Superconducting Detectors:
the Past 30 Years and Future Prospects

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NIST and the University of Colorado, Boulder

Dec. 15, 2017

1ˢᵗ International Workshop on Low Temperature Detectors

31ᵗʰ anniversary: 1986, Ringberg Castle, Germany

Programm

- Update on Neutrinos, Dark Matter, and Cryogenic Detection.
  By L. Stodolsky
- New Results on the Basic Properties of Superheated Granules Detectors.
  By L. Gonzales-Mestres and D. Perret-Gallix
- Investigation of Superconducting Tin Granules for a Low-Energy Neutrino or Dark Matter Detector.
  By K. Pretzl
- SQUID Detection of Superheated Granules.
  By A. Kotlicki
- VLSI Superconducting Particle Detectors.
  By 0. Liengme
- "Minicylinder" Design for Solar Neutrino Detection (A naive proposal).
  By G.Vesztergombi
- Electron Beam Detection with Superheated Superconducting Grains.
  By A. de Bellefon
- Monte Carlo Simulation of a Double-Beta Decay Experiment with Superconducting-Superheated Tin Granules.
  By A.F. Pacheco
- Solar Neutrino Indium Detector Using Superheated Granules.
  By G. Waysand
- An Indium Solar Neutrino Experiment.
  By N.E. Booth
- Cryogenic Detection of Particles, Development Effort in the United States.
  By B. Sadoulet
- Calorimetric Detectors at Low Temperatures.
  By F.v. Feilitzsch, F. Probst, and W, Seidel
- The Possible Impact of Thermal Detectors in Nuclear and Subnuclear Physics.
  By E. Fiorini
- Considerations on Front End Electronics for Bolometric Detectors with Resistive Readout.
  By D.V. Camin
- Coherent Neutrino-Nucleus Elastic Scattering in Ultralow-Temperatures Calorimetric Detectors.
  By T.O. Niinikoski
- Data Acquisition and Analysis of Calorimetric Signals.
  By A. Rijllart
- The Use of Rotons in Liquid Helium to Detect Neutrinos
  By G.M. Seidel

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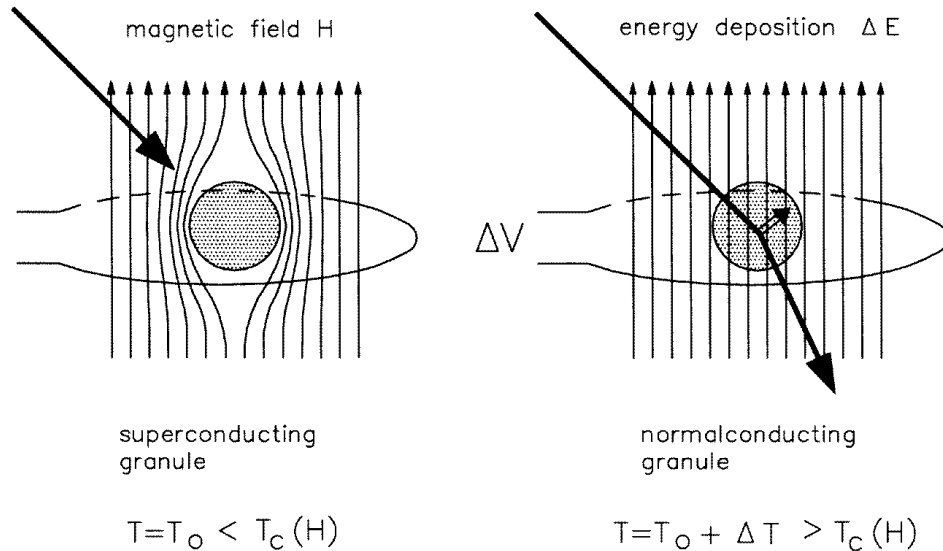- Data Acquisition and Analysis of Calorimetric Signals.
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Cryogenic Detectors in ~ 1987: Superconducting Granules

- Proposed in Bernas et al, Physics Letters, 1967

- Heavy interest (see LTD1 program) in detection of neutrinos and dark matter candidates

- Need detector with large interaction mass but very small energy threshold

- Spheres of type I superconductor in a B field < Hc. Temperature rise from interaction causes field to penetrate sphere

  → change in B field detected with pick-up coil

magnetic field H

energy deposition   Δ E

ΔV

And if that works …
scale up with more
granules

superconducting
granule

normalconducting
granule

$T = T_O < T_C(H)$

$T = T_O + \Delta T > T_C(H)$

$\Delta T = \Delta E / C$
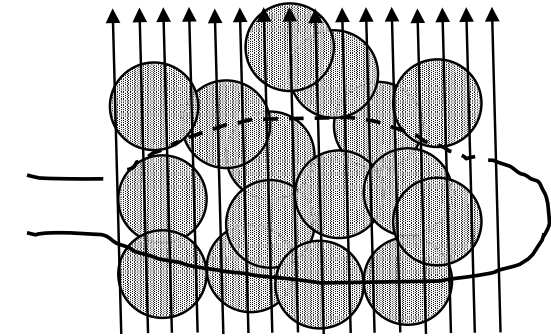
From D. Twerenbold, Rep Prog Phys, 1996, p381

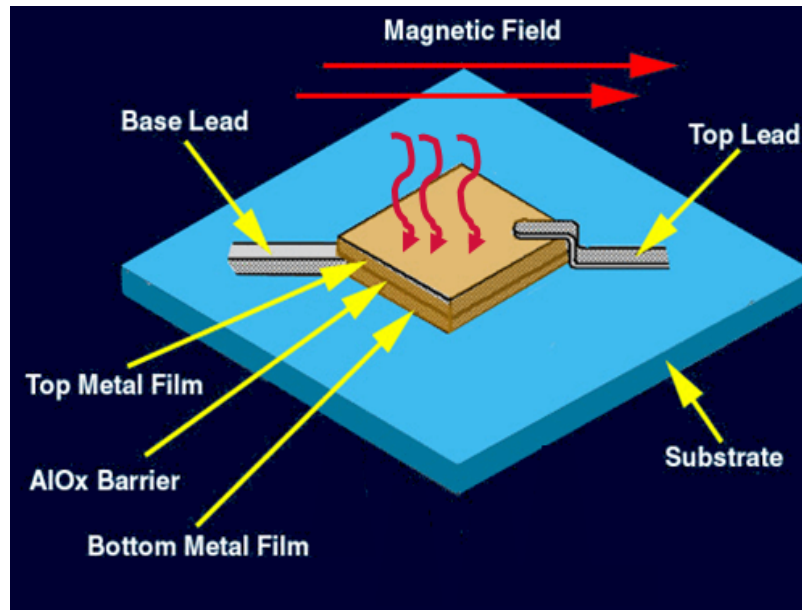$\Delta V = \Delta \phi / \tau$

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Cryogenic Detectors in ~ 1987: Superconducting Tunnel Junctions

Long history subsequent to Giaever's 1960 and 1961 tunnel junction papers:

- Wood and White, APL, 1969, "Pulses induced in tunneling currents between superconductors by alpha-particle bombardment"

- 1970s: Numerous papers on detection of phonons and excess quasiparticles with STJs

- Kurakado, NIM, 1981 & 1982,"Possibility of high resolution detectors using superconducting tunnel junctions"

- Excess QPs created on one side of junction produce detectable current through biased junction

Around 1987, measure energy of single 6 keV x-rays with ~50 eV resolution *(Rothmund and Zehnder, 1988)*
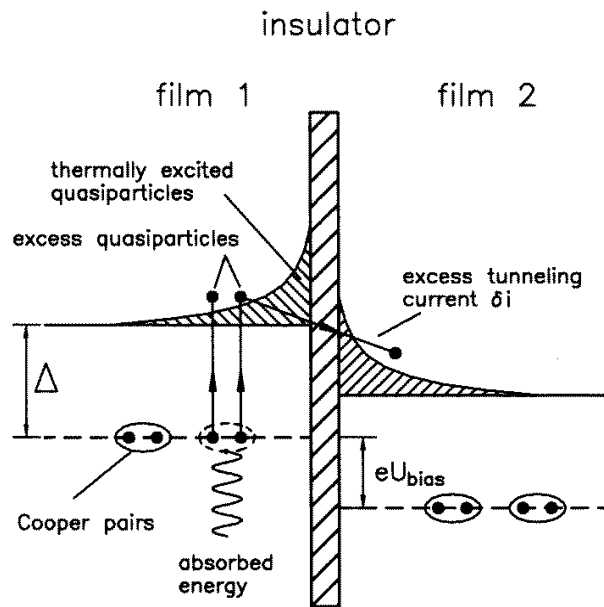
From D. Twerenbold, Rep Prog Phys, 1996, p401

From P. Verhoeve et al, Proc. SPIE, 2010, vol. 7742, p77420O-2

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Cryogenic Detectors in ~ 1987: Thermistors

- Andrews, 1942 and 1949, detection of infrared light and alpha particles with current biased superconductors

- Boyle and Rodgers, 1959, carbon resistor bolometer at 4K

- Modern formulation: Mather, Appl Opt, 1982, "Bolometer noise: nonequilibrium theory"

- Modern formulation: Moseley, Mather, and McCammon, J Appl Phys, 1984, "Thermal detectors as x-ray spectrometers"

- Fiorini and Niinikoski, NIM, 1984, "Low-temperature calorimetry for rare decays"
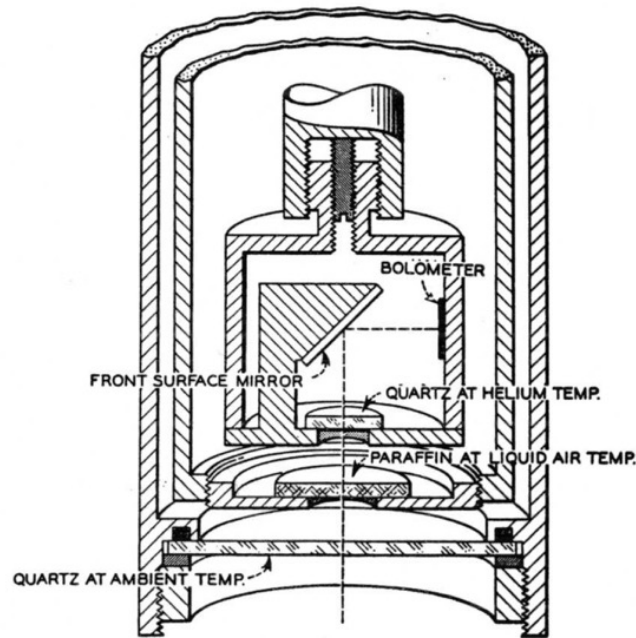
FIG. 1. Low-temperature bolometer assembly.

