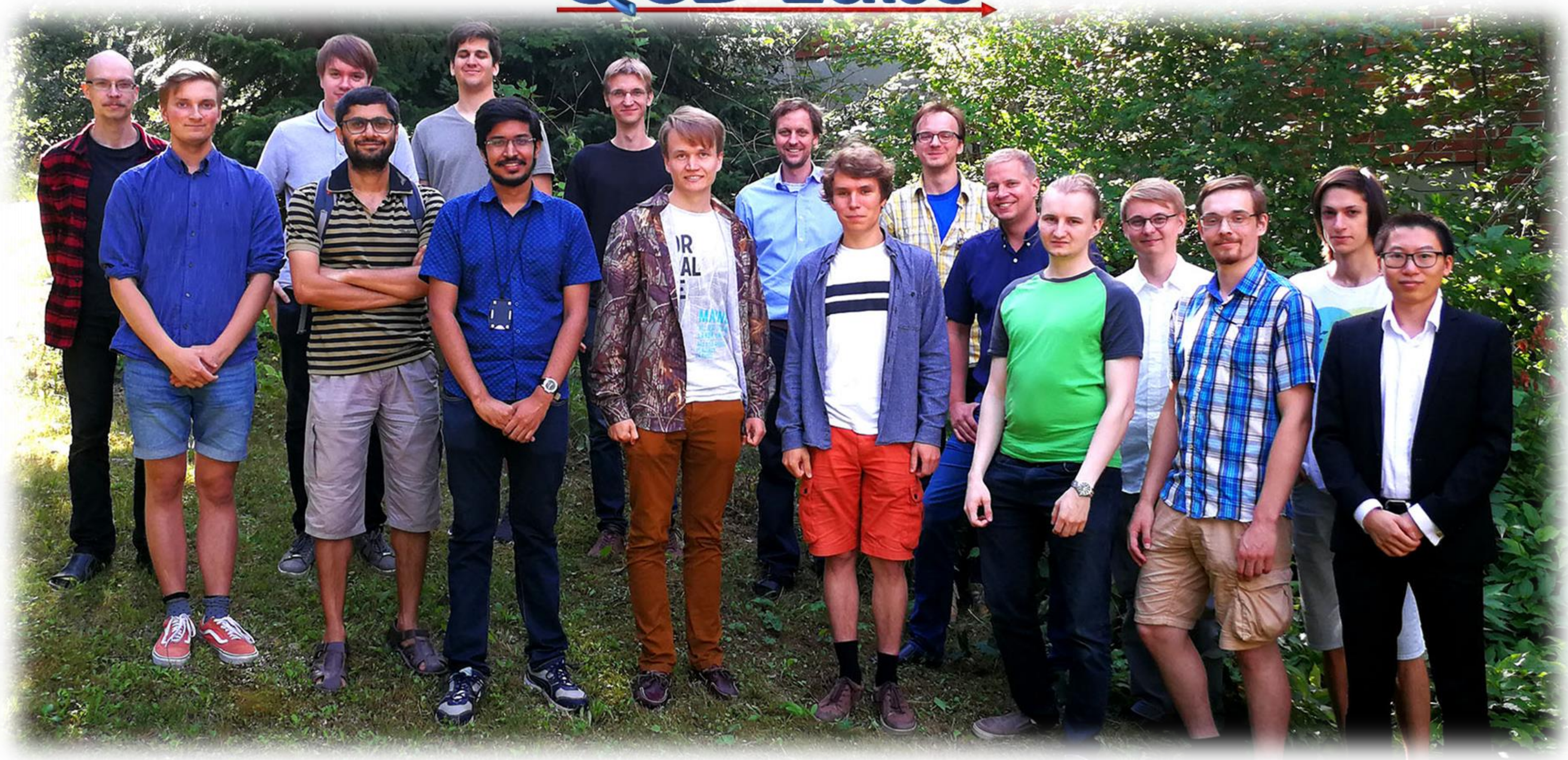
Ultrasensitive Microwave Bolometer

[Kokkoniemi et al., arXiv:1806.09397 (2018)]

Mikko Möttönen

Aalto University and VTT

QCD Labs



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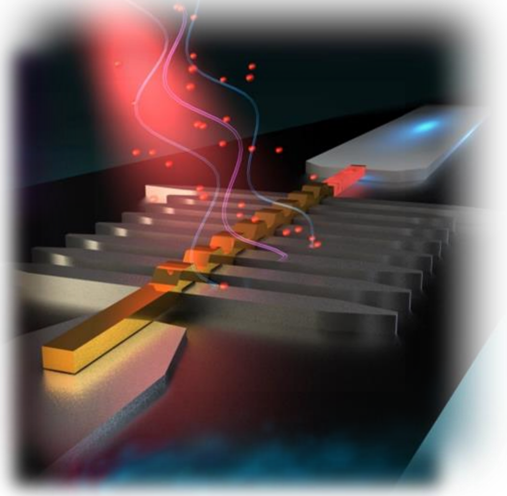
Research themes/goals



Superconducting nanoelectronics

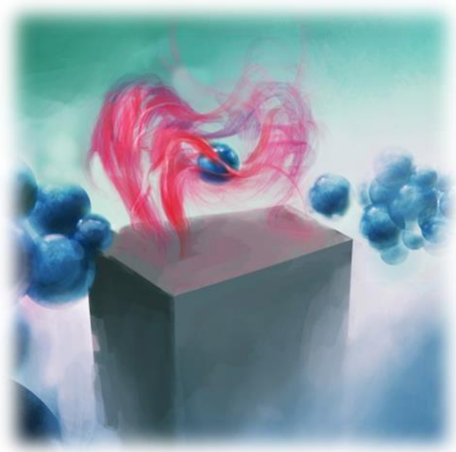
MICROWAVE PHOTON DETECTOR

Govenius et al., PRL **117**, 030802 (2016)

