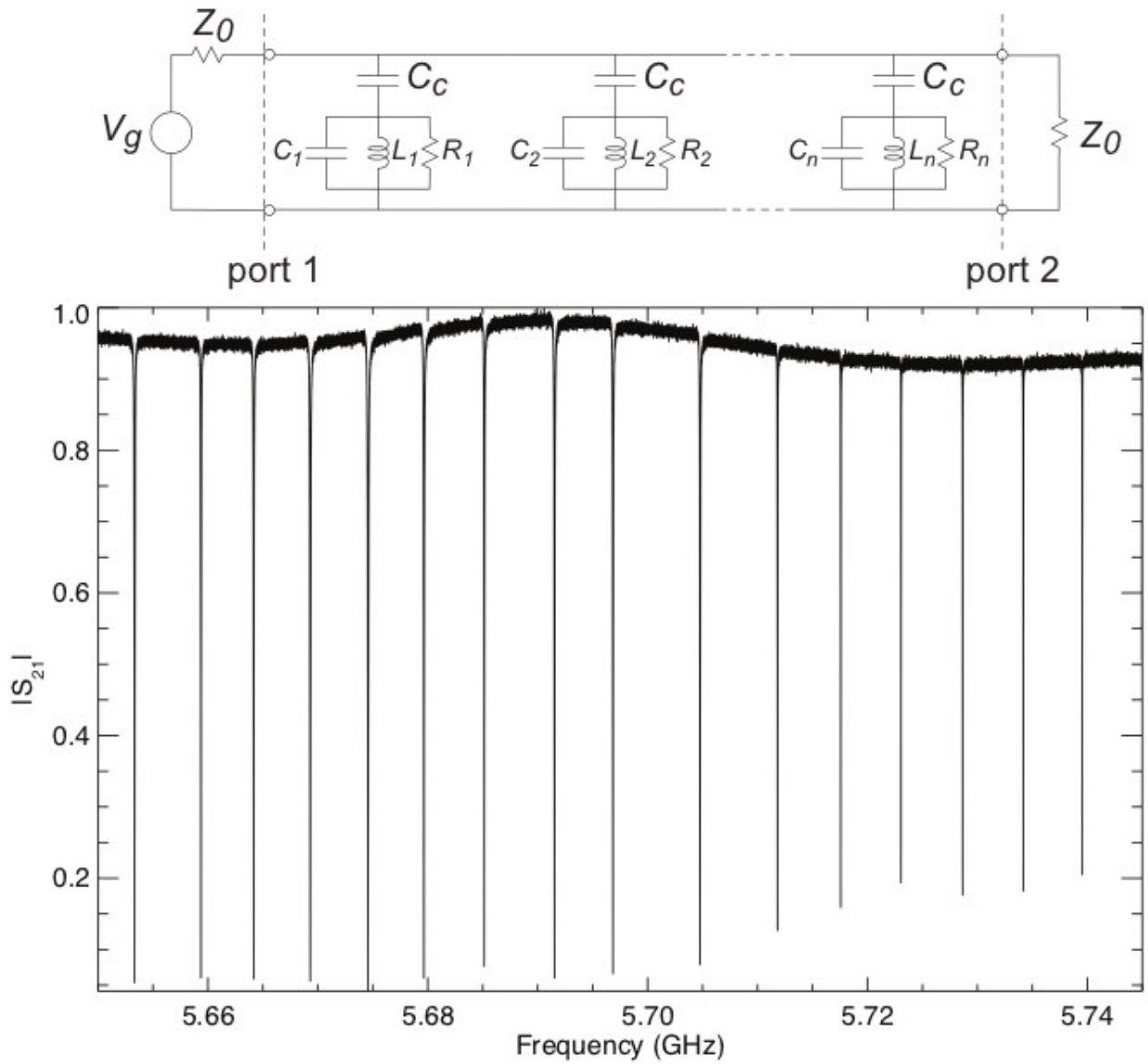


Figure from a Zmuidzinas group proposal

MKID sensitivity in dissipation readout

Use the Mattis-Bardeen equations to solve for $\delta\sigma$ vs. δn_{qp}

Looking only at the dissipation (σ_i), the result is:

$$\mathrm{NEP}^2_{\mathrm{diss}} = \overbrace{2(1+n_0)h\nu P_0}^{\text{Photon noise}} + 16 \cdot \overbrace{\underbrace{\frac{g^2(x)\eta_a}{\chi^c \chi^2_{qp}\eta_0}\left(1+\frac{1}{y_{\min}}\right)}_{\sim 1}}^{\text{QP Generation}} \overset{\text{1st stage Amp}}{kT_a P_o} + \underbrace{\frac{2\Delta_0}{\eta_0}P_o}_{\text{small}} + \underbrace{\mathrm{NEP}^2_{\mathrm{recomb}}}_{\text{small}}$$

Optical freq

Optical power

$$\mathrm{NEP}^2_{\mathrm{diss}} \approx \mathrm{NEP}^2_{\mathrm{phot}} + 16 g^2 k T_a P_o$$

Compare this to a TES bolometer. For reasonable assumptions and after optimizing:

$$\mathrm{NEP}^2_{\mathrm{TES}} = \mathrm{NEP}^2_{\mathrm{phot}} + 4\gamma k T_c^2 \sim \mathrm{NEP}_{\mathrm{phot}} + 20 k T_c P_o$$

But T_c = 400 mK, while $T_a \sim 5K$, thus to be competitive:

- Operate at short wavelengths (eg. 350 μm)
- Replace HEMTs / SiGes with para-amps
- Or, use Frequency Readout

MKID sensitivity in frequency readout

Same strategy, similar results, with two important differences:

Noise from Two Level Systems

Photon noise Diss. Noise

$$\mathrm{NEP}^2_{\mathrm{freq}} = 2(1+n_0)h\nu P_0 + \frac{1}{\beta^2}\mathrm{NEP}^{\mathrm{diss}}_{\mathrm{amp}} + \text{small terms} + \frac{1}{\beta^2}\frac{8N^2_{qp}\Delta^2_0 Q^2_i}{\eta^2_o \chi_c \chi^2_{qp}\tau^2_{qp}} S_{\mathrm{TLS}}$$

Optical freq

Optical power

Can adjust $\Delta(T_c)$,Q_i

$\beta(\omega) = \delta\sigma_2 / \delta\sigma_1$

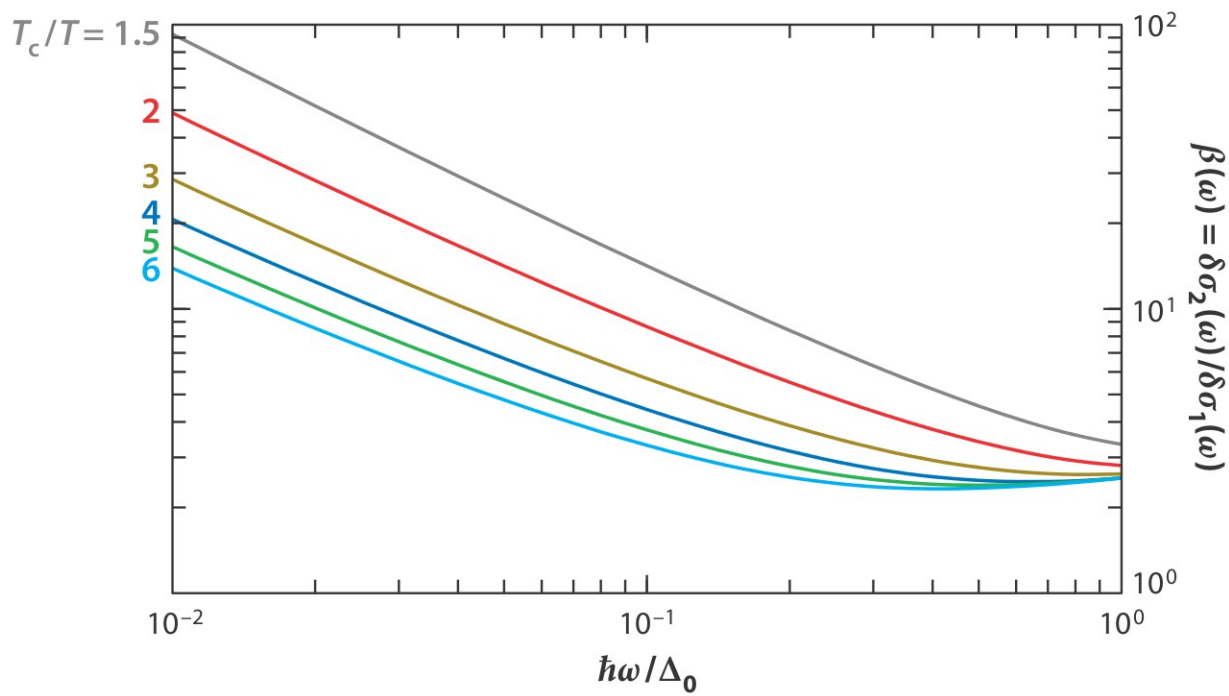


Figure from Zmuidzinas 2012

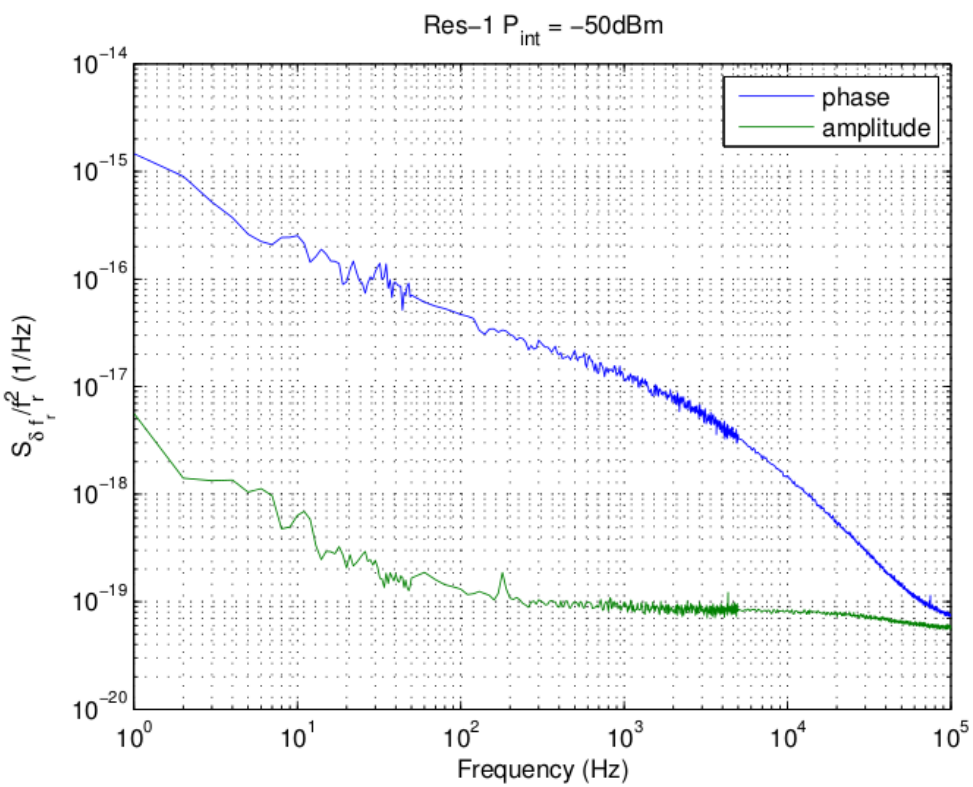
Two Level System Noise

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

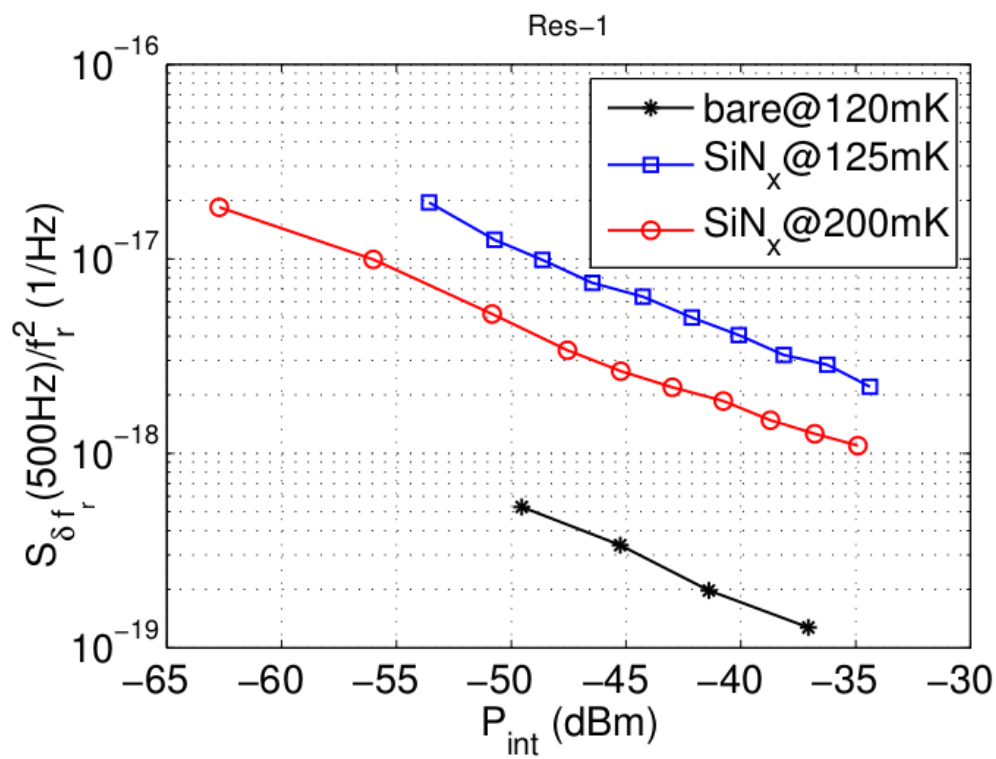
Only present in frequency readout.

