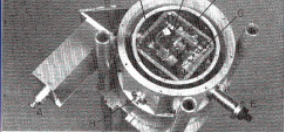


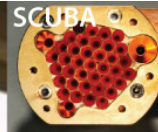
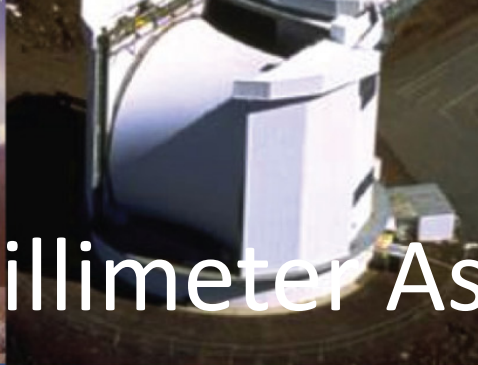
CSO (1988)



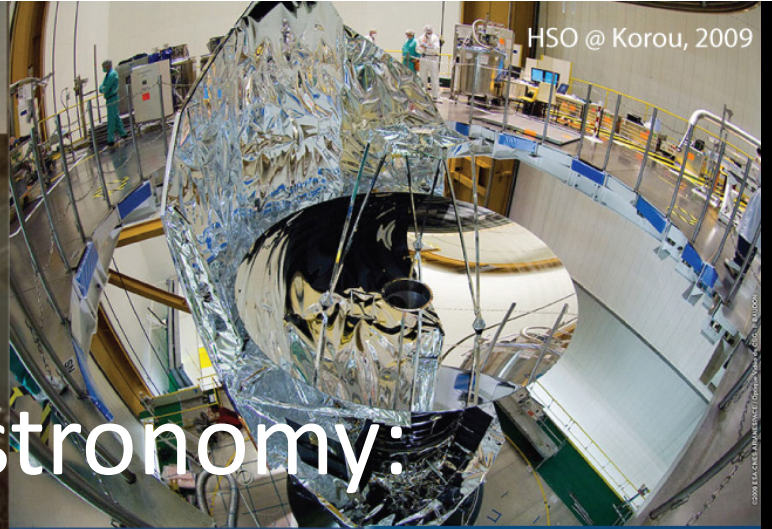
SIS, 1979



JCMT (1988)



HSO @ Korou, 2009



Joyce, Gezari & Simon
350 μ m, Mt Hopkins, 1971



What Happens Next ?

ALMA, 2011



Jonas Zmuidzinas
Caltech

Herschel launch, 2009

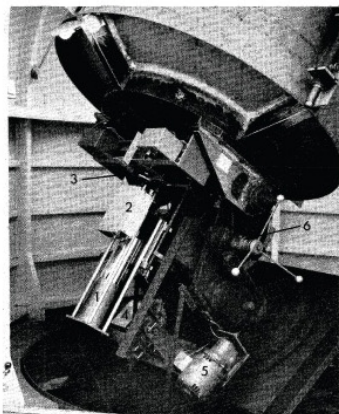


FIGURE 11. Detector mounted on telescope: (1) detector, (2) pre-amplifier and amplifier, (3) chopper, (4) hour angle drive motor; (5) declination drive motor, (6) cams for automatic control.

Clegg, Newstead & Bastin
1.3 mm, QMC, 1969

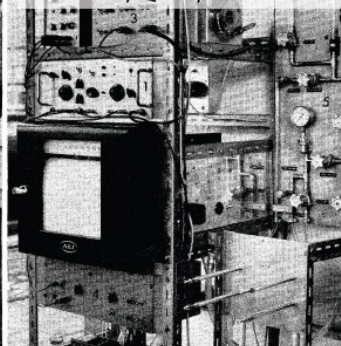


FIGURE 12. Automation and data processing equipment: (1) data control panel, (2) Nuclear Data Inc. 'Enhancetron', (3) automation control unit, (4) Enhancetron-triggering and scan-counting unit, (5) helium-transfer system.

Clegg, Newstead & Bastin

Low, 1.2 mm, NRAO, 1963



Phil. Trans. A, volume 284, plate 13



KAO (1974) & SOFIA (2010)

A brief history

- 1960: Frank Low develops cooled semiconductor (Ge) bolometer
 - Improved over next 40 years
 - Leads to COBE, SCUBA, Planck HFI, SPIRE...
- 1970: Wilson, Jefferts & Penzias detect CO(1-0)
 - 115 GHz Schottky diode heterodyne receiver
 - Extended x40 to 4744 GHz (O I @ 63 μm ; Betz) by 1995
- 1979: SIS receivers demonstrated (Phillips, Richards)
 - Displace Schottky receivers by mid-1990s
 - SIS enables ALMA, Herschel HIFI
- 2000: Semiconductor bolometers superceded by multiplexed superconducting arrays (e.g. SCUBA 2)
- **What happens next ?**

The next 10-20 years will bring:

- Megapixel submm cameras
 - CCAT FOV can approach 1 degree
 - Cost is the key issue
- “3D” redshift machines with $R \sim 700$ and 10^3 or more simultaneous beams on the sky
 - Size and cost are key issues
- 10x sensitivity improvement for ALMA
 - Need to expand instantaneous bandwidth
 - More cost effective than adding dishes