Kokkoniemi et al., arXiv:1806.09397

TUNABLE ENVIRONMENTS

Partanen et al., Nat. Phys. **12**, 460 (2016)
Tan et al., Nat. Commun. **8**, 15189 (2017)
Silveri et al., Nat. Phys. **15**, ?? (2019)



Silicon quantum dots

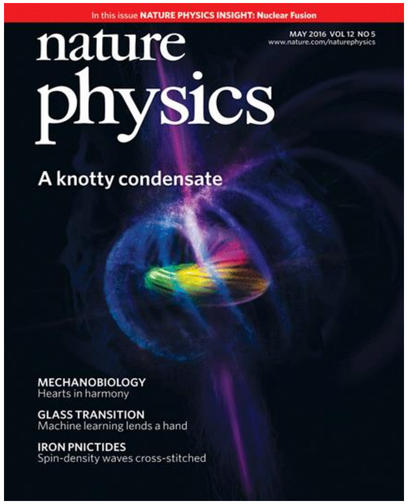
METROLOGICAL CURRENT SOURCE

A. Rossi et al.,
Nano Letters **14**, 3405 (2014)

SUPERCONDUCTING QUANTUM PROCESSOR

Ikonen et al., PRL **122**, 080503 (2019)

Figure credit: Heikka Valja



Bose–Einstein condensates

QUANTUM SIMULATIONS

Ray et al., Nature **505**, 657 (2014)

Ray et al., Science 348, 544 (2015)

Hall et al., Nat. Phys. **12**, 478 (2016)

Ollikainen et al.,
PRX **7**, 021023 (2017)

Lee et al.,
Sci. Adv. **4**, eaao3820 (2018)

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Motivation

- Single-photon microwave detector
  - Quantum computing, cQED, QKD , photon counting [K. Inomata et al., Nat. Commun. **7**, 12303 (2016)][A. Narla et al., PRX **6**, 031036 (2016)] [J.-C- Besse et al., PRX 8, 021003 (2018)] [S. Kono et al., Nat. Phys. (2018)]
- Single-photon microwave calorimeter
  - Quantum thermodynamics, spectral analysis
- Ultrasensitive microwave/THz detector for existing applications
  - THz cameras, cosmic radiation

Thermal detector

[J. P. Pekola, Nature Phys. **11**, 118 (2015); Govenius et al., PRA **92**, 042305 (2015) & references therein]

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Motivation

AXION

- Single-photon microwave dete[illegible]
  - Quantum computing, [illegible]ED, [illegible]KD, photo[illegible] counting [K. Inomata et [illegible]l., Nat. [illegible]mun. **7**, 123[illegible] [illegible]016)]; [illegible]Narla et al., PRX **6**, 031036 (2016)] [J.-C- Besse e[illegible] PRX [illegible] [illegible]003 (2018)]; [illegible]ono e[illegible]., Nat. Phys. (2018)]
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Thermal detector

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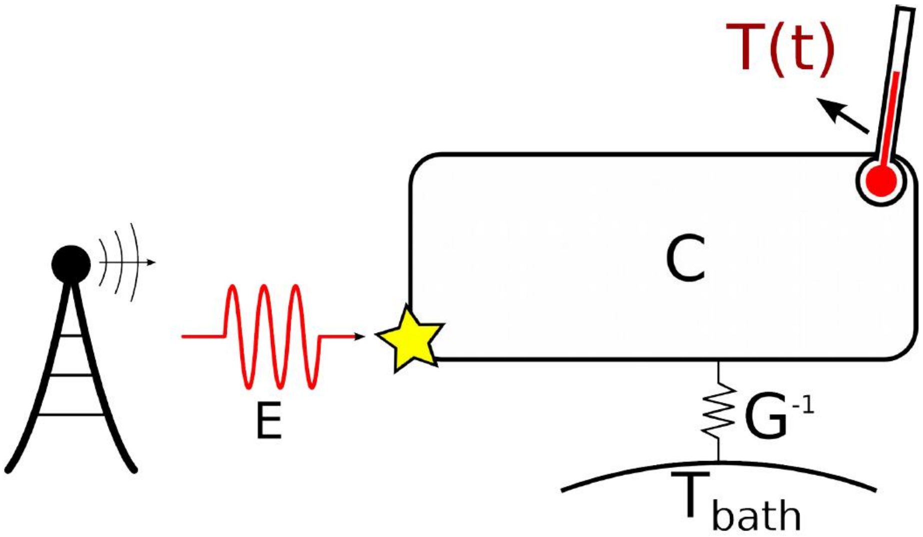
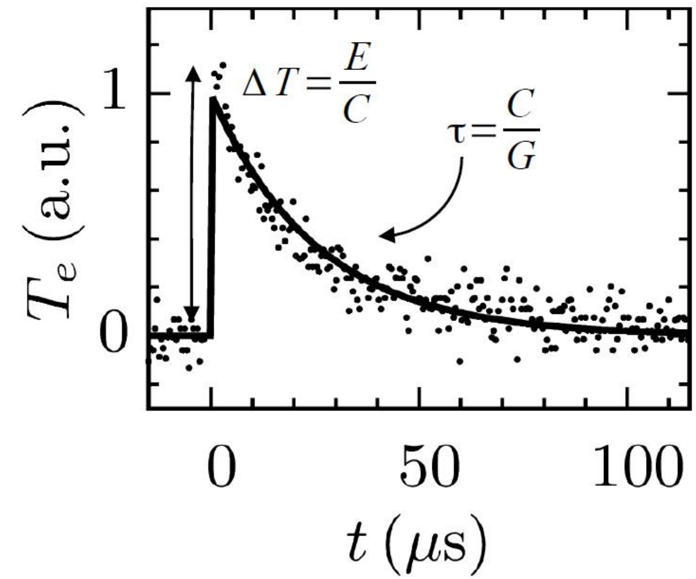
Calorimetry





