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Invited presentation 3A-E-O2.1 given at EUCAS 2015; Lyon, France, September 6 – 10, 2015. Not submitted to *IEEE Trans. Appl. Supercond.*

Jet Propulsion Laboratory
California Institute of Technology

Hot-electron nanobolometers for astrophysics: superconductor vs normal metal

Boris Karasik

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EUCAS 2015 Lyon, September 6-10, 2015

Credits

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Faustin Carter	ANL
Peter Day	JPL
Bertrand Delaet	CEA-LETI
Michael Gershenson	Rutgers University
Dennis Harding	JPL
Jonathan Kawamura	JPL
Chris McKitterick	Yale University
Steve Monacos	JPL
David Olaya	NIST
Sergei Pereverzev	LLNL
Dan Prober	Yale University
Theodore Reck	JPL
Dan Santavicca	North Florida University
Andrei Sergeev	SUNY at Buffalo
Alex Soibel	JPL
Jian Wei	Peking University

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Outline

TES nano-HEB

Thermal conductance and energy relaxation

Nano-HEB for THz power detection

Readout and array multiplexing

Single-photon detection

Normal metal nano-HEB

Summary

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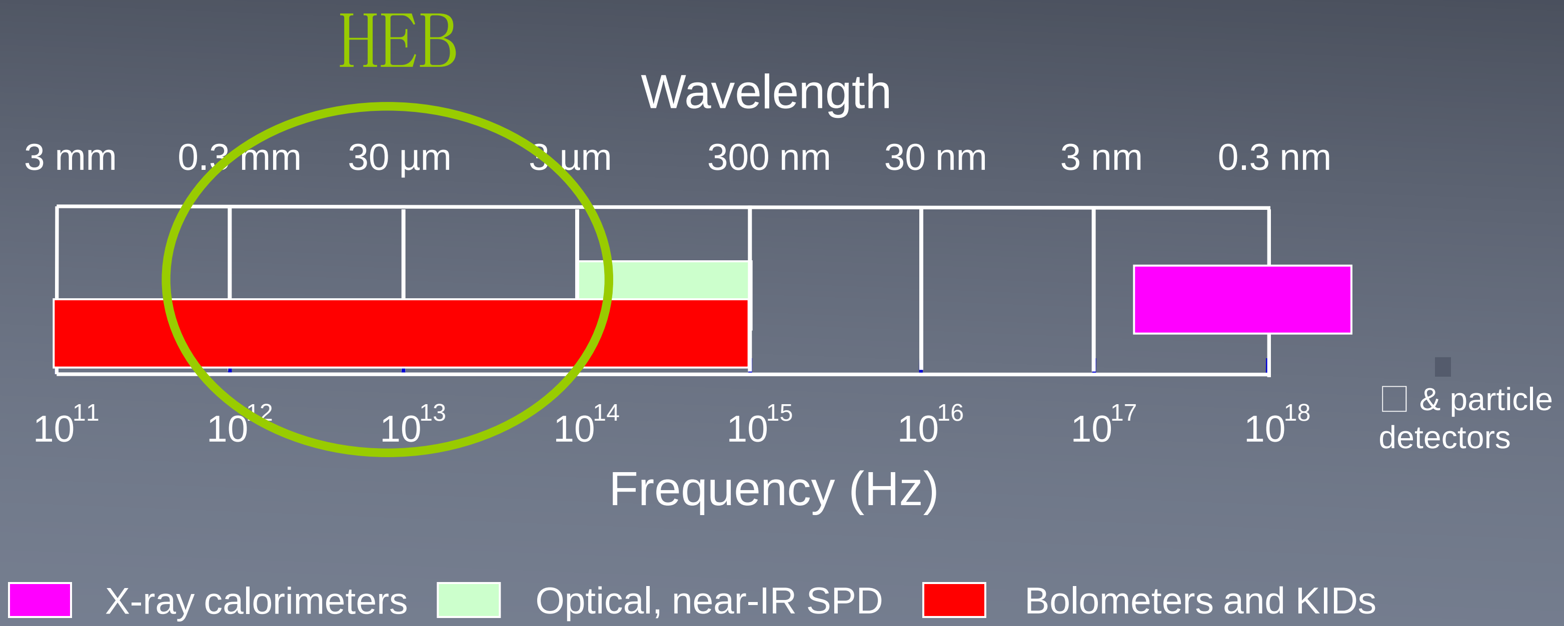
Superconducting direct detectors

- High sensitivity (low NEP)
- High energy resolution
- High speed



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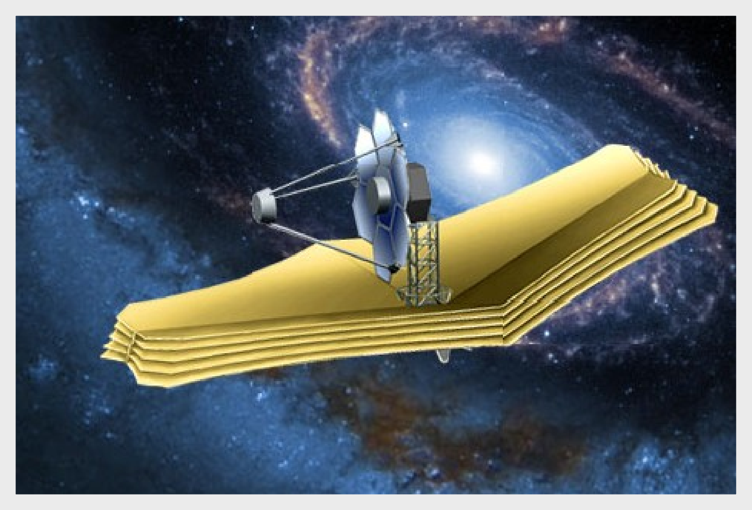
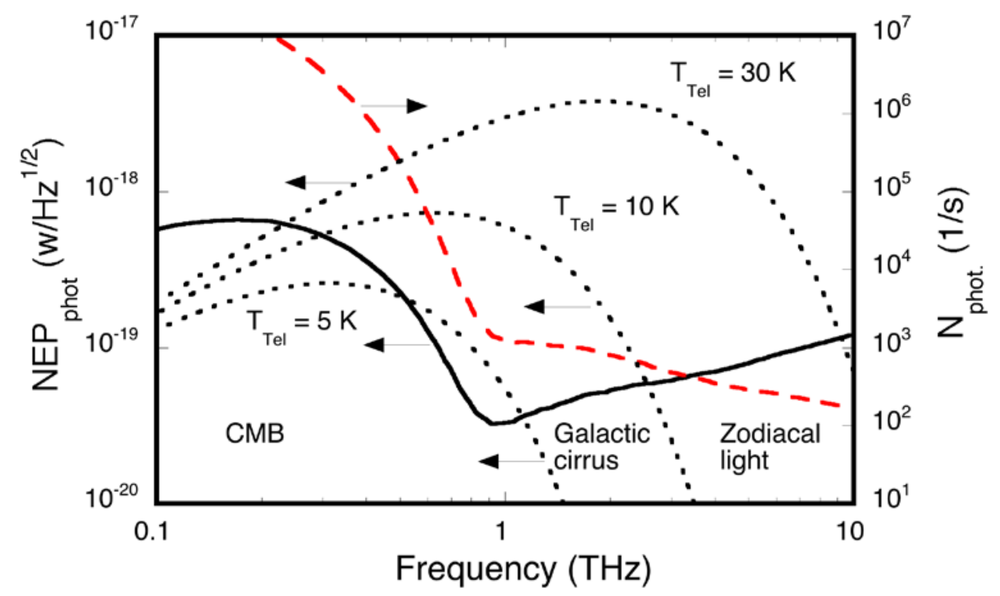
Far-IR line spectroscopy with moderate resolution $\nu/\delta\nu \sim 1000$ in space

SPICA, Millimetron, SAFIR, SPECS, CALISTO



photon-noise limited $NEP_{phot.}$



- Power detection below 1 THz
- Photon counting above 1 THz

Karasik & Sergeev, *IEEE Trans. Appl. Supercond*. **15**, 618 (2005)

$$NEP_{phot} = h\nu(2N_{phot.})^{1/2}$$

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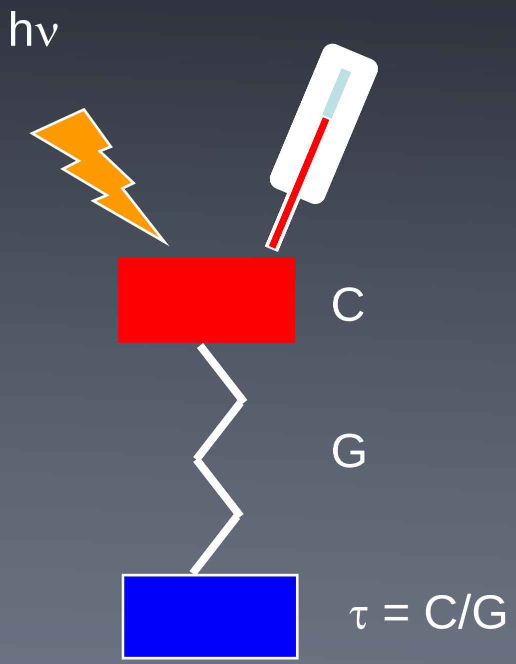
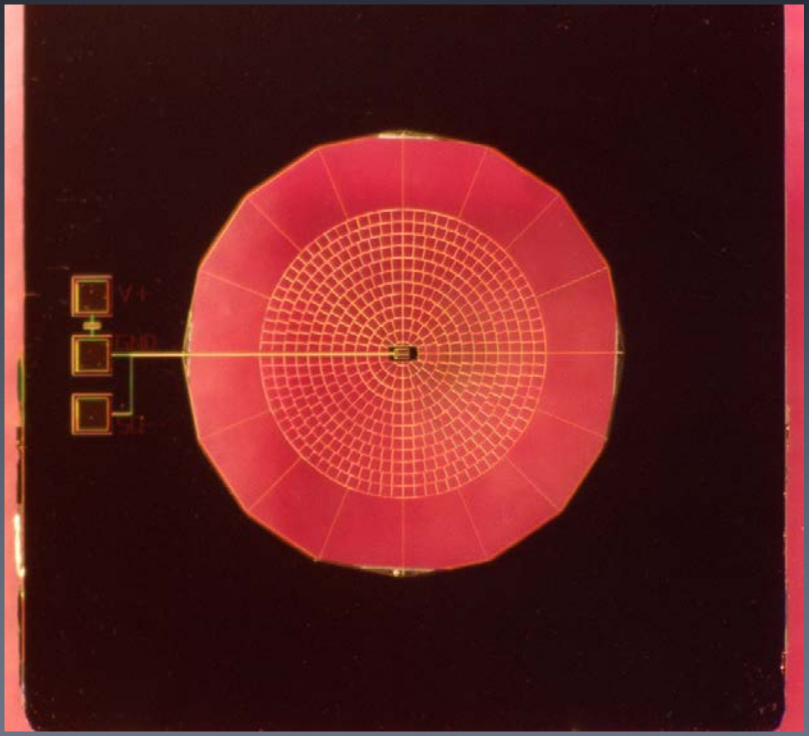
"Leg-isolated" bolometer





Spider-web bolometer (J. Bock/JPL)

$NEP_{TEF} = (4k_B T^2 G)^{1/2}$ "phonon" noise

$\delta\varepsilon \approx (k_B T^2 C)^{1/2}$

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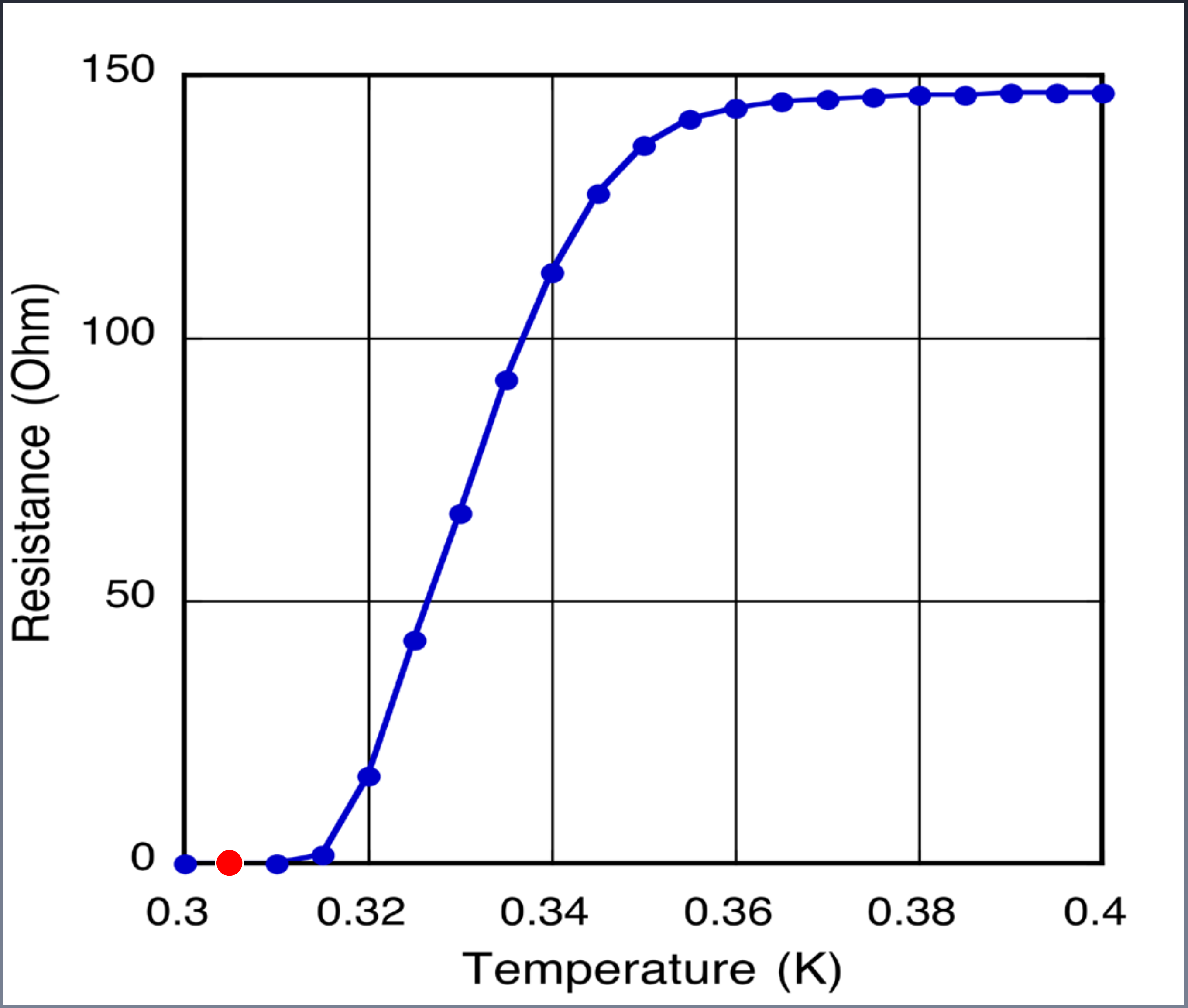
Transition-Edge Sensor (TES)



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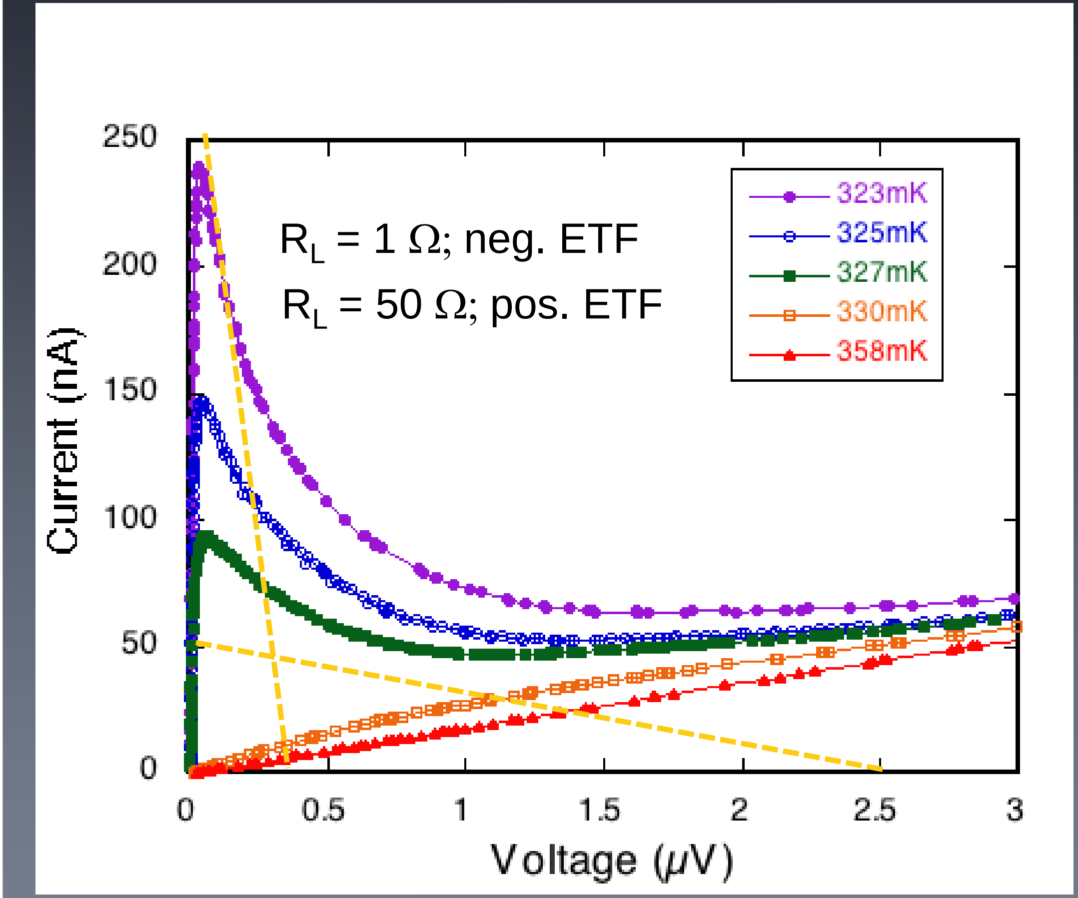
Electro-thermal feedback (ETF)



$$\tau^* = \frac{\tau}{1+\left(\alpha/n\right)f\left(R_L,R\right)} \qquad \alpha = \frac{T_c}{R}\frac{dR}{dT}, \quad n = 2 \div 4$$