CCAT

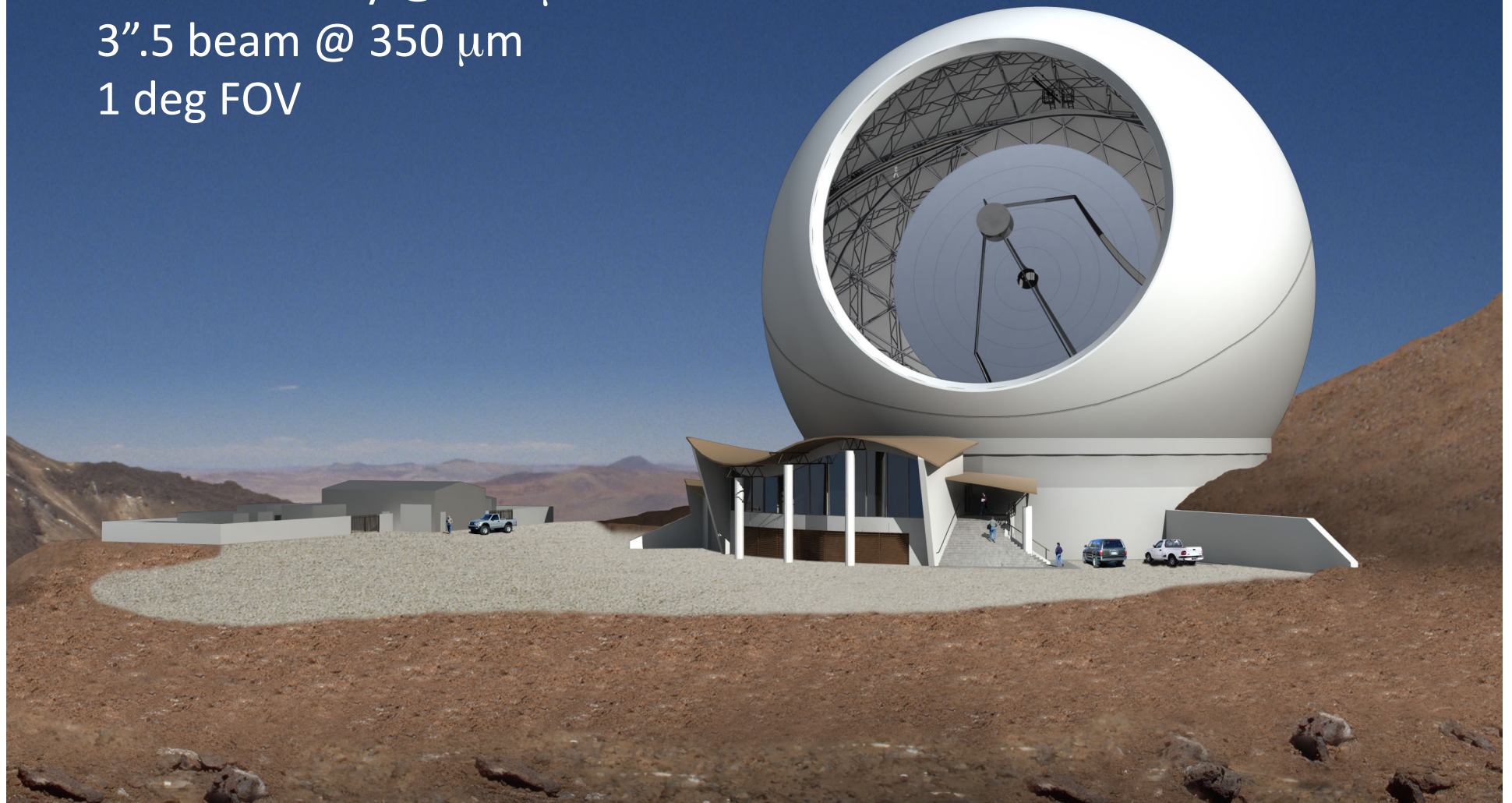
25m diameter

10 μm rms

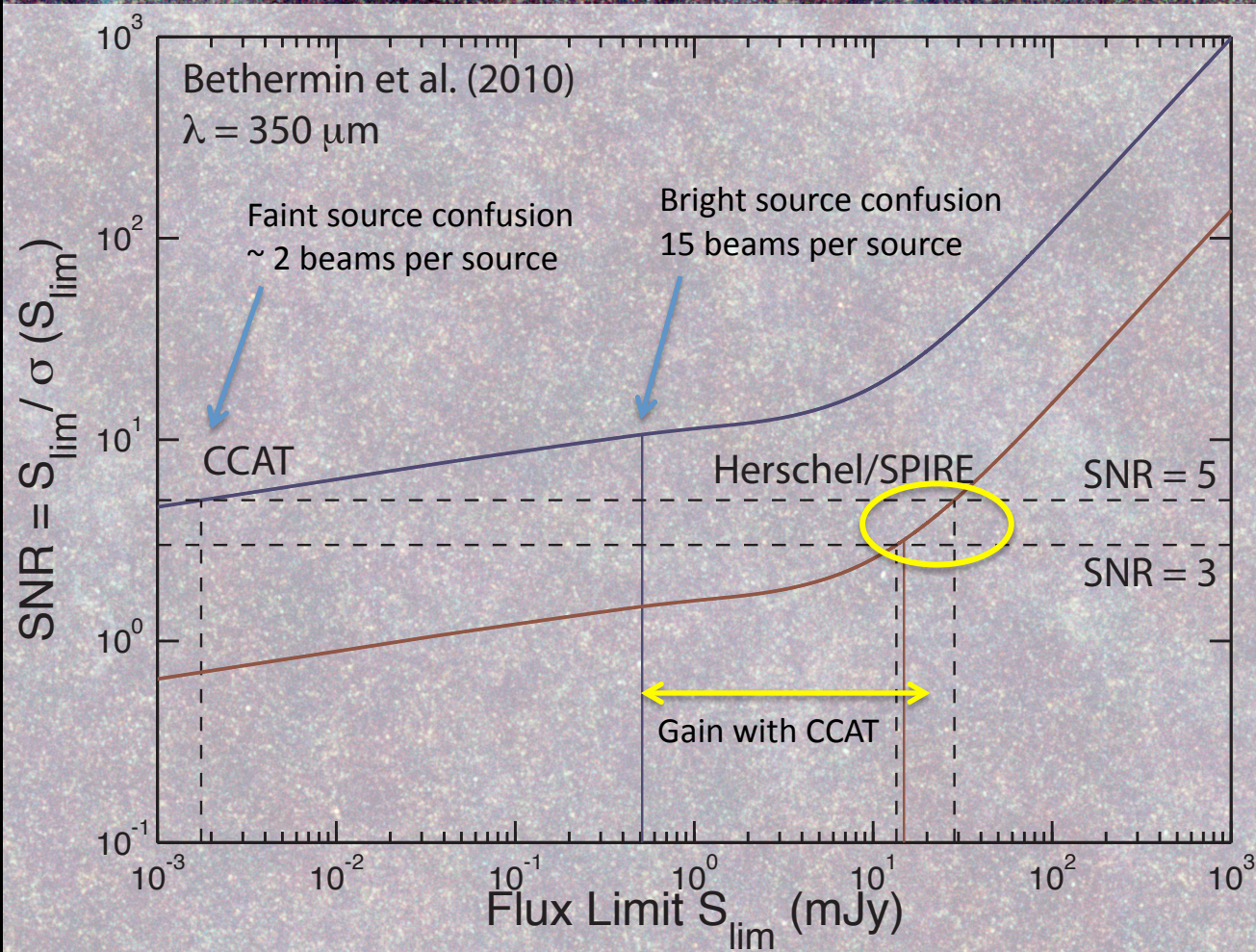
80% efficiency @ 350 μm

3".5 beam @ 350 μm

1 deg FOV



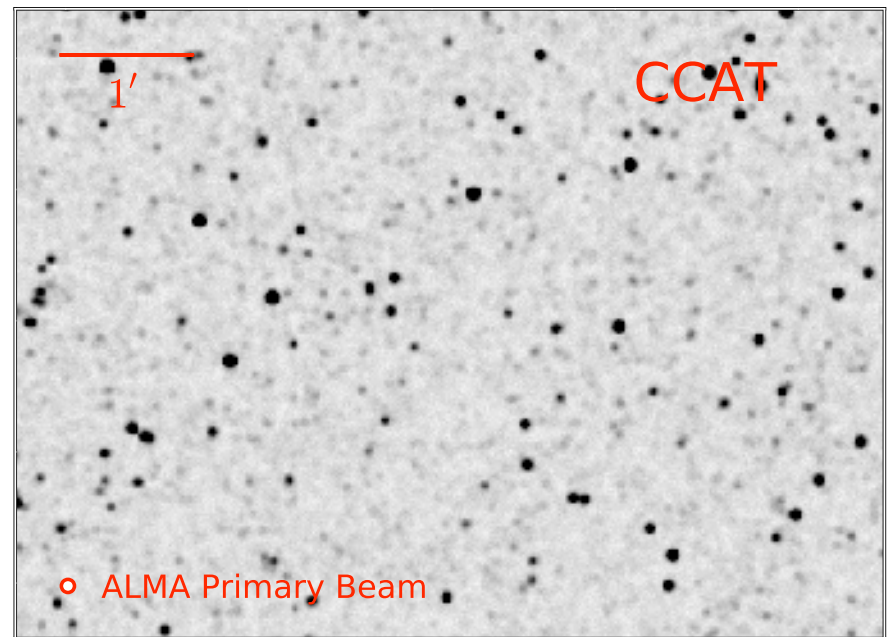
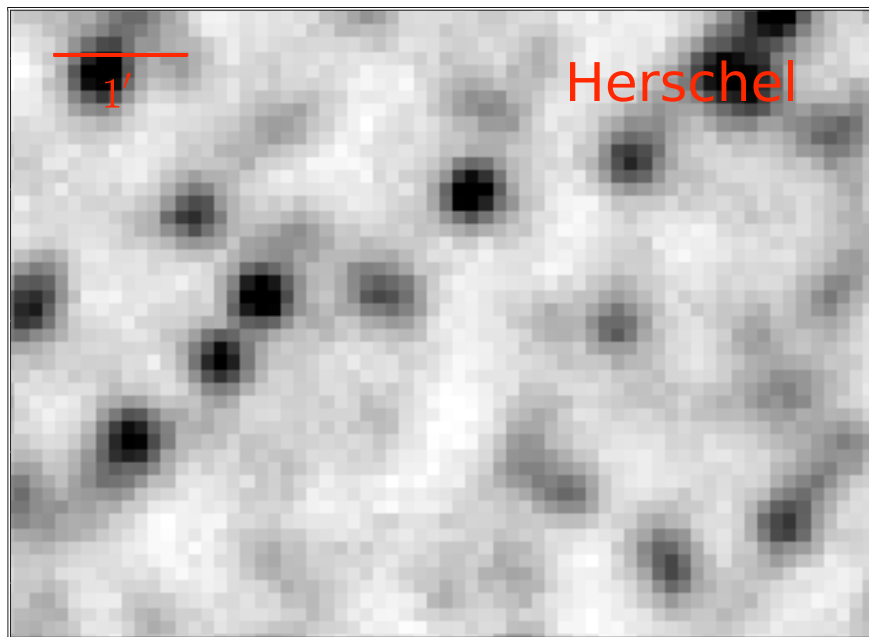
