National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Superconducting hot-electron nanobolometer for FIR and mid-IR single-photon spectroscopy

Boris Karasik (JPL)

Collaboration

Sergey Pereverzev and Alex Soibel
JPL

Daniel Santavicca, Luigi Frunzio, Bertrand Reulet, Faustin Carter, and Daniel Prober
Yale University

David Olaya and Michael Gershenson
Rutgers University

Andrei Sergeev
SUNY at Buffalo

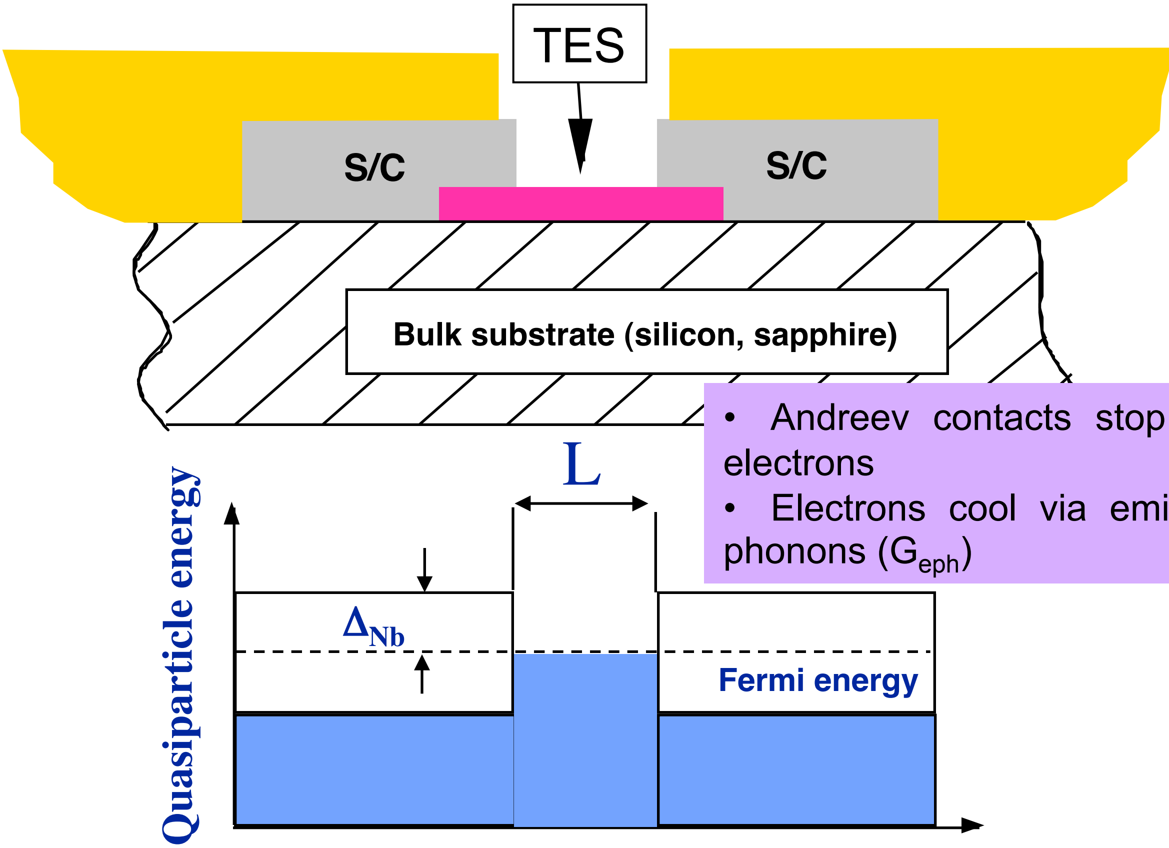
Outline

- Concept of nano-HEB
- Previous study (thermal conductance and phonon noise)
- Electrical noise, NEP, and noise bandwidth
- Detection of single mid-IR (8 μm) photons
- Possible applications

SPCD in mid-IR and FIR

- Quantum dots at THz
- Si:As BIB detector at 0.4-28 μm
- No PNR detectors
- No superconducting detectors

Hot-electron bolometer (HEB)



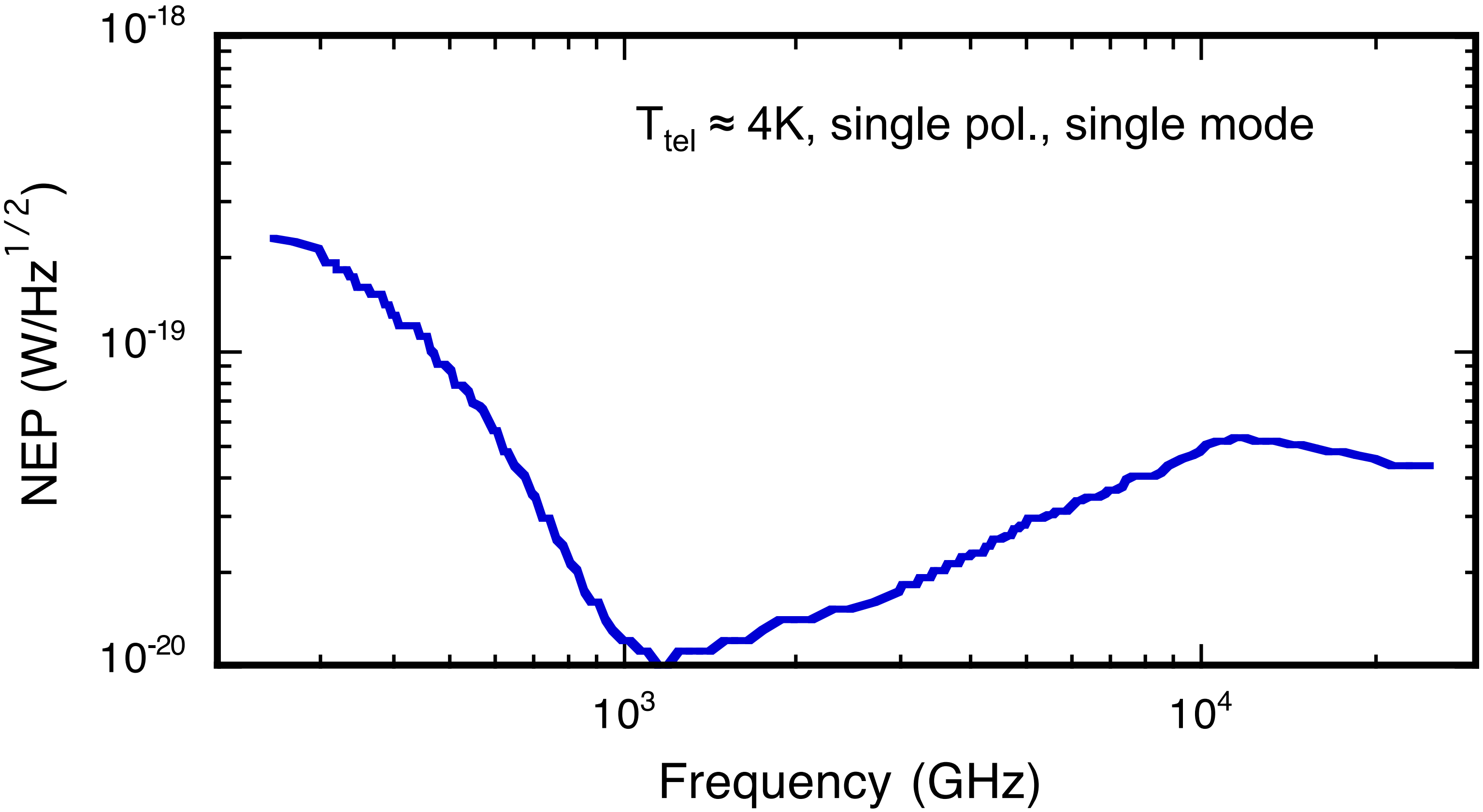
- Andreev contacts stop diffusion of hot electrons
- Electrons cool via emission of thermal phonons (G_{eph})

- Solid state device
- No membrane support
- Fast response ($\tau_{e\text{-}ph}$)

Optical and NIR versions – in talks by Kuo, Nam, and Irwin

Need for very sensitive FIR detectors

Moderate resolution spectroscopy ($\nu/\delta\nu \approx 1000$) in space

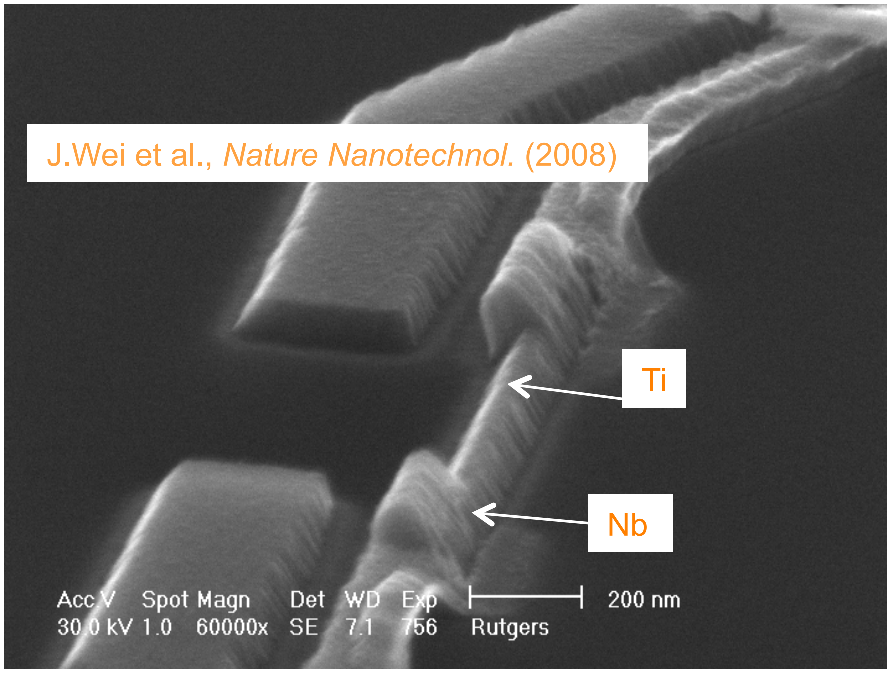


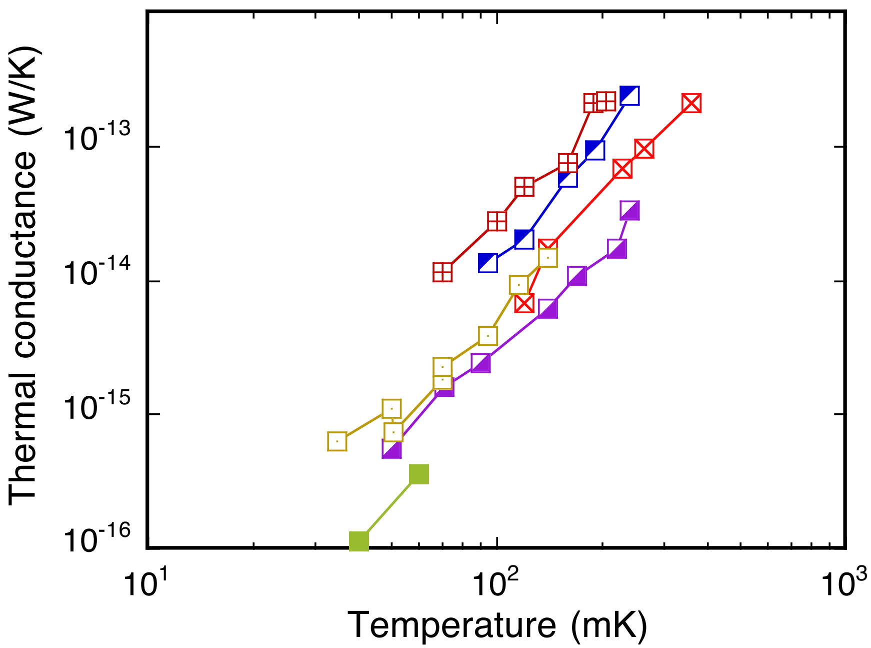
Hot-electron nanobolometer (nano-HEB)