τ* < τ negative ETF

τ* > τ positive ETF

Mather, *Appl. Opt*. **21**, 1125 (1982)
Irwin, *Appl. Phys. Lett.* **66**, 1998 (1995)
Karasik & Elantev, *Proc. ISSTT* (1995)

Nano-HEB

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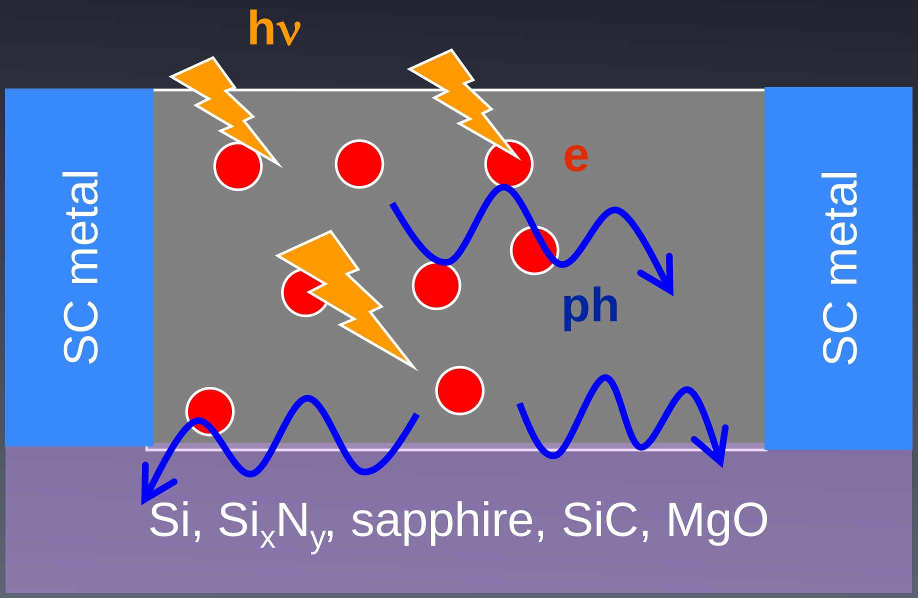
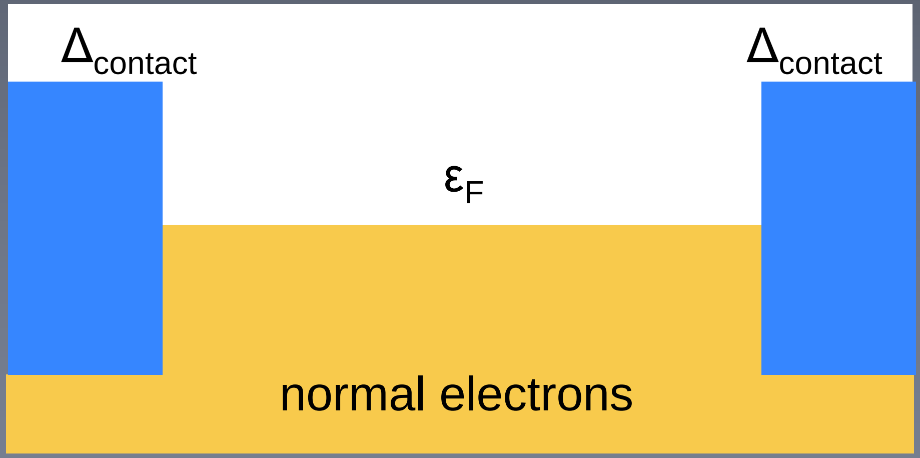
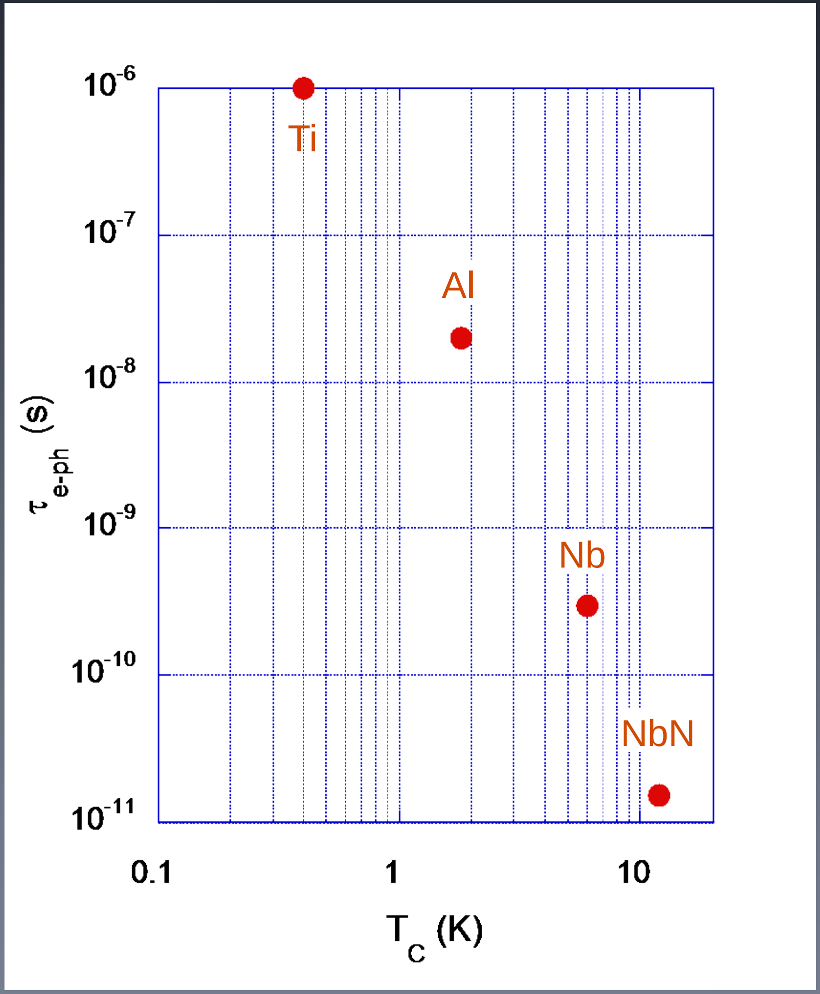
Phonon-cooled nano-HEB







Karasik et al., *SUST* **12**, 745 (1999)
J. Appl. Phys. **87**, 7586 (2000)

G ➔ $G_{e\text{-}ph}$ ~ volume

$\tau_{e\text{-}ph}$ does not depend on volume

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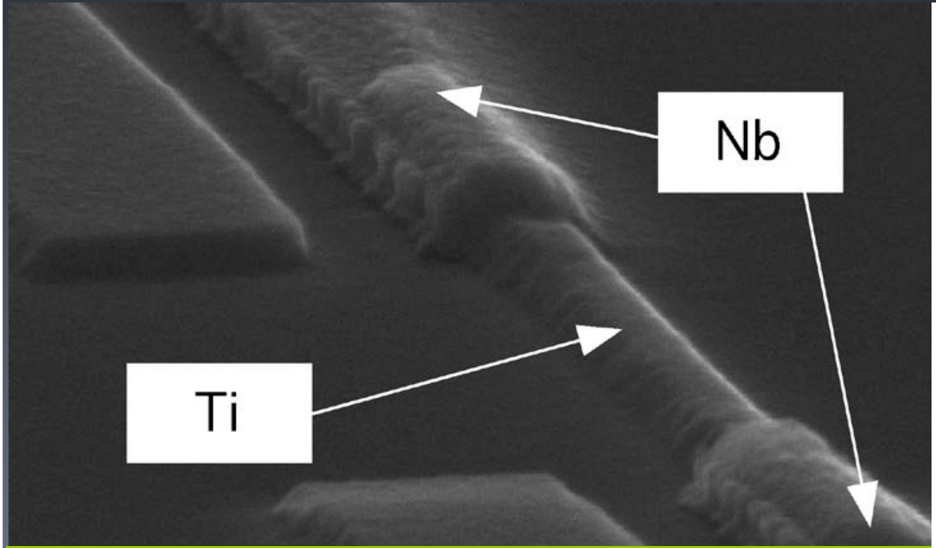
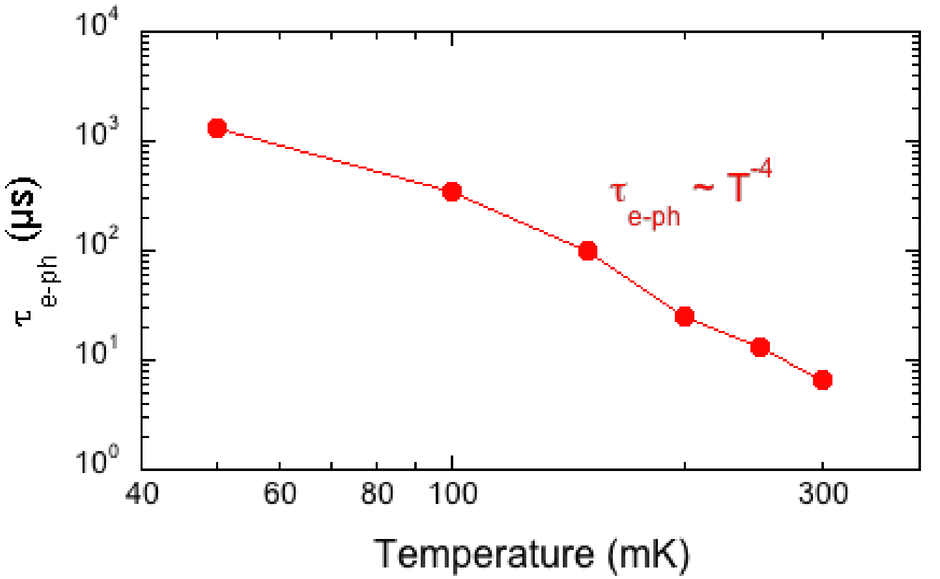


A 0.5-µm-long Ti device with Nb contacts on Si



Wei et al., *Nat. Nano.* **3**, 496 (2008)

$\tau_{dif.} = L^2/\pi^2 D \sim 0.1$ ns

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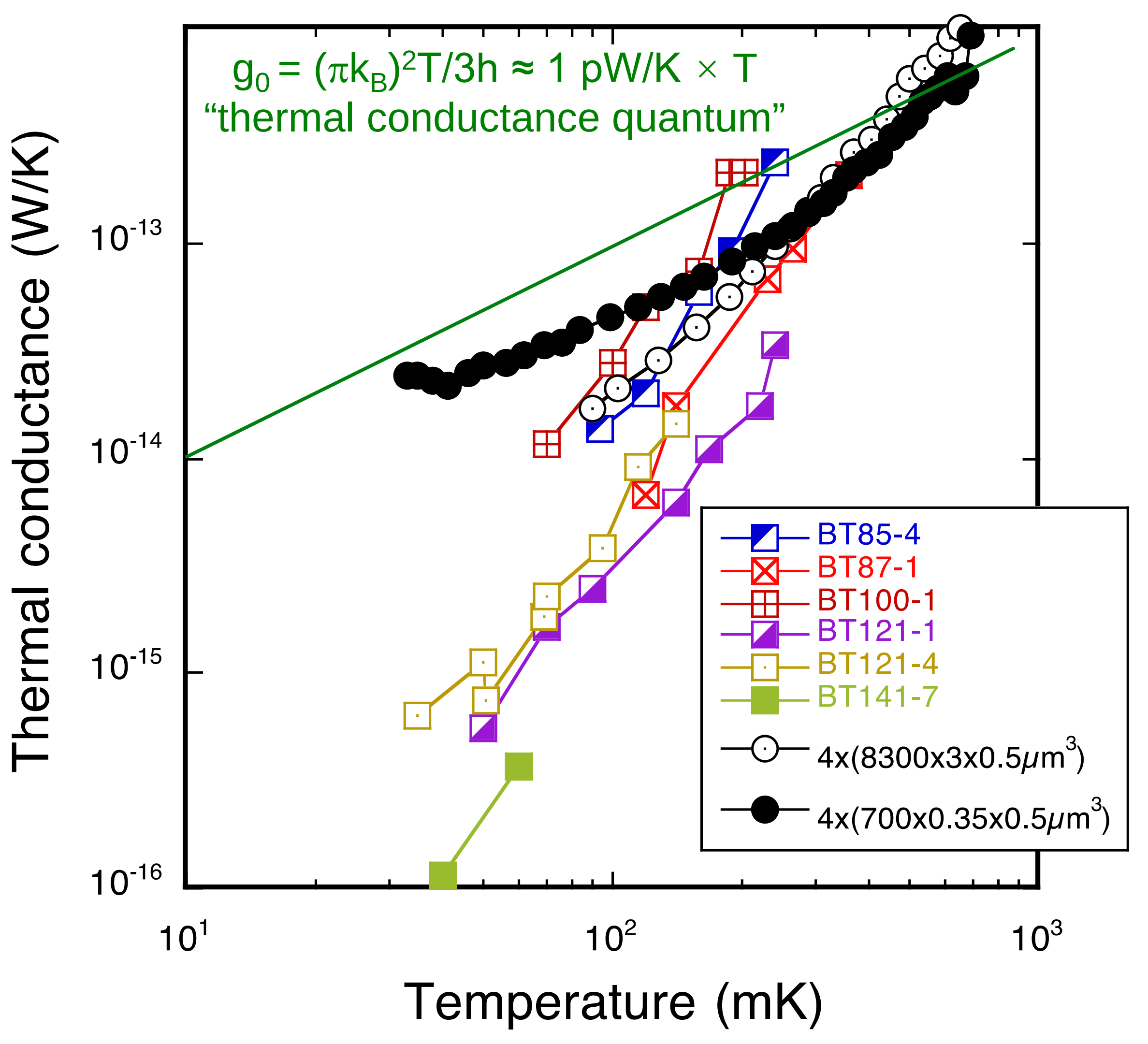

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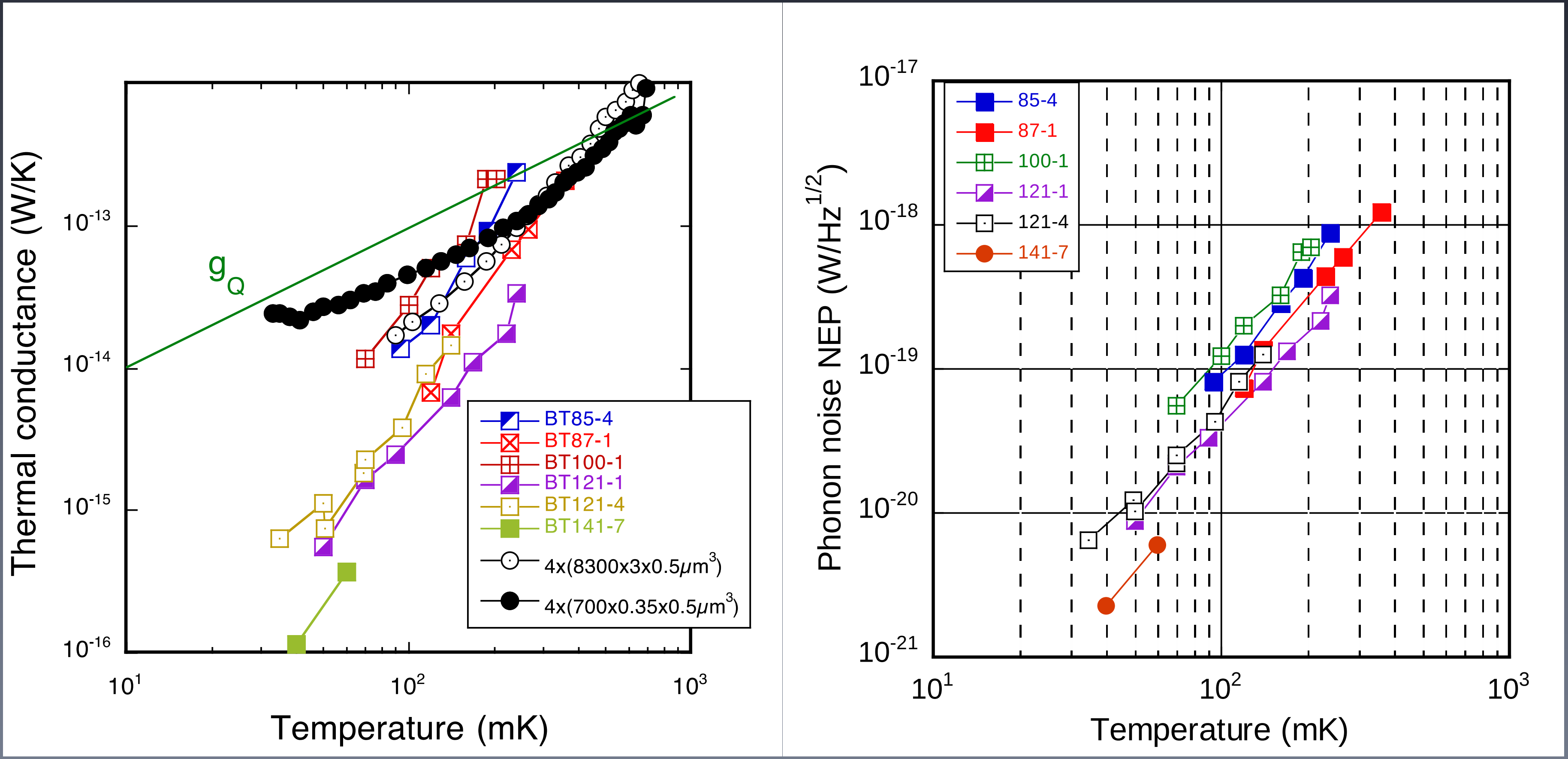

