Novel detectors for next-generation CMB and submm instruments.

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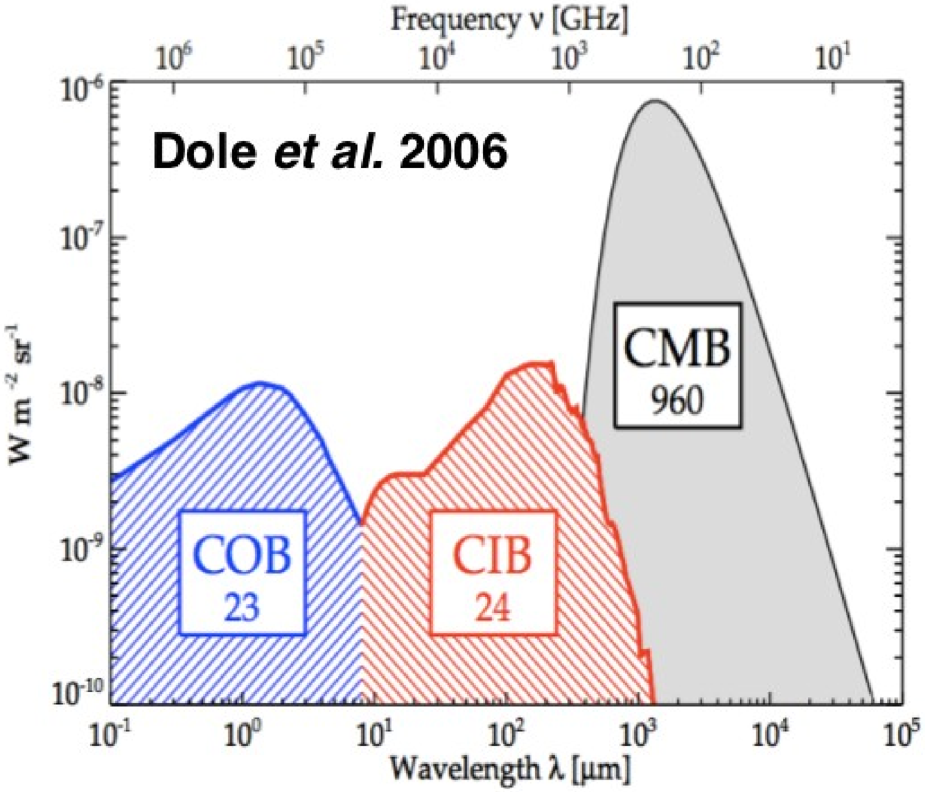
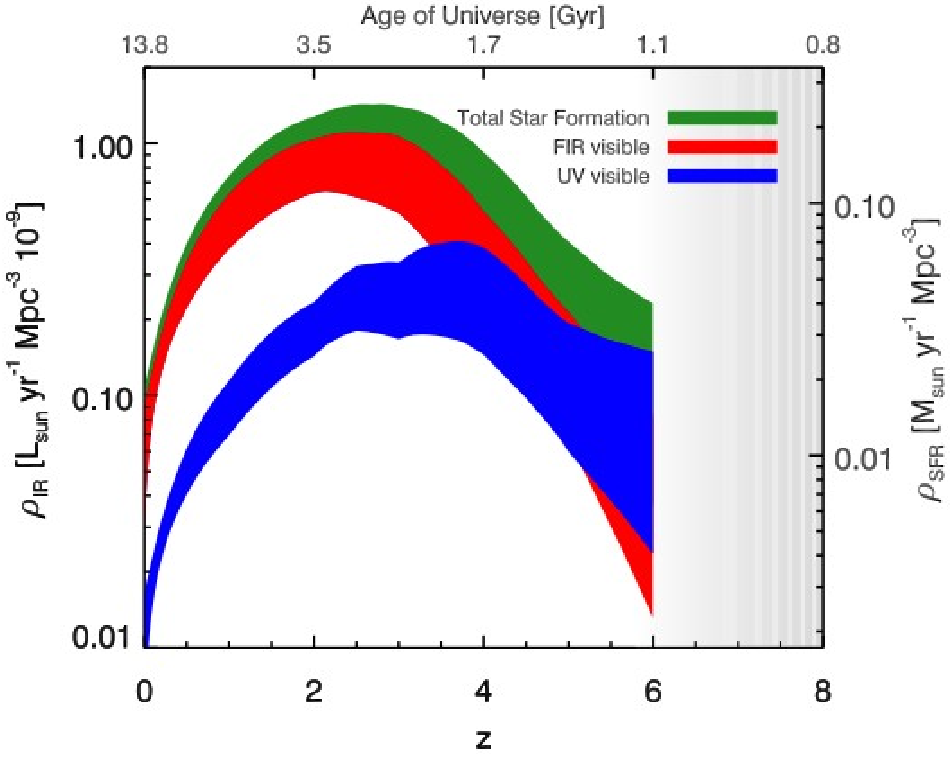
APC Paris
12 April 2017

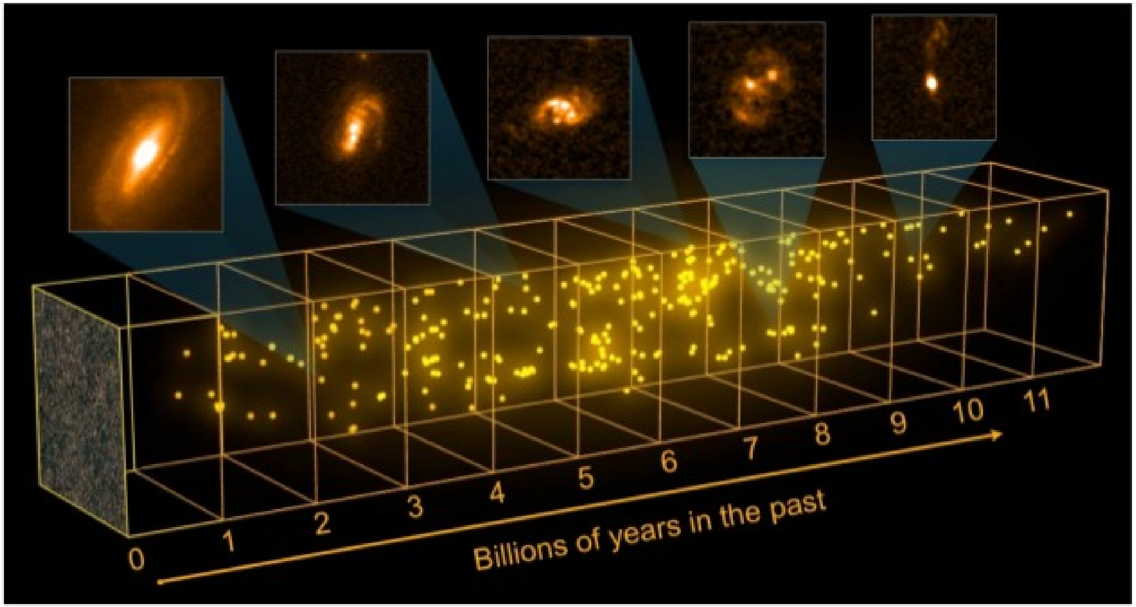
Outline

- The universe at millimeter wavelengths
- The kinetic inductance detector
- SuperSpec: On-chip spectroscopy for high-redshift galaxies
- Future instruments for CMB science.

The Cosmic Infrared Background (CIB)

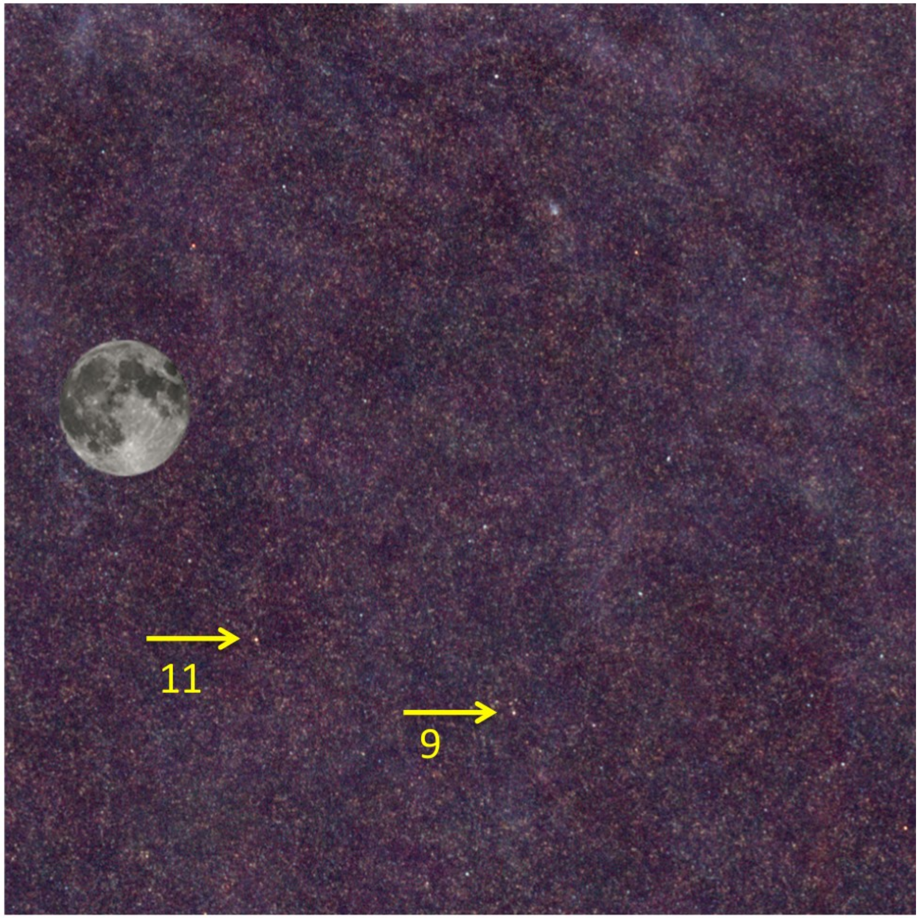




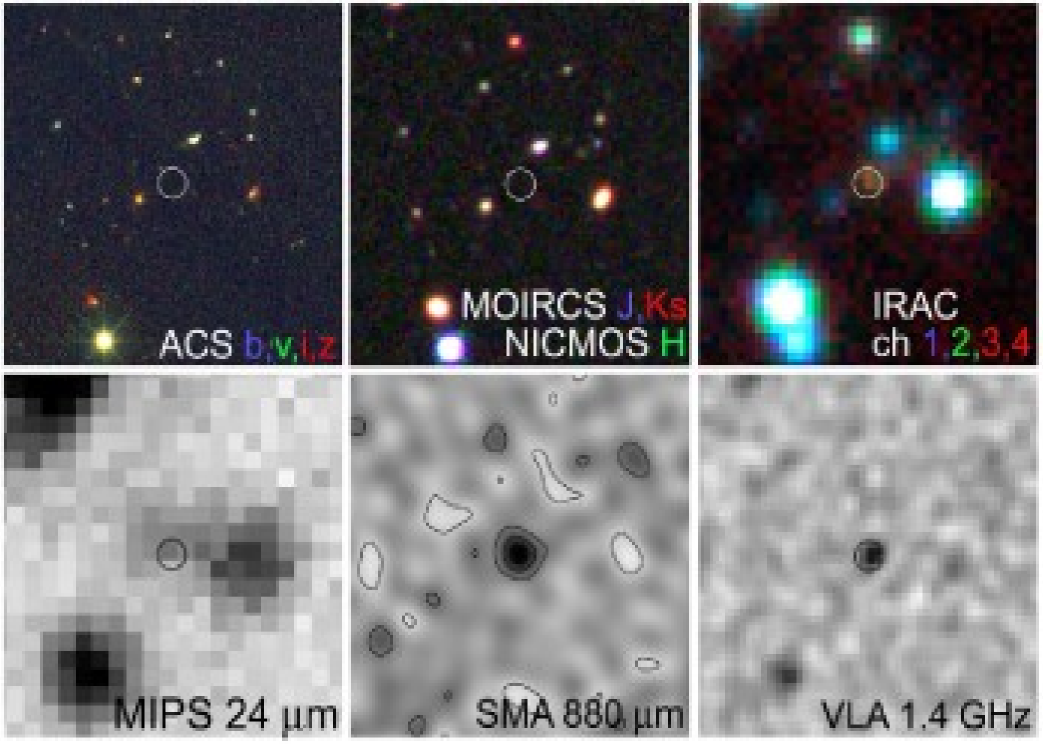


Slide from J. Vieira

Current and near-future submm surveys will find hundreds of thousands of galaxies: spectroscopic followup remains a bottleneck.



Negrello+10

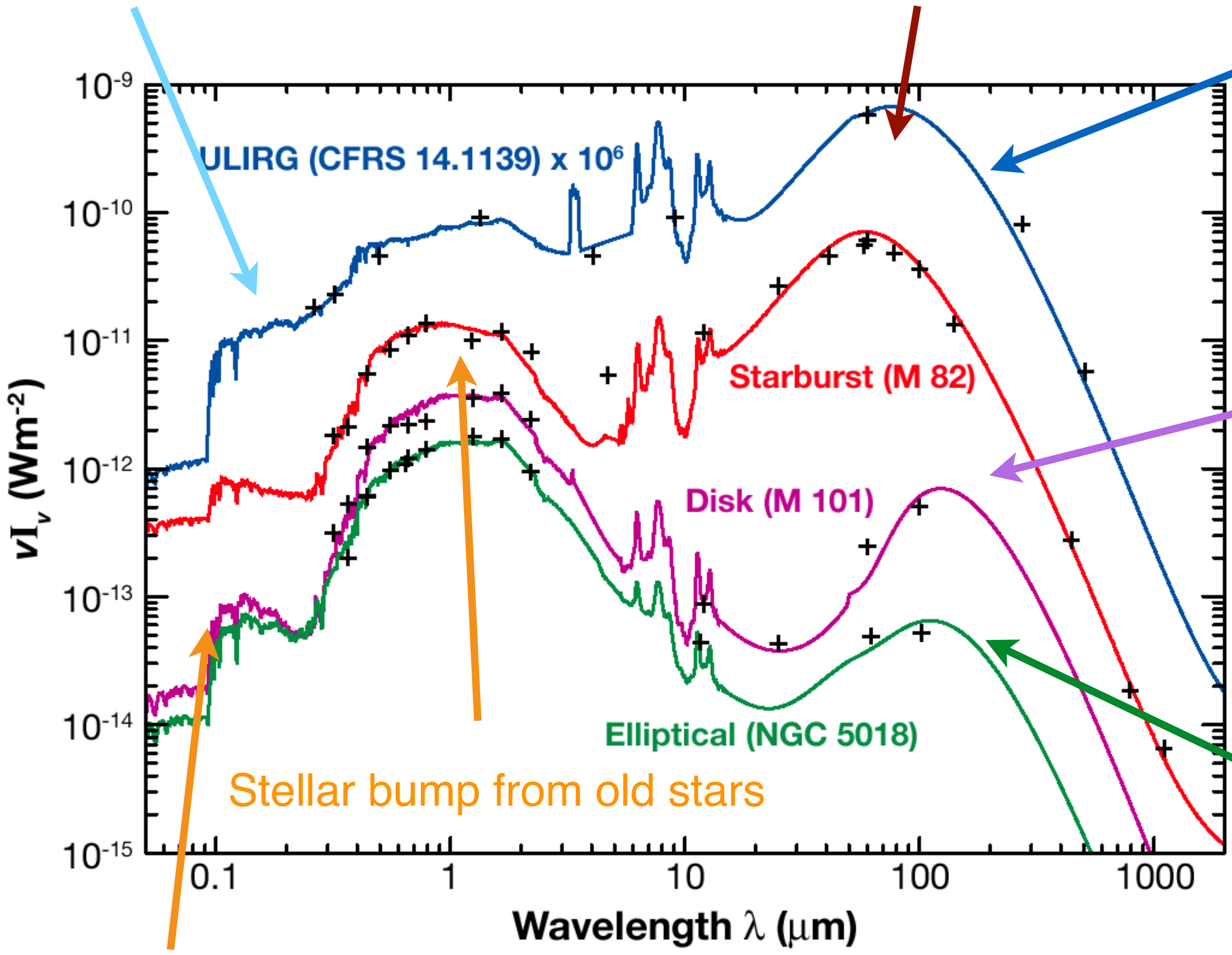


GOODS 850-5; Wang+09

Spectral Energy Densities of Galaxies

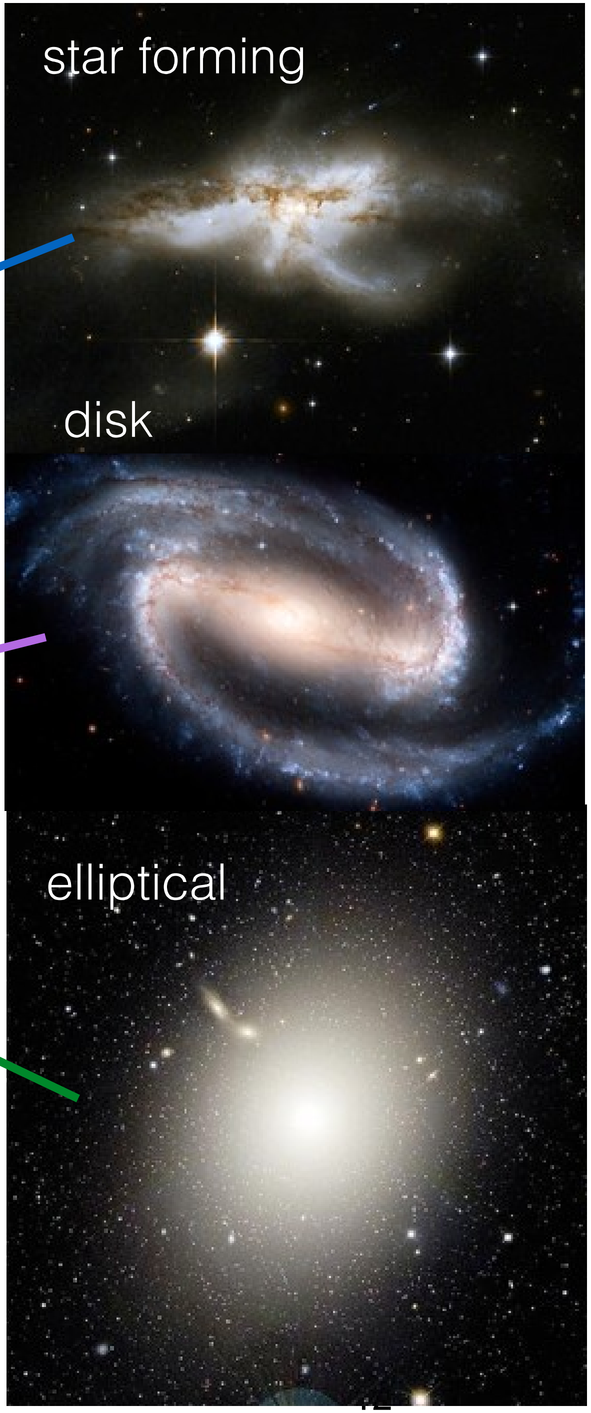
UV radiation absorbed by dust

Dust re-emits in the FIR



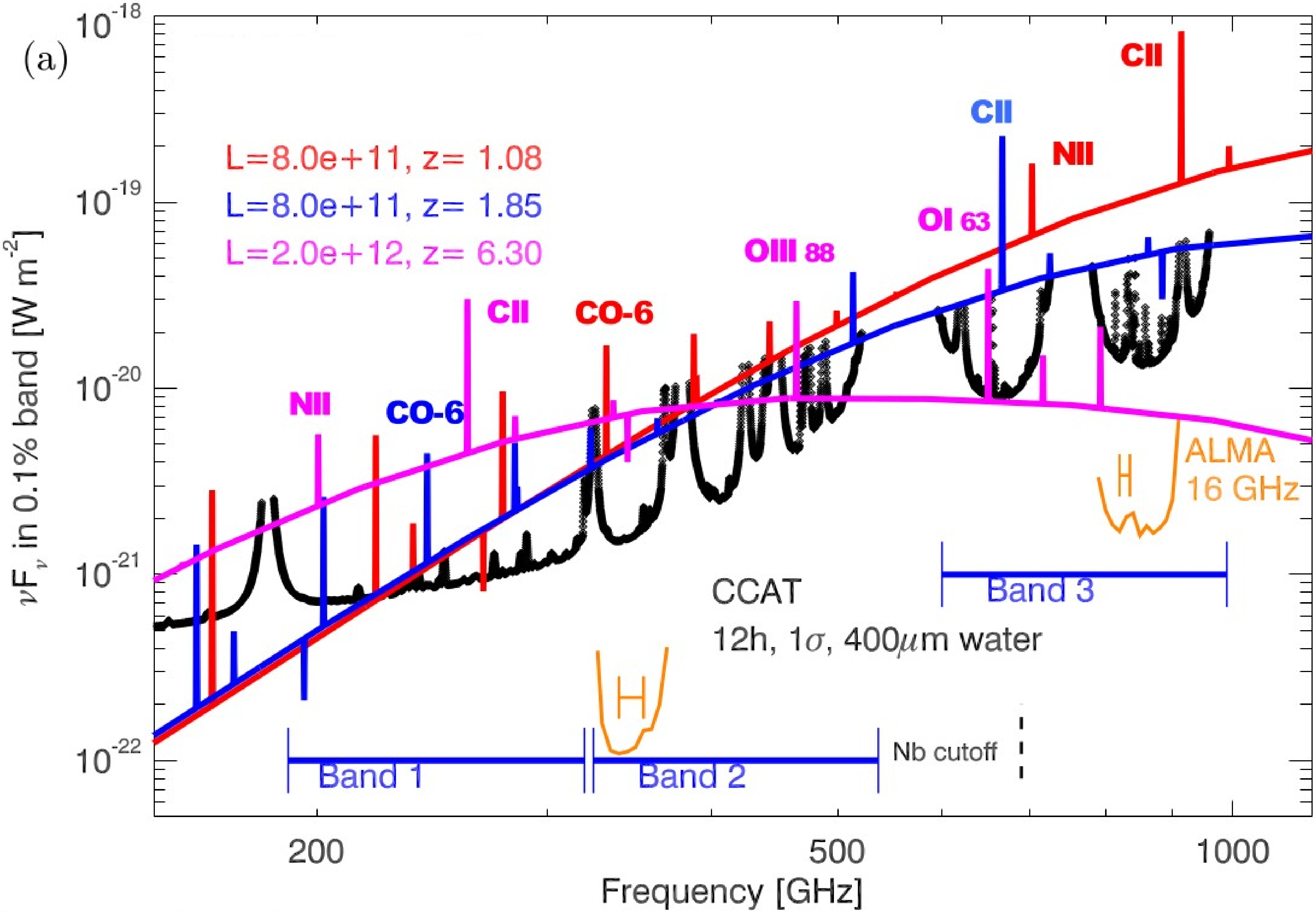
Stellar bump from old stars

UV from young, hot stars



Lagache+ 2005

Sensitivity and example spectra at a large (25m) single-dish telescope at a good site.