$G \sim V \times T^4$, $\tau \sim T^3$ does not depend on volume

Phonon noise $NEP = (4k_B T^2 G)^{1/2}$ does depend on volume

B.Karasik et al., *Supercond.Sci.Technol.* 1999





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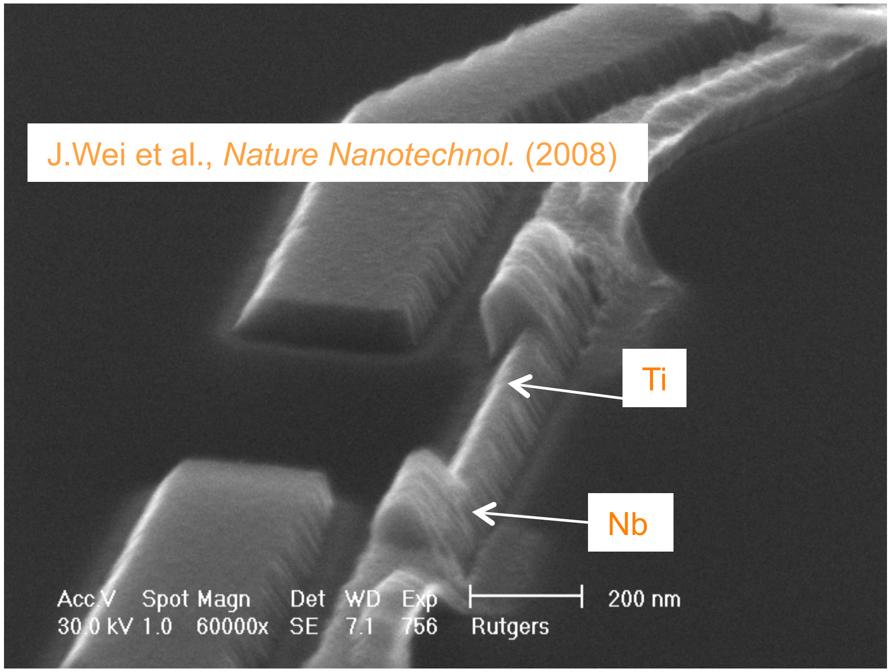
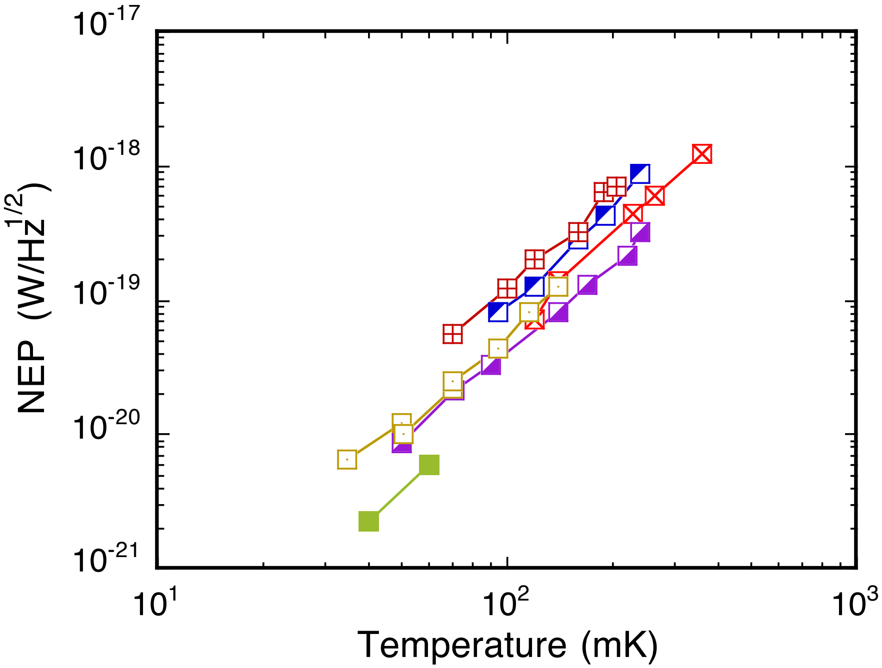
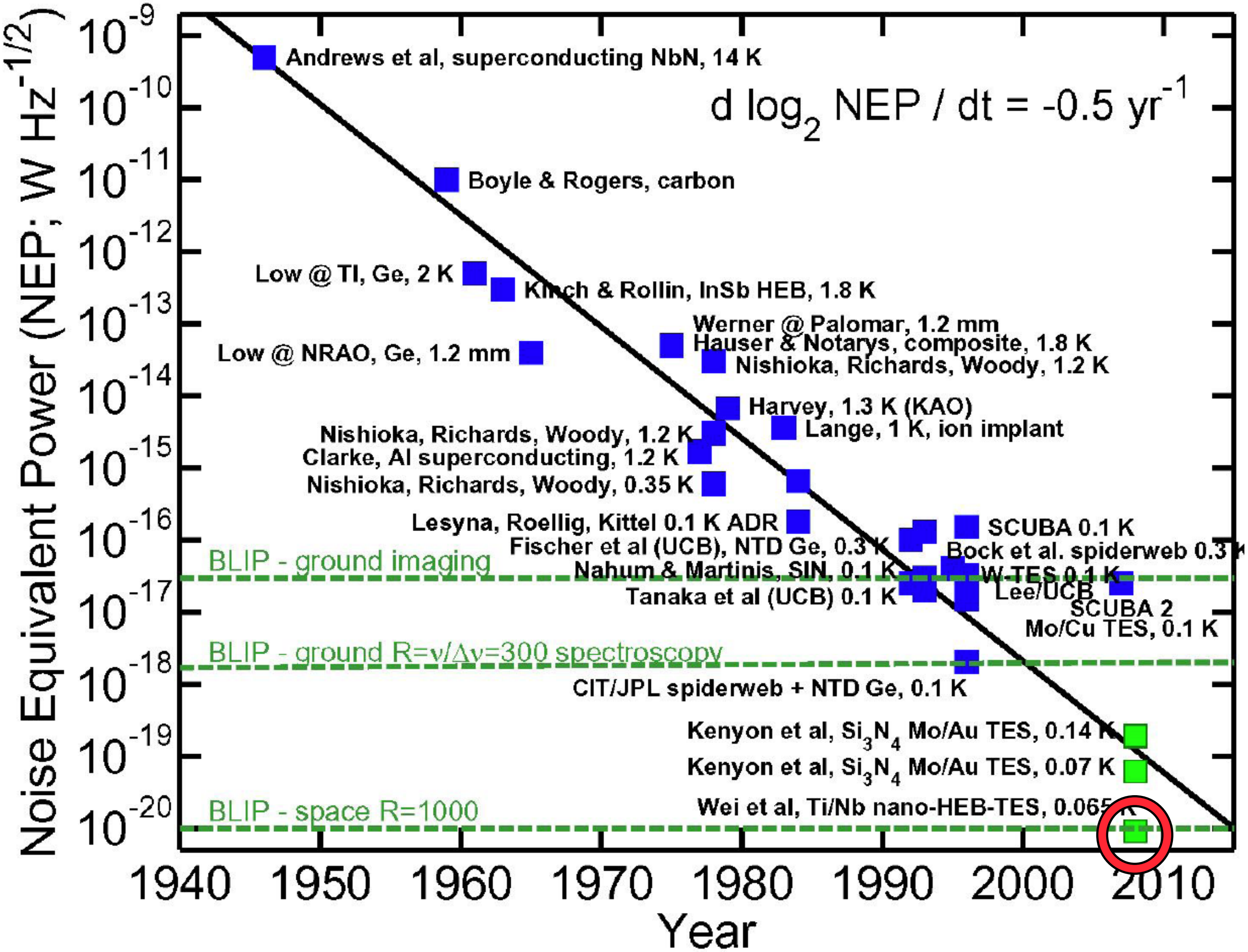


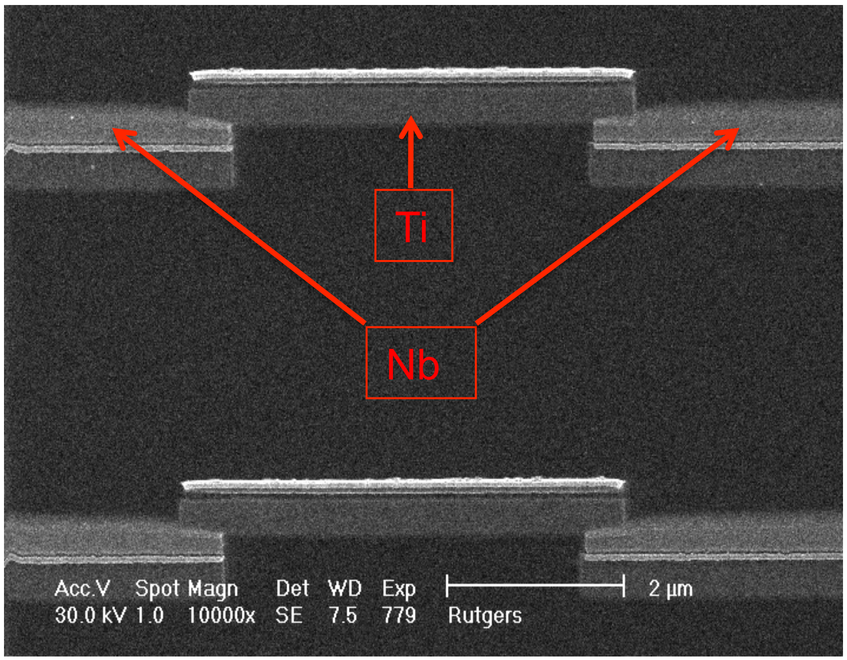


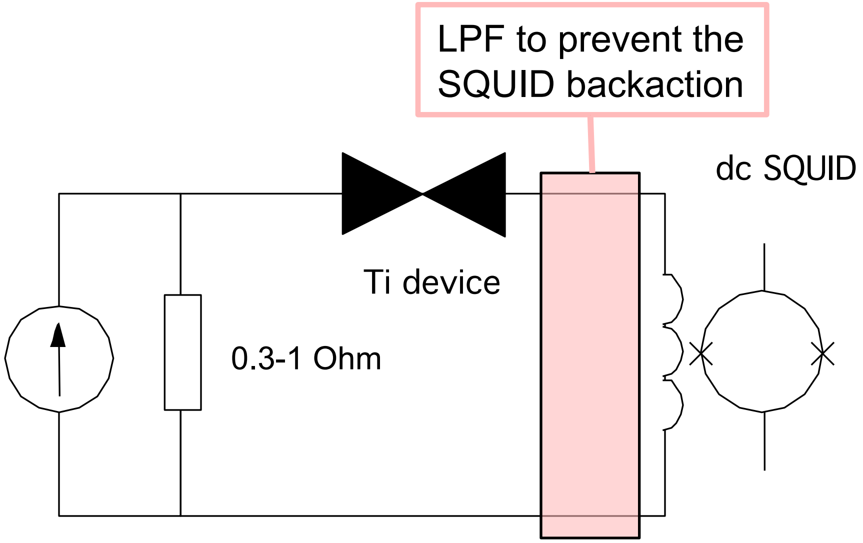
Zmuidzinas' plot



Noise characteristics of nano-HEB

- Using devices made from thin Ti film (56nm), 6-μm long, 0.4-μm wide
- Measuring the output electrical noise and deriving the electrical NEP
- Measuring the time constant using a 3 THz QCL
- Using magnetic field to decrease T_C

