

On-chip spectroscopy using KIDs and mm-wave circuits

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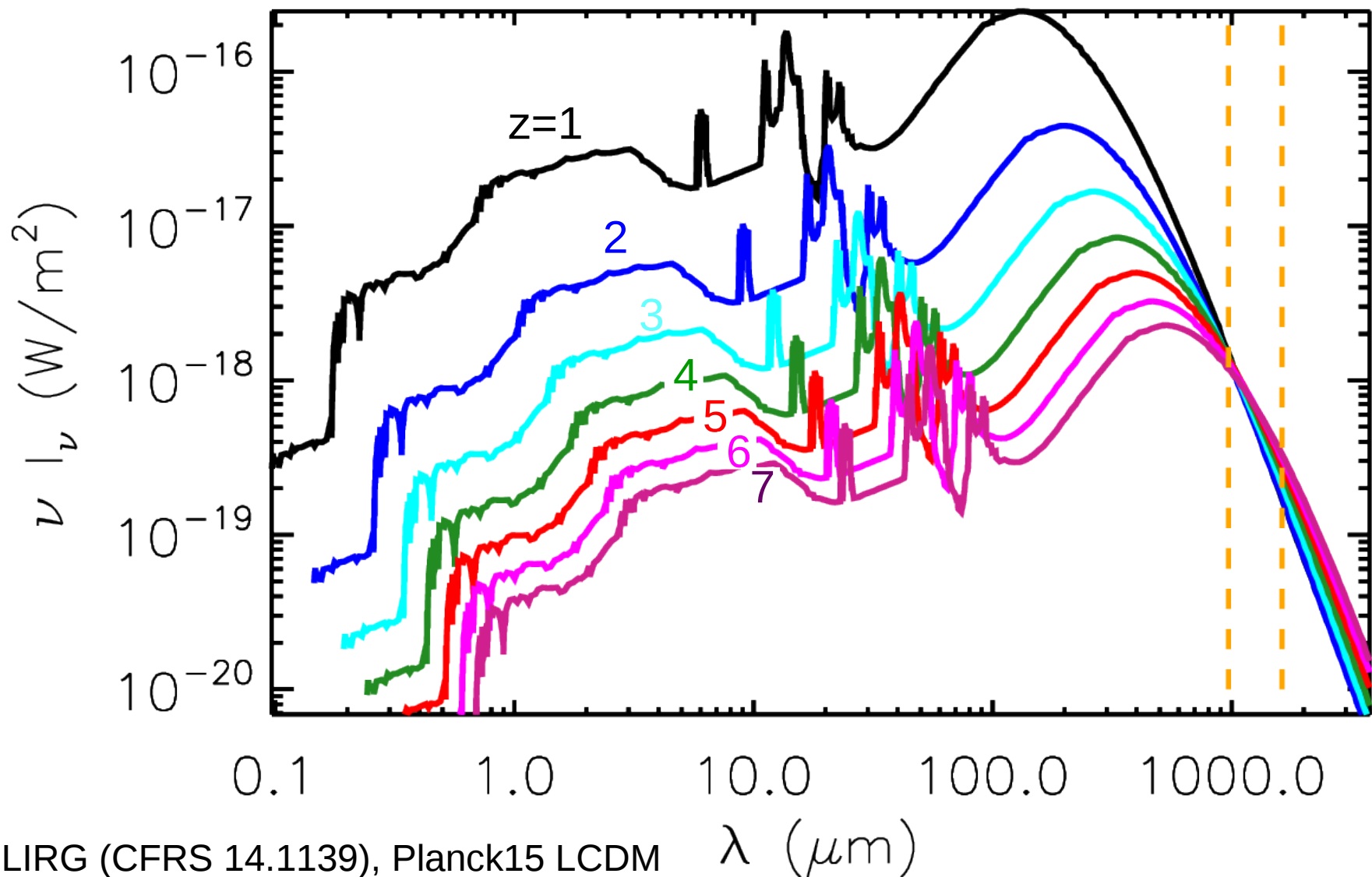


Outline

- Dusty, star forming galaxies at high redshift
- SuperSpec technology: On-chip spectroscopy
- SuperSpec instrument: a redshift finder for the LMT.
- Porting Superspec design features to a broad-band, dual-pol camera

Negative K correction is great for uniform surveys, terrible for finding photo-zs.

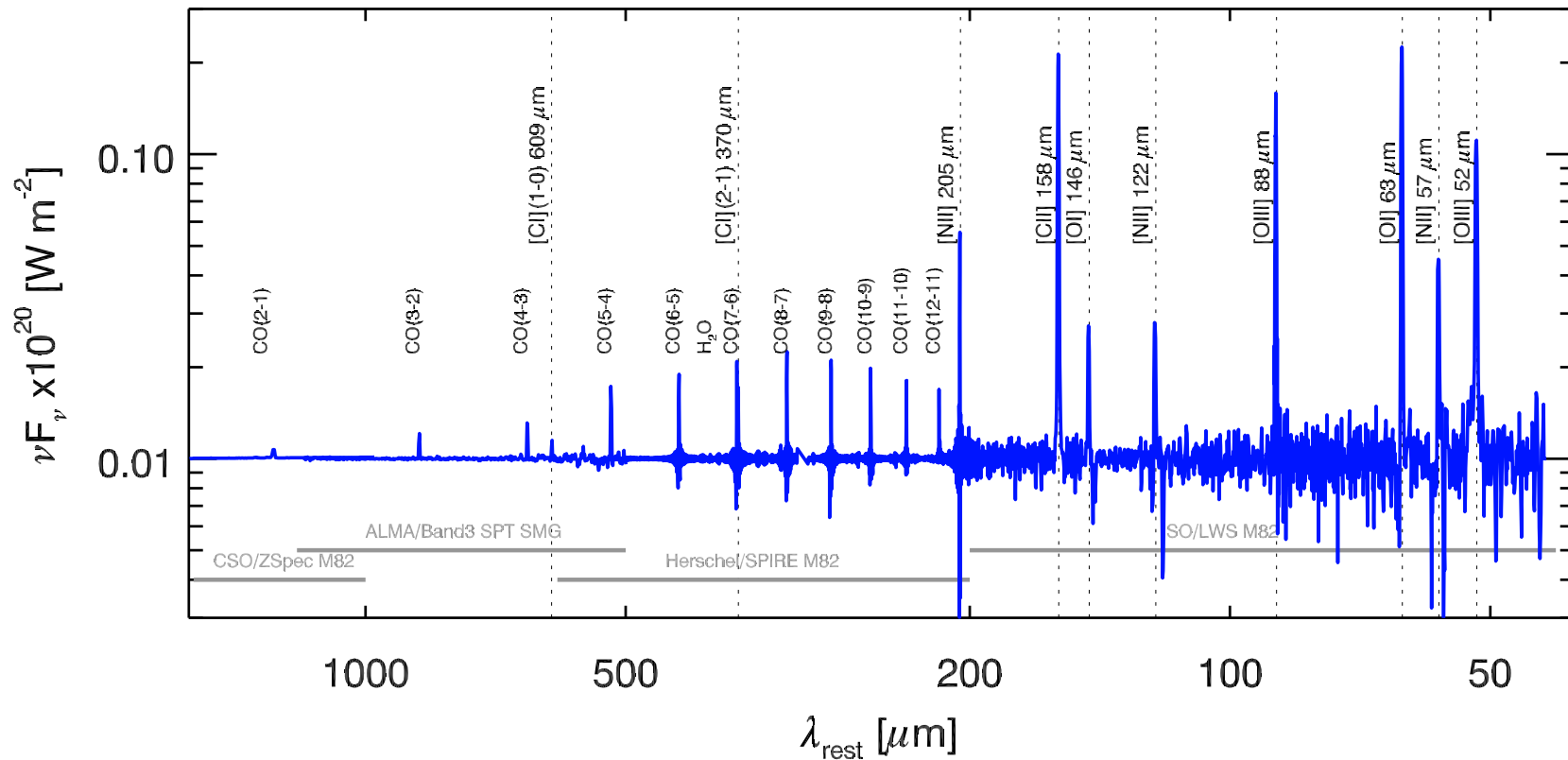
Redshift-scaled SMG spectrum



ULIRG (CFRS 14.1139), Planck15 LCDM scaling, data from Galliano 2007

λ (μm)

Continuum-subtracted spectrum of a starburst galaxy shows atomic and molecular lines at wavelengths of a few hundred microns.



Continuum-subtracted far-IR to mm-wave spectrum of M82 – Figure by J. Vieira

Spectral lines in the 195-310 GHz atmospheric window.

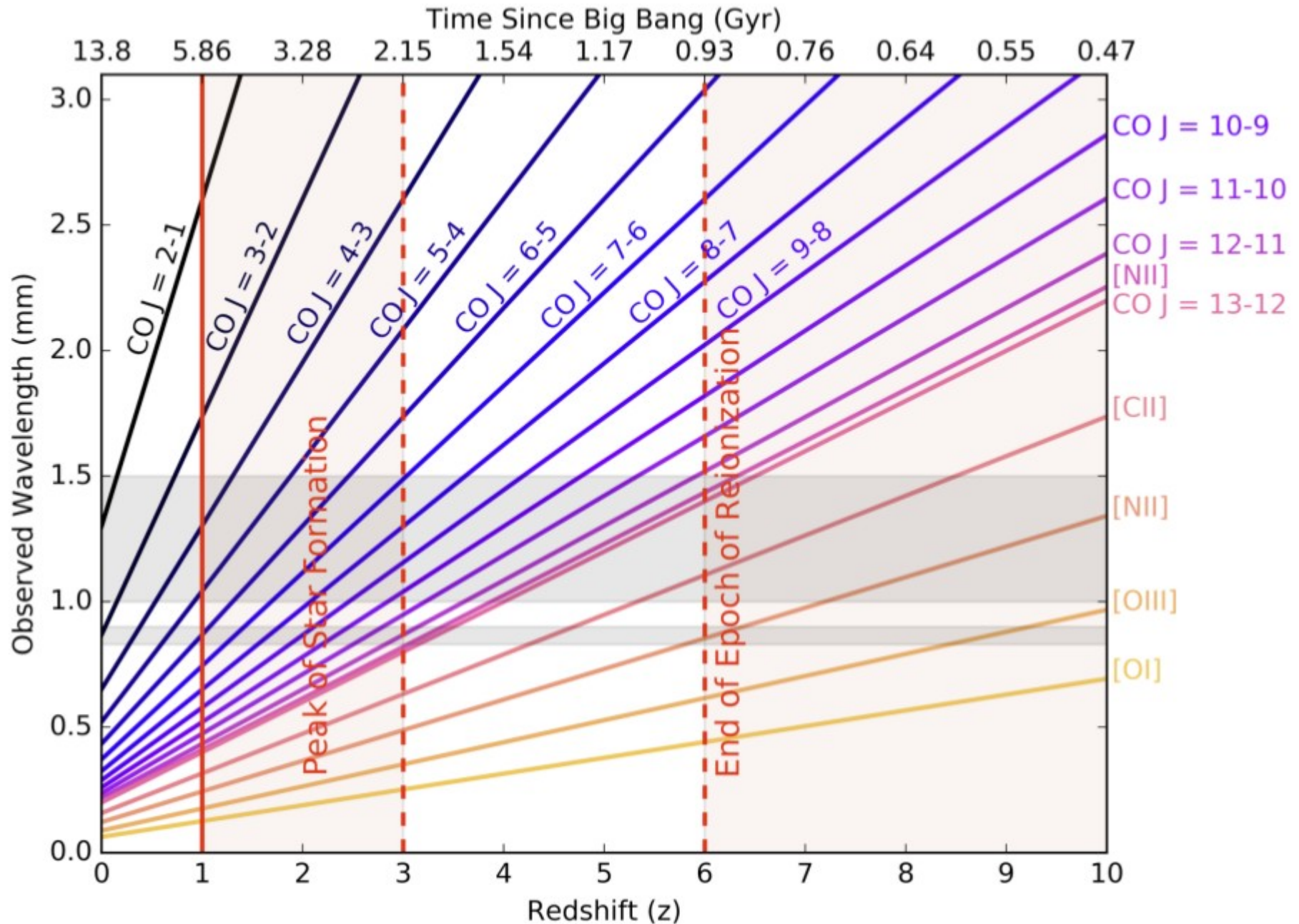
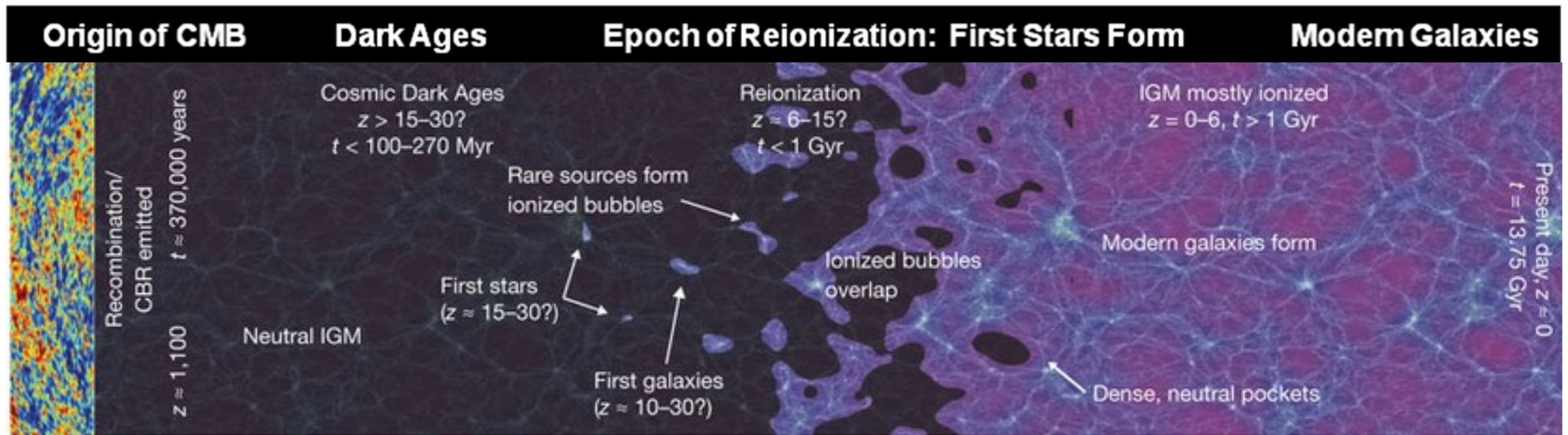
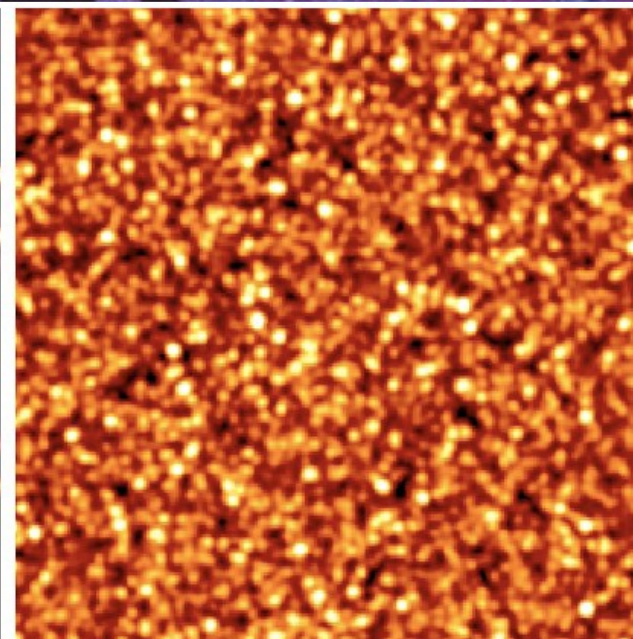
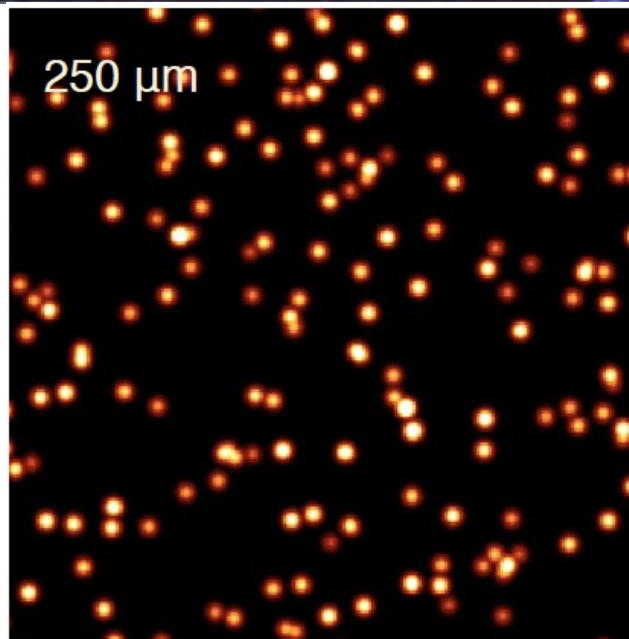


Figure from J. Glenn

Epoch of Reionization: the period when the first stars and quasars ionized most of the hydrogen in the Universe.