$$NEP_{TEF} = (4k_B G_{e\text{-}ph} T_e^2)^{1/2}$$

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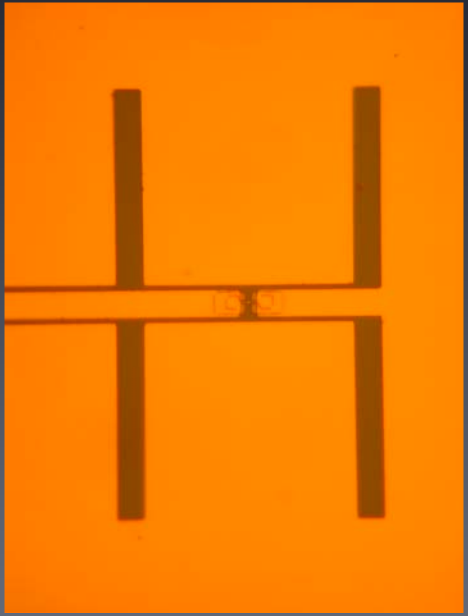
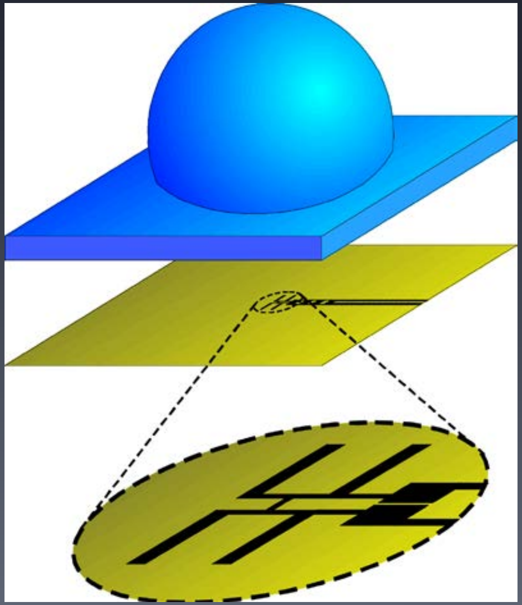
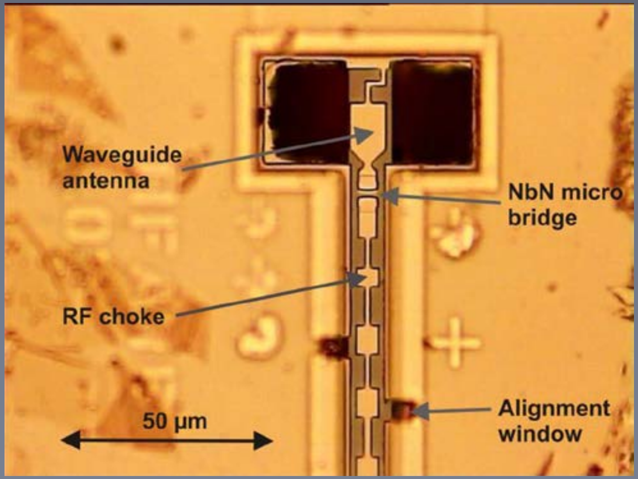
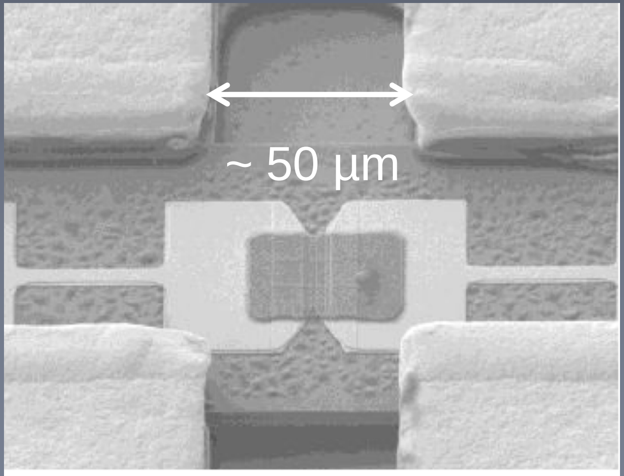






Büchel et al., *IEEE Trans. THz Sci.&Technol.* **5**, 207 (2015)



Boussaha et al., *IEEE Trans. THz Sci.&Technol.* **2**, 284 (2012)

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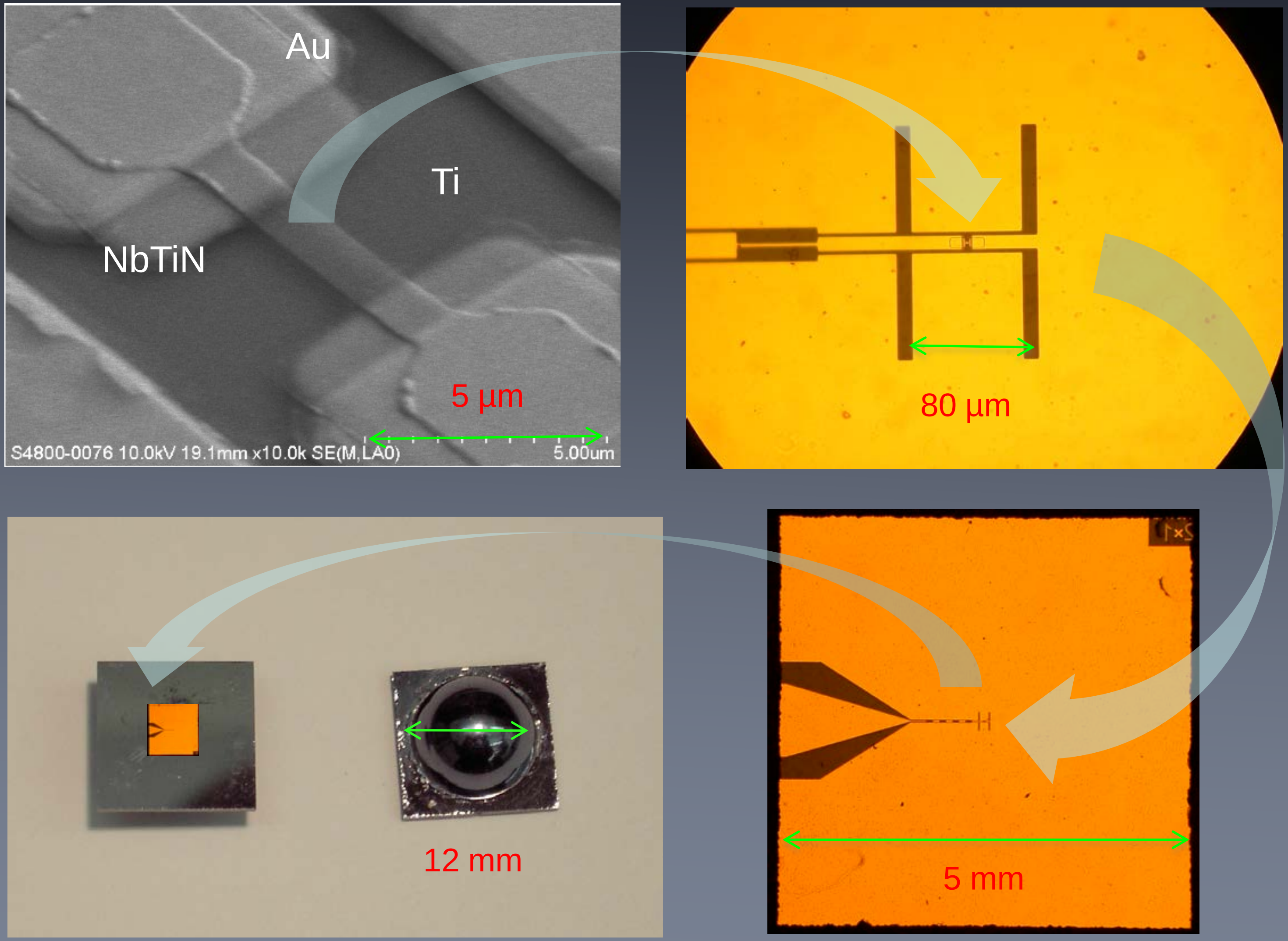

Karasik & Cantor, *Appl. Phys. Lett*. **98**, 193503 (2011)

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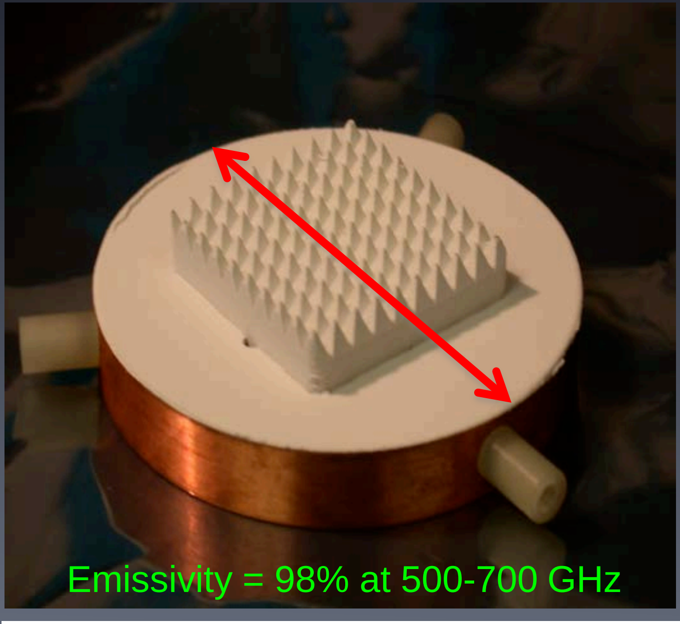
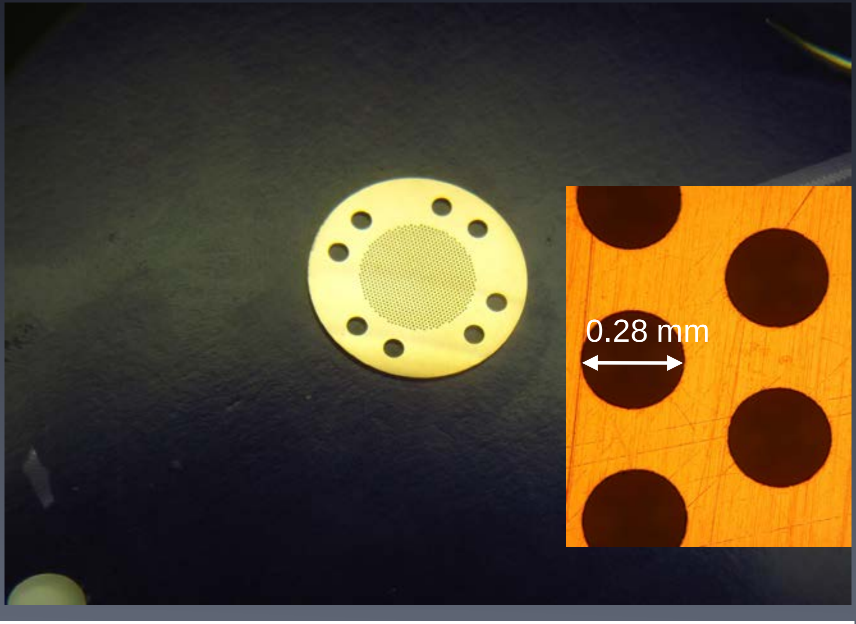
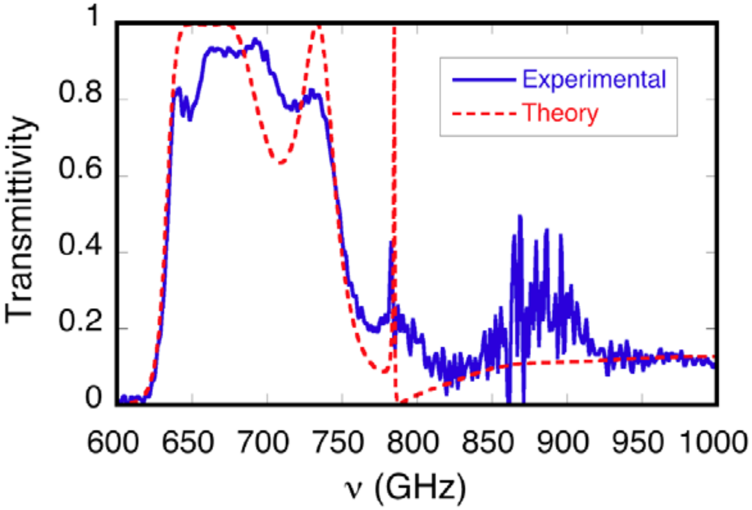
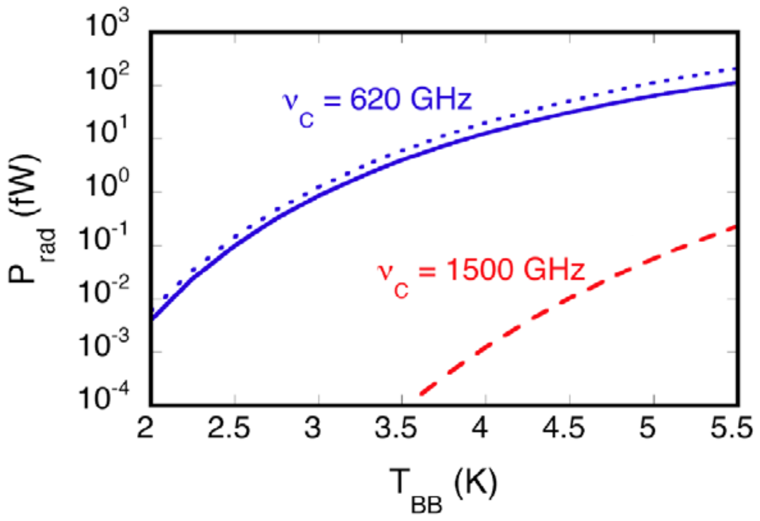
Femtowatt radiation power source



Emissivity = 98% at 500-700 GHz







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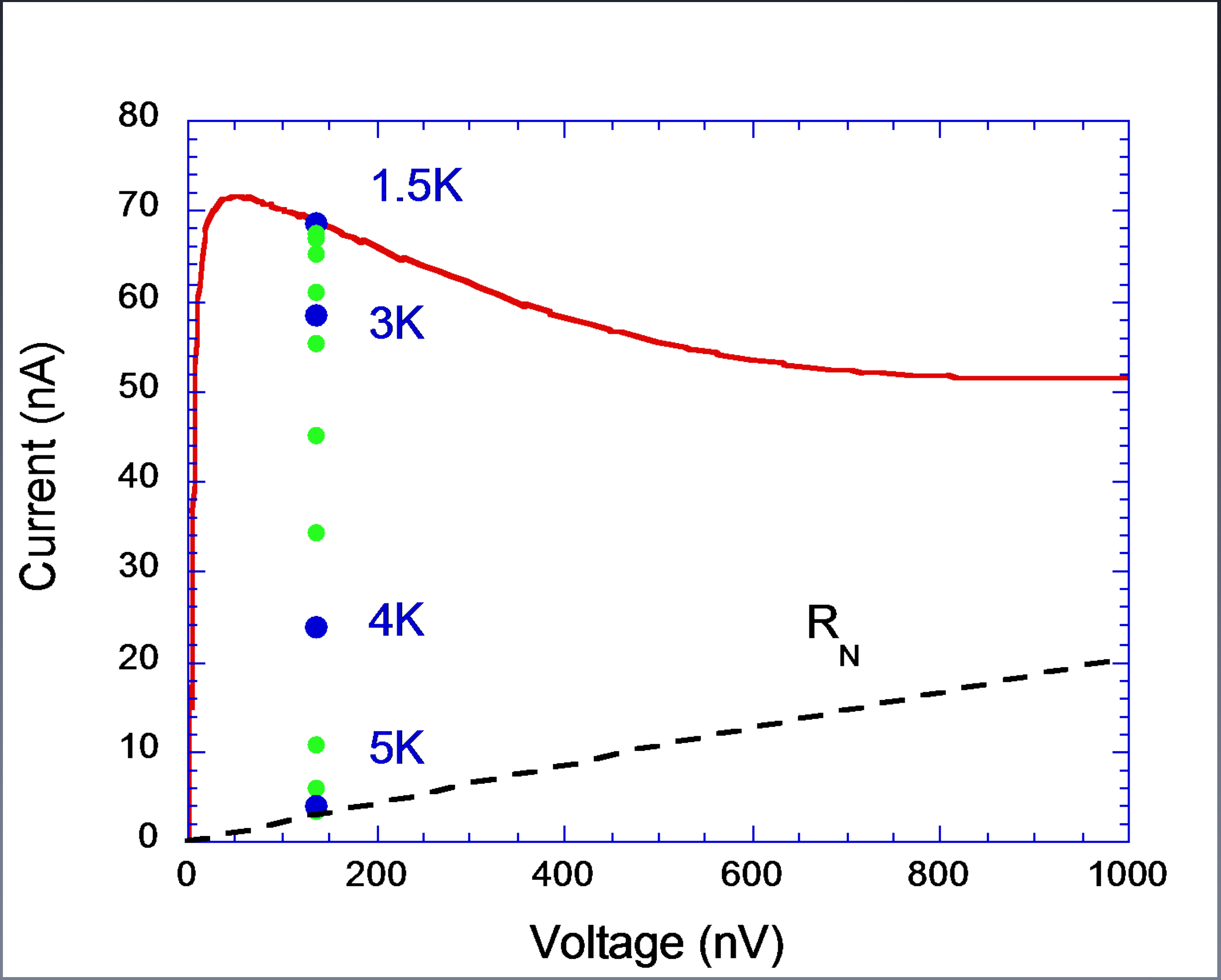

