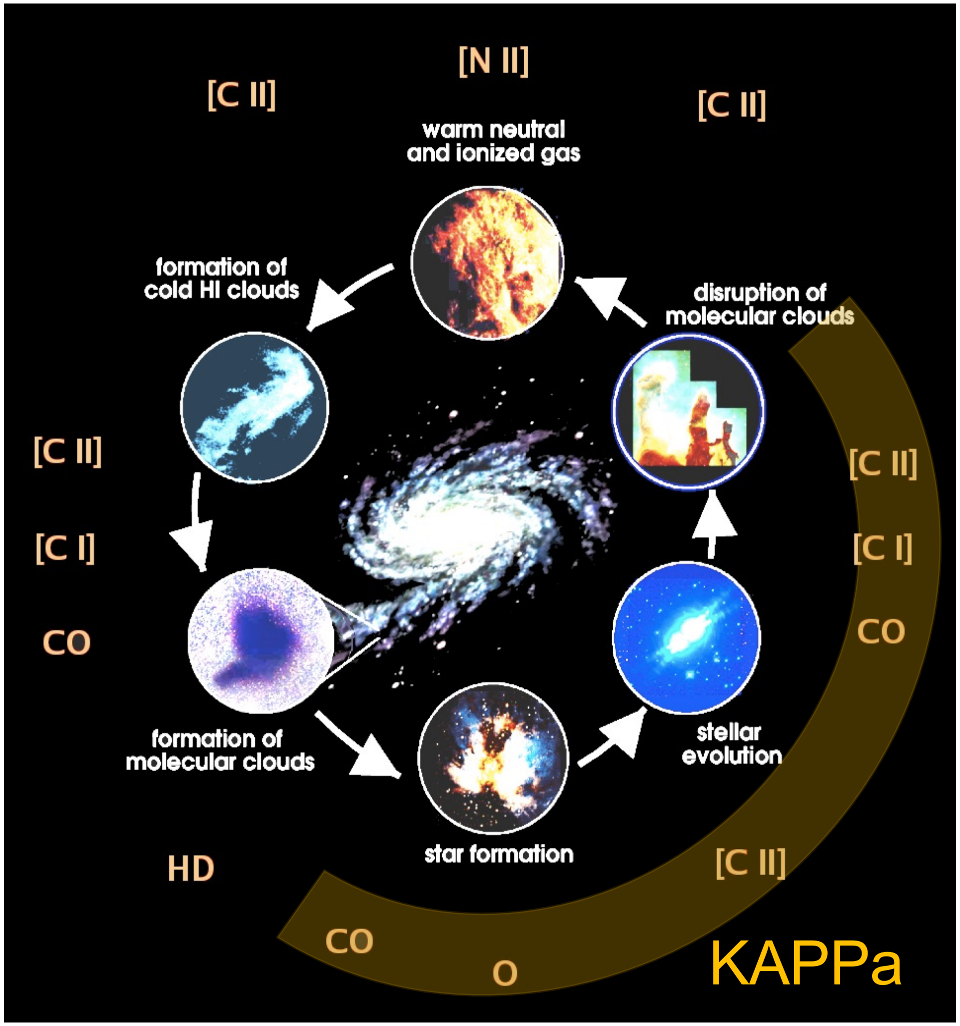
Large pixel count focal plane mm heterodyne arrays

Christopher Groppi, ***for the KAPPa and Supercam Teams***

Arizona State University

School of Earth and Space Exploration

NOVA Heterodyne sub-mm Array Workshop, Nunspeet, March 2017



Craig Kulesa & Chris Walker, UofA

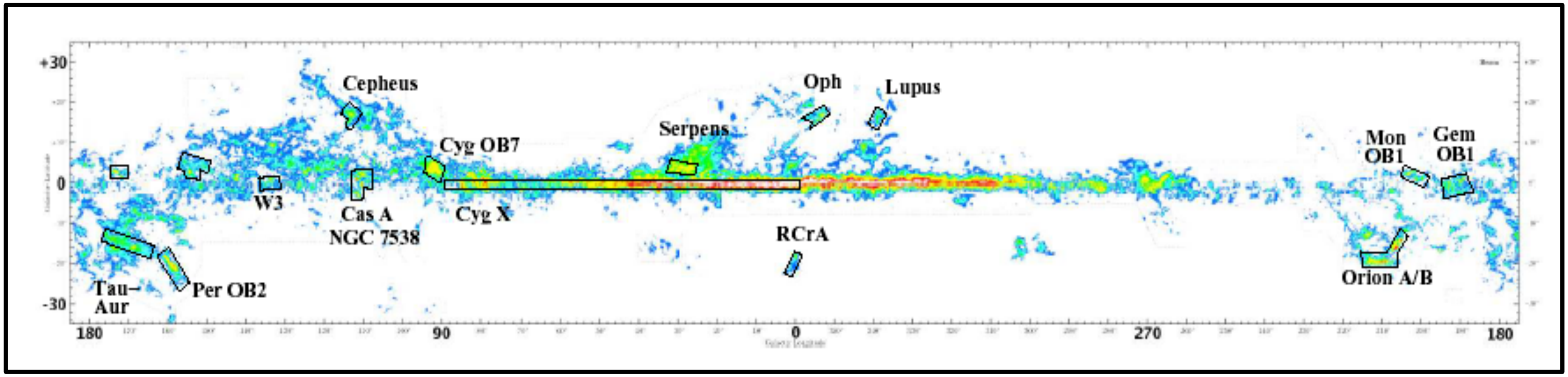
Spectral diagnostics of the interstellar life cycle define a new, pressing need for large-scale, high resolution spectroscopic surveys!

Continuum observations (dust emission) only tells part of the story.

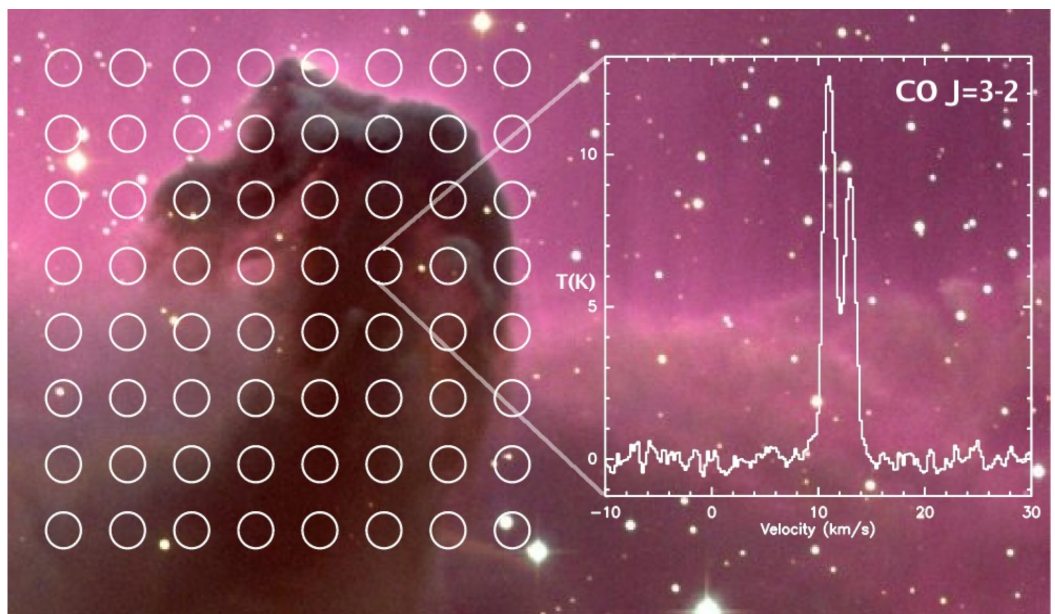
We want to know about the gas too!

We need wide field mapping (many square degrees), ~km/s spectral resolution and sub-arcminute spatial resolution.

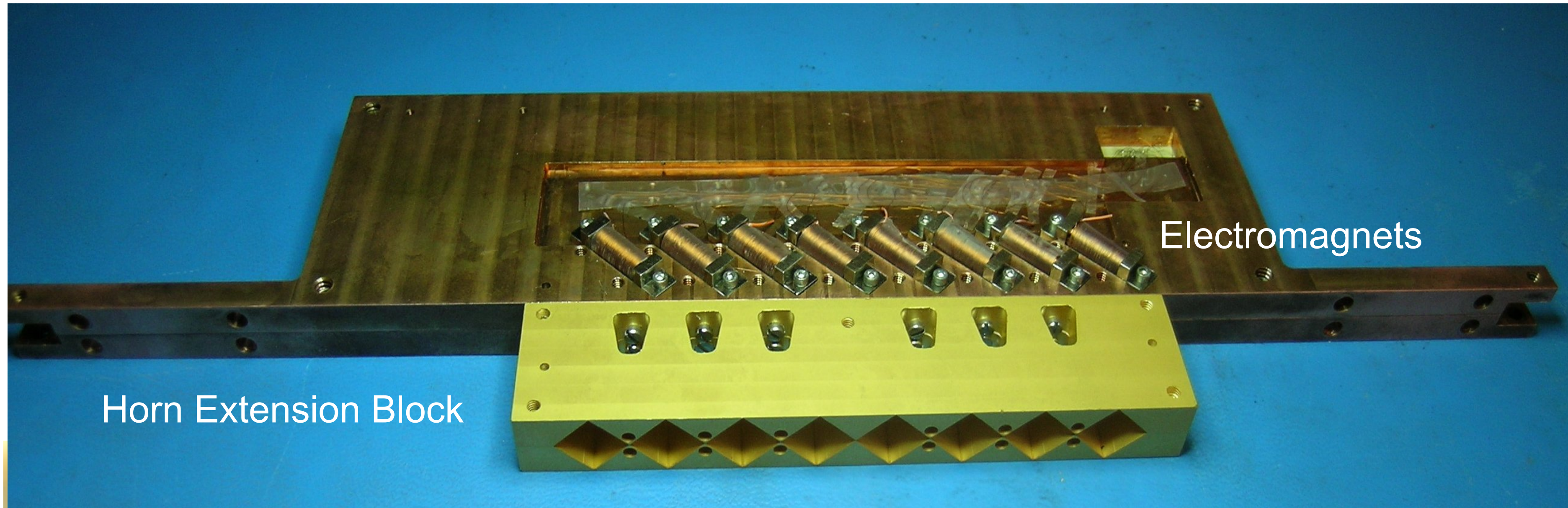
Supercam Survey

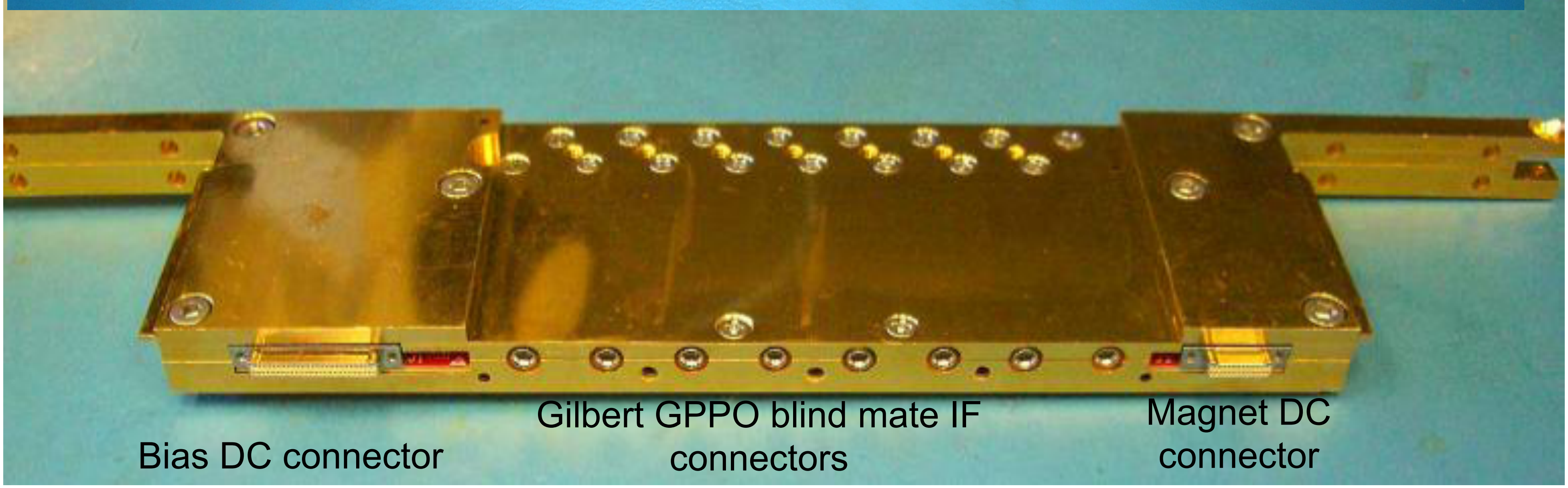


- Fully sky survey in $^{12}CO(3-2)$ and selected mapping in $^{13}CO(3-2)$
- 23" spatial resolution; 0.3 km/s velocity resolution
- Two orders of magnitude faster over single-pixel receivers



1x8 Mixer Module





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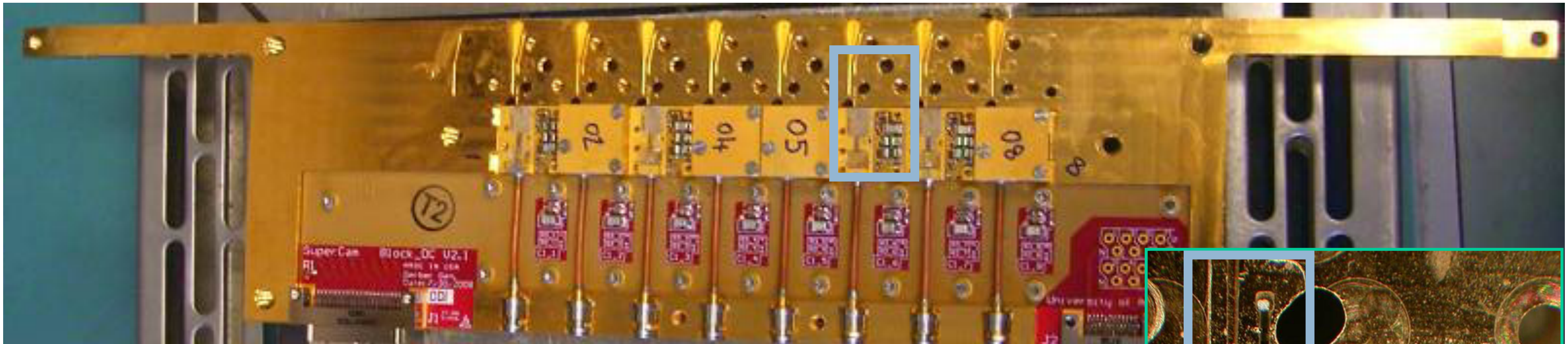
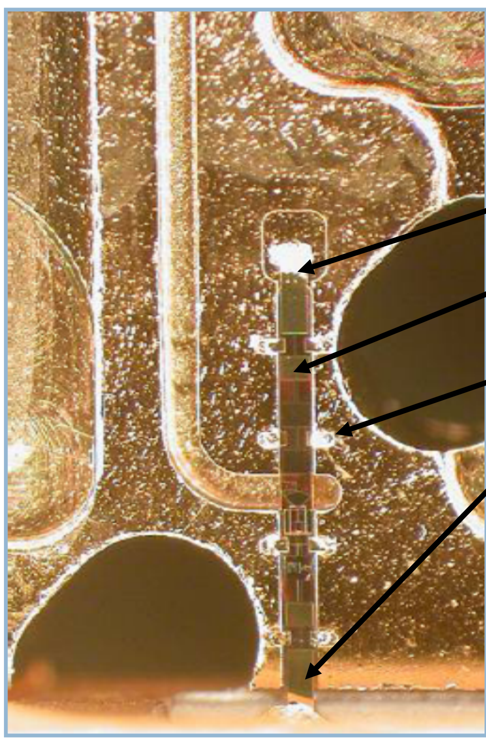
SESE THz Lab