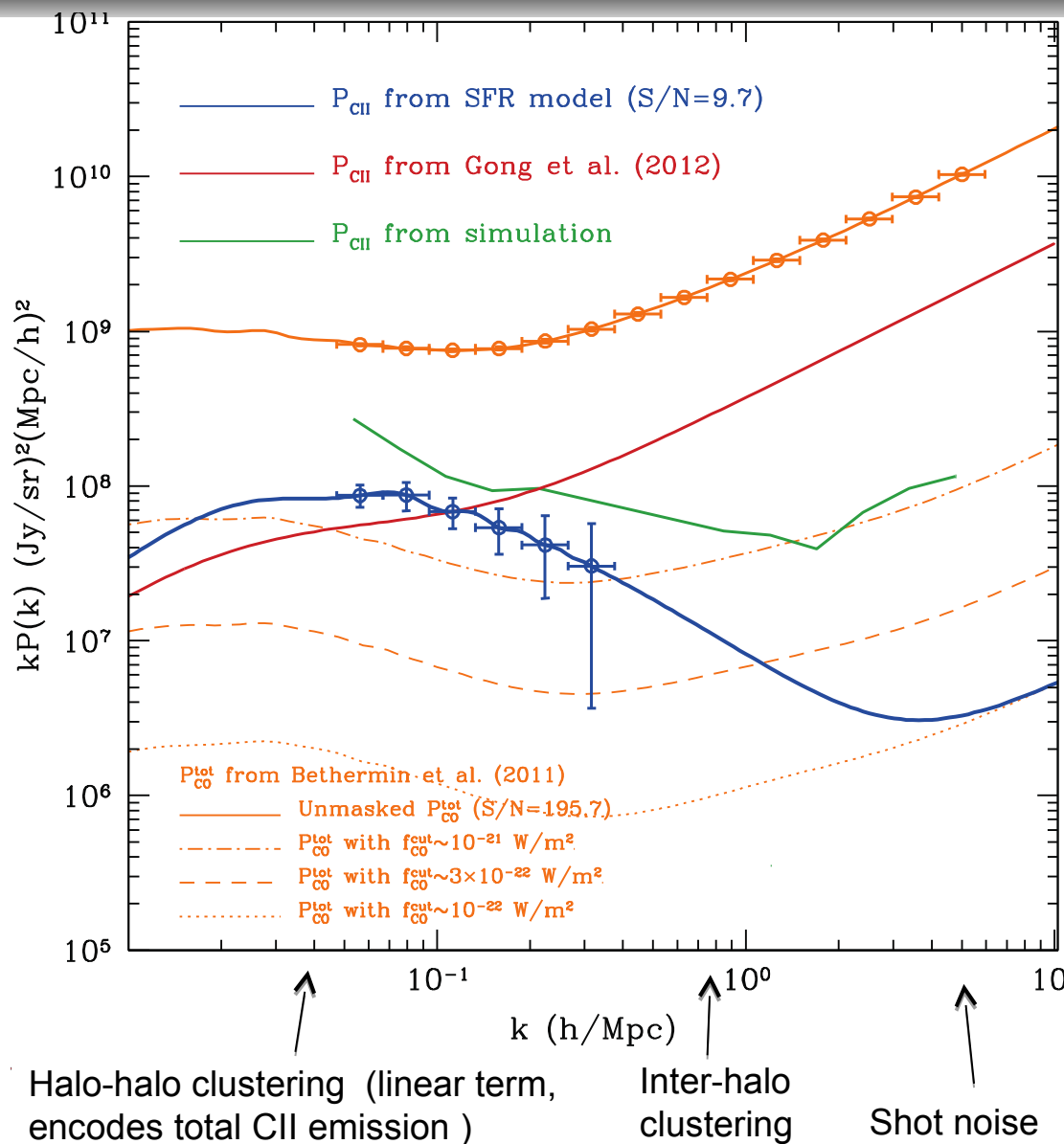
Dunlop & McLure



$S > 20$ mJy : 1,200/deg²

$S < 20$ mJy : 480,000/deg²

CII auto-correlation spectrum shows total star formation, clustering, in fine redshift slices. Cross-correlations with future high-z 21cm surveys will probe EoR bubble size.



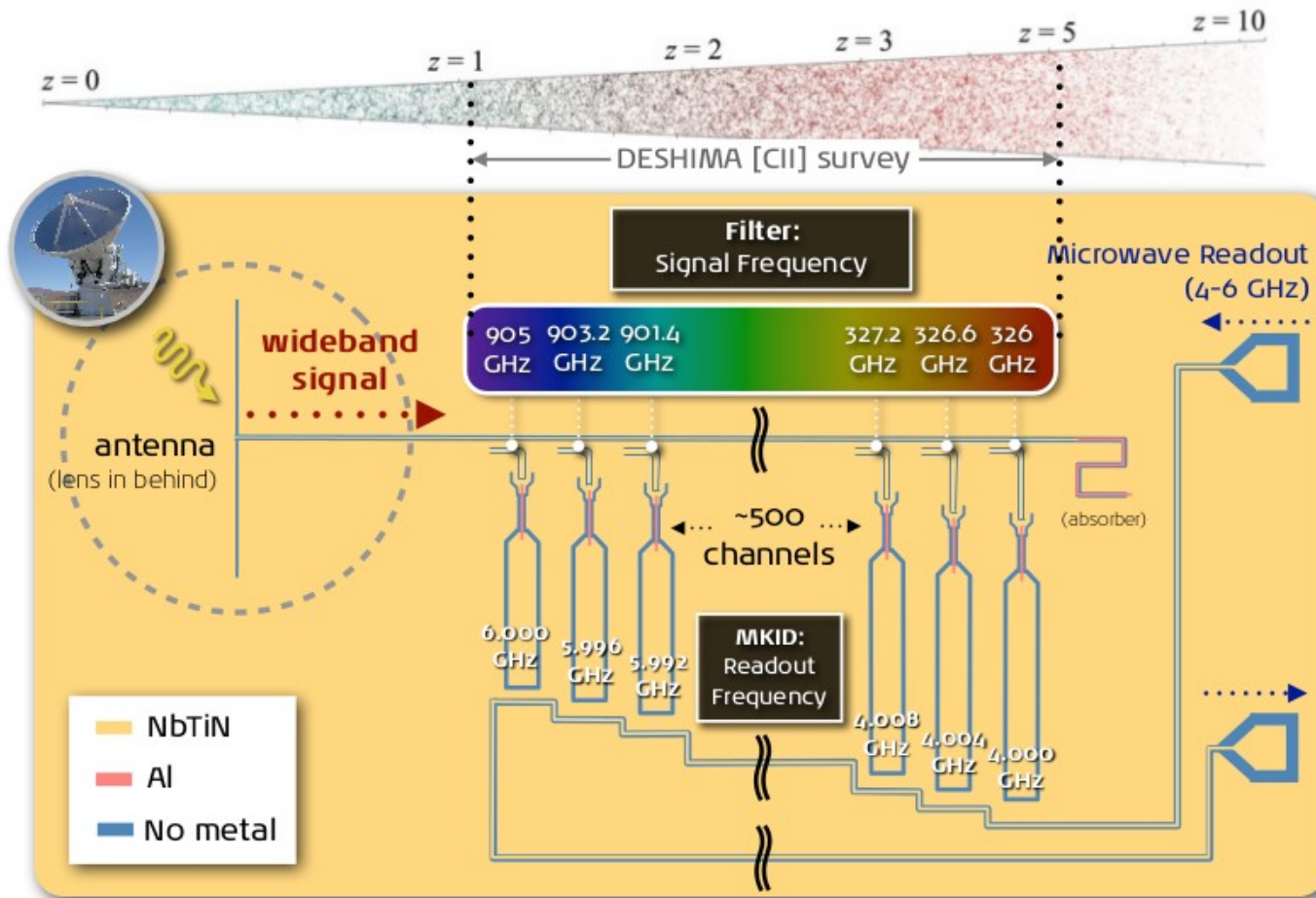
- [CII] autocorrelation spectra over the full TP band.
- [CII] EoR signal strength not known, consider various models.
 Constant SFR
 Gas physics calculation
 Millennium sim x 3e-3
- Error bars correspond to 240 hours on sky w/ JCMT.
- CO from $z \sim 0.5$ to 3 (multiple lines) is dominant signal in raw map (shown referred to CII survey geometry), but can be masked using galaxy catalogs.
- Cross correlations at CO frequencies with galaxy surveys can provide a CO census
- **Smaller beam on the LMT greatly reduces concern about foreground CO emitters**

Figure: Bradford /TIME

We're not the only ones working on these technologies.

DESHIMA

Concept: Superconducting on-chip filterbank spectrometer



Deploying to ASTE this year!

Others:

Micro-Spec (Goddard)

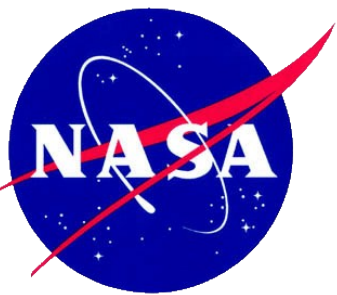
W-Spec (ASU)

Figure: A. Endo; collaboration: TU Delft, SRON, Leiden, U. Tokyo, NAOJ

Caltech



University
of Colorado
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Caltech/JPL

C. M. Bradford

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Cardiff University

S. Doyle

C. E. Tucker

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J. Glenn

J. Wheeler

S. Walker

INAOE Puebla

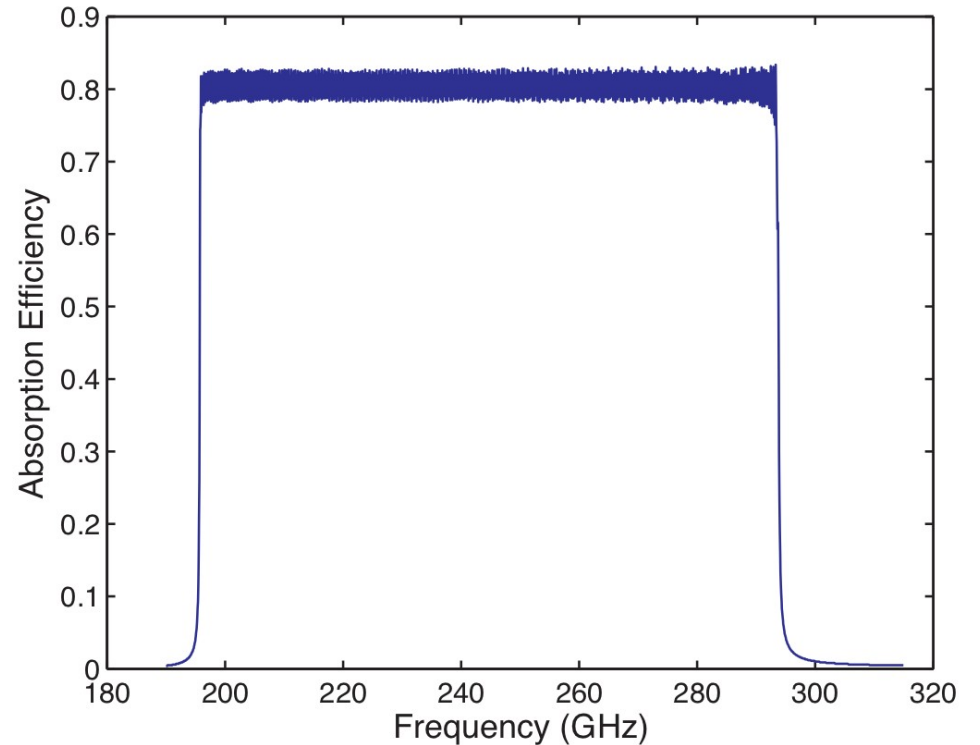
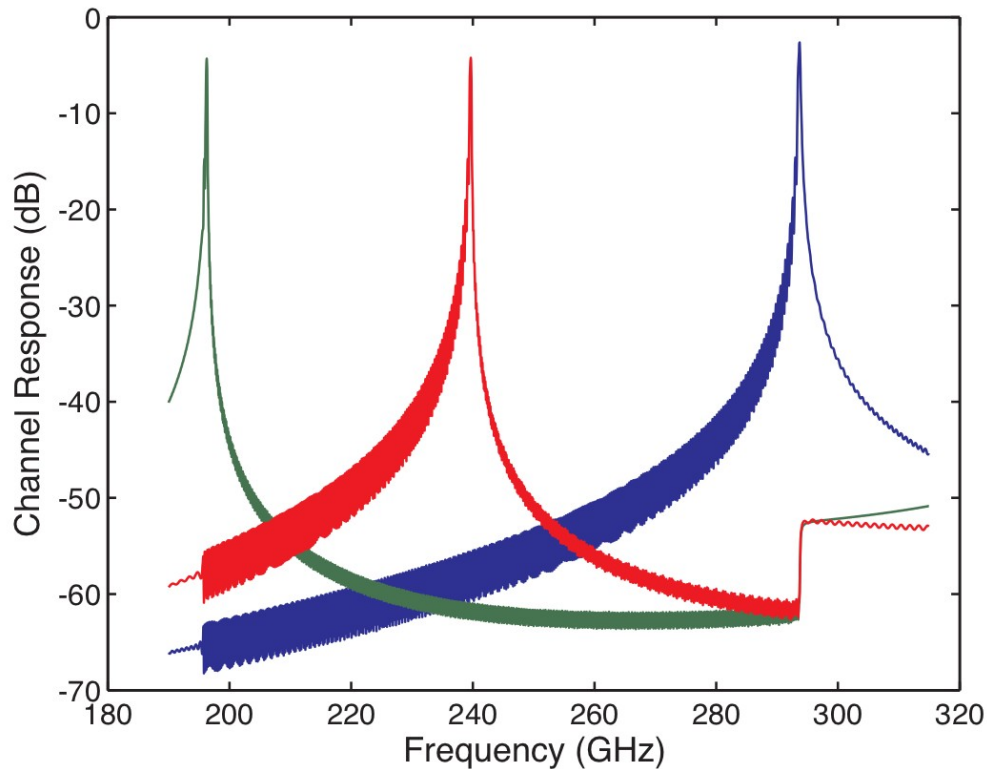
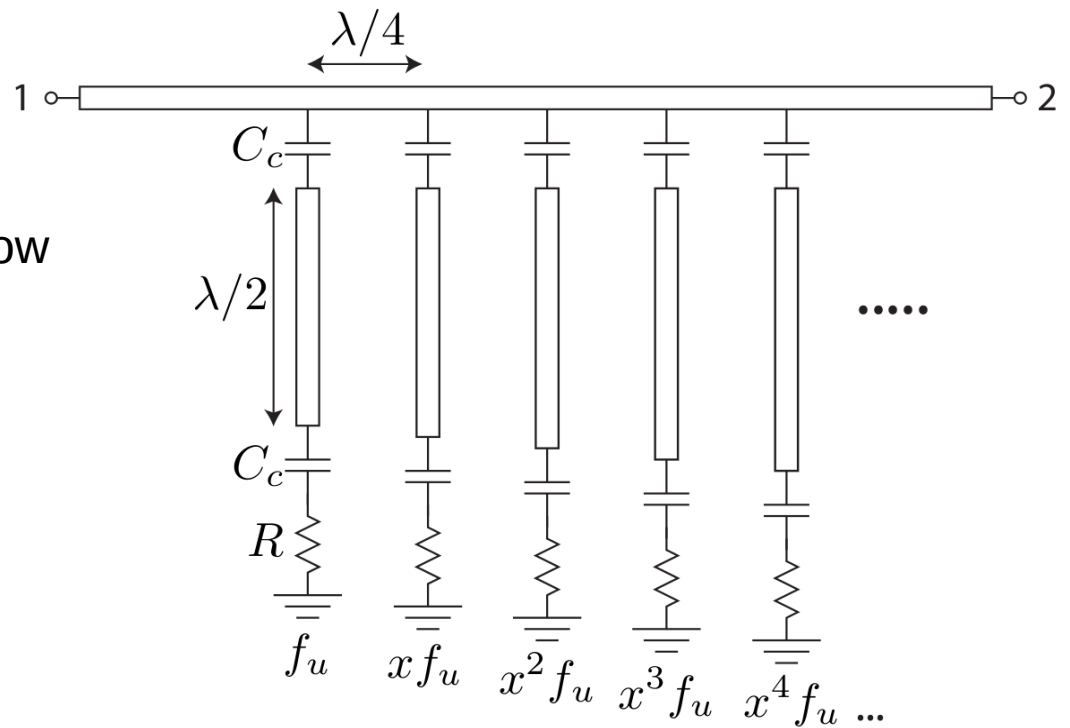