Nano-HEB

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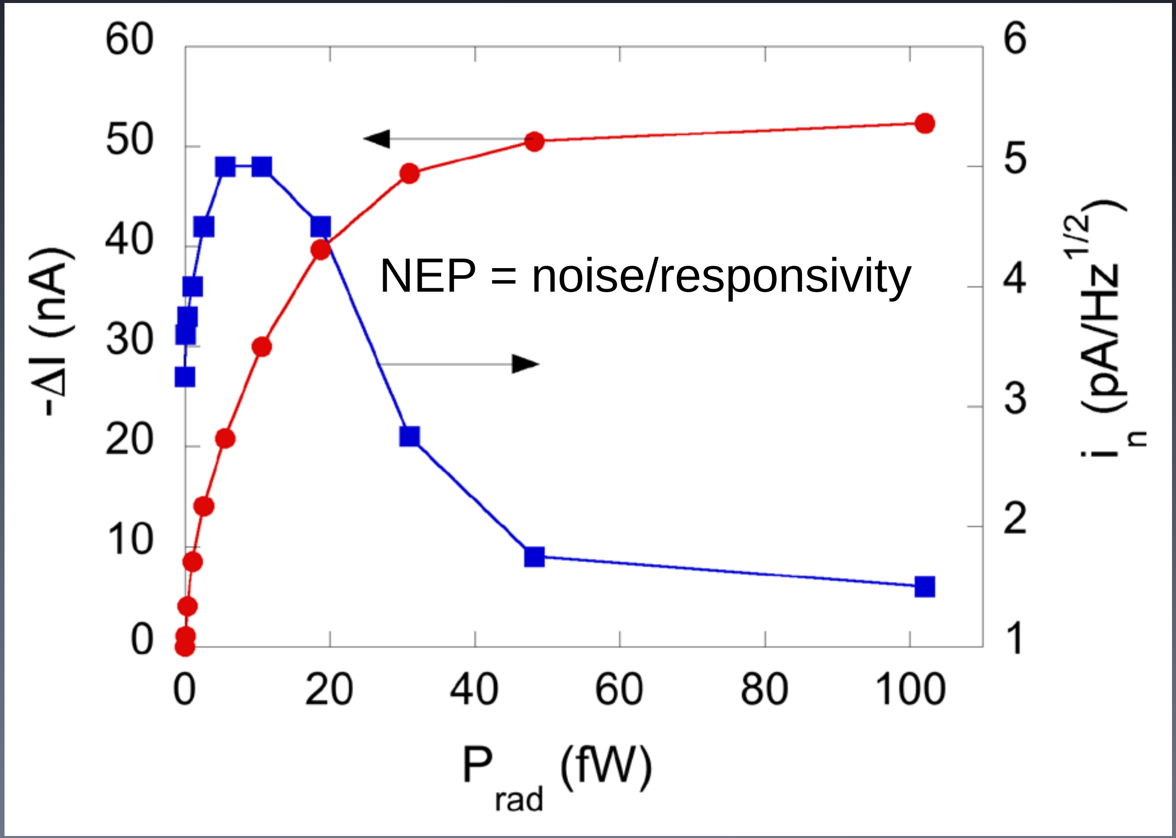

HEB device size	T_C (mK)	NEP (aW/Hz$^{1/2}$)	NEP$_{TEF}$ (aW/Hz$^{1/2}$)	NEP$_{TEF}$/NEP
2µm x 1µm	150	1.4	1.0	0.71
	357	8.6	6.3	0.73
1µm x 1µm	105	0.30	0.23	0.77
	367	3.0	2.5	0.83

good optical coupling efficiency!

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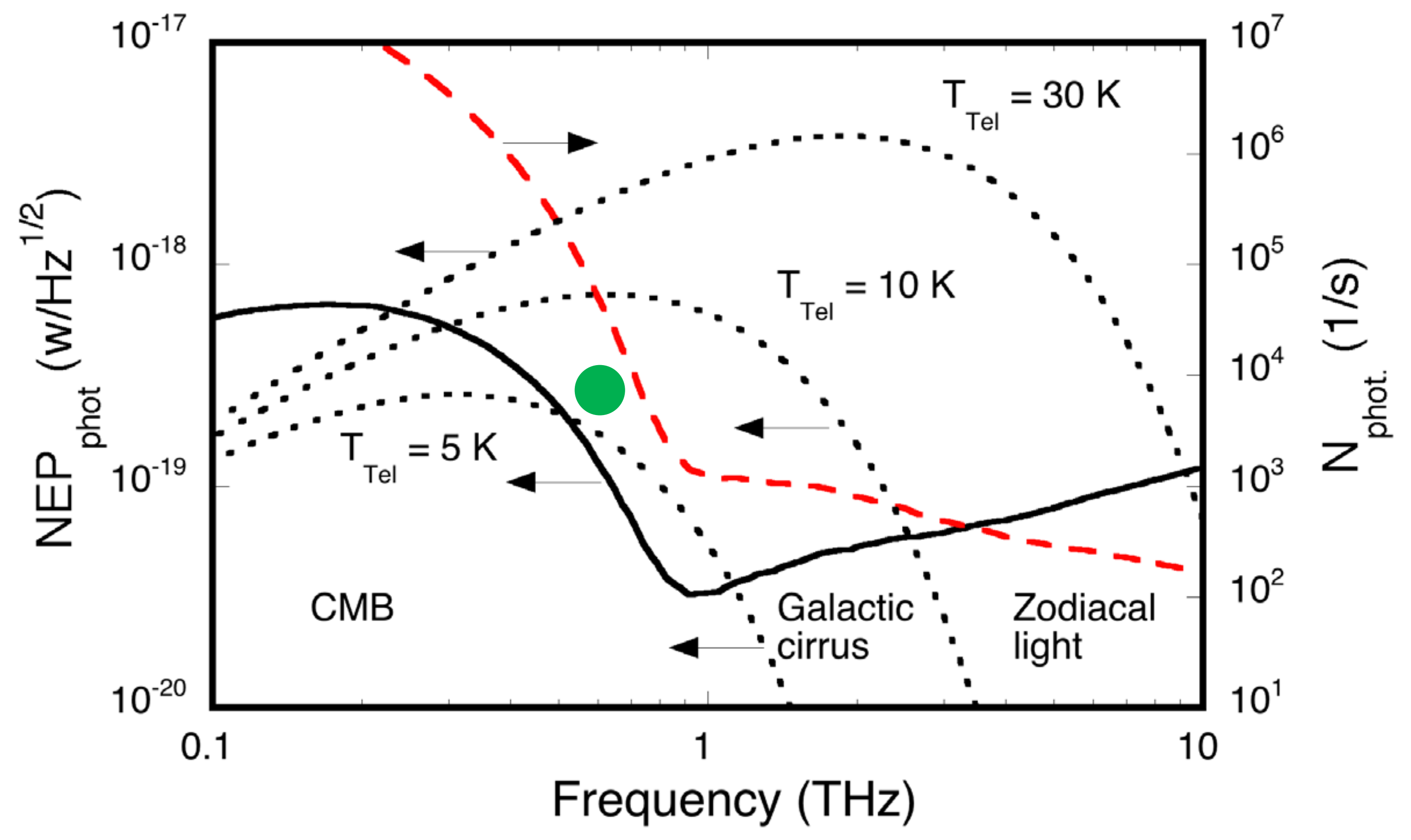

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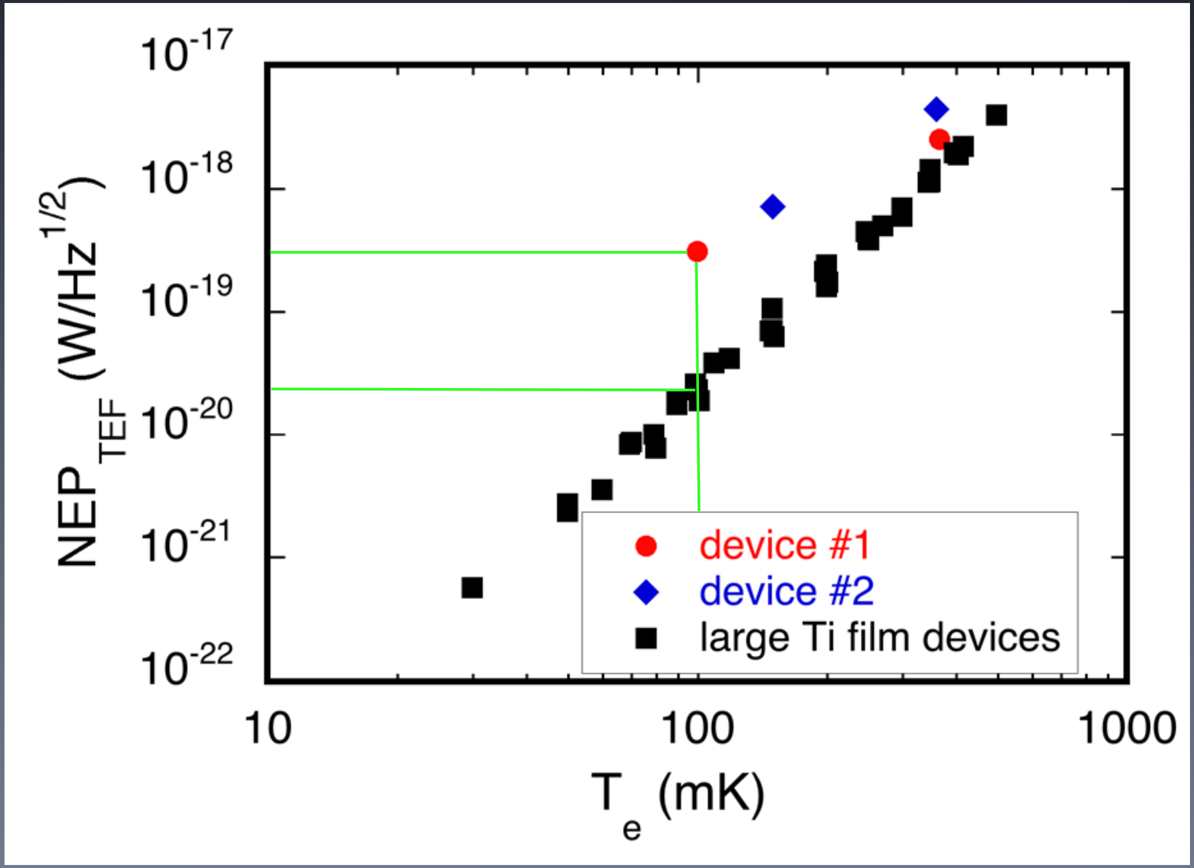

NEP_{TEF} in small devices was 10 times higher than that expected from the G-measurements in very long Ti samples

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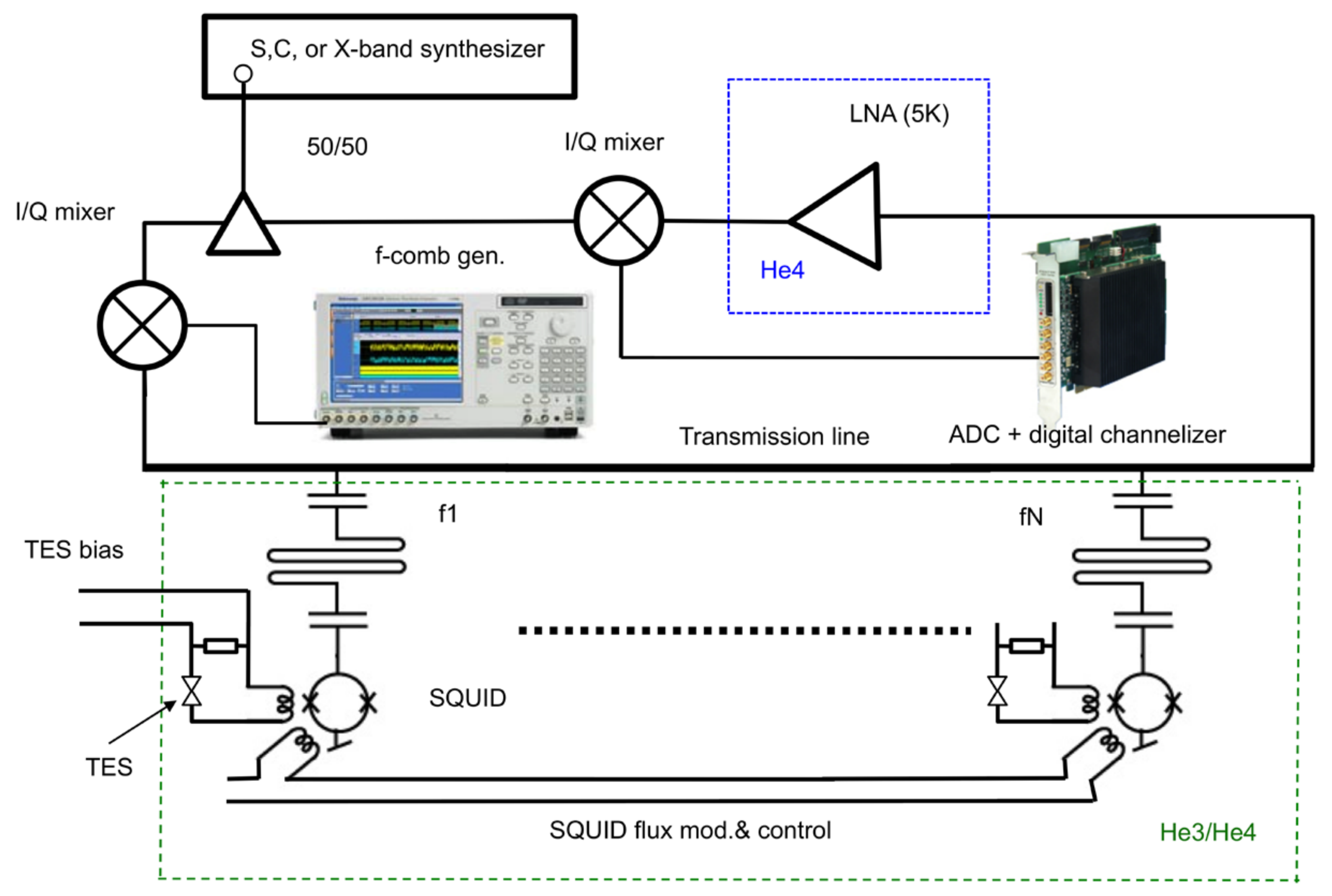
GHz FDM SQUID readout



Karasik et al., *AIP Conf.* **CP1185**, 257 (2009); *SPIE* **7741**, 774119 (2010)

Nano-HEB

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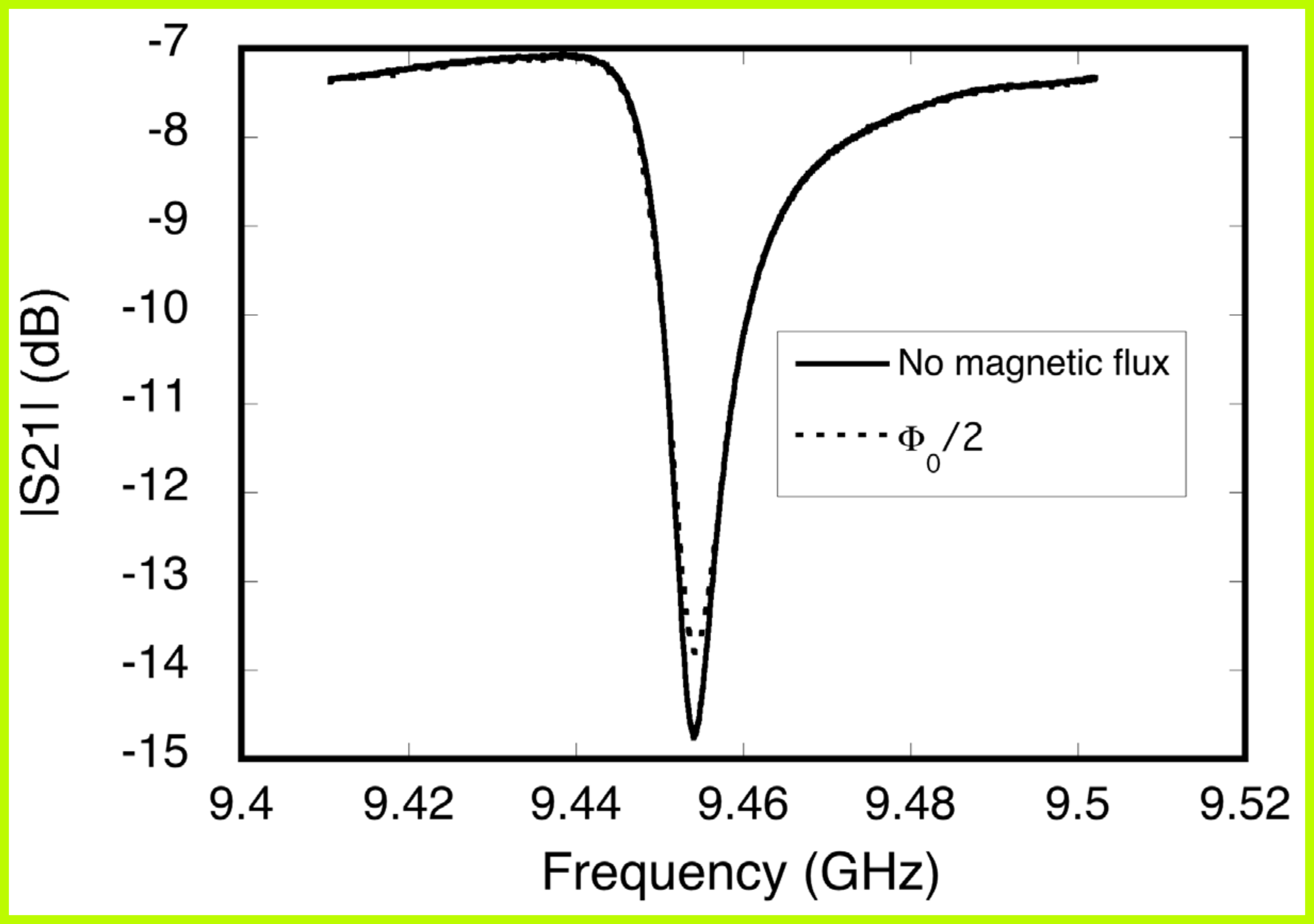