Spectral lines in the 195-310 GHz atmospheric window.

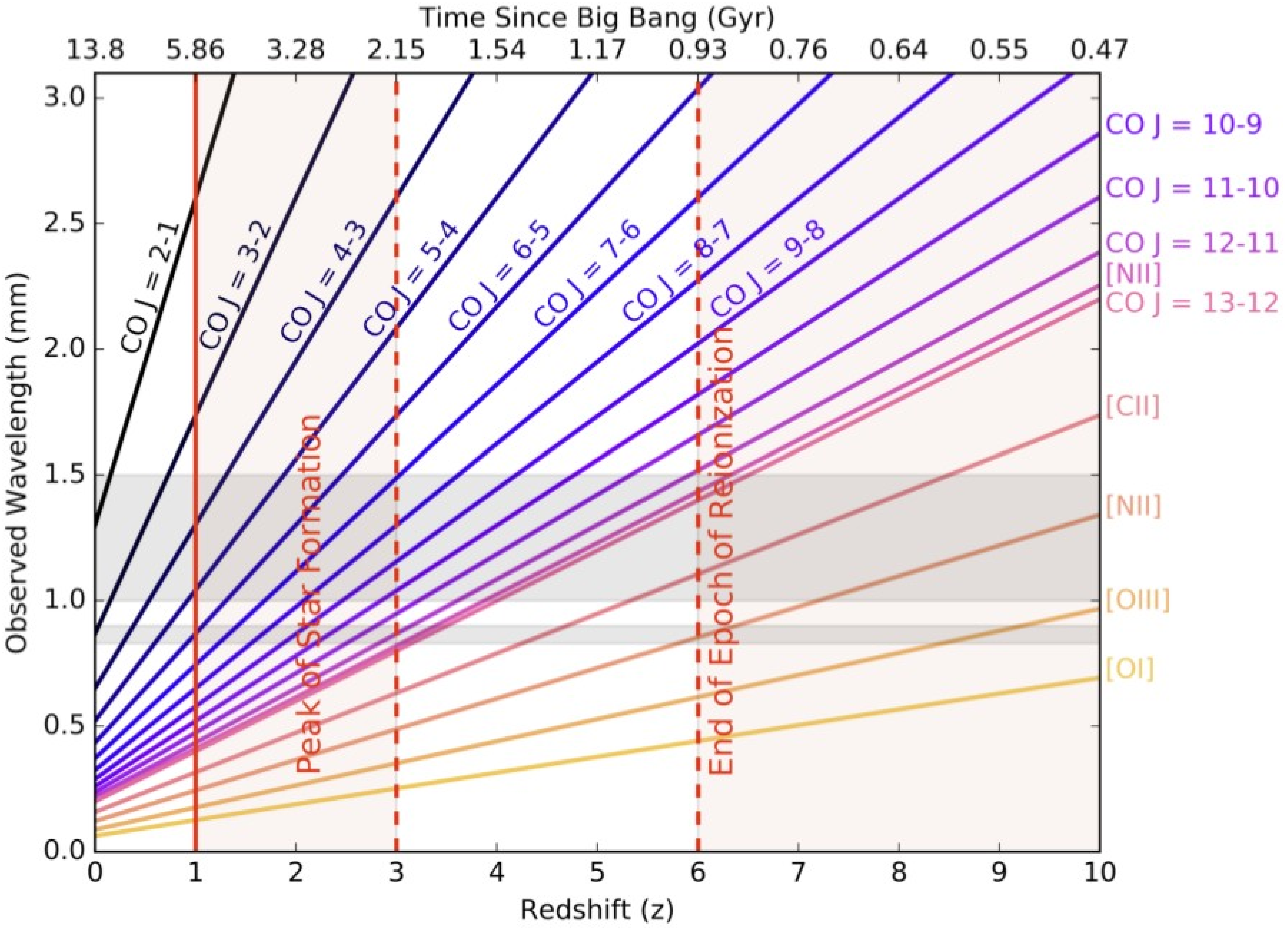
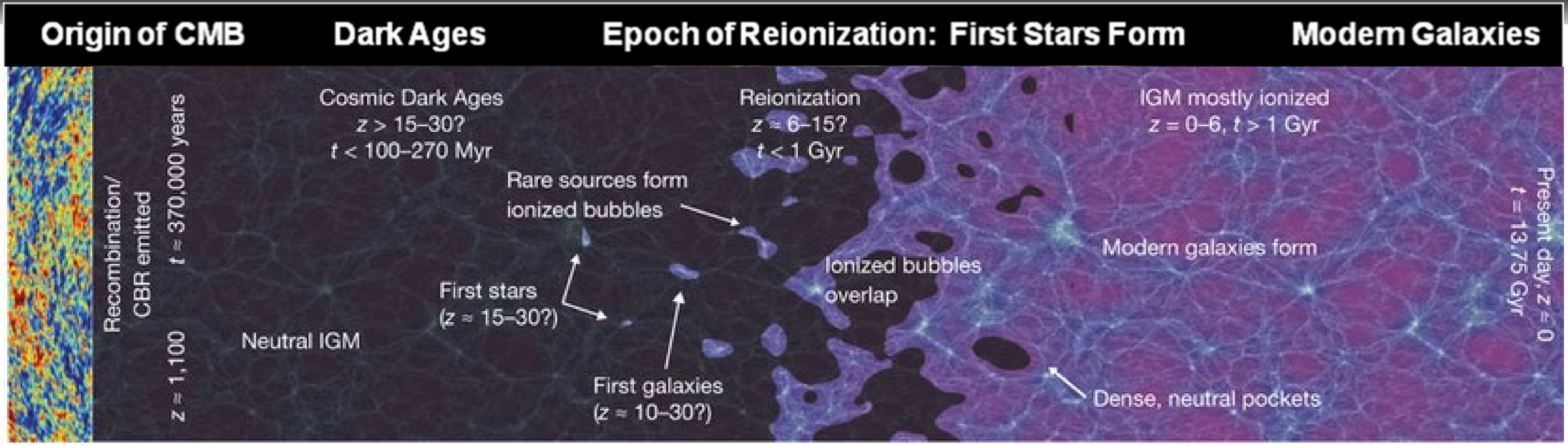


Figure from J. Glenn

Epoch of Reionization with Intensity Mapping



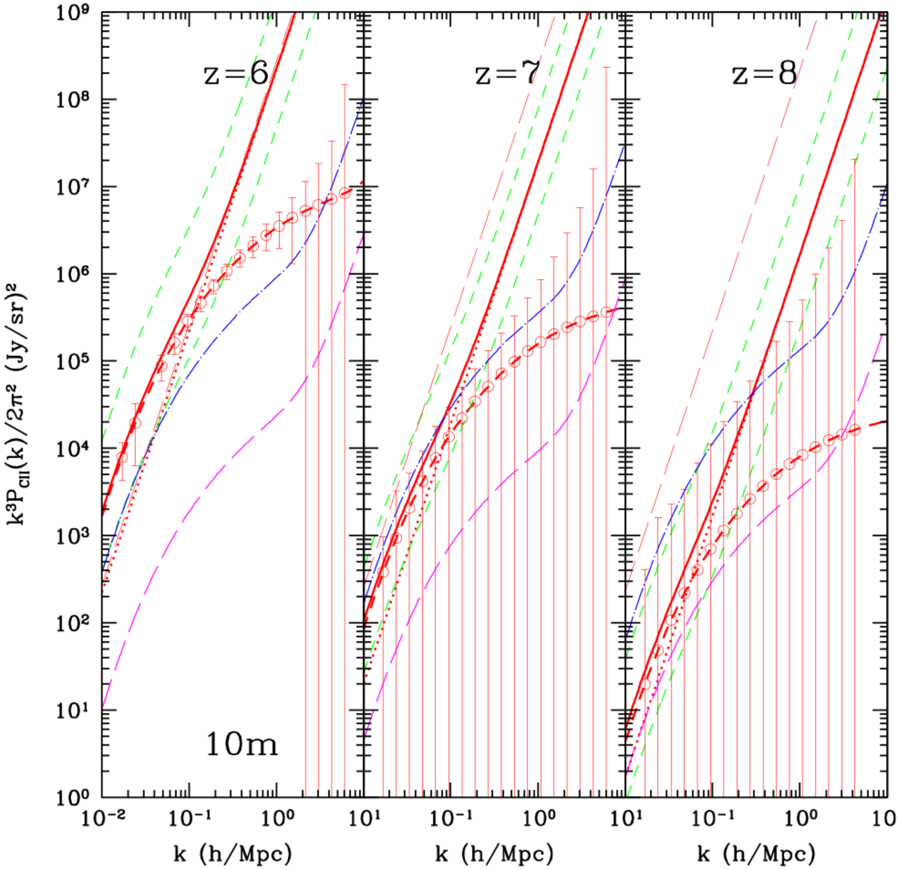
Dunlop & McLure

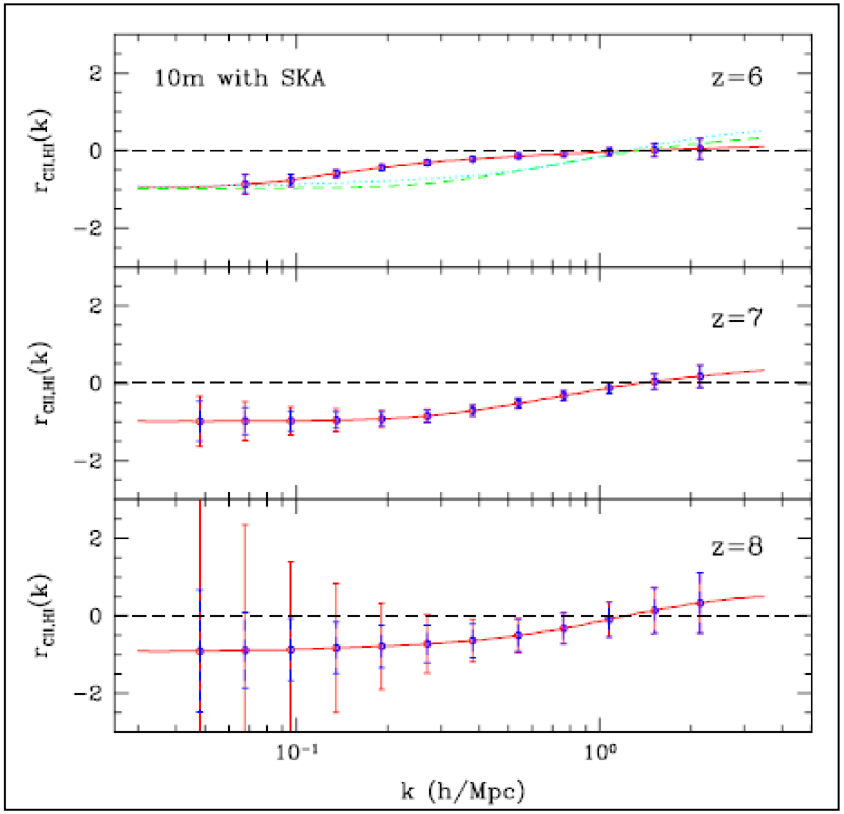
- The first stars and quasars ionized most of the hydrogen in the universe.
- We can map ionizing sources, using ionized carbon (C+) as a tracer.
- Requires a mm-wave imaging spectrometer and hundreds of pixel-months at a good site.

Tomographic intensity mapping during the epoch of reionization

Probes:

- Galaxy clustering
- Mean [CII] intensity and galaxy luminosity function





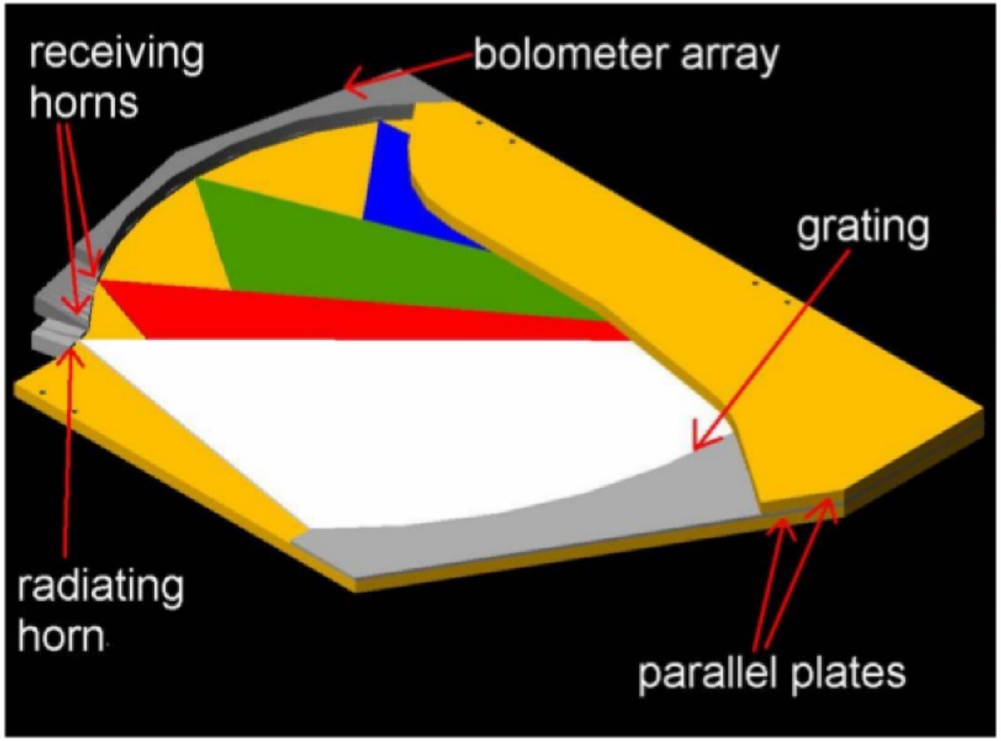
Gong+12

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.



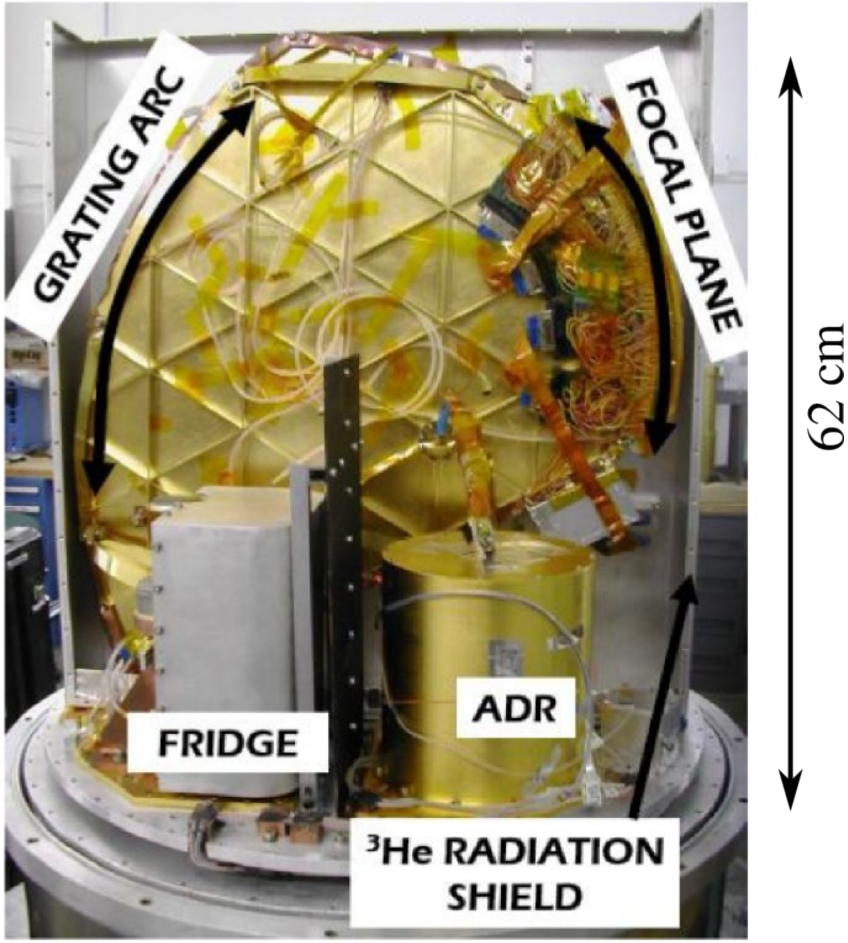
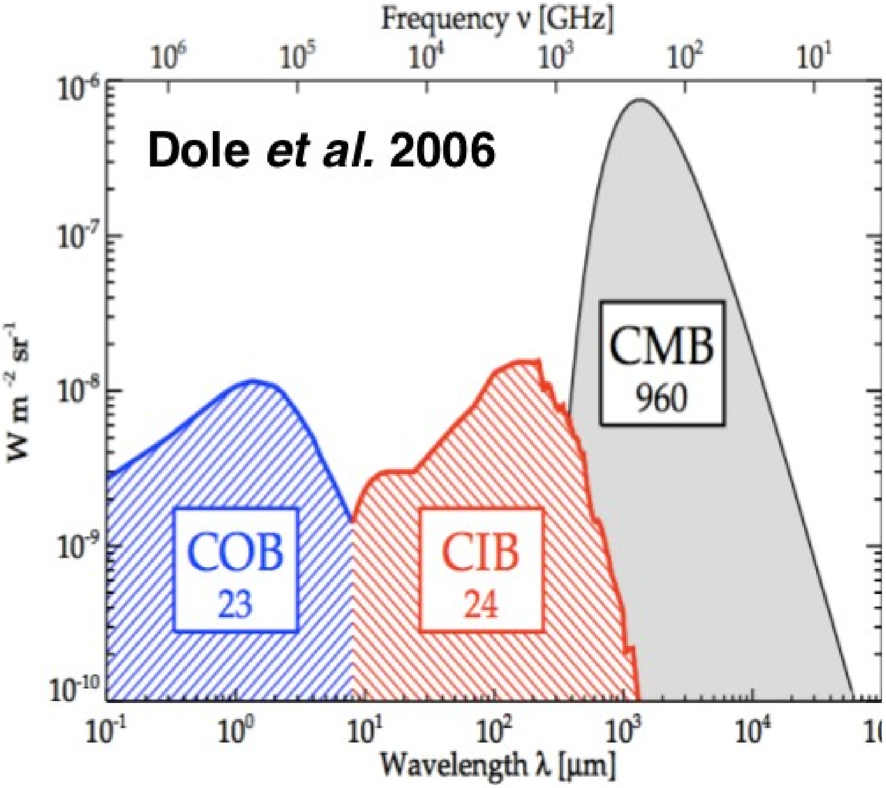
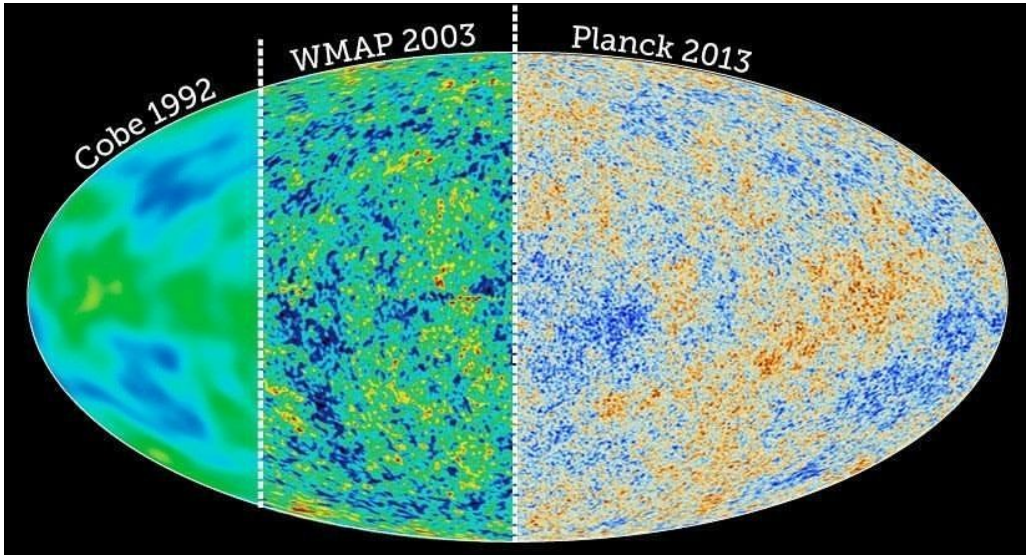
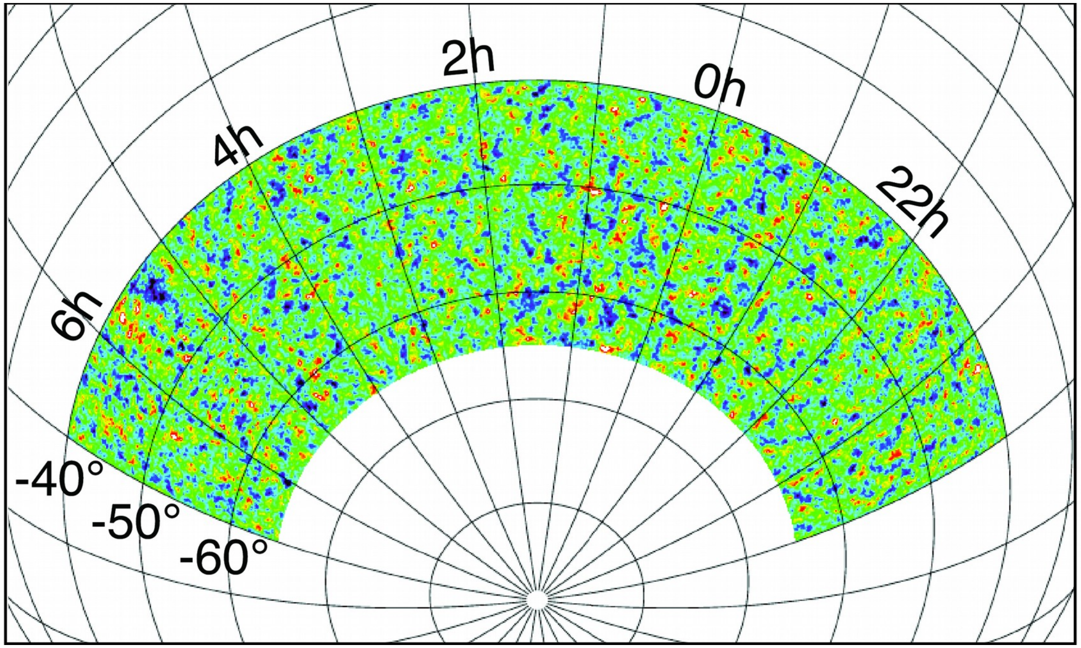


