

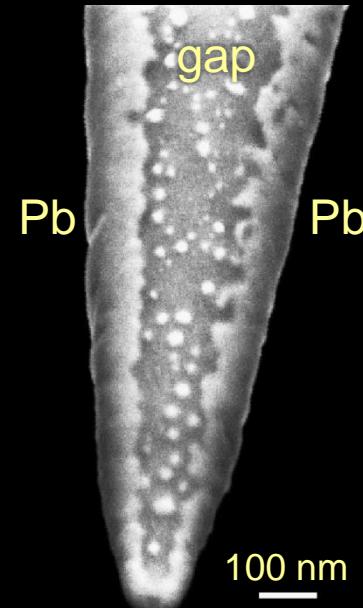
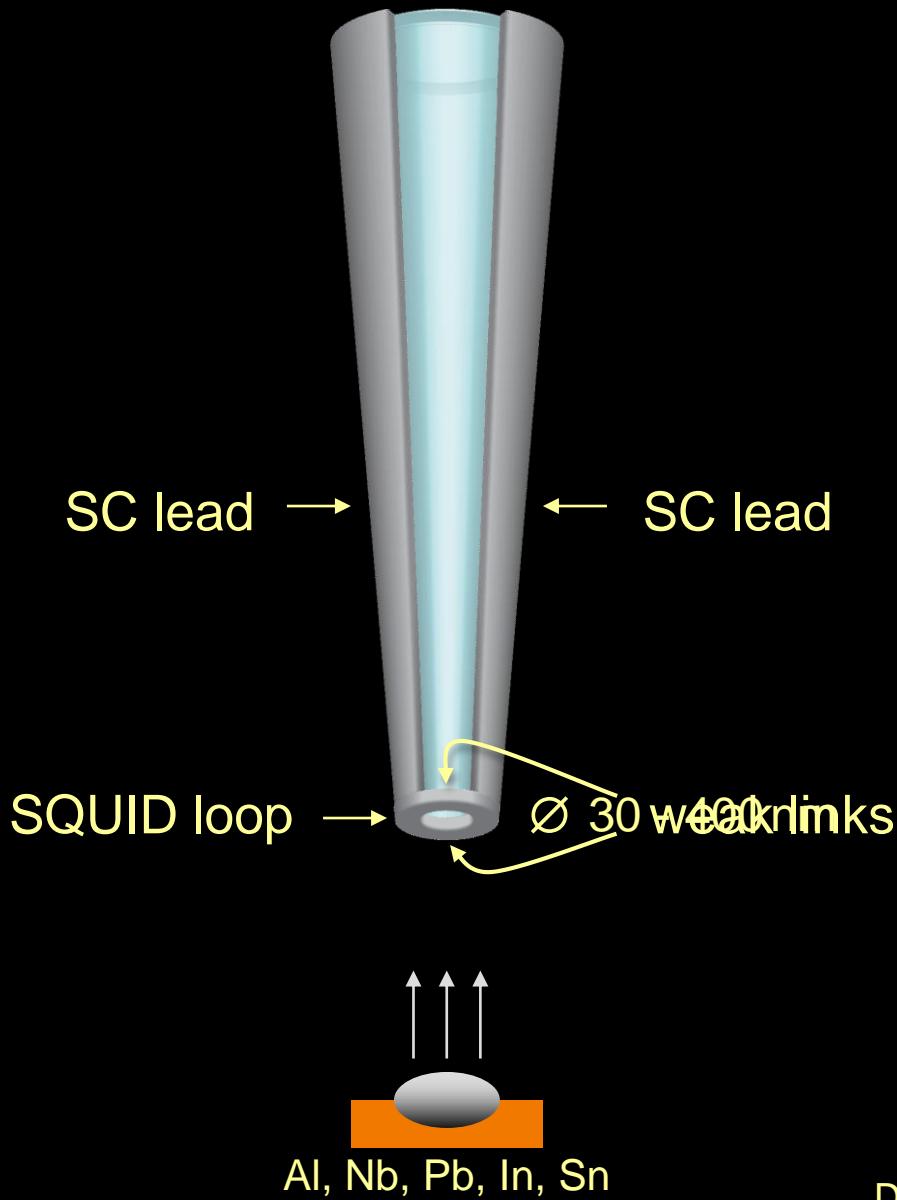
Scanning SQUID-on-tip nanothermometry of quantum systems

Eli Zeldov

Weizmann Institute of Science



SQUID on tip

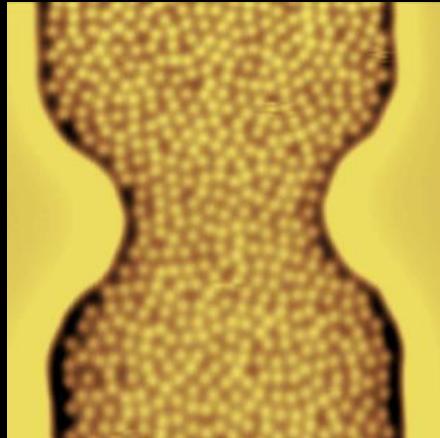


Loop diameter = 46 nm

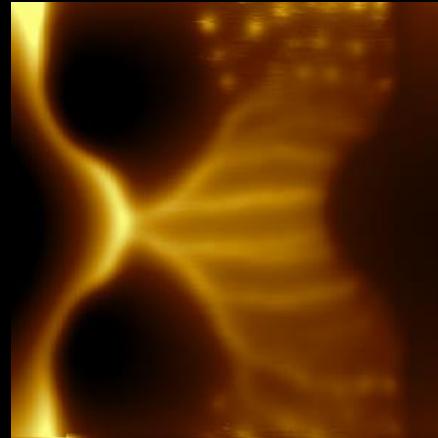
Flux noise: $\sqrt{S_\Phi} = 50 \text{ n}\Phi_0/\text{Hz}^{1/2}$

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

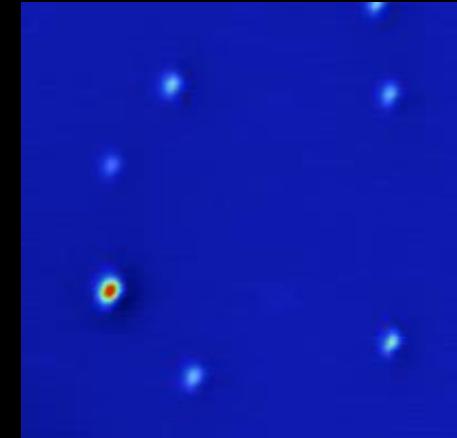
Magnetic phenomena on the nanoscale



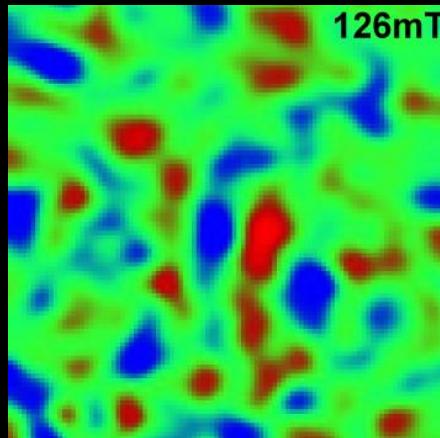
Vortex matter



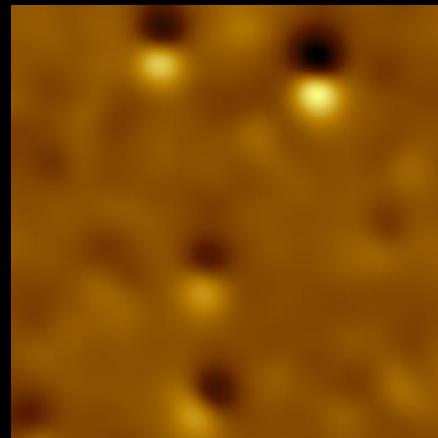
Vortex dynamics



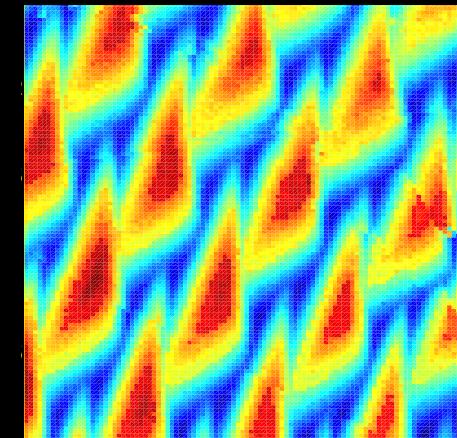
Nanomagnetism



Magnetic TI



Oxide interfaces



Multijunction SOT

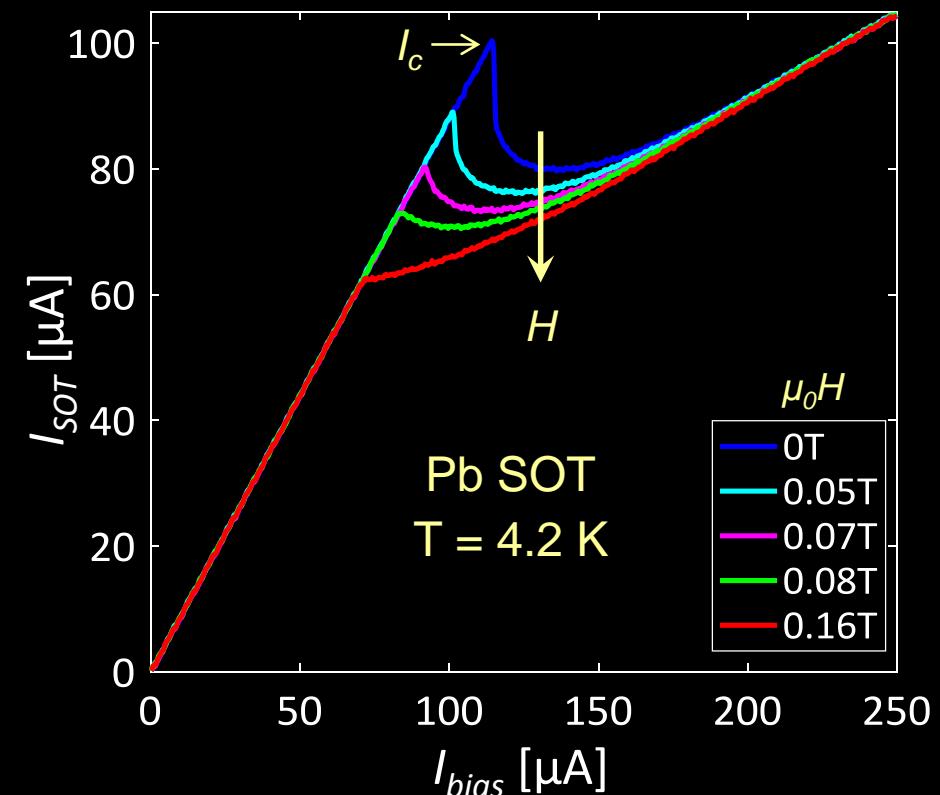
Thermal imaging



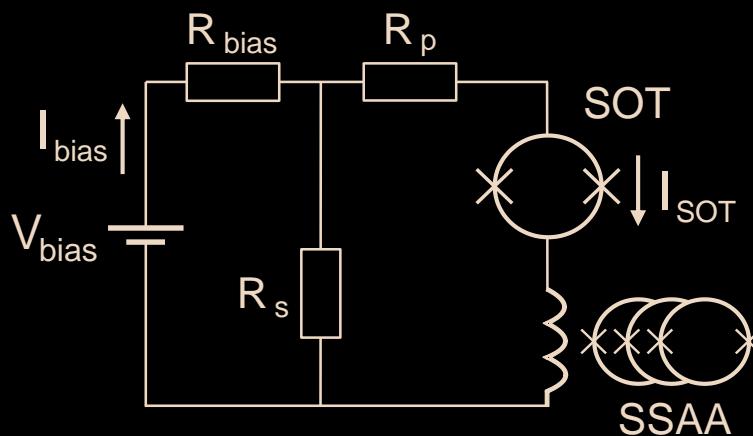
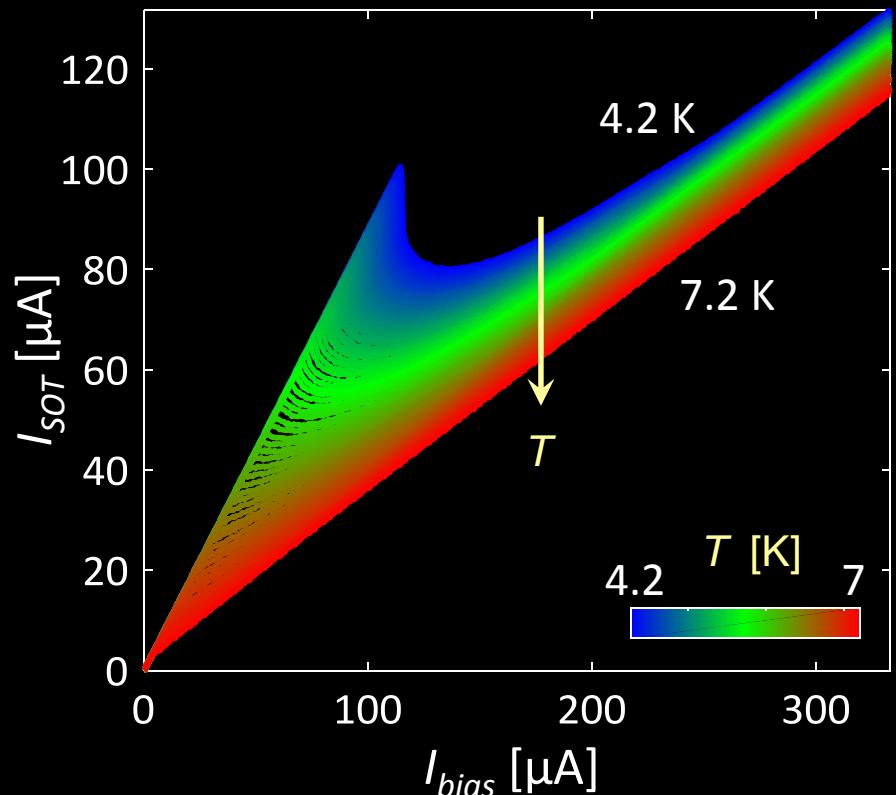
dissipation

SOT thermal and magnetic sensitivity

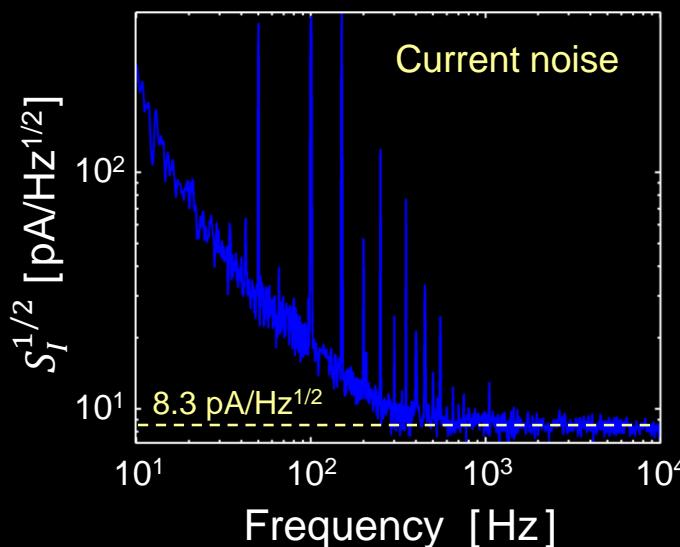
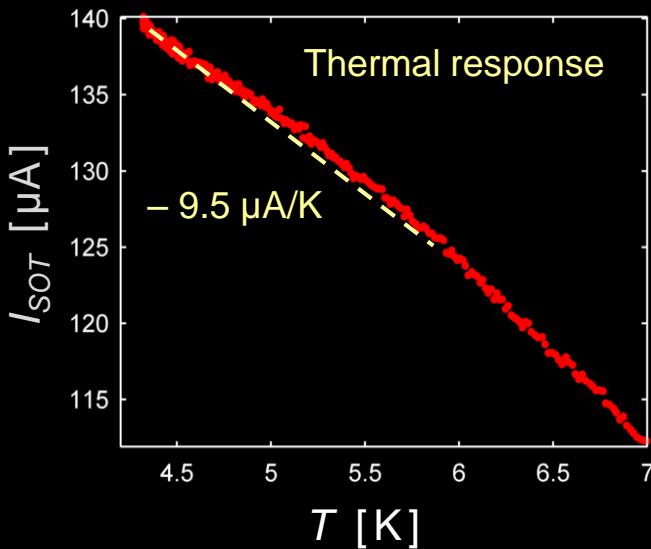
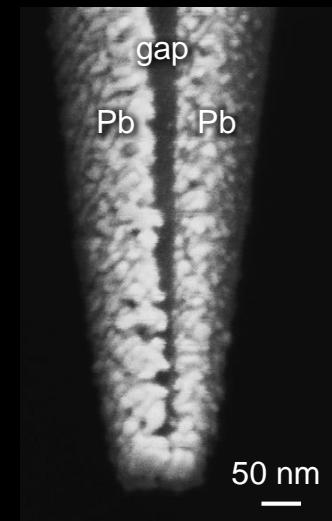
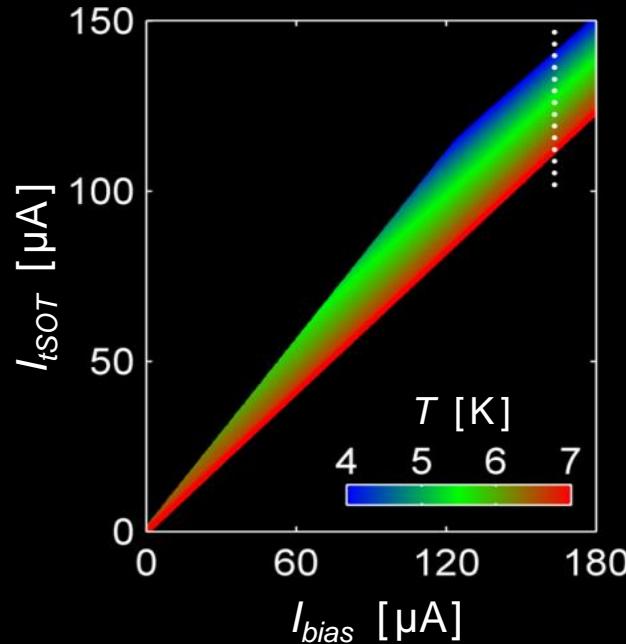
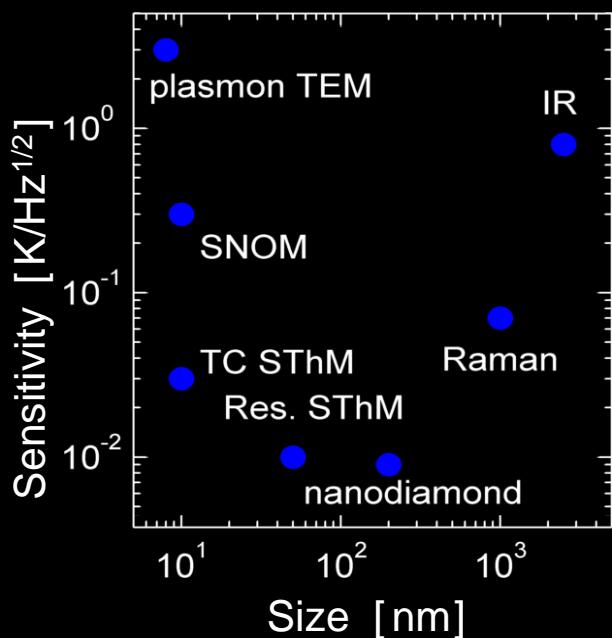
Magnetic sensitivity



Thermal sensitivity

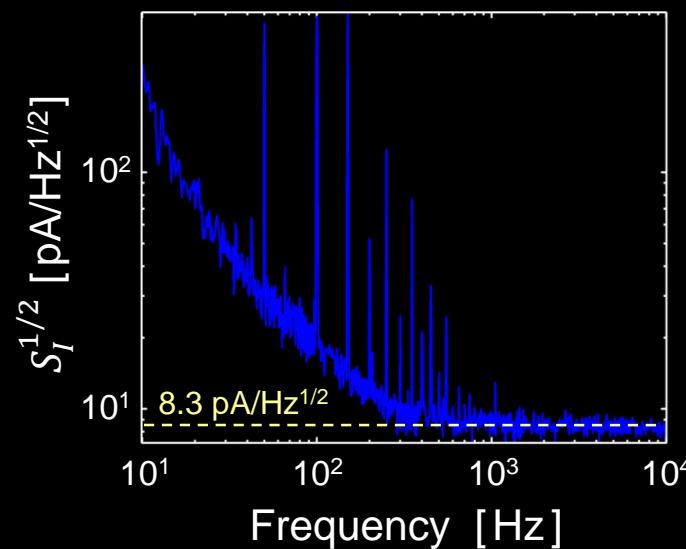
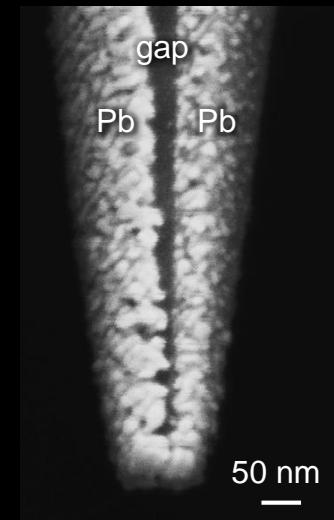
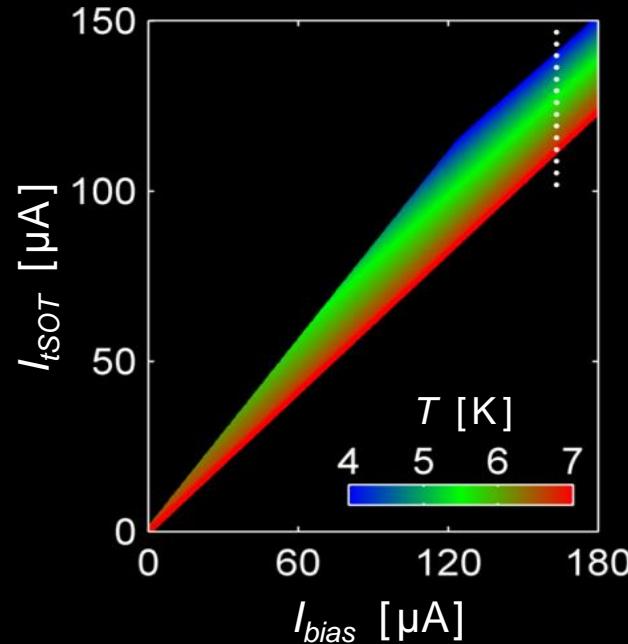
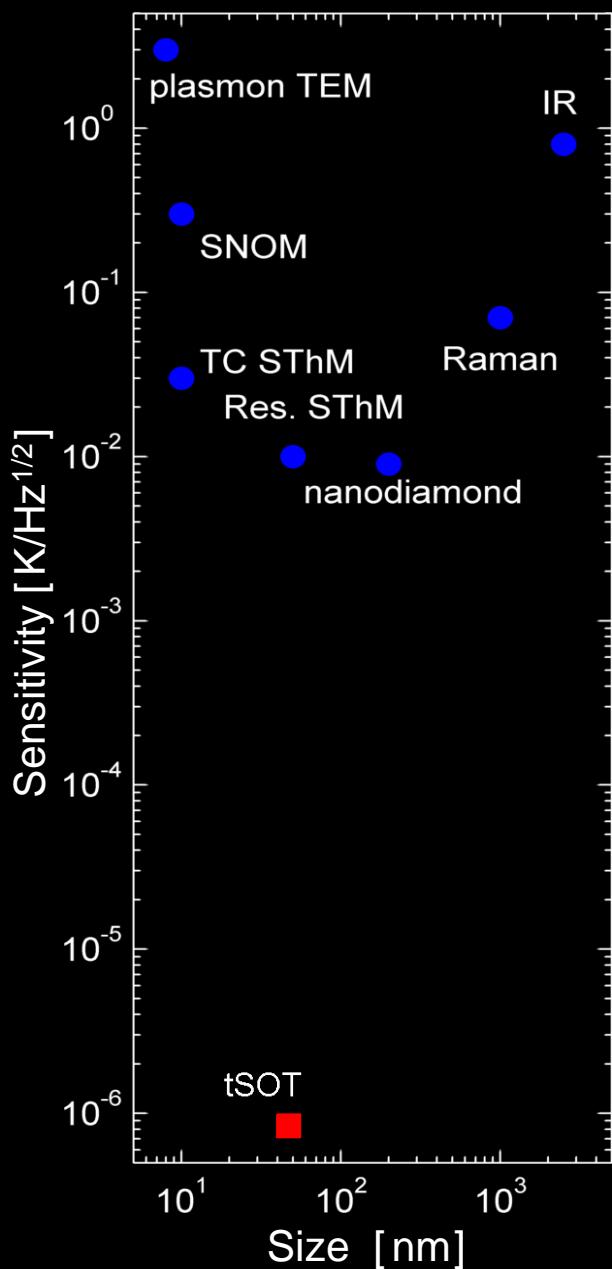