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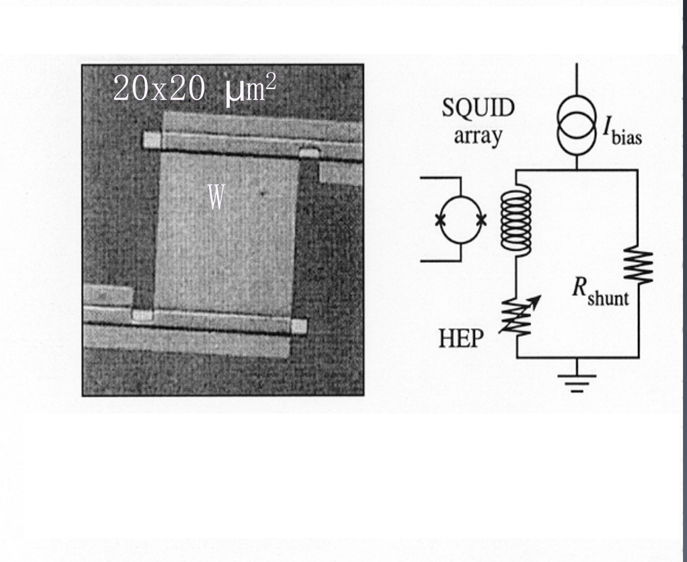
Single-photon HEBs



Tungsten TES for optical astronomy

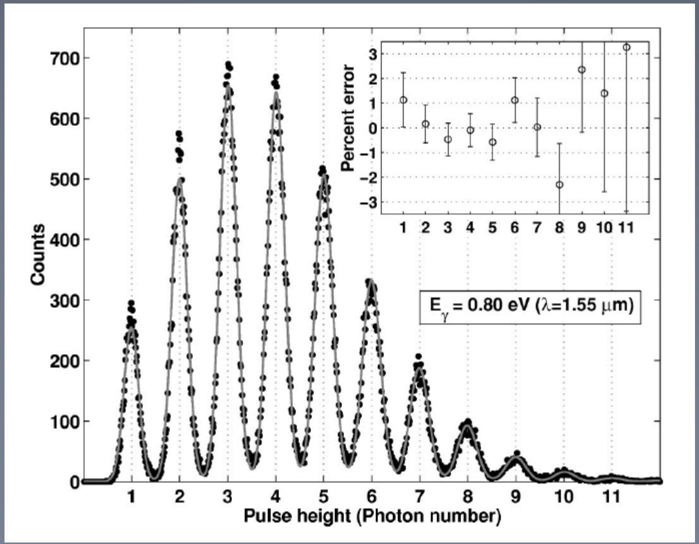
main goal: high energy resolution

operates at very low temperature ≈40 mK

typical bandwidth ~ kHz set by τ_{e-ph}

uses negative electrothermal feedback ETF => more linear and faster response

Cabrera et al., *Appl. Phys. Lett.* **73**, 735 (1998)



Tungsten TES for quantum cryptography

high energy resolution inherent in the detectors allows for photon-number states discrimination

$$P(n) = \left(\mu^n / n!\right) e^{-\mu}$$

Poisson-Gaussian distribution (μ = 4, σ = 0.12 eV)

Miller et al., *Appl. Phys. Lett.* **83**, 791 (2003)

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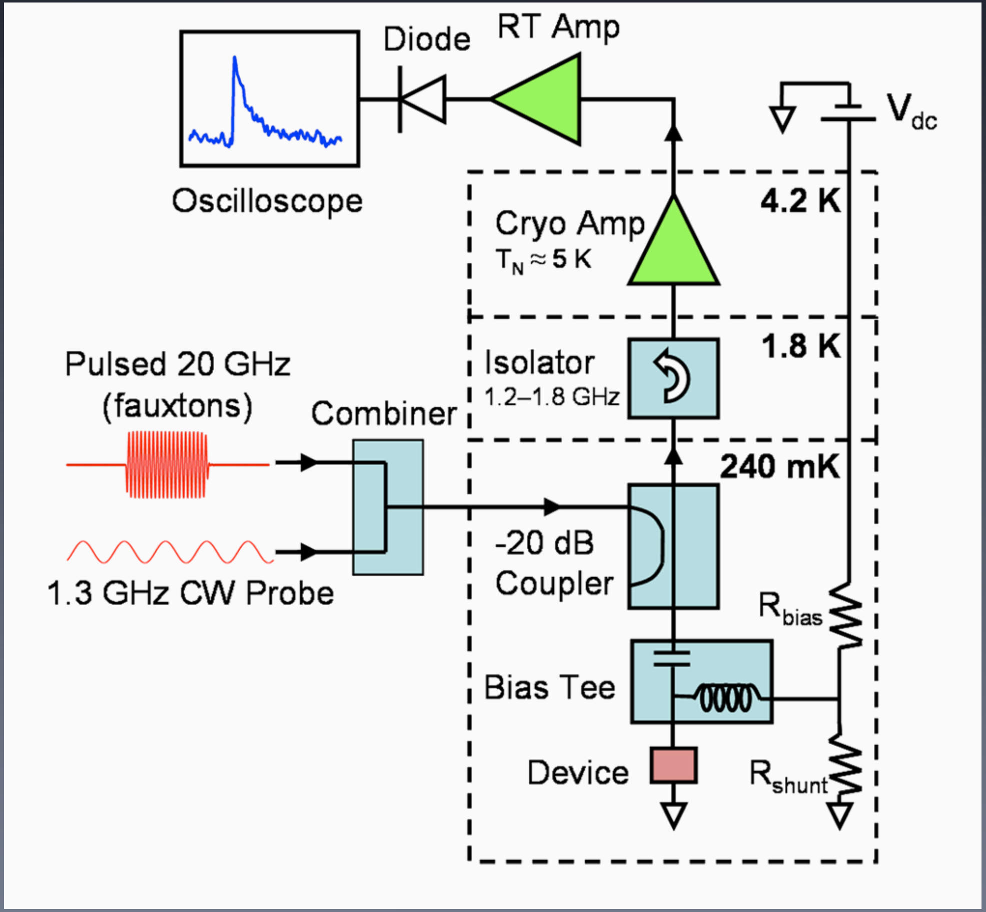
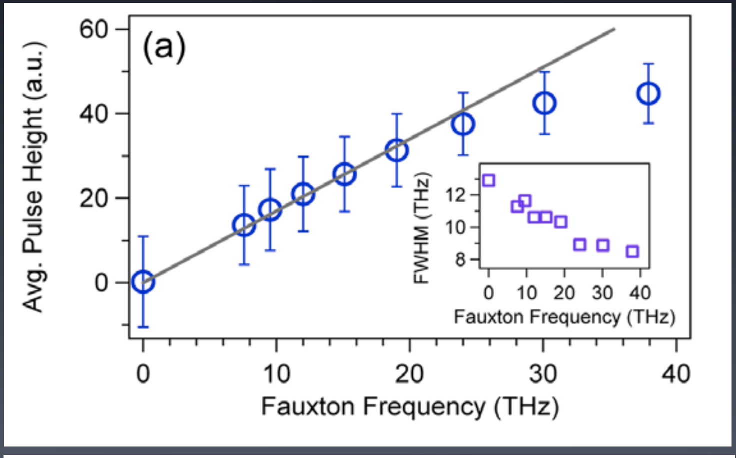
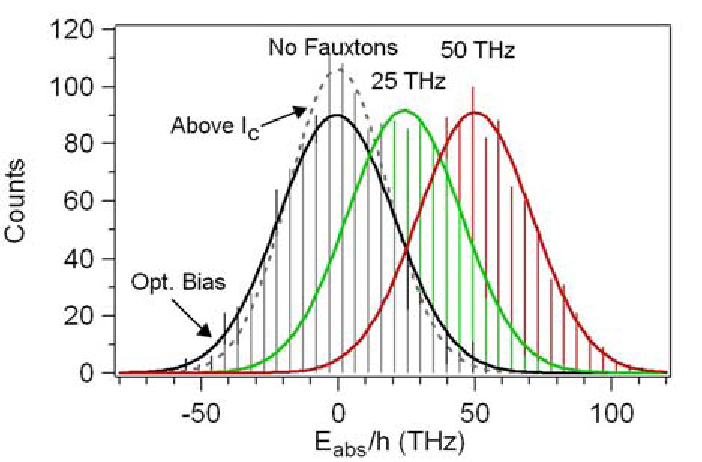
Microwave technique for determination of dE







using a microwave reflectometry technique with 20 GHz short pulses simulating 8-µm photons (fauxtons), $dE_{FWHM} \approx 0.1$ eV at 300 mK has been determined, very close to the theory prediction

Santavicca et al., *Appl. Phys. Lett.* **96**, 083503 (2010)

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Setup for generation & detection of 8-µm photons

a Ti HEB device with a volume ~ 0.1 μm^3 at 50-100 mK

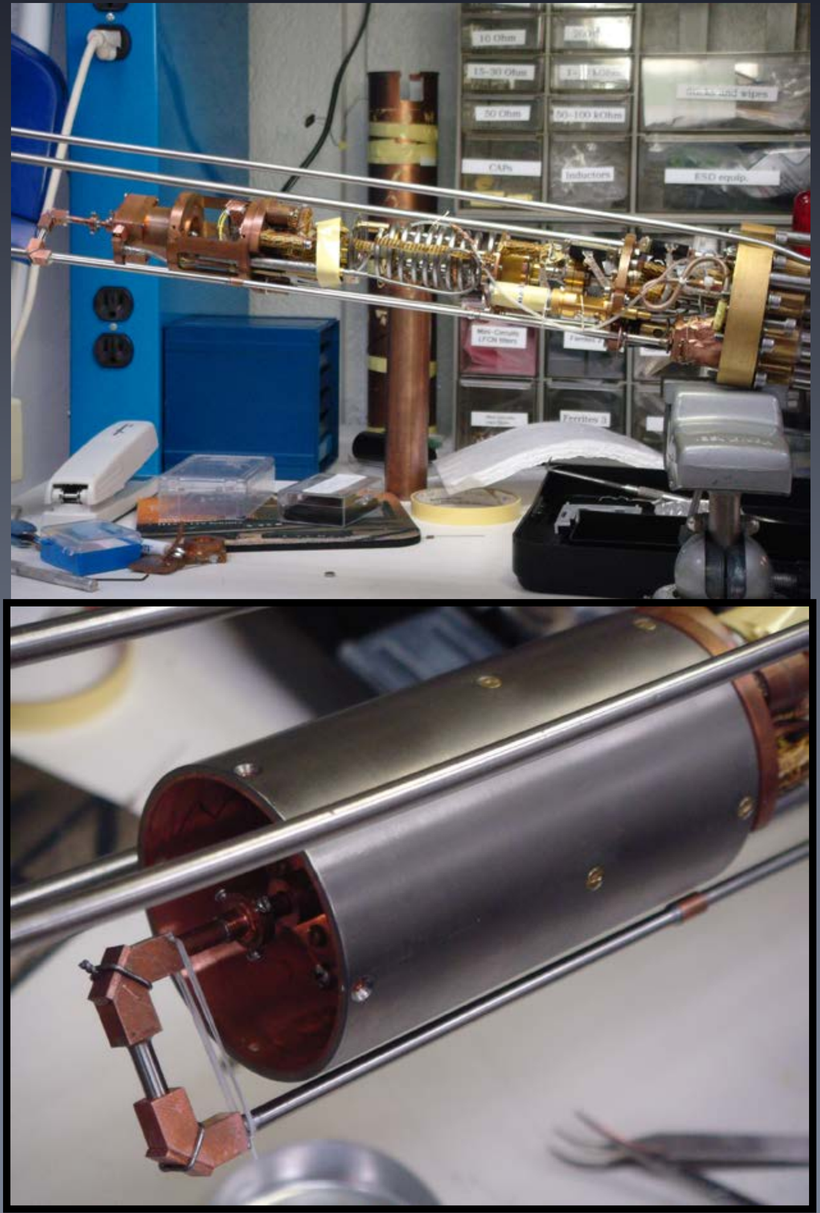
an 8-µm Quantum Cascade Laser (QCL) at 4K

a metal light pipe guides light to the nano-HEB placed in a light tight box

short triggered pulses (<< τ)

attenuation and filtration of radiation at 4K, 0.8K, and at the mixing chamber in order to block any thermal background radiation and to make the average number of photons per pulse $\mu < 1$

collection of 10,000 triggered events. Plotting statistics of the pulse amplitudes at a given time position



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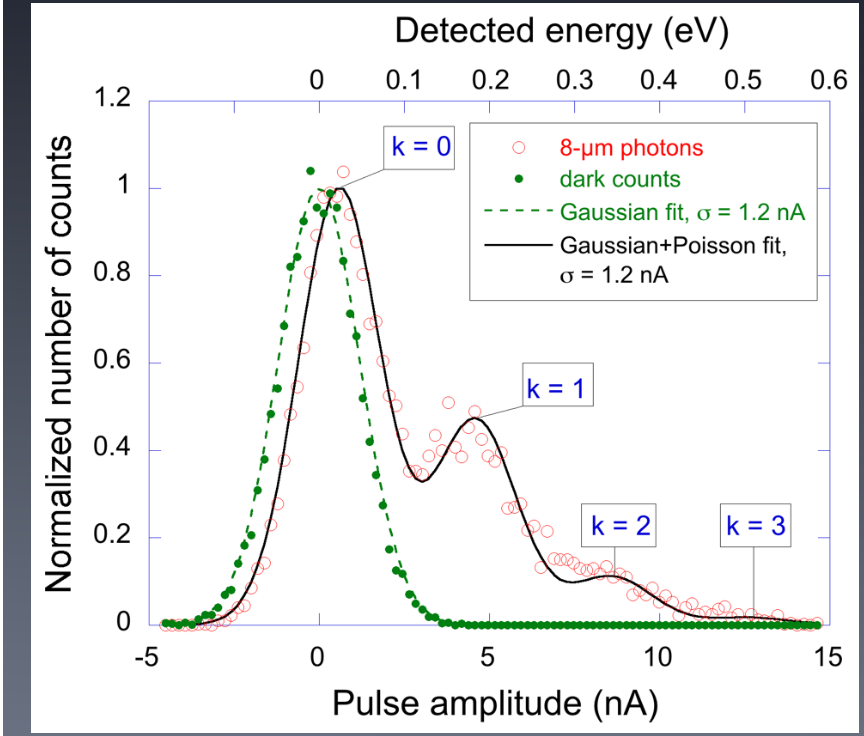
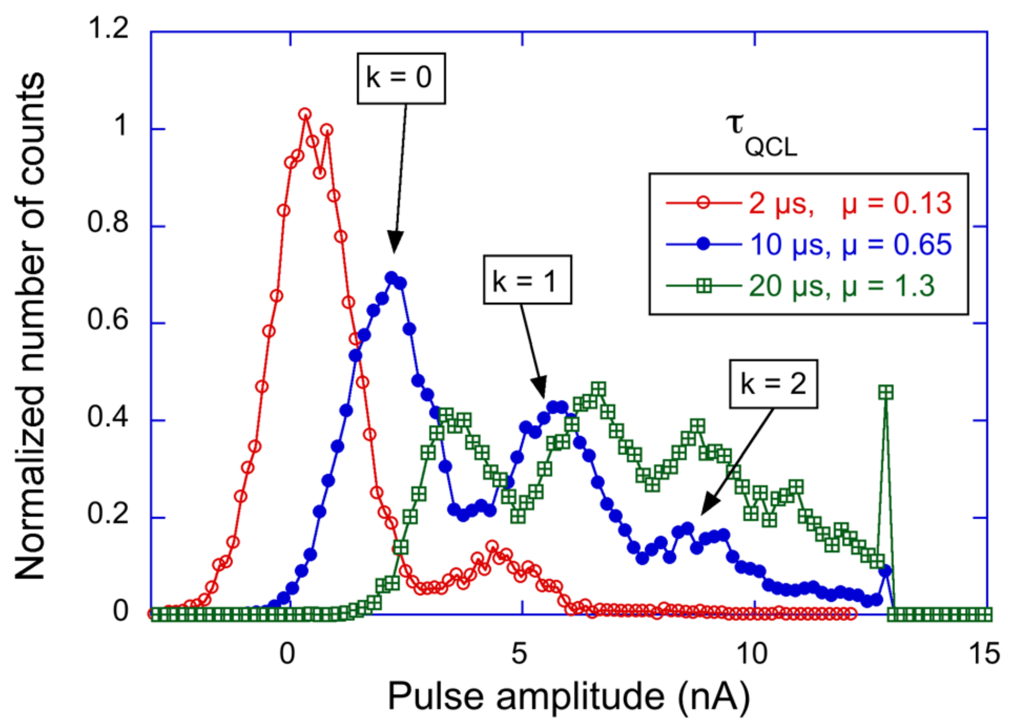
Detection of single 8-µm photons





dE_{FWHM} ≈ 110 meV is the best energy resolution figure for superconducting calorimeters

bolometric theory predicts $dE_{FWHM} \approx 2.35(k_B C_e T^2)^{1/2}$ = 38 meV

single 8-µm photons have been detected with record energy resolution.

