Nanomechanical and Nanothermodynamic Devices

NATO Advanced Research Workshop
“Coherent charge and spin transport on a nanoscale”
Chernogolovka, Russia

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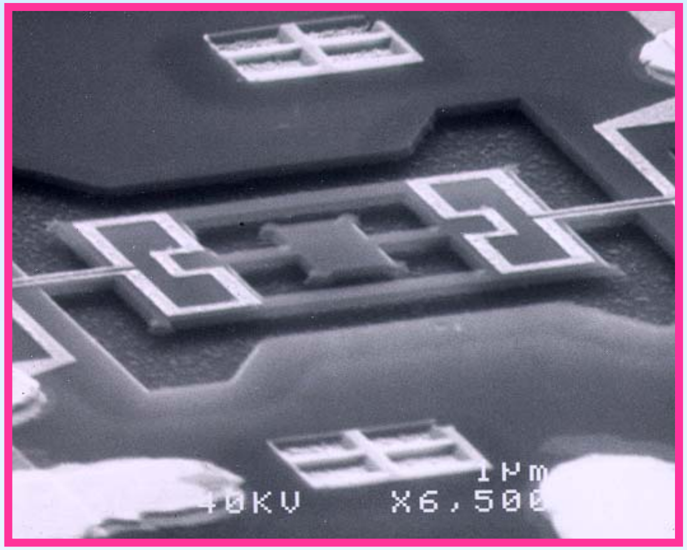
Andrew N. Cleland

Department of Physics / iQuest / CNID
University of California
Santa Barbara

Integration of Nanomechanics and Nanoelectronics



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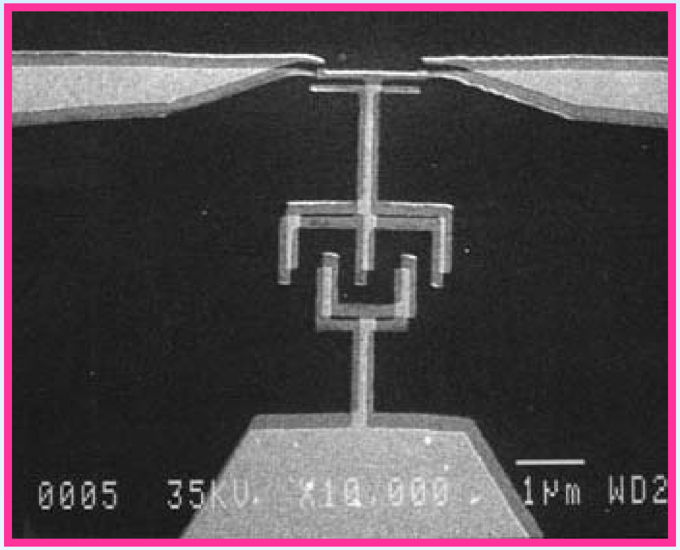
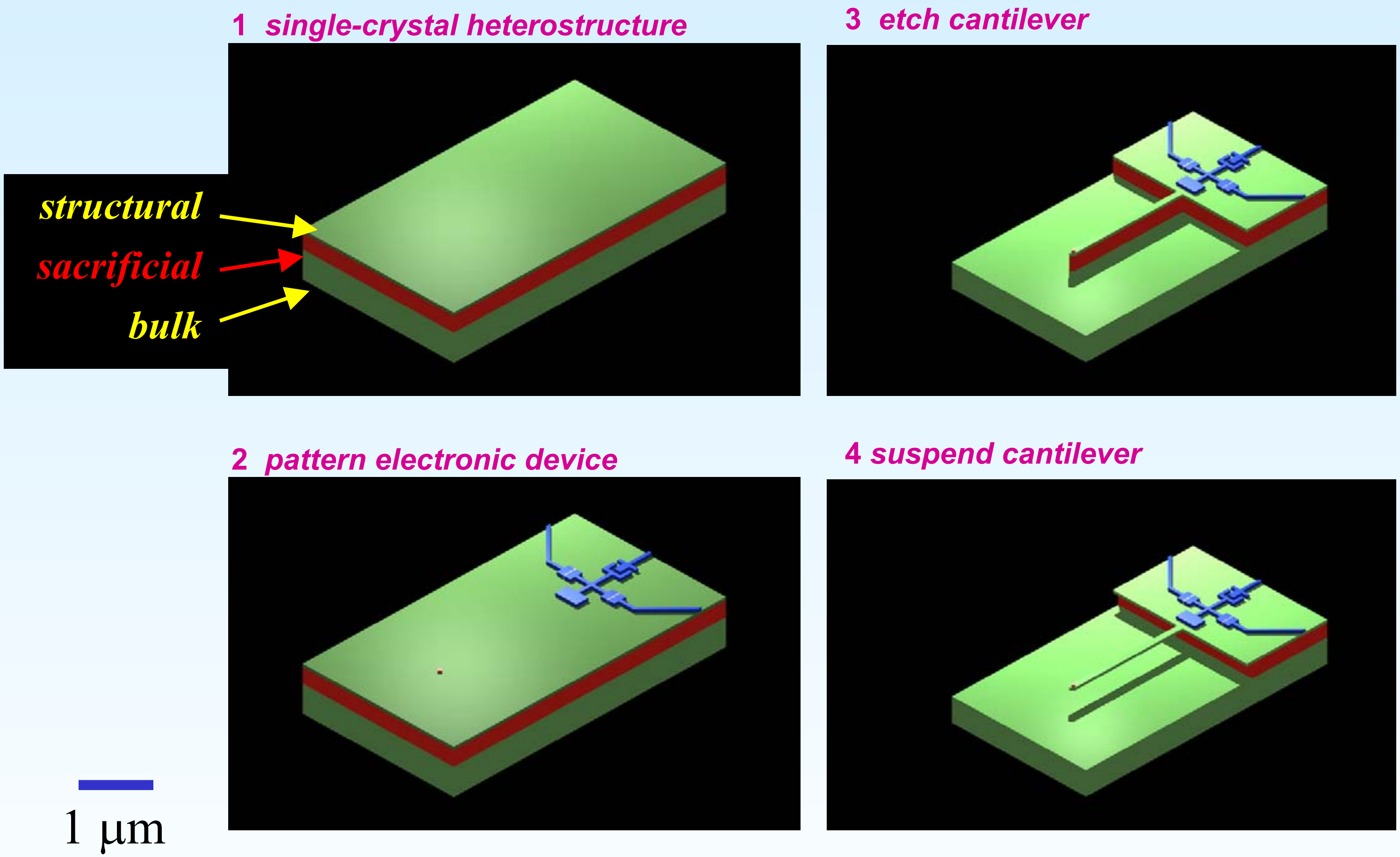


Combine mechanical devices with tunnel junctions to enable new physics and new applications:

- **thermal properties (static and dynamic)**
- **integrated displacement sensing**
- **quantum limited displacement**
- ***quantum computation***

Surface nanomachining: integrated structures



Principal Research Themes

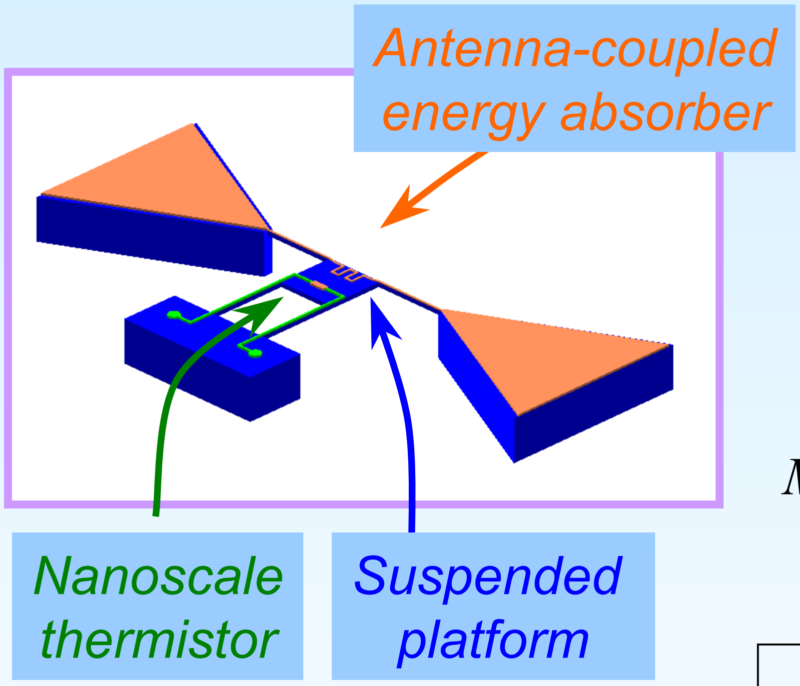
Nanoscale Photons and Phonons

- *Single THz photon detection using bolometry*
- *Energy relaxation in suspended nanostructures*
- *Thermodynamics of magnets, superconductors, nuclear spins*

Displacement sensing

- *Magnetometry*
- *Quantum-limited motion sensing*
- *Quantum control: feedback, squeezing*
- *Coupled coherent mechanical-electronic bistable system*

