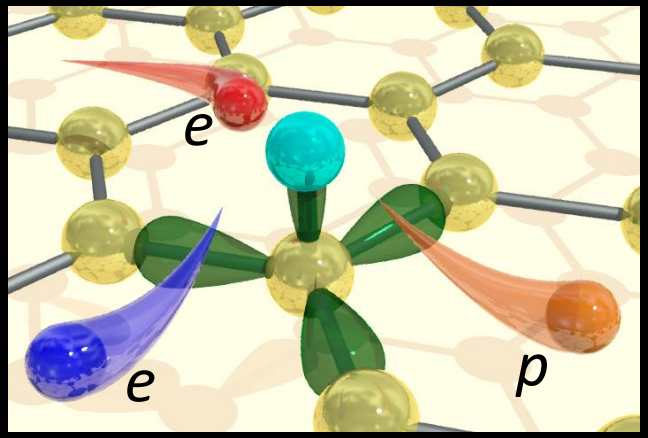
IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), February 2018.
Invited presentation ED4-5-INV was given at ISS 2017, December 13-15, 2017, Tokyo, Japan.

Nanoscale thermal imaging of dissipation in quantum systems and in encapsulated graphene



Dorri Halbertal (Weizmann Institute of Science)

מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

L. Embon, N. Shadmi, Y. Anahory, HR Naren, J. Sarkar, A. Uri, K. Bagani, A. Y. Meltzer, Y. Ronen, Y. Myasoedov, E. Joselevich, E. Zeldov

