Superconducting Direct Detectors

New Concepts

- A variety of new concepts are under development
  - Will enable new instrument architectures
- Superconducting components
  - Low-loss transmission lines
  - Narrow-beam planar antennas
  - High performance lithographic filters
- TES bolometers
  - Antenna coupled (NEP and optical coupling)
  - Absorber coupled (electrical NEP)
  - Leg-isolated and electron-phonon decoupled
  - Broadband "absorber-antenna" concept
- Kinetic inductance detectors
  - Powerful new approach for arrays (multiplexing)
  - Easily fabricated
  - Can substitute for bolometers

Discuss with P. Day or H. G. LeDuc

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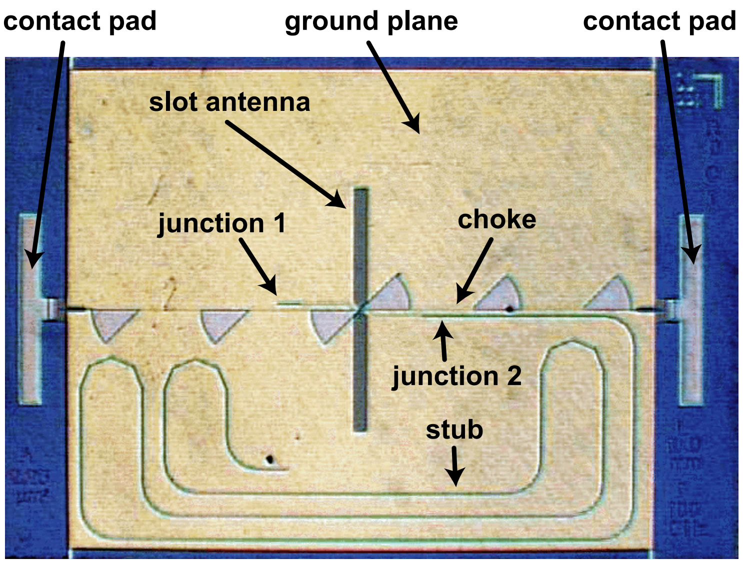
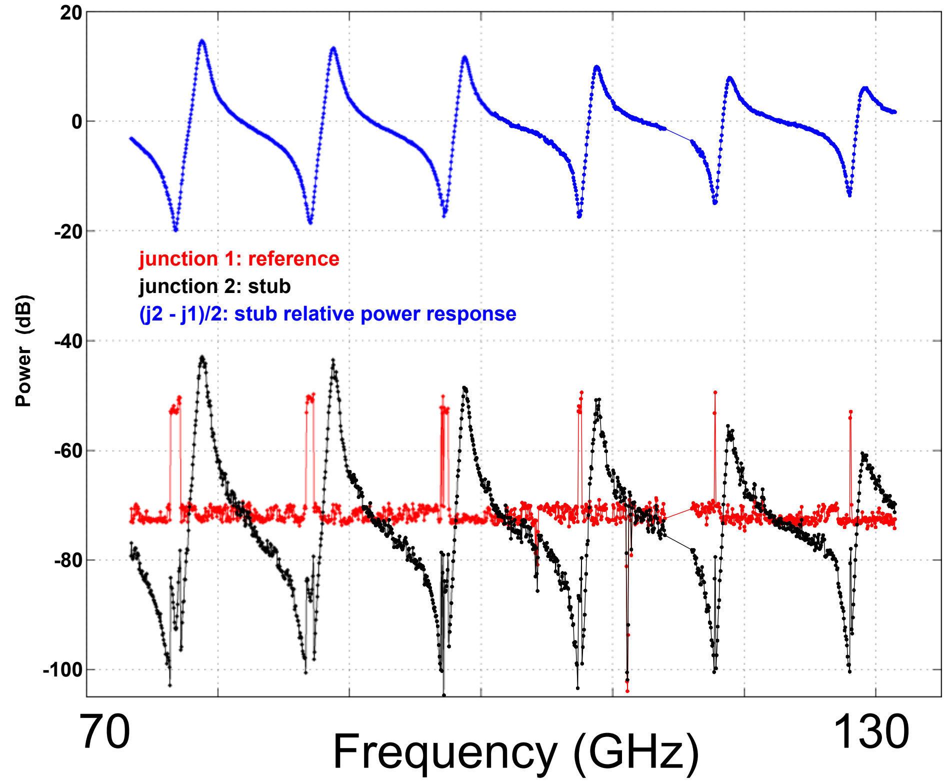
Superconducting Direct Detectors

Low-loss Superconducting Microstrip Lines



Test chip with 10 mm stub



- Loss is quite low
- 20 cm attenuation length (100 GHz)
- Loss continues to be low to at least 500 GHz (0.5% per wavelength)

phase velocity at 4.2 K	**0.3414 ± 0.0001**
phase velocity at 1.5 K	**0.3424 ± 0.0001**
power loss per wavelength at 4.2 K	**(1.95 ± 0.14) %**
power loss per wavelength at 1.5 K	**(0.55 ± 0.12) %**
Characteristic impedance (Ohm)	**10.7 ± 0.6**

A. Vayonakis et al.

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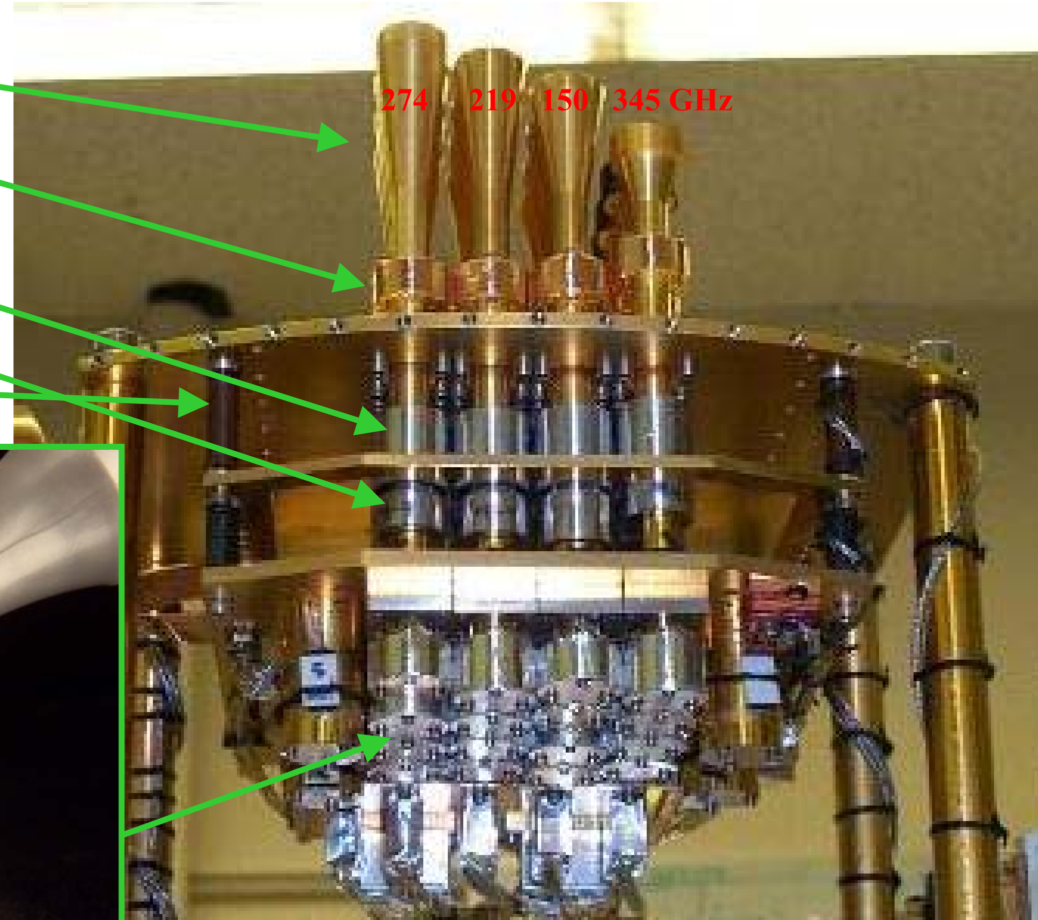
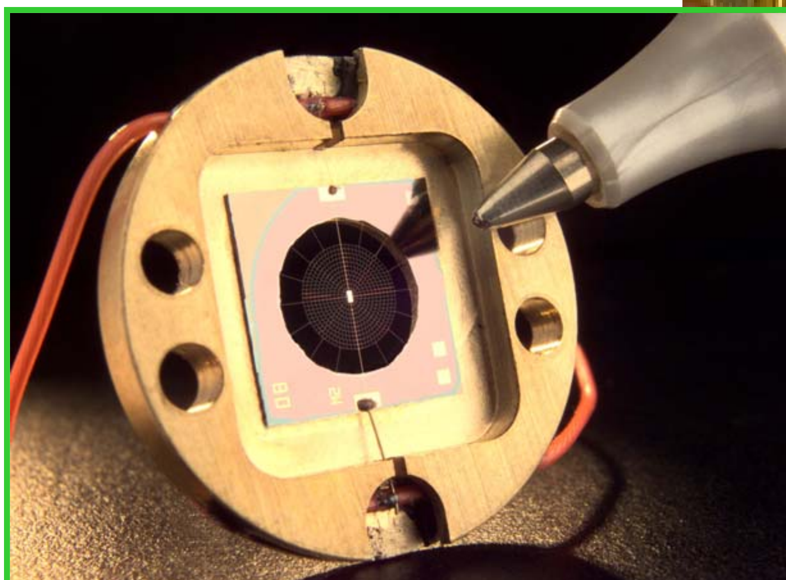
How to Build a Bigger Focal Plane?