Nanoscale bolometry



All absorbed radiant energy ends up in the ***phonons***

⬇

Trap ***phonons*** *as long as possible*
Measure as well as possible

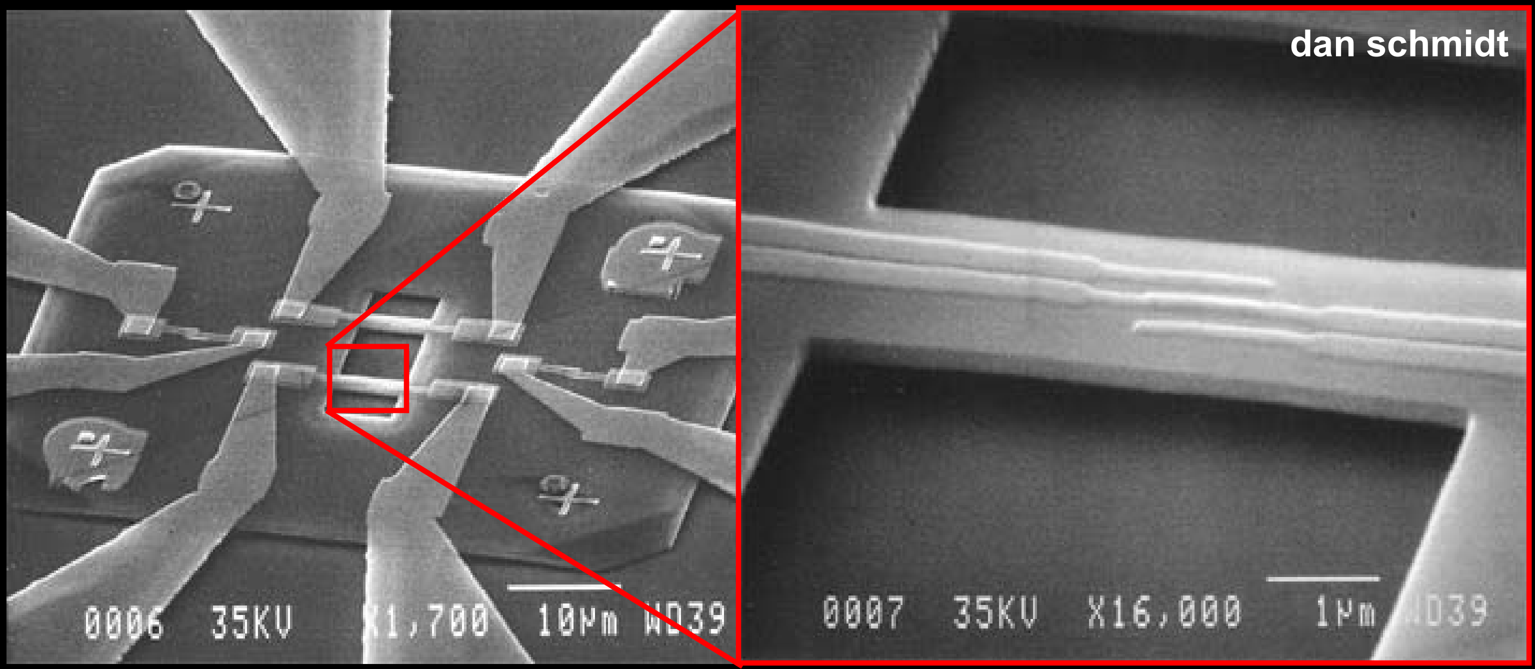
⬇

Minimize heat capacity
Minimize phonon thermal conductance
Maximize temperature sensitivity

⬇

- ***Smallest possible structure***
- ***Operate at low temperatures (~ 0.1 K)***

Nanoscale tunnel junctions

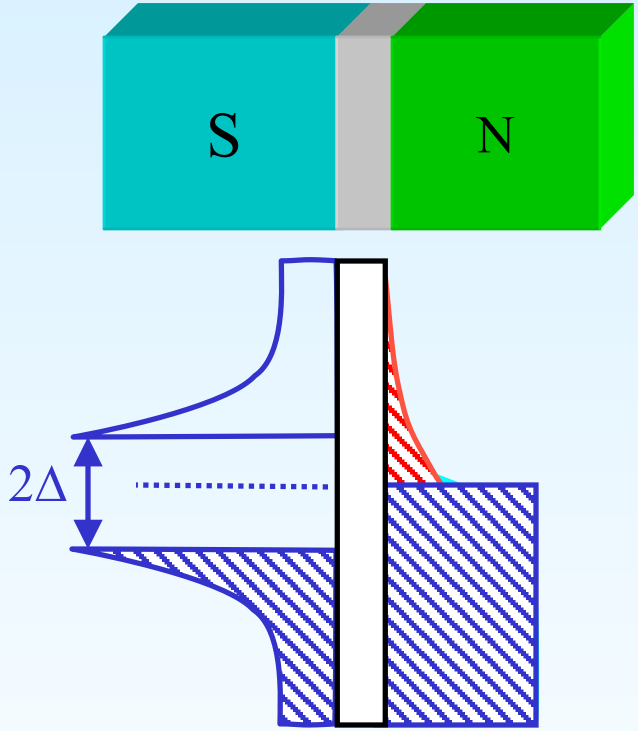


- 0.1 µm geometries possible
- Operates 10 mK - 1.5 K
- SIS and NIS configurations

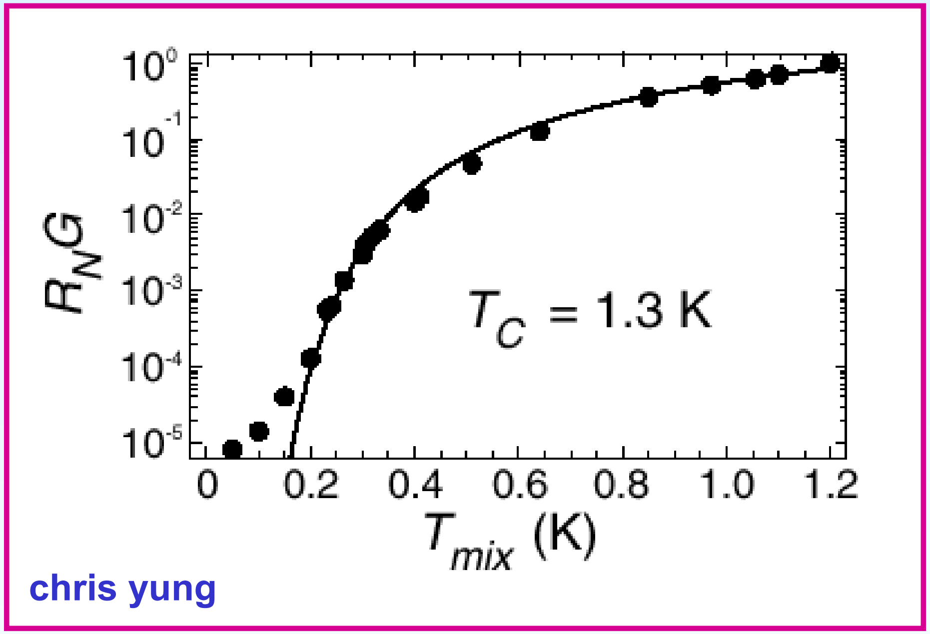
- Nanoscale thermometry
- 1-100 GHz phonon spectrometry
- Single electron transistors

Tunnel junction thermometry: SIN thermometer

superconductor-insulator-normal metal tunnel junction:

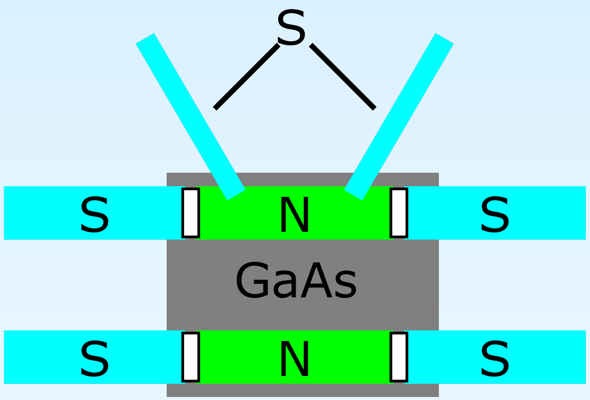


... resistance gives *T* for normal metal electrons

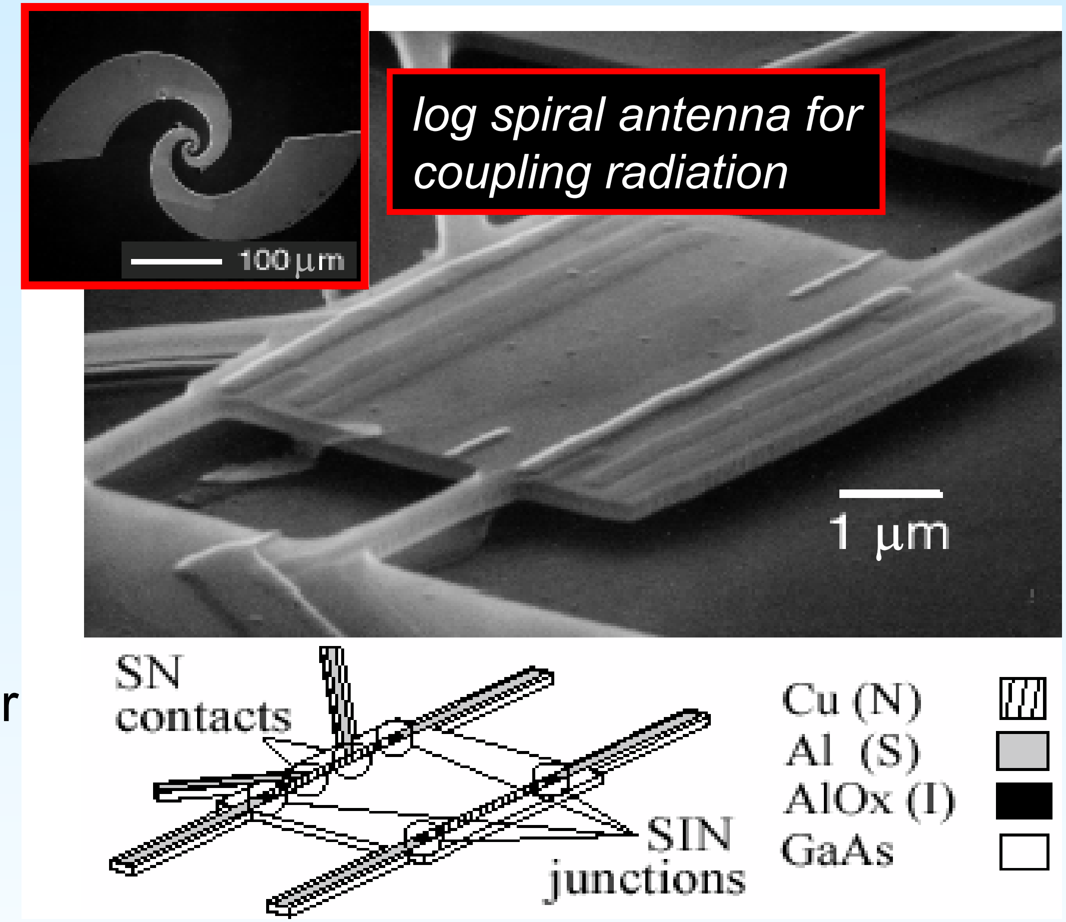


Yung, Knobel, Cleland *APL* 81, 31 (2002)

