Probing the dark ages at mm-wavelength KIDs and on-chip spectometers

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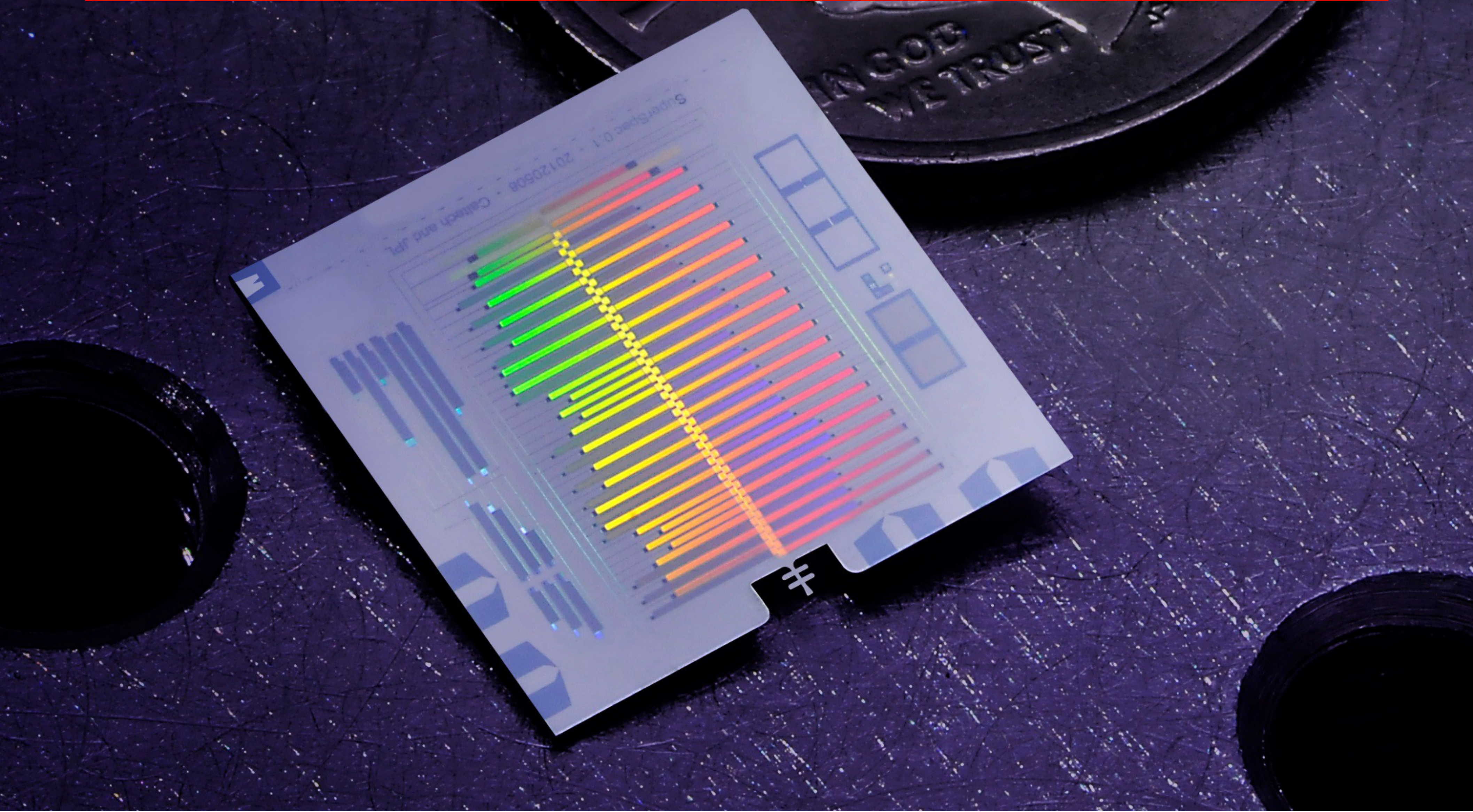
ANL Workshop on Innovative Devices and Systems



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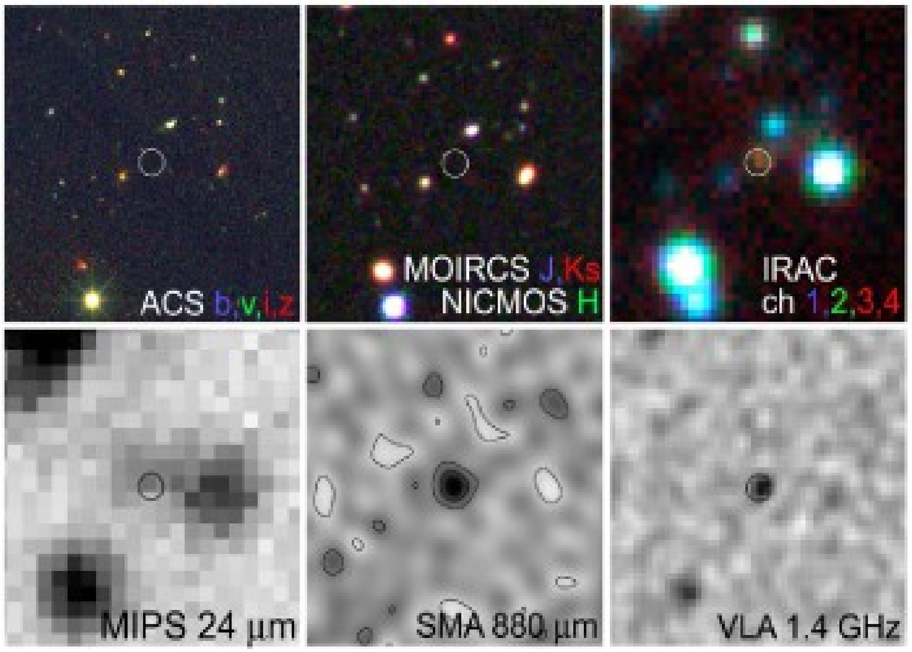
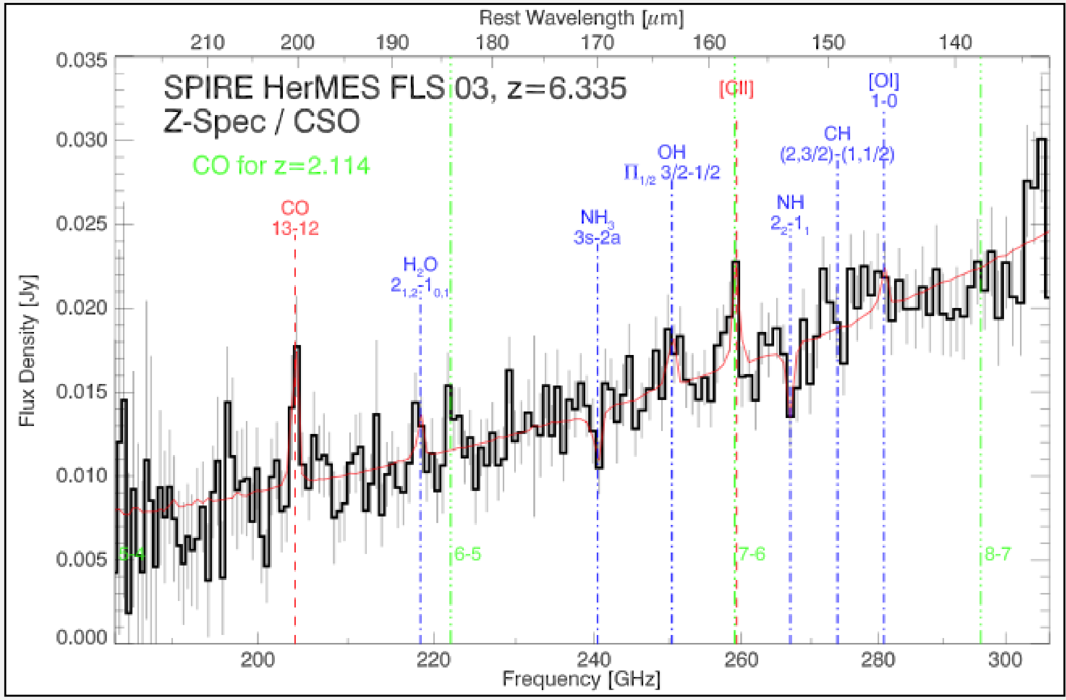
Spectroscopic redshift surveys

- Current and near-future continuum imaging surveys will rapidly discover new populations of Sub-Millimeter Galaxies
- Redshift determination & studies of interstellar medium require spectroscopy of CO, [CII] and other fine-structure lines at mm-wavelength
- A 3 year survey with a 30 – 300 beam instrument such as X-Spec will measure redshifts for thousands of galaxies at z > 3.5



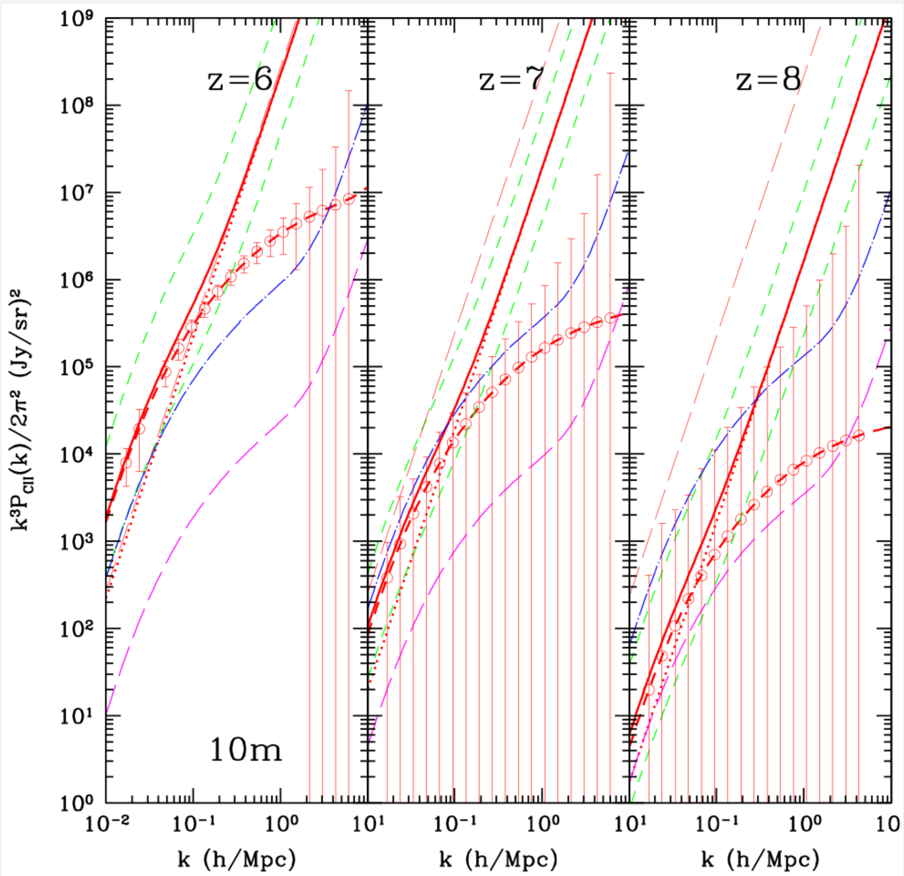
GOODS 850-5; Wang+09

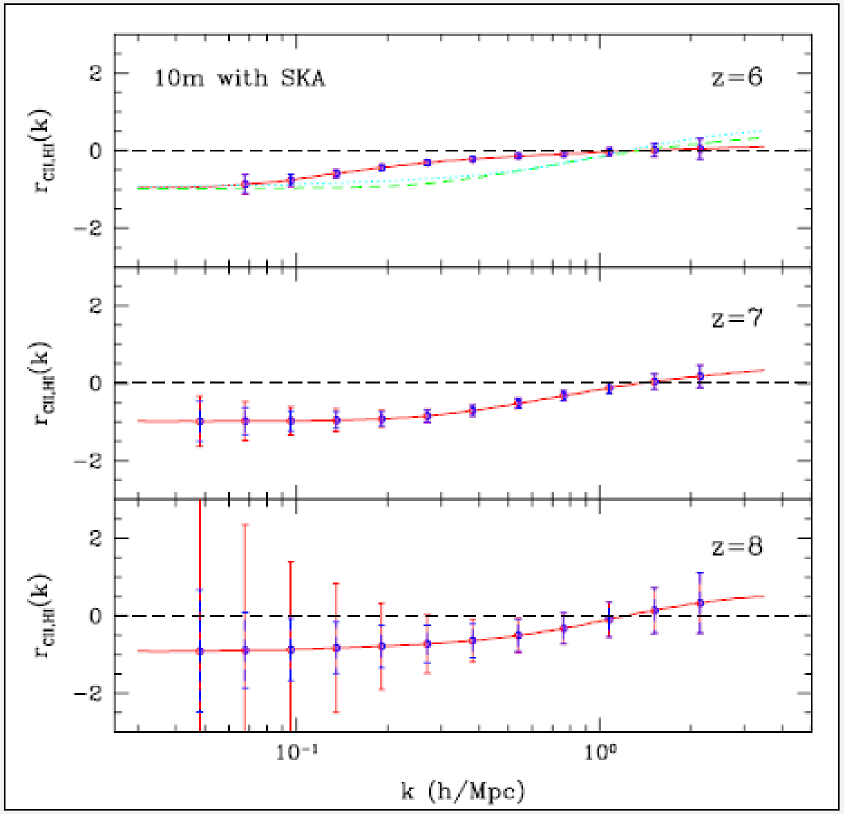


Riechers+13

Tomographic Mapping of [CII] at EoR

- Line intensity mapping of [CII] 158μm during reionization probes
  - Galaxy clustering
  - Mean [CII] intensity and galaxy luminosity function
- Optimum resolving power is R ~ 100





Gong+12

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.