FIG. 1. Concept for 1.1-eV FWHM spectrometer. Heat capacities of component materials are listed in Table I. The design of the device is similar to devices described in Ref. 1, which gives a detailed discussion of the fabrication procedure.

Various thermometers: superconductors, implanted silicon, carbon, neutron transmutation doped germanium

From Boyle and Rodgers, J Opt Sci Am, 1959, v49, p67

From Moseley et al, J Appl Phys, 1984, v56, p1257

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Early Detectors Illustrate Motivating Principles

- Use superconductors and low temperatures because of low specific heat (granules)

$$C_{ph} \sim T^3 \quad \text{and} \quad C_{el} \sim e^{-Tc/T}$$

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$$\Delta_{Si} \sim 1 \text{ eV} \qquad \Delta_{Nb} \sim 1 \text{ meV} \quad \text{if you count excitations,} \quad N = \frac{E_\gamma}{\Delta} \quad \text{and energy resolution} \quad \propto \frac{\sqrt{N}}{N} E_\gamma = \sqrt{E_\gamma \Delta}$$

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$$(T/R)(dR/dT) = 100 - 1{,}000$$

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$$P_N = (4k\,T^2\,G)^{1/2} \text{ W/Hz}^{1/2} \quad \text{and} \quad V_N = (4k\,T\,R)^{1/2} \text{ V/Hz}^{1/2}$$

10

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- Find ways to read out many discrete elements with fewer amplifier channels (granules)

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Big Ideas

1. Microfabrication

2. SQUID Readout

3. TESs

4. Multiplexed Readout

5. Dry Cryogenics

6. MKIDs

7. Microwave Readout

Microfabrication

- mostly optical lithography, physical vapor deposition, wet & dry etches, and silicon micromachining
- conventional techniques and tools that lag the semiconductor industry by 20 years are still incredibly powerful
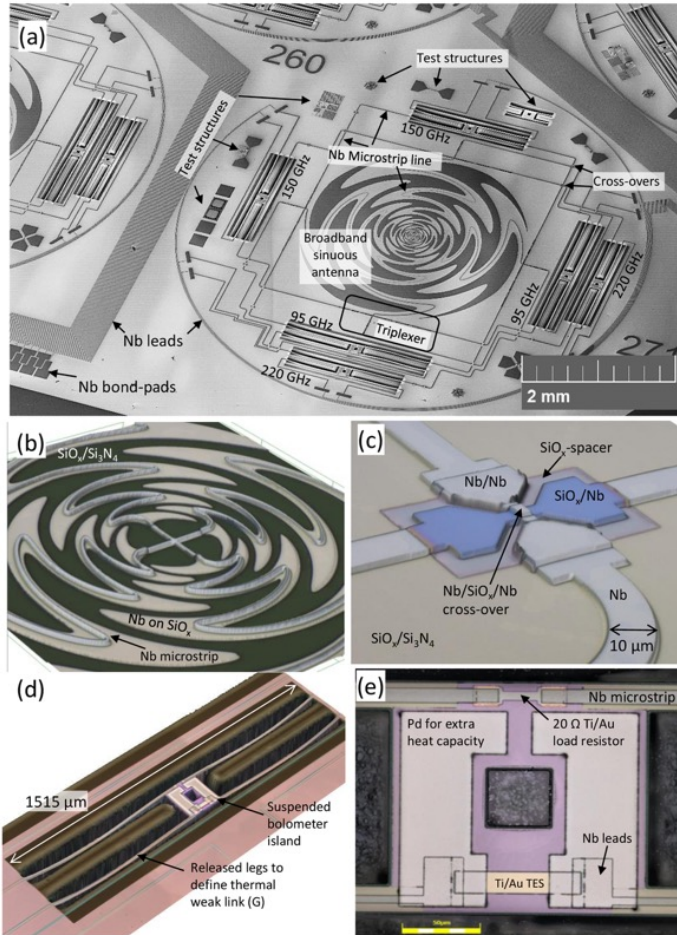
Posada et al, Proc. SPIE, 2016
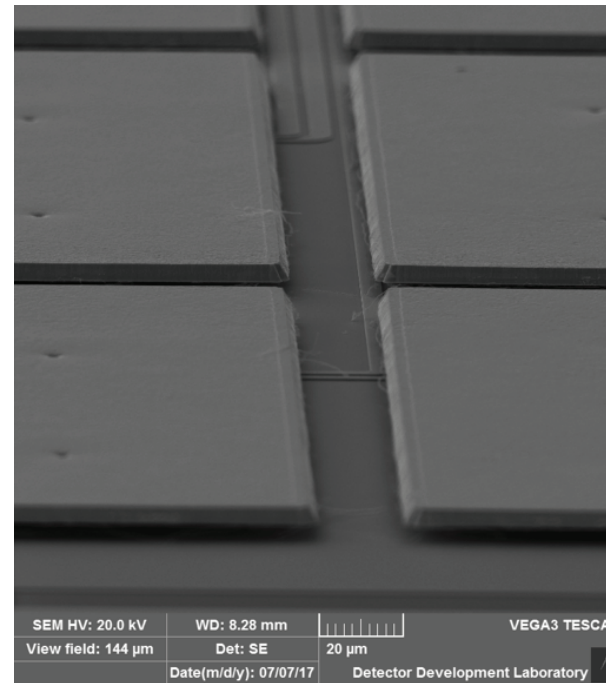
Tilted view of array of sensors with electroplated gold absorbers suspended above sensors and wiring
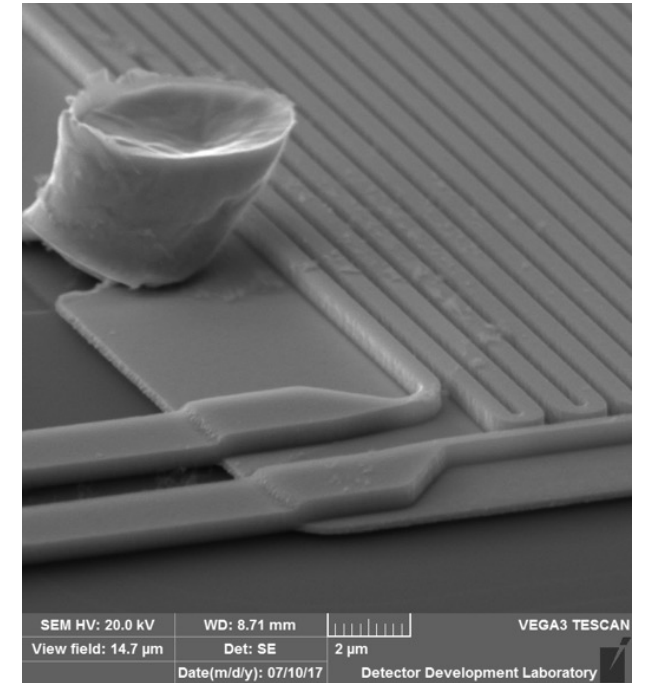
Underneath one absorber: 0.8 um trace and space

images from S. Bandler, NASA GSFC

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Transition Edge Sensors (TESs)

- Thin metal film electrically biased in superconducting-to-normal transition

- Early work used current-biased films and voltage readout (beginning with Andrews in 1940s)

- Current bias has severe problems: thermal run-away and extreme sensitivity to inhomogeneity

- Major breakthrough = voltage bias & electrothermal feedback: Irwin, Applied Physics Letters, 1995 "An application of electrothermal feedback for high resolution cryogenic particle detection"

- Highly successful in many application areas. TESs critical to growth of cryogenic detector field (although no longer alone)