Nanoscale Bolometer/Calorimeter

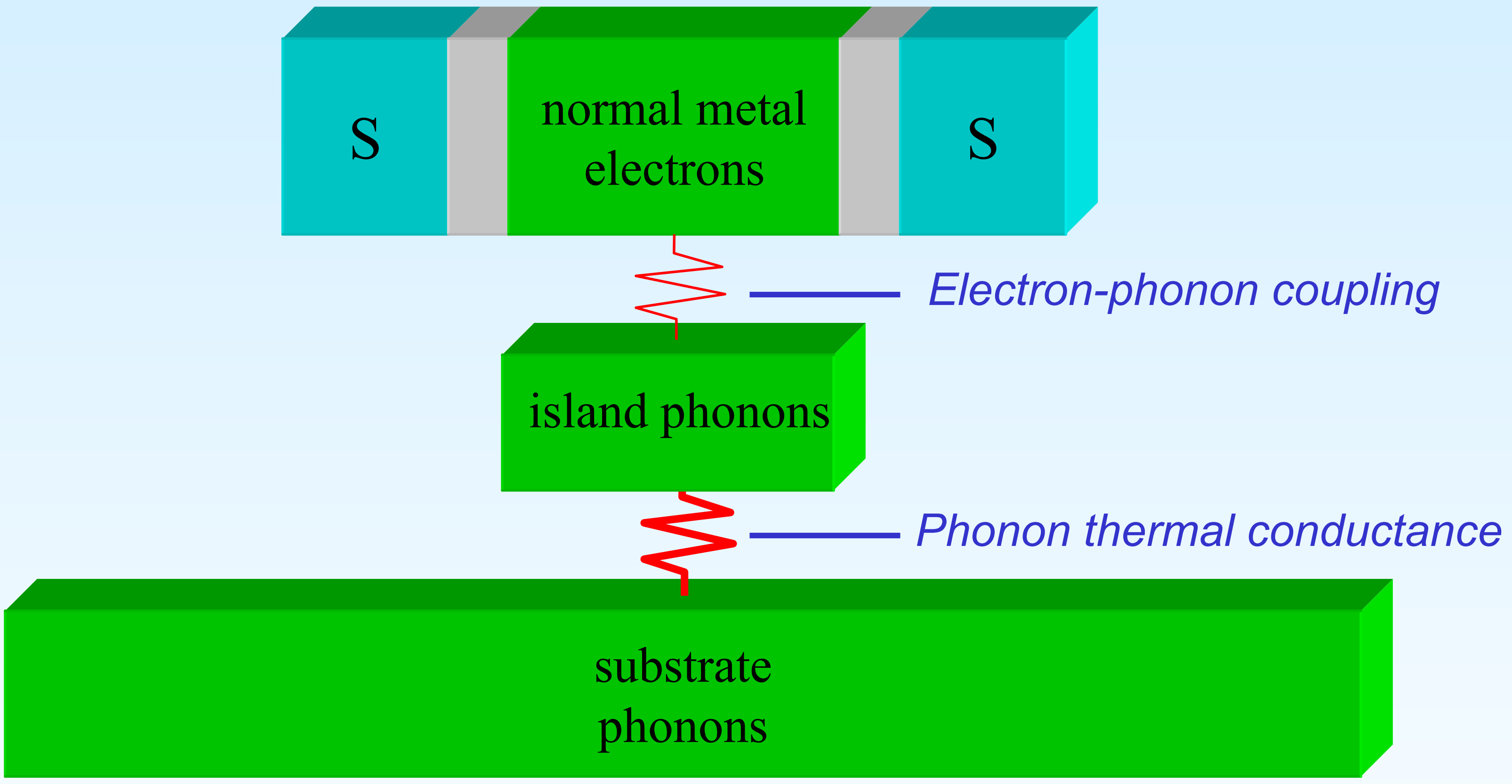


SINIS: Thermistor & heater
SNS: Heater

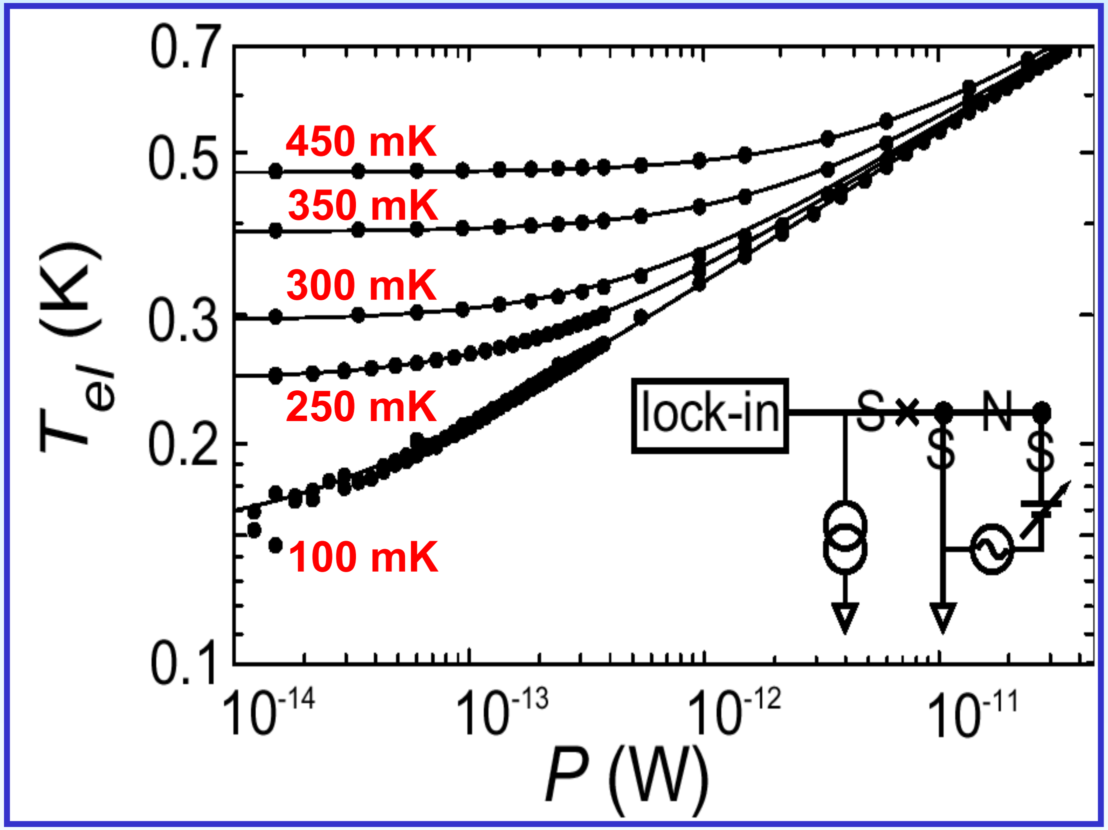


Yung, Knobel, Cleland *APL* 81, 31 (2002)

Nanoscale Bolometer/Calorimeter



Electron-Phonon Coupling



Yung, Knobel, Cleland *APL* 81, 31 (2002)

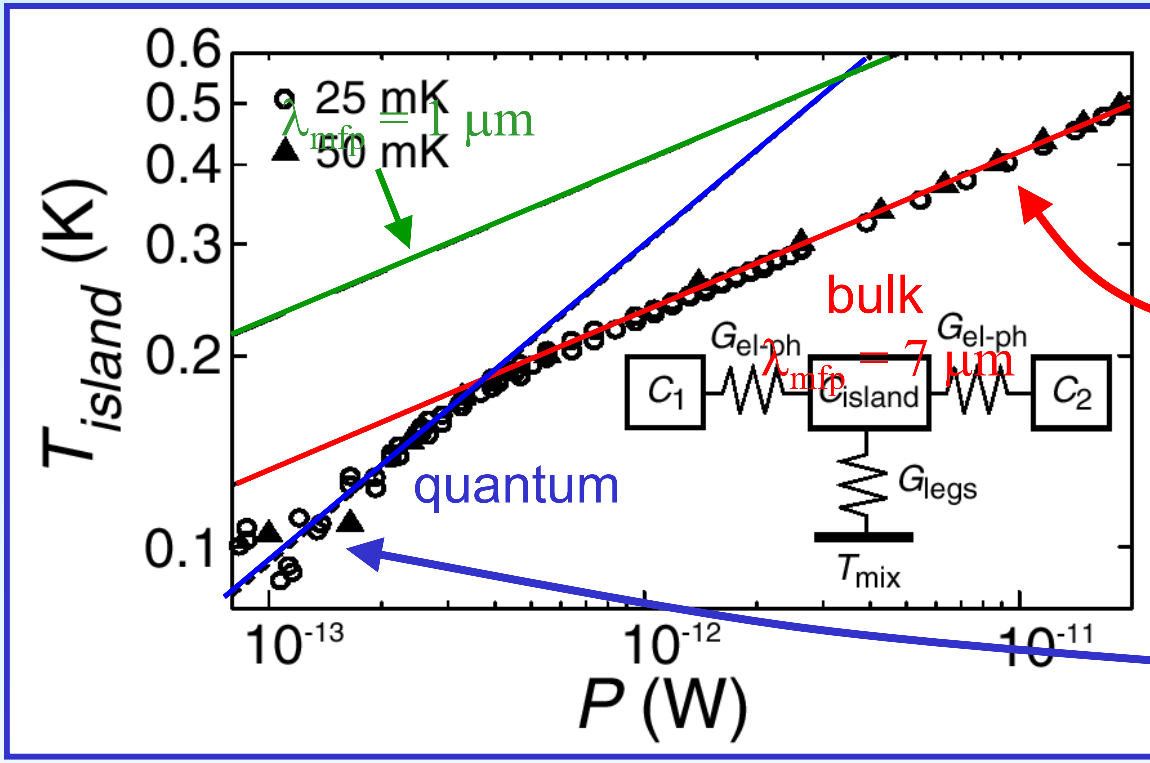
Electrons in normal metal heat up above phonons due to weak coupling:
(Gantmakher 1974)

$$\frac{P}{V} = \Sigma\left(T_{el}^{4.8} - T_{island}^{4.8}\right)$$

Σ = 2 x 10^9 W/m-K^5
Bulk value
$T^{4.8}$
Bulk power = 5
Why do bulk values work?

