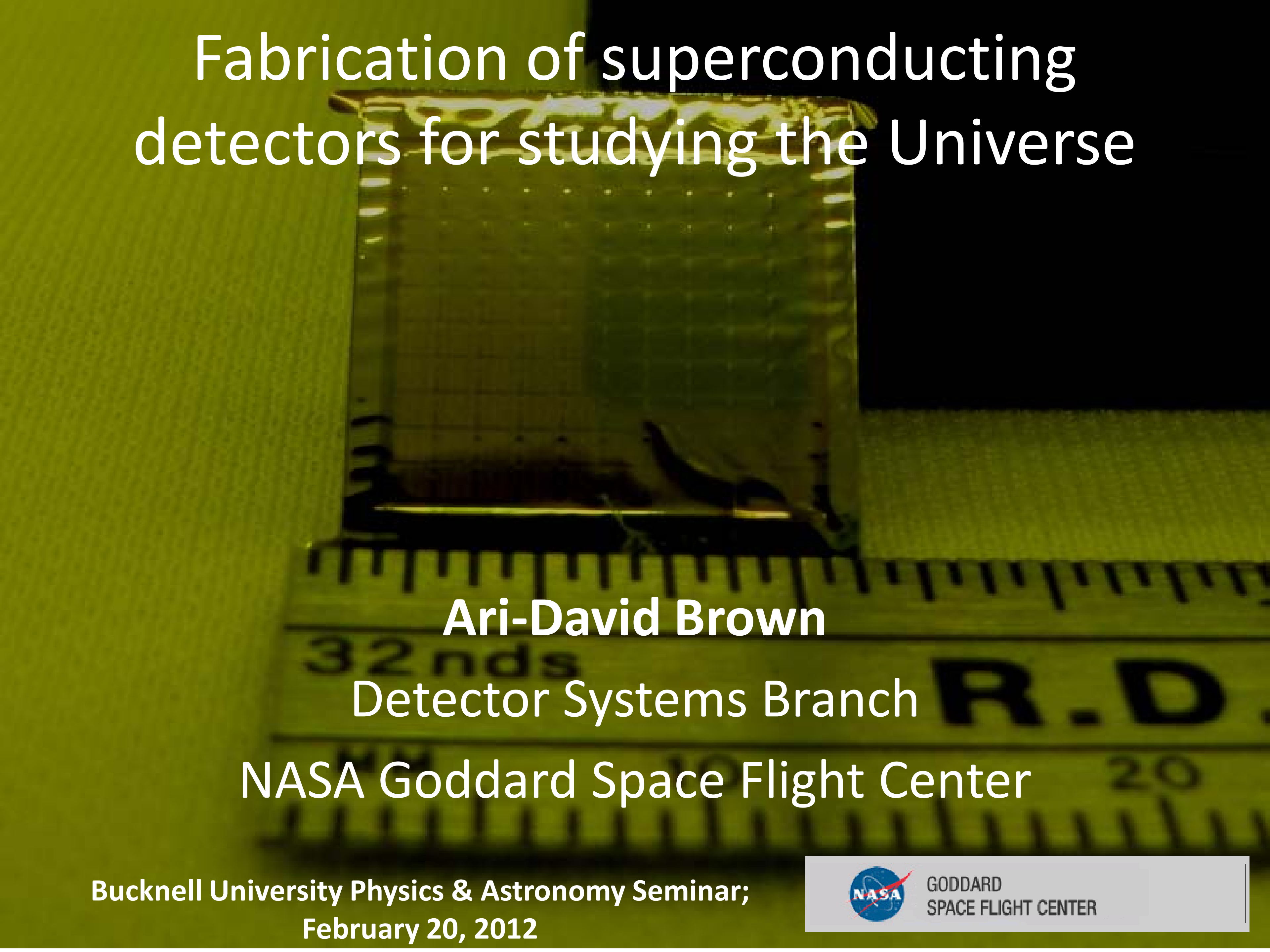

Fabrication of superconducting detectors for studying the Universe

Ari-David Brown

Detector Systems Branch

NASA Goddard Space Flight Center

Bucknell University Physics & Astronomy Seminar; February 20, 2012

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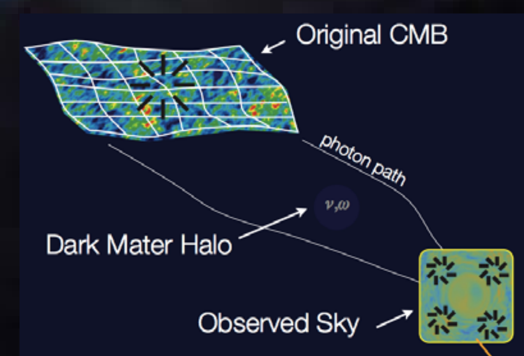
What we can learn by using far-infrared (FIR) astronomical observatories

The age and origins of the Universe.

The presence of water in extra-solar planets.

Stellar formation and evolution.

Searches for dark matter.



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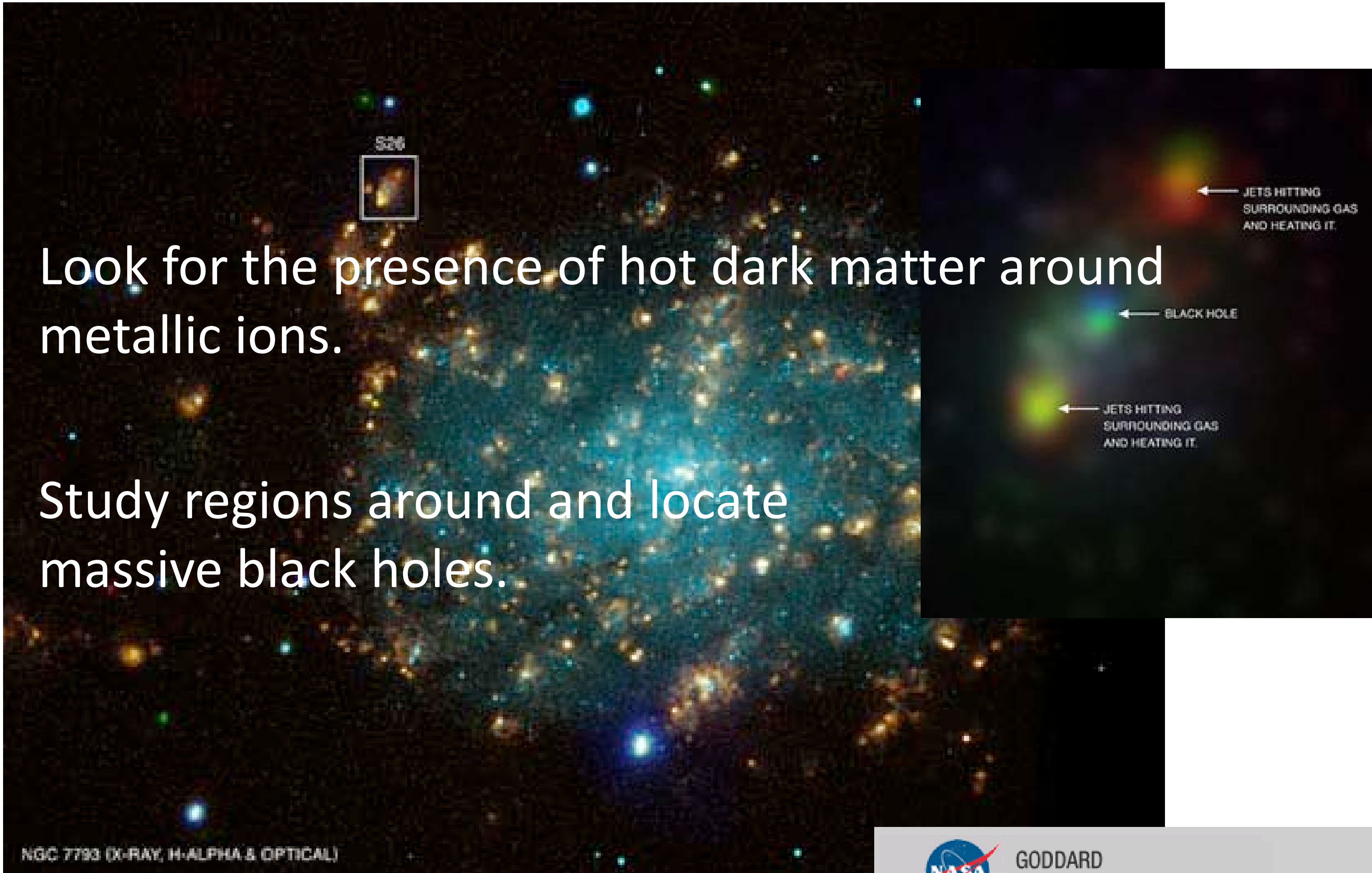
What we can learn by using x-ray astronomical observatories



Look for the presence of hot dark matter around metallic ions.

Study regions around and locate massive black holes.