the minimum resolved energy is h × 27 THz (0.11 eV)

Karasik et al., *Appl. Phys. Lett.* **101**, 052601 (2012)

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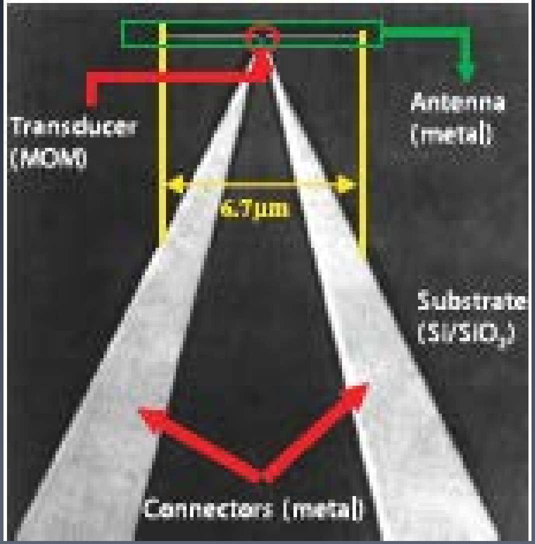
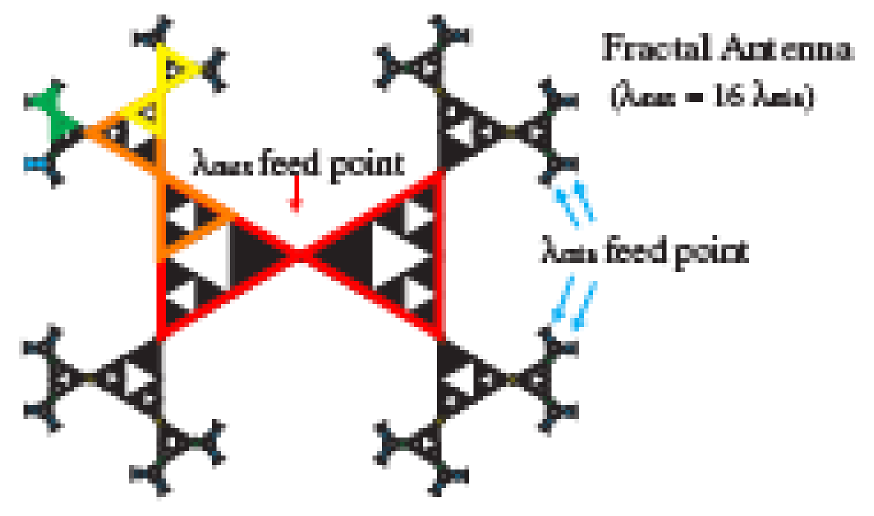
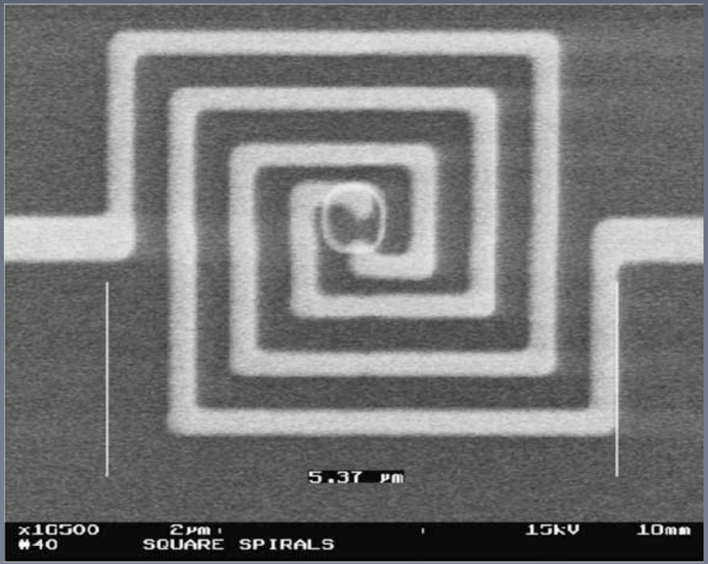
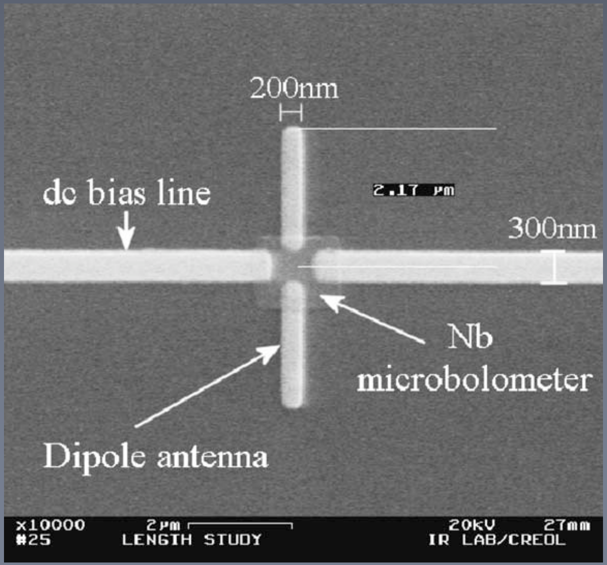
Mid-IR antennas









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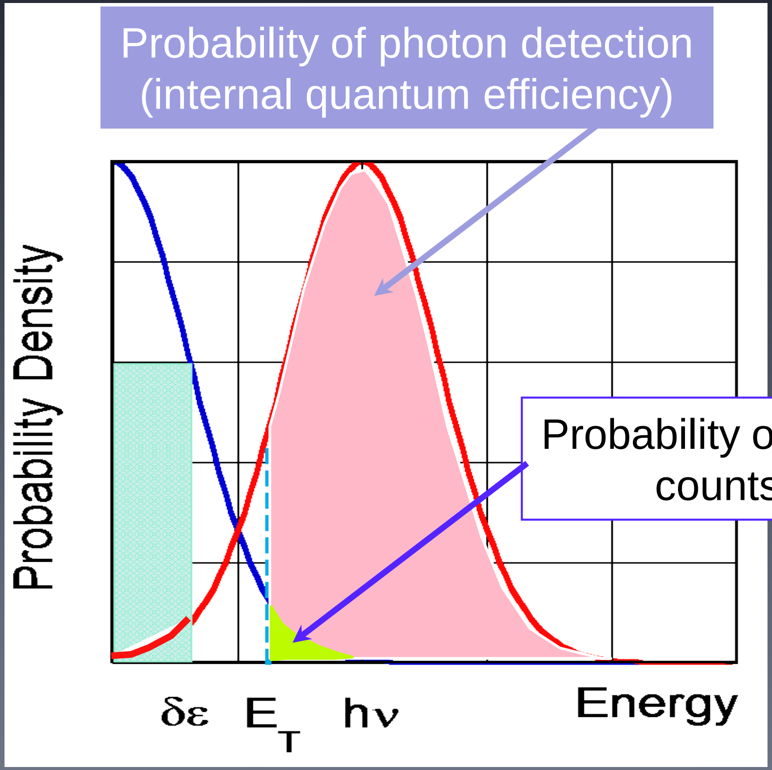
Prospect of single THz photon detection

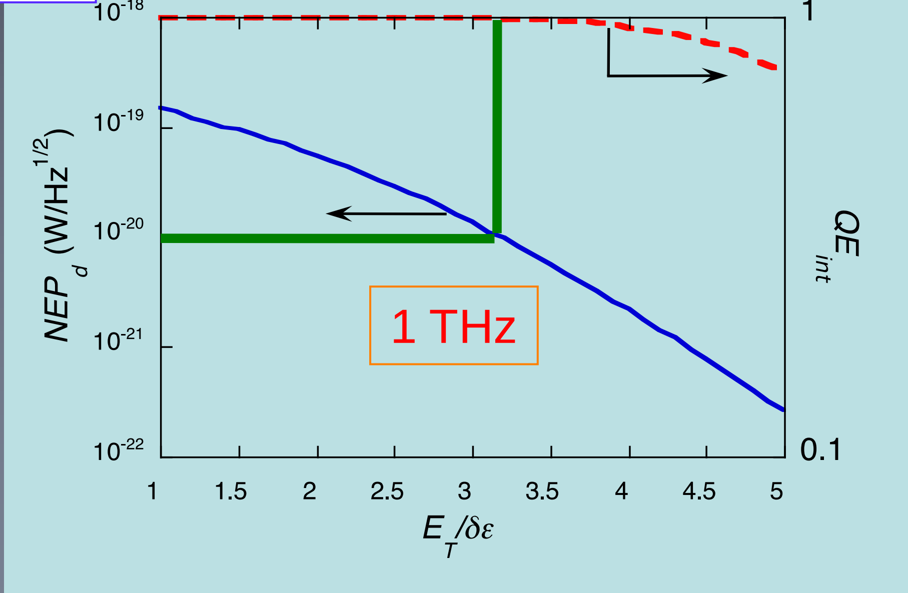


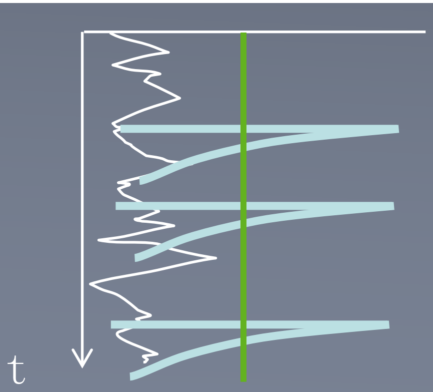
Probability of dark counts

$$Q_{int} = \frac{1}{\sqrt{2\pi}} \cdot \int_{(E_T - h\nu)/\delta\varepsilon}^{\infty} \exp\left(-x^2/2\right)dx$$

$$p_{dark} = \frac{1}{\sqrt{2\pi}} \cdot \int_{E_T/\delta\varepsilon}^{\infty} \exp\left(-x^2/2\right)dx$$

$$NEP_d = h\nu\sqrt{2p_{dark}B}$$





Karasik & Sergeev, *IEEE Trans. Appl. Supercond.* **15**, 618 (2005)

Nano-HEB

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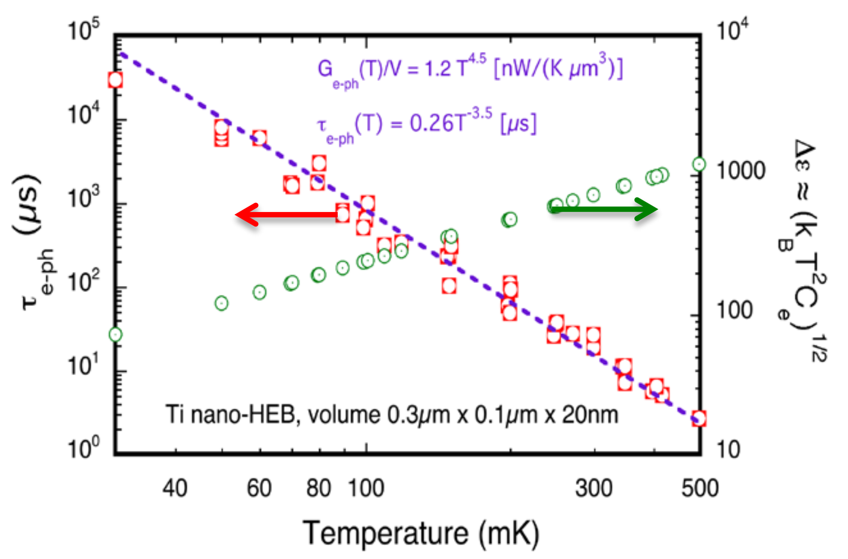
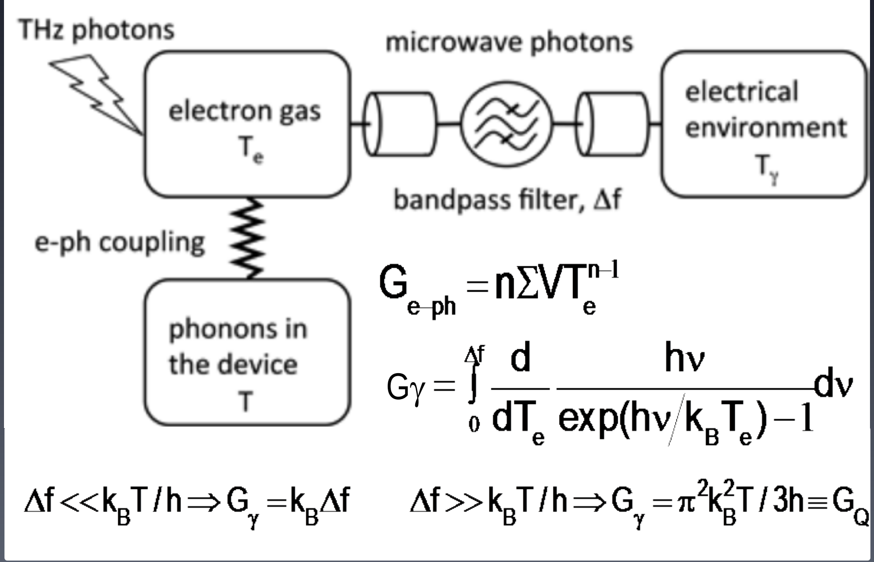
Microwave-photon-mediated cooling





$$G_{e\text{-}ph} = n\Sigma V T_e^{n-1}$$

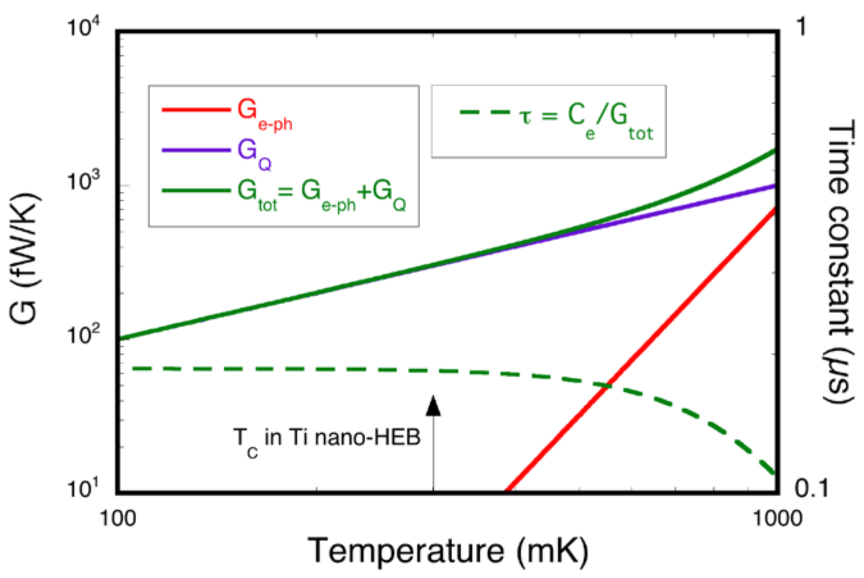
$$G\gamma = \int_0^{\Delta f} \frac{d}{dT_e} \frac{h\nu}{\exp(h\nu / k_B T_e) - 1} d\nu$$

$$\Delta f << k_B T / h \Rightarrow G_\gamma = k_B \Delta f \qquad \Delta f >> k_B T / h \Rightarrow G_\gamma = \pi^2 k_B^2 T / 3h \equiv G_Q$$

Schmidt et al., *Phys. Rev. Lett.* **93**, 045901 (2004)

because of the opposite temperature dependencies of $\tau_{e\text{-}ph}$ and $\delta\varepsilon$, the low NEP requirement (small $\delta\varepsilon$) and the large dynamic range requirement (small τ) are hard to meet simultaneously

connecting a nanodevice to a cold resistor via a transmission line on the same chip will enable an additional efficient cooling mechanism through the emission of 1D microwave (GHz) photons which will reduce the time constant in the the nano-HEB



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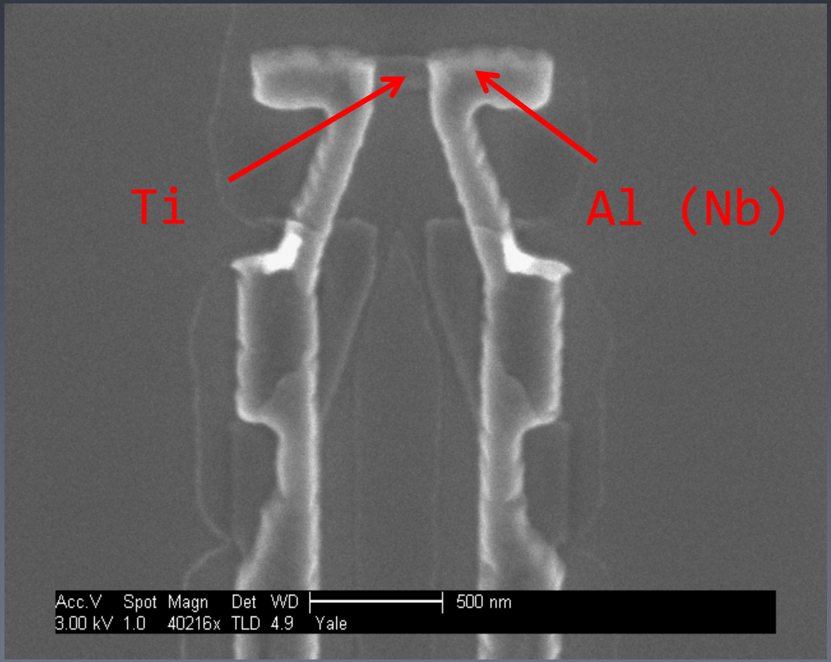