- Many implementations: elemental films, bilayers, and alloys

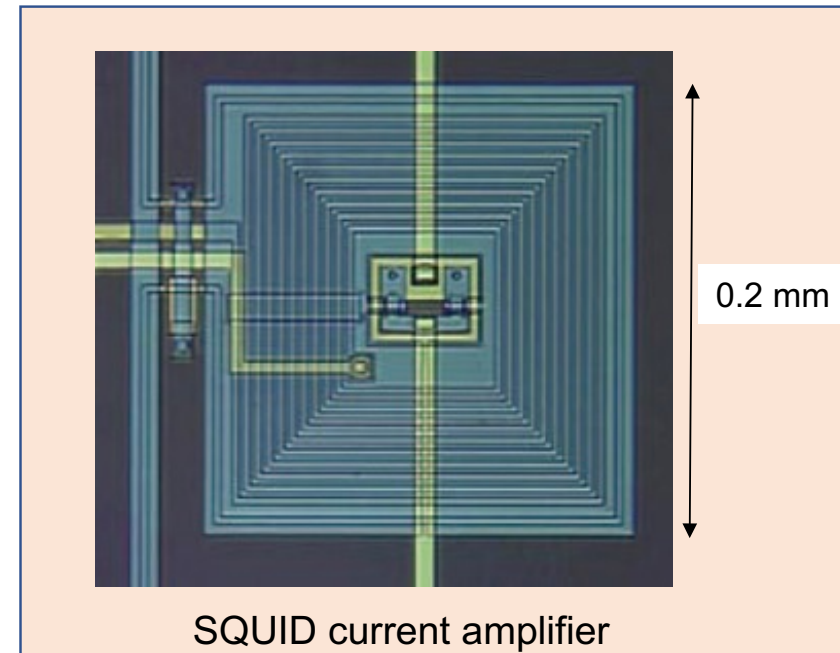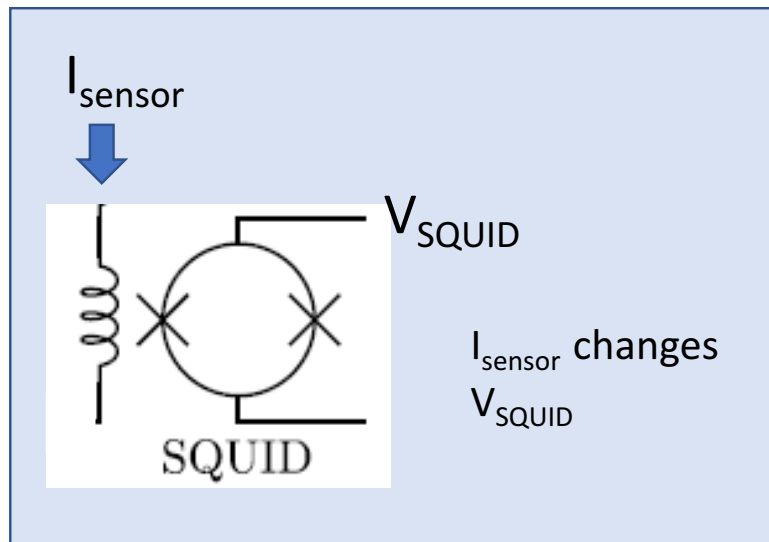- For many years, TES physics poorly understood, but lots of recent progress: weak-links and phase slip lines
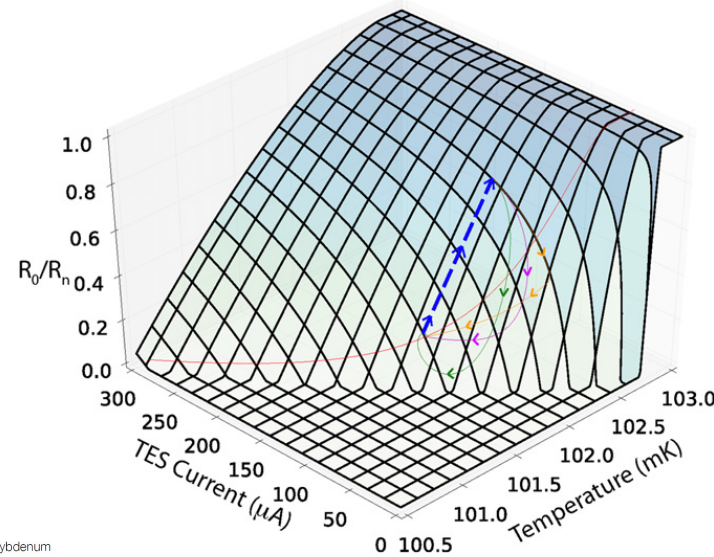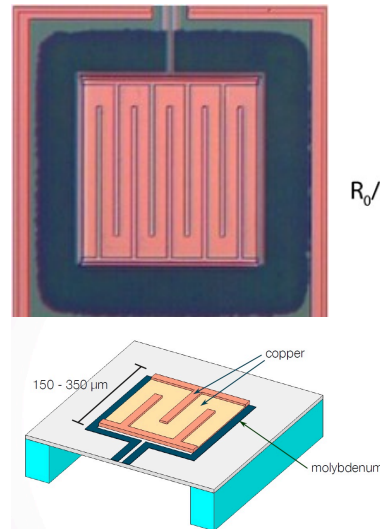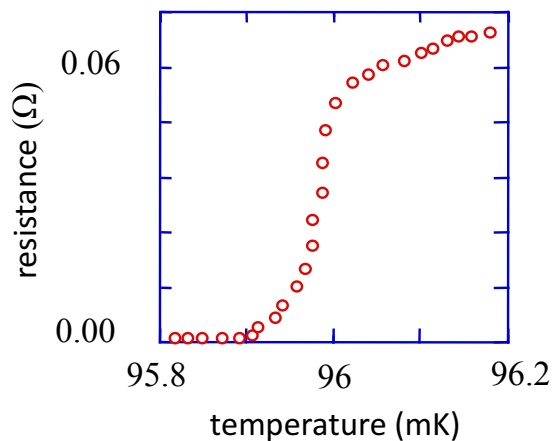
Ullom & Bennett, SuST, 2015
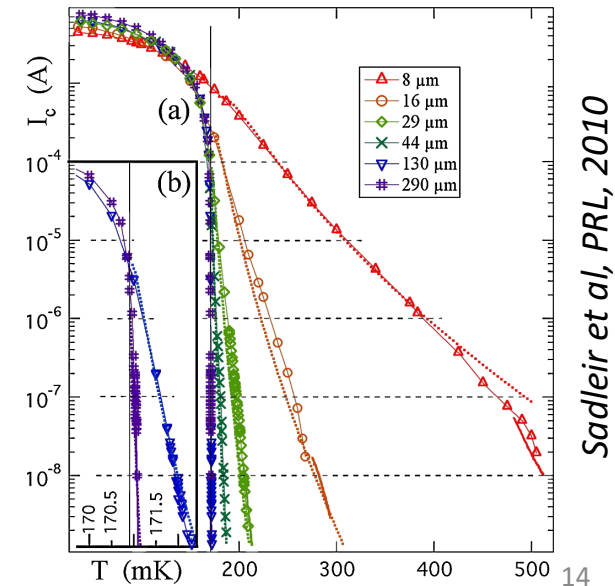
*Sadleir et al, PRL, 2010*

SQUIDs

- low noise current-to-voltage amplifiers with low input impedance; required for TESs

- Welty and Martinis, "A series array of dc SQUIDS", 1991. Matches output voltage noise of cryo components to input voltage noise of conventional preamplifier. Suddenly, readout "easy".

- There are some who complain about SQUIDs but we are lucky to be able to use them:

  o can locate near sensors

  o low noise

  o low power dissipation

  o low input impedance, high bandwidth operation

  o made by microfabrication -> large quantities, many variants

I_{sensor}

V_{SQUID}

I_{sensor} changes V_{SQUID}

SQUID

0.2 mm

SQUID current amplifier

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Multiplexed SQUID Readout

- Most applications require sensor arrays. Having 1 amplifier at 300K for each sensor is challenging. Largest (?) example: Sharc II with 384 implanted Si thermistors

- SQUID circuits have enabled 10-100 sensors per 300K amplifier: multiplexed readout

  o microfabricated amplifiers can "easily" be made in more complex configurations
  o need an orthogonal basis set for each sensor's signal
  o time-division, frequency-division, and code-division (TDM, FDM, and CDM) readout: fairly similar performance, 10 MHz bandwidth per channel


Hijmering et al, Proc. SPIE, 2016
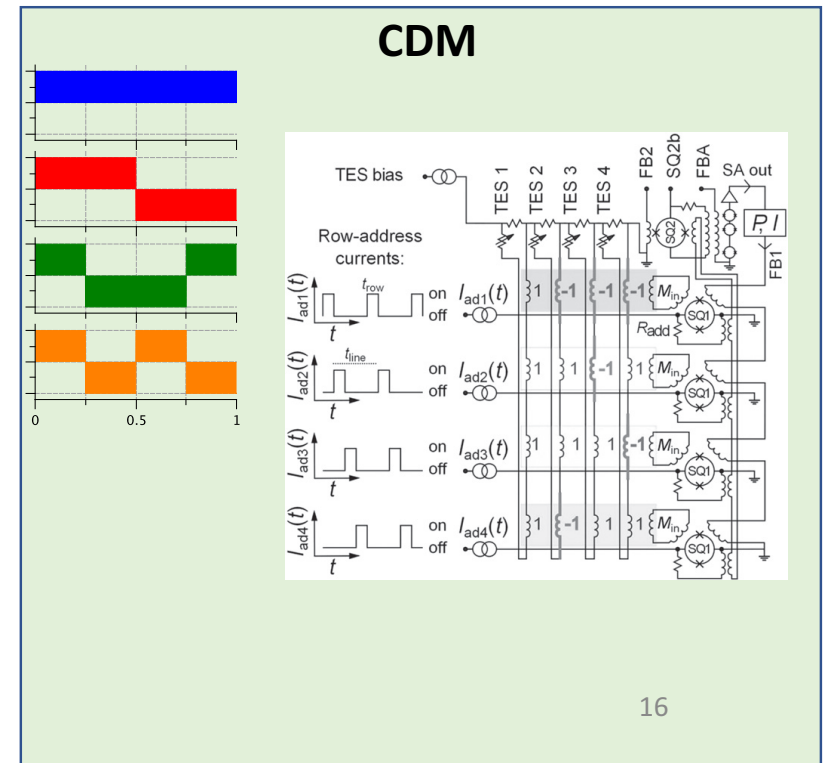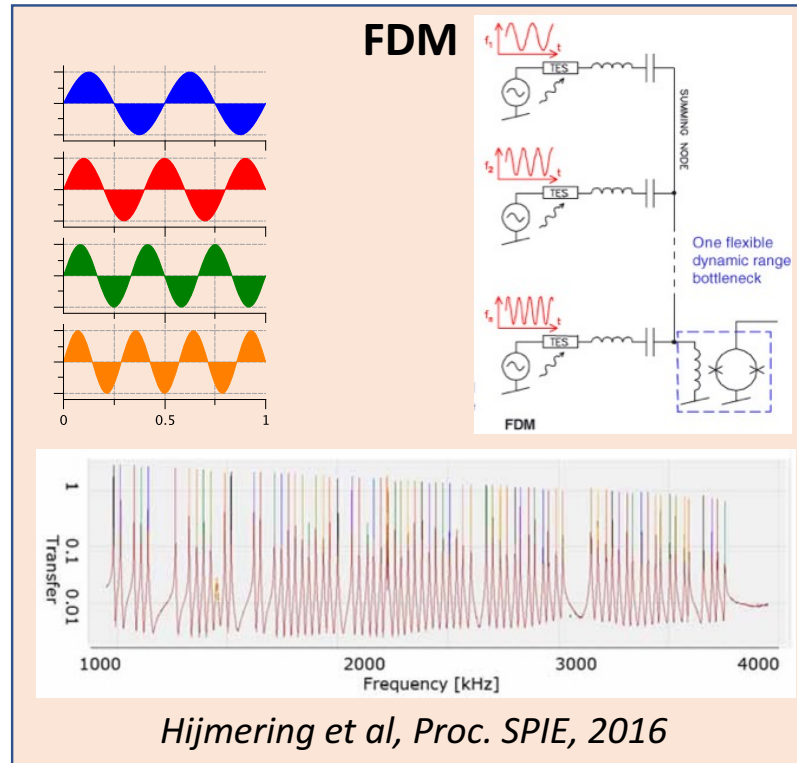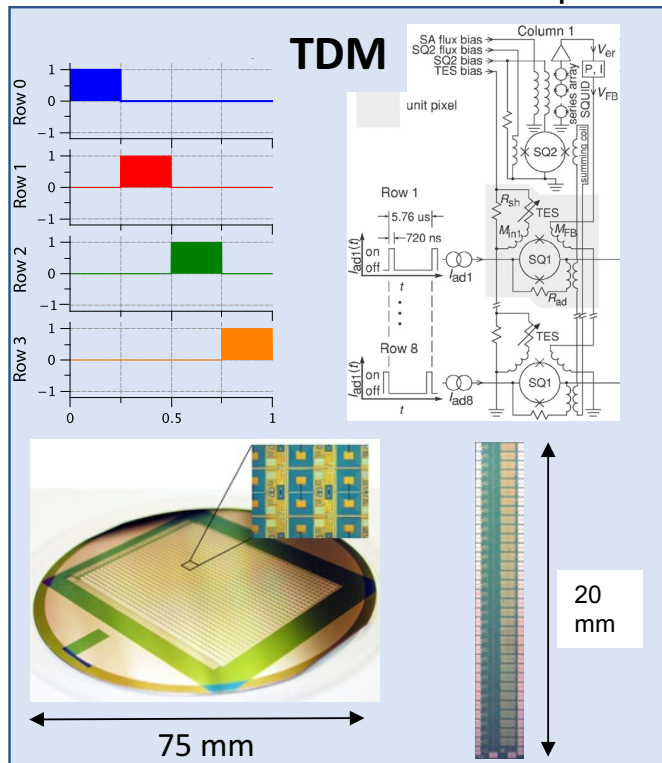
Dry Cryogenics