MANCHESTER 1824
The University of Manchester

M. Ben-Shalom, J. Birkbeck, A. K. Geim

Massachusetts Institute of Technology

L. S. Levitov

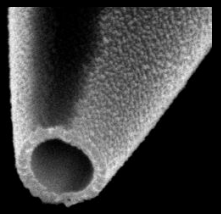
ICN2

J. Cuppens

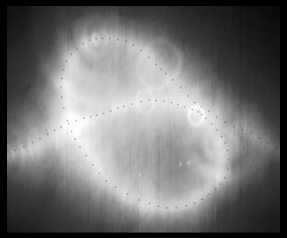
Dissipation: Agent of change

Talk Outline

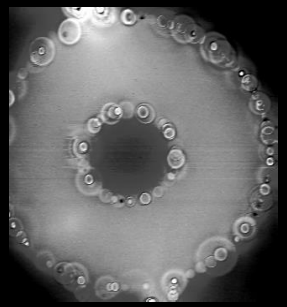
- SQUID-on-tip Thermal imaging



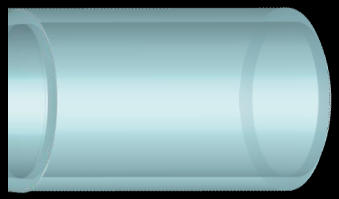
- Warm up example



- Graphene



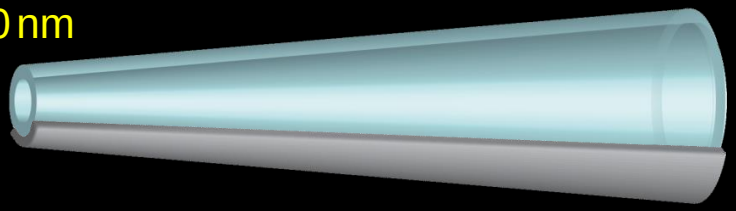
SQUID-on-tip fabrication

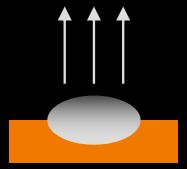


∅1 mm

SQUID-on-tip fabrication

