Future Detector Technologies for Radio Astronomy

Jonas Zmuidzinas

Caltech

Radio Astronomy

- So what is radio astronomy, anyway ?
  - centimeter waves
    - *f* < 30 GHz (λ > 1 cm)
  - millimeter waves
    - 30 < f < 300 GHz (10 > λ > 1 mm)
  - submillimeter waves
    - 300 < f < 1500 GHz (1 > λ > 0.2 mm)
  - Far-infrared (a gray area):
    - 1500 < f < 30,000 GHz (200 > λ > 20 μm)

Astrophysical Measurements

- Photometry (continuum)
  - Spectral resolution $(\nu/\Delta\nu) \sim 3\text{-}10$
  - Science examples: CMB, SZE, dust emission
  - Detector arrays:
    - Bolometers
    - photon detectors
    - HEMTs (arrays)
- Spectroscopy (atoms, molecules, ions)
  - Spectral resolution $(\nu/\Delta\nu) \sim 10^2 - 10^6$
  - Science examples: ISM, star formation, galaxies
  - Detectors:
    - SIS and HEB mixers
    - HEMTs
    - Direct detectors & bolometers (moderate resolution)

also for interferometry

COHERENT vs. INCOHERENT DETECTION

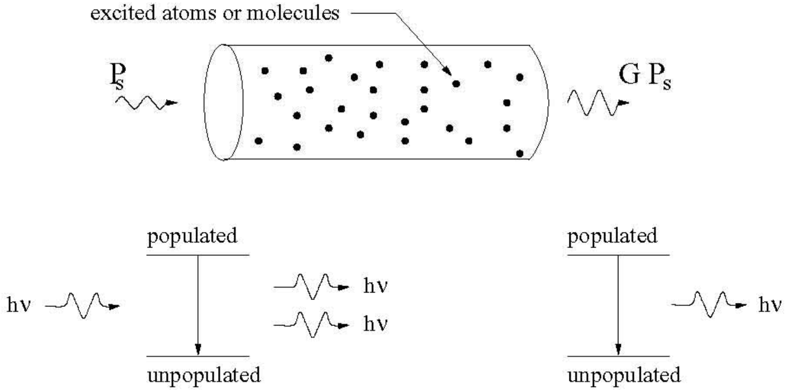
Coherent vs. direct detection

(*or, should I build a radio receiver* ?)

Quantum noise:

(where "radio receiver" = heterodyne or superhet)

coherent detection



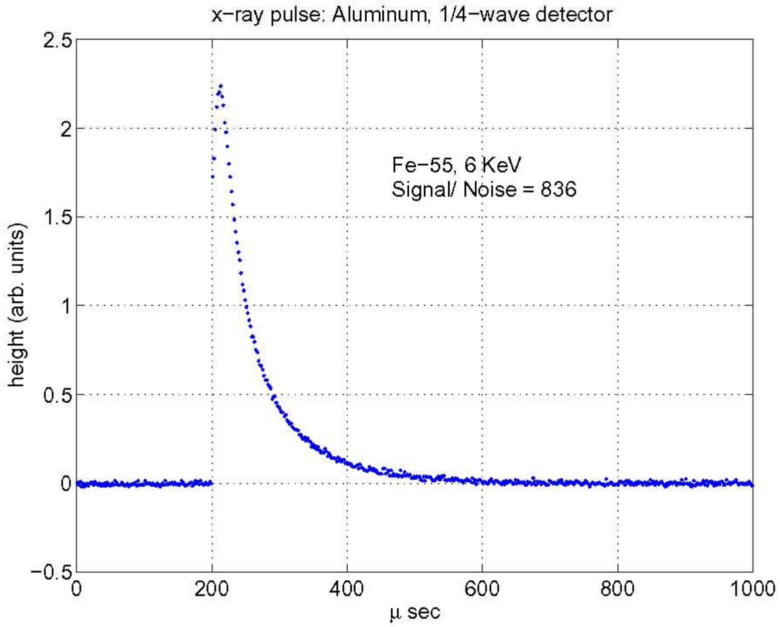
stimulated emission
(amplification)

spontaneous emission
(noise)

Even with no photons at input, a perfect maser amplifier has nonzero output noise due to spontaneous emission. This is an example of quantum noise.

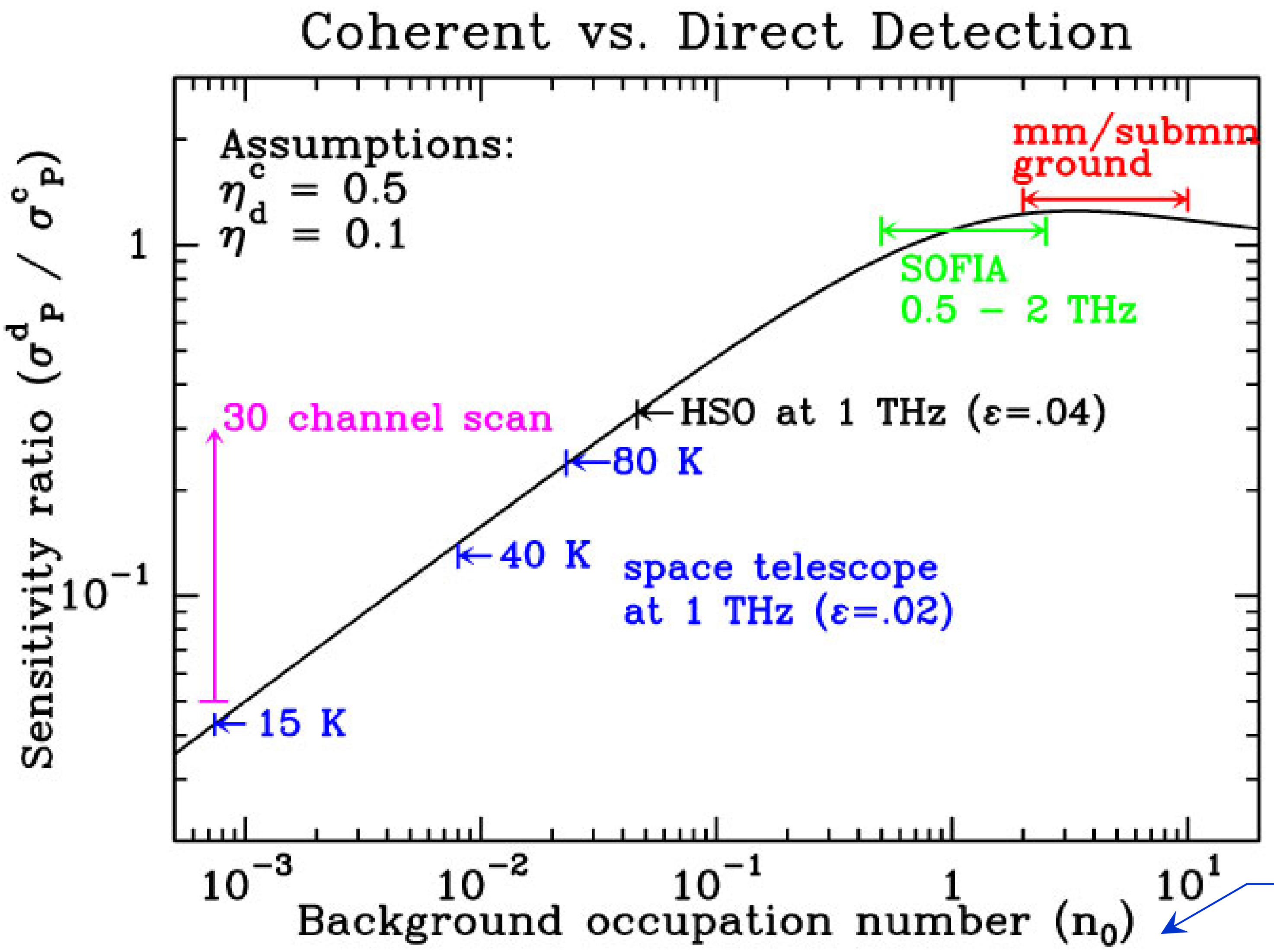
$$T_{QL} = \frac{h\nu}{k_B} \approx 0.05\ \mathrm{K} \left[\frac{\nu}{1\ \mathrm{GHz}}\right]$$

direct detection



An output pulse produced by a superconducting detector due to the absorption of a *single* 6 keV X–ray photon. *Exact* photon counting is possible, in principle.

Should I care about quantum noise ?



Ultimate cm/mm background:

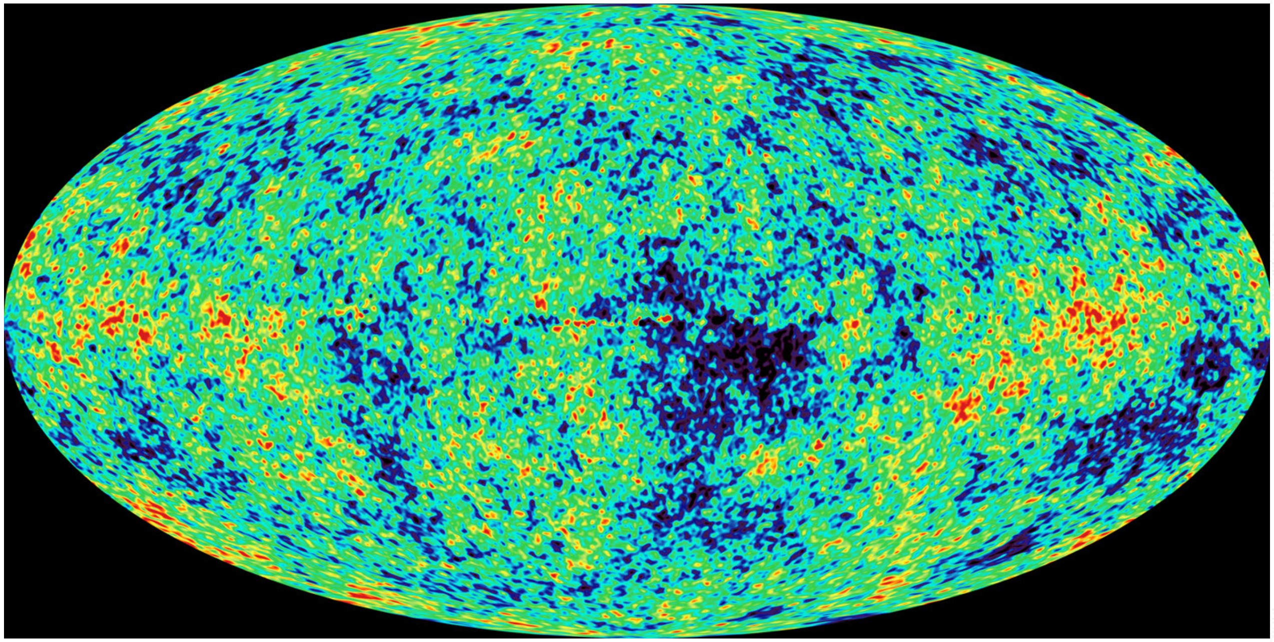
CMB @ 3 K

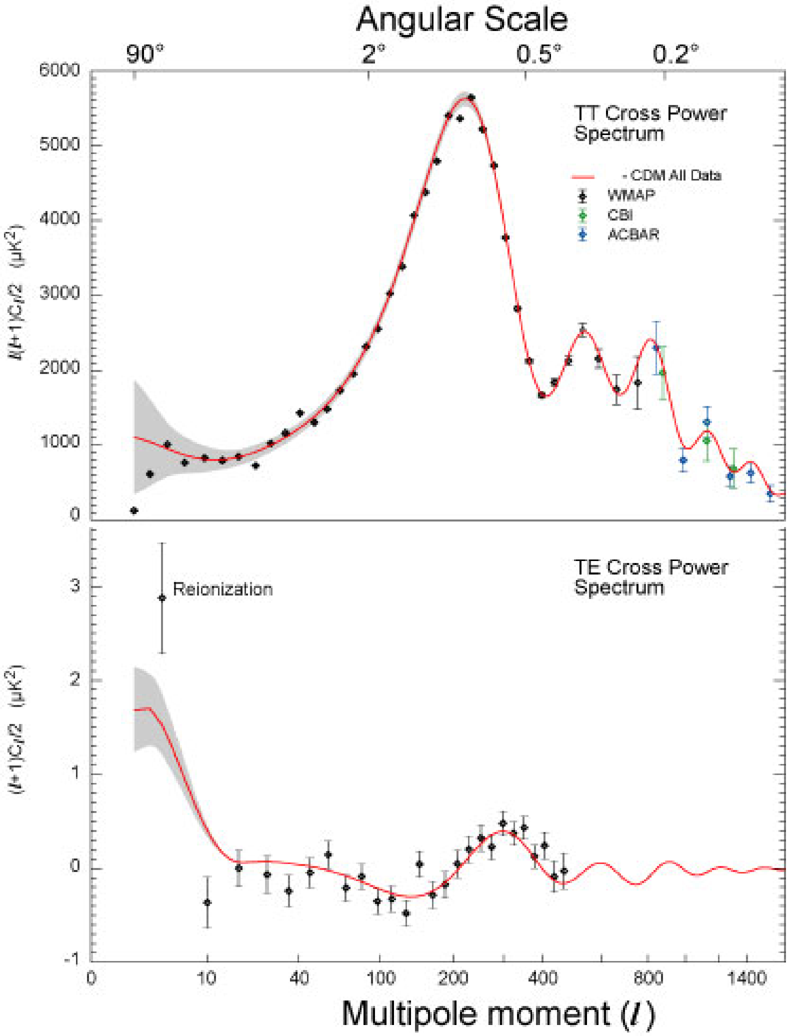
So quantum limit (0.05 K/GHz) is always irrelevant at cm wavelengths.

Usually irrelevant from ground.

 # photons/mode ≈ kT/hν (R-J)

WMAP's HEMT (radio) receivers image the CMB…





Allows determination of cosmological parameters, e.g. the Universe is flat.

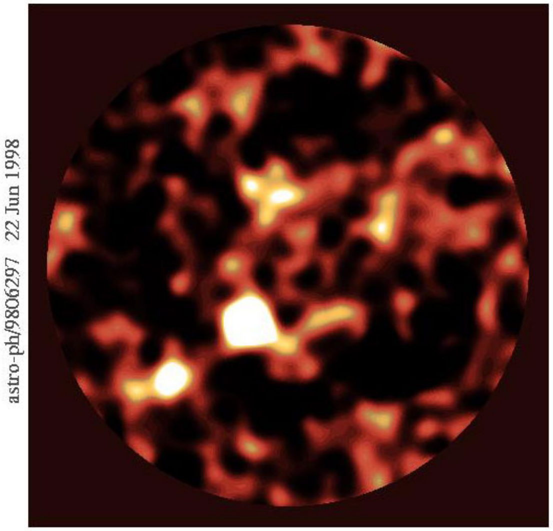
WMAP = NASA CMB (space !) mission

+ BOOMERANG, MAXIMA, DASI,…

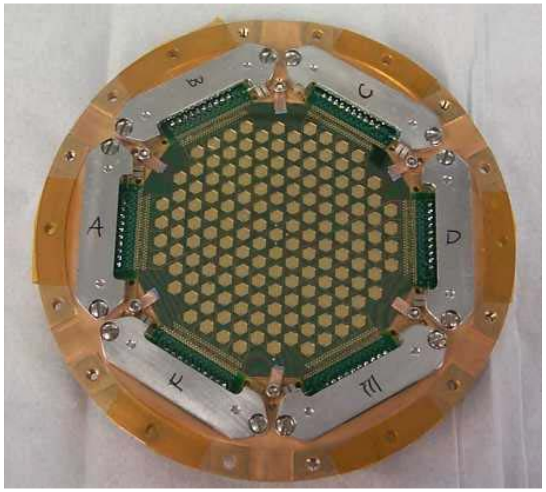
Credit: WMAP science team

…while bolometer cameras search for distant galaxies from the ground

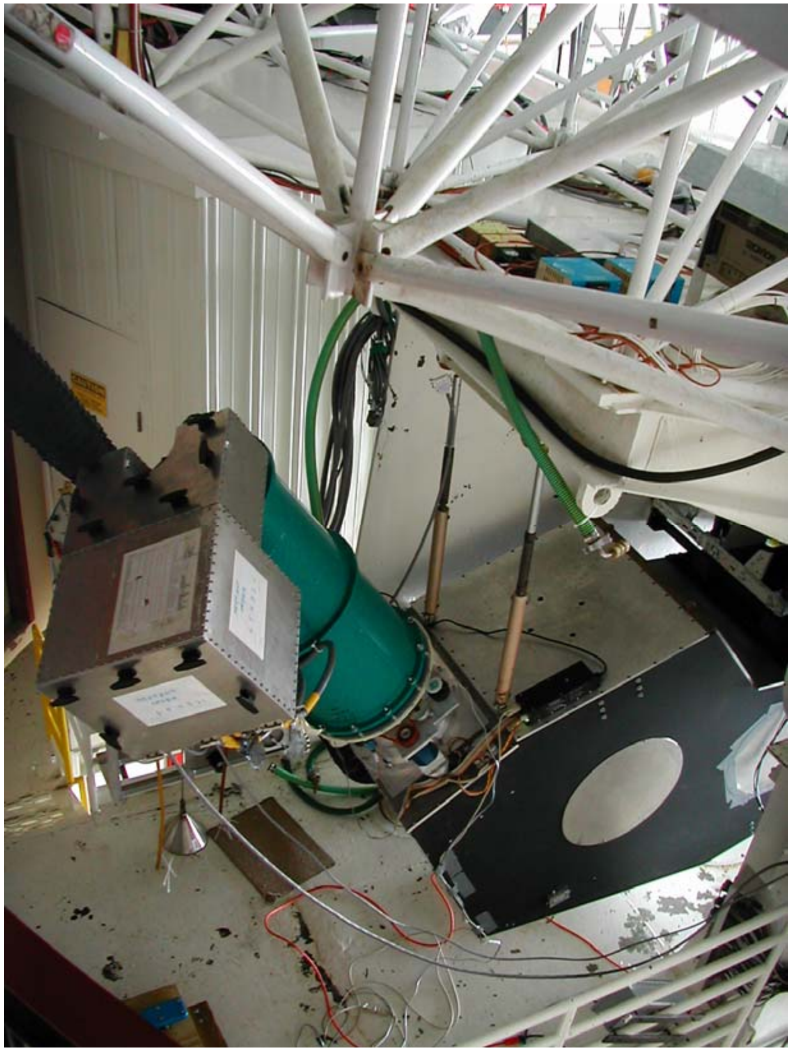
- Bolometer advantages:
  - bandwidth ! (sensitivity)
  - large arrays