Arcminute Cosmology Bolometer Array Receiver





Bolometers from JPL

Get rid of discrete feeds and filters!
Use antenna-coupled planar arrays

Source: J. Bock

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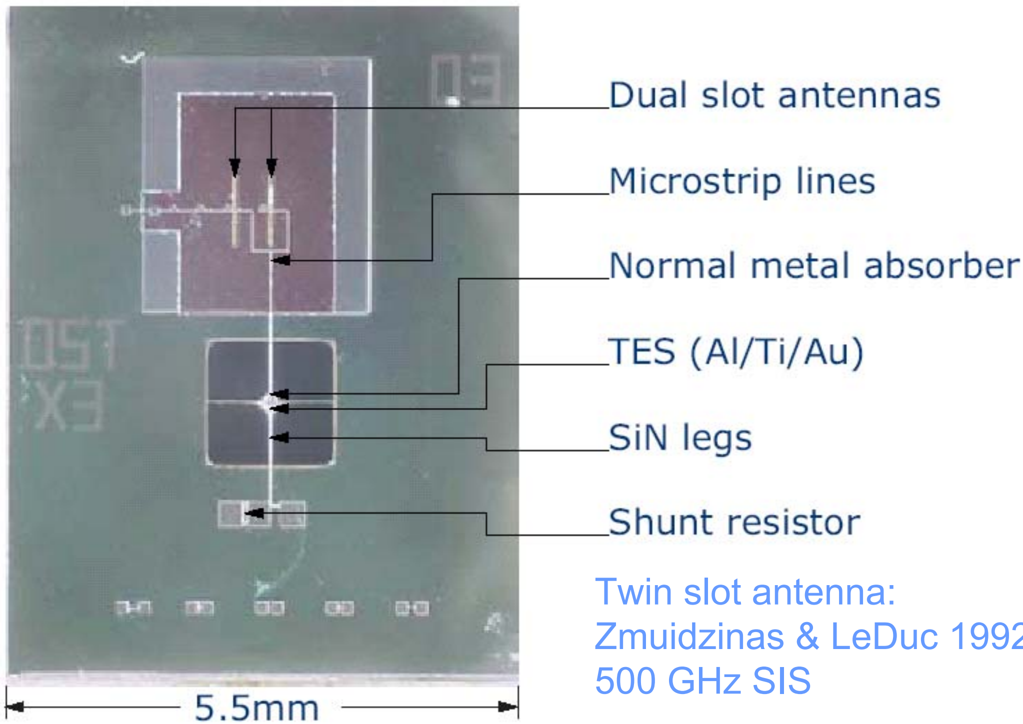
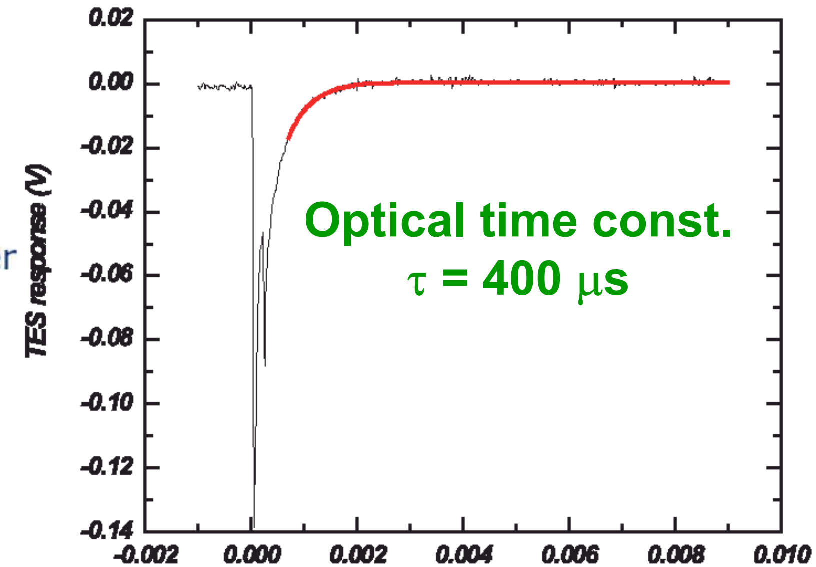
Demonstration of Antenna-Coupled TES

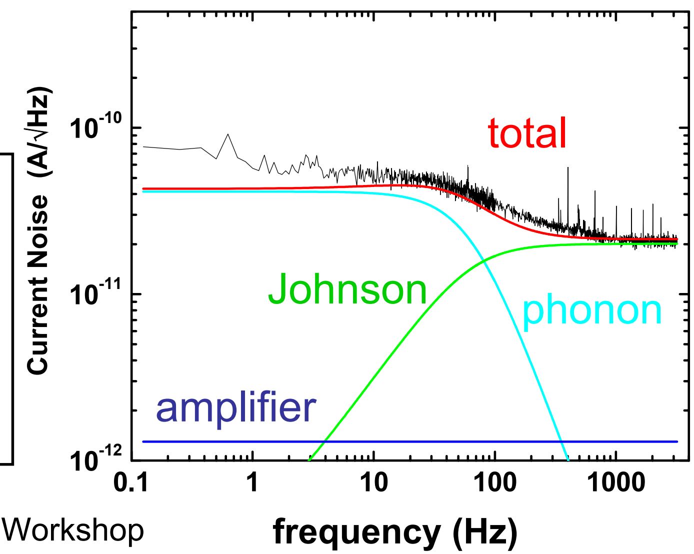




NOTE: twin-slot needs substrate lens

C. Hunt et al. (2003)

NEP = 1.8 e-17 W/√Hz
τ = 400 μs
NEP $\sqrt{\tau}$ = 4 e-19 J
T_0 = 300 mK
High optical efficiency



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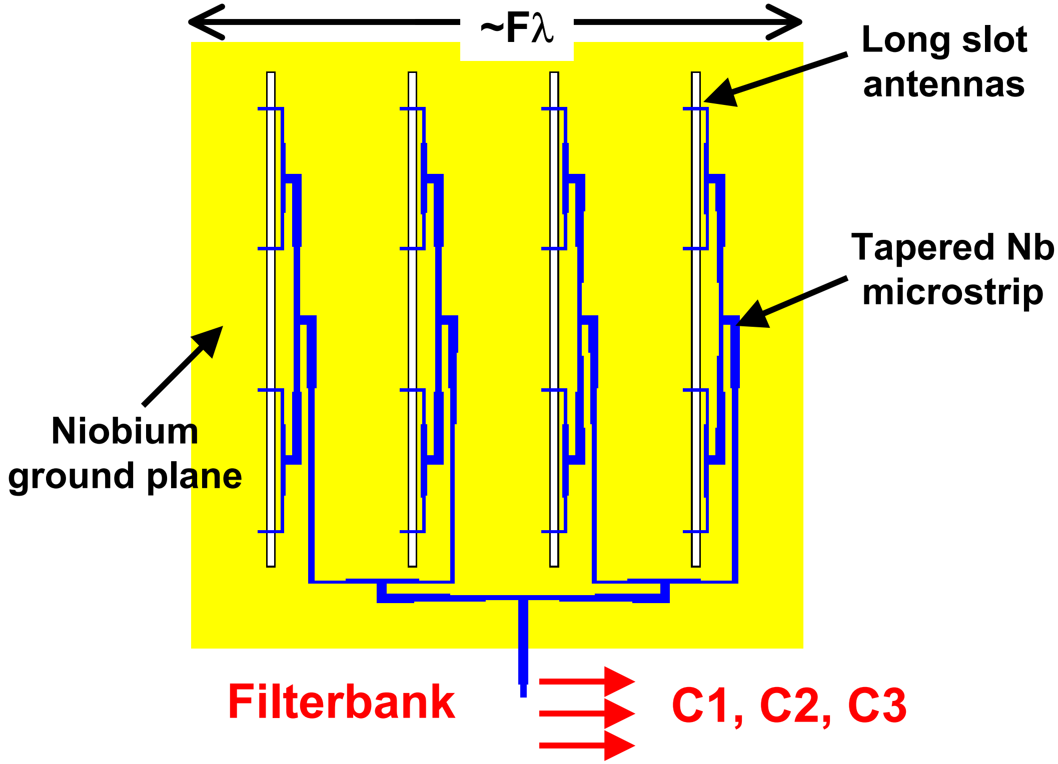
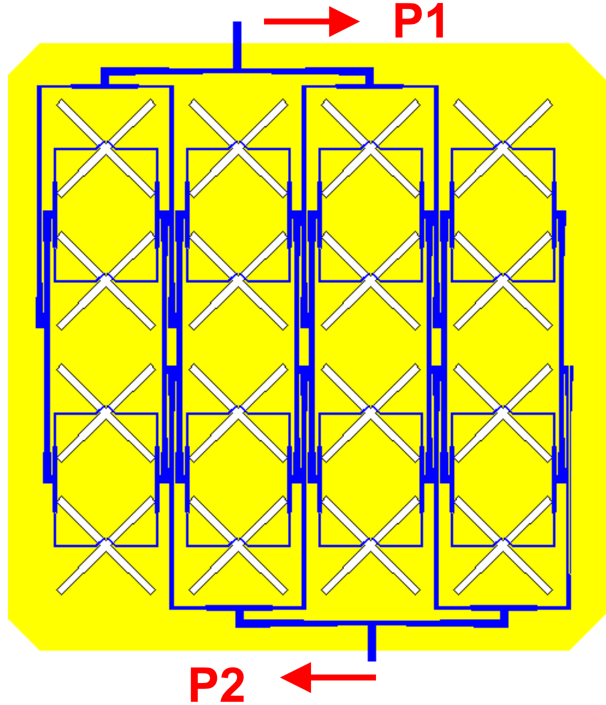
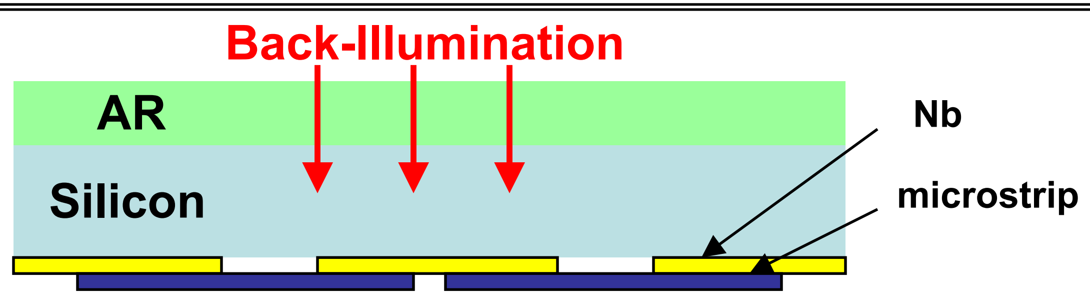
Narrow-beam planar antennas

