Submillimeter Astronomy: What Happens Next ?

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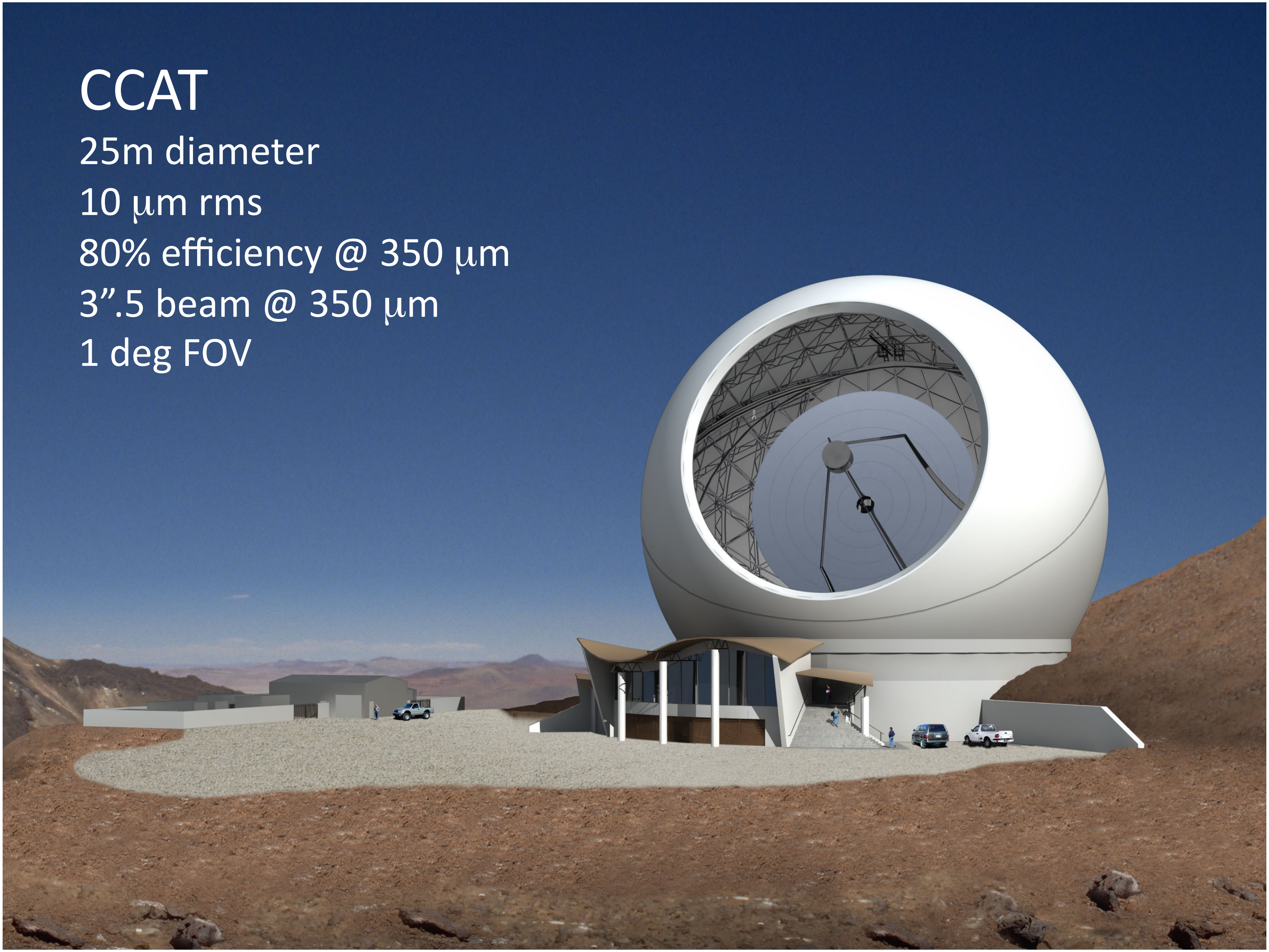
A brief history

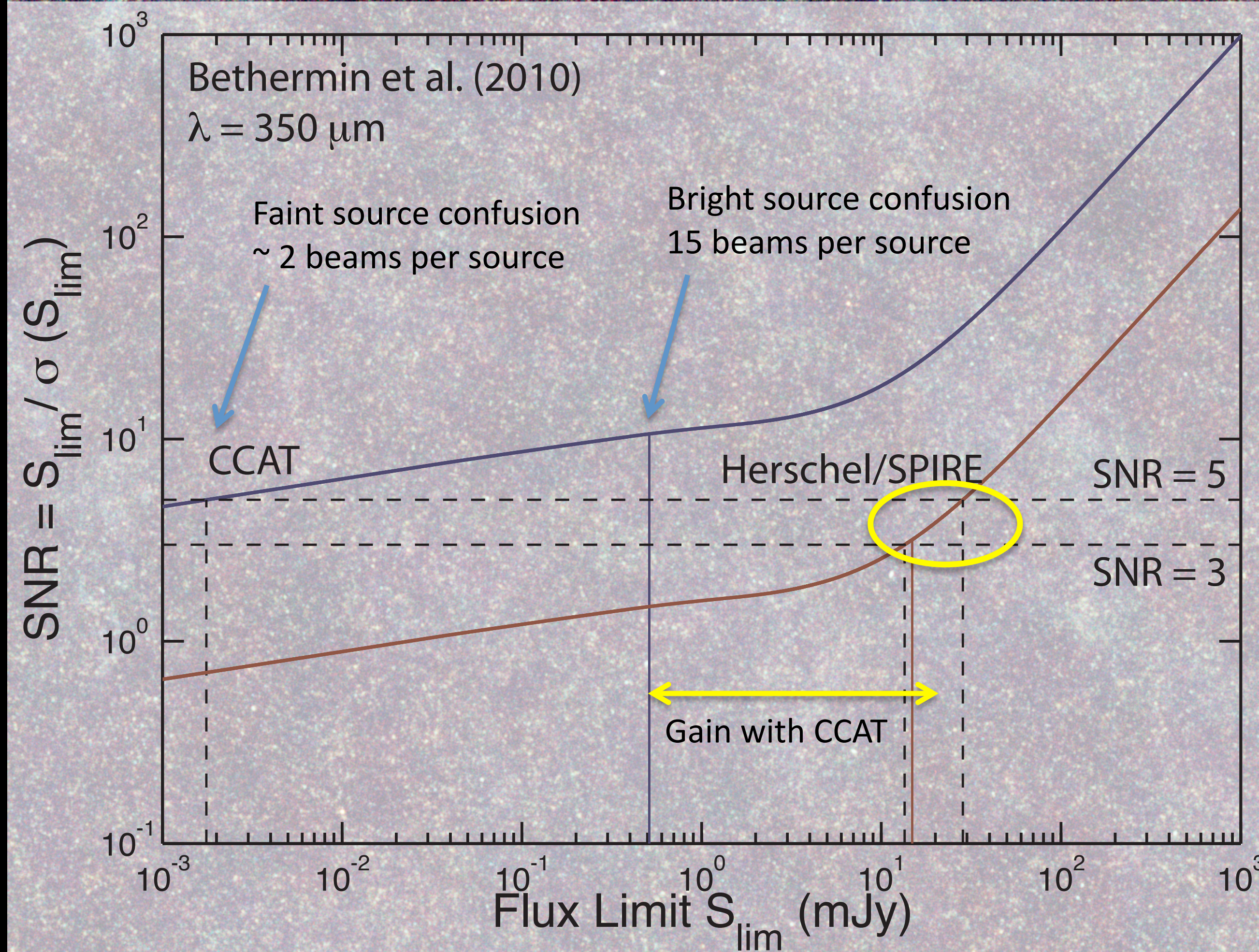
- 1960: Frank Low develops cooled semiconductor (Ge) bolometer
  - Improved over next 40 years
  - Leads to COBE, SCUBA, Planck HFI, SPIRE…
- 1970: Wilson, Jefferts & Penzias detect CO(1-0)
  - 115 GHz Schottky diode heterodyne receiver
  - Extended x40 to 4744 GHz (O I @ 63 μm; Betz) by 1995
- 1979: 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- 2000: Semiconductor bolometers superceded by multiplexed superconducting arrays (e.g. SCUBA 2)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 ~ 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