Confusion



Herschel ATLAS SDP

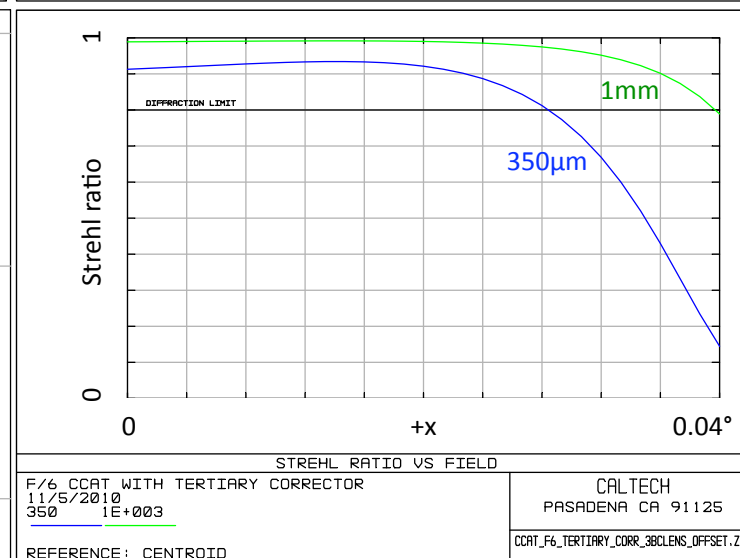
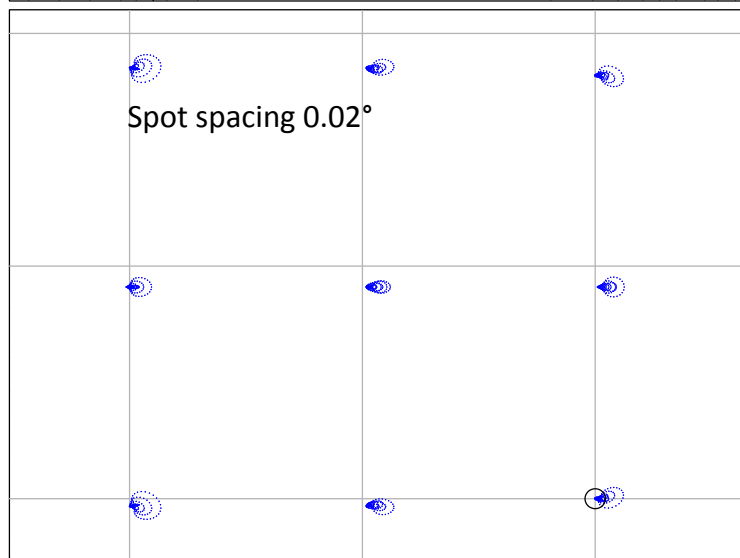
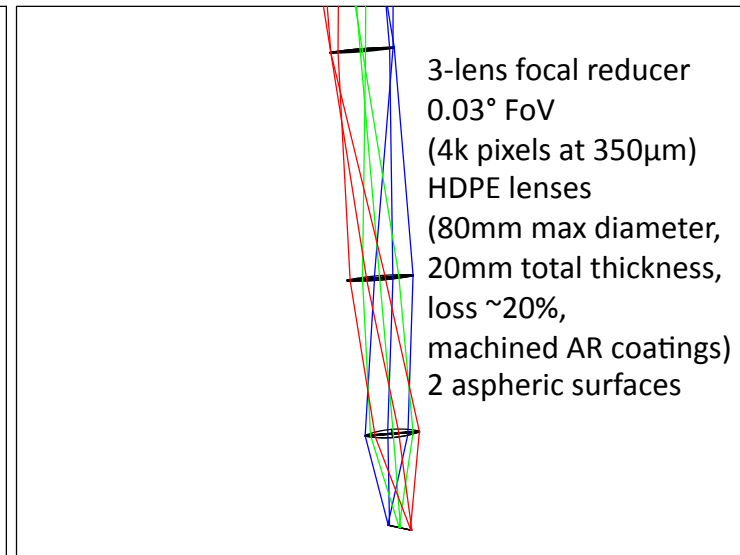
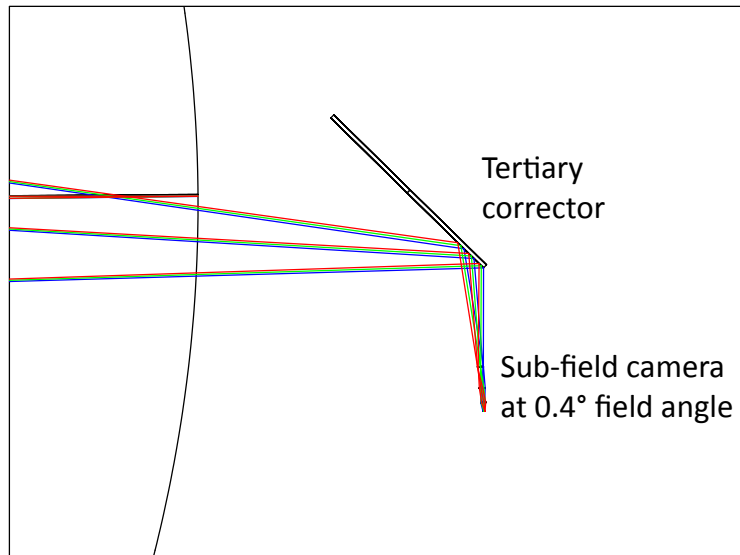
CCAT vs Herschel