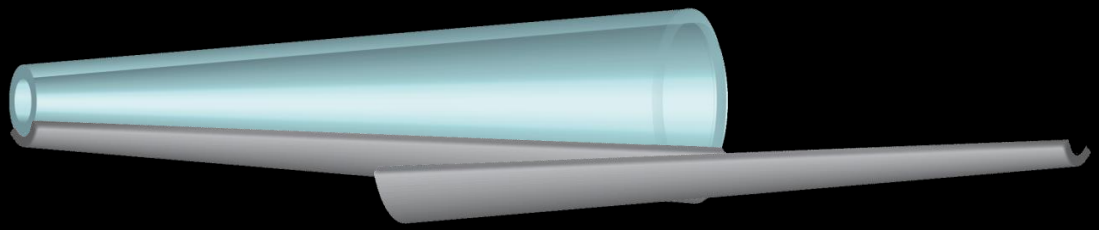
∅ 30 ÷ 300 nm

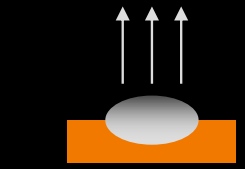




Al, Nb, Pb, In, Sn

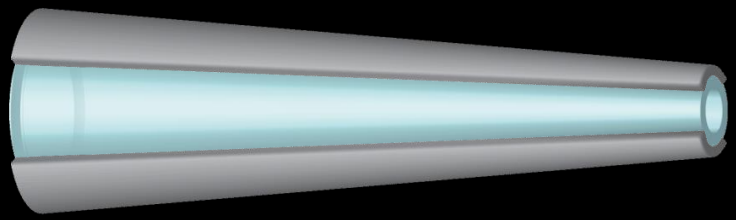
SQUID-on-tip fabrication





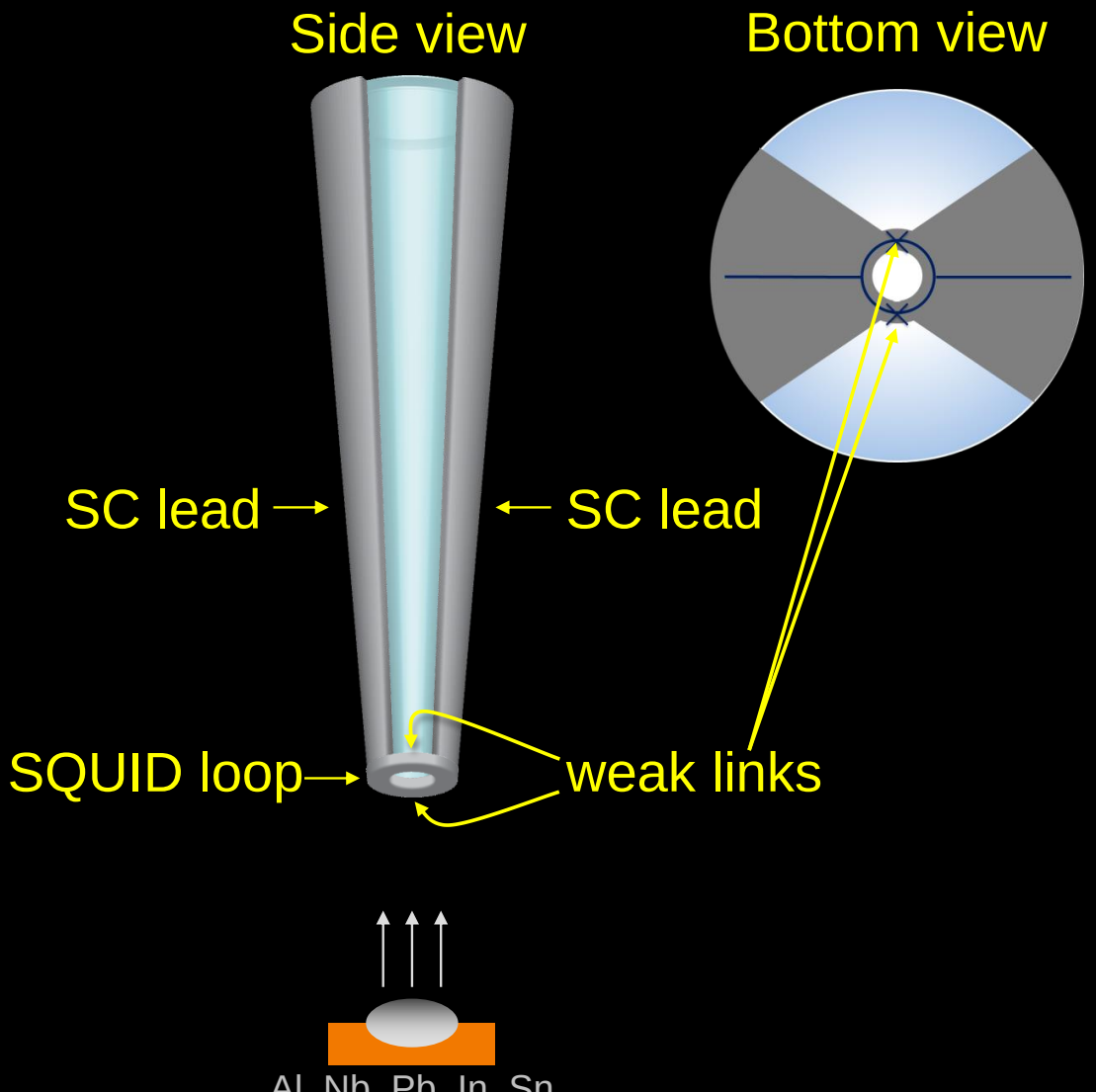
Al, Nb, Pb, In, Sn

SQUID-on-tip fabrication

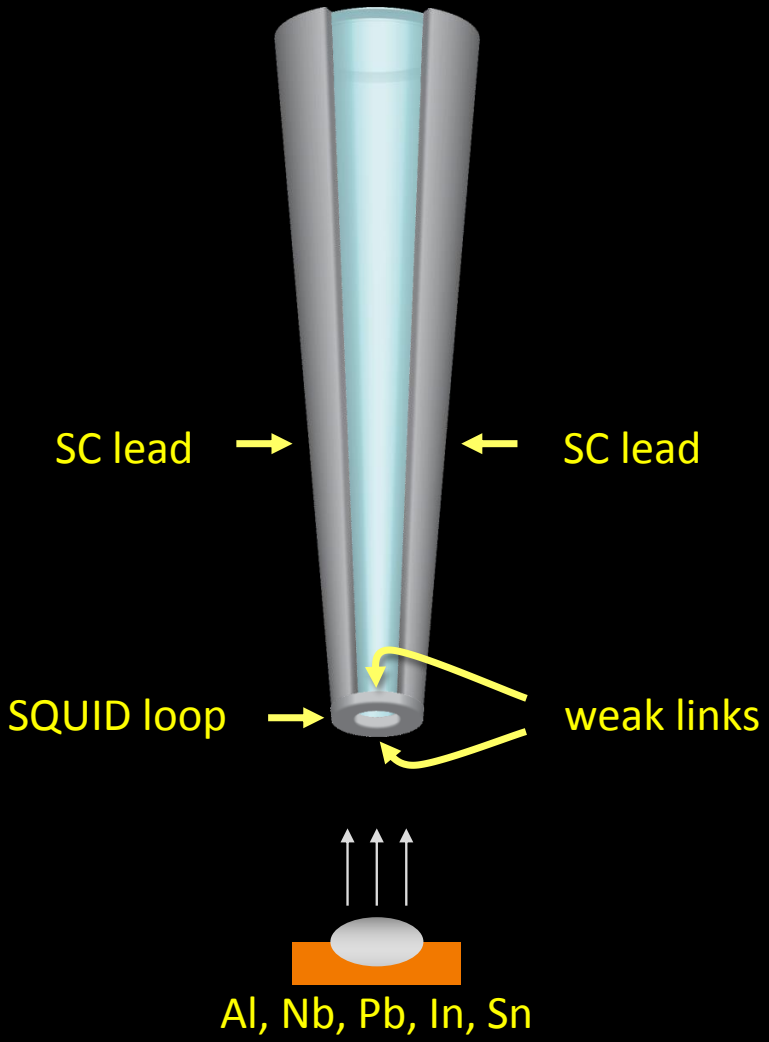


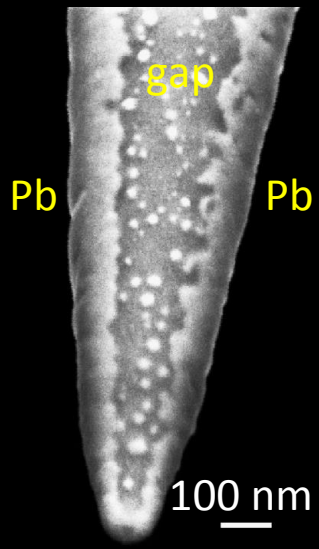
Al, Nb, Pb, In, Sn

SQUID-on-tip fabrication



SQUID on tip





Loop diameter = 46 nm

Flux noise: $\sqrt{S_\Phi}$ = 50 nΦ_0/Hz$^{1/2}$

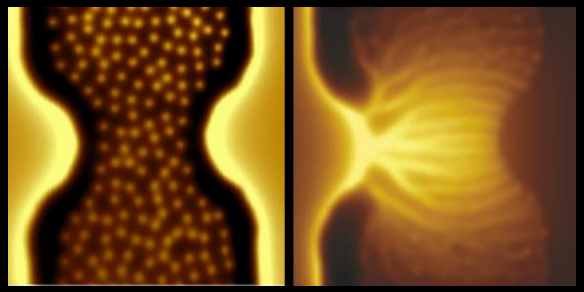
Spin noise: $\sqrt{S_n}$ = 0.38 μ_B/Hz$^{1/2}$