Thermal imaging techniques



Thermal noise:
 $S_T^{1/2} = 870 \text{ nK}/\text{Hz}^{1/2}$

Thermal imaging techniques



Thermal noise:
 $S_T^{1/2} = 870 \text{ nK}/\text{Hz}^{1/2}$

Thermal sensitivity

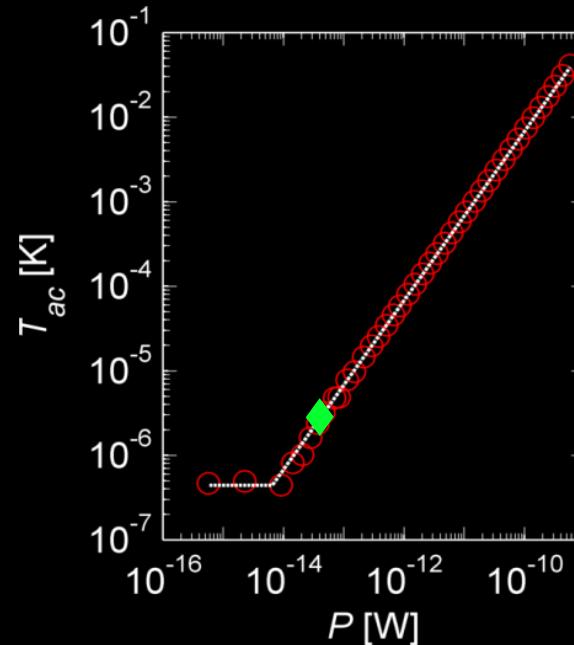
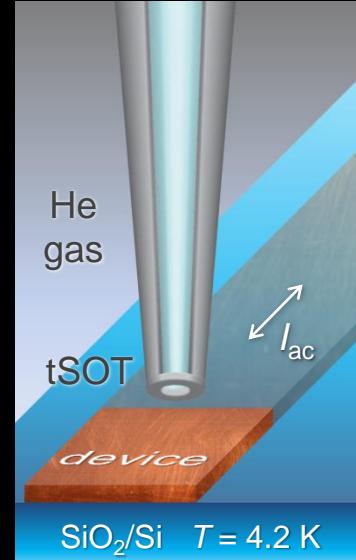
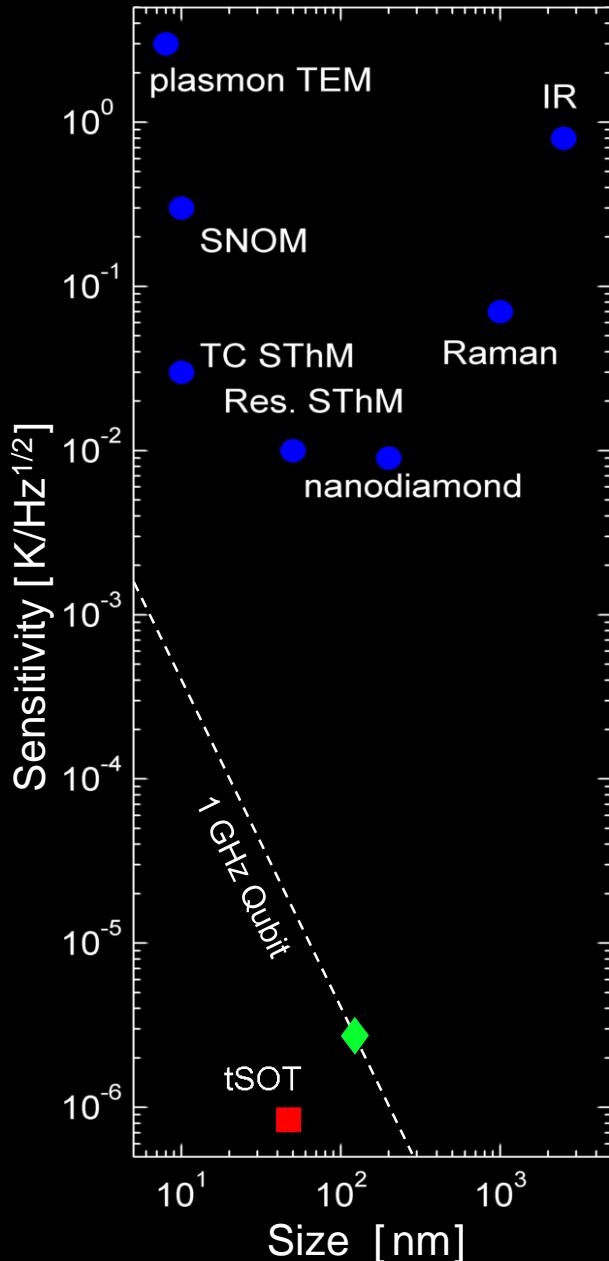


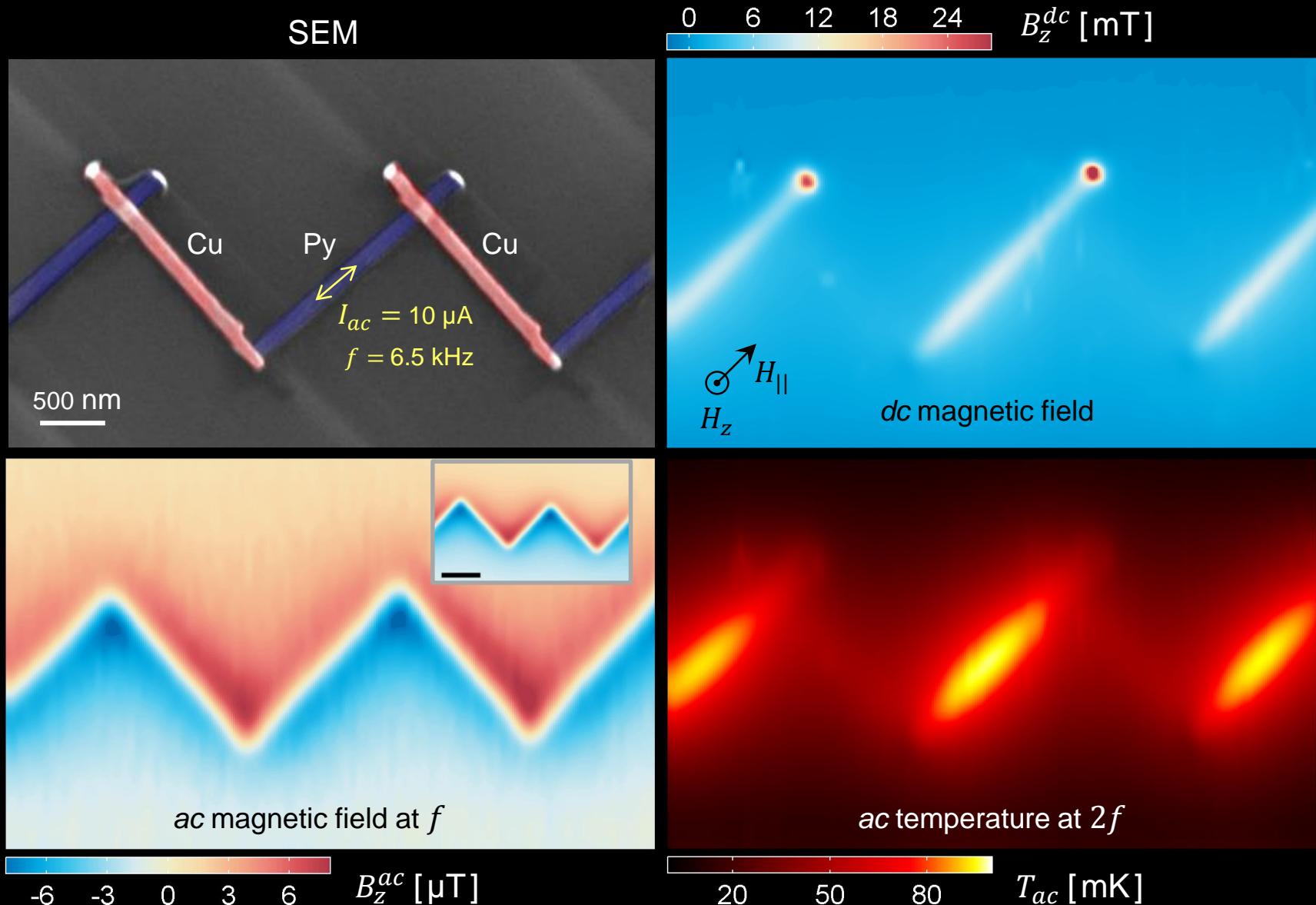
Figure of merit:
Landauer's limit of energy
dissipation for irreversible
qubit readout

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

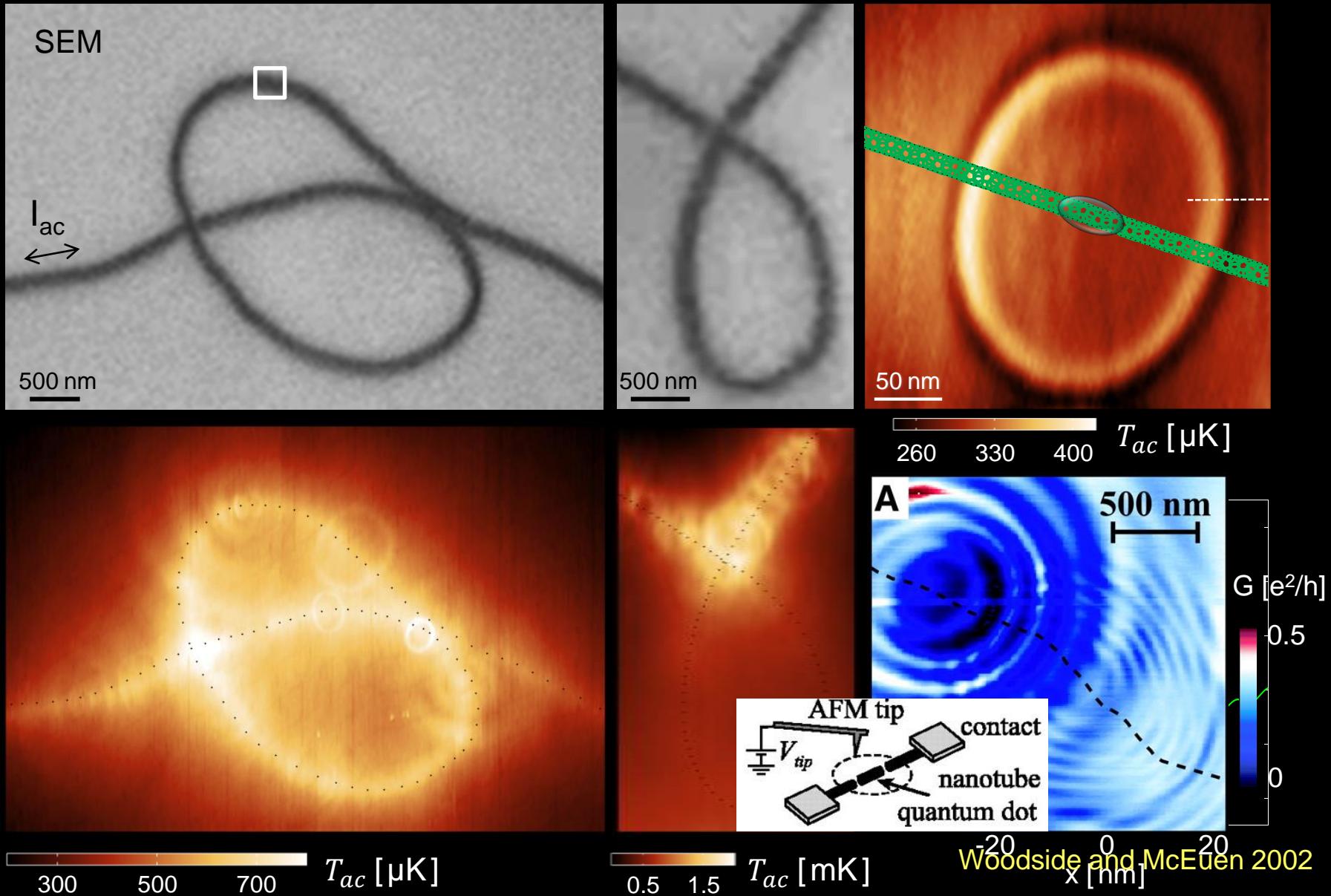
Qubit at 1 GHz:

$$P = 40 \text{ fW}$$

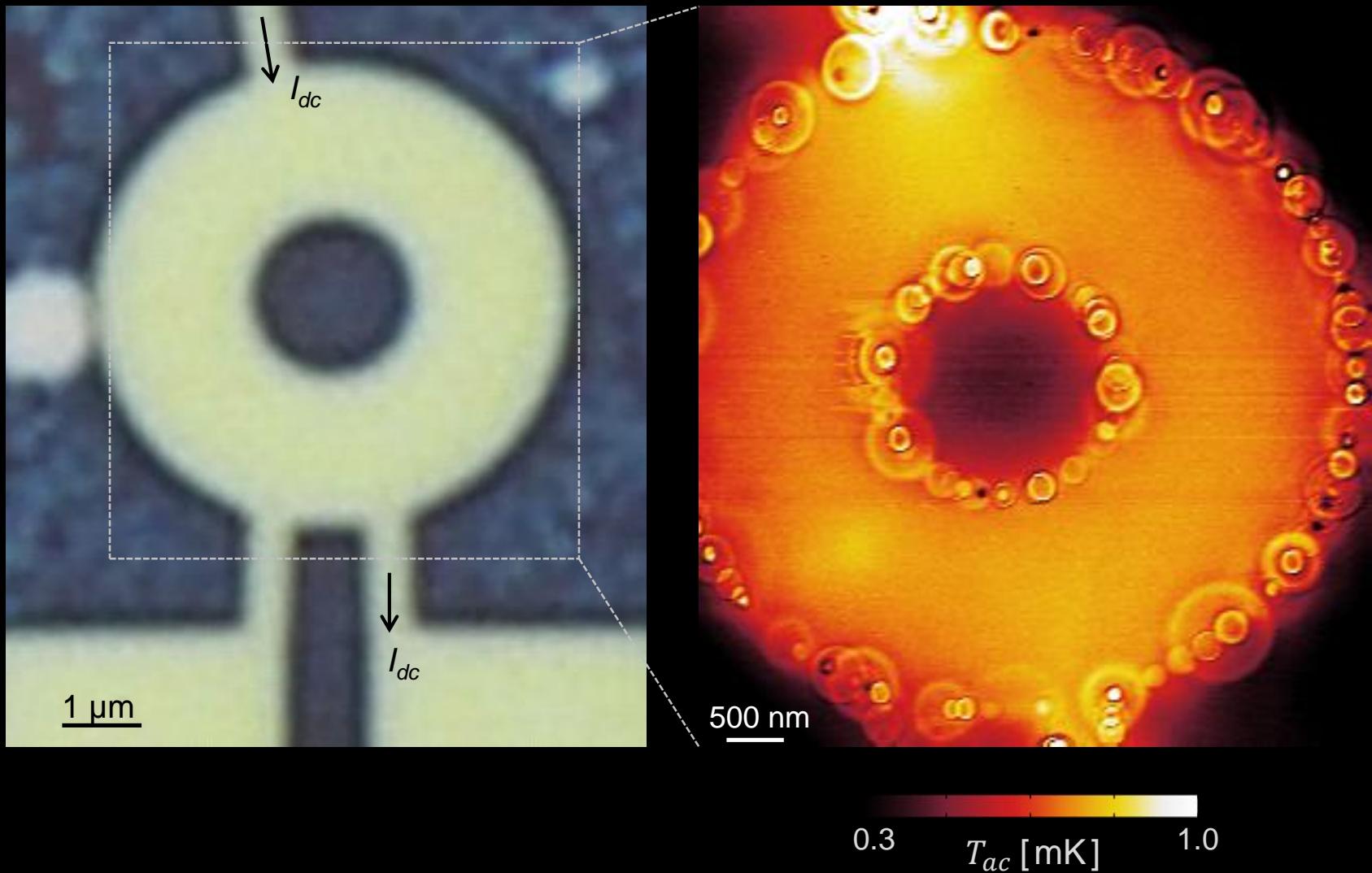
Multifunctional imaging



Dissipation in carbon nanotubes



Dissipation in hBN encapsulated graphene

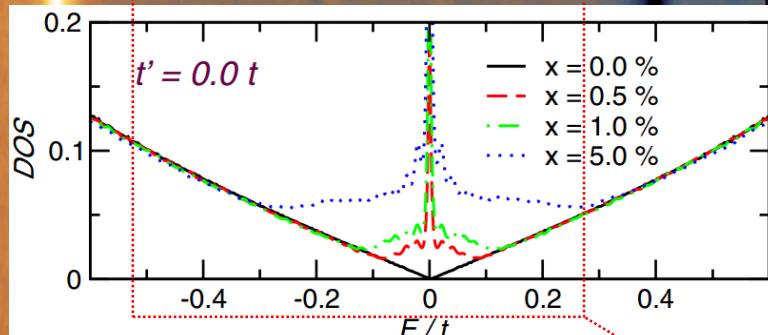


Dissipation in graphene due to impurities

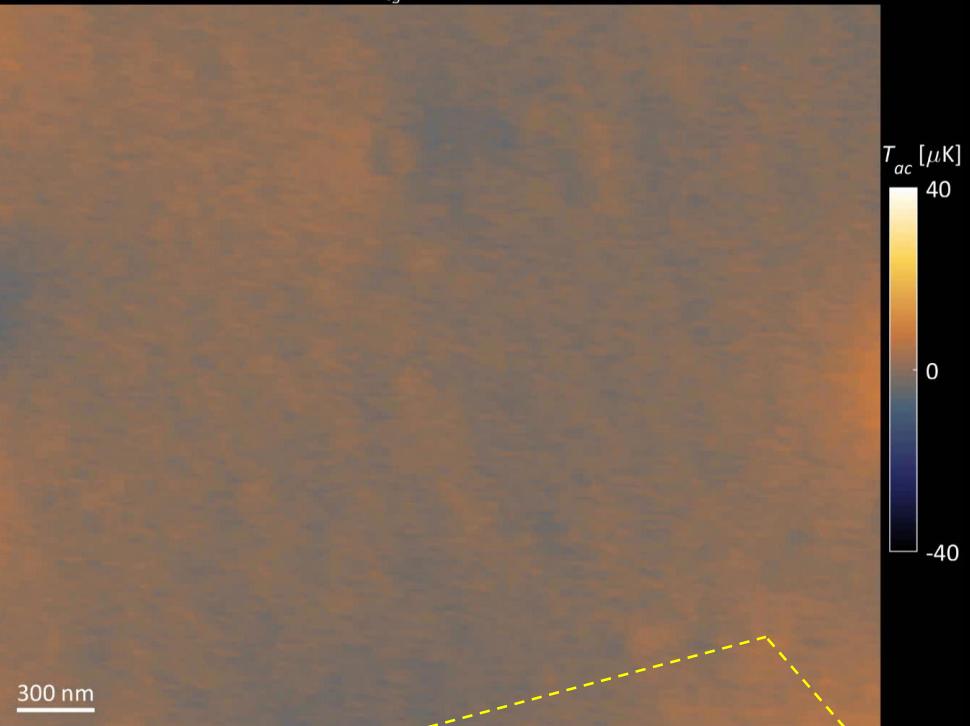
$V_{tg} = 0.0$ [V]

I_{dc}

Vacancies and adatoms form localized states near Dirac point in graphene



$V_{tg} = 2.0$ [V]



Pereira et al., PRL 96 (2006)

Bistritzer & MacDonald, PRL 102 (2009)

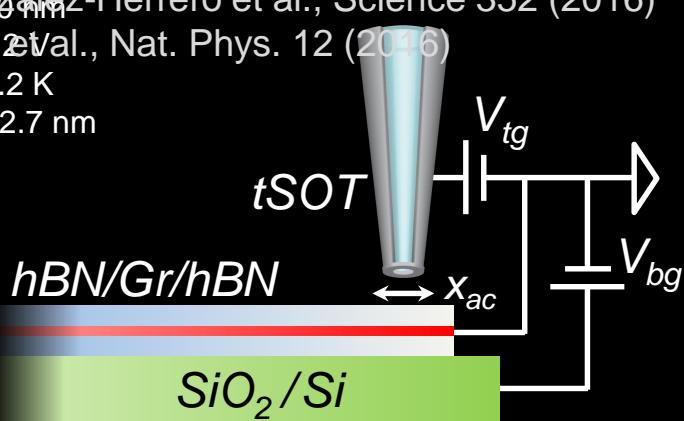
Song, Reizer & Levitov, PRL 109 (2012)

González-Herrero et al., Science 352 (2016)

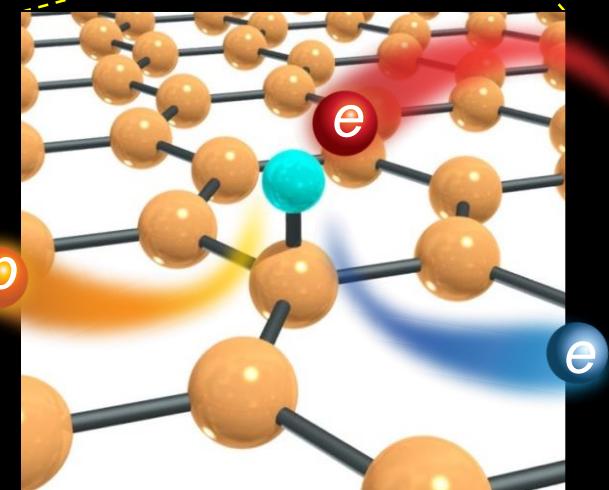
Mao et al., Nat. Phys. 12 (2016)