Previous achievements:

$$\Delta E = h \times 23 \text{ THz} = 15 \text{ zJ}$$

[Santavicca et al., APL **96**, 083505 (2010)]
[Karasik et al., APL **101**, 052601 (2012)]

Our results:

$$\Delta E = 200 \times h \times 8.4 \text{ GHz} = 1.1 \text{ zJ} = 7 \text{ meV}$$

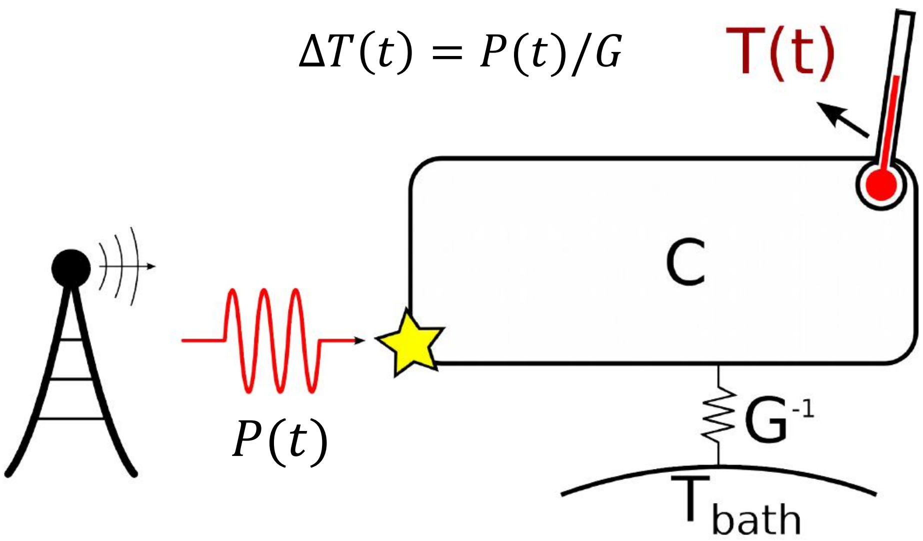
[J. Govenius et al., Phys. Rev. Lett. **117**, 030802 (2016)]

NOT DISCUSSED FURTHER

see also: [Echternach et al., Nat. Astron. 2, 90 (2018)] for 1.5 THz single-photon detection

[Review: B. Karasik et al., IEE Trans. Terahertz Sci. **1**, 97 (2011)]

Bolometry



- Measure T(t) in real time and deduct the power
- NEP gives the detector noise in units of input power

THERMAL FLUCTUATIONS

$$\mathrm{NEP} \geq \sqrt{4k_\mathrm{B}T^2G}$$

$$\tau = \frac{C}{G}$$

Previous achievements (TES):

$$\mathrm{NEP} \approx 3 \times 10^{-19}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$$

[Suzuki et al., IEEE Trans. Terahertz Sci. 4, 171 (2014)]

[Karasik et al., APL **98**, 193503 (2011)]

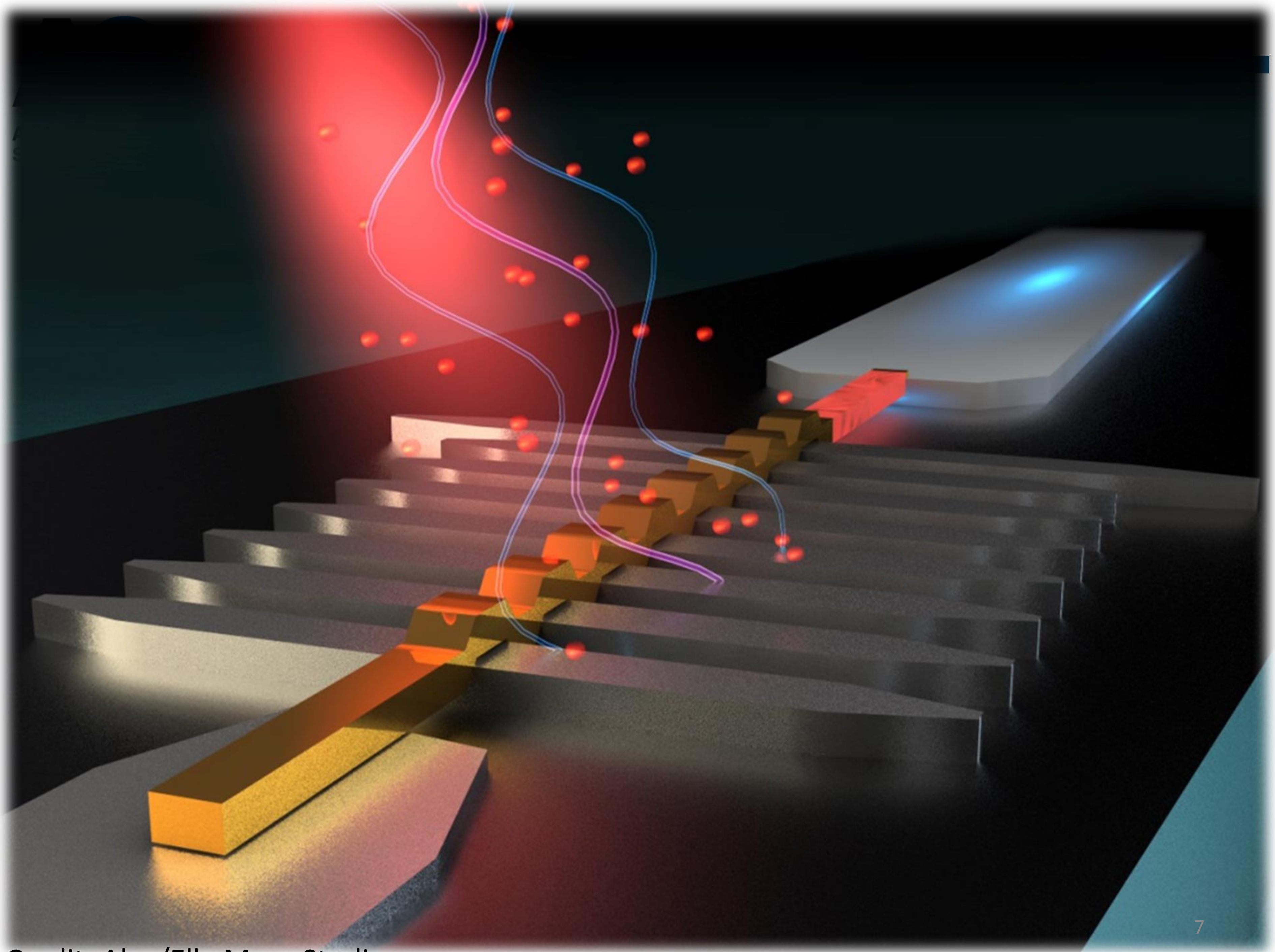
Our result:

$$\mathrm{NEP} \approx 2 \times 10^{-20}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$$

[Kokkoniemi et al., arXiv:1806.09397 (2018)]

LET US TALK ABOUT THIS MORE!

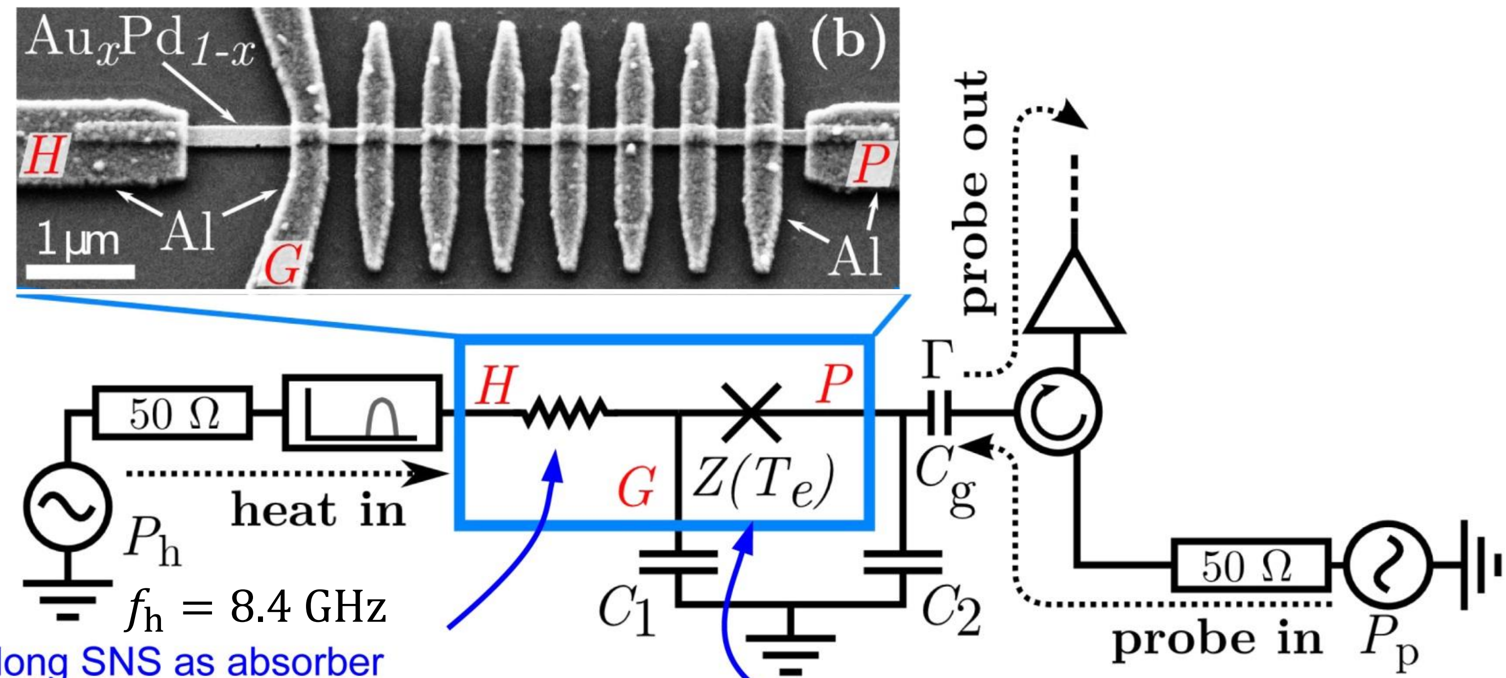
[see also: Komiyama et al., Nature **403**, 405 (2000); Echternach et al., Appl. Phys. Lett. 103, 053510 (2013)]



Credit: Alex/Ella Maru Studio

RF SNS microwave detector

[J. Govenius et al., Phys. Rev. Lett. **117**, 030802 (2016)]



long SNS as absorber

Nahum and Martinis, APL **63**, 3075 (1993)

$T_e \rightarrow$ SNS inductance

Theory: Giazotto et al., APL **92**, 162507 (2008).

