Direct-Detection Spectroscopy in the 1 mm band at the LMT with SuperSpec

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for the SuperSpec Collaboration
February 5, 2016

Summary:

Proposing a long-term collaboration on a new instrument program for wideband 1-mm spectroscopy on the LMT.   Envision working closely with Umass and INAOE on the instrument development and system aspects.

Stage 0:   Demonstrate single chip on sky with existing cryostat in ~12-18 months.

Stage 1:   Propose for NSF ATI (fall 2017) for optimized galaxy follow-up spectrometer.

Stage 2:   Take advantage of 8' field and pursue multi-object steered spectrometer or dedicated tomography experiment.

Sub/mm Spectroscopy Reveals the Early History of Star Formation

- Most of historical energy release in galaxies has been obscured by dust.

- Imaging surveys lack redshifts and detailed diagnostics. **Spectroscopy provides 3D context + astrophysics diagnostics.**

- LMT particularly compelling for high-redshift C+. A mm-wave spectrometer is an excellent complement to deep surveys with TolTEC.

- Suggesting a staged approach.
  – Step 0: First a simple demonstration to enable NSF funding.
  – Step 1: initial science instrument: a single-beam spectrometer (with sky reference pixels).
  – Step 2: (future) -- 8 arcminute field at LMT potentially interesting for a multi-object spectrometer.
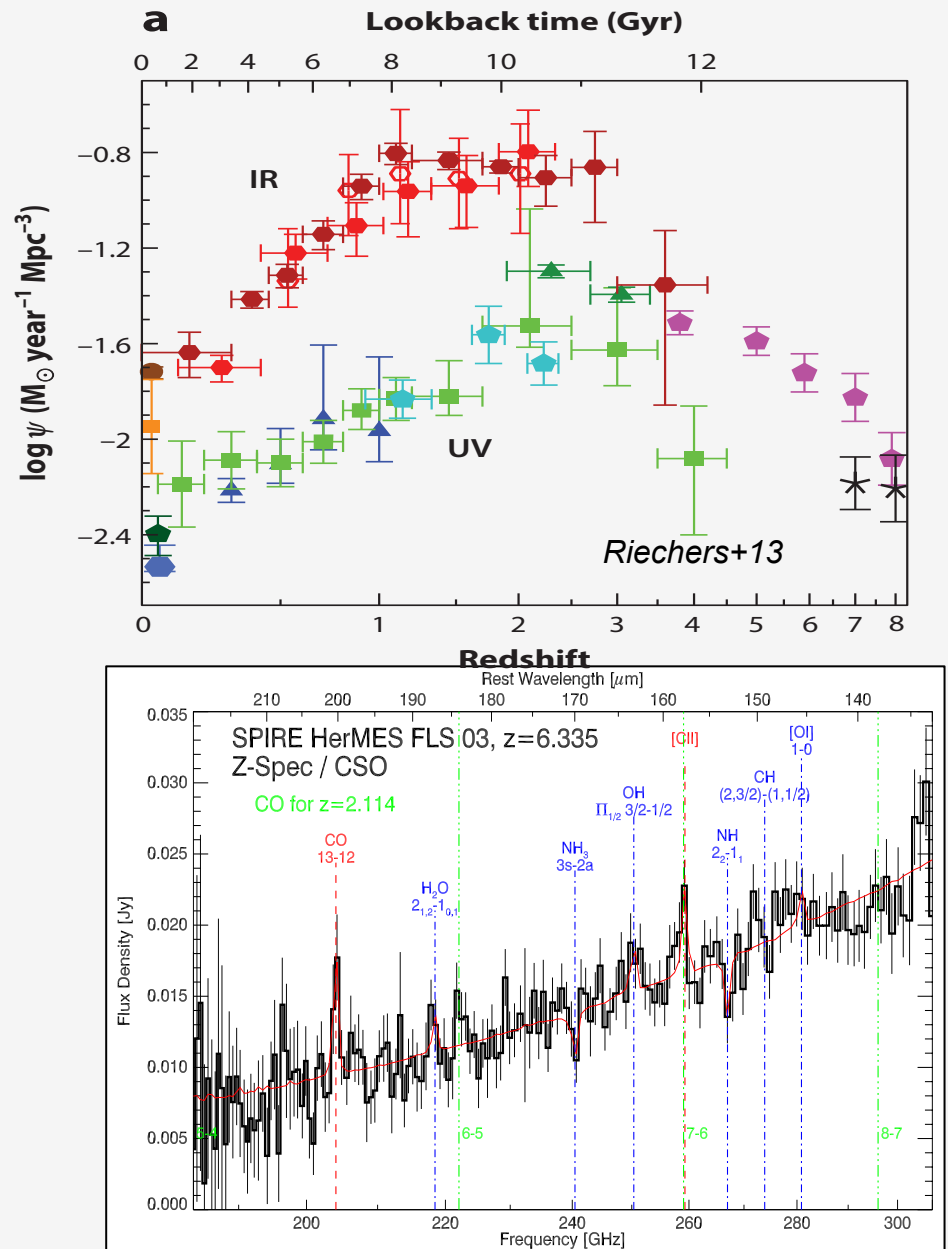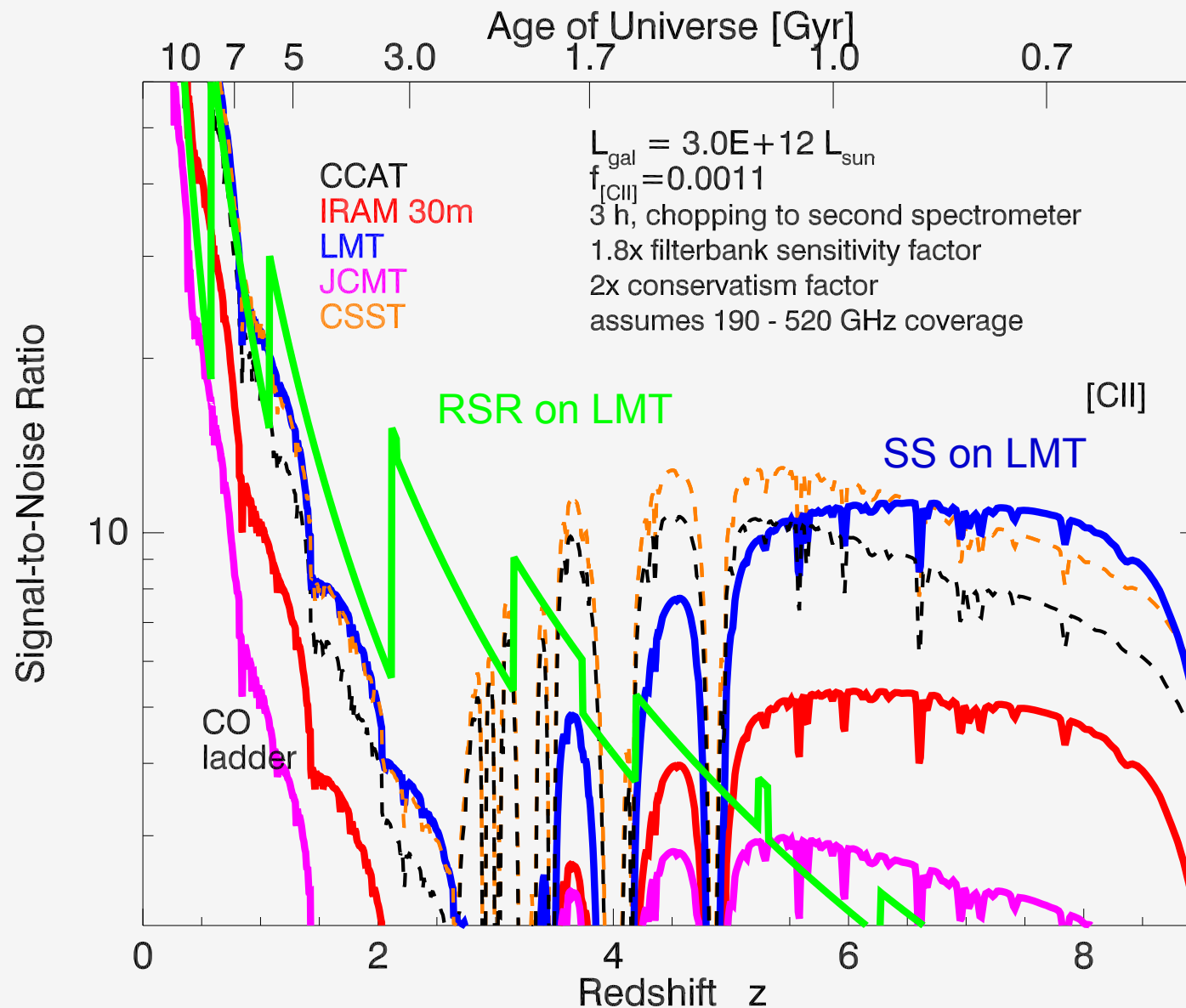
Sensitivity Landscape
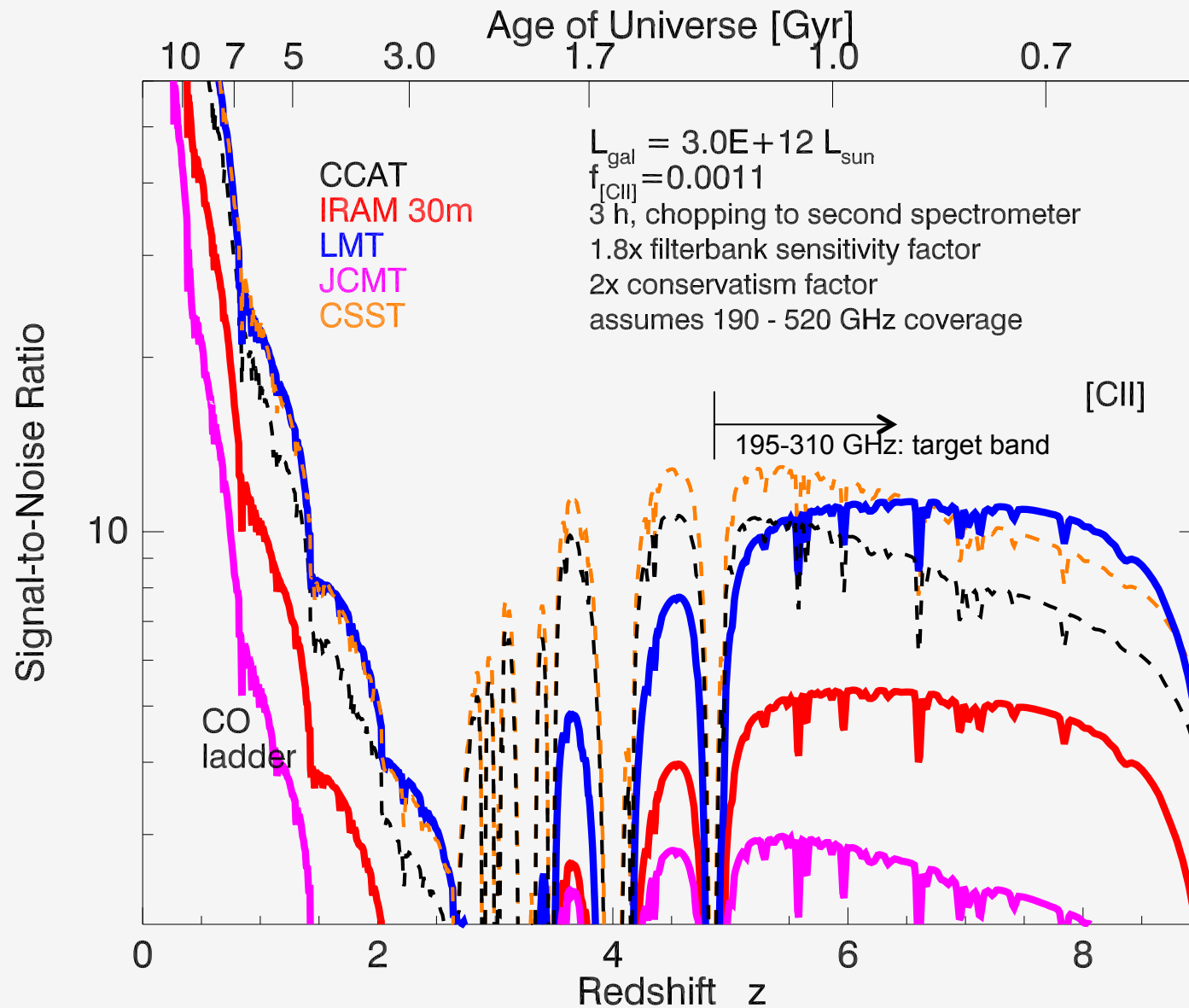
- LMT an unmatched facility at 1 mm.
- Detects ULIRG in 12 h, at any z>5.
- CSST (Caltech proposed 30-m wide field 850-μm telescope in Chile) would complement LMT at higher frequencies.
- Assumes:
-50 meters, 75 μm
-2 mm PWV
-Dual polarization
-Chopping to 2nd beam
-Filterbank degradation factor.

SuperSpec Complements RSR for full-z coverage

Age of Universe [Gyr]

10 7 5   3.0   1.7   1.0   0.7

CCAT
IRAM 30m
LMT
JCMT
CSST

$L_{gal} = 3.0E+12\ L_{sun}$
$f_{[CII]} = 0.0011$
3 h, chopping to second spectrometer
1.8x filterbank sensitivity factor
2x conservatism factor
assumes 190 - 520 GHz coverage

RSR on LMT

[CII]

SS on LMT

Signal-to-Noise Ratio

10

CO
ladder

0   2   4   6   8

Redshift z

- LMT + SuperSpec fill the full z range.

- Provides complete CO SLED sampling for z<2.
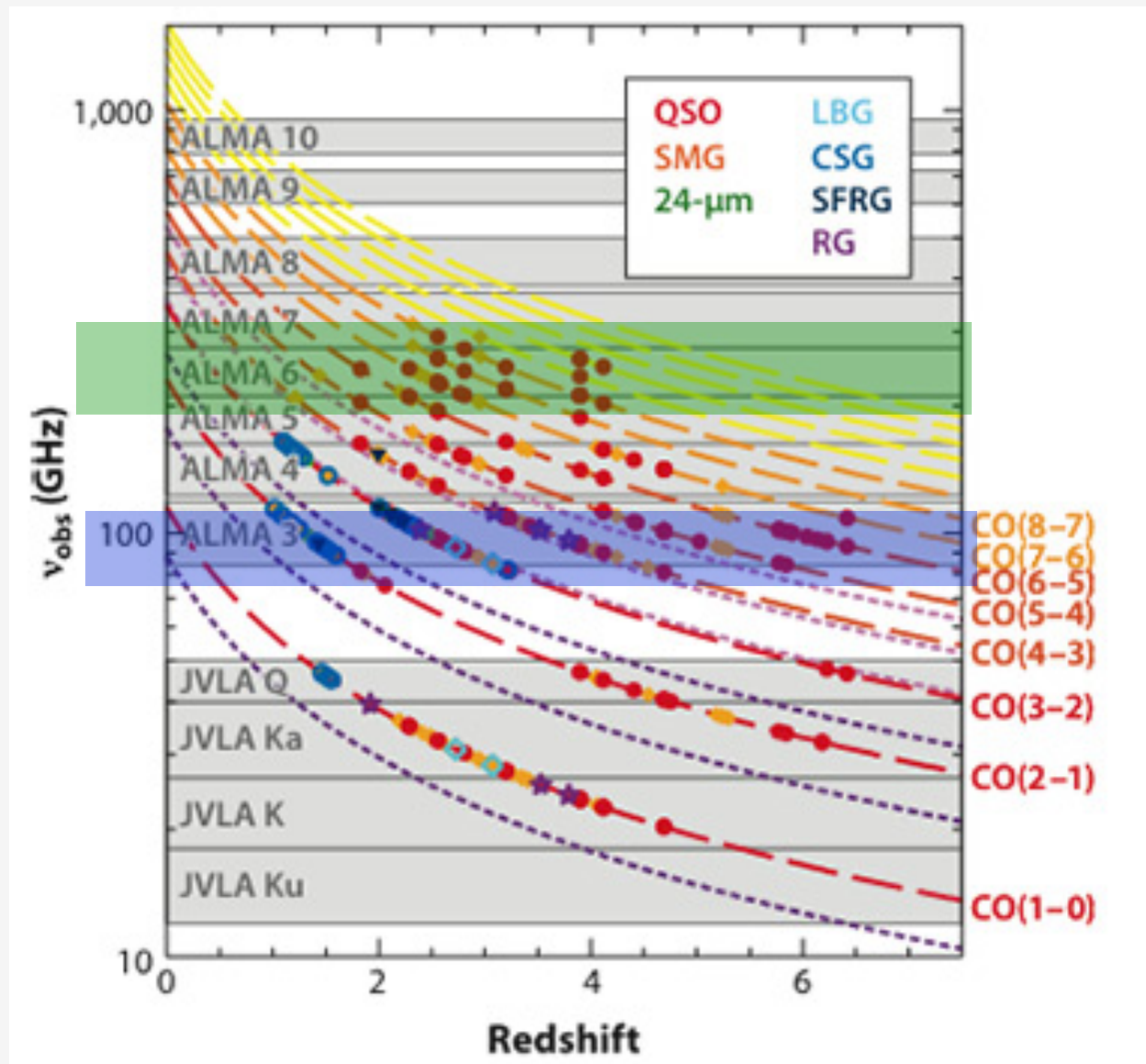
e.g. z=2-3:
SuperSpec: J=4,5,6…
RSR: J=2,3

-> Excited and quiescent molecular gas.