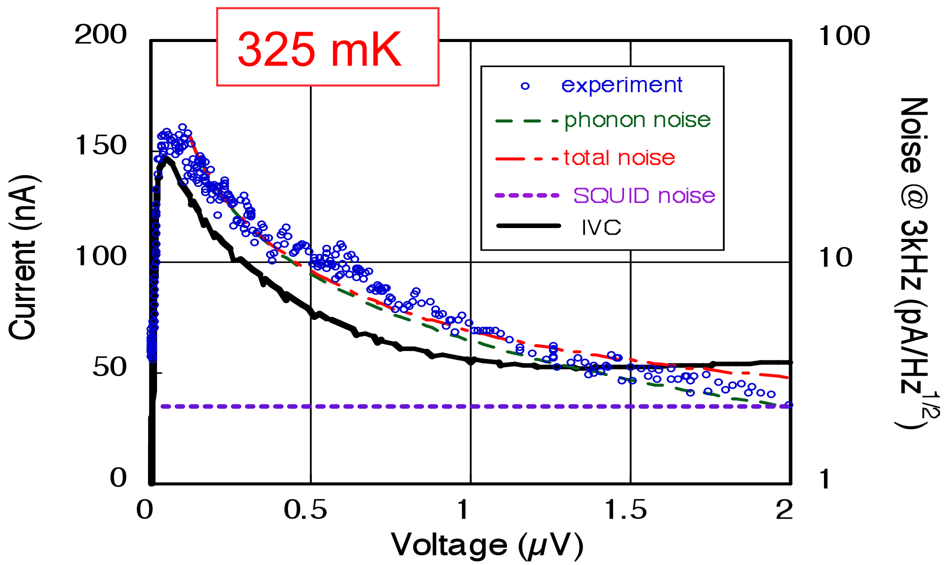


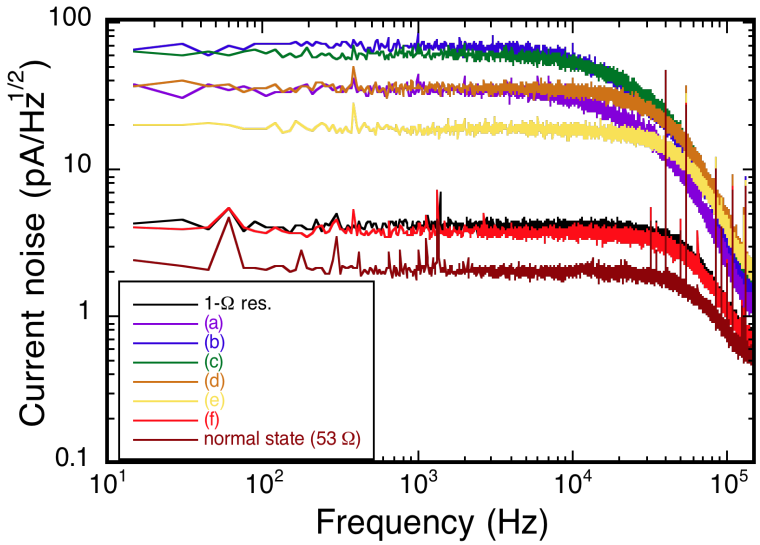


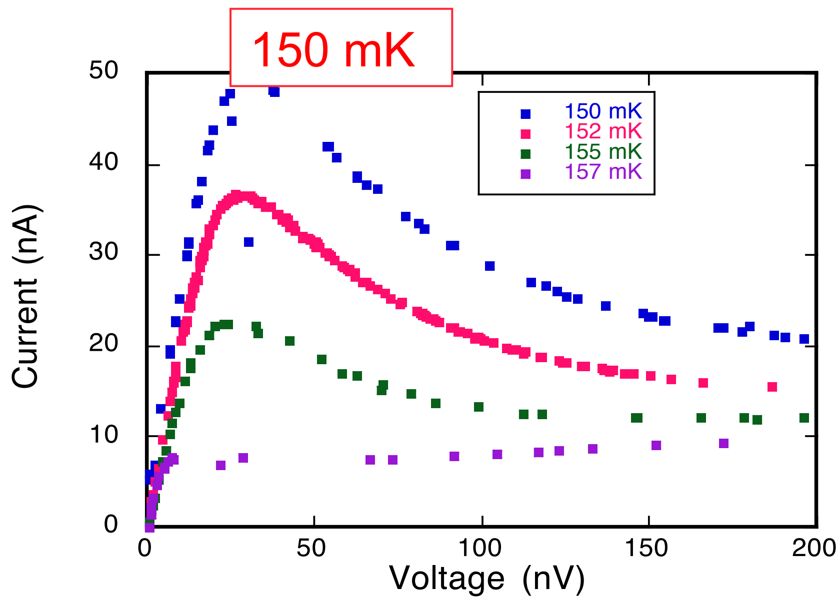
L_s = 1.8 μH
SQUID bandwidth ~ 70 kHz

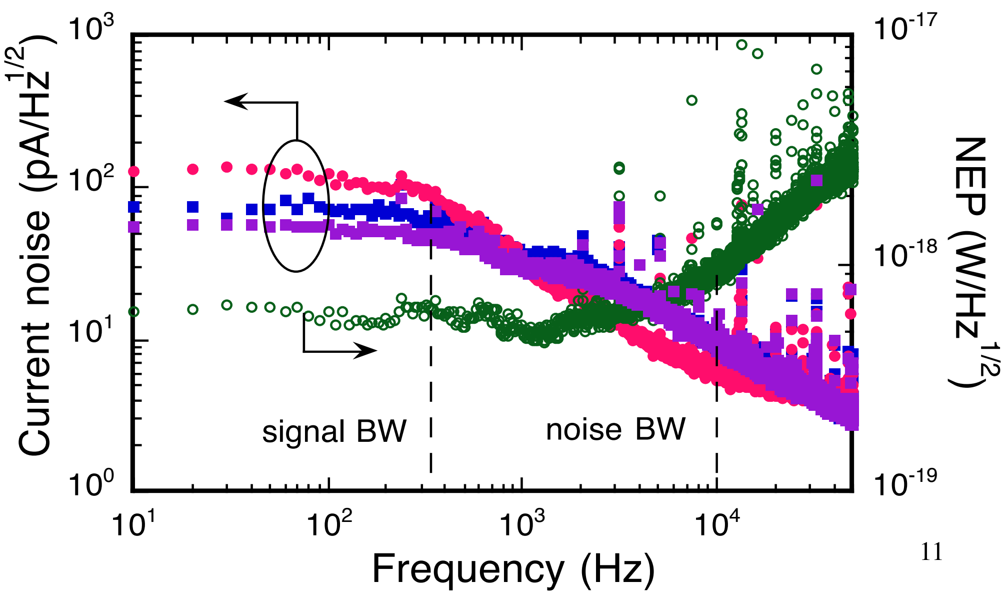
B.Karasik et al., *IEEE Trans. Appl. Supercond,* 2009