... characterizes electron-phonon coupling

Phonon Thermal Conductance of Supports



Yung, Knobel, Cleland *APL* 81, 31 (2002)

Transition from bulk to quantum conductance

Bulk conductance

$$P = \alpha\left(T_{island}^4 - T_0^4\right)$$

Quantum conductance

$$P = 24 G_Q \left(T_{island} - T_0\right)$$

$$G_Q = \frac{\pi^2 k_B^2 T}{3h}$$

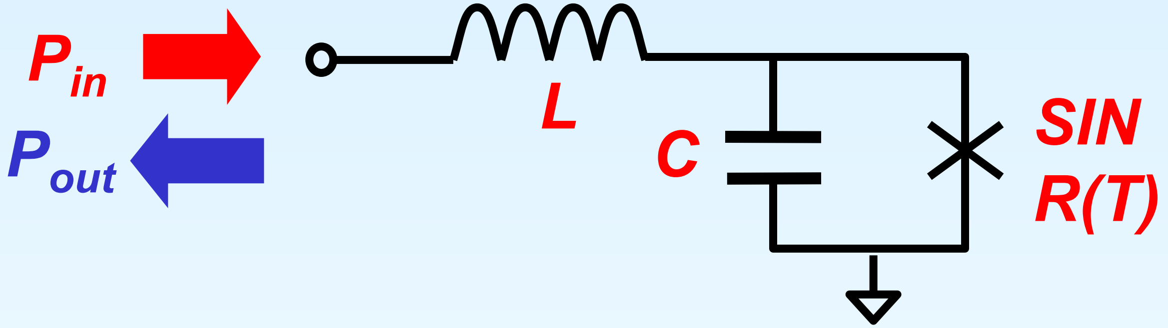
At the lowest temperatures, G is scale- and material-independent

Schwab and Roukes, *Nature* (2000)

Radiofrequency SIN

Nanosecond-scale time-resolved thermometry

Tuned circuit to read out thermometer:

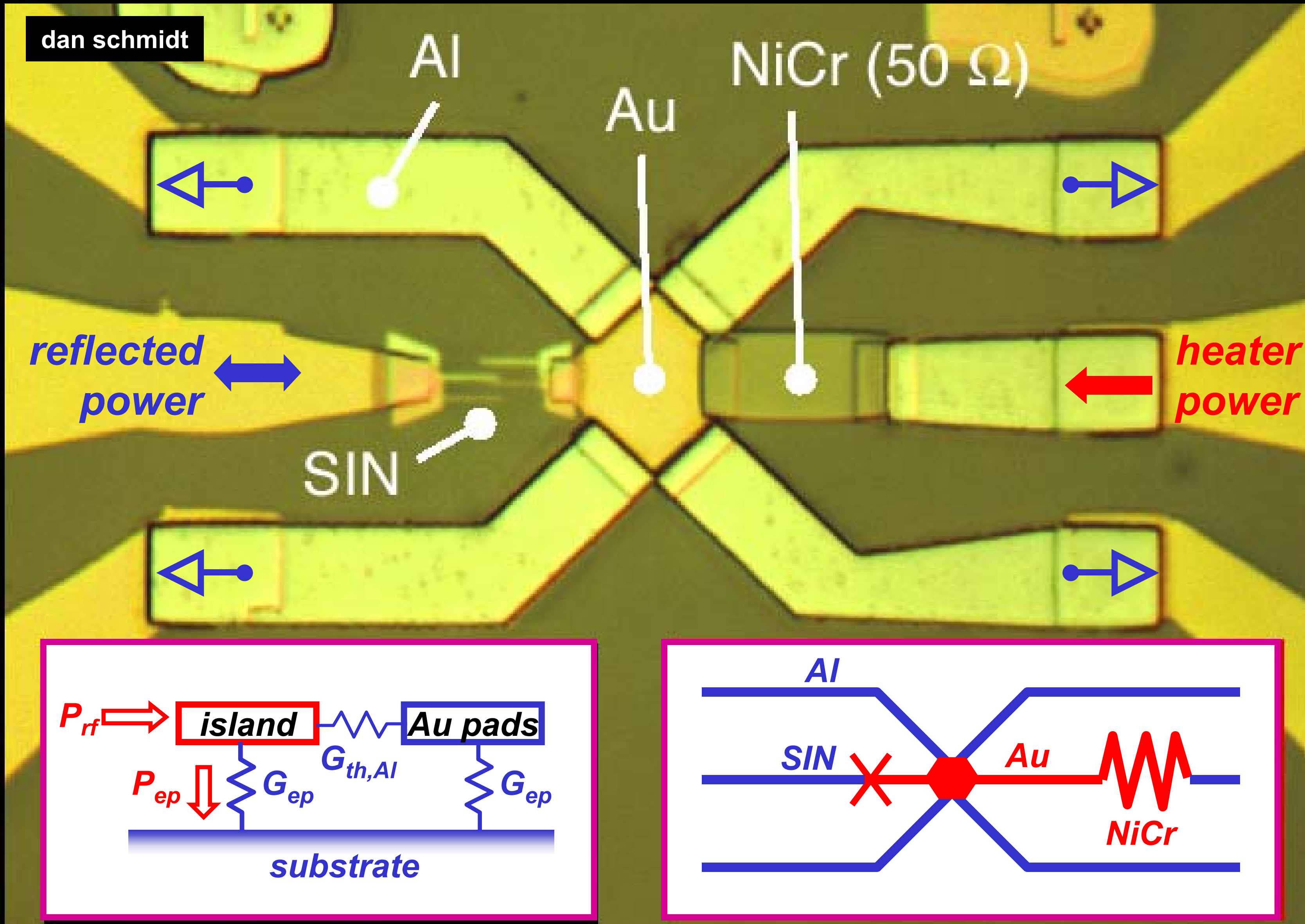


Reflected power yields R(T):

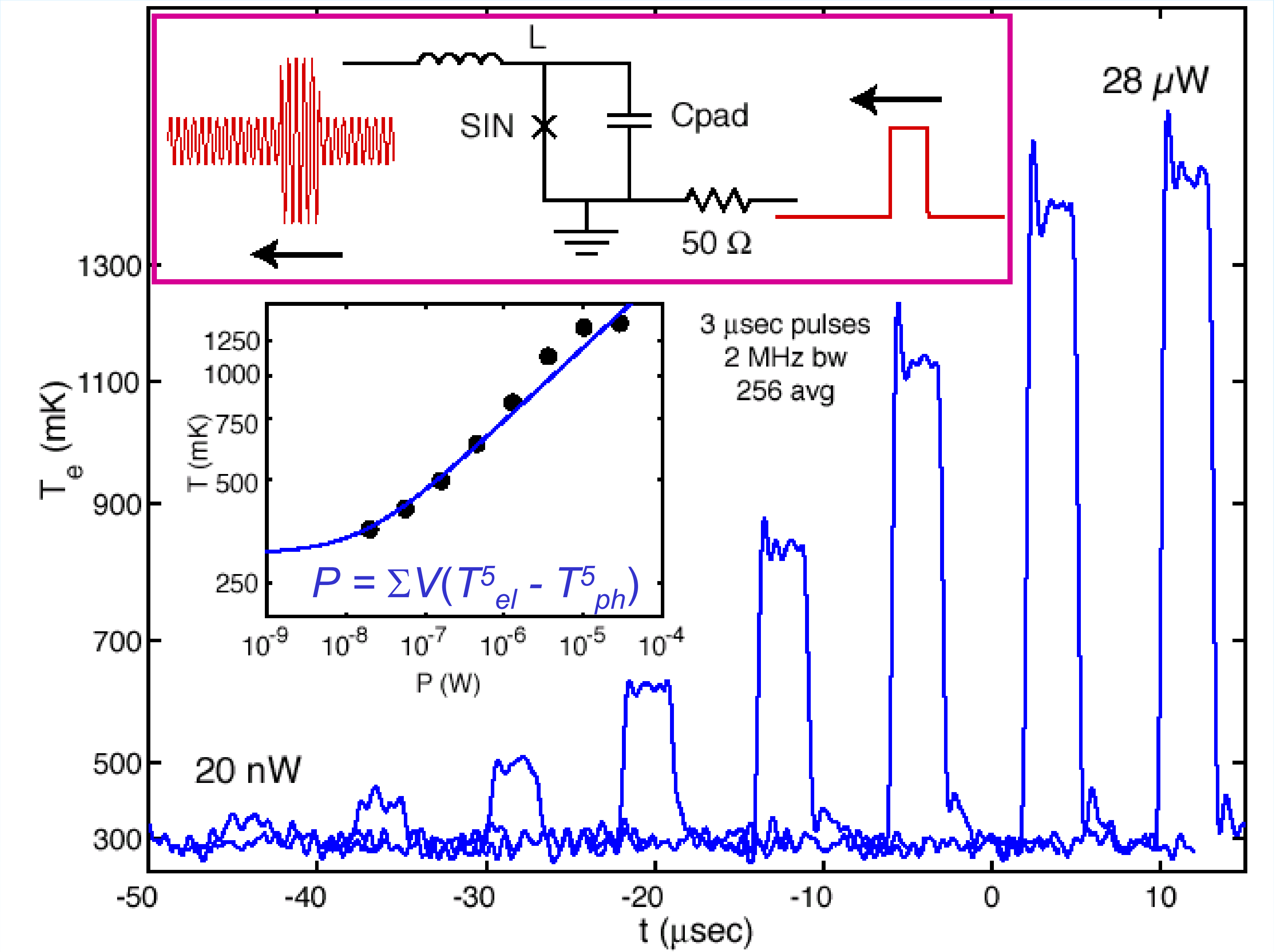
- ***Tuned circuit frequencies to 1 GHz***
- ***Bandwidths to 100 MHz***
- ***Measured temperature noise can reach 1 $\mu K/Hz^{1/2}$***

Schmidt, Yung, Cleland *to appear APL* (2003)