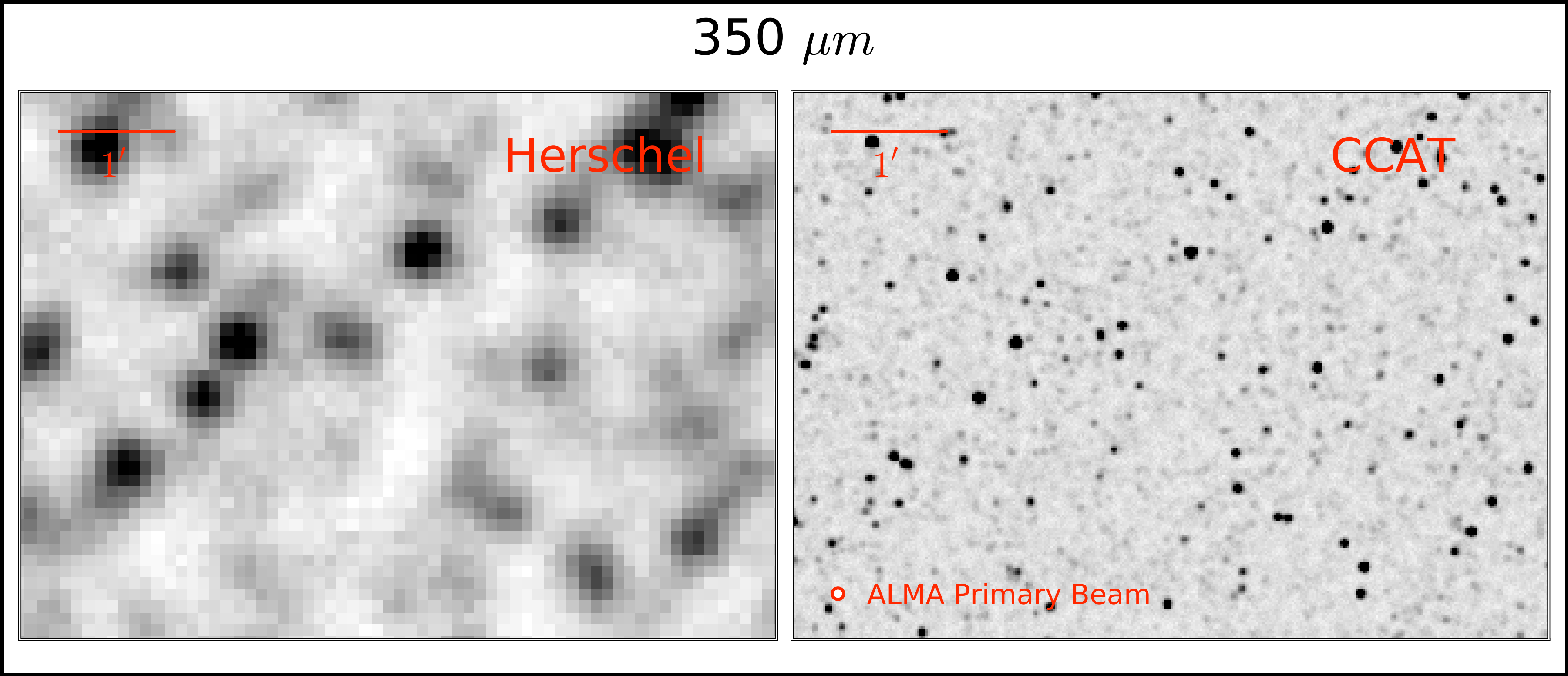

CCAT
25m diameter
10 μm rms
80% efficiency @ 350 μm
3".5 beam @ 350 μm
1 deg FOV

Confusion



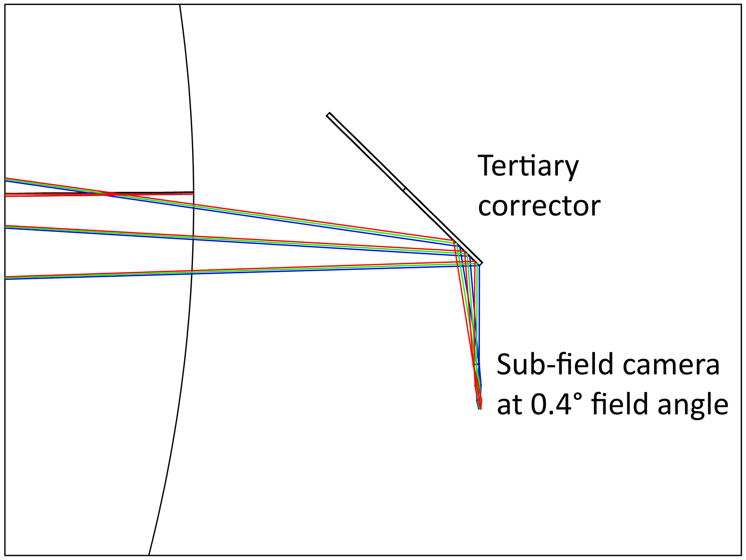
Herschel ATLAS SDP

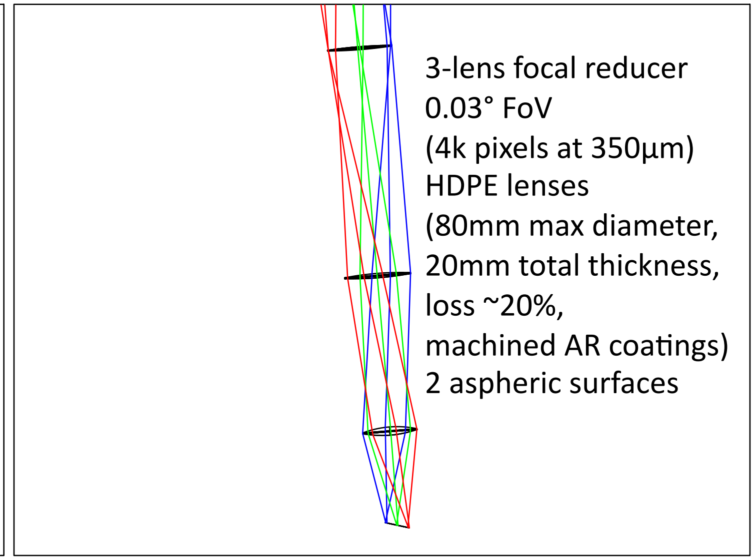
CCAT vs Herschel

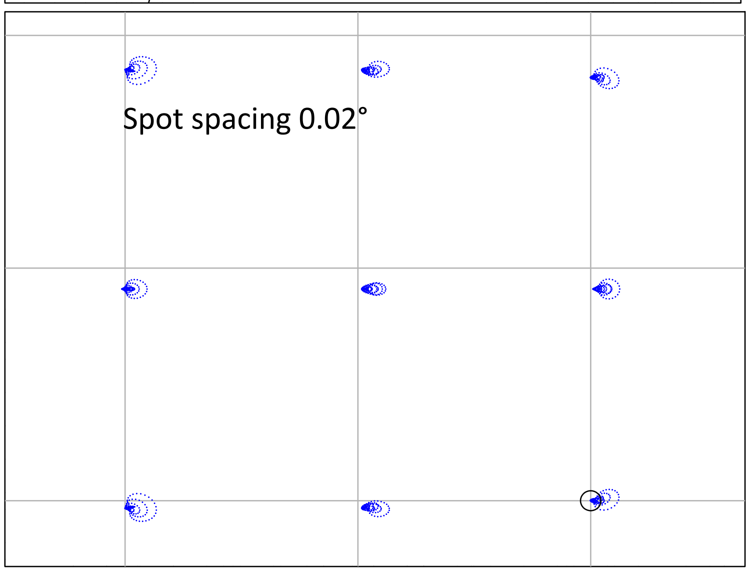


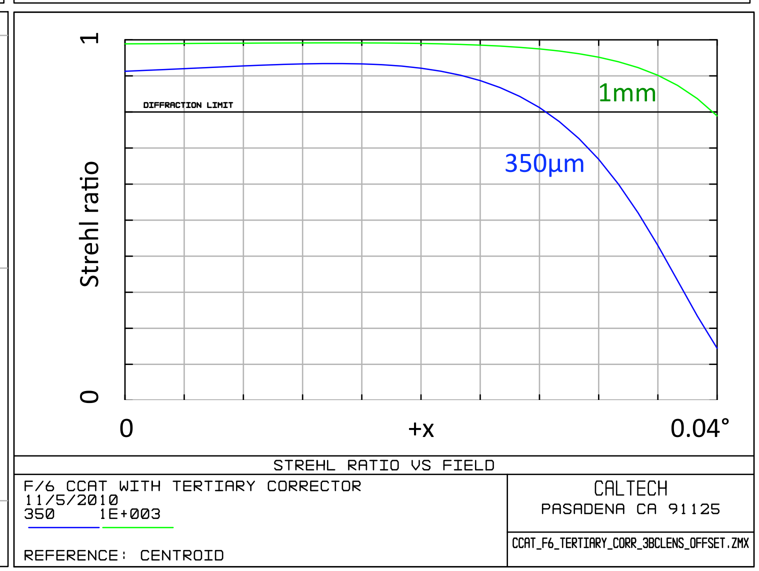