Vasyukov et al., Nat. Nano. (2013)

Recent studies: Scanning Nano-SQUID on Tip

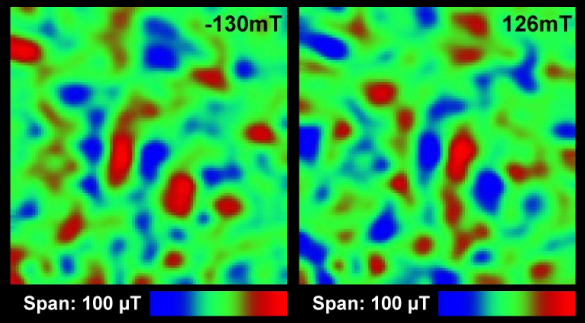
Vortex dynamics in superconductors

Scientific reports (2015)
Nature Communications (2017)



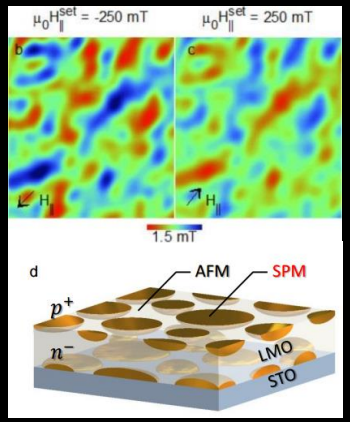
Superparamagnetic dynamics in magnetic TIs

Science advances (2015)

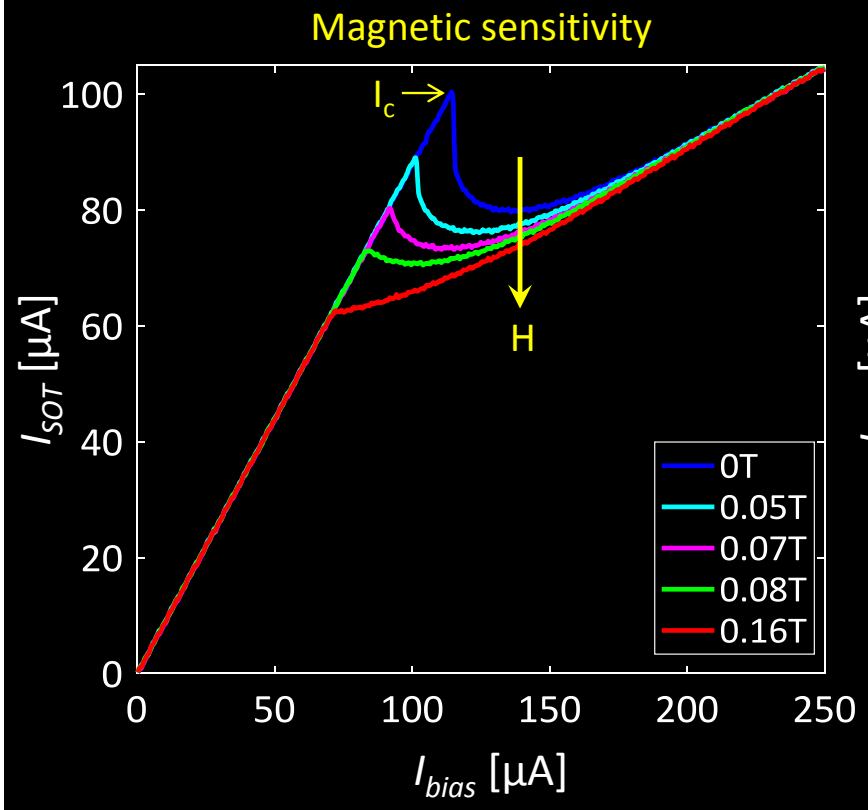


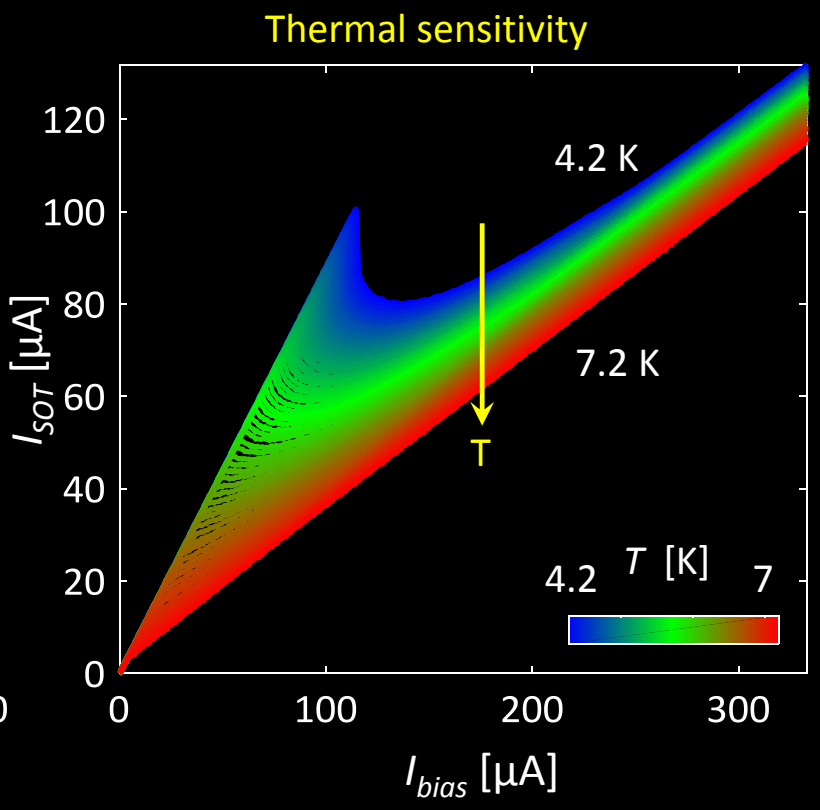
Emergent nanoscale superparamagnetism at oxide interfaces