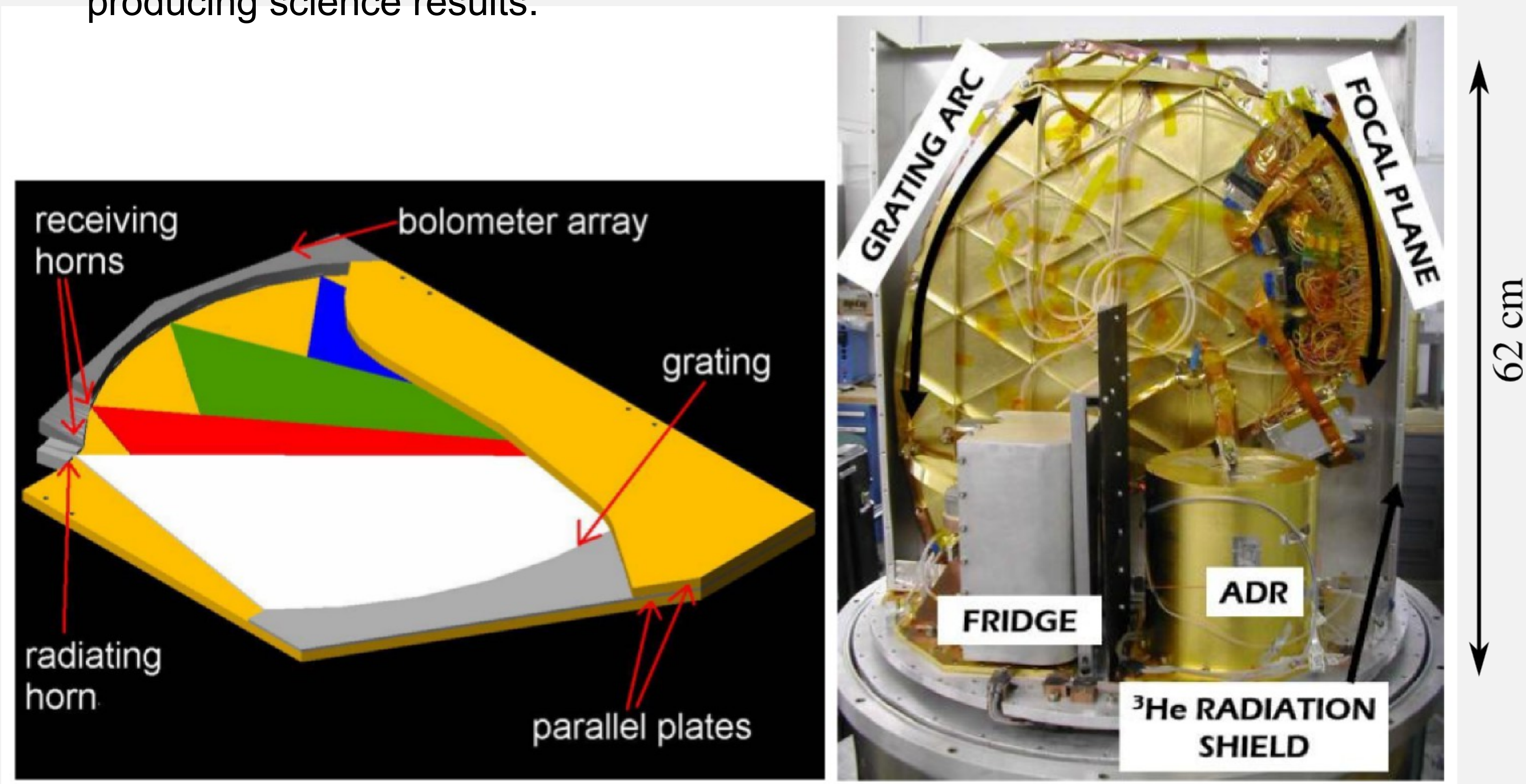
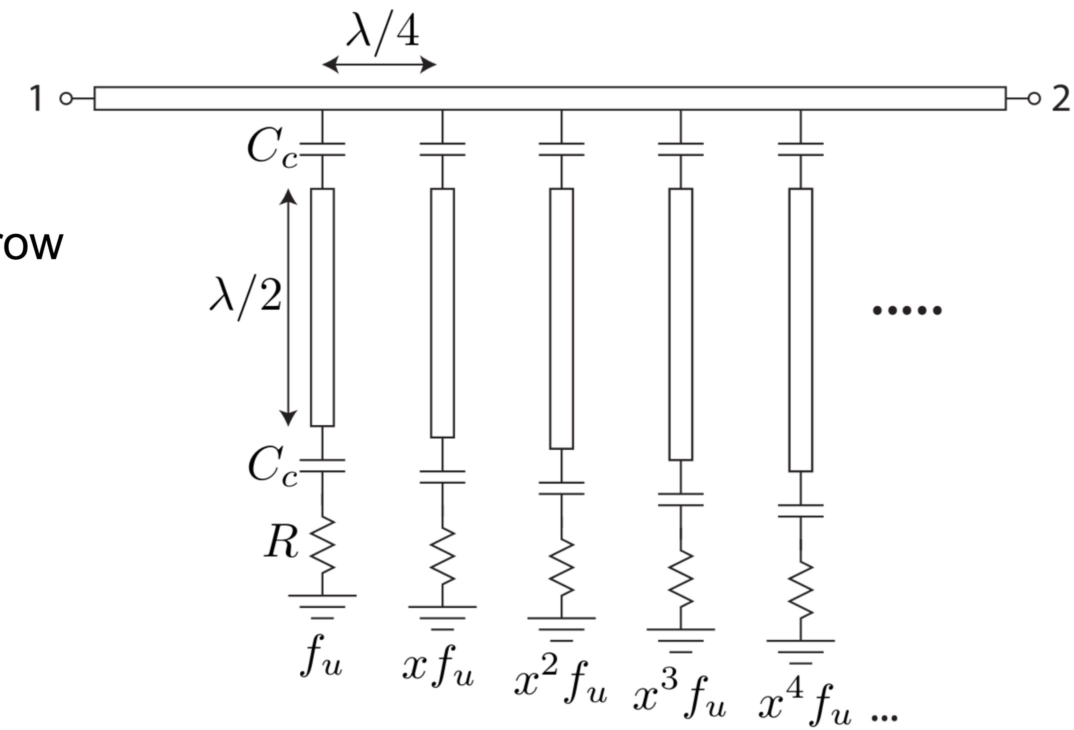


Image: Earle 2006

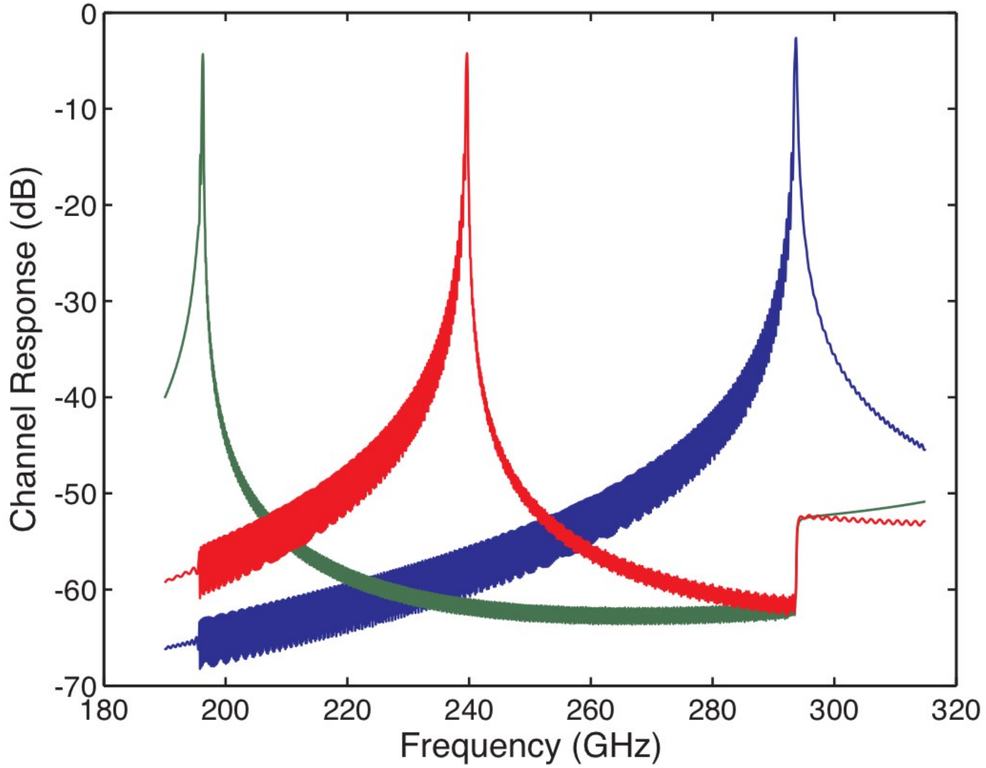
A general filter bank
(or cochlear) spectrometer:

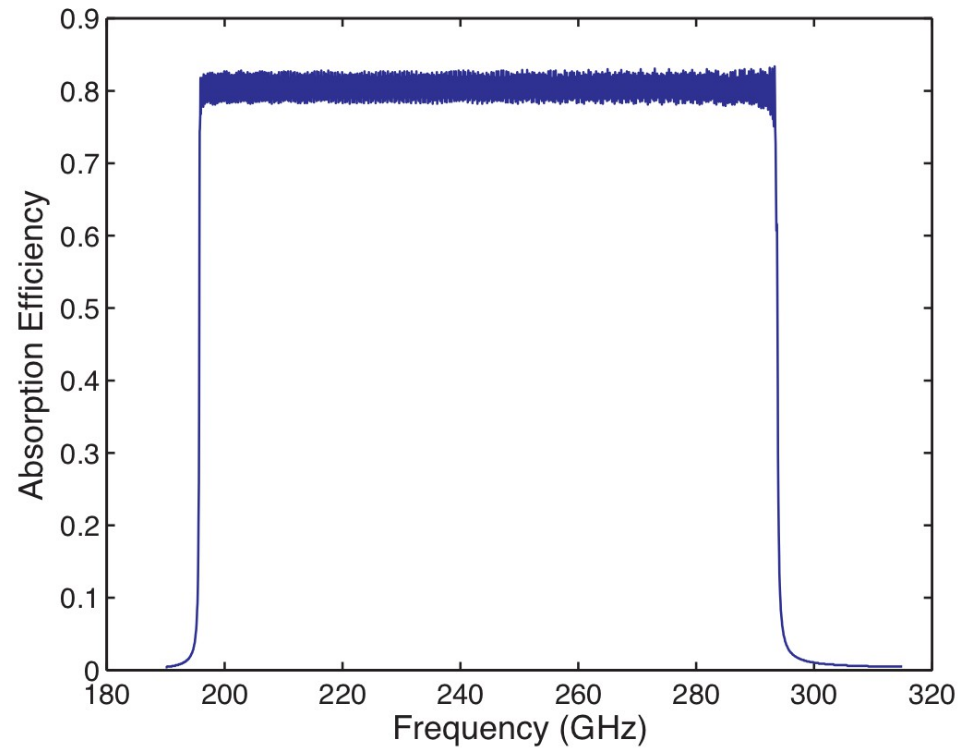


Incoming radiation is sorted by narrow band filters

Each channel couples to a power detector

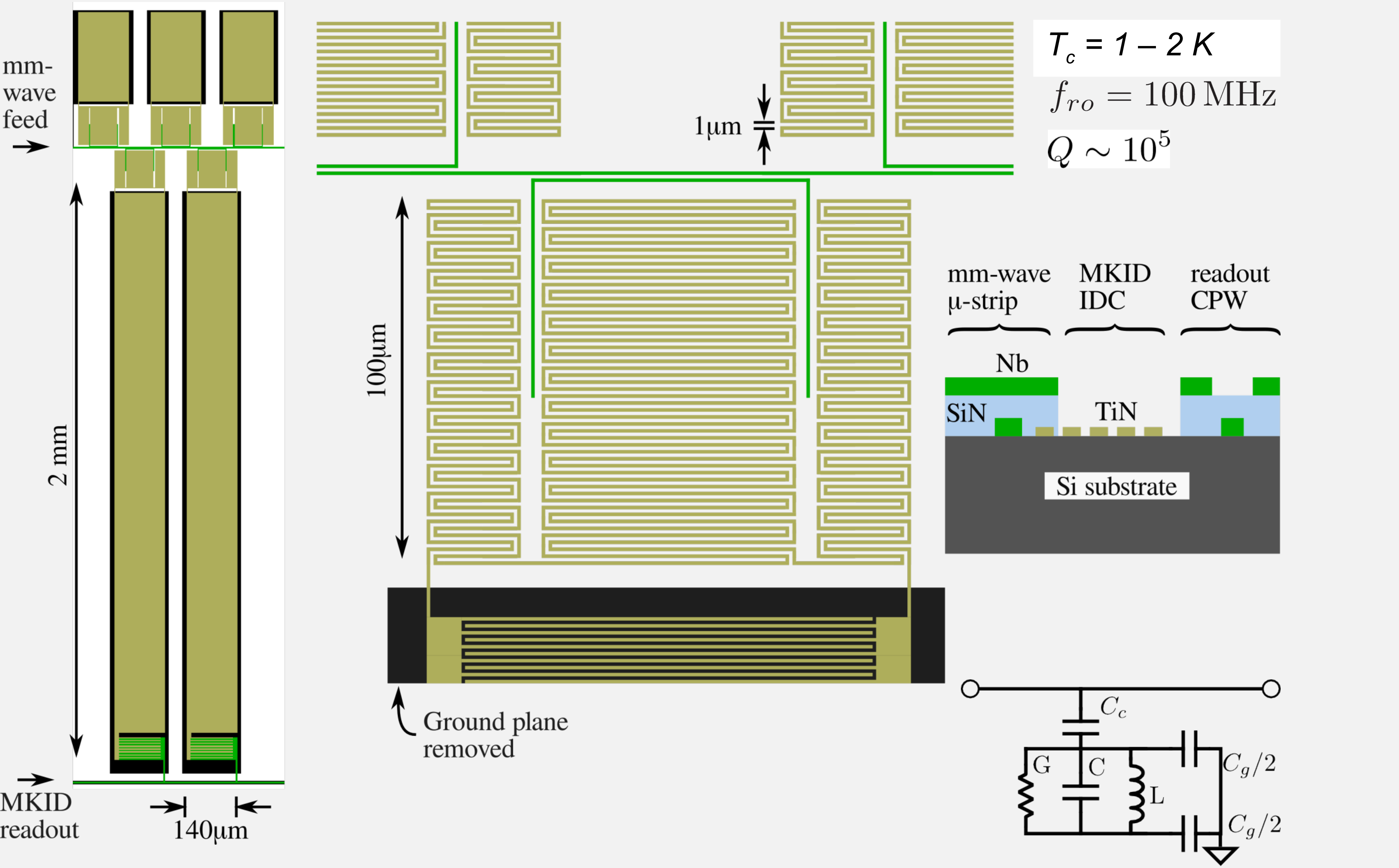
Channel width and spacing are independently adjustable





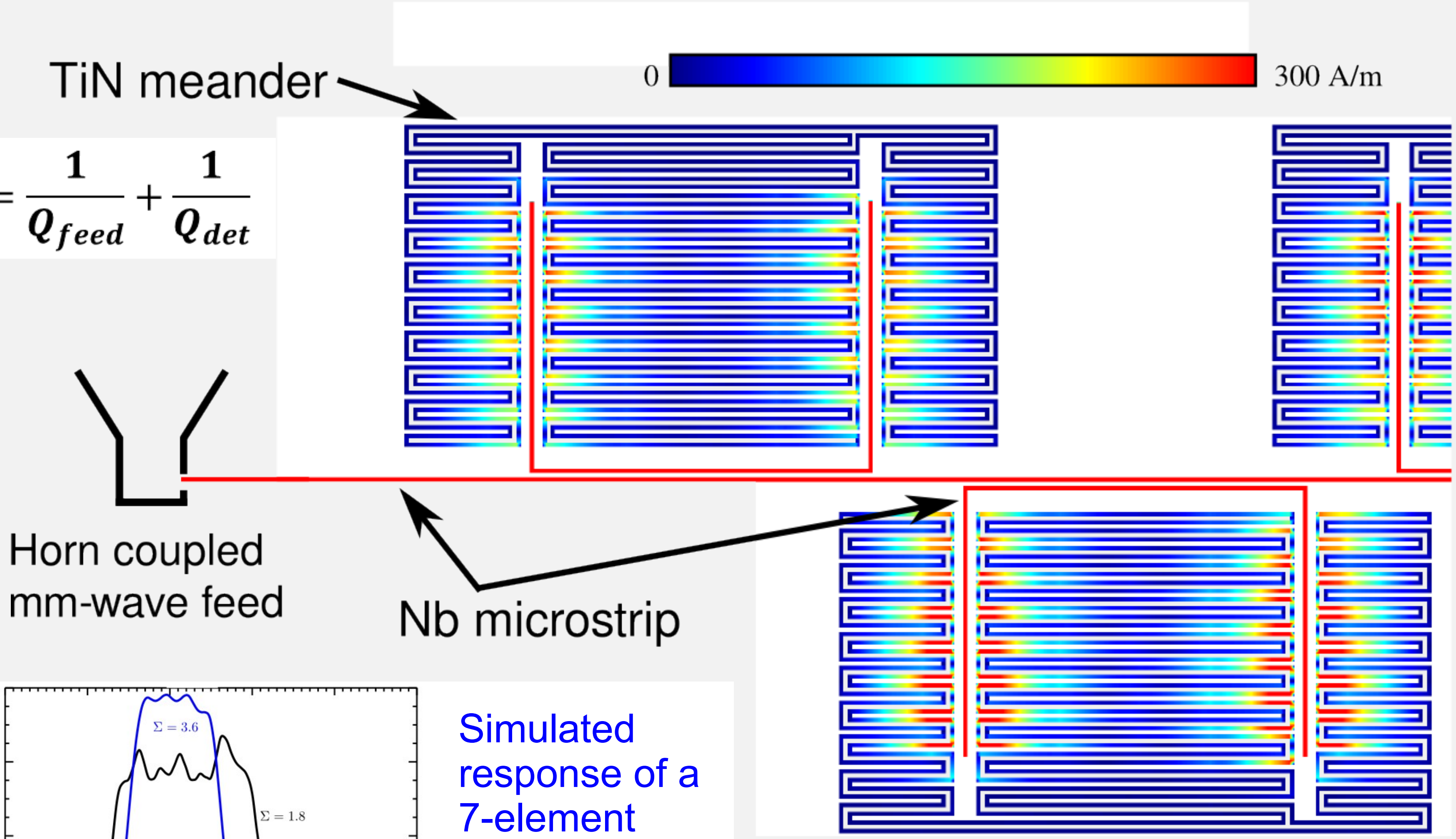
From Kovacs and Zmuidzinas, internal memo

SuperSpec first generation design

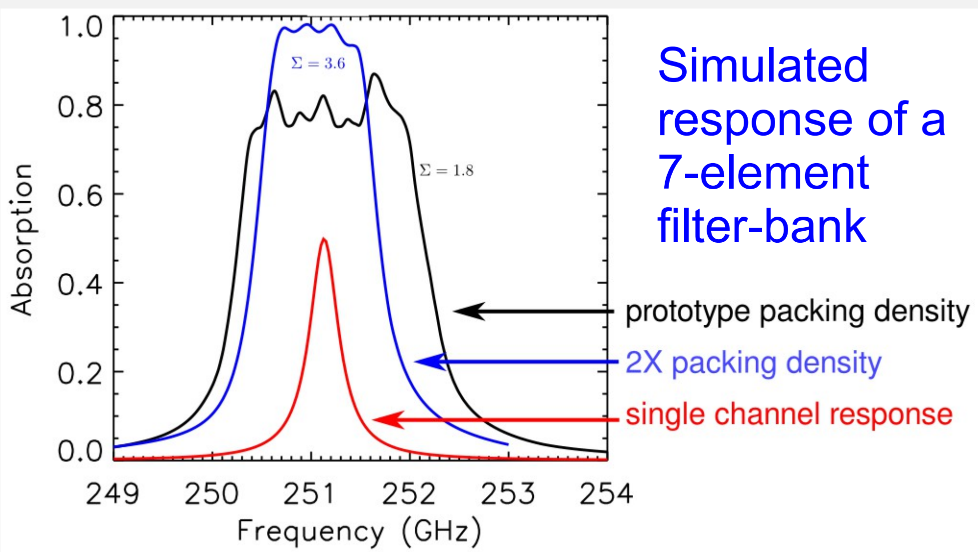


Sonnet Simulations

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



Simulated current at one mm-wave frequency



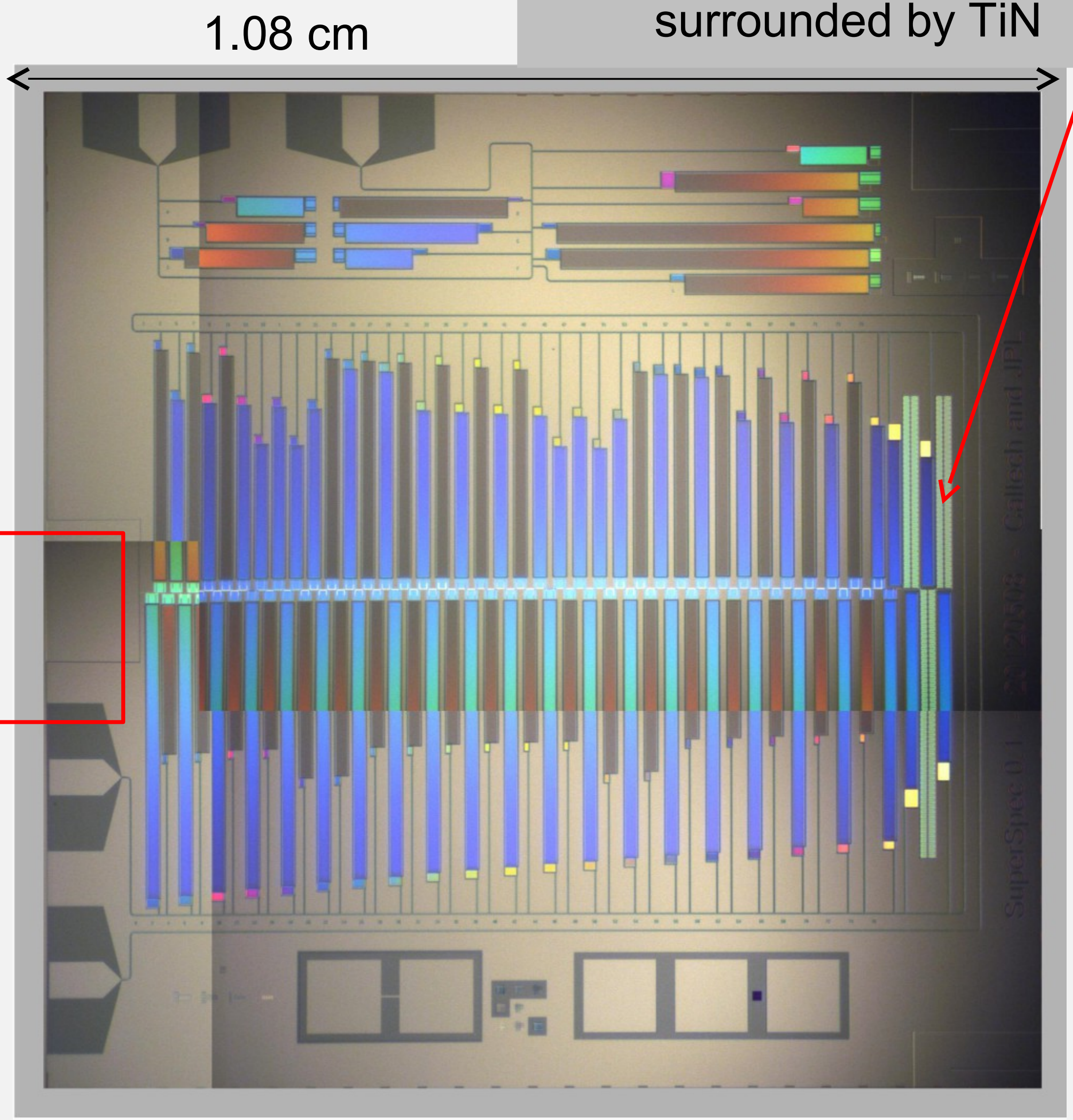
Gen1 Chip

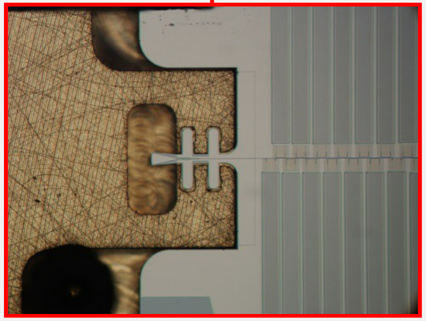
73 spectral channels
- f_0 = 200 – 300 GHz
- Q = 300 – 1400