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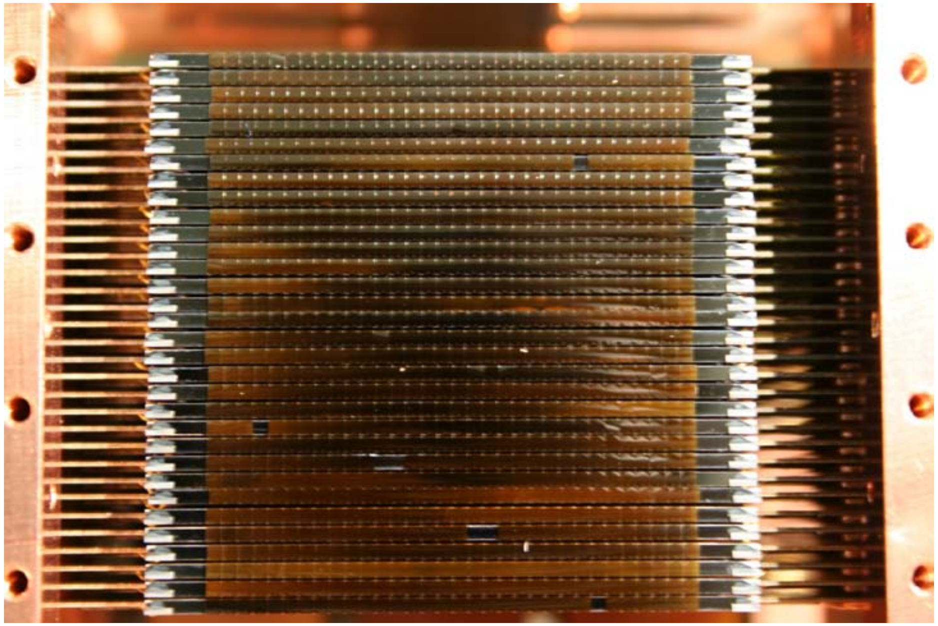
Means of making these measurements: Focal plane detector arrays

- Light is focused onto the focal plane detector arrays via optics.
- Individual detector elements populate the focal plane -> good spatial resolution.
- A focal plane detector has a very small form factor, which allows for low hardware mass.
- A focal plane geometry facilitates integration with other components (e.g., antireflection coatings and backshorts).
- Focal plane array realization is highly dependent on advances in fabrication and packaging.



Pop-up bolometric detector array on the Atacama Cosmology Telescope (ACT).

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Why use superconducting detectors?

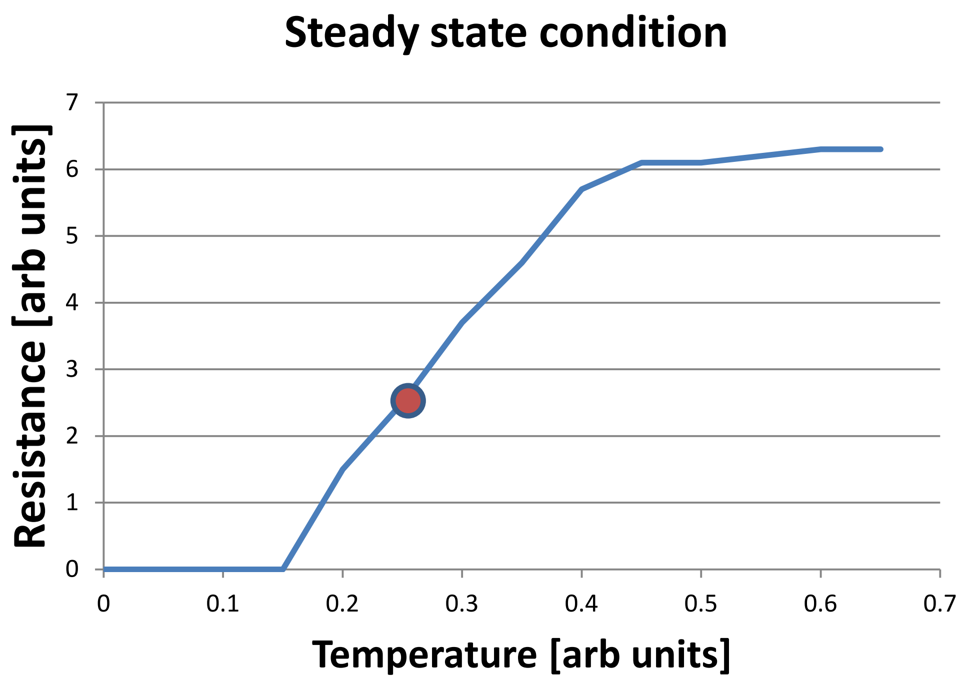
- Operate at cryogenic temperature => Good signal to-noise

- High heat capacity => Large dynamic range

- Somewhat easy/inexpensive to set relevant parameters

Transition edge sensors (TES)

- Bias a superconductor so that it is in the transition region of its R vs T curve.
- A small change in the TES temperature will cause its resistance to increase.
- This will cause the current flowing through the TES to decrease.
- The change in current is detected by a SQUID.



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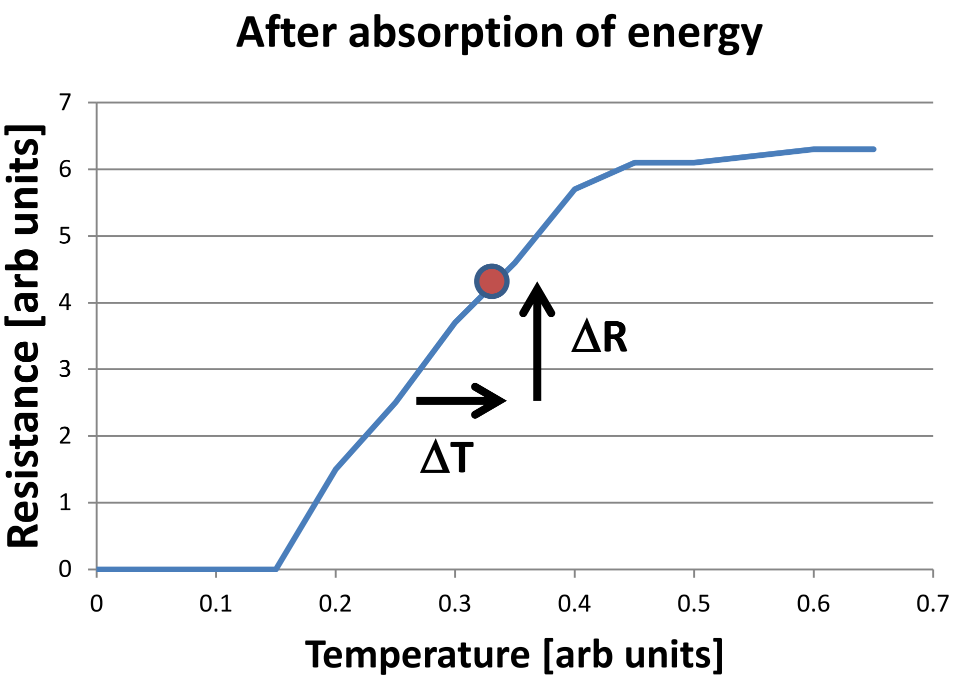