HDF - SCUBA



BOLOCAM array



Credit: BOLOCAM team

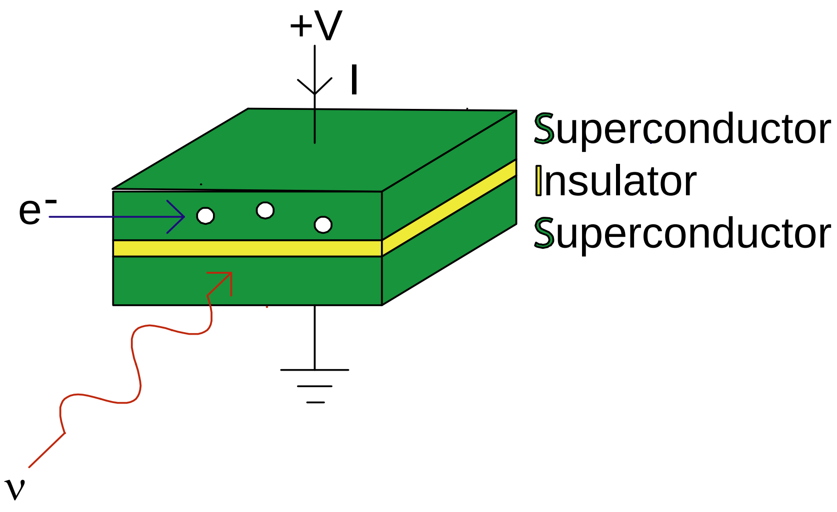
CHALLENGES

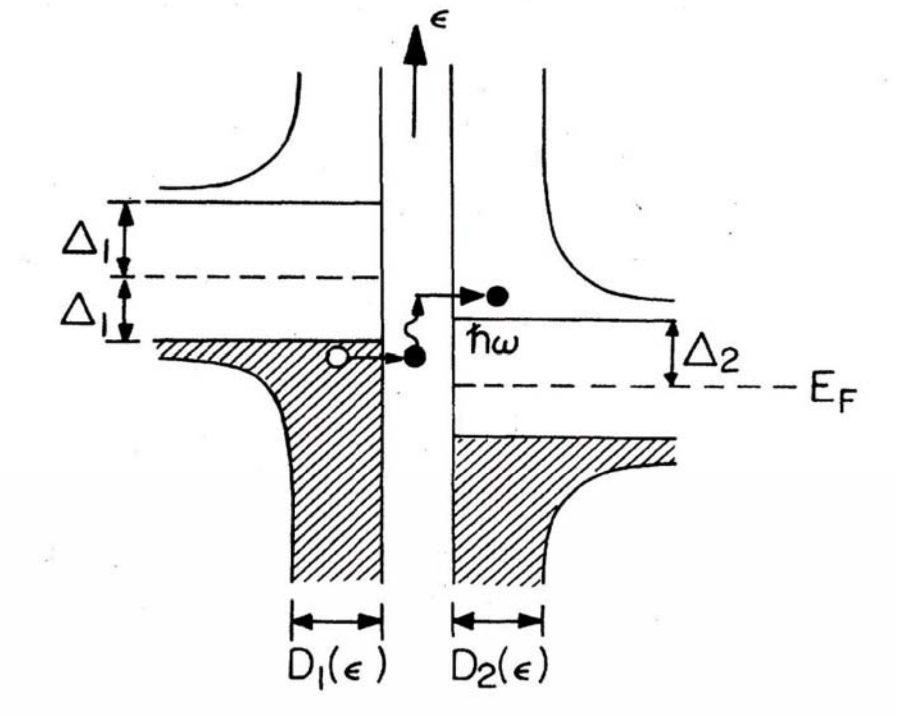
- Direct detectors
  - Array size (multiplexing !)
  - Sensitivity (esp. for space observatories)
  - Functional integration (filtering, polarization sensitivity, etc.)
- Heterodyne systems
  - Sensitivity (approach quantum limit)
  - Frequency range (push into far-IR)
  - Bandwidth (RF and IF)
  - Arrays

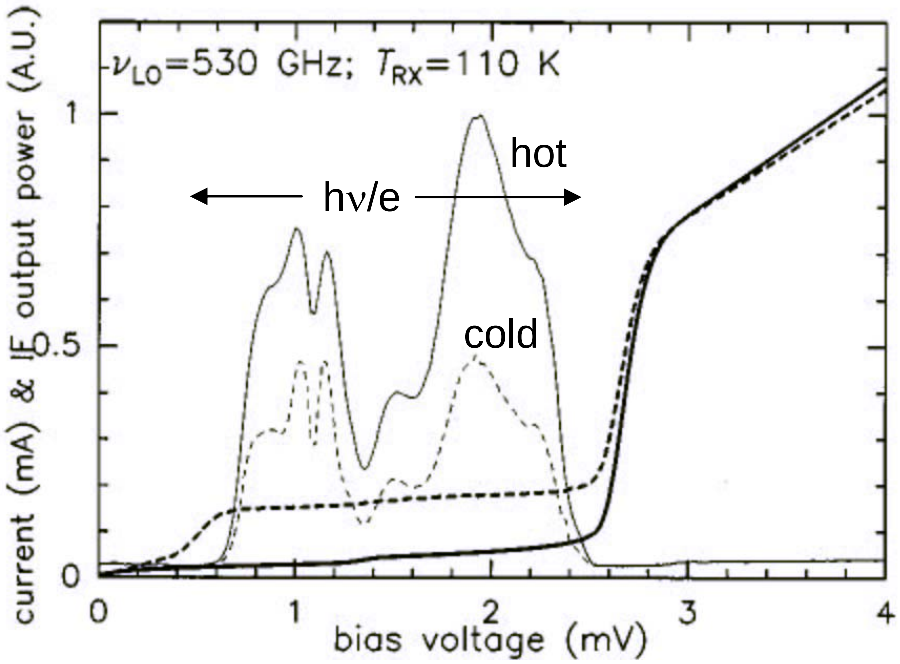
TECHNOLOGIES FOR SPECTROSCOPY

Superconducting Tunnel Junction (SIS) mixers

- SIS: superconducting tunnel junction
- SIS is a "submillimeter photodiode"
  - One electron per photon absorbed
  - "photon-assisted tunneling"
- First demonstrated in 1979
- Reason why ALMA is worthwhile !
- Reverse PAT limits frequency to ~1.6 THz







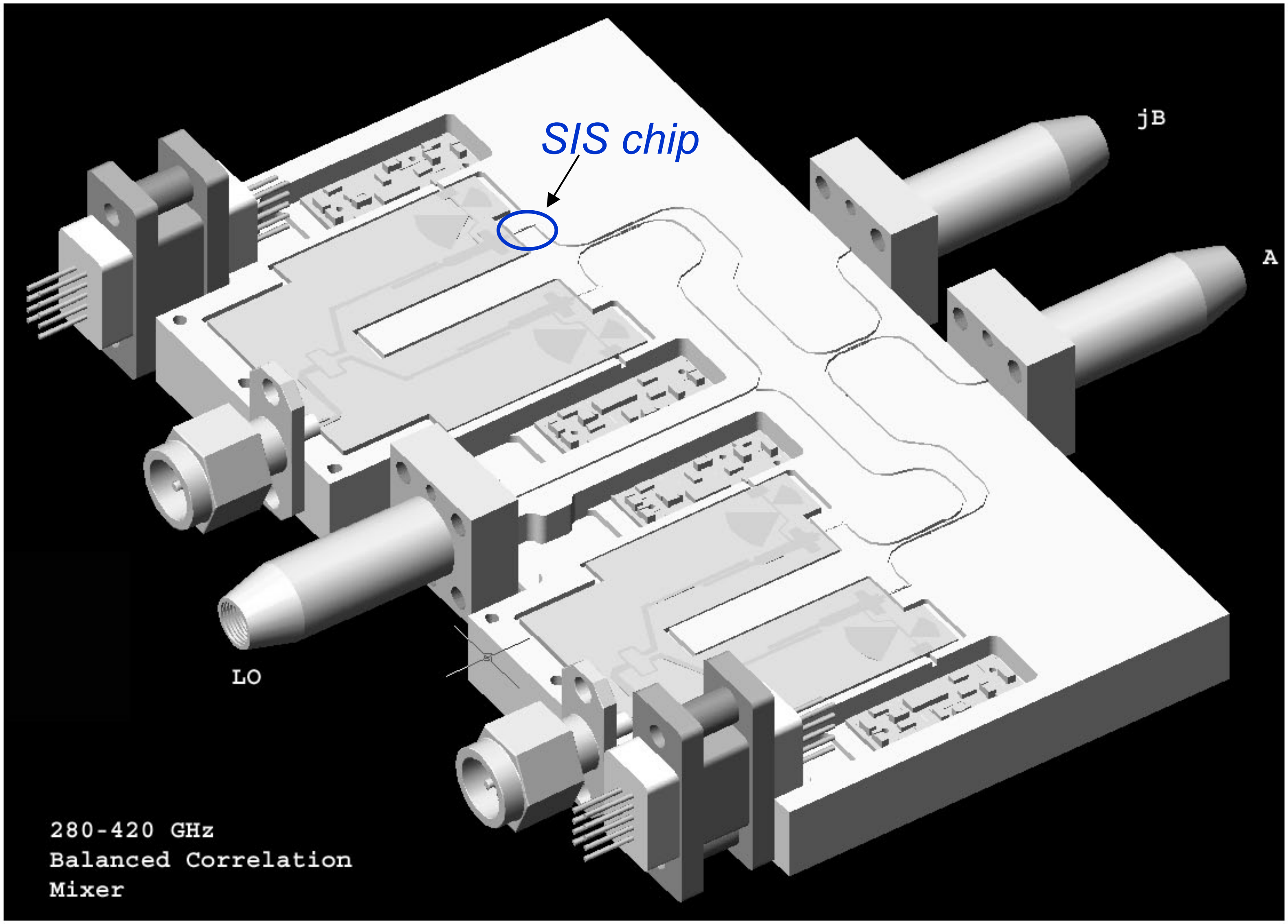
APEX and ALMA

APEX:
12m submm telescope in Chile (MPIfR Bonn)

ALMA:
64 x12m aperture-synthesis interferometer (world’s largest radio astronomy project)