Noise & bandwidth data

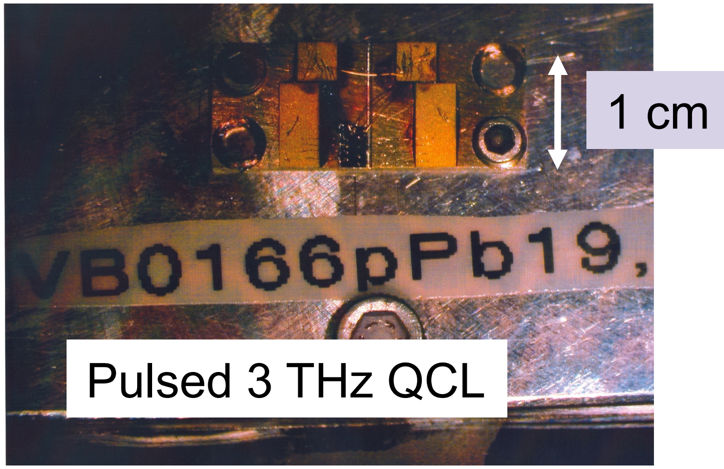


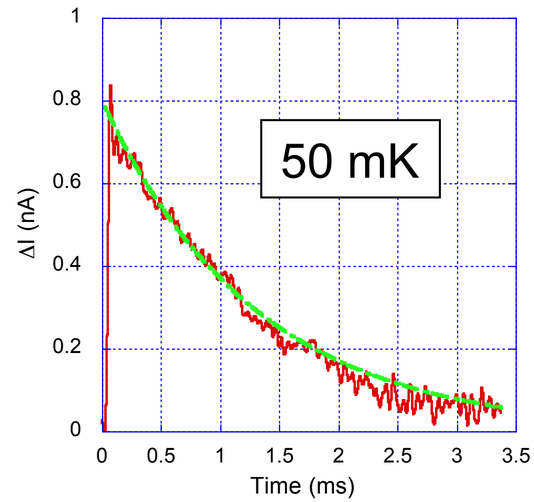


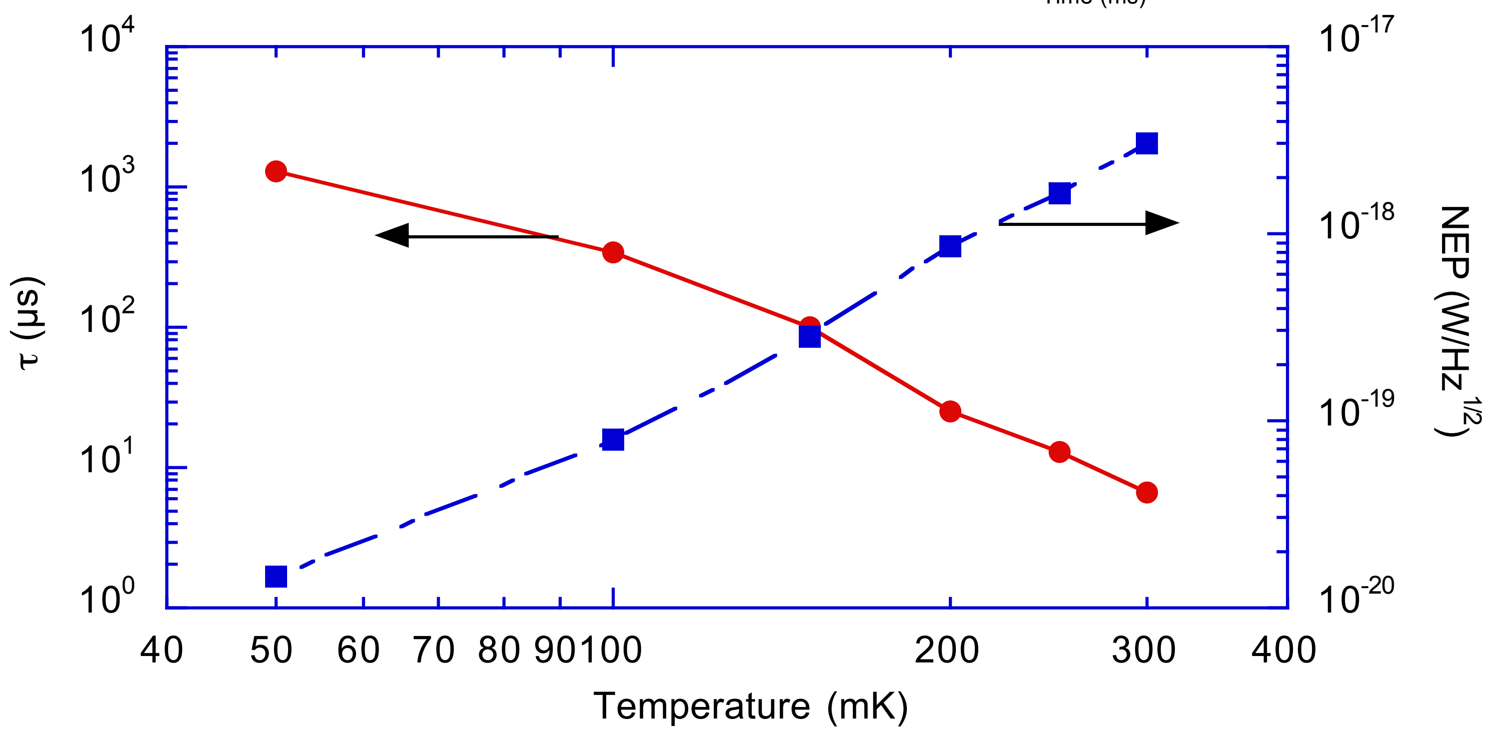




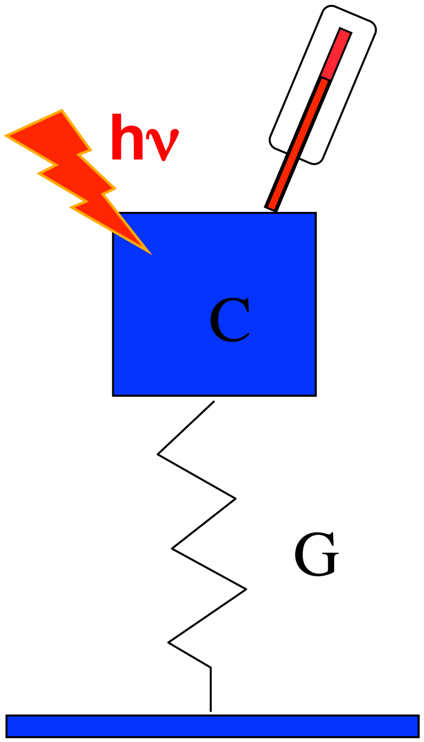
Electrical NEP and time constant

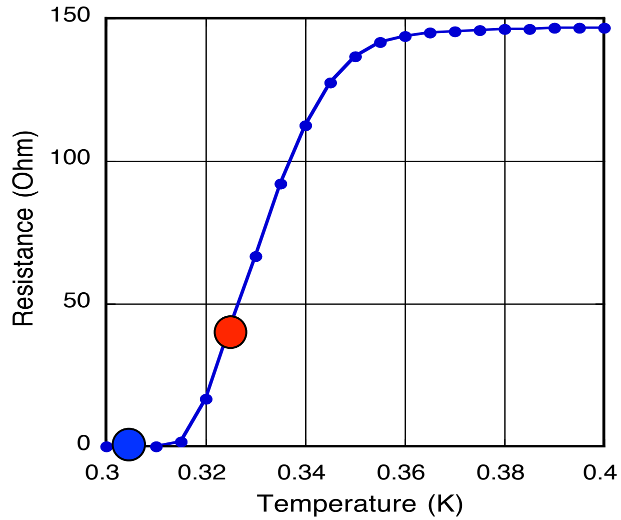


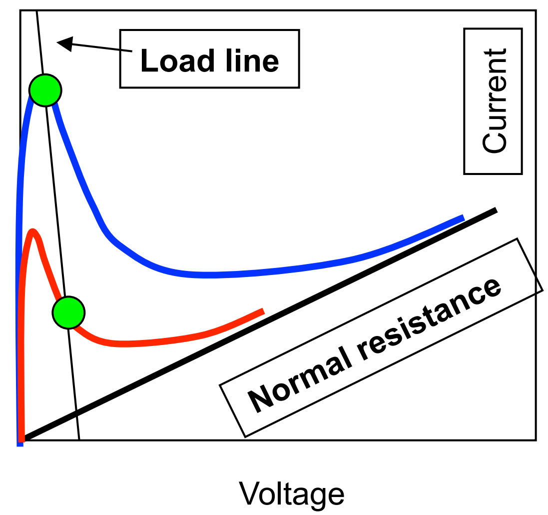




Single-photon TES

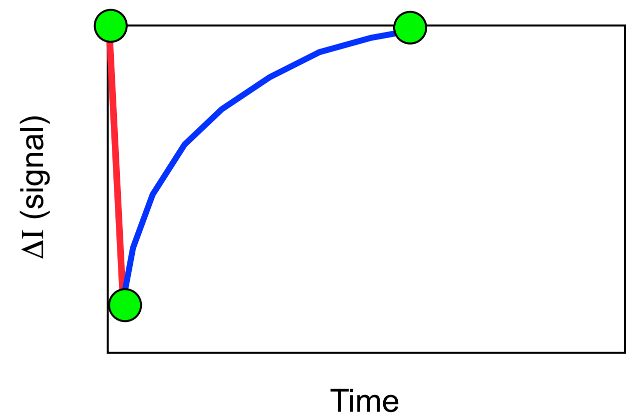






Heating
$\Delta T = h\nu / C$

Cooling
$T(t) \sim \exp(-t/\tau)$

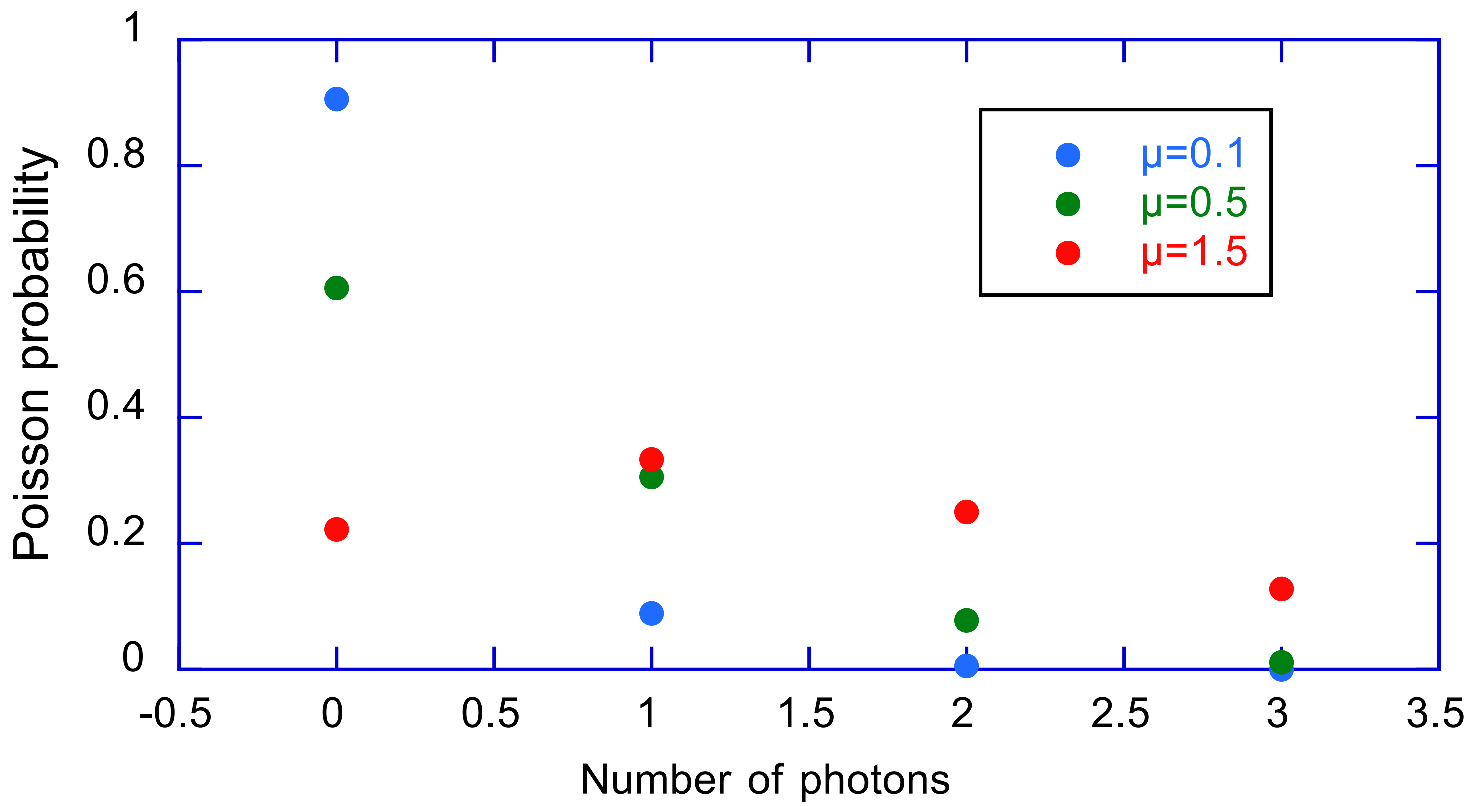


The nano-HEB has an extremely small volume (= heat capacitance ~ 10^{-19} J/K) so ν ~ THz