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

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



(a)



(b)

Images: Gao 2008 (thesis)

Titanium Nitride: high Q, high Rn, tunable Tc

Titanium Nitride Films for Ultrasensitive Microresonator Detectors

Henry G. Leduc,[1] Bruce Bumble,[1] Peter K. Day,[1] Byeong Ho Eom,[2] Jiansong Gao,[3] Sunil Golwala,[2] Benjamin A. Mazin,[4] Sean McHugh,[4] Andrew Merrill,[4] David C. Moore,[2] Omid Noroozian,[2] Anthony D. Turner,[1] and Jonas Zmuidzinas[2]

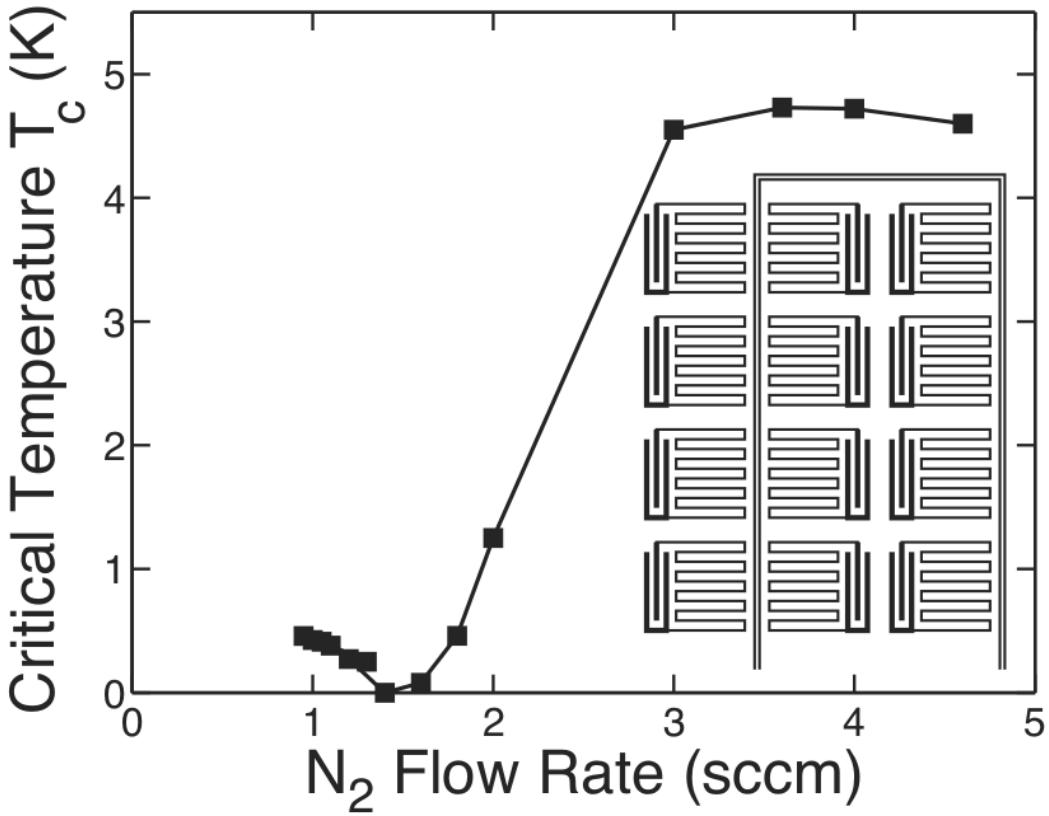
[1] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109*

[2] *Division of Physics, Mathematics, and Astronomy, California Institute of Technology, Pasadena, CA 91125*

[3] *National Institute of Standards and Technology, Boulder, CO, 80305*

[4] *Department of Physics, University of California, Santa Barbara CA 93106-9530*

(Dated: 11 August 2010)



$$\rho_n = 100 \mu\Omega\,\mathrm{cm}$$

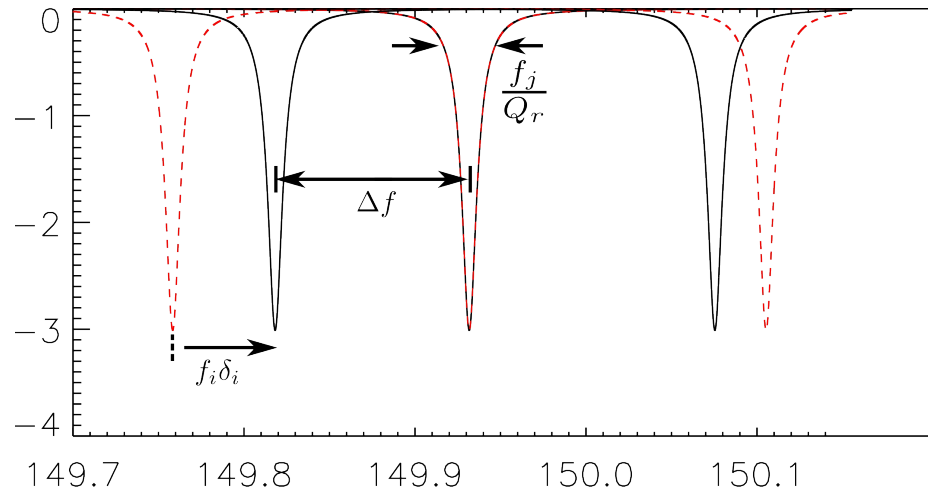
$$Q_i > 10^7$$

Image: titaniumexposed.com

Multiplexing requirements set minimum value of Qi.

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

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



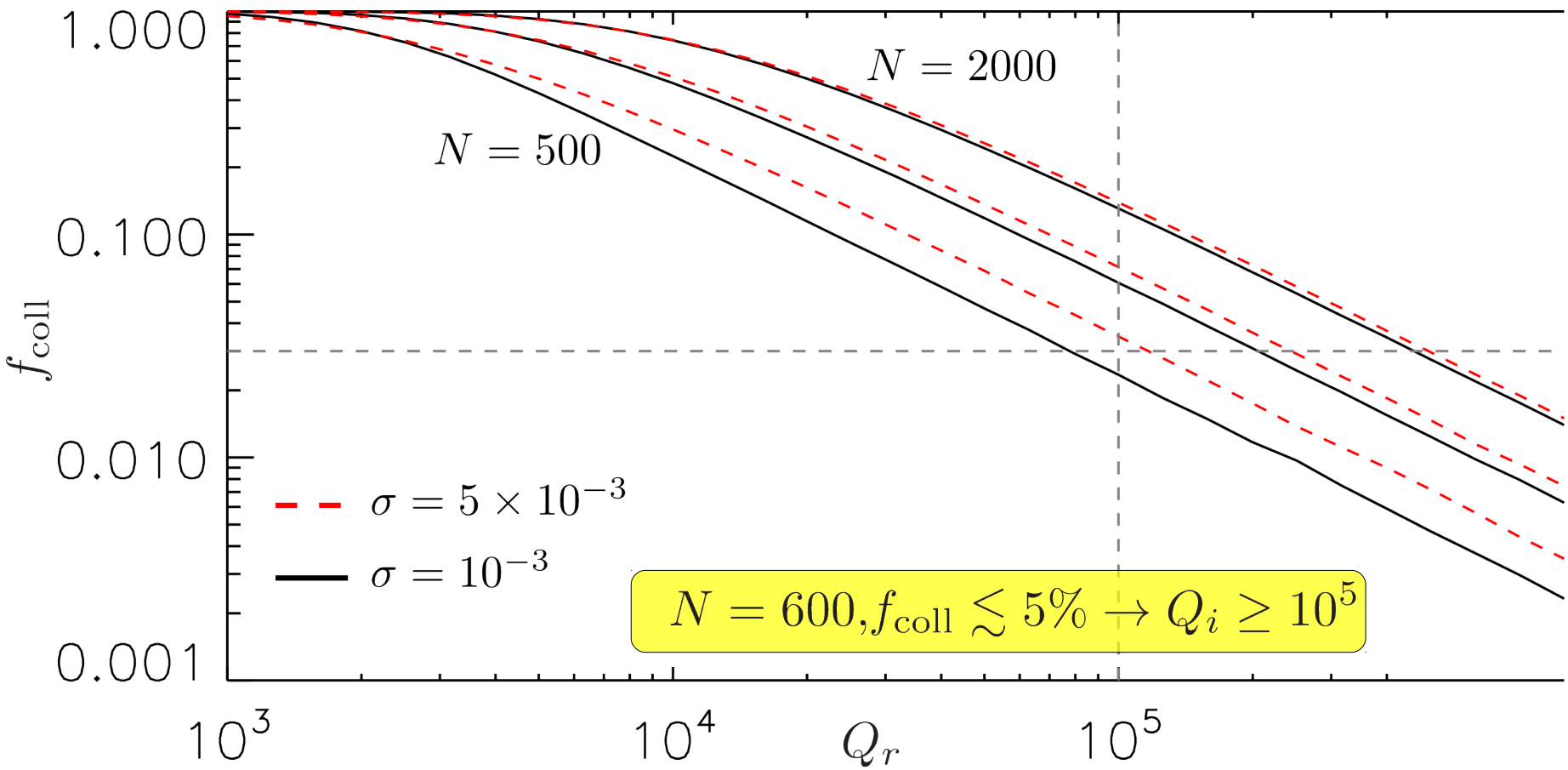


Figure based on Zmuidzinas internal memo

Redacted slides

Several slides from other projects have been removed, since I haven't received permission to post them online.

For more information on this projects, please see:

- A-MKID: http://www3.mpifr-bonn.mpg.de/div/submmtech/bolometer/A-MKID/A-MKID_technology.html
- NIKA: http://www.iram.es/IRAMES/mainWiki/NIKA/Main
- MAKO: https://indico.hep.anl.gov/indico/materialDisplay.py?contribId=3&materialId=slides&confId=368
- Deshima: http://www.cosmonanoscience.tudelft.nl/?page_id=143
- ANL X-Ray detectors: http://adsabs.harvard.edu/abs/2014JLTP..176..497M
- UCSB (& FNAL) optical detectors: http://web.physics.ucsb.edu/~bmazin/Mazin_Lab/Welcome.html

The SuperSpec Team

Caltech/JPL
C. M. Bradford
G. Chattopadhyay
P. Day
S. Hailey-Dunsheath
M. Hollister
A. Kovacs
H. G. Leduc
C. McKenney
R. Monroe
H. Nguyen
R. O'Brient
S. Padin
T. Reck
R. Williamson
J. Zmuidzinas