Alternative: $T_e \rightarrow$ SIN resistance + RF readout

Schmidt, Yung and Cleland, APL 83, 1002 (2003).
Gasparinetti et al., Phys. Rev. Appl. **3**, 014007 (2015)

[see also K. Viisanen et al. New J. Phys. **17**, 055014 (2015)]

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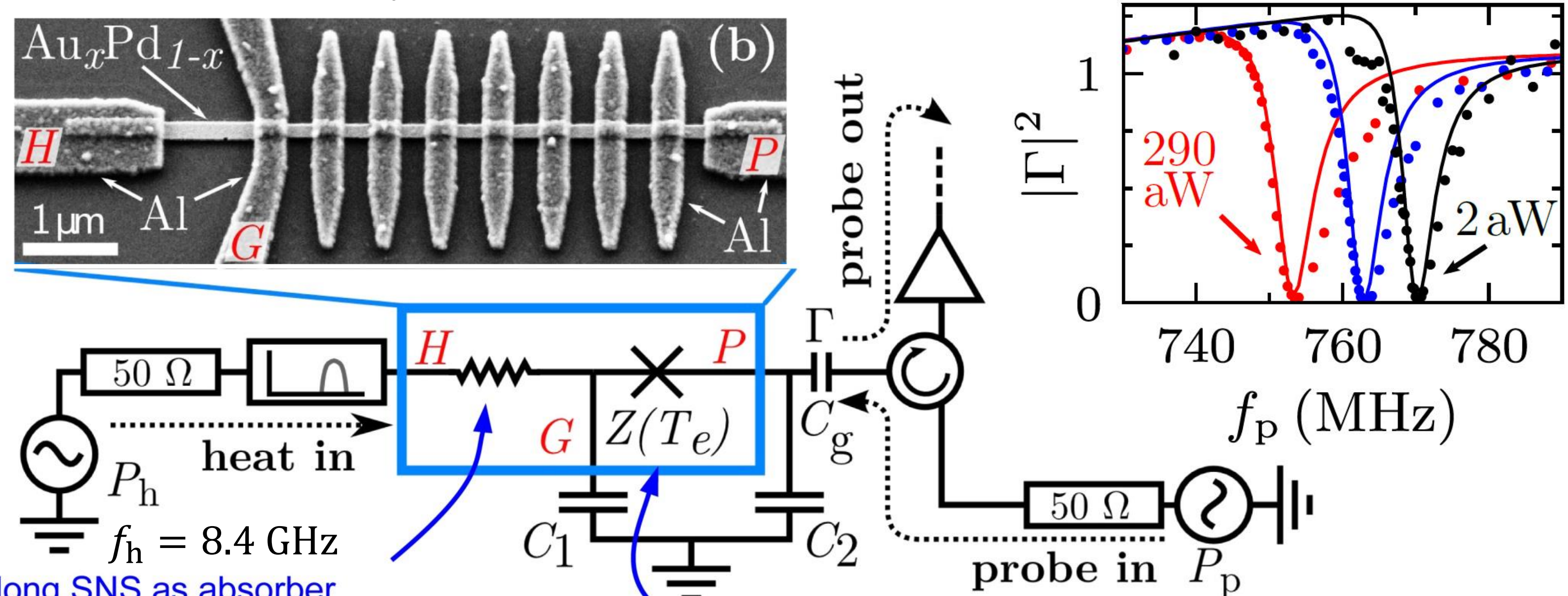
[J. Govenius et al., Phys. Rev. Lett. **117**, 030802 (2016)]



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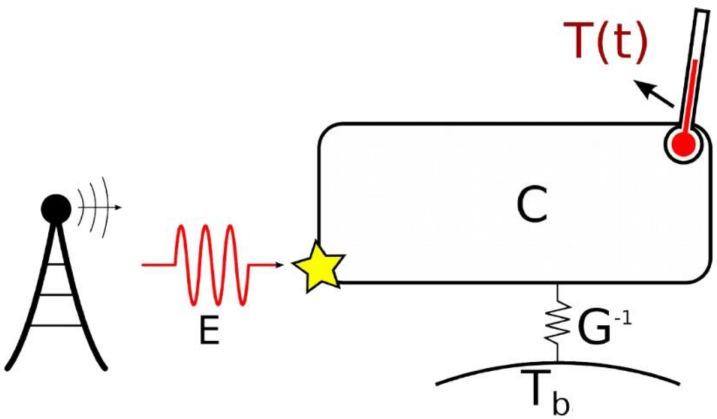
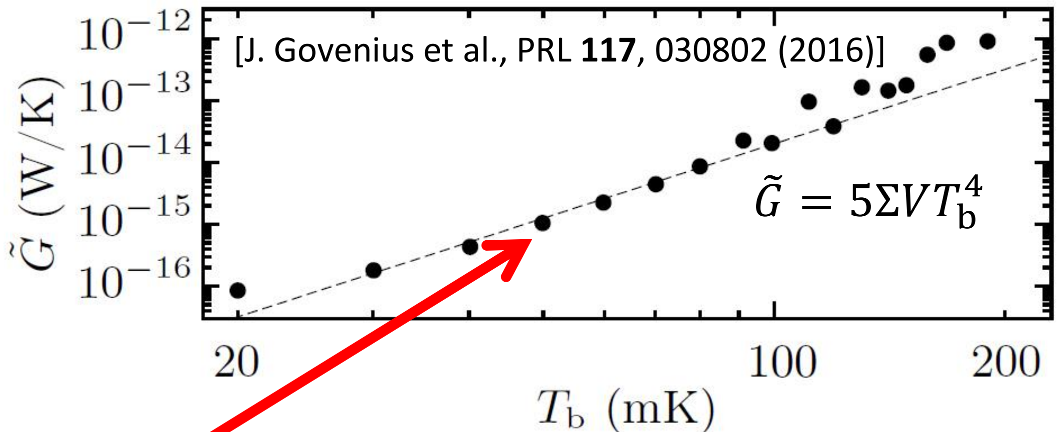
Thermal conductance