A Closer Look





Ground beamlead

SOI SIS Chip

Beamlead alignment tabs

IF Beamlead

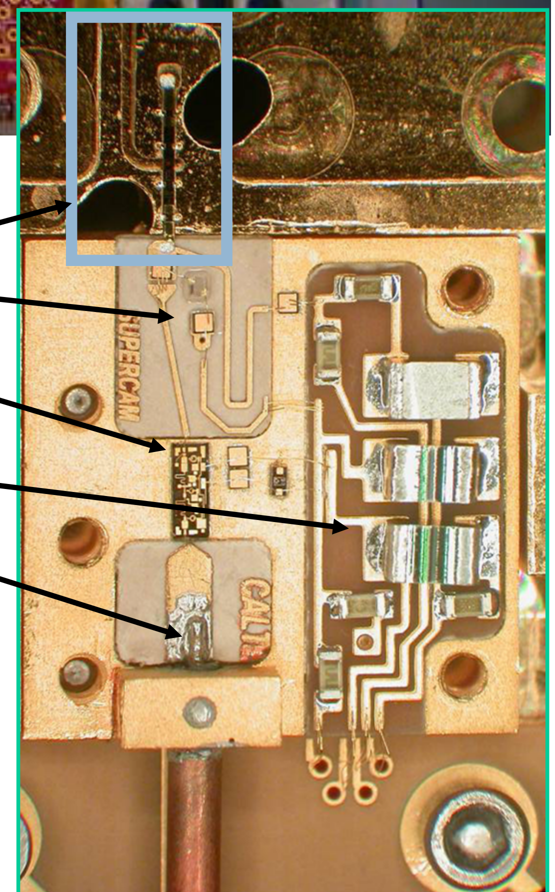
Magnet probes

Input matching network

WBA13 MMIC chip

Bias circuitry

Output coax



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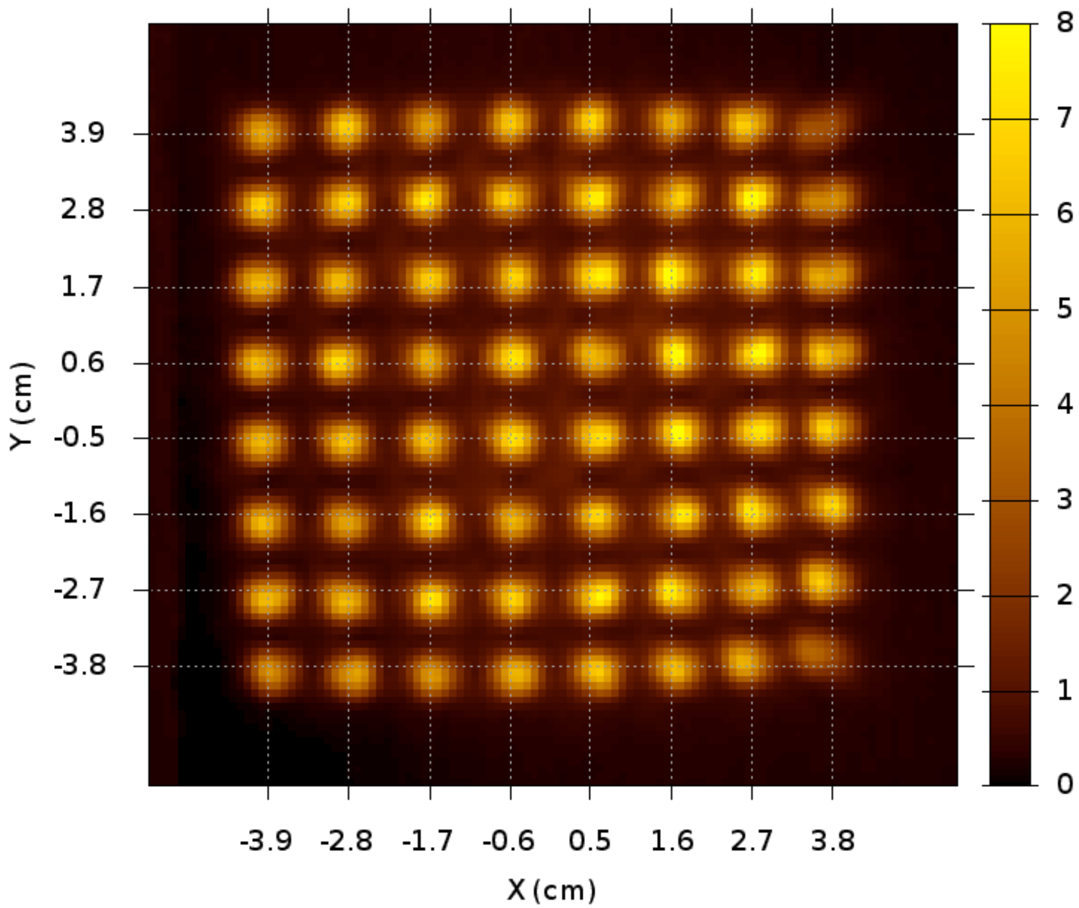
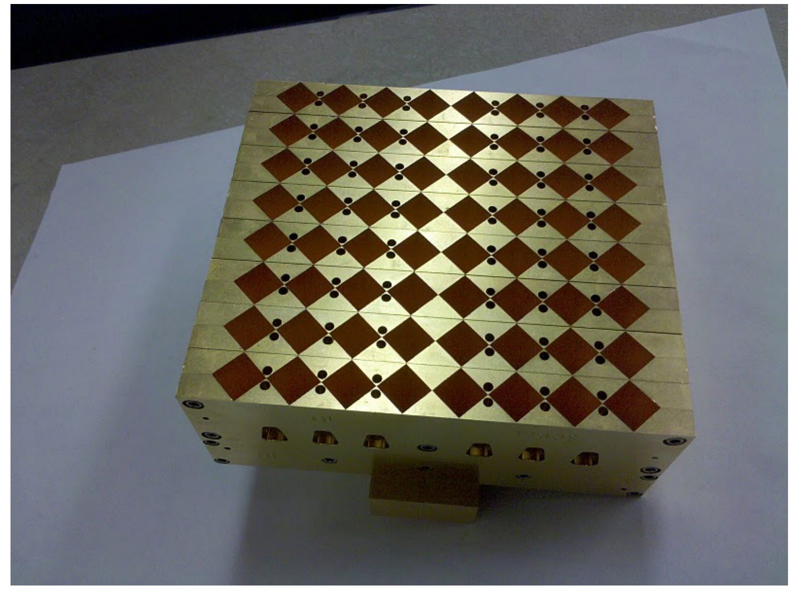
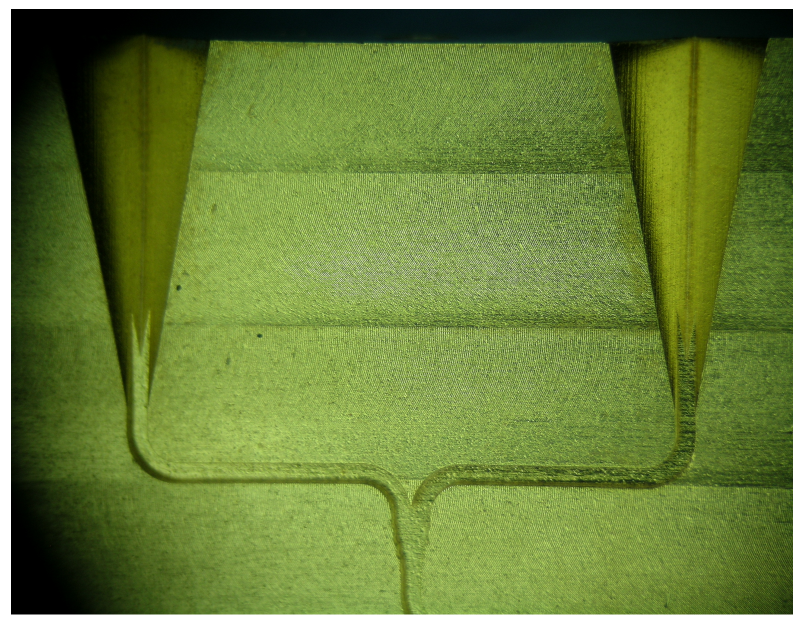
LO Multiplexing
64-way waveguide corporate divider
17 waveguide splitblocks

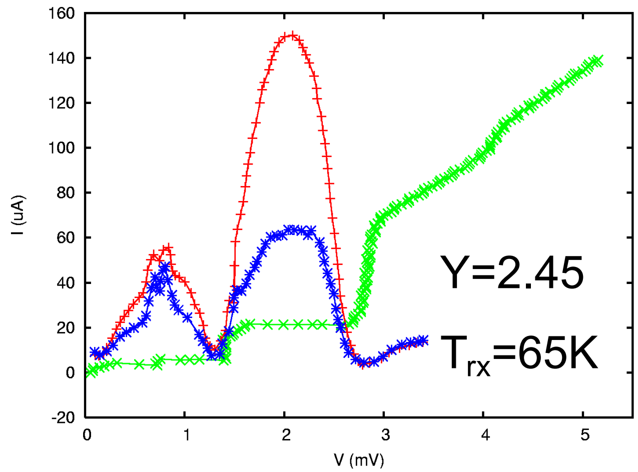


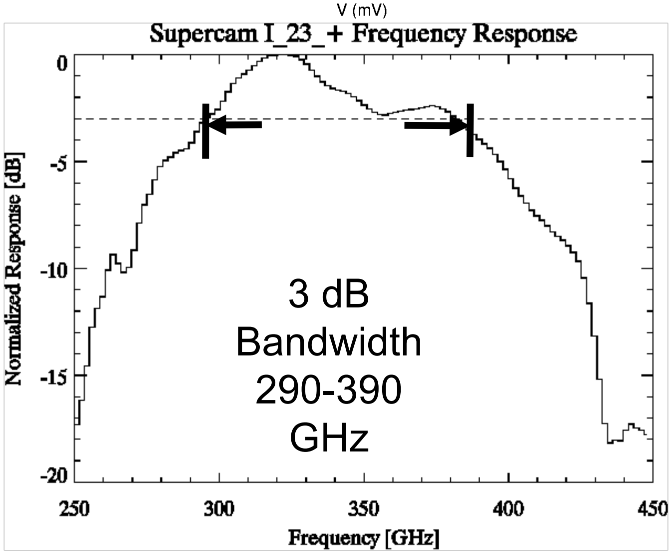




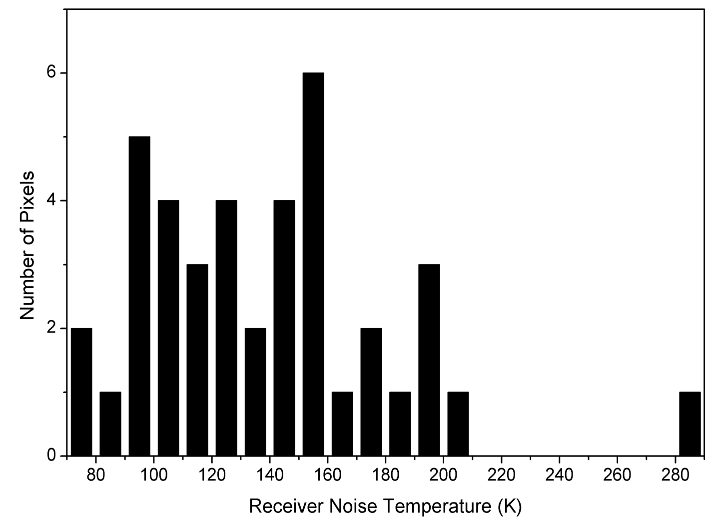
Laboratory Testing

Single Pixel Response





Initial 64 Pixels



- SuperCam focal plane devices were chosen randomly from the UVa wafer
- Yield of live devices ~75%