# RSR and SuperSpec Complementarity for CO

(Borrow ALMA plot)

SuperSpec

RSR

SuperSpec Overview

- SuperSpec is an on-chip spectrometer we are developing for moderate resolution, large bandwidth, (sub)millimeter astronomy.

- A single chip is coupled to one polarization of a single-mode beam and integrates:
  - antenna
  - moderate resolution (R ~ 100 – 500) filterbank with large BW (δv/v ~ 0.6)
  - associated detectors (KIDs) and readout circuitry.

- Each chip is ~few cm^2 in size

- Prototype chips covering 200 – 300 GHz range. Also looking to higher frequencies.
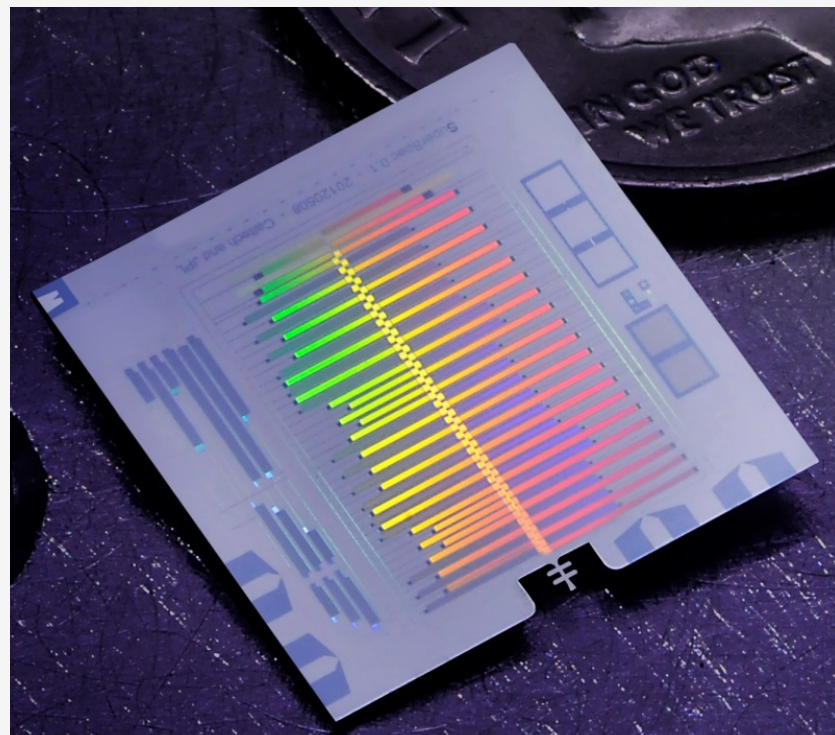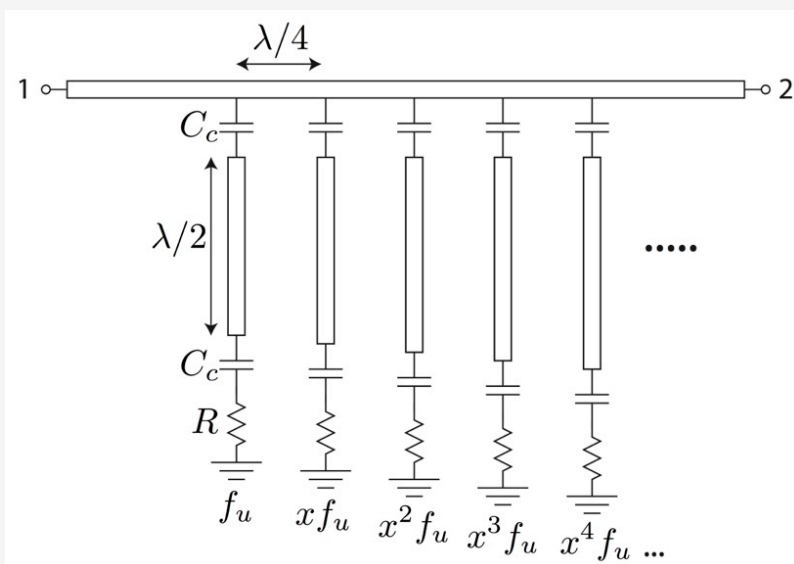
# SuperSpec Technology Status (more details in separate presentation)

- Currently concentrating on 200-300 GHz band (best for LMT anyway).

- Have demonstrated filterbank operation throughout this band.

- Very good understanding of the loss in the Nb / SiN / Nb microstrip that we use.

- Integrated detector white-noise NEPs are low enough to be background-limited on LMT (lowest NEP KIDs in North America).

- **1/f noise still requires study, but may not be an issue for LMT point-source spectrometer which can chop.**

- A tweak to filterbank geometry required to optimize channel Q and efficiencies – underway now.

- Expect science-ready chip by end of 2016.
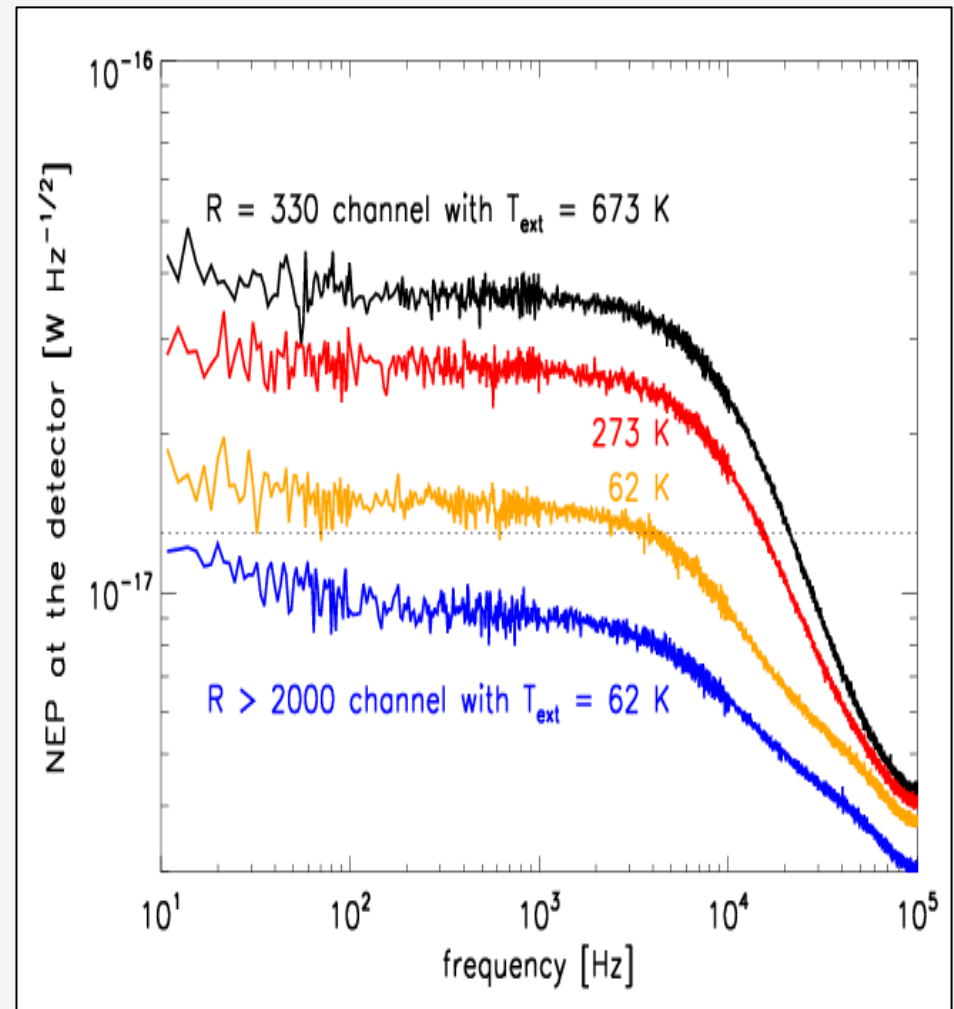
Proposed LMT instrument: Phase 0

- Demonstrate SuperSpec sensitivity on sky with a demo at LMT.

- 1 or 2 chips in existing Caltech cryostat.

- Have existing MAKO readout that we could use for this purpose. ASU readout also a possibility

- Anticipate obtaining a few high-z spectra with the 32-meter sensitivity.

- Strengthens case for subsequent ATI Proposal.

- Target 200-300 GHz band, don't worry too much about frequency range, but make sure that we have high efficiency and photon-limited performance (basically in hand).

- Need to investigate chopping / modulation – can it be done in front of the instrument?

- Need to investigate optical coupling

- Do we have manpower for interface software on the short timescale?
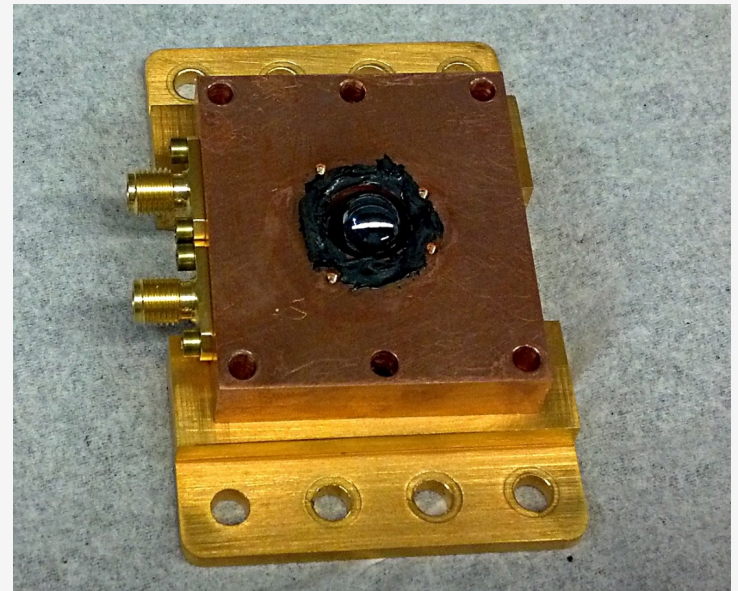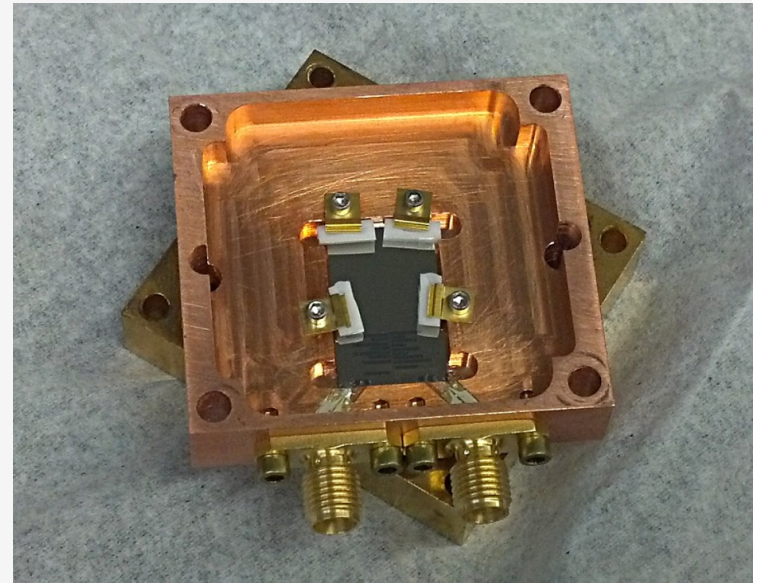
Proposed LMT instrument: Phase 1 w/ 50m

- Optimize for pointed observations of galaxies with known positions.

- Follow up of TolTEC ULIRGS, roughly 1 per night.

- R=400 with 2x spectral oversampling is the optimum design given given our material loss and the properties of the filterbank

- Aim for 195-310 GHz for each chip, so ~370 detectors per chip.

- Chip size on order 20 square cm.

- Resonant frequencies between 100-250 MHz, full chip read out with a single readout line and cold amplifier.

- Warm electronics process 2 chips per ROACH board (maybe 4?) (Readout an area ripe for collaboration from our standpoint.)

- Instrument has polarizing grid feeding both polarizations of each sky position to a separate chip.

- 3-5 sky positions, source is chopped between 2-3 of them.

- So 6-10 chips + readout circuits in the full instrument.

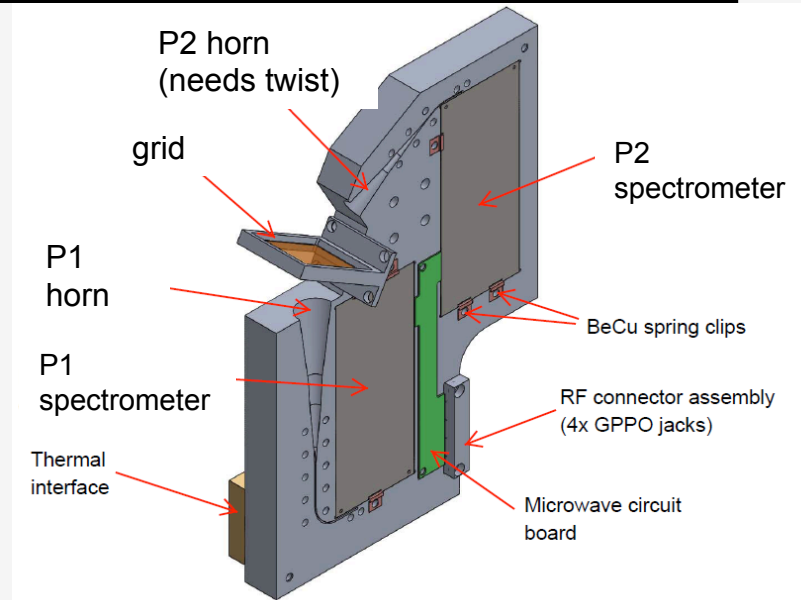- Need to investigate chopping / modulation – can it be done in front of the instrument with the foreoptics?
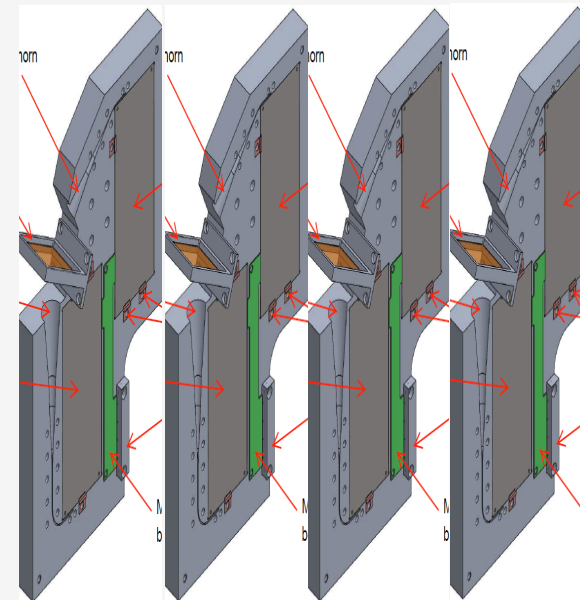

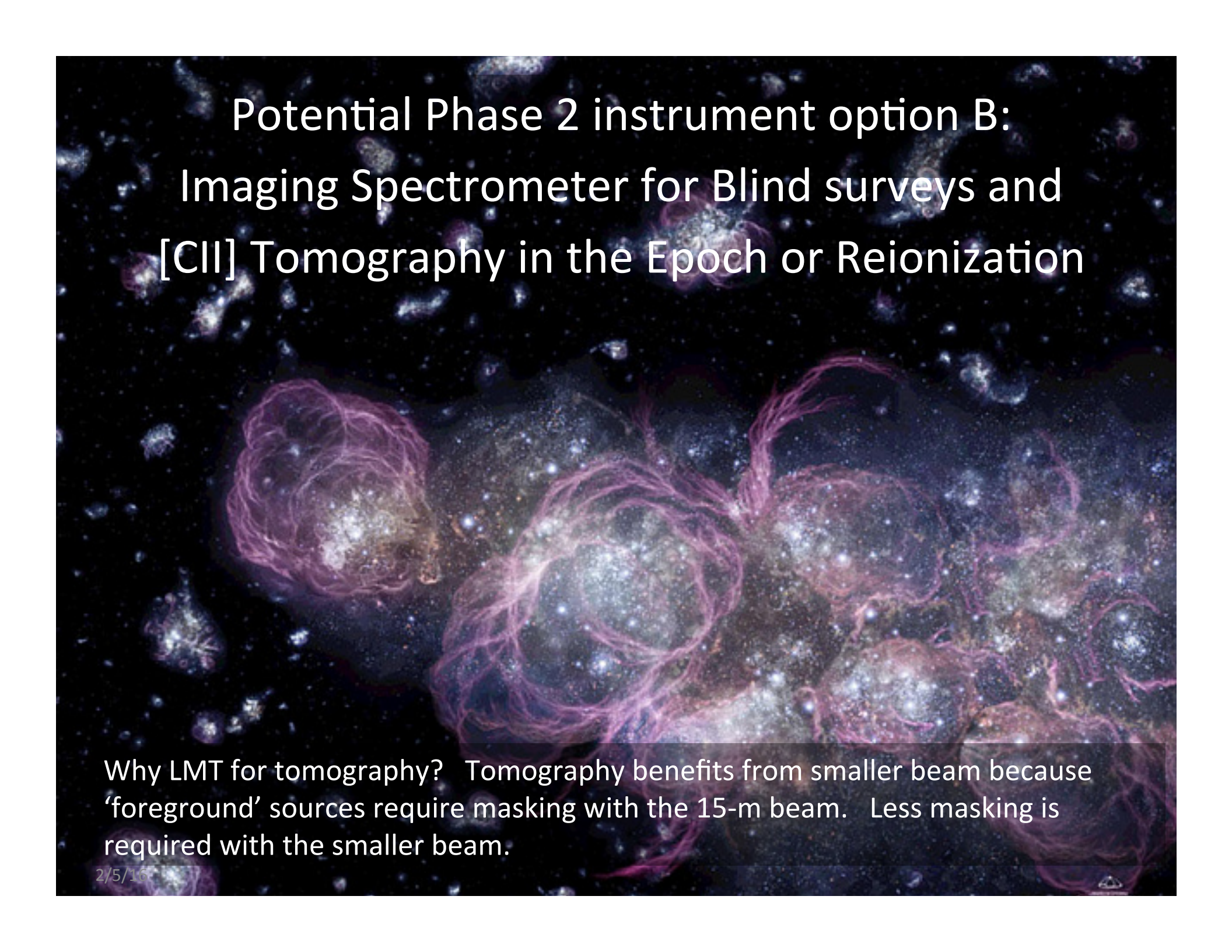Figure adapted from X-Spec / CCAT study

Concept: Small array of chips: Both pols in 3-5 positions.