$T = 4.2$ K

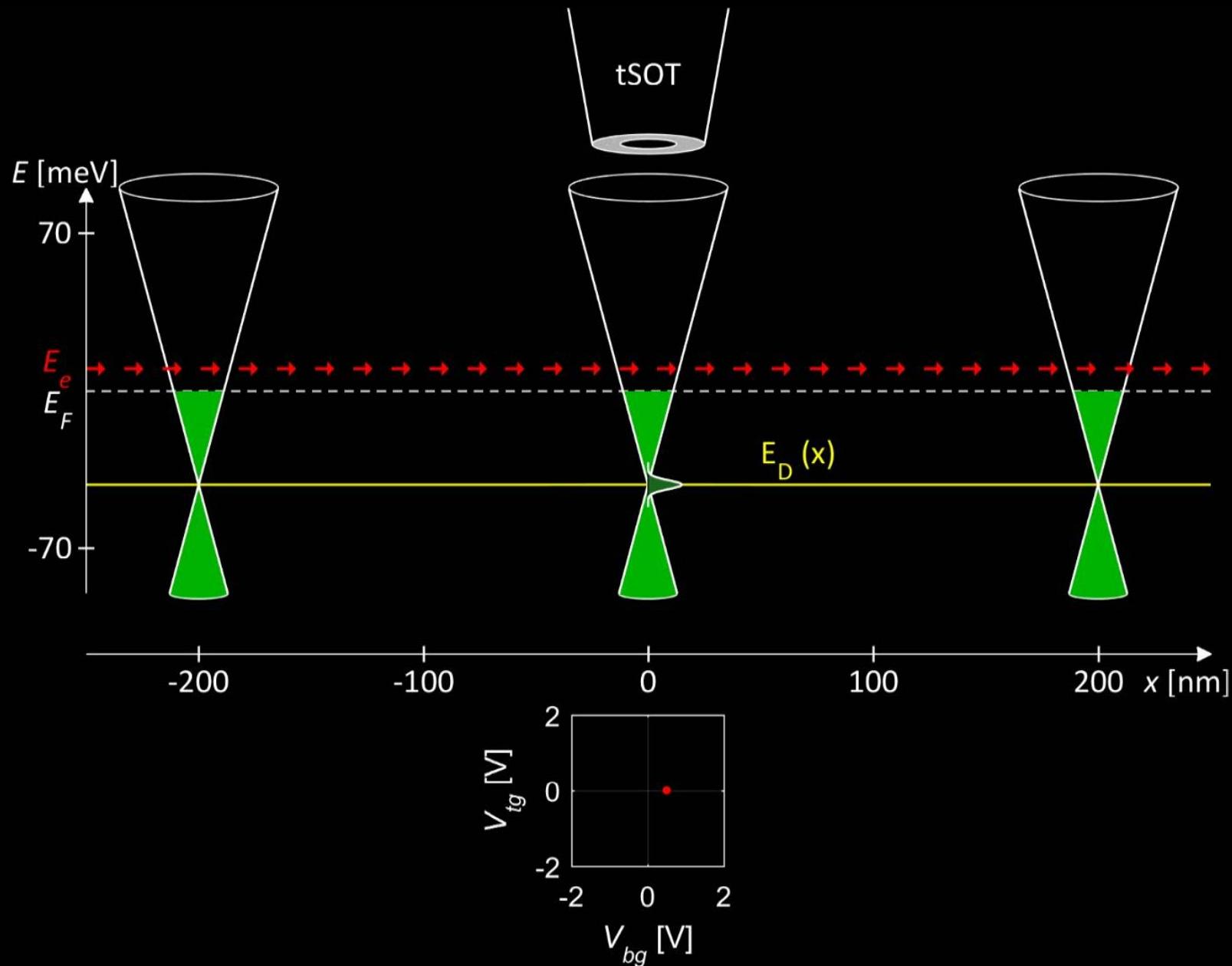
$x_{ac} = 2.7$ nm



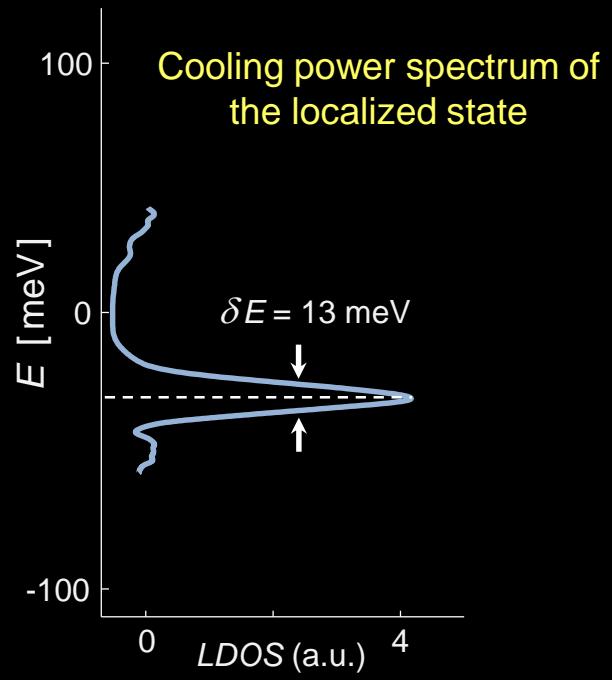
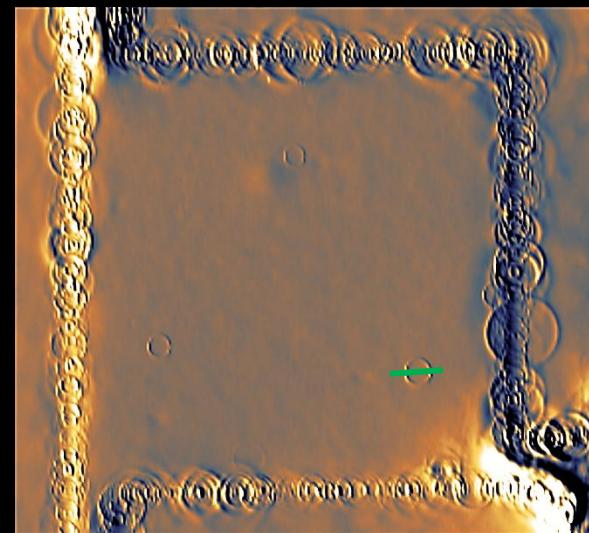
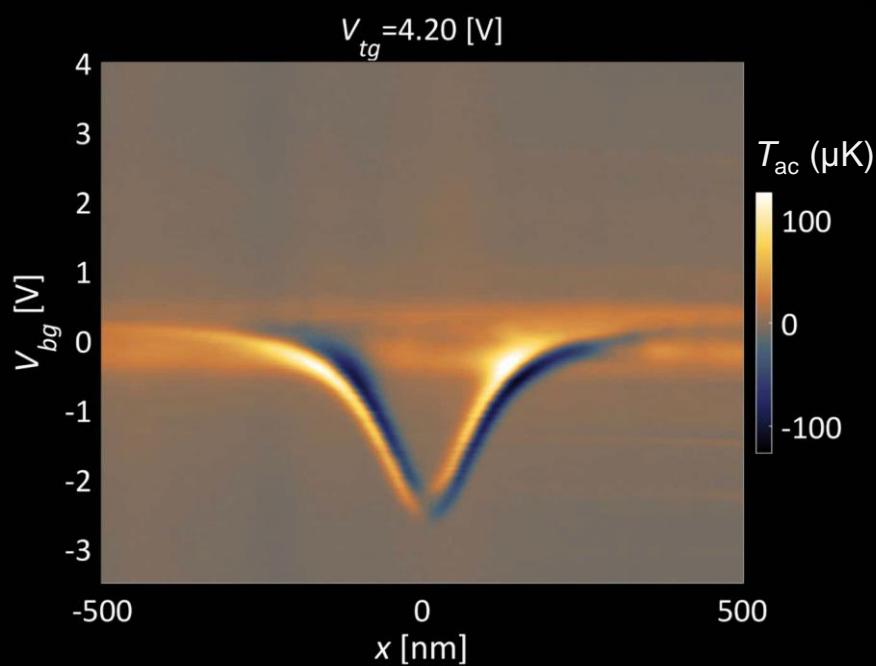
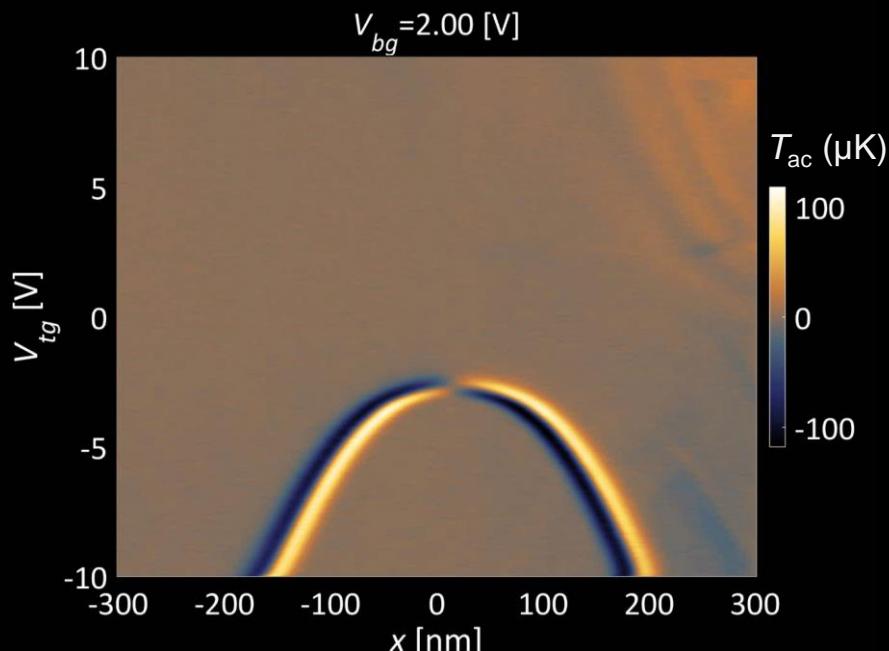
Atomic source
of phonons



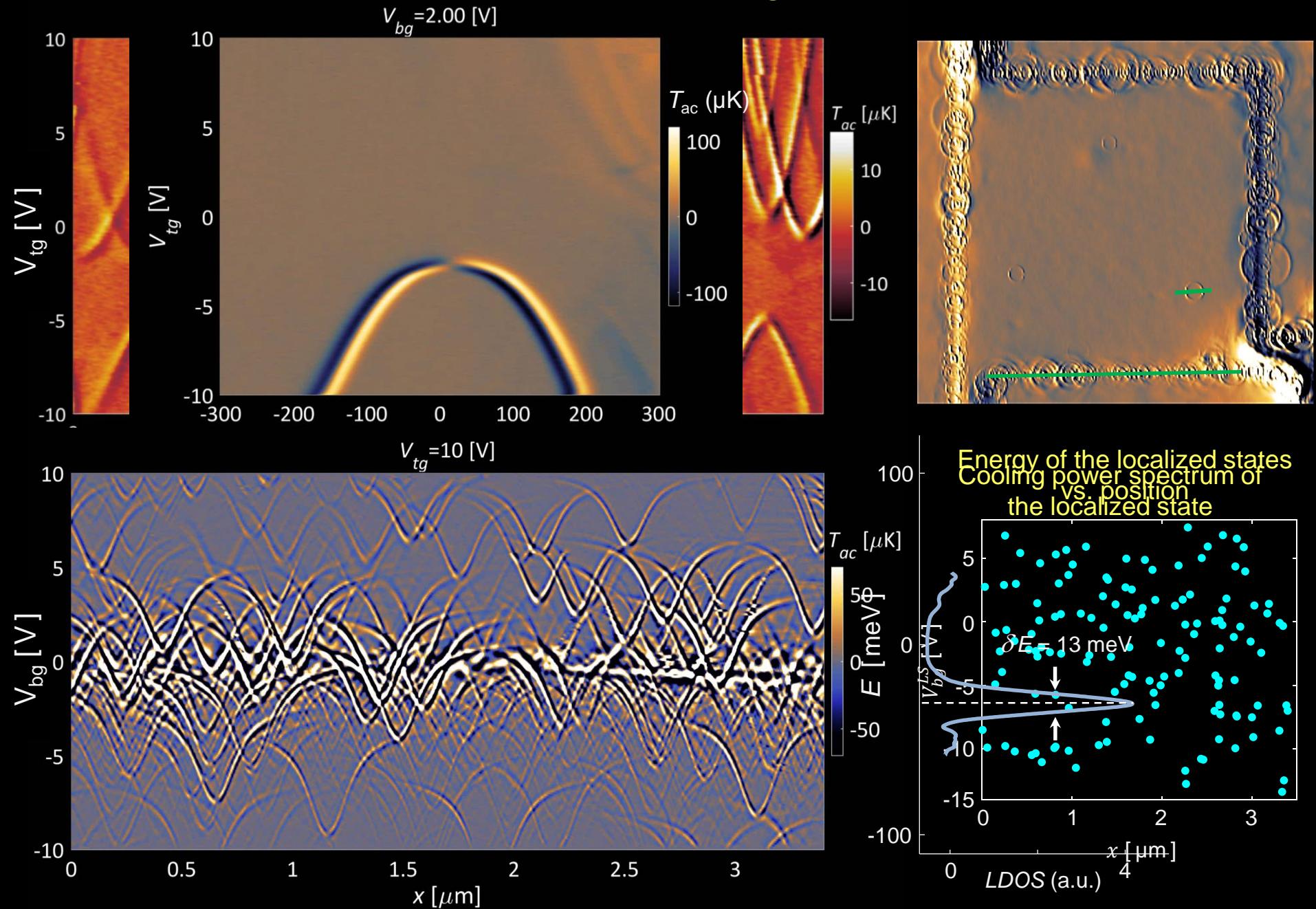
Resonant inelastic scattering by a single localized state



Spectroscopy of bulk defects



Spectroscopy of edge defects



Weizmann team

D. Halbertal

N. Shadmi

K. Bagani

J. Cuppens

E. Joselevich

J. Sarkar

M. Ben Shalom, Manchester

Y. Anahory

A. Meltzer

HR Naren

A. K. Geim, Manchester

A. Uri

L. Embon

D. Vasyukov

J. Birkbeck, Manchester

Y. Myasoedov

Y. Ronen

L. S. Levitov, MIT

M. Rappaport

E. Lachman

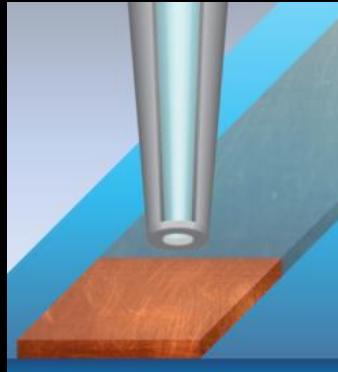
M.E. Huber, Denver



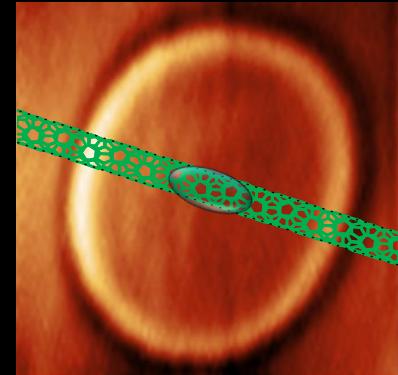
Collaborators

Summary

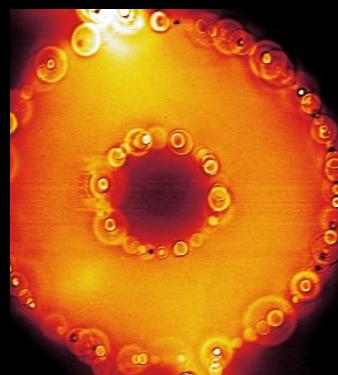
Nanoscale thermal imaging of quantum systems with sub 1 μK sensitivity



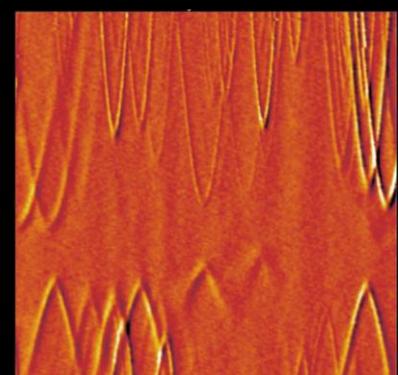
Dissipation in quantum dots in CNT



Dissipation dominated by edge defects in graphene



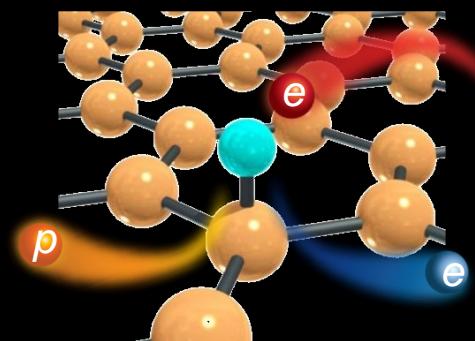
Spectroscopy of edge states in graphene



Inelastic electron scattering by a resonant localized state

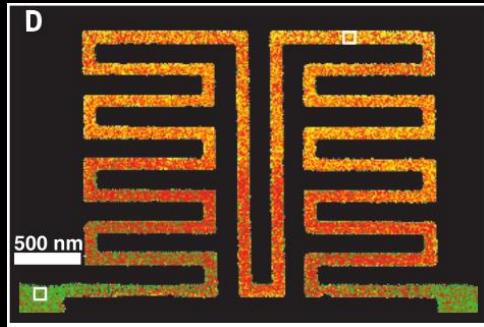


Detection of phonon emission from a single atomic defect



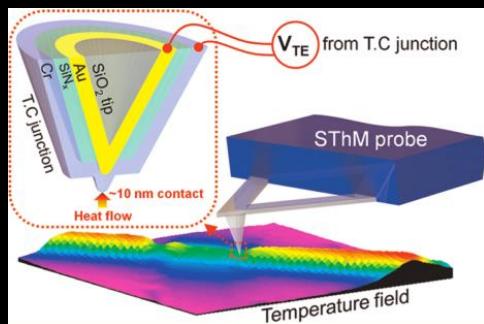
Available thermal microscopy techniques

Plasmon energy expansion

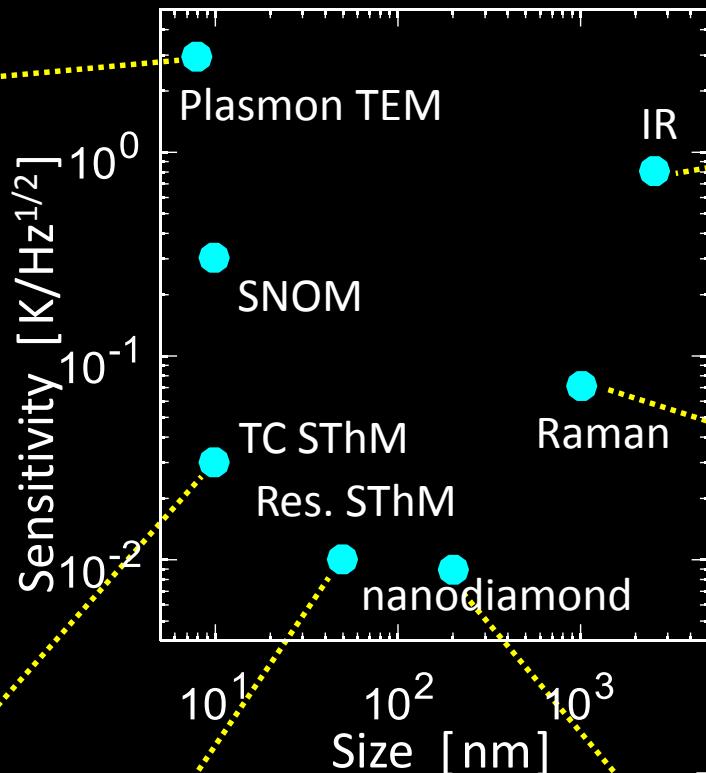


Mecklenburg *et al.*,
Science (2015)

Thermo-couple SThM

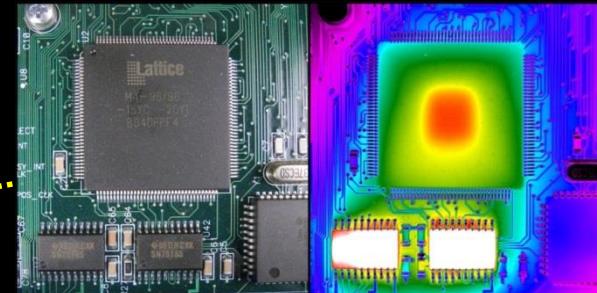


Kim *et al.*, ACS Nano (2012)

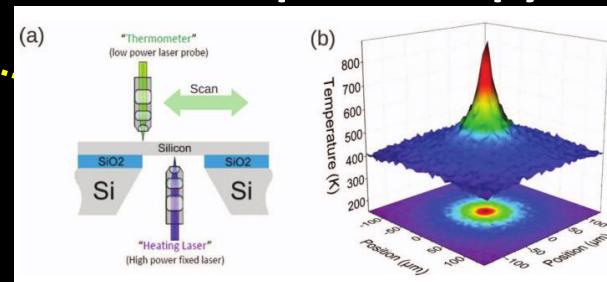


Menges *et al.* Nat. Commun. (2016)