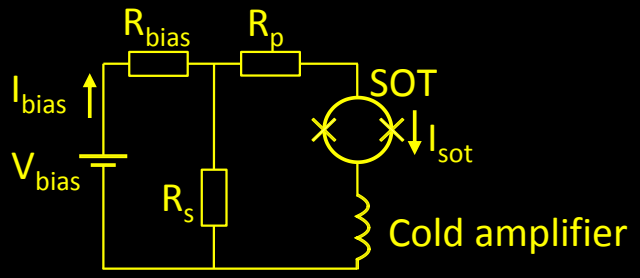
Nature Communications (2016)



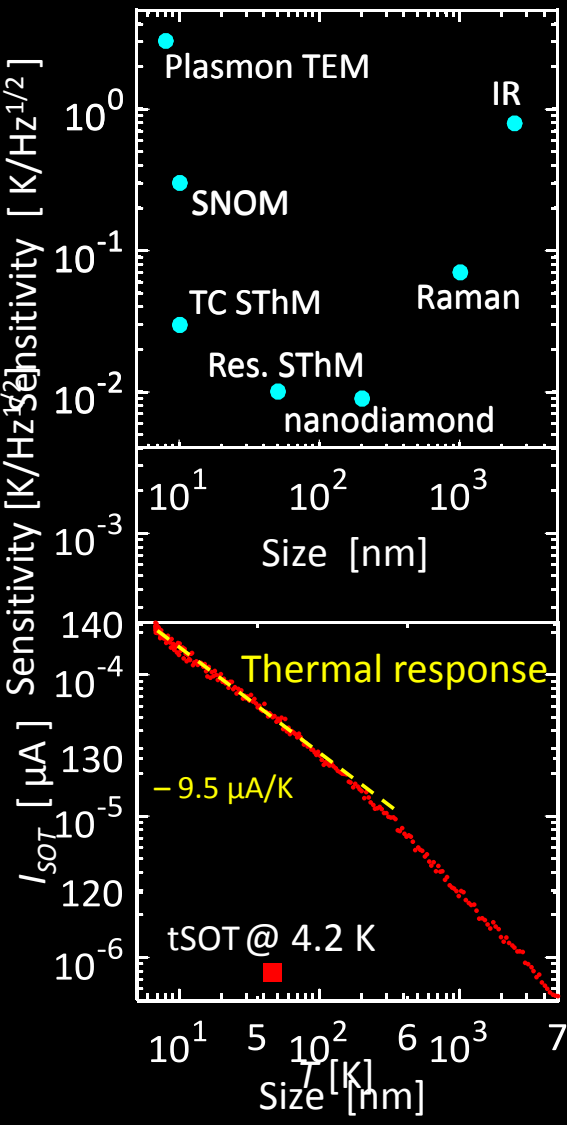
Thermal and Magnetic Sensitivity

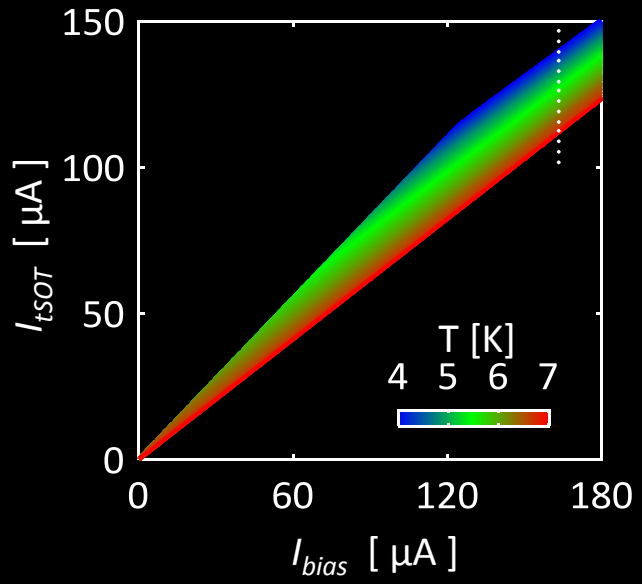


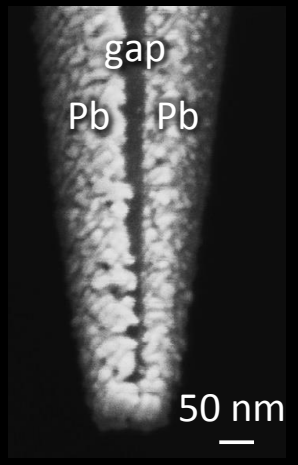


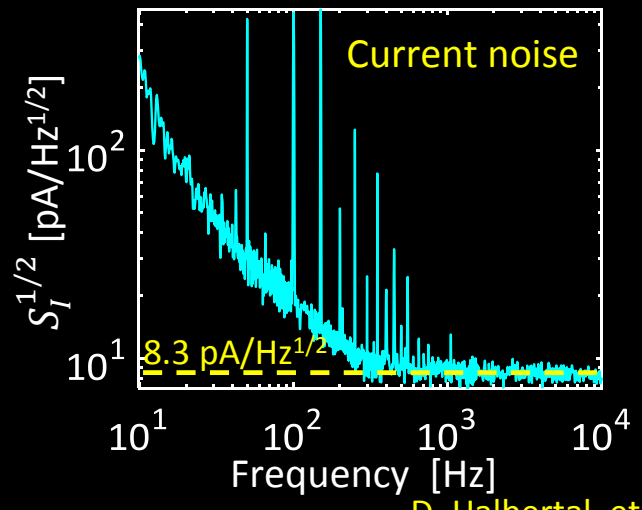


Origin of thermal sensitivity







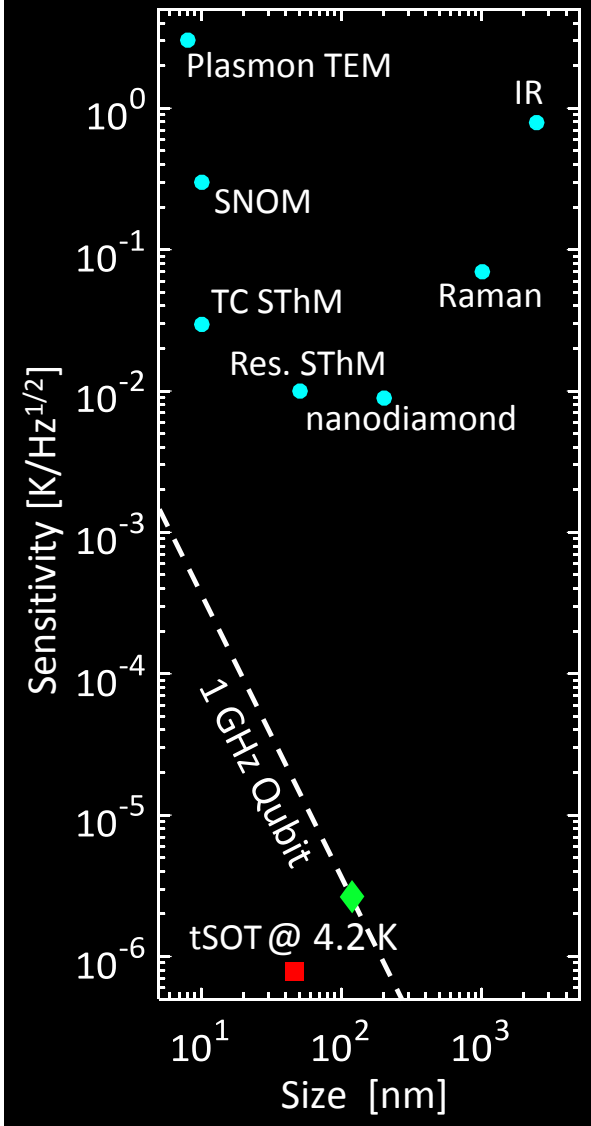


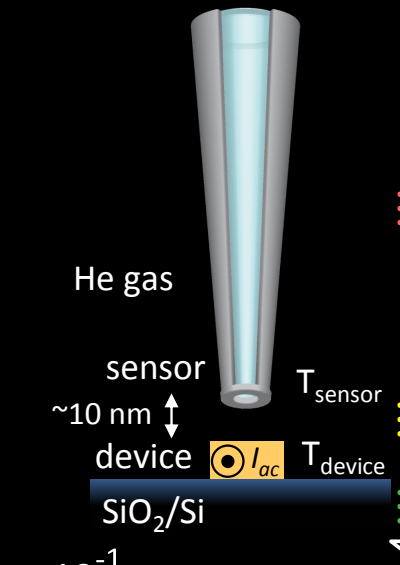
Thermal noise:

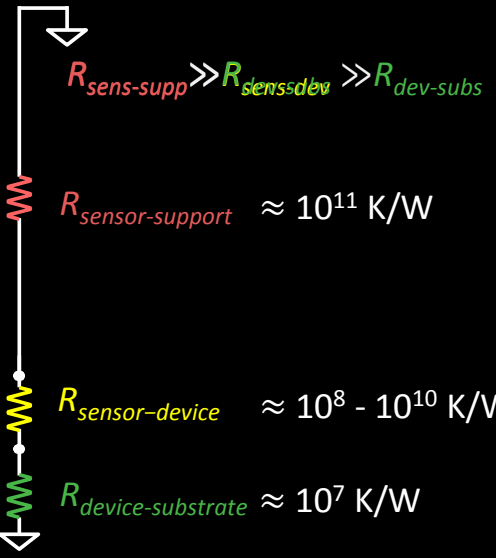
$S_T^{1/2} = 870$ nK/Hz$^{1/2}$

D. Halbertal, et al. Nature 539, 407 (2016)

Thermal coupling to sample







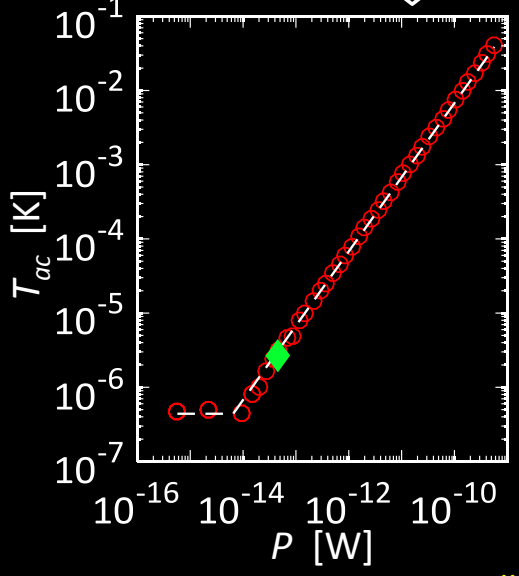


Figure of merit:

Landauer's limit of energy dissipation for irreversible qubit readout

$E = k_B T \ln 2 = 4 \times 10^{-23}$ J

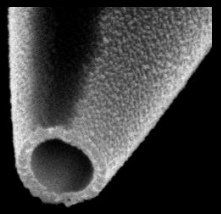
Qubit at 1 GHz:

$P =$ 40 fW

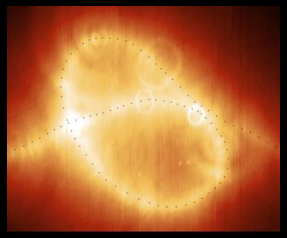
D. Halbertal, et al. Nature 539, 407 (2016)