8 broad-band absorbers

~95% optically active

Terminate with long section of meandered feedline surrounded by TiN

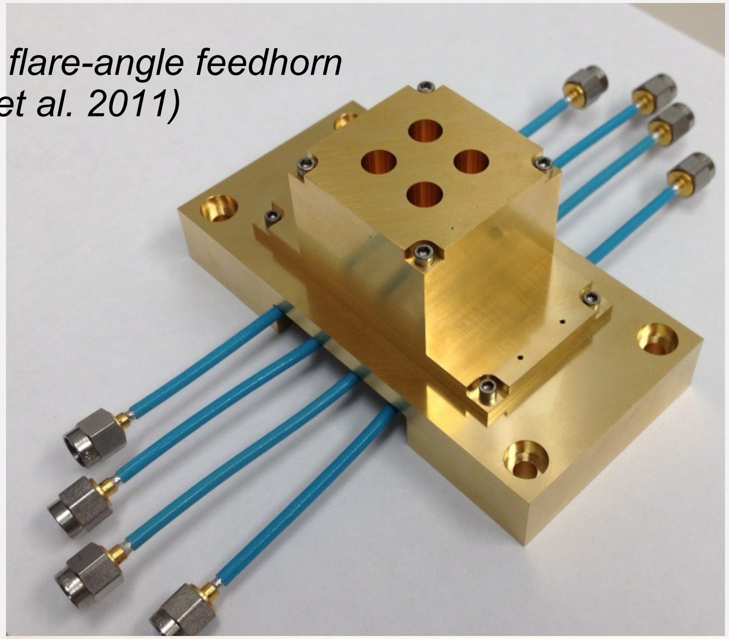


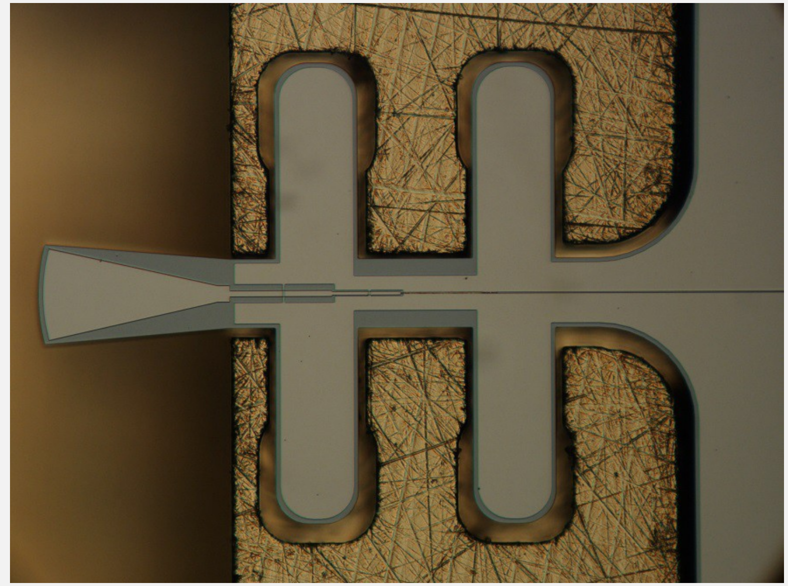


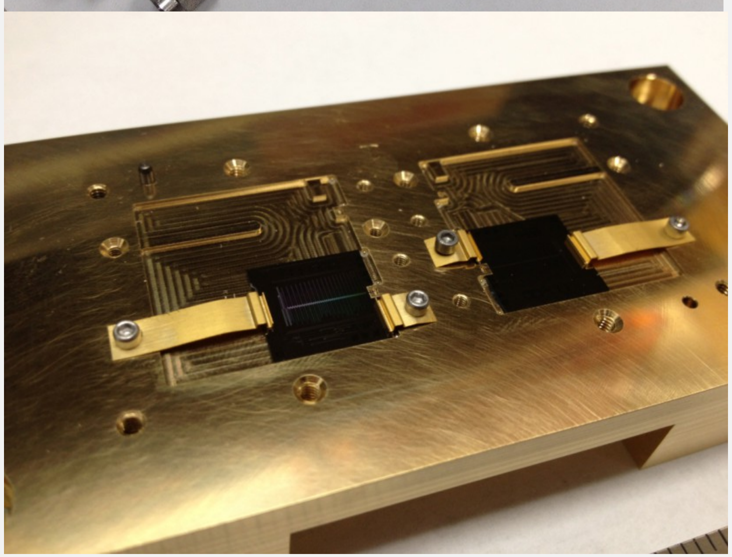
probe-fed waveguide on 25 μm SOI device layer

Gen1 Probe-Fed Waveguide and Horn

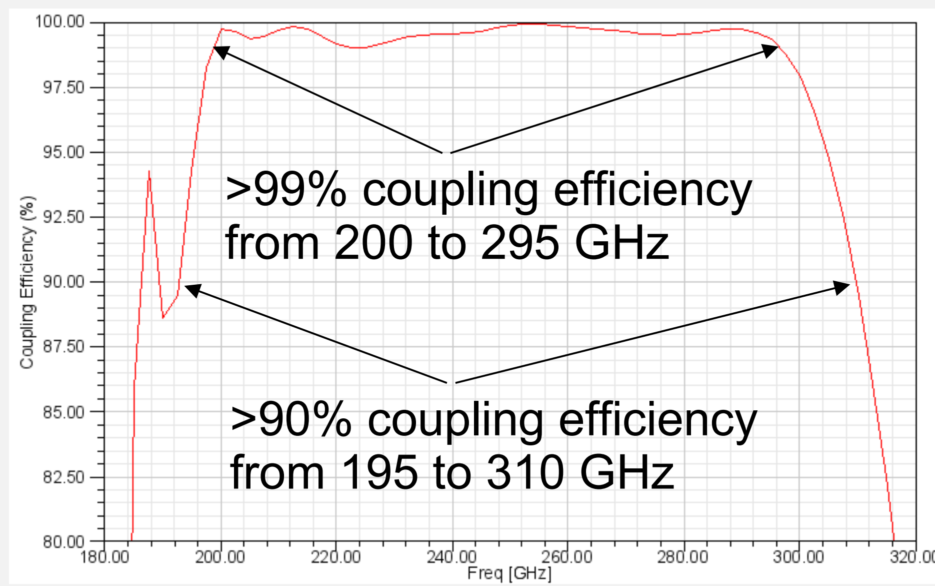
Multiple flare-angle feedhorn (Leech et al. 2011)



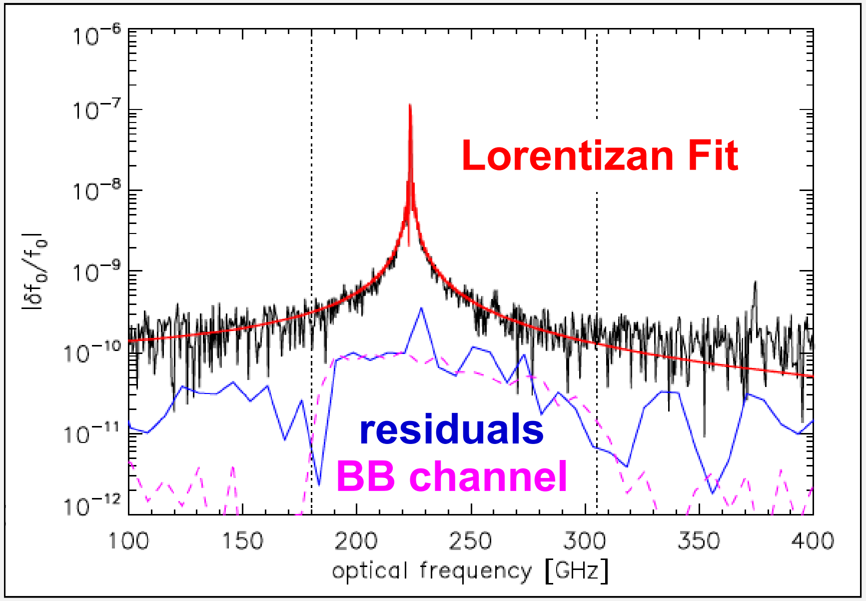




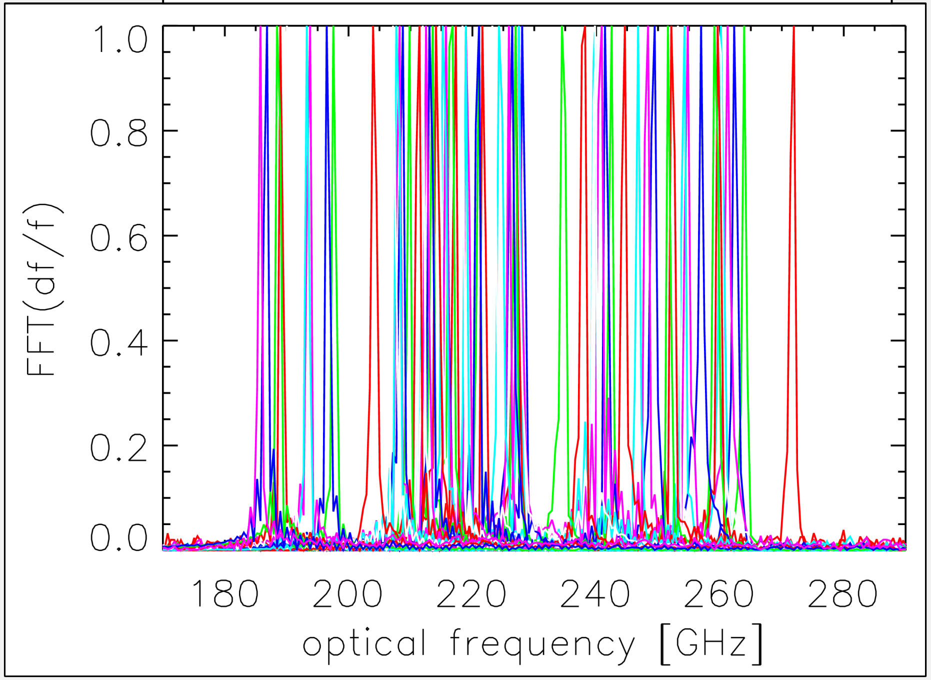
Design and images by T. Reck



FTS Measurements

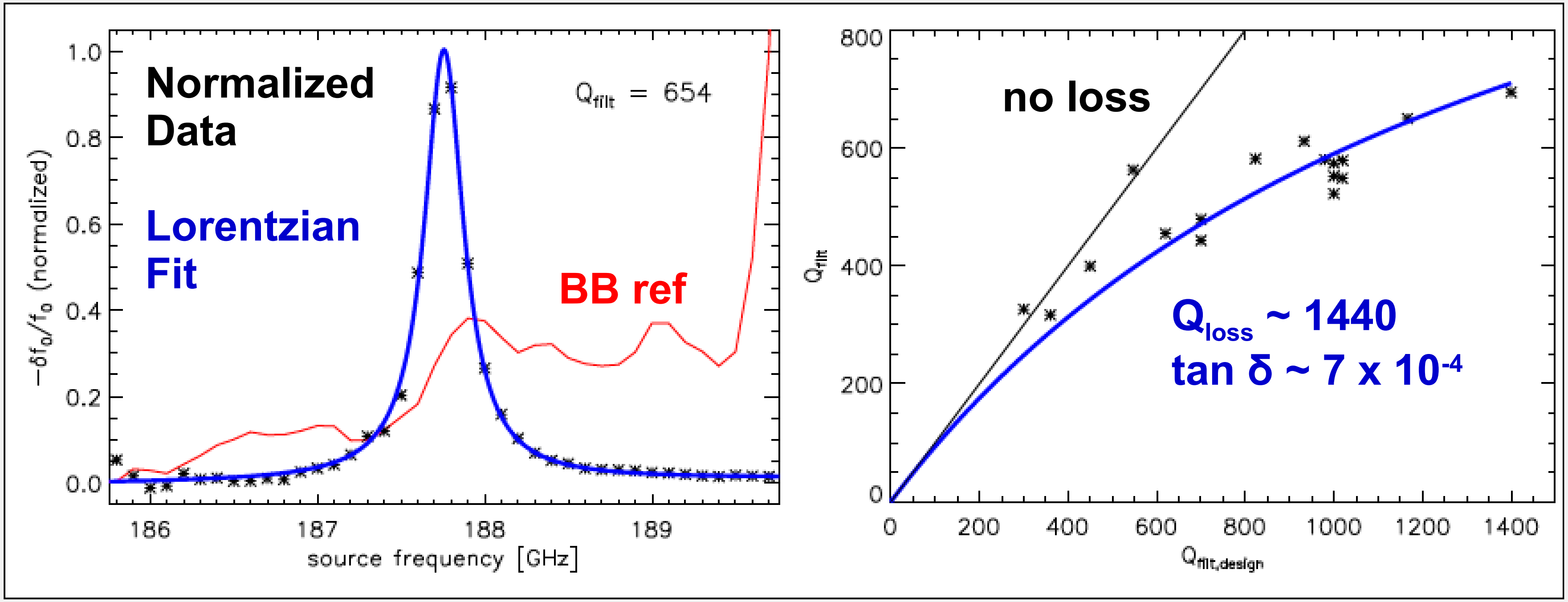


Normalized profiles of 71 spectral channels readout in parallel



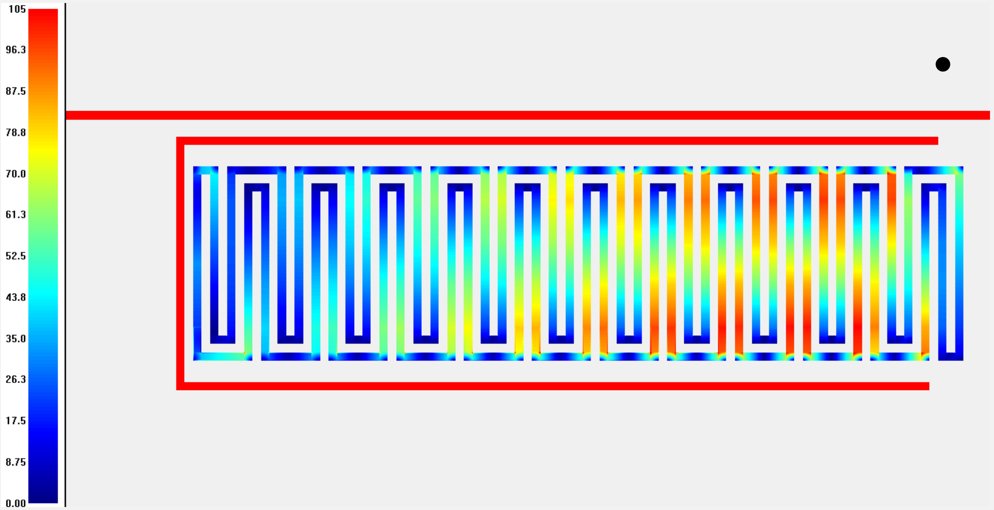
- Full band spectra measured with CASPER-ROACH based FPGA readout system (same system deployed by MAKO/CSO)
- Residual out of band response typically 30dB below peak
- Channel center placement has 2 – 3% scatter – partially systematic with frequency, Q, location in filter bank
- Too large to be errors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