350 μm



Credit: J. Glenn/U. Colorado

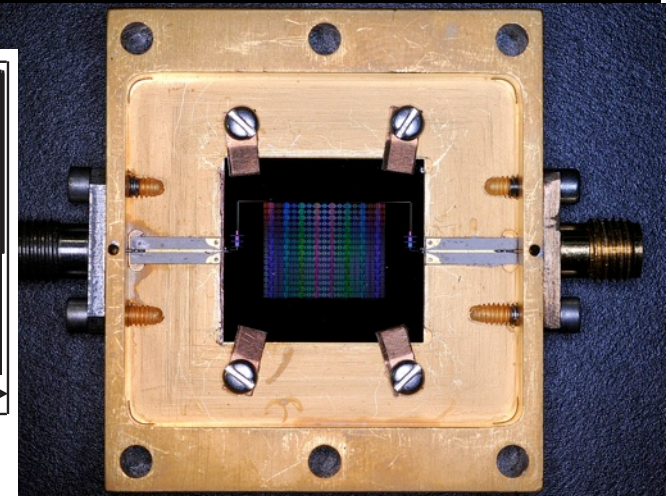
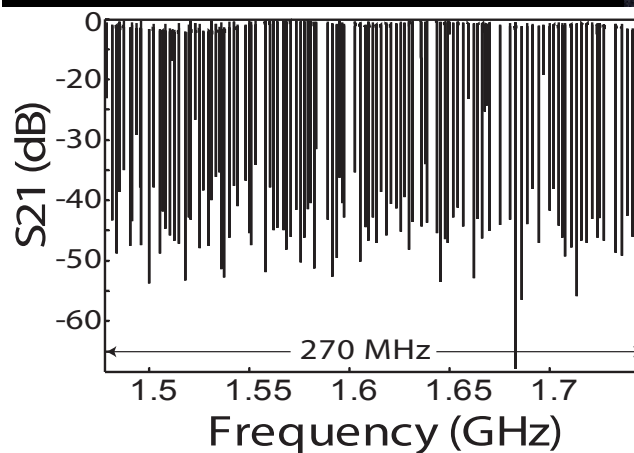
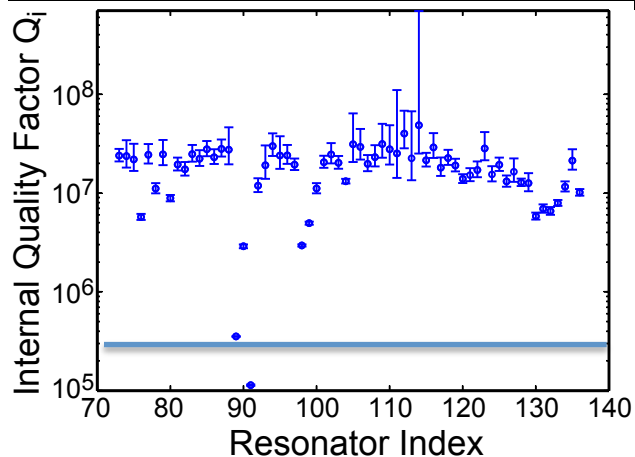
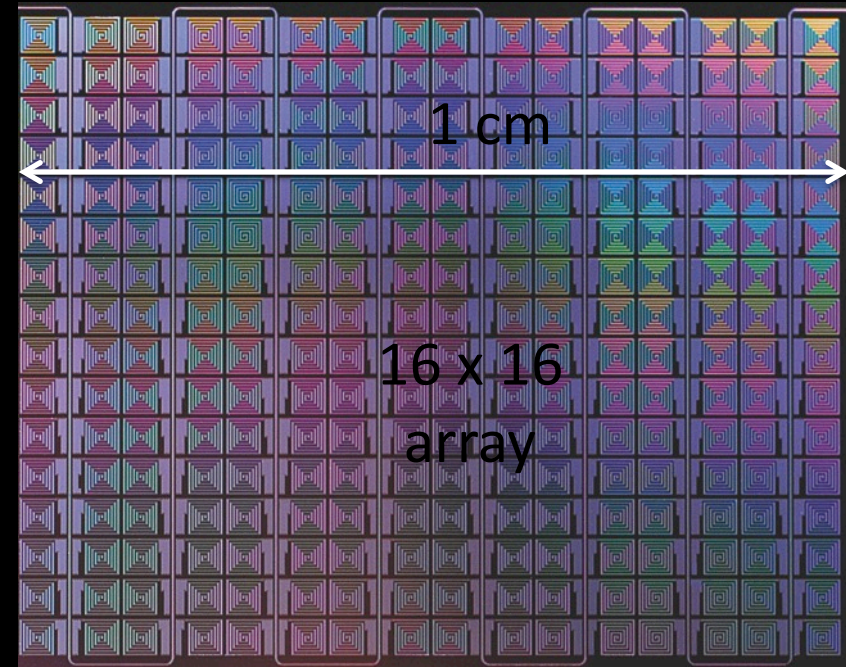
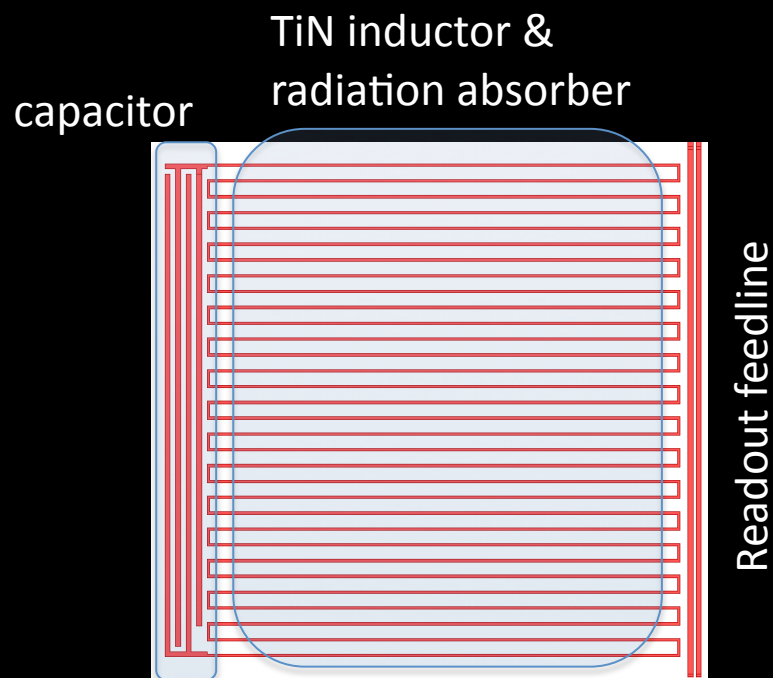
Camera relay with small HDPE lenses