A general filter bank
(or cochlear) spectrometer:

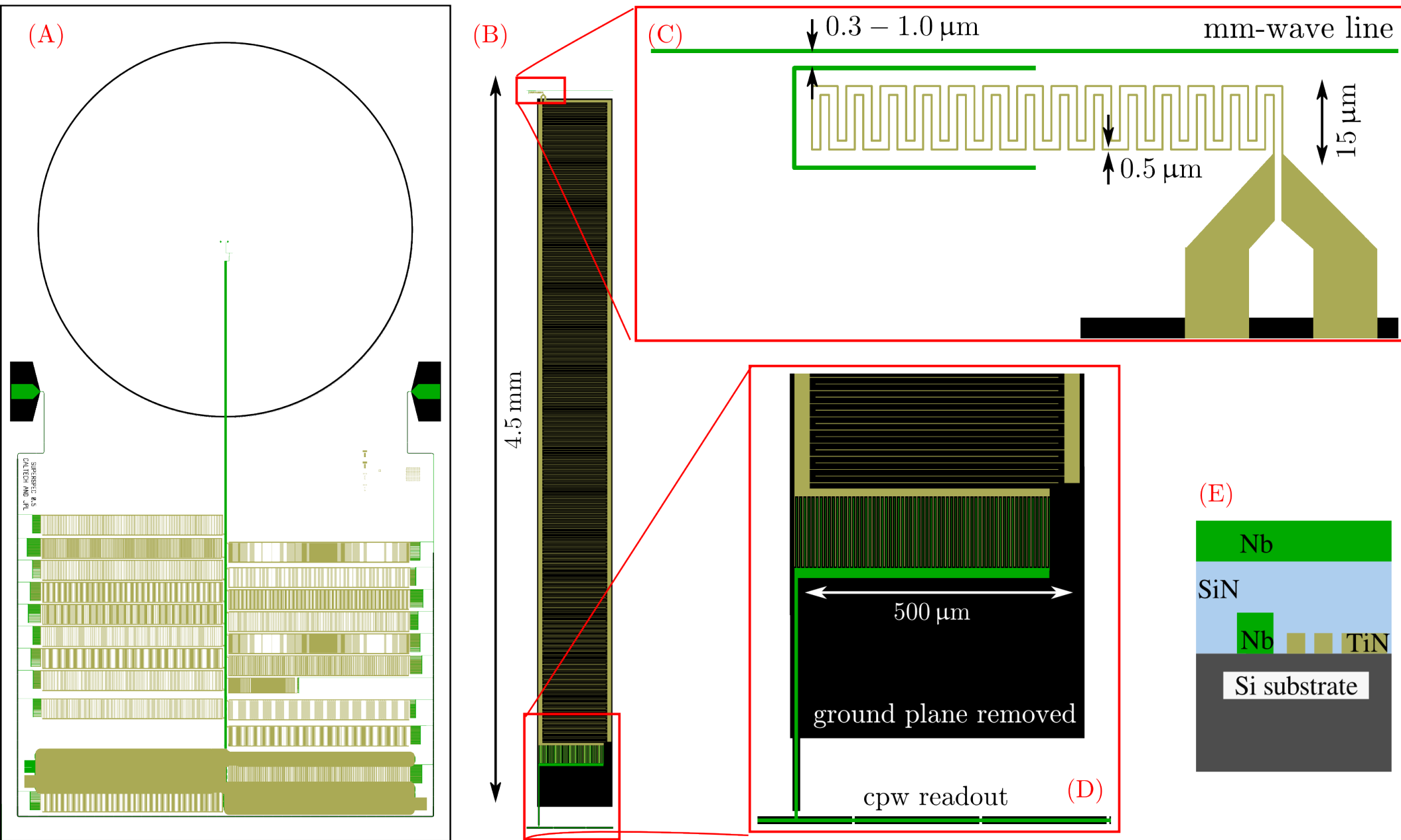
Incoming radiation is sorted by narrow band filters

Each channel couples to a power detector

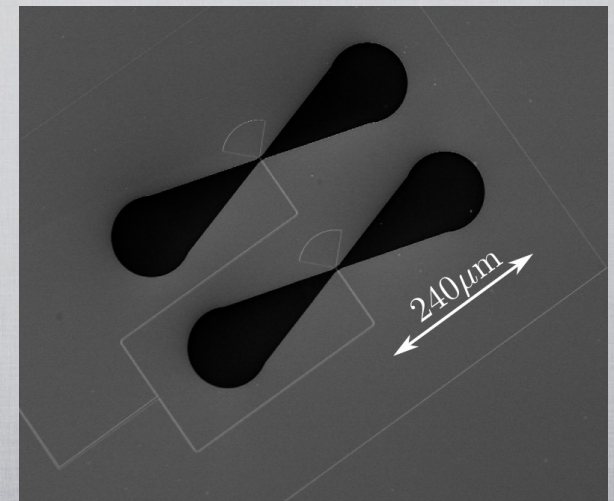
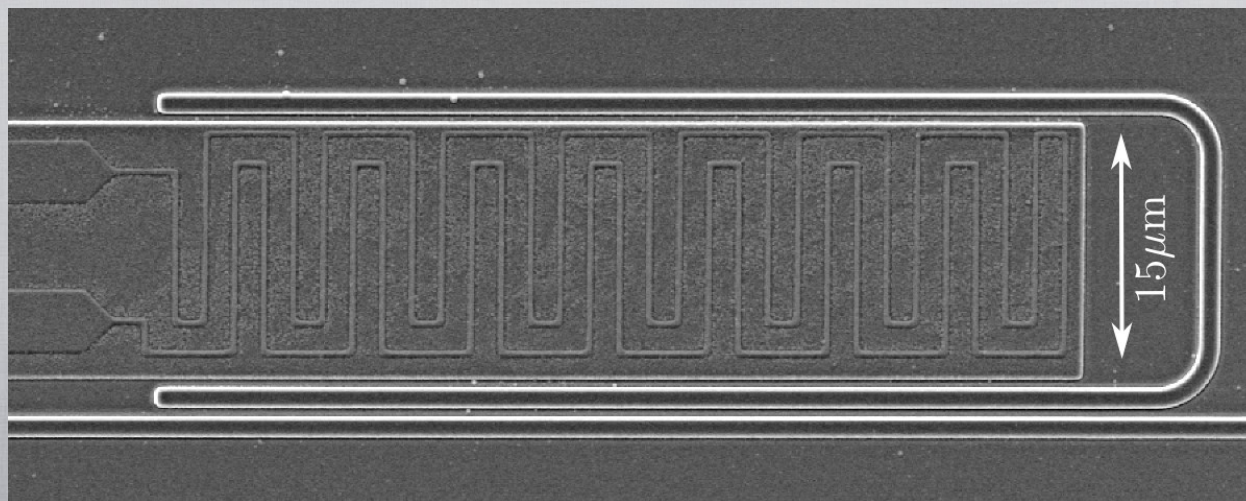
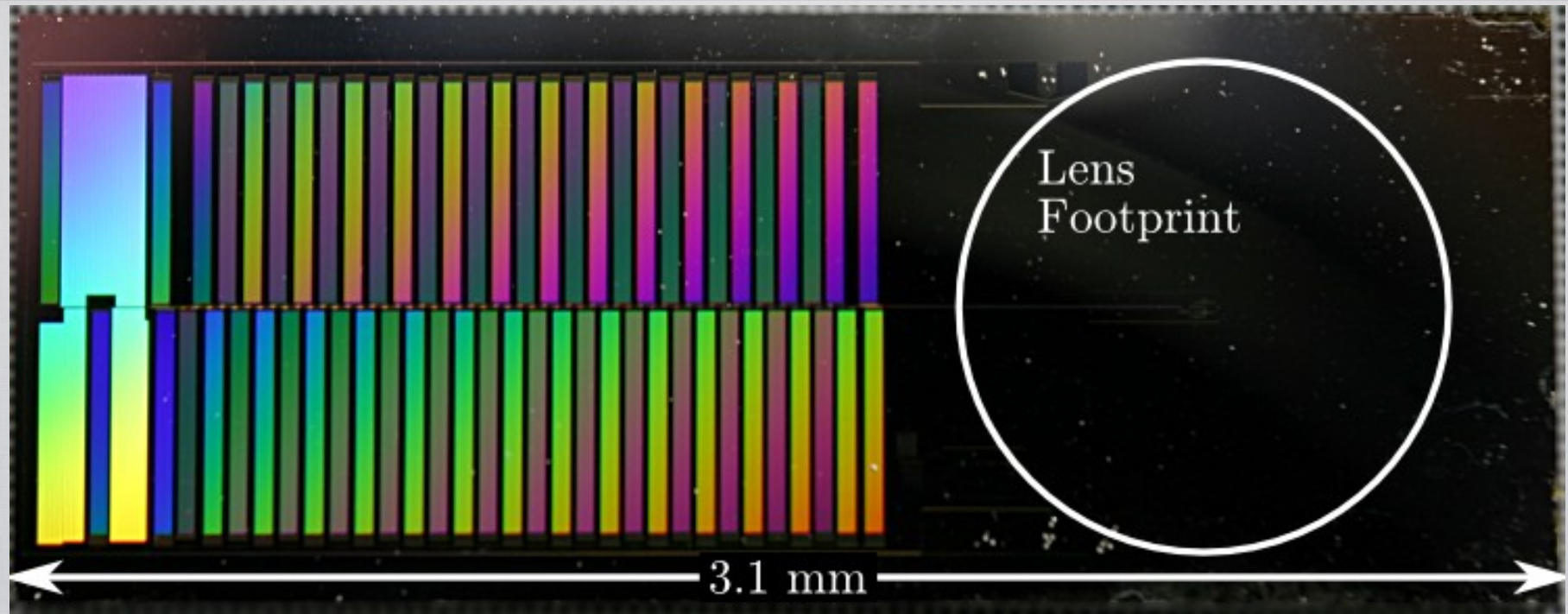
Channel width and spacing are independently adjustable



Implementation using thin-film circuits



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



Detector properties: what's unusual about these KIDs?

Sputtered substoichiometric TiN, T_c 1.2K

$50 \text{ MHz} \lesssim f_0 \lesssim 250 \text{ MHz}$

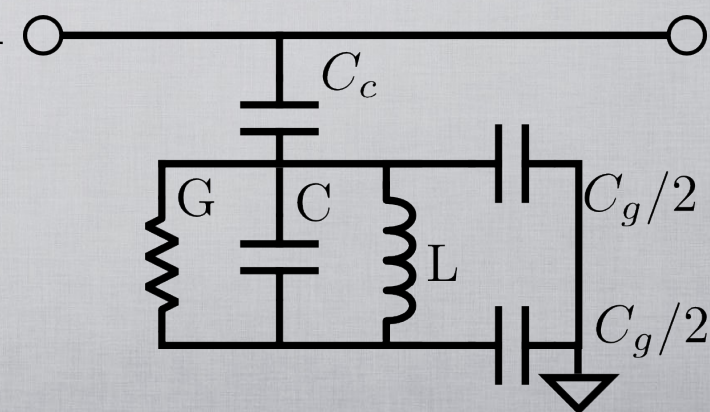
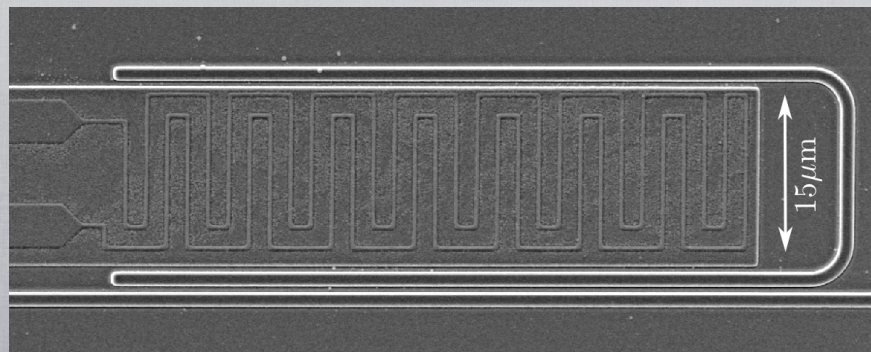
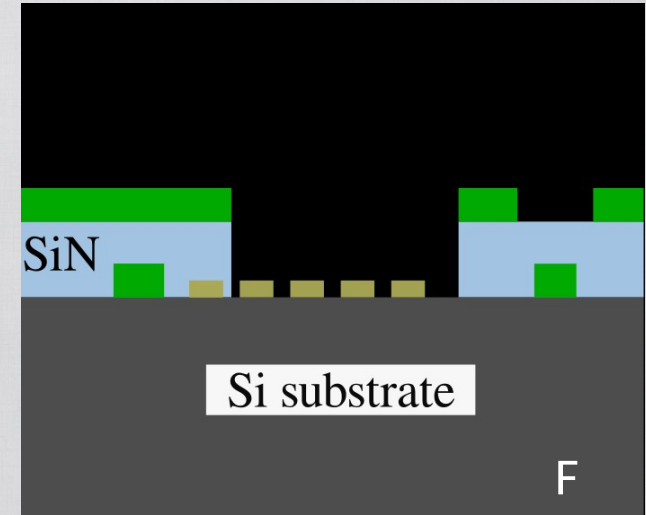
PECVD SiN_x dielectric

Inverted microstrip w. buried inductor.