Coherent Source Measurements

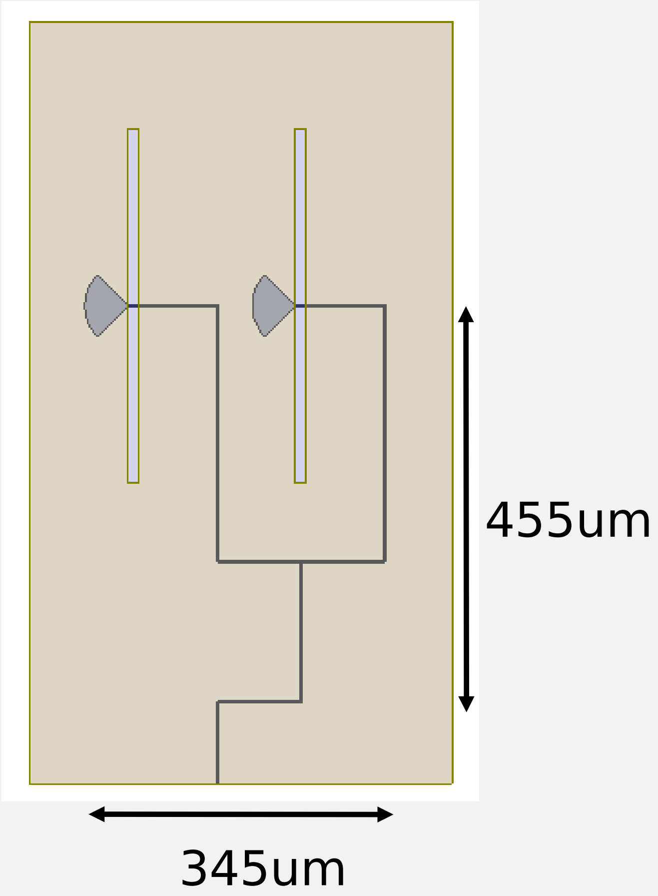


- Spectral response characterized using a swept coherent source
- Normalize response with near simultaneous measurements of BB ref channel – well described by Lorentzian
- Comparison of designed and measured Q indicates a source of loss characerized by Q_{loss} ~ 1440 --> likely SiN_x ILD in microstrip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

Gen2 – Improved NEP and diagnostics

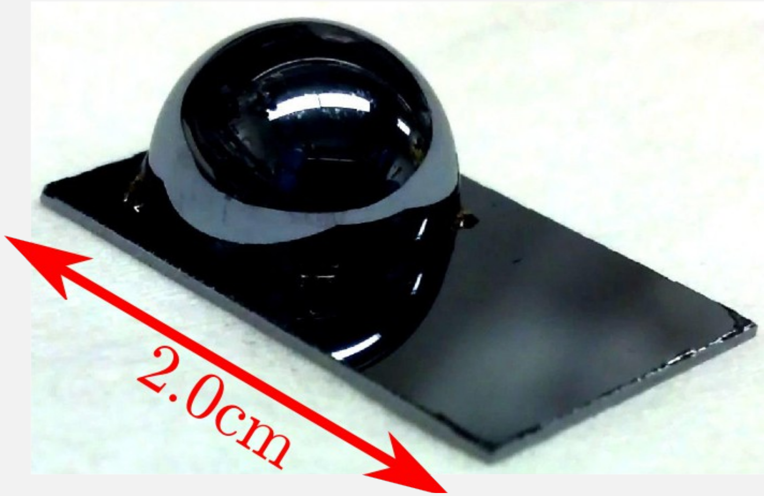


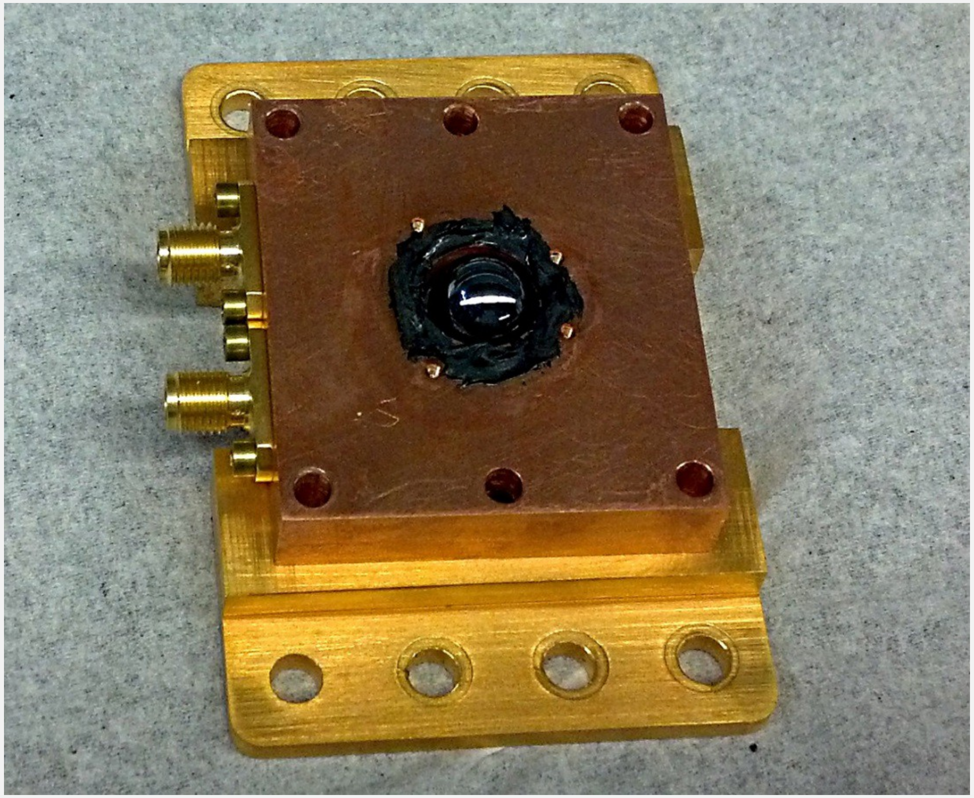
- Modifications to boost sensitivity
  - Shrink inductor volume by x5
  - More uniform current density
  - Wider IDC spacing

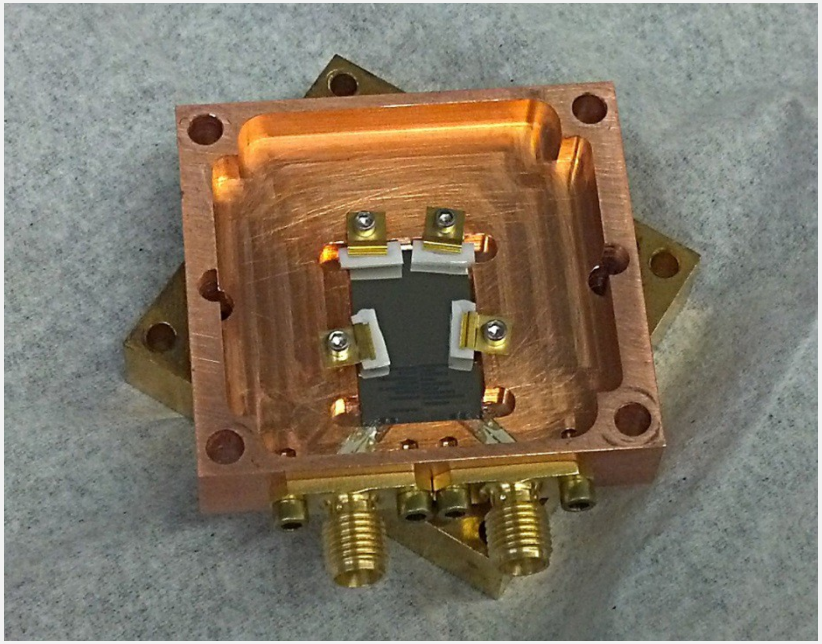


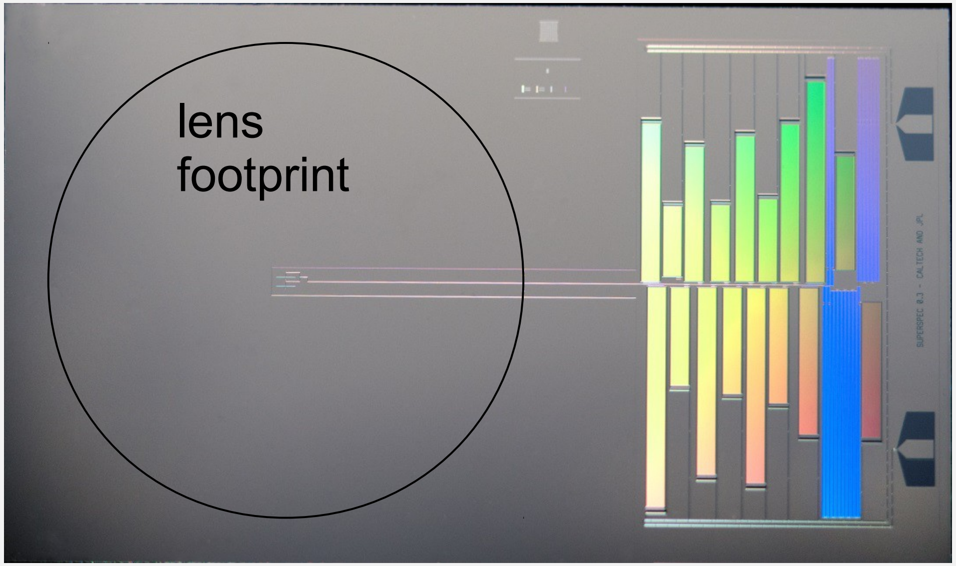
- Modifications to improve diagnostics
  - Simpler planar antenna + hyper-hemispherical lens
  - BB detectors couple to a longer section of the feedline, comparable to a wavelength in length
  - Small number (10) of isolated spectral channels
  - Dark channel