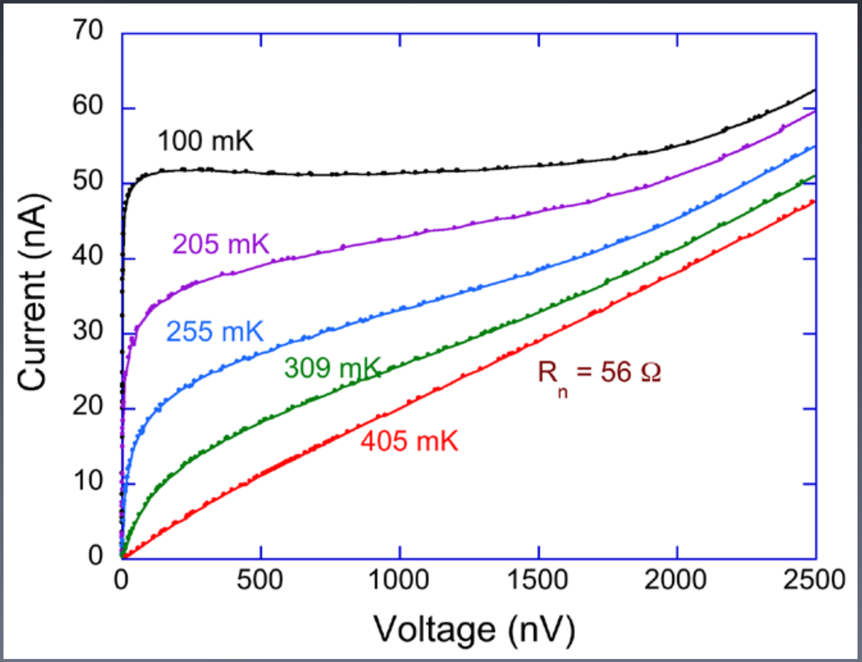

the thermal conductance derived from the IV characteristics turned out to be higher than expected which suggests that the Al contacts did not provide the sufficient Andreev reflection blocking

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Features of superconducting nano-HEB

Real device impedance from MM up to UV wavelengths

Small device size is needed for low NEP ⇒ microantennas and waveguides must be used (available)

Relatively simple fabrication (2-3 layers), does not require membranes

Low intrinsic noise

Sufficiently low NEP for the most demanding applications

Promising single-photon detection capabilities

Operates at or below T_C ⇒ material development is needed for a particular application

The SQUID based readout is quite complex

Small saturation power / Low dynamic range in the power detection mode

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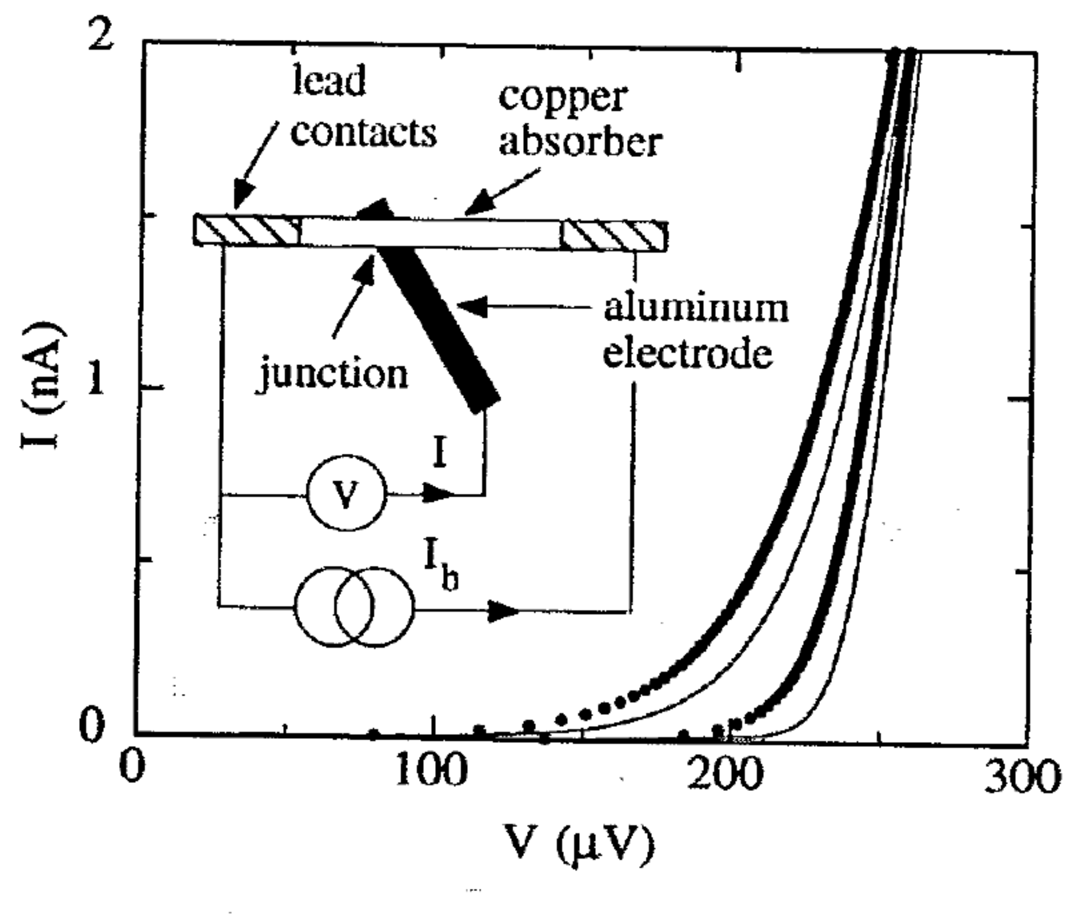
Normal metal HEB (NM HEB)



Nahum & Martinis, *Appl. Phys. Lett.* **63**, 3076 (1993)

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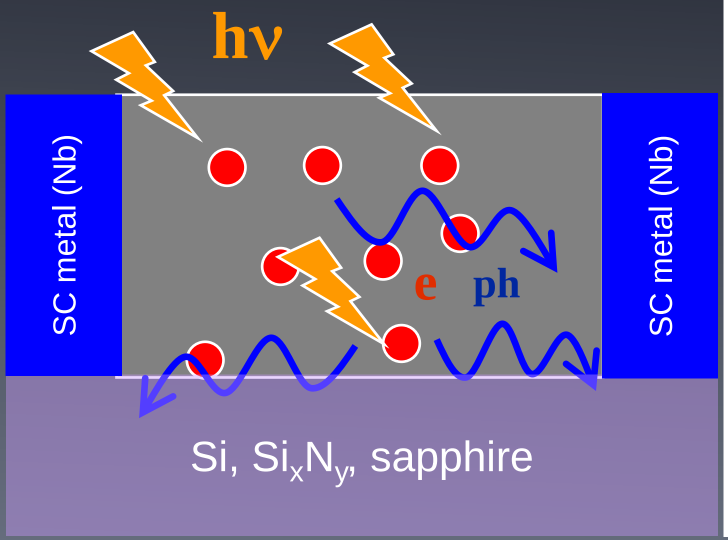
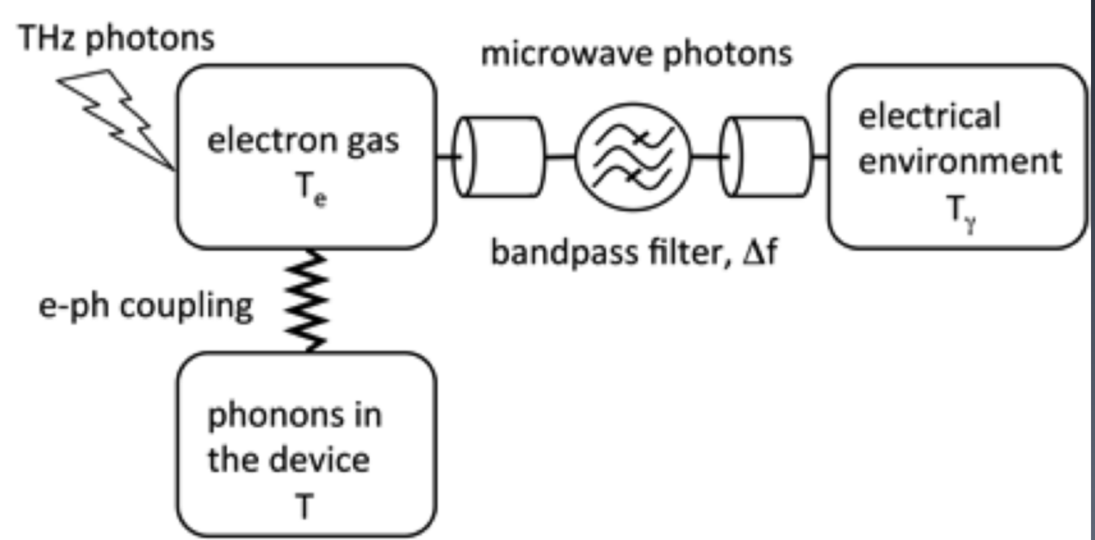
NM nano-HEB with Johnson noise thermometry (JNT) readout





$\Delta T_e \sim P_{rad}/(G_{e\text{-}ph} + G_\gamma)$

Johnson noise power $P_N \approx k_B \Delta f T_e$

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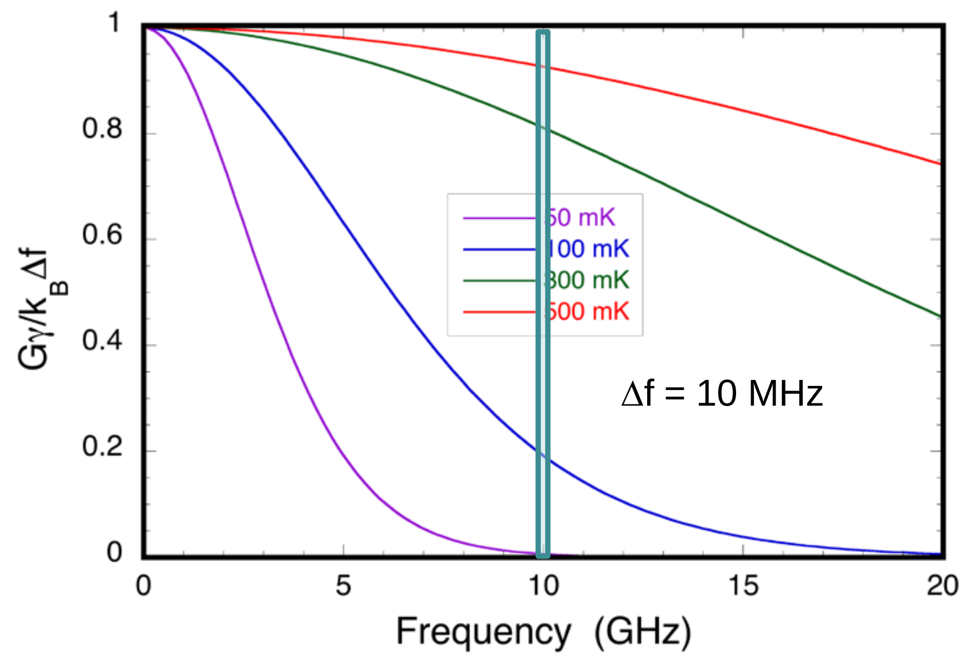
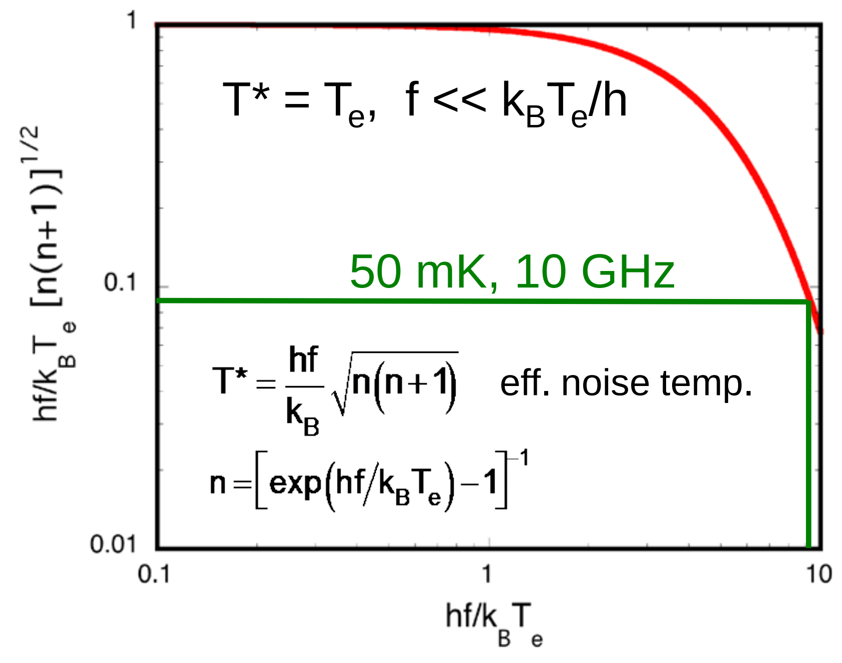
Small photon occupation number effects ($hf >> k_B T_e$)





In the Rayleigh-Jeans limit ($f << k_BT_e/h$), $G\gamma = k_B\Delta f$

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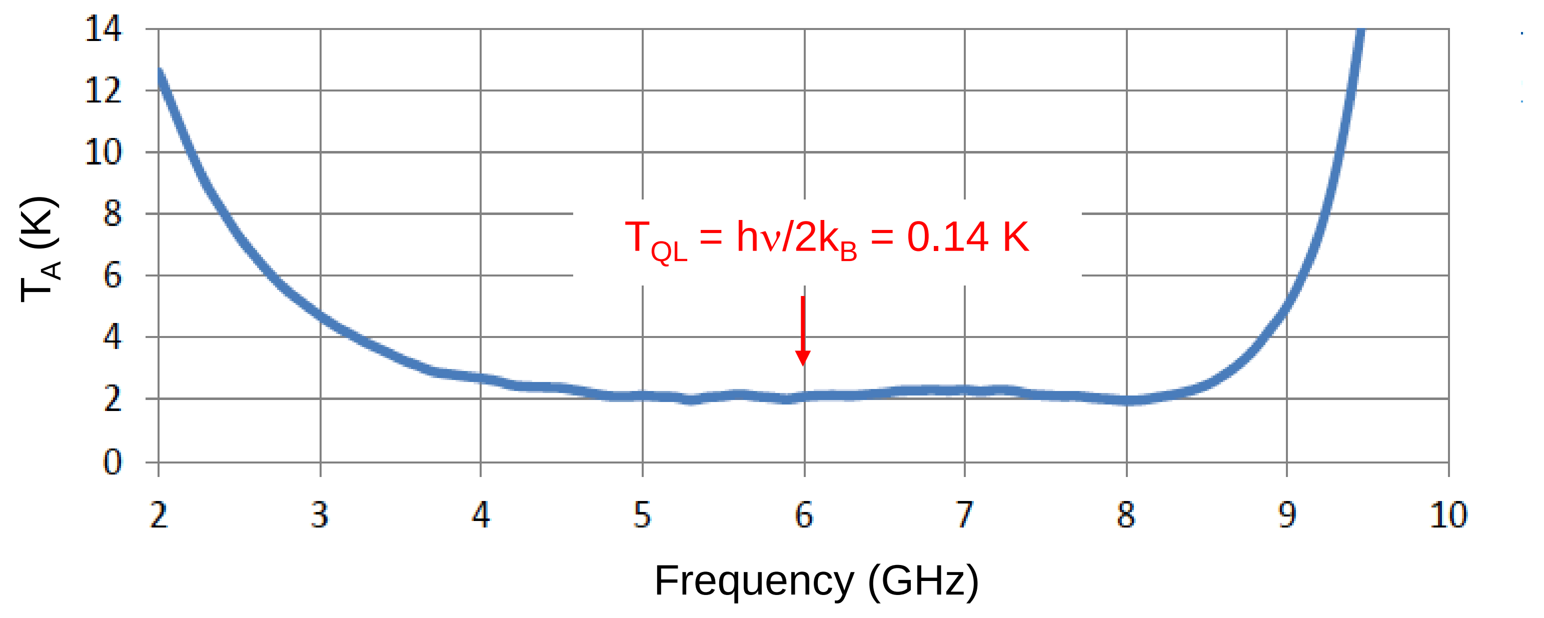