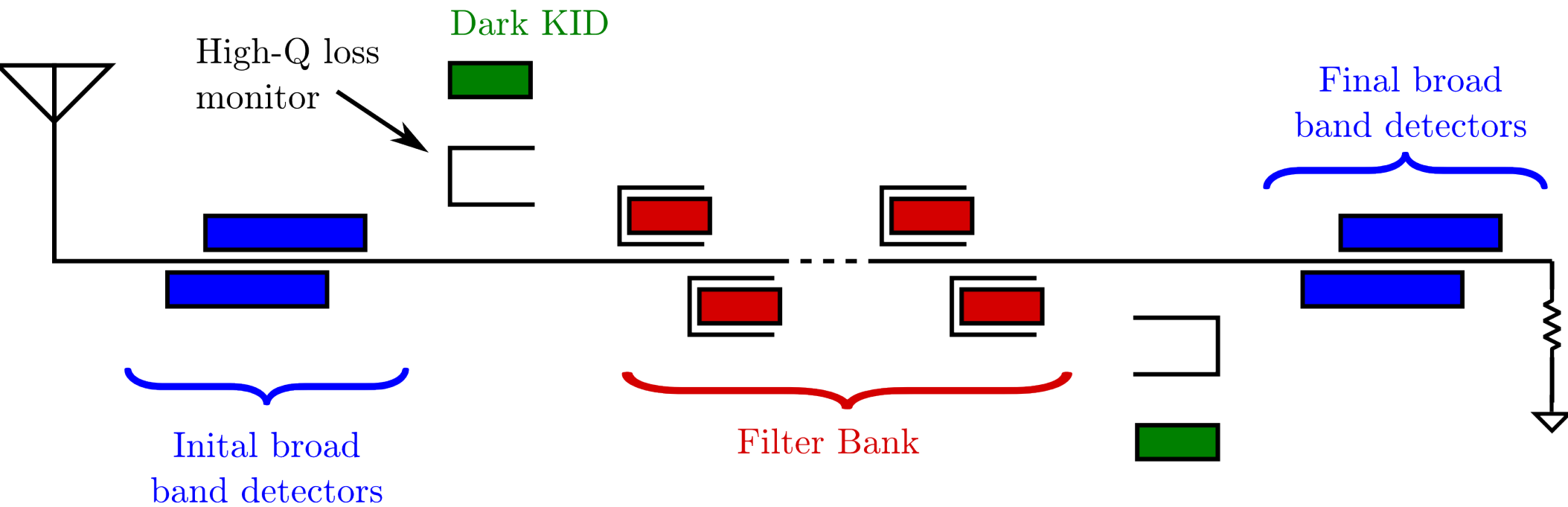
Current return through capacitance to GP.

Thick Nb-on-TiN capacitor features

Tiny inductors: $V = 2.5 \mu\text{m}^3$, $W = 0.25 \mu\text{m}$



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

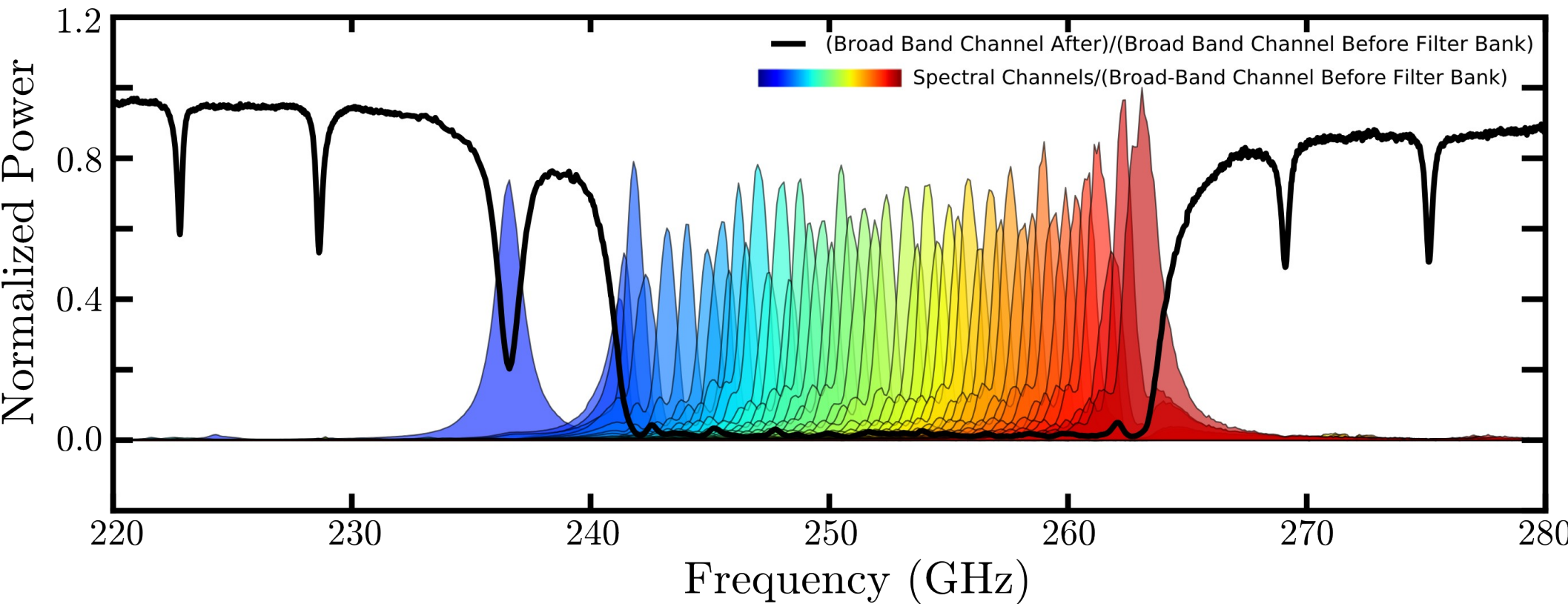


Broad-band detectors absorb $\sim 0.1\%$ of mm-wave power on feedline before and after filter bank.

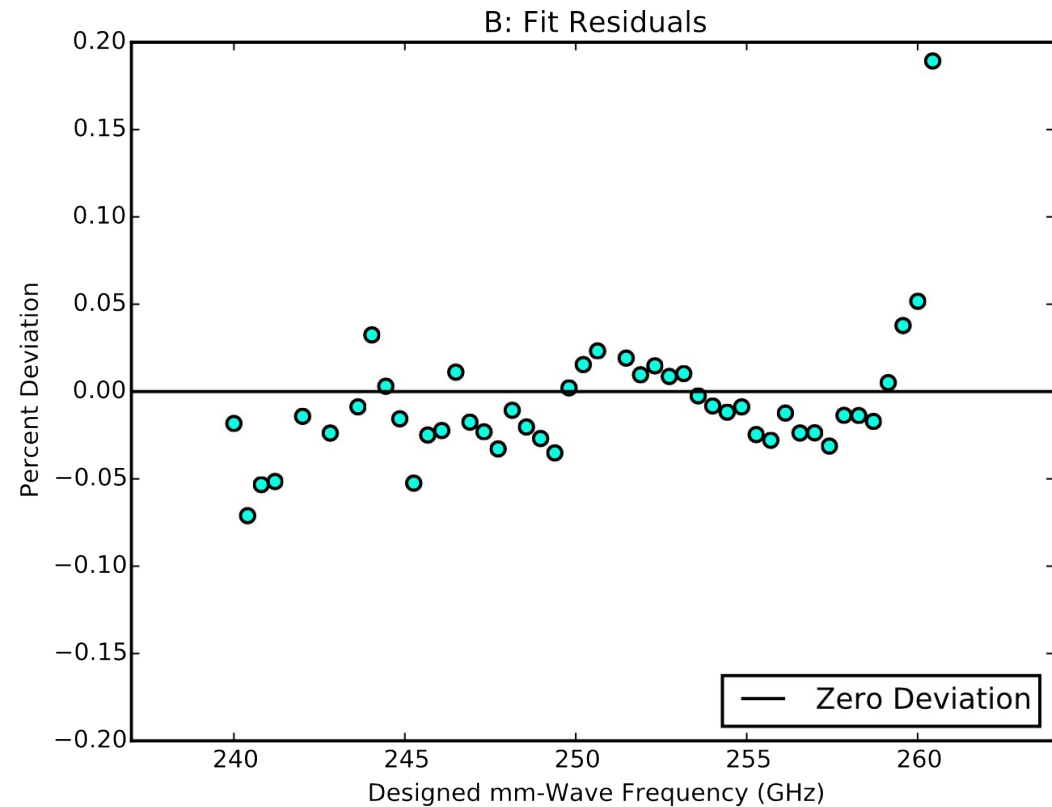
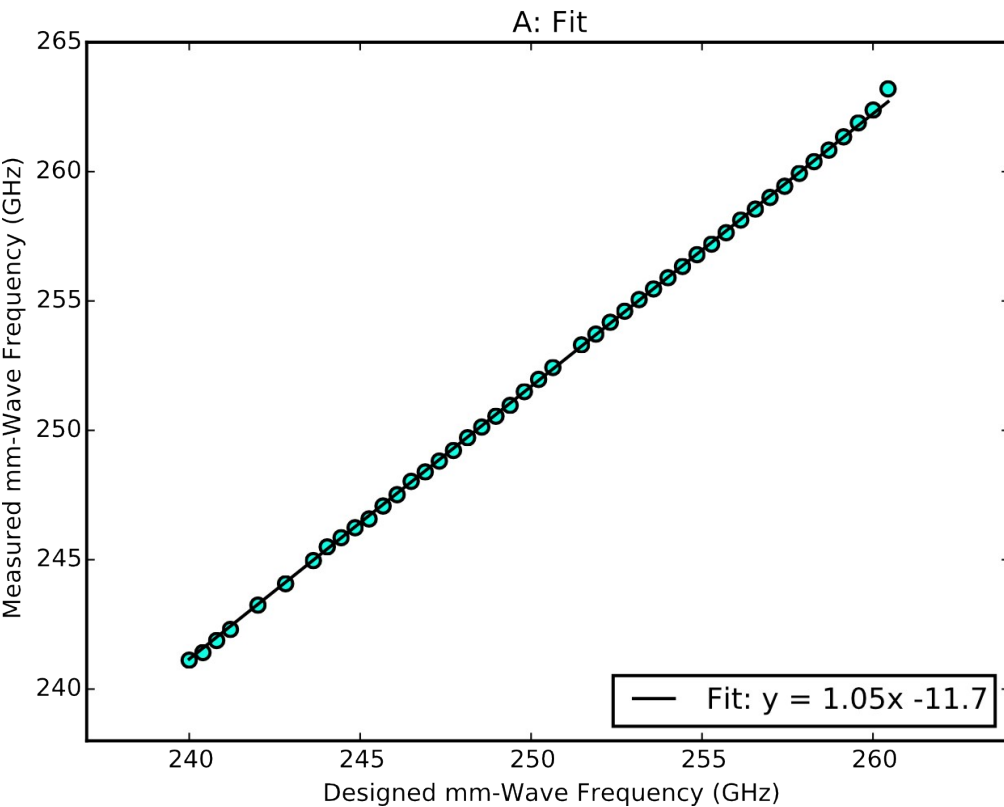
These are long, staggered, to avoid standing wave confusion.

Pairwise differencing of fore/aft/channel KIDs (over) constrain Q_c , Q_r of channels.

50 Channel filter bank prototype shows excellent uniformity, yield

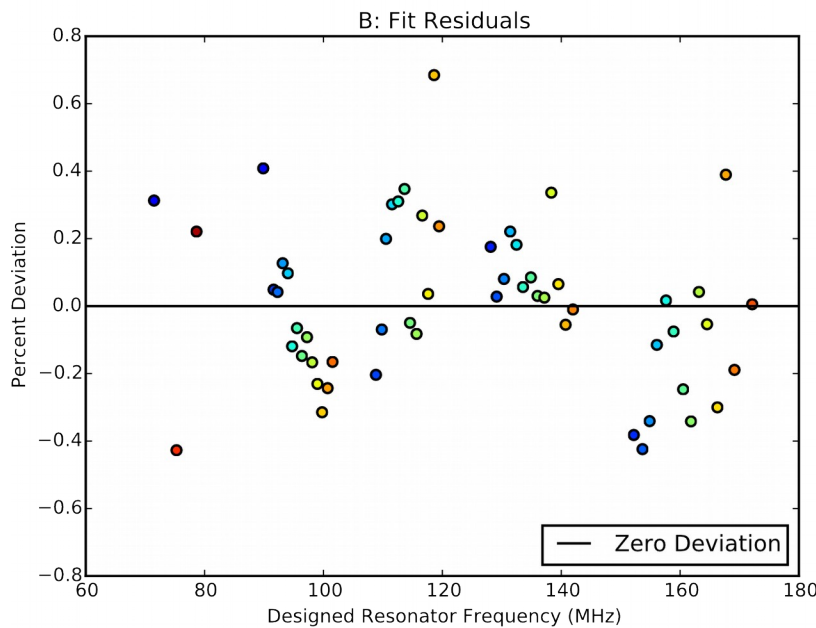
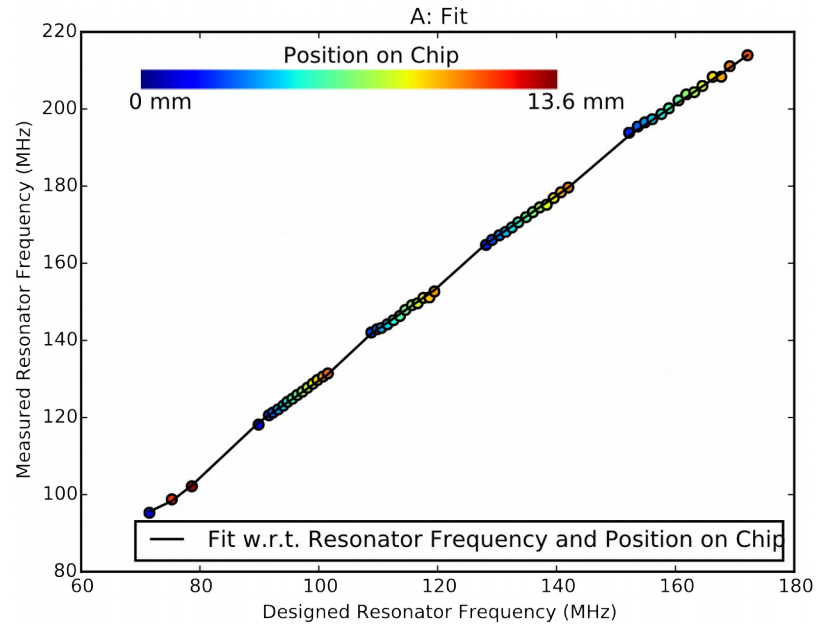


RMS scatter in mm-wave frequencies is 0.04%

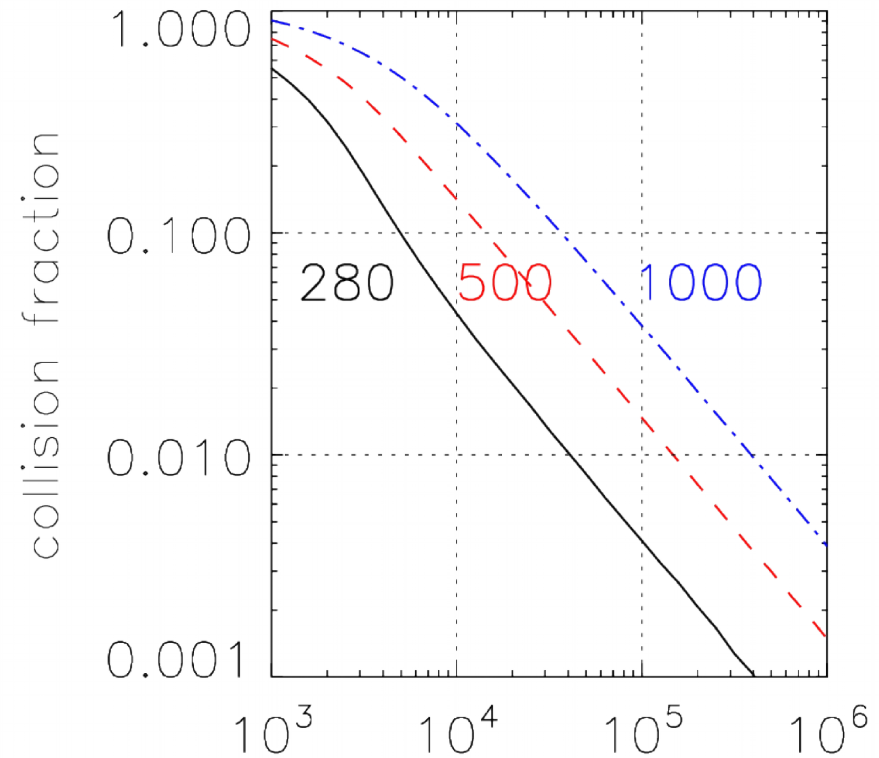


This is $\sim 6X$ FWHM for an $R=400$ channel.