- C. Wang et al, "A two-stage pulse tube cooler operating below 4K", Cryogenics, 1997. Low vibrations of pulse tube well matched to cooling cryogenic sensors.

- MilliKelvin systems precooled by pulse tubes are now common in many fields but particularly impactful for sensors which often must be brought to the photon source

- Many commercial vendors of dilution refrigerators and adiabatic demagnetization refrigerators

ADR that mounts on electron microscope

≲ 1 m
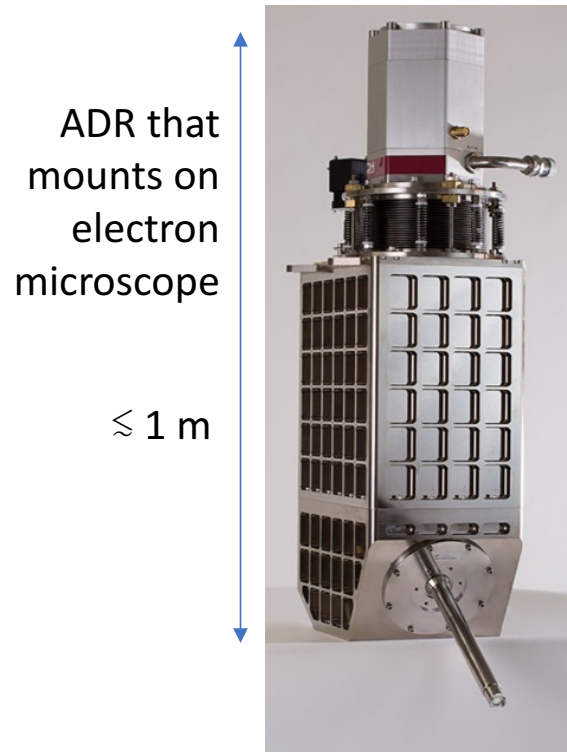
DR in Atacama desert

17
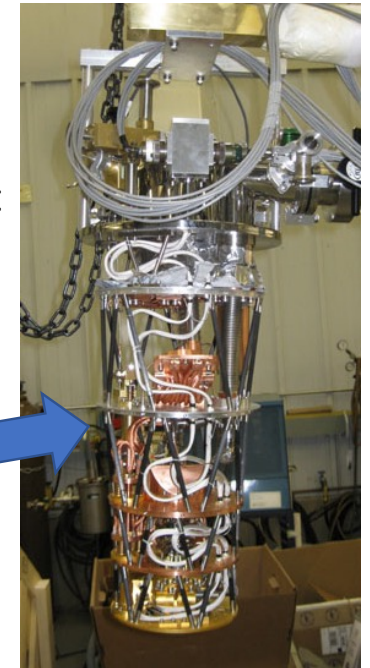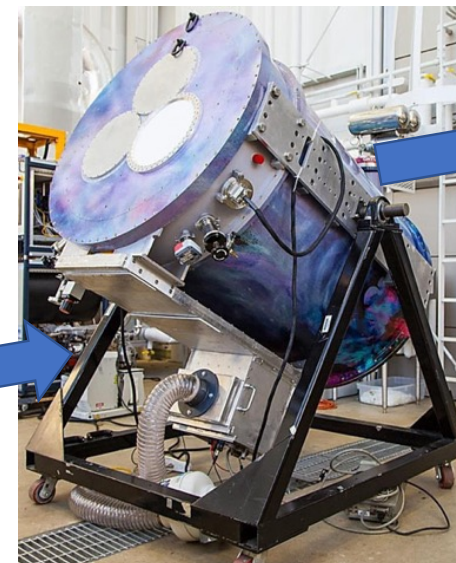
Microwave Kinetic Inductance Detectors

- Cooper pair breaking changes surface impedance of superconducting film: athermal sensors

- Film embedded in μwave resonator and probed by a μwave signal

- Both quarter-wave (Day et al, Nature, 2003) and lumped element (Doyle et al, JLTP, 2008) resonators possible

- Vigorous activity from many groups because of potential for large arrays

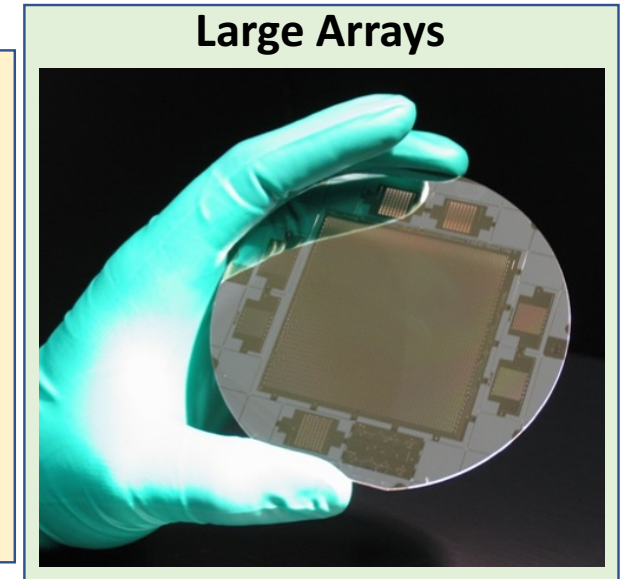- Recent thermal variant exploits L(T/Tc) "TKID". Addresses internal position dependence.
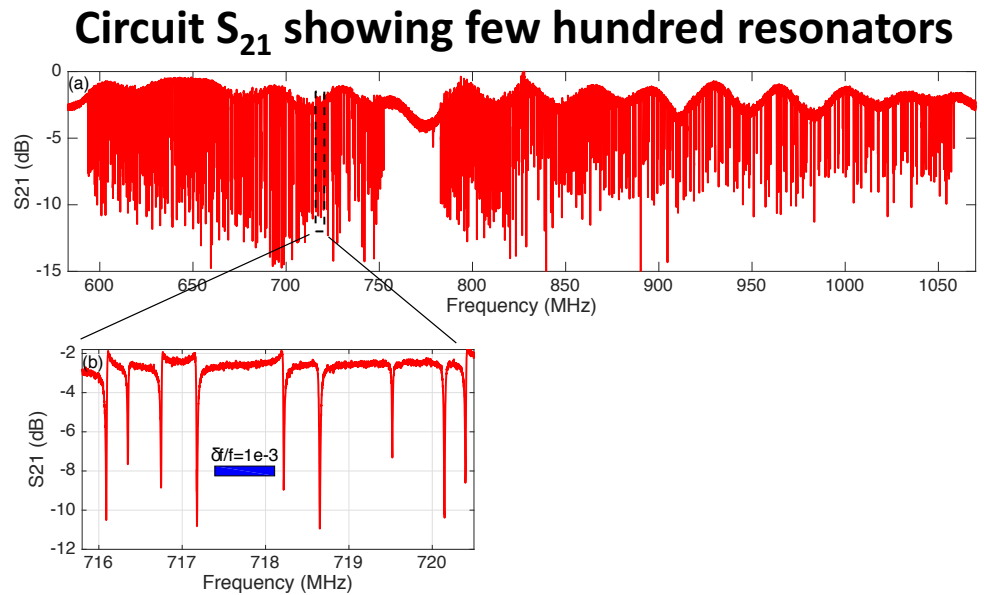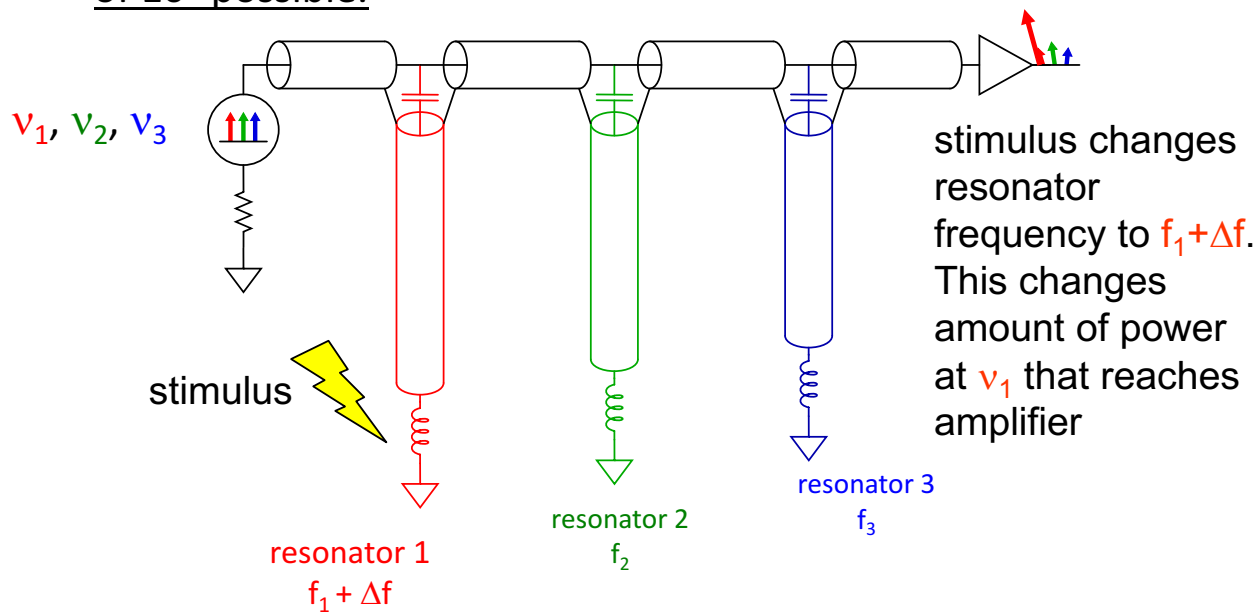
Actually an old idea: D. McDonald, APL, 1987