Image: Earle 2006

The Cosmic Microwave Background







CMB Power spectrum

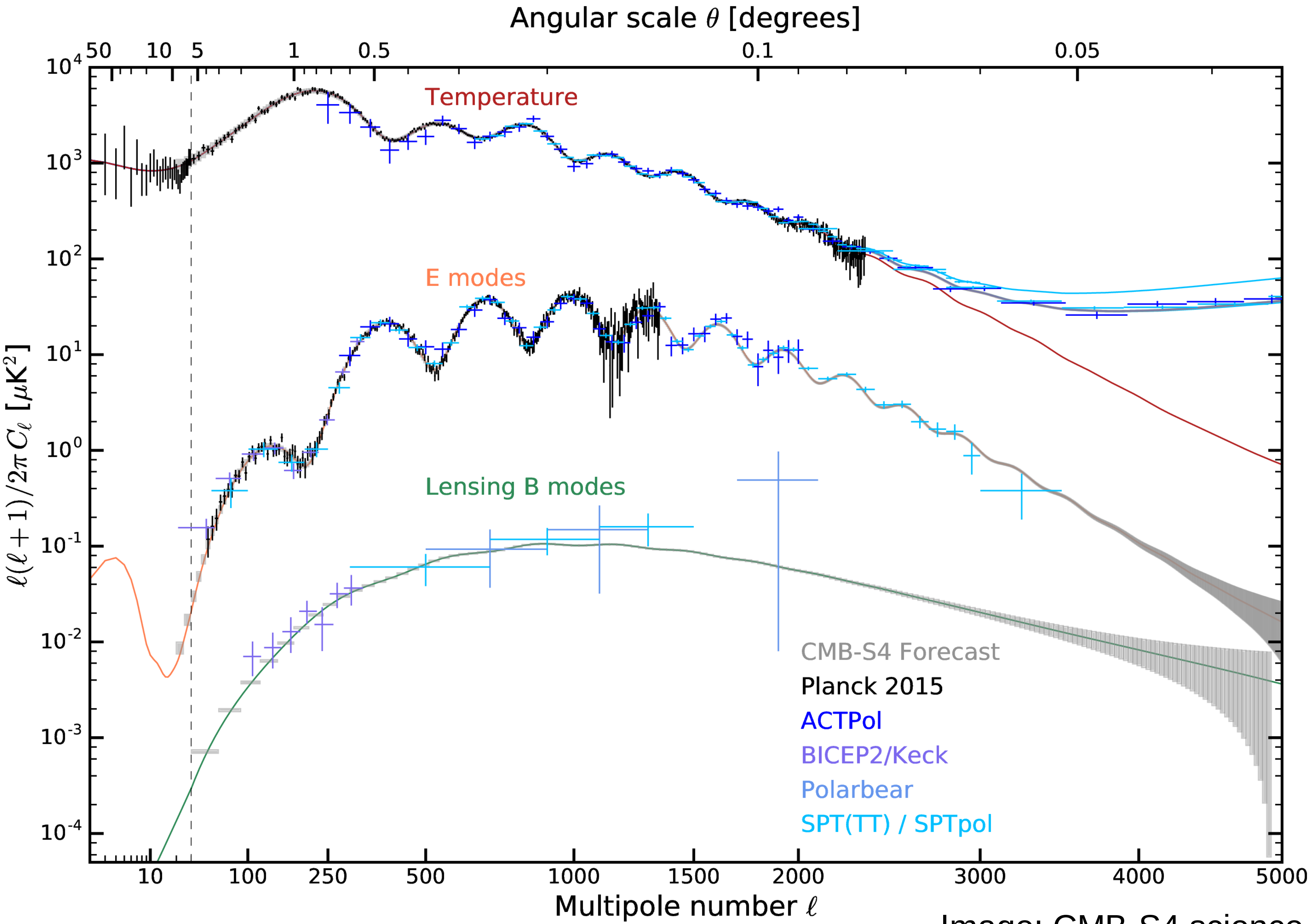
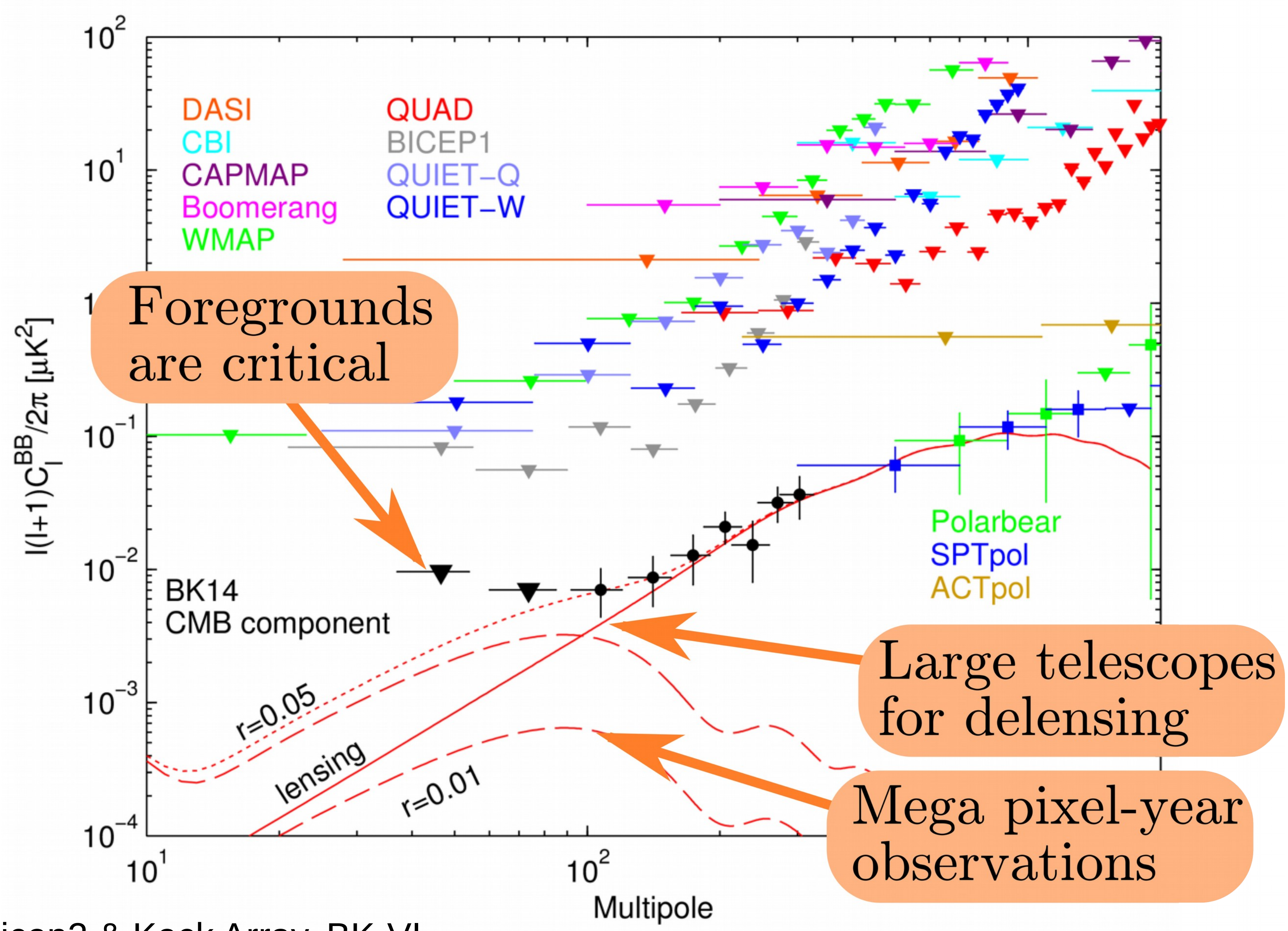


Image: CMB-S4 science book

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



Foregrounds are critical

Large telescopes for delensing

Mega pixel-year observations

Image: Bicep2 & Keck Array, BK-VI

CMB-S4

Next Generation CMB Experiment

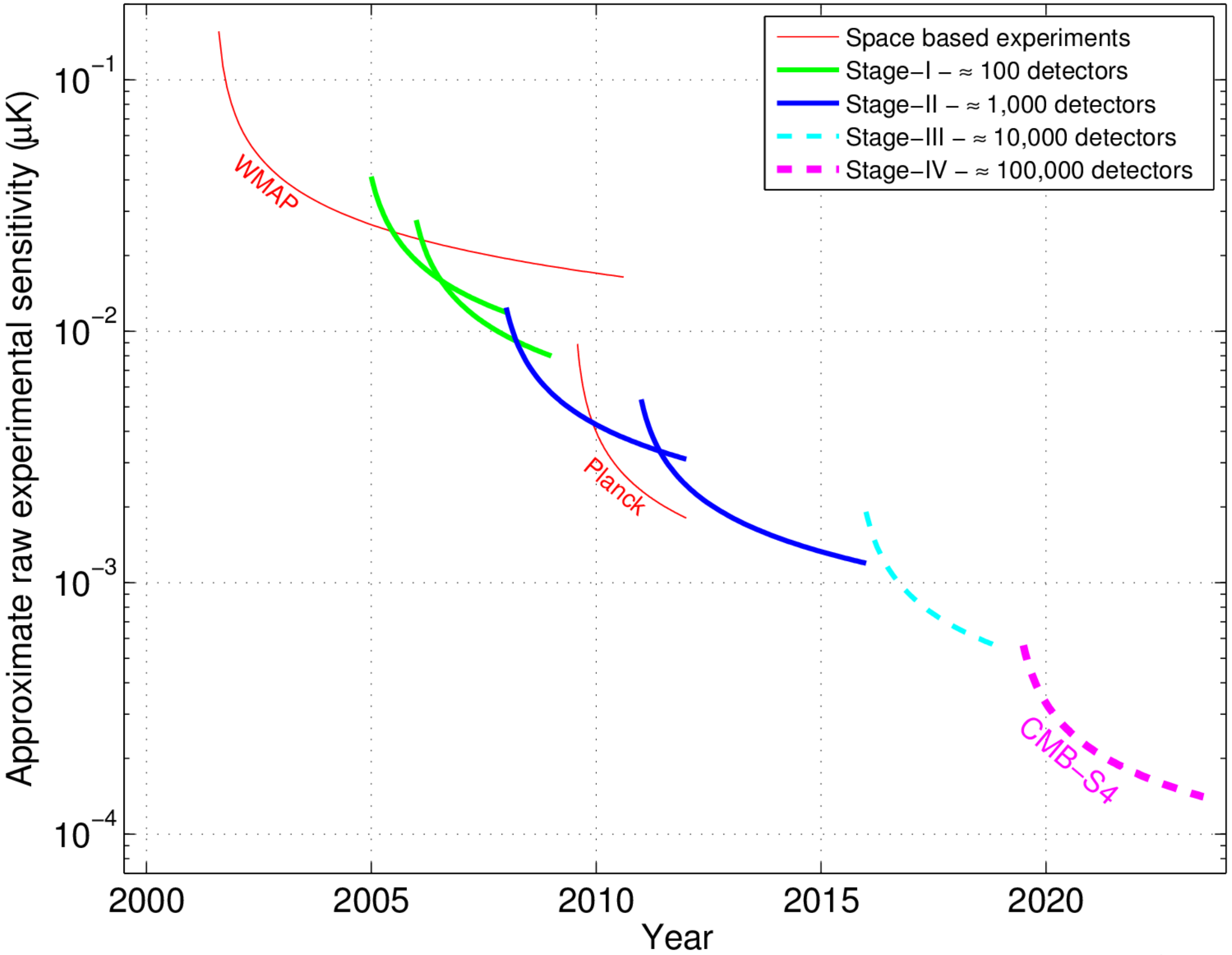
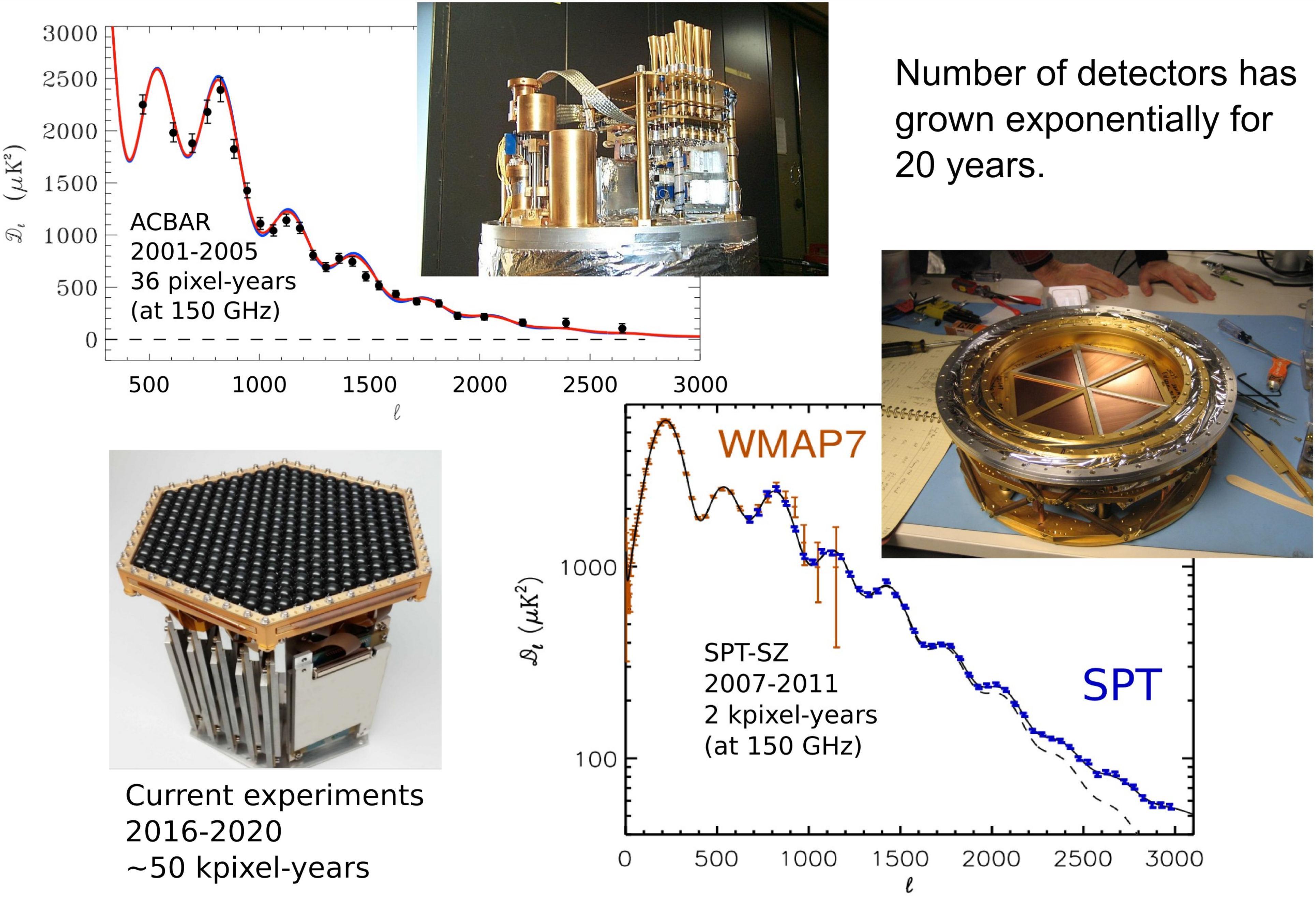


Image: CMB-S4 science book

mm-wave sensitivity is limited by photon arrival statistics: We can't build a more sensitive detector, but we can build more of them.

Number of detectors has grown exponentially for 20 years.



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

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

Current experiments
2016-2020
~50 kpixel-years

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

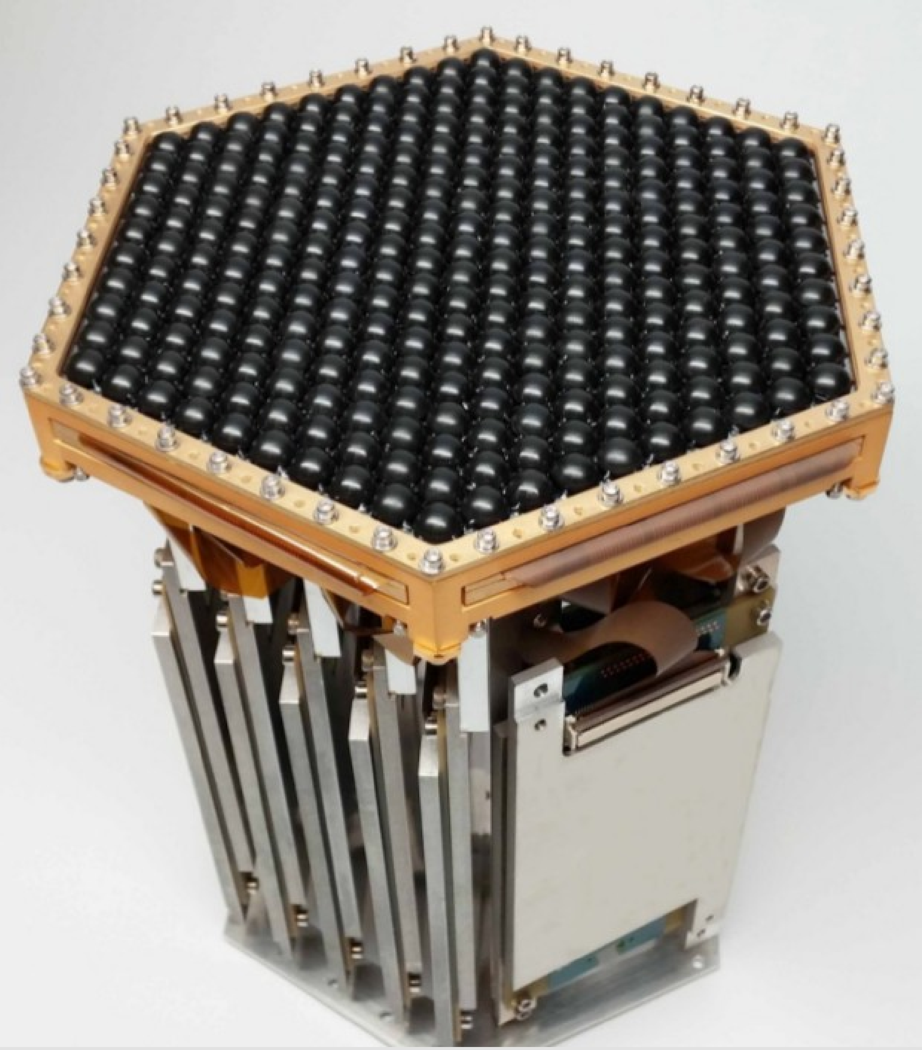
The bad:

- Thin-film thermal properties 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:

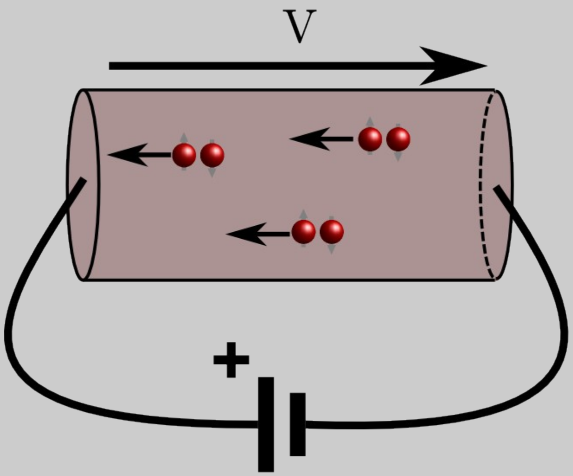
Cooper pairs have momentum.
Acceleration leads to a phase shift between I and V.
This acts like an inductance!