IR thermal imaging

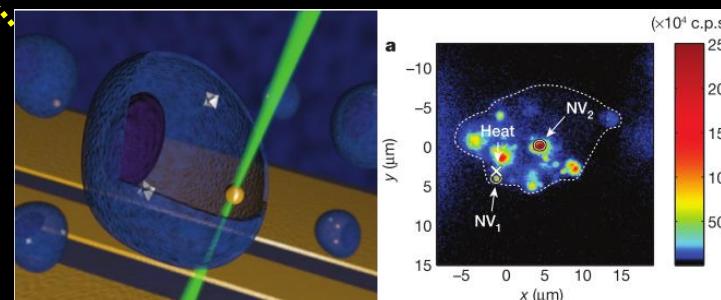


Raman spectroscopy



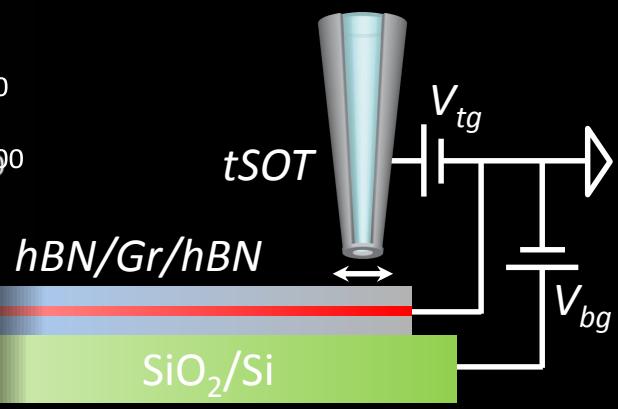
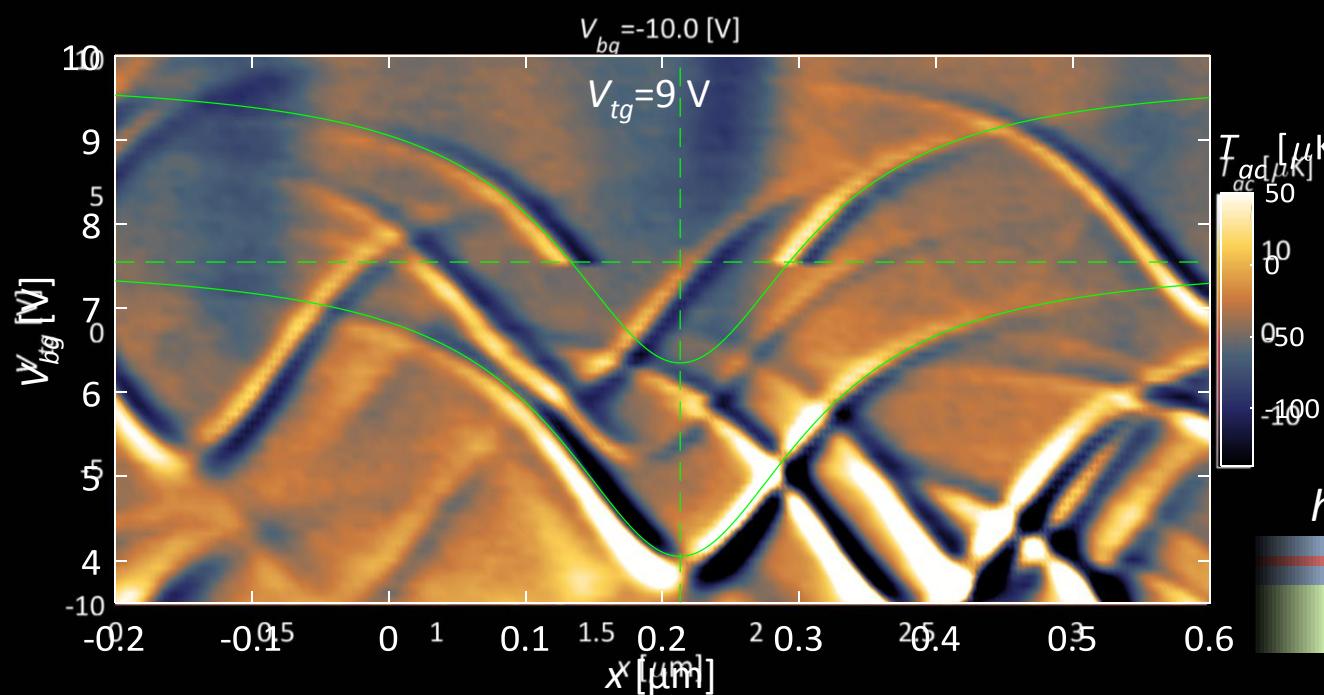
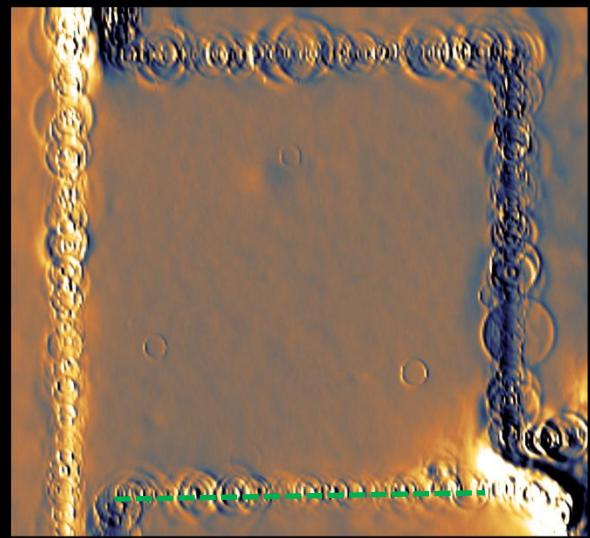
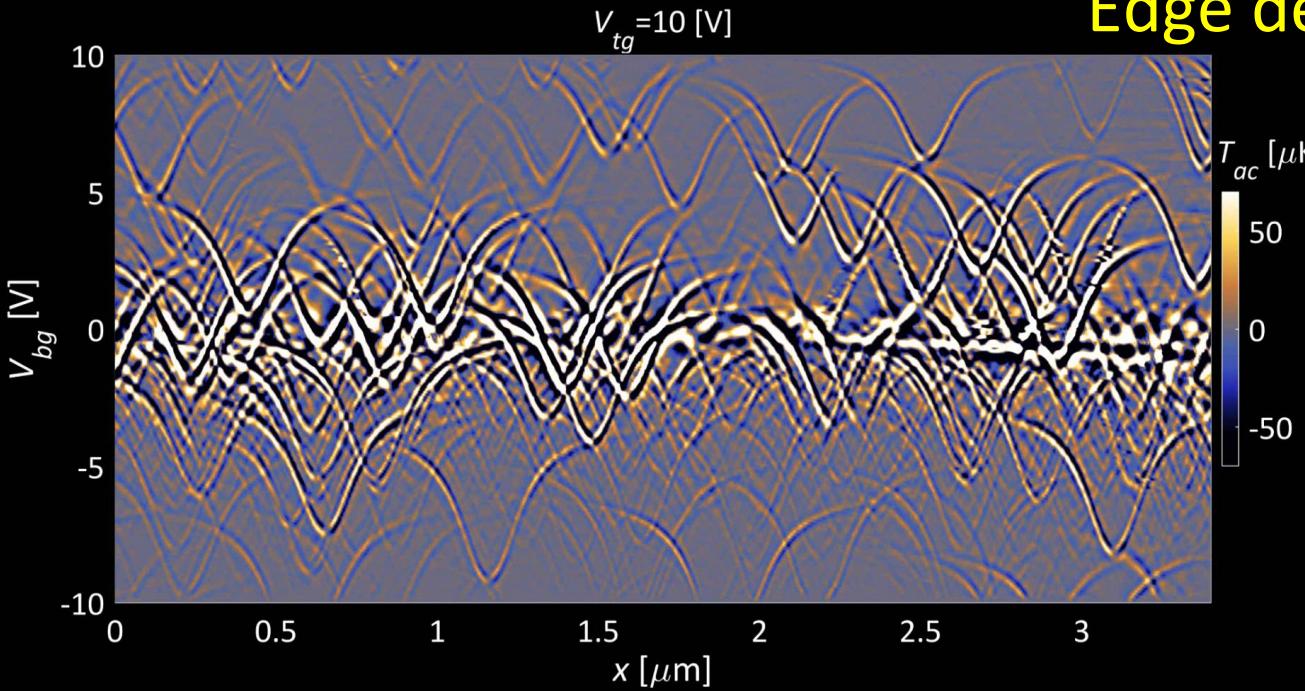
Reparaz *et al.*, Rev. Sci. Instrum. (2014)

Fluorescence in nanodiamonds

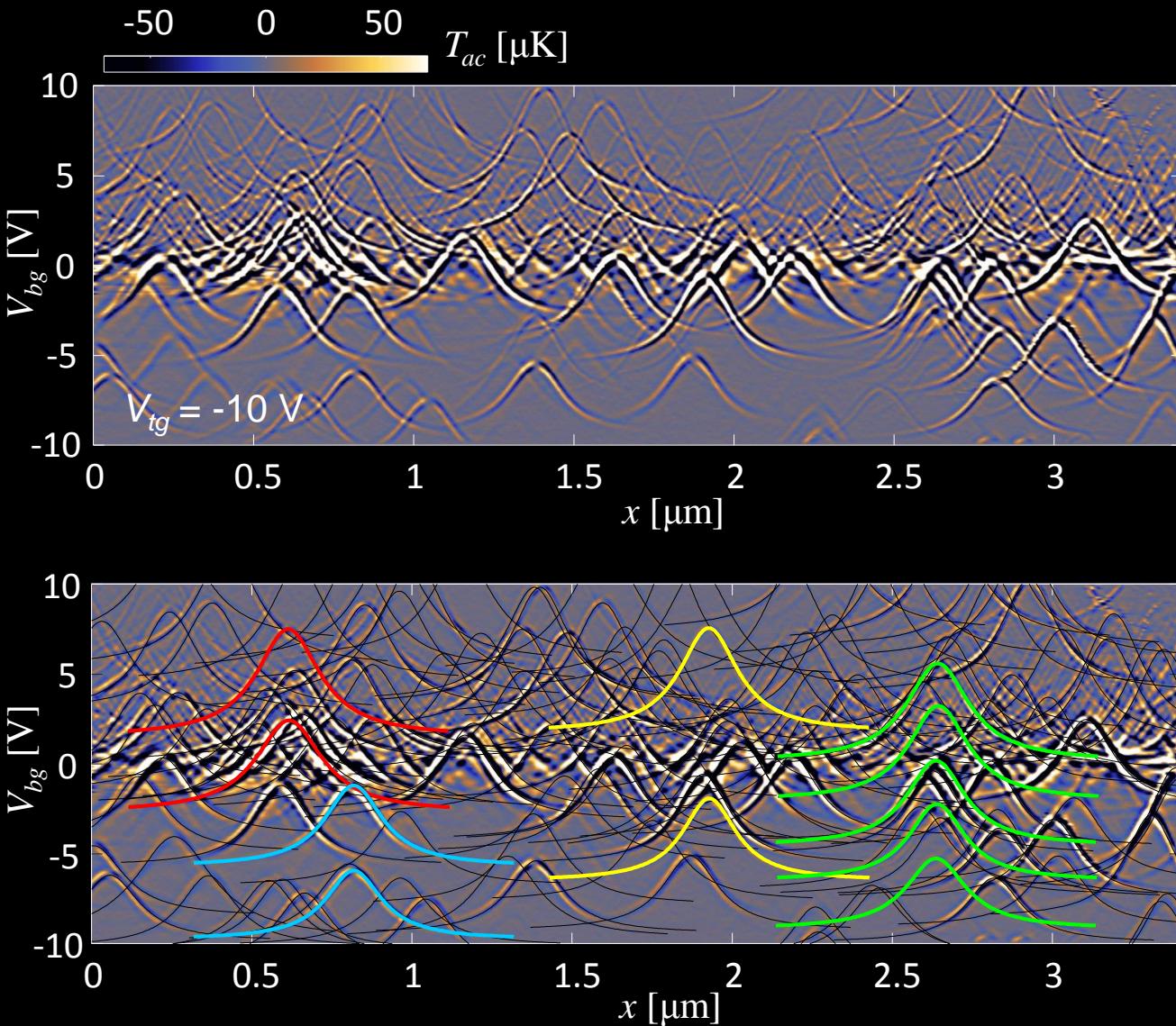


Kucska *et al.*, Nature (2013)

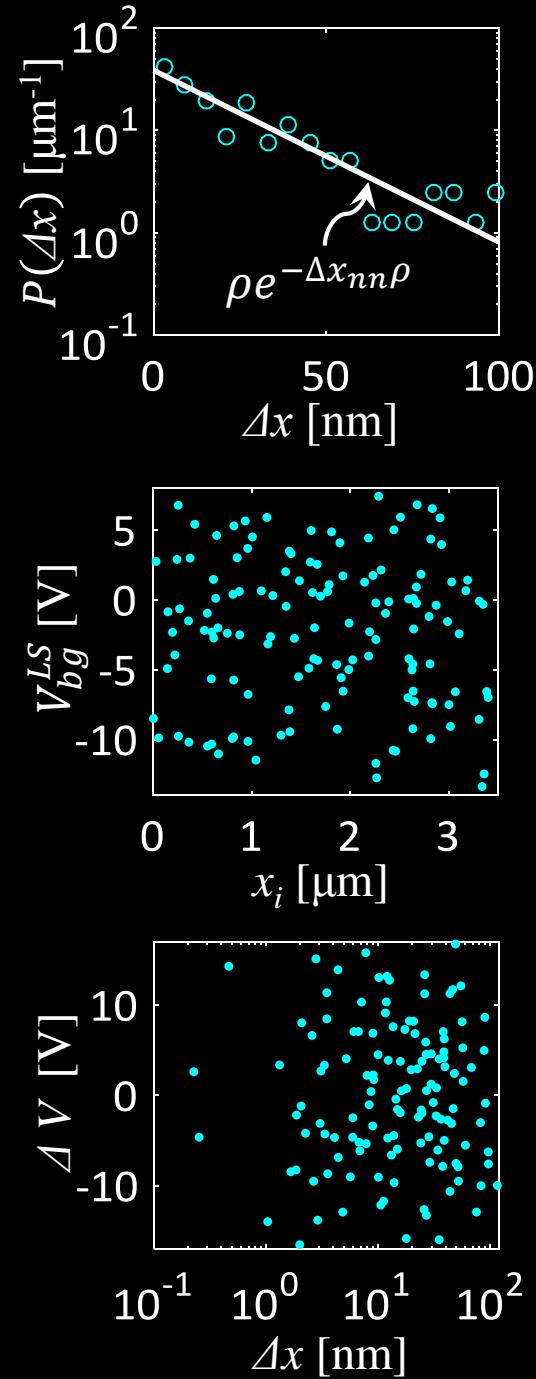
Edge defects spectroscopy



Edge defects statistical analysis

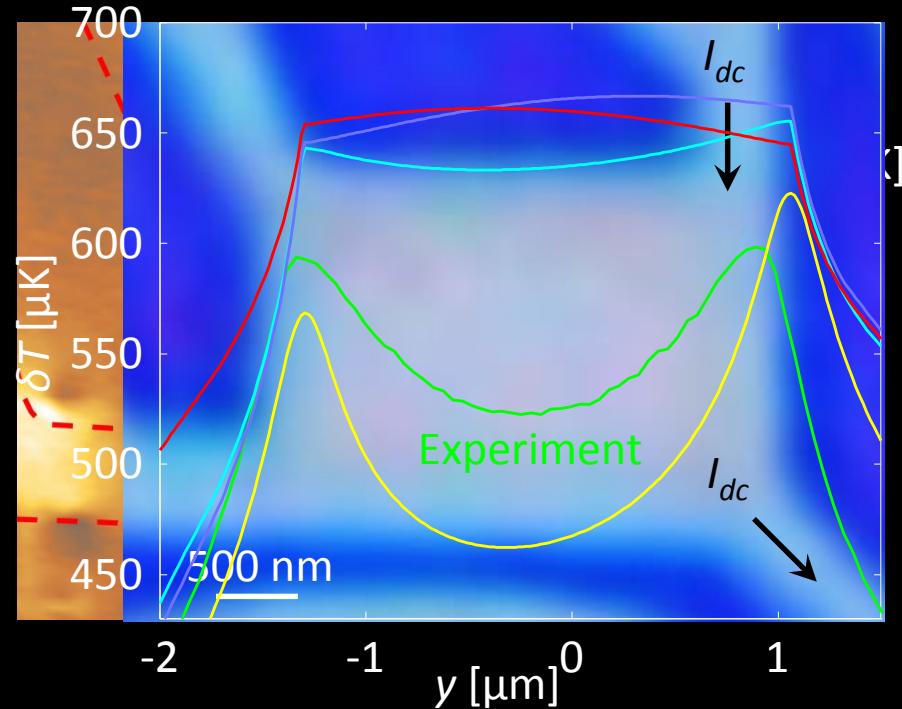
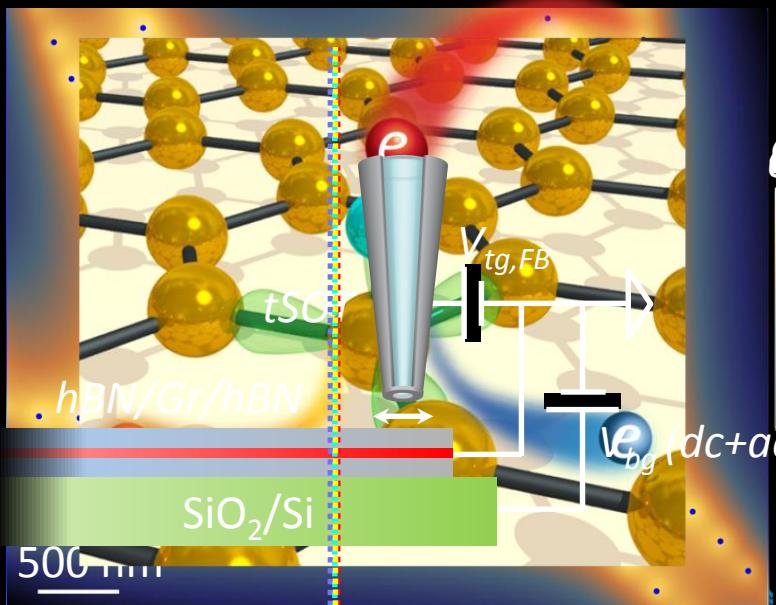
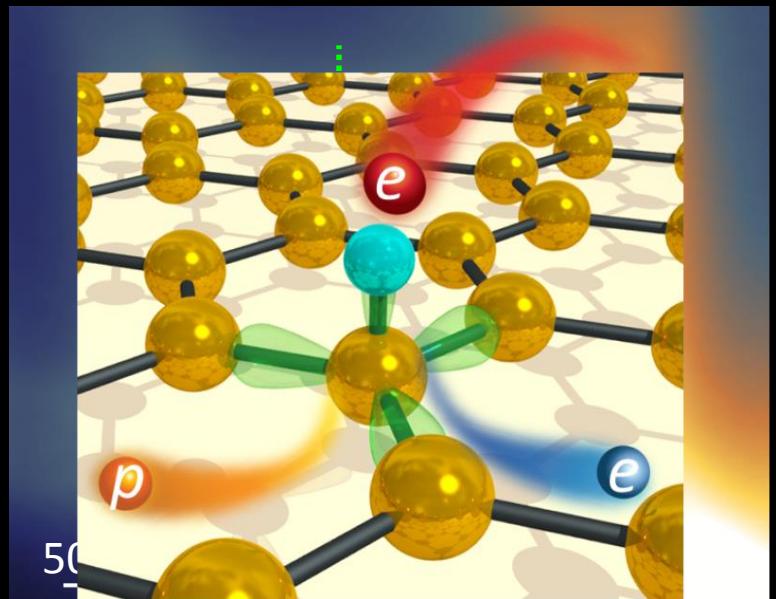


$$\rho = 135 \text{ defects}/3.5 \mu\text{m} \sim 40 \text{ defects}/\mu\text{m}$$



Dominance of atomic defect resonant inelastic scattering

Thermal imaging at Flat-Band conditions reveals undisturbed map



Joule dissipation

Uniform bulk

Edge dissipation (diffusion)

Edge dissipation (ballistic)

Dissipation dominated by
ballistic phonon emission at structure edges

Thermal sensitivity

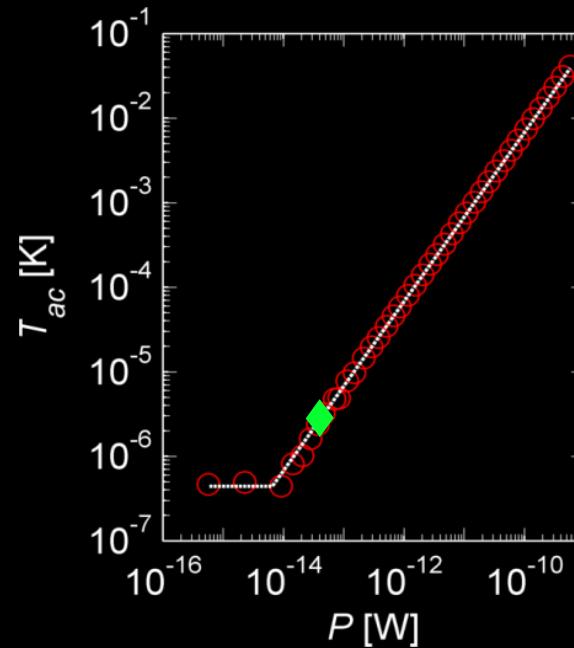
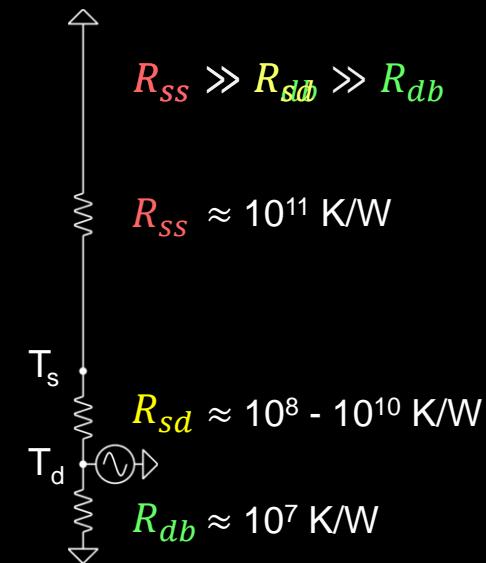
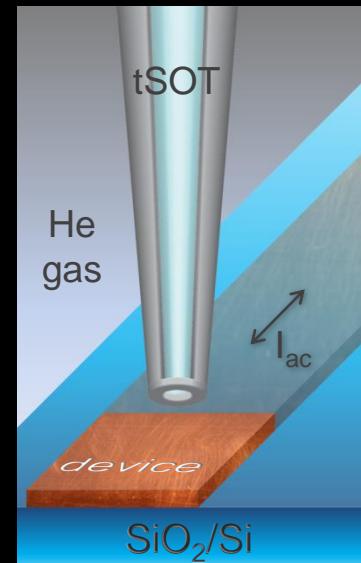
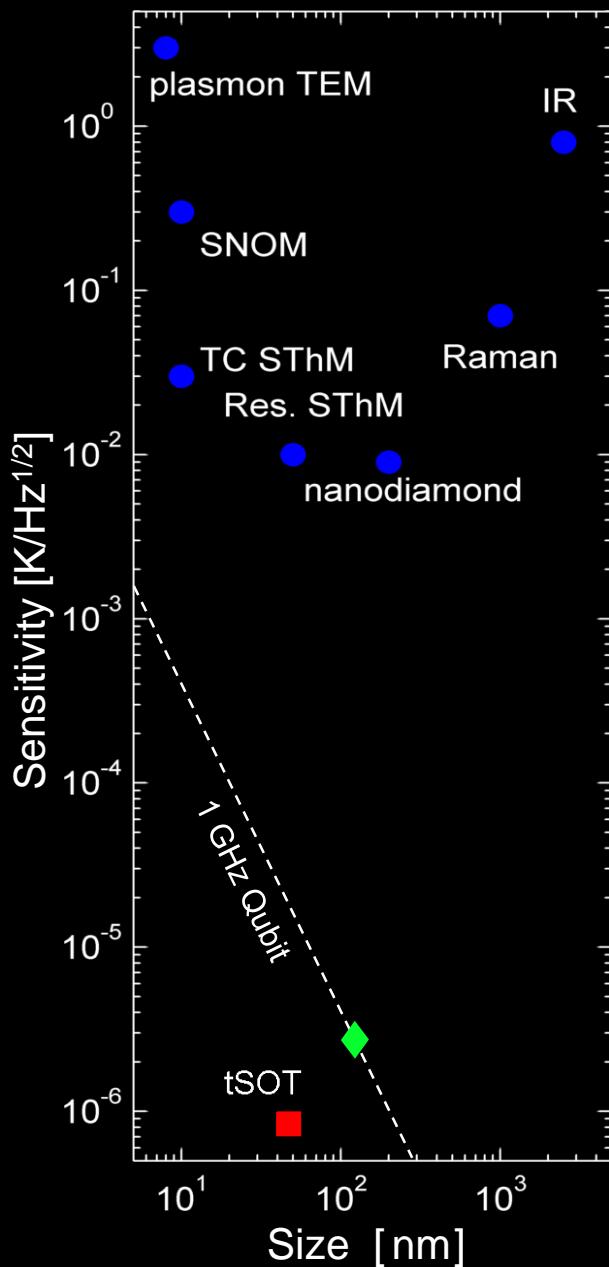
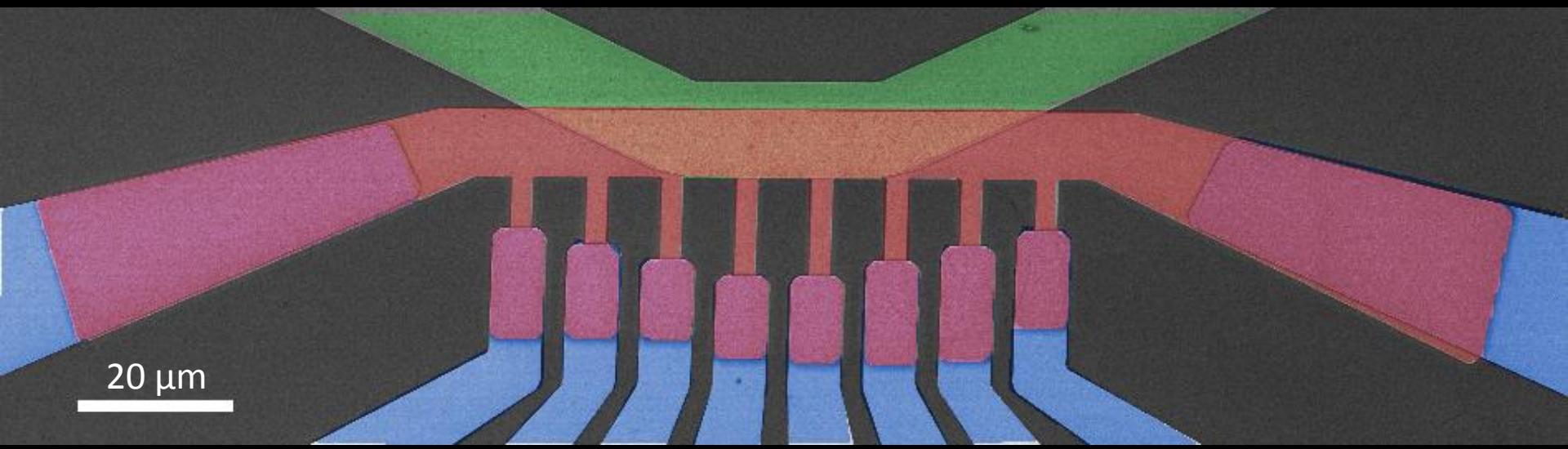