Multi-band, single pol



Single band, dual pol





F ~ 3 feasible !
(since microstrip loss is low)

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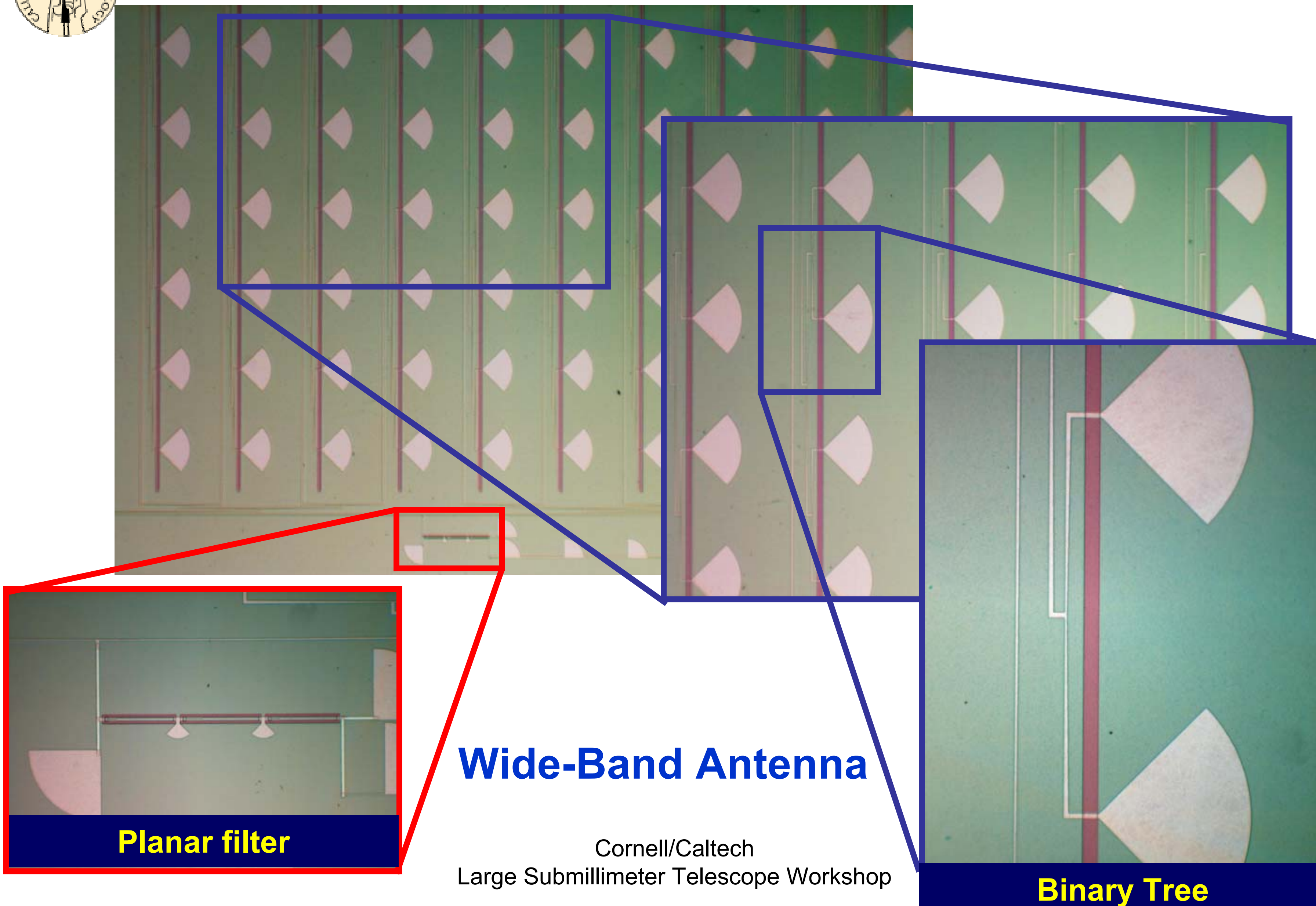
JPL



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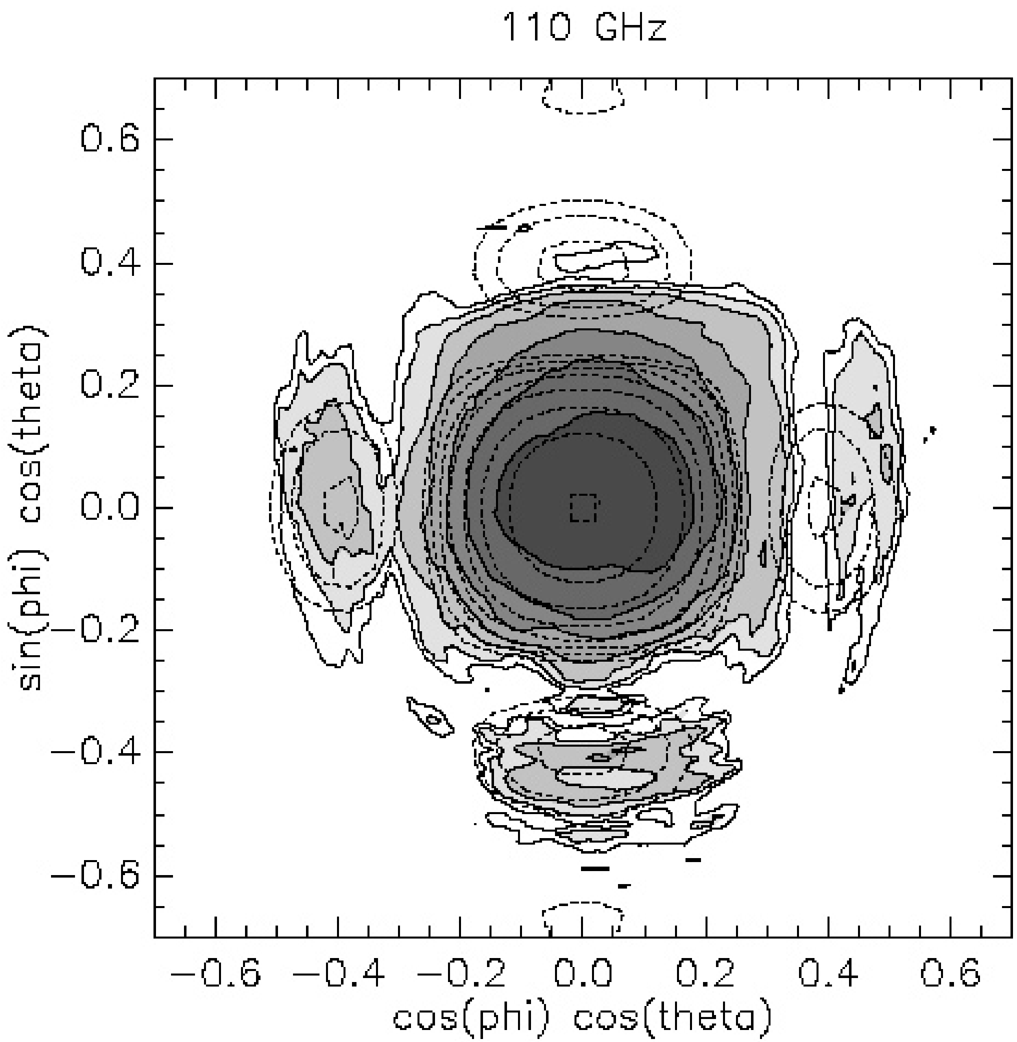
Measured antenna pattern