Operating Principle

λ/4 KID

Lumped Element KID

Large Arrays
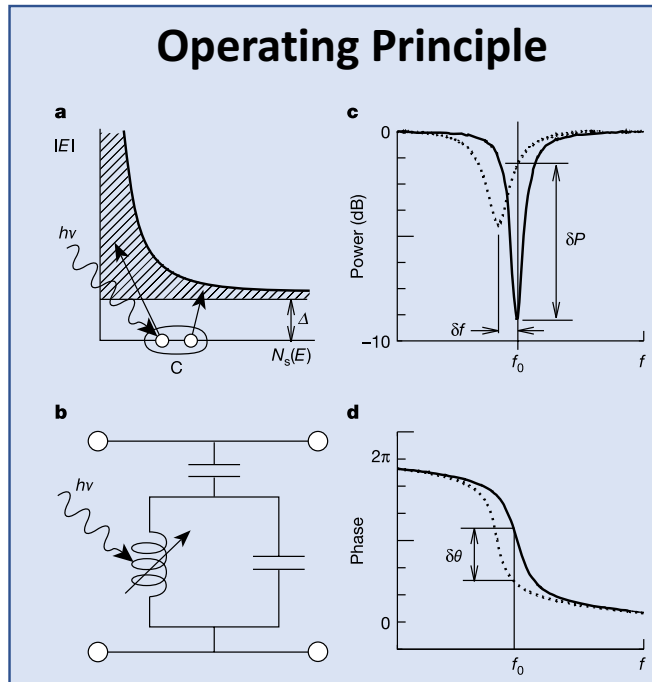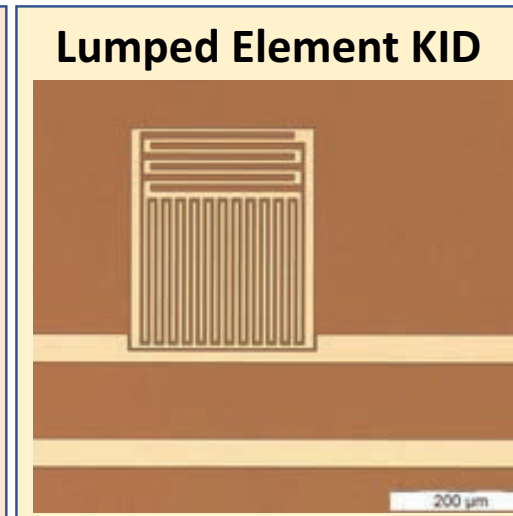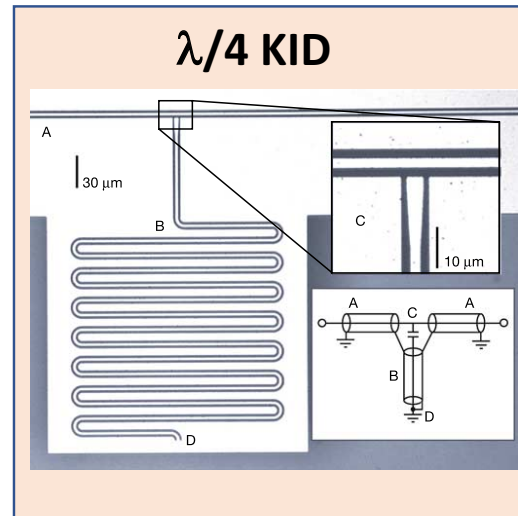
From A. Micelli, Argonne Natl Lab

*5400 FIR MKIDs at center,
from SRON*

P. Day et al, Nature, 2003

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Microwave Readout

- MKID readout is extremely attractive: many resonators on shared feedline with one input and one output. 1 shared amplifier at output port.

- 50 Ohm impedances and commercial HEMT amplifiers provide <u>many GHz</u> of readout bandwidth. <u>Multiplexing factors of 10^3 possible.</u>

ν_1, ν_2, ν_3

stimulus

resonator 1
$f_1 + \Delta f$

resonator 2
f_2

resonator 3
f_3

stimulus changes resonator frequency to $f_1+\Delta f$. This changes amount of power at ν_1 that reaches amplifier

Circuit S$_{21}$ showing few hundred resonators

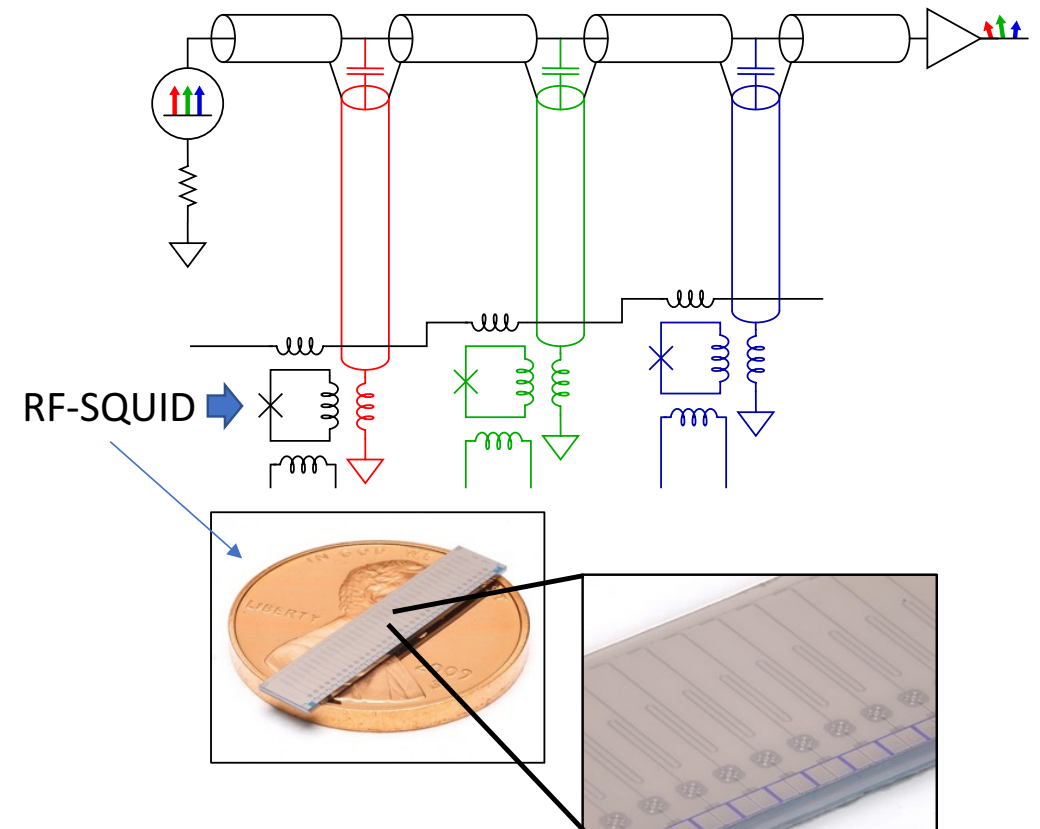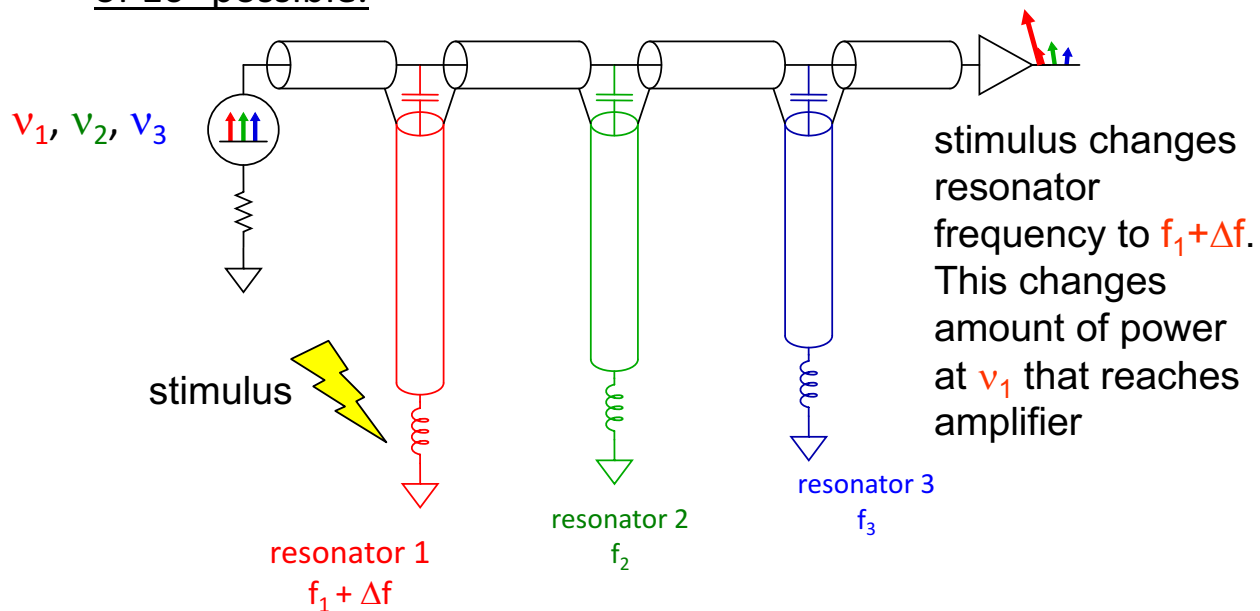From C. McKenney, NIST
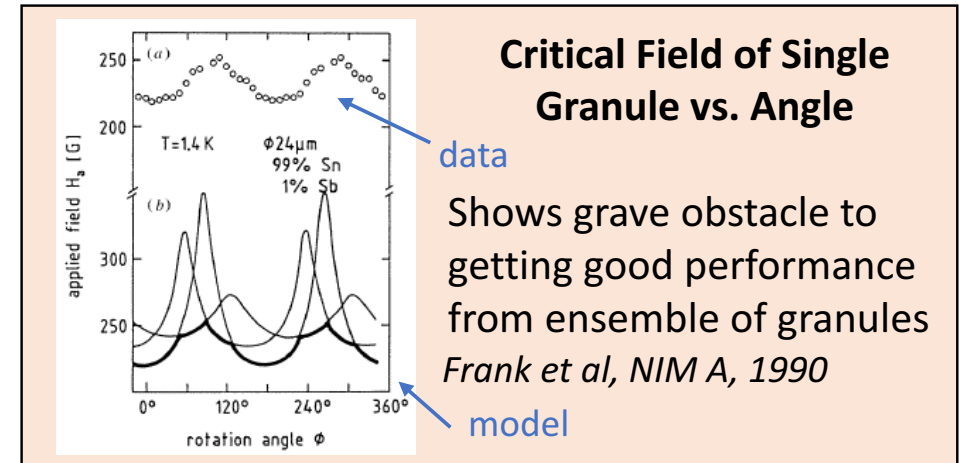
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stimulus