Talk Outline

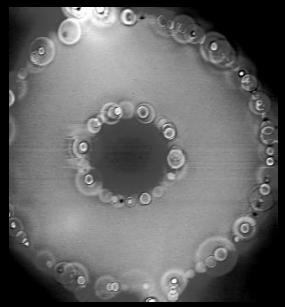
- SQUID-on-tip Thermal imaging



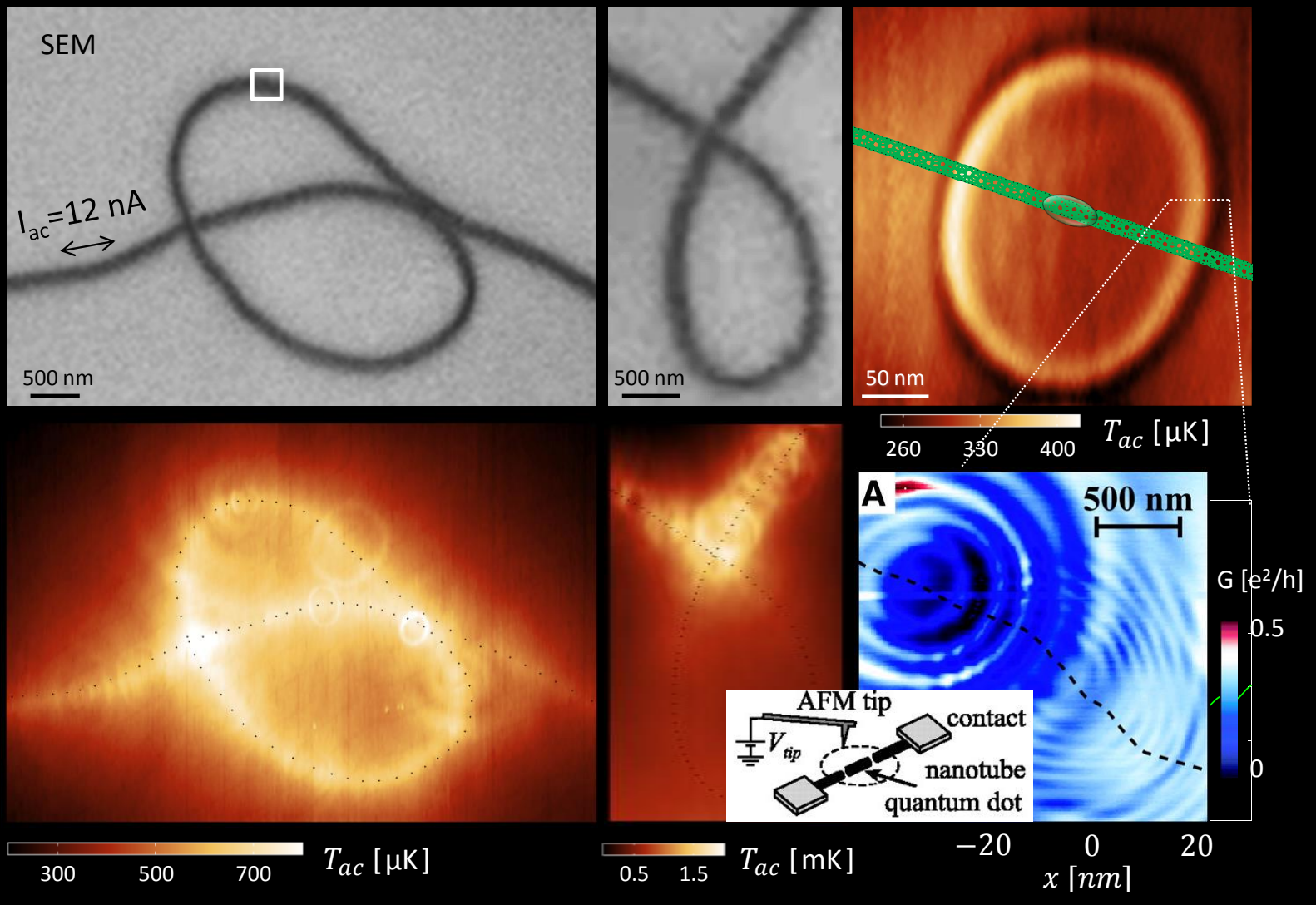
- Warm up example



- Graphene



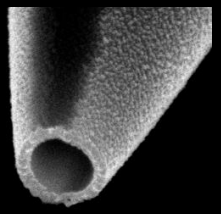
Dissipation in Carbon Nanotubes



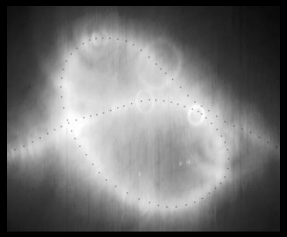
Woodside and McEuen, *Science* **296,** 2002