- use SIS direct detector
- 4 K testing
- silicon substrate
- quartz AR plate
- 19^{o} FWHM
- 95% main beam efficiency

Goldin et al. (2003)

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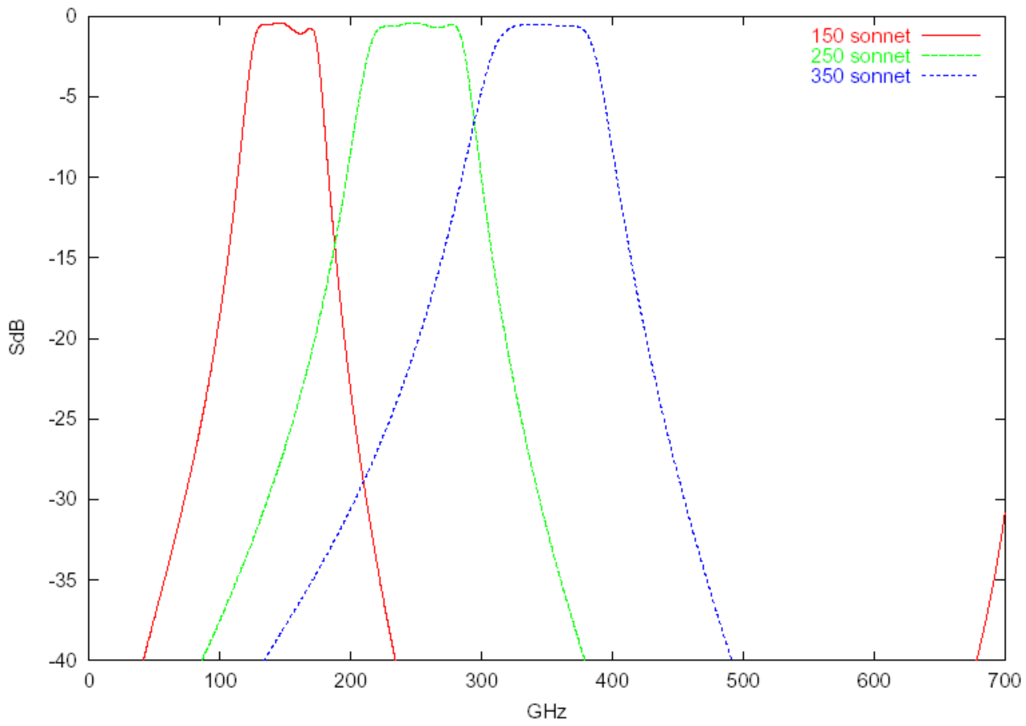
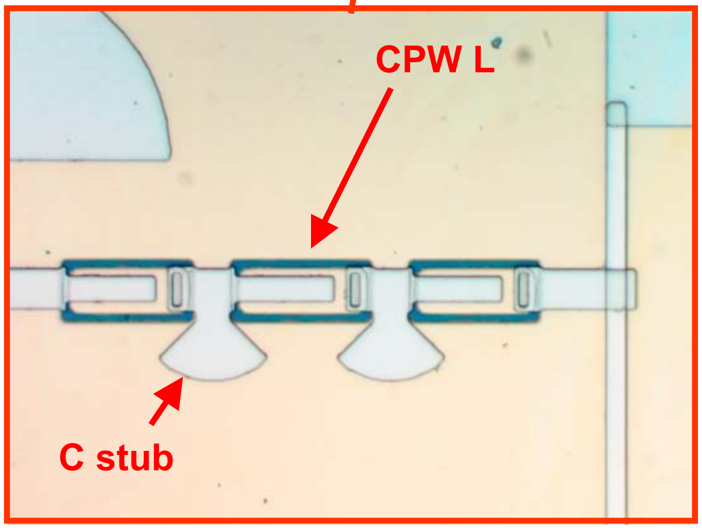
Lumped-Element MM-wave Filters

Calculated Transmittance



- **3-pole lumped-element filter**
- **calculation using Supermix and Sonnet**
- **designed for multichannel applications**

Sample for Filter Test



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Kinetic Inductance Detectors

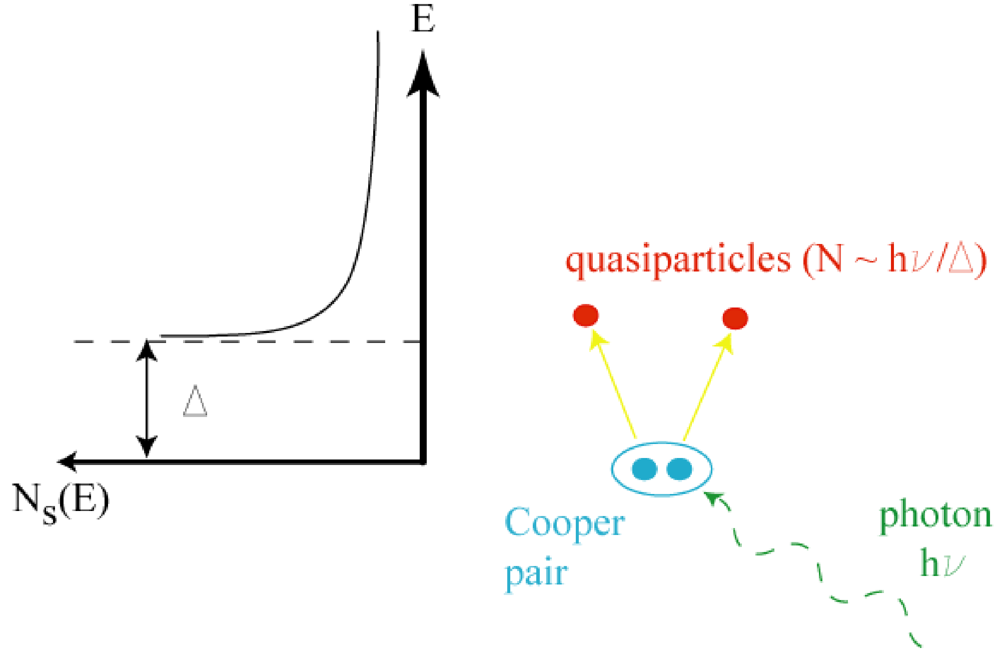
letters to nature

A broadband superconducting detector suitable for use in large arrays

Peter K. Day[1], Henry G. LeDuc[1], Benjamin A. Mazin[2], Anastasios Vayonakis[2] & Jonas Zmuidzinas[2]

[1] *Jet Propulsion Laboratory, Pasadena, California 91107, USA*
[2] *California Institute of Technology, 320-47, Pasadena, California 91125, USA*

Cryogenic detectors are extremely sensitive and have a wide variety of applications[1–3] (particularly in astronomy[4–8]), but are difficult to integrate into large arrays like a modern CCD (charge-coupled device) camera. As current detectors of the cosmic microwave background (CMB) already have sensitivities comparable to the noise arising from the random arrival of CMB photons, the further gains in sensitivity needed to probe the very early Universe will have to arise from large arrays. A similar situation is encountered at other wavelengths. Single-pixel X-ray detectors now have a resolving power of $\Delta E < 5$ eV for single 6-keV photons, and future X-ray astronomy missions[7] anticipate the need for 1,000-pixel arrays. Here we report the demonstration of a superconducting detector that is easily fabricated and can readily be incorporated into such an array. Its sensitivity is already within an order of magnitude of that needed for CMB observations, and its energy resolution is similarly close to the targets required for future X-ray astronomy missions.