(Will flesh out…)

Potential Phase 2 instrument option A: MOS

- 8 arcminute field at LMT is big enough to consider a multi-object spectrometer.

- Field is ~7000 beams at 1.2 mm.

- An opportunity to follow up the bright TolTEC sources directly.

- Estimated source densities based on Planck (should compare with your estimates for Toltec) (z>5 values much less certain):

- ULIRGs (1e12 Lsun) – takes 1 night per observation
  - ~1e4 per square degree at all z: 140 per field
  - ~1e3 per square degree with z>5: 14 per field

- L=3e11 Lsun galaxies – takes 10 nights per observation
  - ~4e4 per square degree at all z: 560 per field
  - ~4e3 per square degree with z>5: 56 per field.

- So a MOS which has a few tens up to ~100 independent backends could make sense.

- 100-element MOS can beat ALMA for blind spectral follow-up

- We have rough design for CSST / CCAT, but this would not work for LMT, need smaller patrol regions.
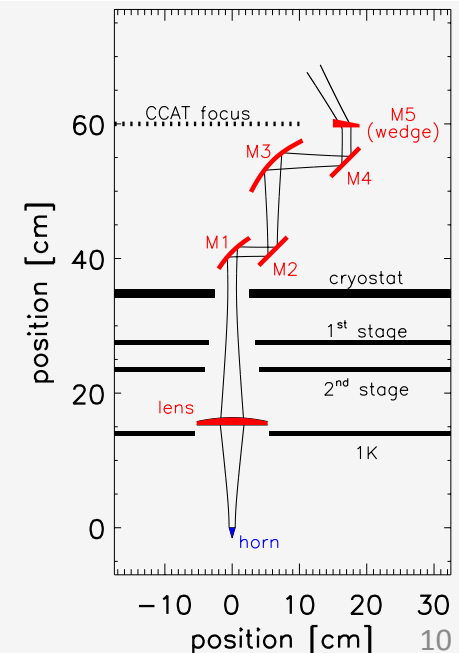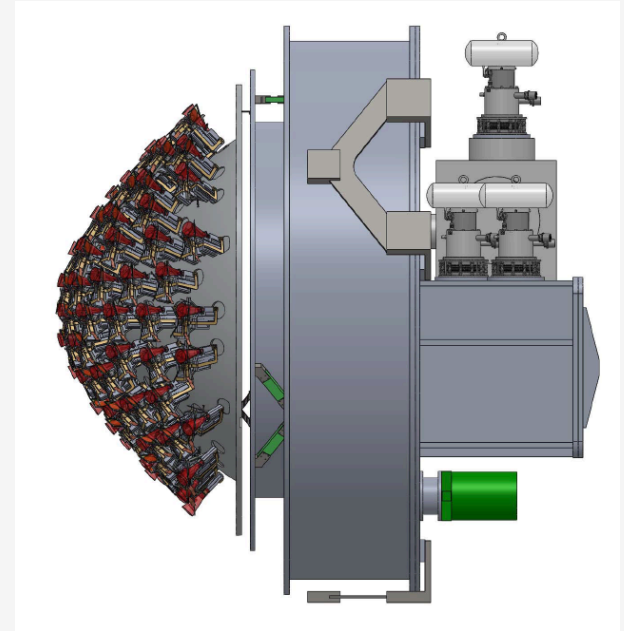
Potential Phase 2 instrument option B:
Imaging Spectrometer for Blind surveys and
[CII] Tomography in the Epoch or Reionization

Why LMT for tomography?   Tomography benefits from smaller beam because 'foreground' sources require masking with the 15-m beam.   Less masking is required with the smaller beam.

2/5/16

Probing the Epoch of Reionization with CII
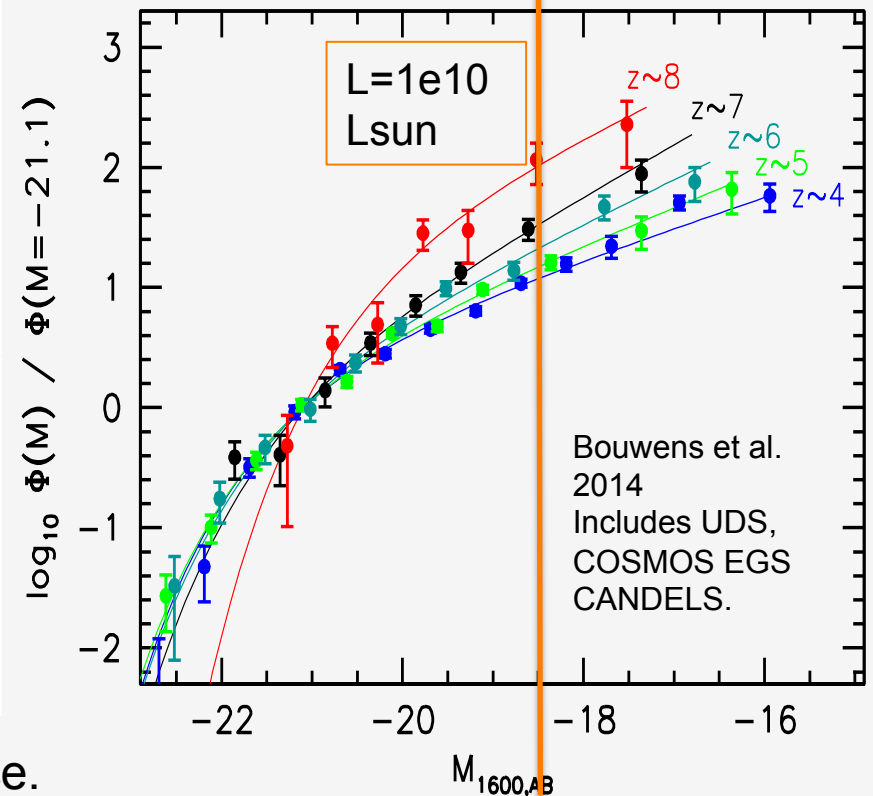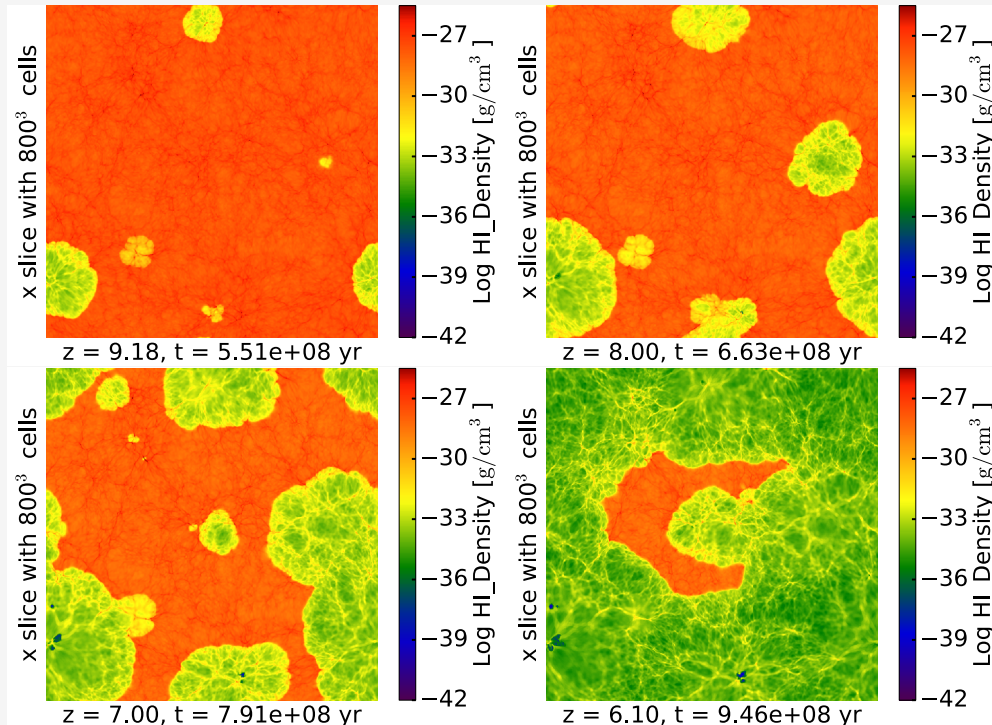
So et al. 2014 model, 20 Mpc comoving slice.

UV surveys have not detected all the galaxies responsible for reionization. Particularly at early times, much of the photon flux is believed to originate in low luminosity dwarfs which are difficult to detect individually, even with JWST and ALMA. E.g. Wise et al. 2014.

Note also the UV measurements indicate an steepening of the LF at early times – in fact, light integral is not bounded. (e.g. Bouwens et la. 2014)

Use maps to measure clustering,
Instead of discrete sources.

250 μm

Herschel SPIRE
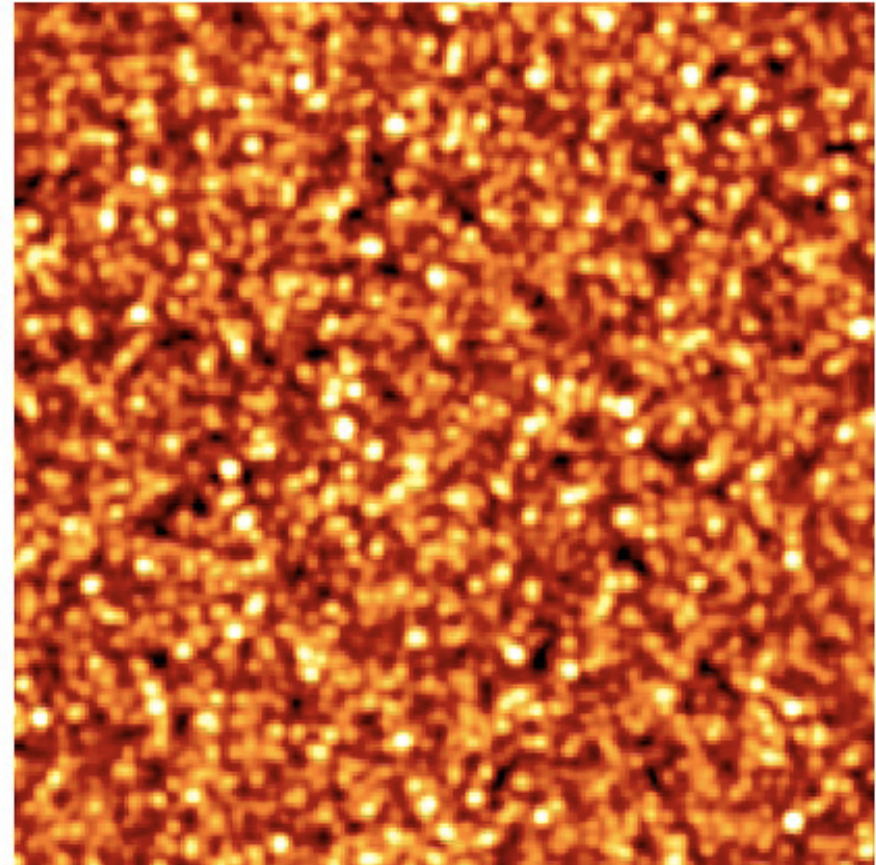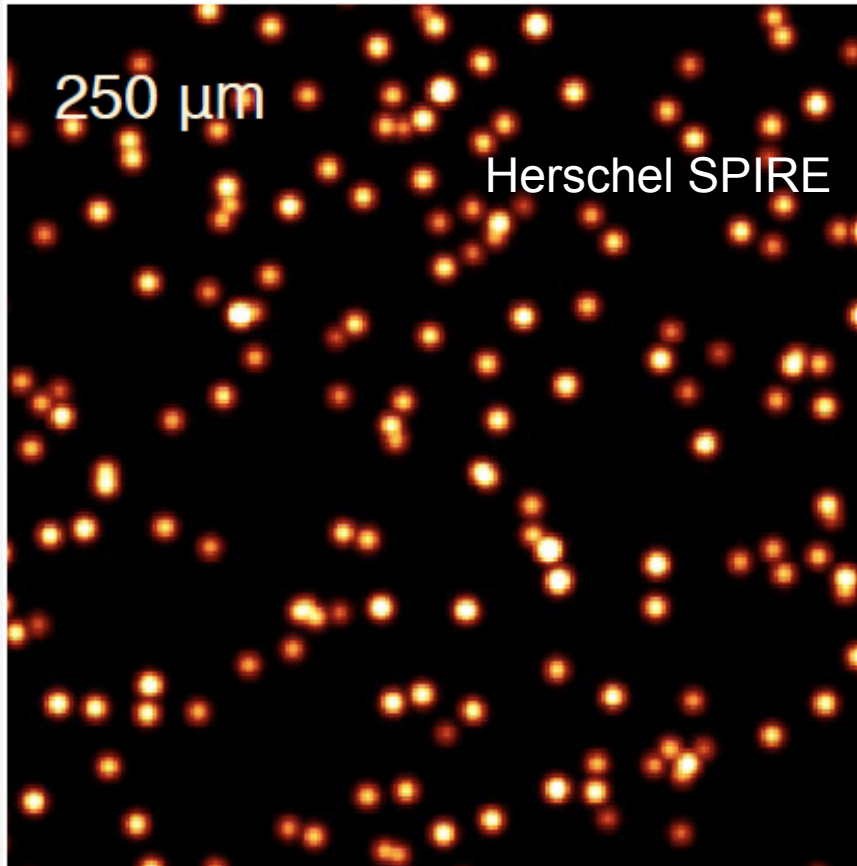
S > 20 mJy : 1,200/deg²   S < 20 mJy : 480,000/deg²

But in 3 dimensions with imaging spectrometer, not 2
Tomographic experiments now under way with CO, 21 cm.
C+ and excellent candidate.

EoR CII tomography key points

- [CII] is an approximately universal star formation indicator, even at low metallicity (obviously not Pop III, but shortly thereafter). Does not require dust. Also is agnostic about the IGM.