Figure of merit:
Landauer's limit of energy
dissipation for irreversible
qubit readout

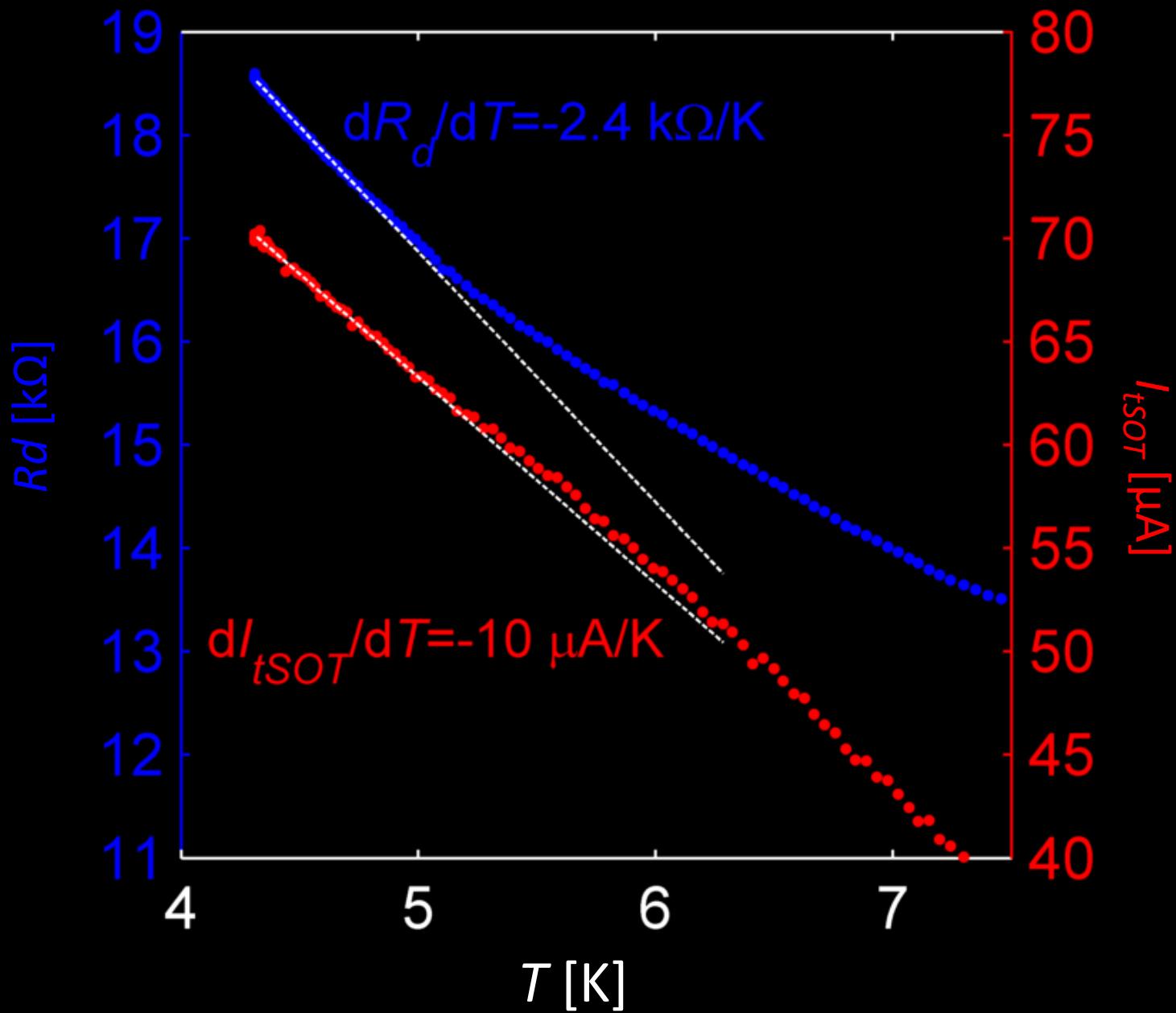
$$E = k_B T \ln 2 = 4 \times 10^{-23} \text{ J}$$

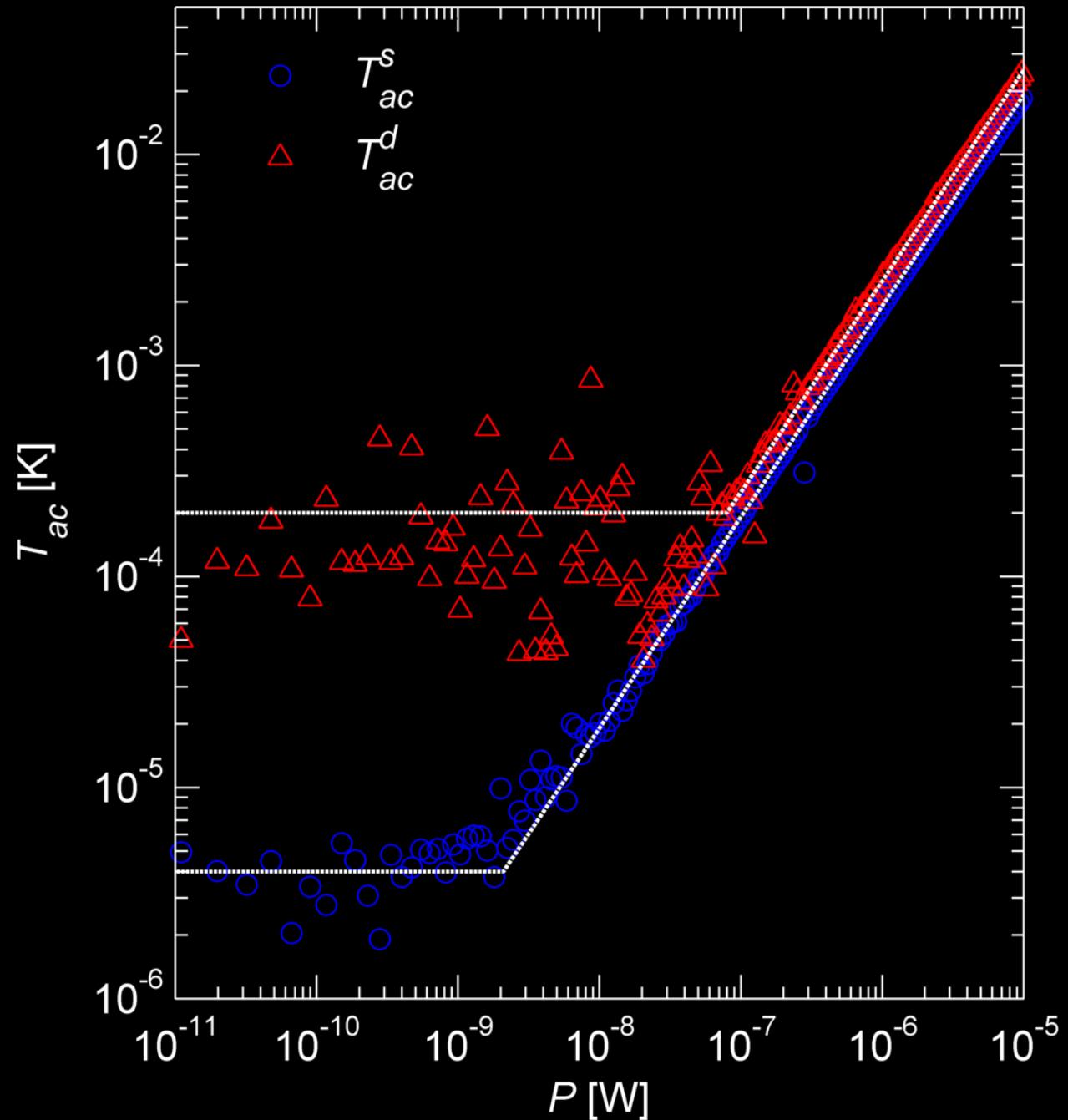
Qubit at 1 GHz:

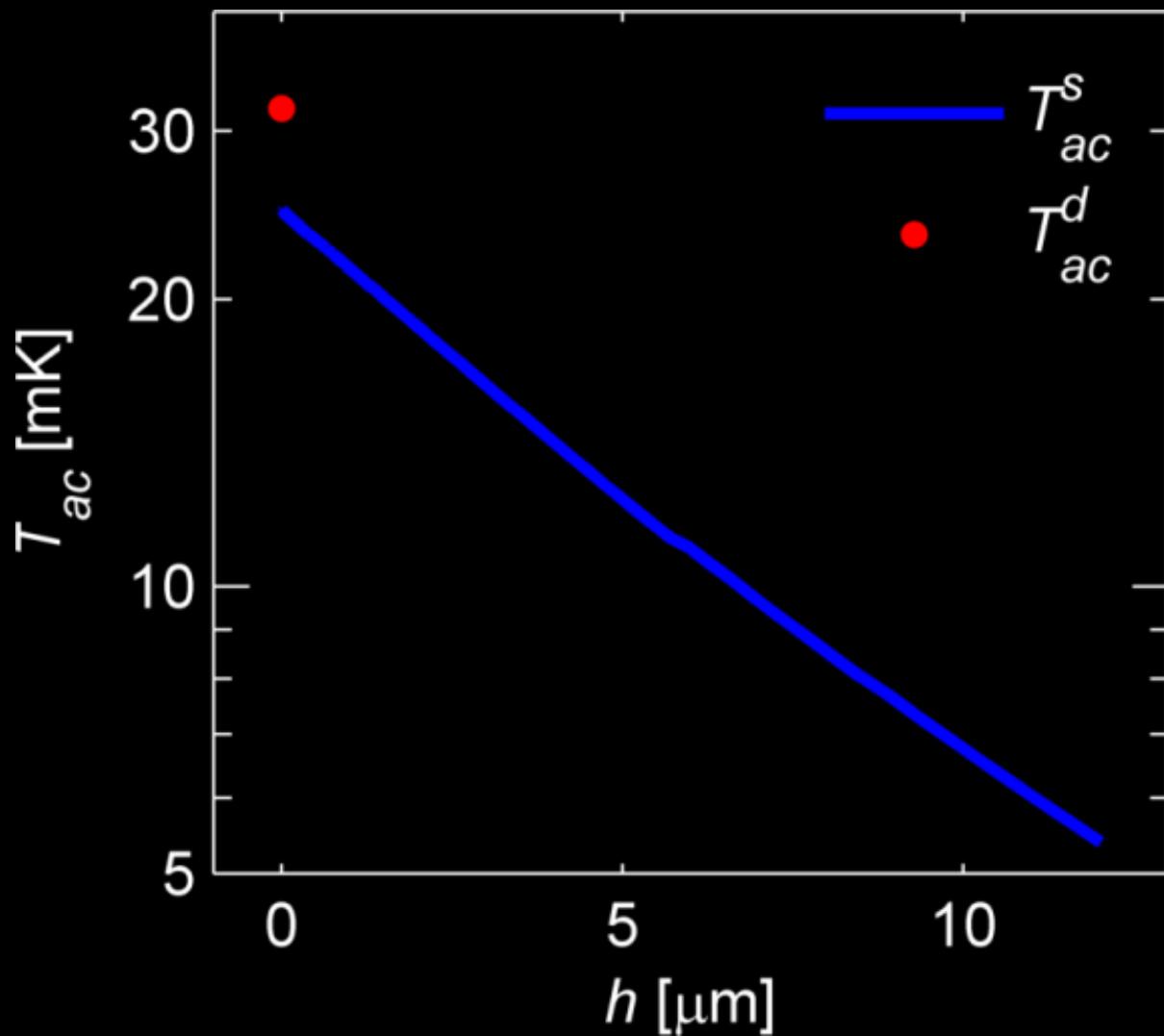
$$P = 40 \text{ fW}$$

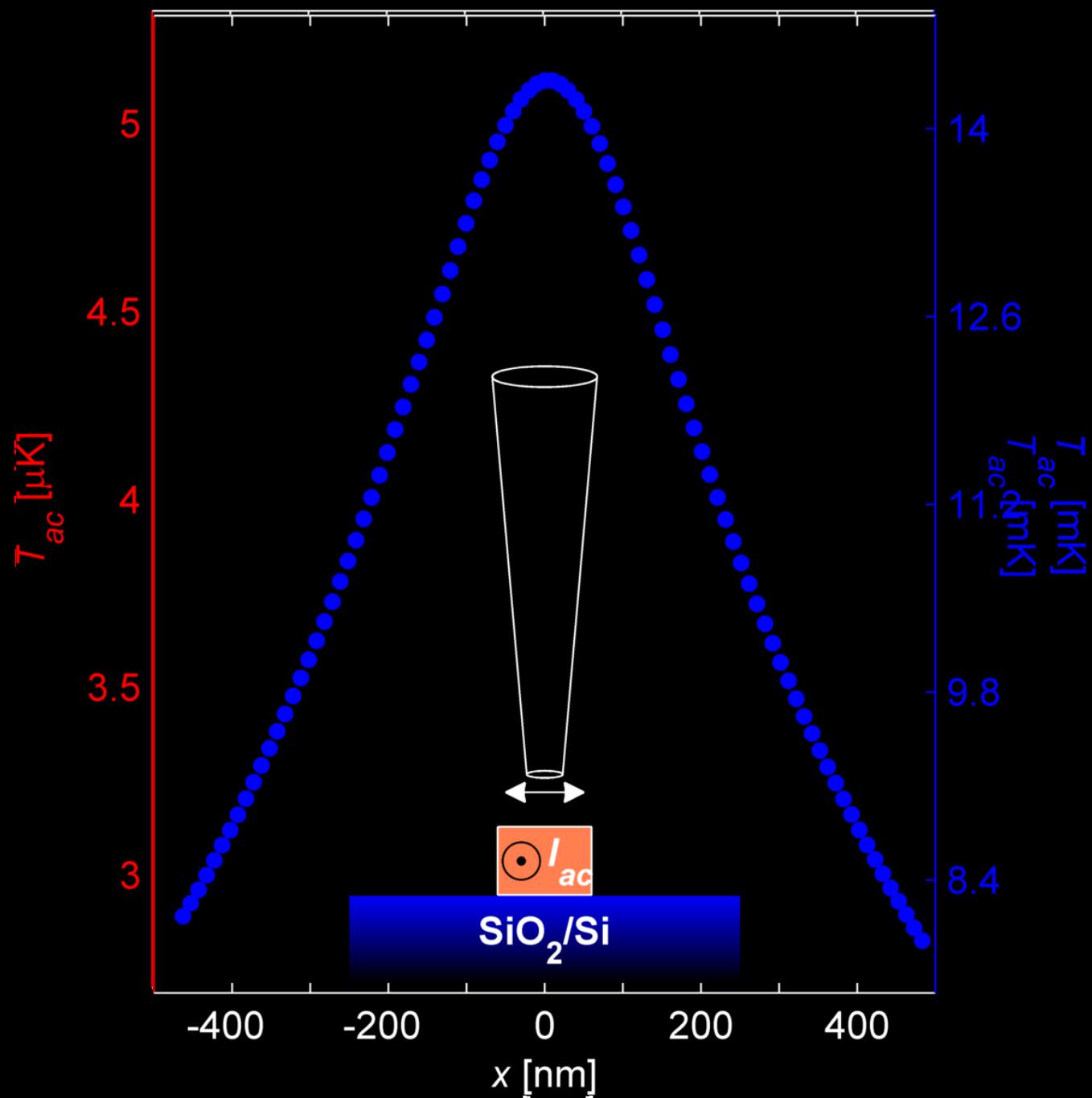


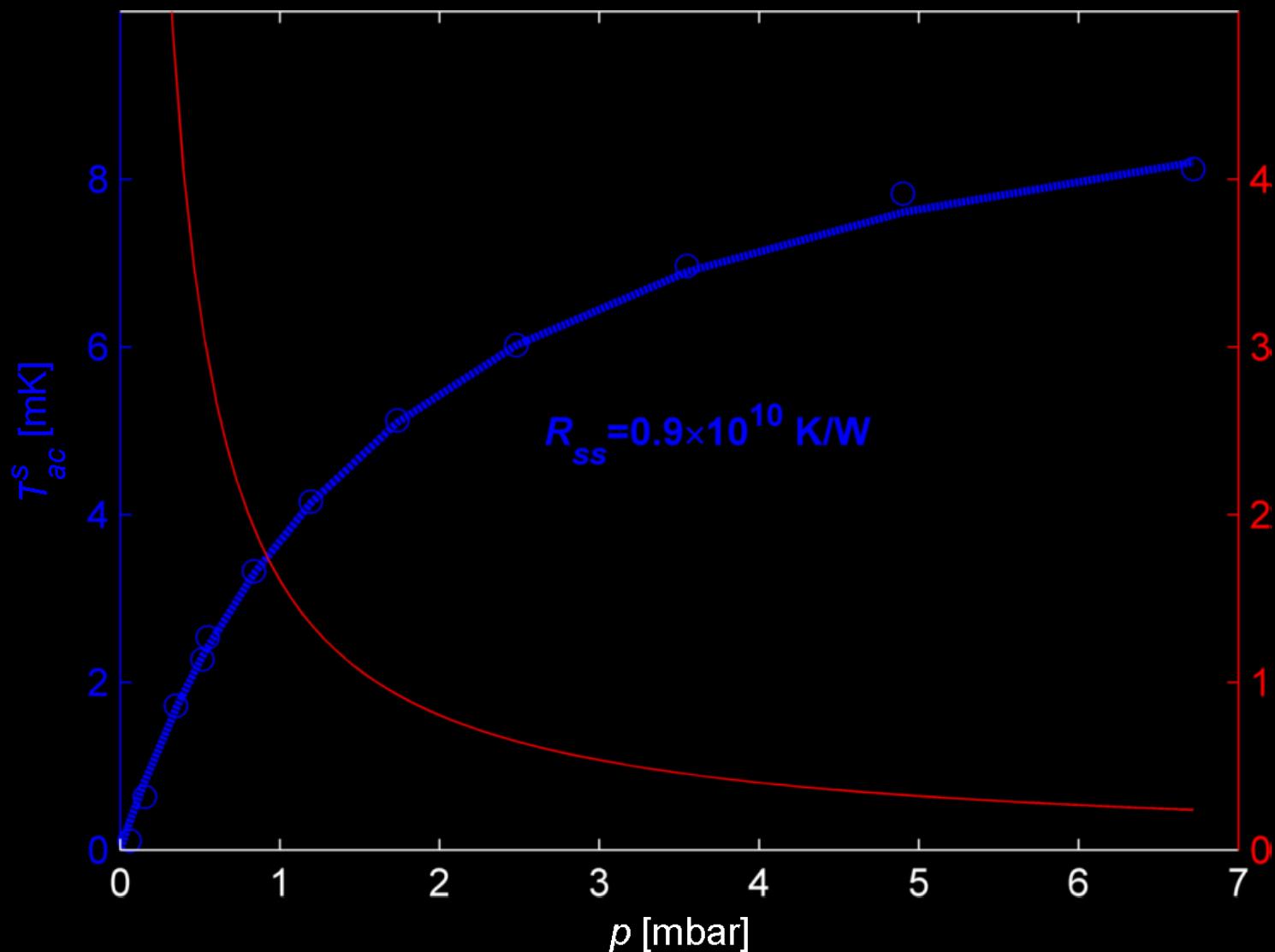
20 μm

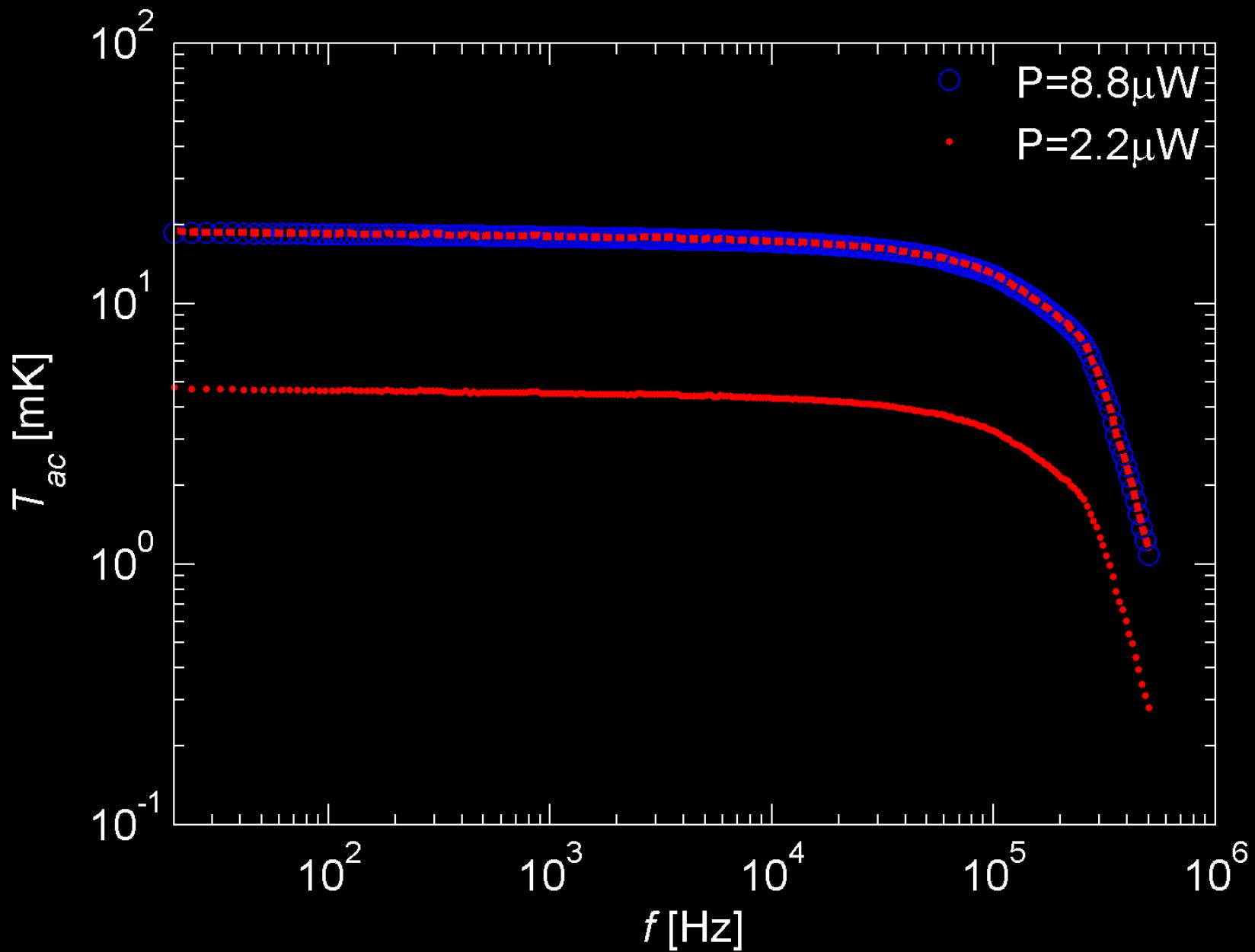


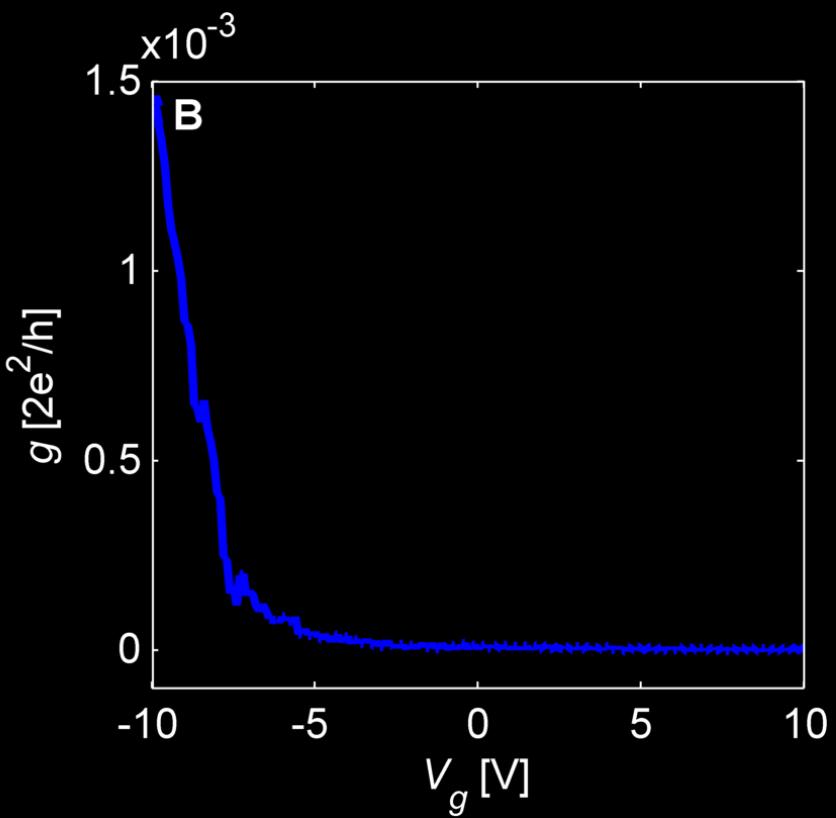
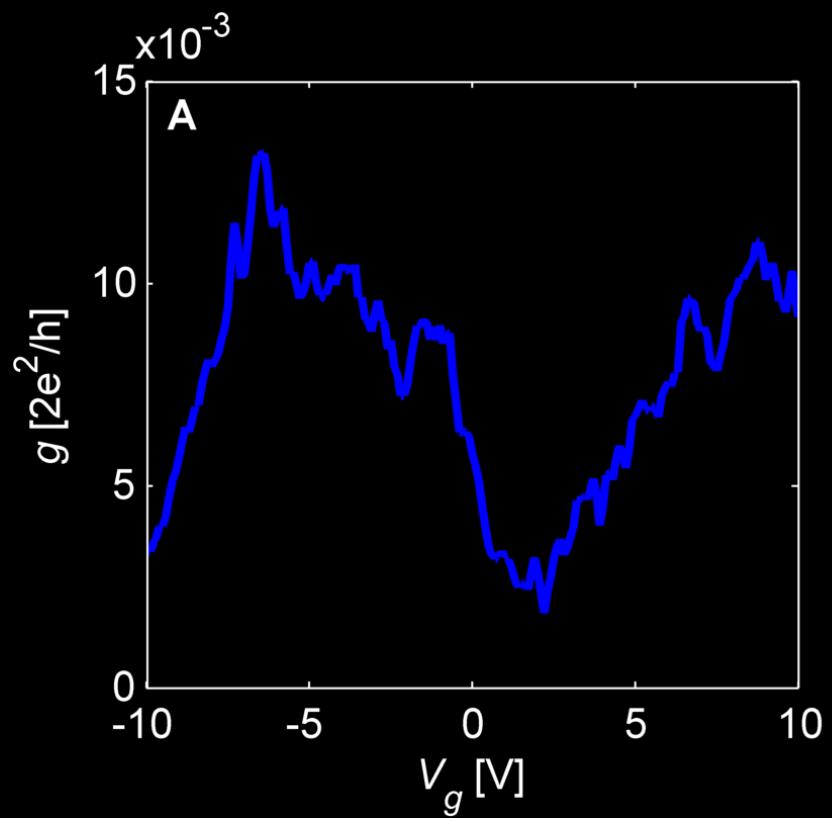




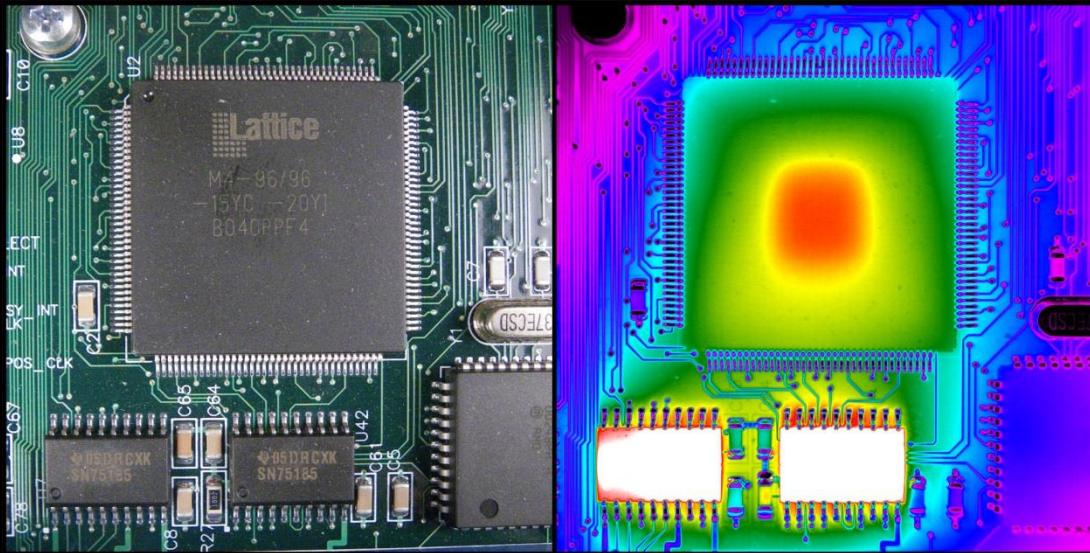




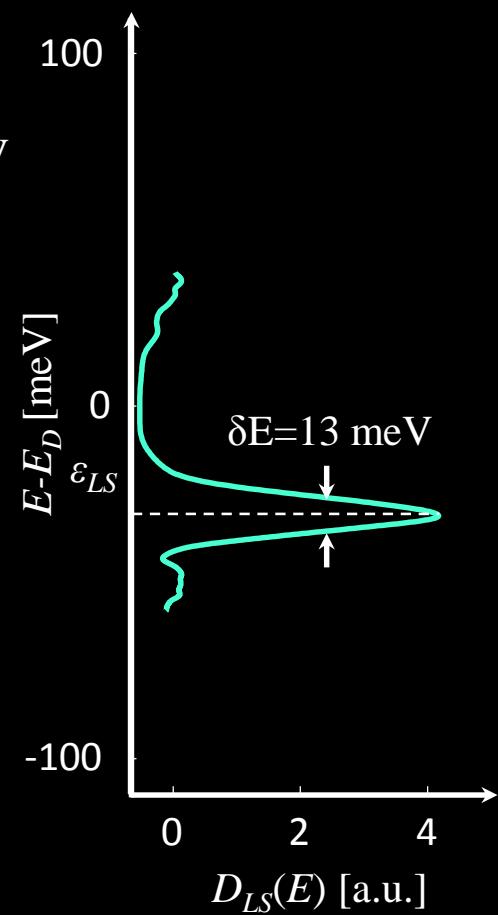
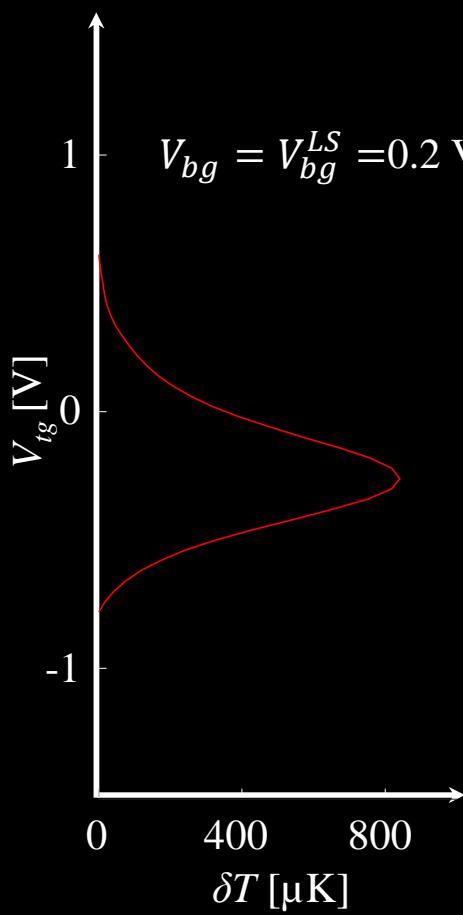
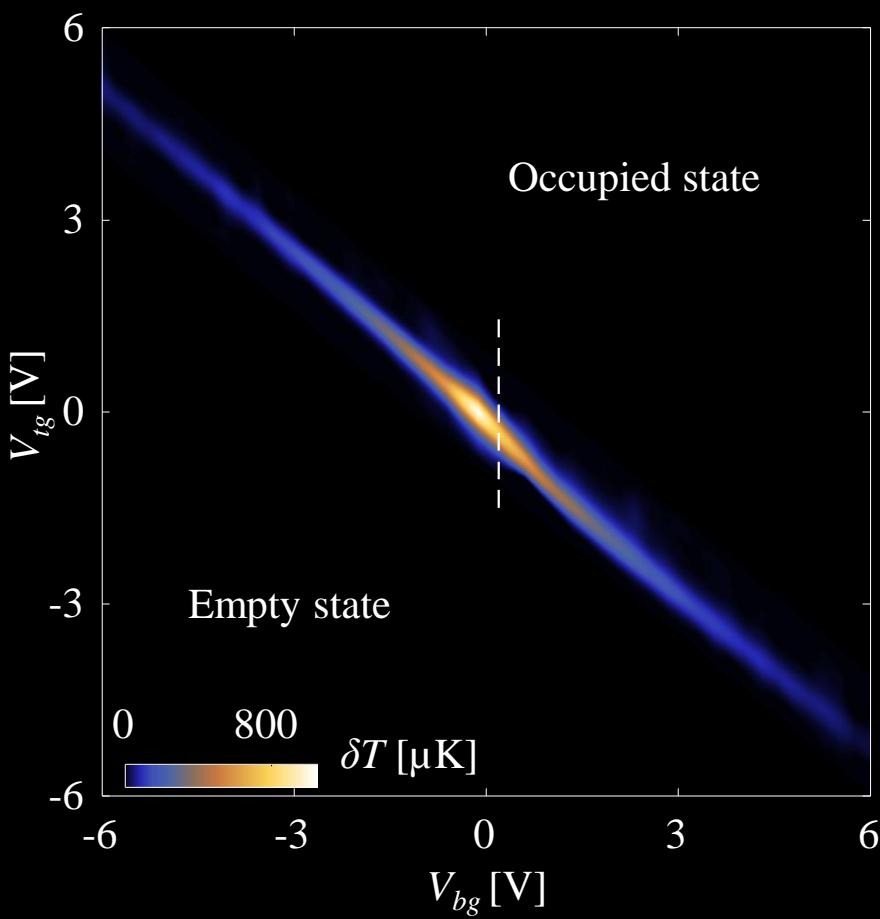
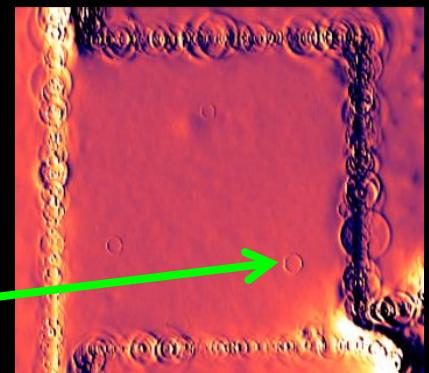




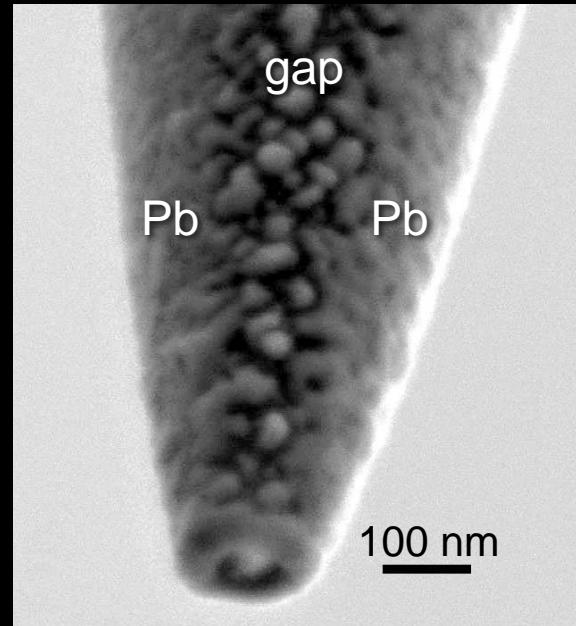
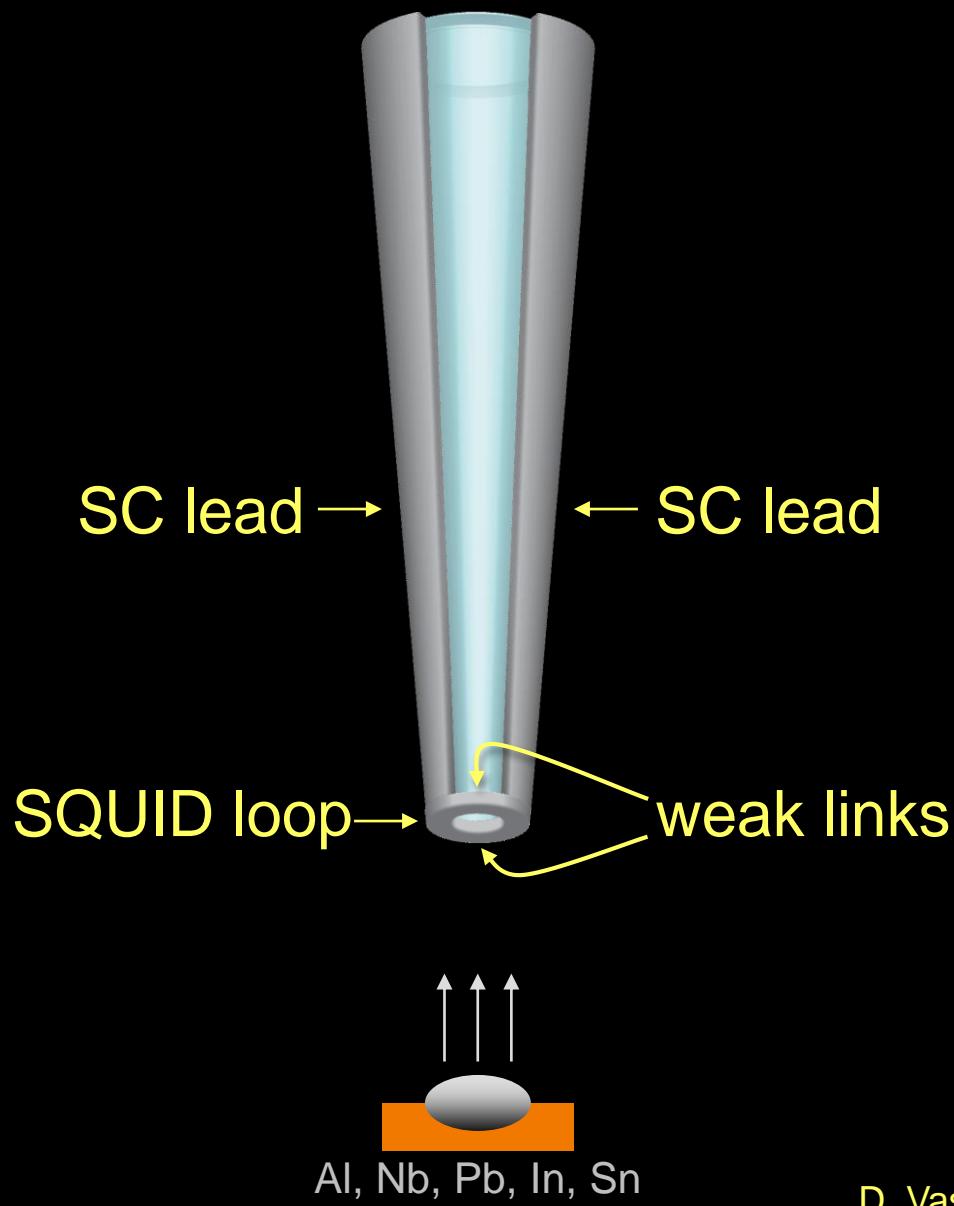
Thermal imaging



Static tSOT spectroscopy - experiment



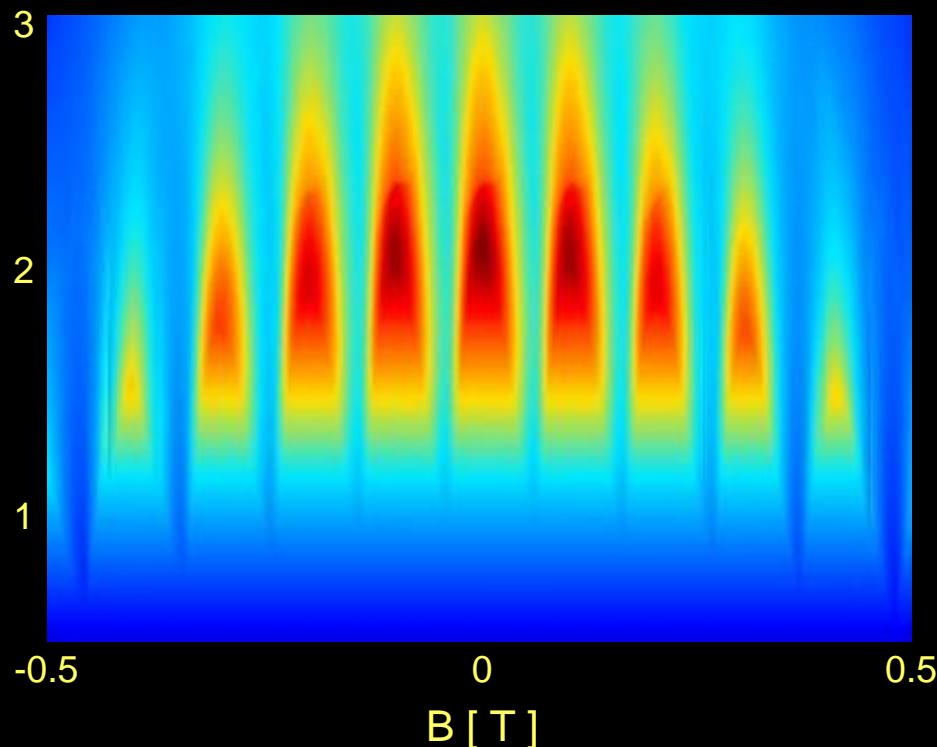
SQUID on tip



SQUID on tip

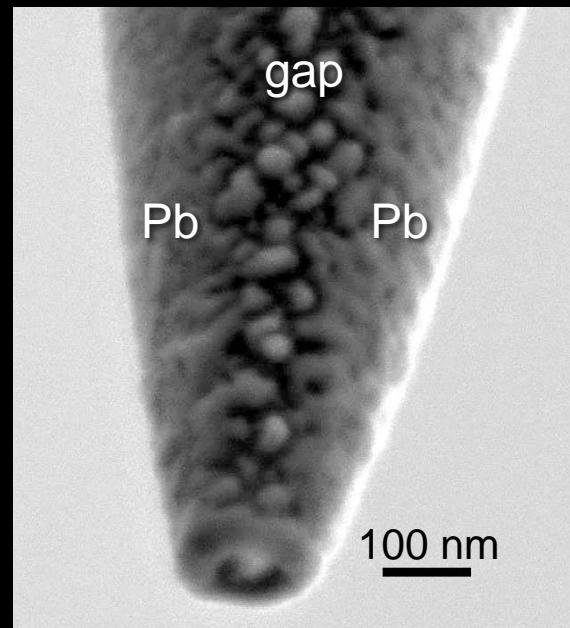
Quantum interference patterns

SQUID current ($T = 4.2 \text{ K}$)



Period = 103 mT

Loop diameter = 160 nm



Flux noise: $\sqrt{S_\Phi} = 50 \text{ n}\Phi_0/\text{Hz}^{1/2}$

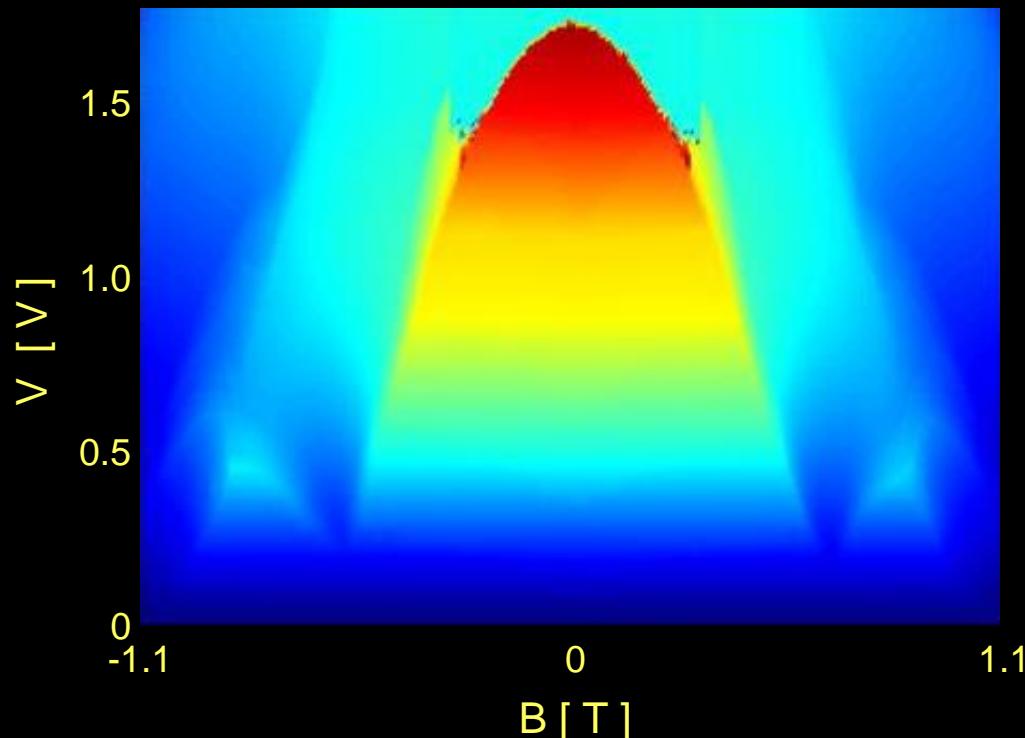
Field noise: $\sqrt{S_B} = 5.1 \text{ nT}/\text{Hz}^{1/2}$