[J. Govenius et al., Phys. Rev. Lett. **117**, 030802 (2016)]





$$\tilde{G}_{e-b} \approx 1 \text{ fW/K @ 50 mK}$$
$$\approx 0.02 \times G_Q$$

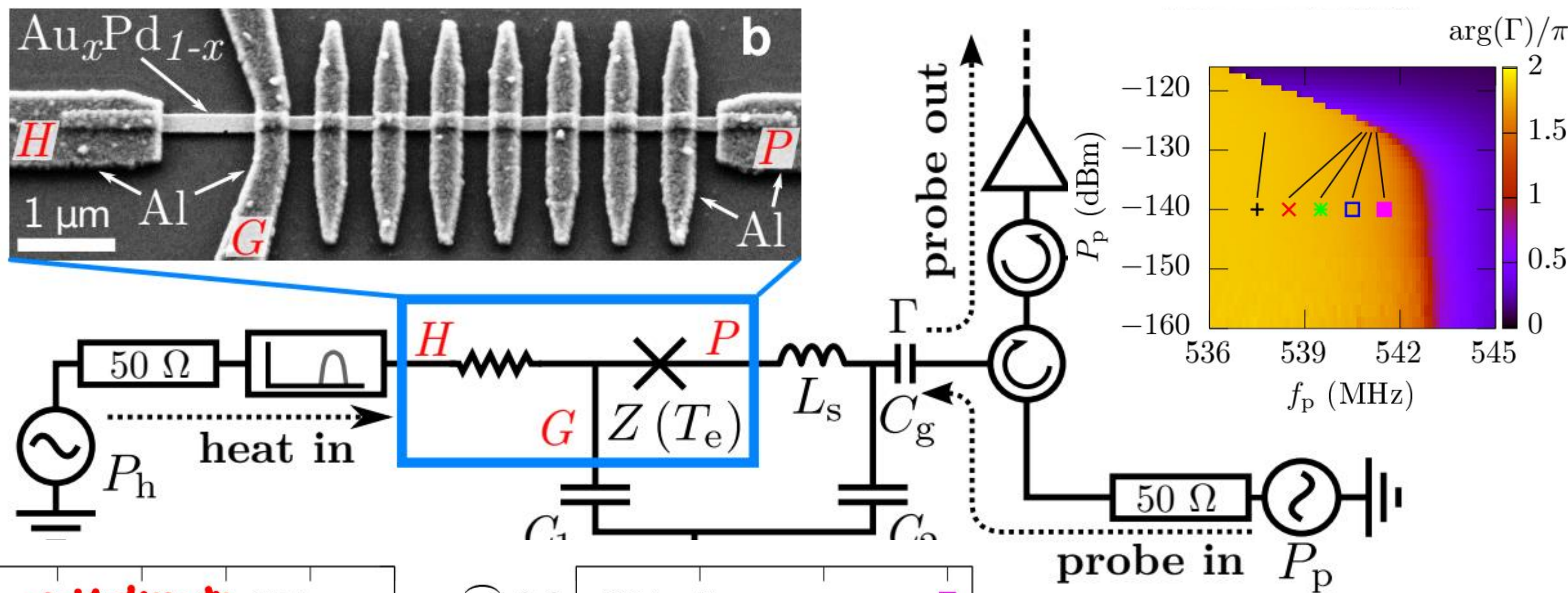
BOUND FROM THERMAL FLUCTUATIONS

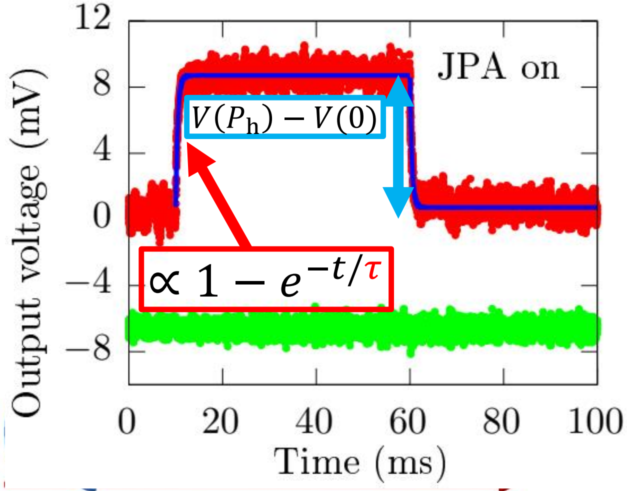
$$\text{NEP} \geq \sqrt{4k_B T^2 G} \approx 1.2 \times 10^{-20} \text{ W}/\sqrt{\text{Hz}}$$