Credit: J. Glenn/U. Colorado

Camera relay with small HDPE lenses







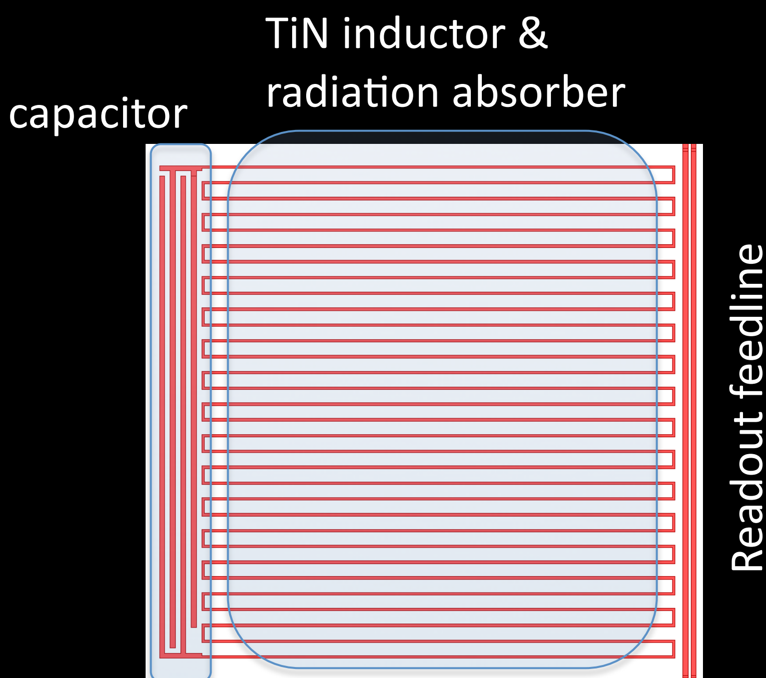


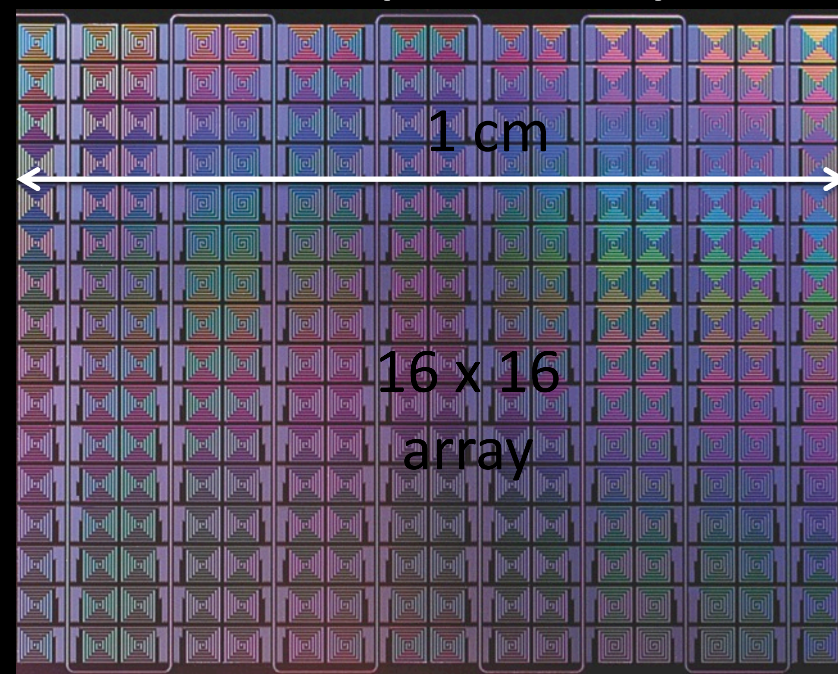
Credit: S. Padin

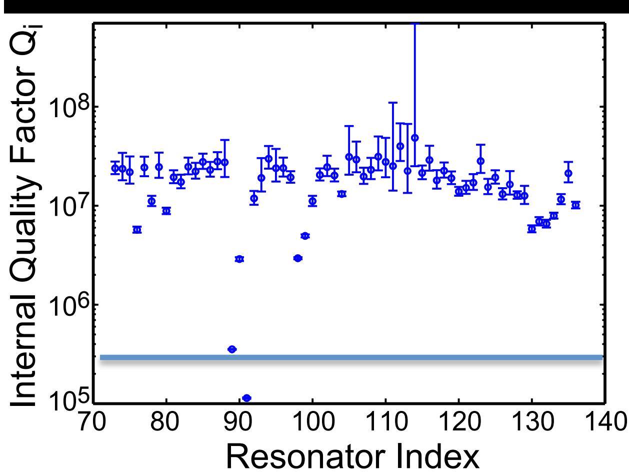
Cost is the overriding issue

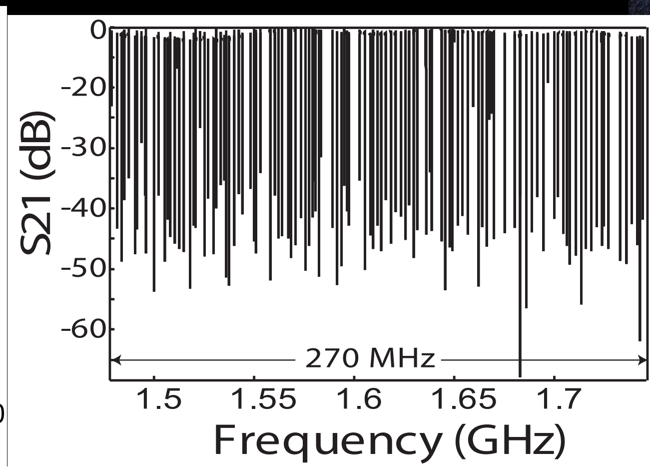
- SHARC 1 (1995)