Advantage: quasiparticle G-R noise scales as

$$(n_{qp} / t_{qp})^{1/2} \sim \exp(-\Delta/kT)$$

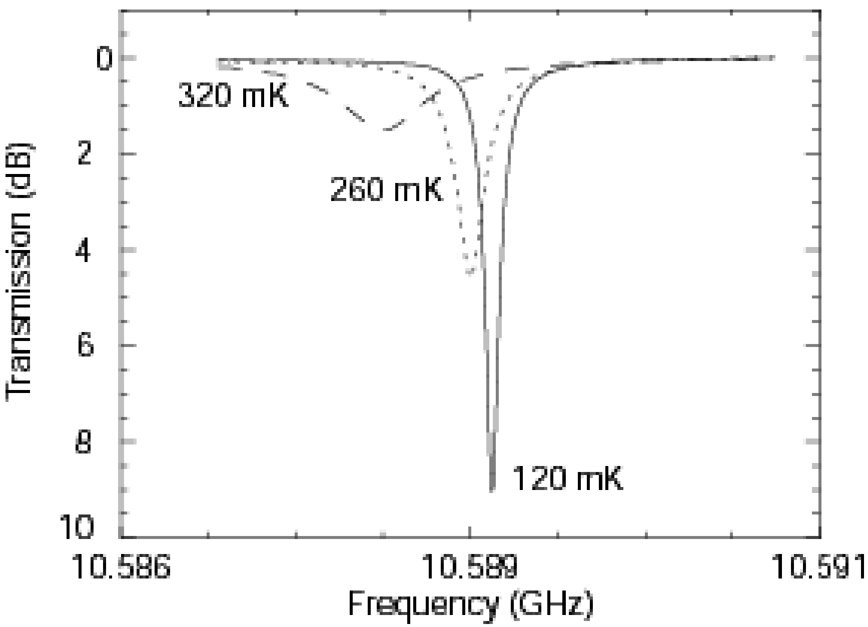
NATURE | VOL 425 | 23 OCTOBER 2003 | www.nature.com/nature **817**

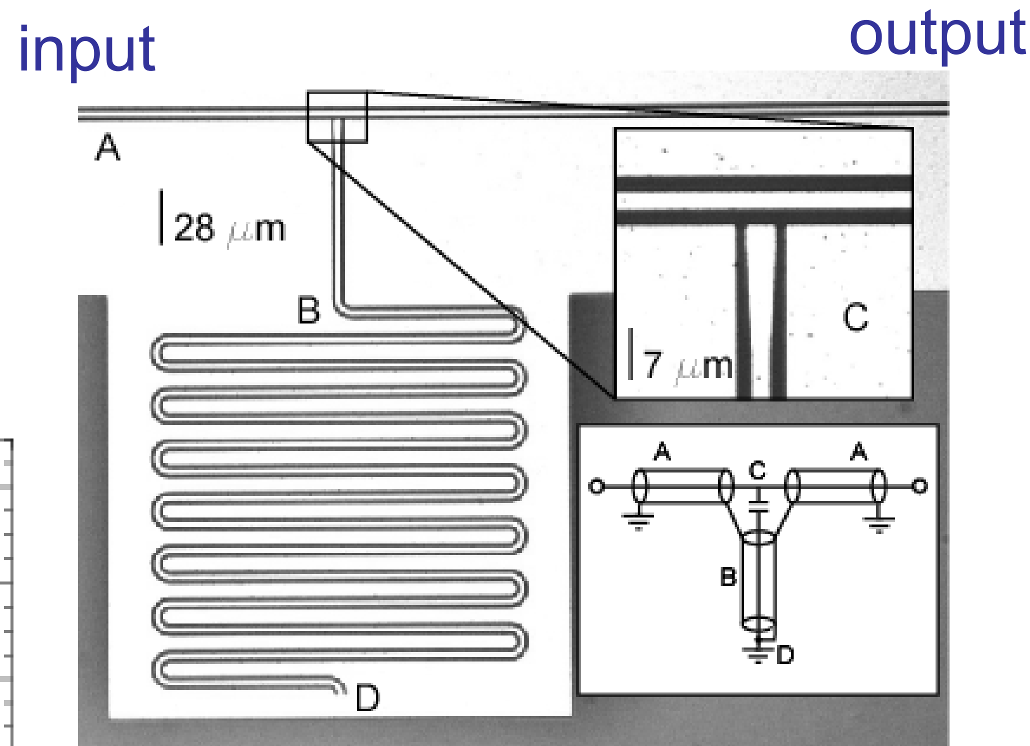
Superconducting Direct Detectors

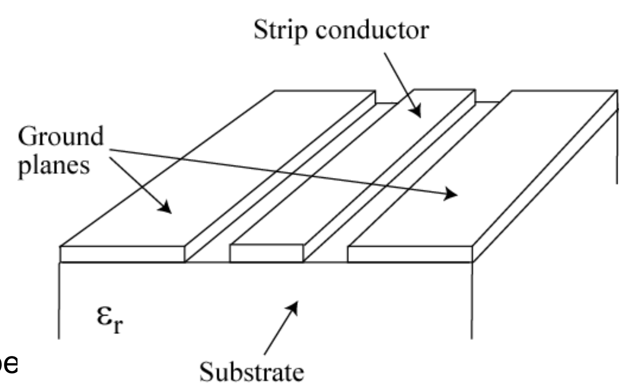
Quarter-wavelength resonator

CPW - 200 nm Al on sapphire
L = 3 mm; V = 2000 μm^3
f_0 = 10 GHz; Q = 55,000
α = 0.04

Expect position-dependent response, ~ $\cos^2(\pi x/2L)$







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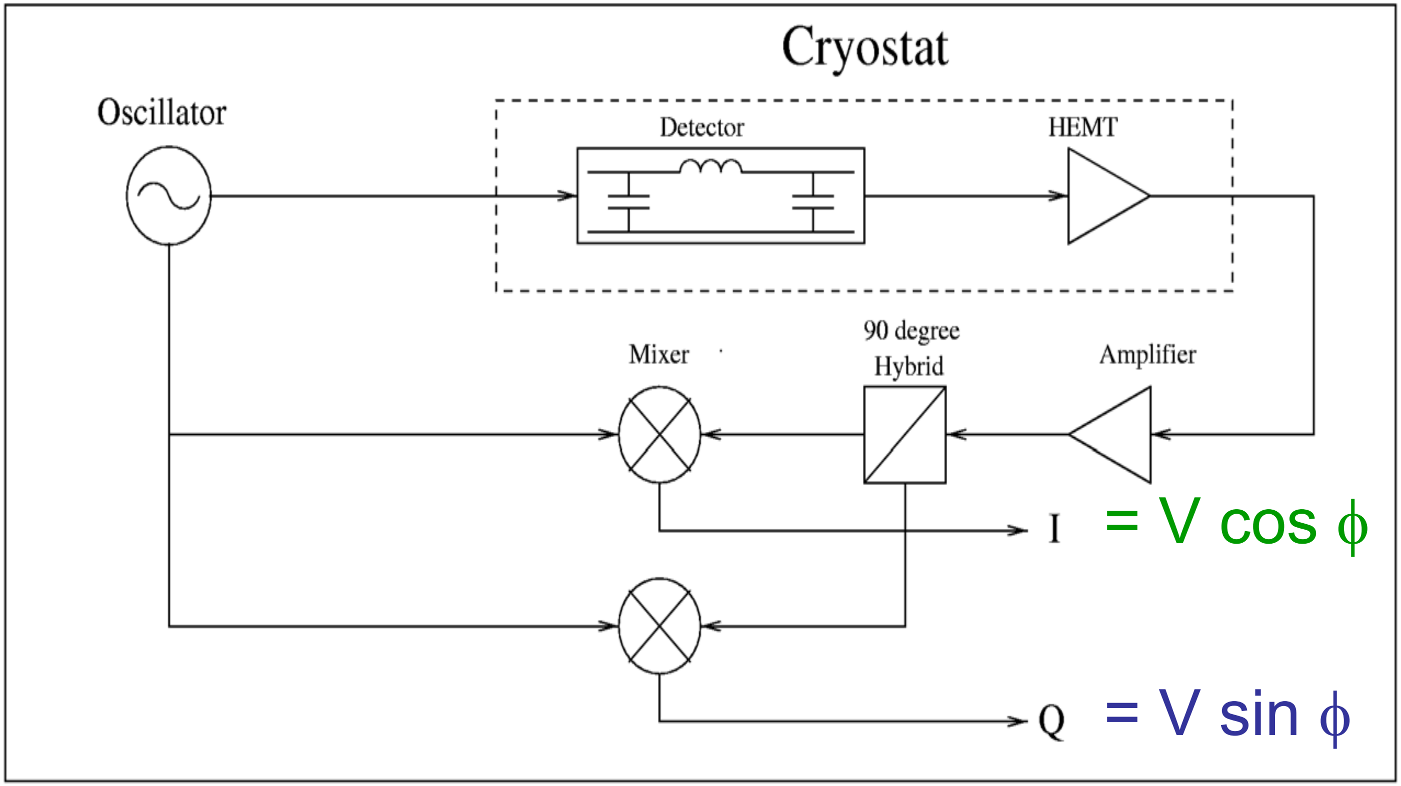
IQ readout of amplitude and phase



$= V \cos \phi$

$= V \sin \phi$

$$V \cos(\omega t - \phi) = V \cos \phi \cos \omega t + V \sin \phi \sin \omega t$$