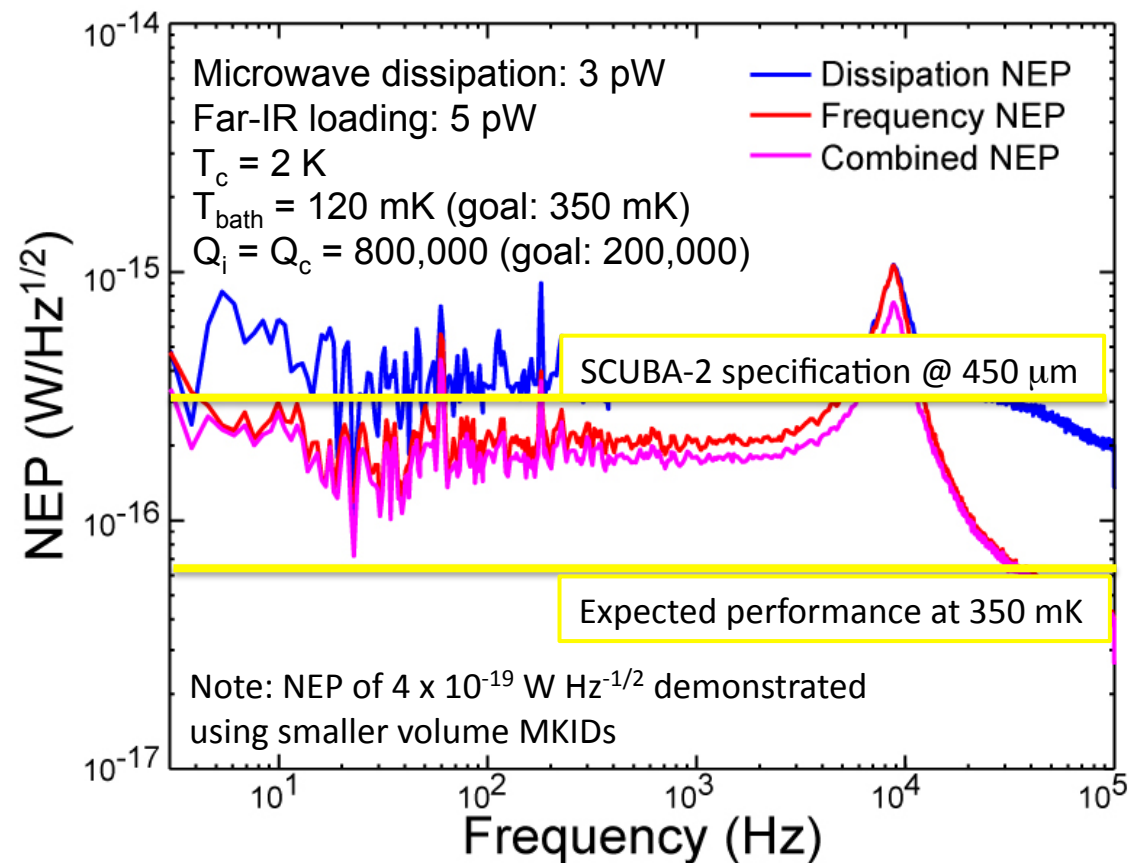
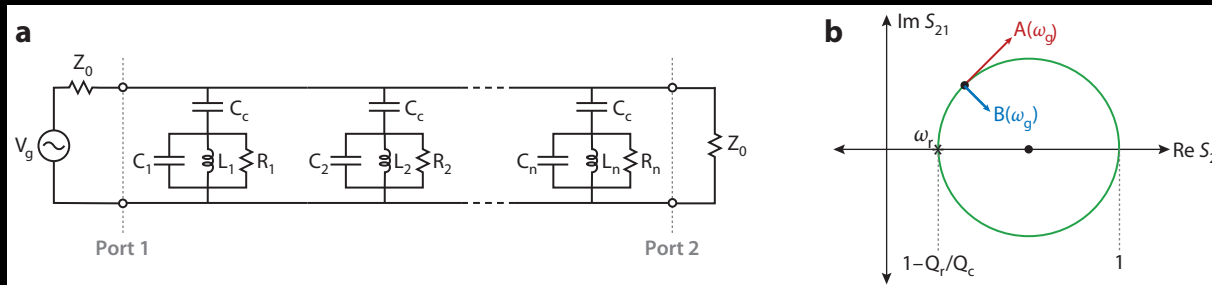
Cost is the overriding issue

- SHARC 1 (1995)
 - \$1M / 20 detectors = \$50k/detector
- SHARC 2 (2000)
 - \$2M / 400 detectors = \$5k/detector
- SCUBA 2 (2010)
 - \$30M / 10k detectors = \$3k/detector
- CCAT goal
 - \$10M / 1M detectors = \$10 / detector
- Keep it simple !