  - $1M / 20 detectors = $50k/detector
- SHARC 2 (2000)
  - $2M / 400 detectors = $5k/detector
- SCUBA 2 (2010)
  - $30M / 10k detectors = $3k/detector
- CCAT goal
  - $10M / 1M detectors = $10 / detector
- Keep it simple !

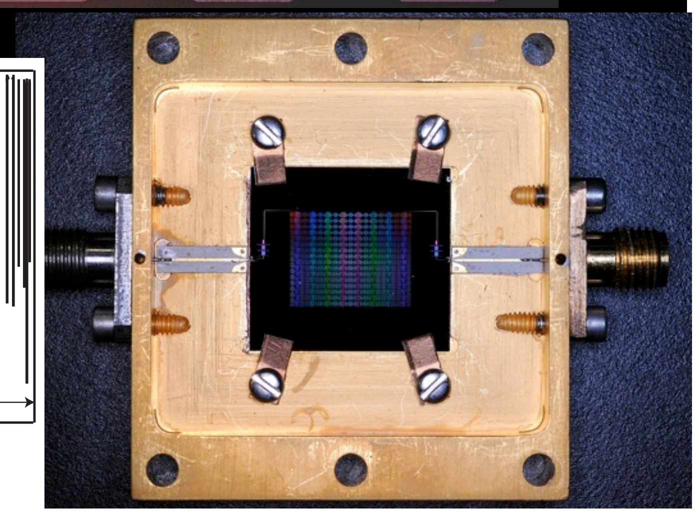
Frequency-multiplexed superconducting microresonator detectors (MKIDs)