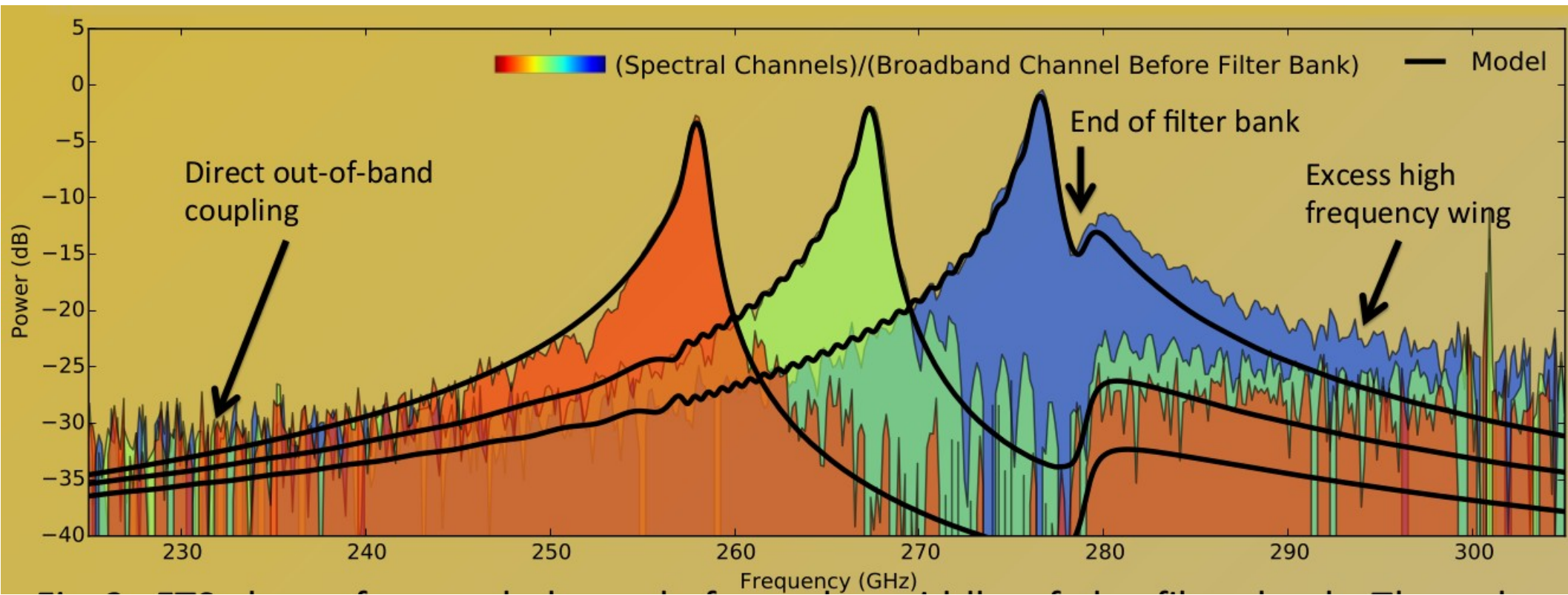
RMS scatter in readout frequencies is 0.2% (in previous generation 0.5 μ m inductors)



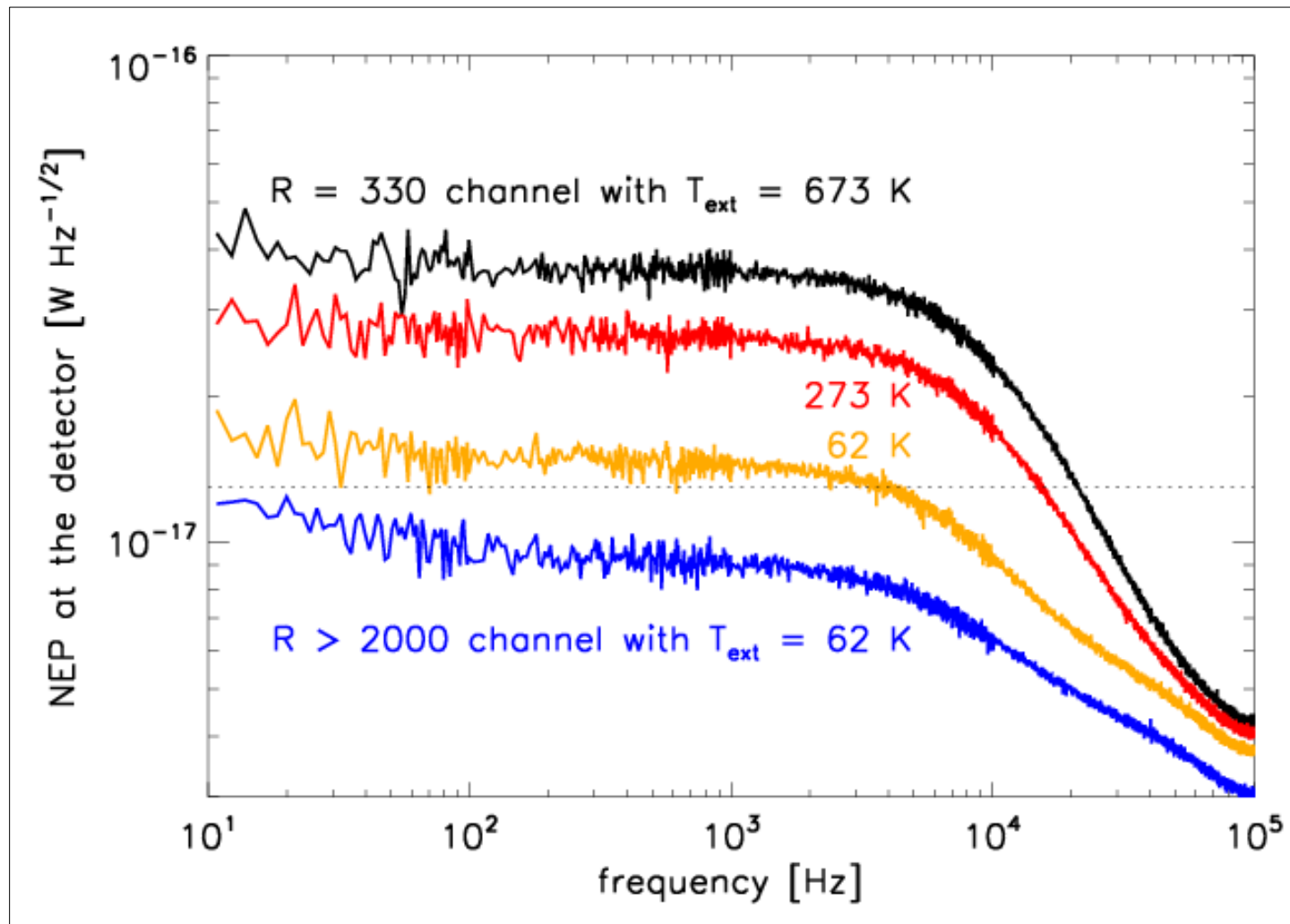
0.2% scatter \rightarrow
1 collision in 280 $Q_r = 10^5$
resonators per octave



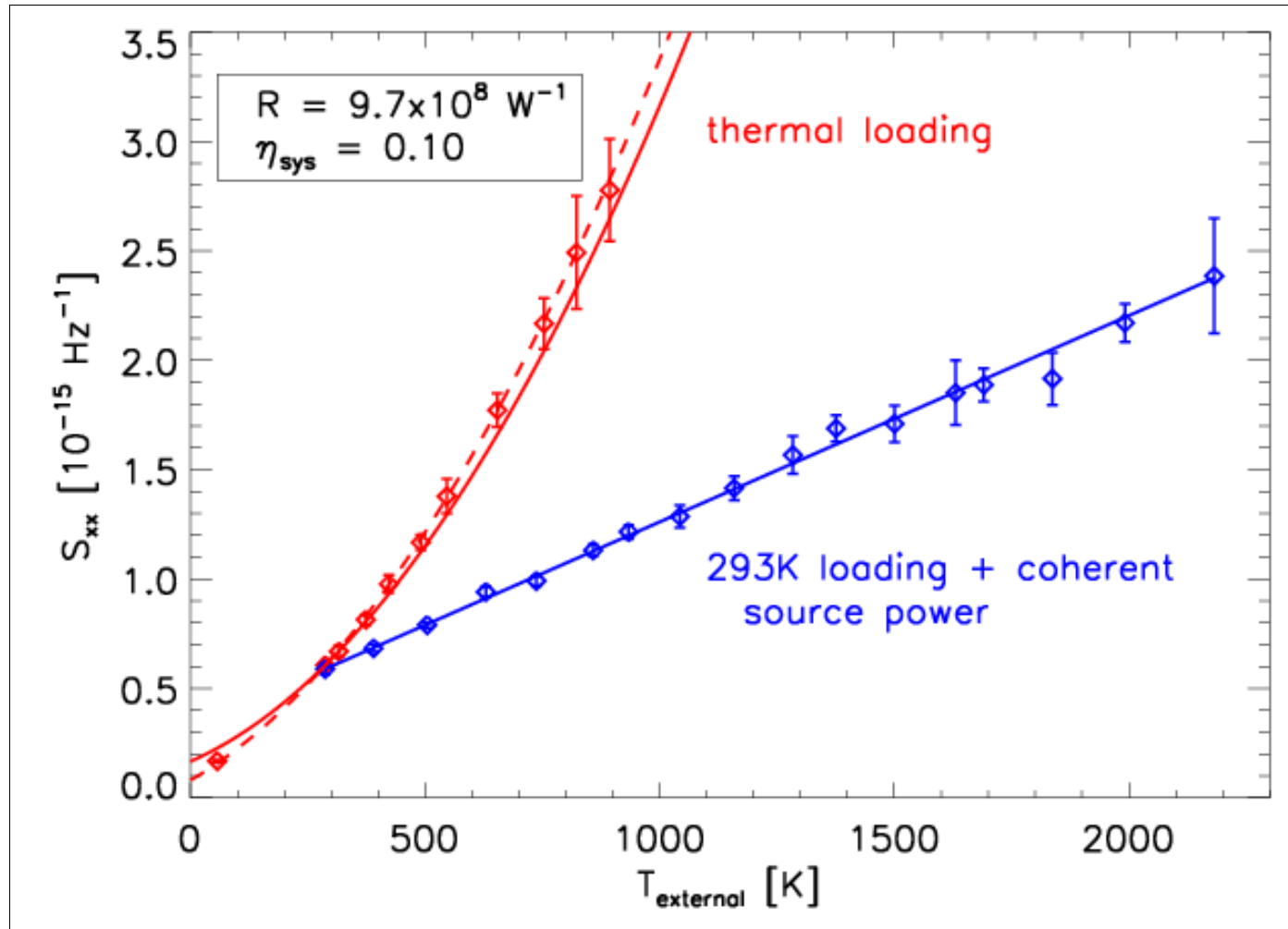
Spectral profiles show out of band coupling at -30dB, some excess response in the wings



Photon-noise measurements allow for total system efficiency calibration.

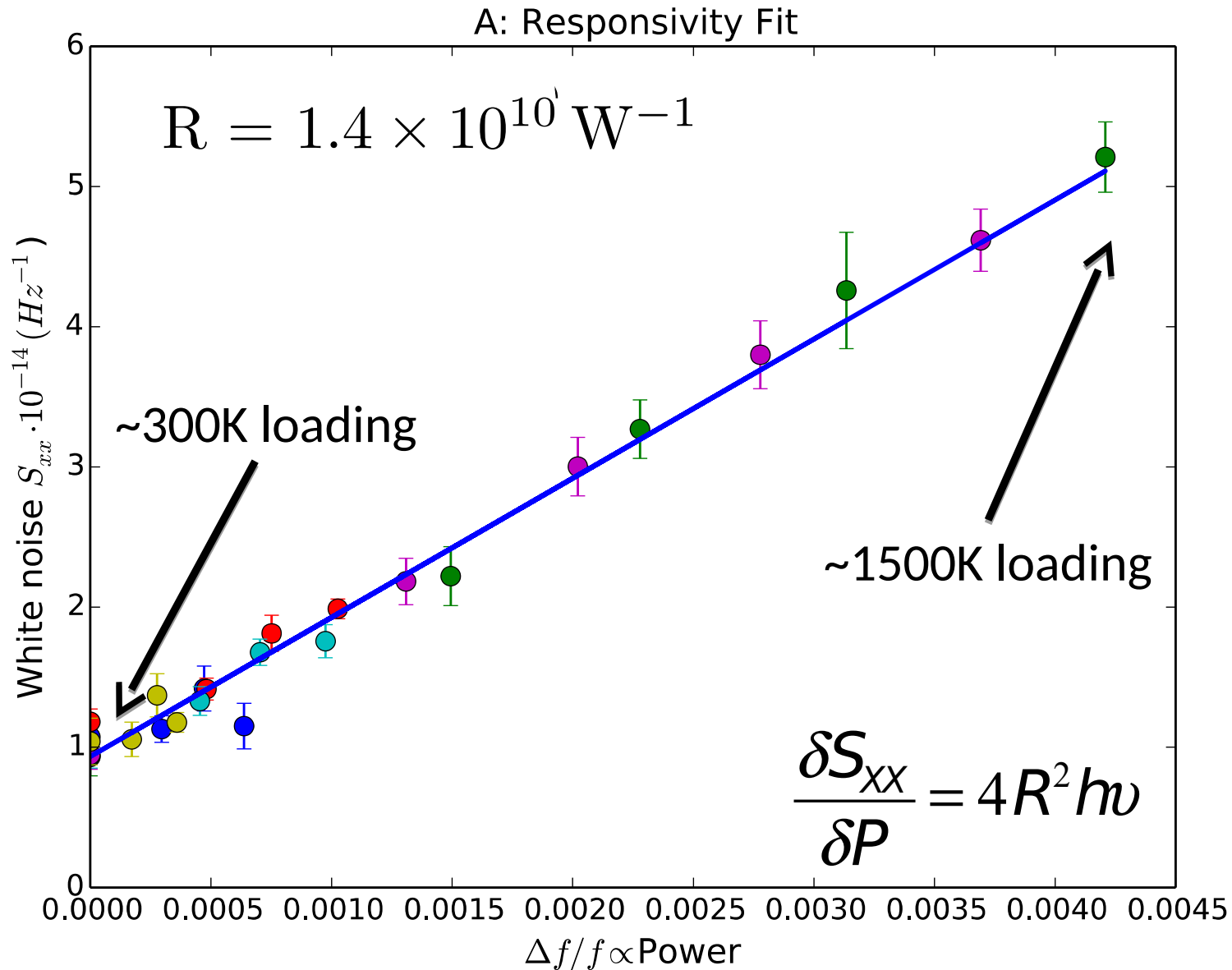


Photon noise allows us to measure efficiency and absolute sensitivity in physical units.