Frequency-multiplexed superconducting microresonator detectors (MKIDs)



Sensitivity

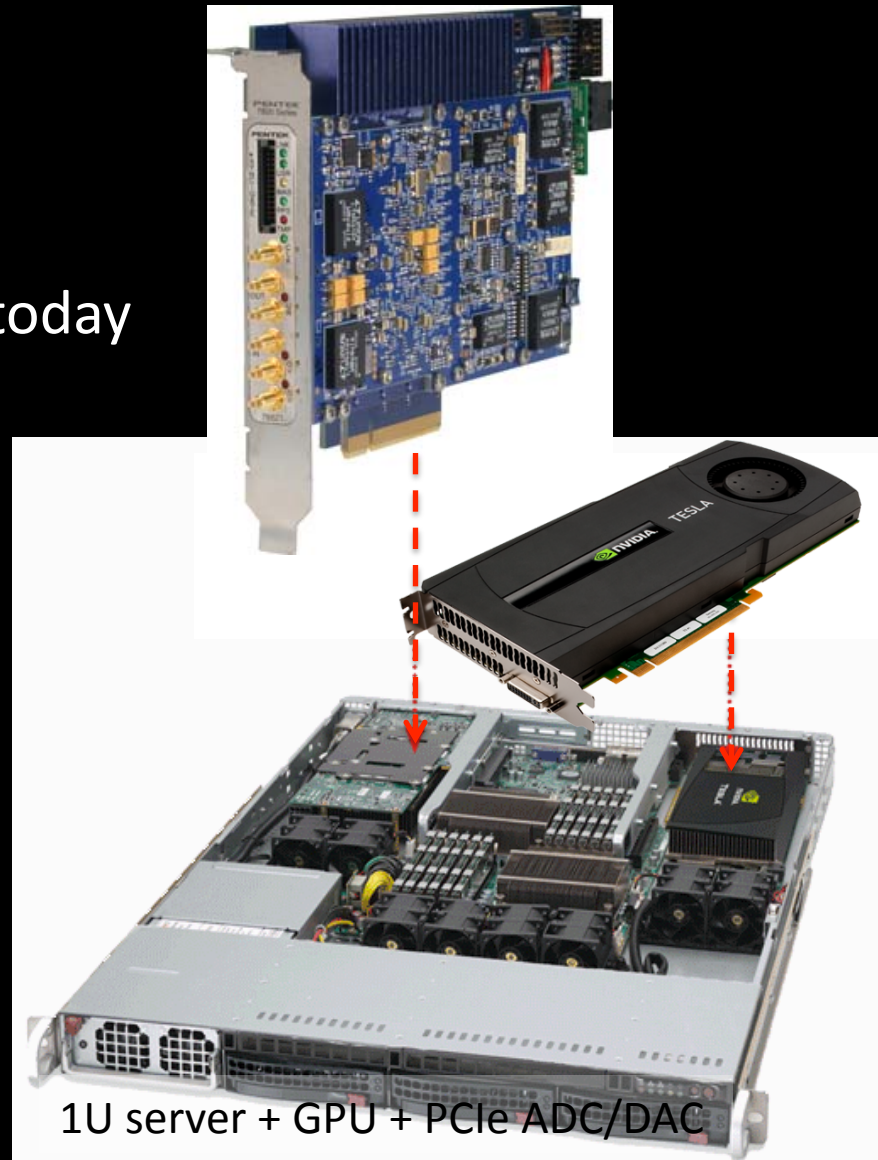
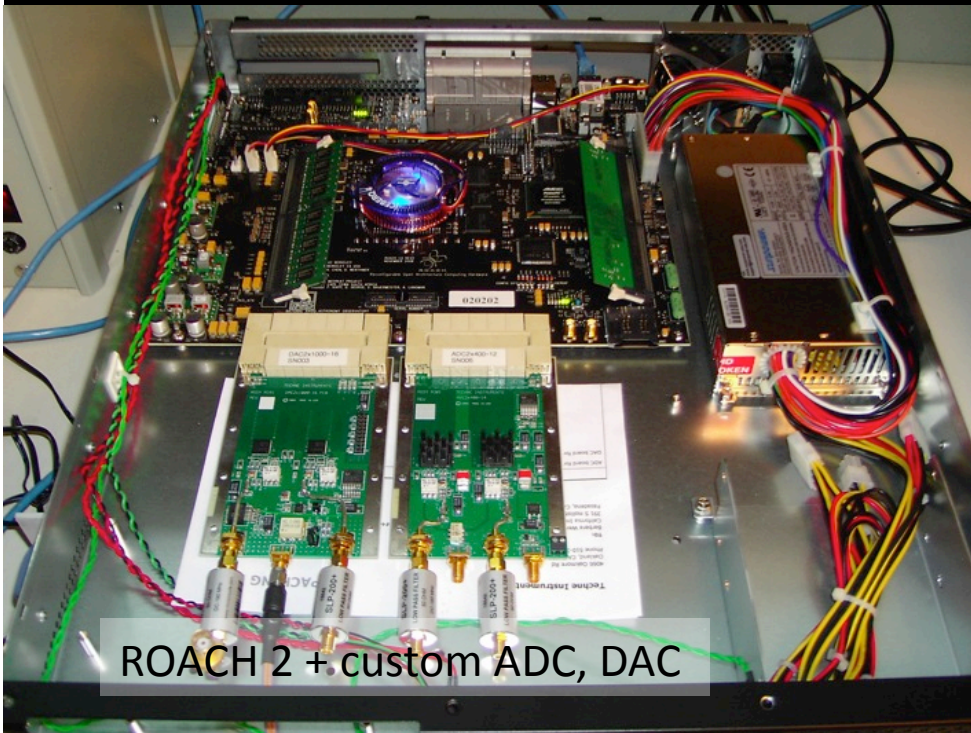


Readout Electronics

- Generate sum of sine waves
 - Store in waveform buffer RAM
 - Play out continuously to DAC
 - Send to array
- Digitize array output
 - 500 MSPS for 250 MHz bandwidth
- Calculate FFT to separate carriers
 - $N_{\text{FFT}} \sim 10 * (f / \Delta f) * Q$
 - Keep $\sim 10^3$ carrier channels, discard rest
 - Decimate to 100 – 200 Hz (complex) data rate
 - Stream to disk

Readout Cost

- Rough estimate
 - few 10^3 detectors per \$10k
 - < \$5 per detector achievable today

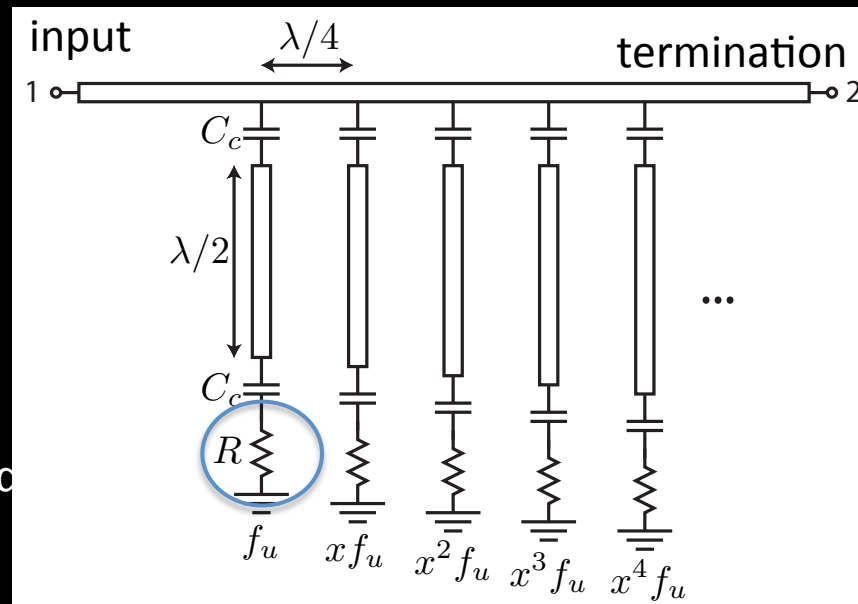


The figure illustrates the development of superconducting photonic filterbanks through several stages:

- 1998: Tapped delay line correlation spectrometer** - A schematic diagram showing an input signal being distributed through a series of delay lines (D) to a correlator, with a note on increasing delay.
- 1997: "Pizza" spectrometer** - A diagram of a spectrometer based on a 1970s design, showing a curved lens and a path length increment for curved lens input.
- 1999: Superconducting microstrip loss test chip** - A micrograph of a test chip showing a slot antenna, junctions, a choke, and a microstrip stub, with a 3.1 mm scale bar.
- 2003: WaFIRS / ZSpec** - A 3D schematic of the instrument, showing a 0.6 m long structure with radiating horns, parallel plates, and a grating.
- 2011: Bradford et al** - A spectral plot of the galaxy APM 08279+5255 at redshift z=3.91, showing flux density versus frequency (GHz) and rest wavelength (μm). The plot includes various CO and H₂O lines, a continuum & CO subtracted spectrum, and a diagram of the receiving horns and bolometer array.

Superconducting mm-wave spectrometer, revisited

(G. Rebeiz: cochlea-inspired channelizing filter)



$$A_{\text{total}} < 1 \text{ cm}^2 \text{ for } R = 700, \lambda = 1 \text{ mm}$$

Will enable MOS/MBS with $N \sim 10^3$.

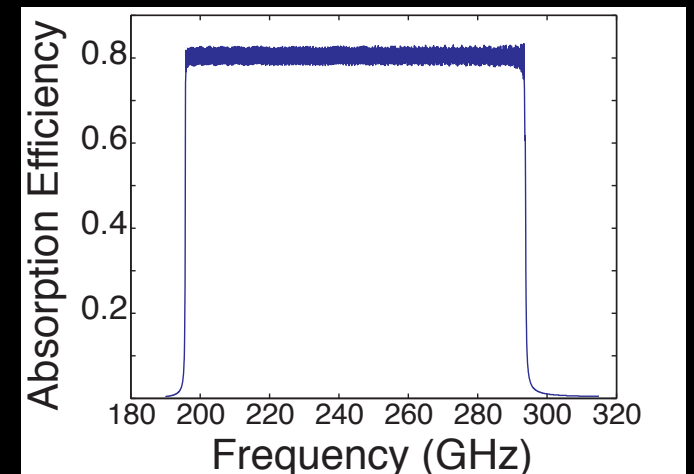
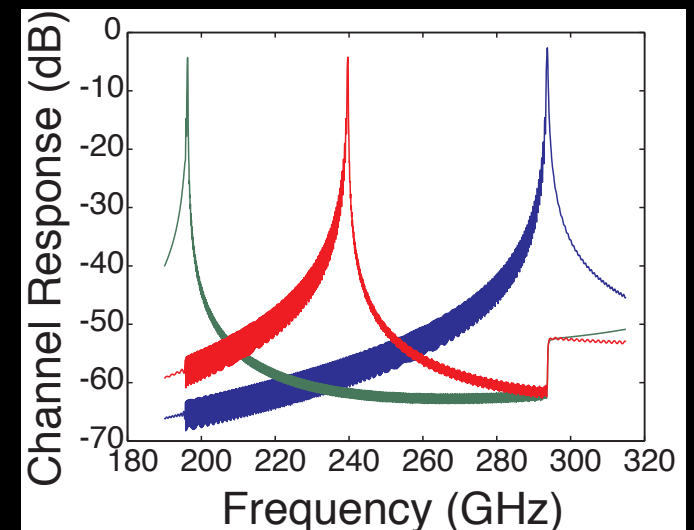
Science: see Visbal & Loeb 2010, 2011;
also Gong, Cooray et al 2011

A. Kovacs & J. Zmuidzinas, 2010

SuperSpec: + P. Barry, M. Bradford, G.

Chattopadhyay, N. Llombart, H. G. LeDuc, D.

Marrone, P. Mauskopf, S. Padin, E. Shirokoff

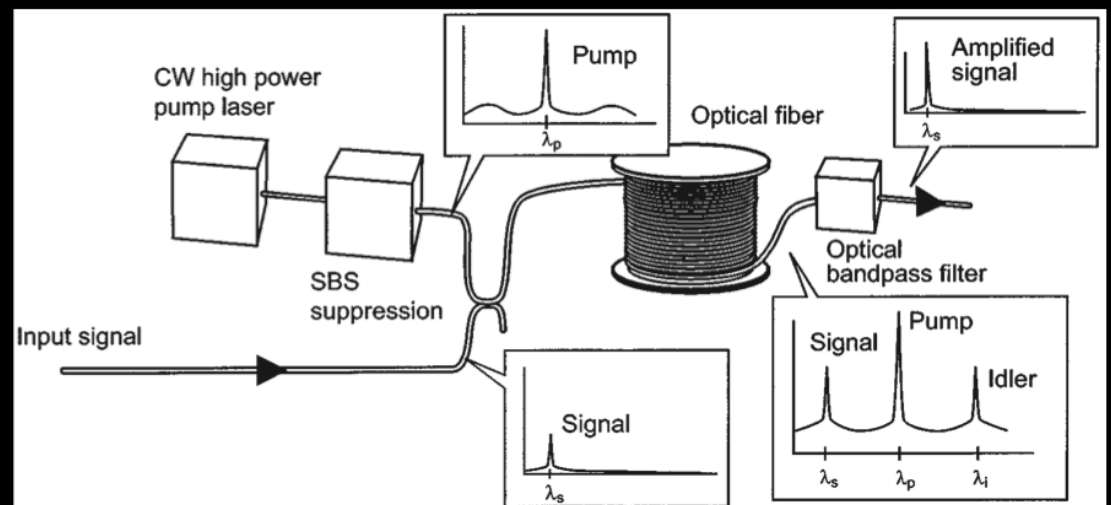
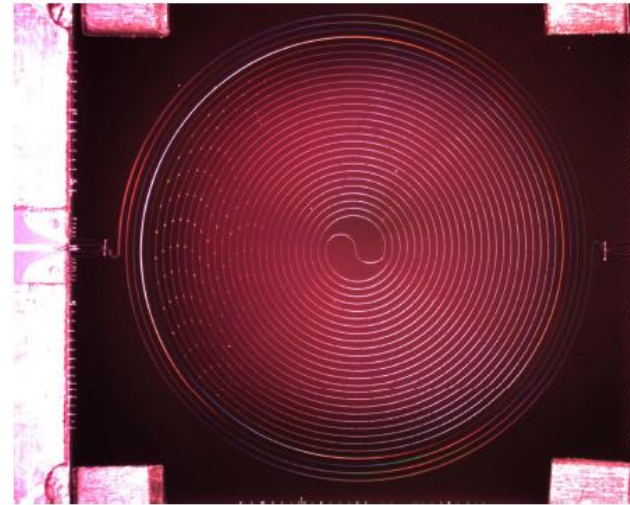
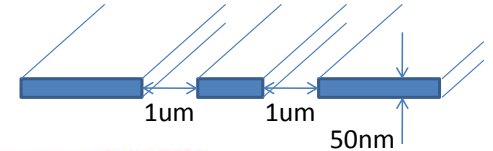


Also: DESHIMA/SRON, A. Endo et al.