Gen2 Packaging



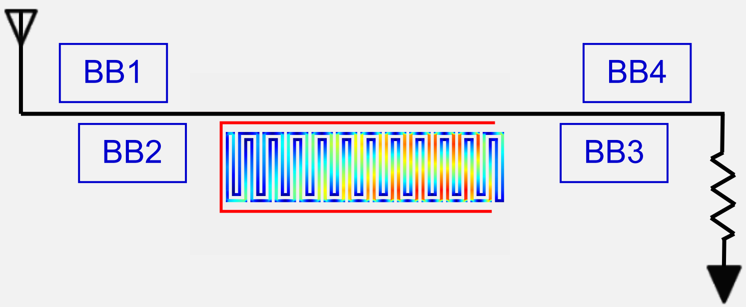






Sockout Measurement

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

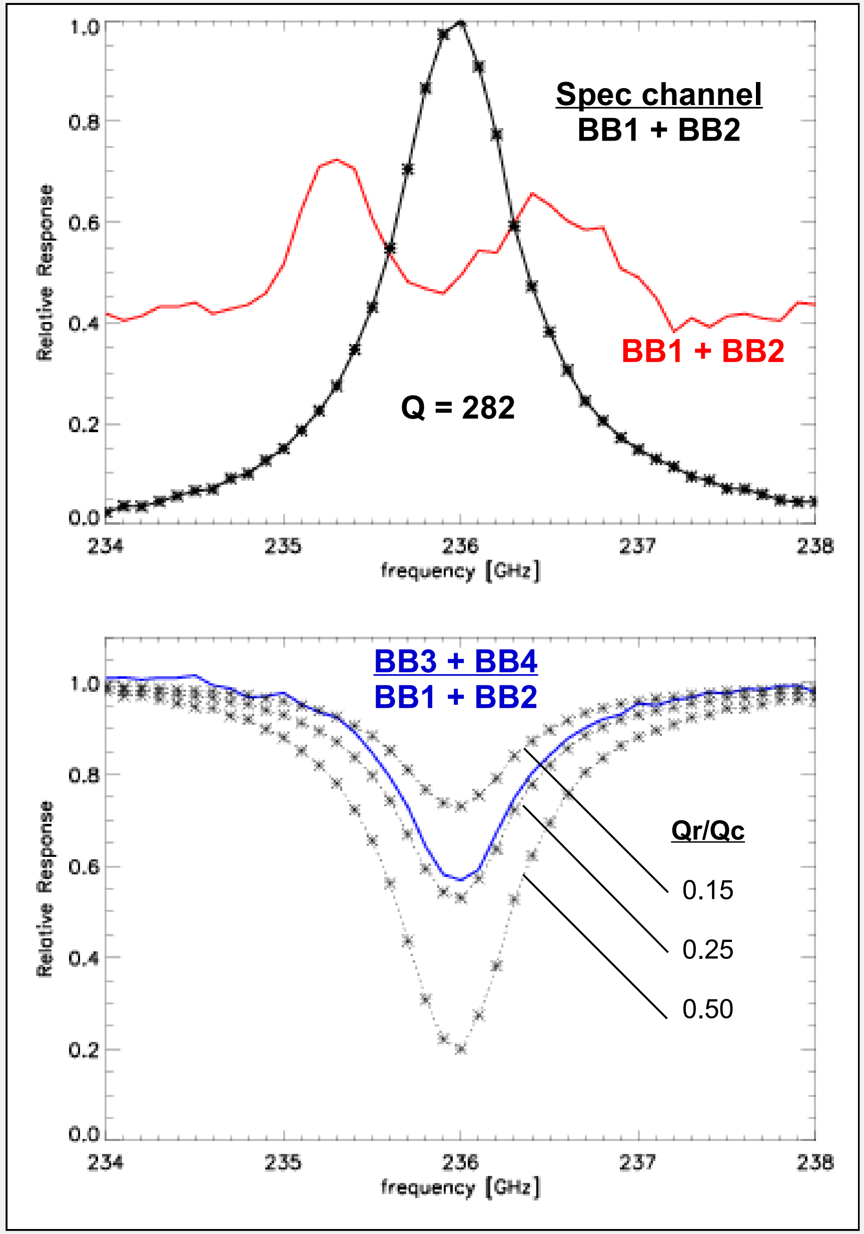


Modeling indicates
- Qr/Qc ~ 0.25
- Absorbed fraction ~ 37%

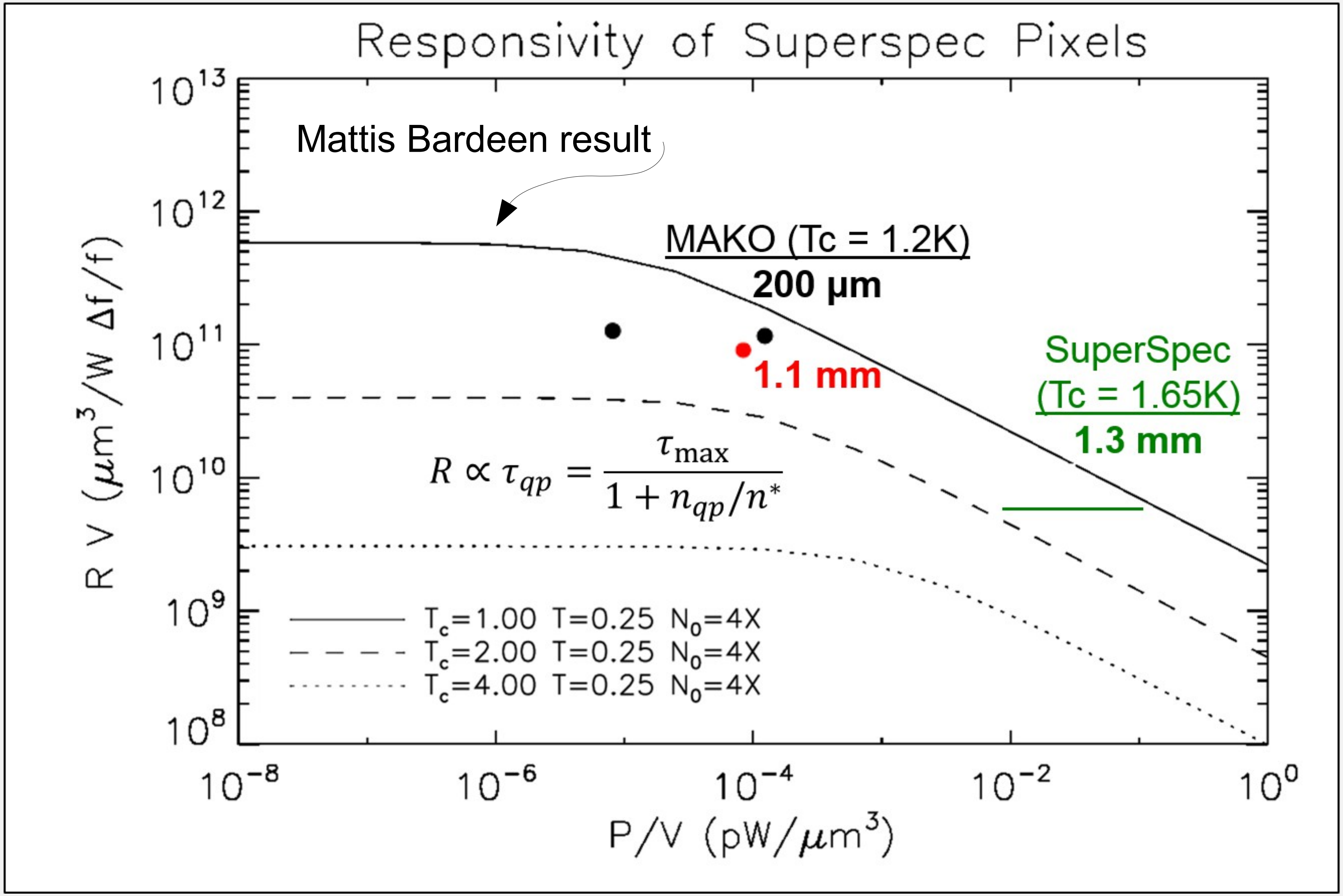
With Q_{loss} = 1440

- Detected fraction ~ 28%

- Can achieve ~ 34% with R = 250, adjusted dimensions

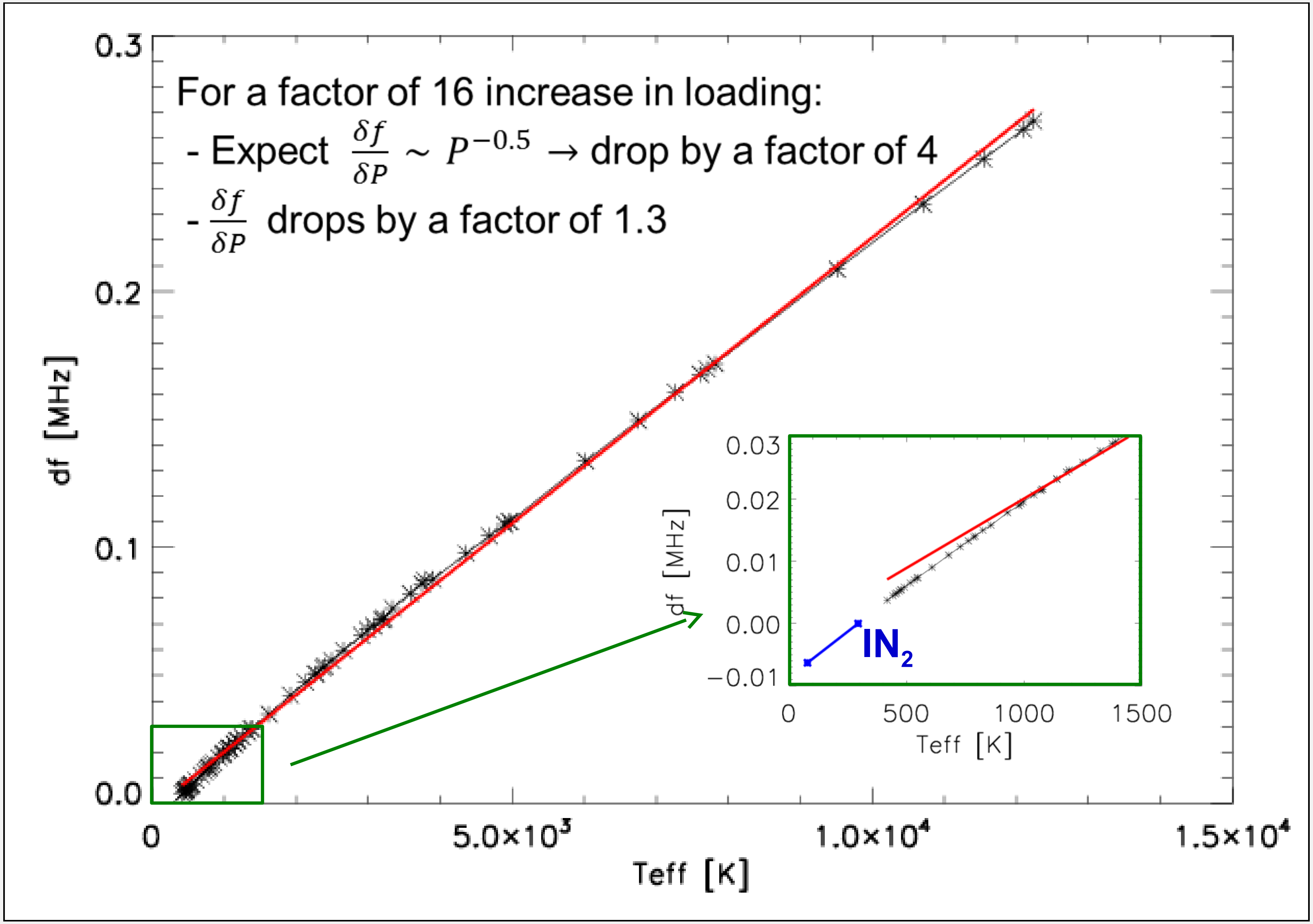


RV vs P/V plot

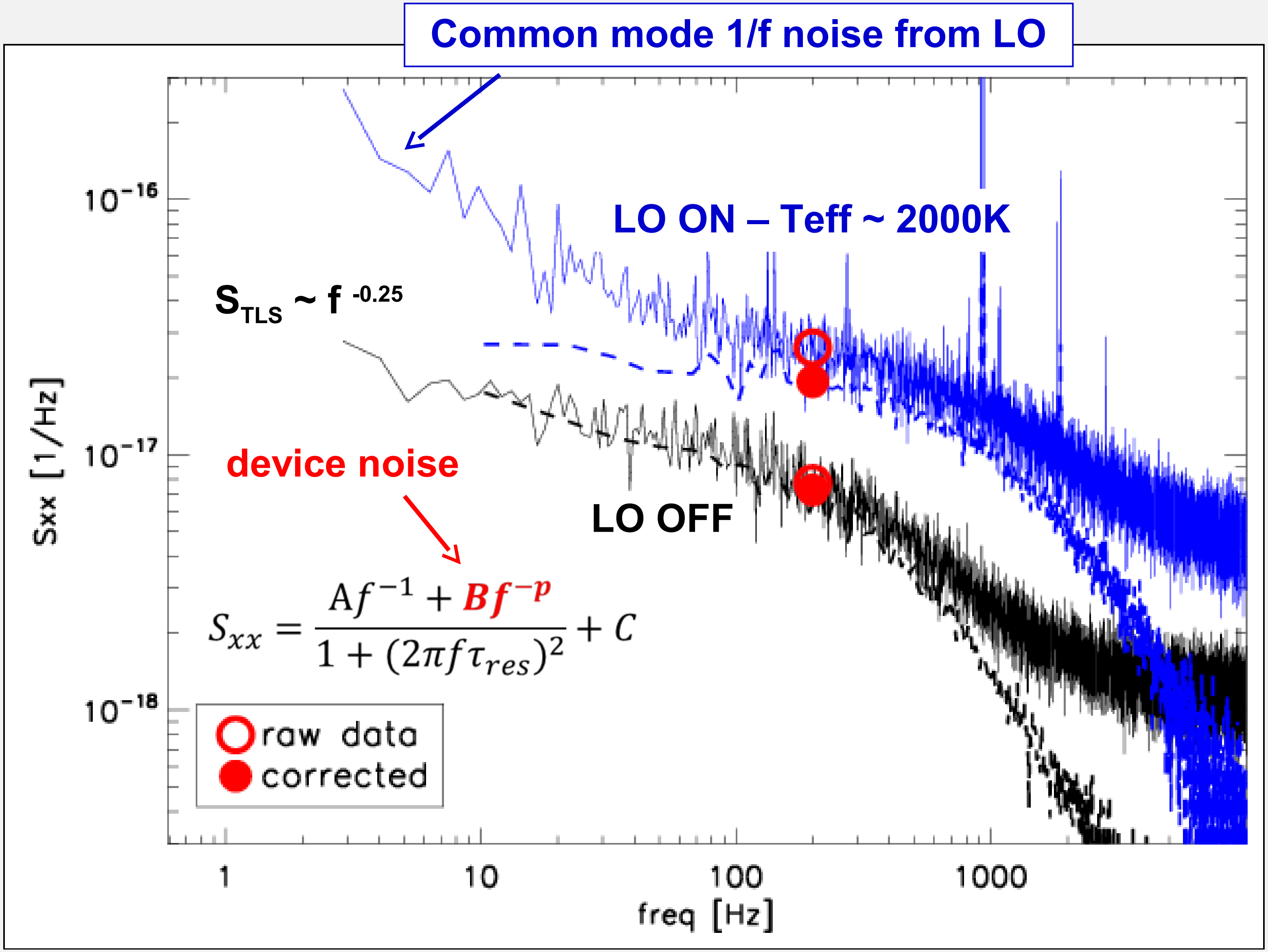


Responsivity of Superspec Pixels
Mattis Bardeen result
MAKO (Tc = 1.2K)
200 μm
1.1 mm
SuperSpec
(Tc = 1.65K)
1.3 mm
$R \propto \tau_{qp} = \frac{\tau_{\max}}{1 + n_{qp}/n^*}$
T_c=1.00 T=0.25 N_0=4X
T_c=2.00 T=0.25 N_0=4X
T_c=4.00 T=0.25 N_0=4X
R V (μm^3/W Δf/f)
P/V (pW/μm^3)
10^{13}
10^{12}
10^{11}
10^{10}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