University of Chicago
E. Shirokoff

Cardiff University
P. Barry
S. Doyle
C. E. Tucker

Arizona State University
P. Mauskopf

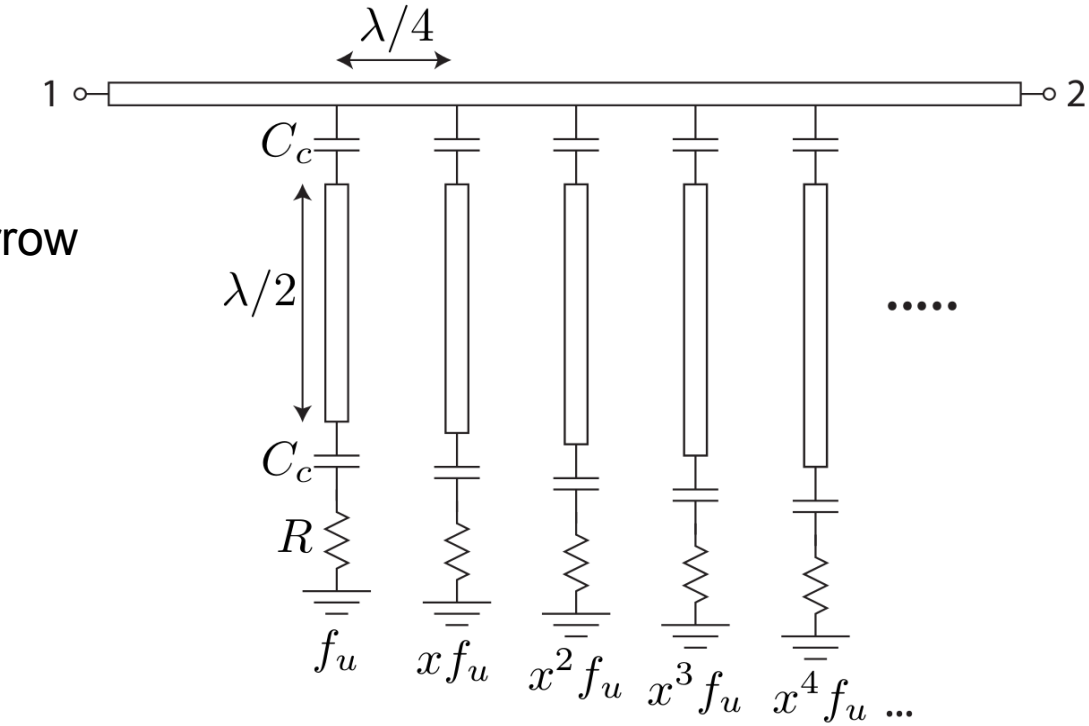
University of Colorado Boulder
J. Glenn

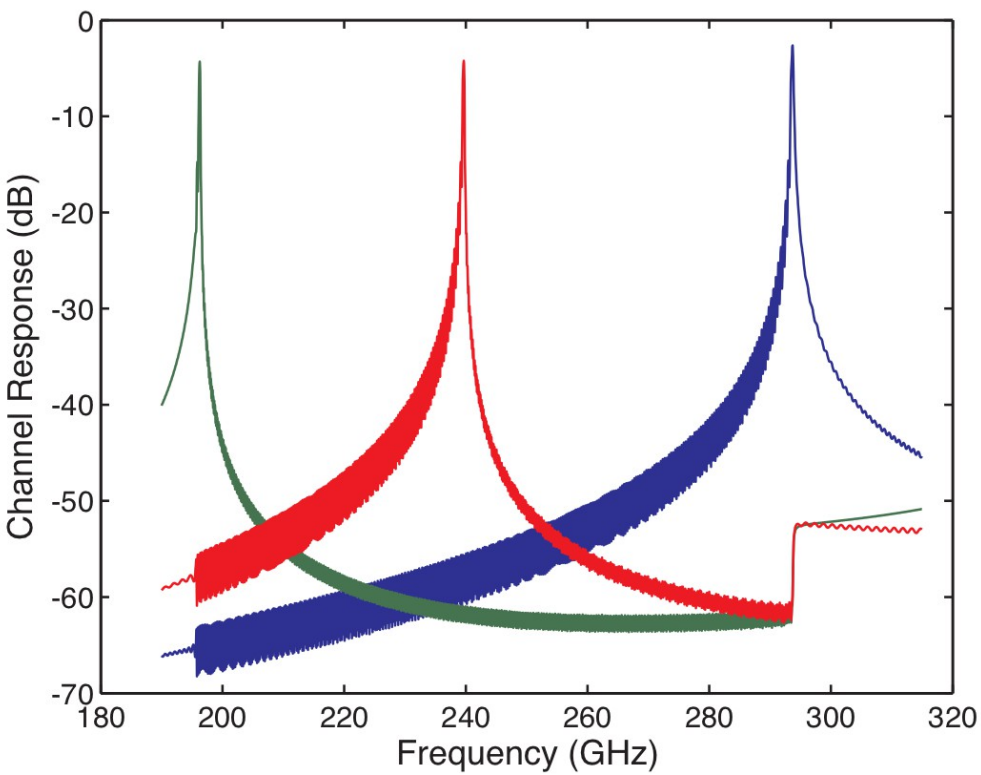
A general filter bank (or cochlear) spectrometer:

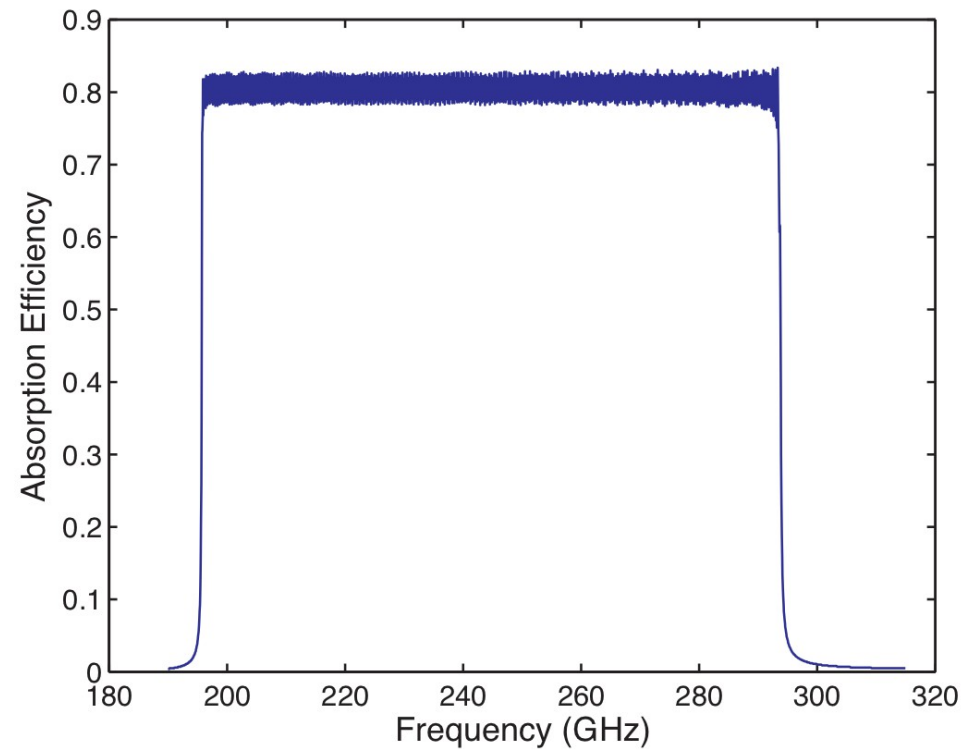
Incoming radiation is sorted by narrow band filters