Traveling-wave KI Amplifier

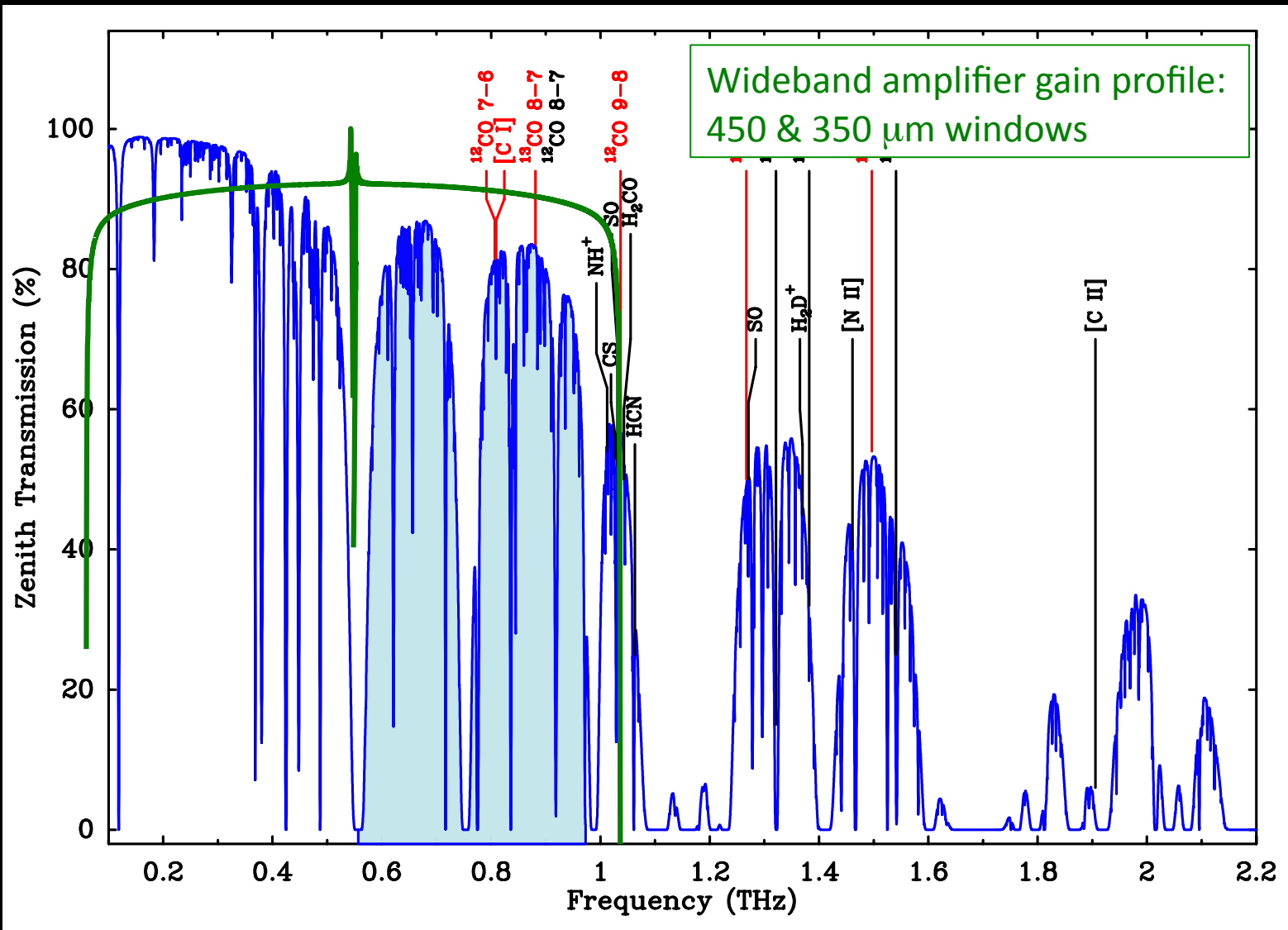
- Amplify 350 and 450 μm windows simultaneously
- Requires ~ 1 mW pump at 500 GHz
- Quantum-limited noise predicted
 - J. R. Tucker & D. F. Walls 1969, Phys. Rev. 178, 2036
 - Measured losses are extremely low ($Q \sim 10^7$)
- Area ~ 1 mm² for 600-900 GHz device
- Use wideband Schottky mixers for downconversion
- Microwave prototype producing 10 dB gain

- 0.8 m NbTiN CPW line



Ultra-wideband coherent receivers

(Atmosphere: Marrone et al 2005, 93 μm PWV)



Summary

- Superconducting devices under development will enable:
 - Megapixel submm cameras
 - “3D” spectroscopic imagers: 1000 x Zspec++
 - Coherent submm receivers with 200+ GHz instantaneous bandwidth
- Enabled by the amazing properties of superconducting nitrides (TiN, NbTiN, ...)
- *The fun is just beginning !*

Credits

- Pete Barry
- Matt Bradford
- Goutam Chattopadhyay
- Saptarshi Chaudhuri
- Peter Day
- Ran Duan
- Darren Dowell
- Byeong Ho Eom
- Jiansong Gao
- Sunil Golwala
- Matt Hollister
- Warren Holmes
- Attila Kovacs
- Rick Leduc
- James Lamb
- Nuria Llombart
- Phil Mausokopf
- Ben Mazin
- Chris McKenney
- David Moore
- Tony Mrockowski
- Omid Noroozian
- Hien Nguyen
- Steve Padin
- Keith Schwab
- Erik Shirokoff
- Loren Swenson
- Rebecca Wernis
- Emma Wollman
- David Woody



For more detail:

(Annual Reviews of Condensed Matter Physics, 2011)

Superconducting Microresonators: Physics and Applications

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Astronomy, 301-17, Pasadena CA 91125*

Key Words Superconductivity, microwaves, resonators, superconducting detectors, two-level systems

Abstract Interest in superconducting microresonators has grown dramatically over the past decade. Resonator performance has improved by several orders of magnitude through the use of improved geometries and materials as well as a better understanding of the underlying physics. These advances have led to the adoption of superconducting microresonators in a large number of low-temperature experiments and applications. This review outlines these developments, with particular attention given to the use of superconducting microresonators as detectors.