Poisson distribution of photon counts

$P(k,\mu) = \mu^k e^{-\mu}/k!$

μ is the average number of photons per pulse



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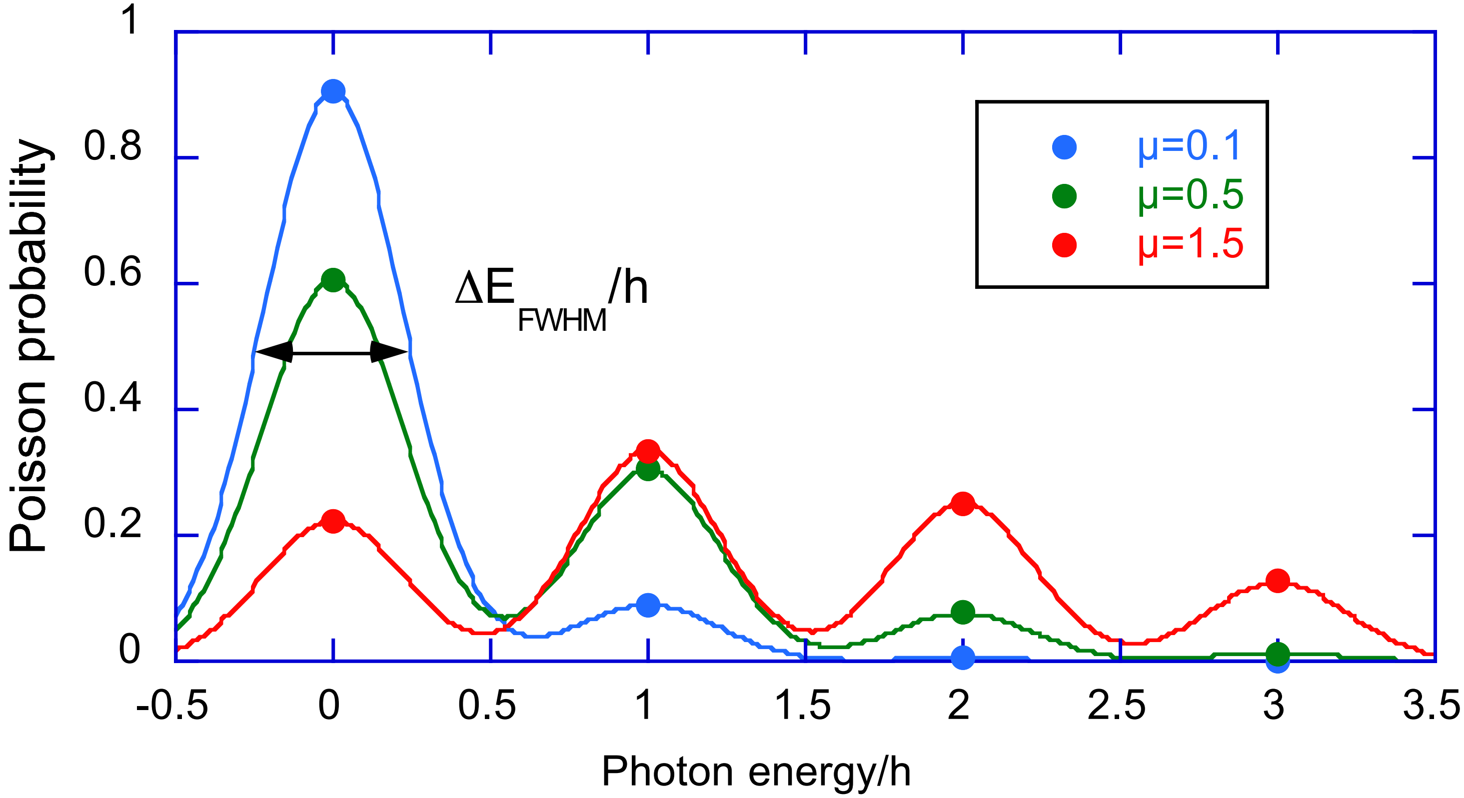
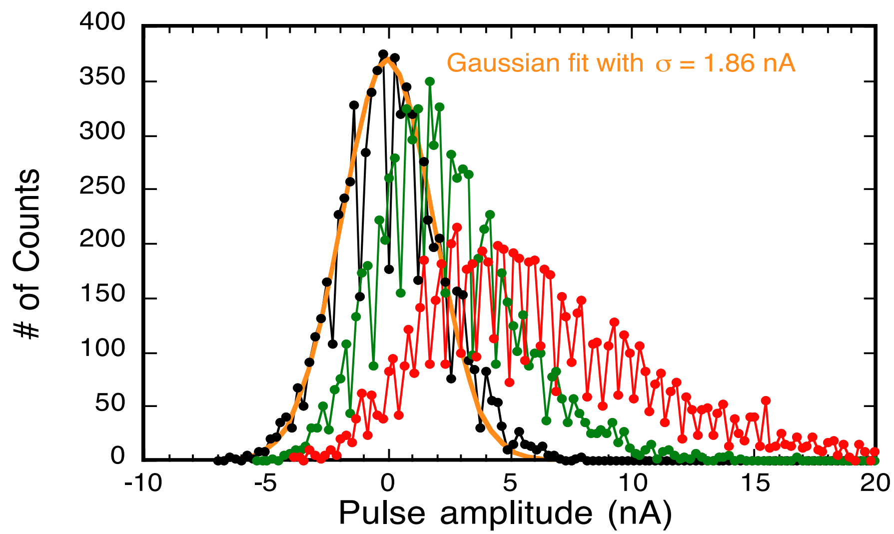
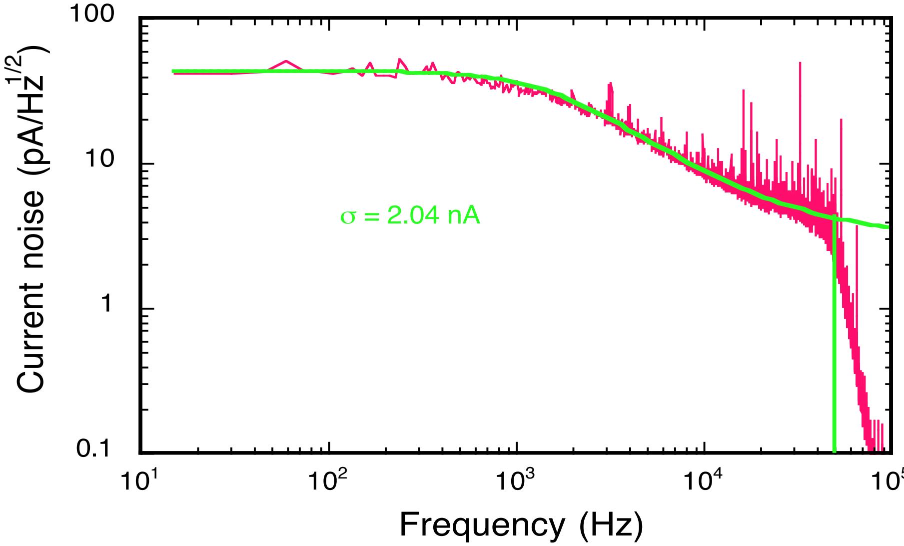
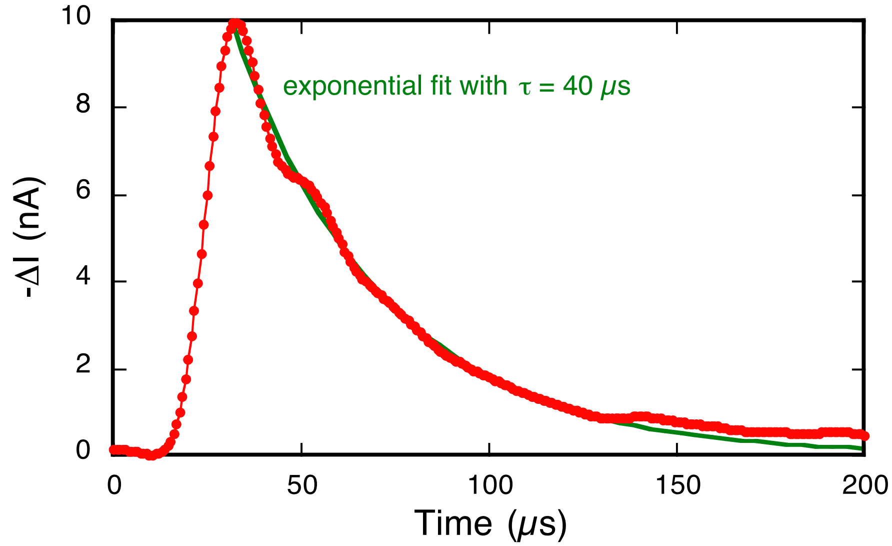