Each channel couples to a power detector

Channel width and spacing are independently adjustable

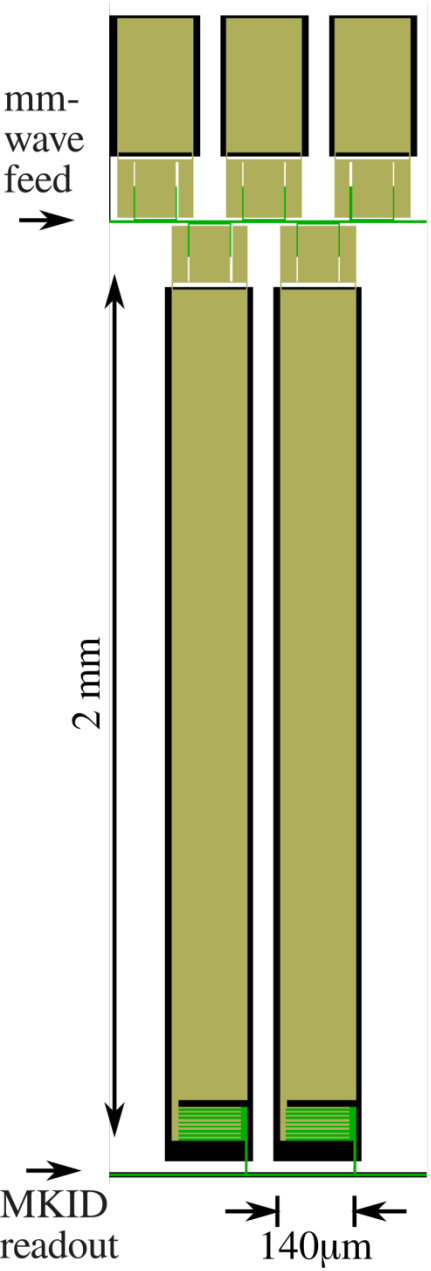


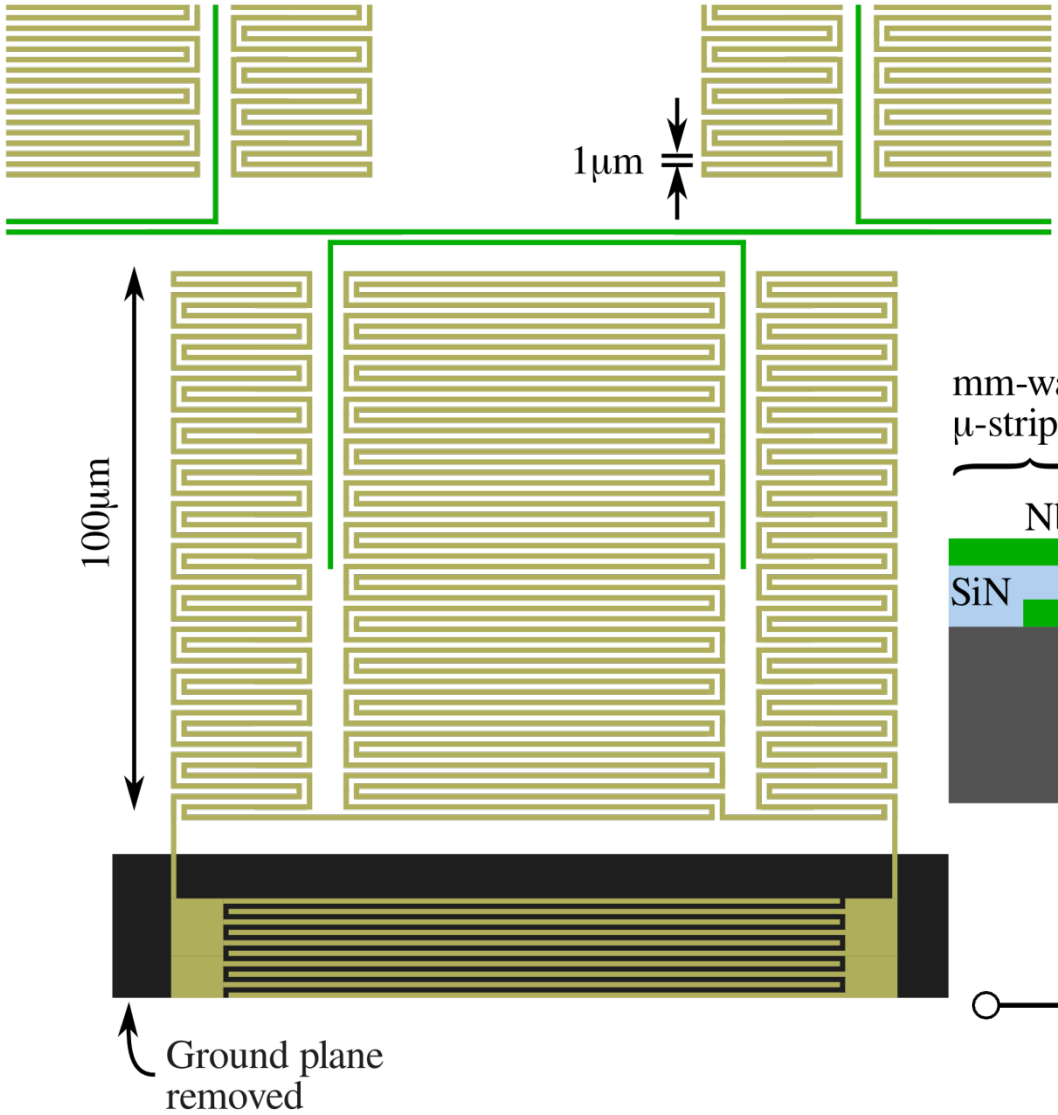




From Kovacs and Zmuidzinas, internal memo

SuperSpec first generation design

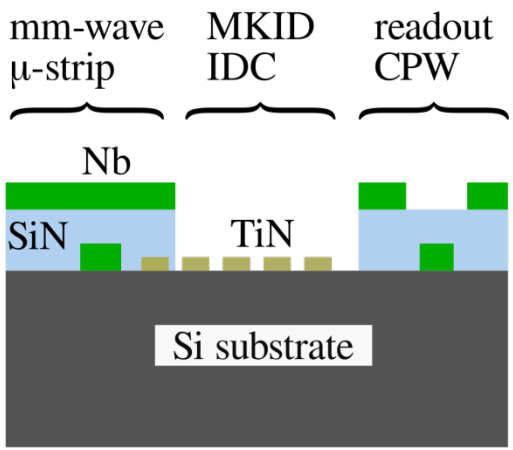


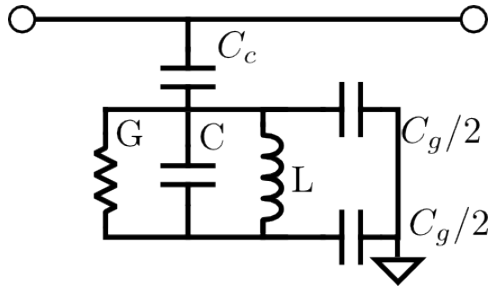


$T_c = 1 - 2\,K$

$f_{ro} = 100\,\mathrm{MHz}$

$Q \sim 10^5$

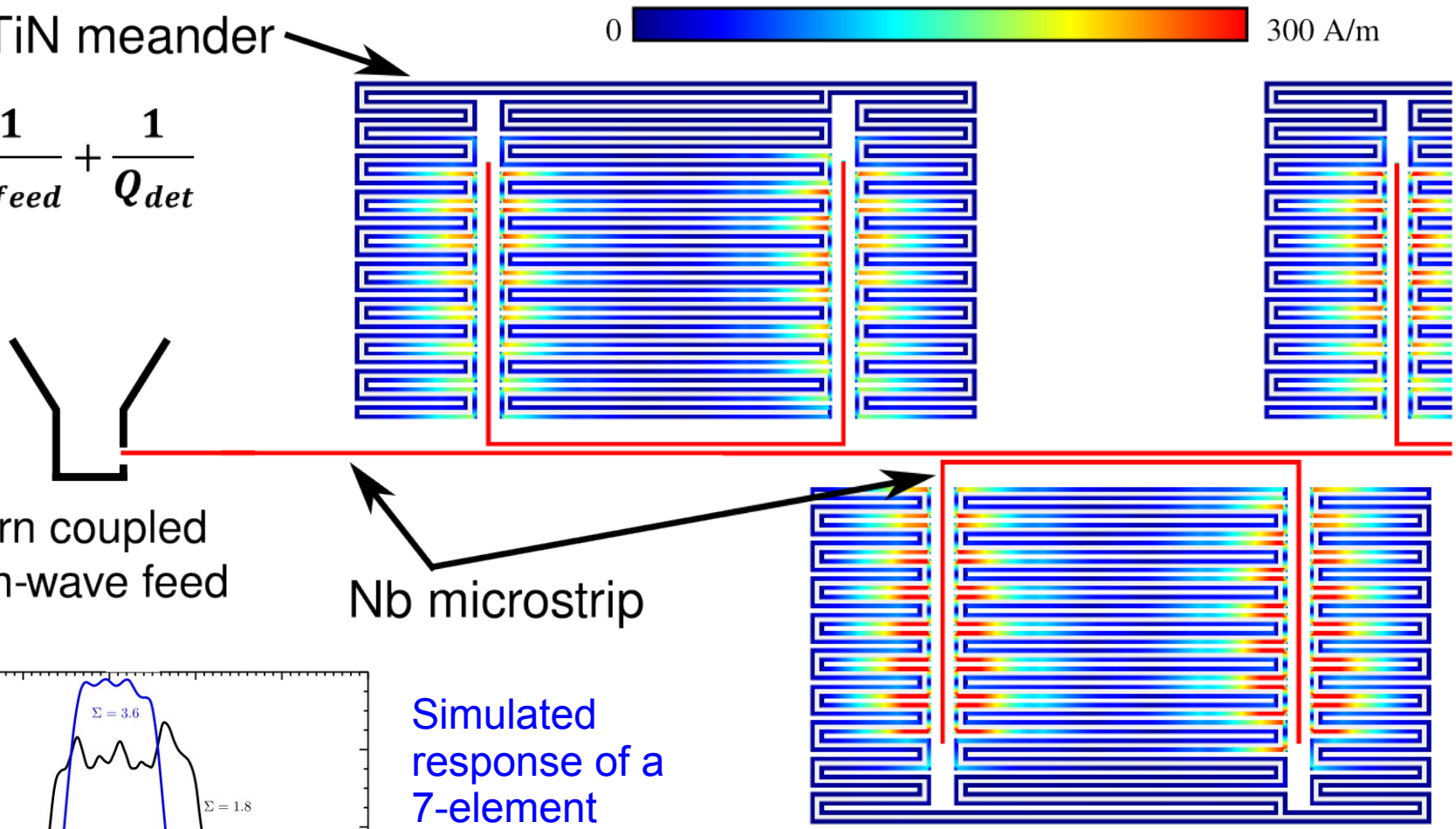




Sonnet Simulations

TiN meander

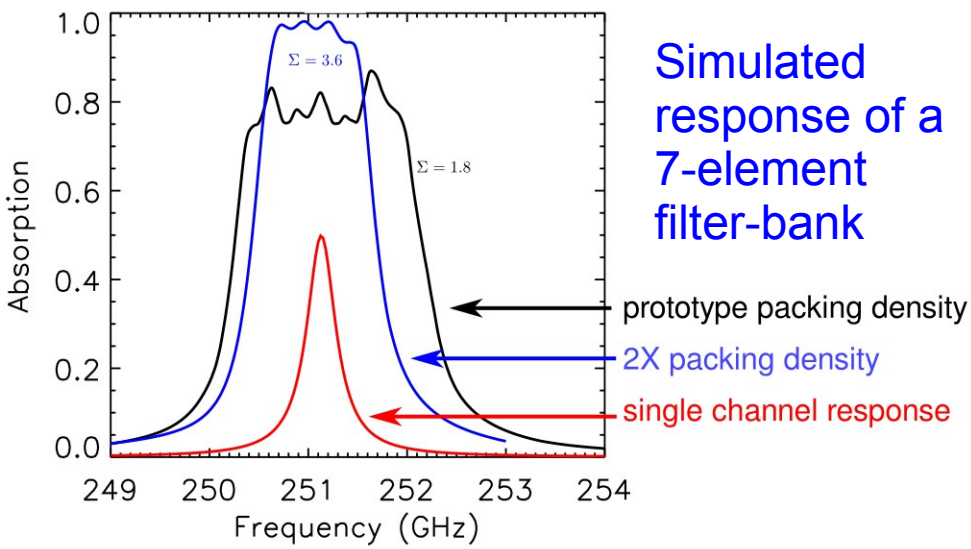
$$\frac{1}{R} = \frac{1}{Q_{feed}} + \frac{1}{Q_{det}}$$



Horn coupled mm-wave feed

Nb microstrip

Simulated current at one mm-wave frequency



Simulated response of a 7-element filter-bank

Gen1 Chip

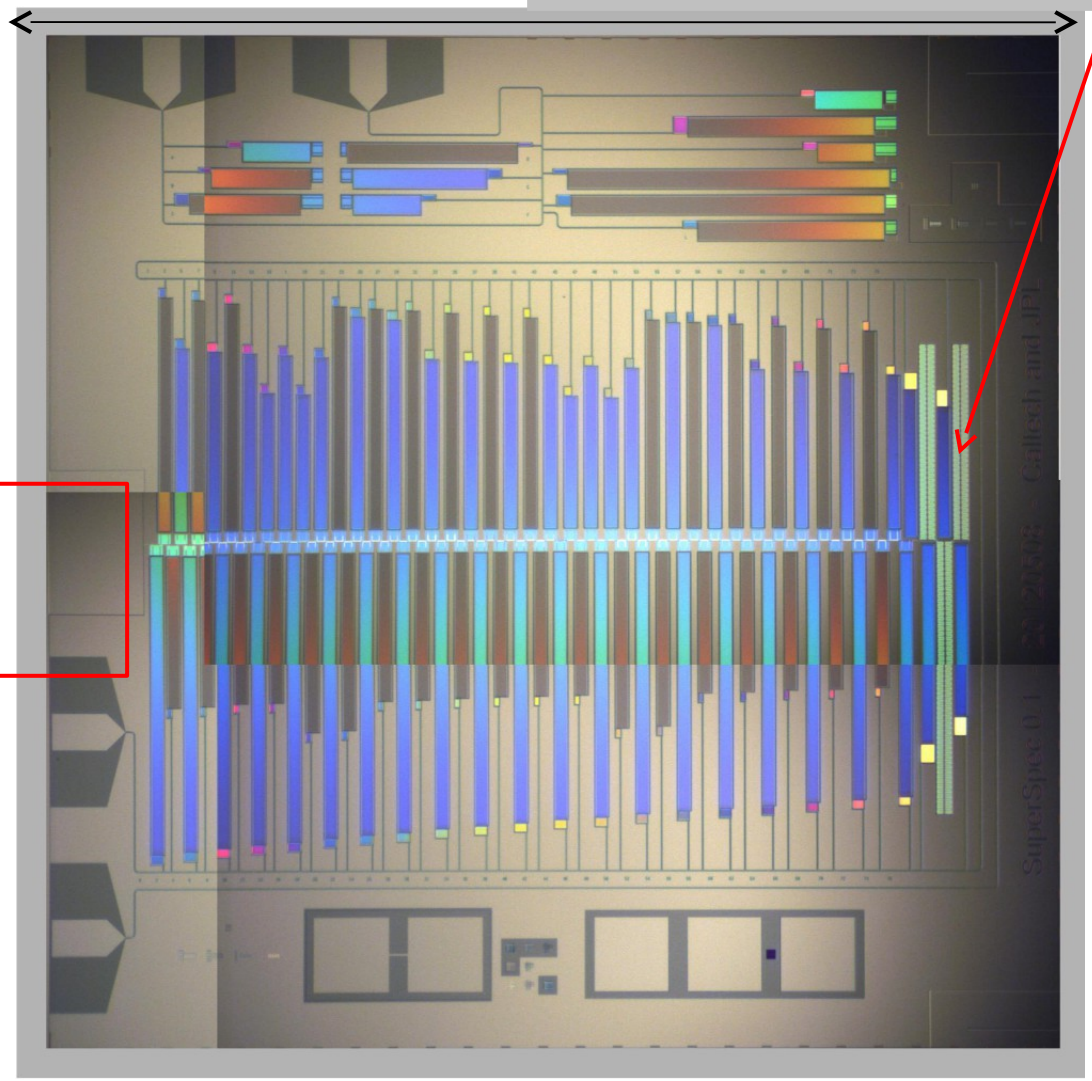
73 spectral channels
- f_0 = 200 – 300 GHz
- Q = 300 – 1400