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$f_1 + \Delta f$

resonator 2
f_2

resonator 3
f_3

RF-SQUID

- Circuit can be adapted for TES readout by addition of RF-SQUID:
  J.A.B. Mates, PhD thesis, 2011

Evolution of Technologies
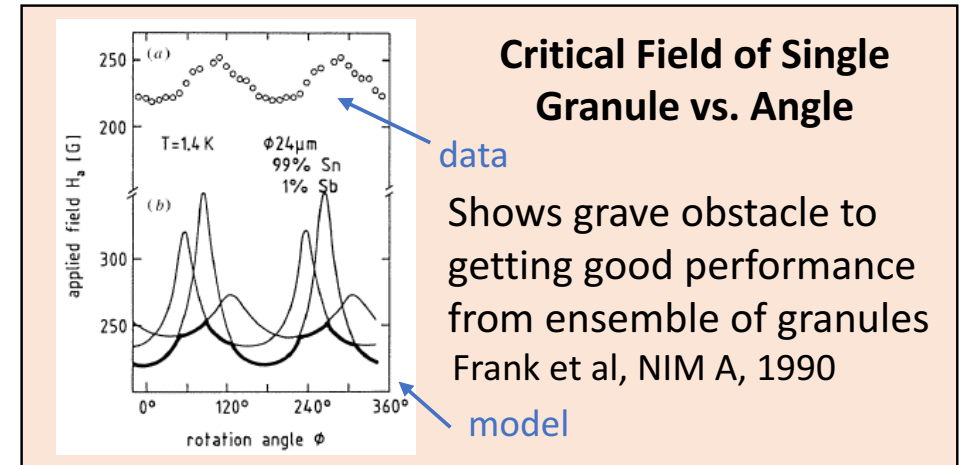
- Granules gone

Critical Field of Single Granule vs. Angle

data

Shows grave obstacle to getting good performance from ensemble of granules
Frank et al, NIM A, 1990

model

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- Thermistors: notable successes but now rare

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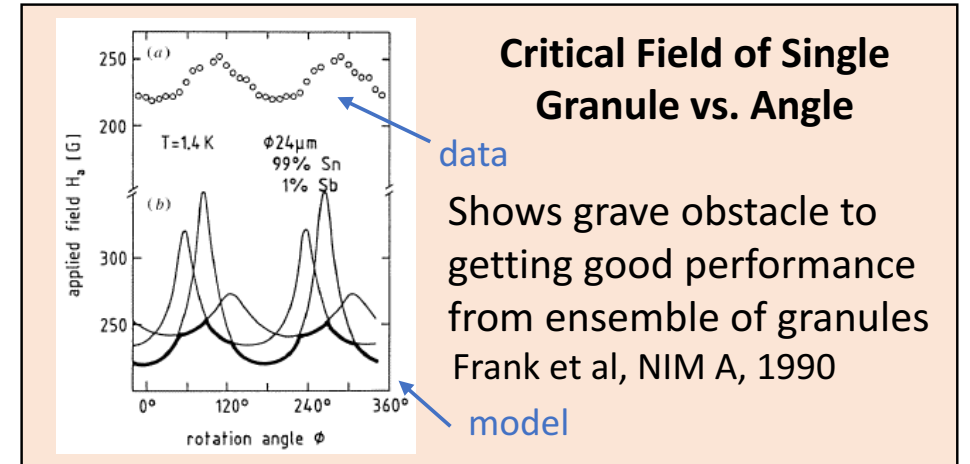Frank et al, NIM A, 1990

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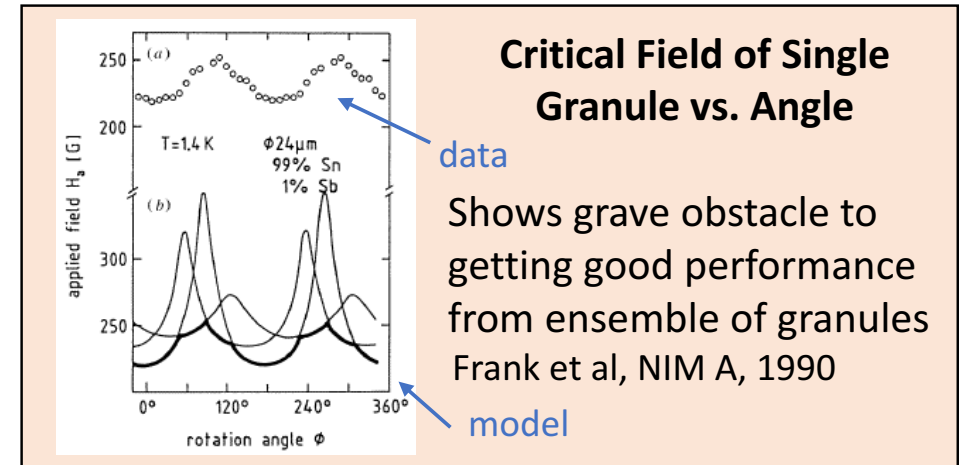
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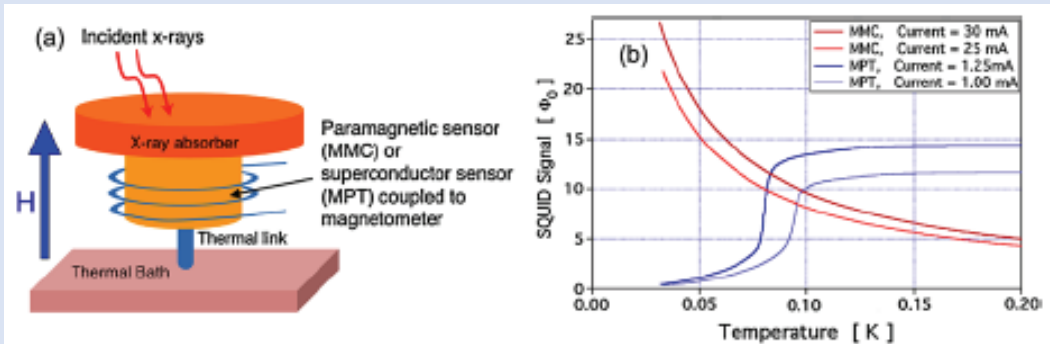Frank et al, NIM A, 1990

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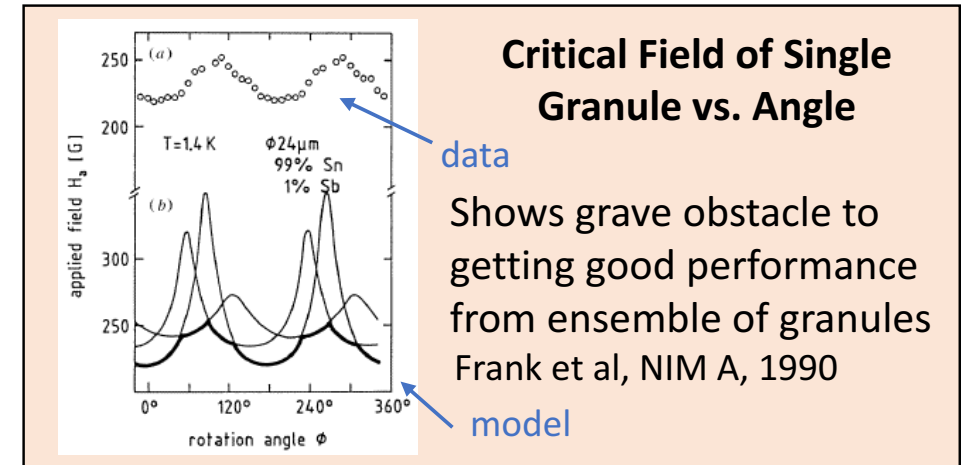- TESs flourish, many versions