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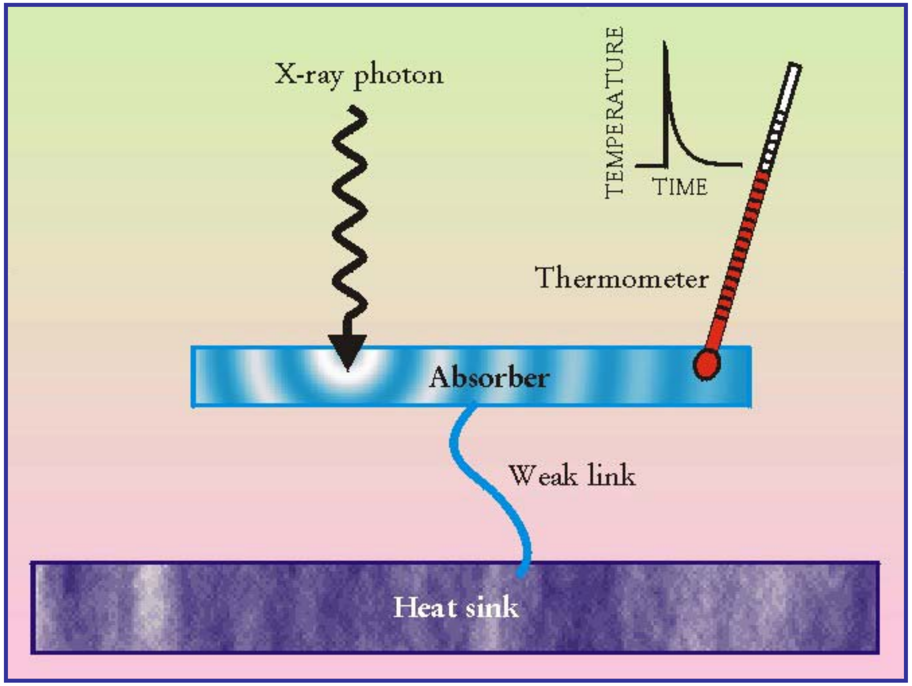
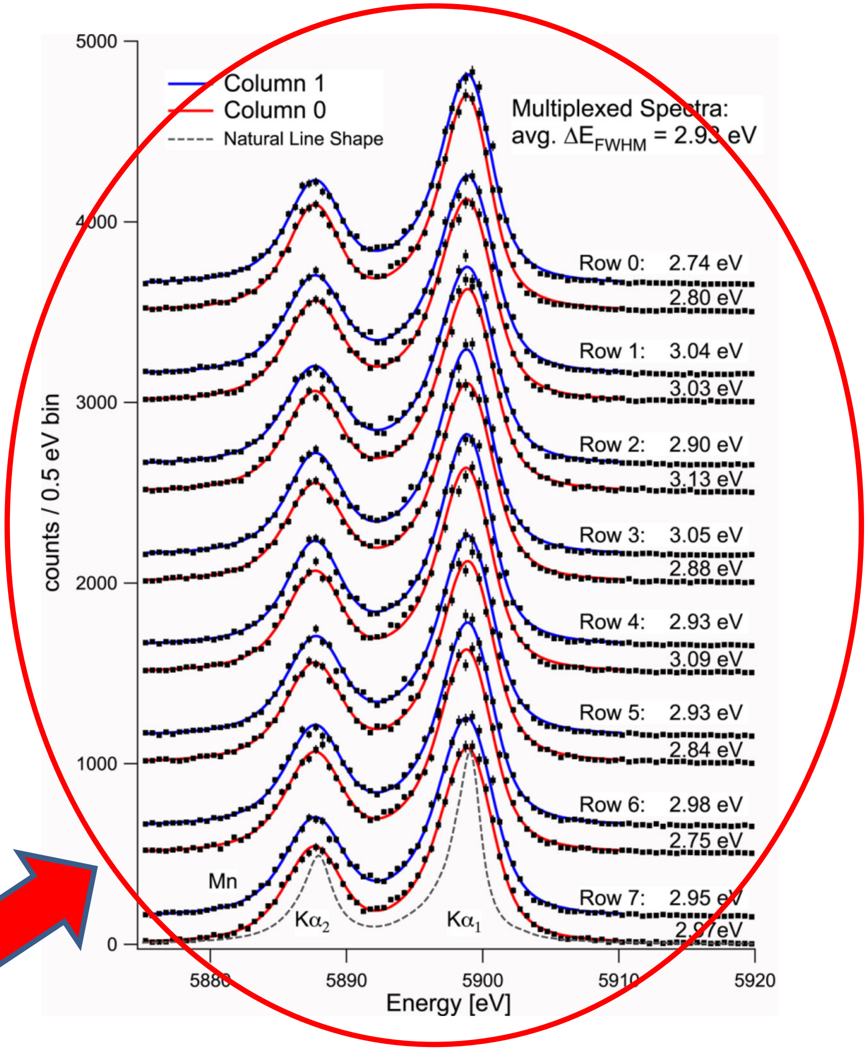
TES for x-ray instrumentation





World-record breaking energy resolution for high quantum efficiency x-ray detectors!

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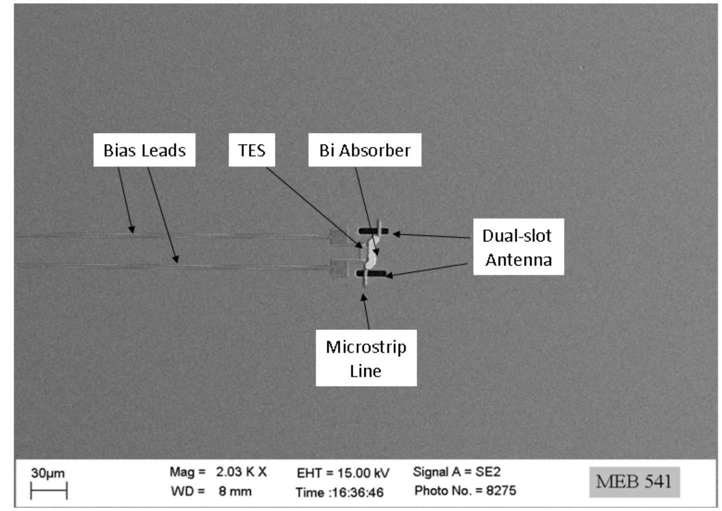
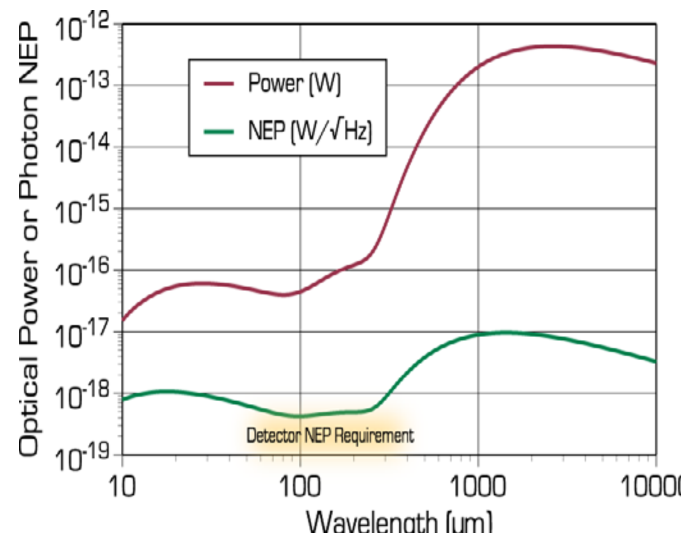
TES for FIR

- Radiation couples to antenna.
- Resistive absorber heats TES.
- Electron/phonon temperature difference dominates noise.
- The noise equivalent power (NEP) of these sensors is approaching the background-limited noise of the cosmic microwave background.





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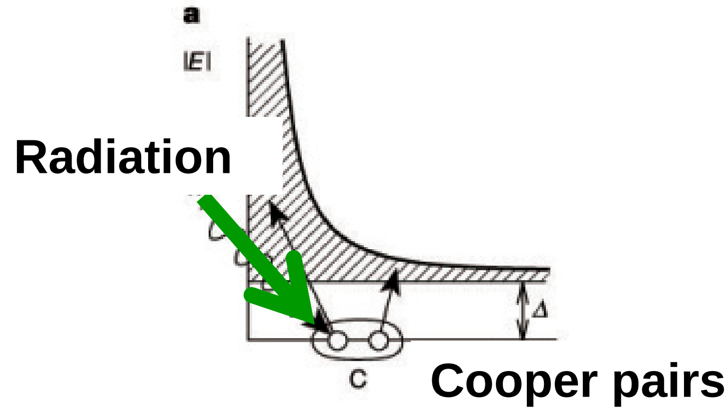
Microwave kinetic inductance detectors (MKIDs)

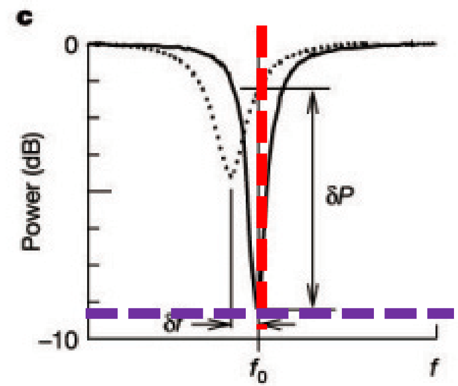
Break a superconducting detector's Cooper pairs with incoming (sub-mm, FIR) radiation.

- This increases in the detector's kinetic inductance L_k and surface resistance R_S.