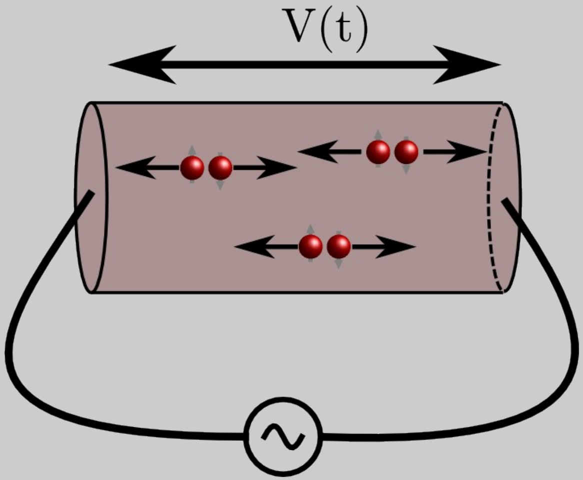
At low temperature:

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

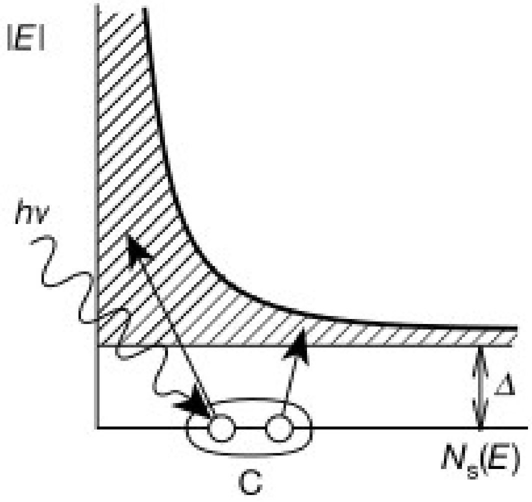
Phase shift leads to E field inside the conductor:

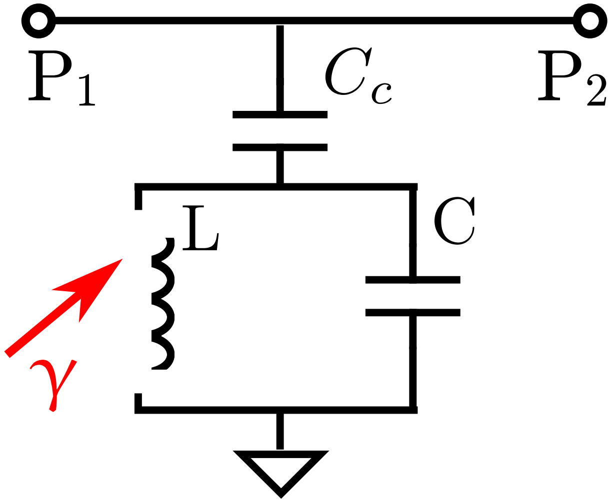
Non-zero resistance from quasiparticle currents
R also varies linearly with number of pairs

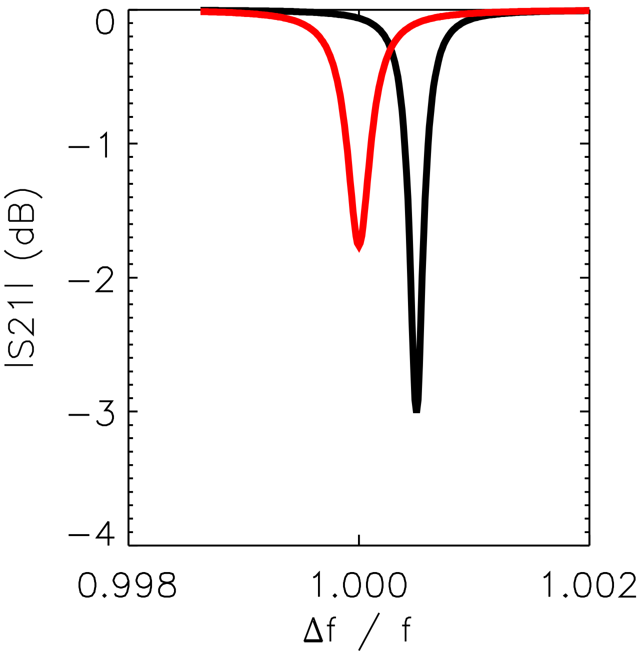


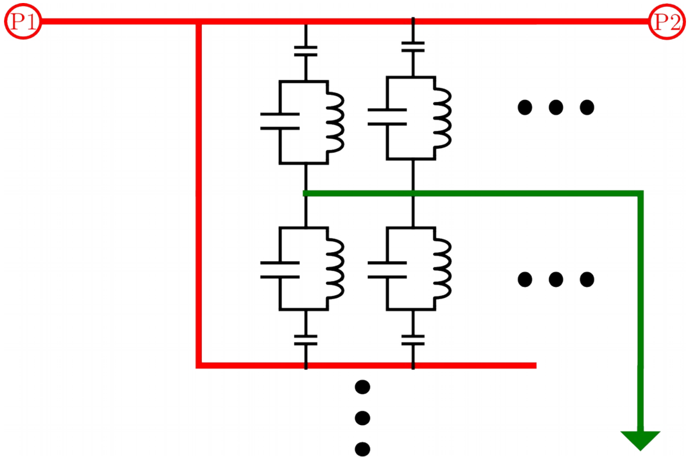


We can make a detector out of this.









Microwave resonance leads to natural multiplexing:

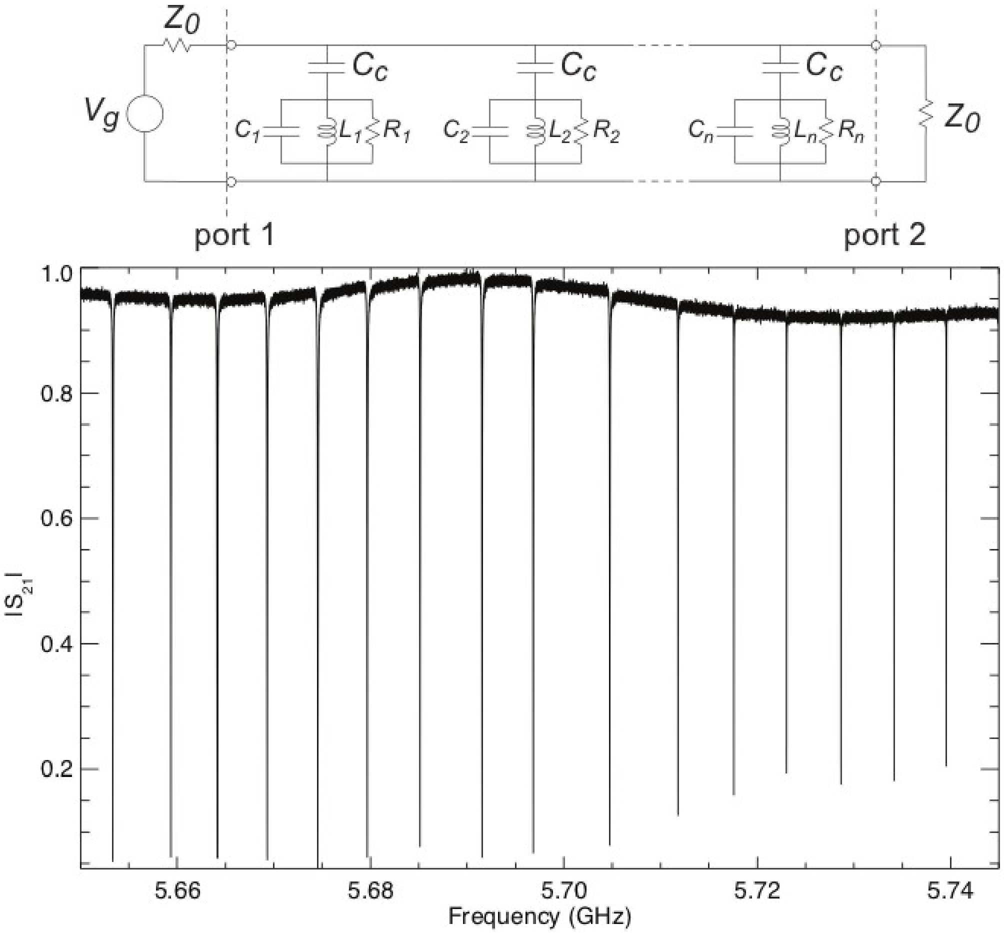
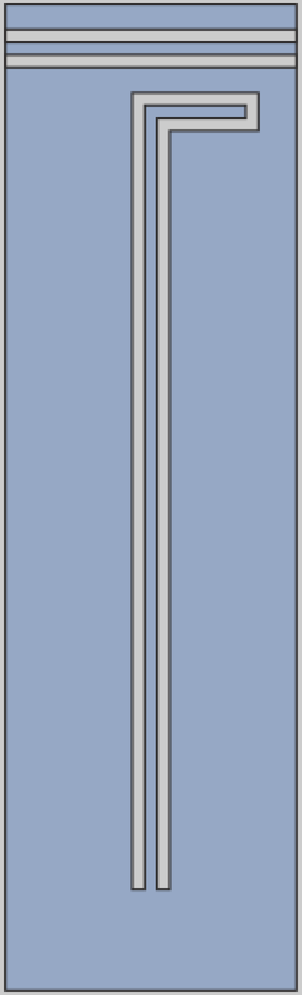
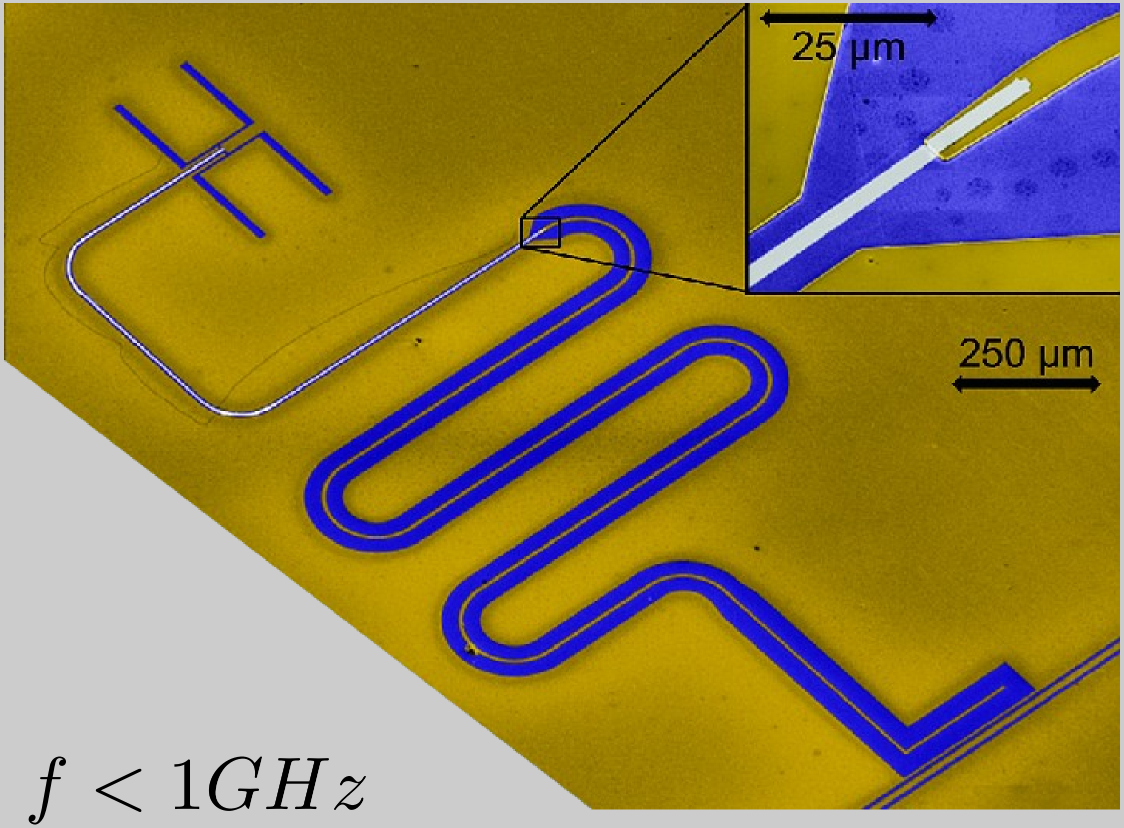


Figure: Zmuidzinas group

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





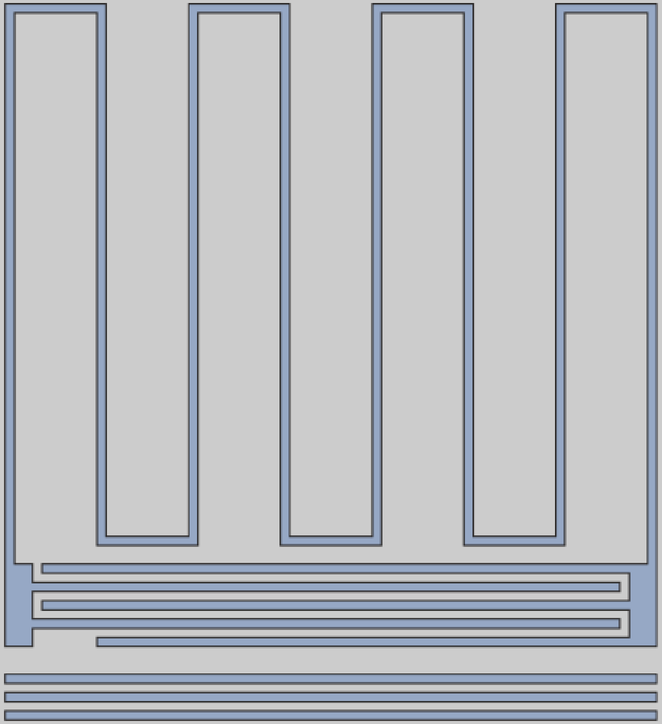
Hard to achieve $f < 1GHz$

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



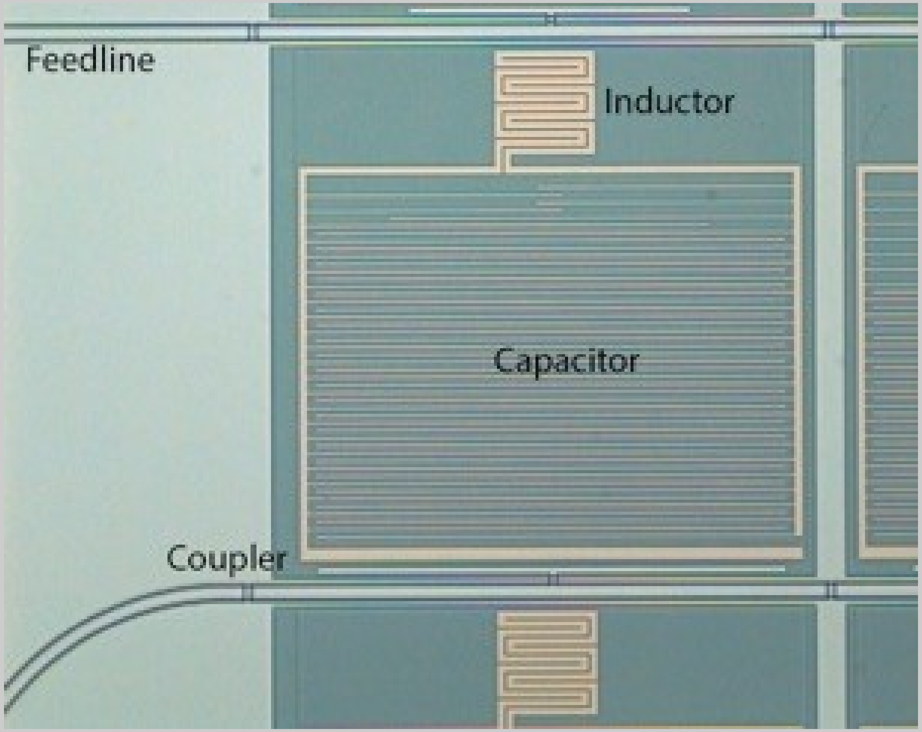


Image from Mazin group, UCSB

Decouple L and f.

Easy to achieve low frequencies.

But, matching free space impedance constrains inductor.

Dual-pol & multi-band designs are challenging

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

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

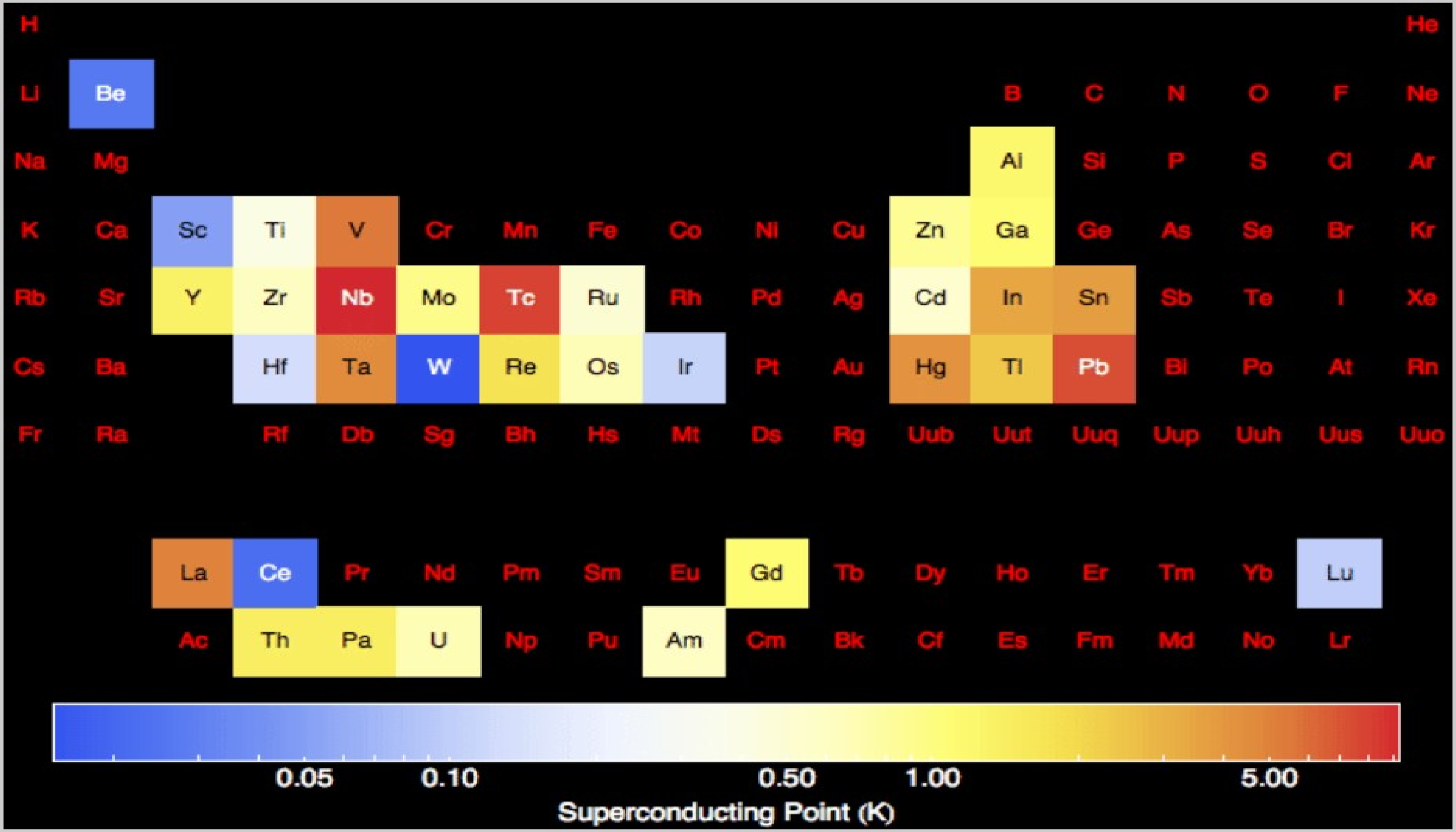
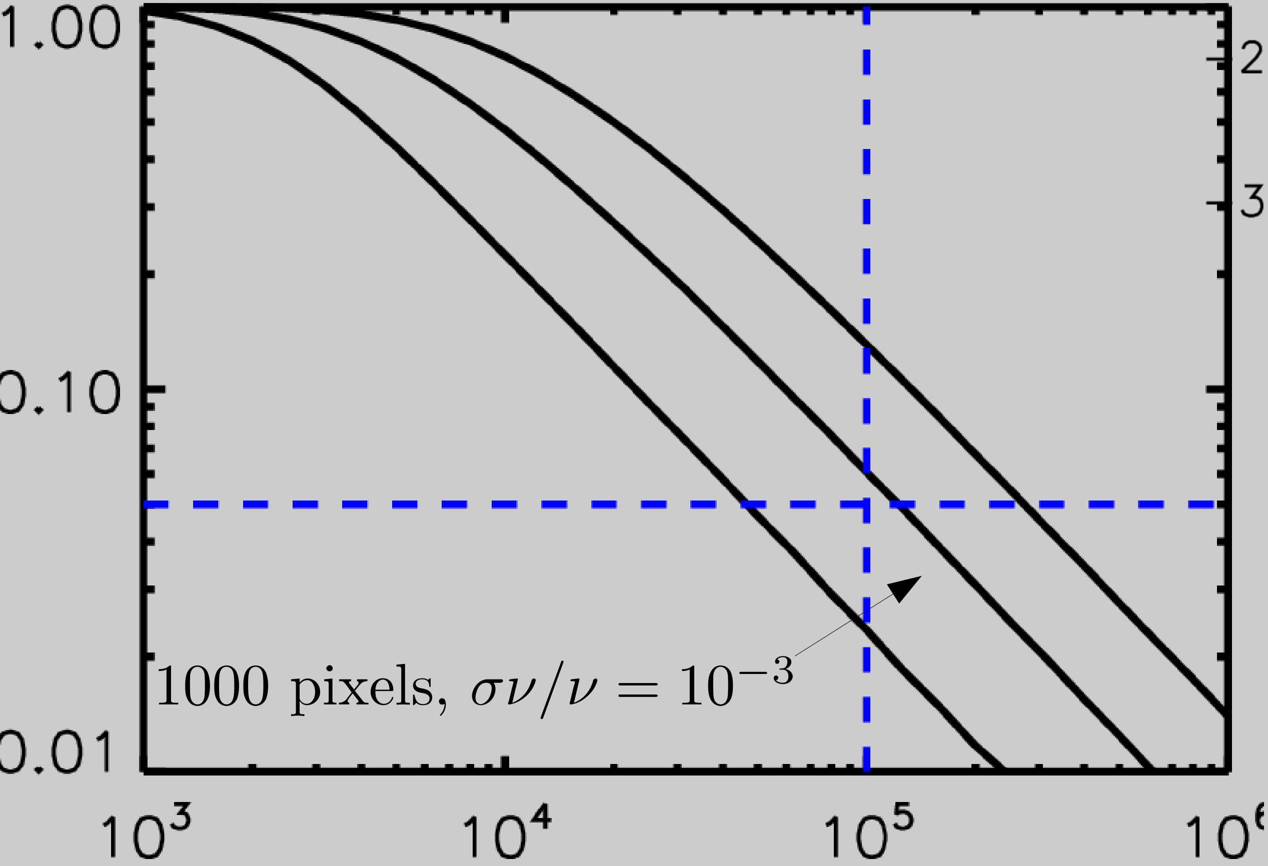