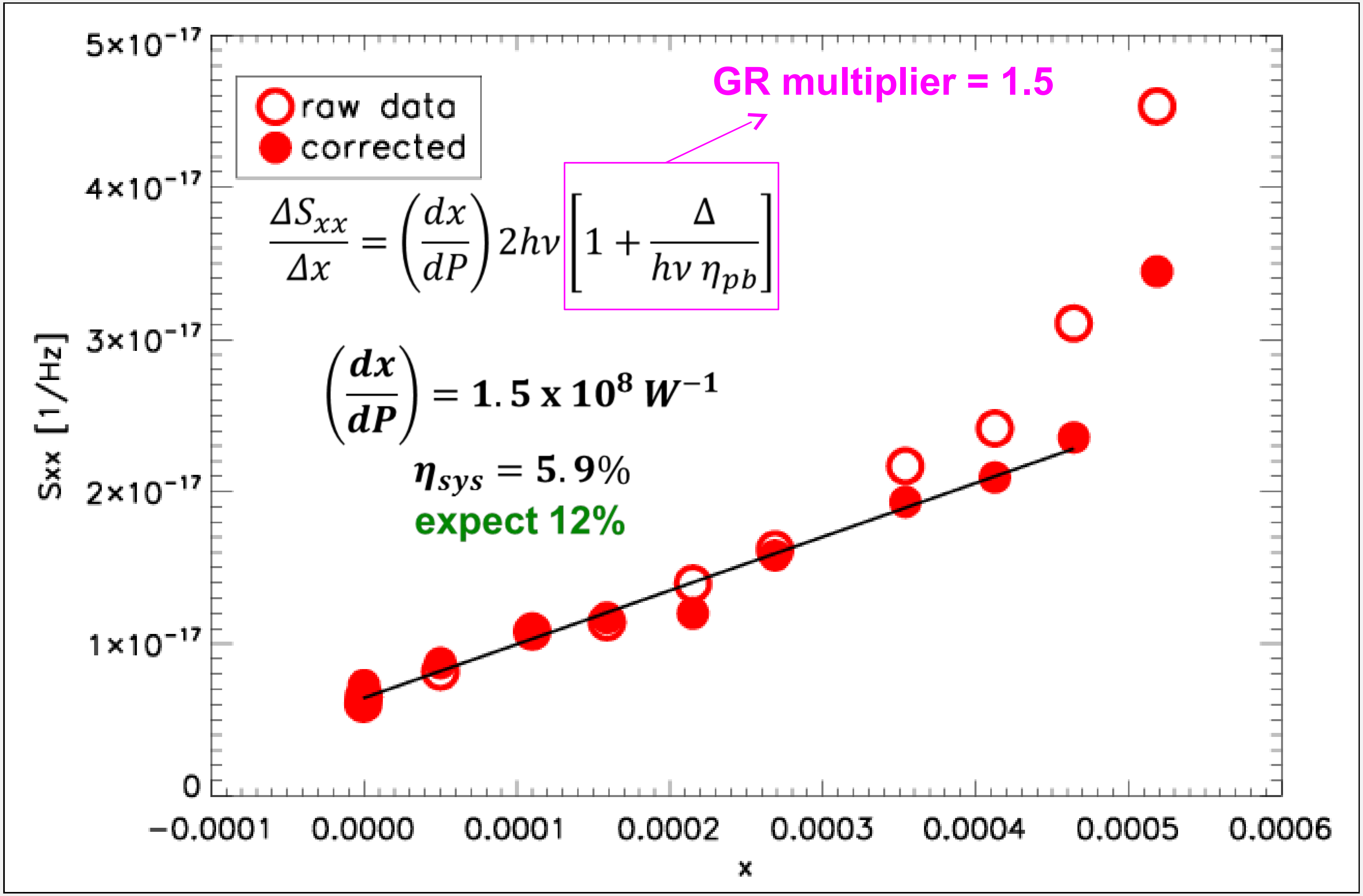
Close to linear frequency shift with loading



Excess Noise with Loading



Excess Noise with Loading



System NEP and Future Improvements

- Our current R = 250 channels provided NEP_{TLS}(1Hz) = 5.2 x 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:

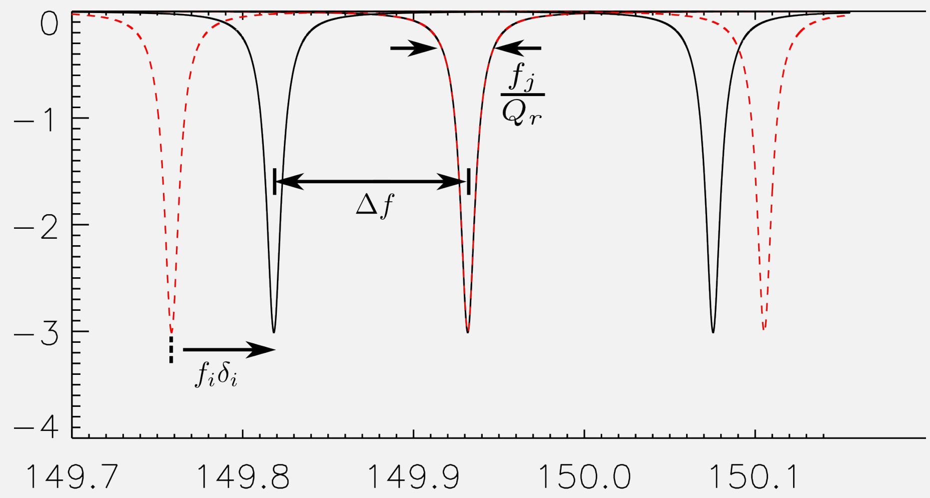
- New design for higher response
- Understanding TiN response
- Channel placement accuracy
- Lower loss dielectrics for high-R channels

Extra Slides Follow

Multiplexing requirements set minimum value of Qi.

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

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



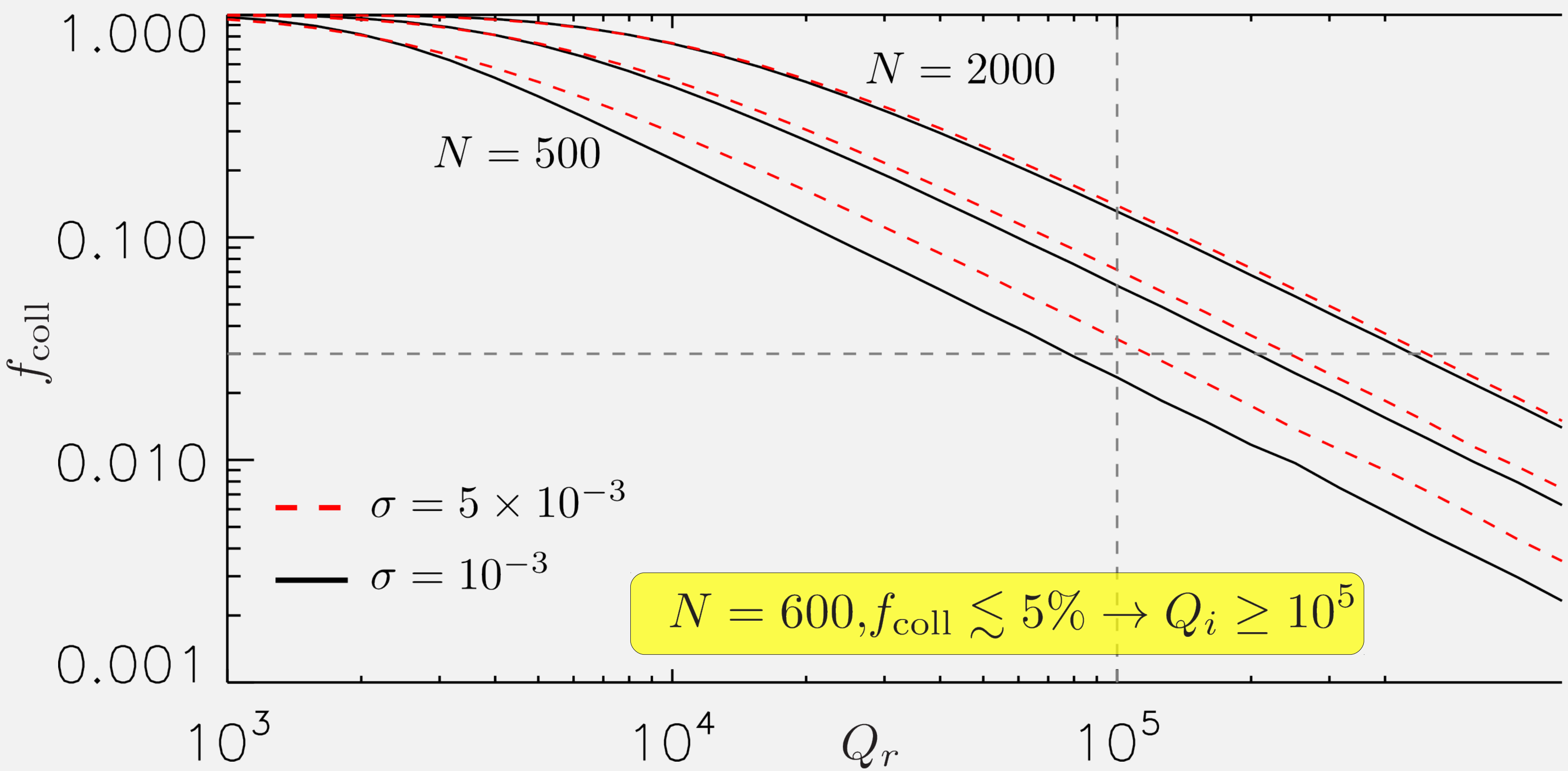
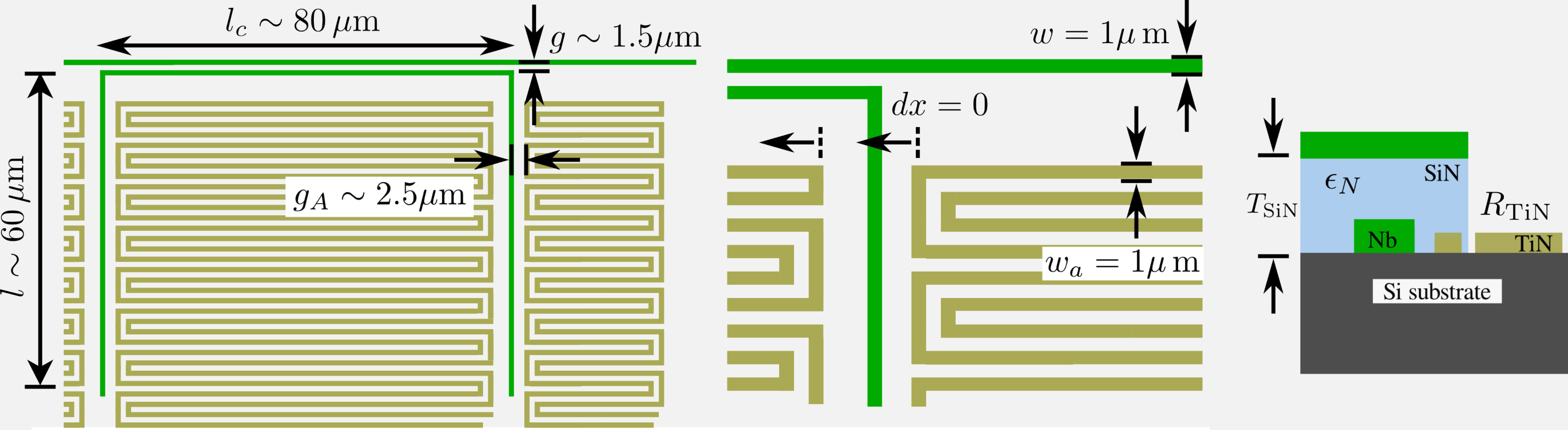