When the detector is integrated as part of a resonant circuit, the change in L_k, R_S results in:

- A decrease in resonant frequency
- A decrease in power absorbed by the resonator



*P. Day et al, *Nature* (2003)

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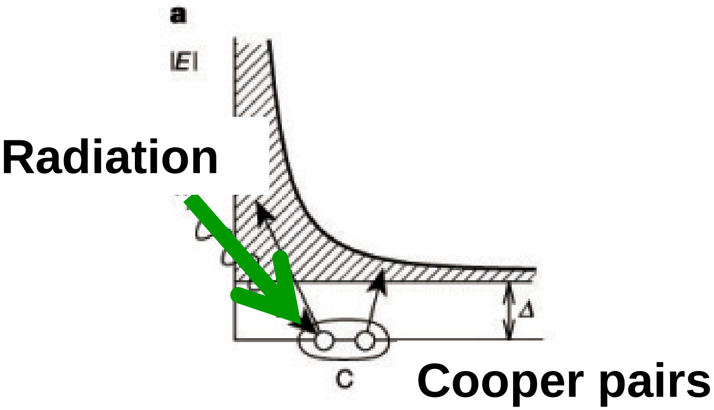

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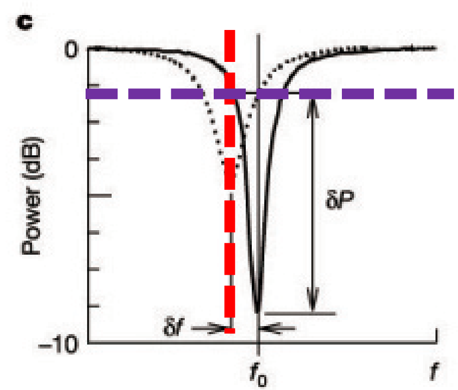

*P. Day et al, *Nature* (2003)

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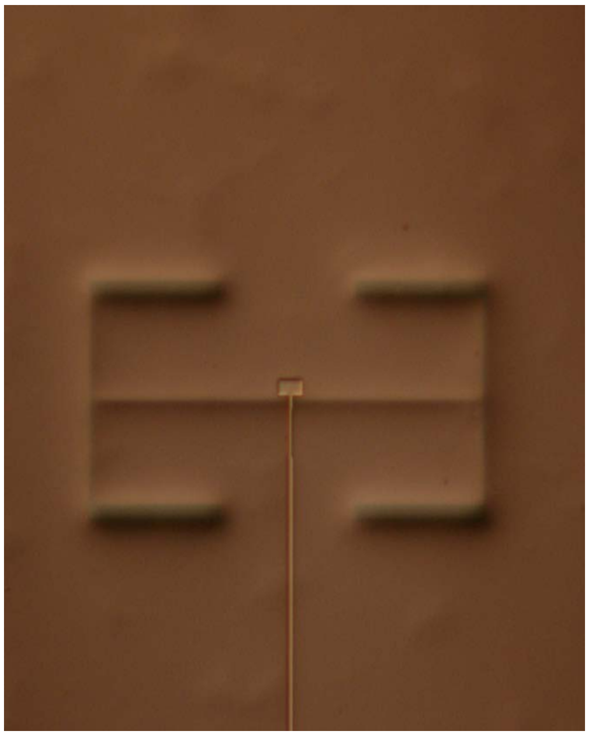
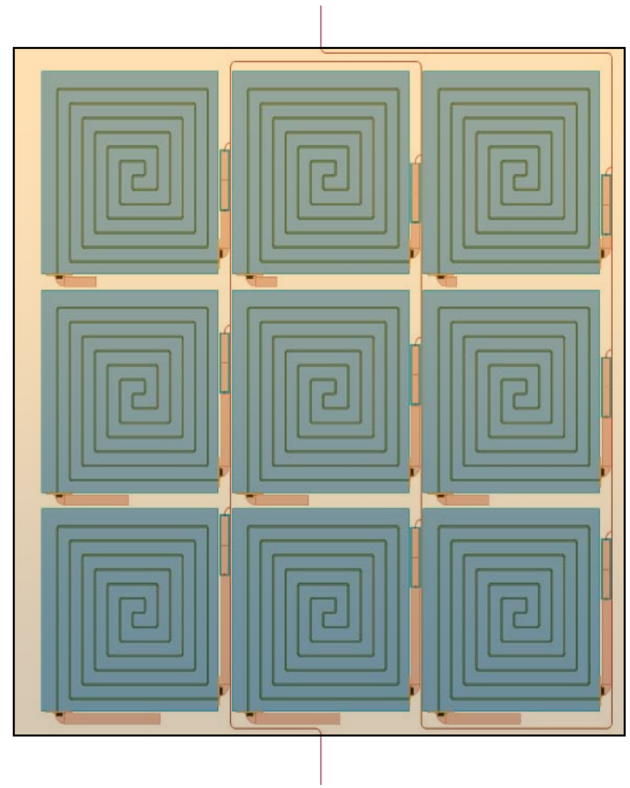
MKIDs as far-infrared detectors

Antenna-coupled



Incident power is coupled to antenna, which is then absorbed by a resistive(at that *f*) KID.

Absorber-coupled



Incident power is coupled to broadband absorber which acts simultaneously as KID.

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Device Fabrication

Fabrication Tools Inside Cleanroom

Physical vapor deposition systems

For depositing thin dielectric and metal films on Si wafers

Fabrication Tools Inside Cleanroom

Photoresist spinners and mask aligners

For creating masks to pattern the thin films

Fabrication Tools Inside Cleanroom

Plasma etchers and corrosive chemicals

To etch the thin films as well as the silicon substrates

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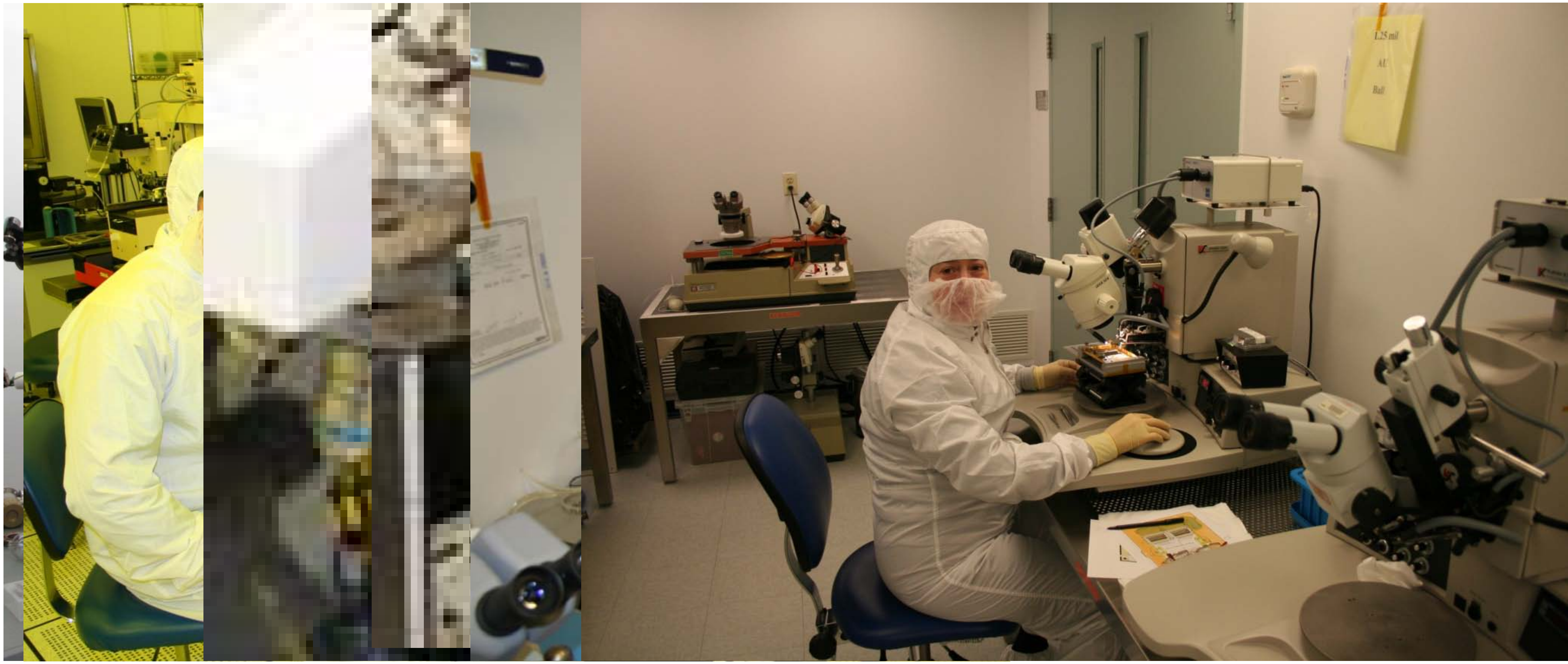
Fabrication Tools Inside Cleanroom