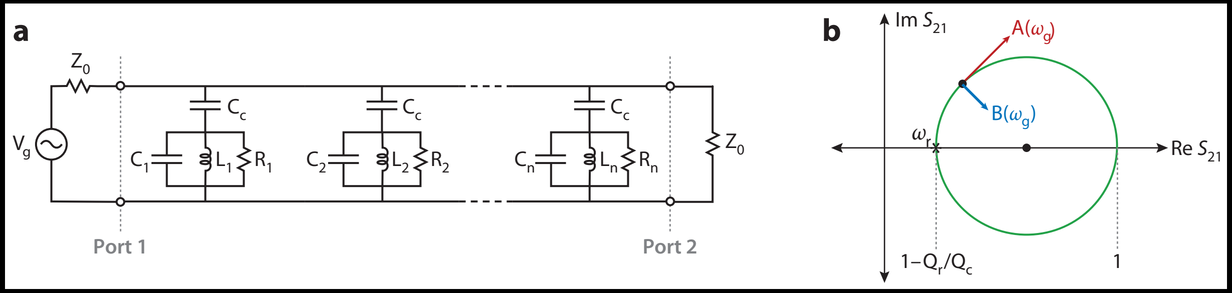


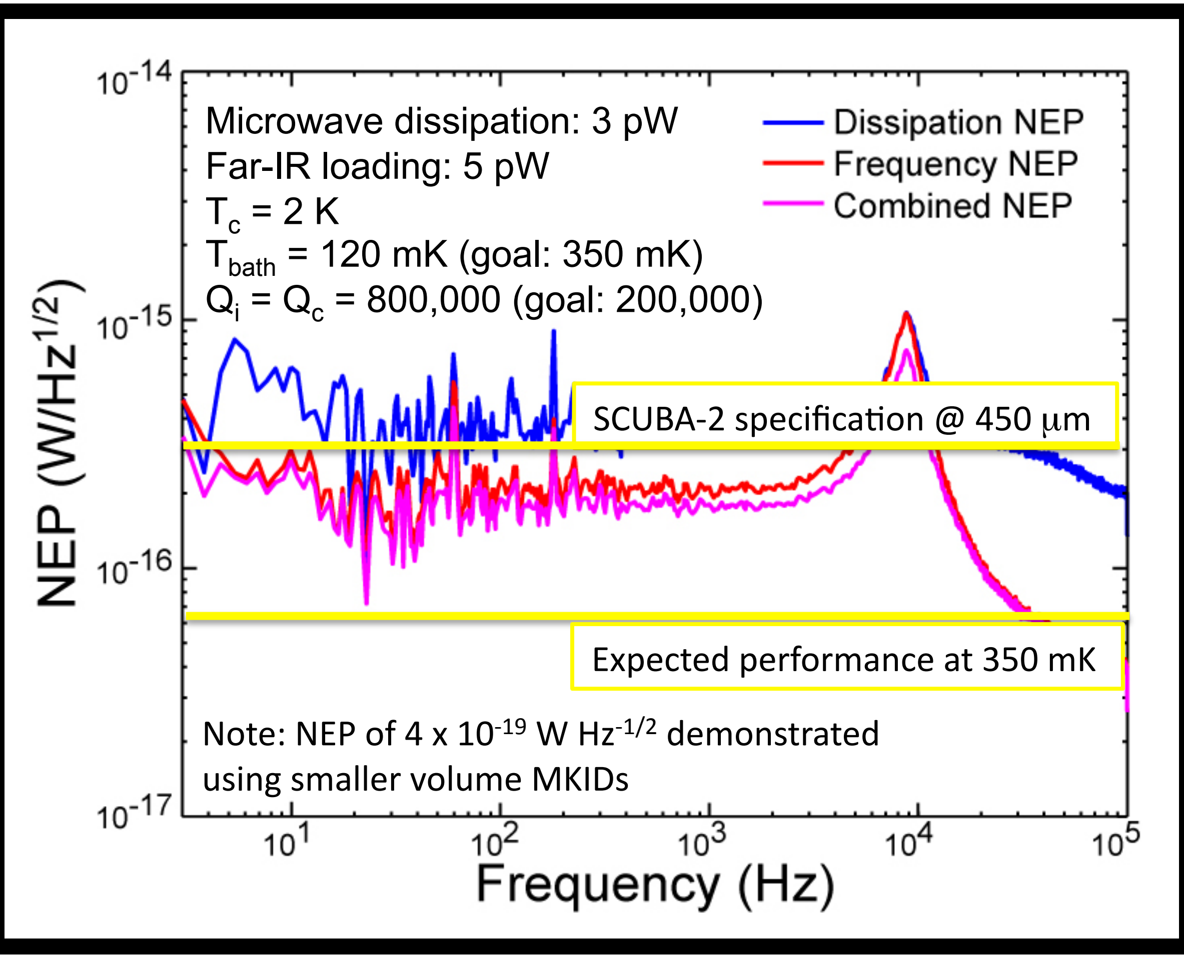






Sensitivity



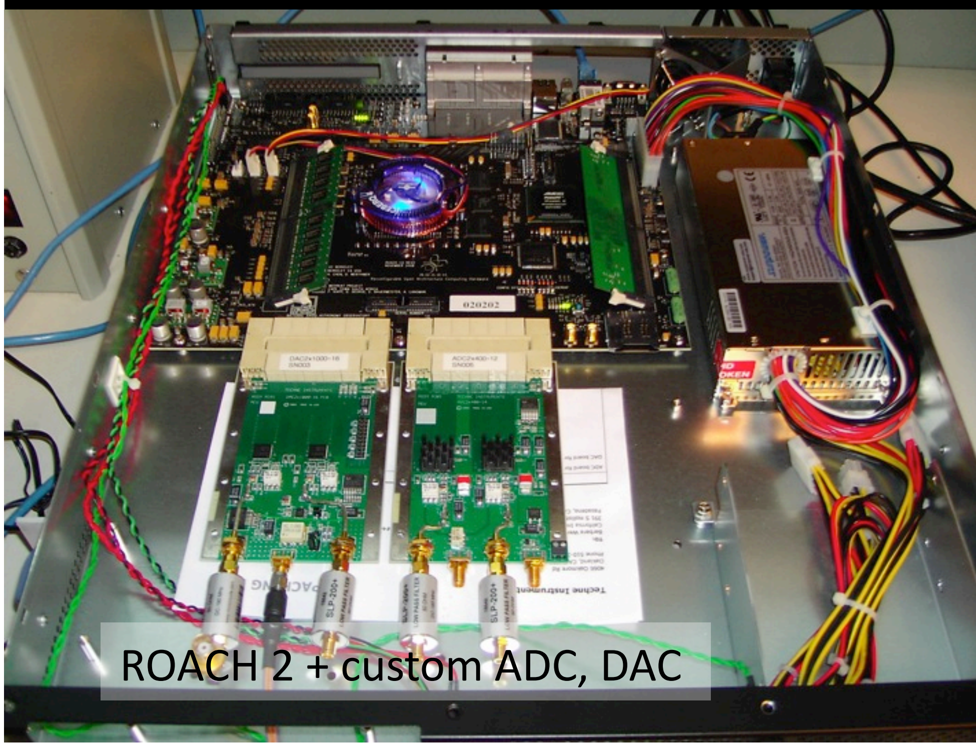


Readout Electronics

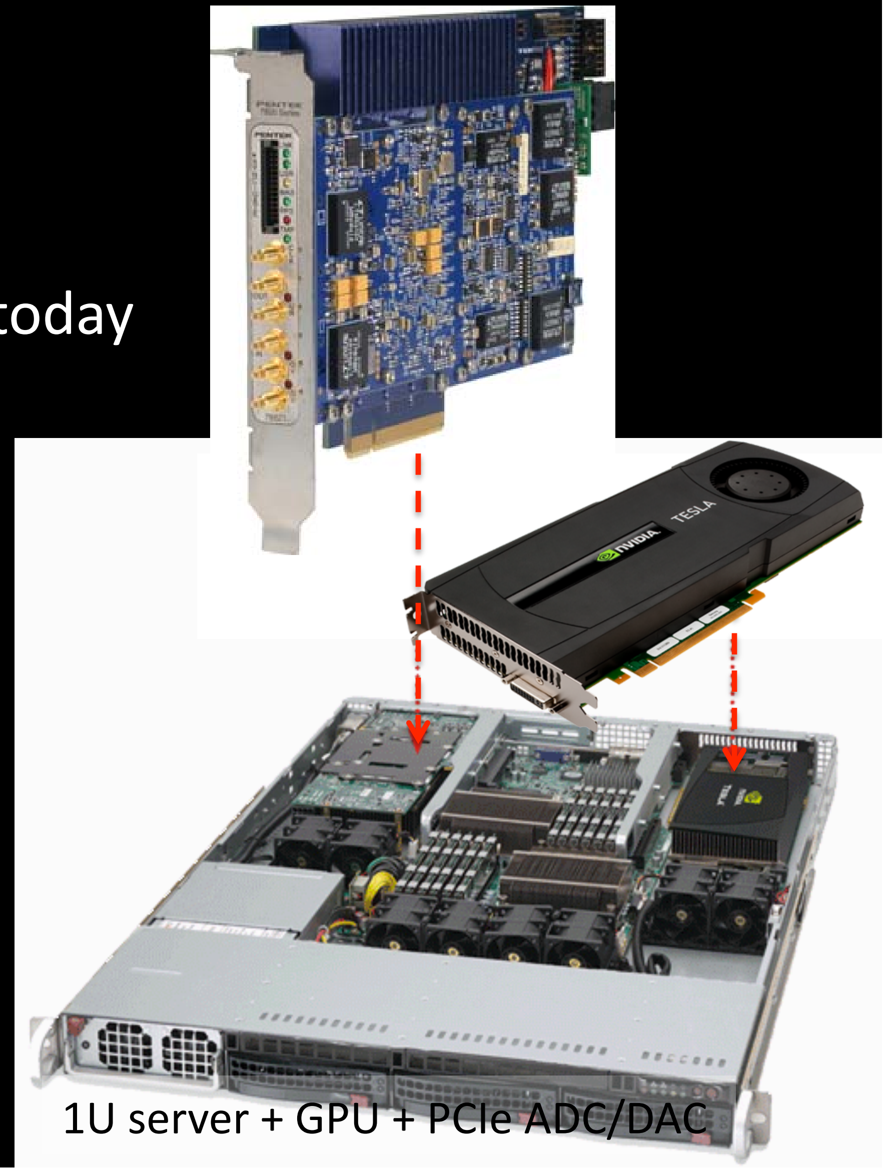
- Generate sum of sine waves
  - Store in waveform buffer RAM
  - Play out continuously to DAC
  - Send to array
- Digitize array output
  - 500 MSPS for 250 MHz bandwidth
- Calculate FFT to separate carriers
  - $N_{FFT} \sim 10 * (f / \Delta f) * Q$
  - Keep ~10^3 carrier channels, discard rest
  -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