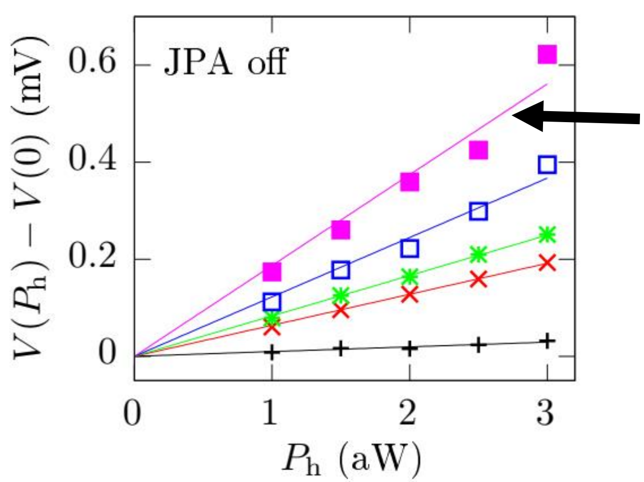
[c.f. Partanen et al., Nat. Phys. **12**, 460 (2016)]

Measurements with JPA

[Kokkoniemi et al., arXiv:1806.09397 (2018)]







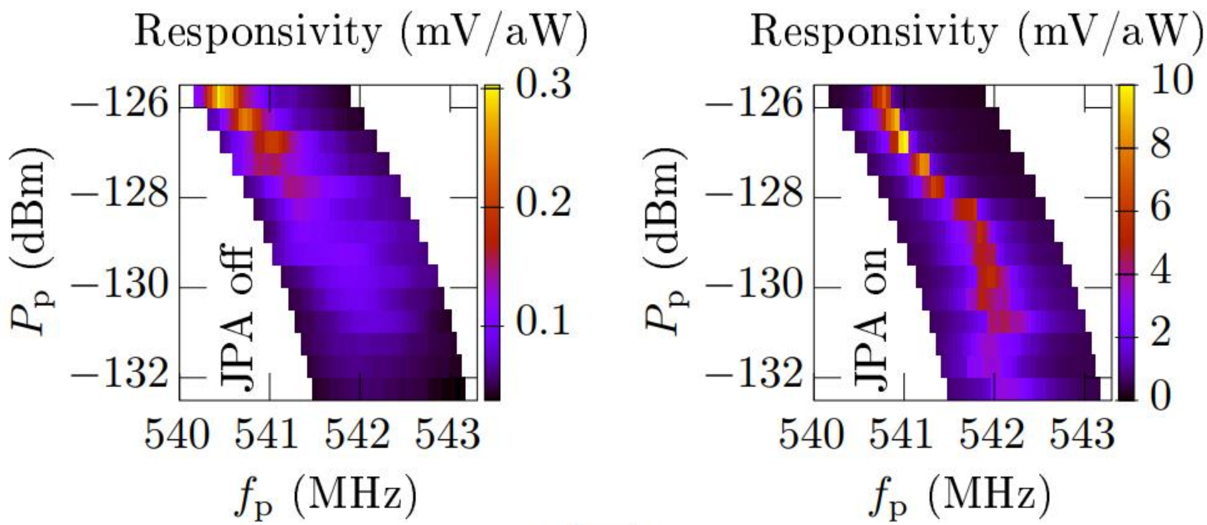
SLOPE YIELDS THE ZERO-FREQUENCY RESPONSIVITY:

$$R_{P\to V}(f_n = 0) = |\partial_{P_h} V|$$

τ

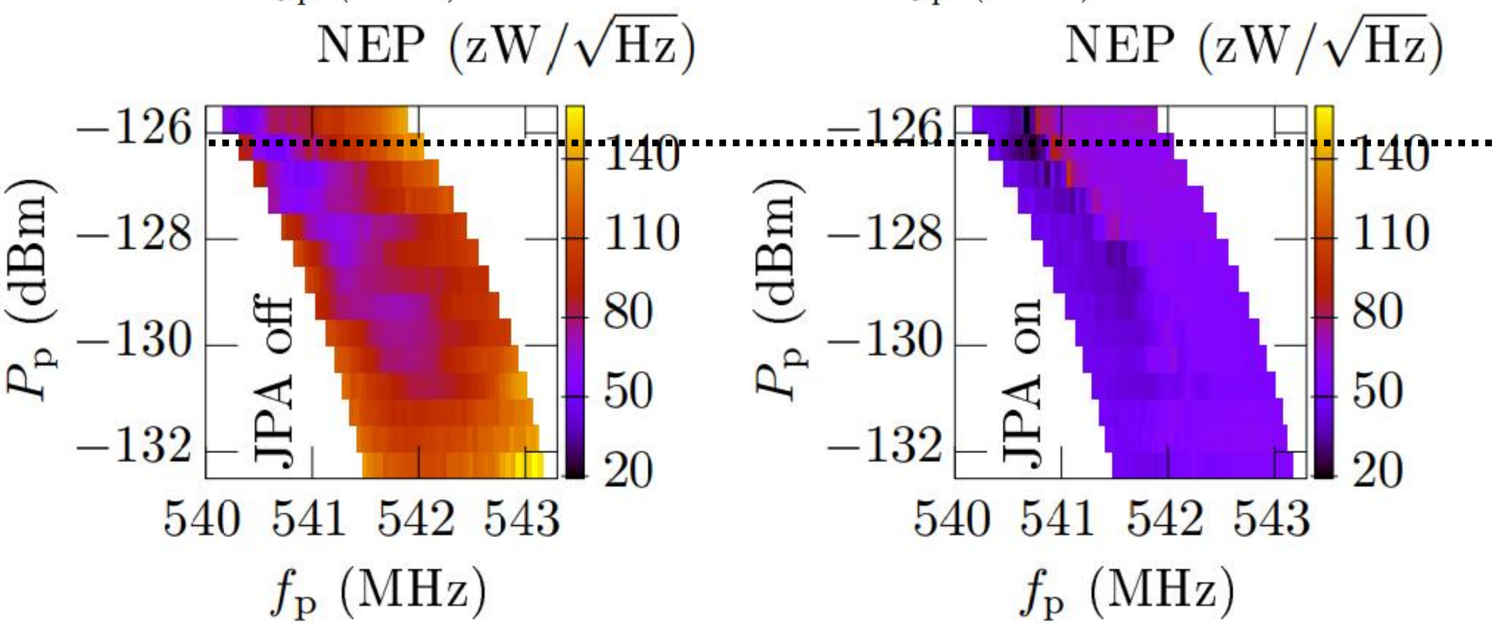
$$R_{P\to V}(f_n) = \frac{|\partial_{P_h} V|}{\sqrt{1 + (2\pi f_n \tau)^2}}$$