Wafer bonders

To bond Si wafers together

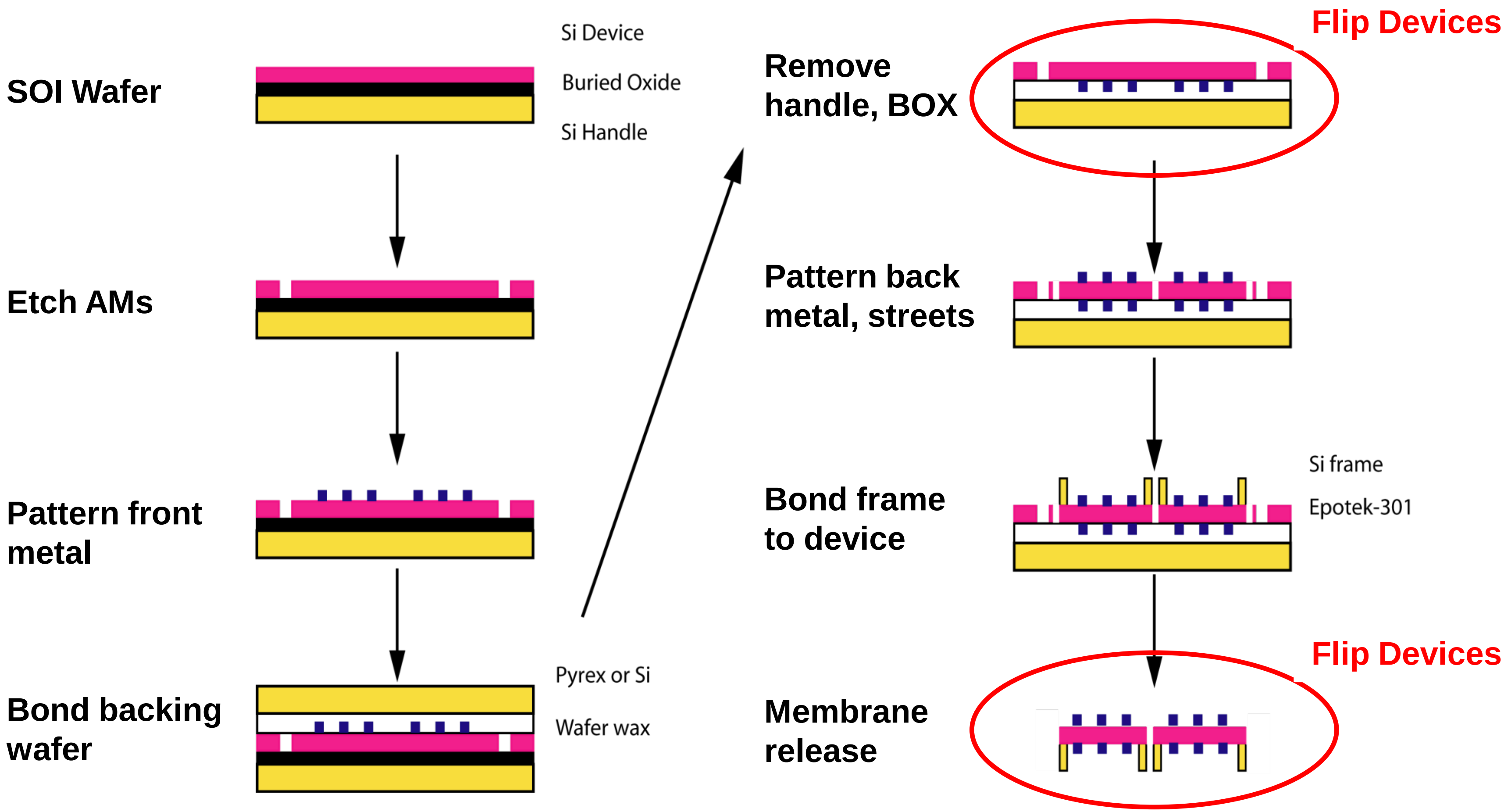
Fabrication Tools Inside Cleanroom

Wire bonders



To integrate detectors with readout electronics and/or amplifiers

Example of an MKID Fabrication Process



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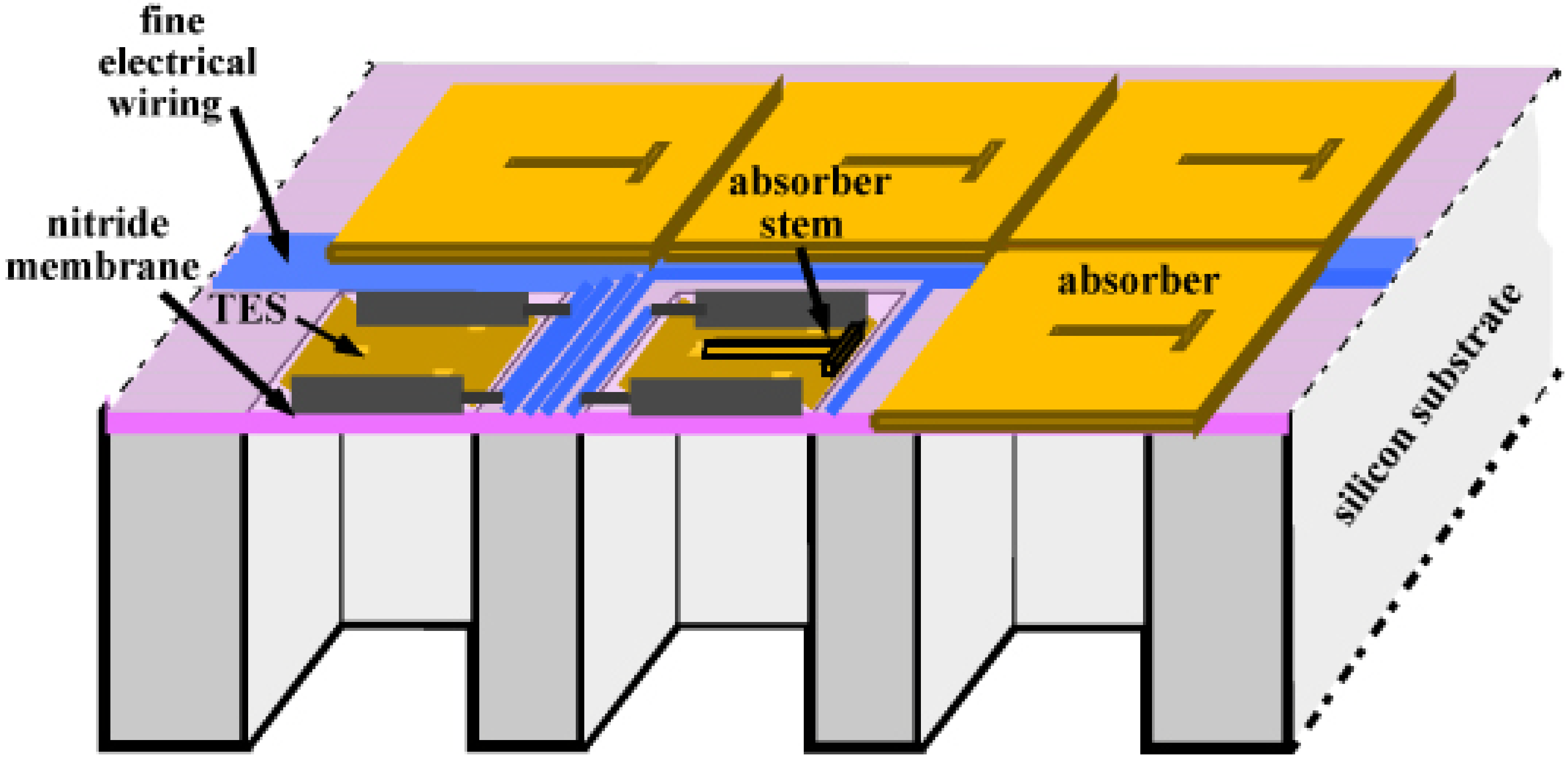
Architecture of x-ray TES



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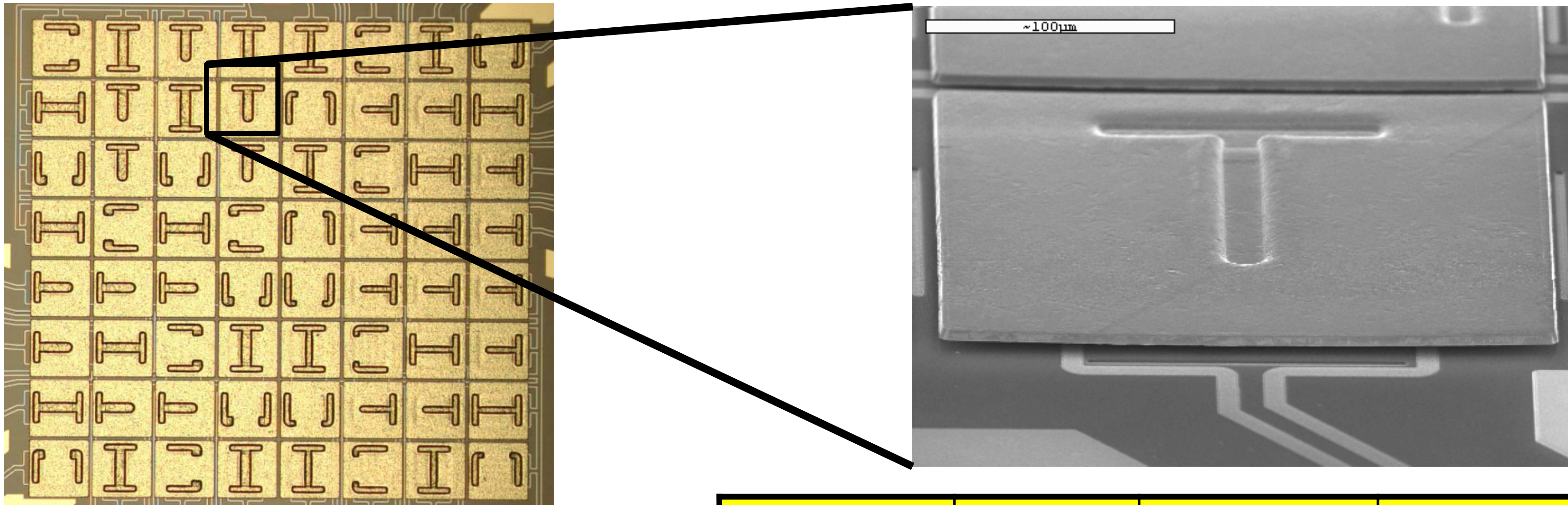
Fabrication developments for x-ray TES: Cantilevered "mushroom" absorbers