- Use of a spectral line enables true 3-D tomography, key for the early universe. 2-D approaches are swamped by the z=1-3 galaxies.
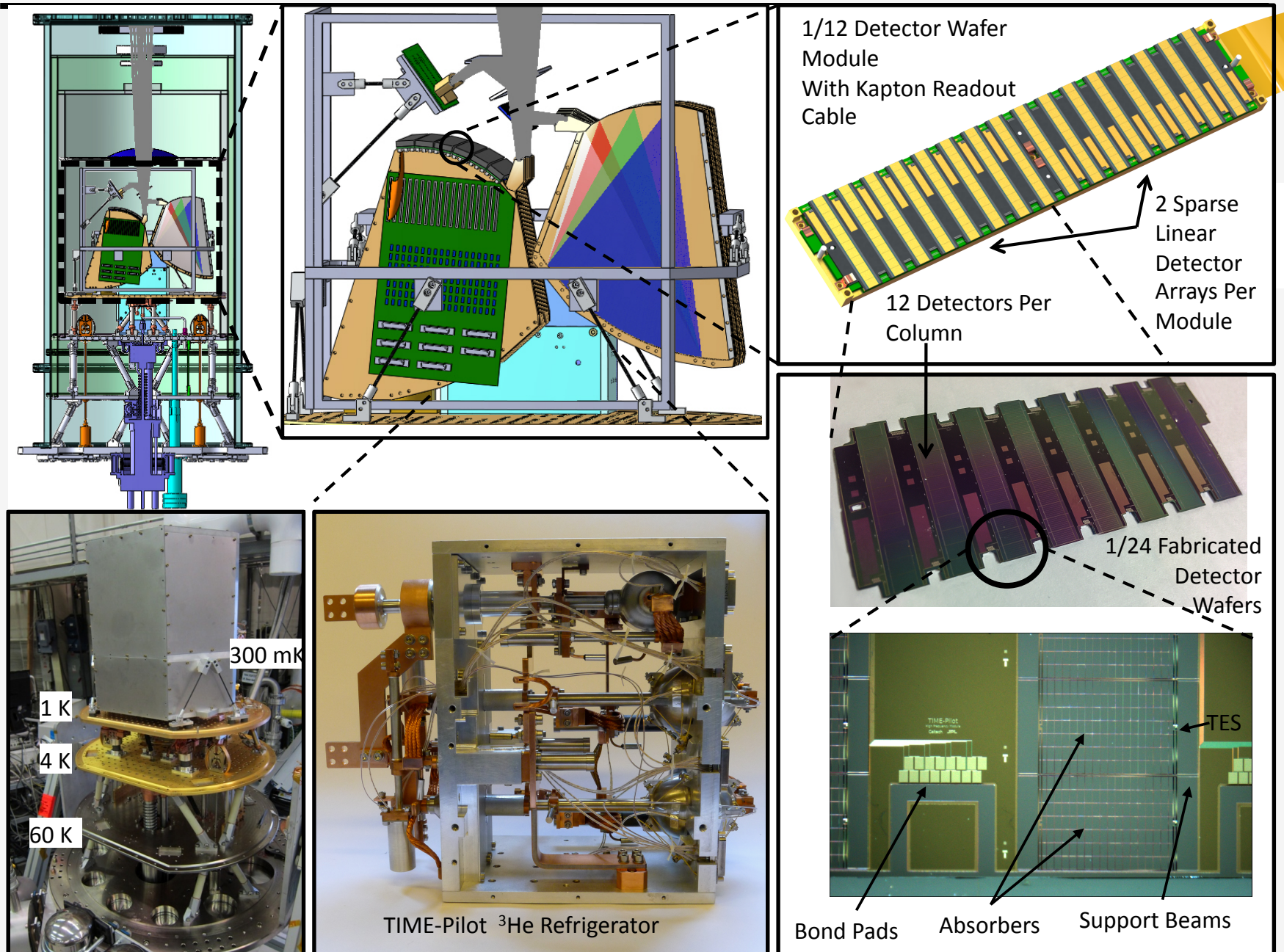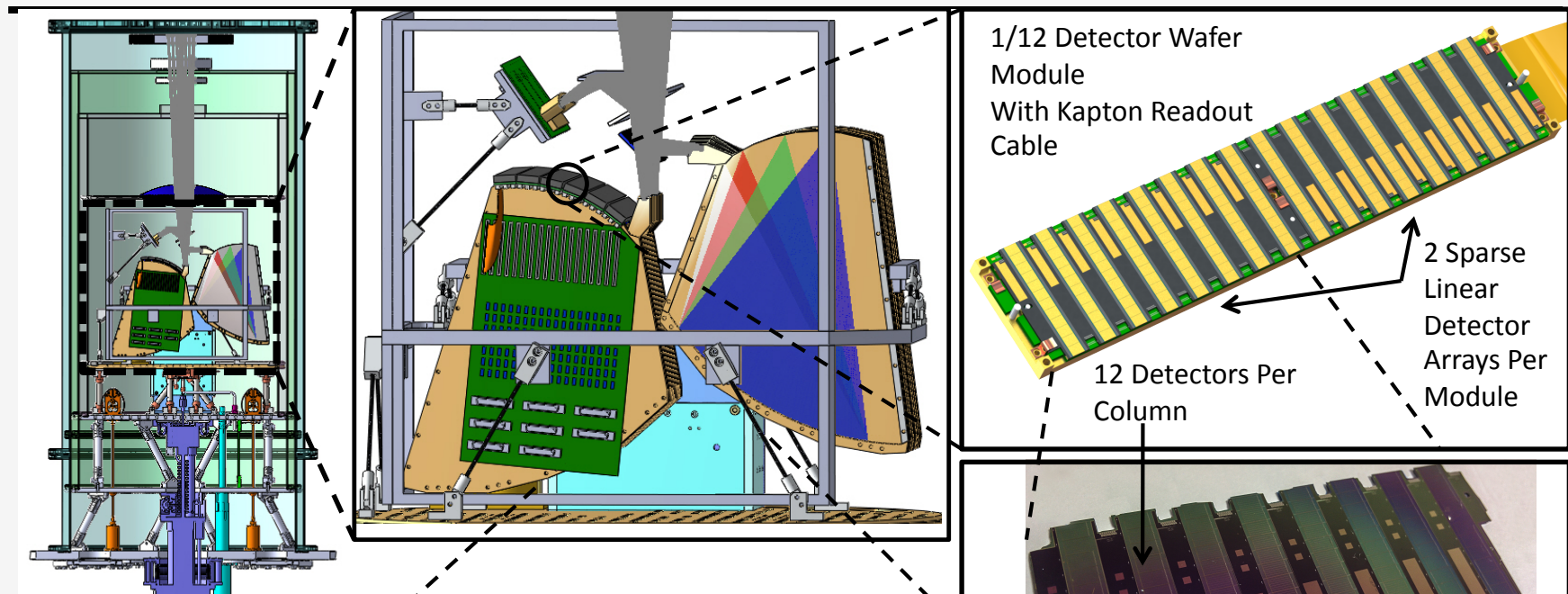
- Fourier-space power spectrum measures two-halo clustering, intra-halo clustering and Poisson noise.

  - 2-halo term is linear in the mean (total) intensity x galaxy bias, so can be used to measure the total CII emission as a function of redshift. A path to total star formation rate which naturally integrates the full luminosity function.

  - And residuals to bright sources measure the low-L part of the Luminosity function.

  - Poisson term measures second moment of luminosity function (integral of L^2 dL), so favors bright sources.

- **CII datasets will eventually be correlated with HI, to reveal the interplay between the ionizing galaxies and the forming 'bubbles,' specifically the bubble size. (see Gong et al., 2012)**

- **We are exploring this approach with 10 -15 meter telescopes, but we already know that the CO-emitting 'foregrounds' (z=1-3 galaxies) are likely to dominate the fluctuations, and need to be removed (or 'masked') from the dataset. A smaller beam such as that on the LMT enables more efficient masking of 'foreground' CO emitters.**

- CII tomography papers:
  - Gong et al., 2012: http://adsabs.harvard.edu/abs/2012ApJ...745...49G — ~affiliated with our group
  - Silva et al, 2015: http://adsabs.harvard.edu/abs/2015ApJ...806..209S
  - Kogut et al., 2015: http://adsabs.harvard.edu/abs/2015ApJ...806..234K
  - Yue et al., 2015 http://adsabs.harvard.edu/abs/2015MNRAS.450.3829Y

An example [CII] tomography instrument: TIME-Pilot

1/12 Detector Wafer Module With Kapton Readout Cable

2 Sparse Linear Detector Arrays Per Module

12 Detectors Per Column

1/24 Fabricated Detector Wafers

300 mK

1 K

4 K

60 K

TIME-Pilot ^{3}He Refrigerator

TES

Bond Pads   Absorbers   Support Beams

An example [CII] tomography instrument: TIME-Pilot

1/12 Detector Wafer Module With Kapton Readout Cable

2 Sparse Linear Detector Arrays Per Module

12 Detectors Per Column

- **32 waveguide grating spectrometers**
  - As used in Z-Spec
  - R=100, 60 detectors each covering 186-324 GHz.
  - At least 42 channels each for science, up to 18 can be atmospheric monitors.
- **1800 absorber-coupled TES bolometers**
  - time-domain (NIST) SQUID MUX, as per SCUBA-2, BICEP-2.
  - NEP of 3e-18 well in hand after BLISS / SPICA development.
- **Novel 'slab' survey geometry with most of low-k information coming from spectral dimension.**
  - Requires careful deconvolution between instrument modes and astrophysical k bins.

TIME-Pilot survey geometry and instrument modes.

z=8.5

0.9

1230 Mpc

140 Mpc

z=5.2
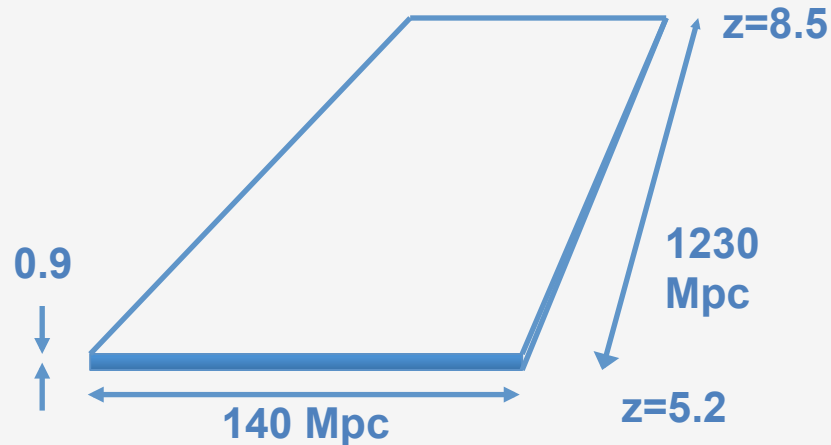
- Want to maximize per-pixel sensitivity – go deep with small area. But need to sample small k, drives to large size (don't want to rely on spectral direction solely).

- Our approach: 156-beams wide x 1 beam-thick rectangle on the sky (140 Mpc x 0.9 Mpc on the CSO).

- Spectral coverage mapped into comoving coordinates gives large z direction: 195 to 318 GHz is z=5.0 to 8.7, a total of 1440 Mpc.
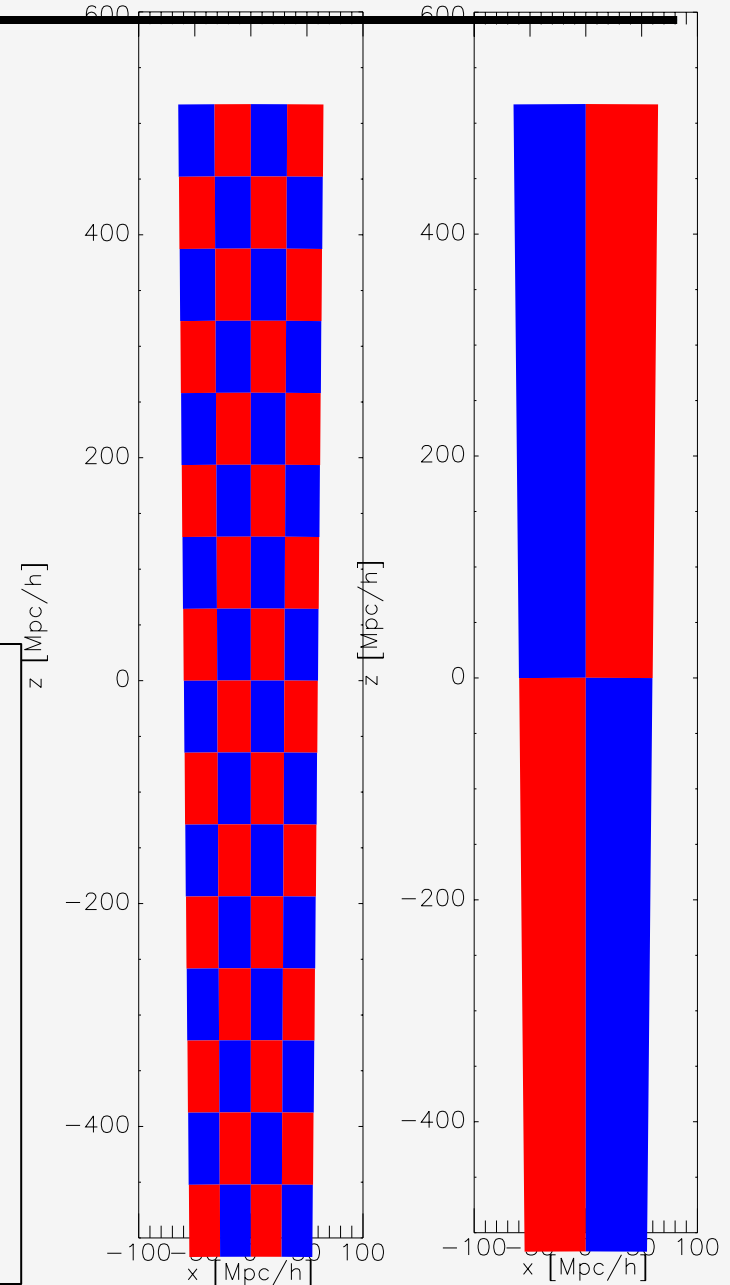
TIME-Pilot Dataset – Expected Sensitivity

- [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 ~ 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**

Chart legend:
- P_{CII} from SFR model (S/N=9.7)
- P_{CII} from Gong et al. (2012)
- P_{CII} from simulation
- P_{CO}^{tot} from Bethermin et al. (2011)
- Unmasked P_{CO}^{tot} (S/N=195.7)
- P_{CO}^{tot} with $f_{CO}^{cut} \sim 10^{-21}$ W/m²
- P_{CO}^{tot} with $f_{CO}^{cut} \sim 3 \times 10^{-22}$ W/m²
- P_{CO}^{tot} with $f_{CO}^{cut} \sim 10^{-22}$ W/m²

Axis labels:
- $kP(k)$ $(Jy/sr)^2 (Mpc/h)^2$
- k (h/Mpc)

Annotations:
- Halo-halo clustering (linear term, encodes total CII emission)
- Inter-halo clustering
- Shot noise

The SuperSpec Team

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Sonnet Simulations
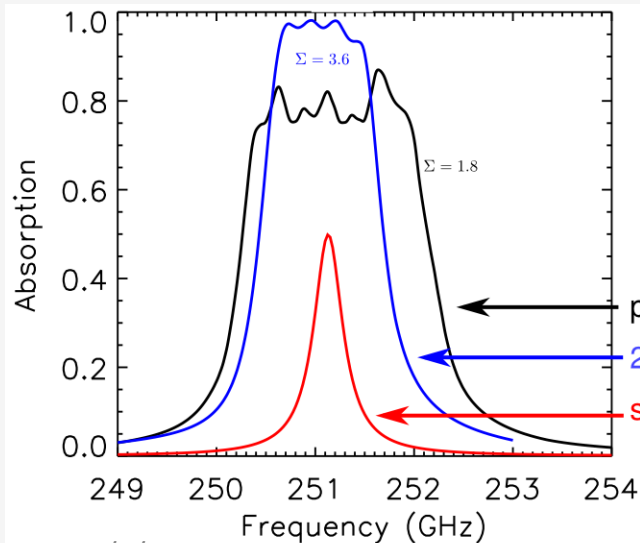
TiN meander

0   300 A/m

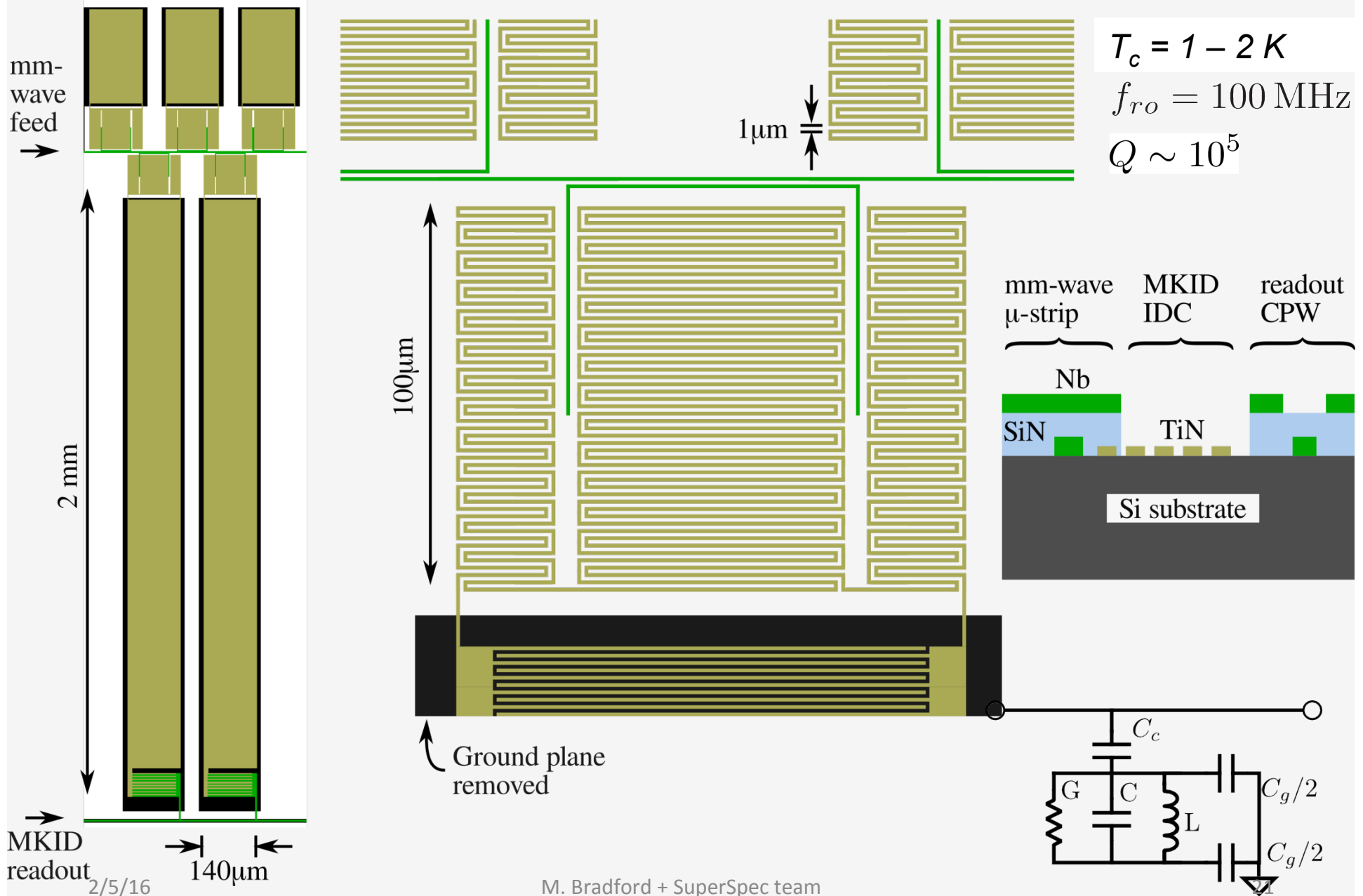$1/R = 1/Q_{feed} + 1/Q_{det}$

Horn coupled
mm-wave feed

Nb microstrip

Simulated
response of a
7-element
filter-bank

$\Sigma = 3.6$

$\Sigma = 1.8$

prototype packing density

2X packing density
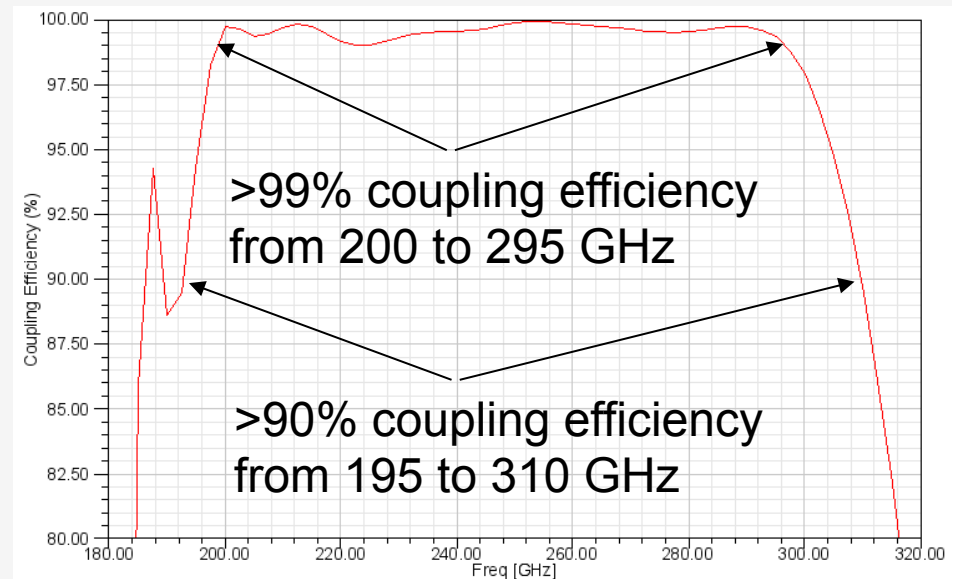
single channel response