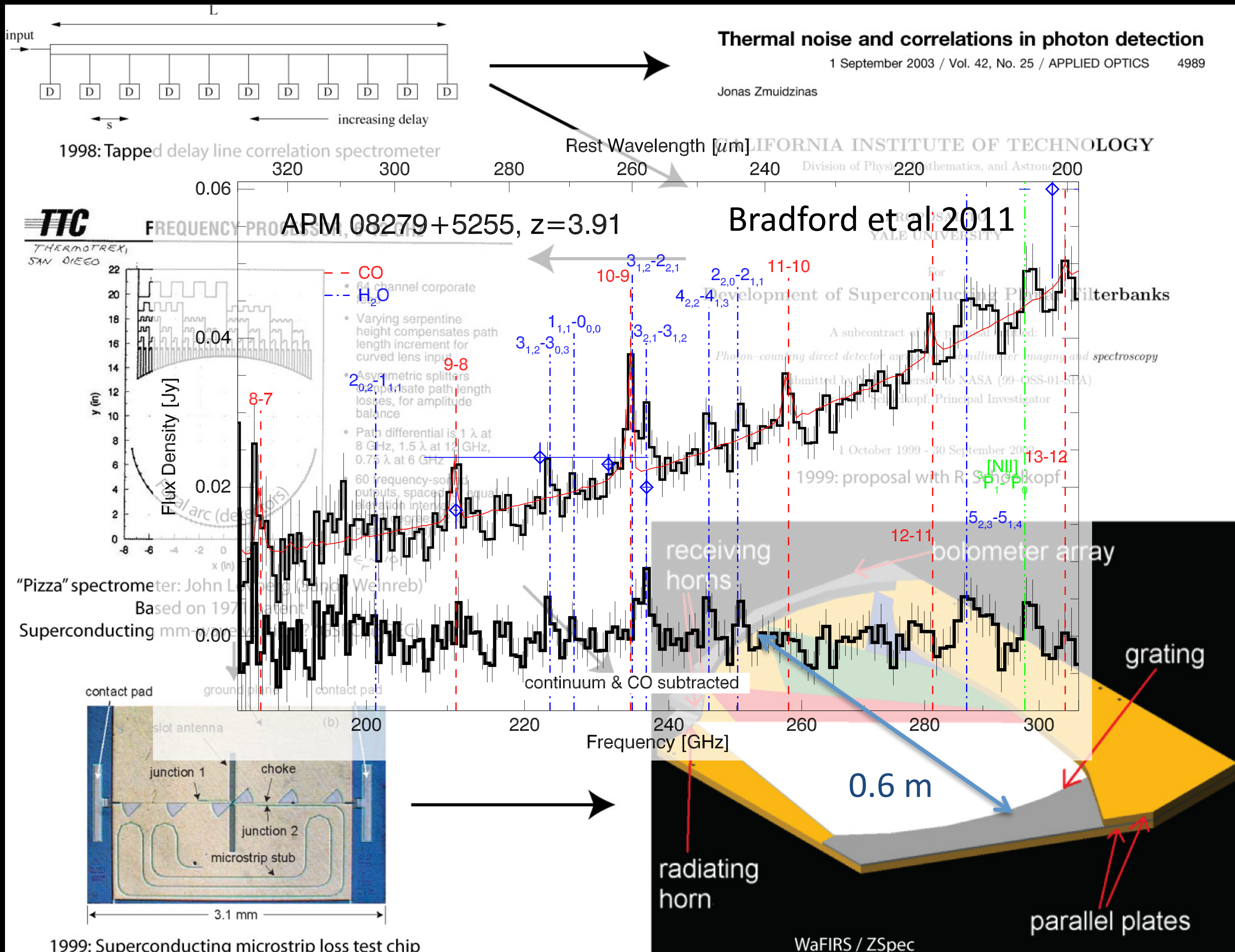


ROACH 2 + custom ADC, DAC

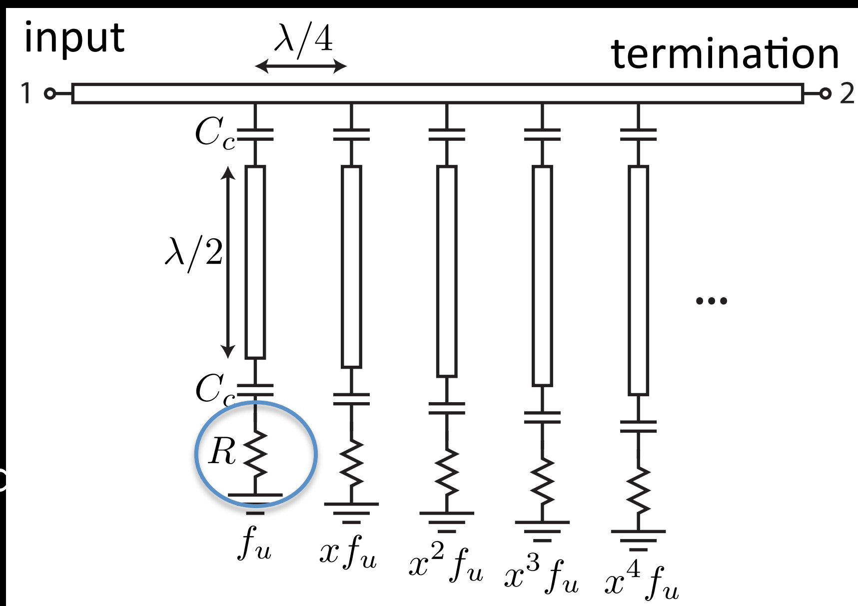


1U server + GPU + PCIe ADC/DAC

Evolution of the Z-spec concept



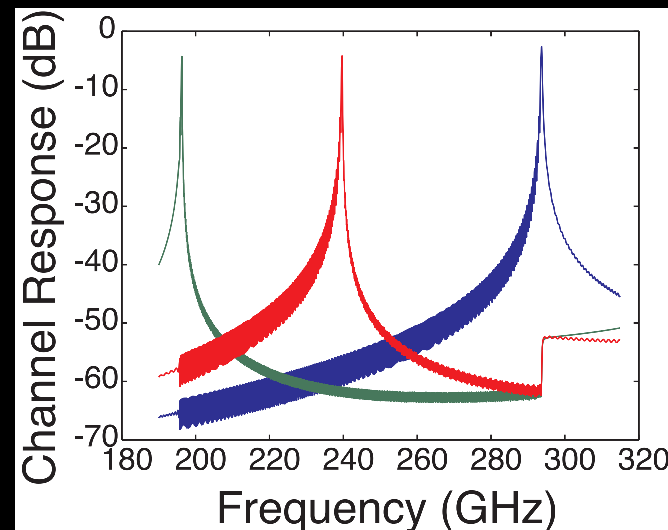
Superconducting mm-wave spectrometer, revisited
(G. Rebeiz: cochlea-inspired channelizing filter)

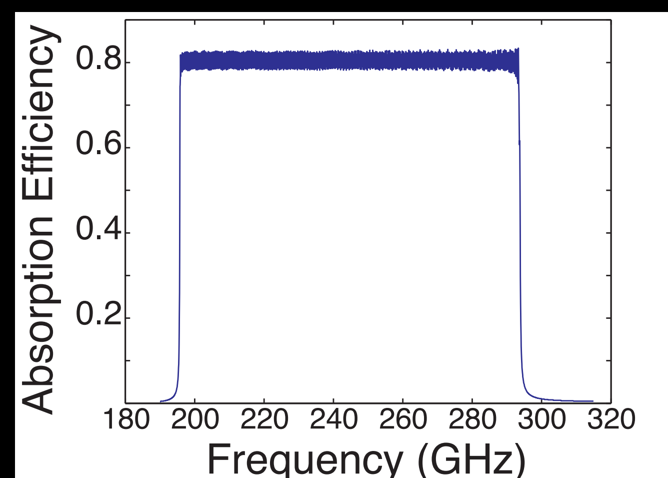


$$A_{\text{total}} < 1\ \text{cm}^2 \ \text{for}\ R = 700,\ \lambda = 1\ \text{mm}$$

Will enable MOS/MBS with N~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



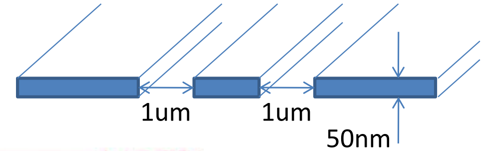


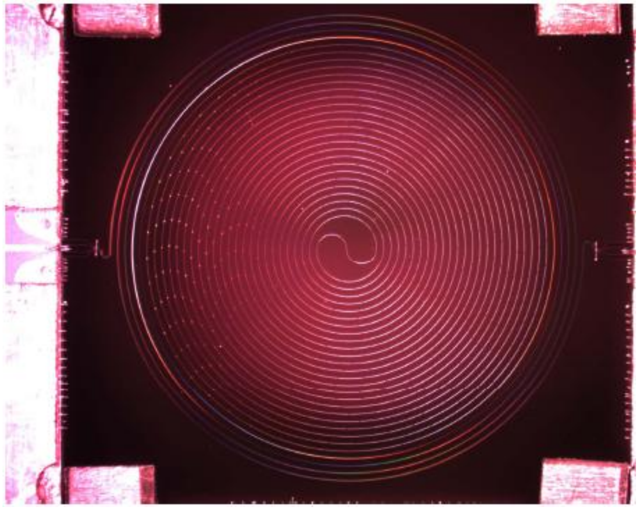
Also: DESHIMA/SRON, A. Endo et al.