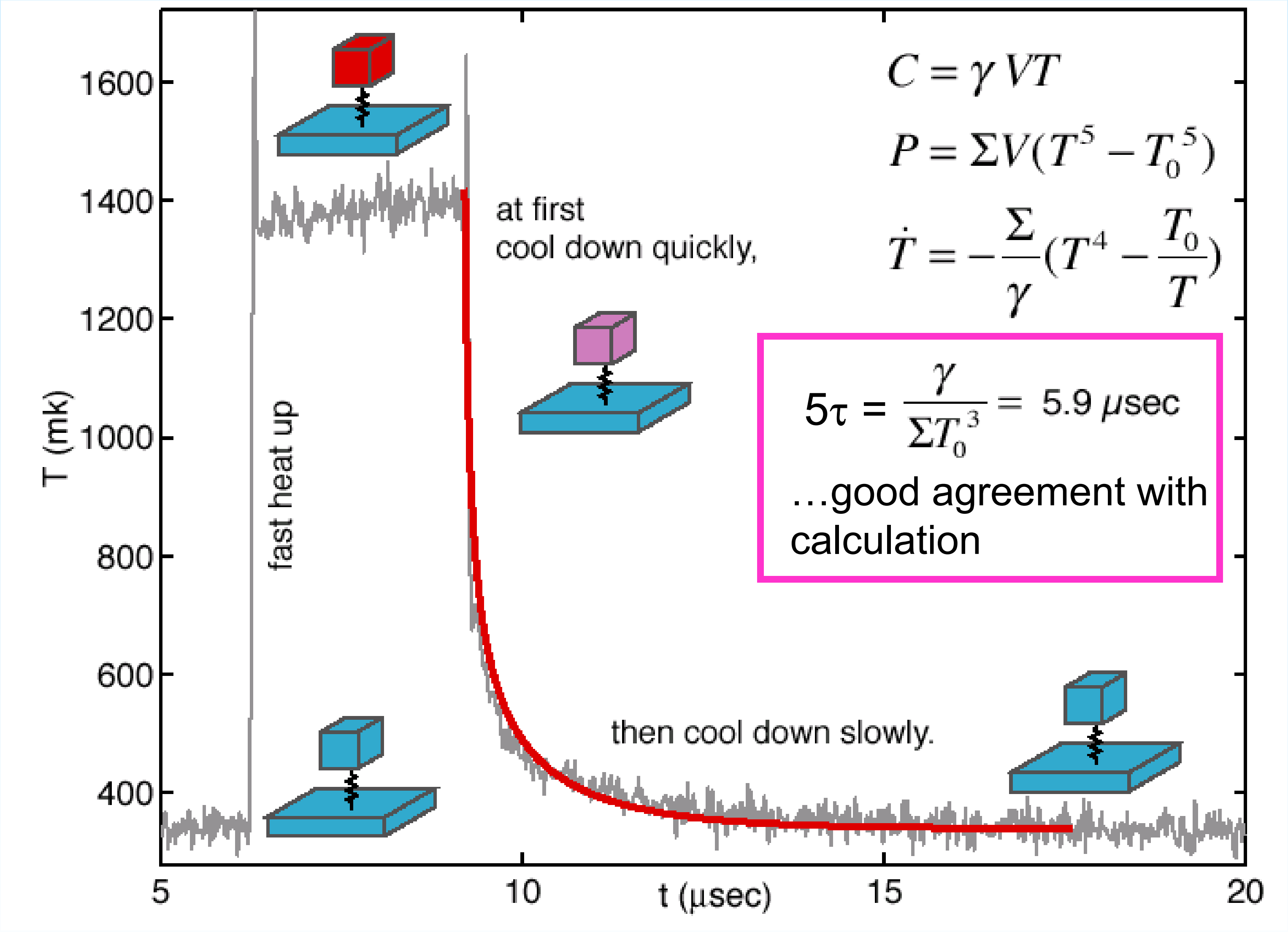
rf-SIN coupled to heater



rf pulse heating



Dynamic measurement of electron-phonon cooling



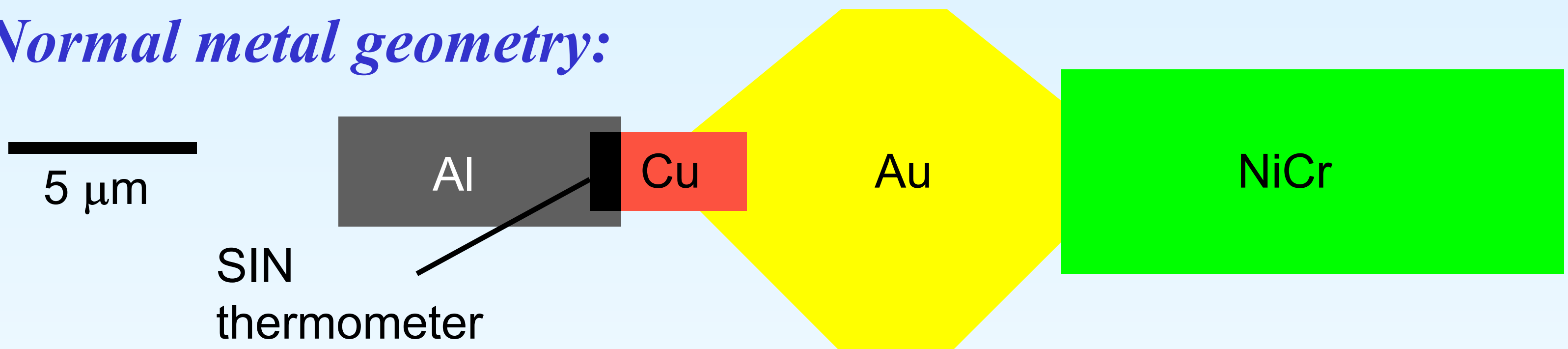
Calorimetry

This measurement:

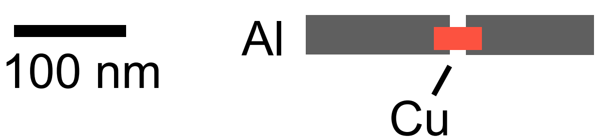
Metal volume V = 1.5 μm^3 ➡ Heat capacity C = 200 aJ/K at 0.3 K

or, 1.5 x 10^7 k_B

Normal metal geometry:



Smallest volumes:



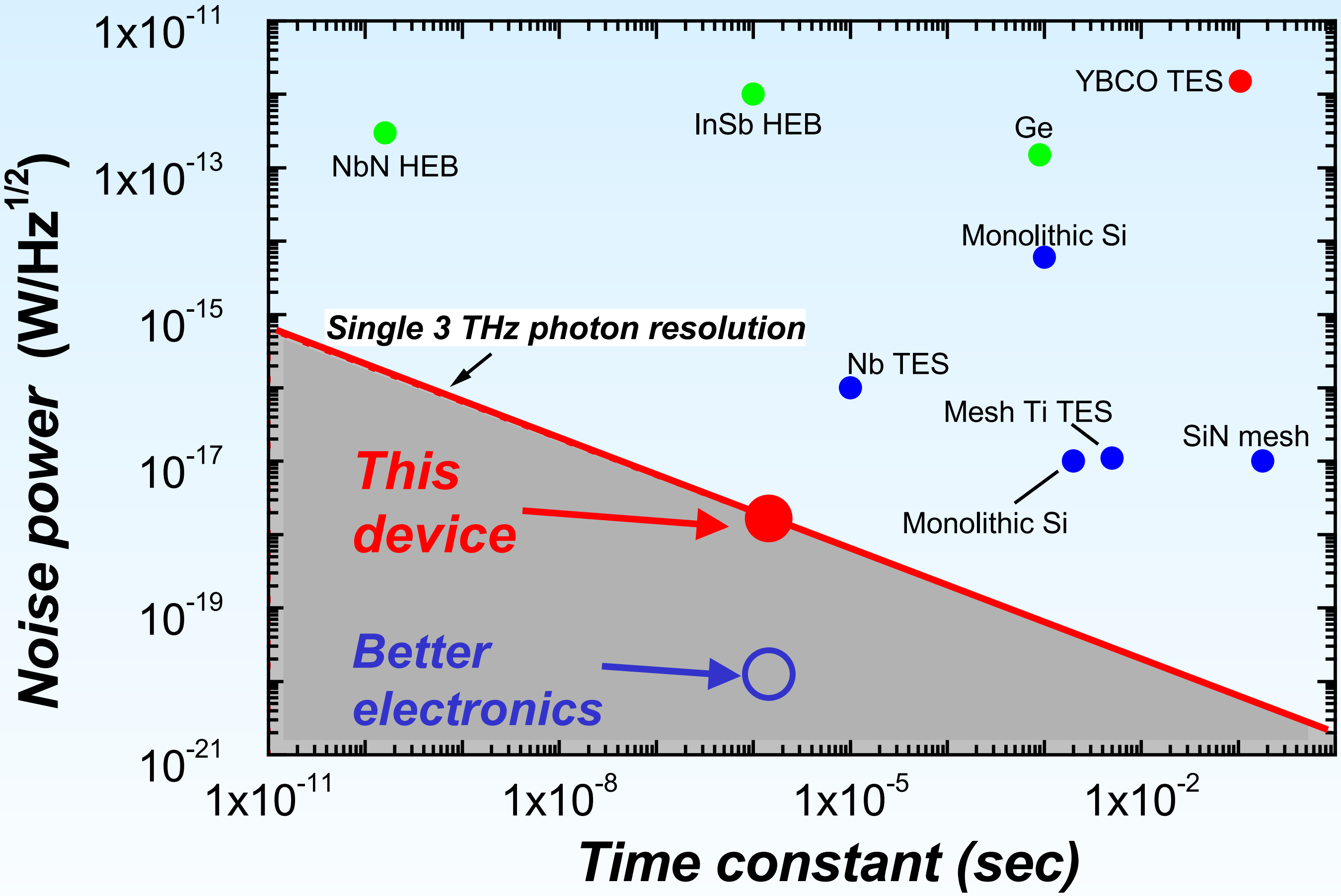
Normal metal volume ~ 10^{-5} μm^3
Heat capacity C ~ 10 k_B at 30 mK

… detect change from *one* degree of freedom

Nanoscale Bolometer

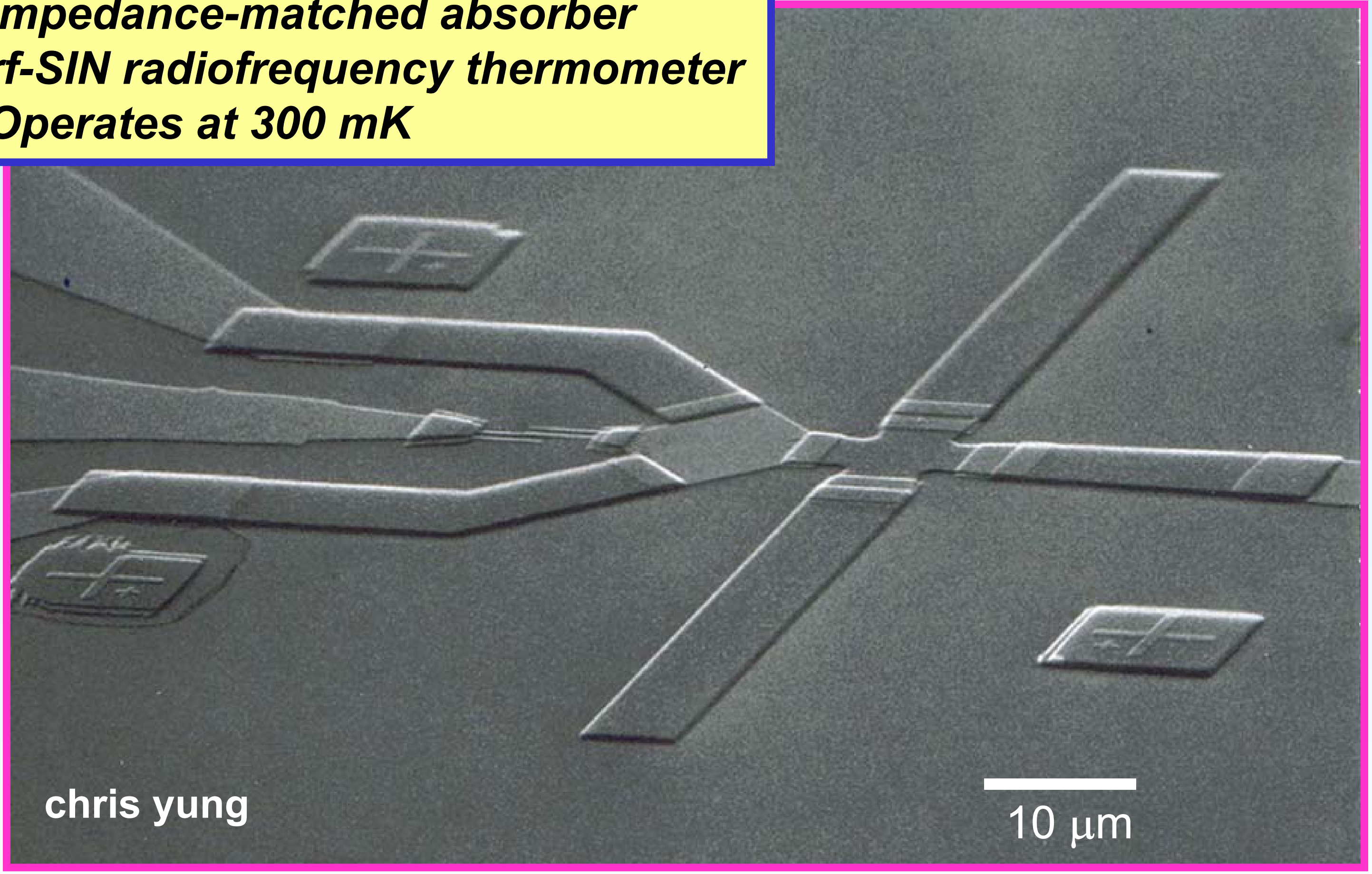
Progress thus far:

- T_{min} = 200 mK
- $\tau_{thermal}$ = 1.2 μsec
- NEP = 2¥10^{-18} W/Hz$^{1/2}$

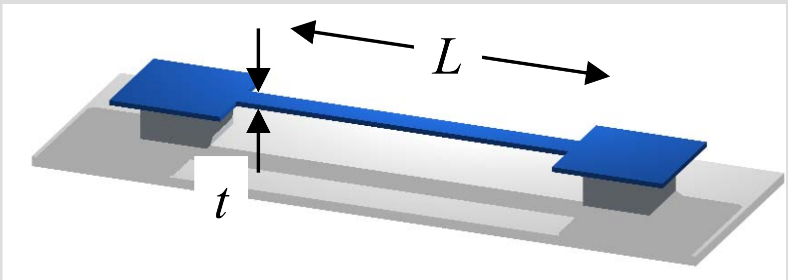


Nanoscale Bolometer

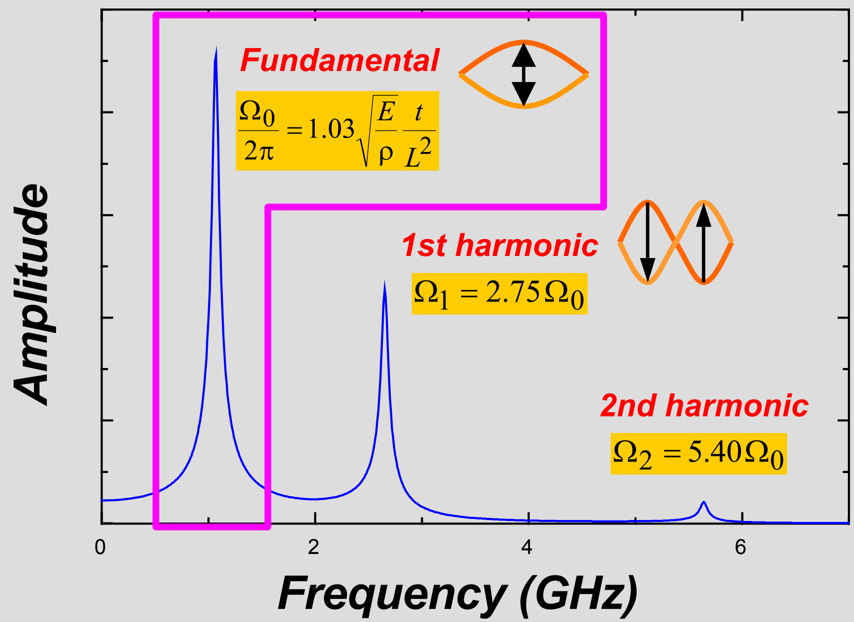
- ***Dipole antenna: 1-10 THz***
- ***Impedance-matched absorber***
- ***rf-SIN radiofrequency thermometer***
- ***Operates at 300 mK***



Doubly Clamped Flexural Resonator



Length (μm)	Frequency (GHz)
5	0.03
2	0.2
0.9	1.0
0.5	3.0
Width 0.1 μm	Thickness 0.1 μm