Absorption

Frequency (GHz)
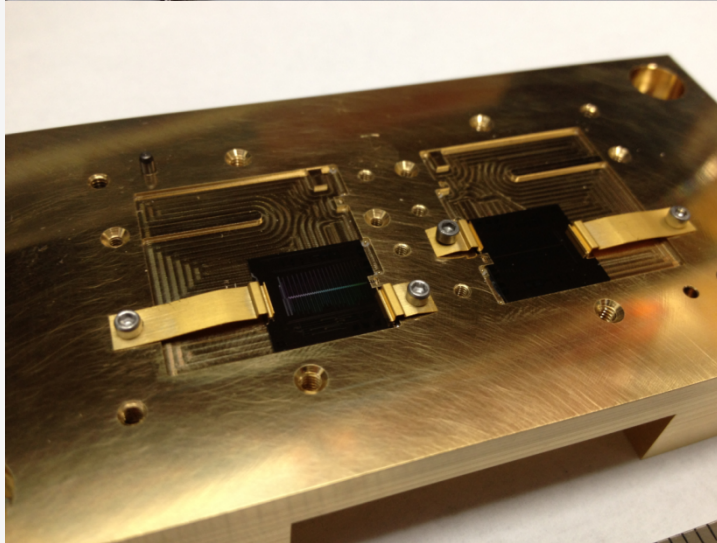
Simulated current at
one mm-wave frequency

Superspec first generation design

mm-wave feed →

2 mm

100μm

1μm

140μm

MKID readout

Ground plane removed

$T_c = 1 - 2\,K$

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

$Q \sim 10^5$

mm-wave μ-strip   MKID IDC   readout CPW

Nb

SiN   TiN

Si substrate

C_c

G   C   L

$C_g/2$

$C_g/2$

M. Bradford + SuperSpec team

Gen1 Probe-Fed Waveguide and Horn

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

>99% coupling efficiency from 200 to 295 GHz

>90% coupling efficiency from 195 to 310 GHz

Design and images by T. Reck
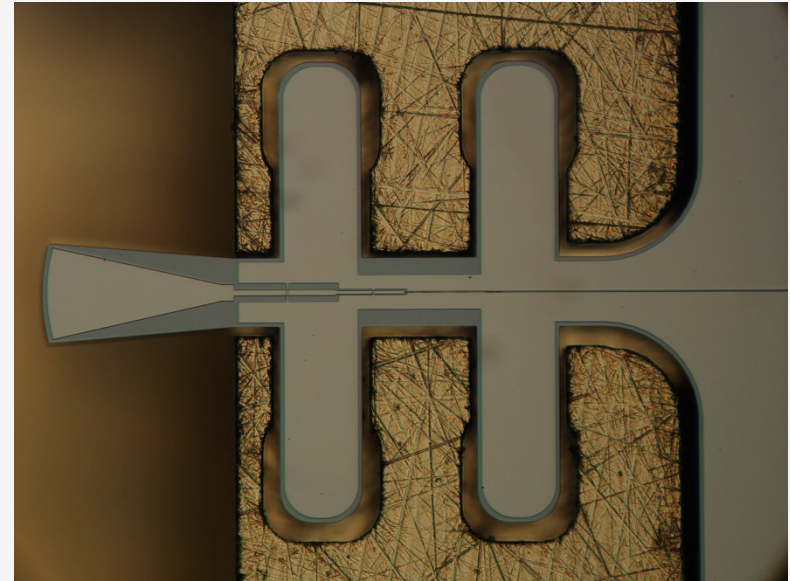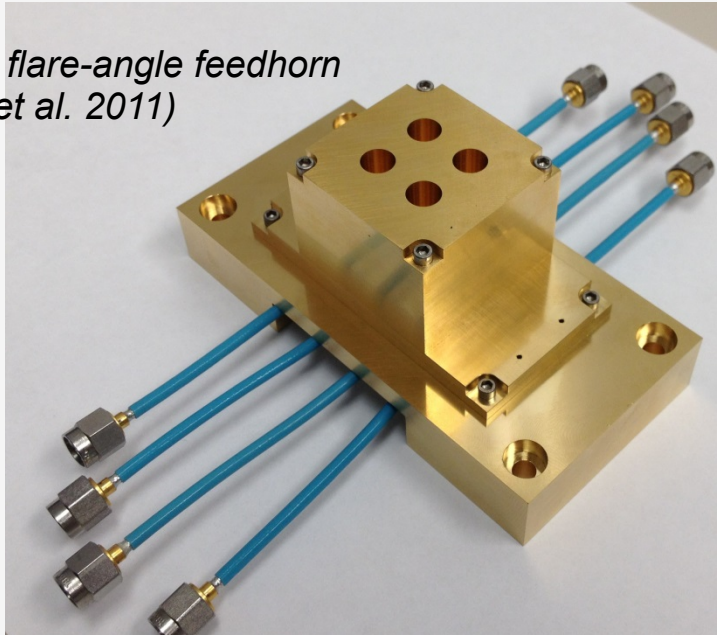
FTS Measurements
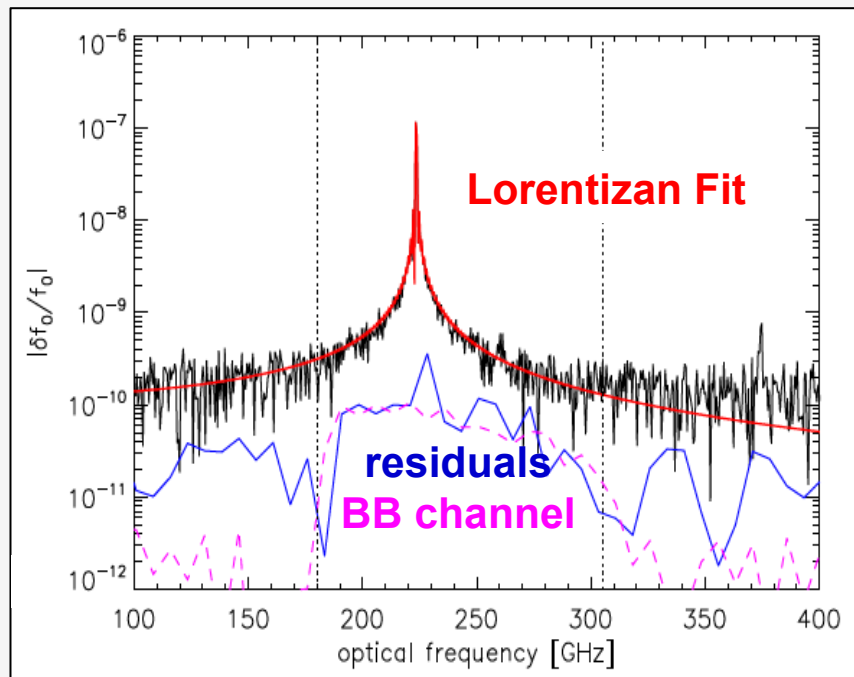
Normalized profiles of 71 spectral channels readout in parallel

Lorentizan Fit

residuals
BB channel
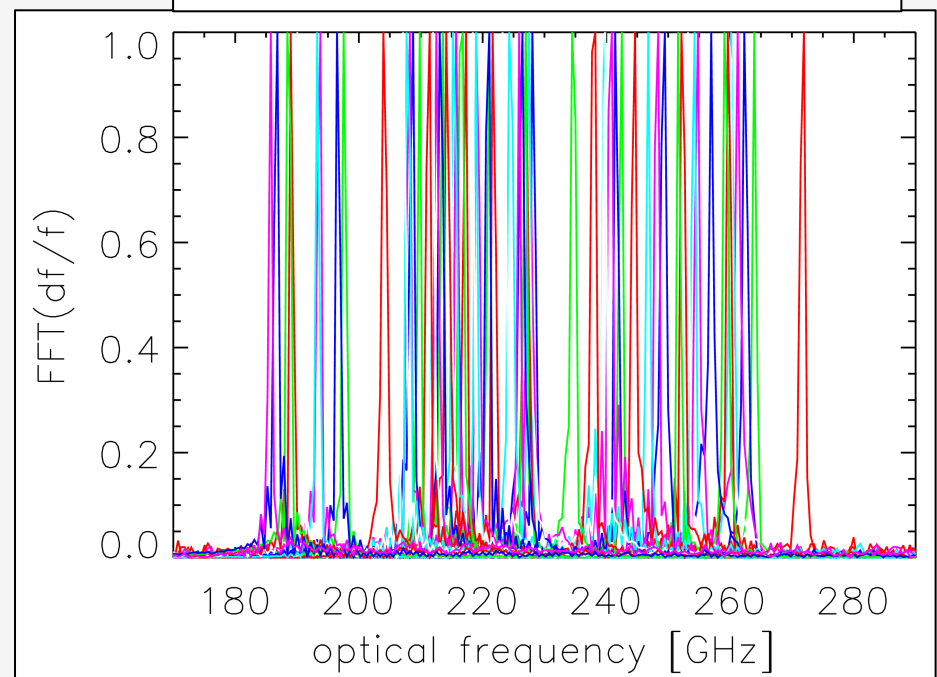
- Full band spectra measured with CASPER-ROACH based FPGA readout system (same system deployed by MAKO/CSO)

- Residual out of band response typically 30dB below peak

Spectral Sockout + Channel Response Reveals Coupling
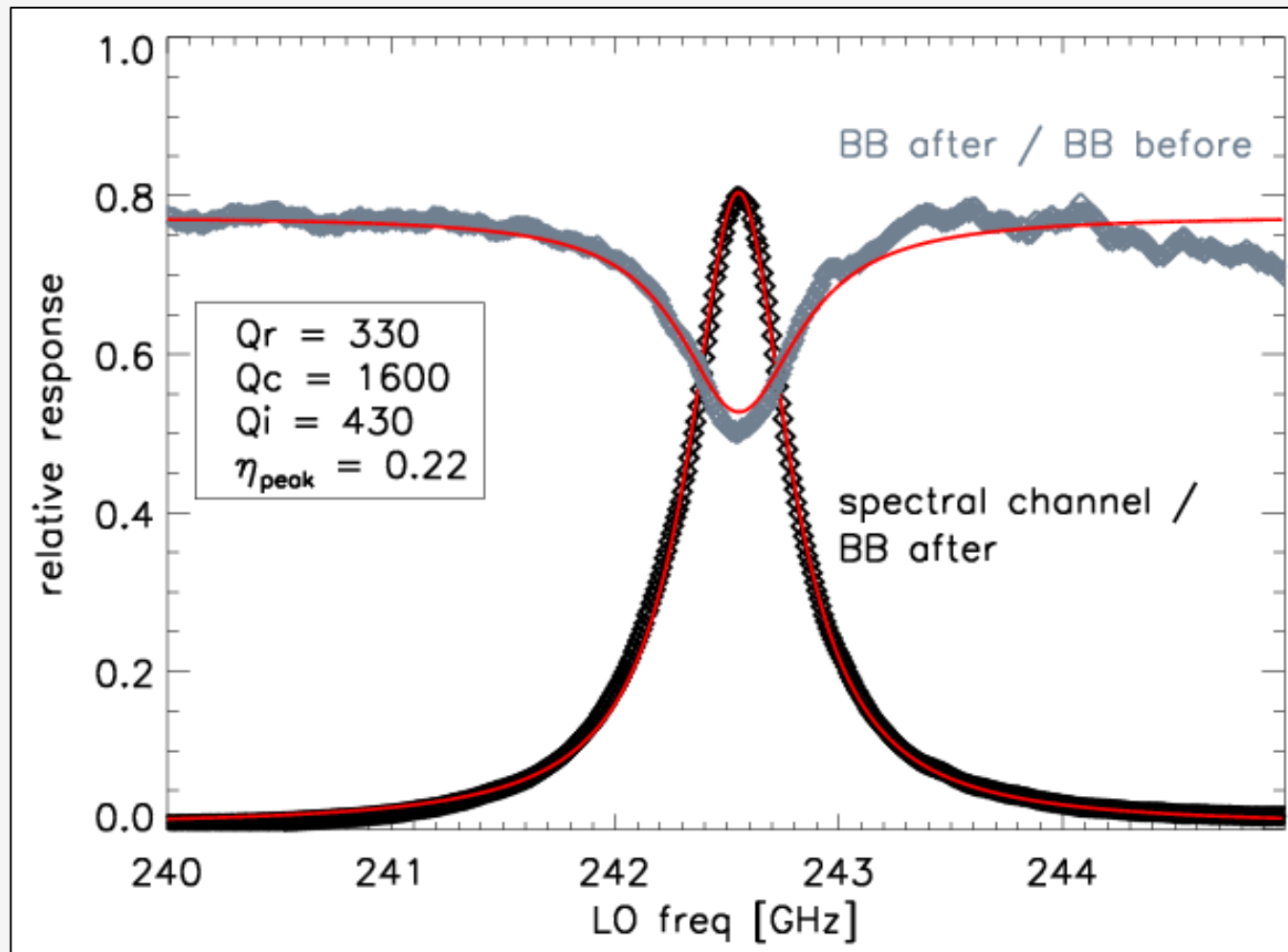
- Ratio of the spectral channel response to that of a broadband absorber, + the ratios of broadband absorbers before and after the channel, fully characterize the channel.
- This channel that is undercoupled, so achieves a peak coupling efficiency of only 22%.

M. Bradford + SuperSpec team

Spectral Sockout + Channel Response Reveals Coupling

BB before: segments of TiN brought in proximity to the feedline before the channel

BB after

BB1
BB2
BB3
BB4

Plot legend:
BB after / BB before
spectral channel / BB before Q < 300
spectral channel / BB before Q > 300

Relative Response vs LO frequency [GHz]
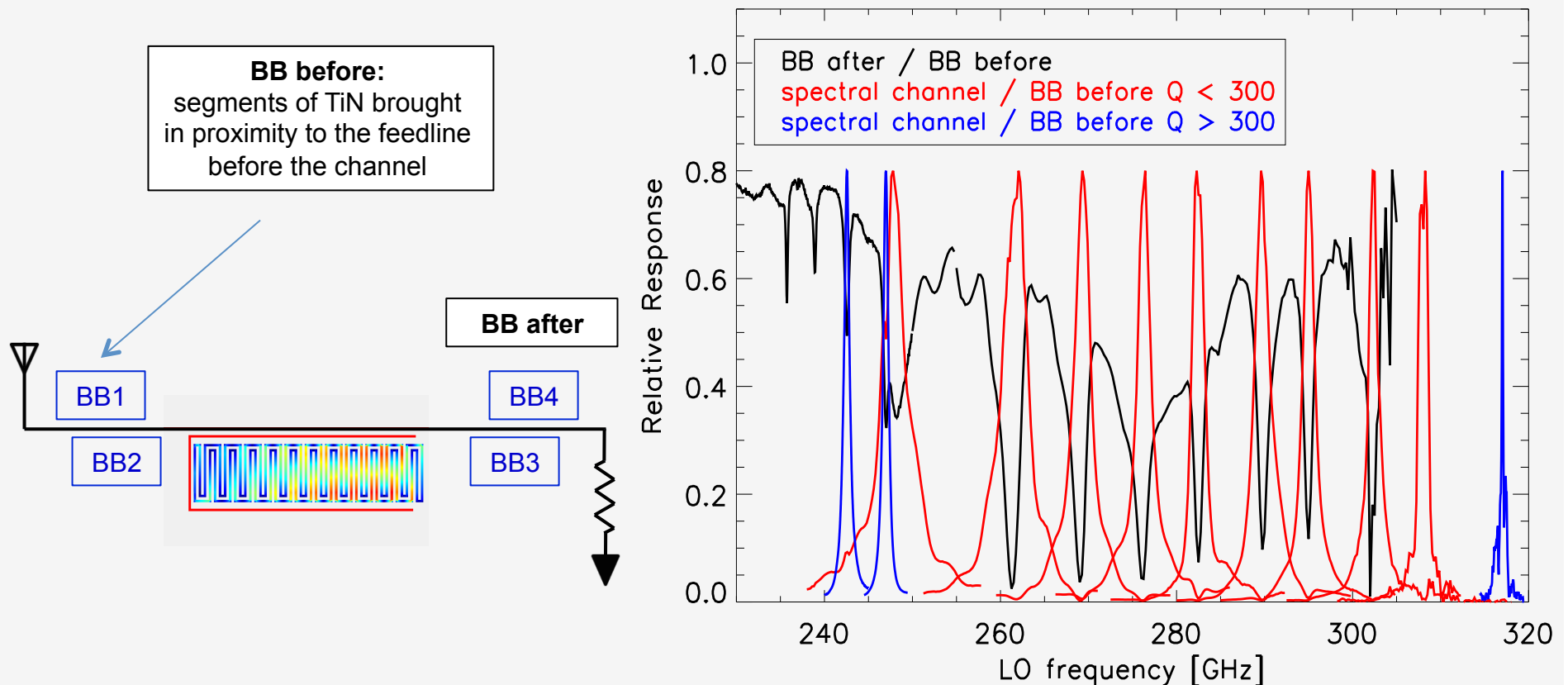
- Spectral response characterized with a coherent source radiating directly into the cryostat.
- Broadband absorbers coupled to the feedline before and after the spectral channels are used to quantify the fraction of the power on the line removed by the filter.
- A well-matched channel detects 50% of the power, and on-resonance the BB after / BB before ratio drops to 0.20. Shallower/deeper dip depths indicate weaker/stronger coupling, and less than 50% efficiency.