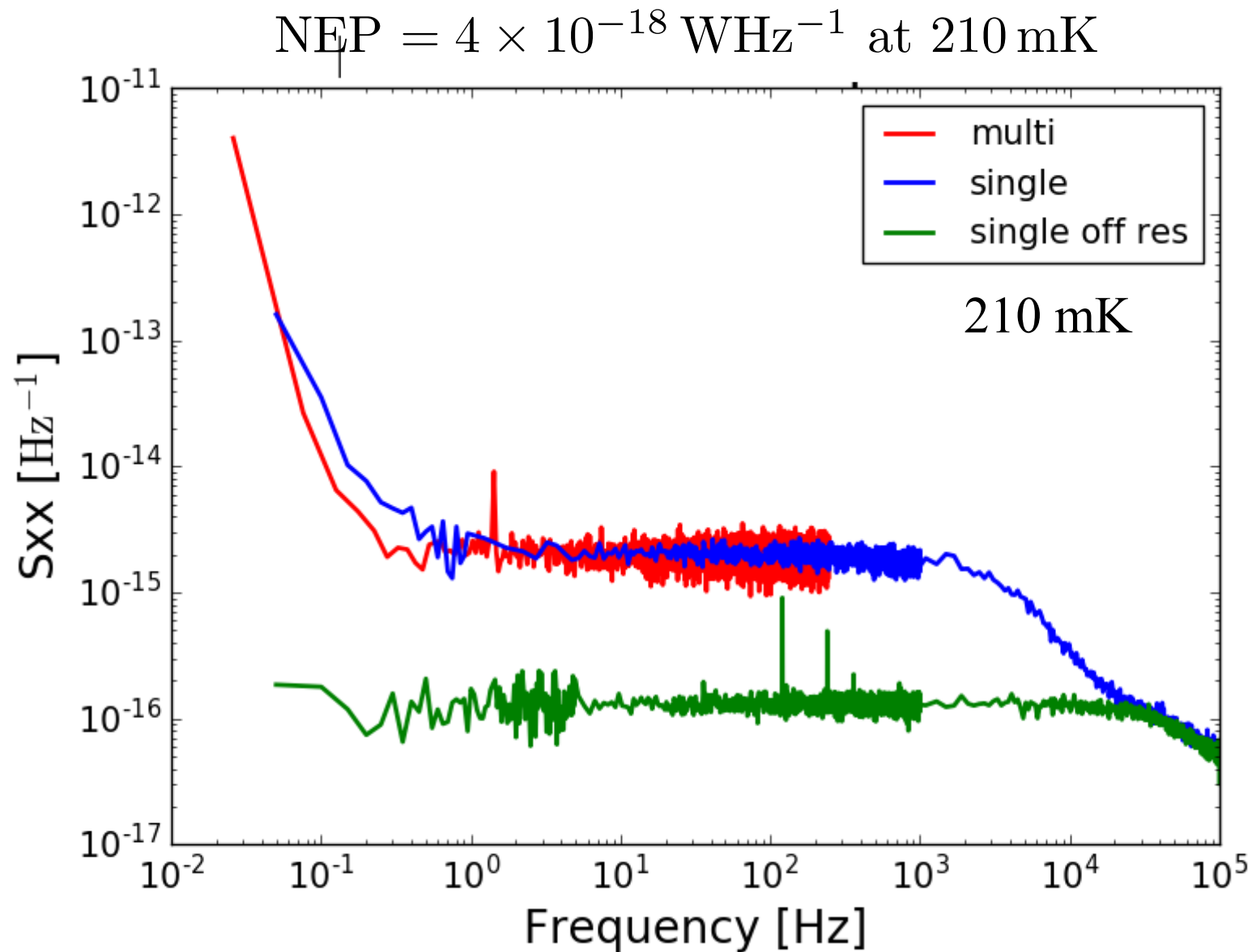


(Data from previous generation 0.5um inductor devices.)

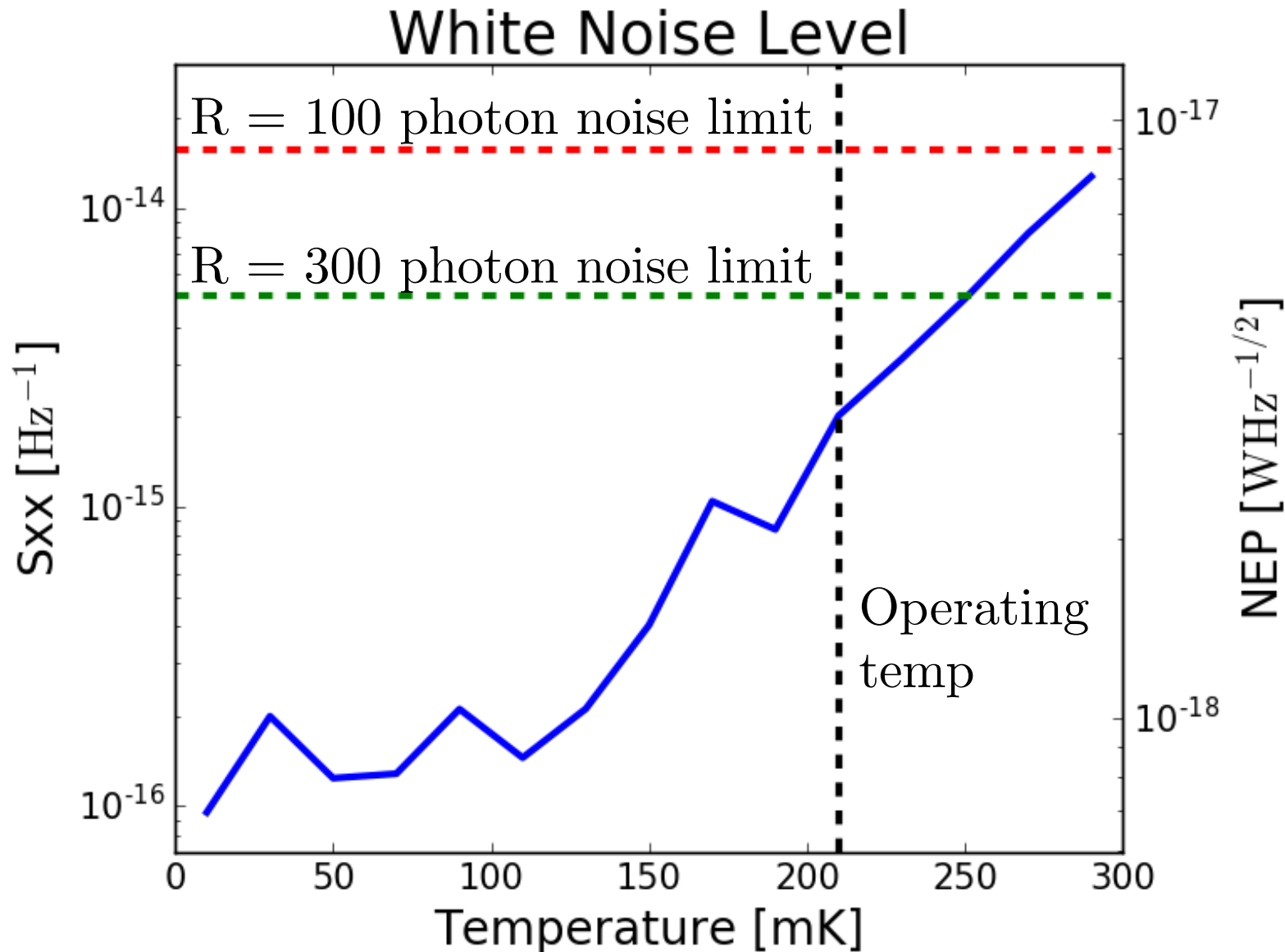
New 0.25 μ m devices show improved response, still no evidence of QP lifetime change with loading.



Single tone and multi-tone readout are background limited under realistic conditions

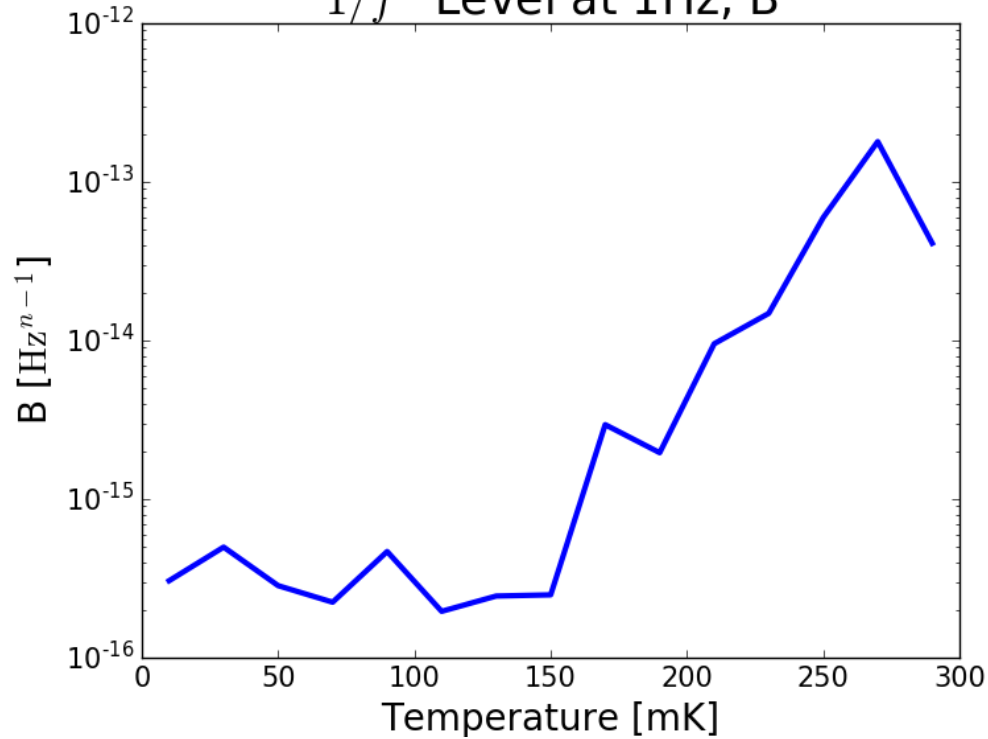


Measured white noise vs. temperature for dark devices, scaled to NEP using measured response from same die.



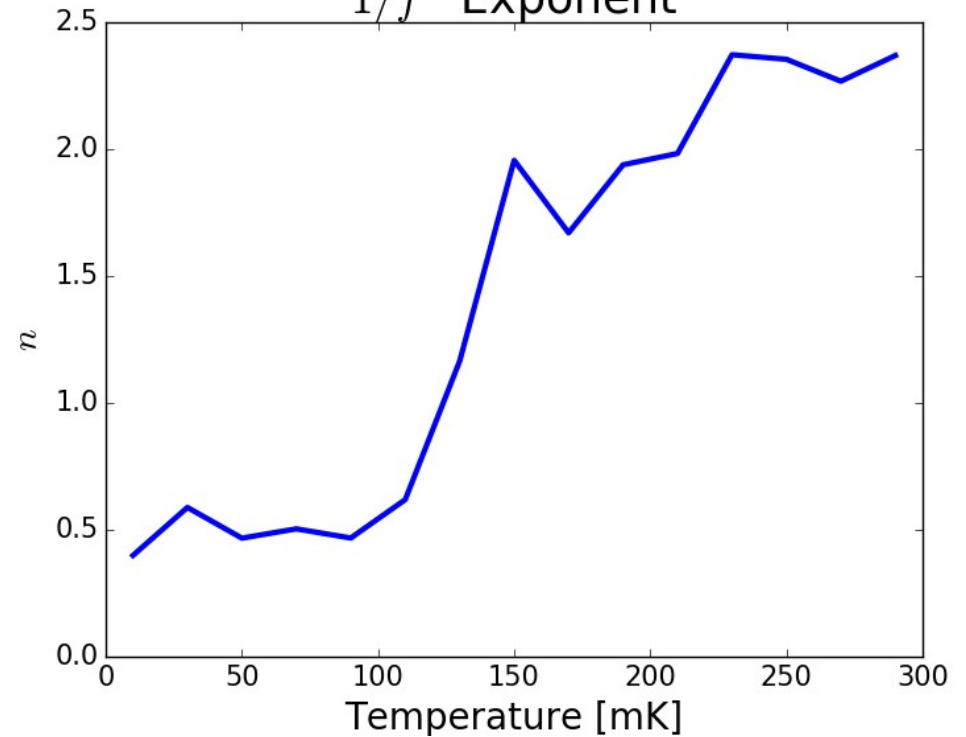
Measured low frequency noise vs. temperature (very preliminary)