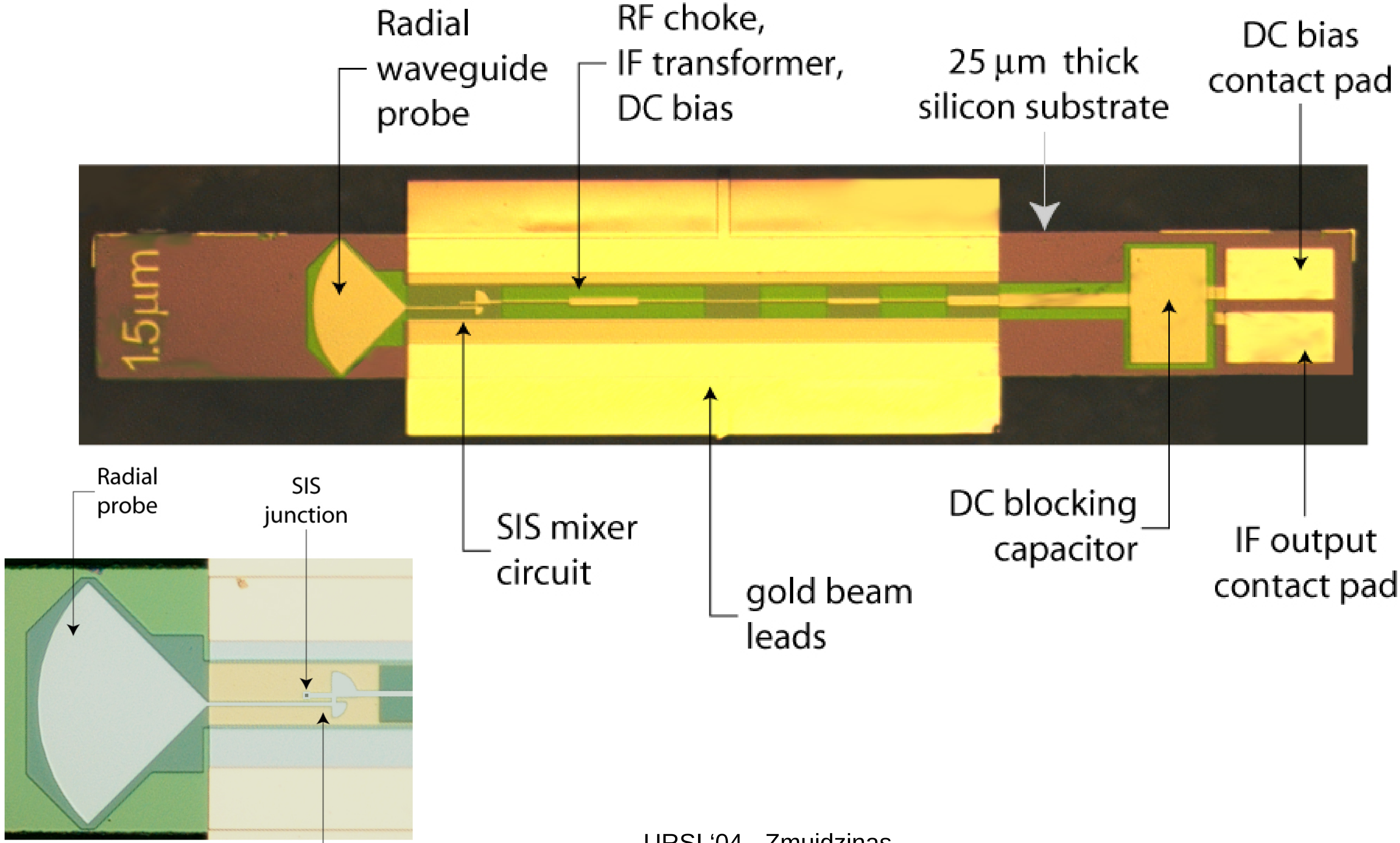
Credit: APEX/MPIfR

Waveguide Coupling



Credit: J. Kooi

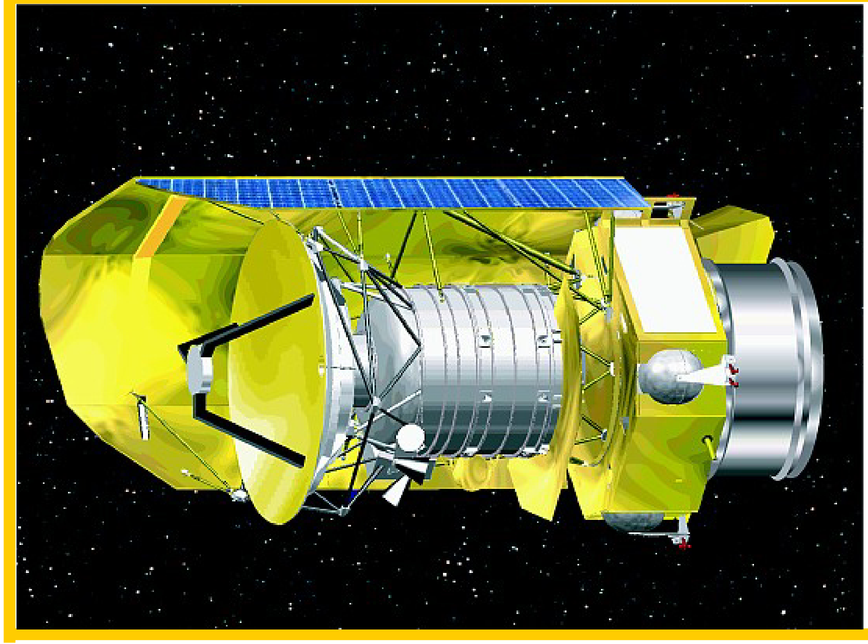
200-300 GHz waveguide SIS chip



Credit: A. Bhat and H. G. LeDuc

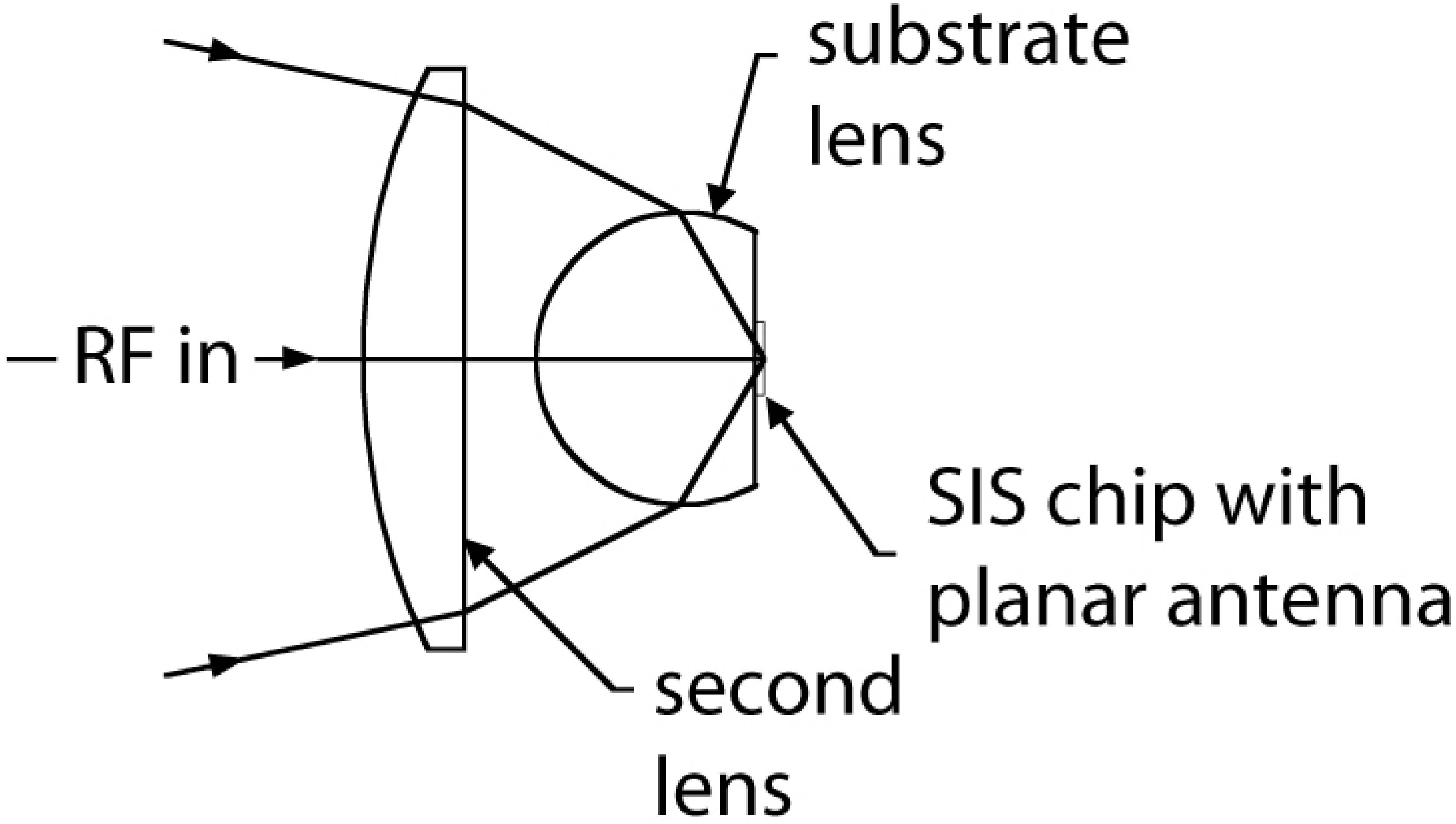
Far-IR Observatories: SOFIA and Herschel

- NASA/USRA/DLR
- 2.5m telescope
- 747 SP aircraft
- 6+2 first-light instruments
- first science in 2005



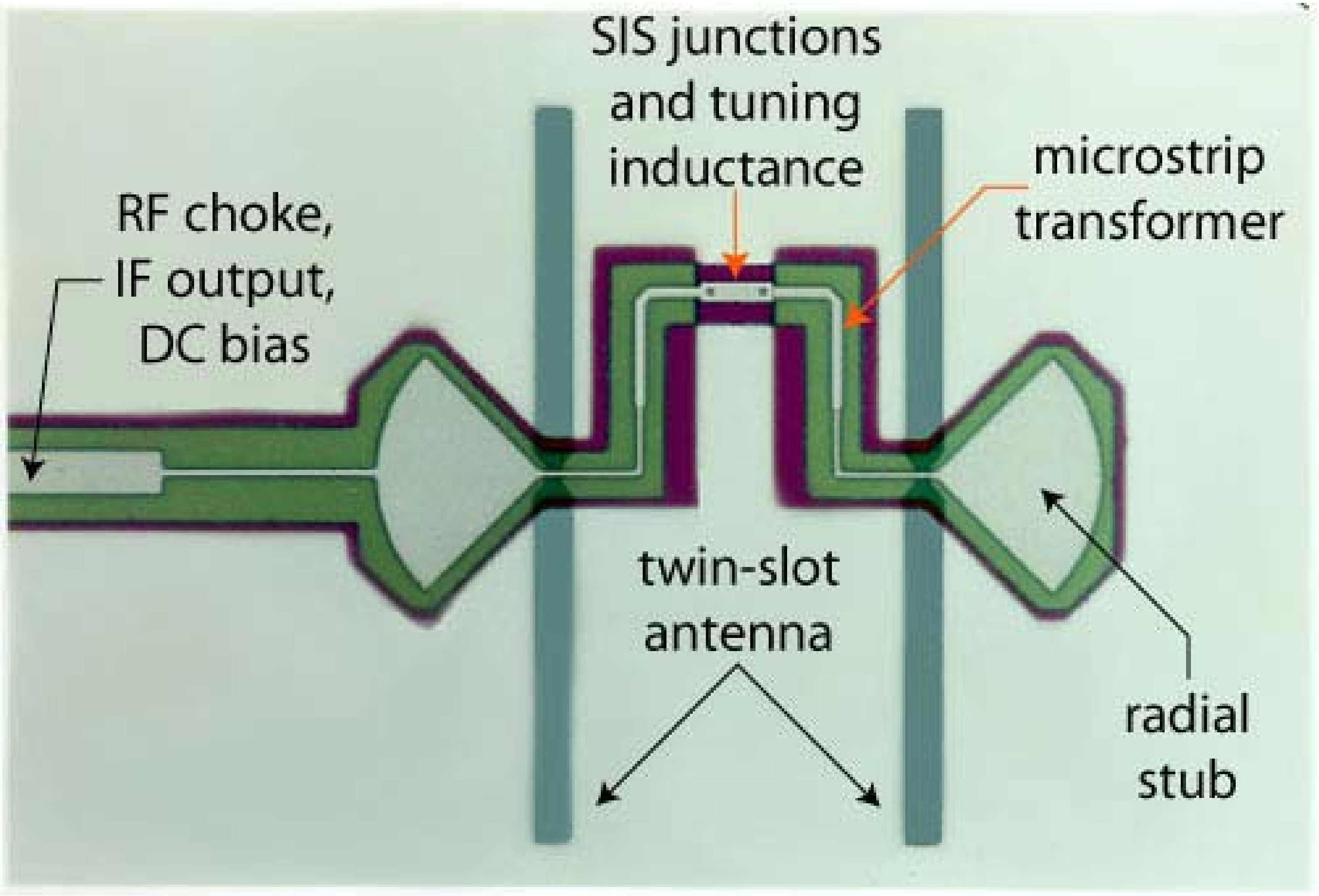
- ESA/NASA
- 3.5m telescope
- 3 instruments
  - **PACS**
  - **SPIRE**
  - **HIFI**
- 2007 launch

Quasioptical coupling

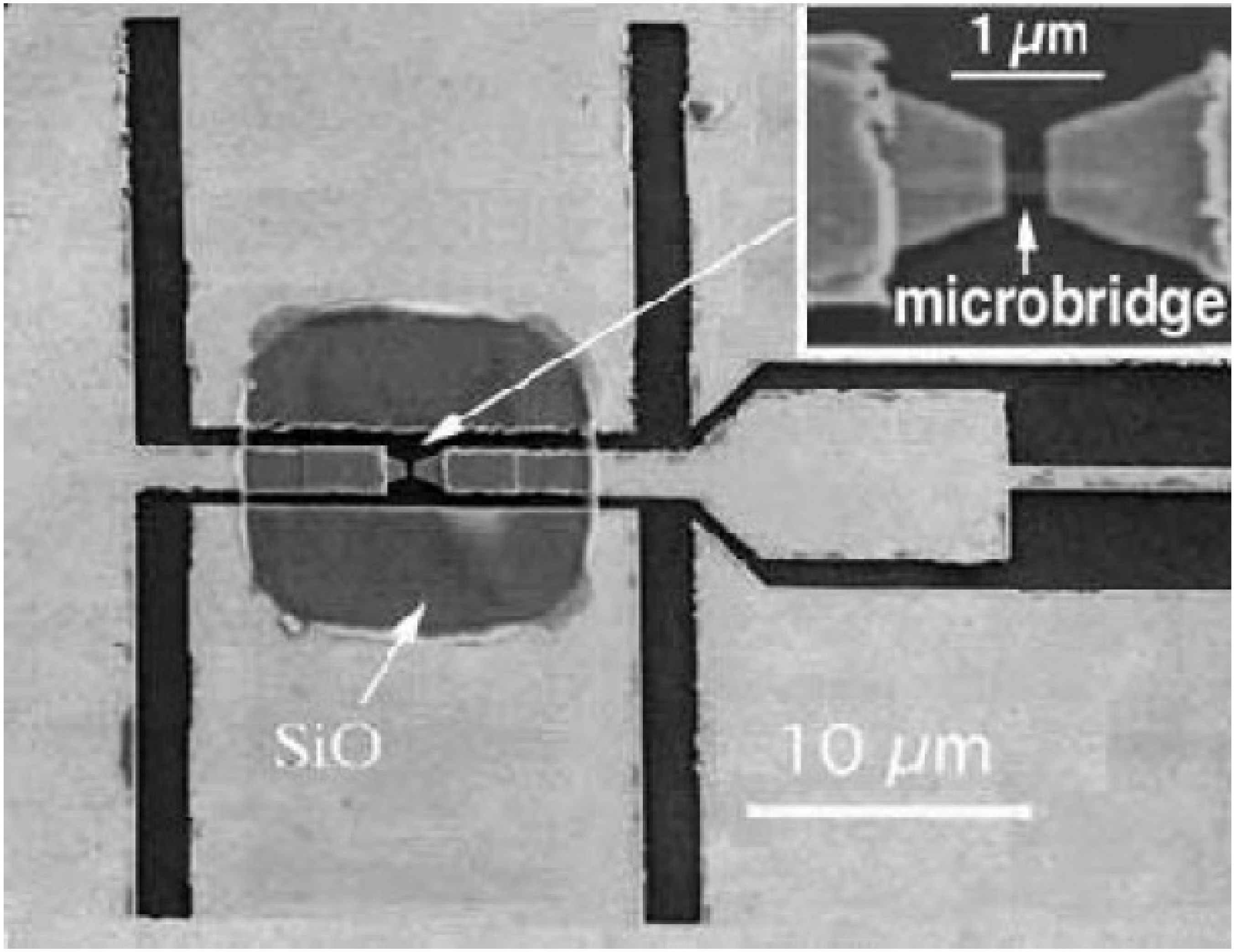


Credit: D. Rutledge

Quasioptical SIS chip

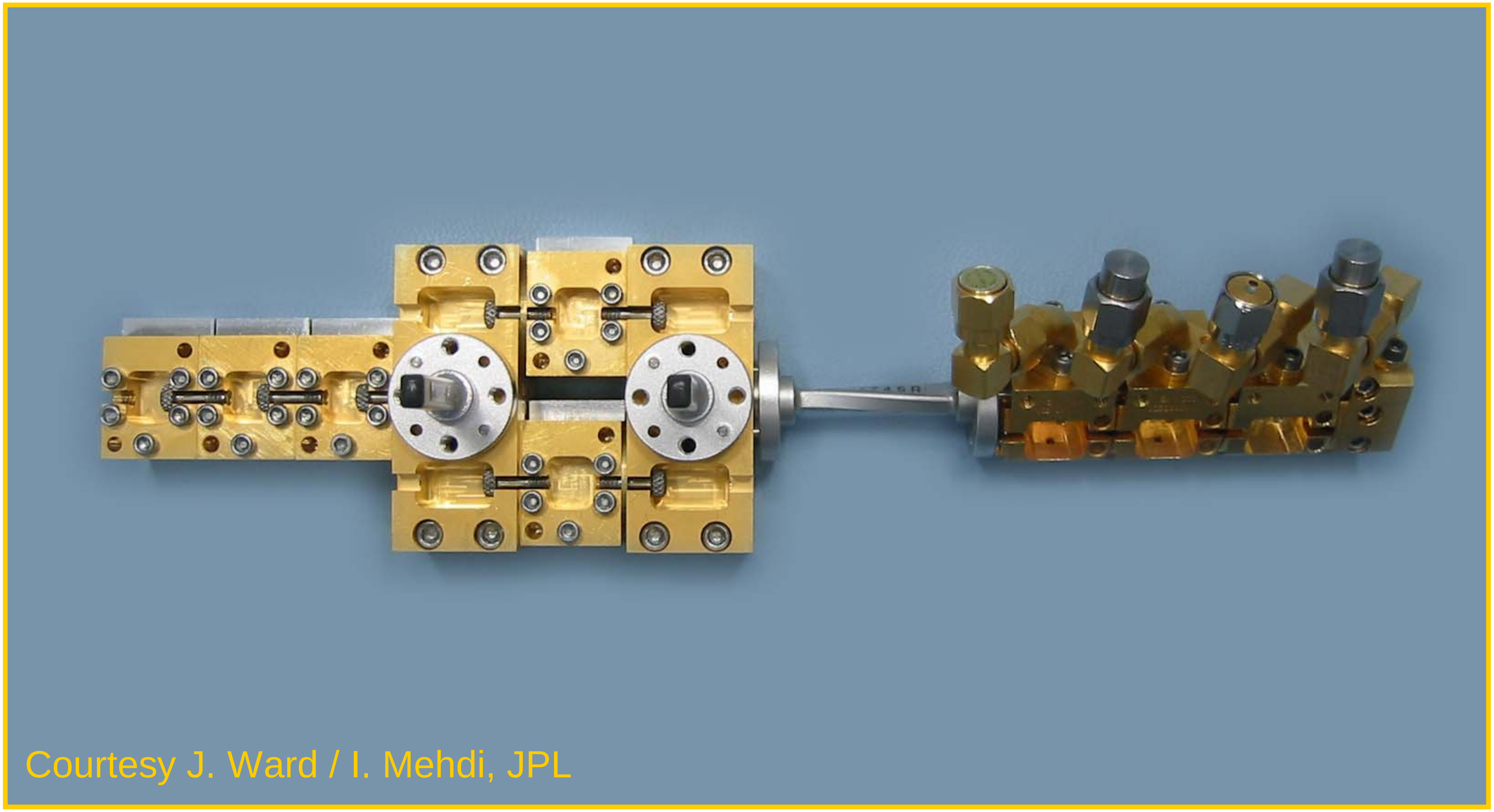


Far-infrared mixers: Superconducting Hot Electron Bolometers (HEB)