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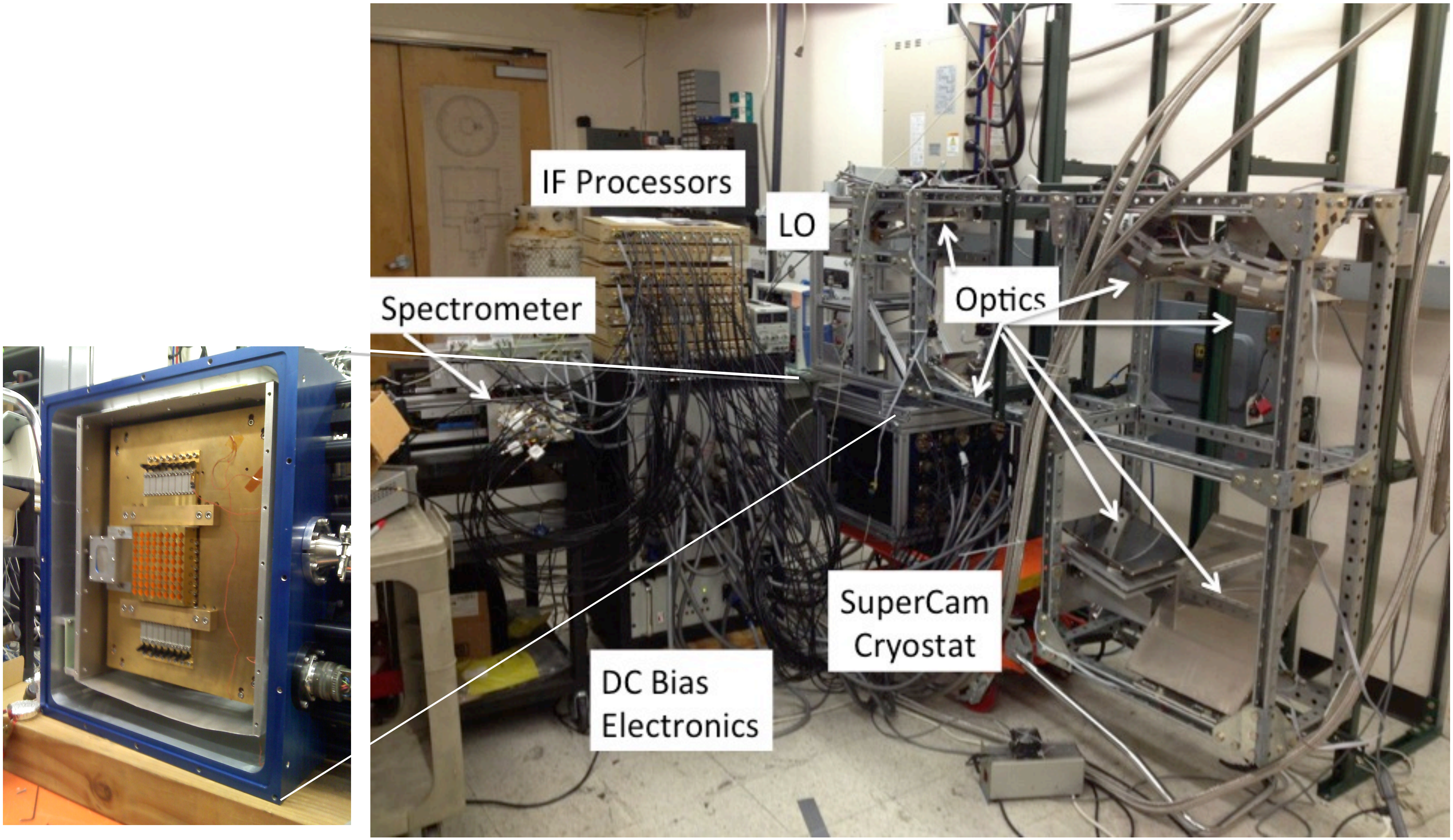
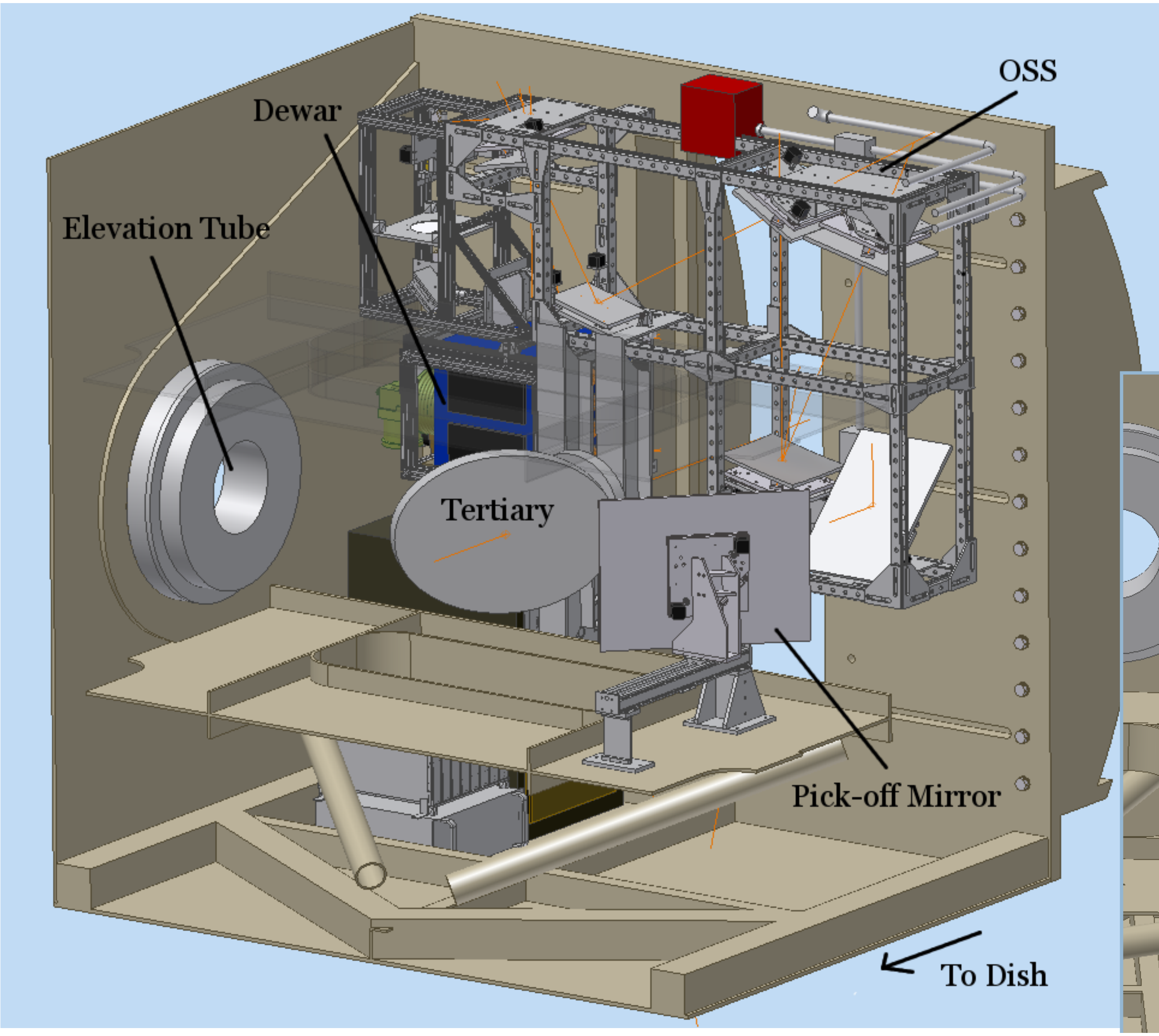
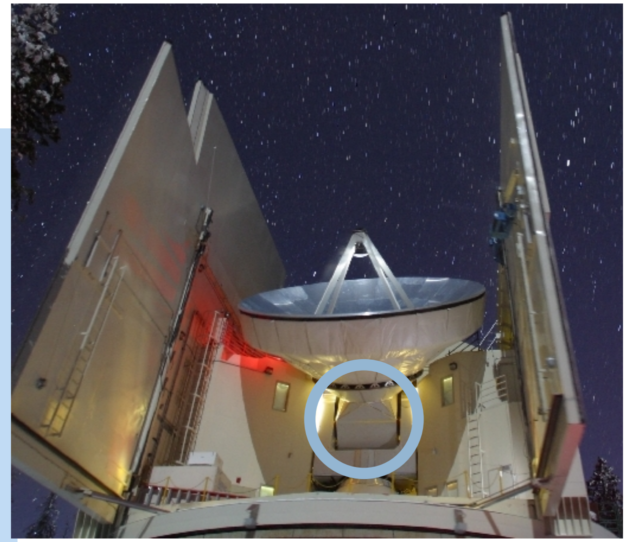
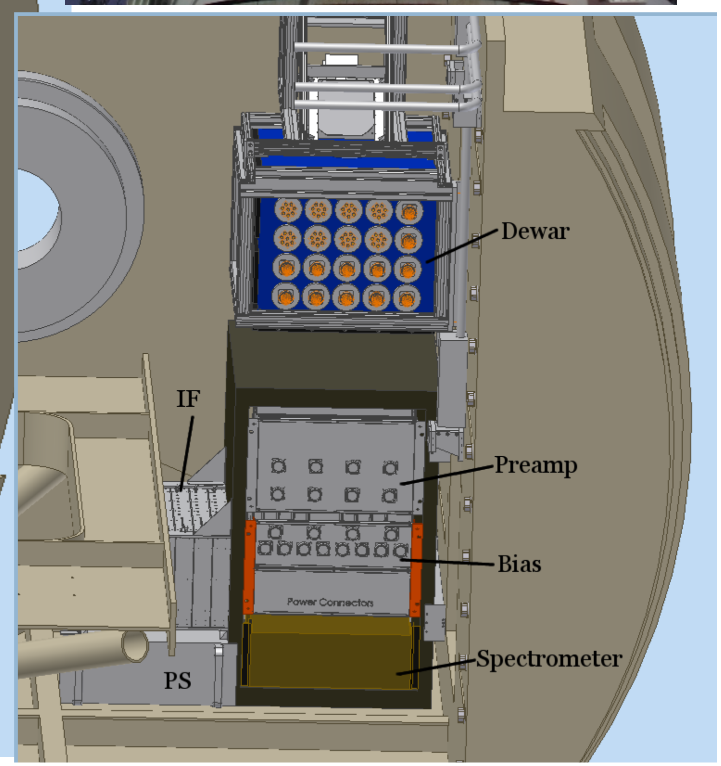