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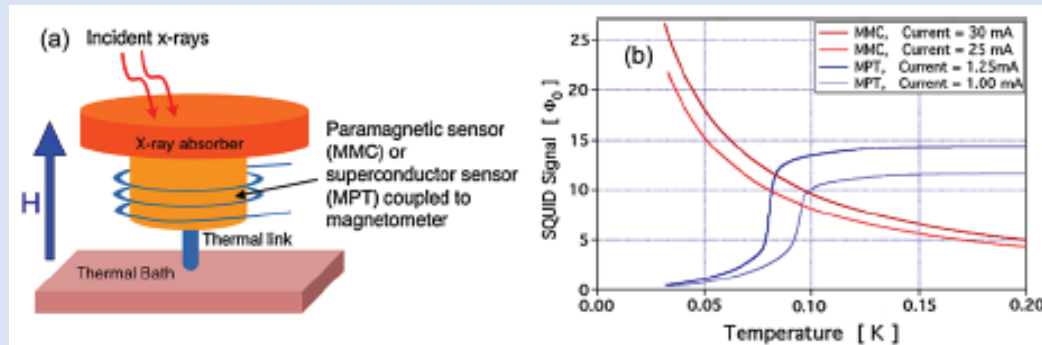Frank et al, NIM A, 1990

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Magnetic MicroCalorimeters (MMCs)

- Deposited energy changes paramagnetic or diamagnetic response
- SQUID sensor sees this as change in flux
- Excellent E/ΔE results from Heidelberg, KRISS, and NASA GSFC

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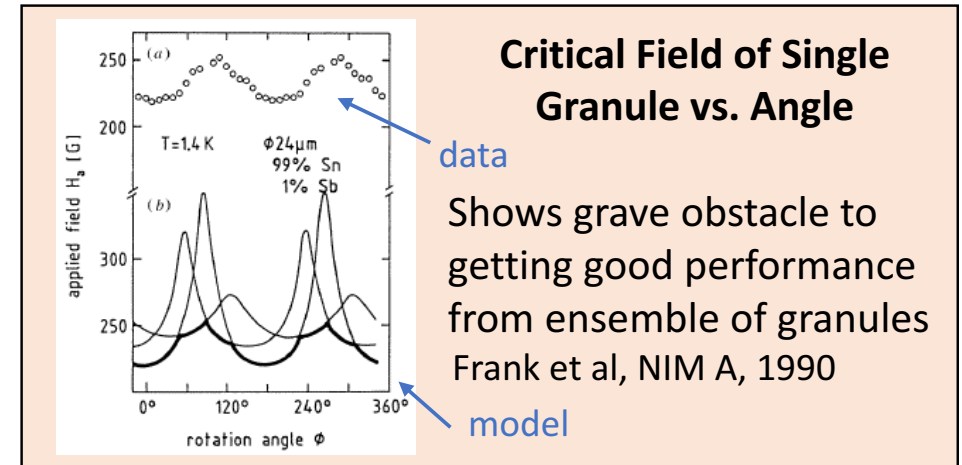- MKIDs flourish, many versions, some limits on applications

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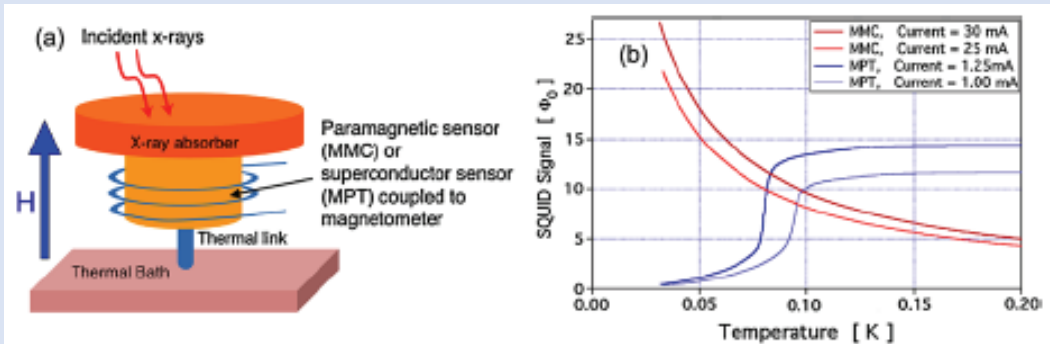Frank et al, NIM A, 1990

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- SNSPDs emerge and flourish

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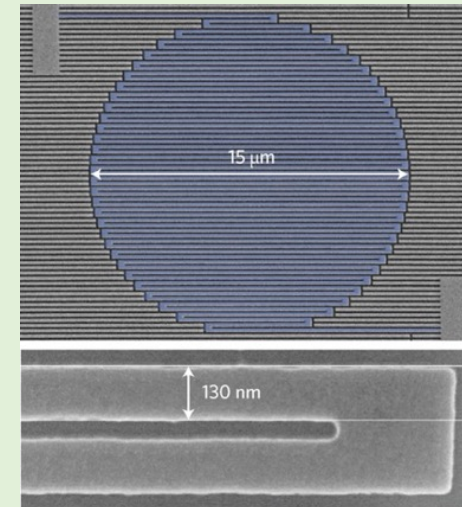Frank et al, NIM A, 1990

Magnetic MicroCalorimeters (MMCs)

- Deposited energy changes paramagnetic or diamagnetic response
- SQUID sensor sees this as change in flux
- Excellent E/ΔE results from Heidelberg, KRISS, and NASA GSFC

Superconducting Nanowire Single Photon Detectors (SNSPDs)

- Gol'tsman et al, APL, 2001
- Superconducting wire (few nm thick, ~100 nm wide) under current bias
- Absorption of single optical photon produces resistance and voltage
- Fast response, low jitter

F. Marsili et al, Nature Photonics, 2013

Explosion of Applications

x-rays
- astrophysics
- beamline science
- tabletop time-resolved science
- microbeam analysis
- fundamental parameters

γ-rays
- nuclear materials analysis

mm waves
- cosmic microwave background

sub-mm waves
- astrophysics
- concealed weapons detection

astroparticle physics
- WIMP searches
- hidden photon searches

neutrino physics
- $0\nu\beta\beta$
- neutrino mass

mass spectrometry
- biomolecules
- neutral fragments

optical and near-IR
- astronomy
- quantum information
- laser-based communication
- LIDAR

alpha particles and neutrons
- nuclear materials analysis

decay energy spectroscopy
- nuclear materials analysis
- nuclear data

# Cosmic Microwave Background Science

- Measurements of the Cosmic Microwave Background (CMB) shape our understanding of the Universe

- Cryogenic, and especially superconducting sensors, are now used in almost every CMB experiment

- In recent past, measurements of temperature anisotropy. Planck (NTD Ge) results definitive.

- Now, searches for B-mode polarization: signature of inflationary epoch
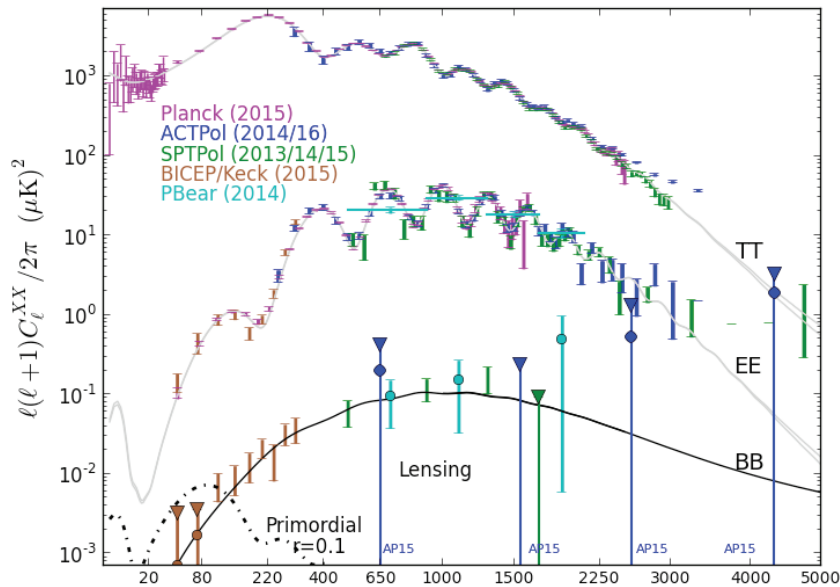
**Temperature and Polarization Signals vs Angular Scale**

B-mode search requires finding nK signals on top of K background

- Same works also constrains sum of neutrino masses, age of universe, Hubble parameter, baryon density, dark matter and dark energy densities