B.Karasik 01/28/10

Single-photon detection with 8-µm (38 THz) QCL at 150 mK





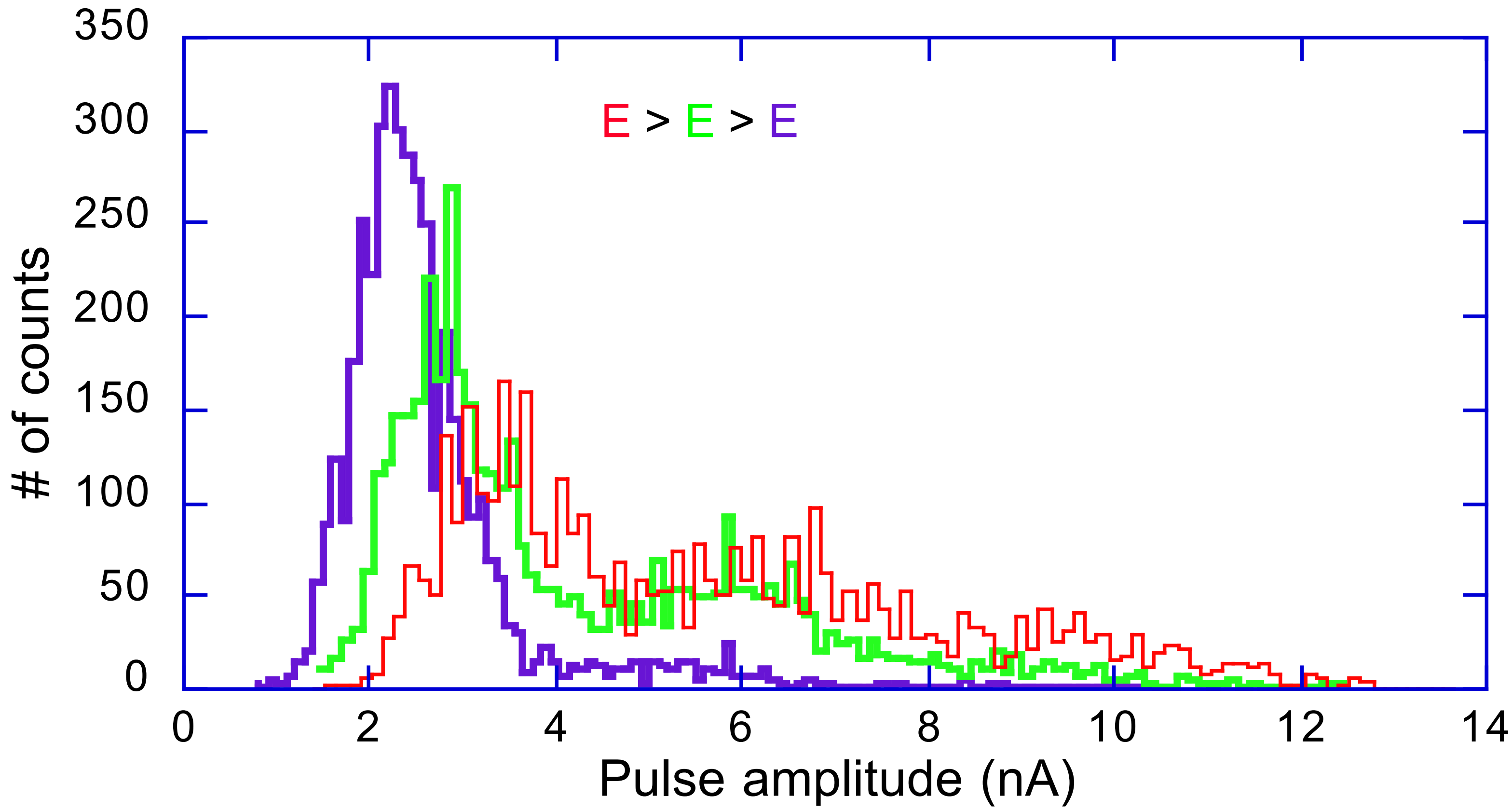


- The dark count noise is well described by the detector phonon noise

- An excess noise in presence of photons may be due to

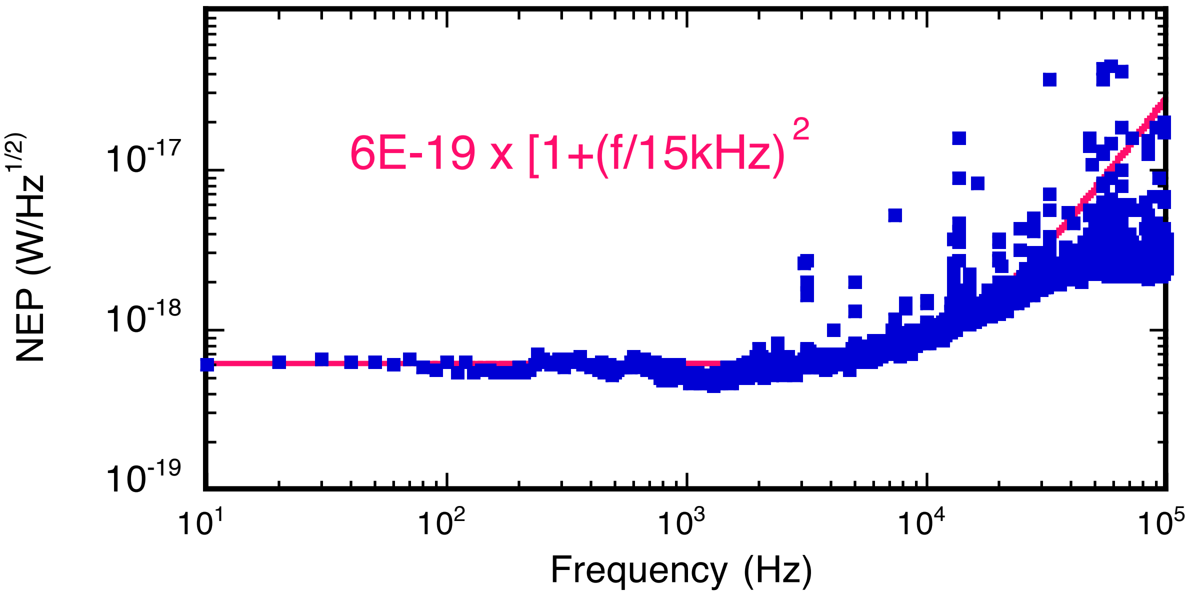
1. absorption in Nb leads and in Si
2. nonmonochromatic laser radiation

λ = 8 μm, 150 mK with HPF



$\Delta E_{FWHM} \approx$ 13 THz assuming $\Delta I \sim E$

NEP and energy resolution at 150 mK

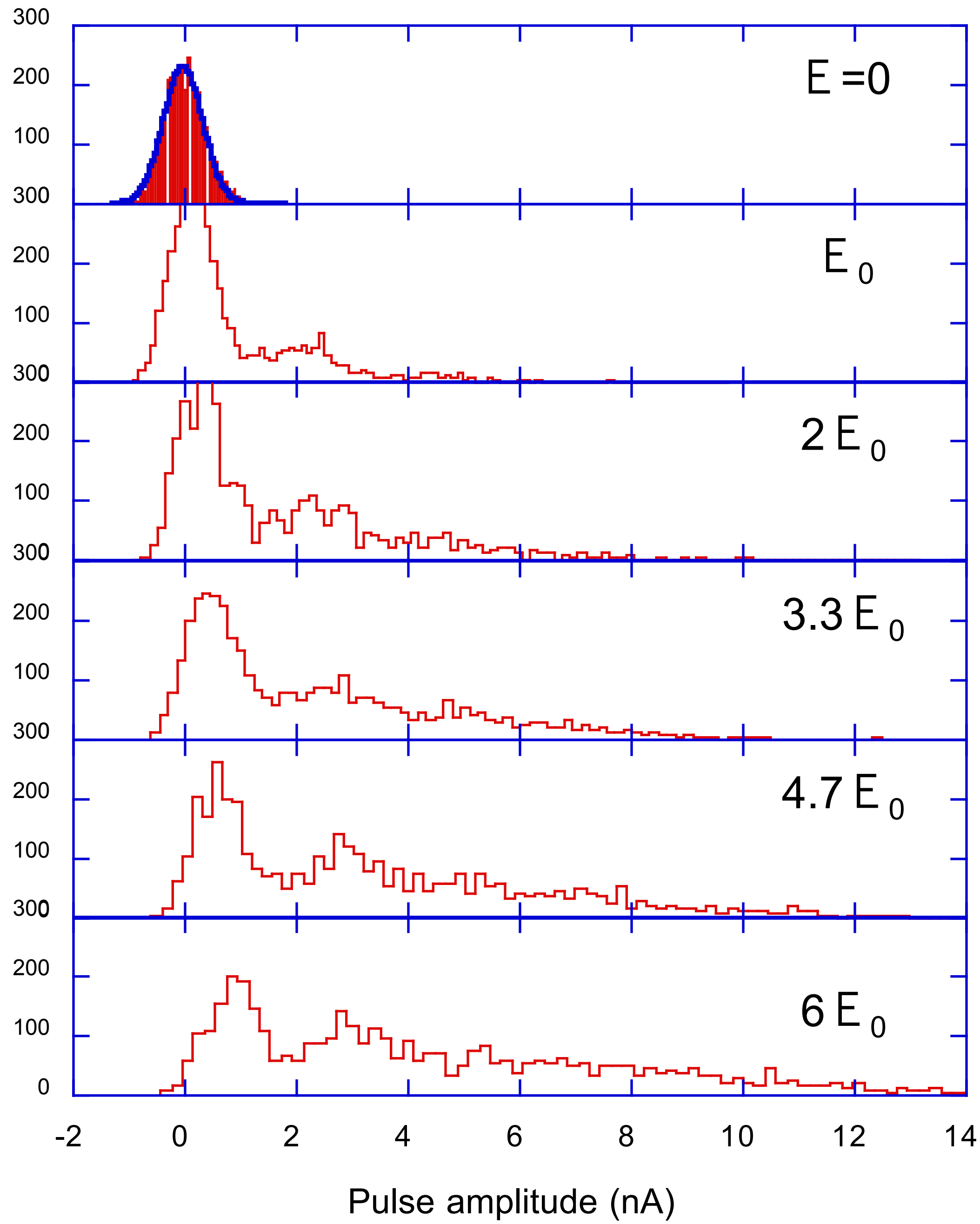


$$\Delta E_{FWHM} = 2.36 \Big/ \sqrt{\int \frac{4df}{NEP^2(f)}} = 4.6THz$$

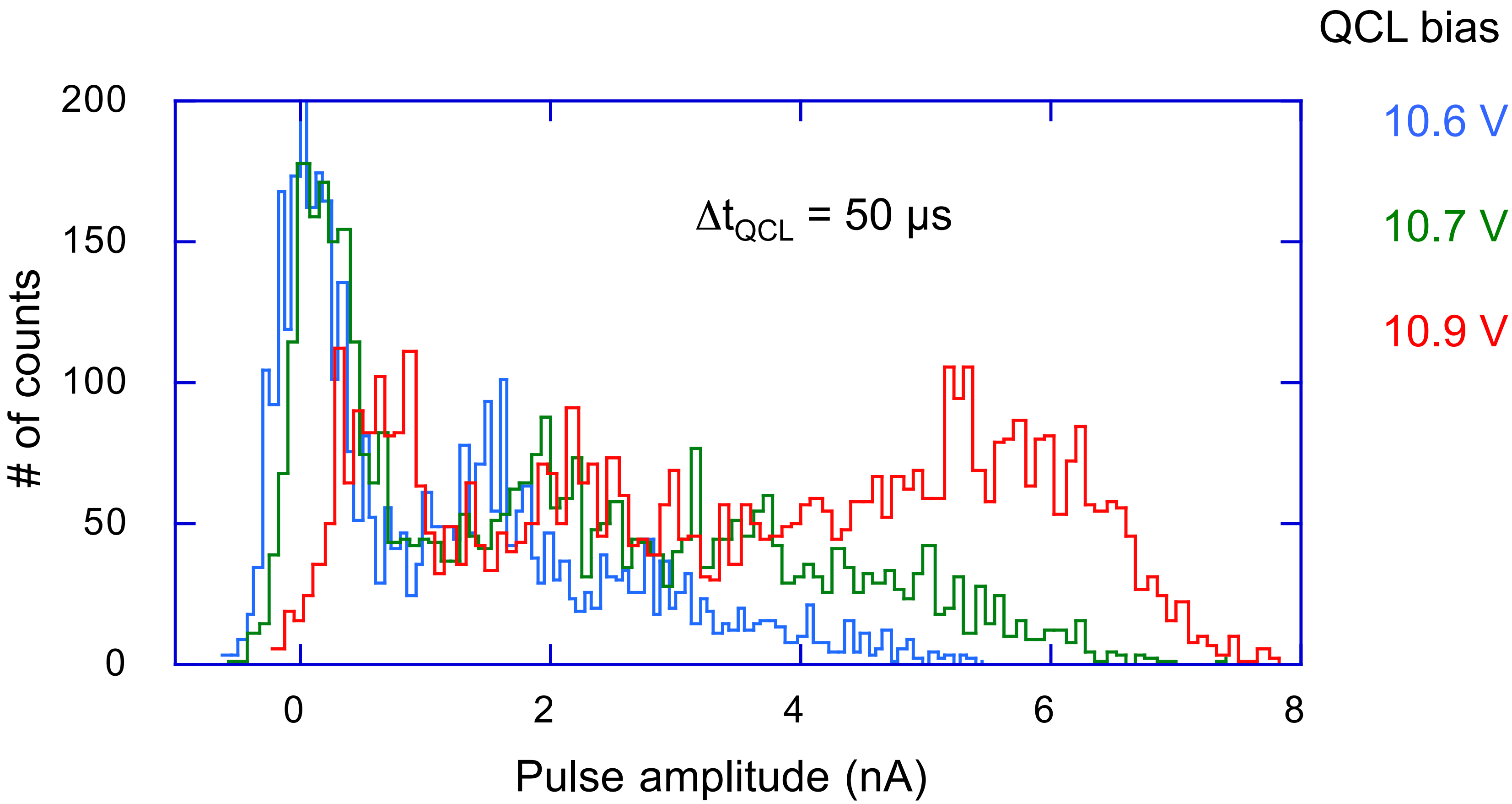
S.H.Moseley et al., *J.Appl.Phys.* 1984.