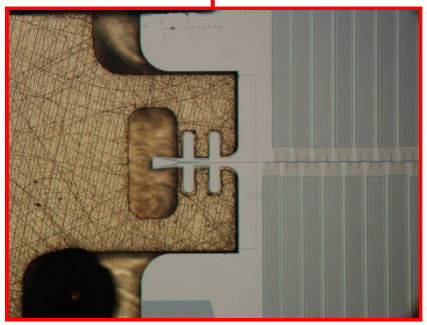
8 broad-band absorbers

~95% optically active

Terminate with long section of meandered feedline surrounded by TiN

1.08 cm

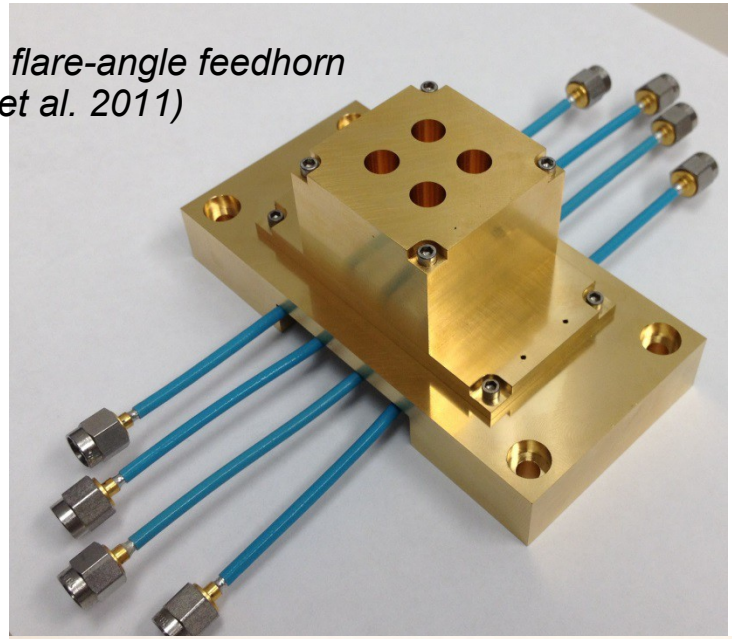


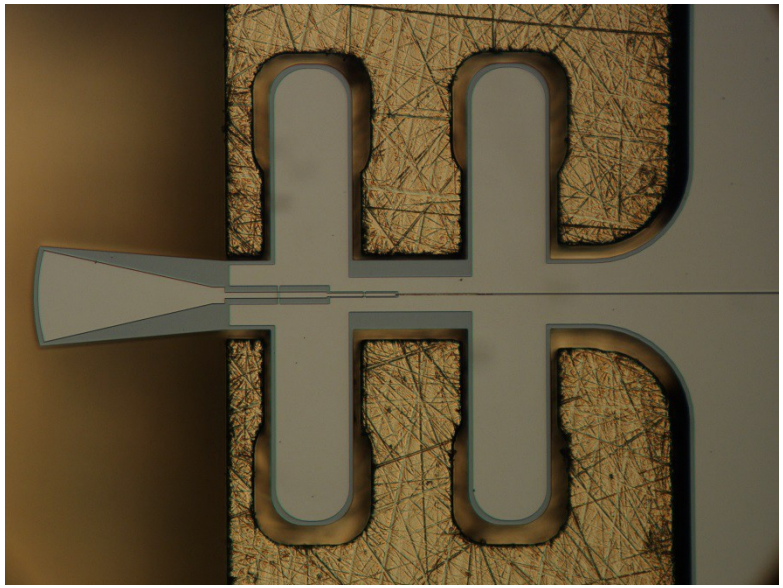


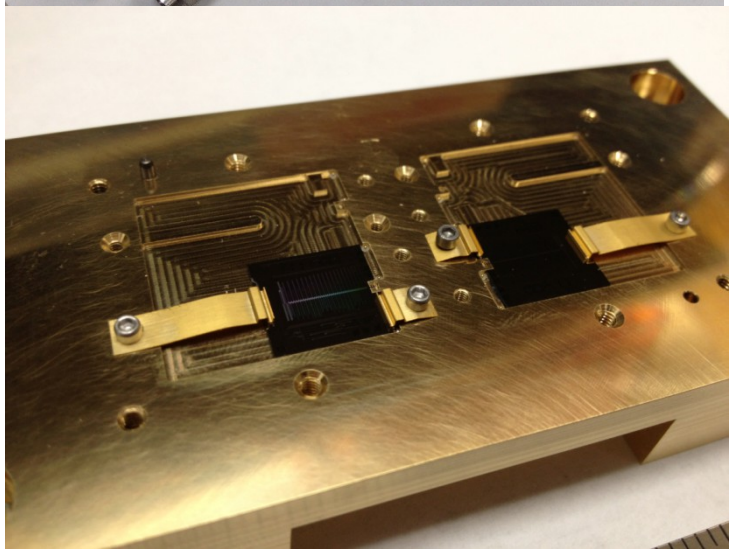
probe-fed waveguide on 25 μm SOI device layer

Gen1 Probe-Fed Waveguide and Horn

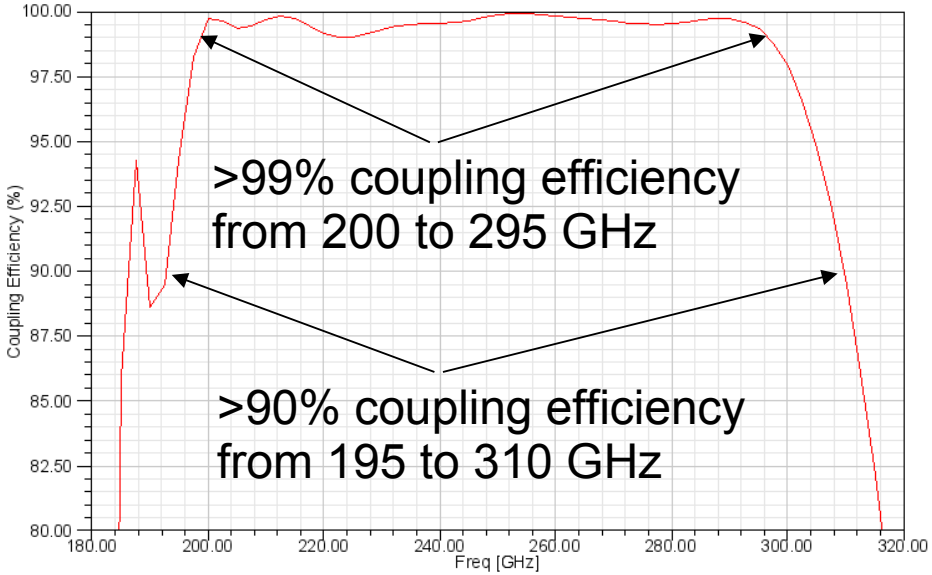
Multiple flare-angle feedhorn (Leech et al. 2011)



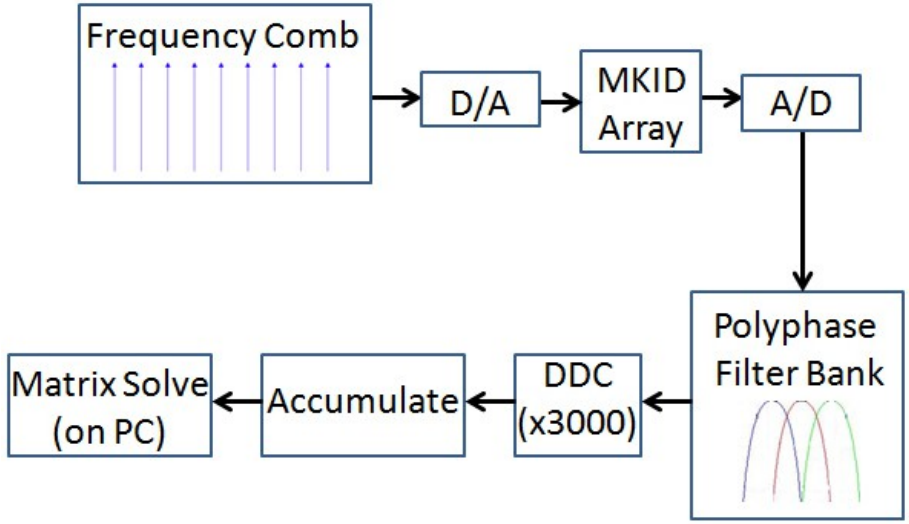




Design and images by T. Reck



CASPER-ROACH based FPGA readout system

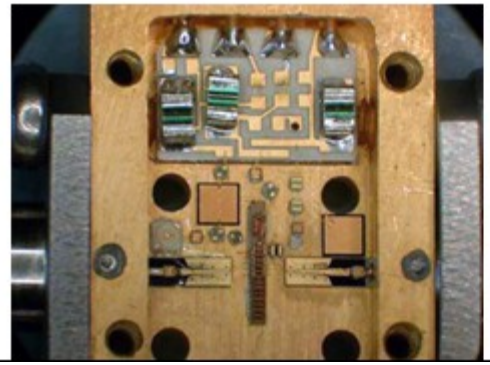


Virtex 5 FPGA, ROACH board operated at baseband frequencies (0-250, or 250-500 MHZ)

On-sky data with ~500 pixels with MAKO at the CSO

1st stage: $3500
Weinreb SiGe Cryo Amps

2st stage: $500
Miteq .001-500 MHz

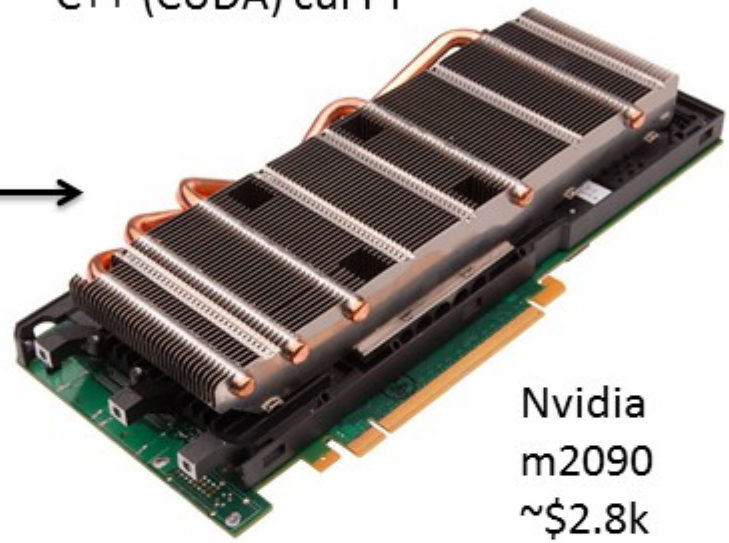


Developed by R. Monroe, L. Swenson, R. Williamson

GPU-based rapid prototyping and chirp-readout test bed

Pentek 2x ADC, 2x DAC
500 MSPS $15k

C++ (CUDA) cuFFT



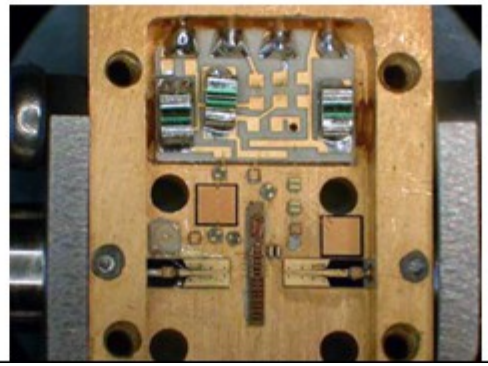
Nvidia
m2090
~$2.8k

Server
price
$2k

CPU
or Disk

Full instrument.
C/C++ programming.
250 MHz bandwidth
$30k for 2 lines ($15k/line)