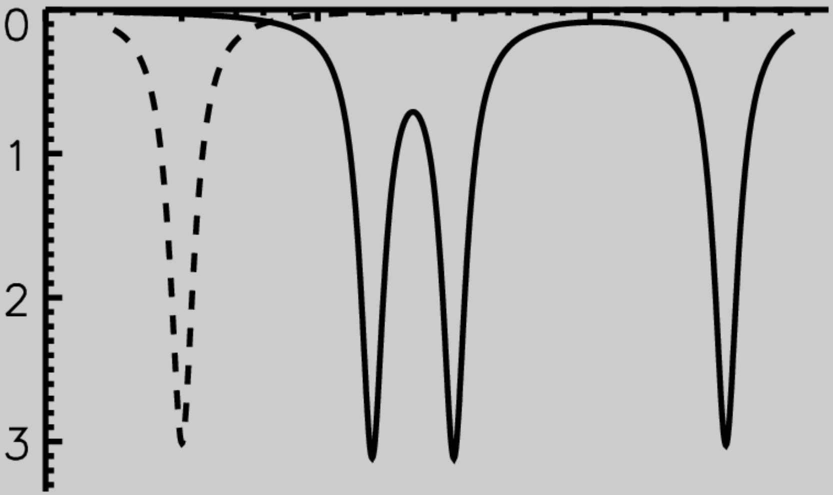
Image: periodictable.com

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

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

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

Background limit for all detectors

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

All pair breaking detectors.
For ground based CMB case:

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

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

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

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

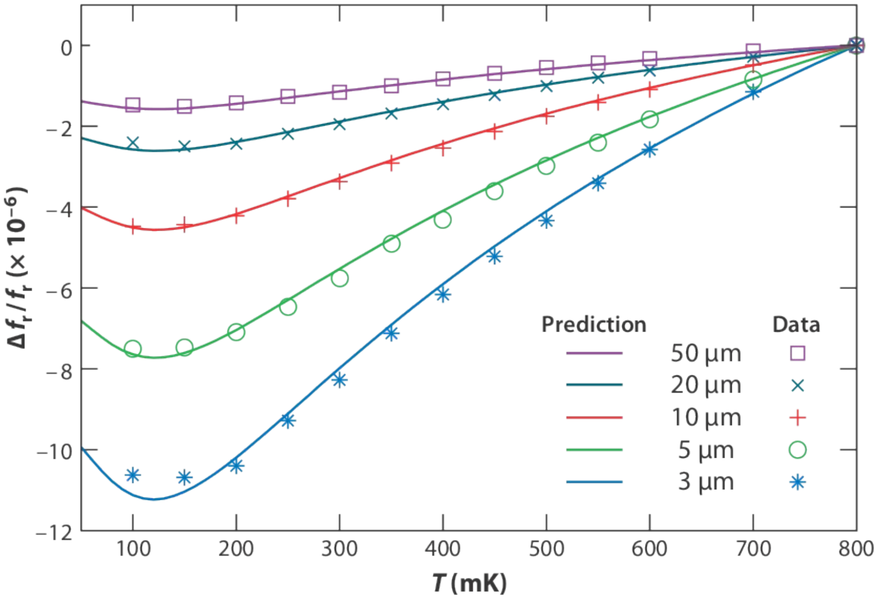
$$+ \ (\text{small terms})$$

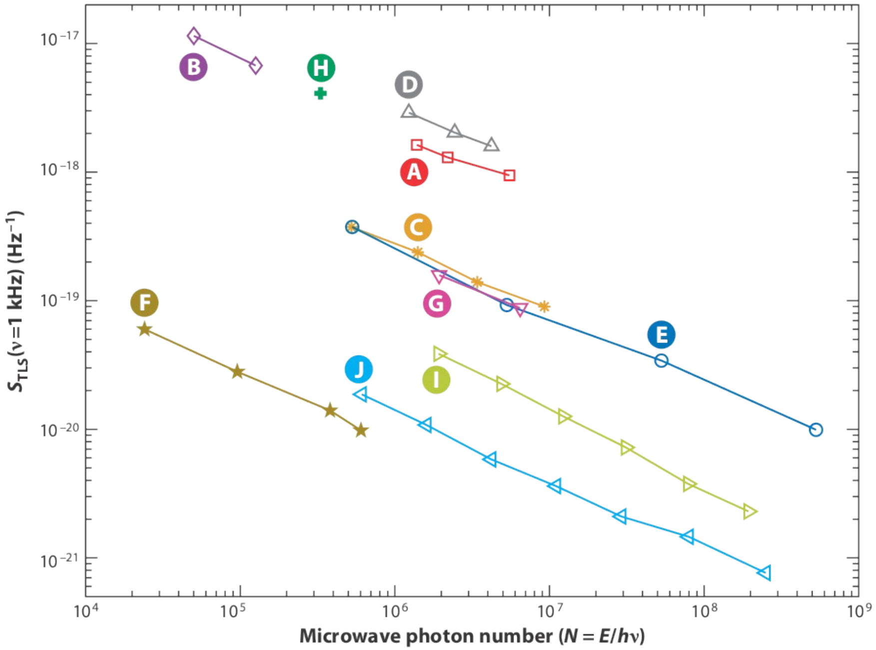
Two Level System Noise: hard to predict a priori, but follows known scaling laws

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.

The SuperSpec Team

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C. E. Tucker

University of Colorado Boulder

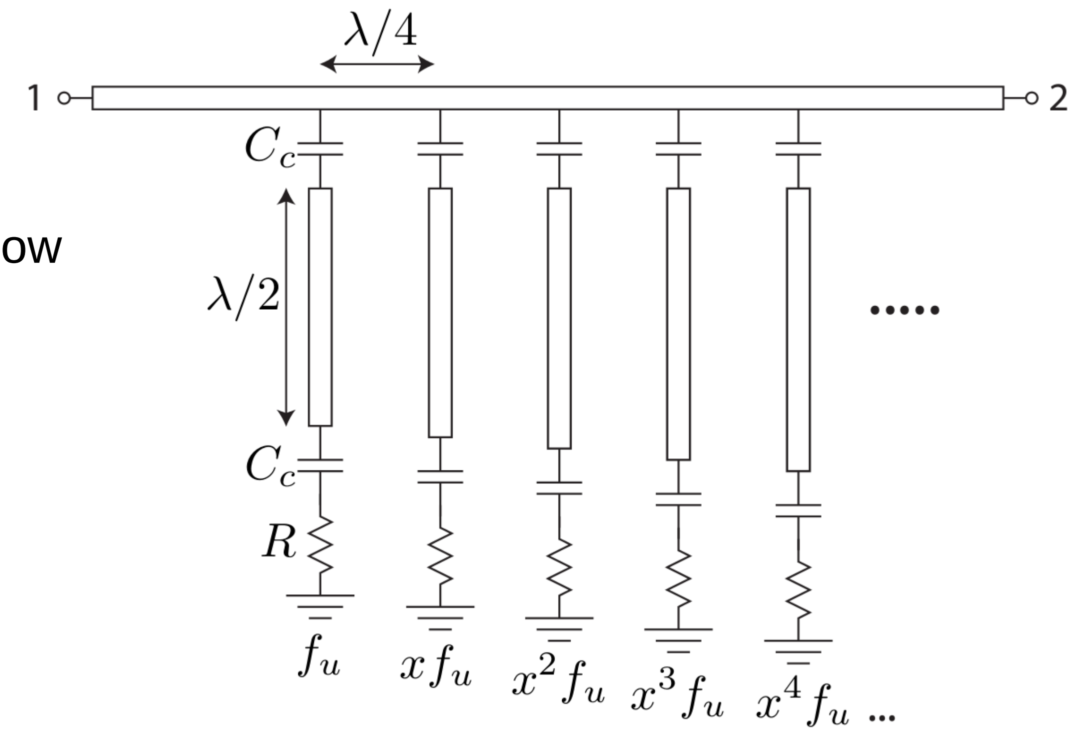
J. Glenn
J. Wheeler

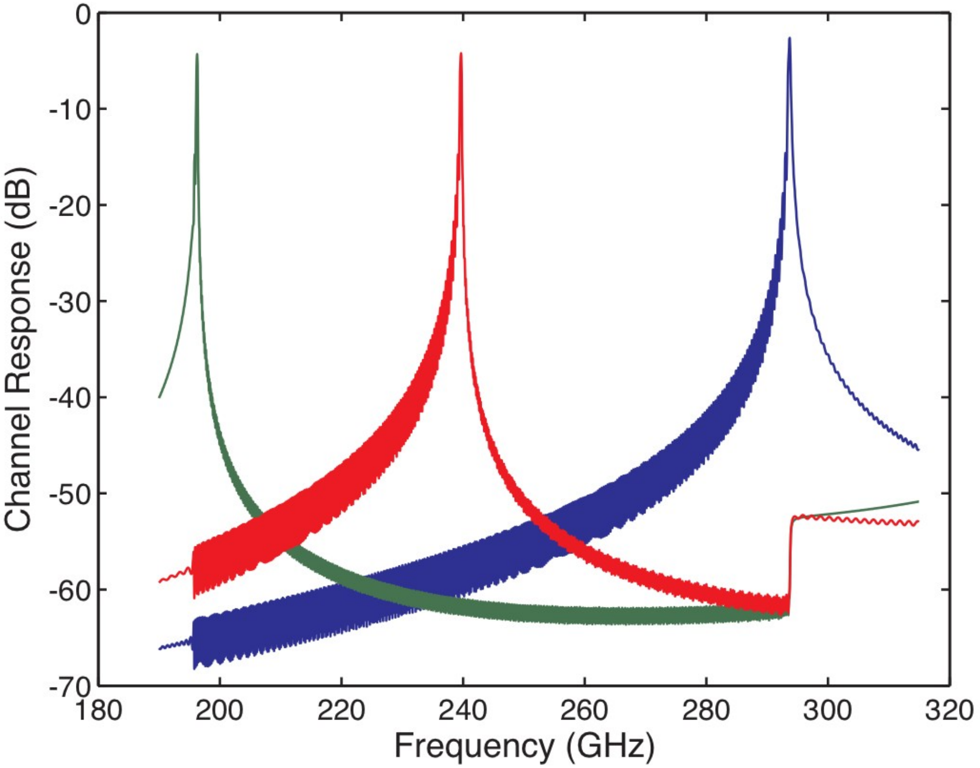
A general filter bank (or cochlear) spectrometer:

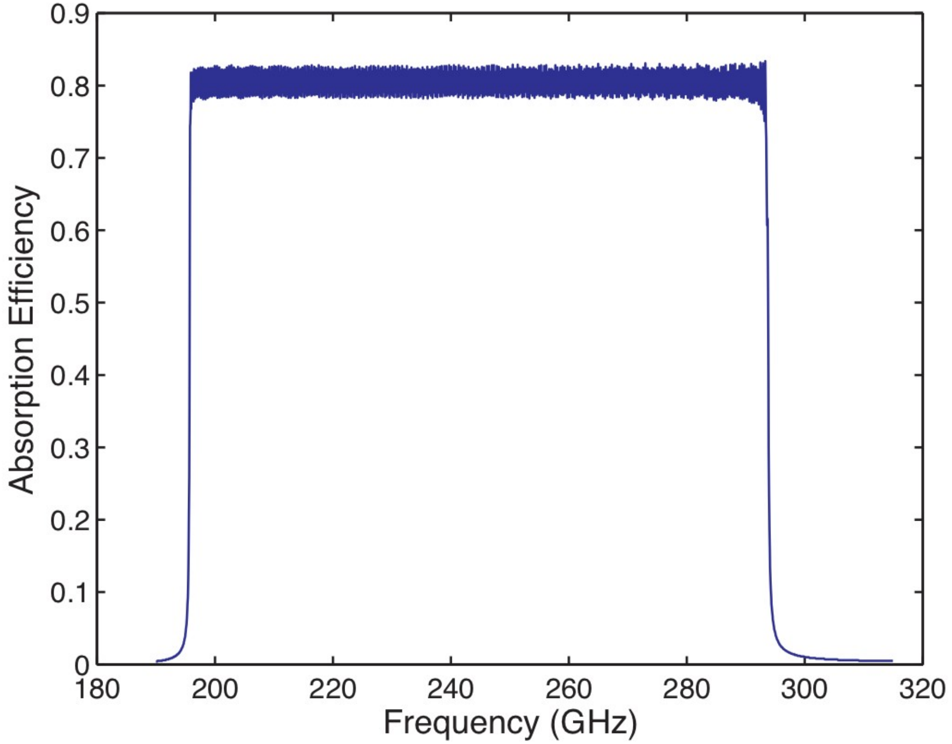
Incoming radiation is sorted by narrow band filters

Each channel couples to a power detector

Channel width and spacing are independently adjustable

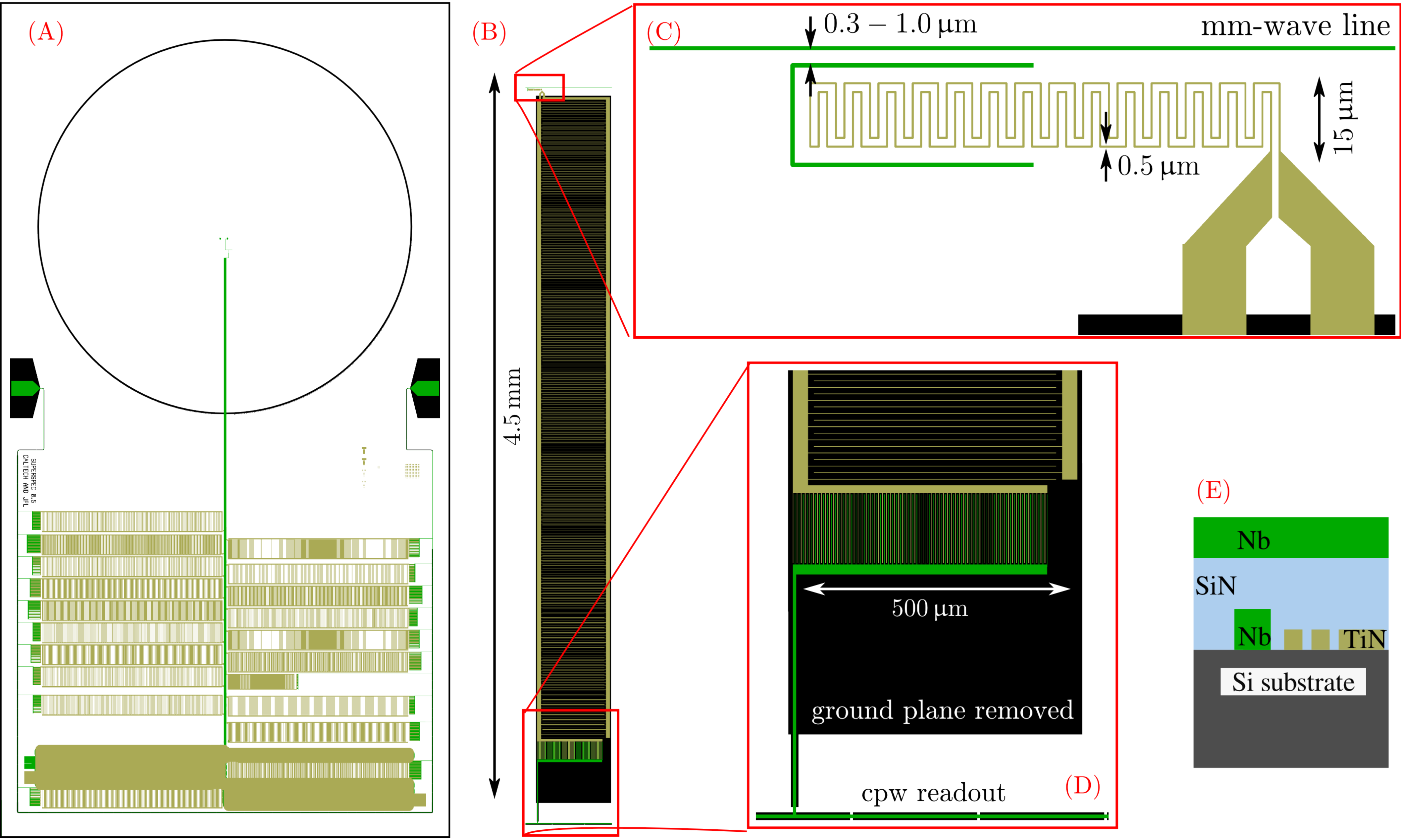




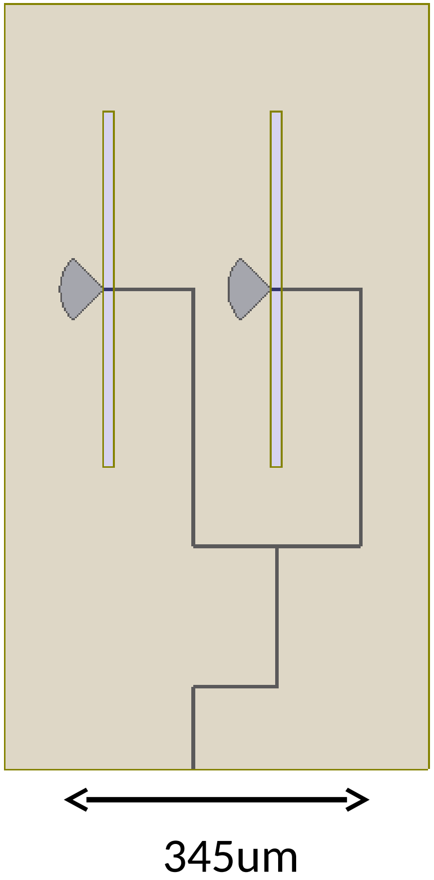


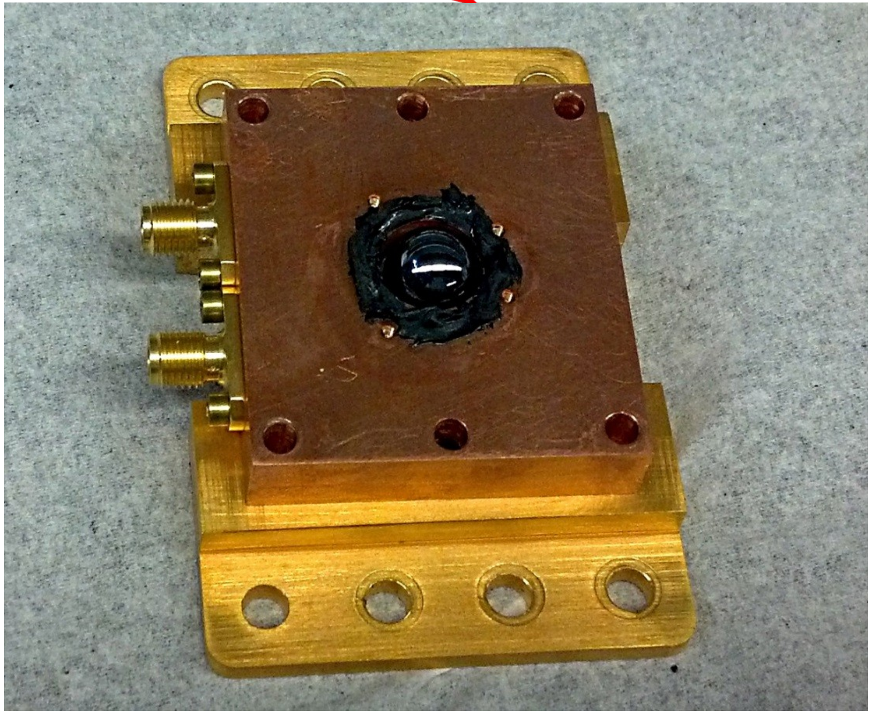
From Kovacs and Zmuidzinas, internal memo