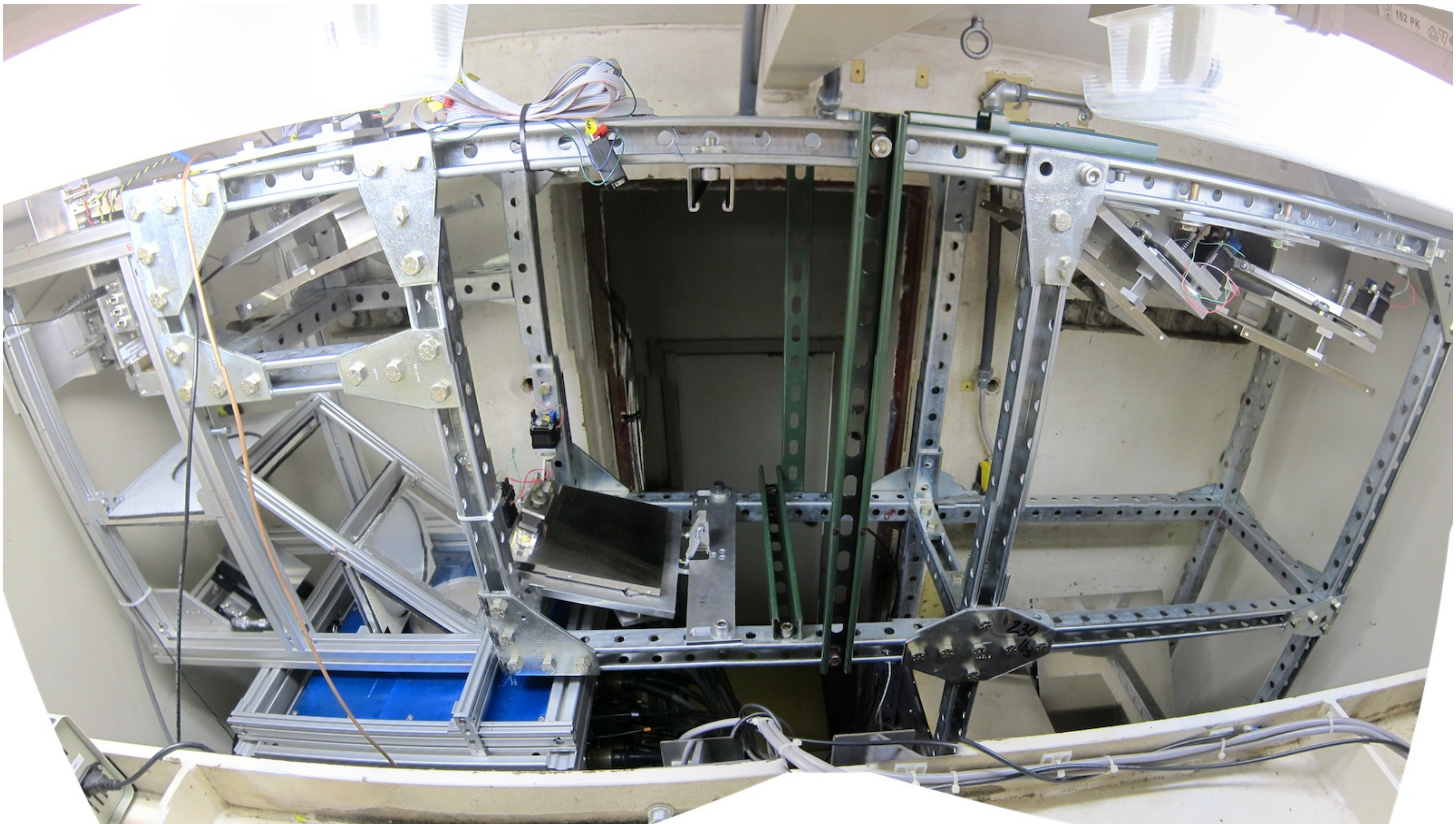
3-D CAD Model of Apex Room

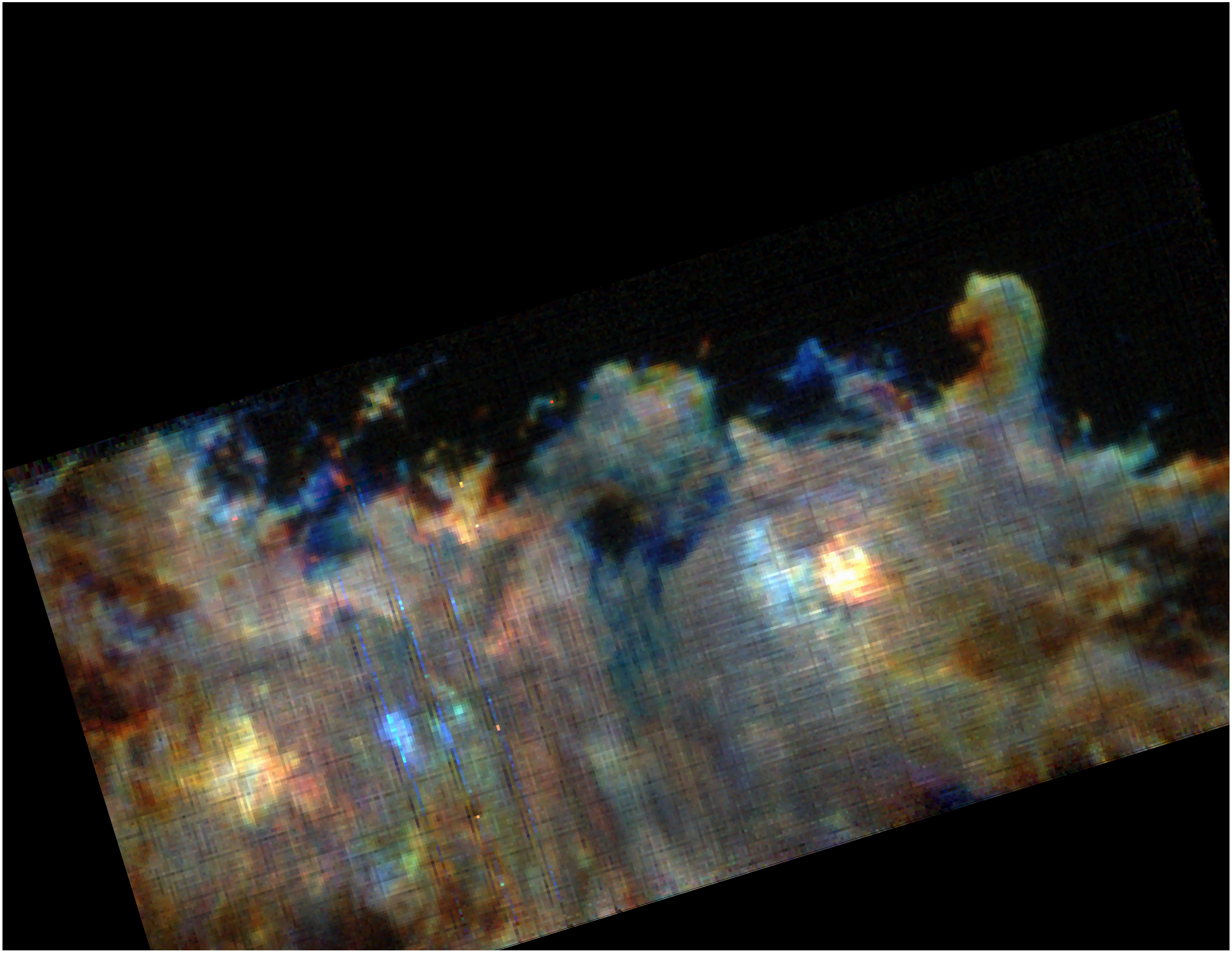






SuperCam in the Apex Room of the SMT



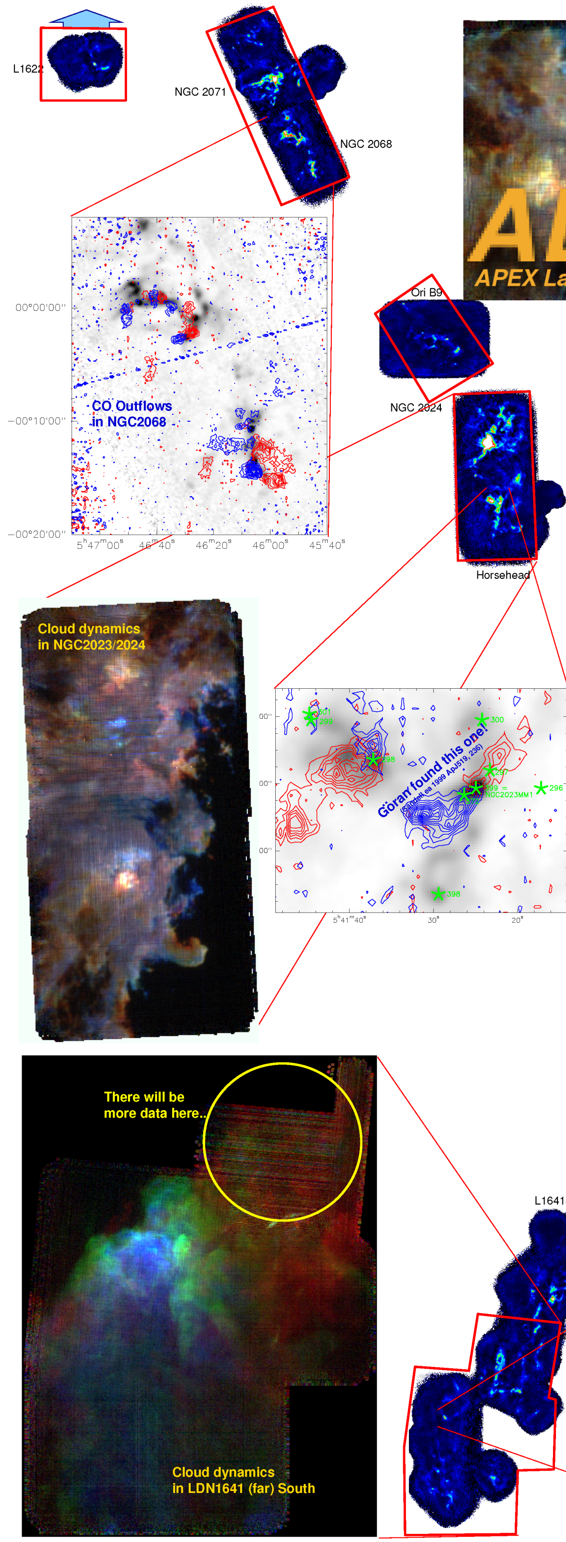


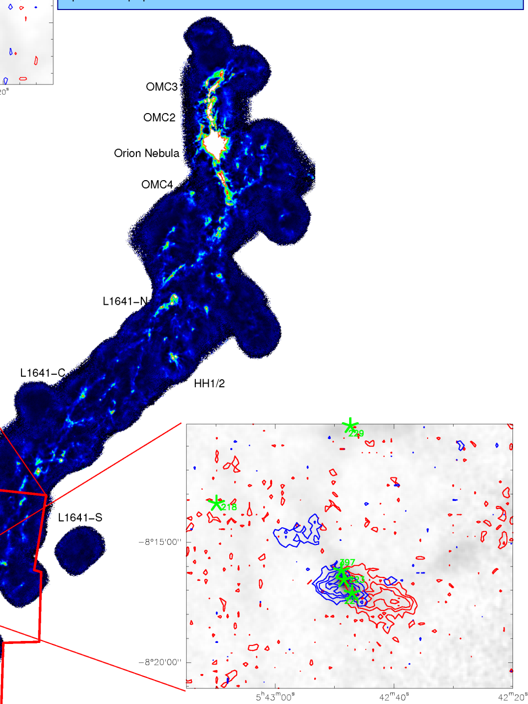
The ALCOHOLS team:
Thomas Stanke (ESO); H. Arce; J Bally; P. Bergman; J. Carpenter;
C.J. Davis; W. Dent; J. Di Francesco; J. Eisloeffel; D. Froebrich;
A. Ginsburg; M. Heyer; D. Johnstone; D. Mardones; M.J. McCaughrean;
S.T. Megeath; F. Nakamura; B. Reipurth; M.D. Smith; A. Stutz;
K. Tatematsu; C. Walker; J.P. Williams; H. Zinnecker
Brandon Swift; Craig Kulesa; Bill Peters; Brian Duffy;
Jenna Kloosterman

The ALCOHOLS survey:
Coverage:
2.3 square degrees in Orion A and Orion B (red outlines)
Orion A: L1641, south of Declination −7.5 degrees
Orion B: dense areas: NGC2023, 2024, 2068, 2071; Ori B9; L1622
–> complementary to JCMT Gould Belt legacy survey

CO(3−2) at 0.25km/s resolution

Instrument: SuperCam at APEX 12m (Chajnantor)
– 64 pixel Heterodyne receiver array operating at 345GHz
(~42 pixels working) –> 12 000 000 spectra!
– data taken in December 2014 in ESO and Swedish time
– freely available from ESO archive
BUT NOT YET PROPERLY CALIBRATED – AND INCOMPLETE!
–> shown here are PRELIMINARILY reduced data and results
Main Goal:
get a complete account of high−velocity gas in protostellar outflows over an entire giant molecular cloud with a well characterized protostar population





Lessons Learned from Supercam

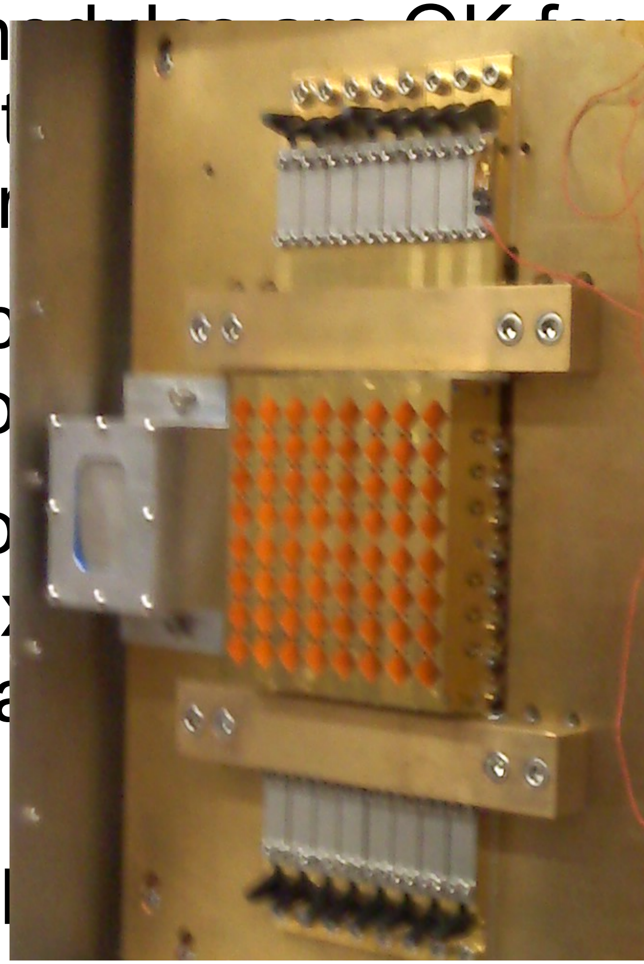
- Using the instrument itself to test detectors cold is very difficult. This is the main reason the pixel yield is 75% and the average detector noise is higher than desired.
- While SOI devices are easier to mount than quartz devices, pixels were still too time consuming to construct.
- Careful cryogenic engineering is important.
- Mixer optimization is time consuming without automated software. Supercam has automated setup software, but it needs to be better.

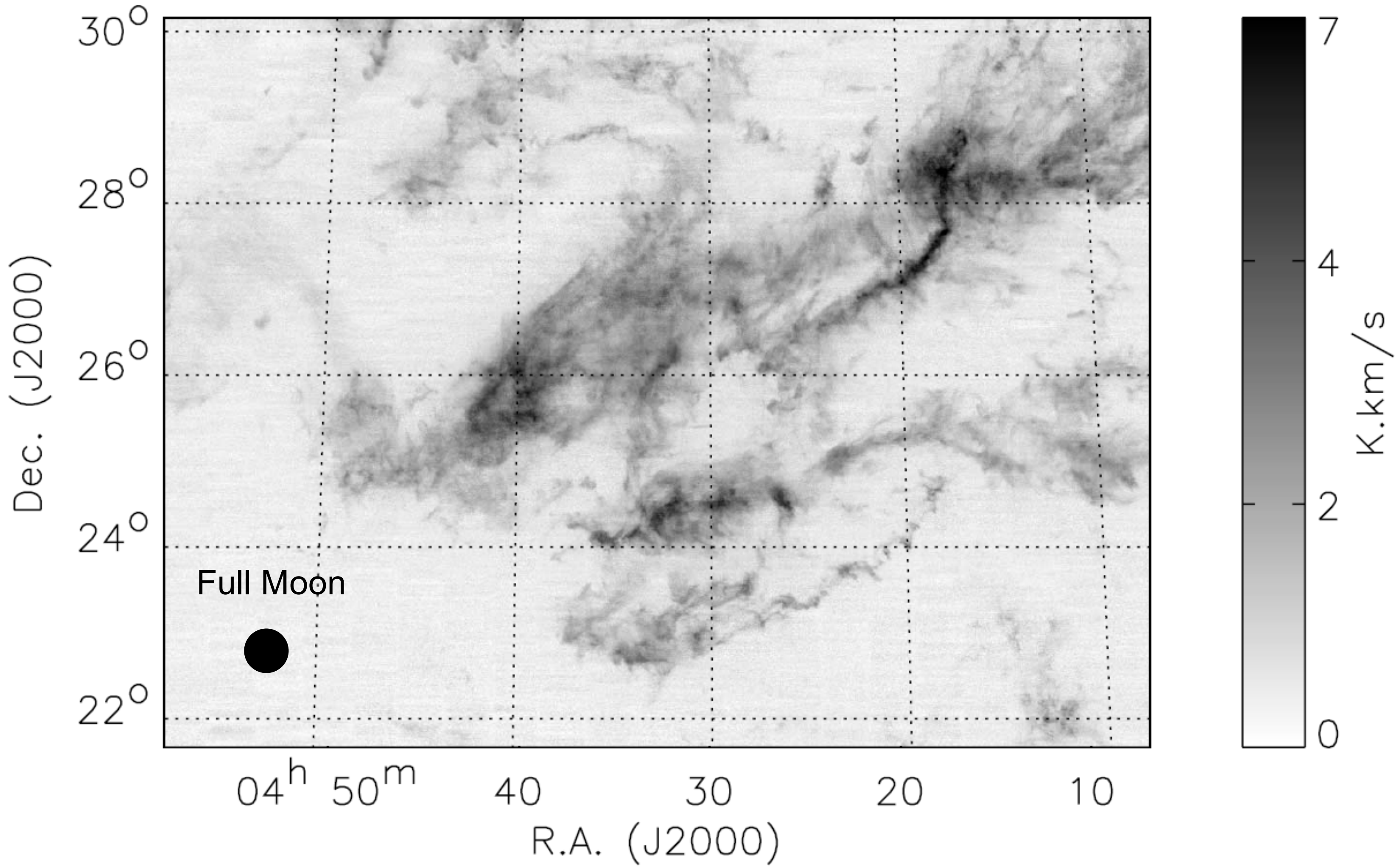
More lessons learned from Supercam

- 1D array modules are OK for up to ~100 pixels, but the aspect ratio will become to extreme for many hundreds of pixels.
- Individual coaxes for the IF will become too unwieldy for more pixels.
- The electromagnet dominates the physical size of a pixel element. Eliminating it through the use of a permanent magnet would be great.
- Wiring will become very complicated for large arrays.

More lessons learned from Supercam

- 1D array m … up to ~100 pixels, but t … l become to extreme for … f pixels.
- Individual c … ll become too unwieldy fo…
- The electro … the physical size of a pi… ating it through the use of a … et would be great.
- Wiring will … licated for large arrays.





~120 square degree image of the Taurus molecular cloud in $^{13}CO(1\text{-}0)$ from Goldsmith et al. (2008).

FOV of ALMA is 1/4th of a pixel in this map with 6.2×10^7 pointings

The previous image was taken using the FCRAO 15m telescope and the 32 pixel SEQUOIA array receiver.

Approximately how many pixels would a receiver need to have to acquire the same image in $^{12}CO(6-5)$ on a future 25m telescope in the same amount of observing time?

$$32\left(\frac{690GHz \times 25m}{115GHz \times 15m}\right)^2 = 3200$$

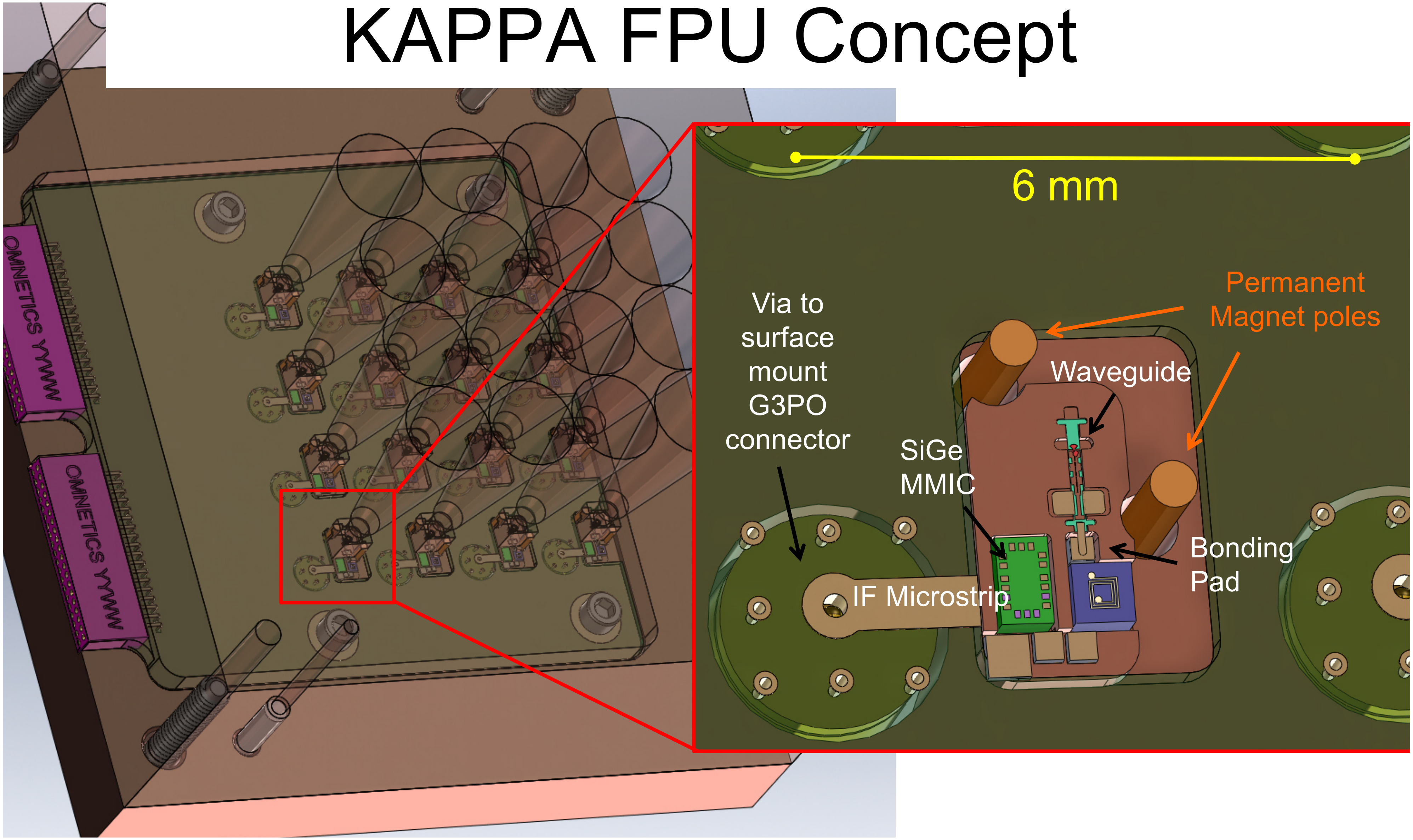
Assuming you have the same T_{sys}.