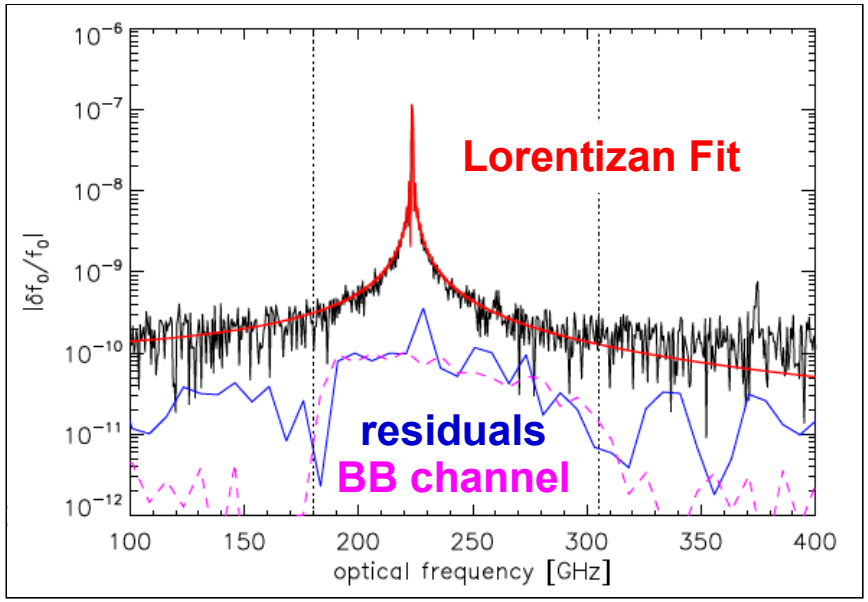
1st stage: $3500
Weinreb SiGe Cryo Amps



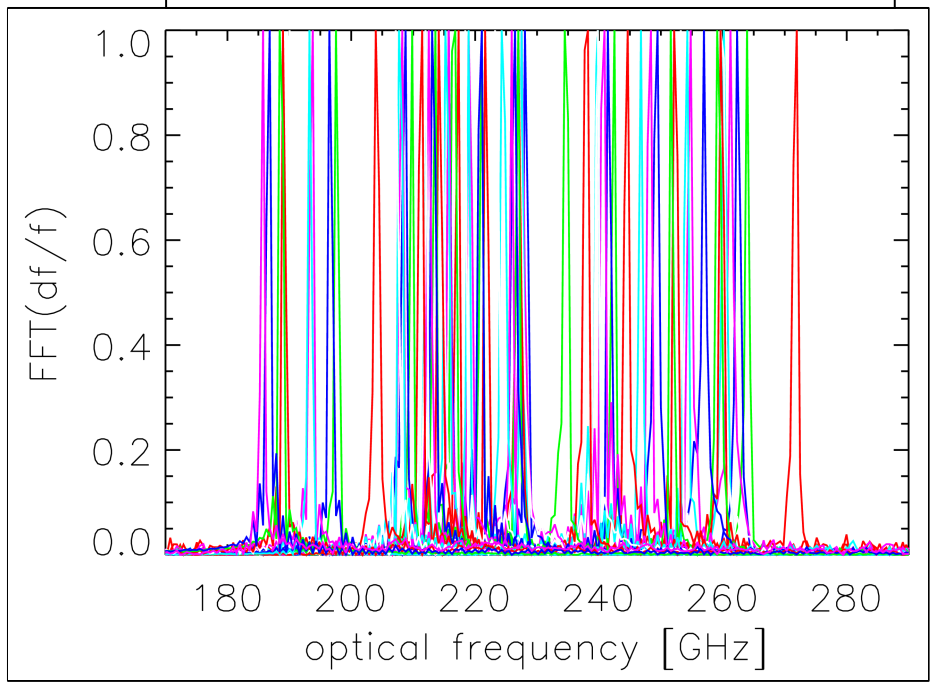
2st stage: $500
Miteq .001-500 MHz

Currently being developed by A. Kovacs, L. Swenson

FTS Measurements

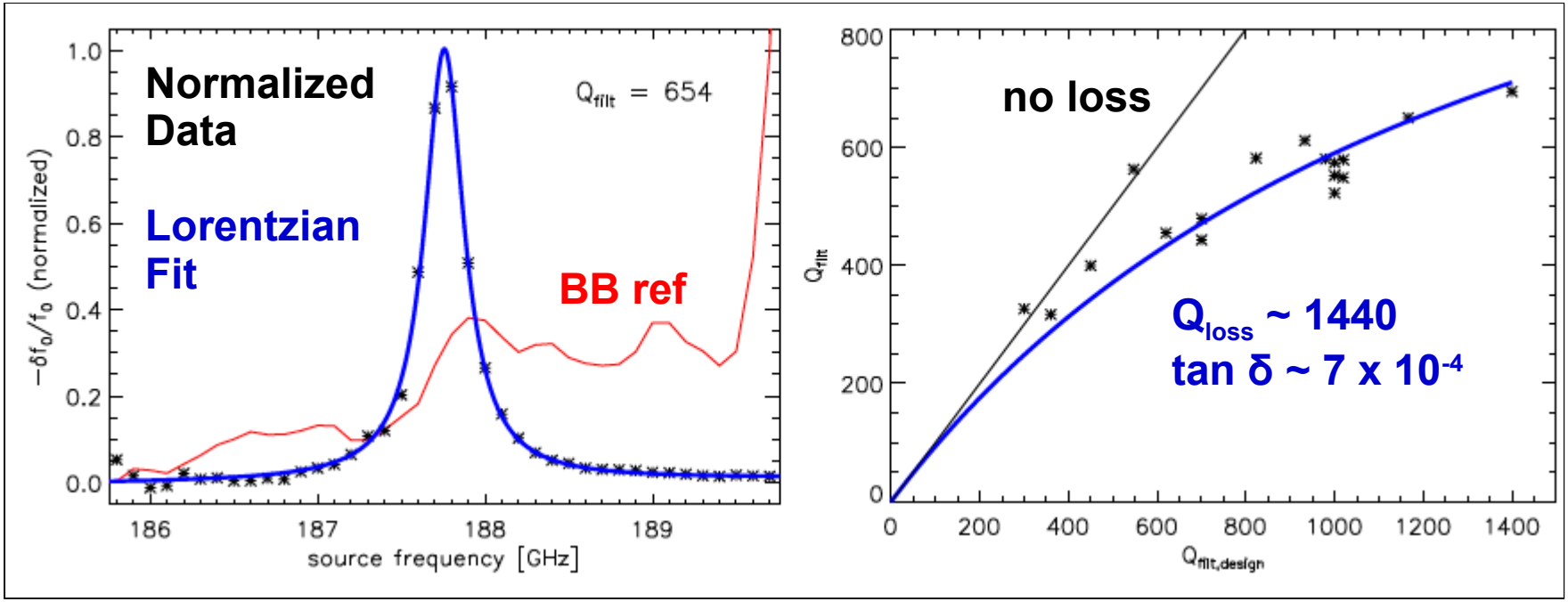


Normalized profiles of 71 spectral channels readout in parallel



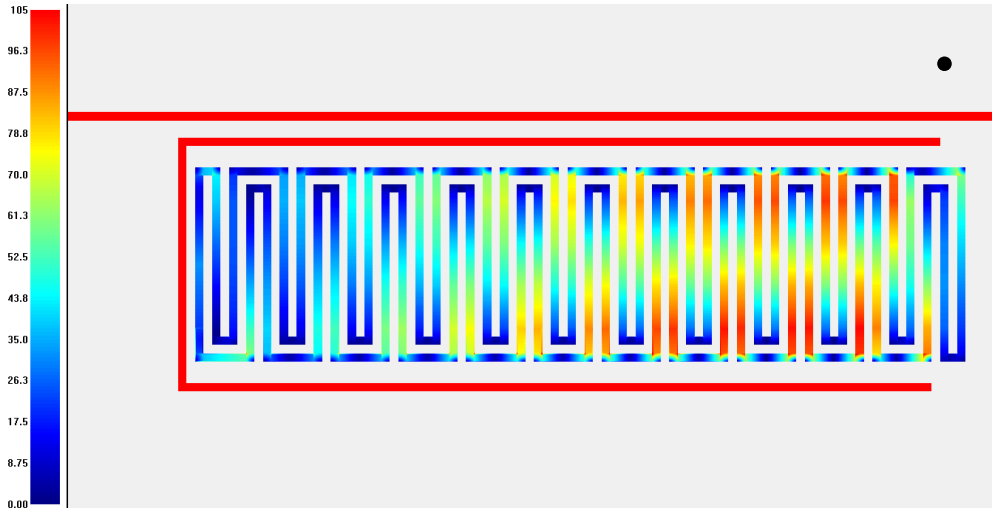
- Full band spectra measured with CASPER-ROACH based FPGA readout system (same system deployed by MAKO/CSO)
- Residual out of band response typically 30dB below peak
- Channel center placement has 2 – 3% scatter – partially systematic with frequency, Q, location in filter bank
- Too large to be errors in resonator length --> wavespeed variation
- Will soon test chips with large bank of near-identical channels to measure real dispersion.

Coherent Source Measurements



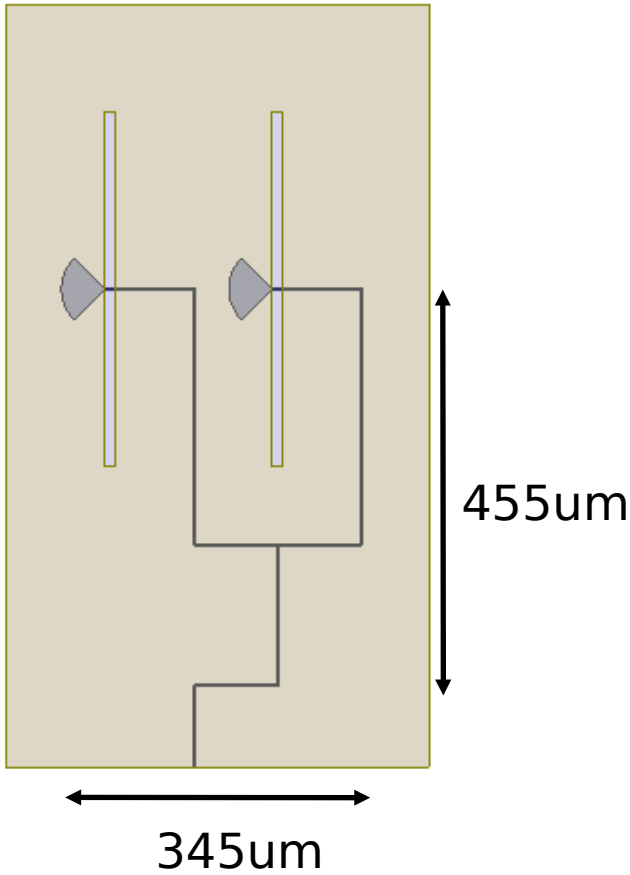
- Spectral response characterized using a swept coherent source
- Normalize response with near simultaneous measurements of BB ref channel – well described by Lorentzian
- Comparison of designed and measured Q indicates a source of loss characerized by Q_{loss} ~ 1440 --> likely SiN_x ILD in microstrip
- **Greater than 50% of the incident power lost for R > 420**
- Better dielectrics (a-Si, crystal Si)

Gen2 – Improved NEP and diagnostics

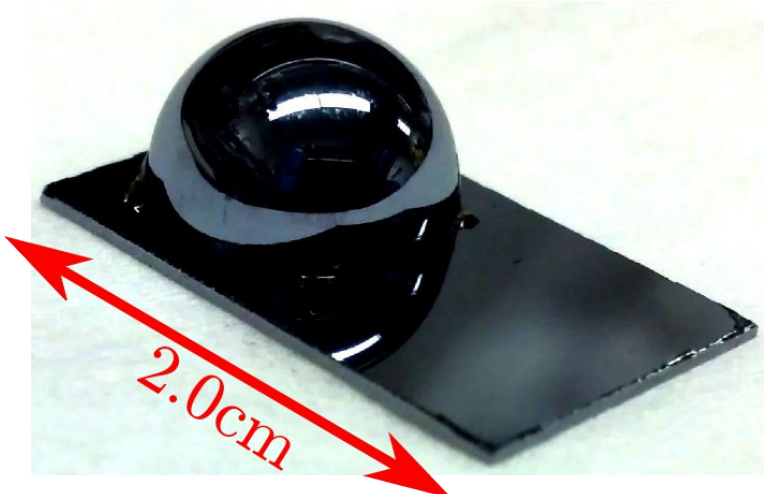


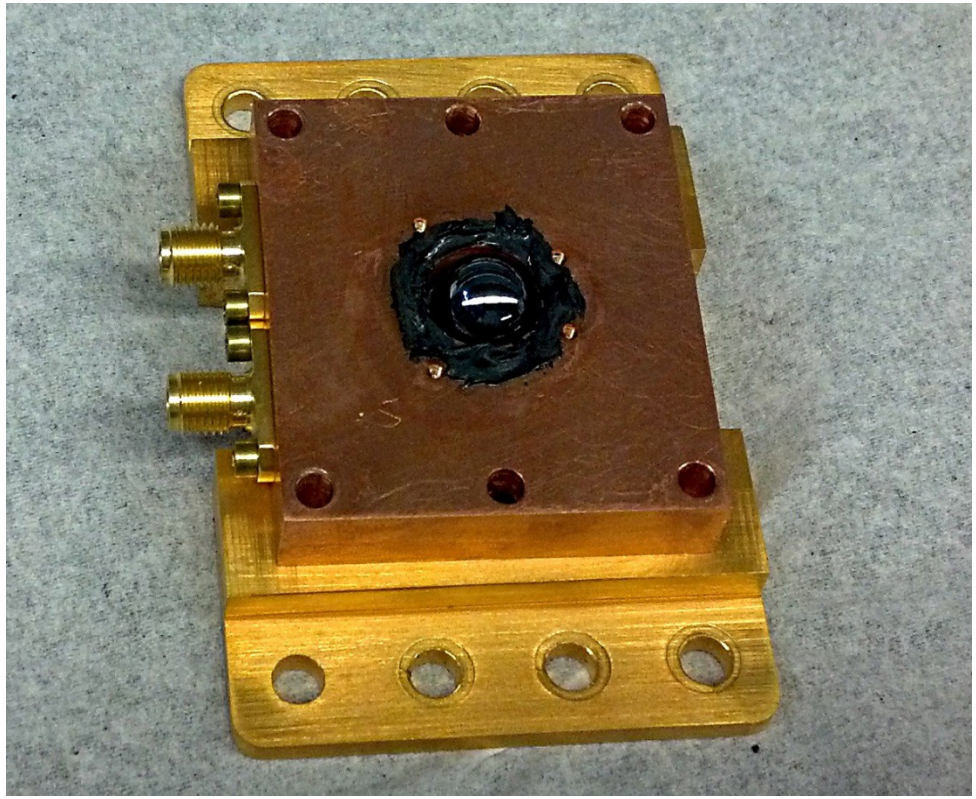
- Modifications to boost sensitivity
  - Shrink inductor volume by x5
  - More uniform current density
  - Wider IDC spacing

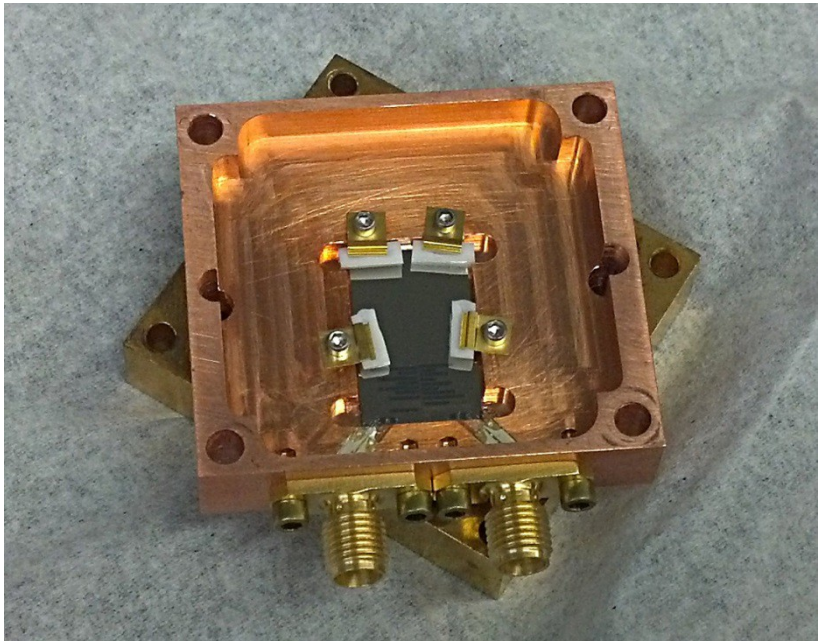
- Modifications to improve diagnostics
  - Simpler planar antenna + hyper-hemispherical lens
  - BB detectors couple to a longer section of the feedline, comparable to a wavelength in length
  - Small number (10) of isolated spectral channels
  - Dark channel