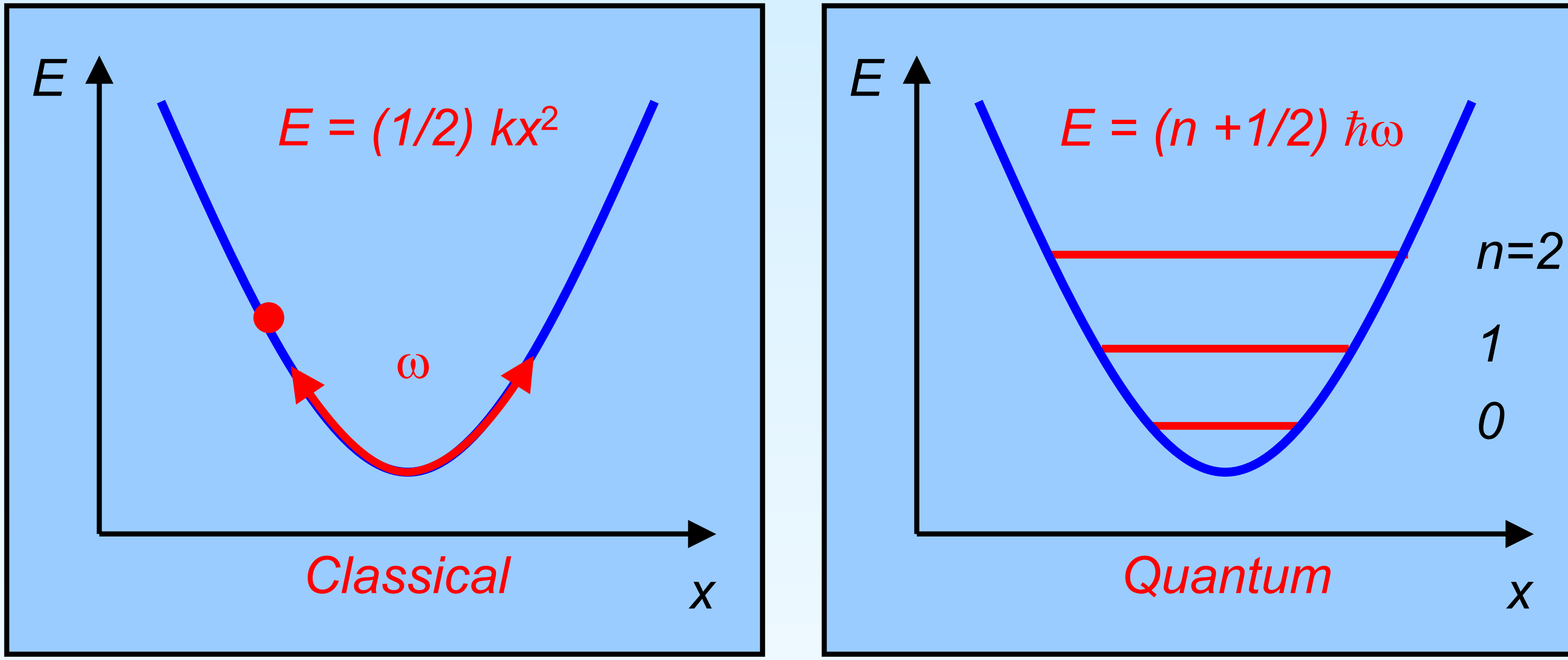
DC response: $\Delta z = F / k_{eff}$

Fundamental: $\Delta z = Q\, F / k_{eff}$

$Q \sim 10^4$ for nm-resonators

Deep submicron technology allows L band resonators

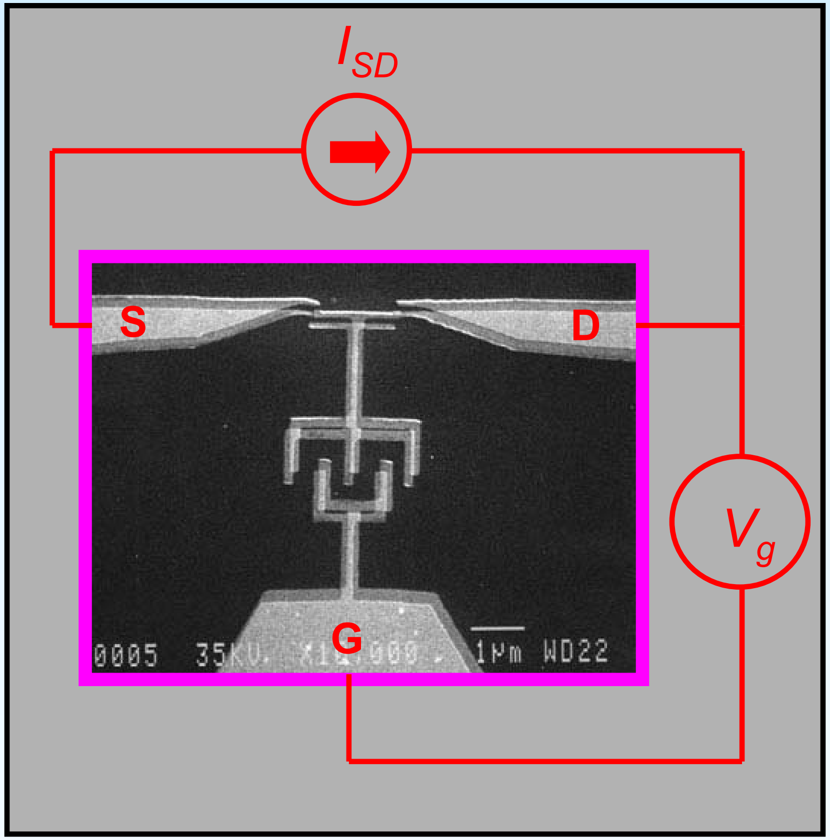
Simple Harmonic Oscillator

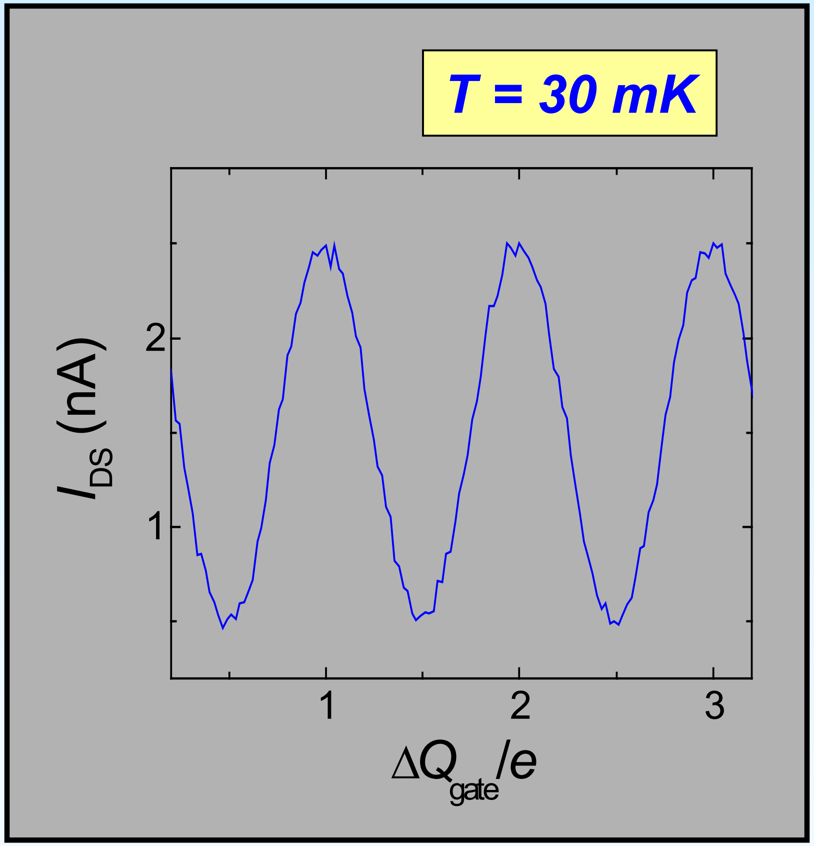


To measure transition:

- $k_B T < \hbar\omega$: T_{min} ° 50 mK ➡ ω/2π ° 1 GHz
- *(nearly) quantum limited detection:* $\varepsilon \sim (1\text{-}10)\ \hbar\omega$

Angle-Evaporated SETs

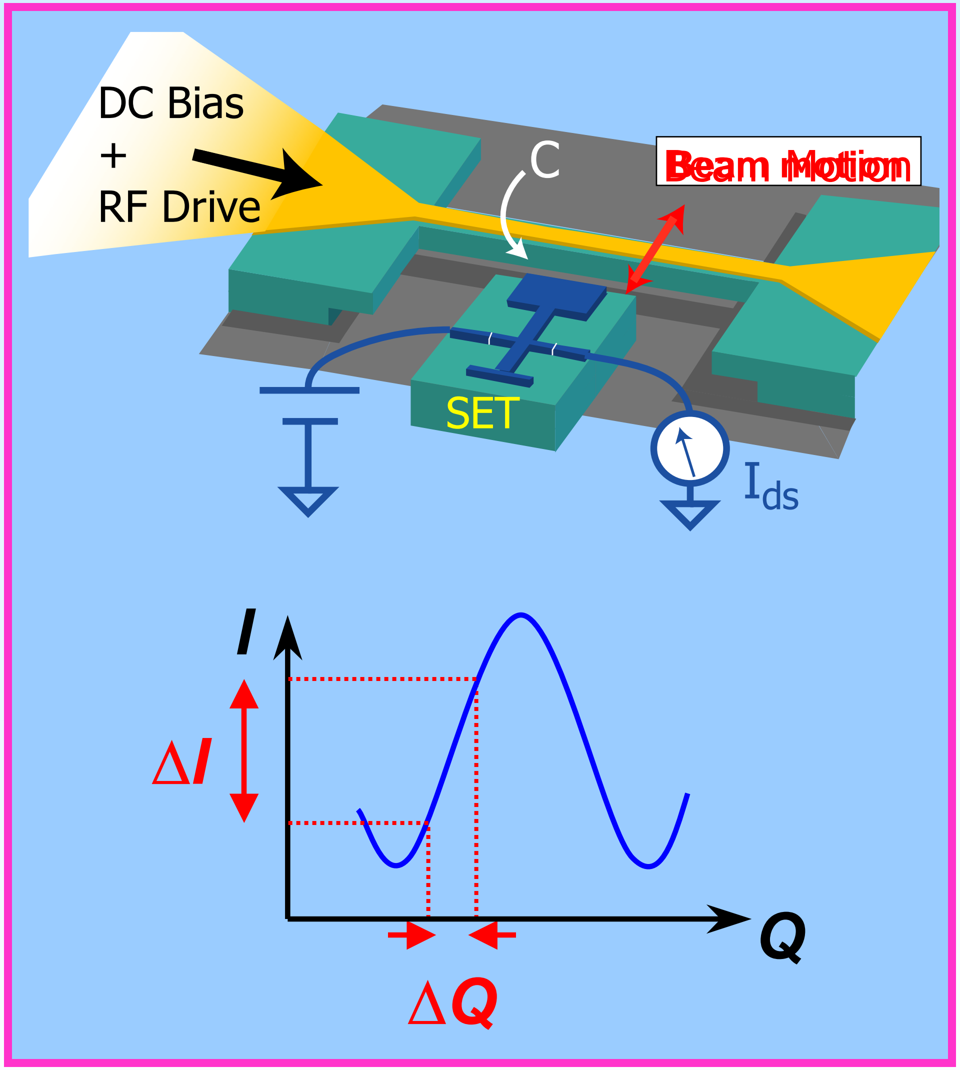




Junction C ~ 0.5 fF
Junction R ~ 100 kΩ

I(Q) periodic, period e
$S_Q^{1/2} \sim 10^{-5}\ e/Hz^{1/2}$

Capacitively-coupled SET



Beam motion Δx *changes* C:

$$\Delta C = \frac{\partial C}{\partial x}\Delta x$$

Voltage V *changes* Q:

$$\Delta Q = \Delta C \cdot V$$

Charge ΔQ *induces change* ΔI:

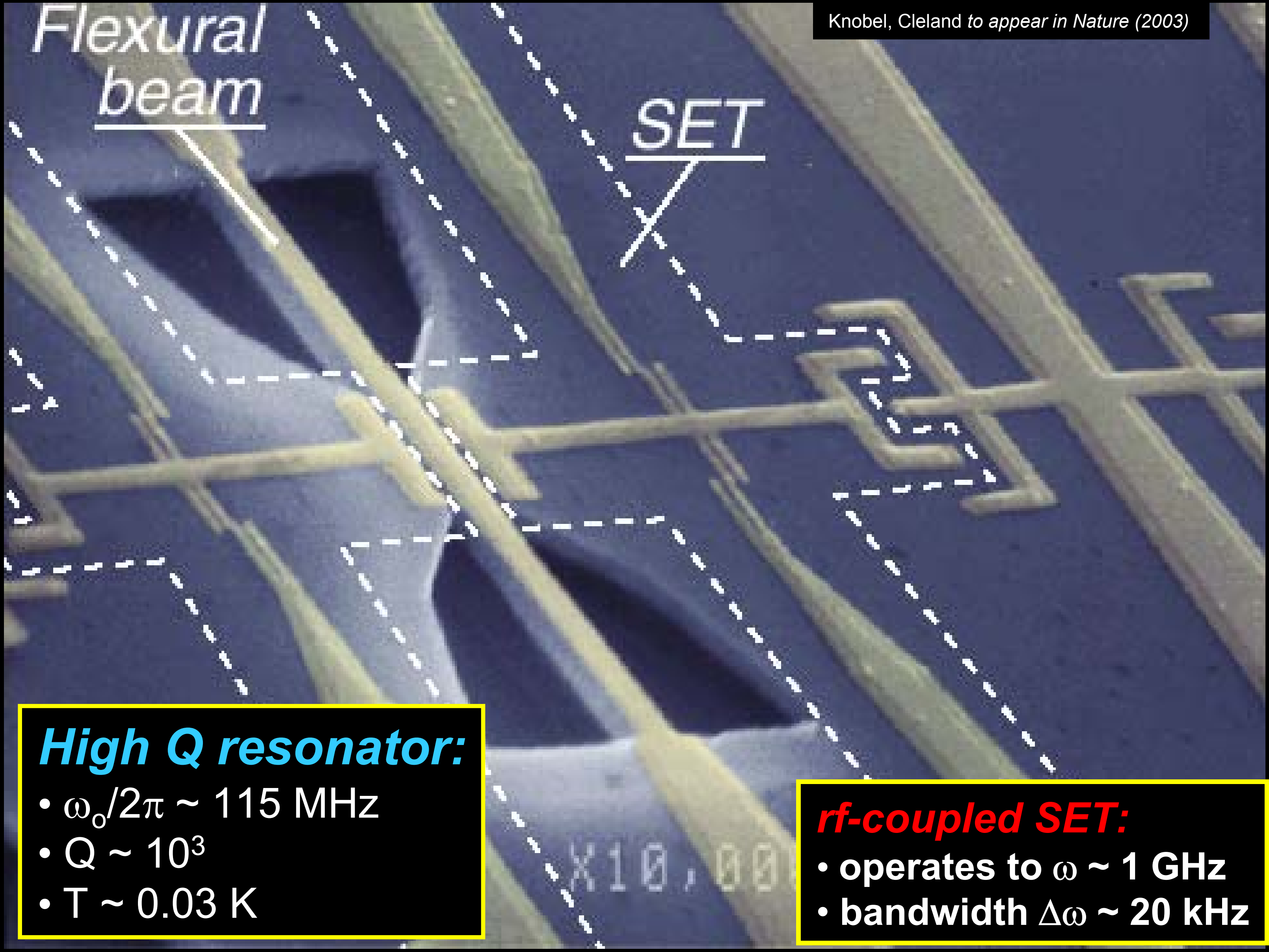
$$\Delta I = \frac{\partial I}{\partial Q}\Delta Q$$

$$= \frac{\partial I}{\partial x}\Delta x$$

Sensitivities of 10^{-16} *m/Hz*$^{1/2}$ *at 1 GHz are possible*

Blencowe and Wybourne (2000)

Quantum limited detection using an SET



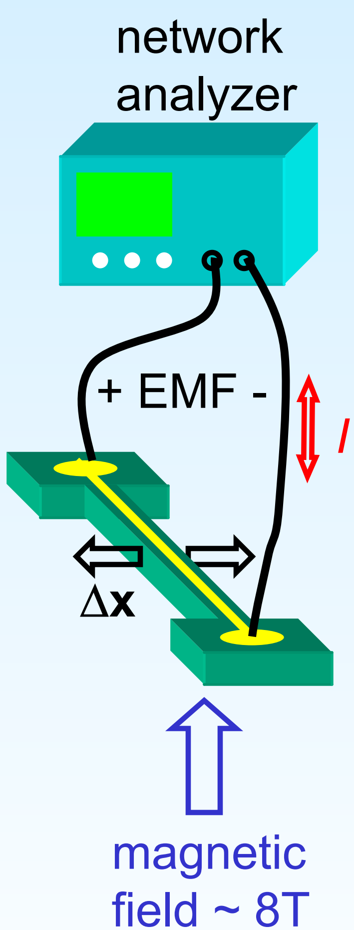
High Q resonator:

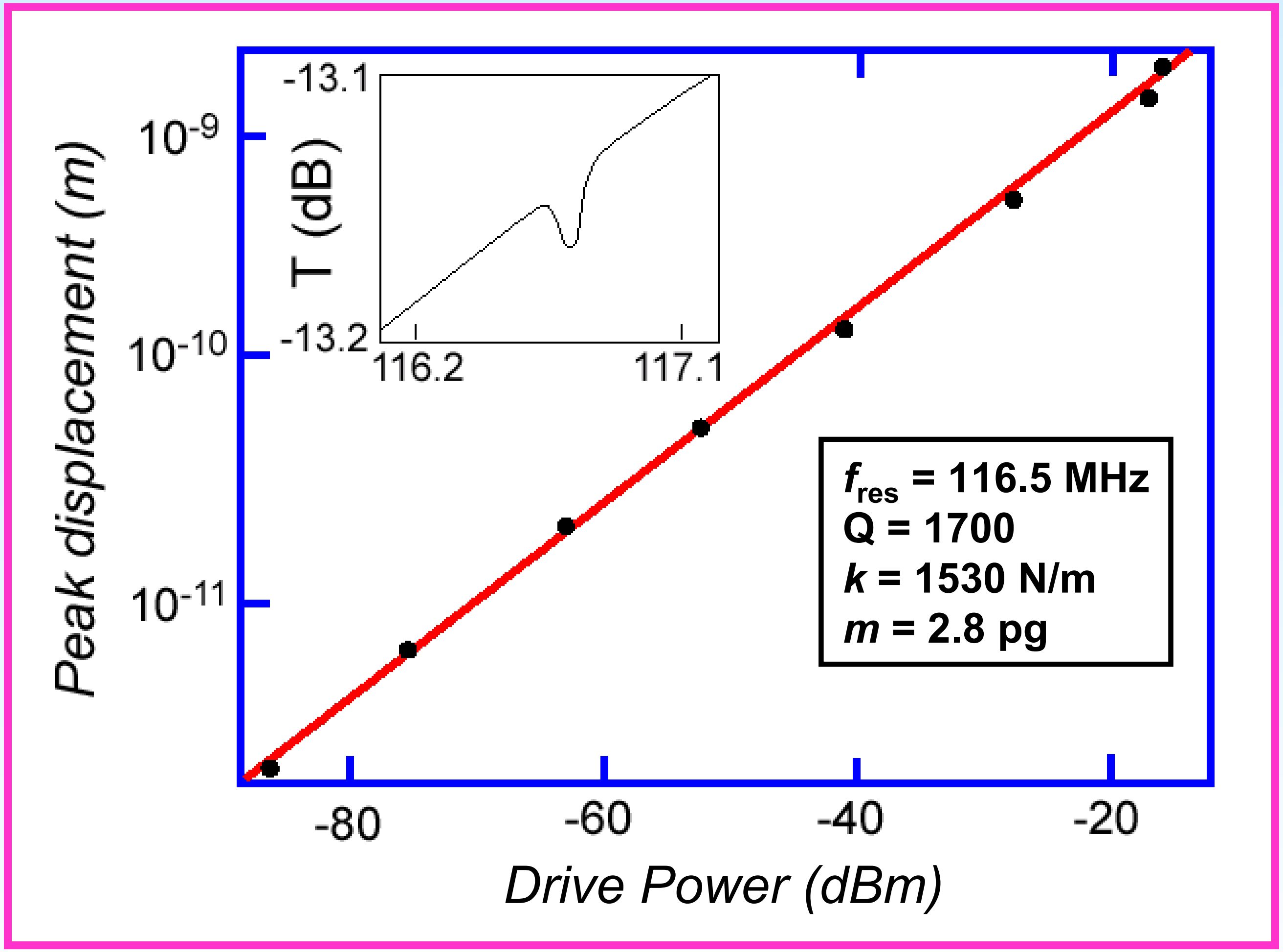
- $\omega_o/2\pi \sim 115$ MHz
- $Q \sim 10^3$
- $T \sim 0.03$ K

rf-coupled SET:

- **operates to $\omega \sim 1$ GHz**
- **bandwidth $\Delta\omega \sim 20$ kHz**

Magnetomotive characterization





Knobel, Cleland *to appear in Nature (2003)*

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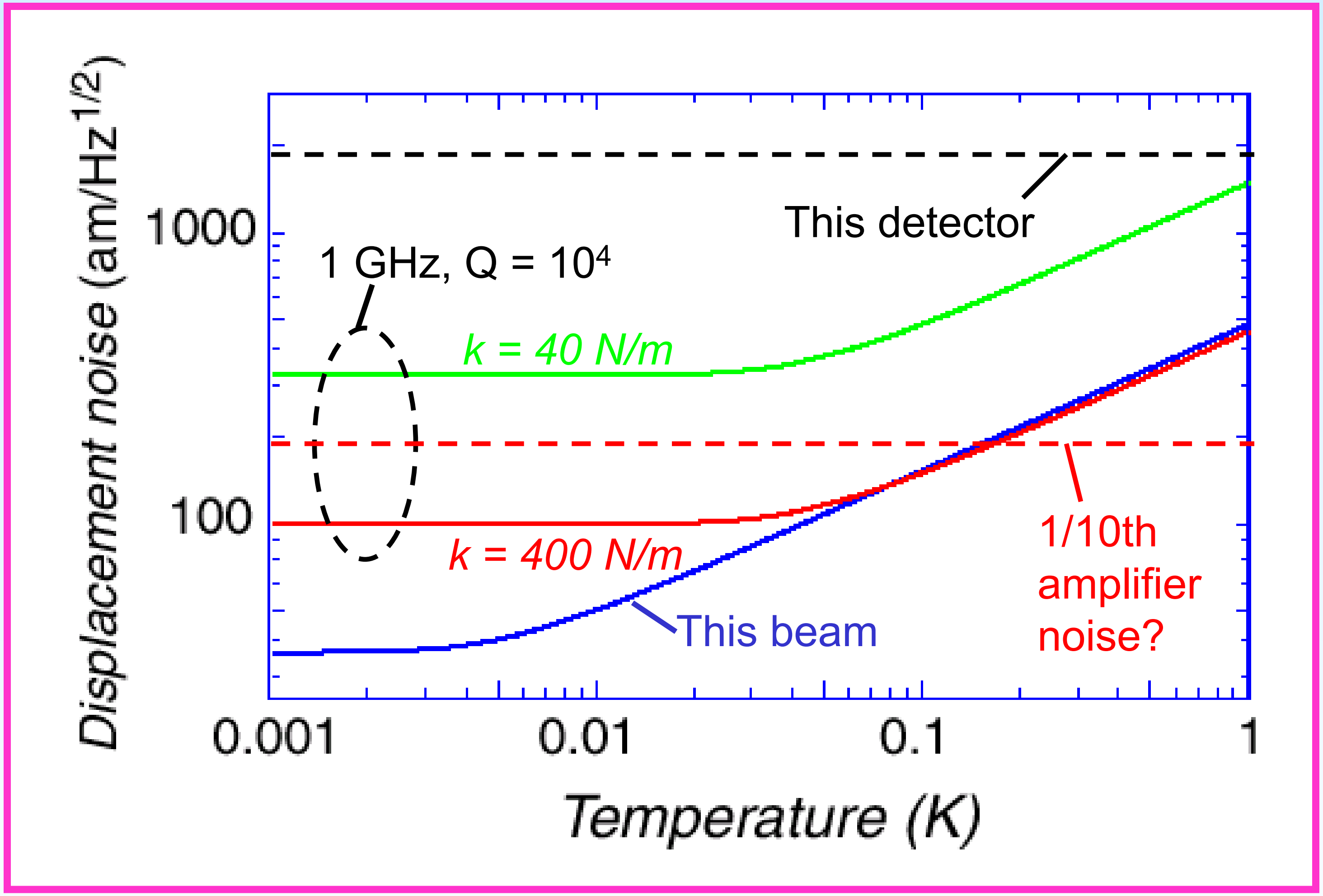
Quantum limited requirements



Conclusions

Nanoscale and nanosecond bolometry

Thermal conductance at the quantum limit
Electron-phonon coupling in a suspended structure
Dynamic electron-phonon coupling

Nanoscale displacement sensing

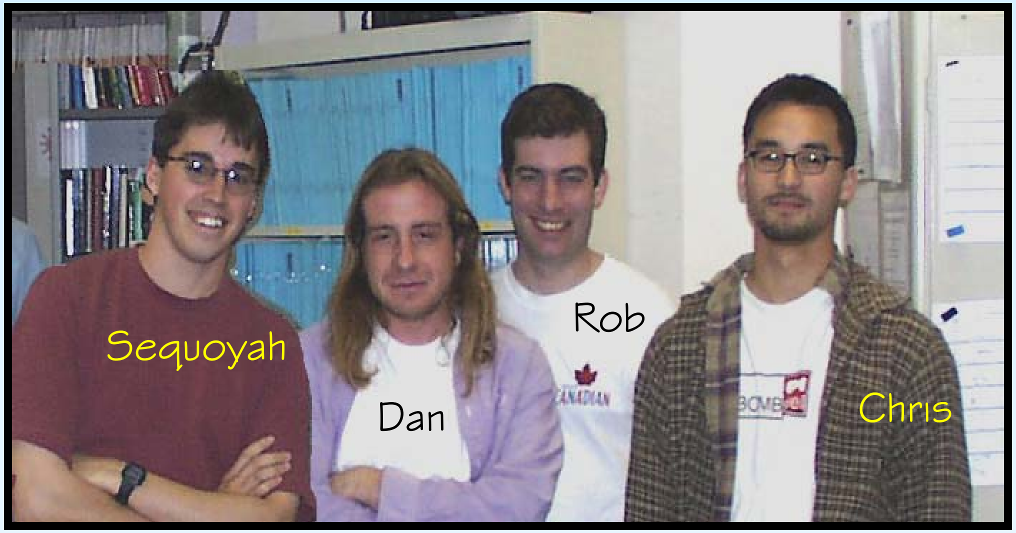
Integrated SET with resonators
Displacement noise 2 x 10^{-15} m/$Hz^{1/2}$

Cleland Group Members

Graduate students:
Sequoyah Aldridge
Chris Yung
Loren Swenson
David Wood
Benjamin Huff

Postdoctoral Scientists:
Dan Schmidt
Rob Knobel

Undergraduates:
Kang-kuen Ni



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