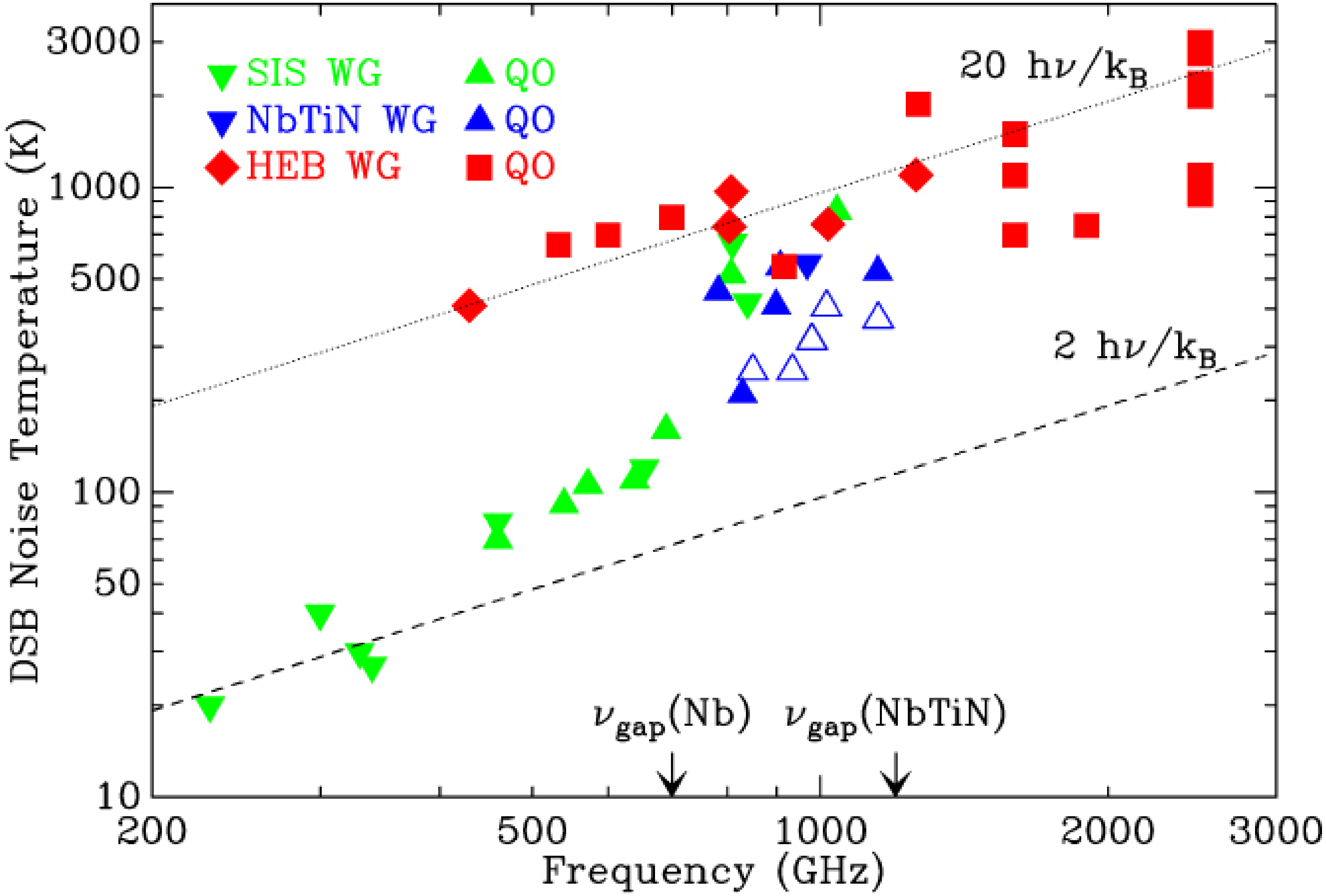
Credit: B. Karasik

Solid-state tunable 1.6 THz local oscillator for HIFI



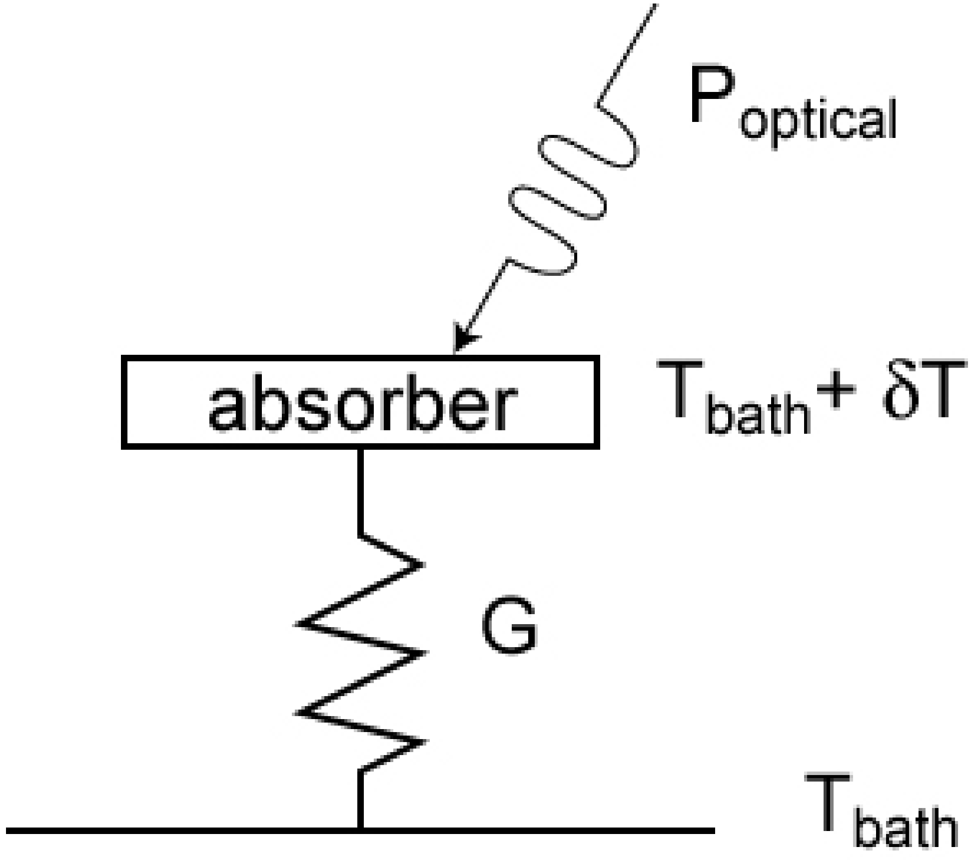
Courtesy J. Ward / I. Mehdi, JPL

Superconducting mixers: state of the art



TECHNOLOGIES FOR PHOTOMETRY

Bolometers



Challenges:

Low G (controls NEP)

Good $\tau = C/G$

Sensitive measurement of δT

Low 1/f noise

Microphonics

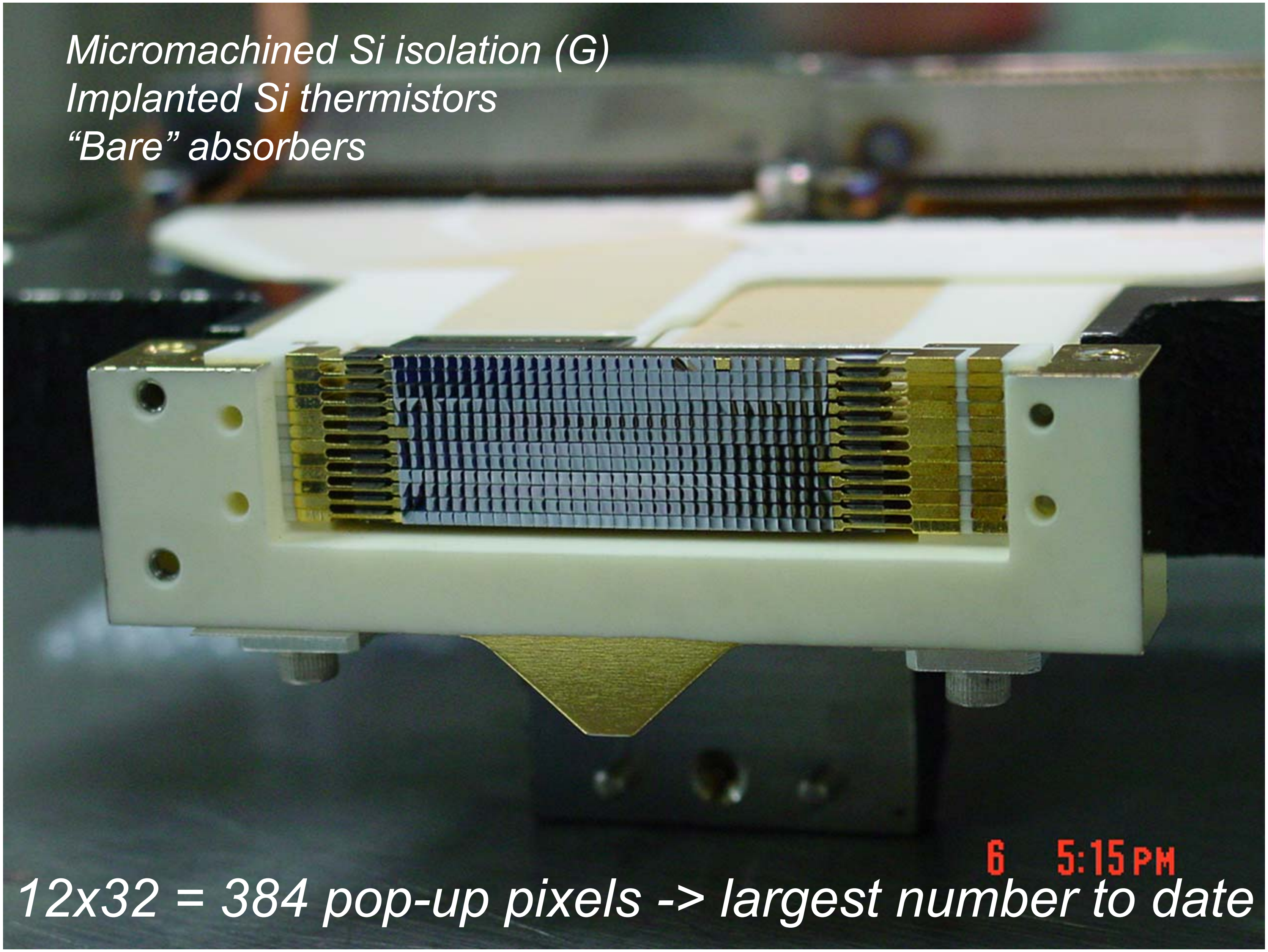
Cosmic rays

Arrays !!!