So, to simply *maintain* the imaging speed of existing arrays on future telescopes, we need arrays with ~1000 pixels.

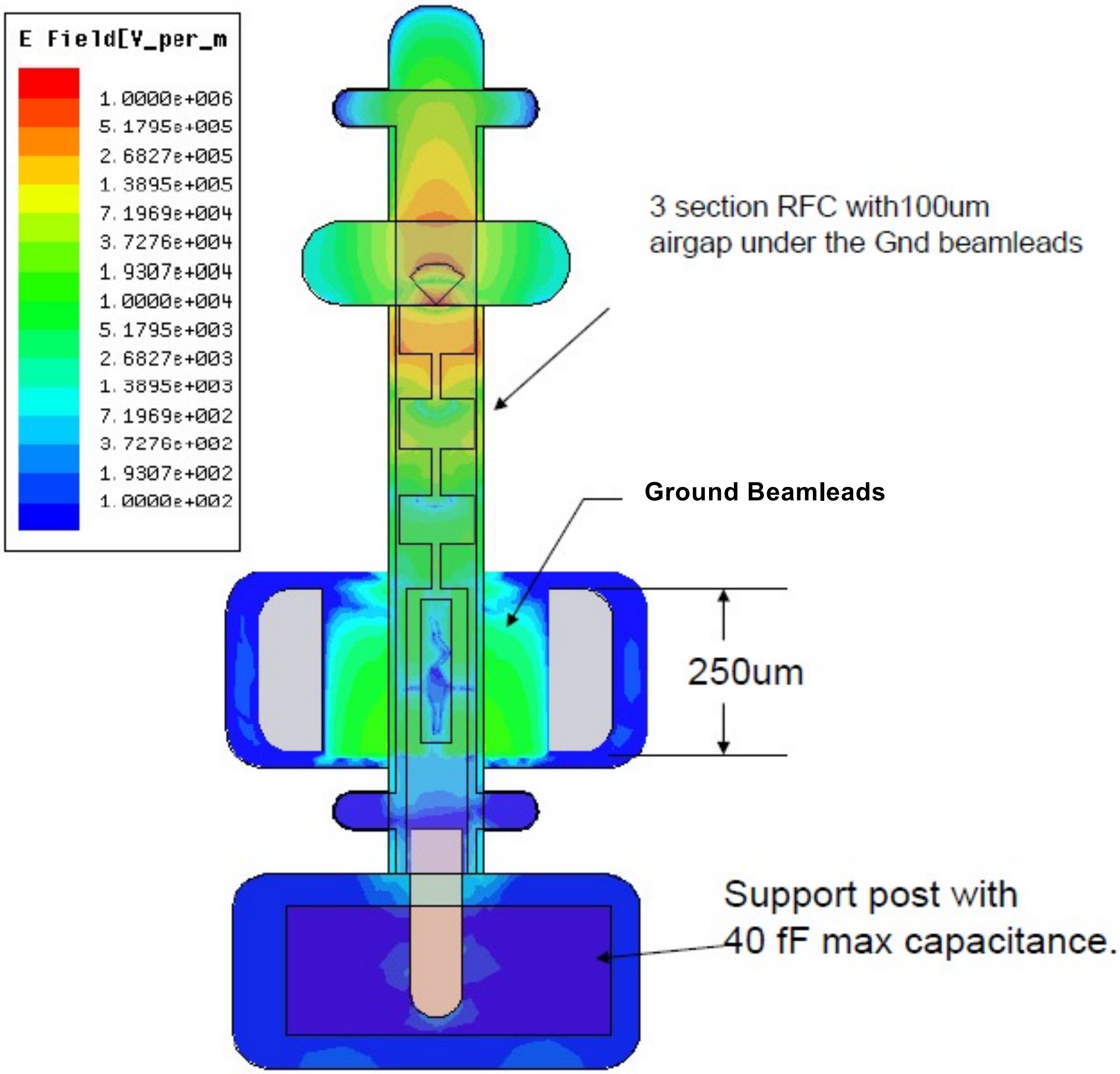
The next step: 2D integration

- KAPPA (the Kilopixel Array Pathfinder Project) is a project to design and build a pathfinder 2D integrated heterodyne focal plane array.
- The KAPPA project aims to solve many of the technological problems presented by the development of a ~1000 pixel heterodyne array receiver.
- KAPPA has developed a fully integrated pixel cell that houses a complete SIS receiver with LNA and magnet under the feedhorn aperture.
- This pixel cell can be tiled to arbitrary array size.

KAPPA FPU Concept

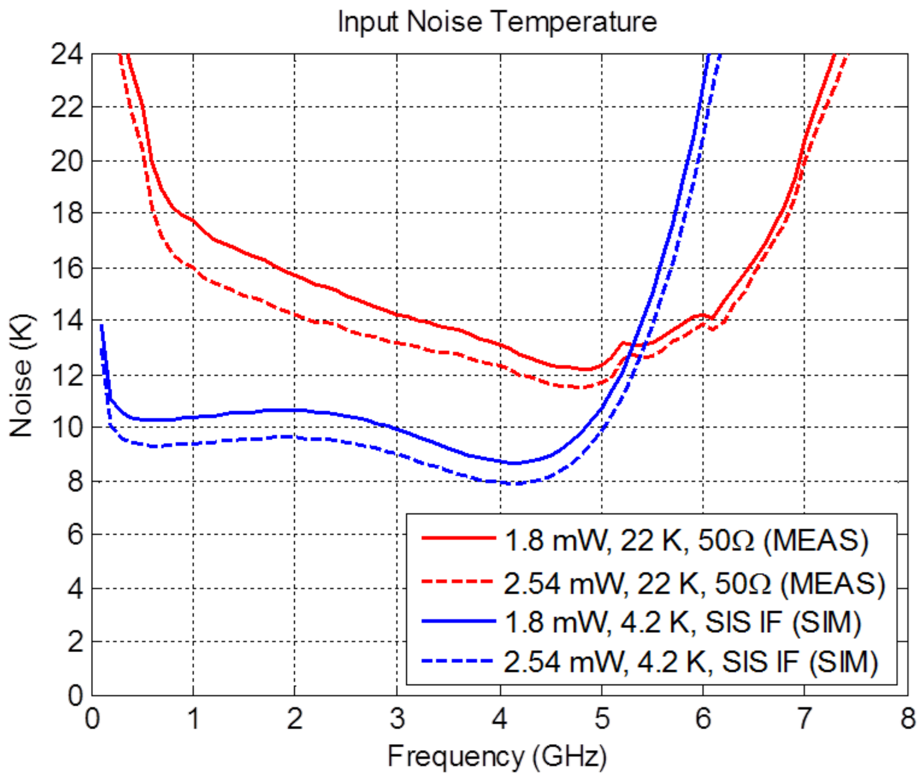


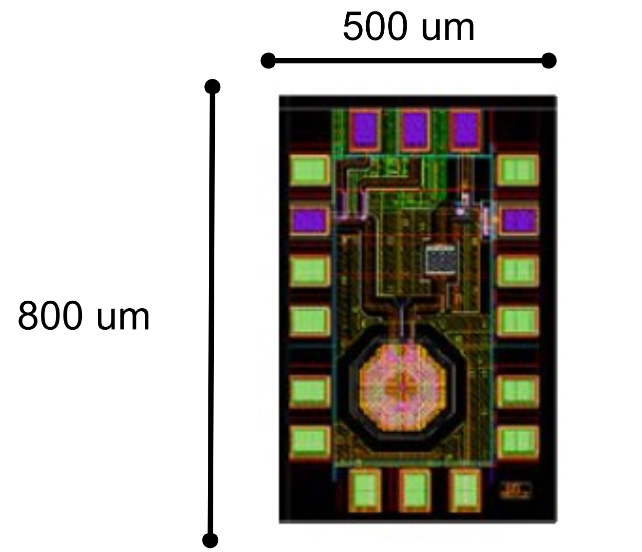
KAPPA SIS Device



- 5um SOI substrate
- Beamleads for IF, Gnd and alignment
- Radial stub WG probe
- Simple Nb/AlOx SIS junctions for maximum yield.

KAPPA SiGe LNA



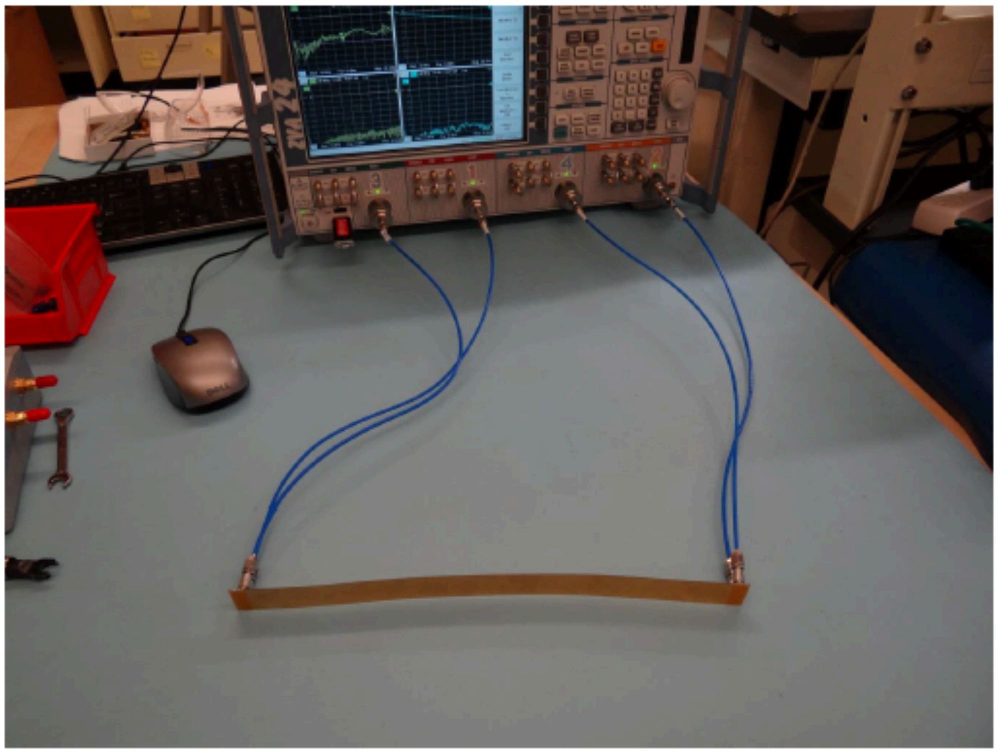


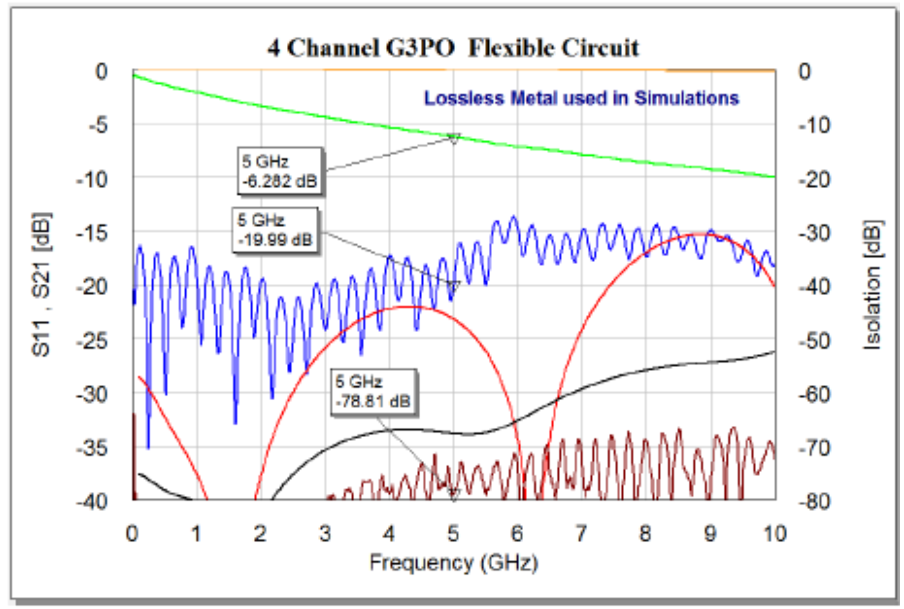
SiGe MMIC Chip

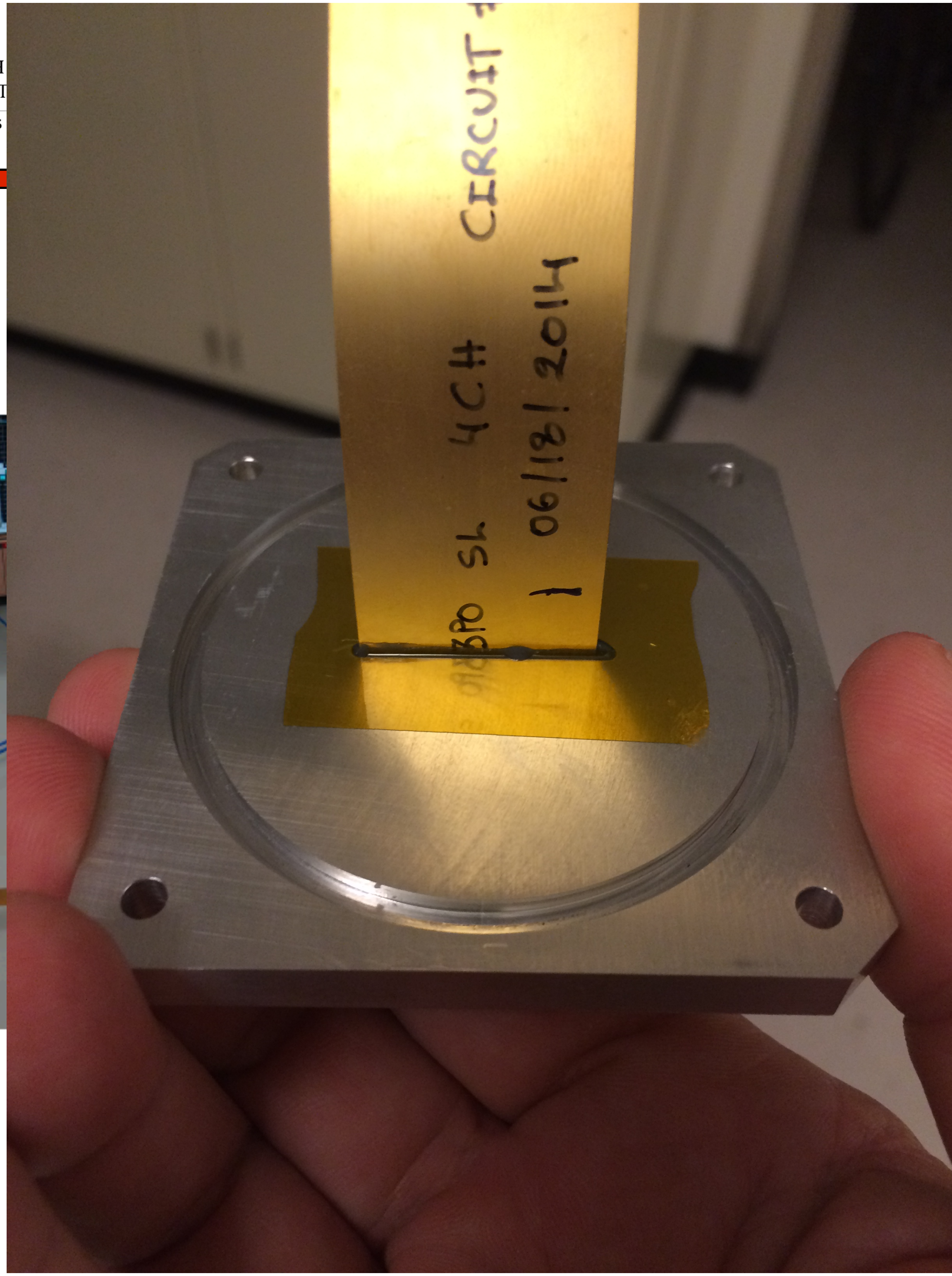
- 0.5-4.5 GHz
- 16 dB Gain
- 7K noise temperature (predicted)
  9K (measured)
- **~2 mW power dissipation**