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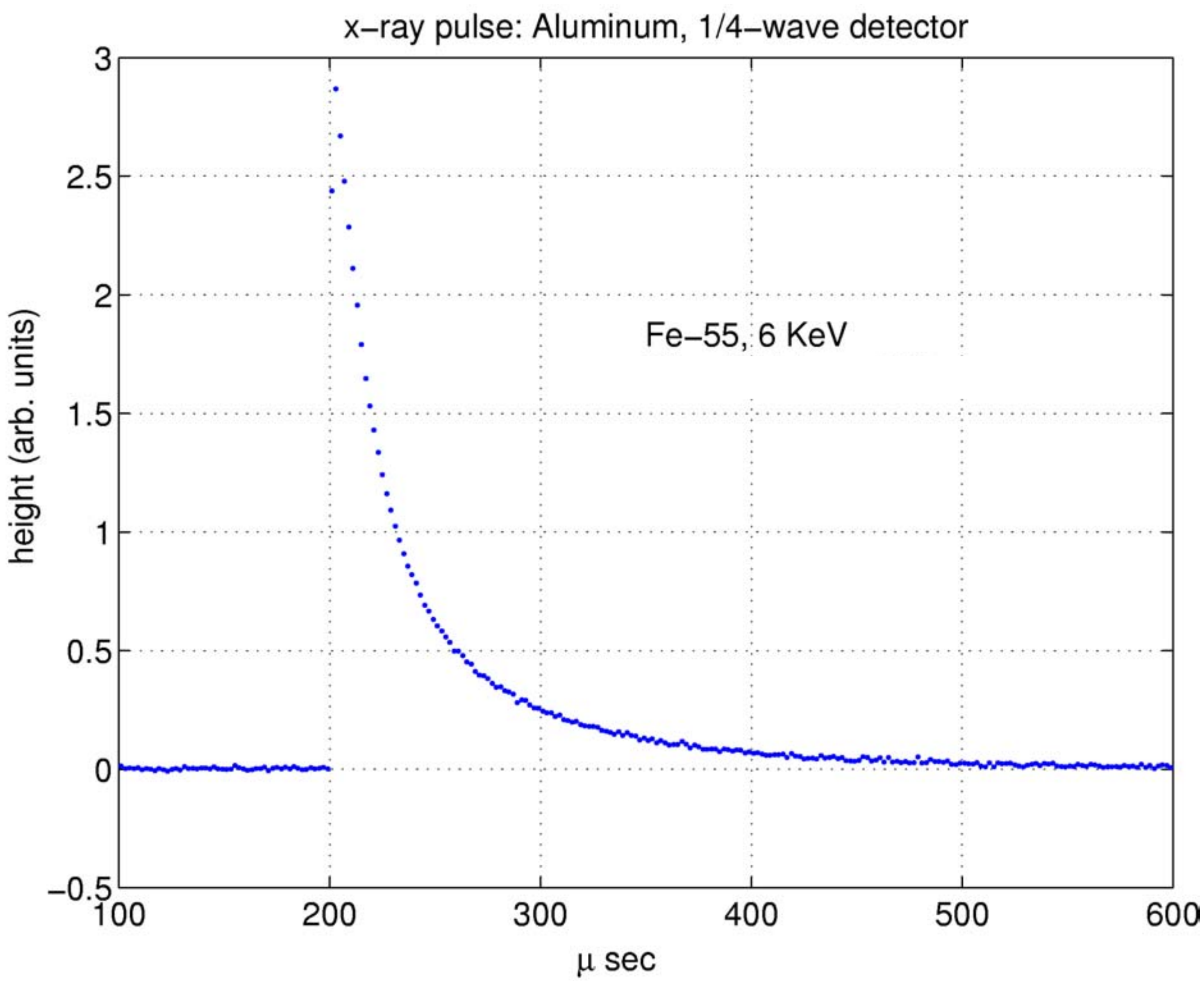
It works !!!



- Rise time: resonator bandwidth
- Fall time: quasiparticle decay
- Nyquist sampled readout
- High pulse SNR:
  - $\Delta E \sim 11$ eV
- Output noise spectrum measured
  - Appears to be dominated by resonator noise
  - Origin not yet determined
  - Readout NEP contribution ~10 dB lower
  - NEP ~ 10^{-16} W / $Hz^{1/2}$
  - NEP consistent with observed pulse ΔE

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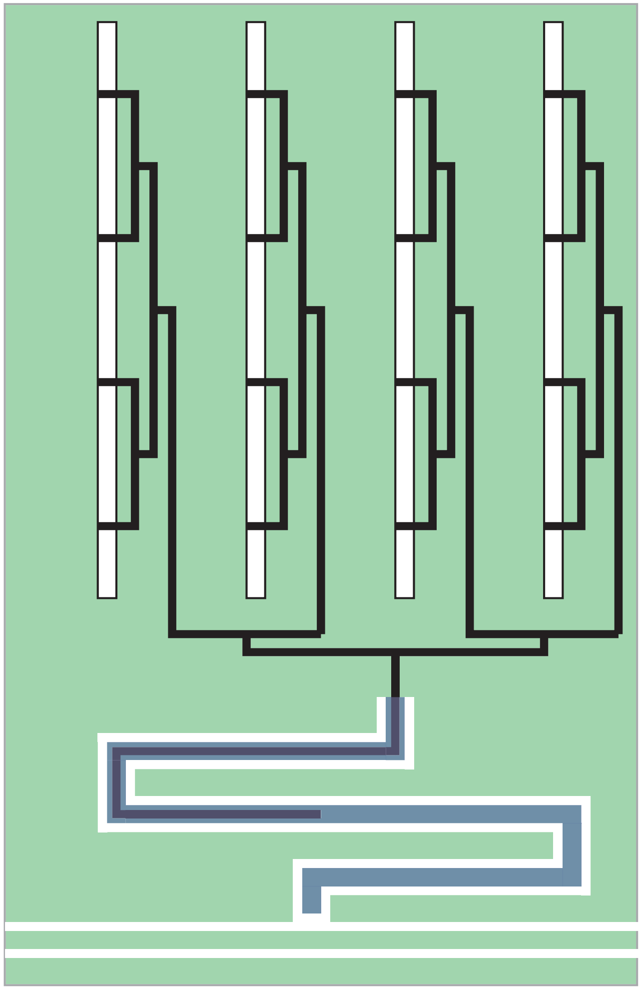
Antenna-coupled kinetic inductance detector



- *Niobium* - ground plane (green) and top microstrip conductor (black)
- *Aluminum* – center conductor of CPW KID resonator (blue)
- Simple to fabricate !
- KID is easy to couple to antenna
- Ultimate NEP limit < 10^{-19} W/Hz$^{1/2}$
- *Demonstrated* NEP already useful for ground-based submm imaging
- Single-pixel or small array lab demo at λ=850 μm expected in 2004
- Prototype instrument on CSO by end of 2005 ?

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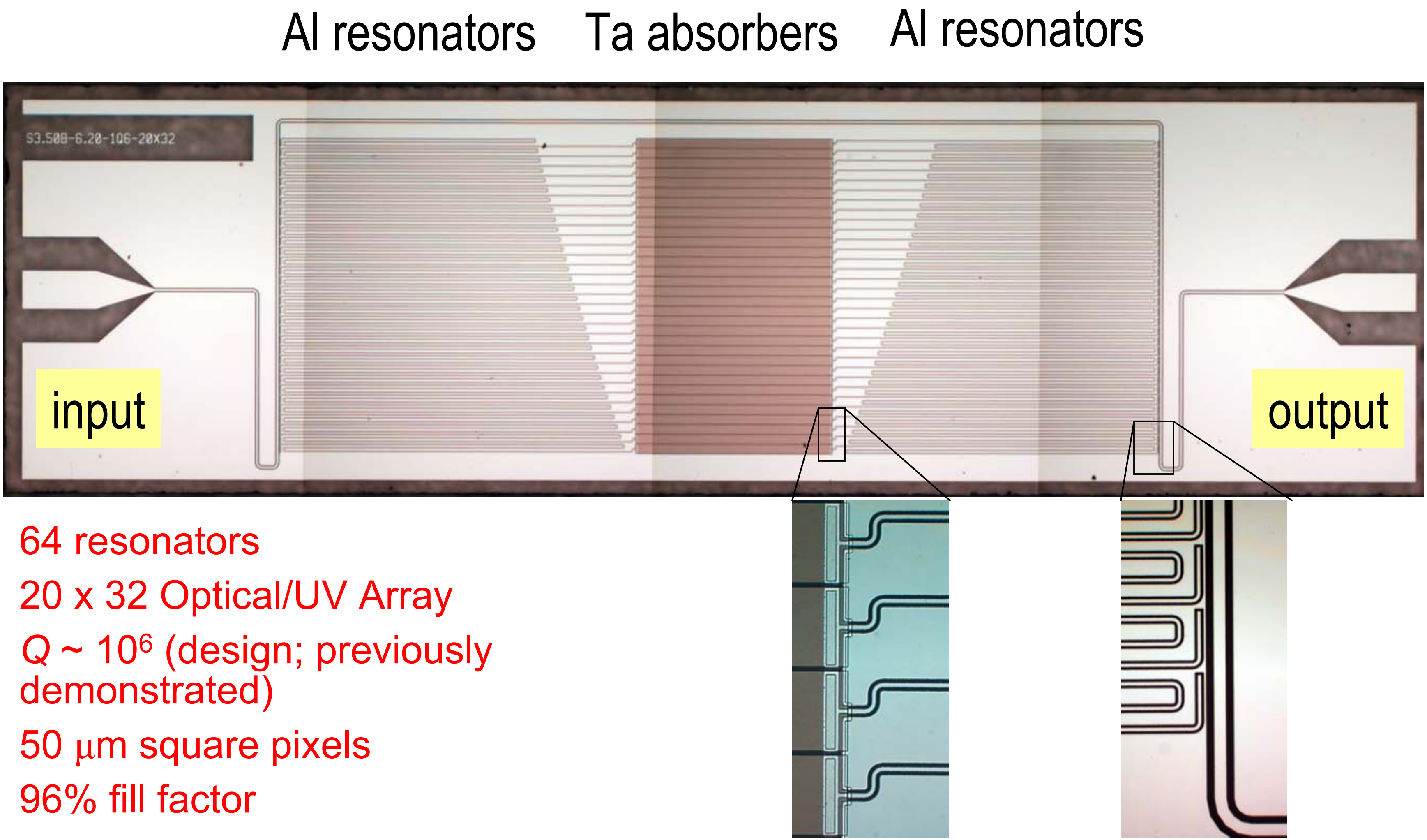
Example of a UV/Optical Array