$$2.36\sqrt{k_B C_e T^2} \approx 5THz$$

100 mK
λ = 8 µm

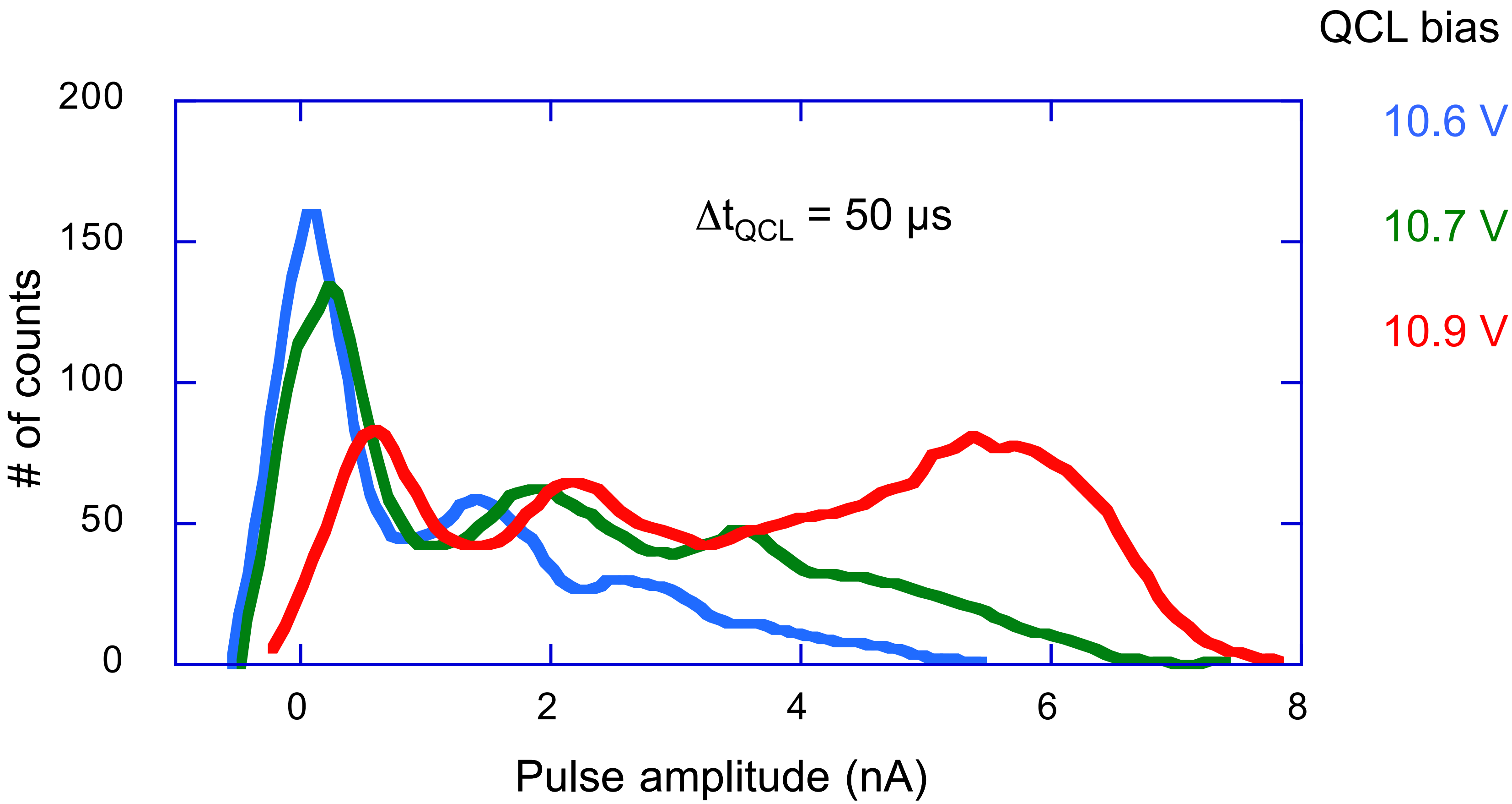


50 mK, λ = 8 μm



QCL bias
10.6 V
10.7 V
10.9 V
Δt_{QCL} = 50 μs
200
150
100
50
0
0
2
4
6
8
# of counts
Pulse amplitude (nA)

50 mK, λ = 8 μm



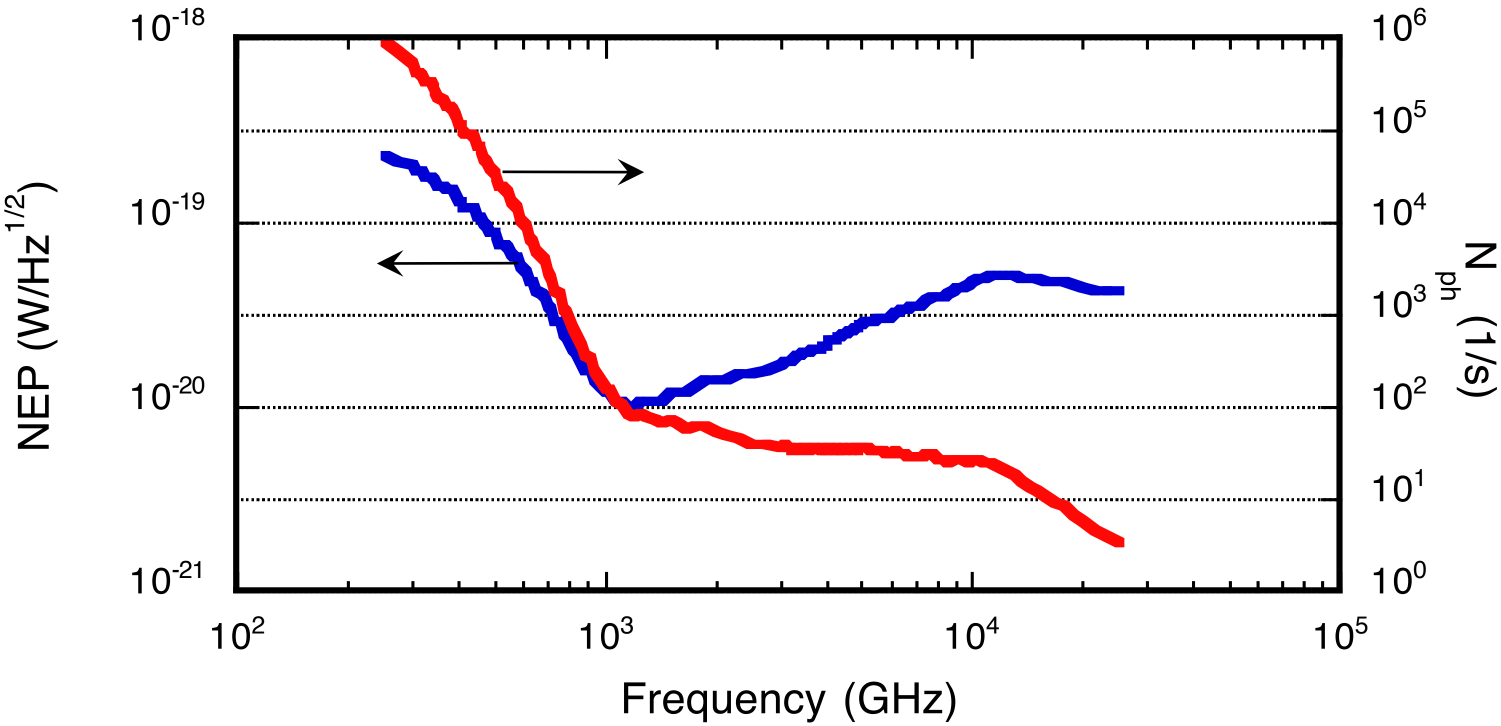
Issues to be addressed

• Improving the LP filtering between the device and the SQUID (absence of the temperature dependence of ΔE may be the result of this)

• Better filtering of the laser radiation

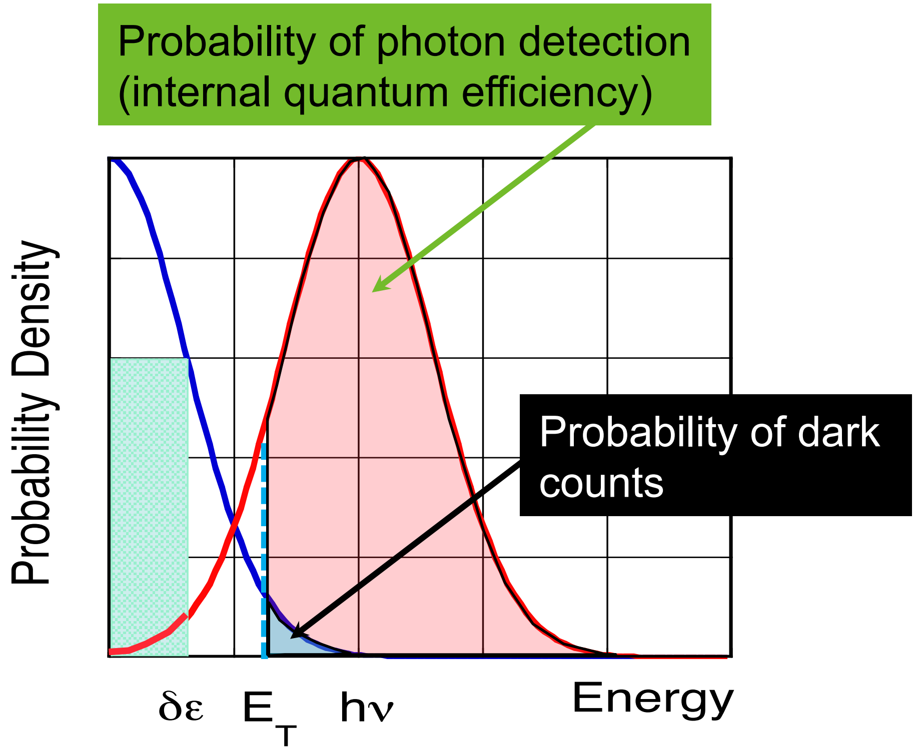
• Reducing the impact of the radiation on the substrate (smaller aperture, use of planar antenna in future)