8x8 TES Array

Absorber Material	Grain Size	Heat Capacity (at 0.1 K)	Energy Resolution (at 5.9 keV)	Time Constant
Electroplated Au	~ 1 µm	1.4 pJ/K	2.4 eV	2 ms
Electroplated Au/Bi	2-5 µm	0.4 pJ/K	2.1 eV	400 µs
Evaporated Au/Bi	0.2-0.5 µm	0.4 pJ/K	4.0 eV	1 ms

***A. Brown et al, *J. Low Temp. Phys.* (2008)**

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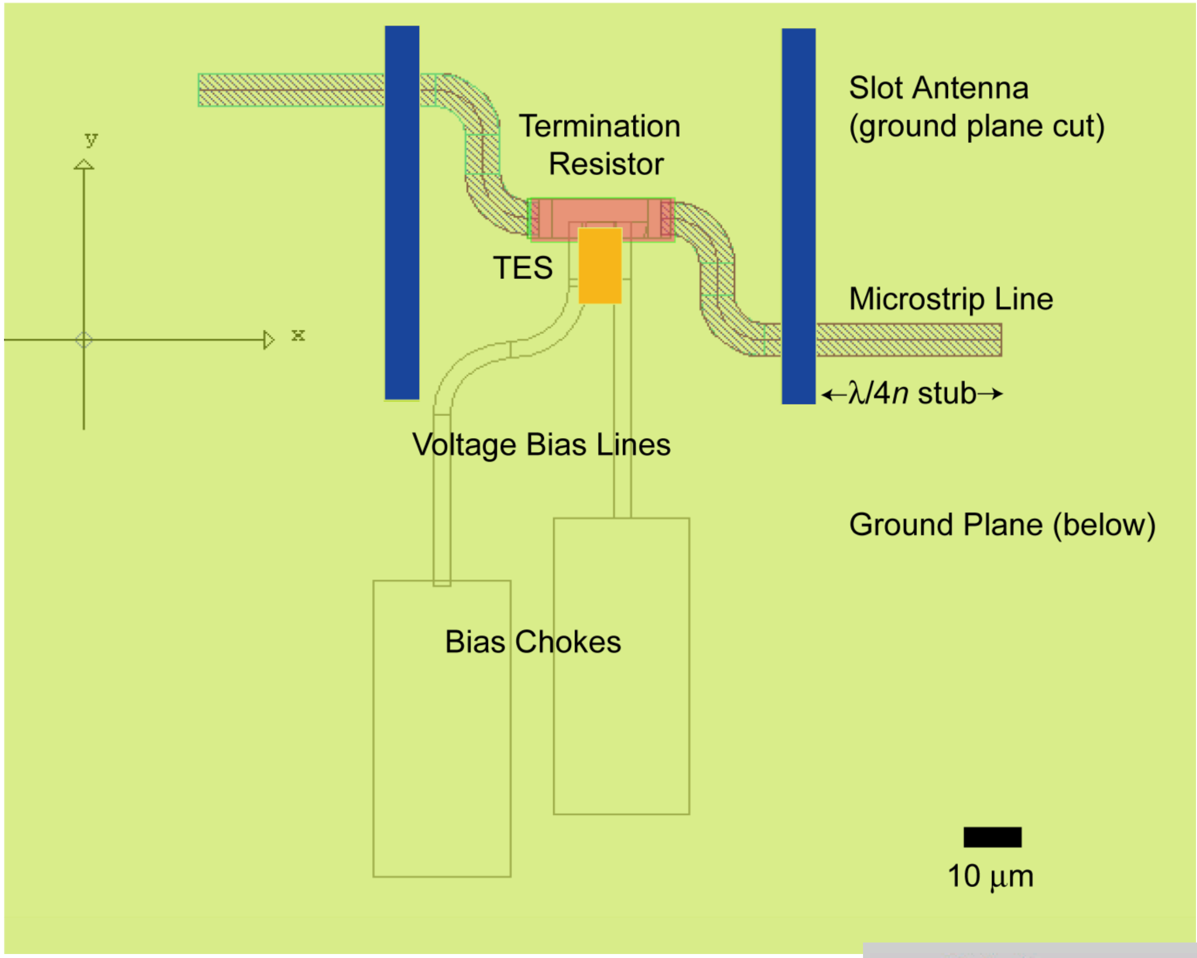
Architecture of FIR TES

1 THz Antenna-Coupled Bolometric Transition-Edge Sensor (TES)



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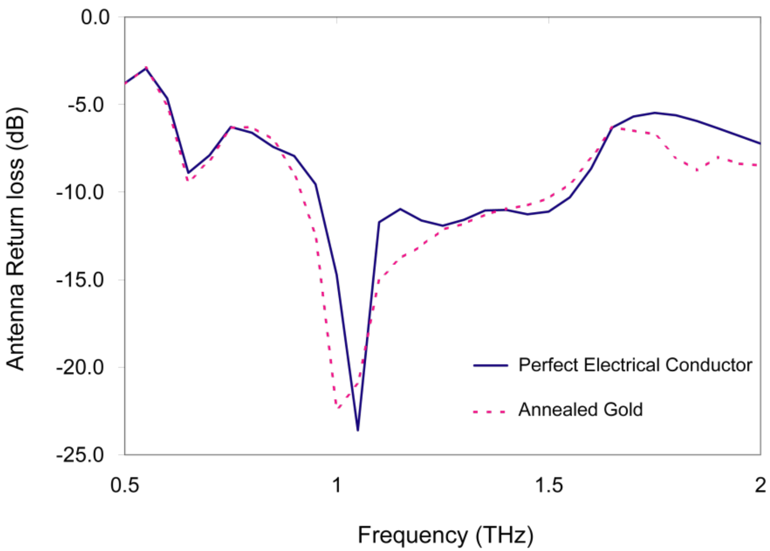
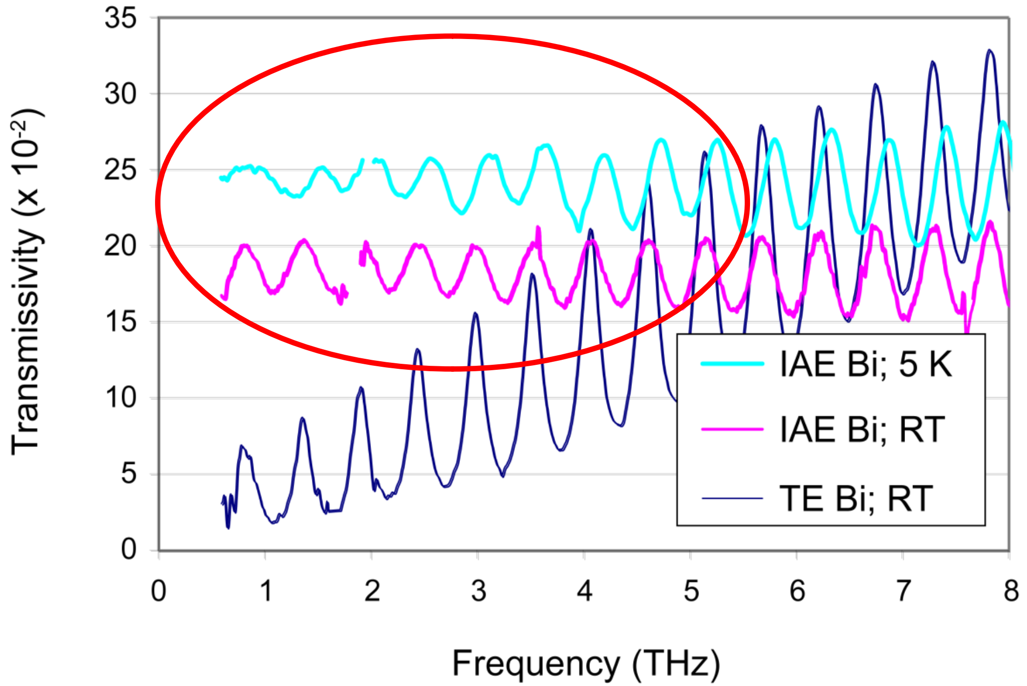
Fabrication developments for FIR TES: Novel ground plane and absorber materials

Novel microstructured Au thin films as ground plane material



Our Au films act very similar to perfect electrical conductors.

Novel microstructured Bi thin films as THz absorbers



Our Bi films act like purely resistive elements over a broad frequency range.