Spin noise: $\sqrt{S_n} = 1.4 \mu_B/\text{Hz}^{1/2}$

Pb SQUID on tip

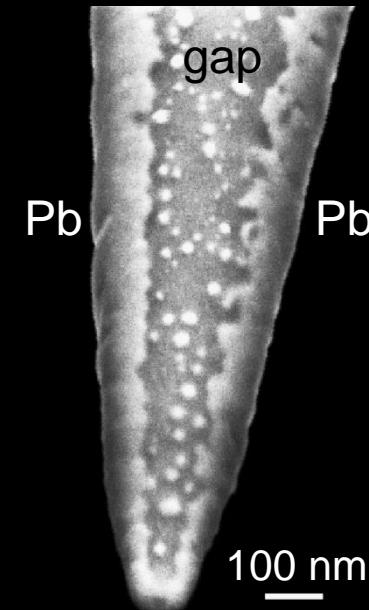
Quantum interference patterns

SQUID current ($T = 4.2 \text{ K}$)



Period = 1.27 T

Loop diameter = 46 nm

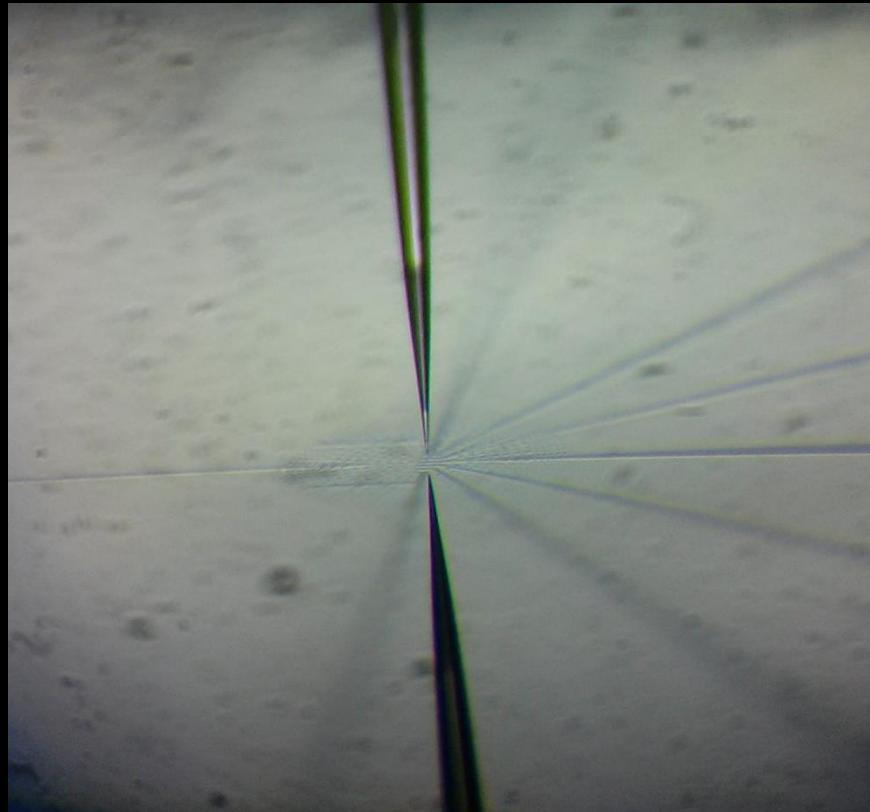


Flux noise: $\sqrt{S_\Phi} = 50 \text{ n}\Phi_0/\text{Hz}^{1/2}$

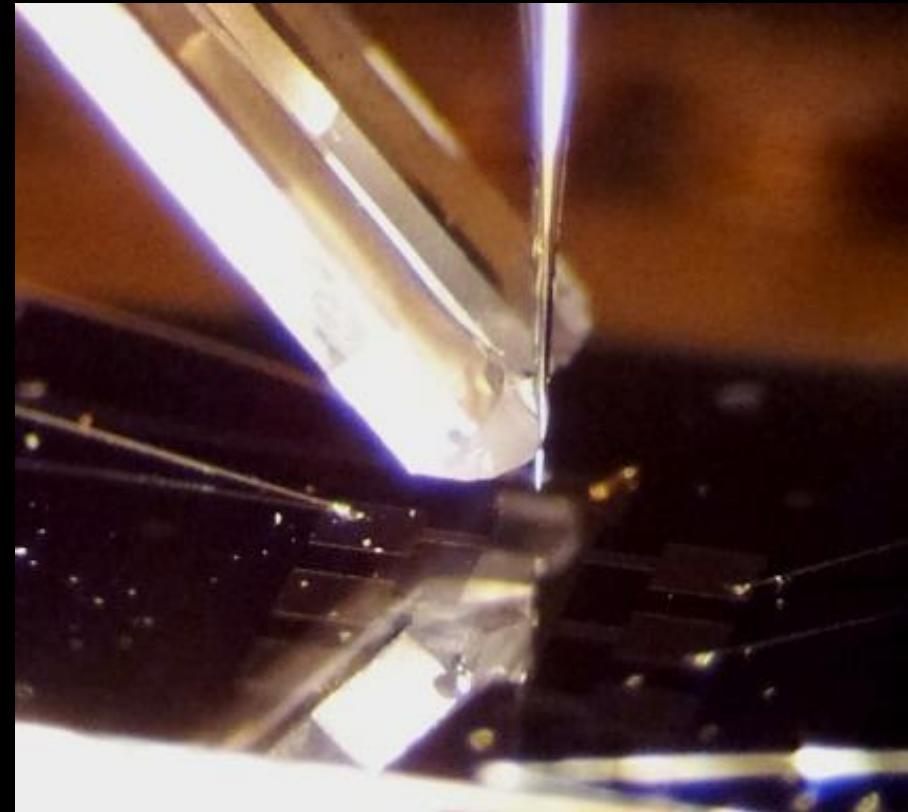
Field noise: $\sqrt{S_B} = 62 \text{ nT}/\text{Hz}^{1/2}$

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

Sample approach

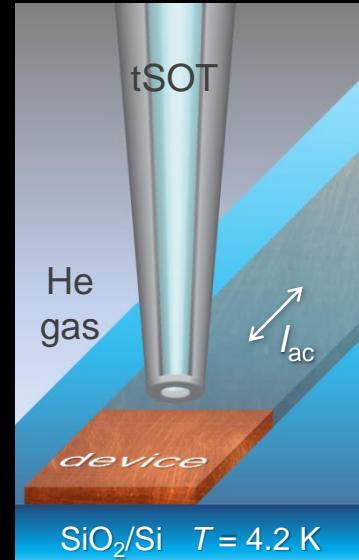
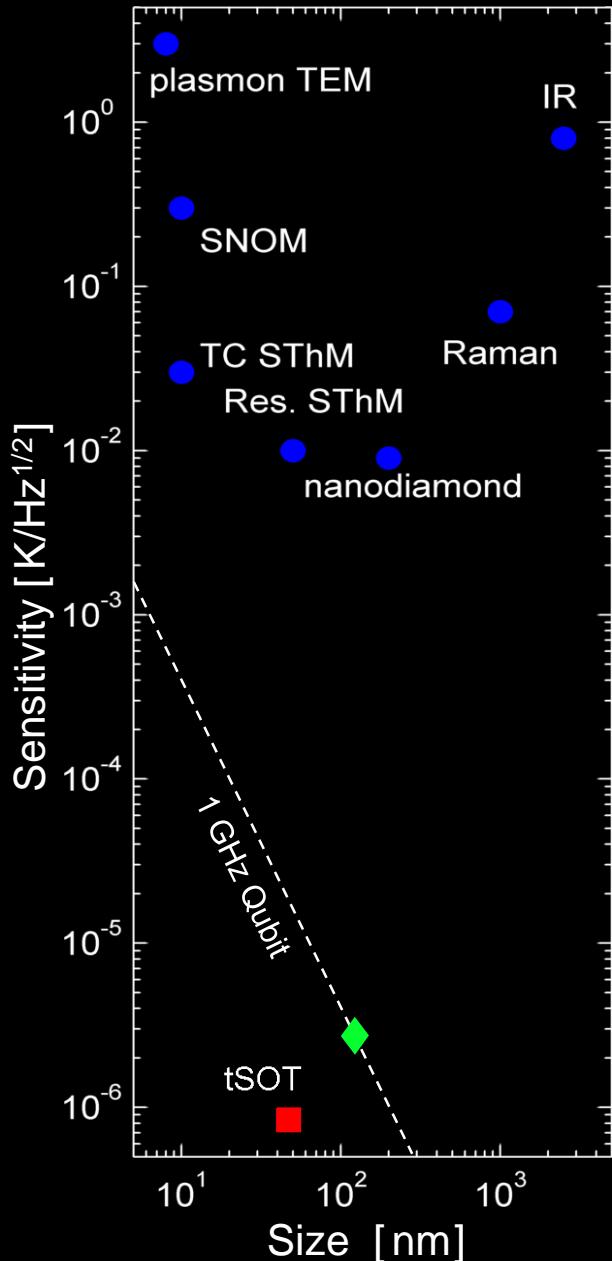


Bare SQUID on tip



SQUID on tip glued to tuning fork

Thermal sensitivity



$$R_{ss} \gg R_{sd} \gg R_{db}$$

\uparrow

$$R_{ss} \approx 10^{11} \text{ K/W}$$

$$R_{sd} \approx 10^8 - 10^{10} \text{ K/W}$$

$$R_{db} \approx 10^7 \text{ K/W}$$

T_s T_d

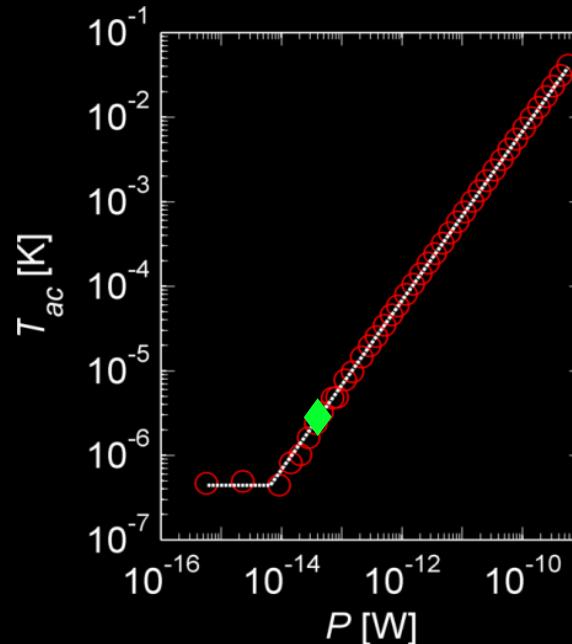


Figure of merit:
Landauer's limit of energy
dissipation for irreversible
qubit readout

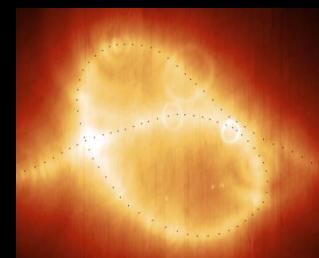
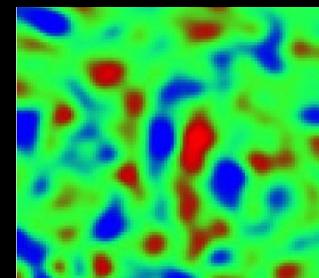
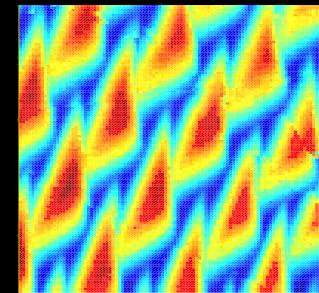
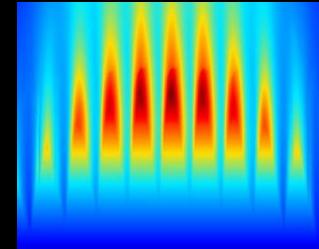
$$E = k_B T \ln 2 = 4 \times 10^{-23} \text{ J}$$

Qubit at 1 GHz:

$$P = 40 \text{ fW}$$

Outline

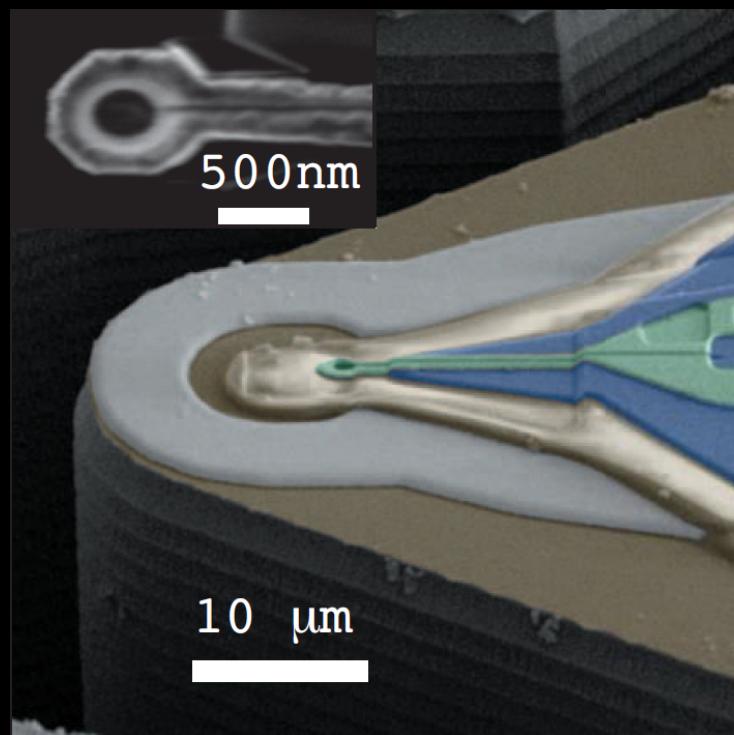
- Introduction
- SQUID-on-tip
- Superparamagnetism in TI
- Thermal nanoscale imaging



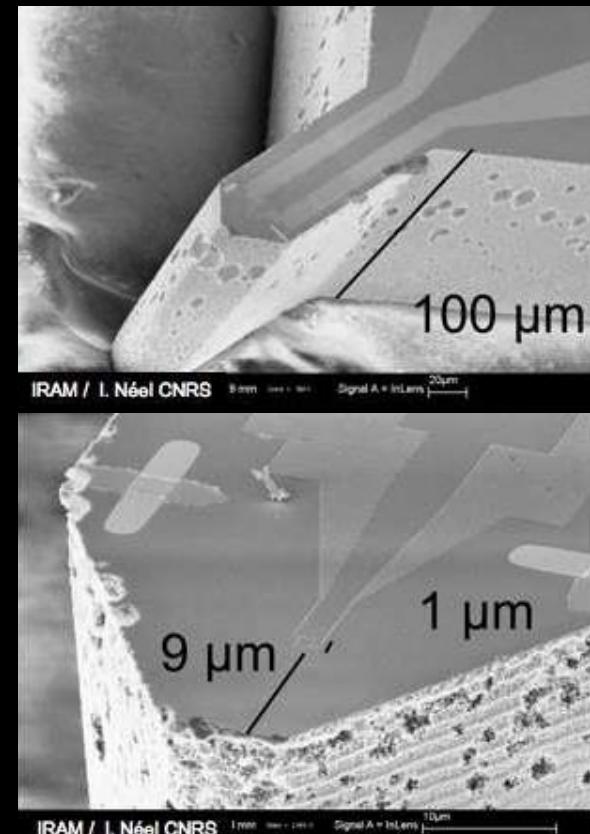
Scanning SQUID microscopy methods



Wissberg *et al.*
Physica C (2017)

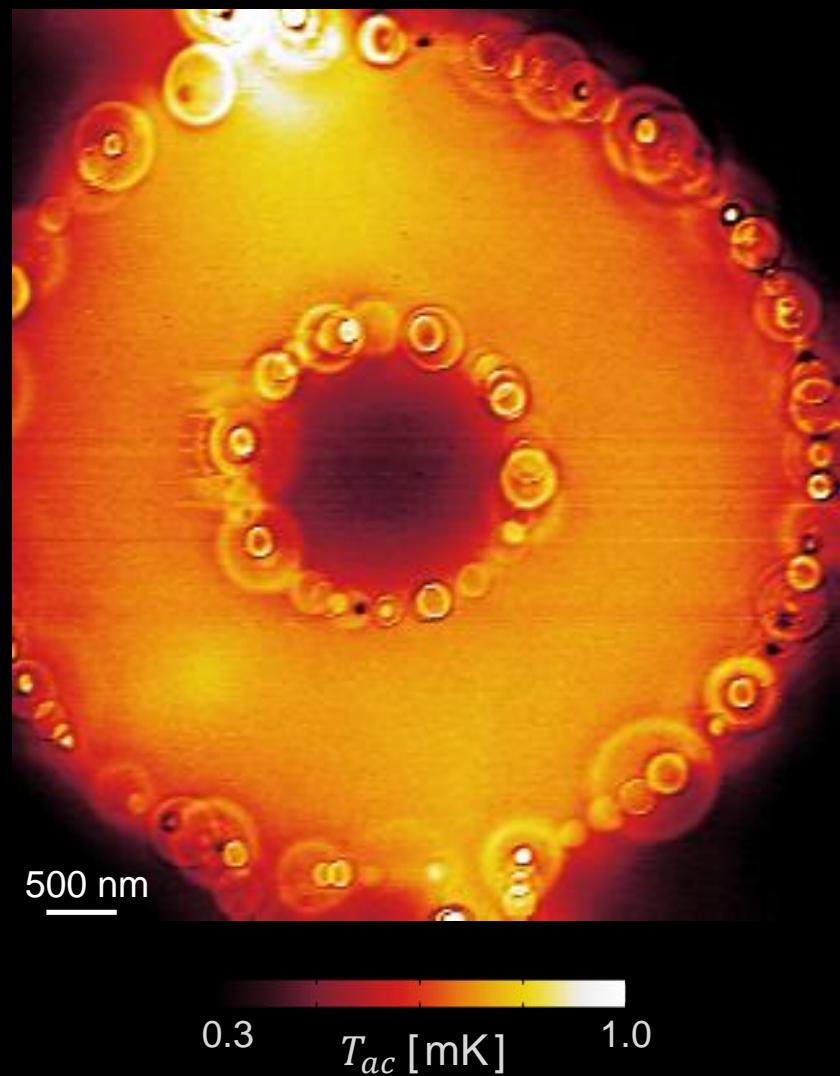
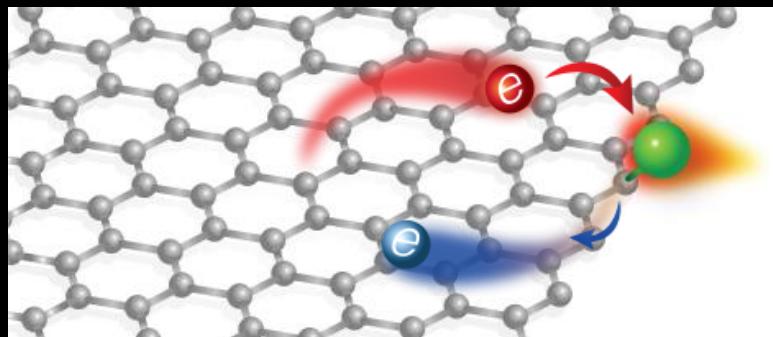


Koshnick *et al.*
APL (2008)

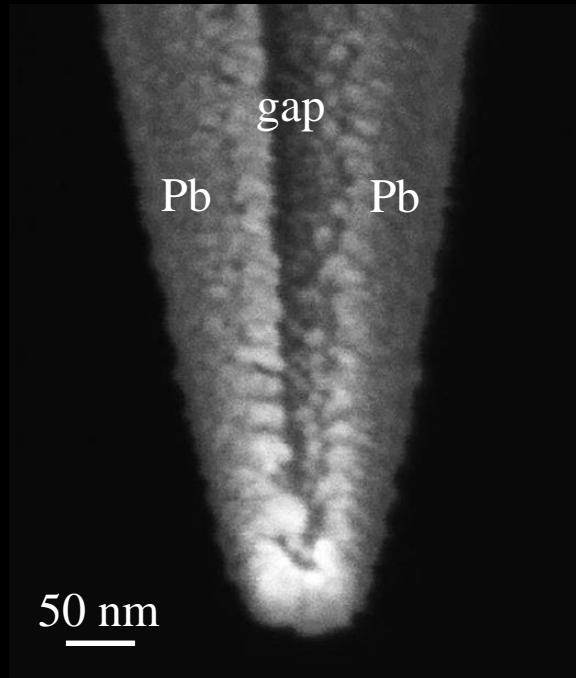


Hasselbach *et al.*
J. Phys. (2008)

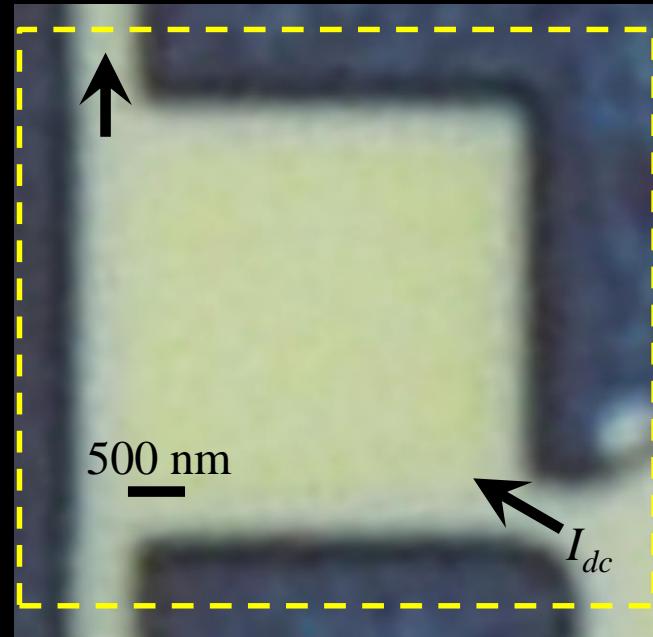
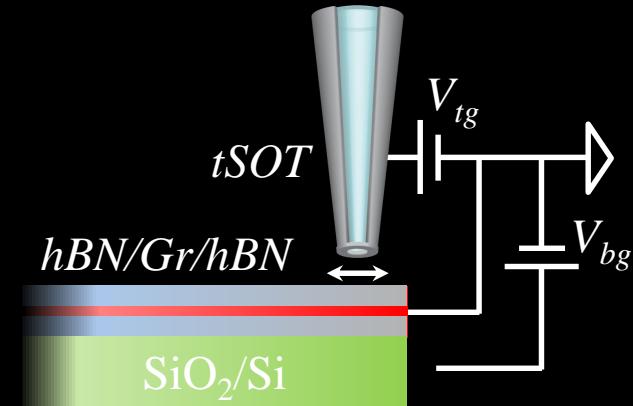
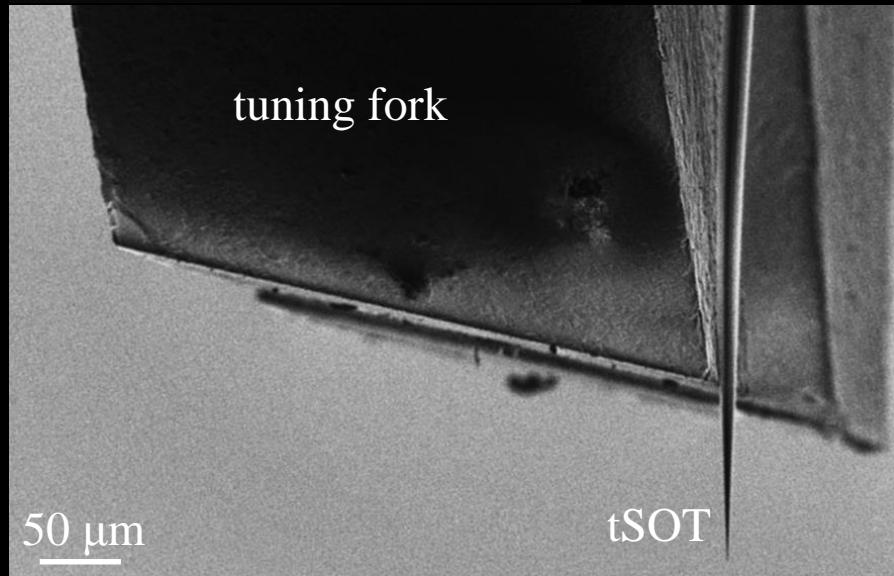
Dissipation in hBN encapsulated graphene