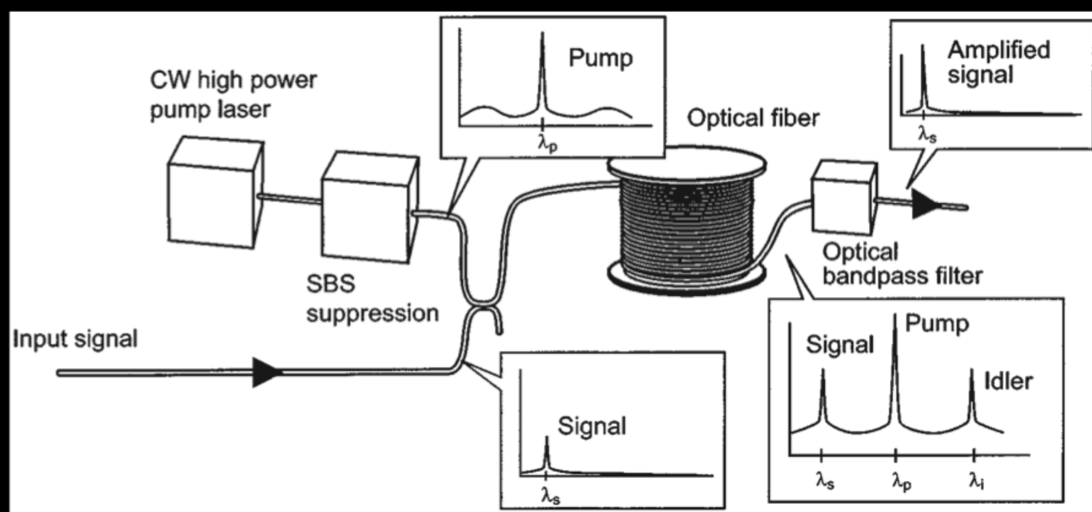
Traveling-wave KI Amplifier

- 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 mm^2 for 600-900 GHz device
- Use wideband Schottky mixers for downconversion
- Microwave prototype producing 10 dB gain

- 0.8 m NbTiN CPW line



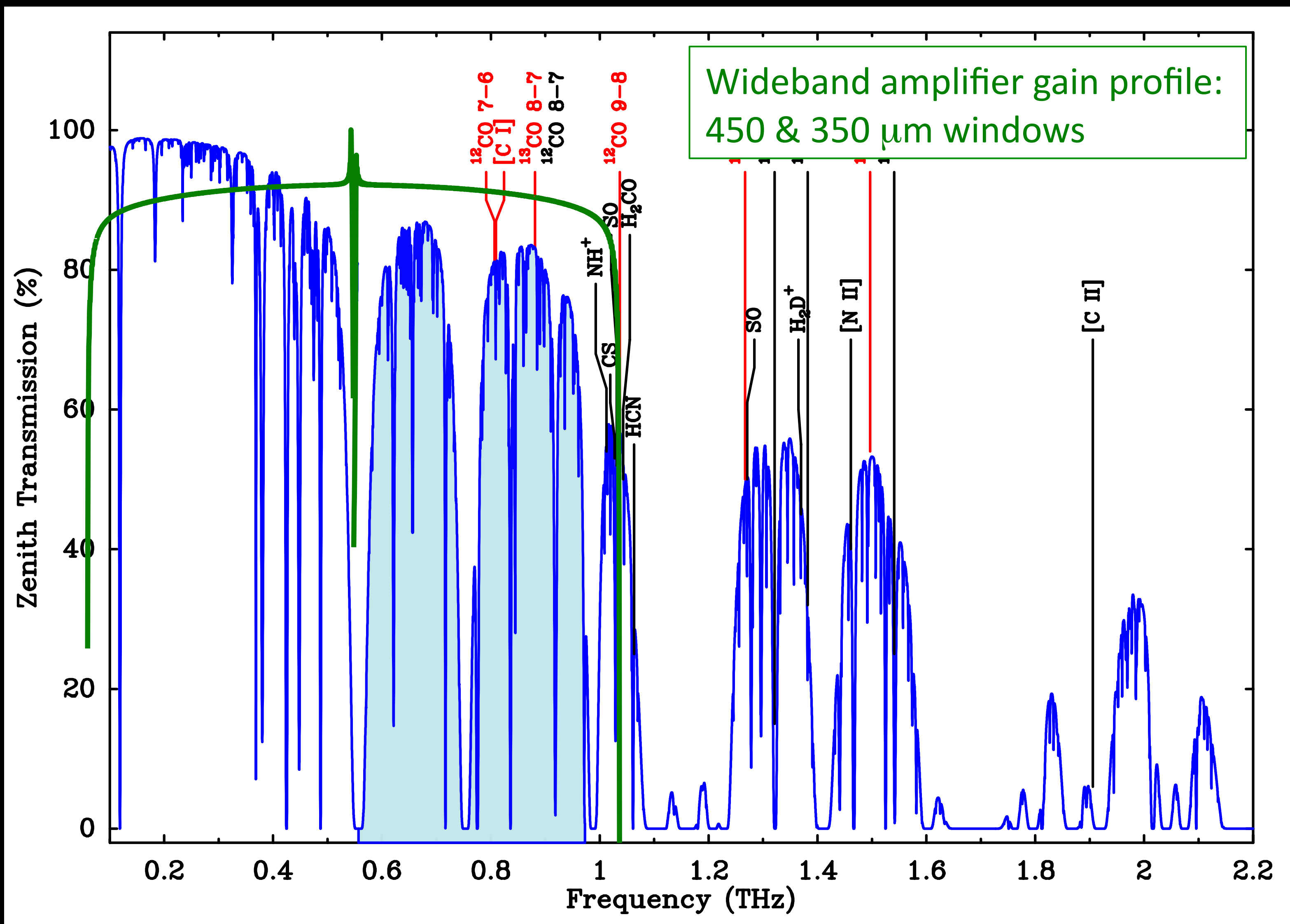




J. Zmuidzinas & P. K. Day, 2010

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

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For more detail:

(Annual Reviews of Condensed Matter Physics, 2011)

Superconducting Microresonators: Physics and Applications

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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.