Etc…

Future detector technologies for radio astronomy

Bolometer Arrays – SHARC II at 350 μm

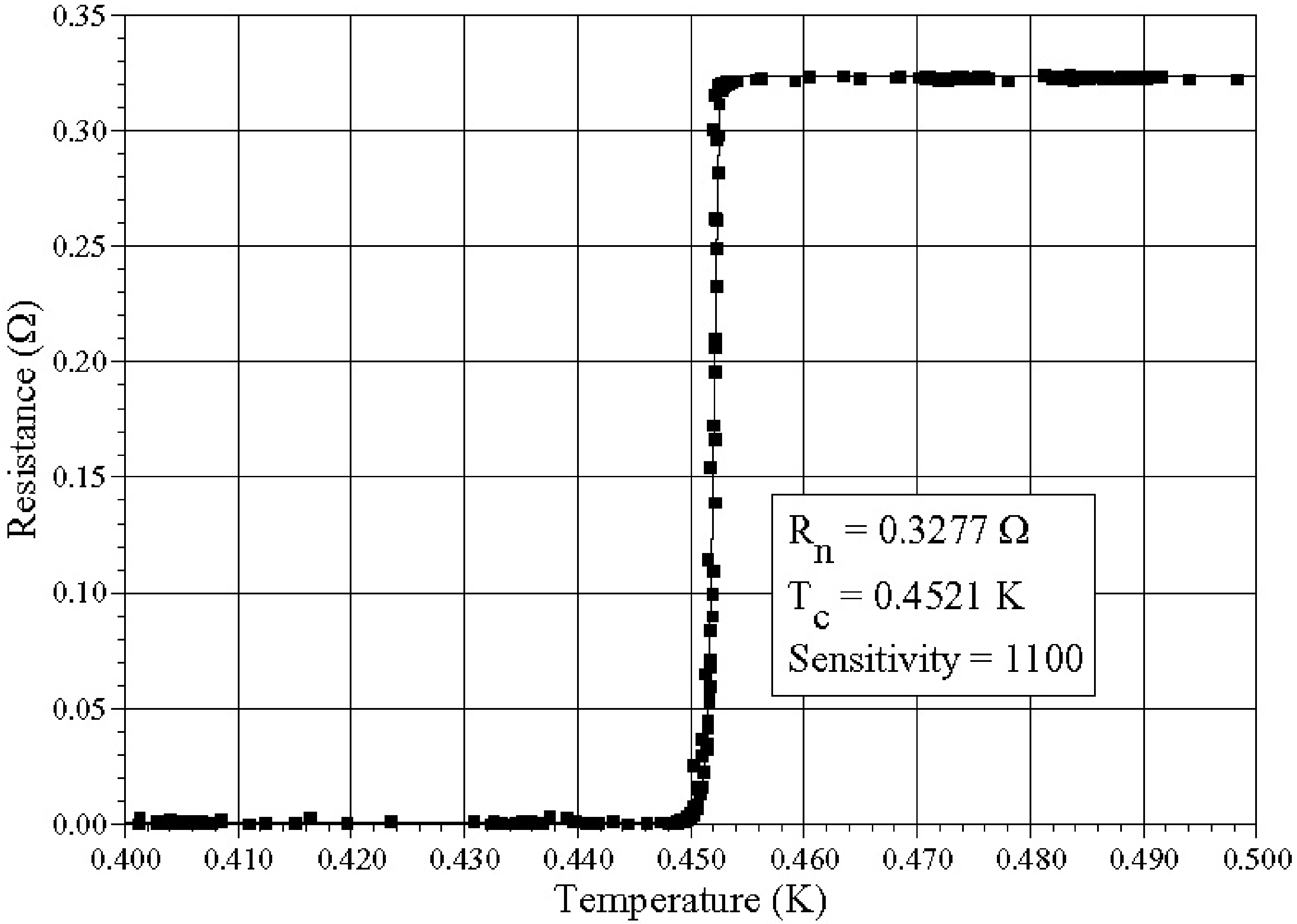


Micromachined Si isolation (G)
Implanted Si thermistors
“Bare” absorbers

12x32 = 384 pop-up pixels -> largest number to date

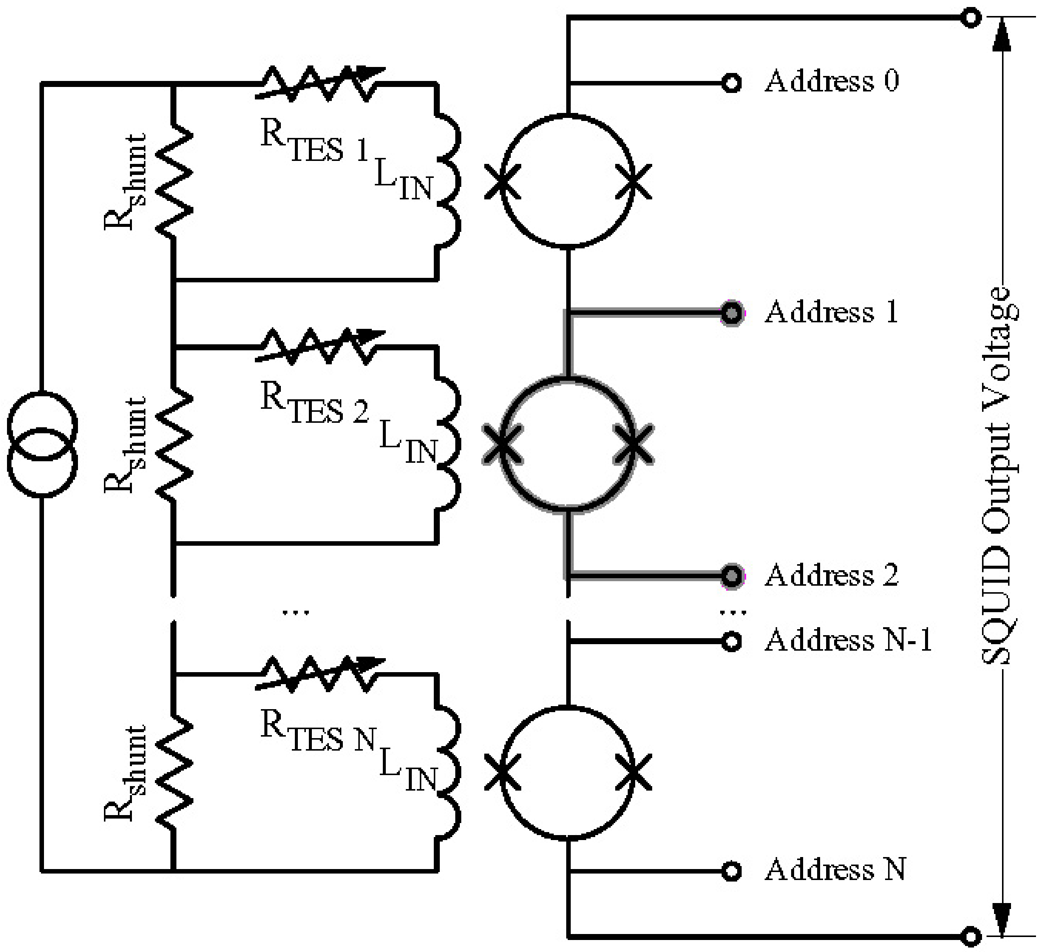
Credit: C. D. Dowell & GSFC

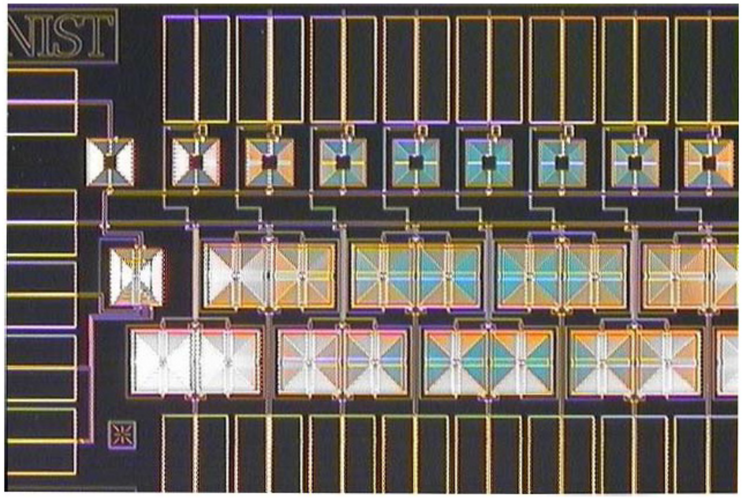
Superconducting (TES) thermistors



Credit: D. Benford

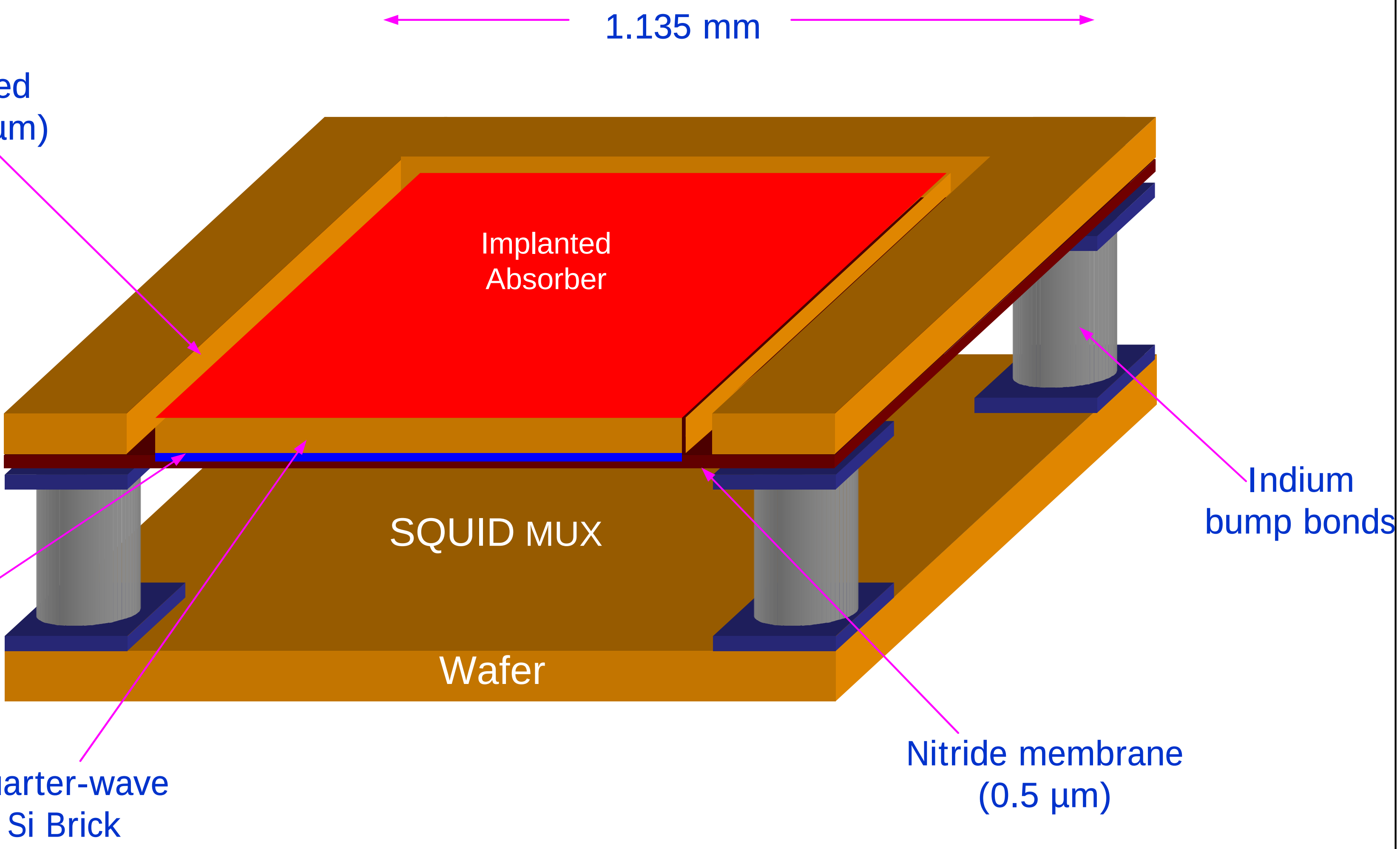
Multiplexing !!! (using SQUIDs)





K. Irwin et al, NIST-Boulder

SCUBA-2 pixel design

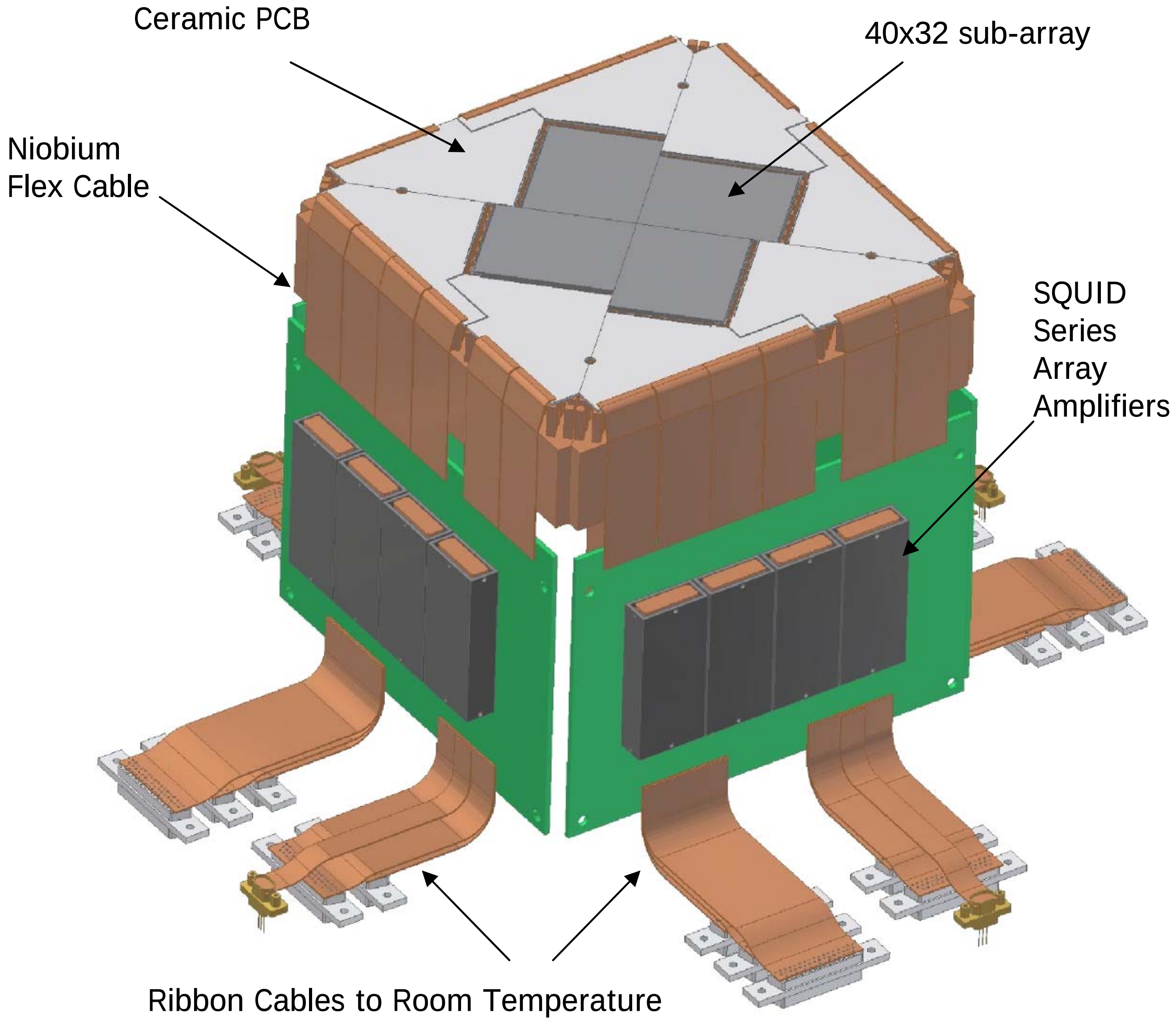


Credit: W. Holland UK ATC

Future detector technologies for radio astronomy

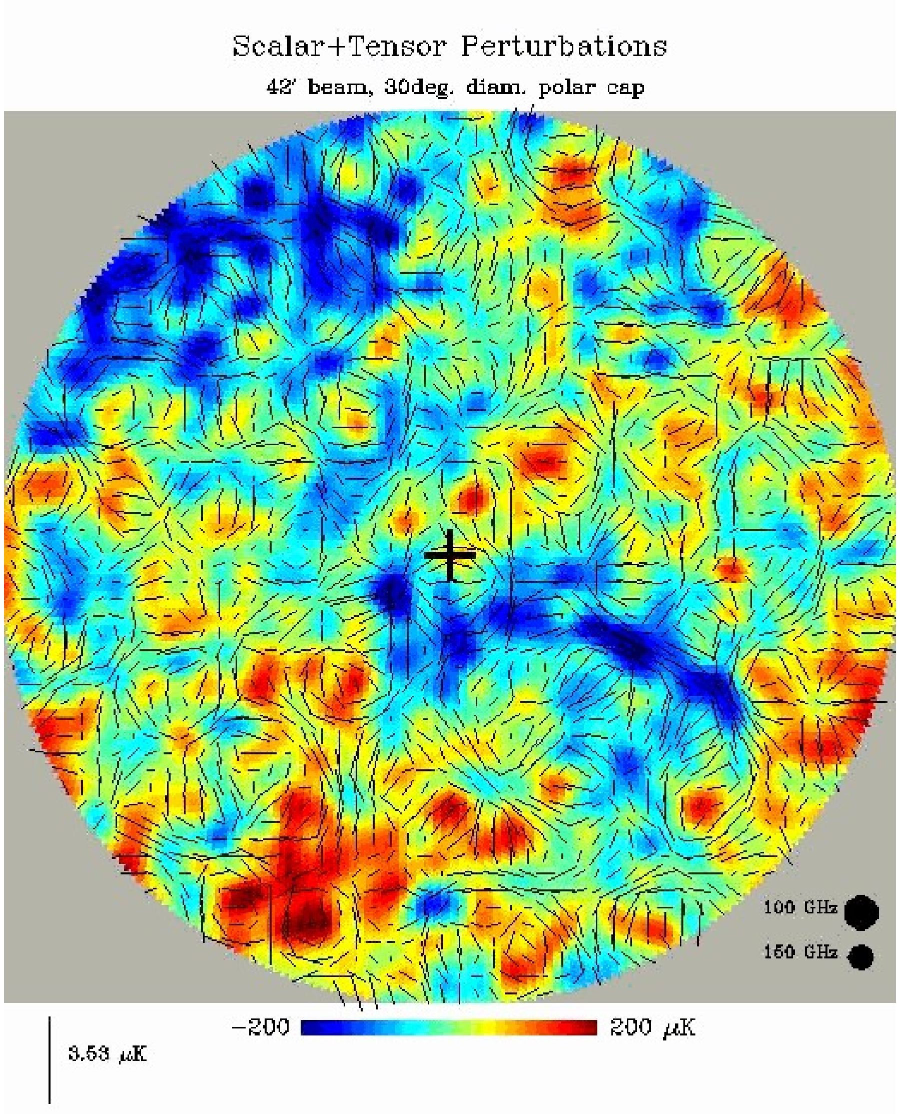
Multiplexed TES bolometer arrays

SCUBA2: 5000 close-packed pixels



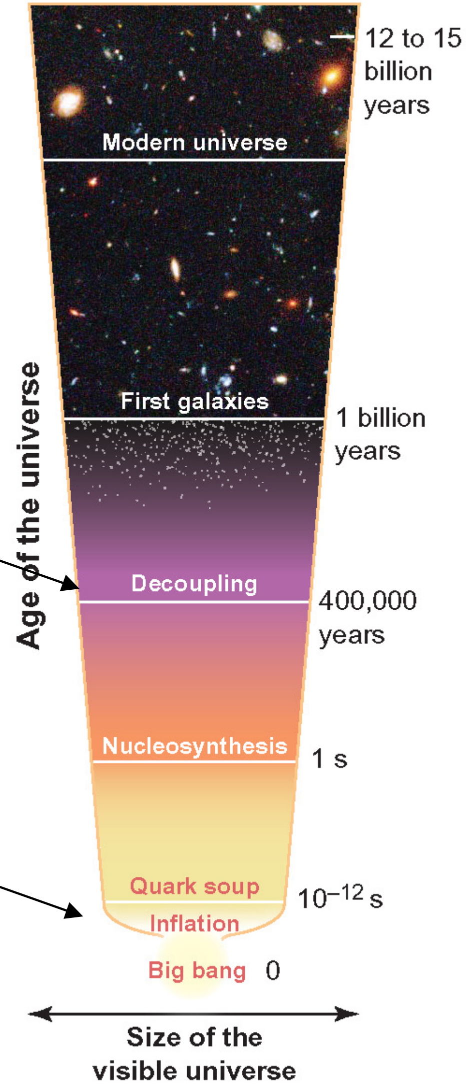
Credit: W. Holland UK ATC

Why more CMB measurements ?
POLARIZATION



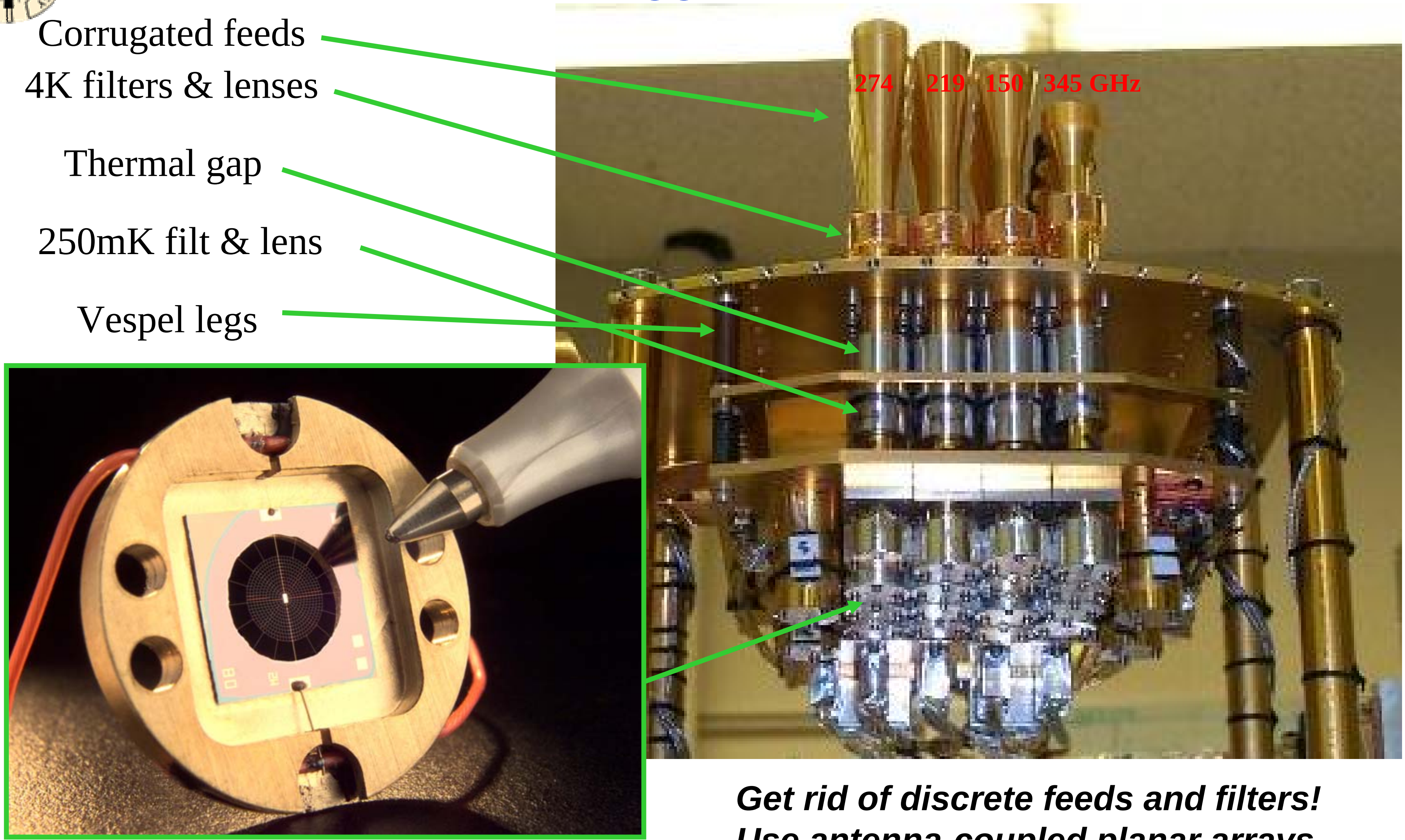
CMB produced

INFLATION



How to Build a Bigger CMB Focal Plane?