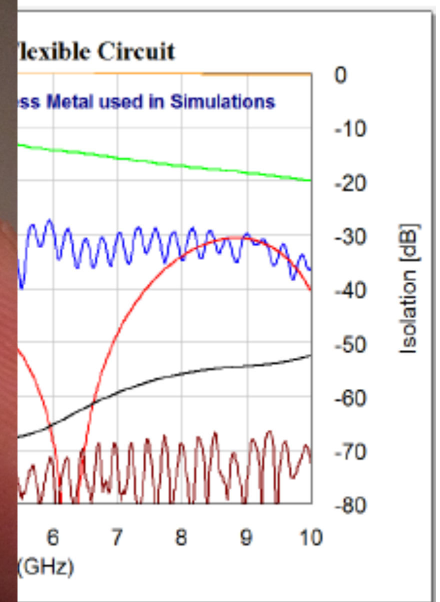
- |S11|<-11 dB
- **On-chip bias tee**
- Small chip size
- 2 stage version also fabricated (32 dB gain, 4-5 mW power dissipation)

IF Flex Circuit






CIRCUIT
SL 4CH
06/18/2014


lexible Circuit
ss Metal used in Simulations
0
-10
-20
-30
-40
-50
-60
-70
-80
Isolation [dB]
6
7
8
9
10
(GHz)

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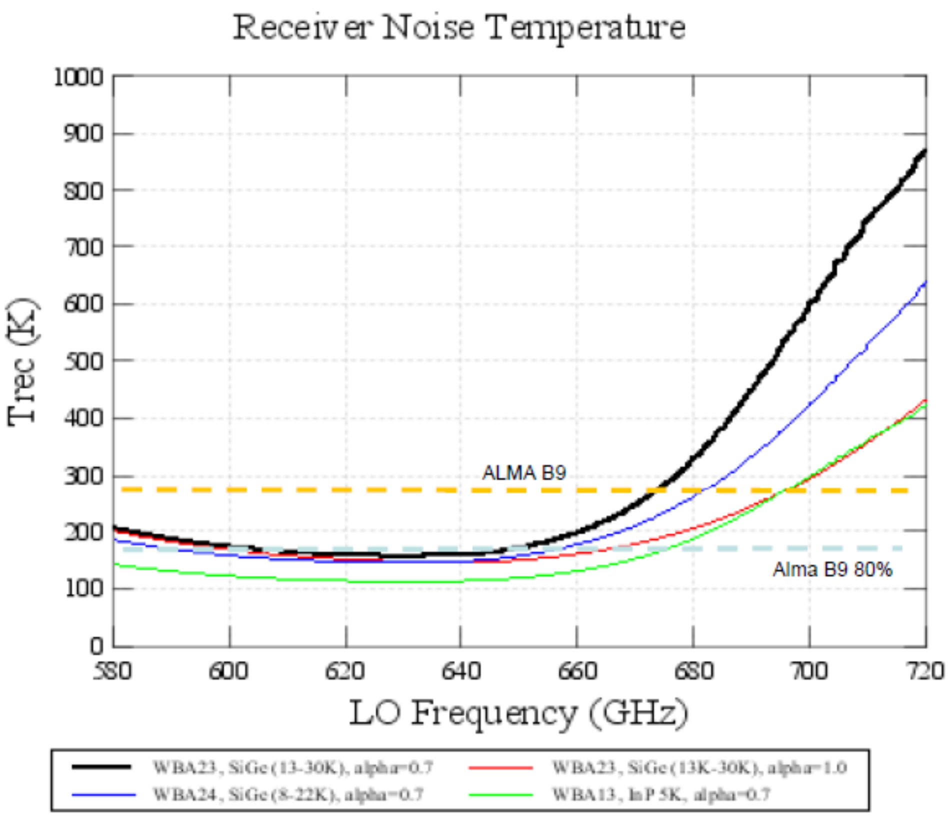

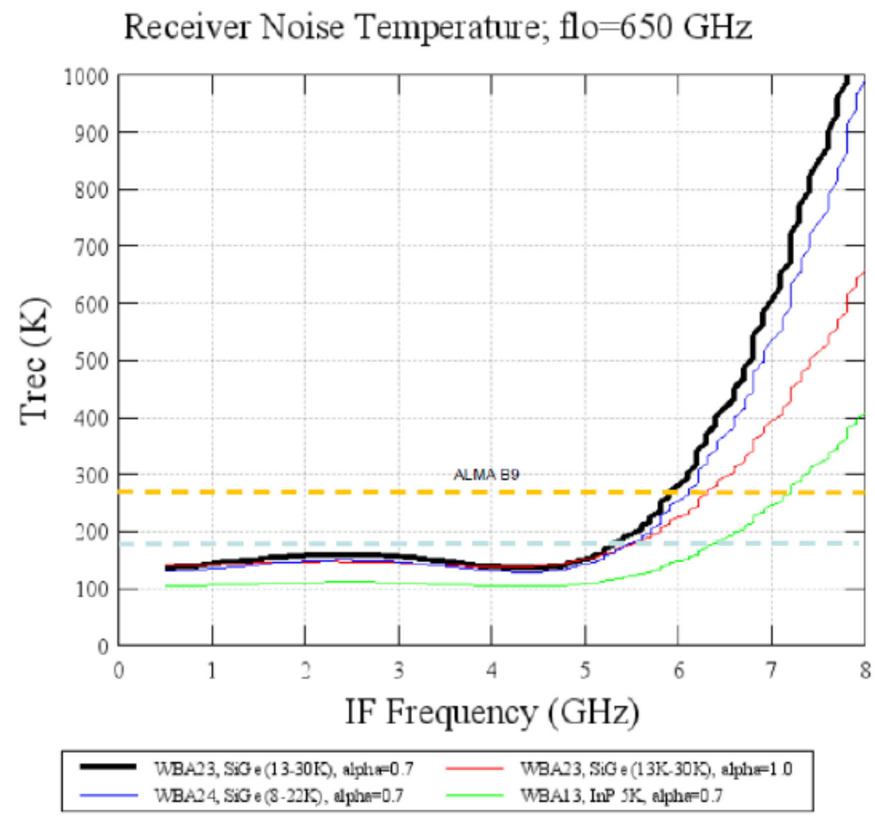

- Simple IF matching network used for flat IF noise across 0.5-4.5 GHz band.
- Insensitive to junction IF resistance.
- Trade-off of LNA noise temp and power dissipation. Large arrays <u>*require*</u> low power dissipation IF amps.

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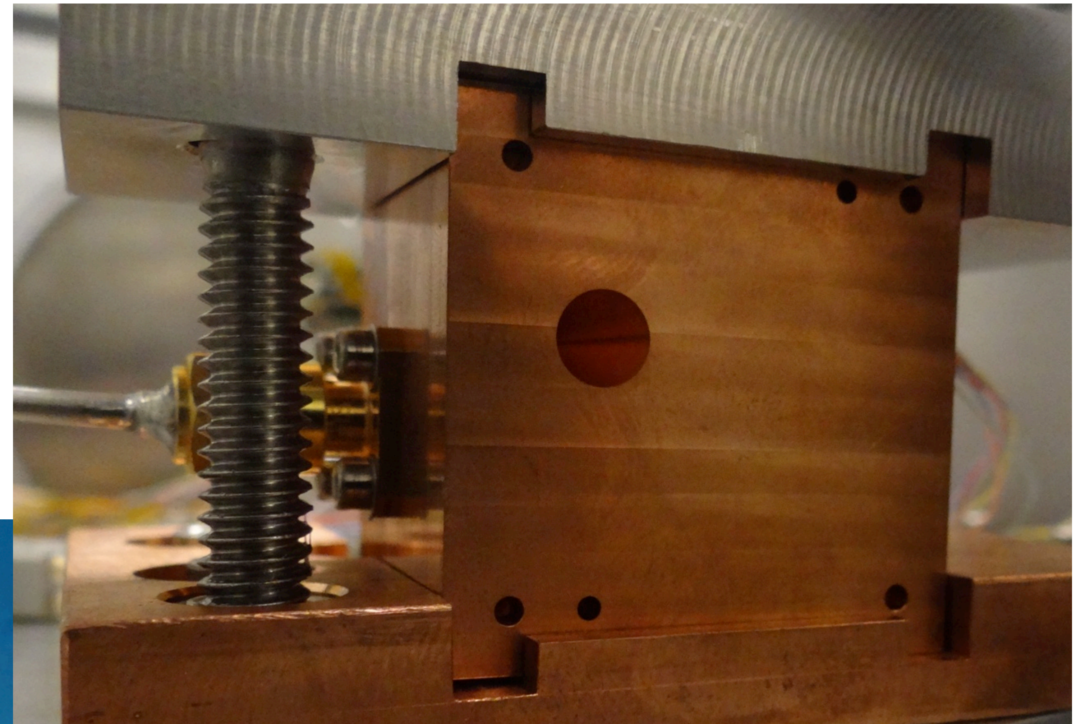
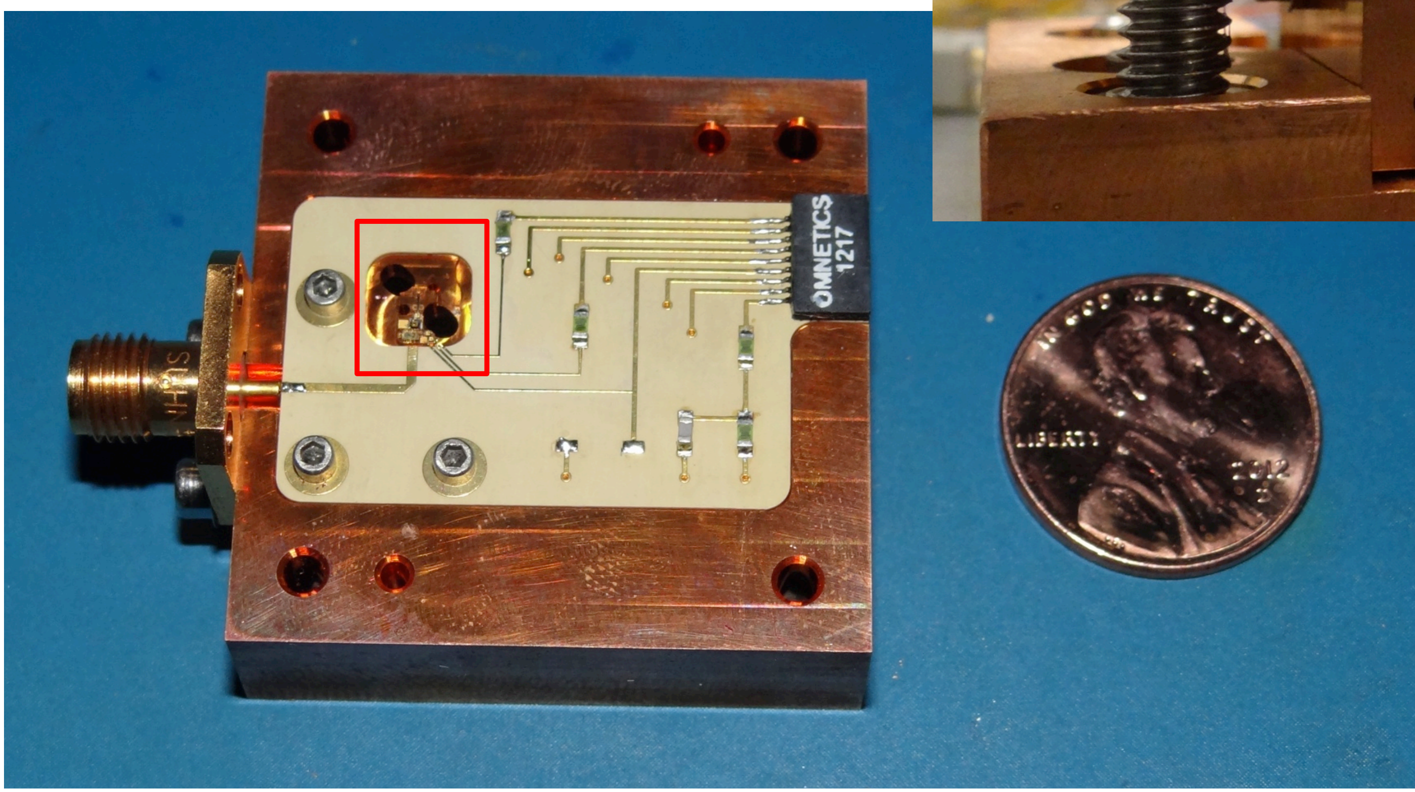
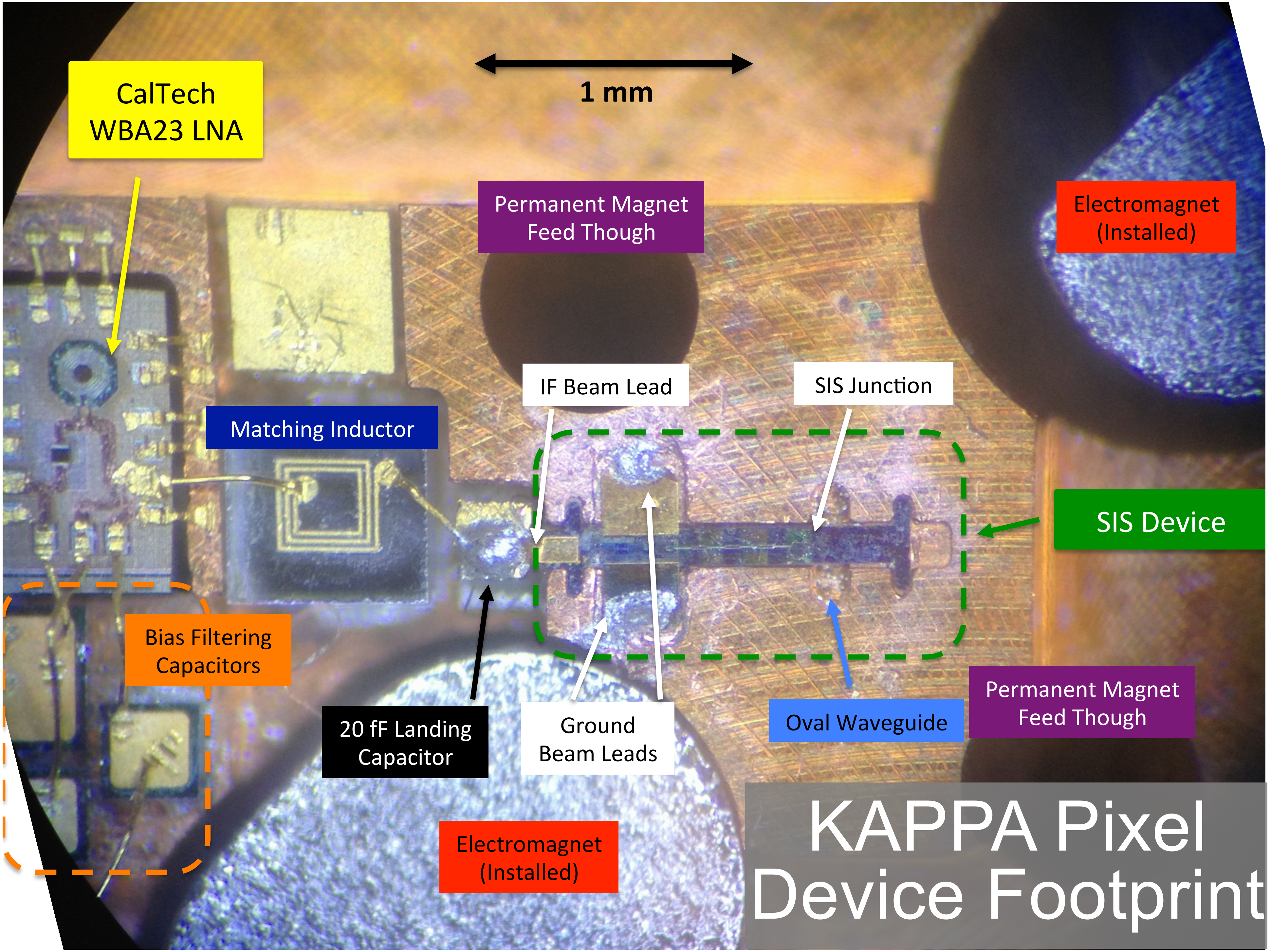
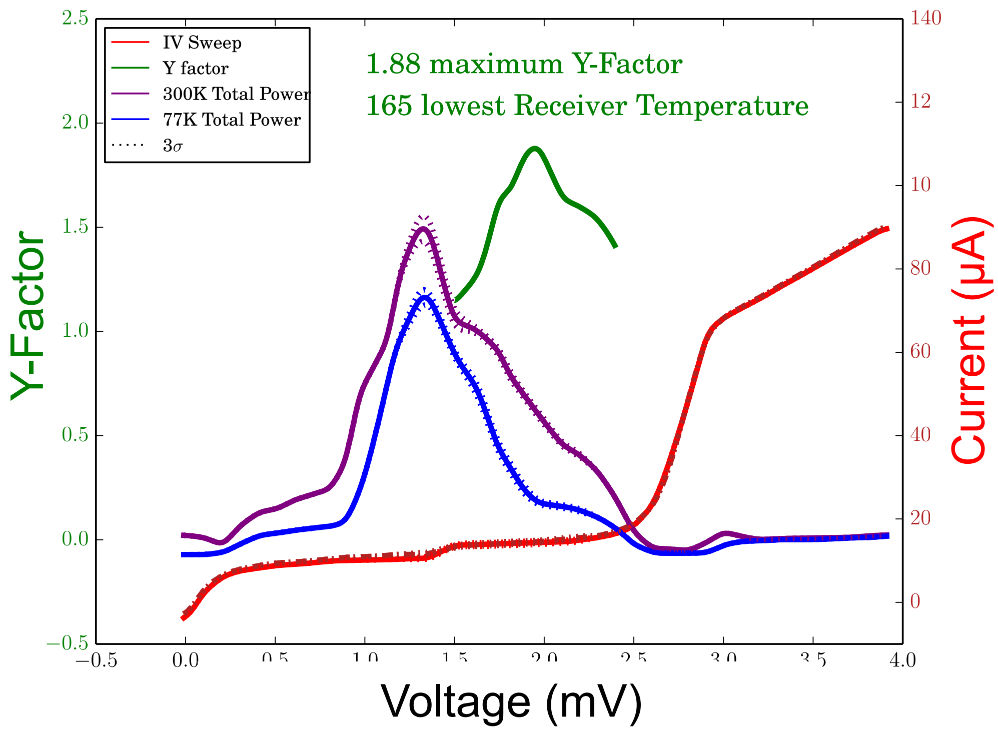