Temperature Anisotropy

-300 μK   +300 μK

Credit: Planck Team
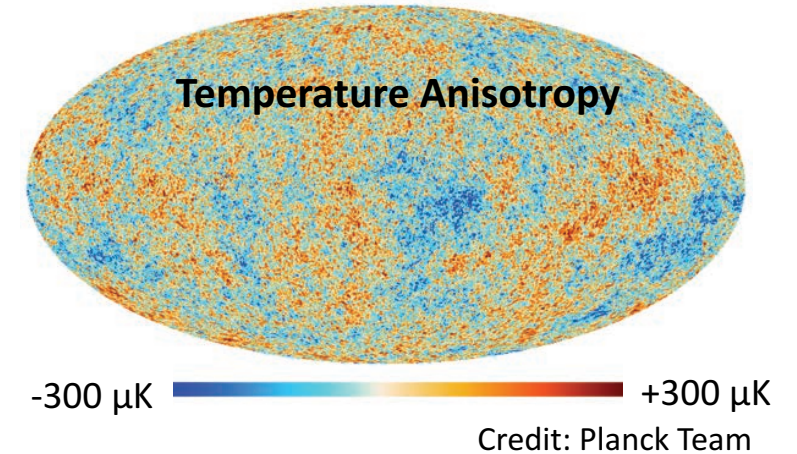
Technology
- Sensitivity of individual sensors limited by photon noise from sky map faster by having more sensors and multichroic sensors
- Instruments typically have several thousand multiplexed TESs
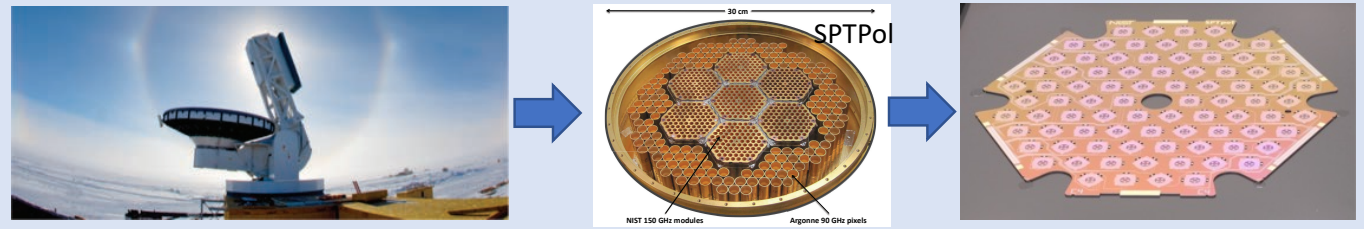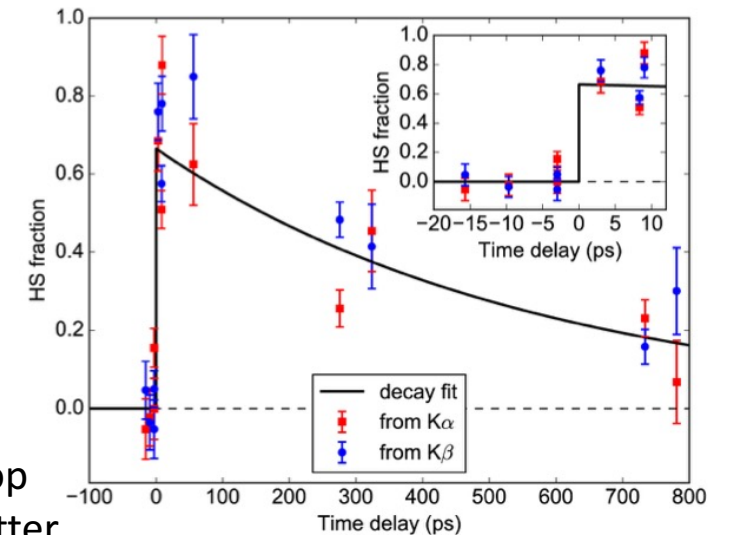
X-ray Science

- Why superconducting sensors? Unique combination of resolving power and collecting efficiency

  o Resolving power gives access to chemical and spin effects, reduces backgrounds and overlapping lines

  o Collecting efficiency (100-1,000x better than xtals or gratings) good for dilute and radiation sensitive materials, also good for weak laboratory sources

- Case for superconducting sensors in laboratory x-ray science was always strong. Recent work shows sup. sensors also have role at large facilities. Several spectrometers at synchrotrons, one under development for LCLSII XFEL.

- Case for use in ultrafast time-resolved x-ray science particularly strong

- Most x-ray techniques now demonstrated: XRF, XES, XAS, RIXS, elastic scattering, PIXE, …
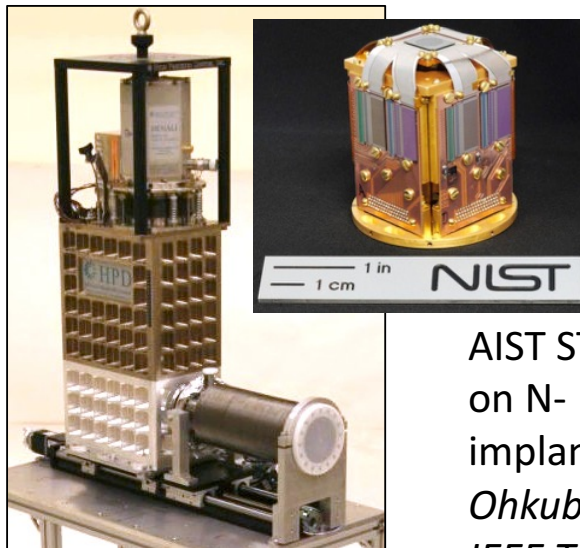
NIST TES spectrometer

AIST STJ data on N-implanted SiC: *Ohkubo et al, IEEE TAS, 2014*
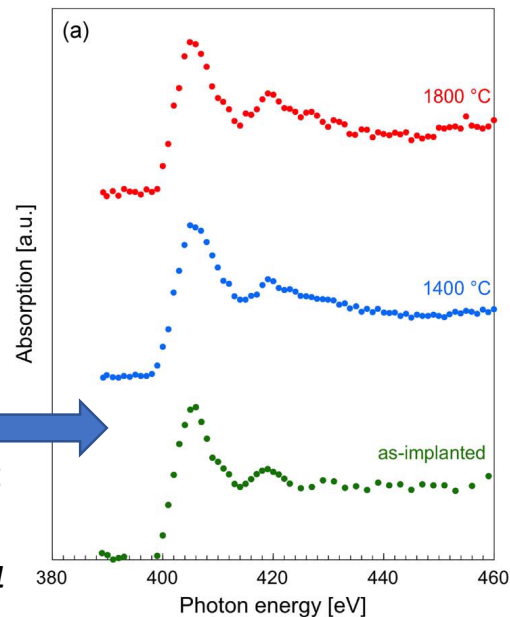
Spin cross-over measured at APS (above) and NIST tabletop. Tabletop result has 10x better time resolution and uses ~10^4x fewer photons: *Miaja-Avila et al, PRX, 2016*

Single Optical and NIR Photon Detection

- Done with TESs, SNSPDs, and MKIDs, each with different strengths
- Wide range of applications:

Quantum Information

Loophole-free tests of Bell's inequalities ➡ exclude theories of local realism

- Giustina et al, PRL, 2015
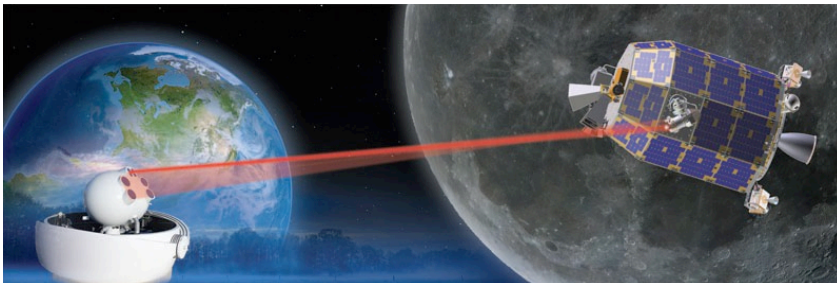- Shalm et al, PRL, 2015

> Excellent talks earlier by H. Terai and L. You

Quantum Key Distribution

Provably secure communications.

Laser-Based Communication

Lunar Laser Communication Demonstration (LLCD), 2013-2014

SNSPDs in ground station receive information via laser light from satellite in lunar orbit (JPL, MIT LL)

Microscopy

K. Hattori presentation this past Weds.

Astronomy

Exoplanet searches, maybe redshift surveys

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Future Trends

**Bigger and more ambitious systems?   Absolutely**

- DOE planning CMB Stage 4 (CMB S4): $O(10^5)$ sensors
- X-ray spectrometer for LCLSII: 10^4 sensors each counting at several kHz
- Litebird (CMB) and Athena (x-ray) satellites

Ubiquity? Meaning some widespread application of cryogenic sensors? Maybe

- Cost of mK cryogenics is a significant obstacle: >$200K. Maybe a Kelvin-range instrument will be first. SNSPDs for a communication application?
- Commercial XRF continues to look promising

Colder?   Yes

- Magnetic calorimeters already at 10-20 mK
- Desire for soft x-ray TESs with resolution of 0.5 eV at 500 eV: will see TESs move from ~100 mK to ~40-50 mK

~15 cm
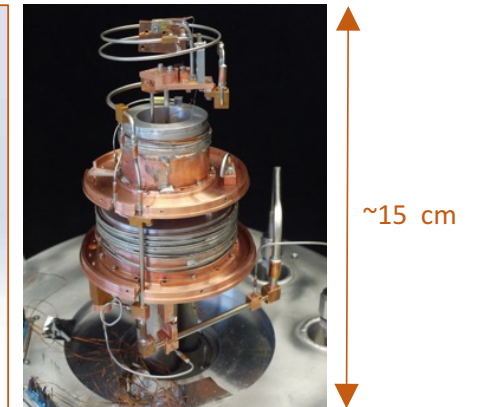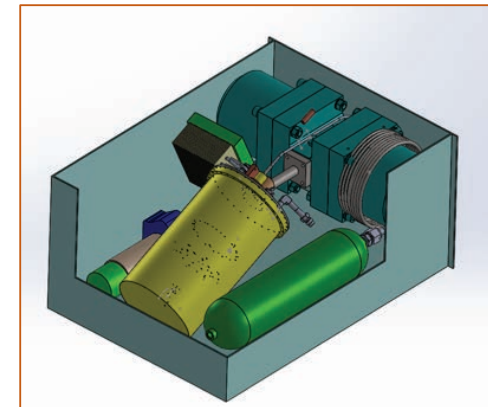
1.7K cooler with 300 W wall draw:
V. Kotsubo et al, IEEE TAS, 2017

Microwavier?   Absolutely

- Microwave readout architectures (MKIDs and uwave SQUIDs) compelling. Expect them to dominate.
- HEMT amplifiers used in uwave readout have input noise T of few K: mismatch to mK sensors. Expect to see quantum amplifiers play a growing role.

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Thank you!

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