3rd Generation, more sensitive device
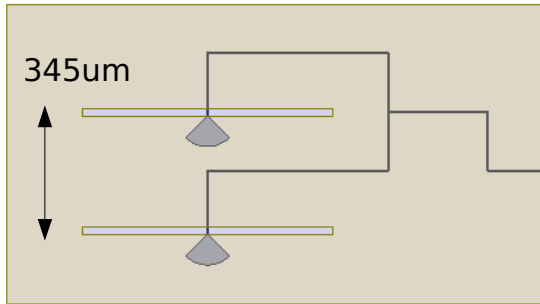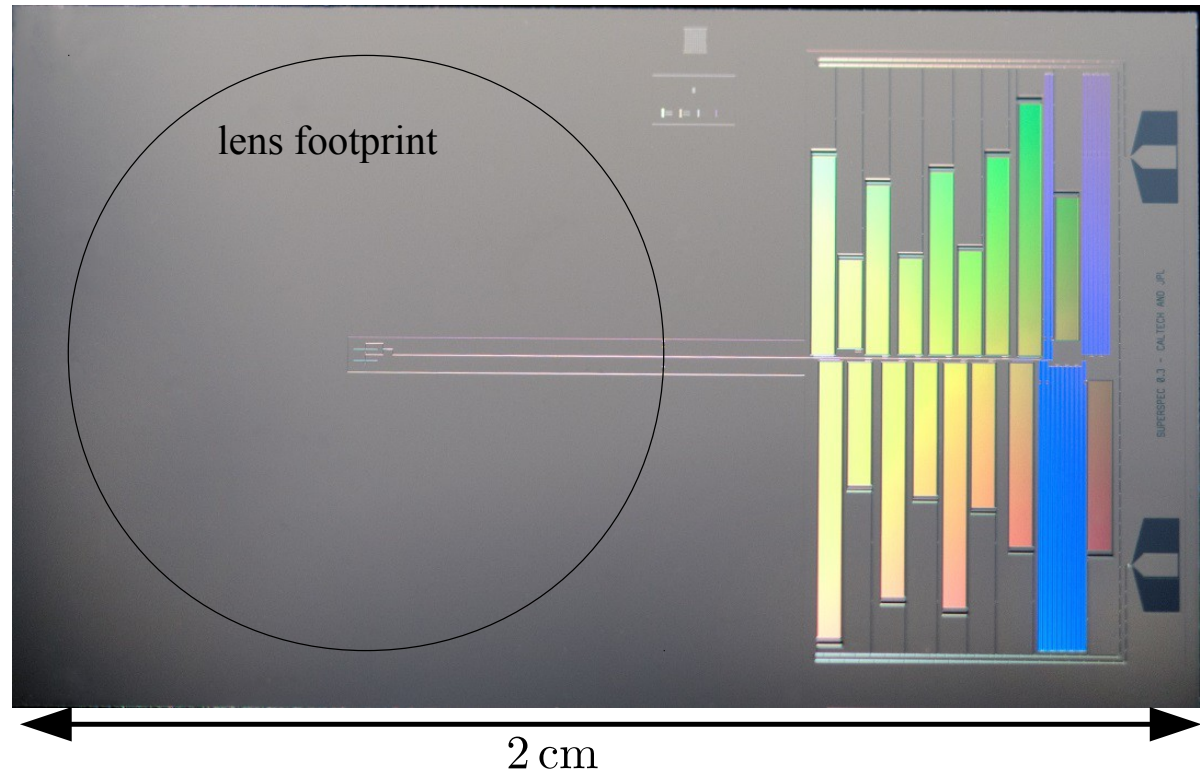
(above) Twin slot antenna layout.
(below) Photograph of an antenna-coupled SuperSpec die with 1cm hyper-hemispherical Si lens. The current test devices include a Stycast epoxy AR
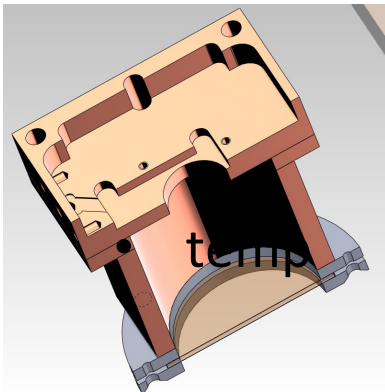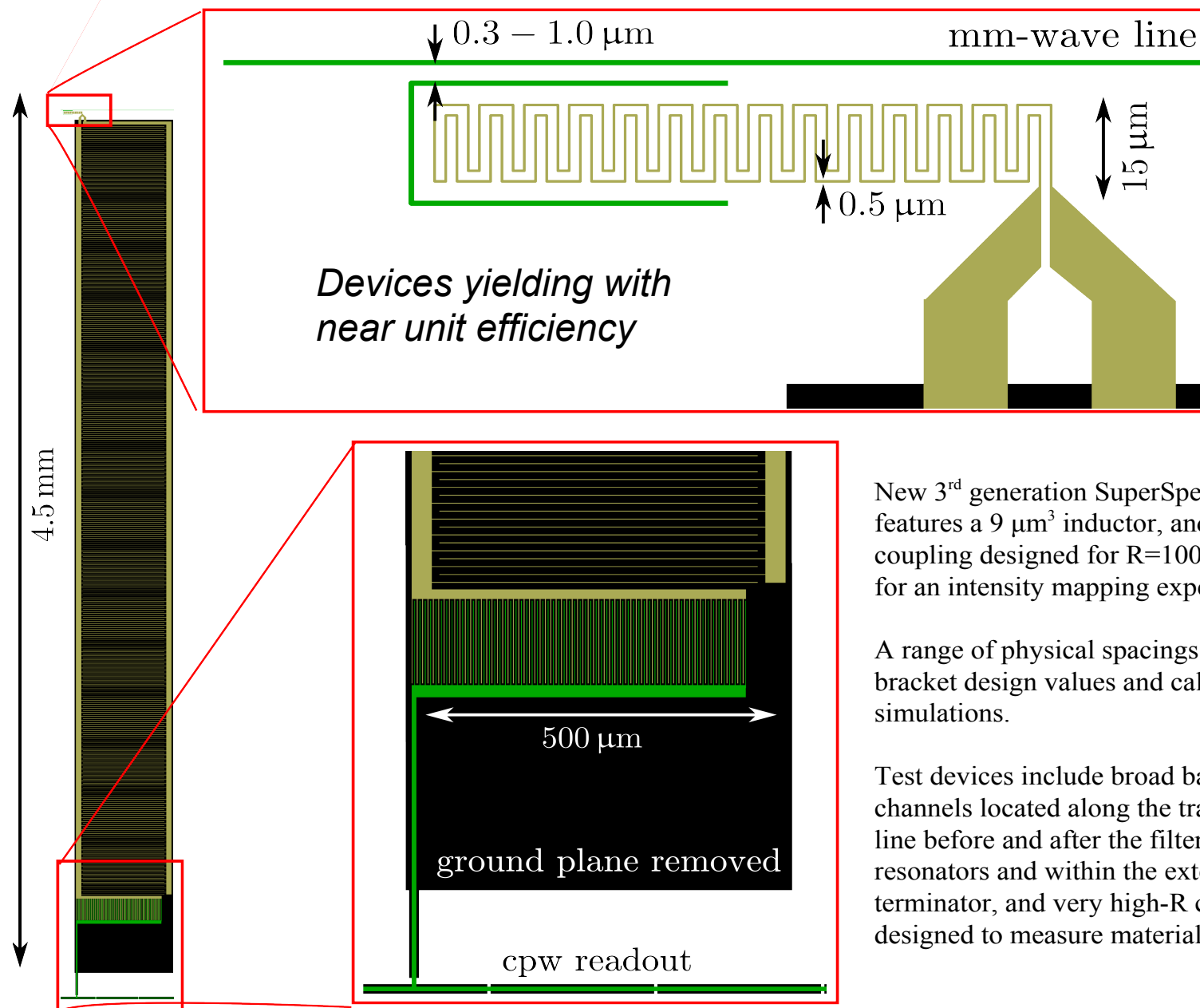
lens footprint

2.0cm

2 cm

temp

Cross section of the antenna-coupled device mounting hardware. The die sits in the recess at top and look down through a blackened cylinder and a metal-mesh low pass filter.

3rd Generation, more sensitive device

$0.3 - 1.0\,\mu m$

mm-wave line

$15\,\mu m$

$0.5\,\mu m$

Devices yielding with near unit efficiency

500 μm

ground plane removed

cpw readout

4.5 mm

New 3rd generation SuperSpec design features a 9 μm³ inductor, and mm-wave coupling designed for R=100, optimized for an intensity mapping experiment.

A range of physical spacings are used to bracket design values and calibrate simulations.

Test devices include broad band channels located along the transmission line before and after the filter bank resonators and within the extended terminator, and very high-R channels designed to measure material losses.

Loss in Nb / SiN Microstrip

Normalized Data

Lorentzian Fit

BB ref

$Q_{filt} = 654$

Gen-1 data

no loss
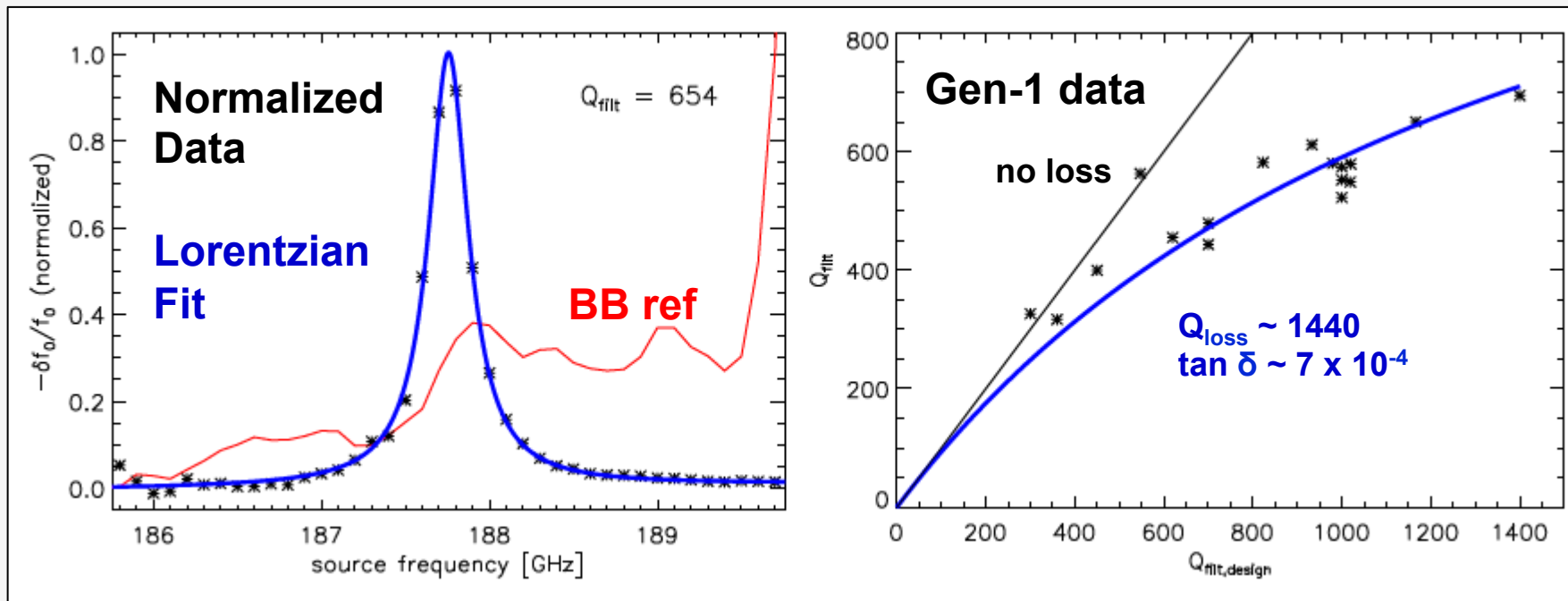
$Q_{loss} \sim 1440$
$\tan \delta \sim 7 \times 10^{-4}$

- Comparison of designed and measured Q indicates a source of loss characerized by $Q_{loss} \sim 1440$ --> likely SiN_x ILD in microstrip

- Similar result found with dedicated loss test device.

- Greater than 50% of the incident power lost for $Q > 420$

- Additional frequencies included in coming devices.