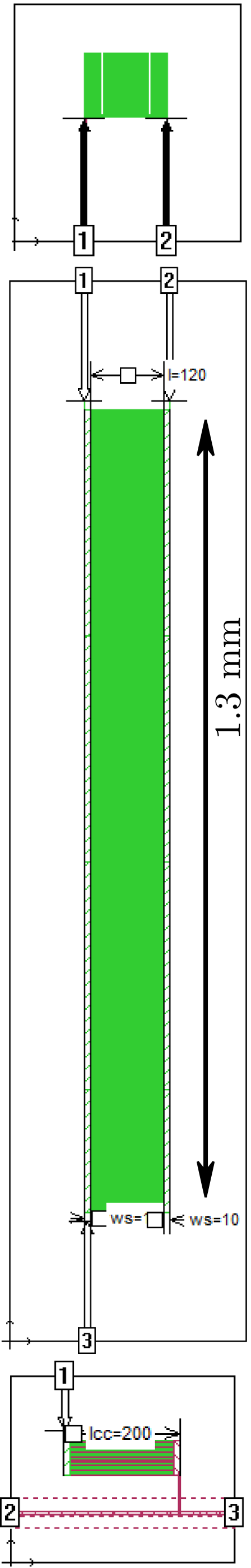
Figure based on Zmuidzinas internal memo

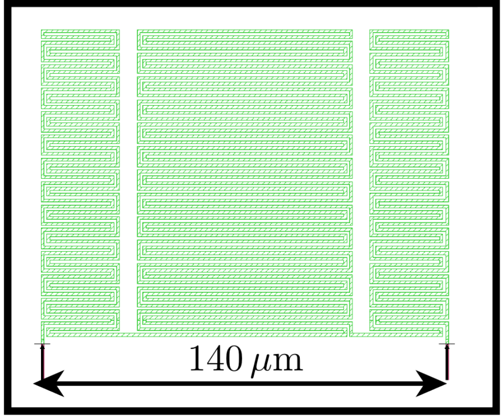


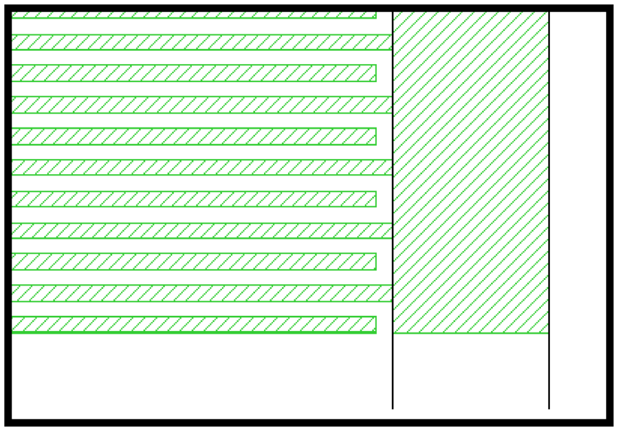
Tolerances for an R = 700 μ-strip resonator on 0.5μ silicon nitride

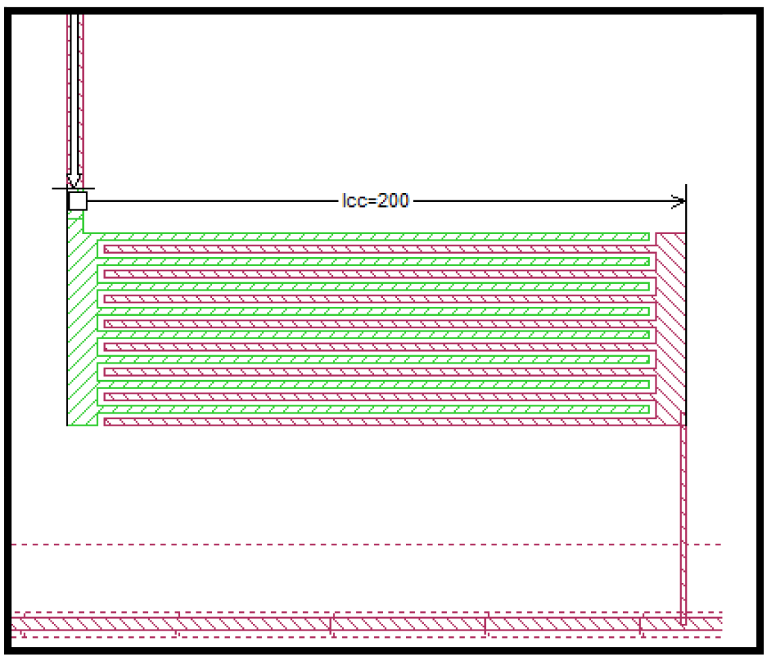
				Fractional change in			
	variable	**description**	**change**	**Freq**	**Qi**	**Qc**	**Qr**
Lithography	l	resonator length	$0.1\ \mu m$	1×10^{-3}	–	–	–
	g	feed to reso gap	$0.1\ \mu m$	8×10^{-5}	–	0.19	0.09
	g_A	absorber to reso gap	$0.1\ \mu m$	4×10^{-5}	0.05	–	0.03
	w	Nb line width	$0.1\ \mu m$	3×10^{-3}	0.06	0.11	0.08
	w_A	TiN line width	$0.1\ \mu m$	6×10^{-5}	0.06	–	0.03
	dx	Nb/TiN offset in x	$0.1\ \mu m$	5×10^{-6}	0.006	–	0.003
Materials	$R_{\rm TiN}$	Resistivity	20%	6×10^{-5}	0.03	-	0.02
	ϵ_N	SiN permitivity	10%	0.03	0.20	-0.03	0.09
	T_N	SiN Thickness	10%	2×10^{-3}	0.30	0.40	0.35
	$\tan - \delta$	SiN loss	$+10^{-4}$	–	0.04	–	0.02

$$\frac{\Delta Q_r}{Q_r} \sim 10\%$$

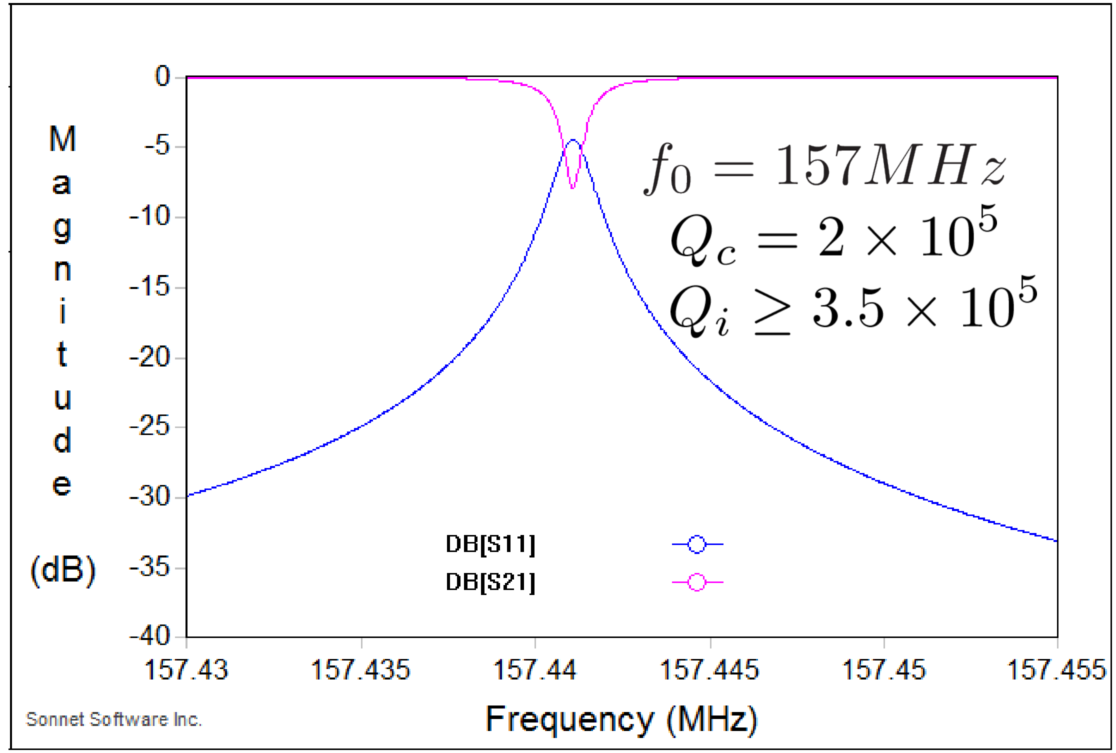


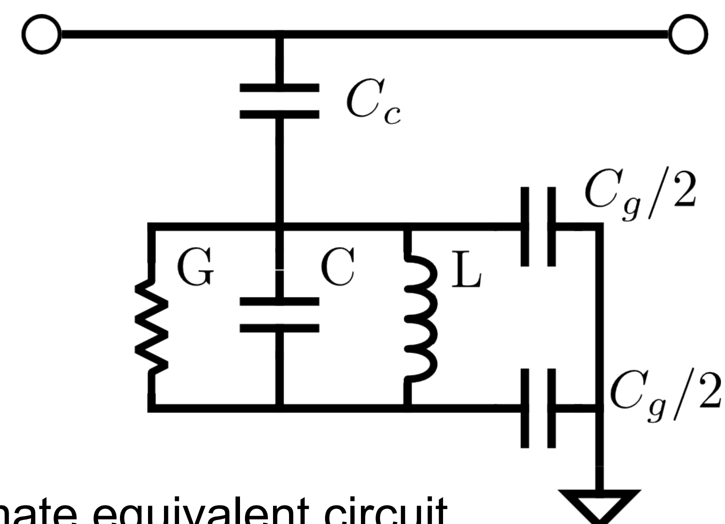






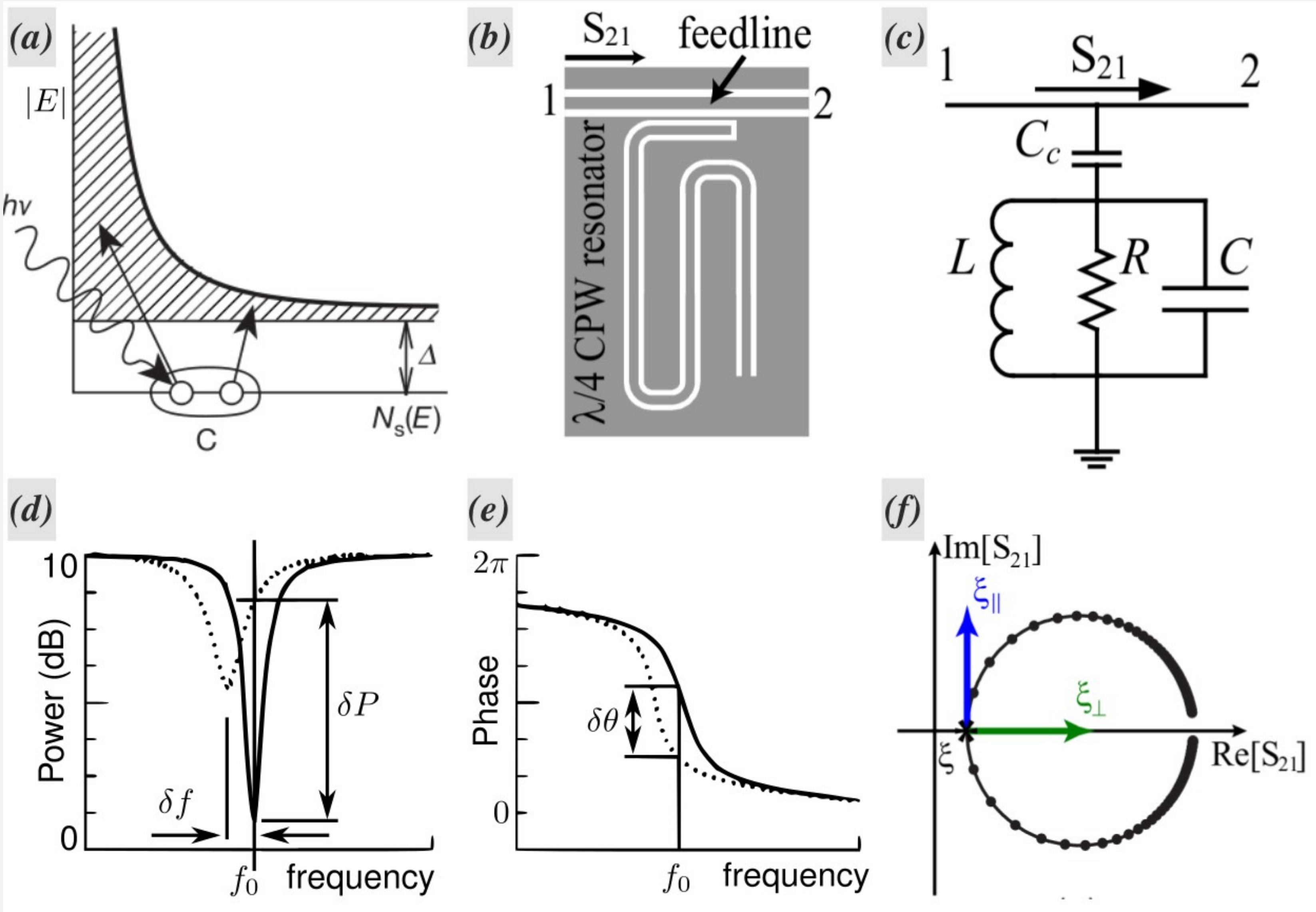
Sonnet simulation of a single MKID resonator





Approximate equivalent circuit.

We can use this as a radiation detector.



Figures from Mazin 2009 and Gao 2010