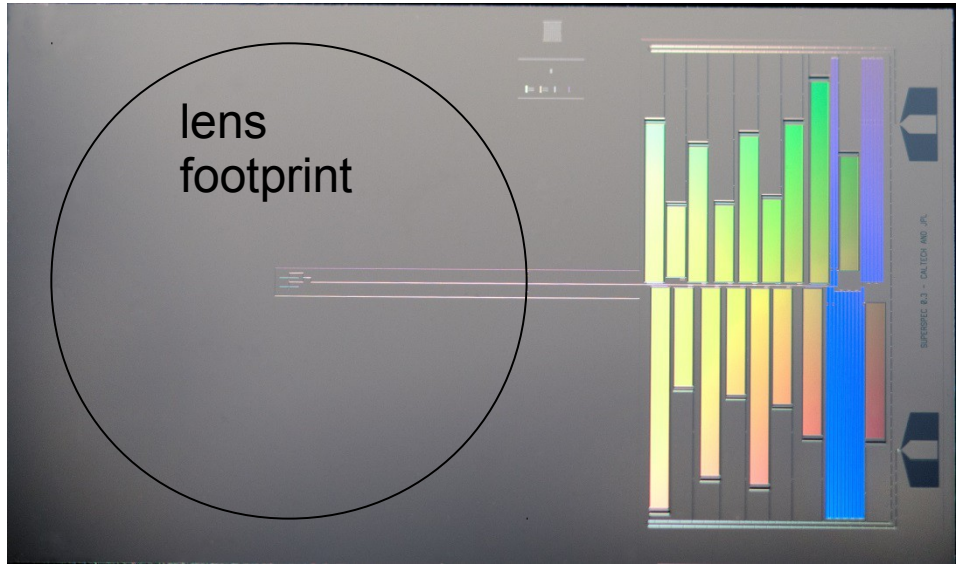


Gen2 Packaging



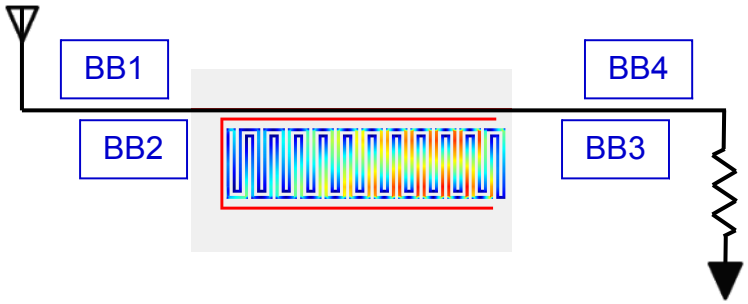


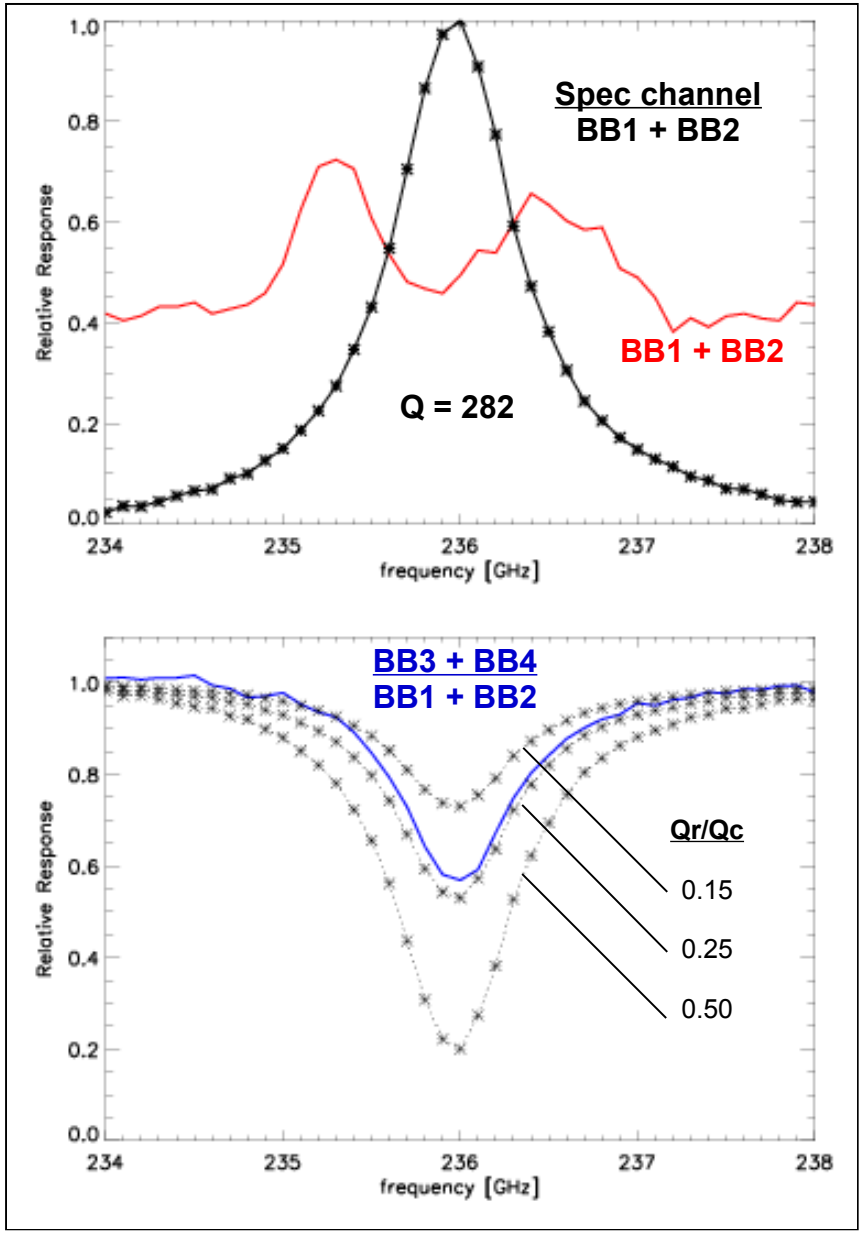




Sockout Measurement

BB channels – sections of meandered TiN in proximity to feedline, approx λ in length

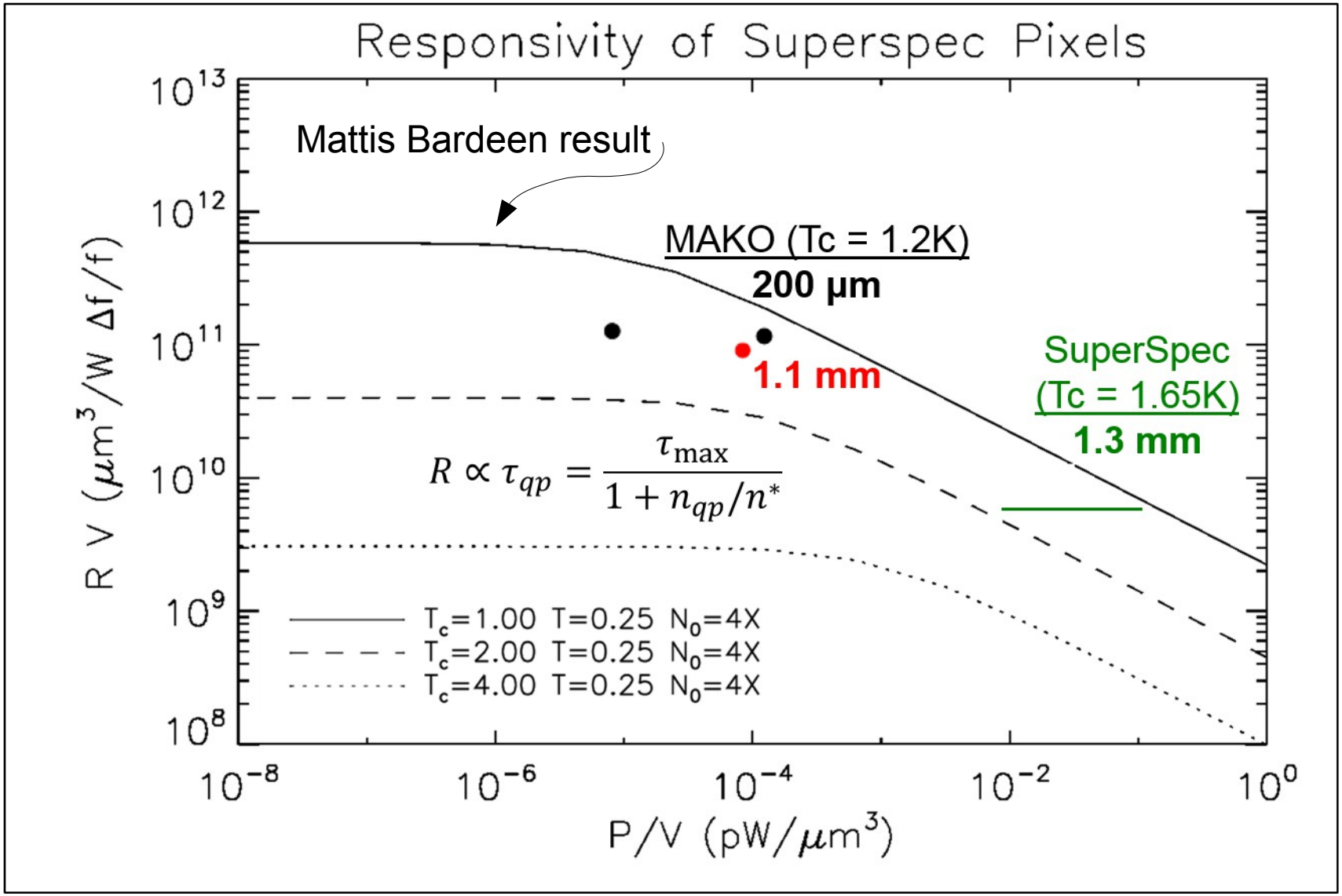




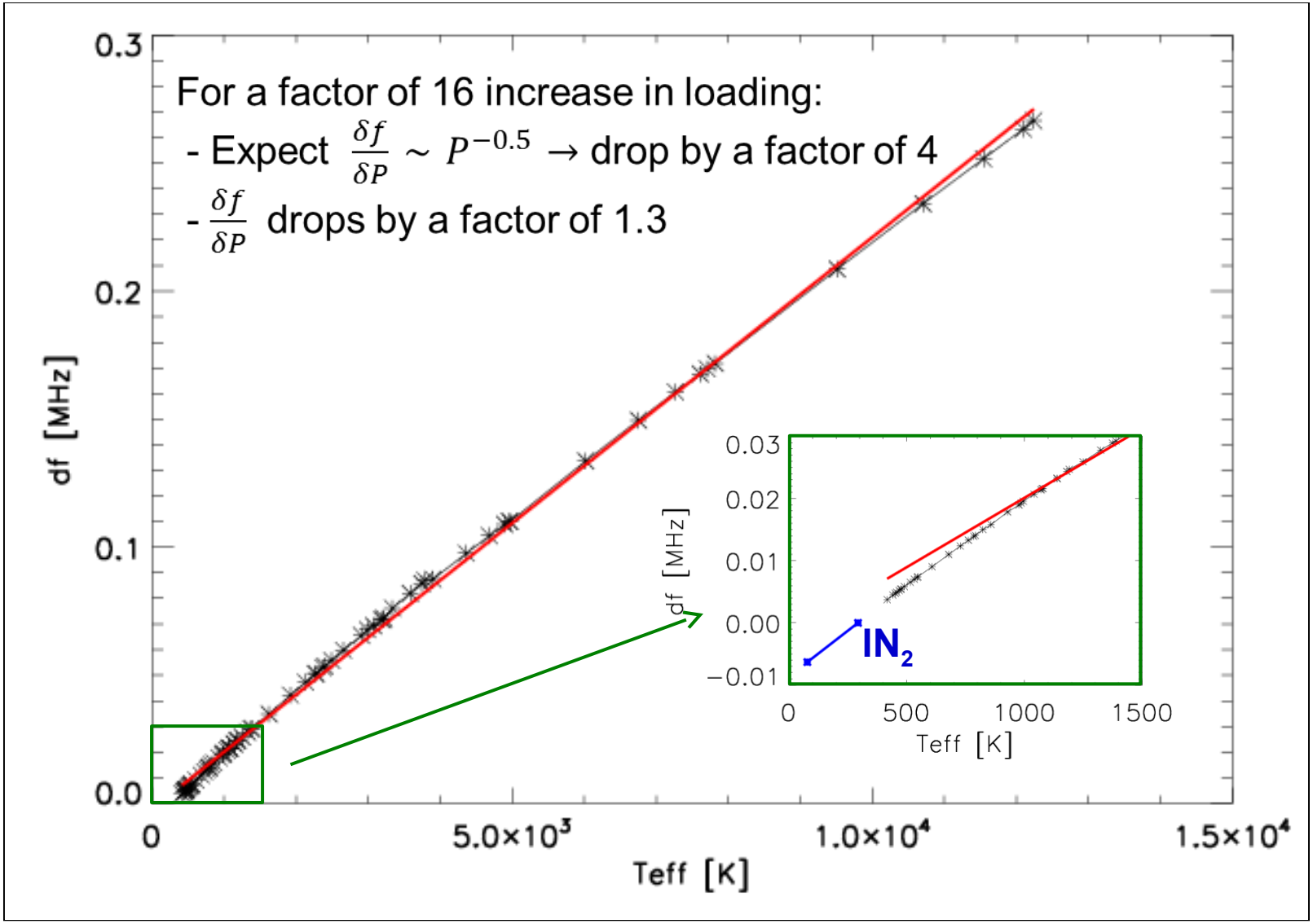
Modeling indicates
- Qr/Qc ~ 0.25
- Absorbed fraction ~ 37%