$T_{QL} = h\nu/2k_B = 0.14$ K

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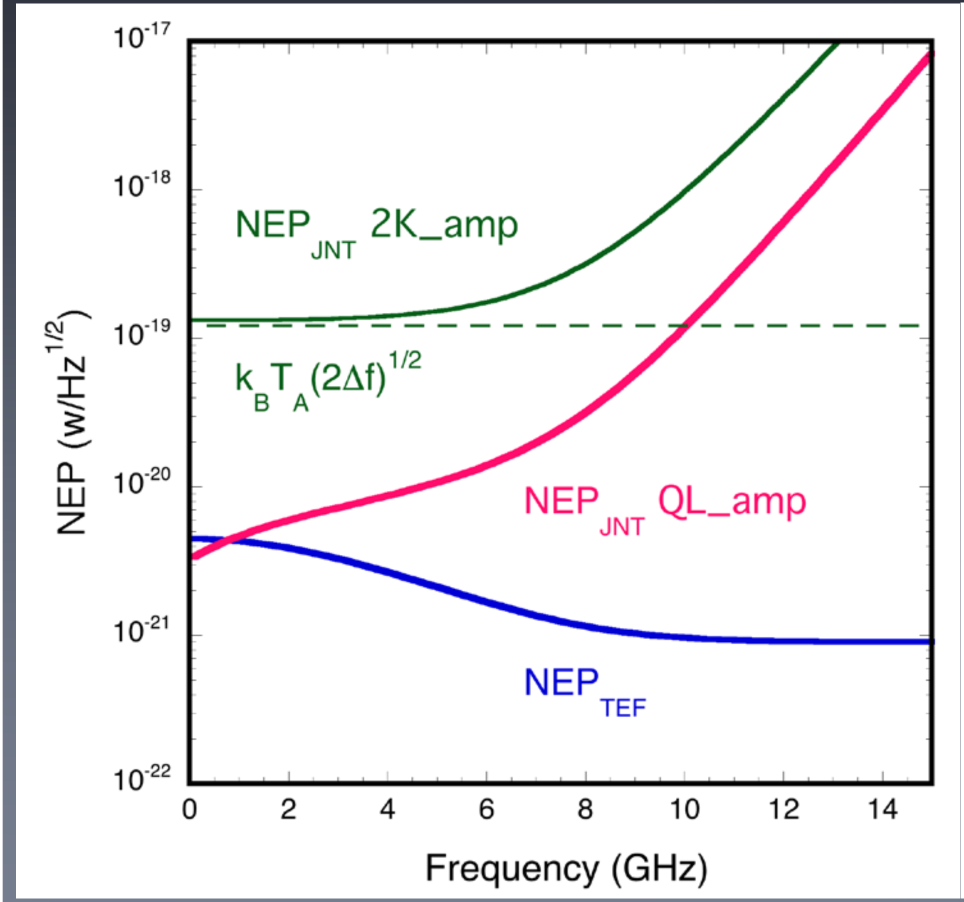
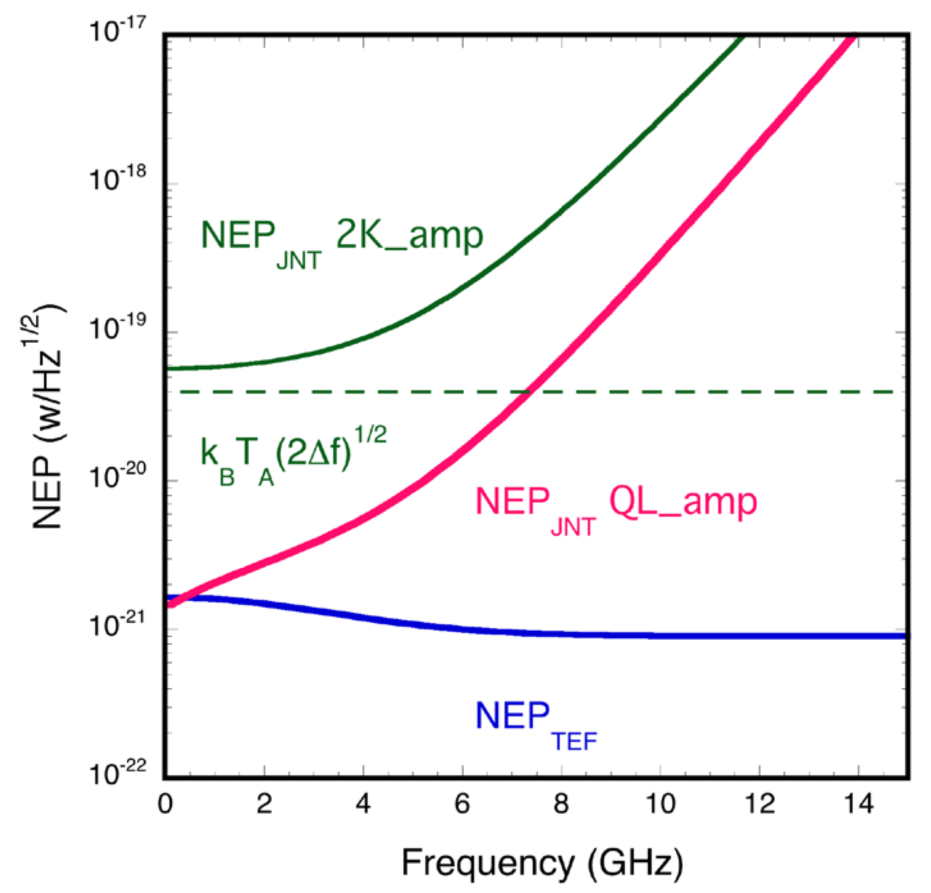
$\Delta f = 10$ MHz



$\Delta f = 1$ MHz



QL amplifier: $T_A = hf/2k_B$

Karasik et al. *IEEE Trans. THz Sci. Technol*. **5**, 16 (2015)

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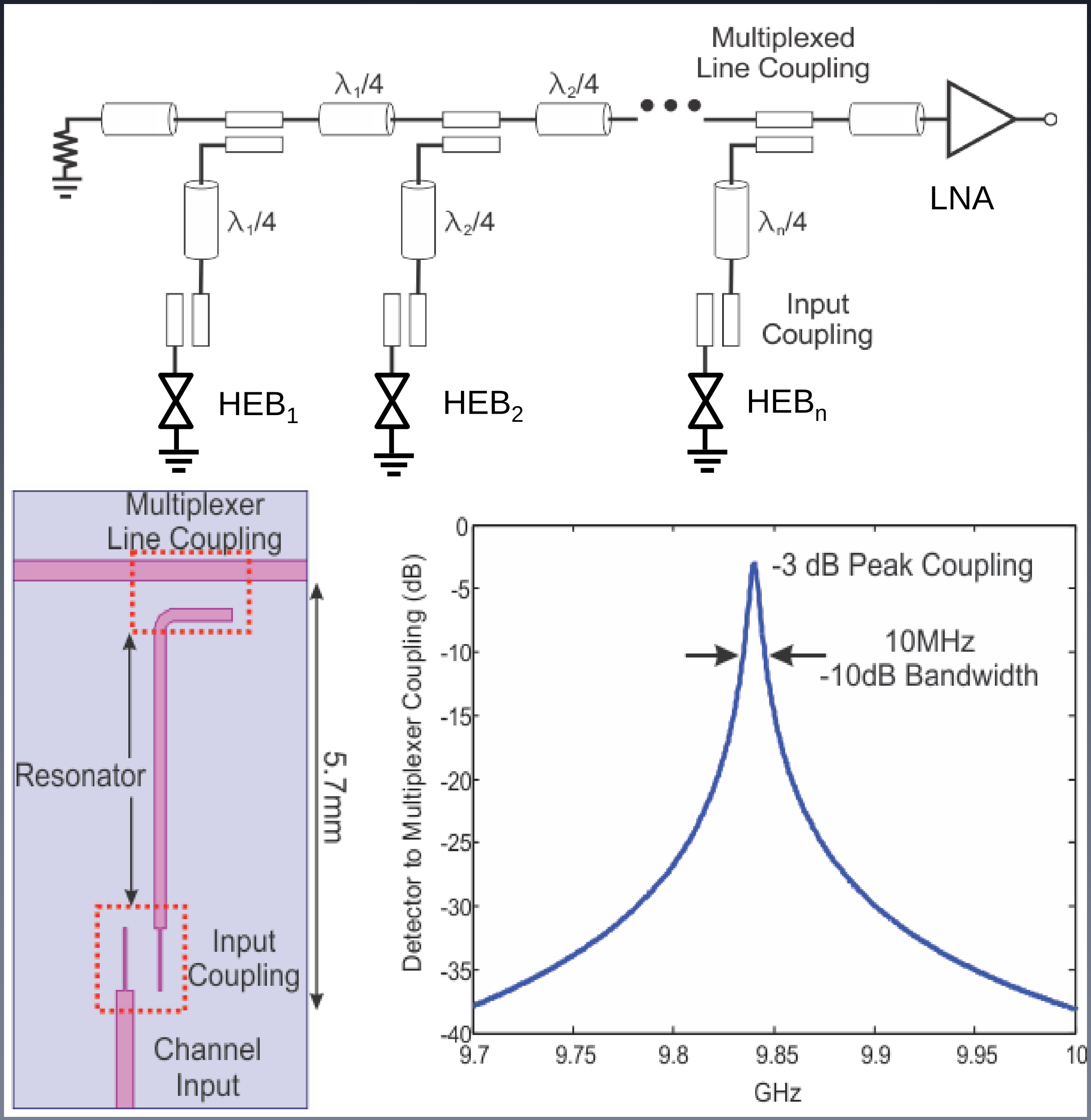

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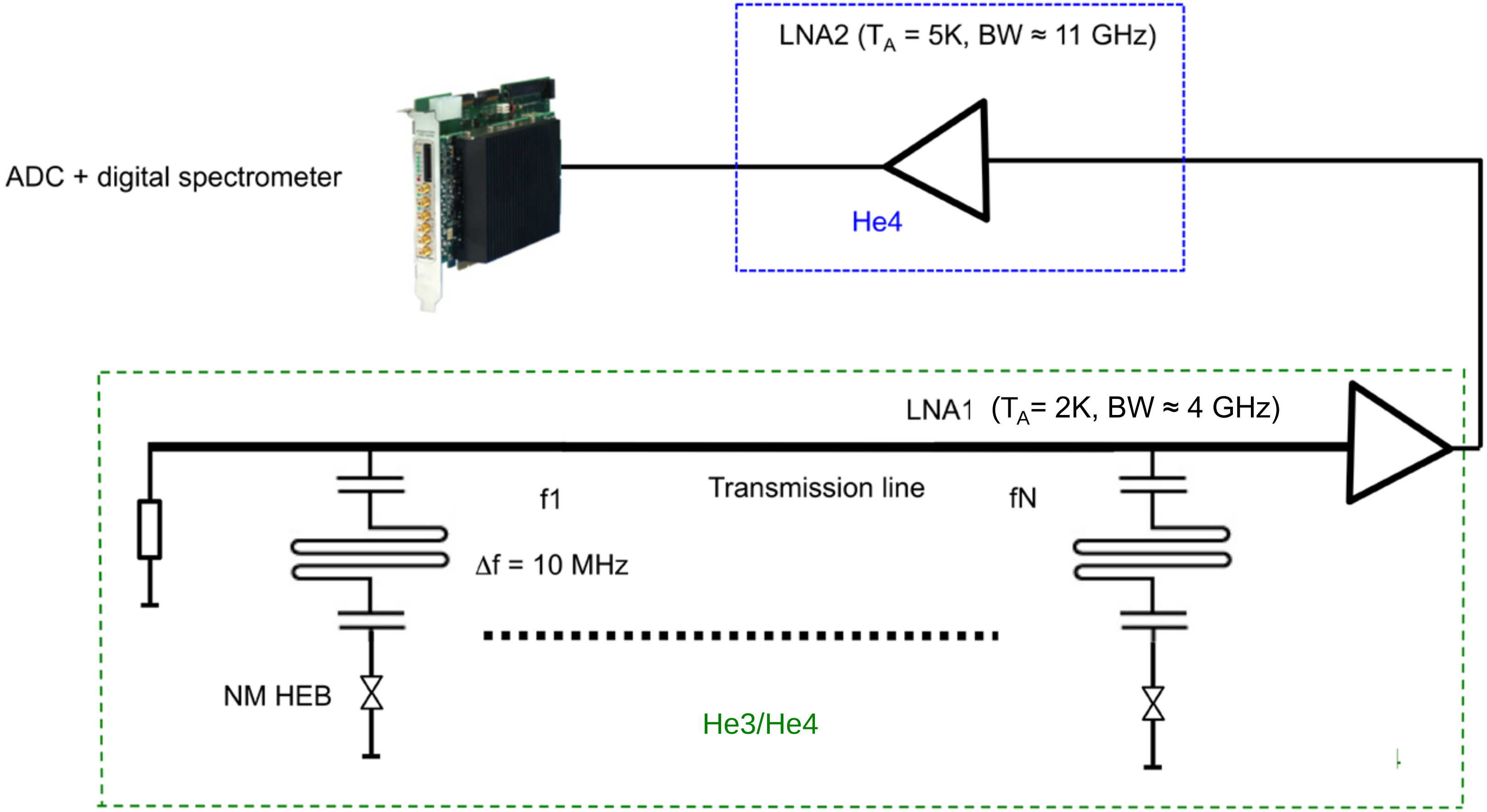

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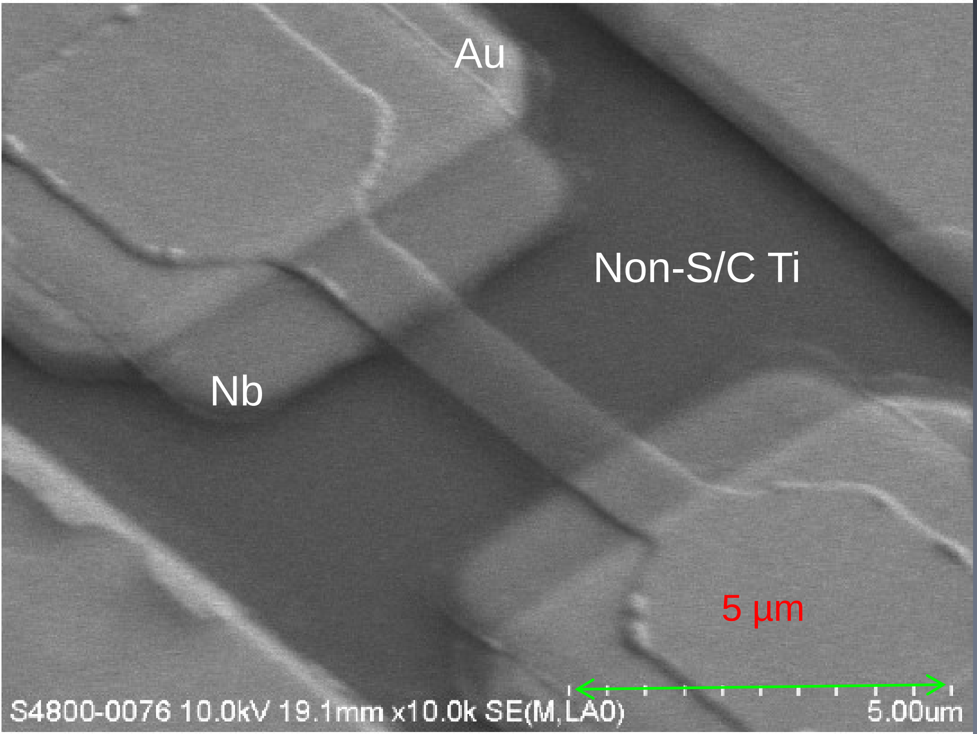

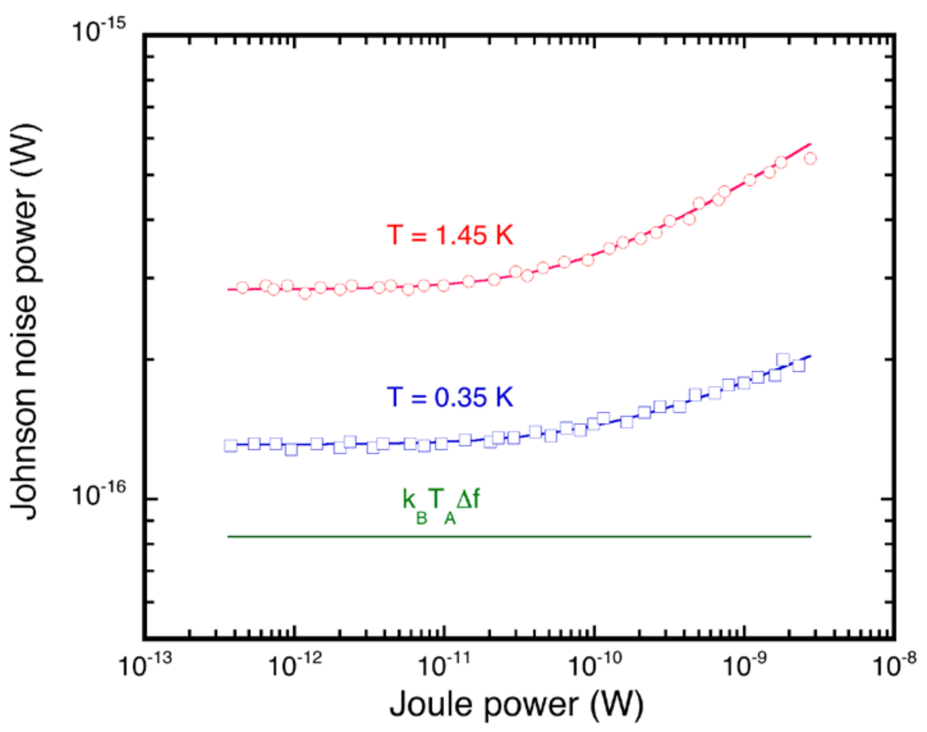

$T_A \approx 0.6$ K (SQUID rf amp.)
$\Delta f = 10$ MHz
NEP = 3×10^{-16} W/Hz$^{1/2}$

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S/C	NM
NEP ~ 10^{-20} W/Hz$^{1/2}$	NEP ~ 10^{-19} W/Hz$^{1/2}$
Small dynamic range ~ 30 dB, hard saturation	Large dynamic range > 100 dB, no hard saturation
Tuning T_C for a large array needs serious material development	Works at any temperature up to ~ 10 K
A SQUID based transceiver is needed for array readout	A spectrometer is needed for readout
Karasik et al., *IEEE Trans. THz Sci. Technol*. **1**, 97 (2011)	Karasik et al. *IEEE Trans. THz S*ci. Technol. **5**, 16 (2015)

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Summary

The TES nano-HEB detector has demonstrated an excellent sensitivity in the far-IR

With some improvement of the fabrication technique, the NEP could be lowered to ~ 10^{-20} W/Hz$^{1/2}$

Normal metal nano-HEB offers the simplicity of fabrication and architecture with the benefit of large dynamic range and low NEP ~ 10^{-19} W/Hz$^{1/2}$

The ability to detect single mid-IR photons is quite unique and may find applications in astrophysics, free-space quantum communication, single-molecule spectroscopy, etc.

Experimental astrophysics remains to be the area where the demand for better detectors is strong and drives the search for new detection mechanisms

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