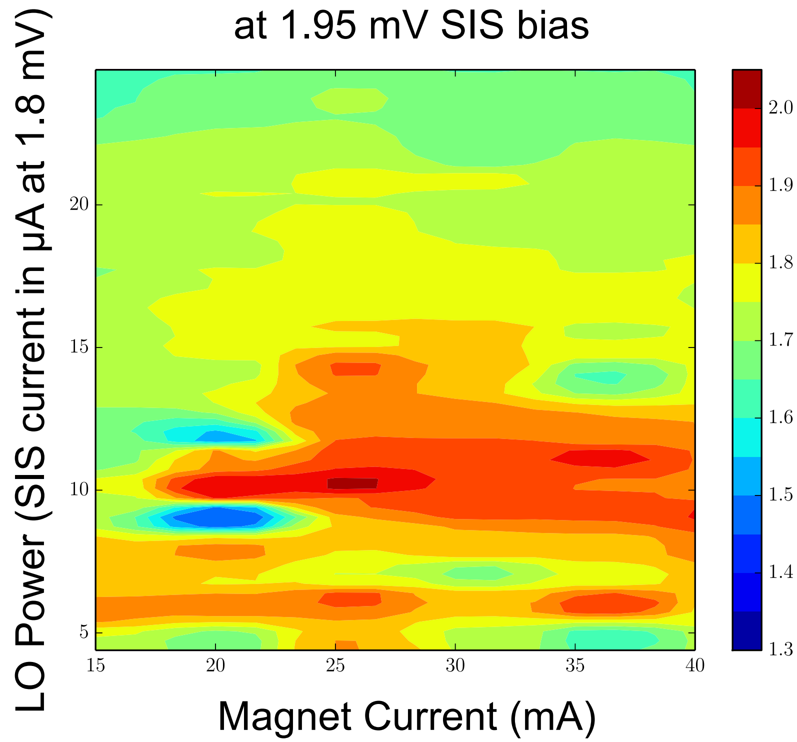

1 mm
CalTech WBA23 LNA
Permanent Magnet Feed Though
Electromagnet (Installed)
IF Beam Lead
SIS Junction
Matching Inductor
SIS Device
Bias Filtering Capacitors
20 fF Landing Capacitor
Ground Beam Leads
Oval Waveguide
Permanent Magnet Feed Though
Electromagnet (Installed)
KAPPA Pixel Device Footprint

Y-Factor Results



IF band is 60MHz at 1420MHz
LO frequency is 672.0 GHz
E-magnet current of 30 mA
LO power of 14 µA at 1.80mV SIS bias

Color scaled Y factor at 1.95 mV SIS bias



IF band is 60MHz at 1420MHz
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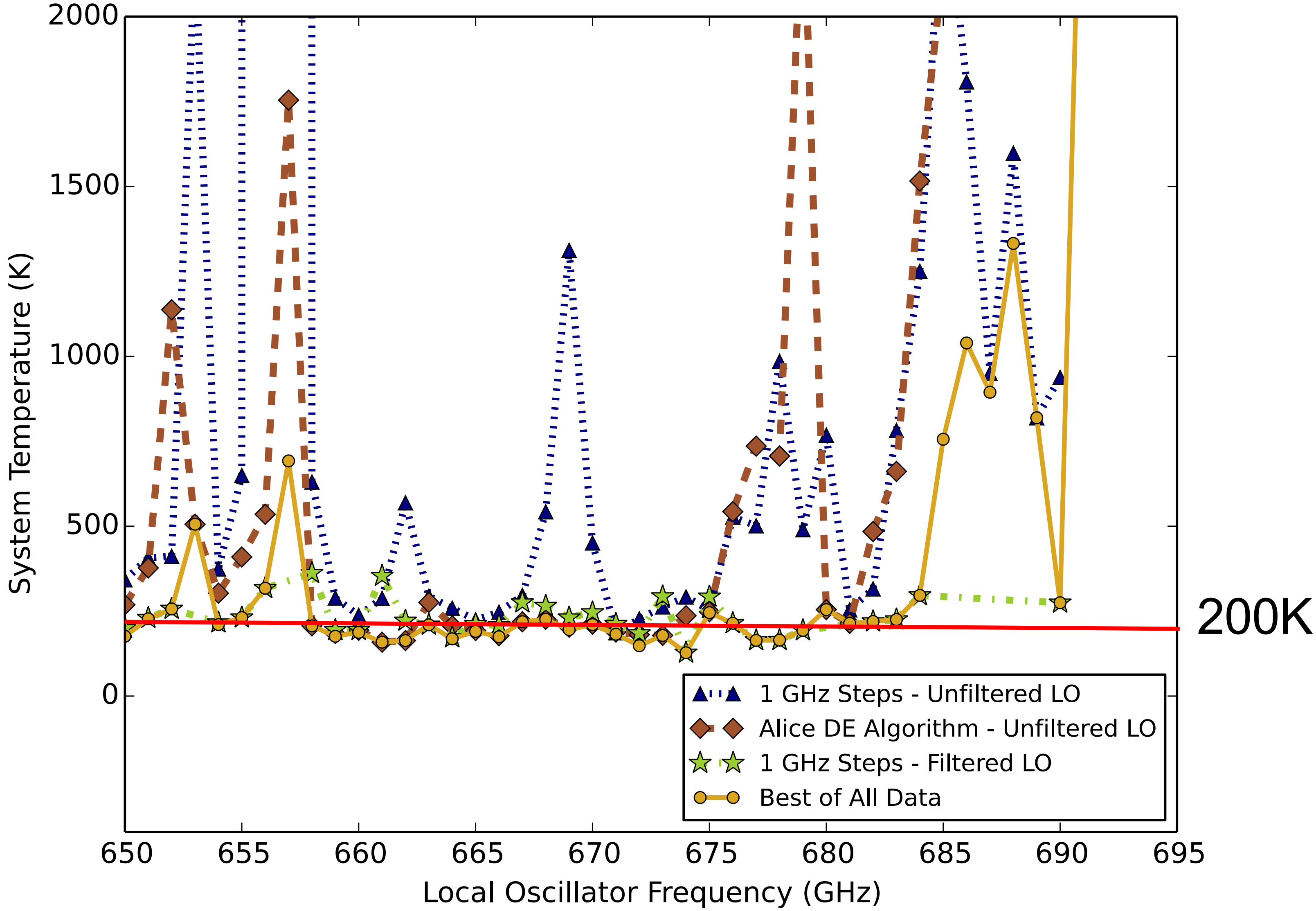
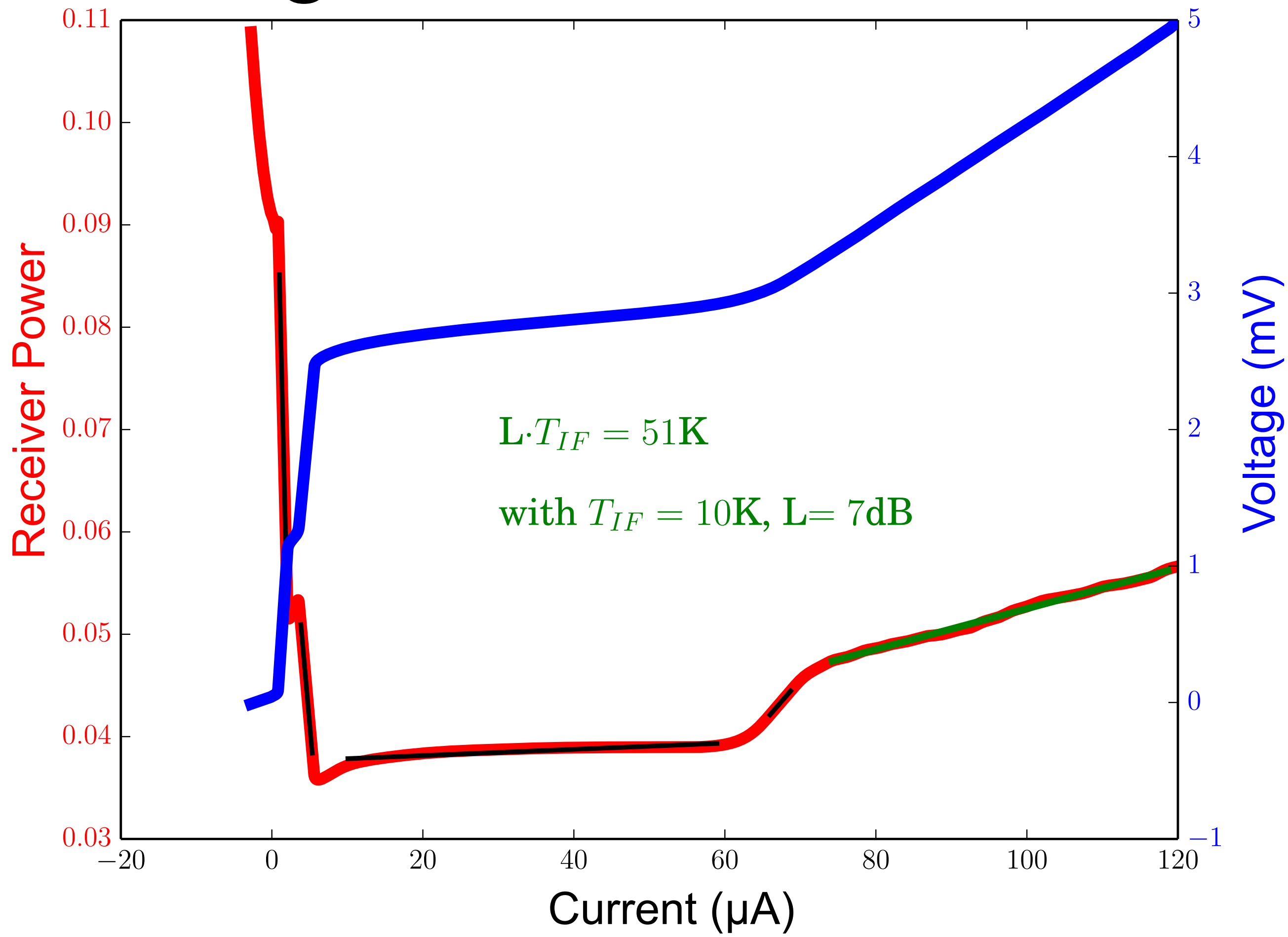
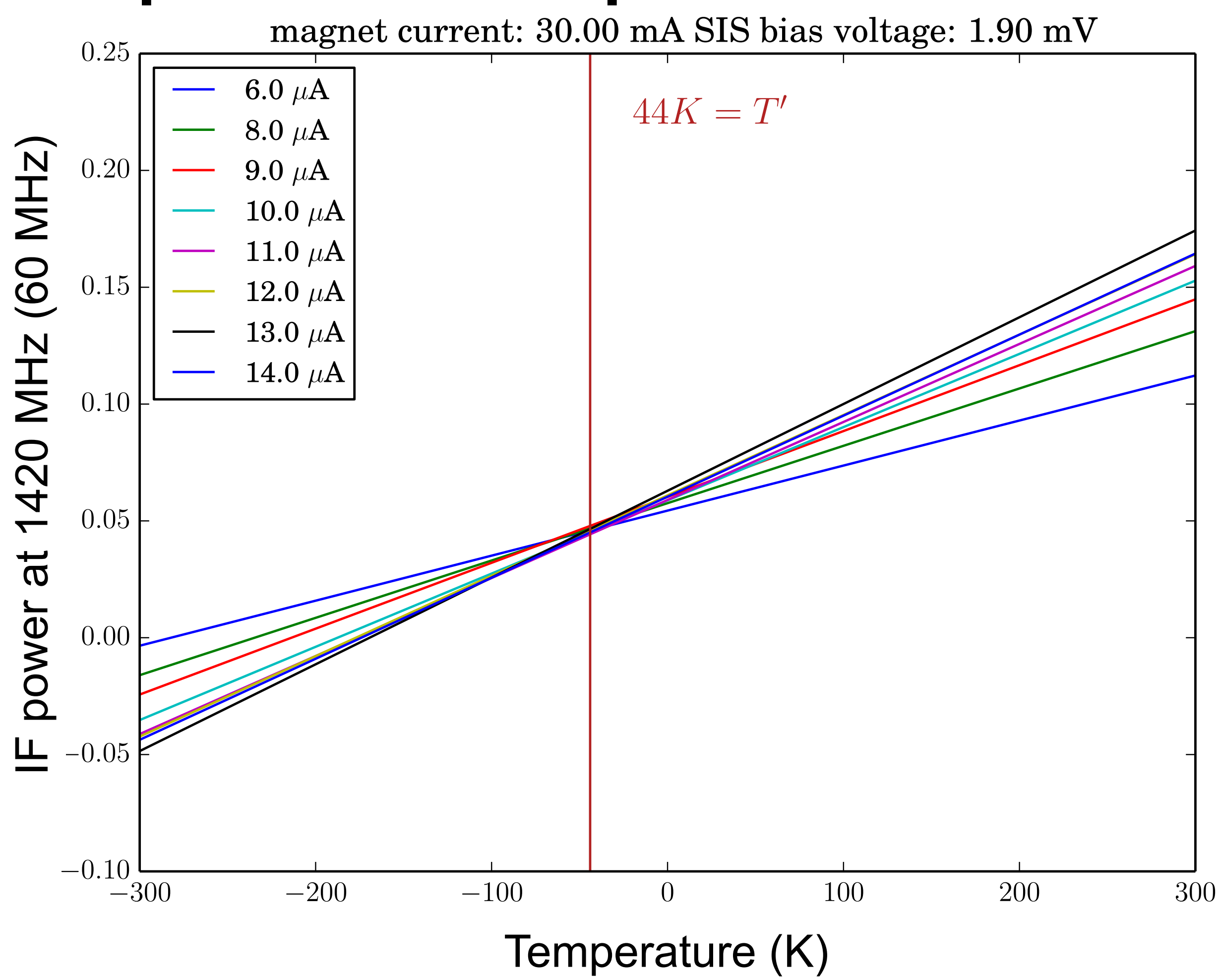