Gen-3: S21 of dedicated loss-test resonator

$Q_r = 1094$
$Q_c = 7509$
$Q_i = Q_{loss} = 1281$
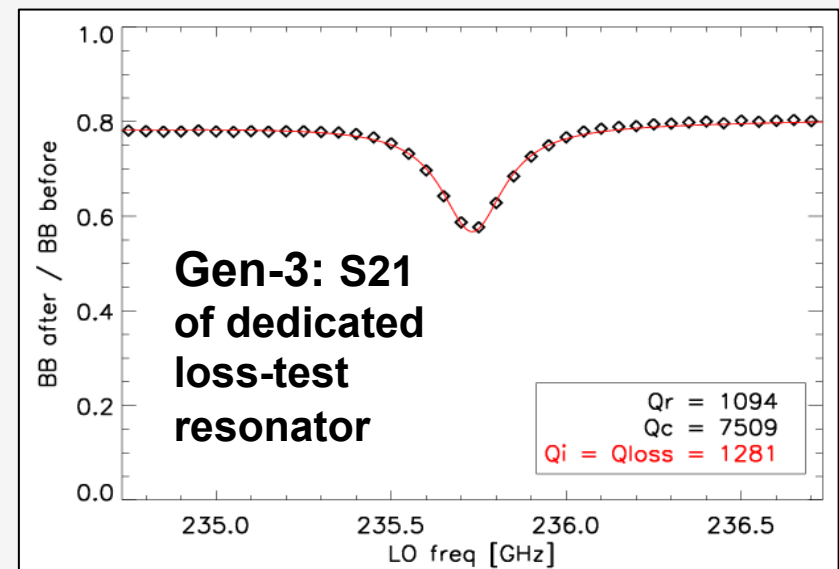
Responsivity of TiN
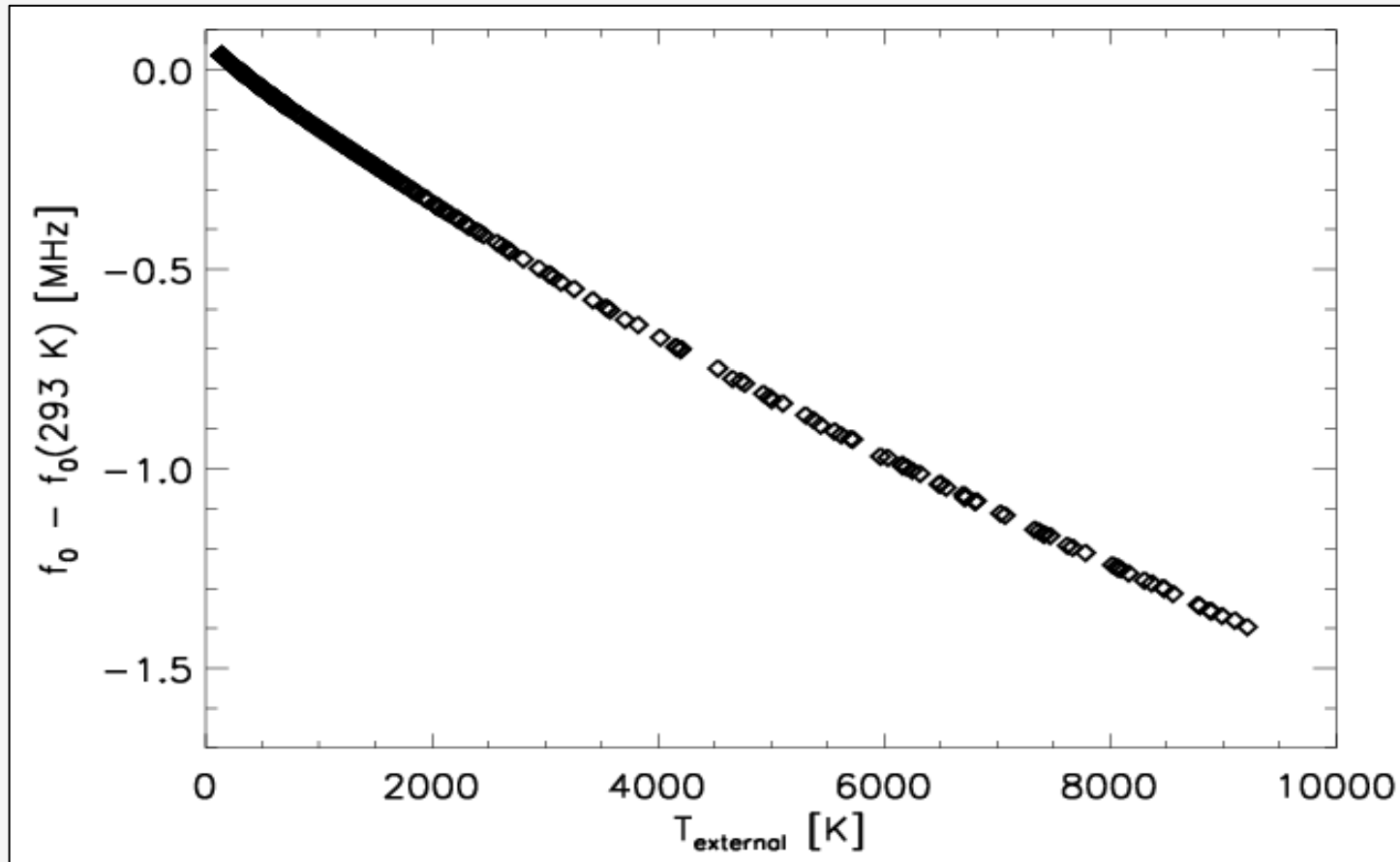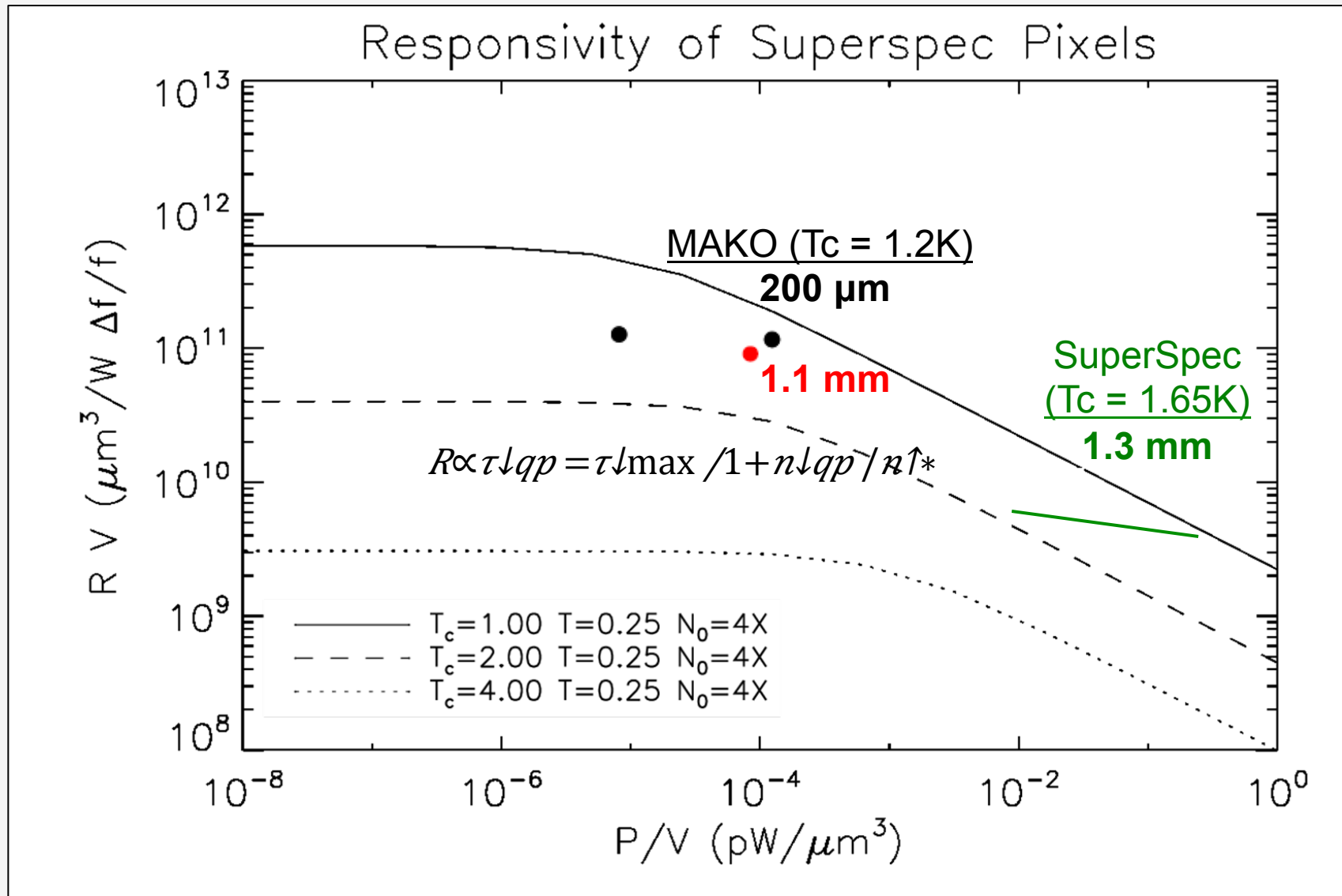

- Coherent source used to measure response as a function of loading.
- We find only weak reduction in response out to very high loading.
  - At high loadings the large quasi-particle density is expected to reduce the tau_QP, and this responsivity.
- To a good approximation the frequency shift is linear with power (=constant responsivity). Anomalous but promising for instrumentation.

RV vs P/V plot

Responsivity of Superspec Pixels

MAKO (Tc = 1.2K)
200 μm

1.1 mm

SuperSpec
(Tc = 1.65K)
1.3 mm

$$R \propto \tau_{qp} = \tau_{max} / 1 + n_{qp} / n_*$$

Legend:
- $T_c = 1.00$ $T = 0.25$ $N_0 = 4X$
- $T_c = 2.00$ $T = 0.25$ $N_0 = 4X$
- $T_c = 4.00$ $T = 0.25$ $N_0 = 4X$

Y-axis: R V (μm^3/W $\Delta f/f$)

X-axis: P/V (pW/μm^3)

Noise Measurements
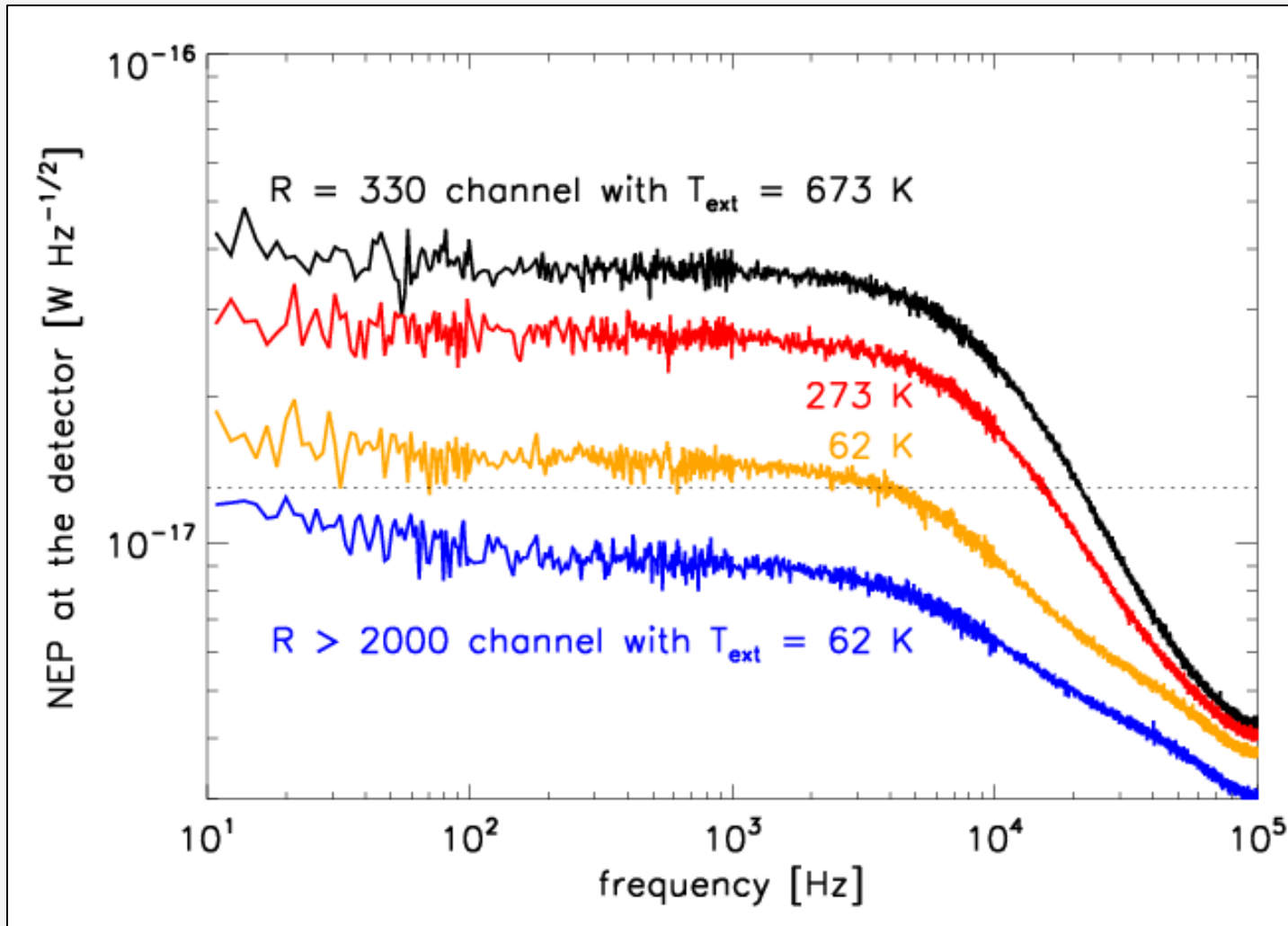
R=100 on
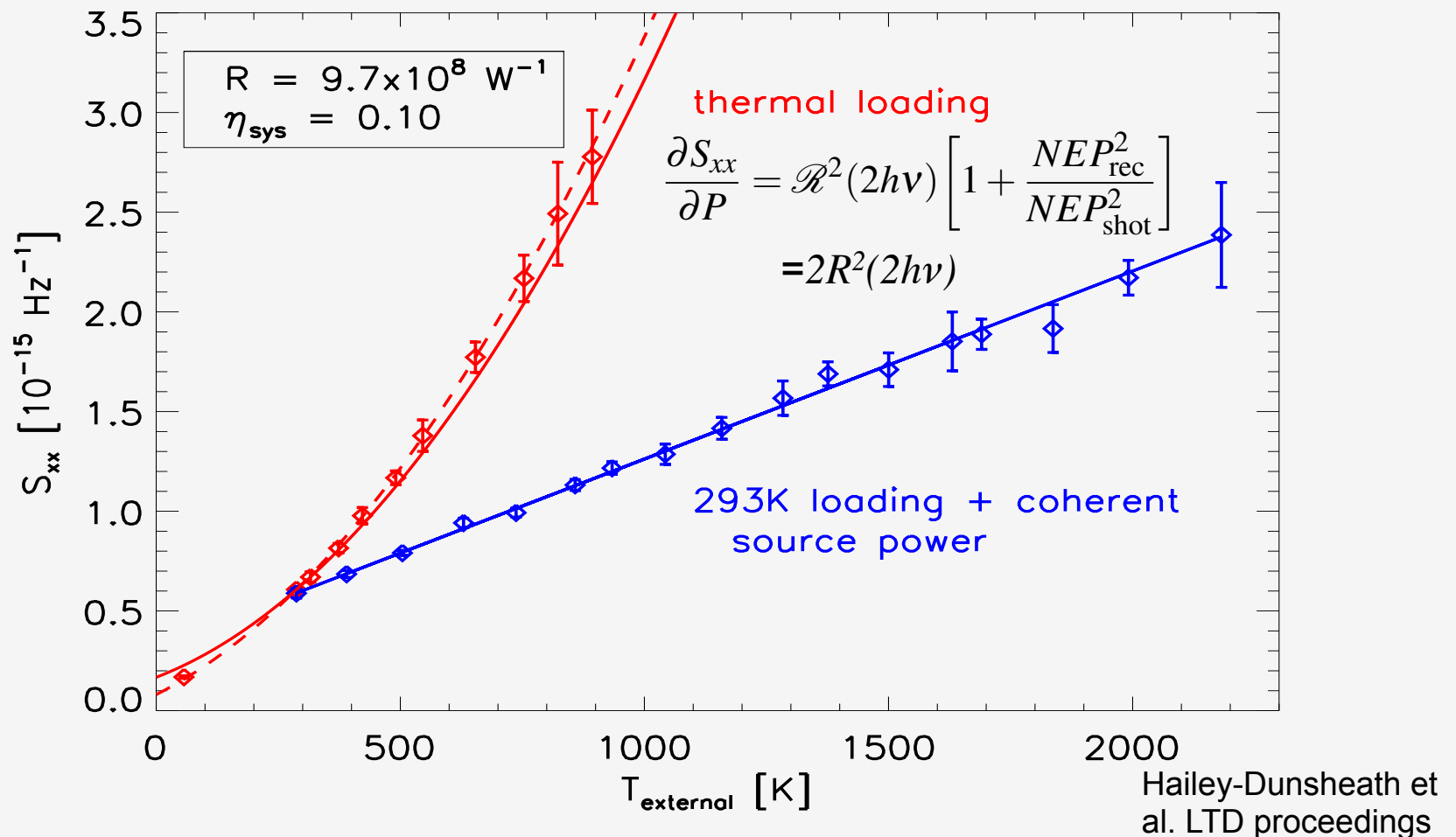Mauna Kea

- Smaller inductor, 1.2 K Tc have increased response.
- Now clearly photon noise limited, even for science-grade loadings.

Inferring Total System Efficiency

The figure shows a plot with axes S_{xx} [10^{-15} Hz^{-1}] versus $T_{external}$ [K]. Annotations:

$R = 9.7 \times 10^8 \ W^{-1}$

$\eta_{sys} = 0.10$

thermal loading

$$\frac{\partial S_{xx}}{\partial P} = \mathscr{R}^2 (2h\nu)\left[1 + \frac{NEP_{rec}^2}{NEP_{shot}^2}\right]$$

$$= 2R^2(2h\nu)$$

293K loading + coherent source power

- Coherent source is shot noise source (no wave noise)
- Slope of shot noise with variance gives absolute system responsivity.
- With bandwidth then get total system efficiency.

System Transmission, Next Steps

Source	Efficiency
Windows/Filter	0.7
Beam Truncation	0.9
Antenna / Lens	0.9
Spectrometer	0.22
Expected Total	**0.13**
Measured	**0.10**

→ **0.34 with stronger coupling, 0.50 with better dielectric**
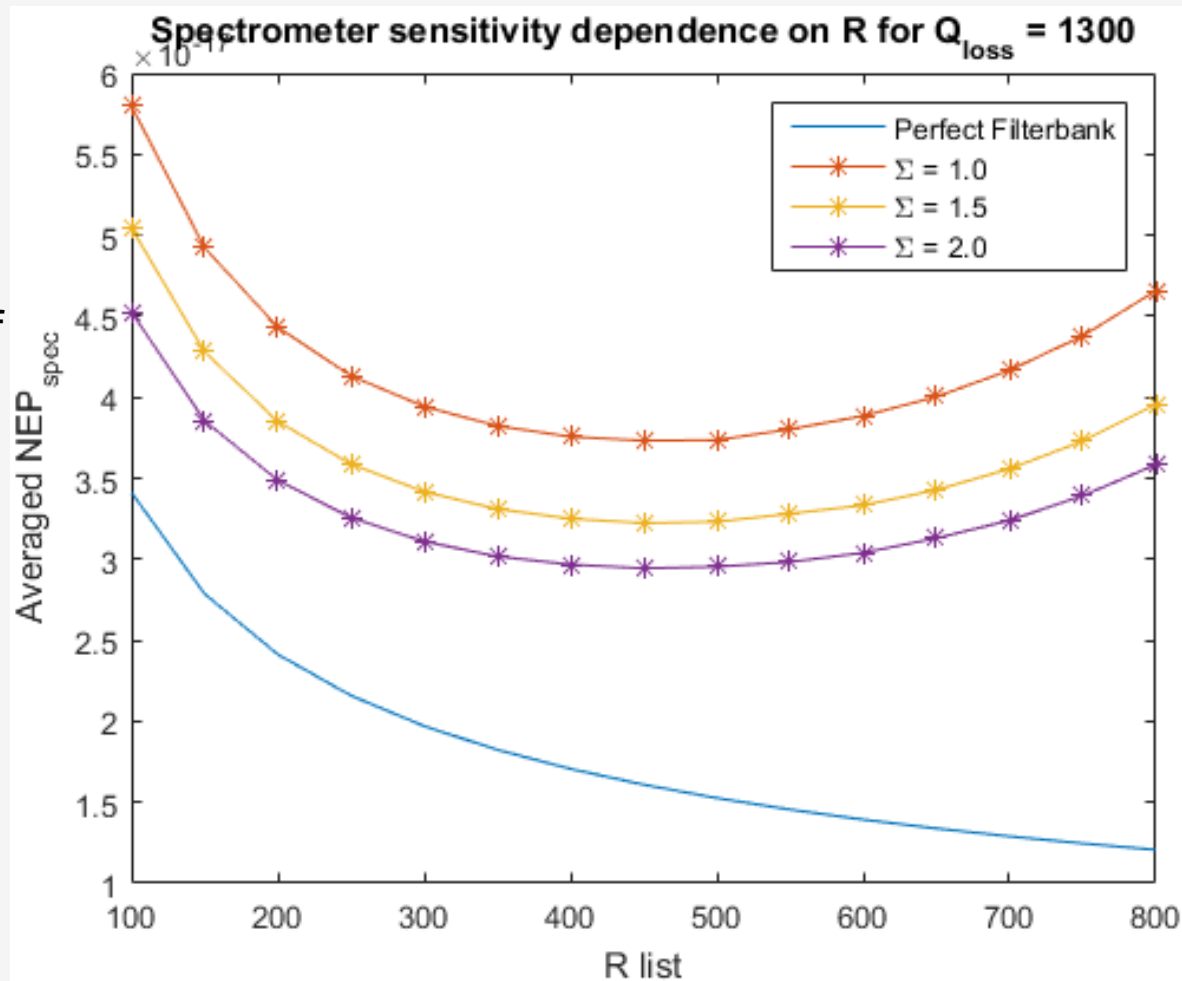
→ **missing ~30%**

- Still need to match Qs to achieve optimal coupling.
    - Especially Nb / Nb coupling Q.
- Have generated both under-coupled and over coupled devices with high yield, so obtaining desired Q is possible.   Developing designs with lithographically adjustable Qs.
- Next step is R~100 50-channel device covering nearly full band.
- Study low-frequency performance – common mode noise or device 1/f?
- Exploring instrument opportunities on mm-wave telescopes
    - 1) Galaxy follow up spectroscopy, single-beam but atmospheric subtraction pixels.
      (eventually multi-object system on new 30-meter telescope.)
    - 2) Tomography instrument for CII / CO.