64 resonators

20 x 32 Optical/UV Array

Q ~ 10^6 (design; previously demonstrated)

50 μm square pixels

96% fill factor

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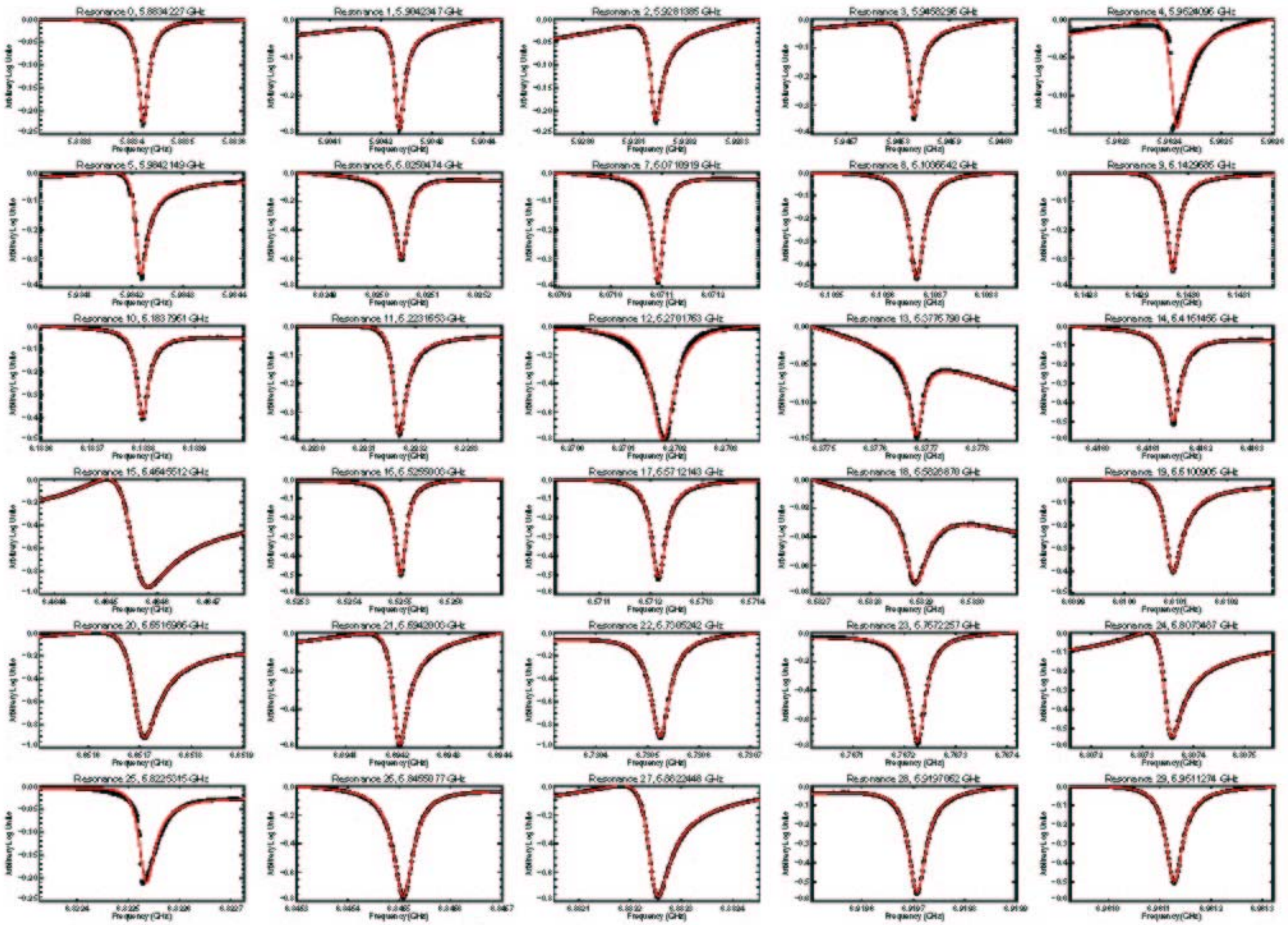
Measurements – 30 resonators; Q ~ 200,000



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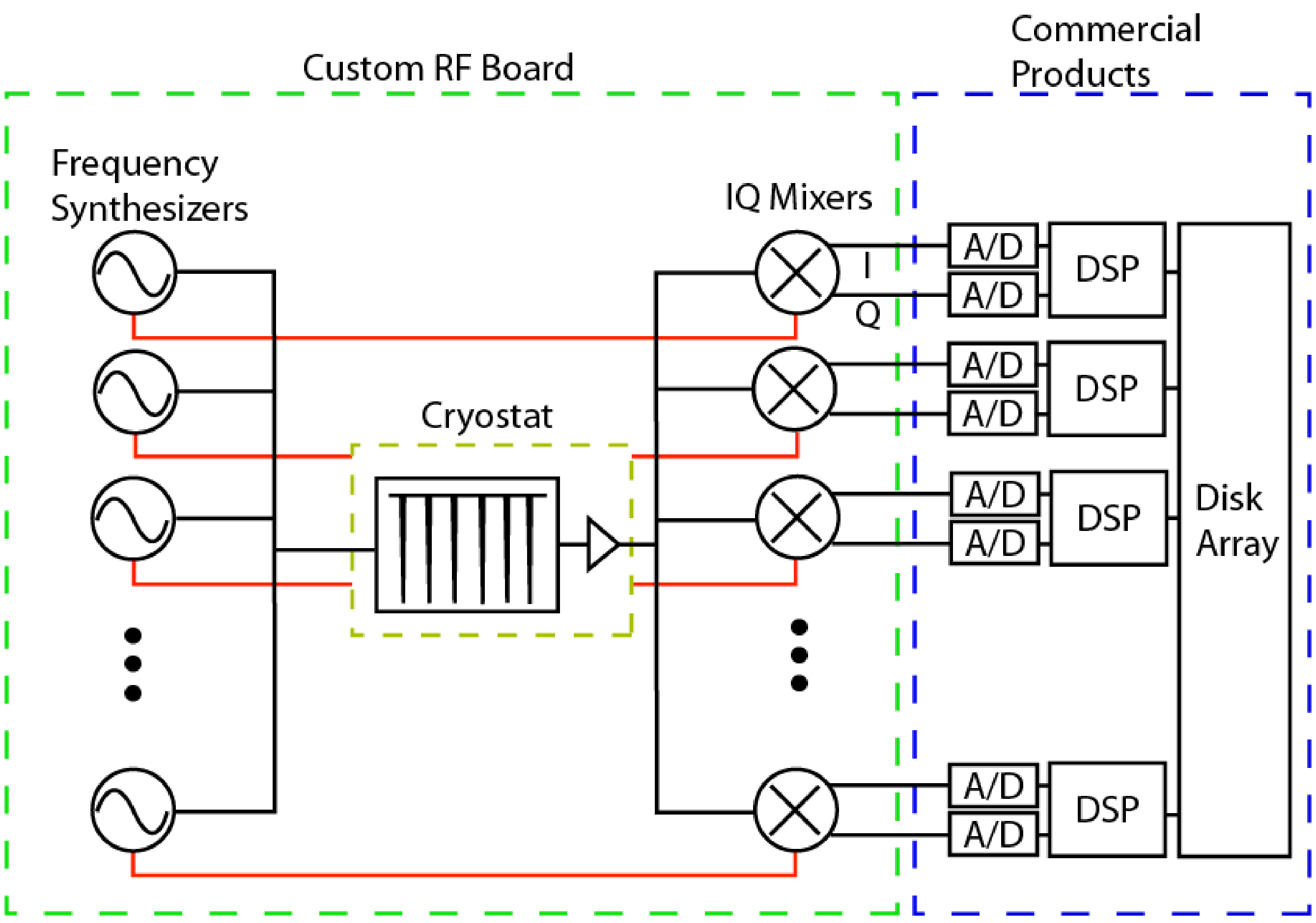
Frequency-domain Multiplexing