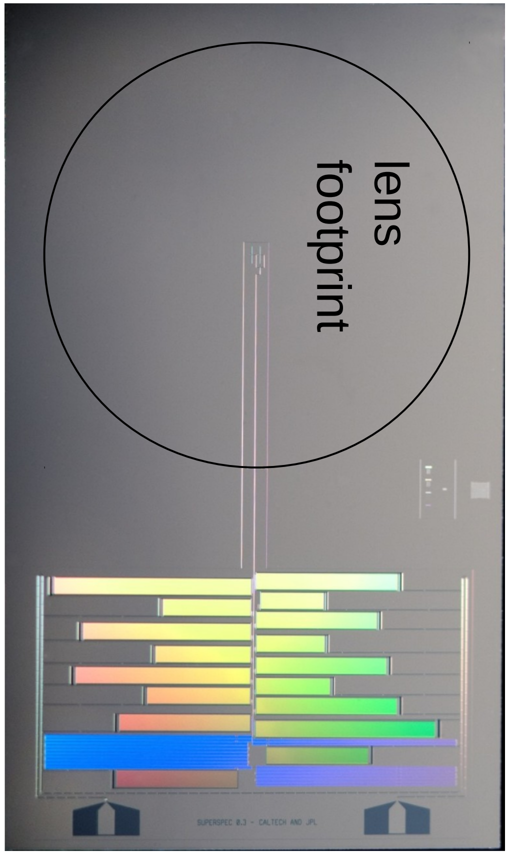
Implementation using thin-film circuits



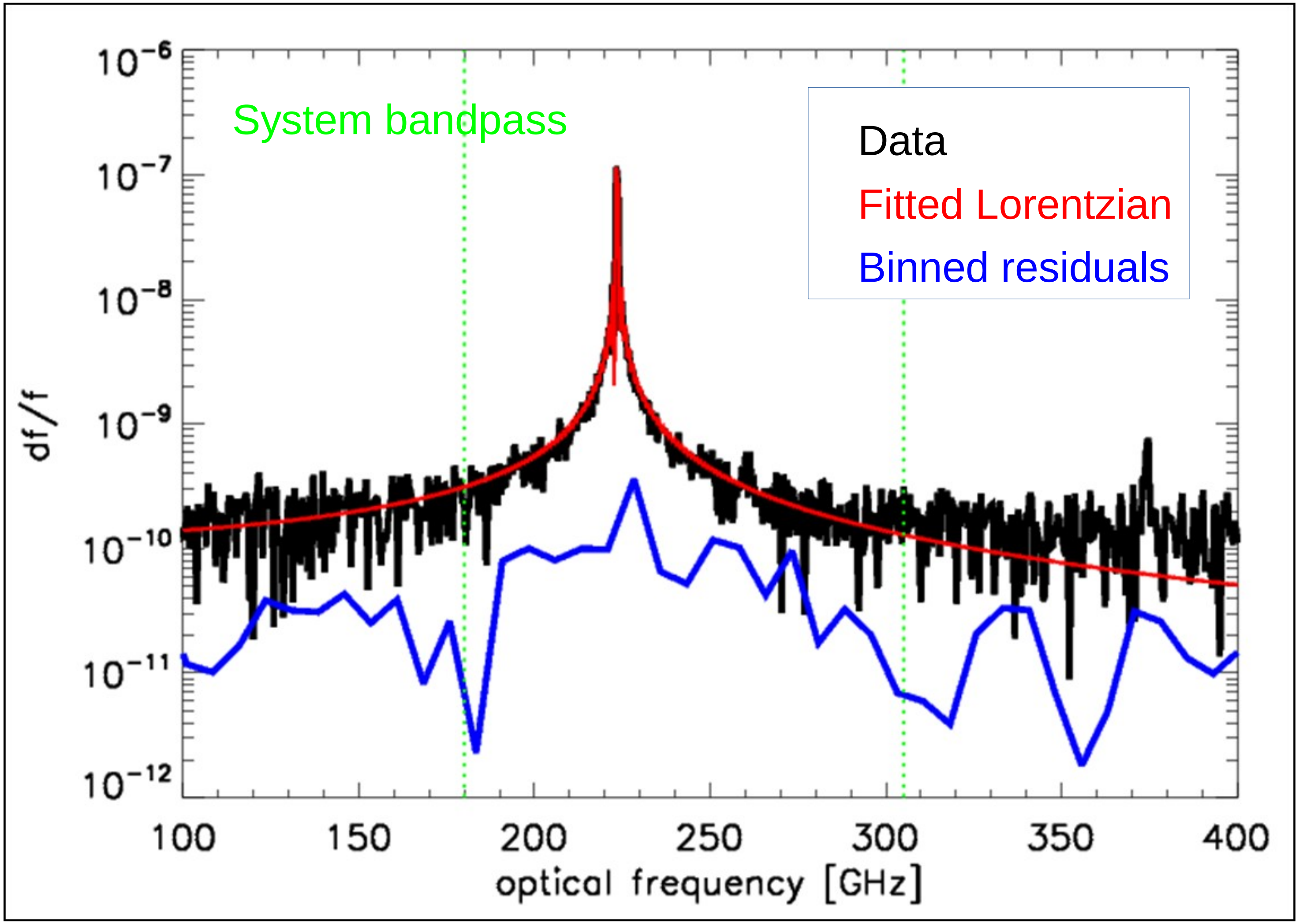
Lens-coupled twin-slot antenna design for fast prototyping



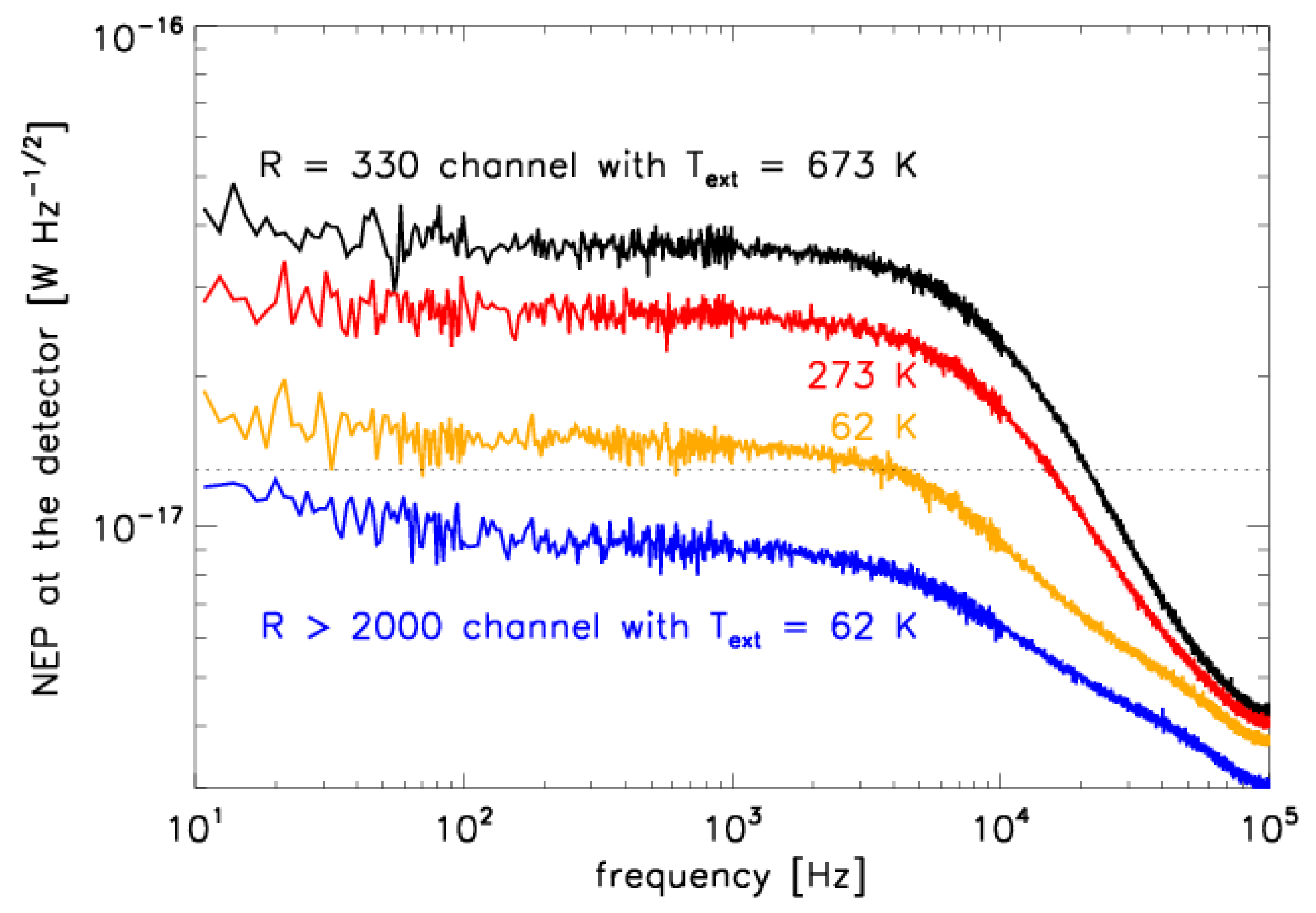




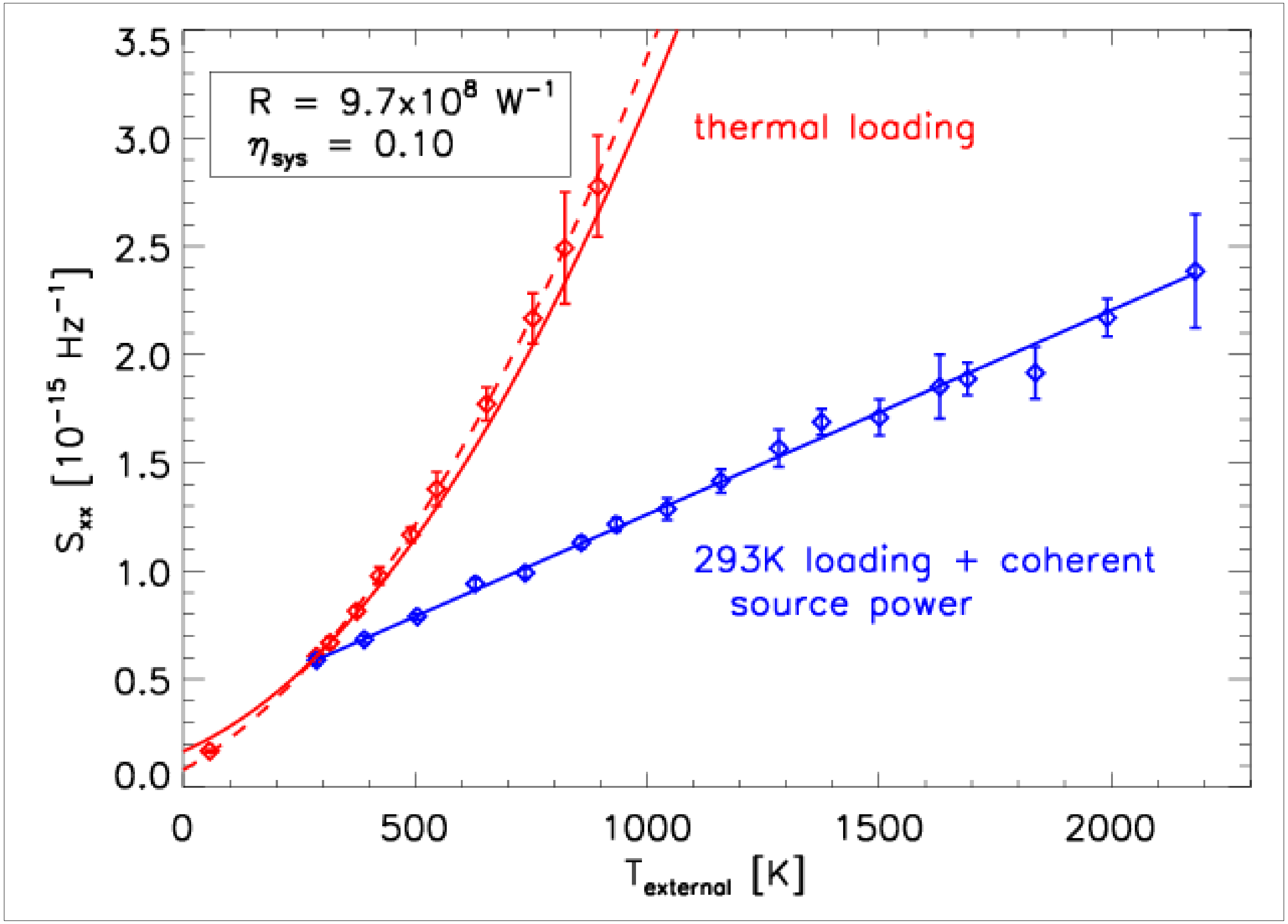
Horns offer excellent out-of-band rejection ($1:10^4$), but fabrication is challenging.



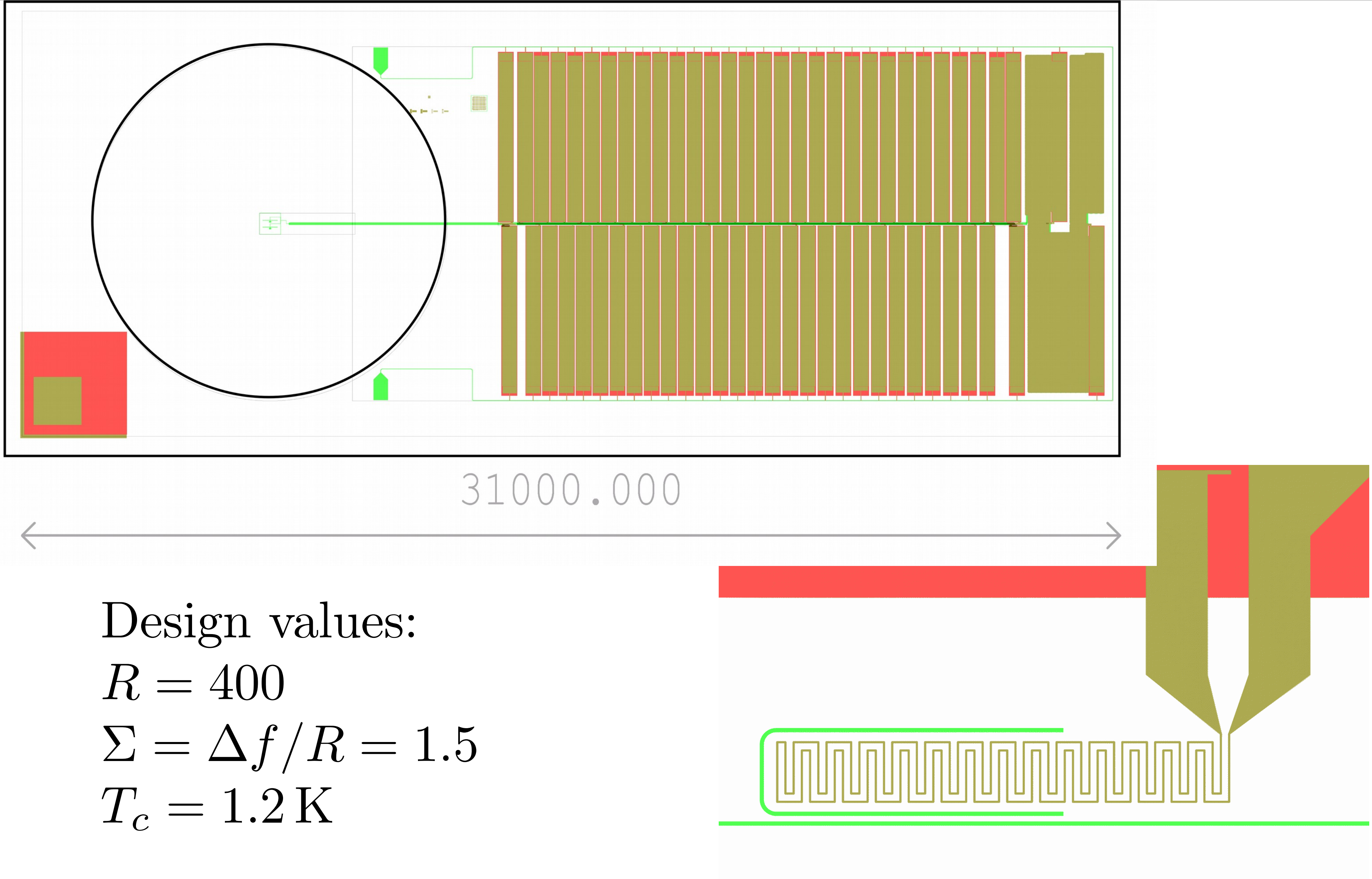
Photon-limited NEP



Photon noise allows us to measure efficiency and absolute sensitivity in physical units.



New 50 channel uniform filter bank with lithographically adjustable mm-wave features



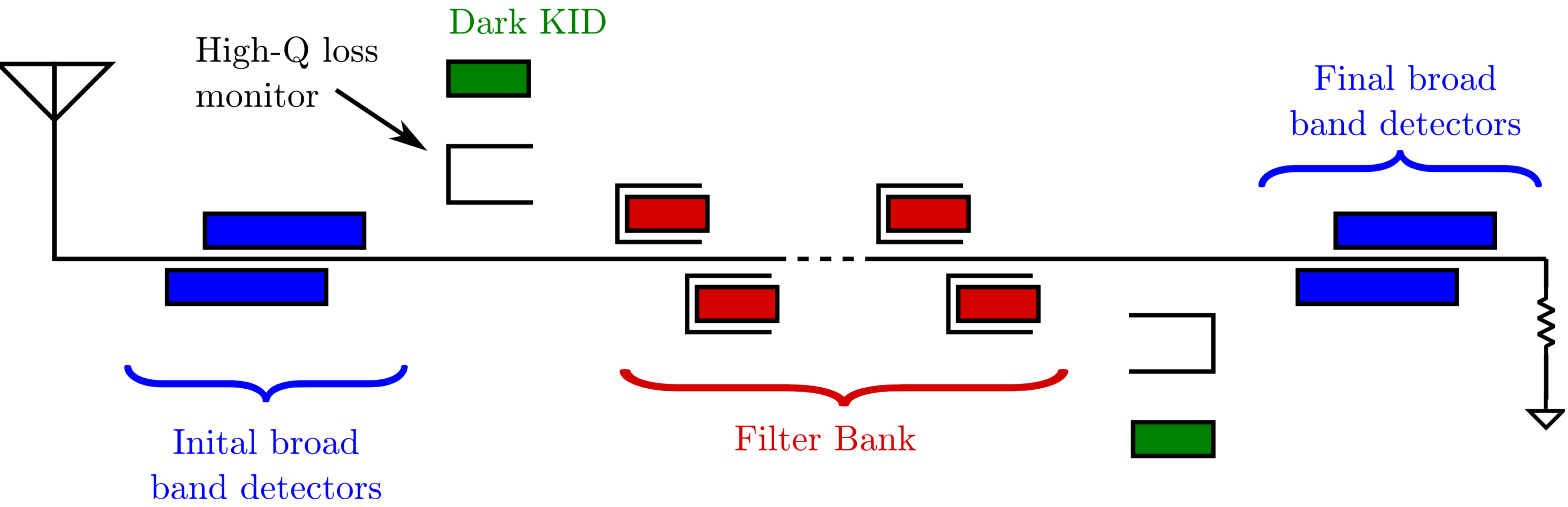
Design values:

$R = 400$

$\Sigma = \Delta f / R = 1.5$

$T_c = 1.2\,\mathrm{K}$

Test structures allow for unambiguous fitting to mm-wave channel properties.

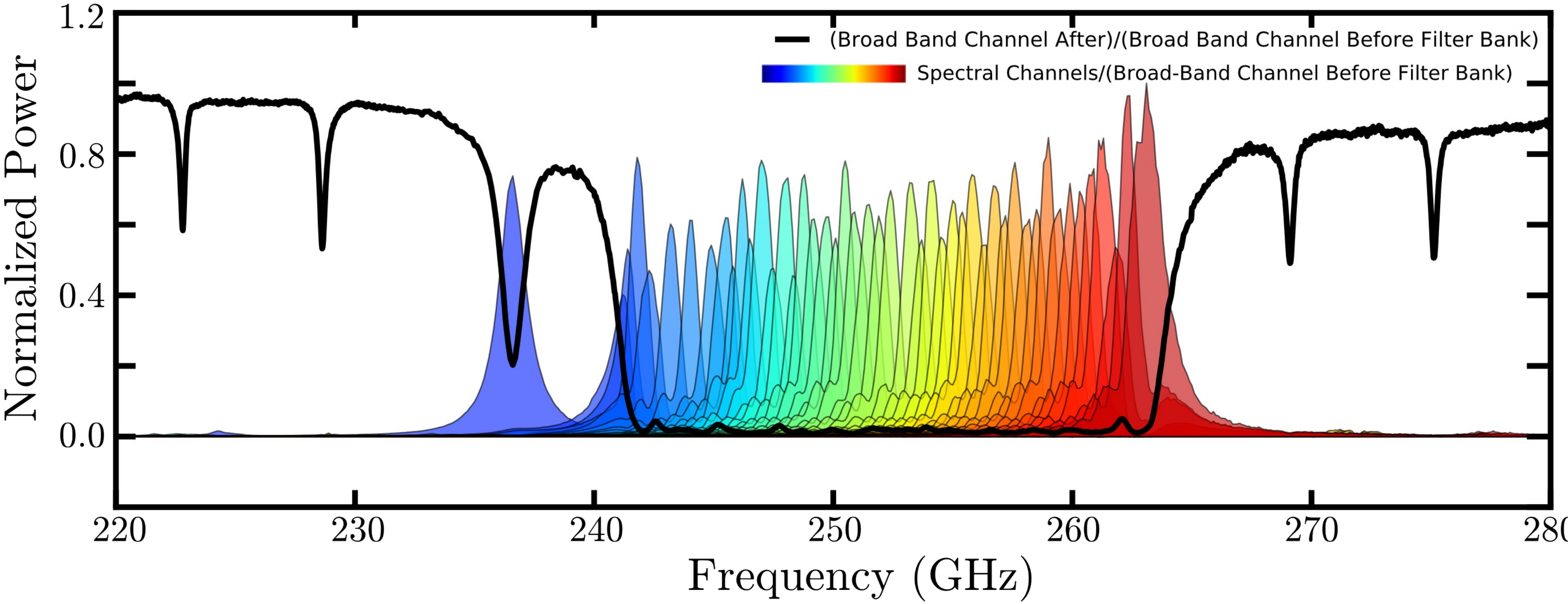


Broad-band detectors absorb ~0.1% of mm-wave power on feedline before and after filter bank.

These are long, staggered, to avoid standing wave confusion.

Pairwise differencing of fore/aft/channel KIDs (over) constrain Qc, Qr of channels.