With Q_{loss} = 1440
- **Detected fraction ~ 28%**
- **Can achieve ~ 34% with R = 250, adjusted dimensions**

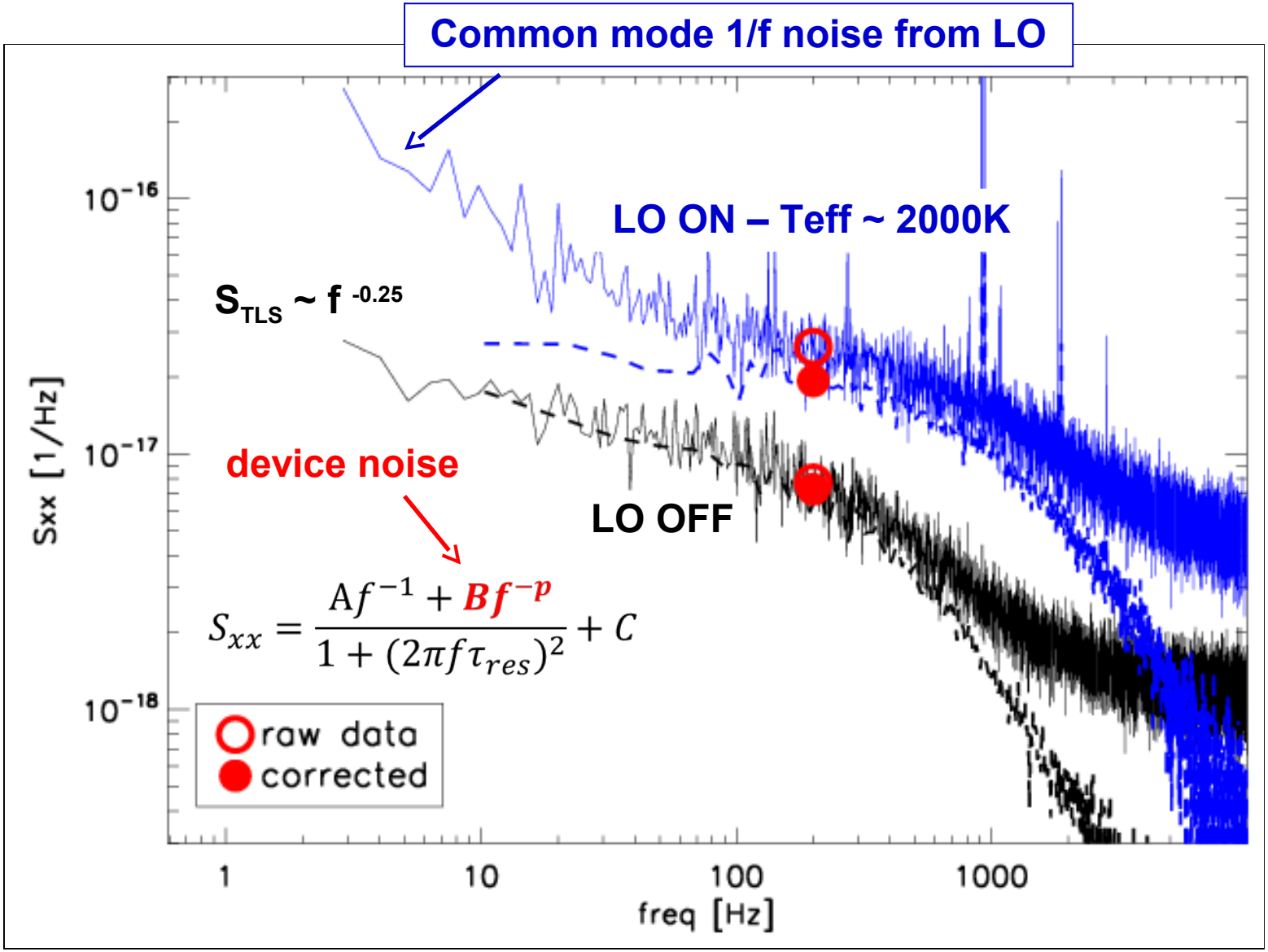
RV vs P/V plot


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}

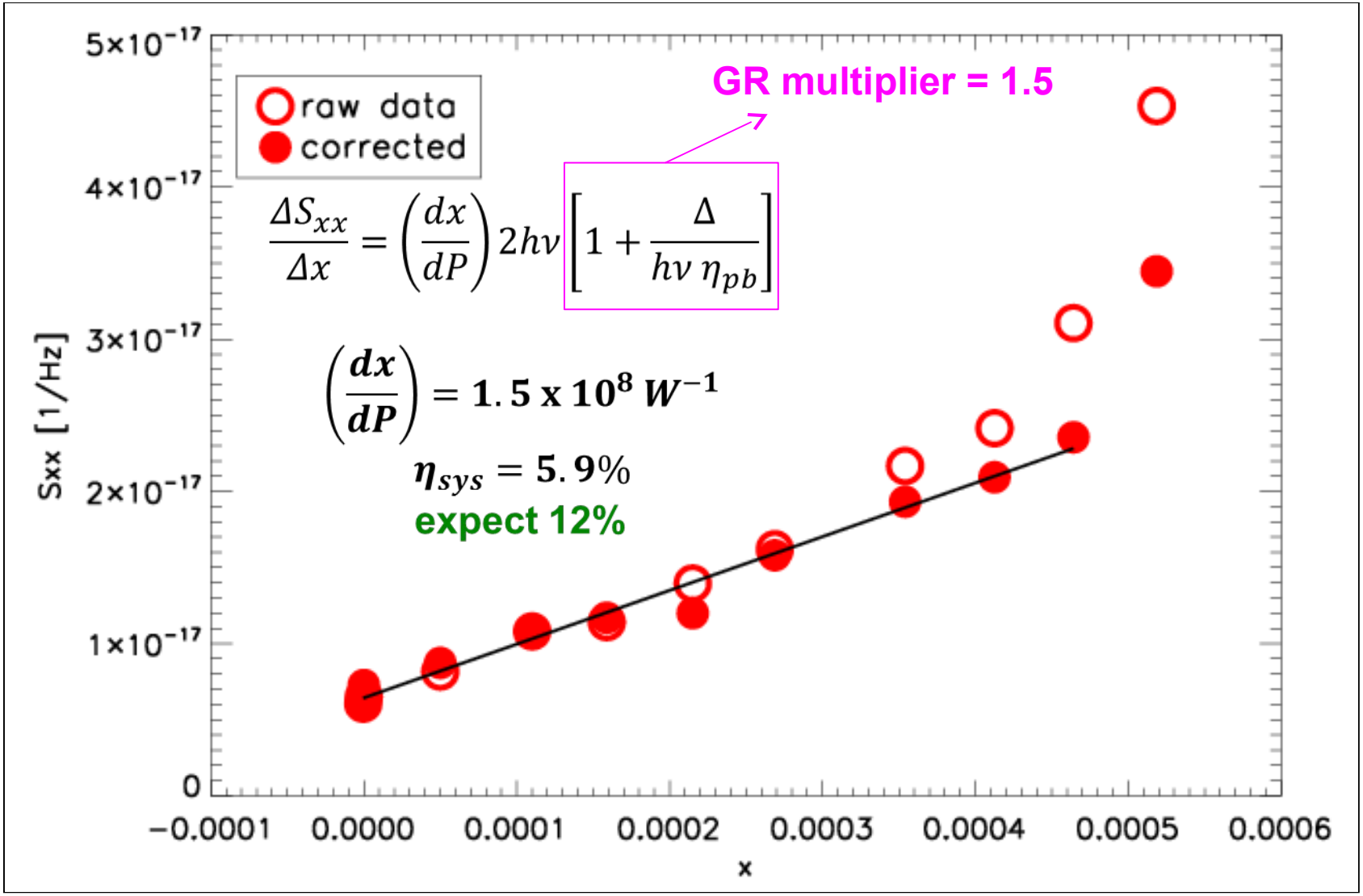
Close to linear frequency shift with loading



Excess Noise with Loading



Excess Noise with Loading



System NEP and Future Improvements

- Our current R = 250 channels provided $NEP_{TLS}(1Hz) = 5.2 \times 10^{-16}$ $W/Hz^{1/2}$, front of cryostat –> **factor of 16 above NEPγ at CSO**

- Near term improvements –> **factor of 3.4 increase**
  - AR coating lens
  - Adjusting spectrometer coupling strength
  - Dropping Tc from 1.65K to 1.2K

–> factor of 2 better than NEPγ for R = 50!
–> candidate for tomography

- Moderate term improvements –> **factor of >6 increase**
  - Reducing inductor linewidth from 1μm to 0.5μm
  - Anomalous factor of 2 in system optical efficiency
  - Thicker capacitor, wider IDC spacing

- Longer term improvements
  - Switching to Tc = 0.8K –> **factor of 2.5 increase**
  - Better dielectric –> **factor of 1.4 increase**

Summary

We've achieved:

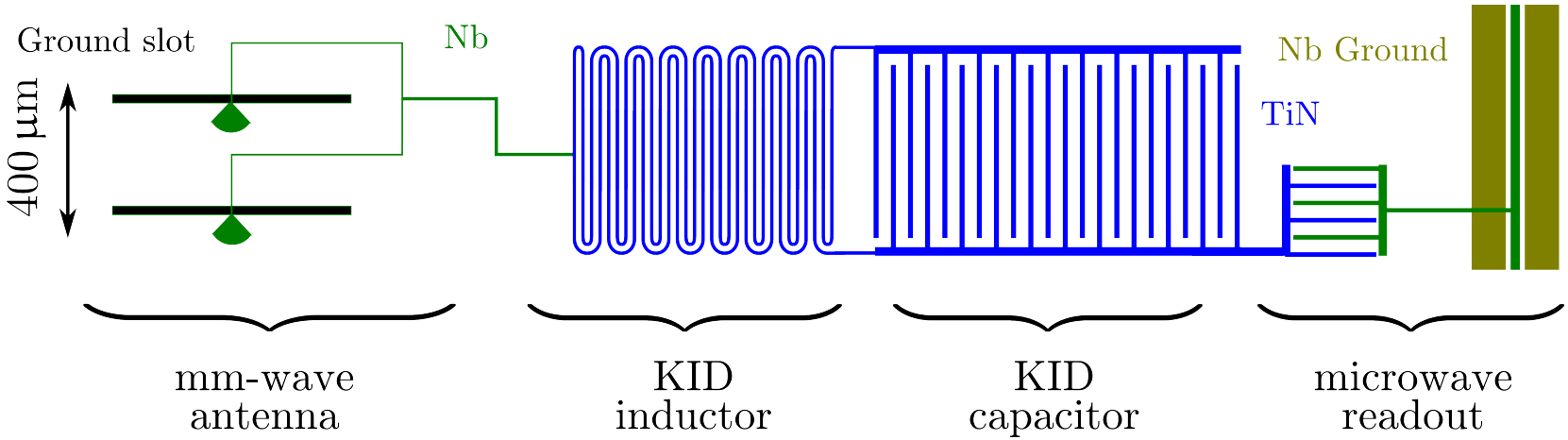
- Working mm-wave filter bank
- Narrow (R~700) channels
- Low out-of-band loading (1 part in 10^4)
- High-Q (>10^5), 100 MHz KIDs
- Background limited operation at R~50
- Hundreds-of-pixel FPGA MUX readout

We're working on:

- New design for higher response
- Understanding TiN response
- Channel placement accuracy
- Lower loss dielectrics for high-R channels

Future directions

- Antenna-coupled mm-wave detectors made at ANL and tested at U. Chicago



- Characterizing response of thin Al and TiN, including single-crystal MBE films

- Kinetic inductance resonator para-amps and transimpedance devices for KID and TES readout.