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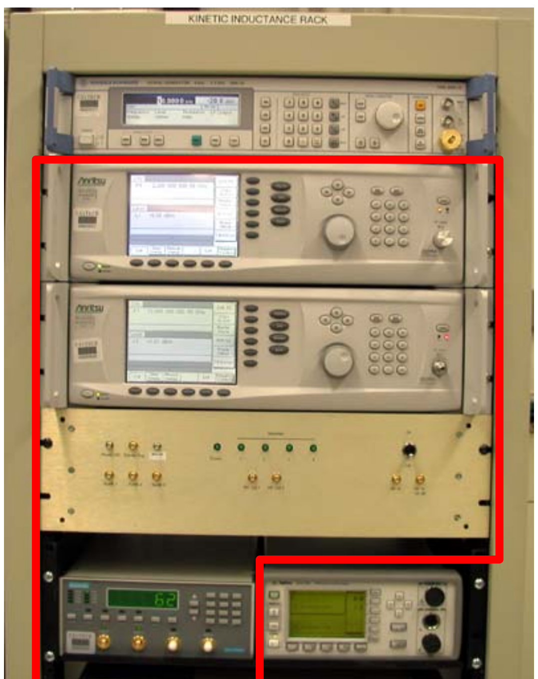
Wireless Technology for Readouts

- Many readout channels can be condensed onto a single circuit board using cell phone ICs (at 1-2 GHz, plus block upconversion if necessary)



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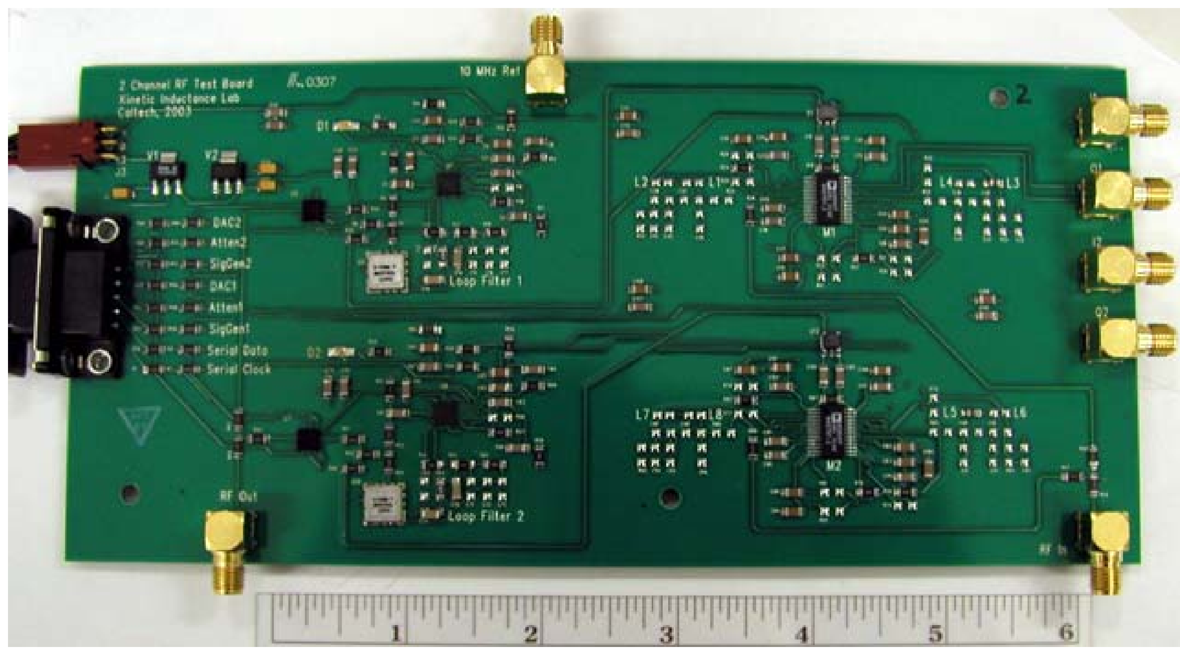

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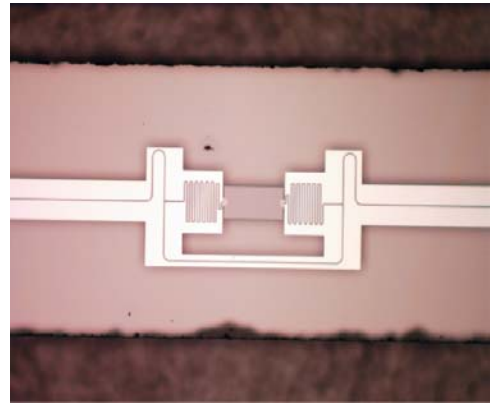
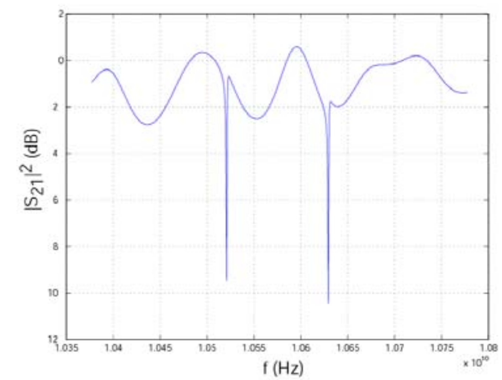
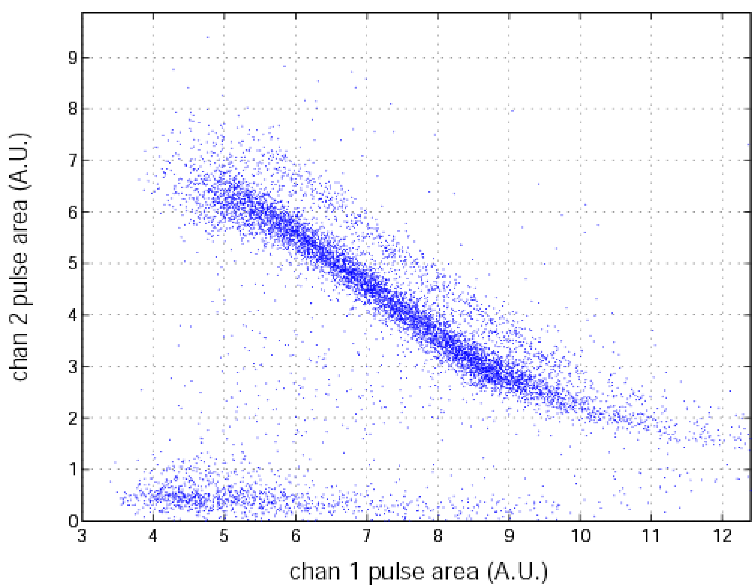
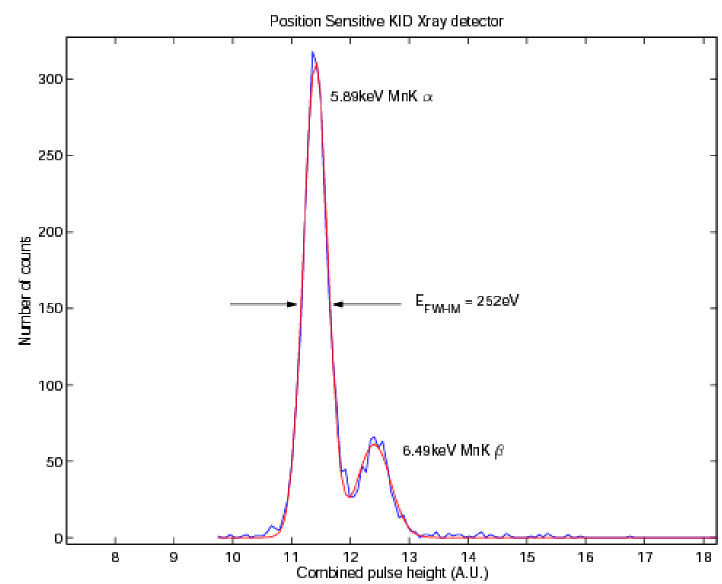
Demonstration of Frequency Multiplexing

- demonstrates qp trapping (Ta-Al) and frequency mux
- ΔE is limited by low Q, around 10^4









Superconducting Direct Detectors

Summary and Conclusions

- New elements for direct detection instruments
  - Low-loss transmission lines
  - Narrow-beam planar antennas
  - Planar lithographed filters
  - Microstrip-coupled bolometers
- Kinetic Inductance Detectors
  - Already interesting for ground-based submm
  - Must develop prototype arrays and readout electronics
  - Continue study of device physics, noise, materials

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Superconducting Direct Detectors

Personnel

Jamie Bock	JPL/Caltech	Bolometers, TES, Antennas…
Peter Day	JPL	KIDs, TES
Brian Dougherty	Caltech	KIDs for dark matter
Darren Dowell	JPL	Instruments, polarimetry, …
Megan Eckart	Ph.D. student	KIDs for X-rays
Jiansong Gao	Ph.D. student	KID device physics
Alexey Goldin	JPL	Array antennas, filters
Sunil Golwala	Professor	KIDs for dark matter
Fiona Harrison	Professor	KIDs for X-rays
Cynthia Hunt	Ph.D. ’03	Twin-slot TES
Andrew Lange	Professor	CMB applications
Rick LeDuc	JPL	Low-Tc Lead
Chris Martin	Professor	UV/optical applications for KIDs
Ben Mazin	Ph.D. student	KIDs, UV/optical applications
Tasos Vayonakis	Ph.D. student	Microstrips, antennas, KIDs
Minhee Yun	JPL	Antenna-coupled TES
Jonas Zmuidzinas	Professor	KIDs, antennas, etc.