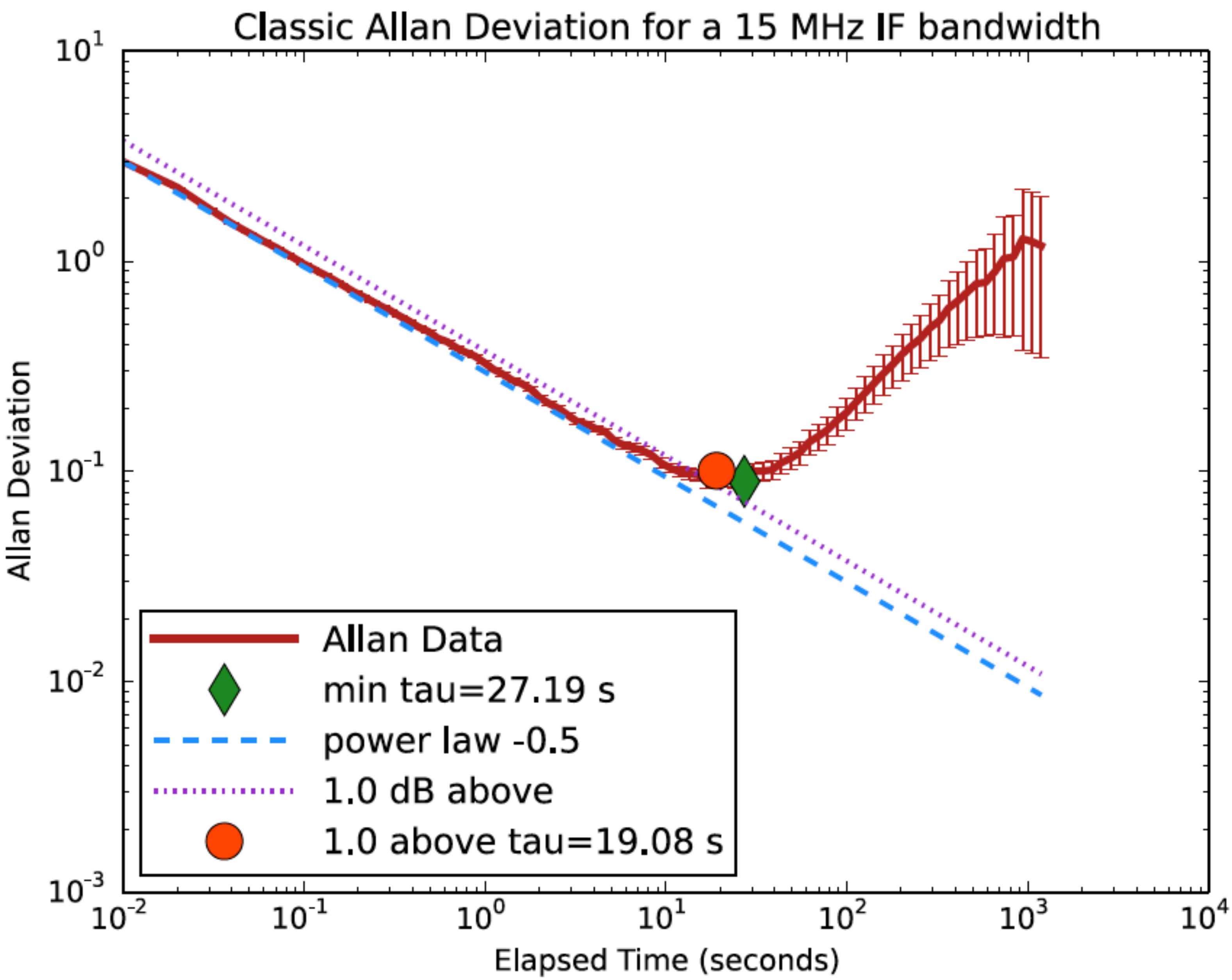
Conversion Loss, Using Shot Noise Method



$$P = 2eBI$$

Intersecting Line Test, Optics Temperature 44K

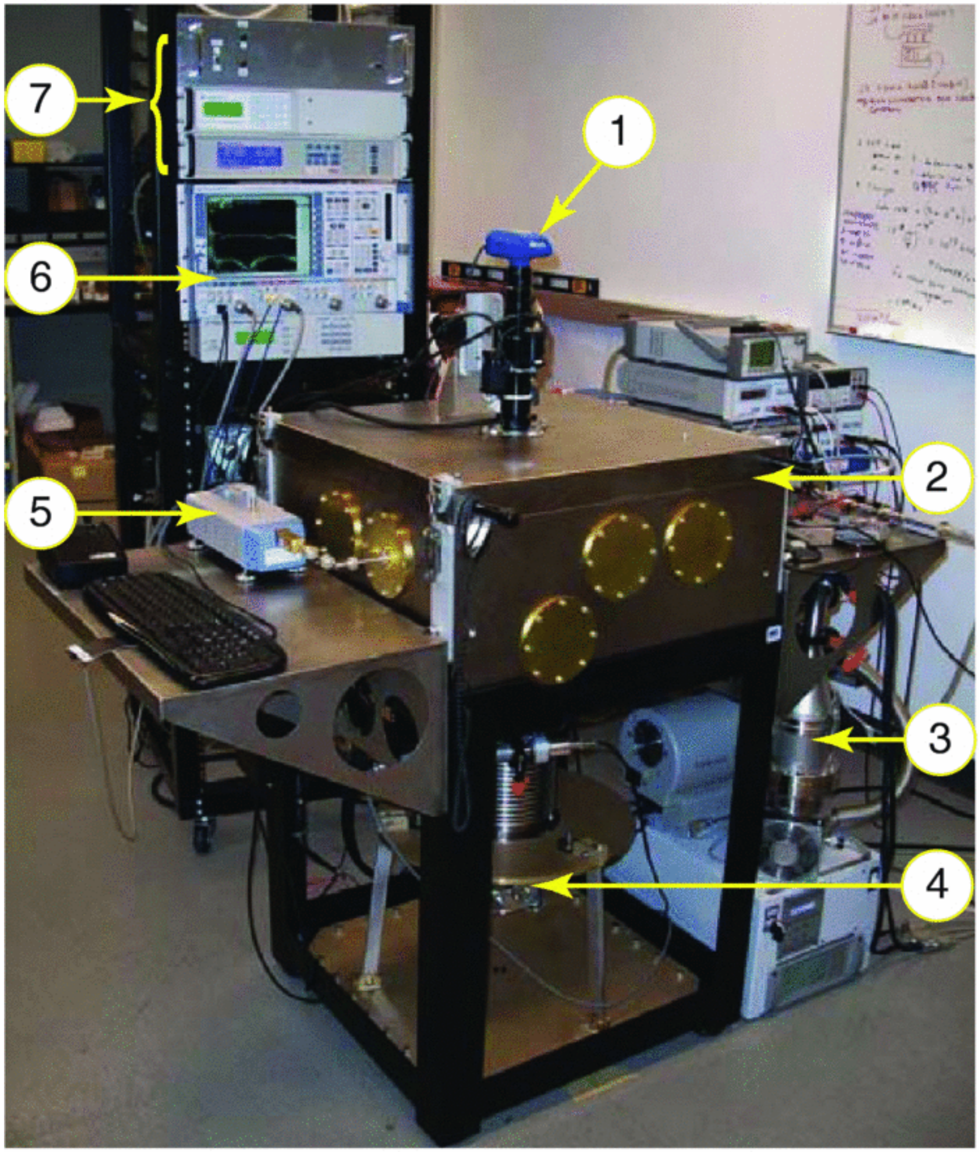


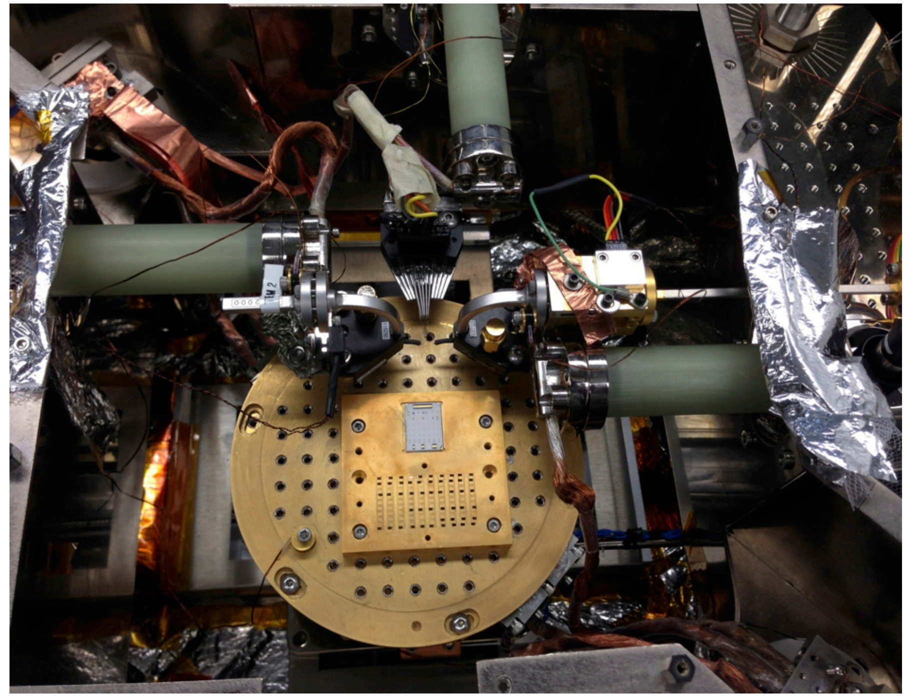

Classic Allan Deviation for a 15 MHz IF bandwidth
Allan Deviation
Elapsed Time (seconds)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Allan Data
min tau=27.19 s
power law -0.5
1.0 dB above
1.0 above tau=19.08 s

KAPPa Conclusions

- We have developed a heterodyne pixel cell that packages an entire receiver, including LNA and magnet, into a 6mm x 6mm footprint.
- The performance of this pixel, while not state of the art, meets most of the performance requirements for ALMA band 9.
- With this development, construction of heterodyne focal plane arrays with essentially arbitrary pixel count are possible. The limiting factor is likely now the ability to afford the instrument, not the technical challenge of building it.
- Dipping junctions individually is not feasible for large arrays. We need a better way.

Cryogenic probe station





We could use a 4K probe station to measure the IV curve of EVERY mixer on-wafer.

So, what could we do right now?

- It should be reasonably straightforward to build a 256 pixel focal plane array using this technology anywhere from ~300 GHz to 950 GHz. I'd probably build it out of four 64 pixel sub-arrays.
- You'd need one cryocooler, one LO (albeit very powerful, 5-10 mW), and a FPGA based spectrometer (e.g. ROACH2).
- At 256 pixels, it's still feasible to build a waveguide LO power divider. Or a phase grating, whatever is more convenient. A silicon etalon for each line observed saves LO power.
- It would be expensive (~$3M-$5M) depending on how much of the IF bandwidth you want to process instantaneously, but not unreasonable. Note, you don't need to process all of the IF for most science applications.
- A convenient ROACH2 based solution would be to process 1 or 2 GHz of IF bandwidth per pixel using the SMA dual 2.5 GS/s ADC board. You'd need 128 ROACH2 boards and 256 ADC boards for 2 GHz, 64 /128 for 1 GHz. Expensive, but you could just buy it today.