Arcminute Cosmology Bolometer Array Receiver



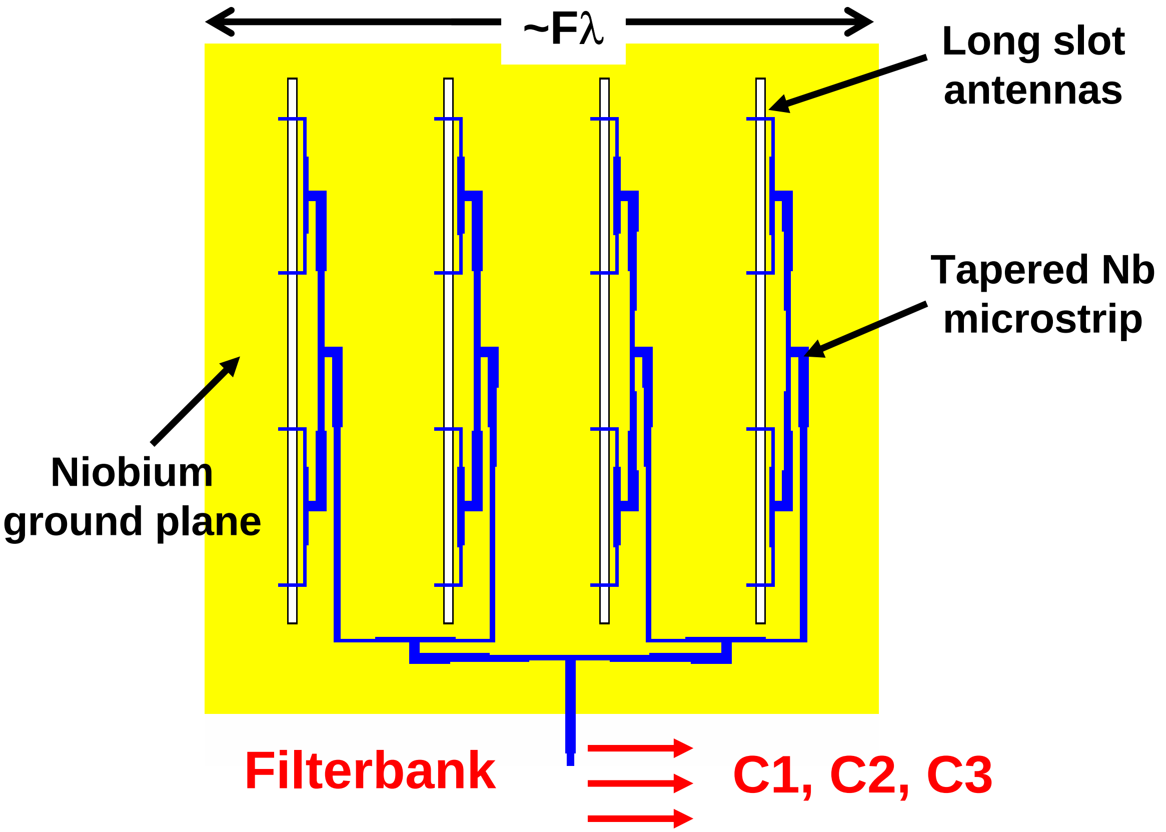
Bolometers from JPL

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

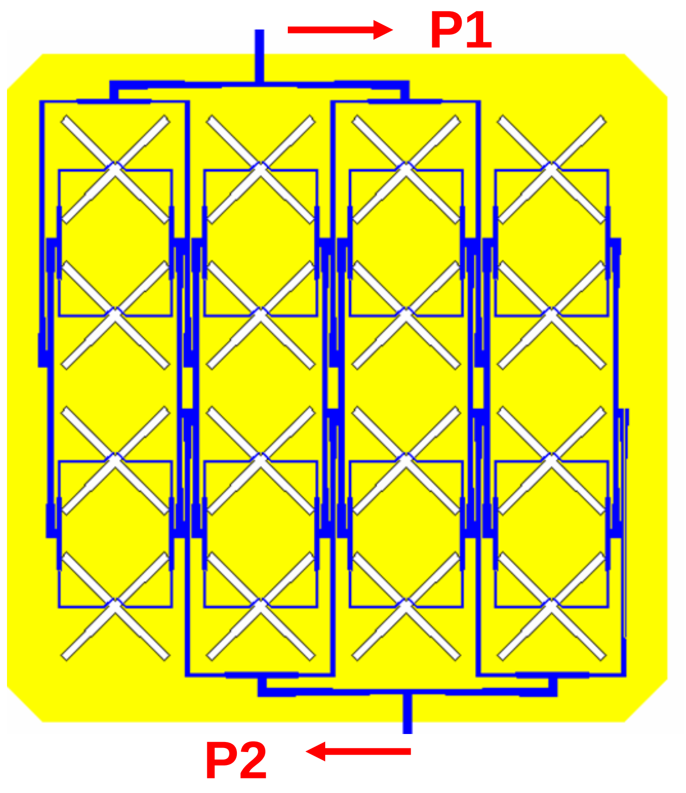
Credit: J. Bock

Narrow-beam planar antennas

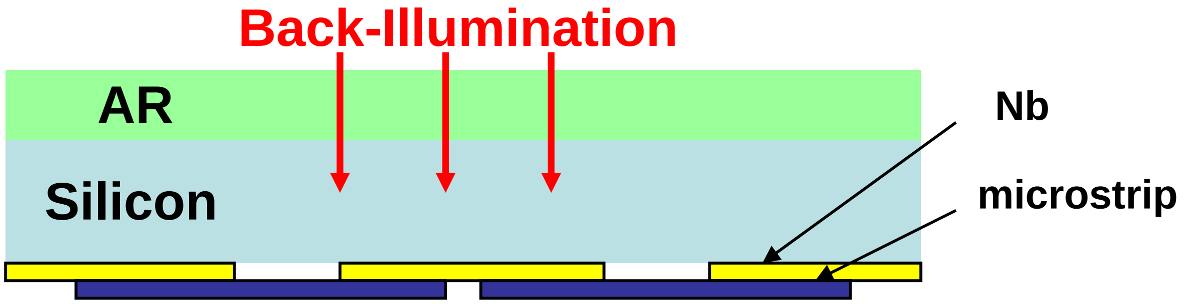
Multi-band, single pol



Single band, dual pol

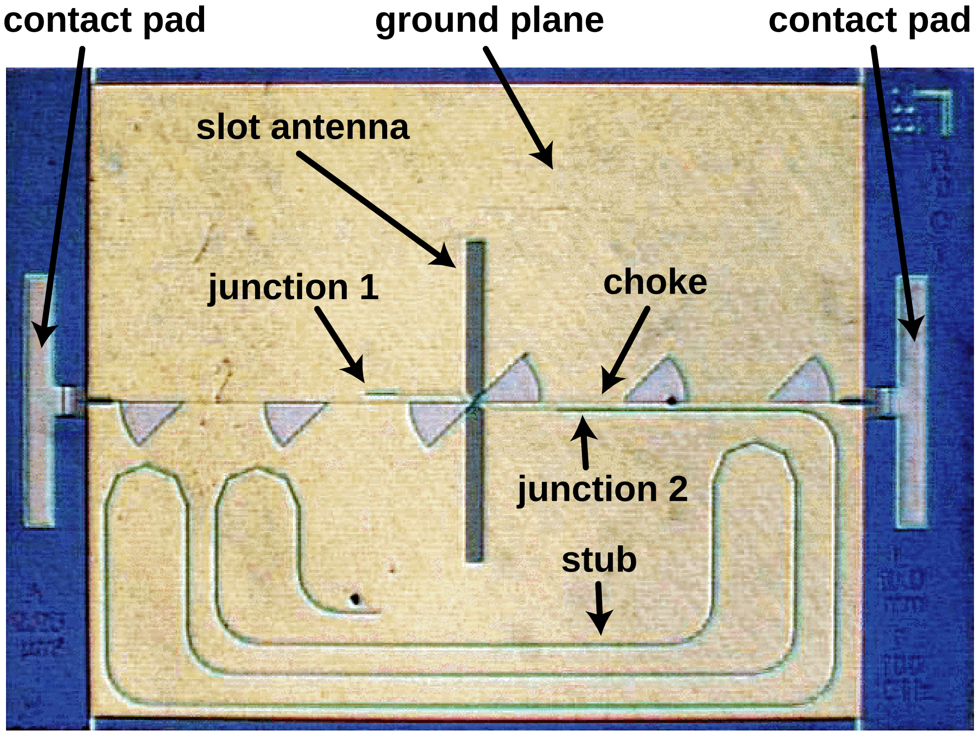


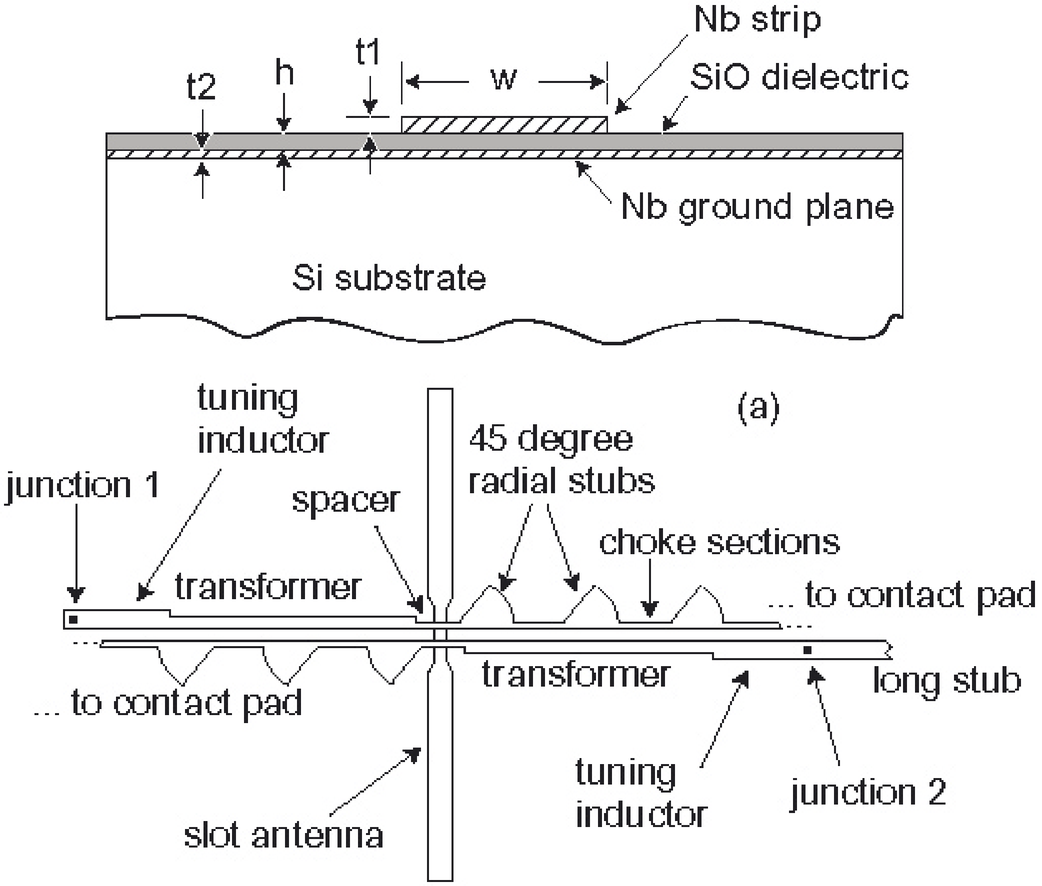
F ~ 3 feasible !
(since microstrip loss is low)



Precision MM-Wave Measurements of Superconducting Microstrip Lines

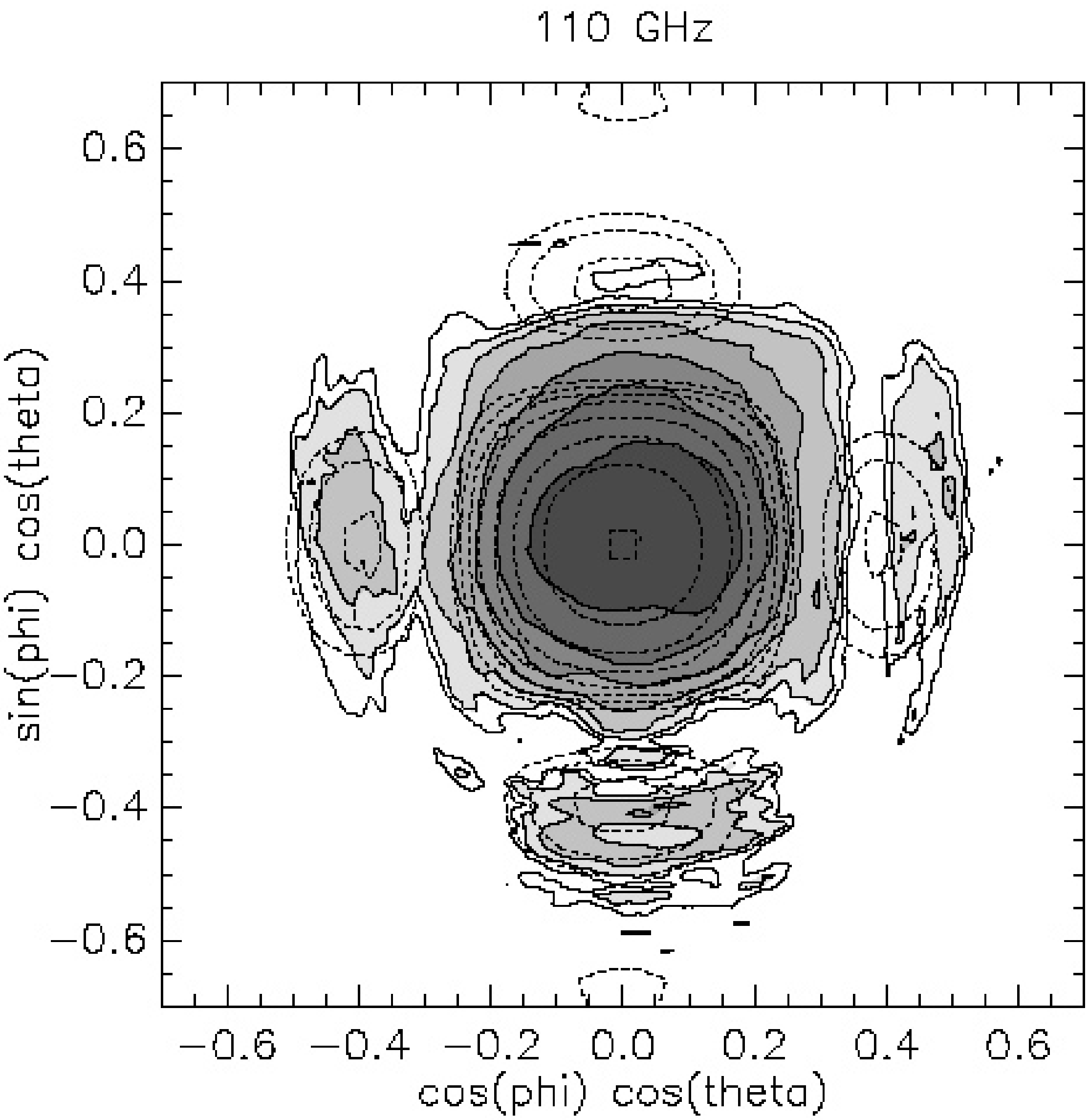
A. Vayonakis et al. (2003), in prep.