50 Channel mm-wave prototype shows good uniformity, reasonable parameters



PRELIMINARY RESULTS:

100% yield (on 2 dies)

$T_c = 1.8\,\mathrm{K}$, (designed for 1.2)

$\mathrm{NEP} \approx 1.5 \times 10^{-17} \mathrm{W}/\sqrt{\mathrm{Hz}}$

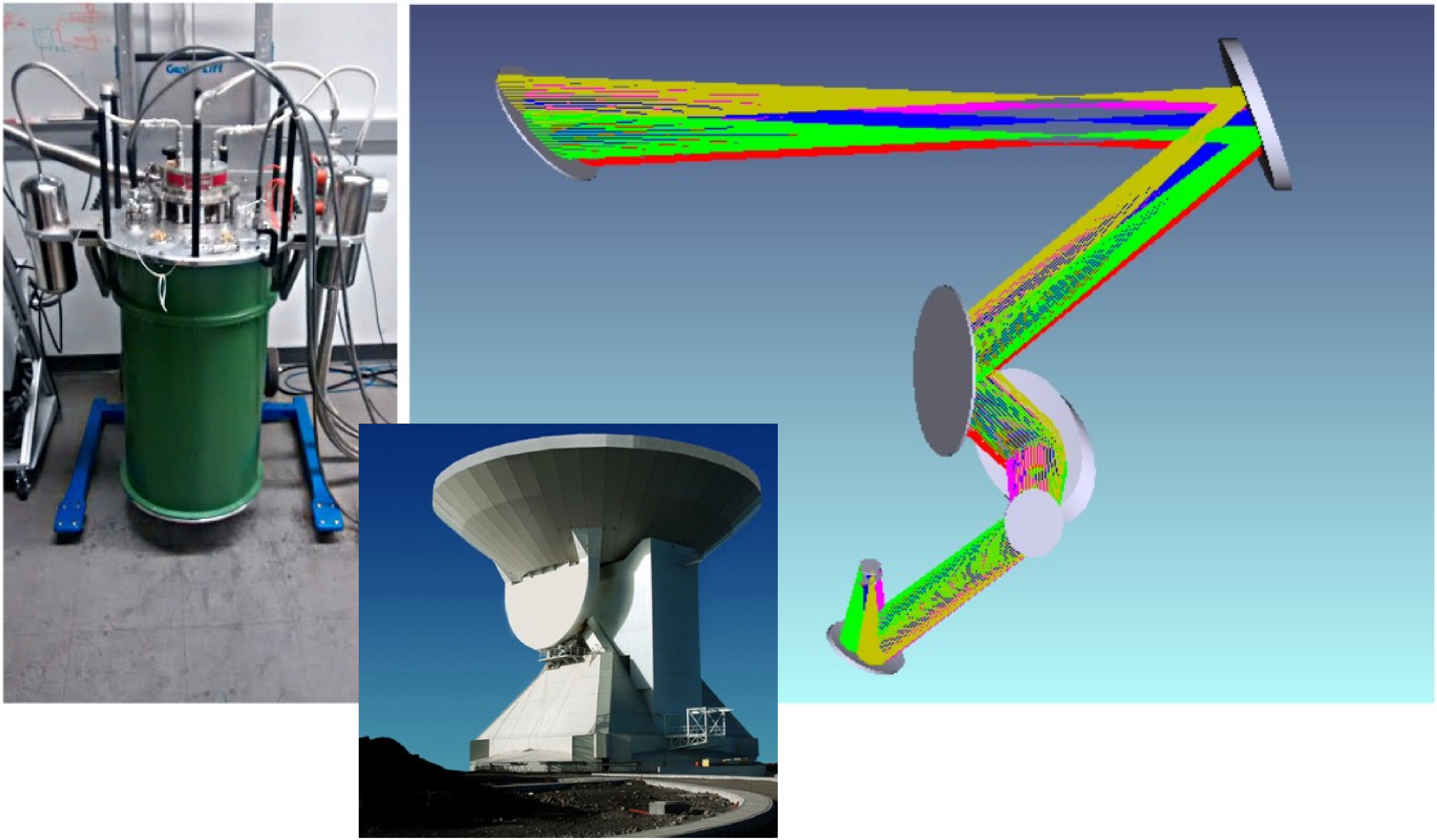
$Q_i^{\mathrm{mm}} \approx 600$

$Q_c^{\mathrm{mm}} \approx 400$

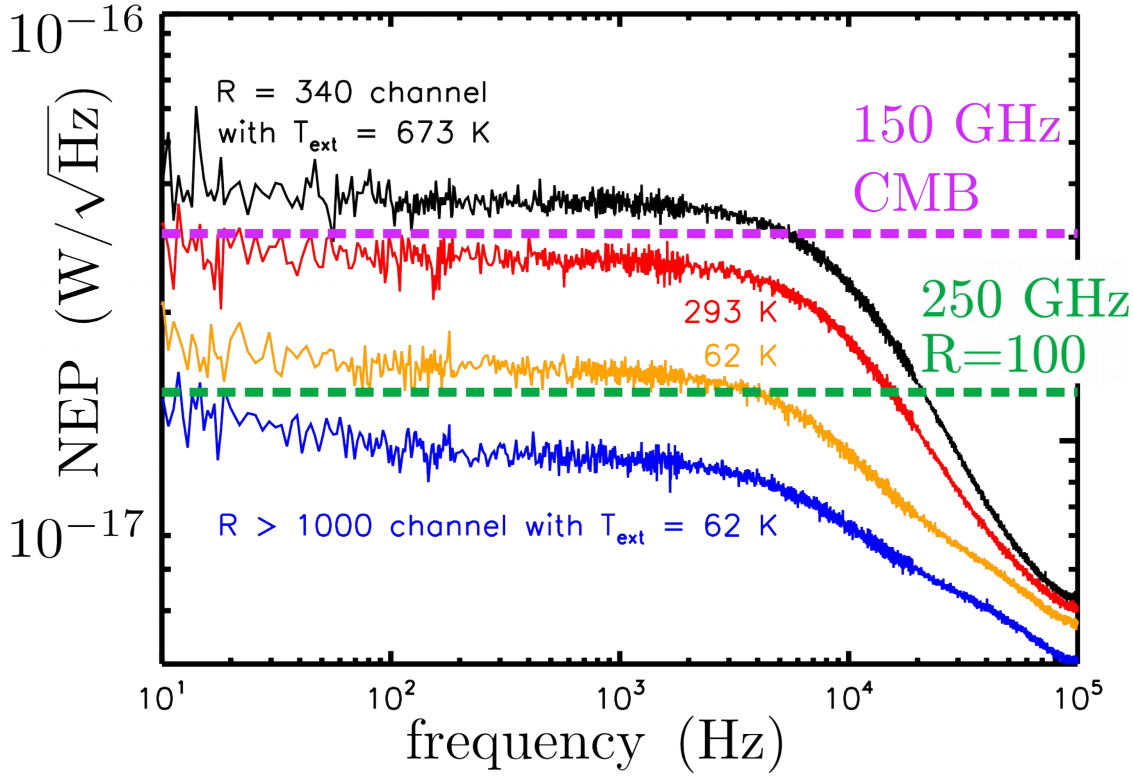
$Q_{\mathrm{loss}}^{\mathrm{mm}} \approx 1400$

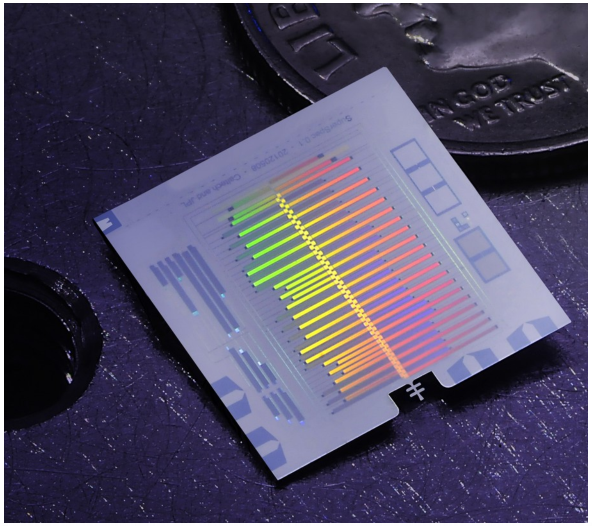
$R^{\mathrm{mm}} \approx 200$

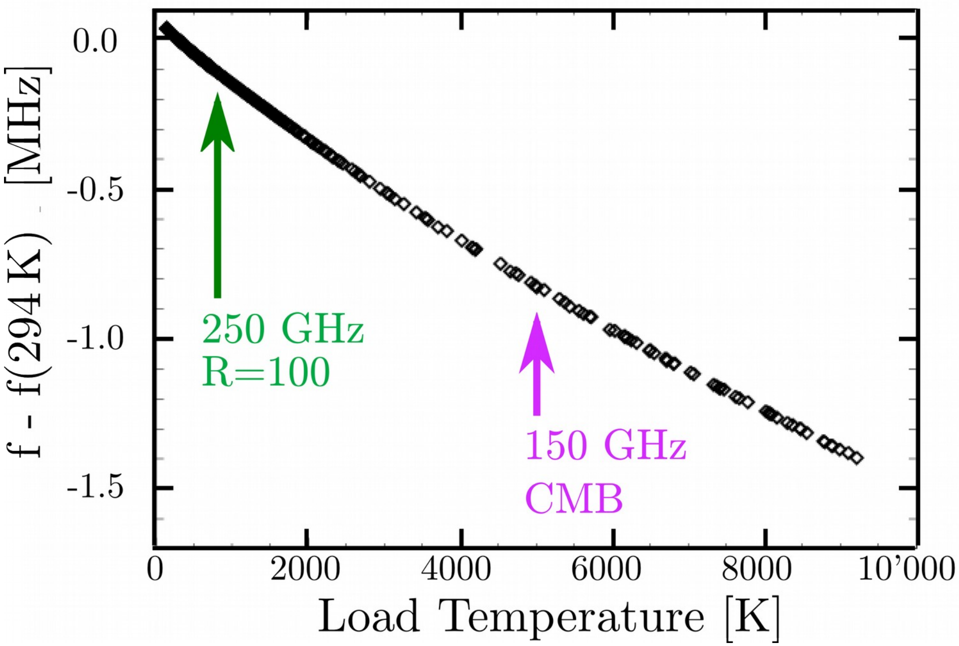
Early 2018: deploy a 4 pixel demonstration instrument at the 50 meter LMT in Mexico



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







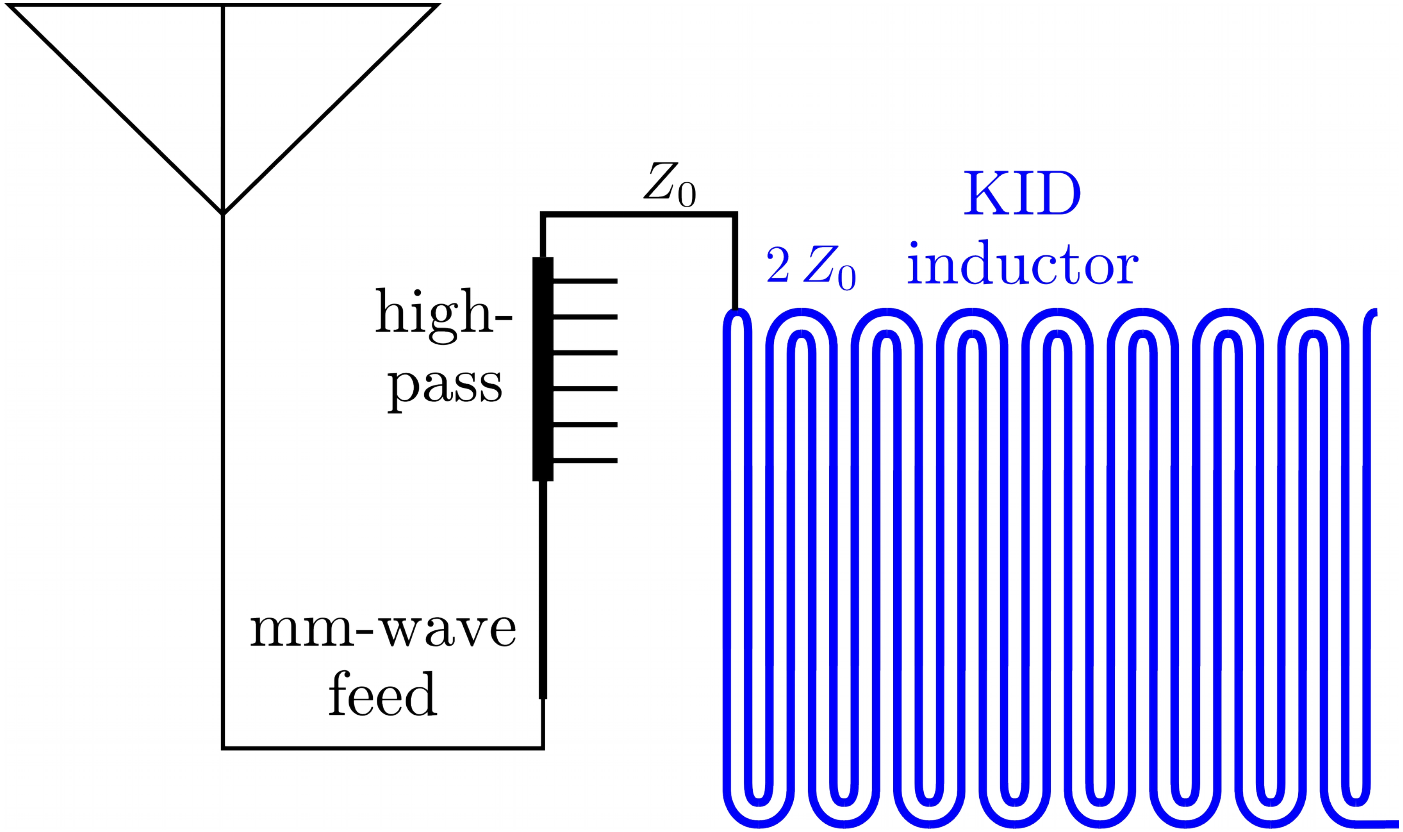
Conservative, P/V conserving estimates:

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

6× below background limit

Fig by S. Hailey-Dunsheath

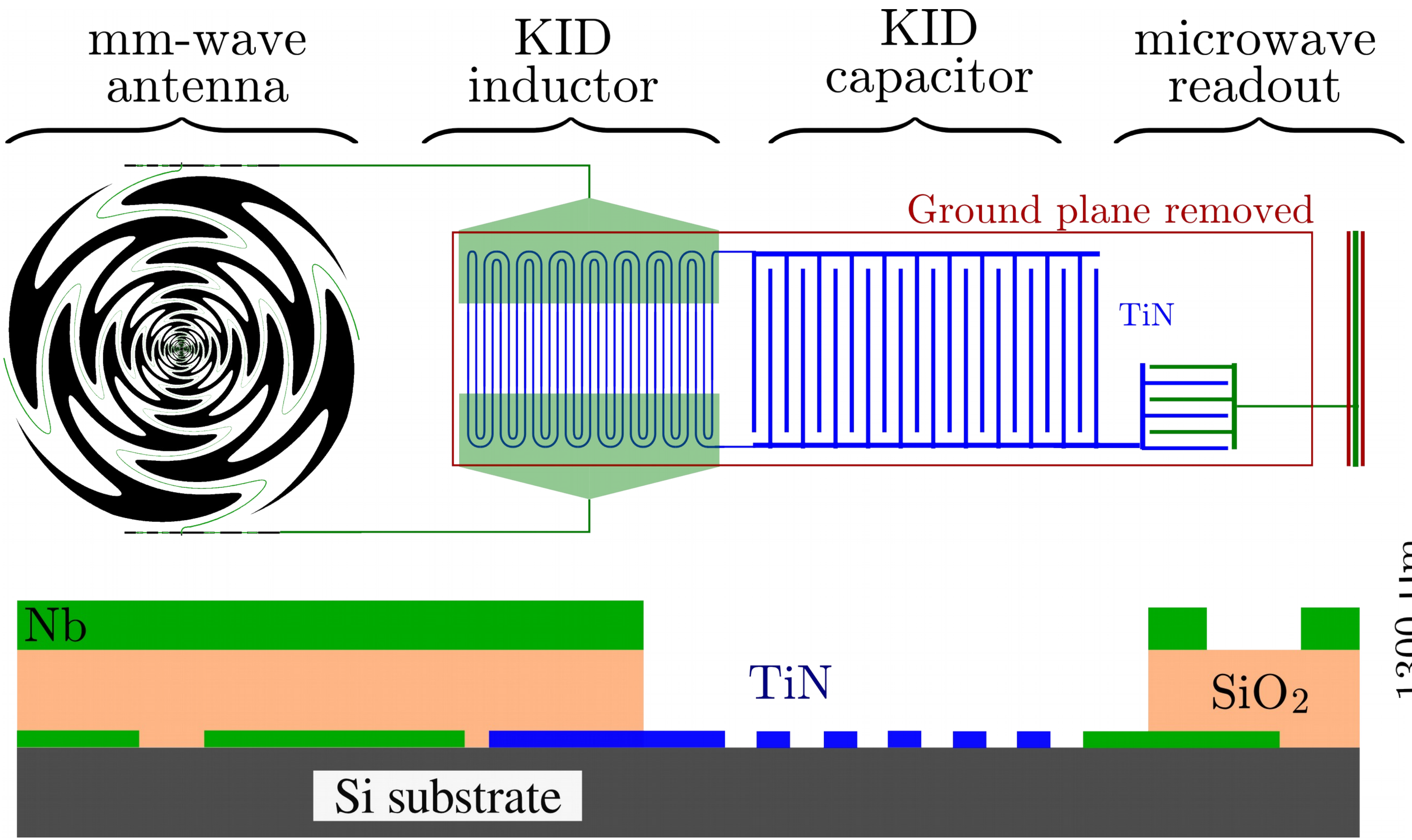
Impedance matched microstrip works for low-impedance materials (Al)

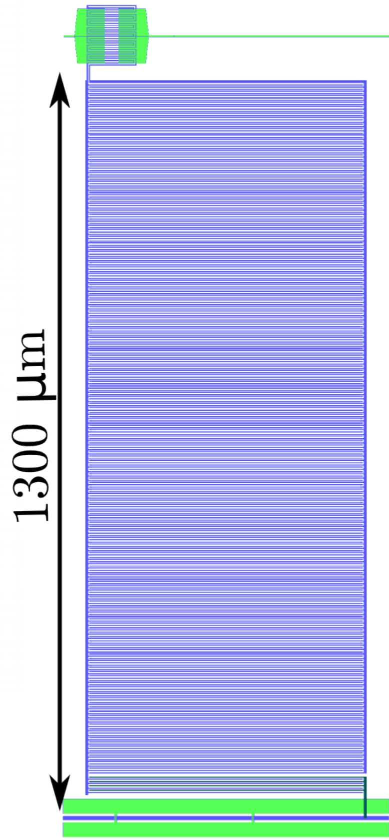


For materials with R_{normal} few $\Omega/\square$, either transmission-line KID or LeKID can work as dissipative mm-wave microstrip.

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

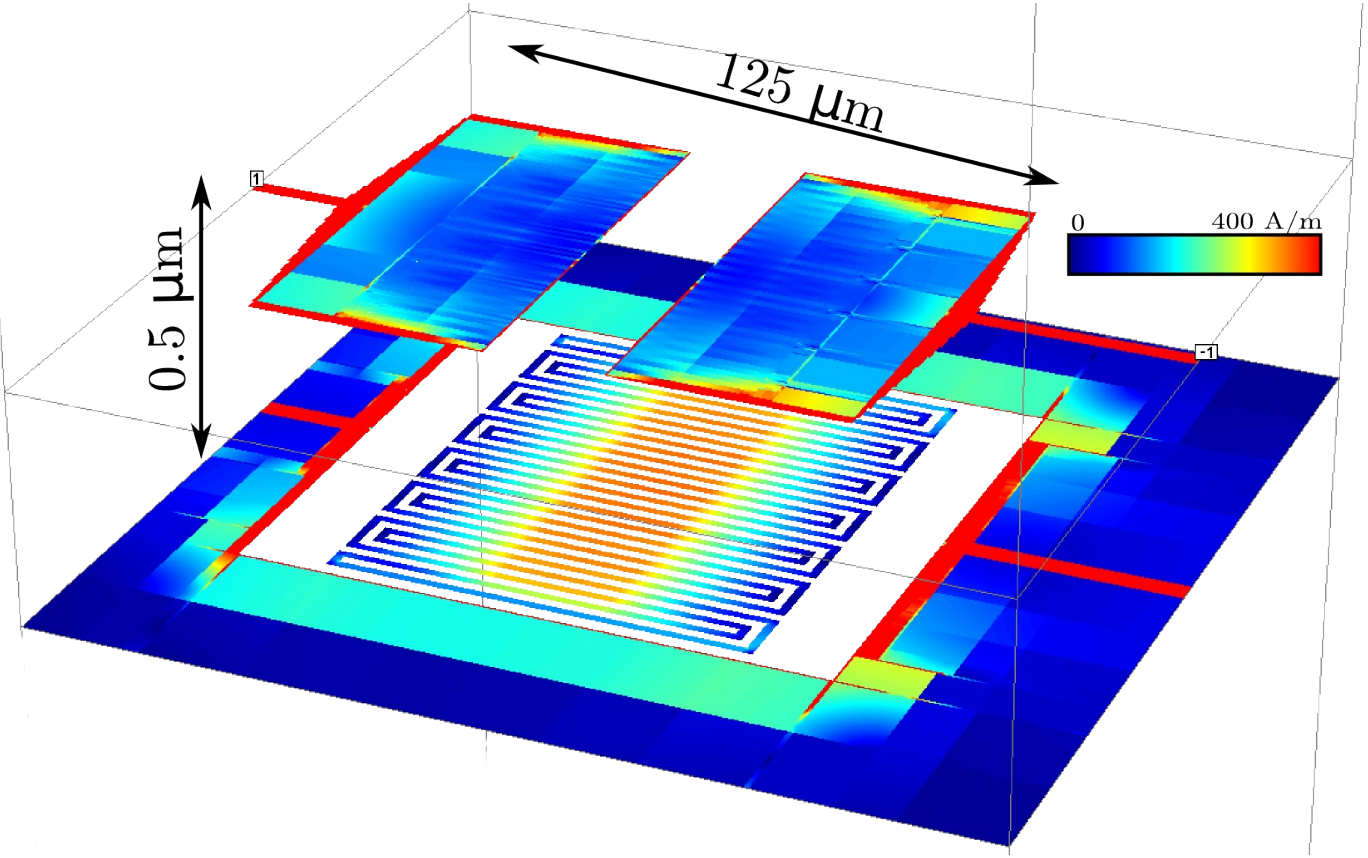
Chicago's CMB-KIDs program: Antenna-coupled, multi-band CMB pixels

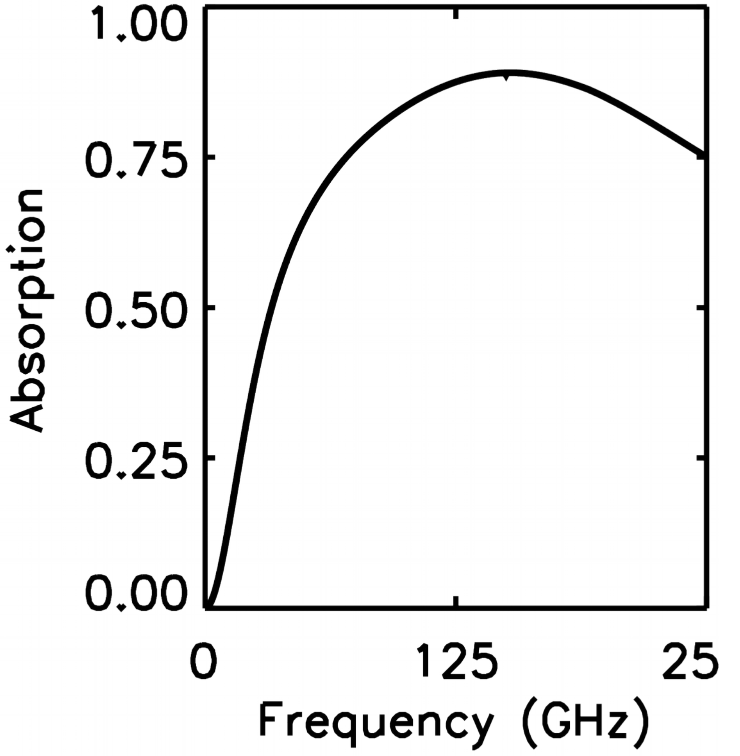




Note: figure is not (even remotely) to scale.