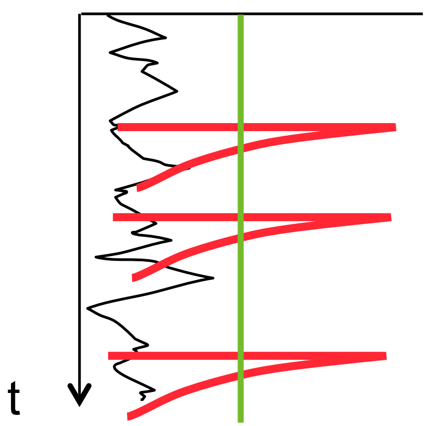
Moderate resolution spectroscopy in space ($\nu/\delta\nu$ ~ 1000)



$$NEP = h\nu(2N_{ph})^{1/2}$$

Dark counts, NEP, and quantum efficiency

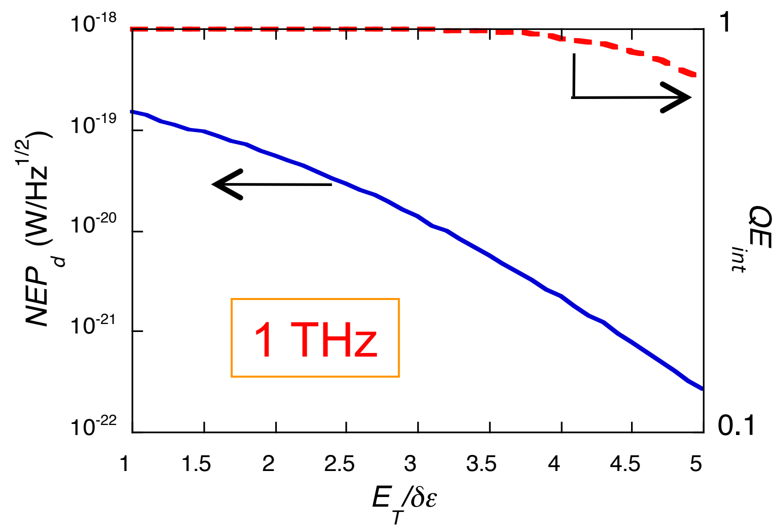




$$Q_{\mathrm{int}} = \frac{1}{\sqrt{2\pi}} \cdot \int_{(E_T - h\nu)/\delta\varepsilon}^{\infty} \exp\left(-x^2/2\right) dx$$

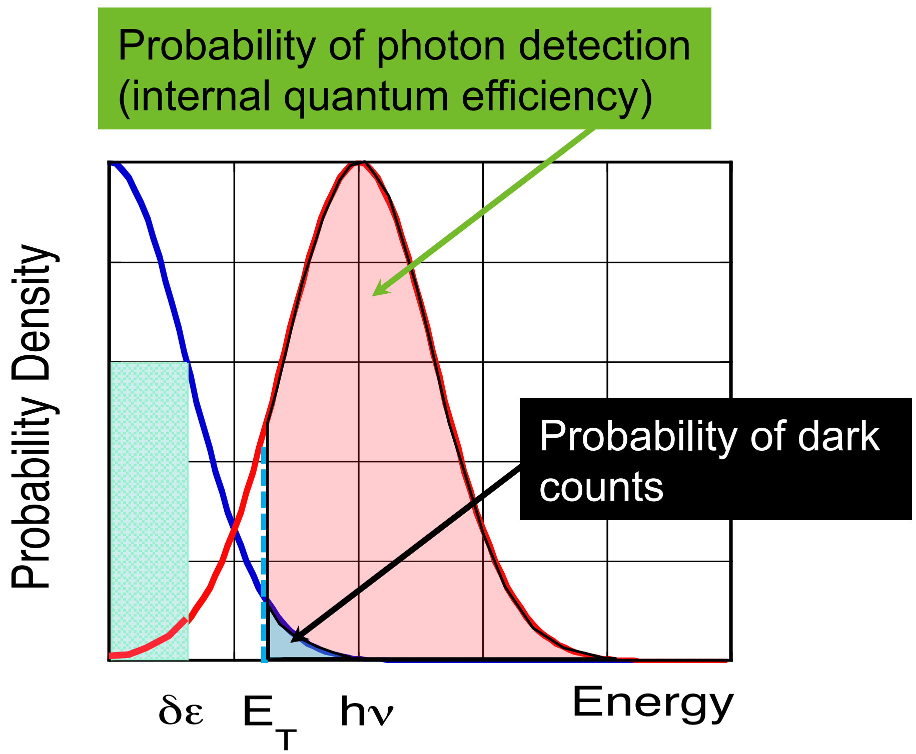
$$P_{dark} = \frac{1}{\sqrt{2\pi}} \cdot \int_{E_T/\delta\varepsilon}^{\infty} \exp\left(-x^2/2\right) dx$$

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



B. Karasik and A.Sergeev, *IEEE Trans. Appl. Supercond.* 2005

Dark counts, NEP, and quantum efficiency



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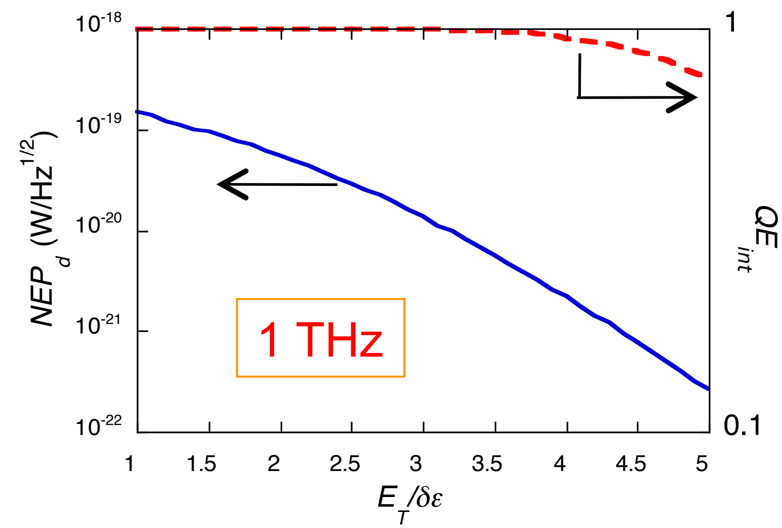


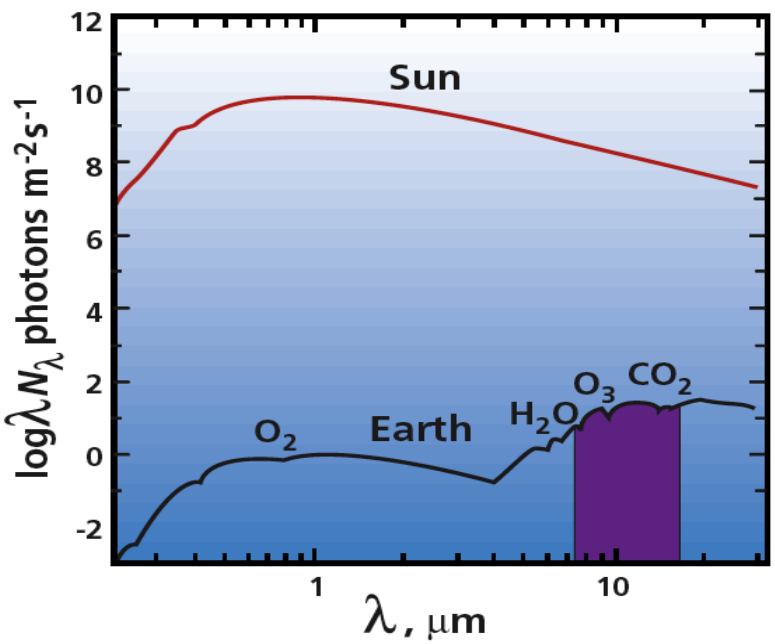
• Need $h\nu/\delta\varepsilon$ ~ 5-6

• $\delta\varepsilon = (k_B C_e T^2) \approx$ 200 GHz for the 1μm x 0.15μm x 40nm nano-HEB at 50 mK

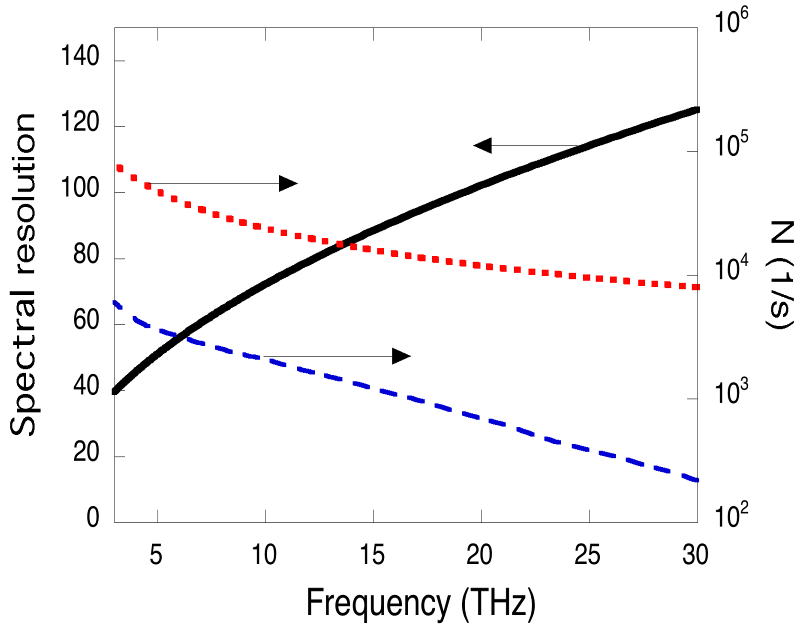
• Photon or diffusion cooling can be employed to increase the detector speed (dynamic range)

B. Karasik and A.Sergeev, *IEEE Trans. Appl. Supercond.* 2005

Low-resolution mid-IR spectroscopy in space



The spectral energy distribution of the Sun and Earth as seen from 10 pc. At 10 µm, the total photon flux from the planet is ~ 0.5 photon/sec (= 50). The photon flux from the star (which is 6 orders of magnitude higher) will be cancelled using interferometric techniques developed for TPF-I.



Performance figures of the expected IR calorimeter at 50 mK with a 10% fractional optical bandwidth. Dashes – the background photon arrival rate, dots – the maximum detector count rate provided by the photon-cooling channel.

Summary

• Low electrical NEP (~ 10^{-20} W/$Hz^{1/2}$ at 50 mK) has been demonstrated

• Single 8-μm photons have been detected (PNR, E/ΔE ~ 3)

• The nano-HEB has a potential for single-photon detection/calorimetry in FIR and mid-IR