100 GHz test chip with 10 mm microstrip stub

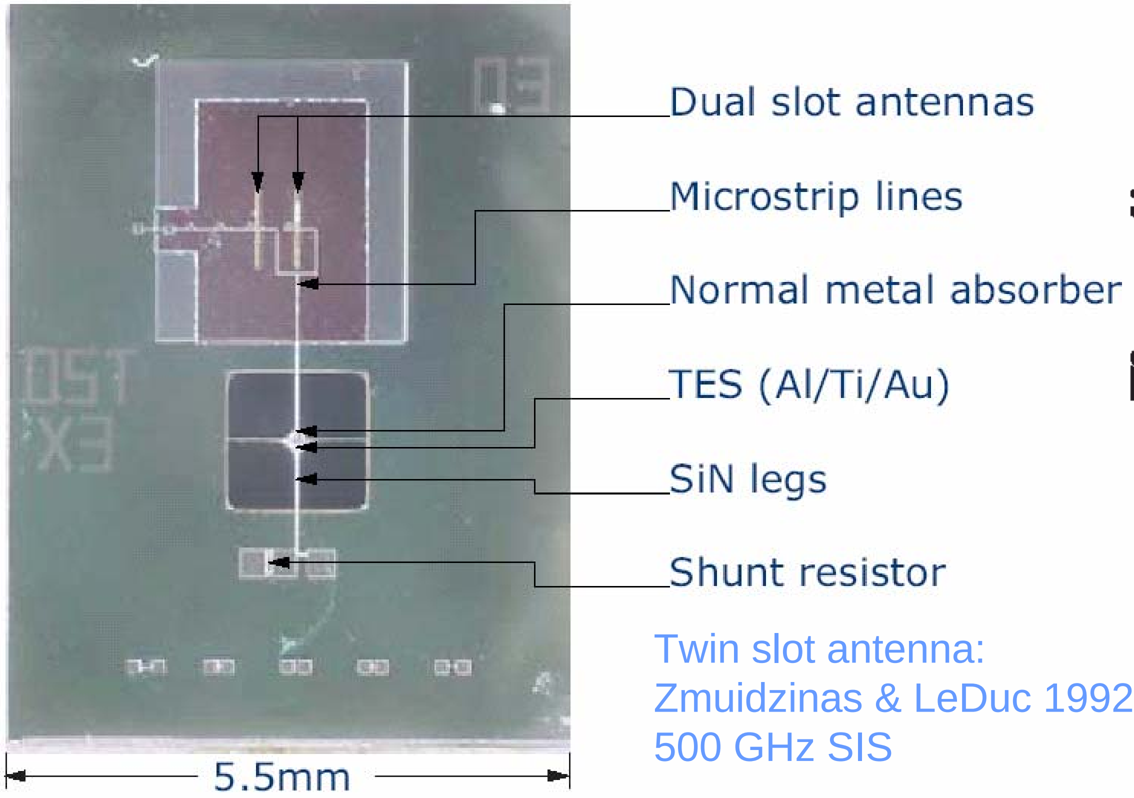
Measured antenna pattern



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

Goldin et al. (2003)

Demonstration of Antenna-Coupled TES



Dual slot antennas

Microstrip lines

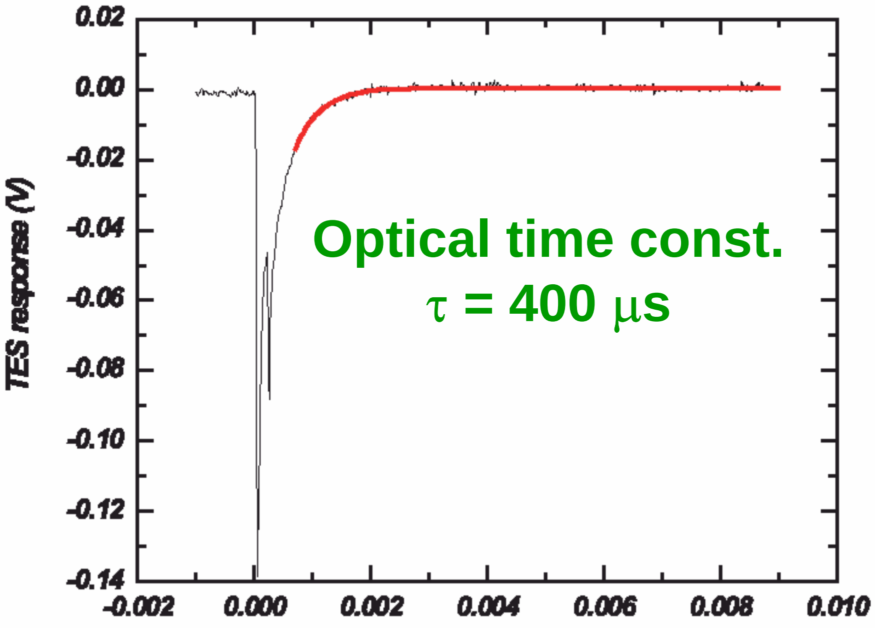
Normal metal absorber

TES (Al/Ti/Au)

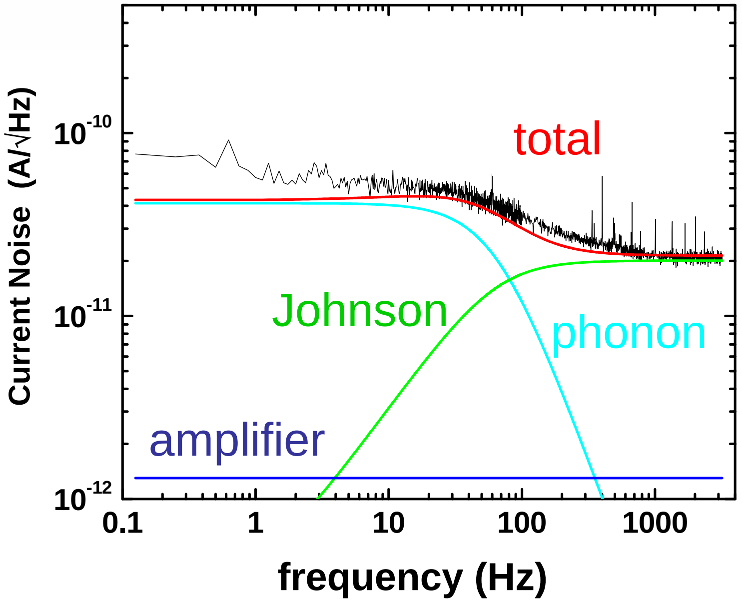
SiN legs

Shunt resistor

Twin slot antenna:
Zmuidzinas & LeDuc 1992
500 GHz SIS



Optical time const.
τ = 400 μs

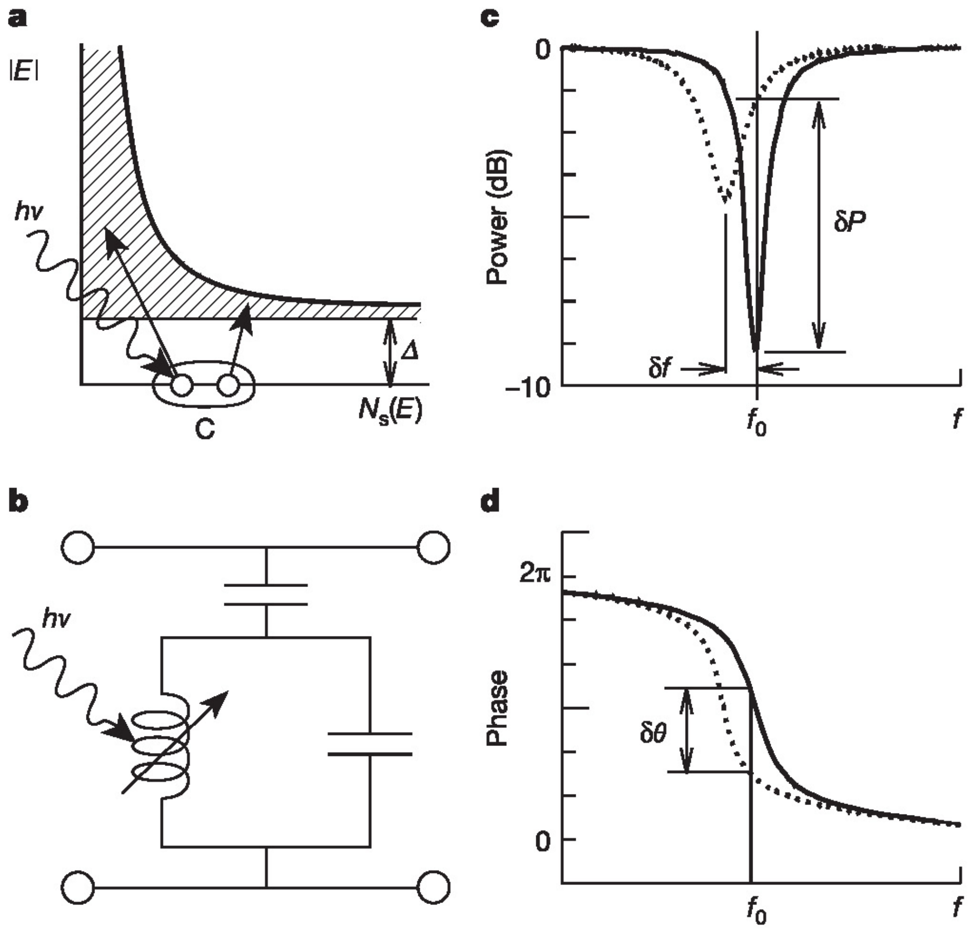


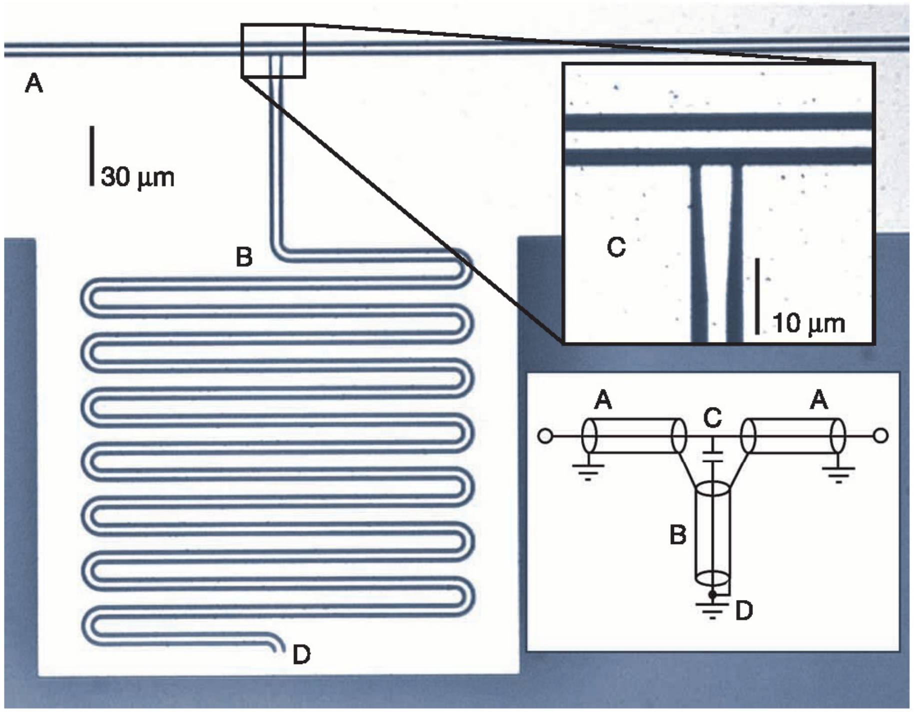
NOTE: twin-slot
needs substrate lens

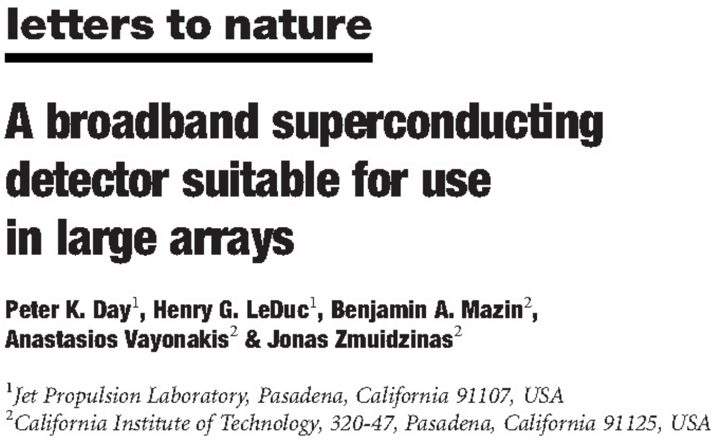
C. Hunt et al. (2003)