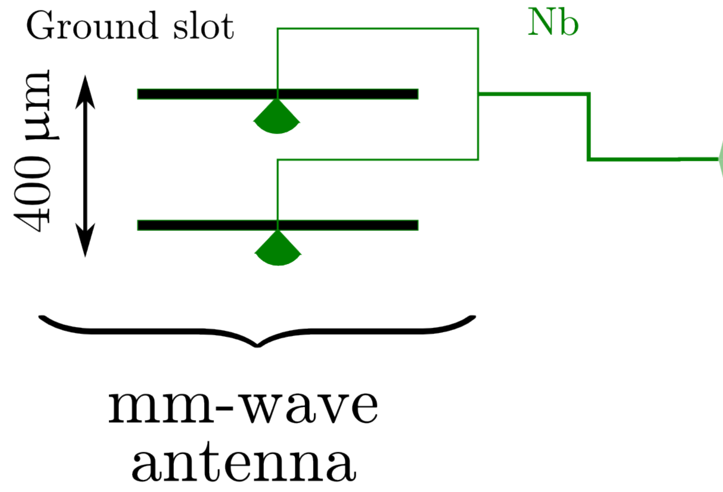
Broad-band mm-wave feed line to detector coupling is a new challenge.

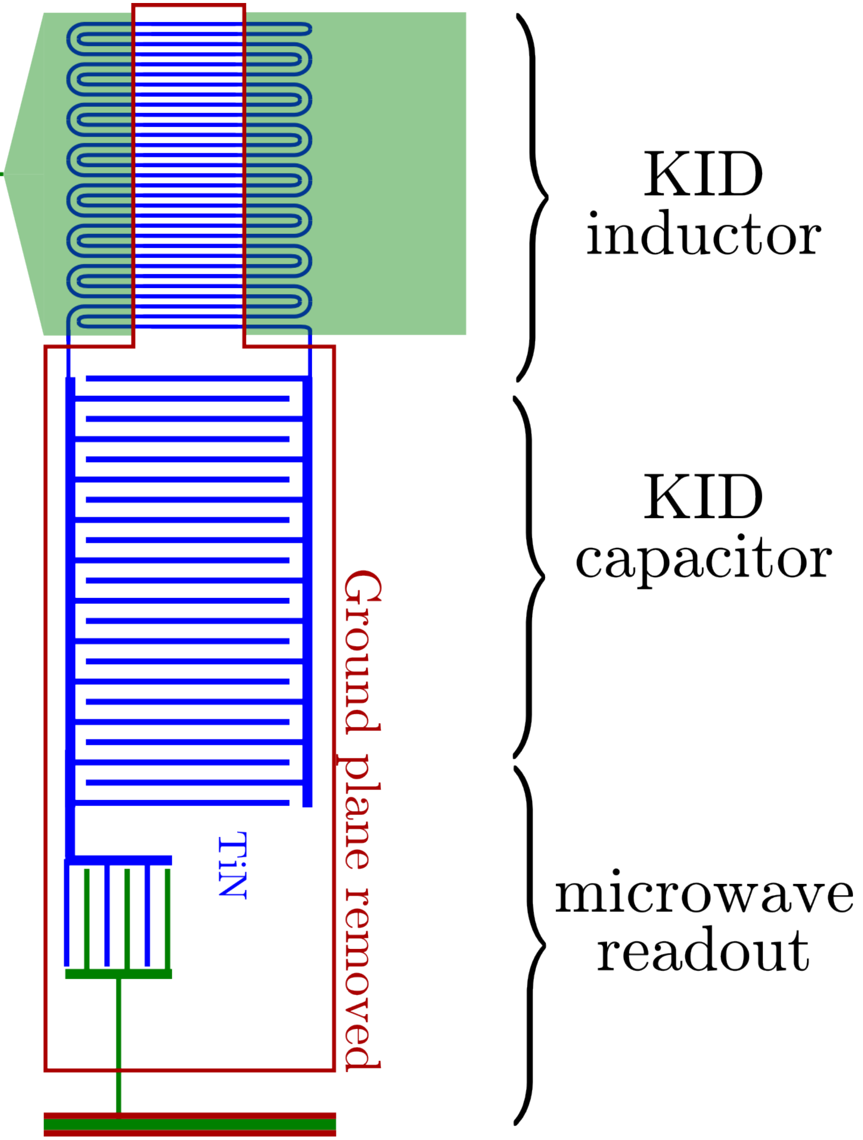


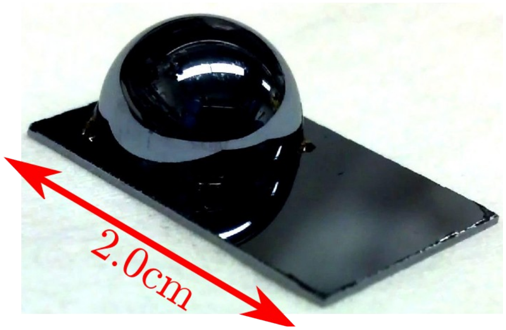


With very little optimization, this approach achieves >90% over any single CMB band. Further optimization seems likely to yield universal, multi-band coupling designs.

The single-band CMB demonstrator: a KECK-Array compatible KID focal plane.







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

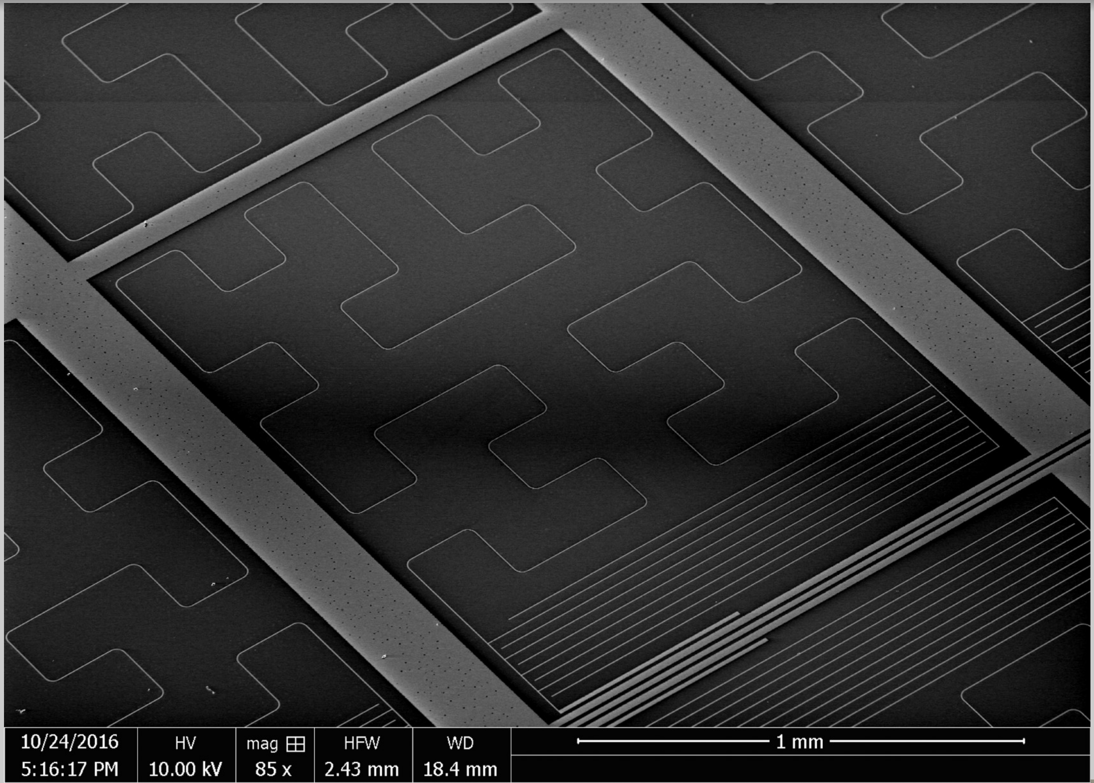
Current status

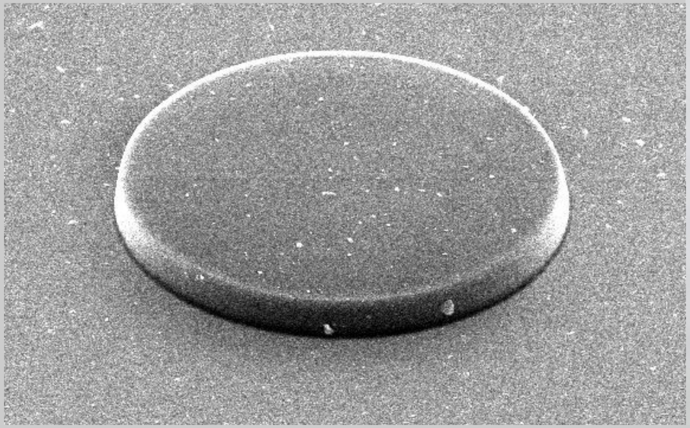
<u>Completed:</u>

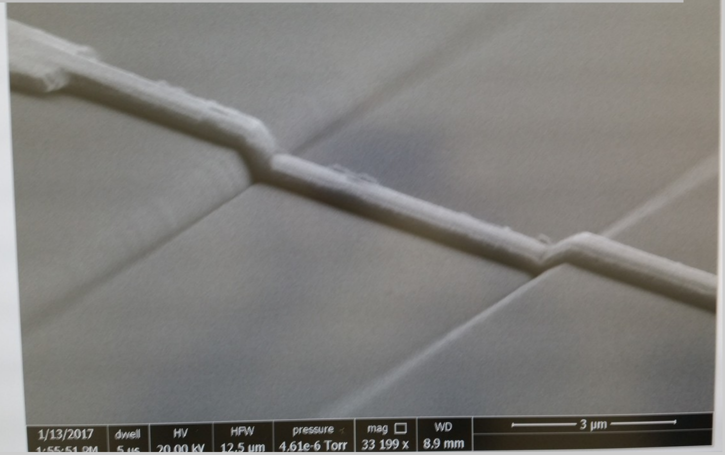
- Al resonators
- ALD TiN resonators
- Nb and Nb-Al bilayer microstrip
- DRIE & SU-8 lenslet mounting posts
- Twin-slot antenna design
- Cross-under microstrip design
- mm-wave KID coupling design

<u>In progress</u>

- AlMn resonators
- Ti/TiN multilayer resonators
- Full array layout
- Optical tests
- Multi-band filters





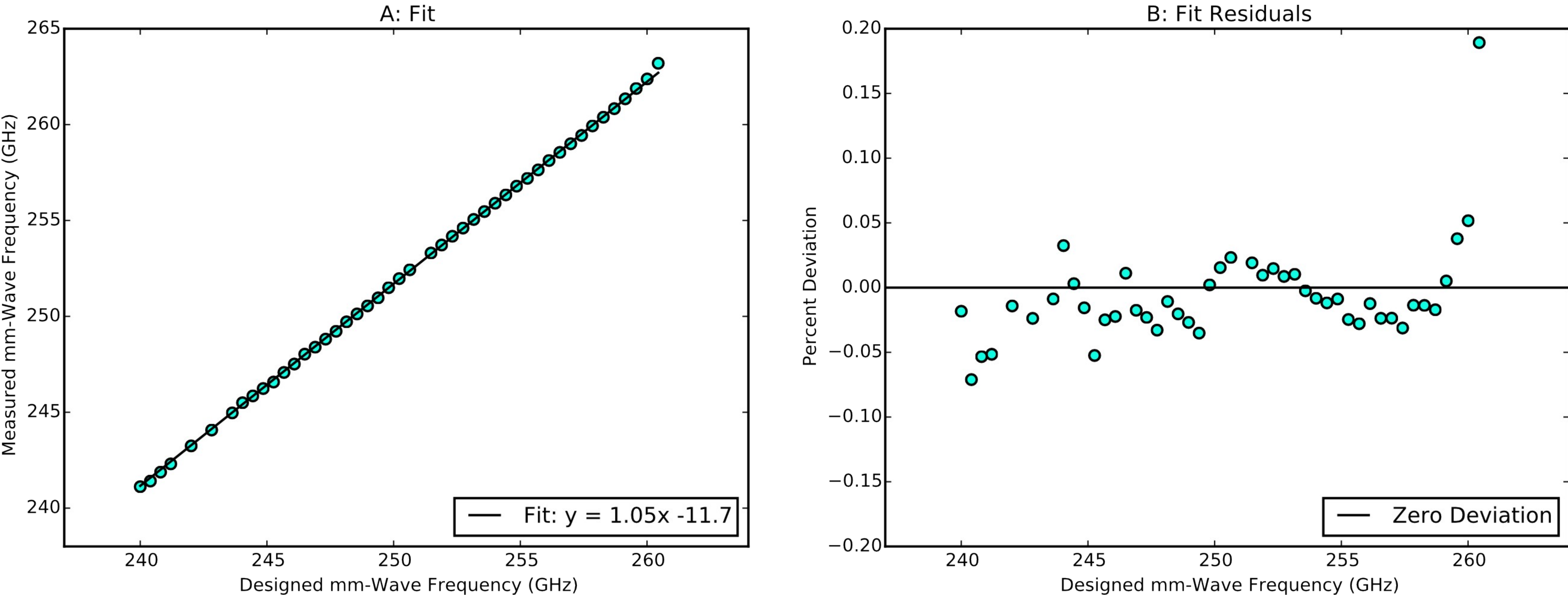


Conclusions

- There's a lot of exciting survey science at mm-wavelengths waiting to be done.
- KIDs have achieved background-limited performance.
- On-chip mm-wave circuits will revolutionize the science return of a single focal plane.
- It's time to deploy real instruments!

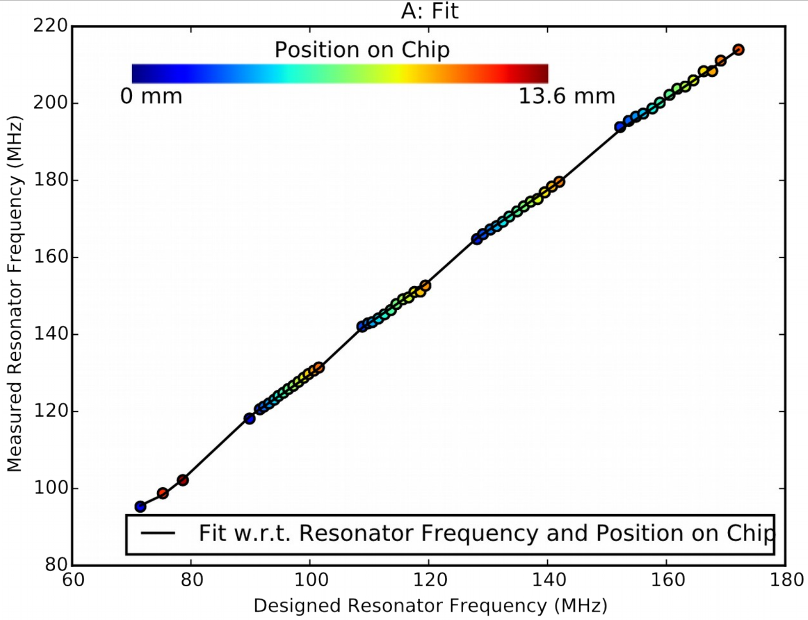
Extra slides follow

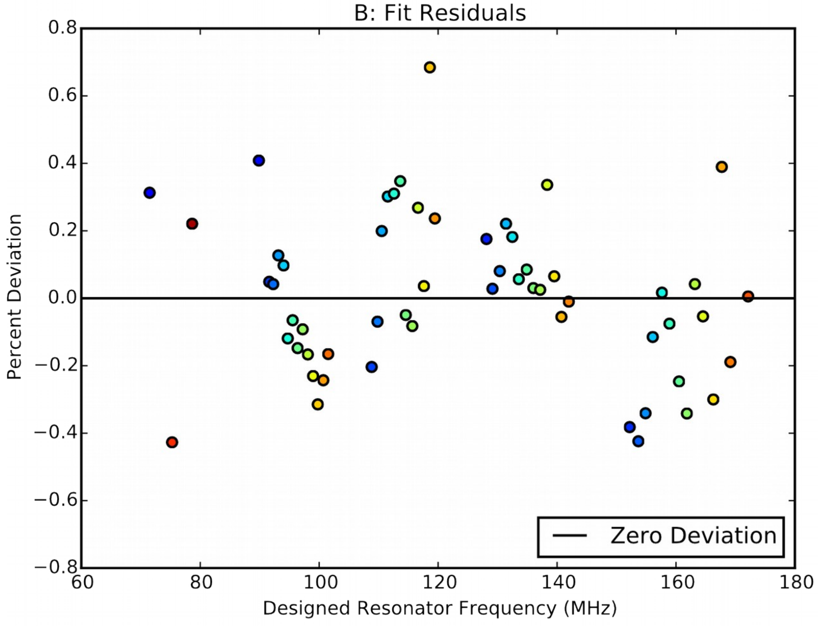
RMS scatter in mm-wave frequencies is 0.04%



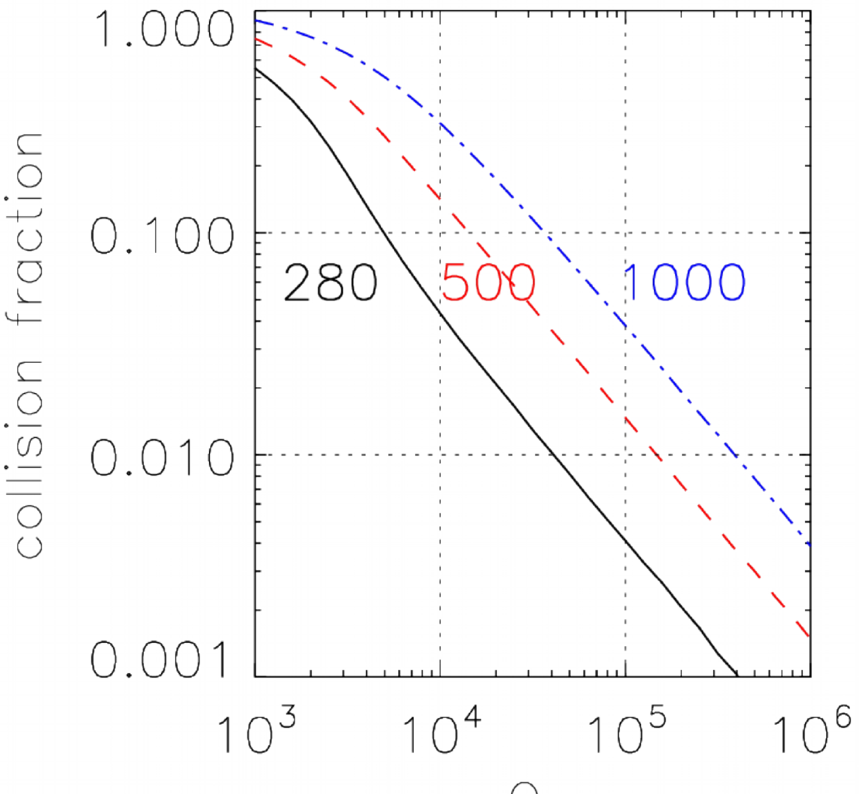
This is ~6X FWHM for an R=400 channel.

RMS scatter in readout frequencies is 0.2%





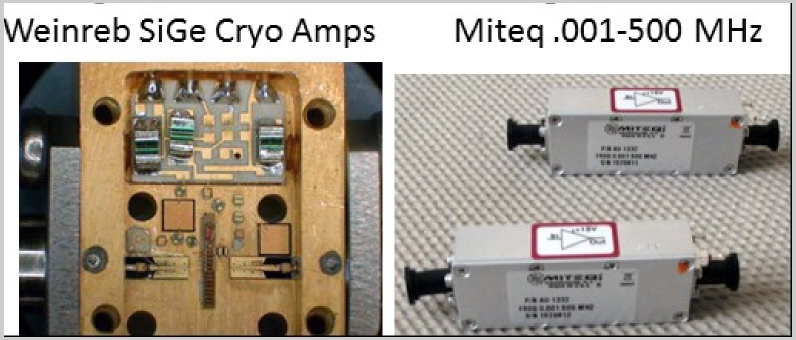
0.2% scatter →
1 collision in 280 $Q_r = 10^5$
resonators per octave



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

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

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



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

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

		Sensitivity (μK^2)	$\sigma(r)$	$\sigma(N_{\mathrm{eff}})$	$\sigma(\Sigma m_\nu)$	Dark Energy F.O.M
2015	Stage 2 1000 detectors				Boss BAO prior	DES+BOSS SPT clusters
2016		$\gtrsim 10^{-5}$	0.035	0.14	0.15eV	~180
2017	Stage 3 10,000 detectors					
2018						
2019					Boss BAO prior	DES + DESI SZ Clusters
2020		10^{-6}	0.006	0.06	0.06eV	~300-600
2021	Stage 4 CMB-S4 ~500,000 detectors					
2022						
2023					DESI BAO $+\tau_e$ prior	DESI +LSST S4 Clusters