Talk Outline

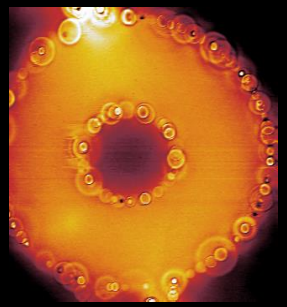
- SQUID-on-tip Thermal imaging



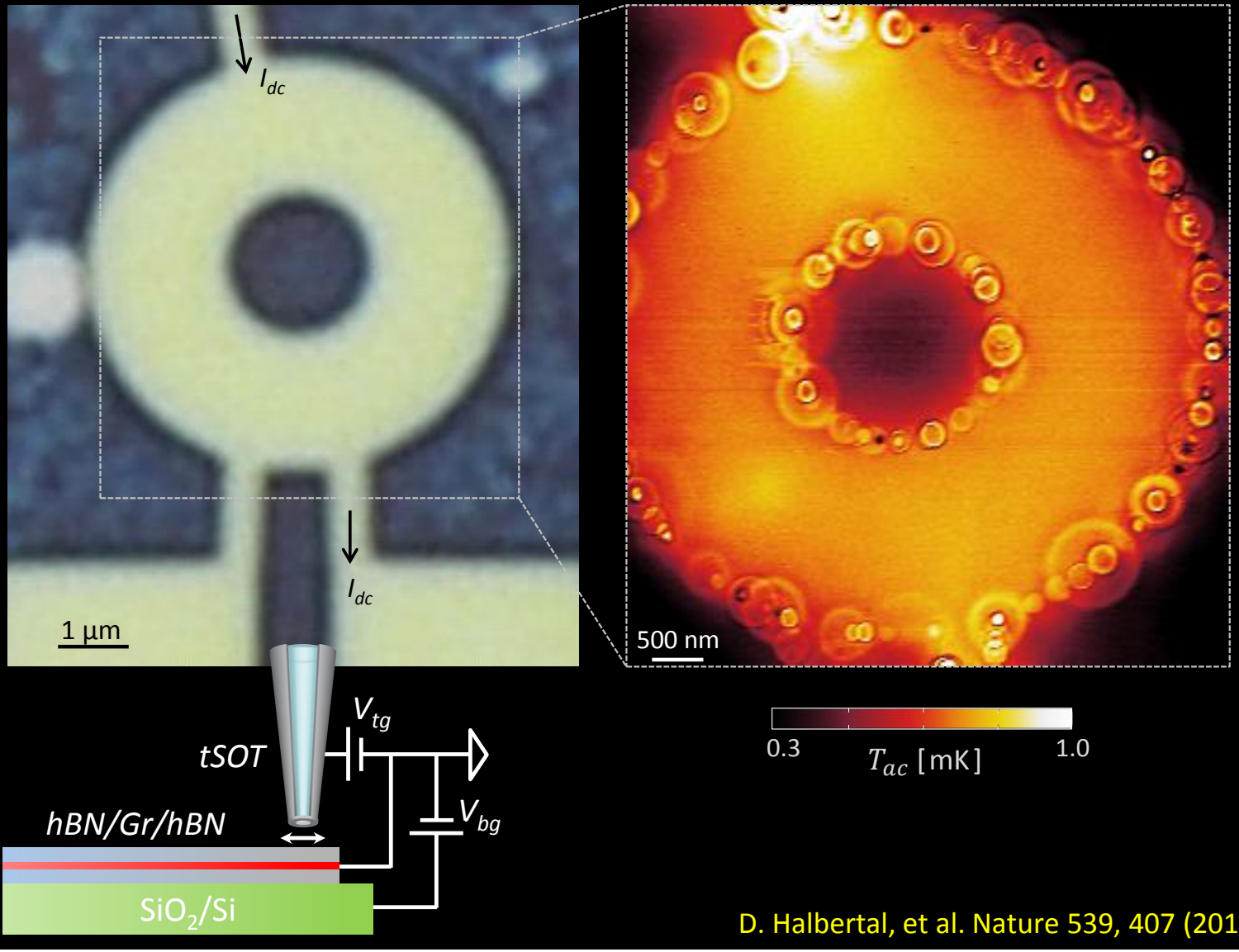
- Warm up example



- Graphene



Dissipation in hBN encapsulated graphene

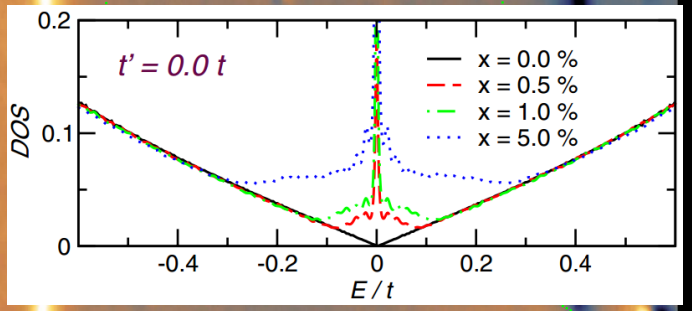


D. Halbertal, et al. Nature 539, 407 (2016)

Dissipation from single atomic defect in graphene

V_{tg}=0.0 [V] -40 0 40 T_{ac} [μK]

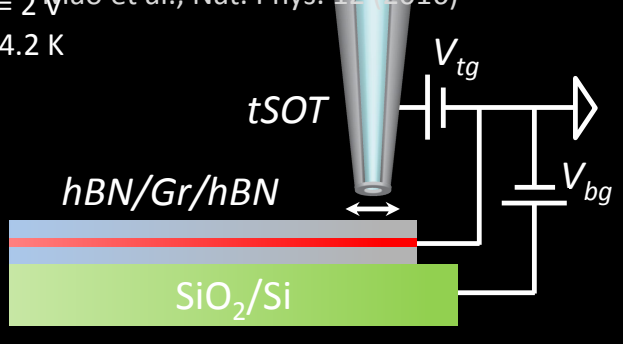
Vacancies and adatoms form localized states near Dirac point in graphene



300 nm

Pereira et al., PRL 96 (2006)
Bistritzer & MacDonald, PRL 102 (2009)
Song, Reizer & Levitov, PRL 109 (2012)
González-Herrero et al., Science 352 (2016)
Mao et al., Nat. Phys. 12 (2016)

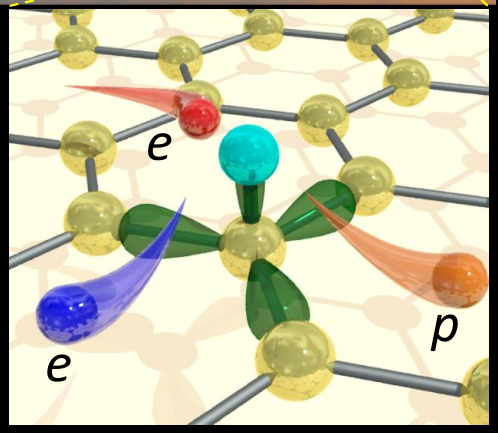
I_{dc} = 3 μA
h = 20 nm
V_{bg} = 2 V
T = 4.2 K



V_{tg}=2.0 [V] -40 0 40 T_{ac} [μK]