*A. Brown et al, *AIP Conf. Proc.* (2009)

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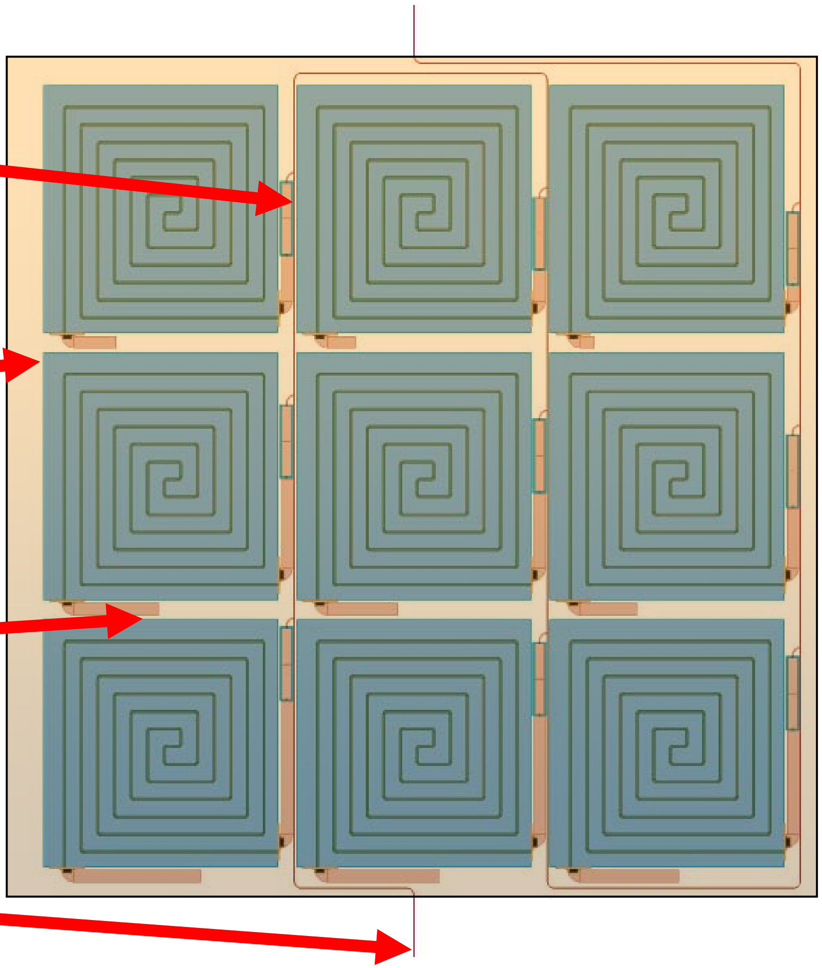
Architecture of Absorber-Coupled MKID

Superconducting Al KIDs/resonators

Single crystal Si membranes

Low impedance Nb traces

Nb microstrip feedline



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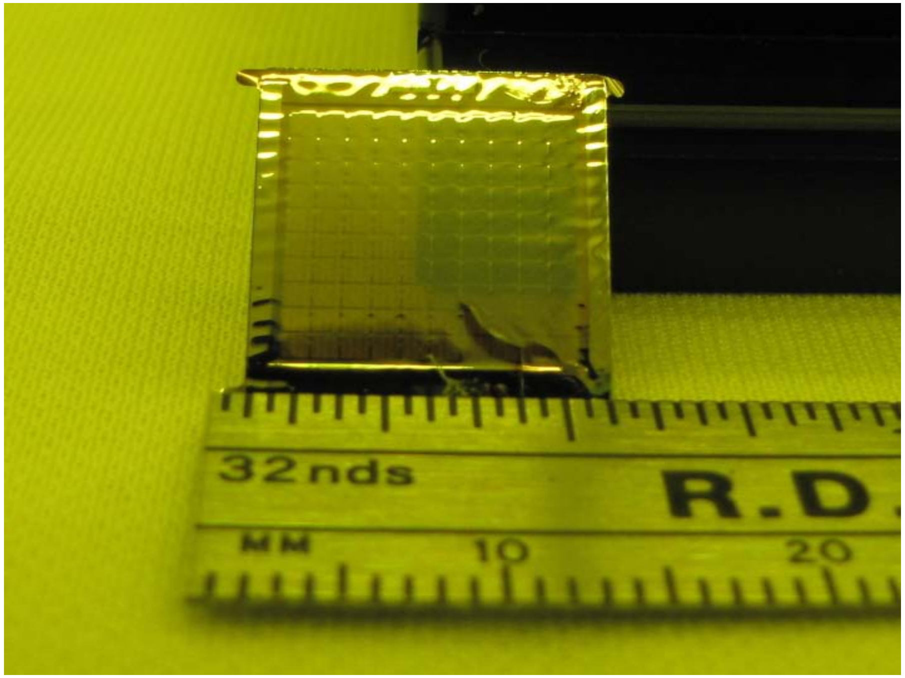
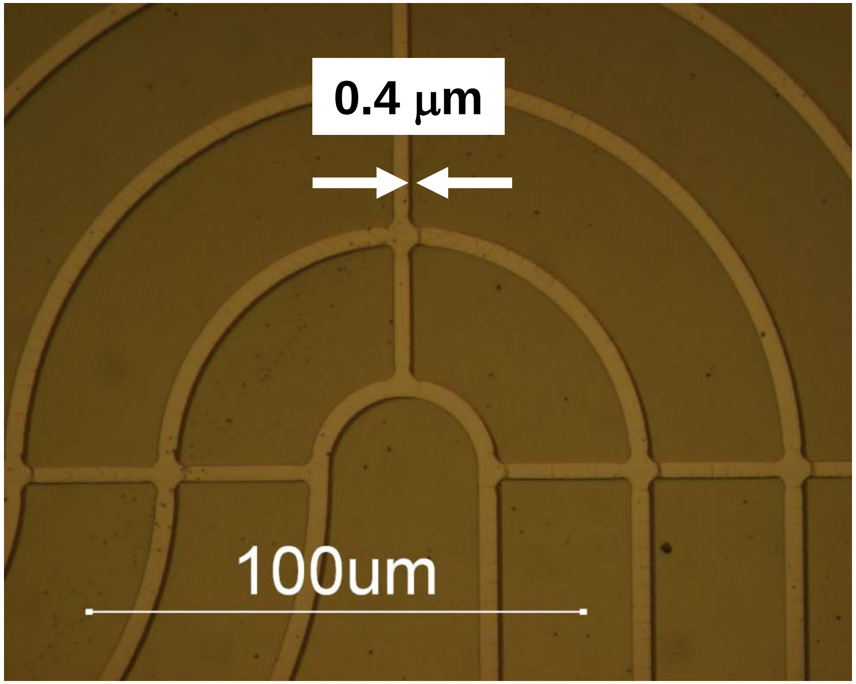
Fabrication developments for Absorber-Coupled MKID: Novel fabrication methodology in which…

An entire camera can be fabricated on a single 1.5 micron thick Si membrane.

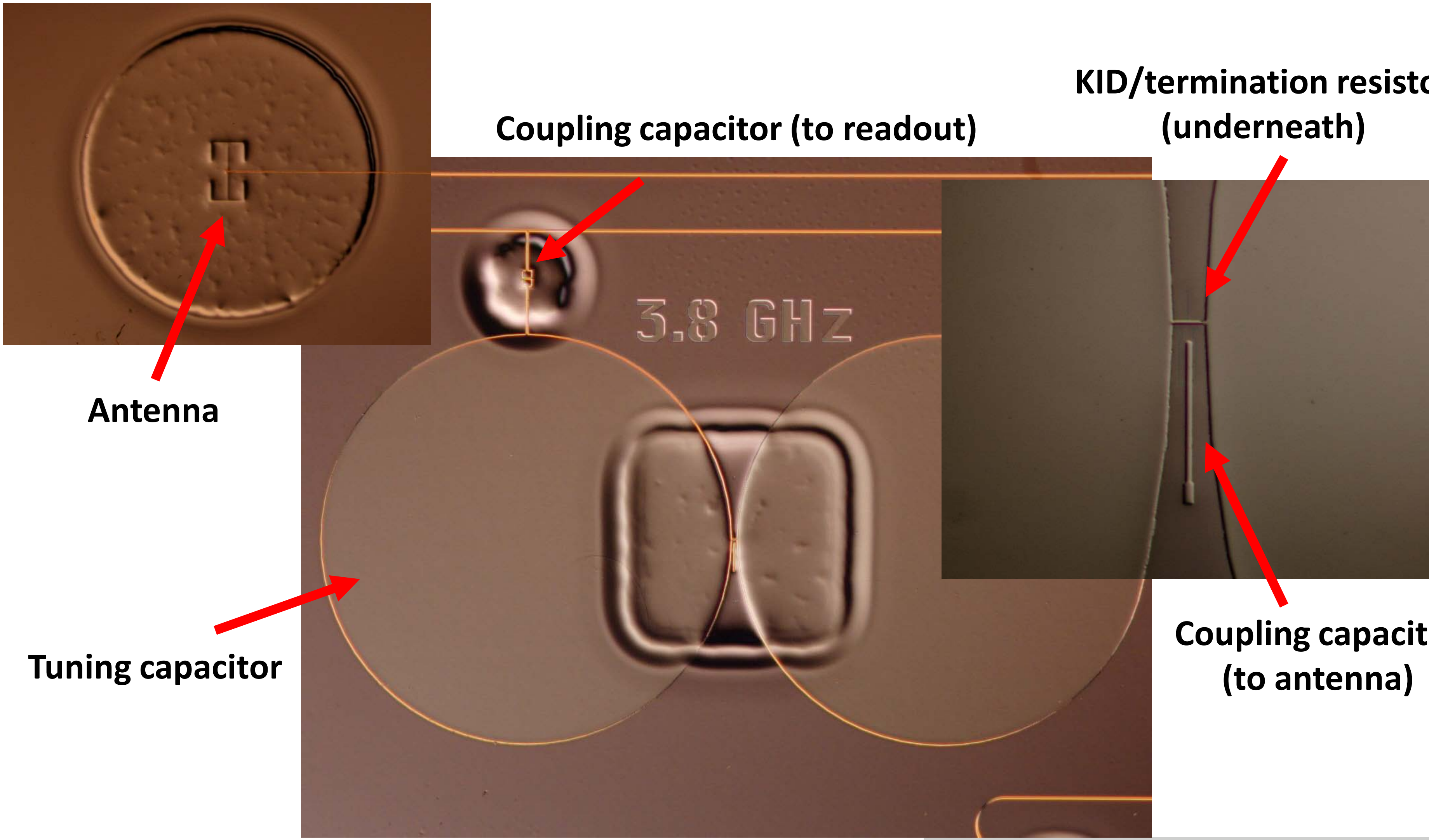
There is a very small front-to-back misalignment, which results in low transmission line loss, without having to use front-to-back lithographic techniques.