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

A new superconducting detector







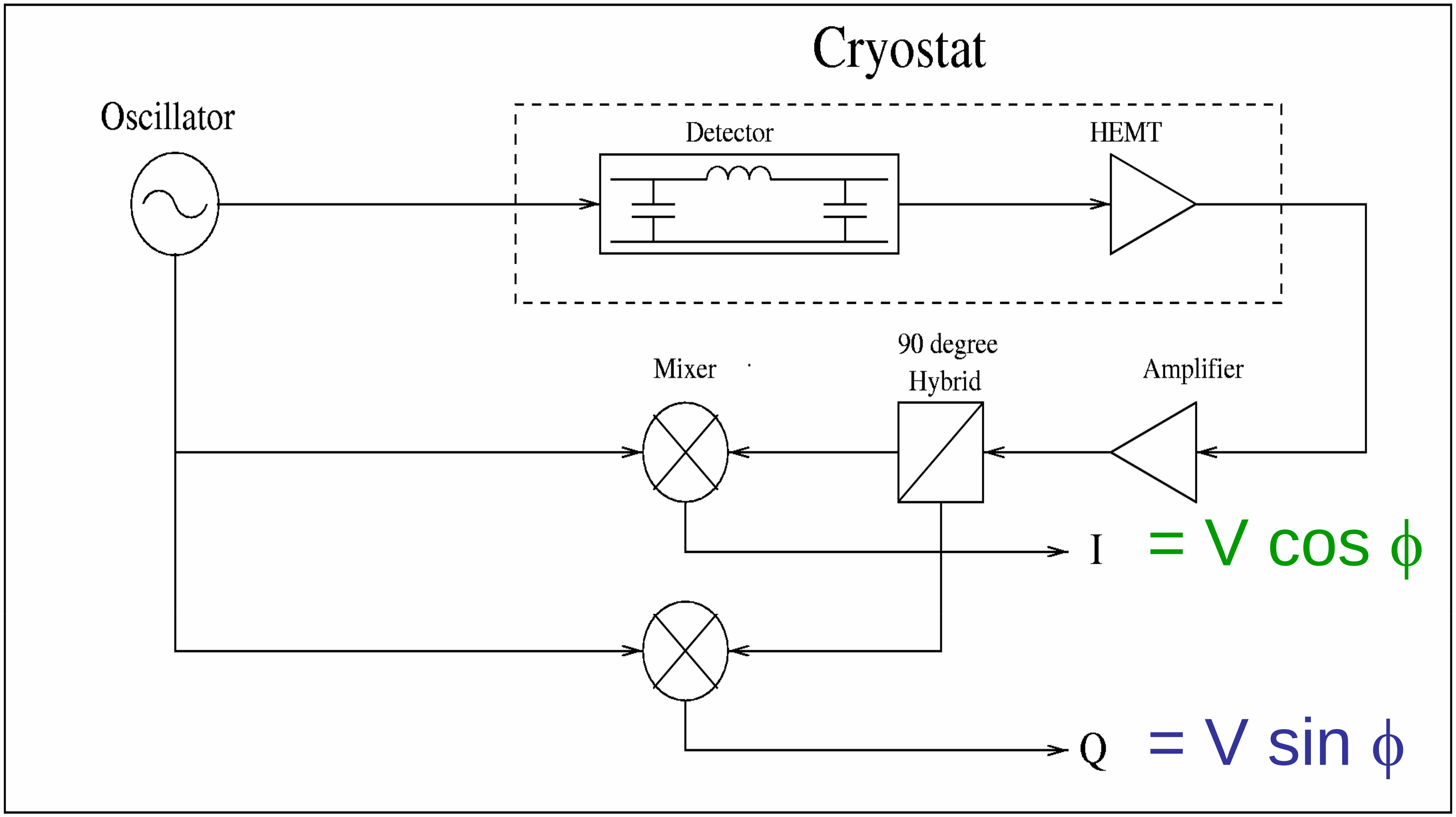
letters to nature

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*

IQ readout of amplitude and phase

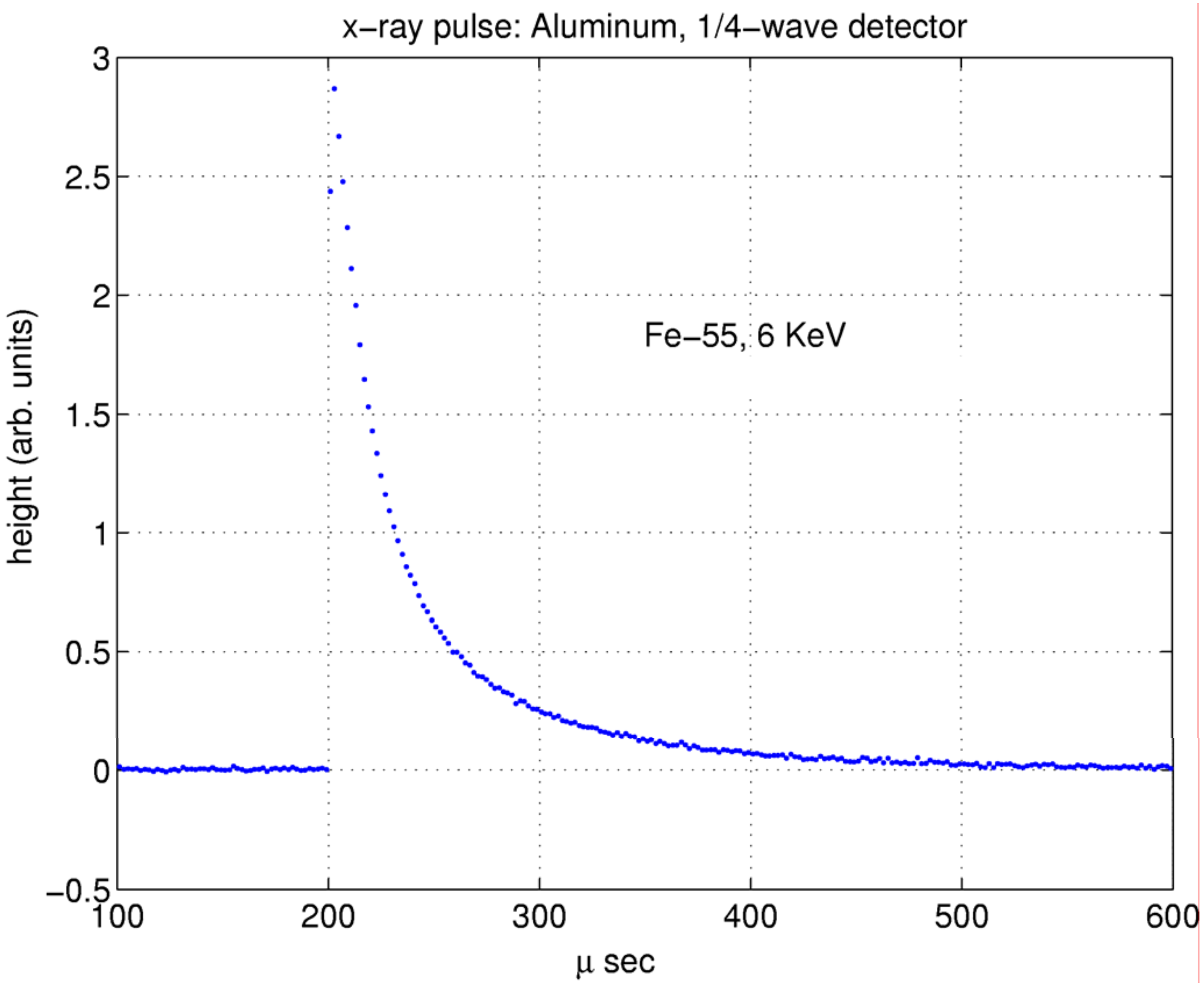


$= V \cos \phi$

$= V \sin \phi$

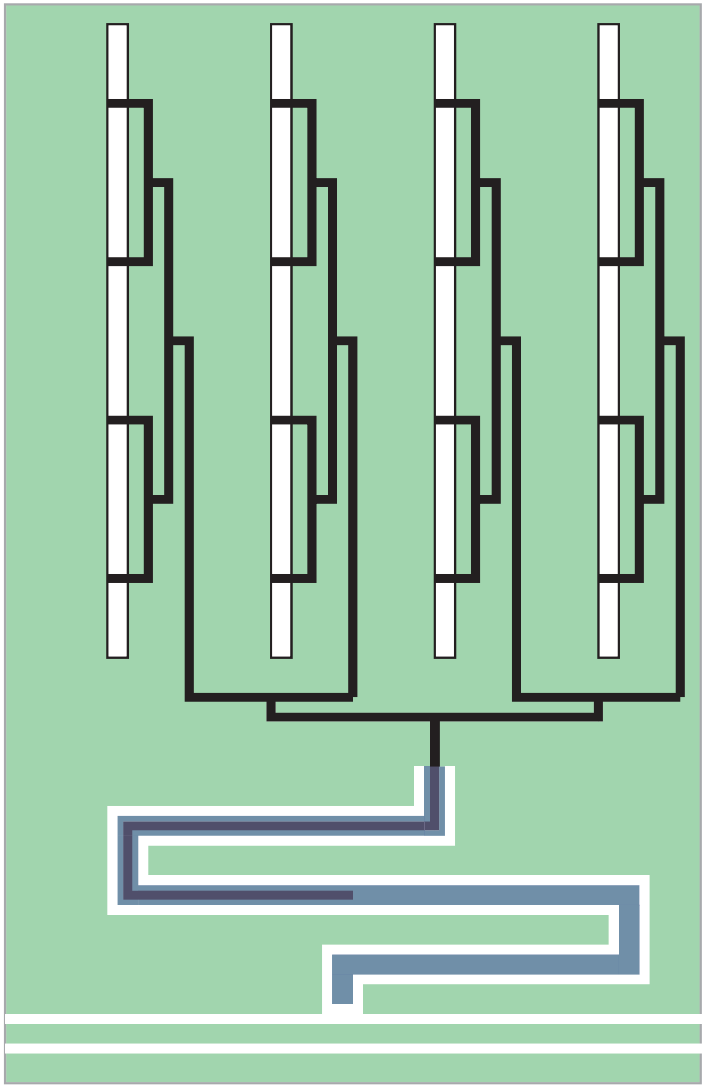
$$V \cos(\omega t - \phi) = V \cos \phi \cos \omega t + V \sin \phi \sin \omega t$$

It works !!!



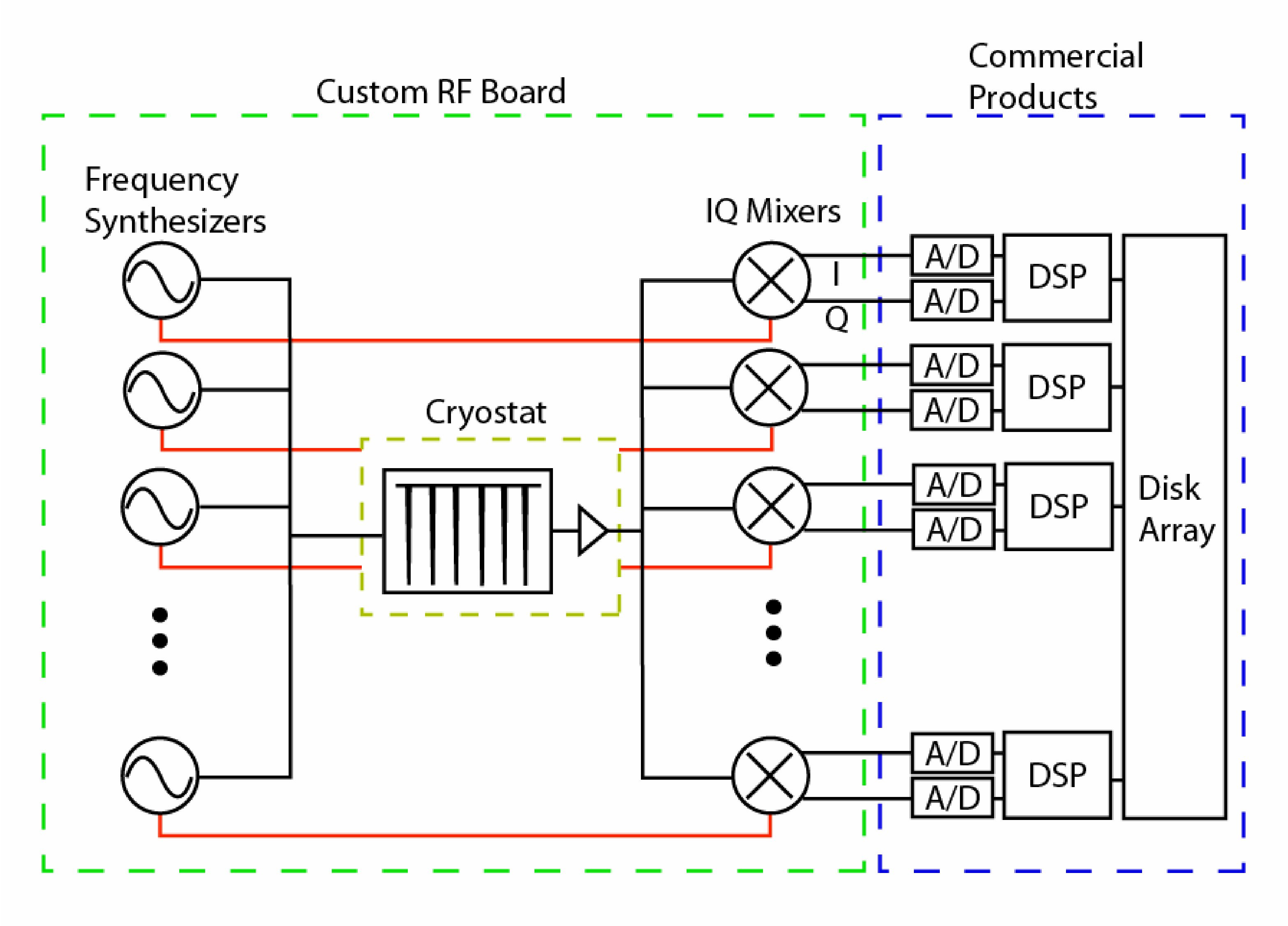
- Rise time: resonator bandwidth
- Fall time: quasiparticle decay
- Nyquist sampled readout
- High pulse SNR:
  - 👎E ~ 11 eV
- Output noise spectrum measured
  - Appears to be dominated by resonator noise
  - Origin not yet determined
  - Readout NEP contribution ~10 dB lower
  - NEP ~ 10^{-16} W / $Hz^{1/2}$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

Antenna-coupled kinetic inductance detector



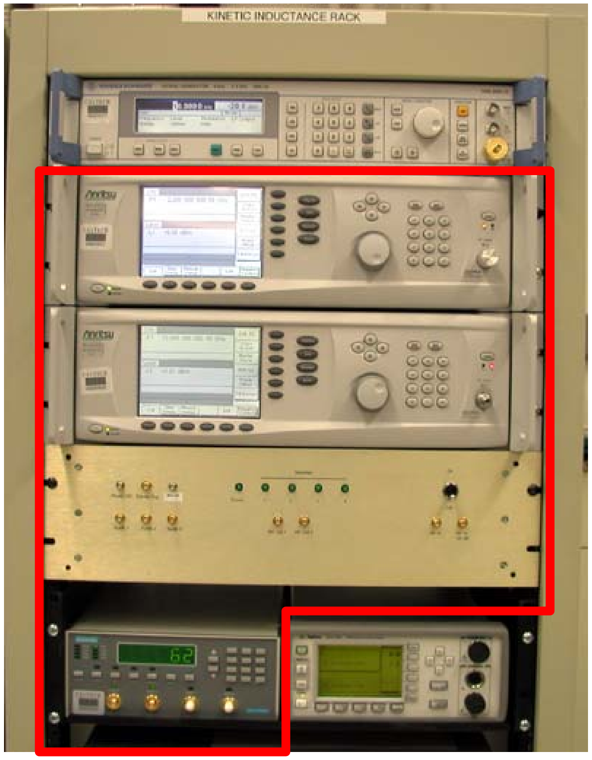
- *Niobium* - ground plane (green) and top microstrip conductor (black)
- *Aluminum* – center conductor of CPW KID resonator (blue)
- Simple to fabricate !
- KID is easy to couple to antenna
- Ultimate NEP limit < 10^{-19} W/Hz$^{1/2}$
- *Demonstrated* NEP already useful for ground-based submm imaging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

Frequency-domain Multiplexing

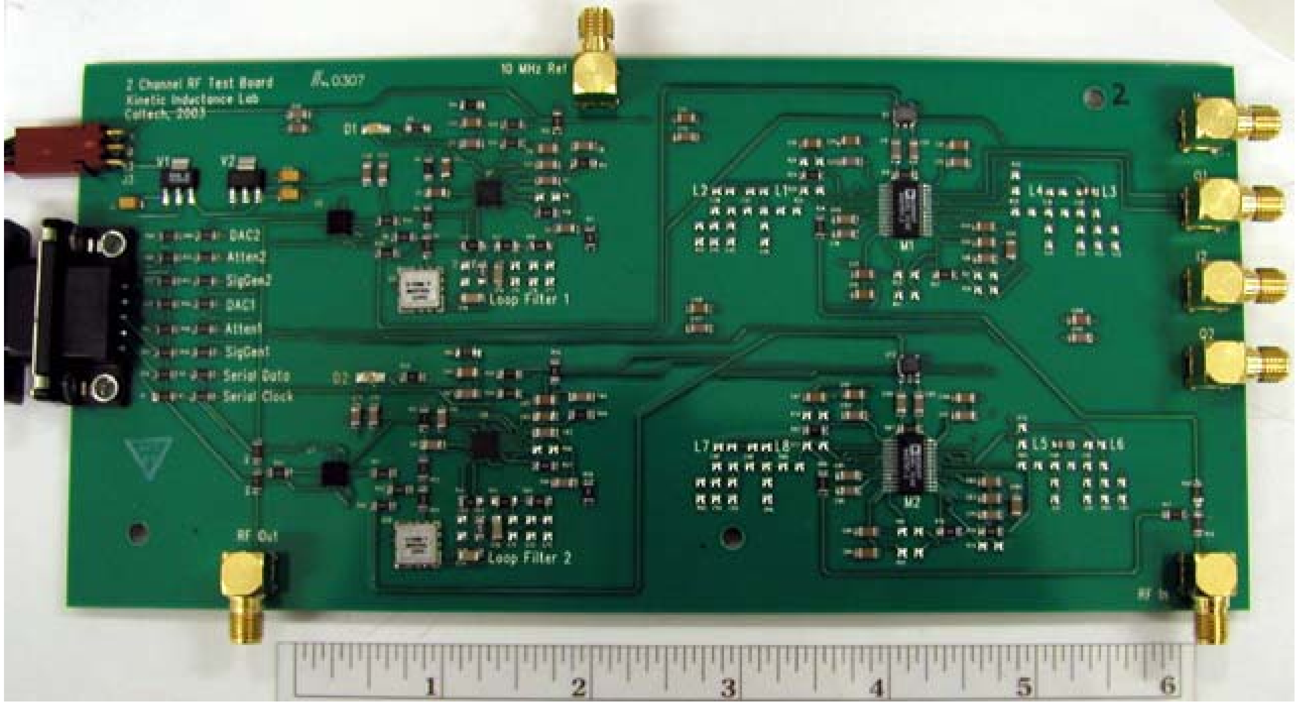


Wireless Technology for Readouts

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

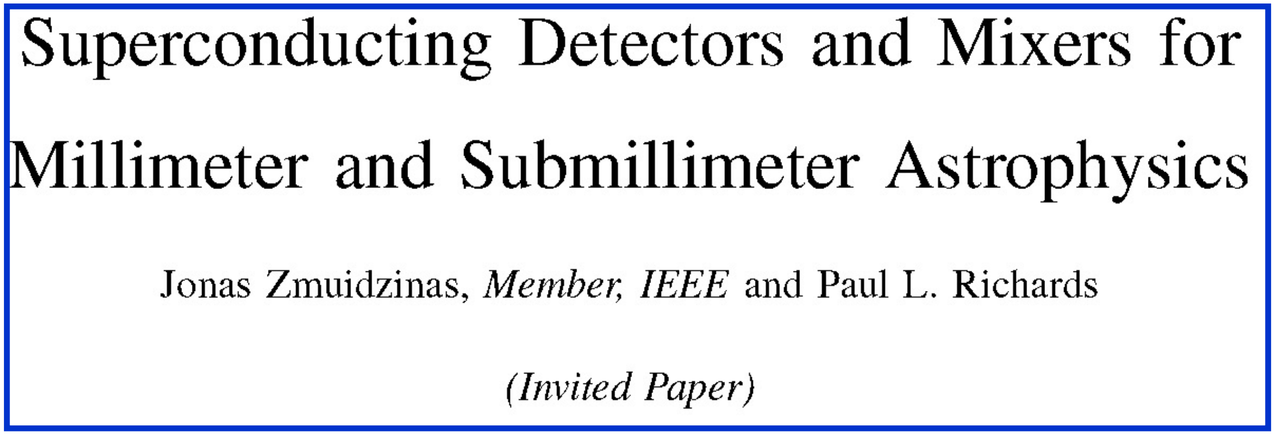


=



Conclusions

- Superconducting detectors are proving to be critical for mm/submm radio astronomy
  - SIS mixers
  - HEB mixers
  - TES/SQUID bolometers ?
  - Integrated CMB focal planes ?
  - KIDs ?



Superconducting Detectors and Mixers for Millimeter and Submillimeter Astrophysics

Jonas Zmuidzinas, *Member, IEEE* and Paul L. Richards

(Invited Paper)

Proc. IEEE, in prep.