Responsivity and NEP



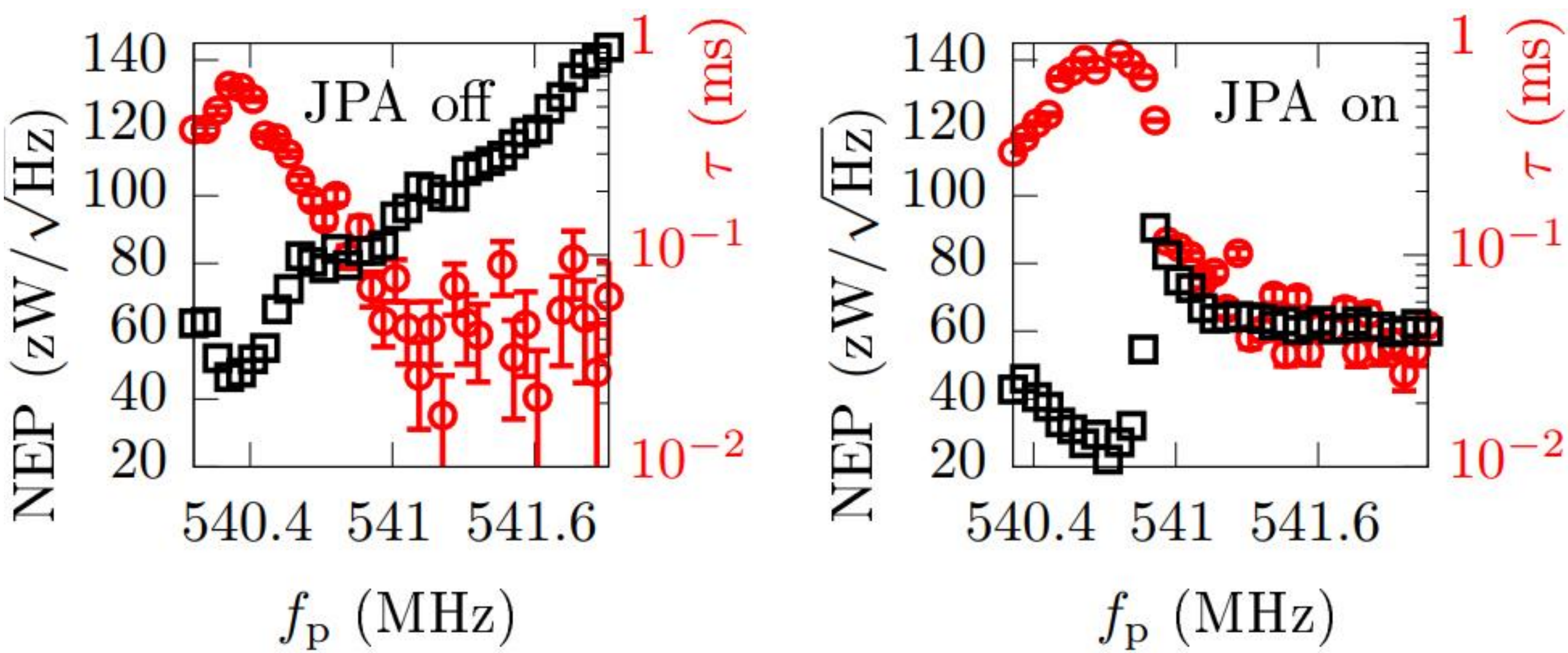
$$\mathrm{NEP} = \frac{\sqrt{S_V(f_n)}}{R_{P\to V}(f_n)}$$

Averaged over
f_n = 20 Hz – 100 Hz



$P_p = -126.5$ dBm

Noise-equivalent power and time constant



energy resolution $\epsilon = \left(\int_0^\infty \frac{4\,\mathrm{d}f_\mathrm{n}}{\mathrm{NEP}(f_\mathrm{n})^2} \right)^{-1/2} \approx 0.3\ \mathrm{zJ} \approx 2\ \mathrm{meV}$

Conclusions

- Bolometer with $\mathrm{NEP} \approx 20\ z\mathrm{W}/\sqrt{\mathrm{Hz}}$ @ $\tau = 1$ ms ($\mathrm{NEP} \approx 60\ z\mathrm{W}/\sqrt{\mathrm{Hz}}$ @ $\tau = 30\ \mu s$)
- Preliminary results with graphene

Bolometer team
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M. A. Gunyho, K. Y. Tan, Wei Liu
J. Goetz, D. Hazra, M. M.

Graphene fabrication
P. Hakonen and A. Laitinen

POSTDOCS/ STUDENTS WANTED (email Mikko)

JPA team
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L. Grönberg, J. Lehtinen,
M. Prunnila, J. Hassel,
O.-P- Saira, J. P. Pekola

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