$1/f^n$ Level at 1Hz, B



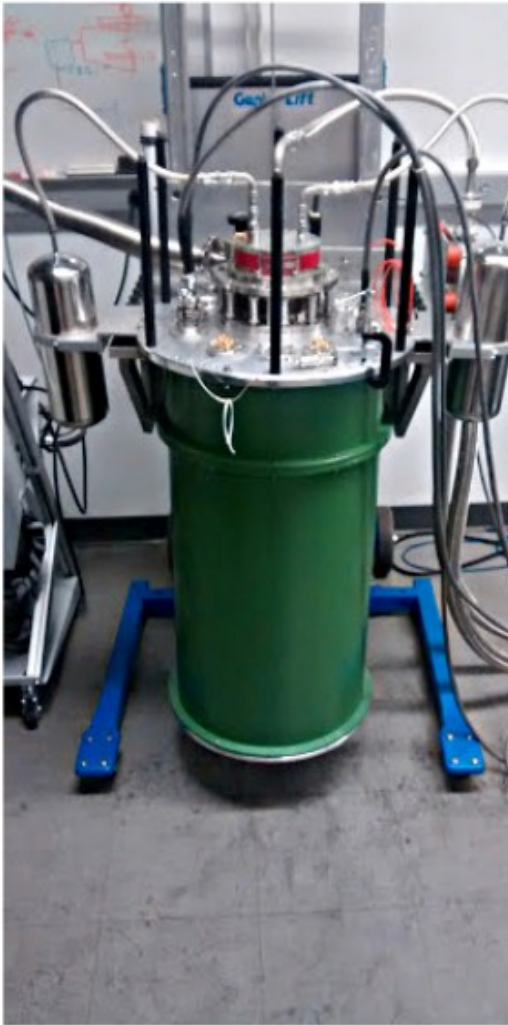
No significant change $T < 150$ mK

$1/f^n$ Exponent

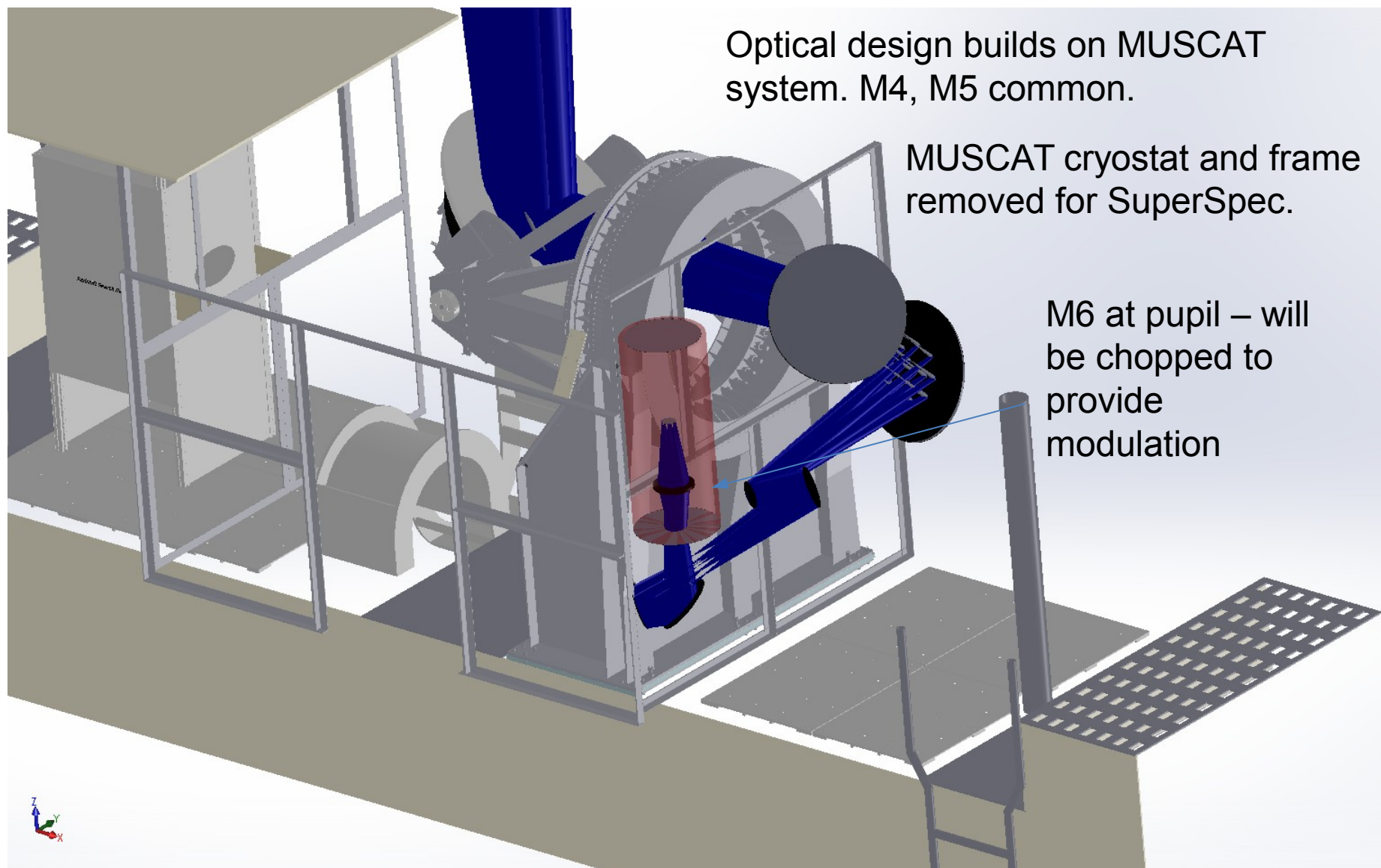


Low T, find previously observed
TLS-like scaling $f^{1/2}$

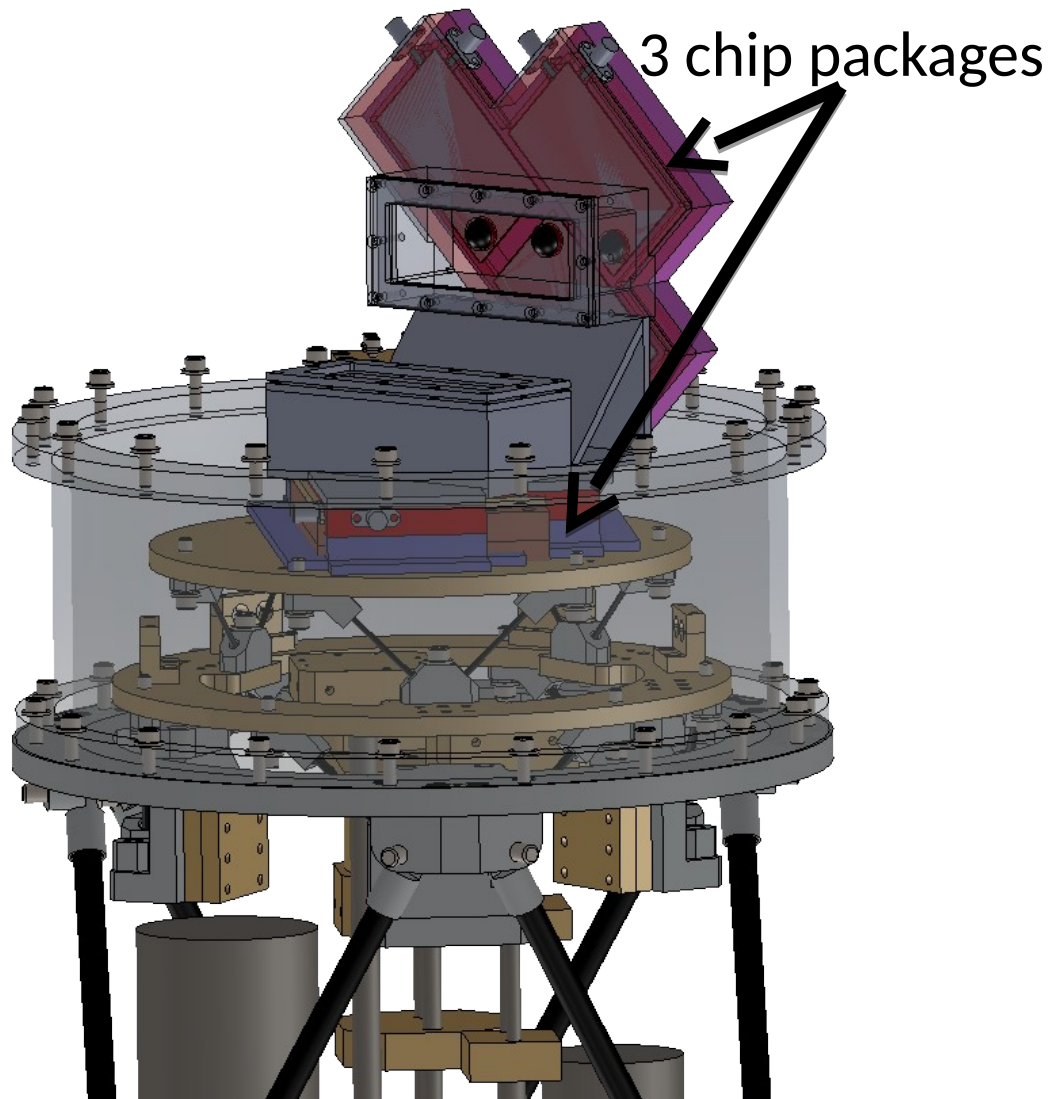
Early 2018: collaboration with INAOE to deploy a 3 pixel demonstration instrument at the 50 meter Large Millimeter Telescope (LMT/GTM) in central Mexico



Optics are nearly final: we just need two small mirrors, a flat chopper, and a cold lens.



Pathfinder instrument



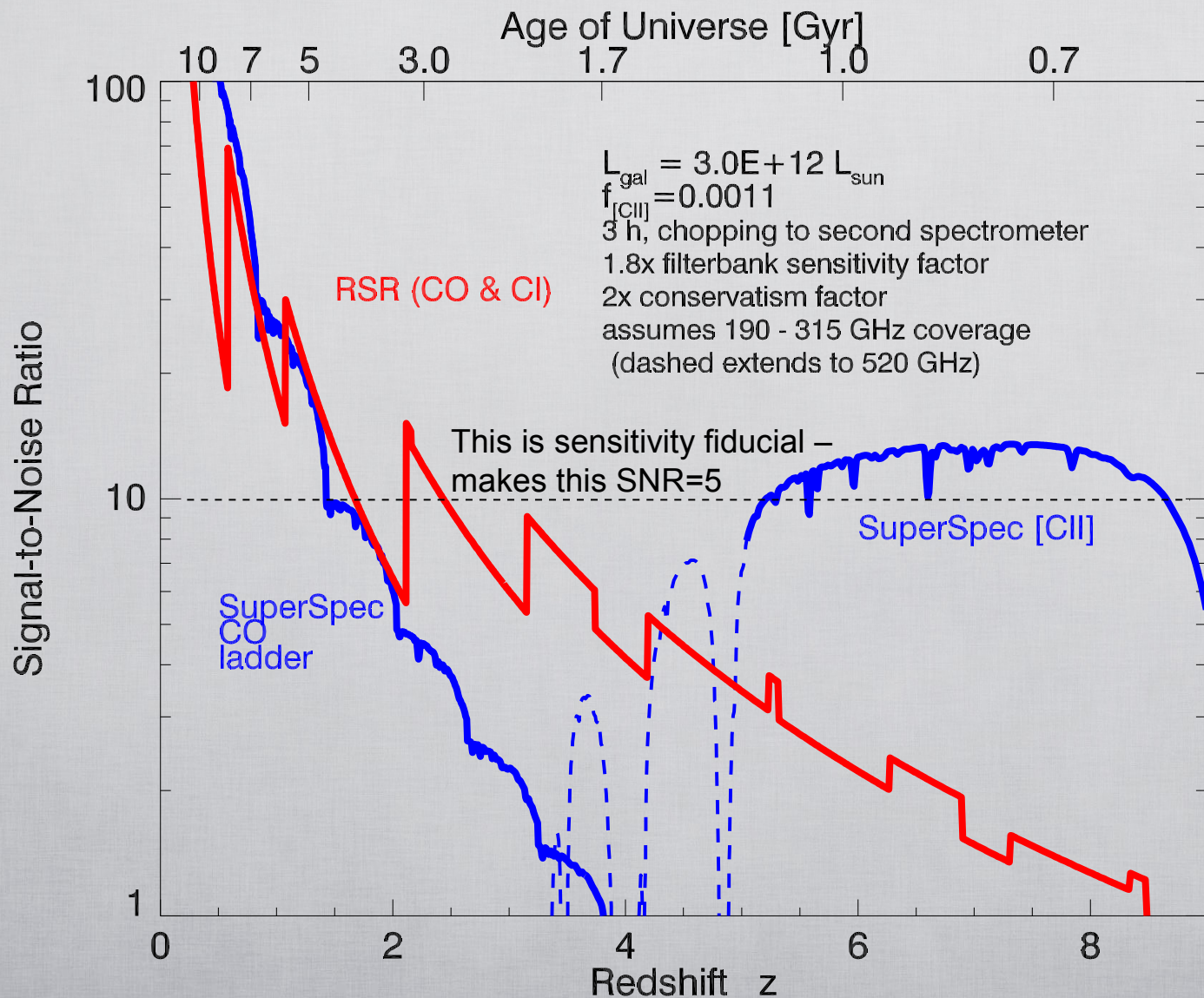
Baseline plan:

3 spatial pixels in each of
2 polarizations on-sky

$R=300$, covering 195-210
GHz

Readout: Roach2 +
MUSIC boards; ASU/Blast
firmware

Sensitivity Landscape per superspec pixel at 30m class telescope for a $3e12 L_{\text{sun}}$ galaxy



- LMT + SuperSpec fill the full z range.

- Provides complete CO SLED sampling for $z < 2$.

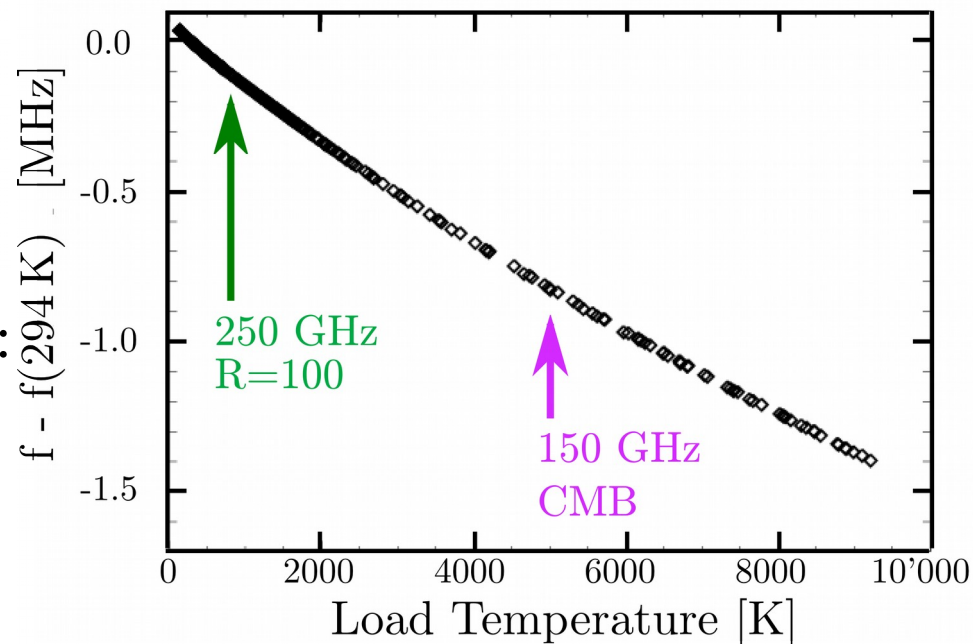
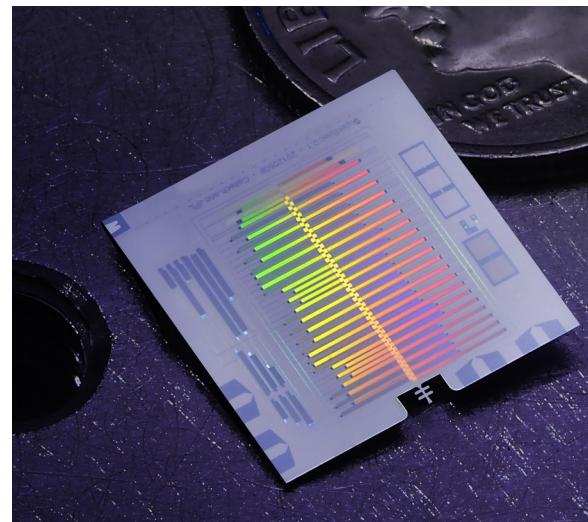
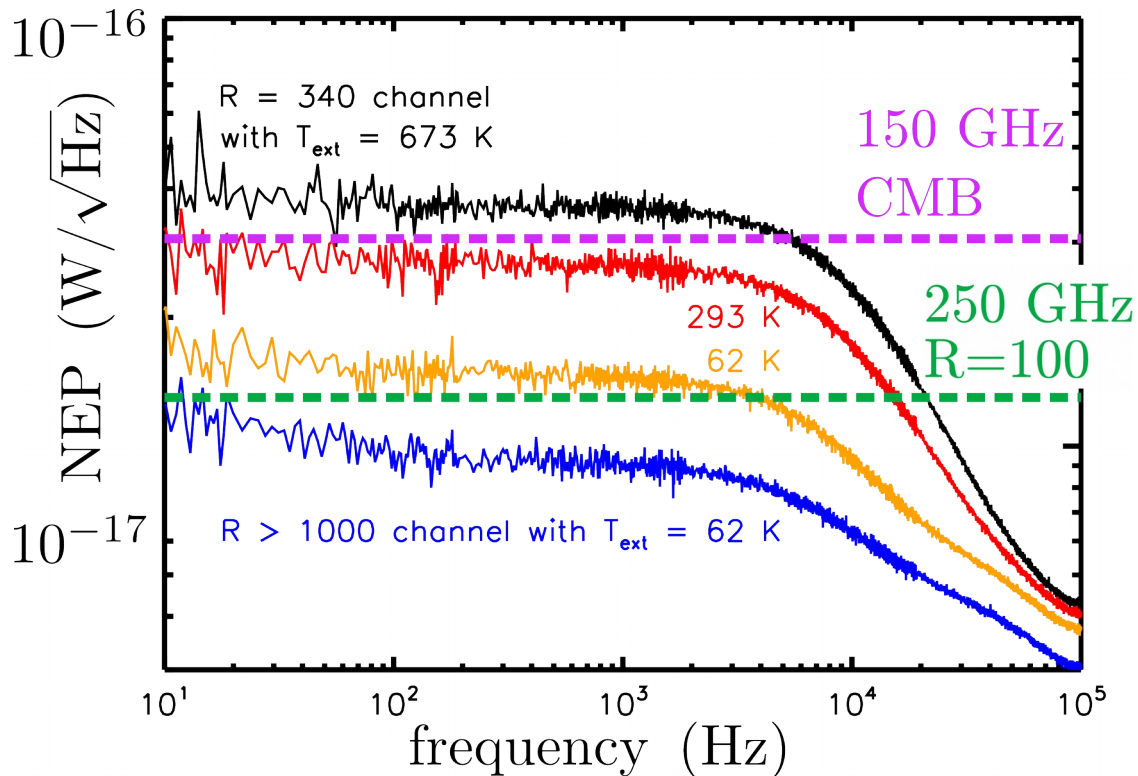
e.g. $z=2-3$:

SuperSpec: $J=4,5,6\dots$

RSR: $J=2,3$

-> Excited and quiescent molecular gas.