*A. Brown et al, *SPIE Conf. Proc.* (2010)

Architecture of Antenna-Coupled MKID



Thin silicon membranes are never roughened.

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Fabrication developments for Absorber-Coupled MKID: Keep Si membrane smooth throughout fabrication

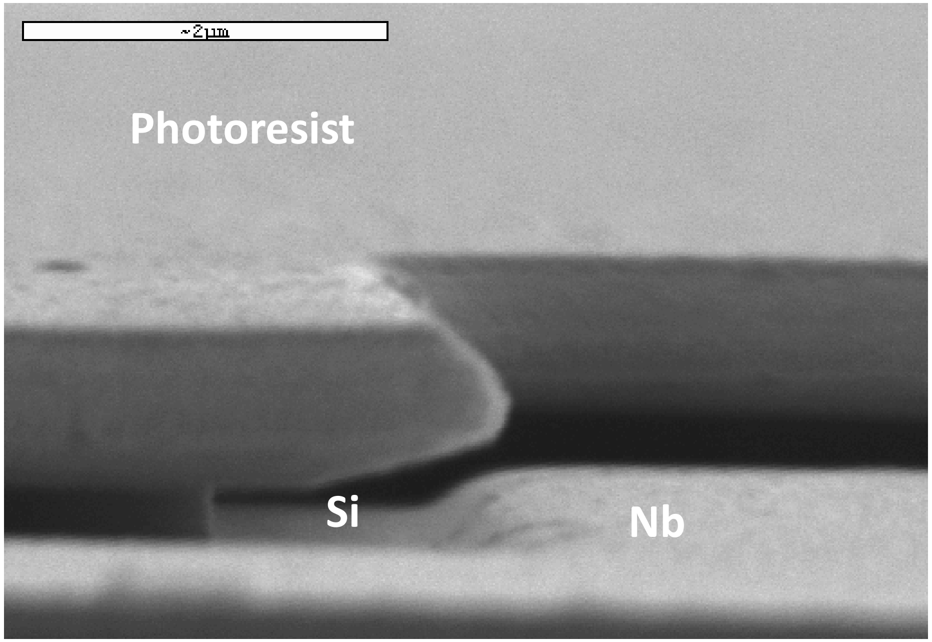
Roughening of Si during fabrication can introduce noise in the detectors.

Solution: Develop many different liftoff techniques in order to avoid having to etch the metals (Nb).

Liftoff involves:

1. **Depositing liftoff material(s).**
2. **Patterning that material with a negative image of what is desired.**
3. **Depositing the desired material.**
4. **Selectively removing the liftoff material.**

Novel liftoff process to pattern the Nb thin films used for the capacitors and transmission lines.



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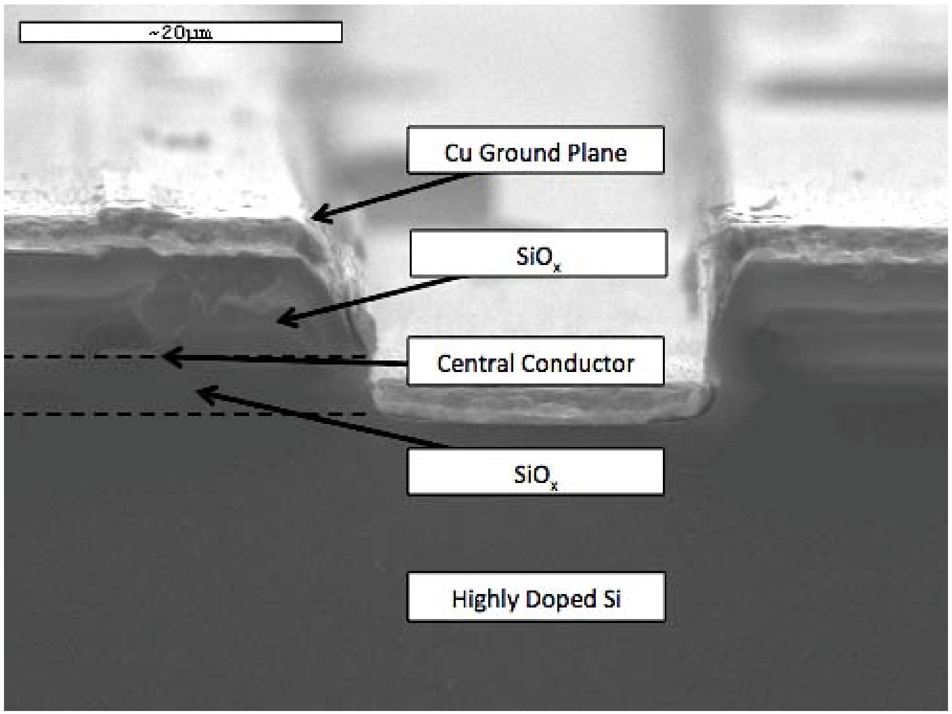
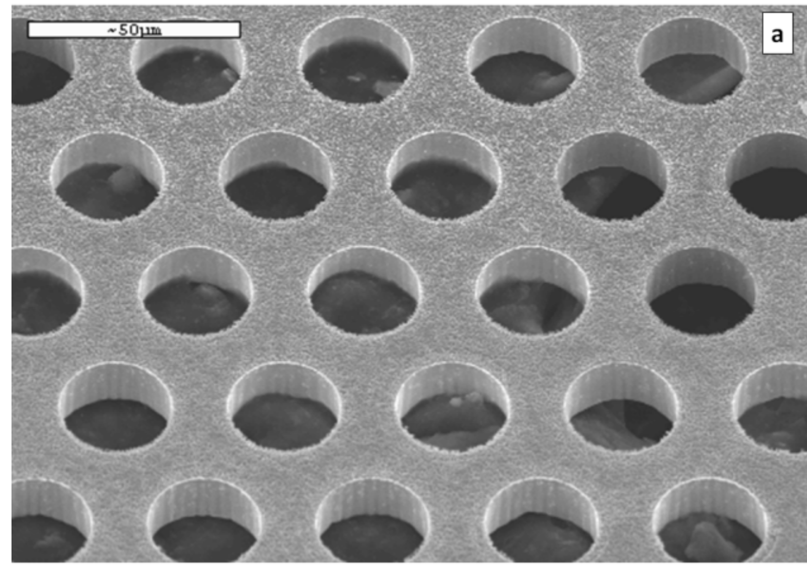
Ancillary devices: Filters

Boxed microstrip lowpass filter



Needed for ultrahigh sensitivity detector operation.

Bandpass grill filter



Needed for rejecting out-of-band thermal noise

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Summary

- Superconducting detectors offer unparalleled means of making astronomical/cosmological observations.

- Fabrication of these detectors is somewhat unconventional; however, a lot of novel condensed matter physics/materials scientific discoveries and semiconductor fabrication processes can be generated in making these devices.

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Acknowledgments

- NASA GSFC:
  - Code 553 *Detector Systems Branch*
  - Code 551 *Optics Branch*
  - Code 555 *Microwave Instruments Branch*
  - Code 567 *Microwave Systems Branch*
  - Code 662 *X-ray Astrophysics Laboratory*
  - Code 665 *Observational Cosmology Laboratory*
  - Code 693 *Planetary Instruments Laboratory*

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