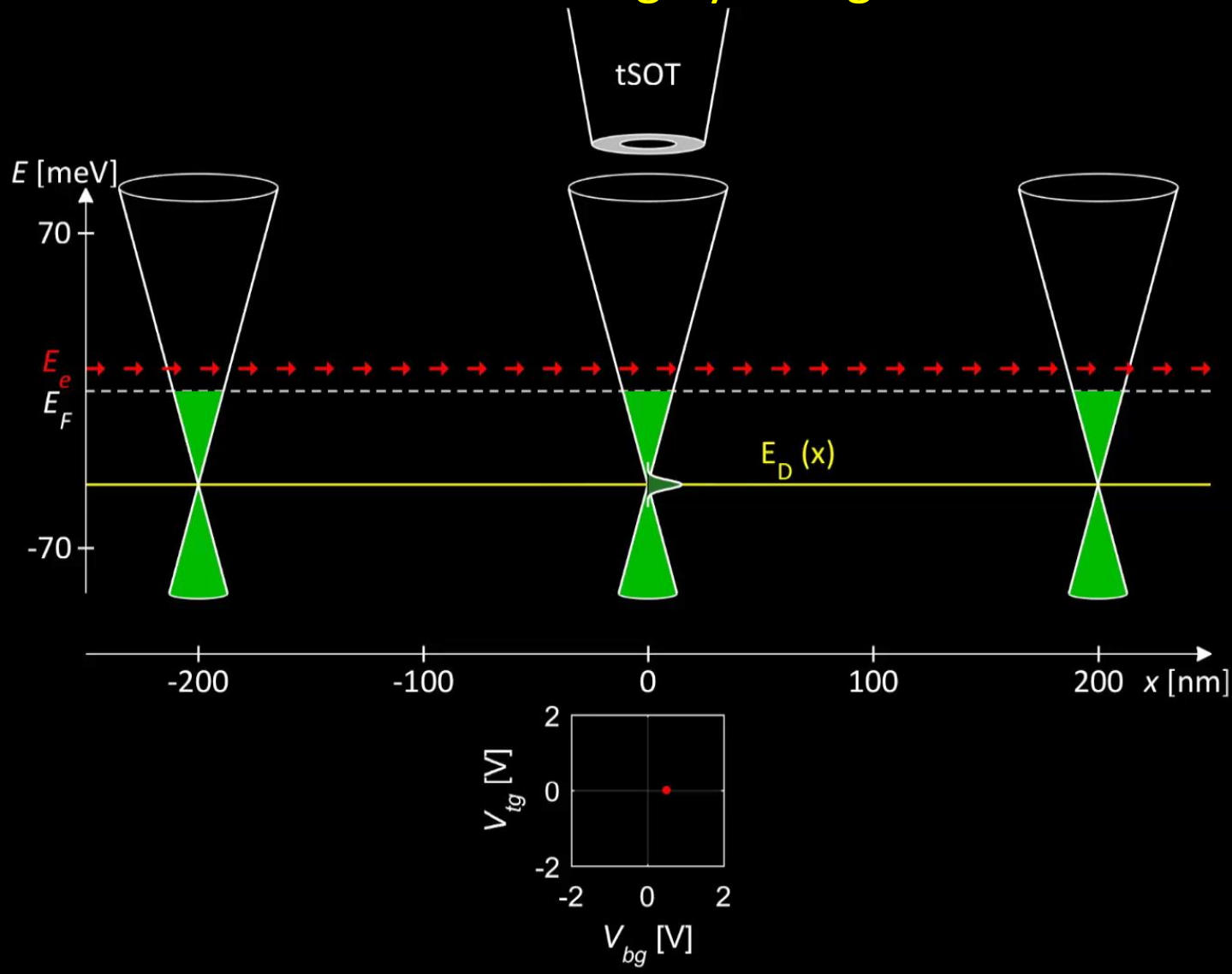
300 nm

Atomic source of phonons



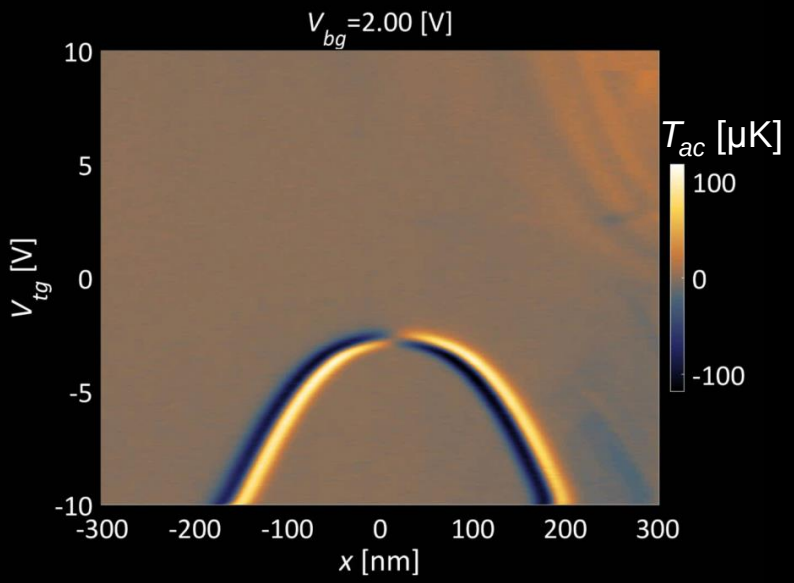
D. Halbertal, et al. Science 358, 1303 (2017)

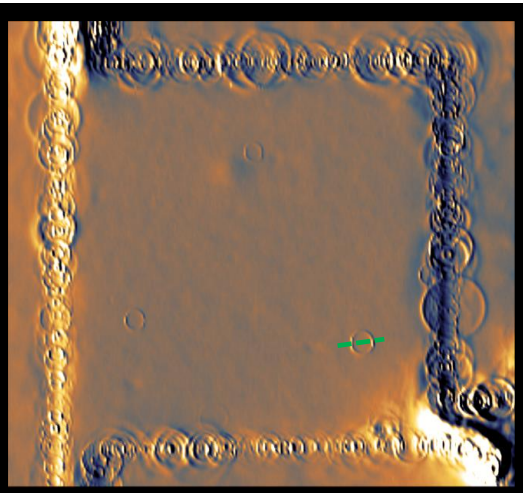
Resonant inelastic scattering by a single localized state

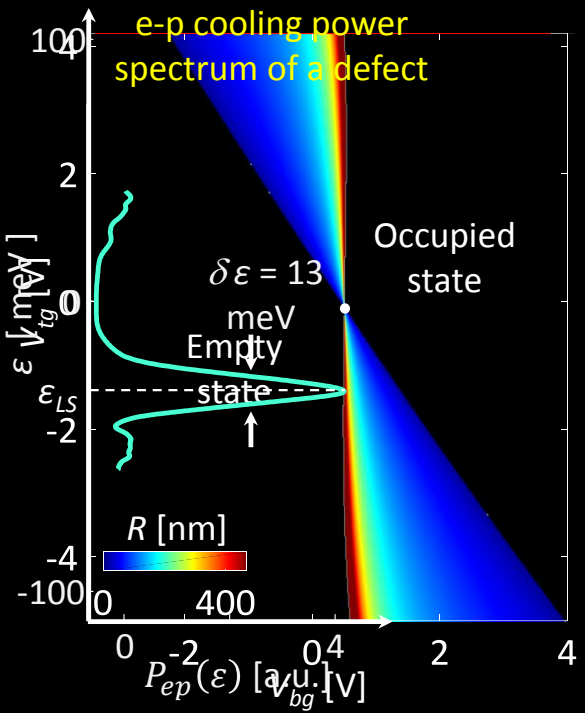


D. Halbertal, et al. Science 358, 1303 (2017)

Moving tSOT spectroscopy - experiment



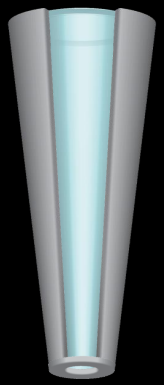




D. Halbertal, et al. Science 358, 1303 (2017)

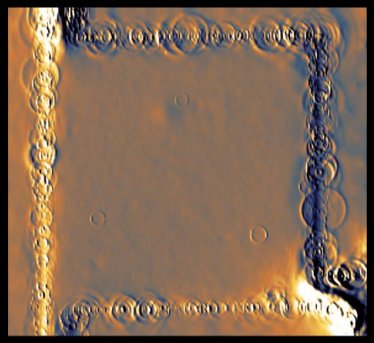
Summary

Nanoscale thermal imaging of quantum systems with sub 1 μK sensitivity



Dissipation in quantum dots in CNT

Dissipation dominated by edge defects in graphene



Spectroscopy of localized states

Inelastic electron scattering by a resonant localized state

Detection of phonon emission from a single atomic defect