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

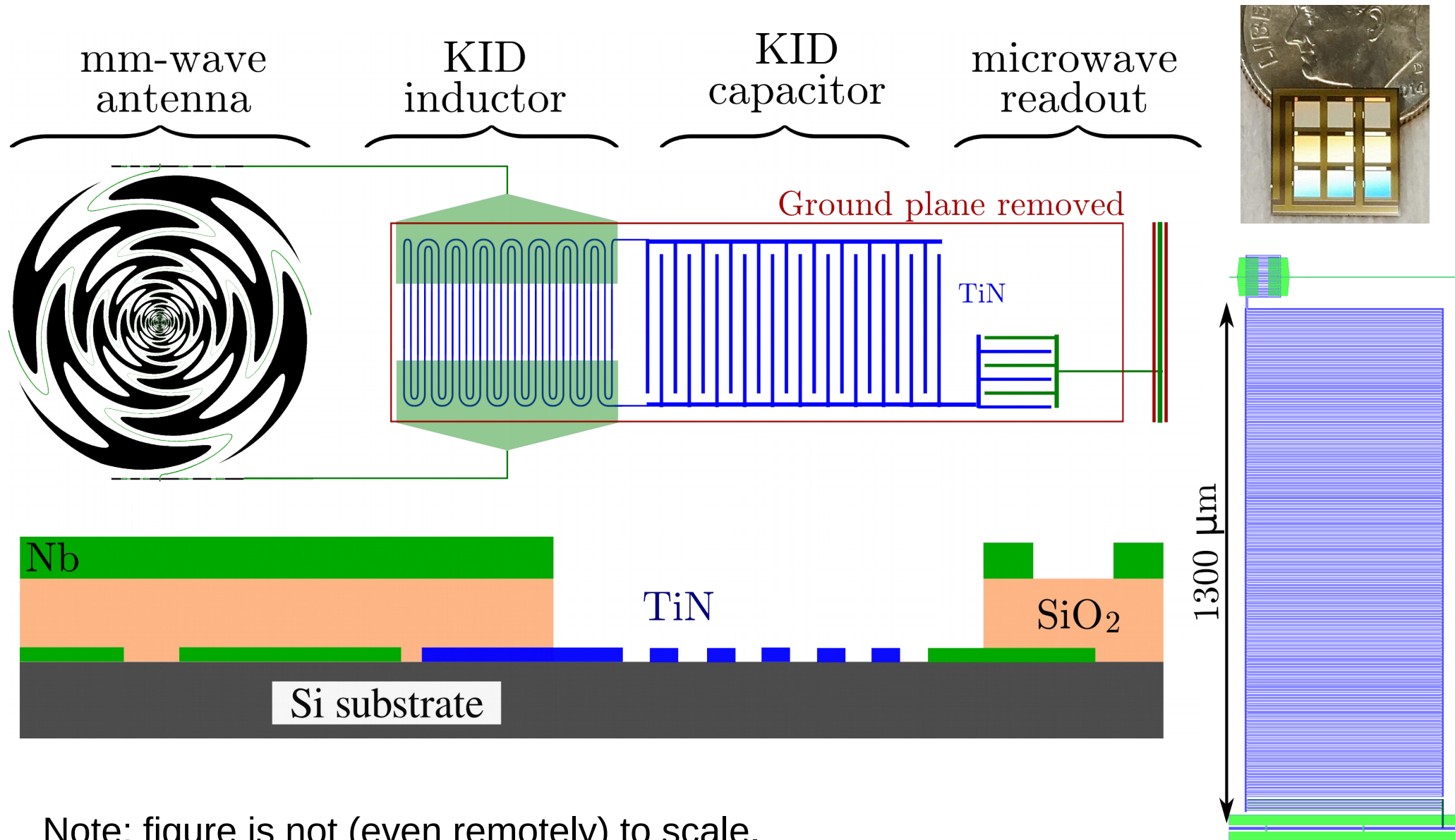


Conservative, P/V conserving estimates:

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

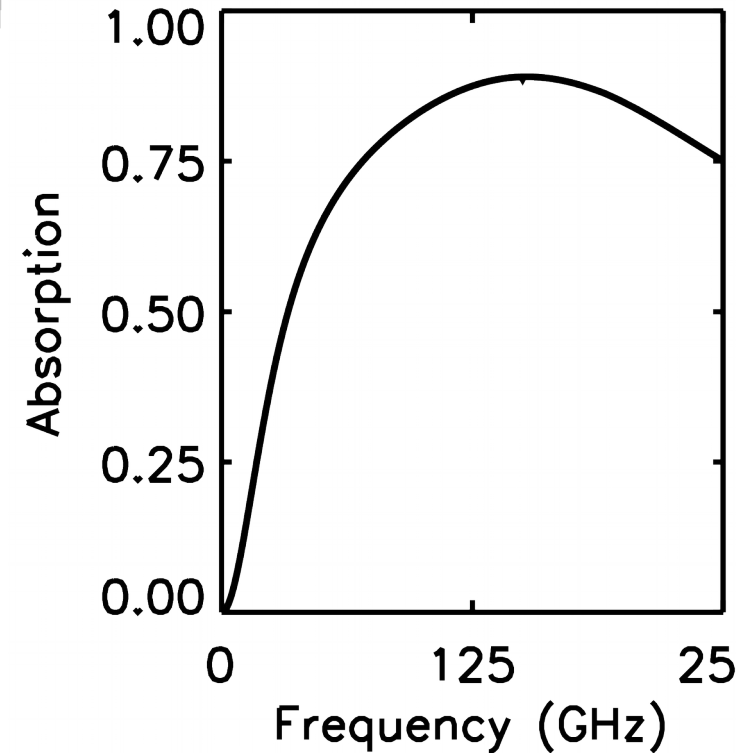
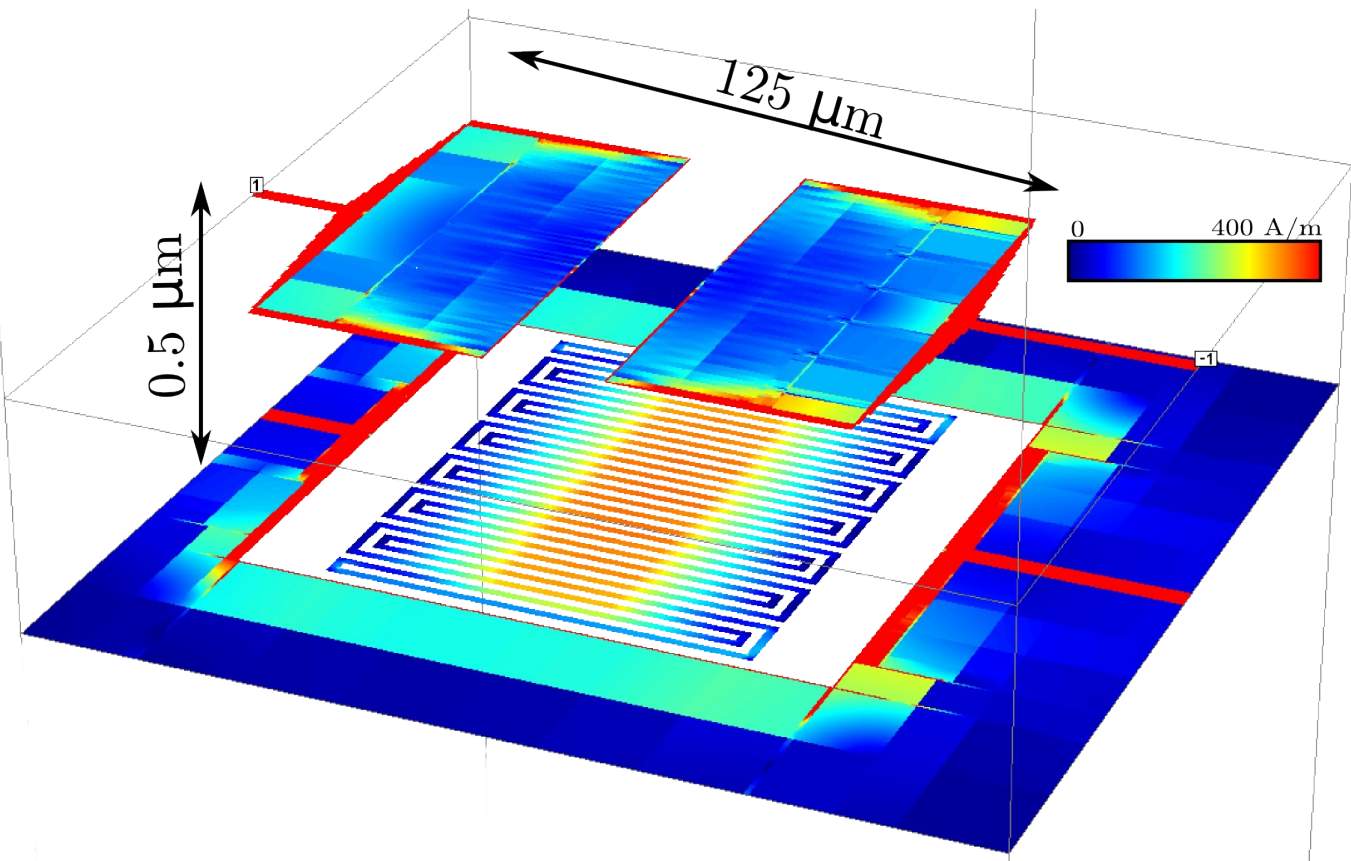
6× below background limit

Longer term CMB-KIDs plan: multi-band, polarization sensitive large arrays similar to SPT-3G tiles.



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 well-tuned, multi-band coupling designs.

ALD TiN deposition at U. Chicago: toward antenna-coupled tiny TiN KIDs for the CMB.

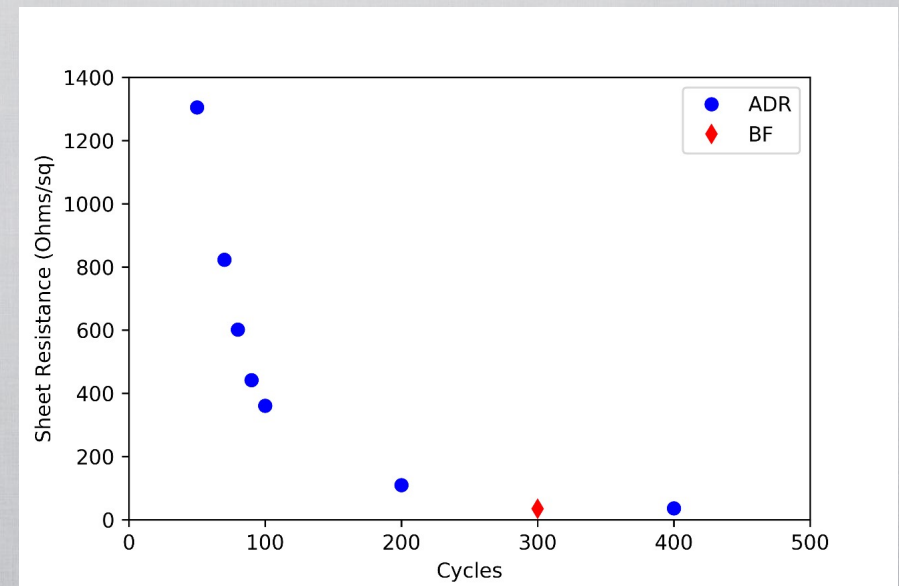
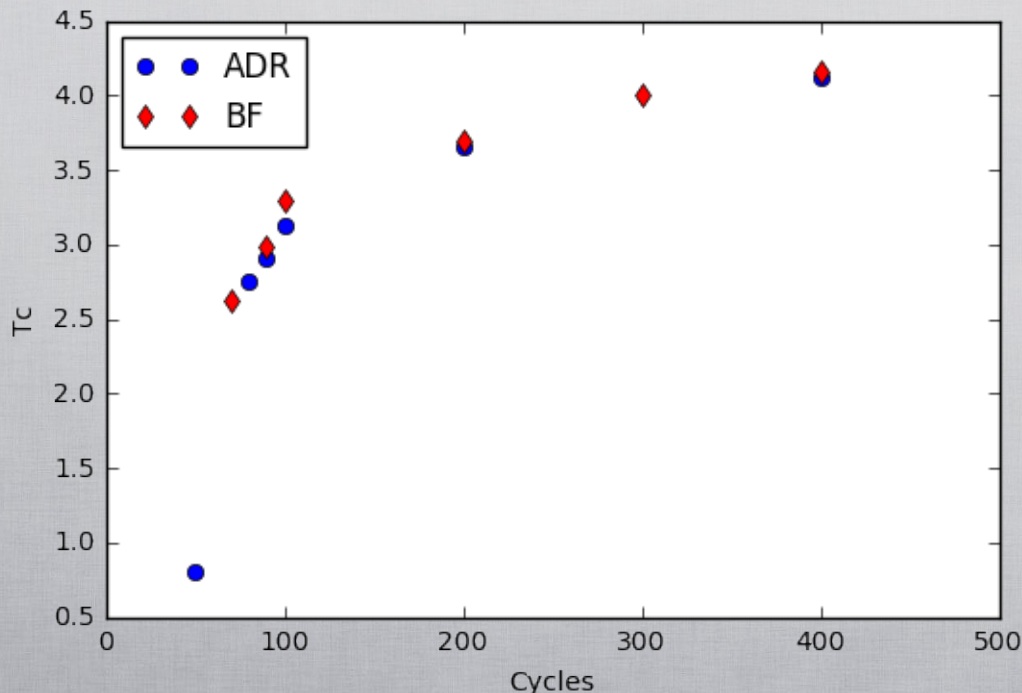
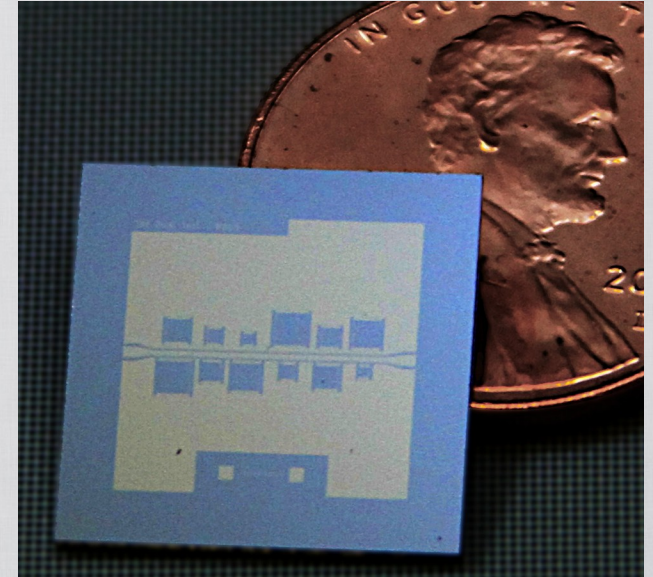
Resonators work!

$Q_i \sim 500'000$ for 4K material

$0.5 < T_c < 4.0$

Thickness approaching 3nm

Wafer-scale uniformity, composition,
and optical tests under way



Conclusions

On-chip spectroscopy is (almost) field ready.

SuperSpec will field a background-limited instrument in 2018.

Our small volume TiN devices show:

- High responsivity

- Expected noise properties

- Decent low frequency noise behavior

Some of these techniques may be useful for broader science goals.