Optimizing Filterbank Design w/ Loss

NEP at front of instrument, assume 50% efficiency to filterbank

'Ideal' filterbank: square bandpasses, 50% efficiency, no loss

Corwin Shiu + Steve HD

Spectrometer sensitivity dependence on R for $Q_{loss} = 1300$

Legend:
- Perfect Filterbank
- $\Sigma = 1.0$
- $\Sigma = 1.5$
- $\Sigma = 2.0$

Y-axis: Averaged NEP_{spec} ($\times 10^{-17}$)
X-axis: R list

- Optimization favors higher Σ (oversampling) because it obtains more signal.
- Broad optimum of channel R between 300-700 for Q_{loss} of 1300.
- Penalty on order 2x relative to idealized perfect system.

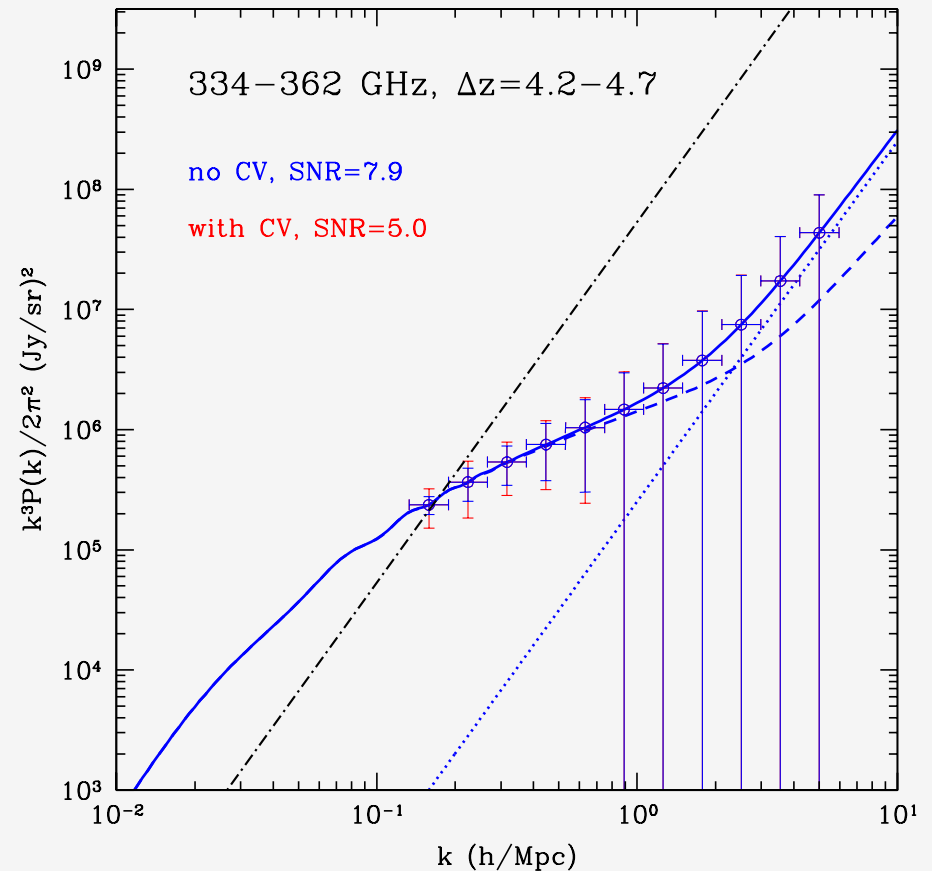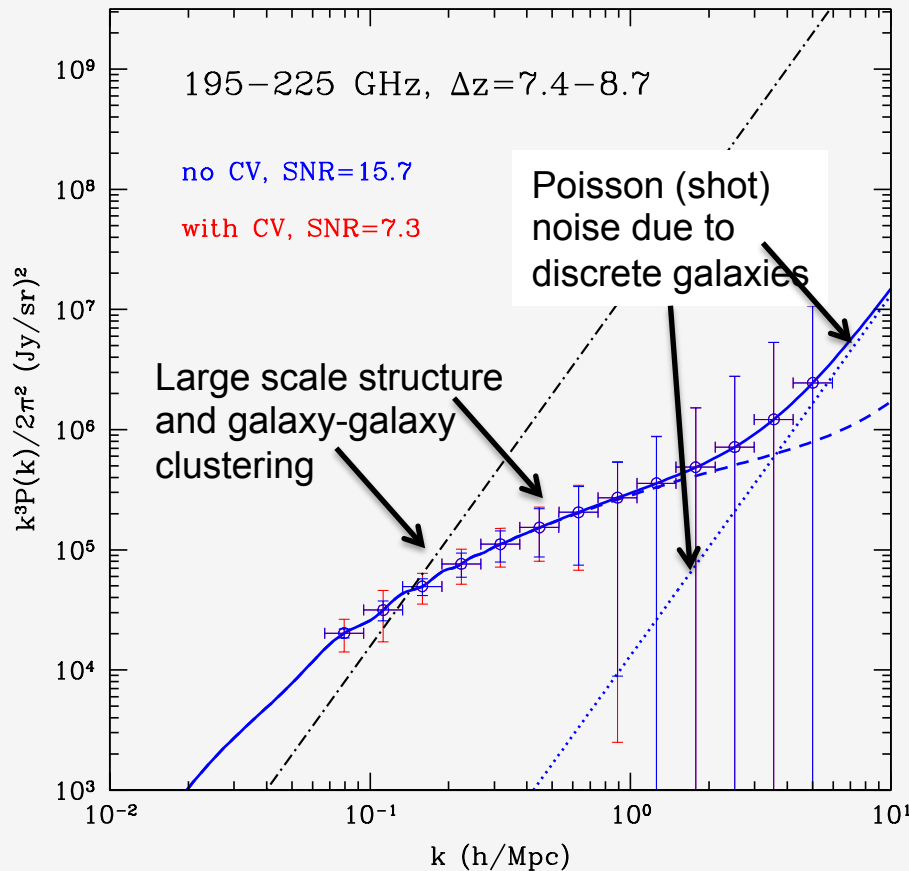# Extra Slides

Masking CO for TIME-Pilot
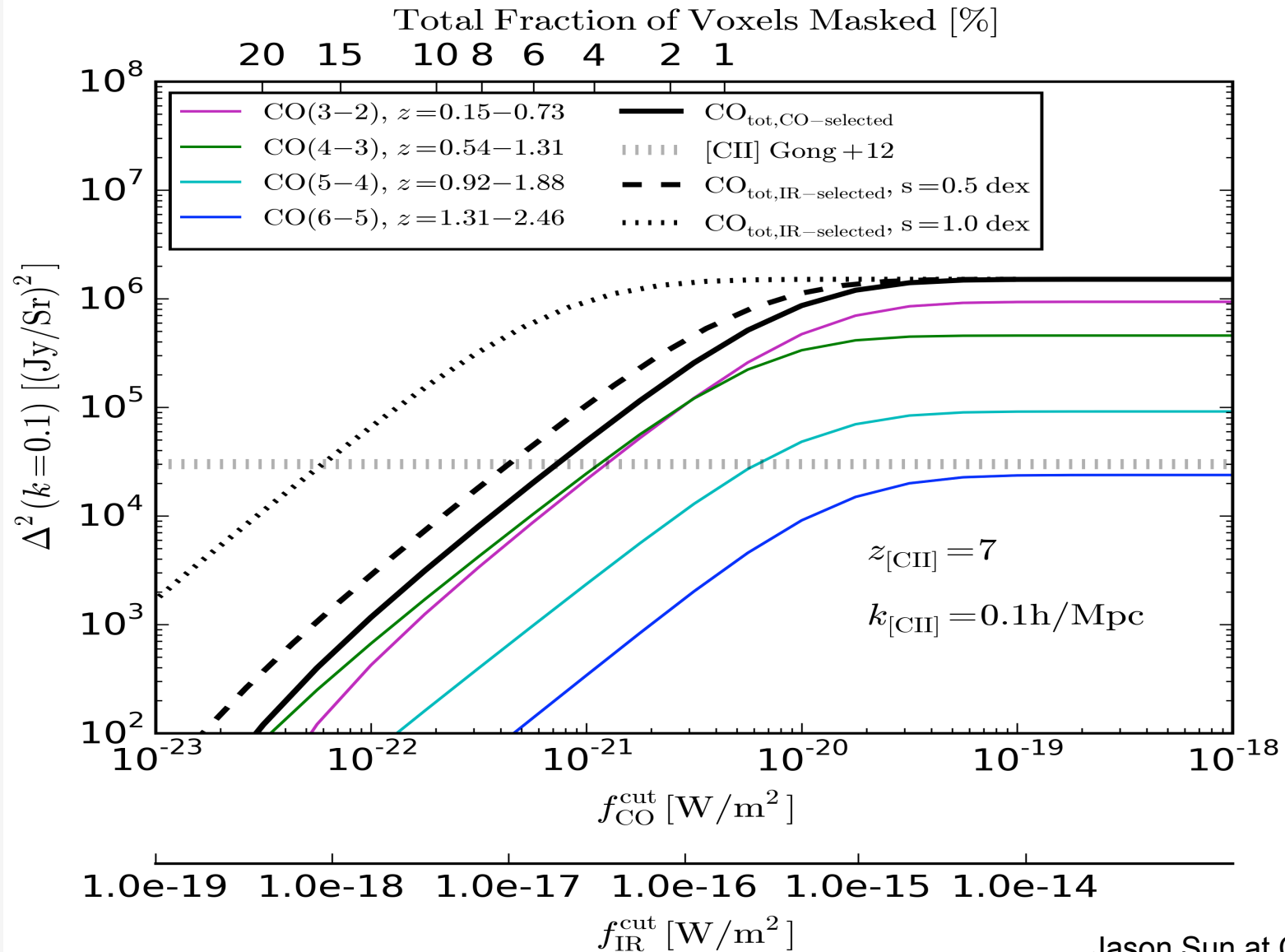
Expect we need to mask ~10% of our voxels to reduce CO variance, but need to ID CO sources

Example [CII] power spectra

(this for 0.1 Msun/yr / Mpc^3, constant CII fraction)

- Example power spectra calculations for 300 hours at goal sensitivity assuming 84-element spectrometer. (Y. Gong / A. Cooray @ UC Irvine)
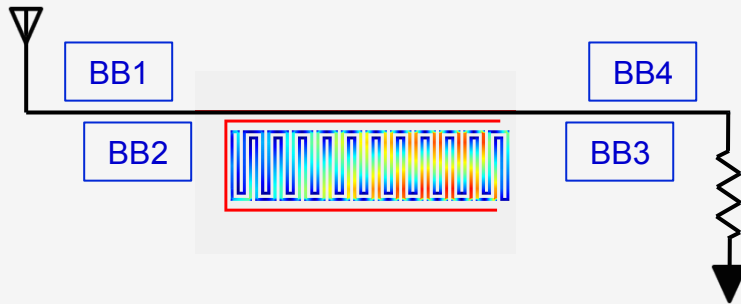- Halo-halo clustering term encodes mean intensity (with galaxy bias).

$$P_{i,i}^{clust}(k, z) = \bar{S}_i^2(z)\bar{b}_i^2(z)P_{\delta\delta}(k, z). \qquad \text{SNR on } \bar{S}_{[CII]} = 2 \times \sqrt{\sum_{\text{linear k-bins only}} \left(\frac{P_{i,i}^{clust}(k)}{\sigma_{clust}(k)}\right)^2}$$

- MOS or IFU approximately equally capable for this experiment.

Sockout Measurement

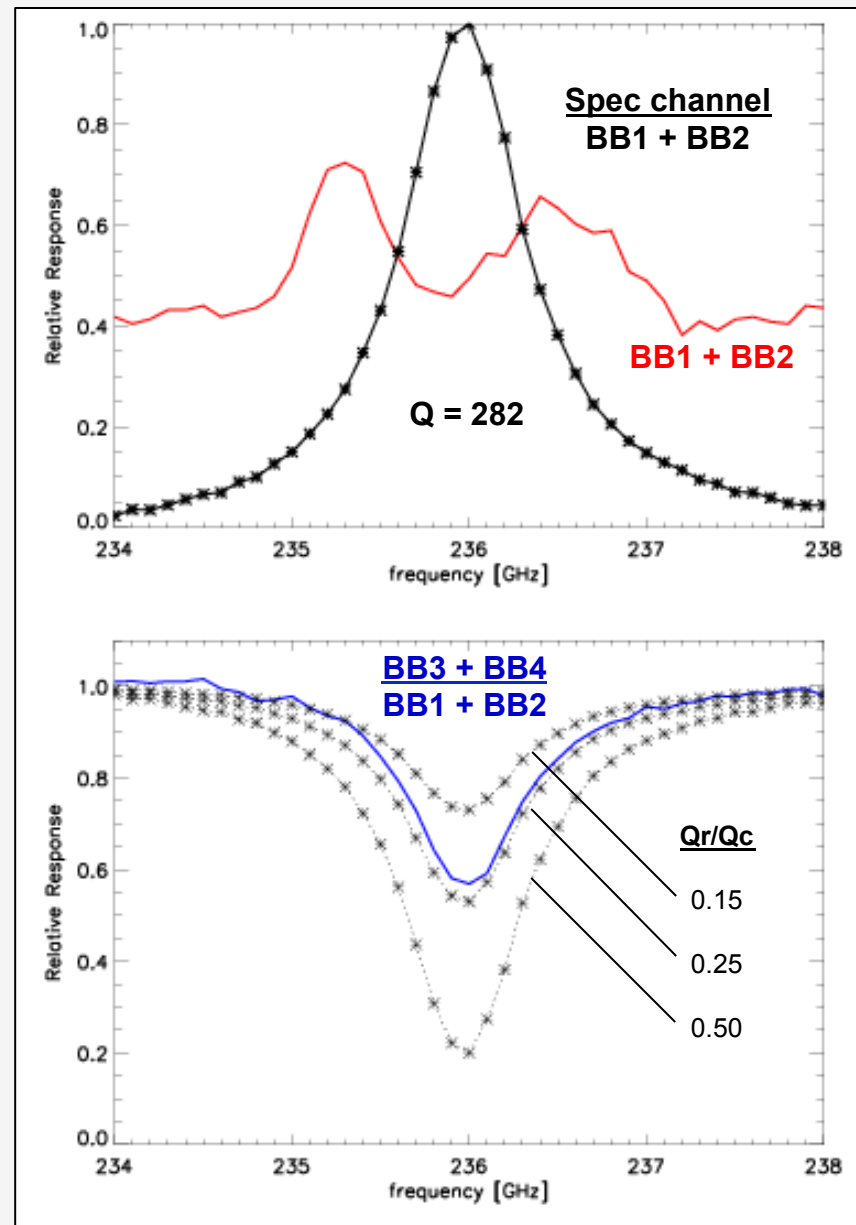BB channels – sections of meandered TiN in proximity to feedline, approx λ in length

BB1   BB4

BB2   BB3

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

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

Spec channel
BB1 + BB2

BB1 + BB2

Q = 282

BB3 + BB4
BB1 + BB2

Qr/Qc

0.15

0.25

0.50

Close to linear frequency shift with loading

For a factor of 16 increase in loading:
- expect $\delta f/\delta P \sim P^{-0.5}$, should drop by 4x
- find $\delta f/\delta P$ drops by only 1.3x

-> *TiN can be run at high power density*