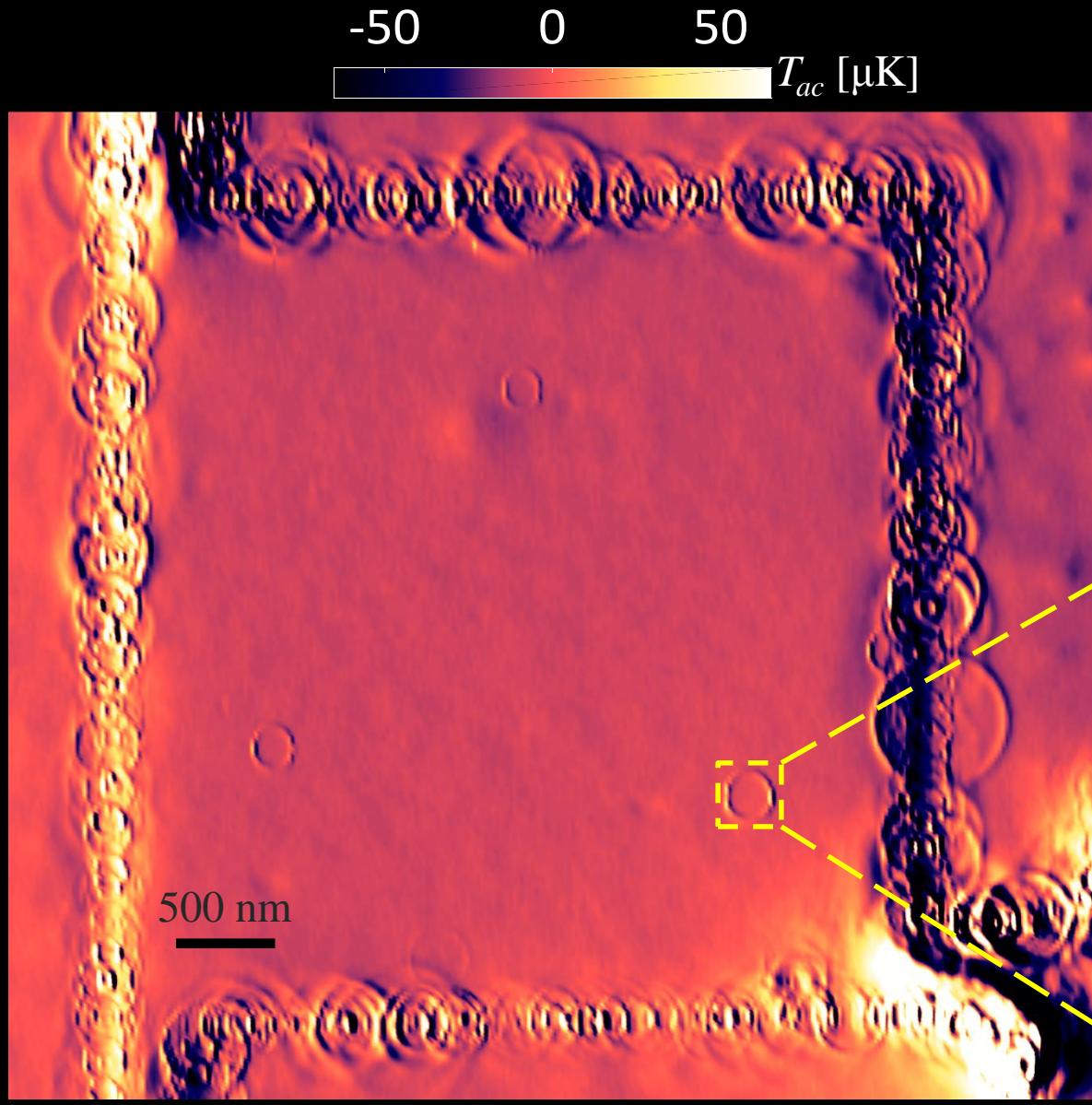
Dissipation in Graphene – measurement setup



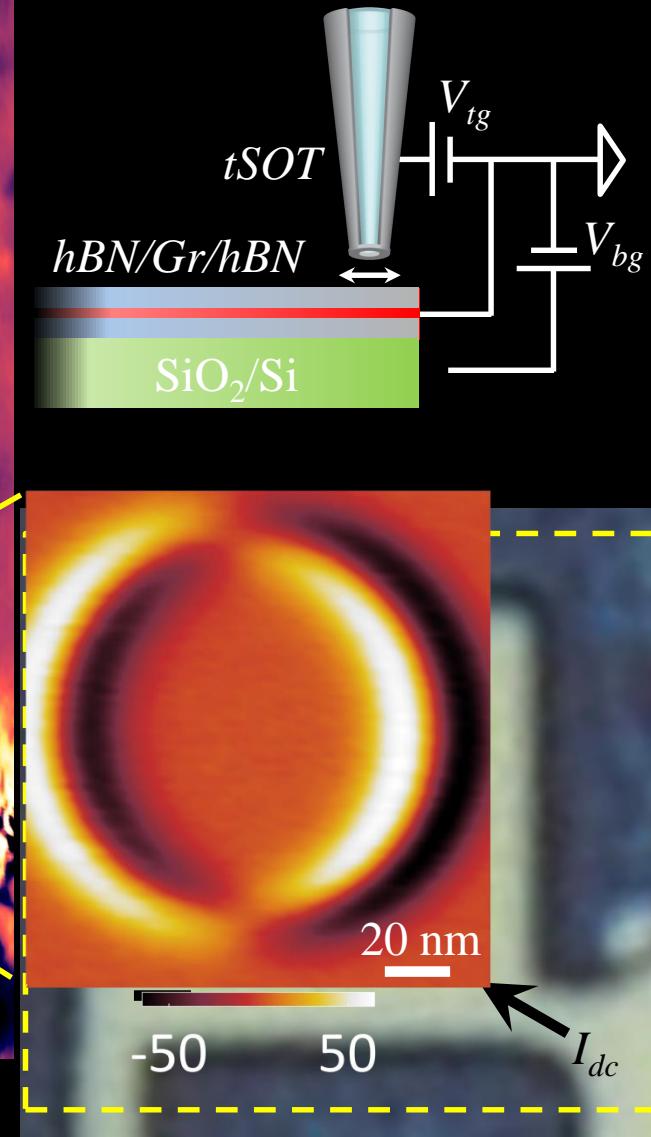
$D = 33 \text{ nm}$
Sens. = $510 \text{ nK}/\sqrt{\text{Hz}}$
 $h = 10\text{-}20 \text{ nm}$



Dissipation in Graphene

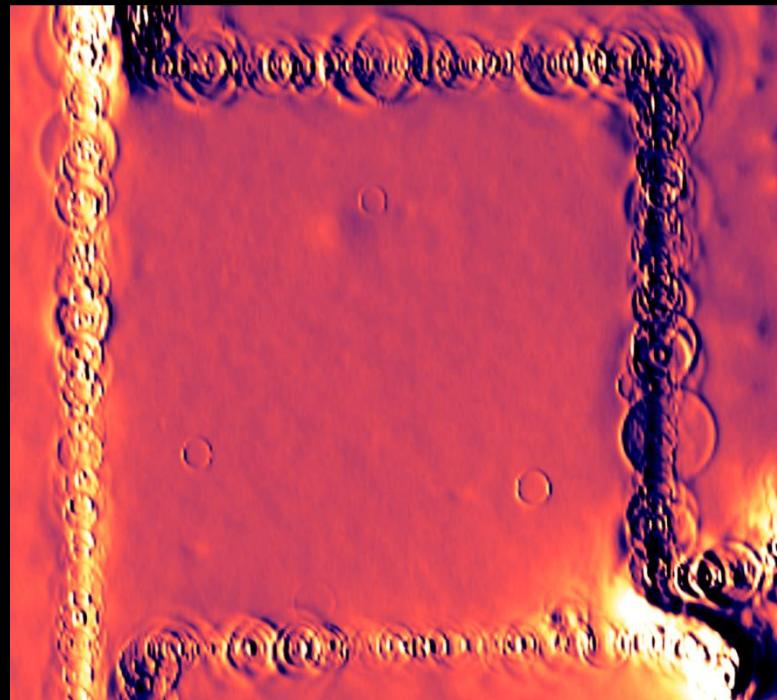


$I_{dc} = 3 \mu\text{A}$, $h = 20 \text{ nm}$, $V_{bg} = 2 \text{ V}$



Dissipation by Localized States at Graphene Defects

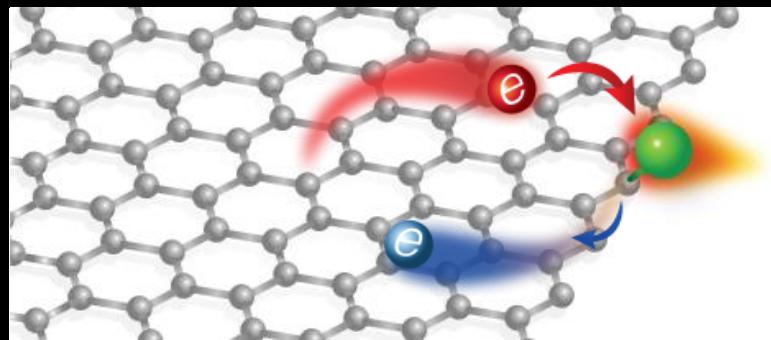
- Large inelastic λ_{e-ph}
→ Non-thermalized electrons are everywhere
- Localized states allow electron relaxation
- Defects exist
 - Create localized electronic states
 - States pinned to graphene CNP



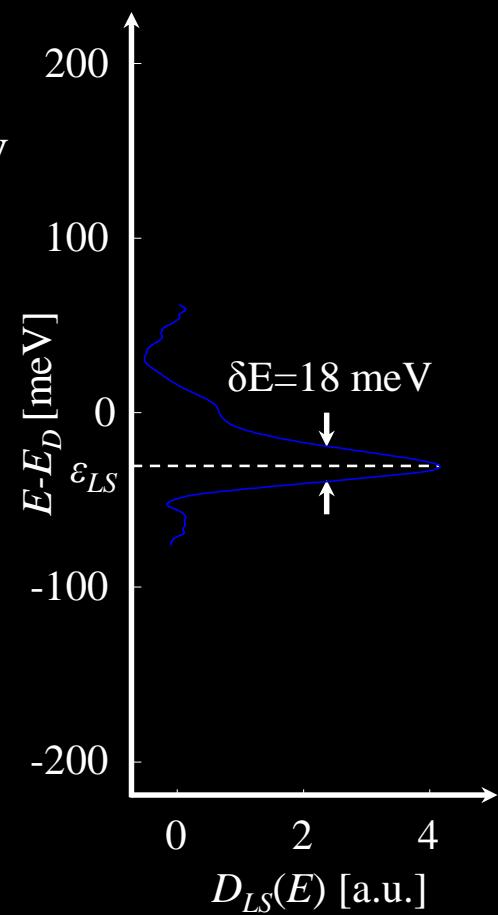
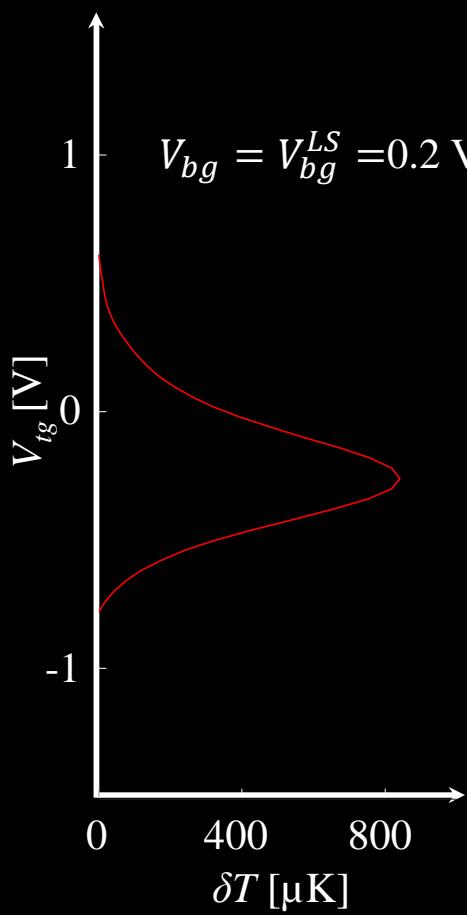
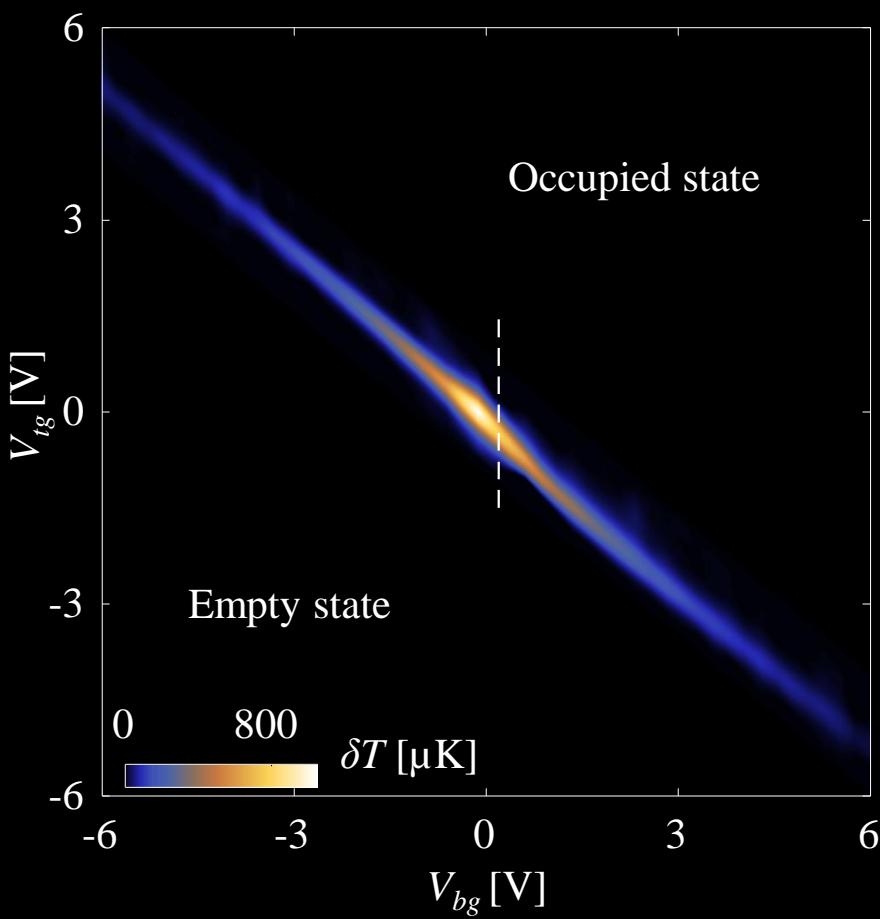
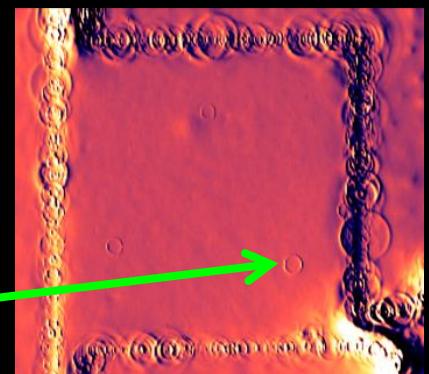
Defects

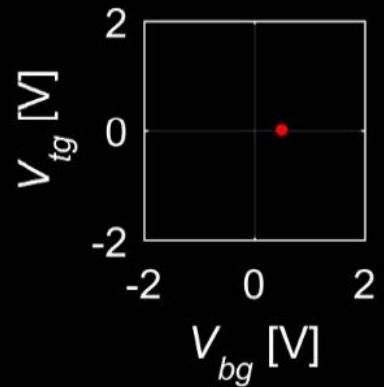
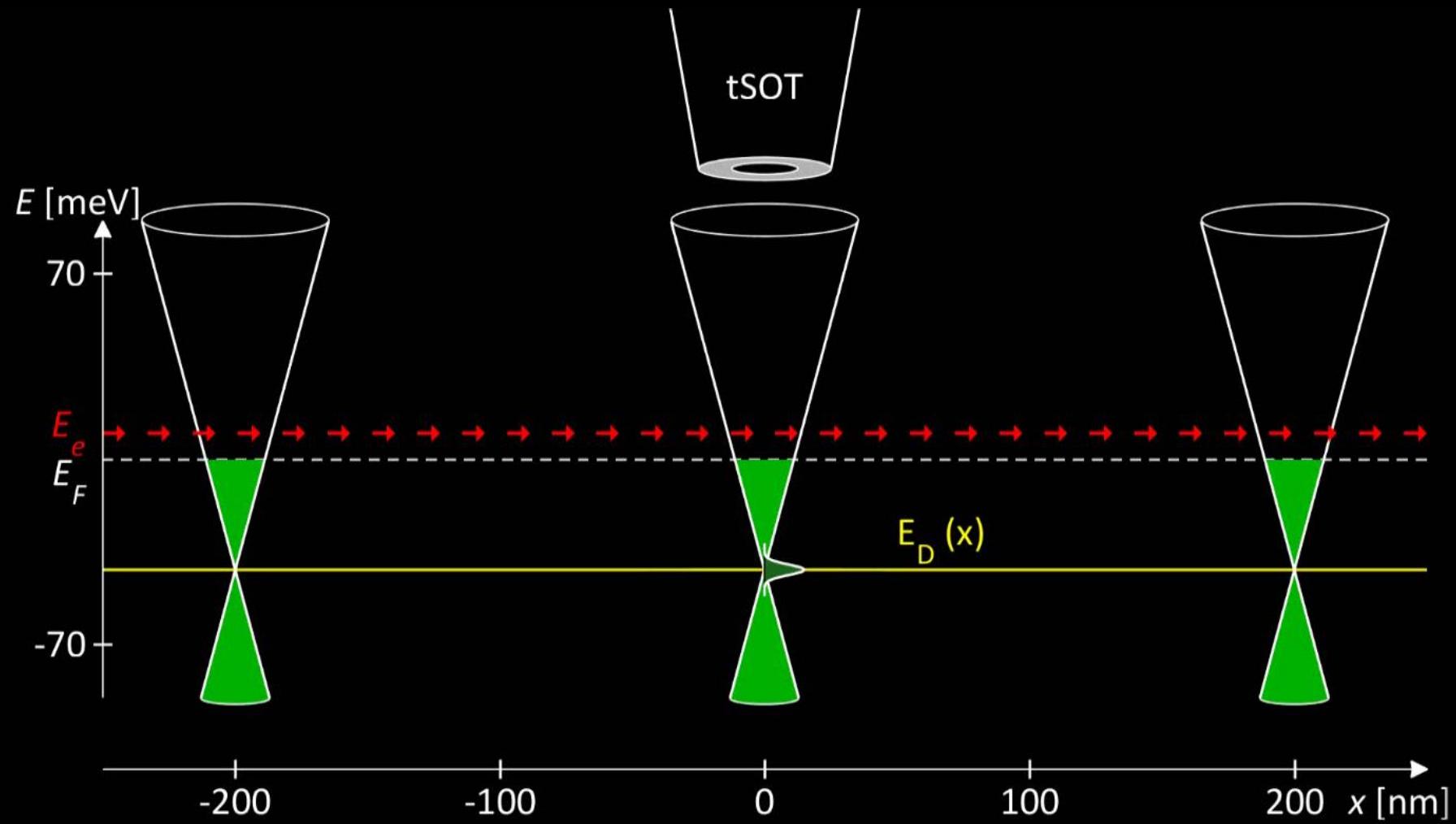
- Localized states
- Heat Dissipation by non-thermalized e

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

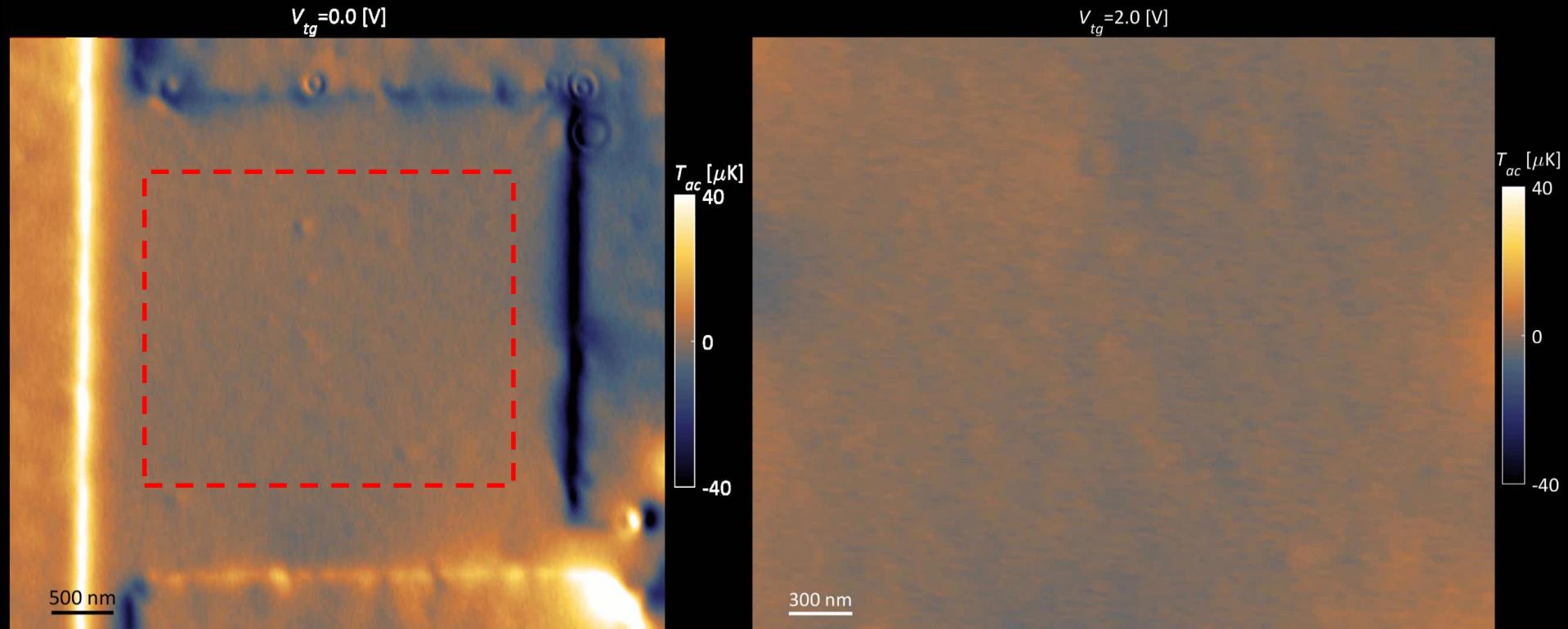


Static tSOT spectroscopy - experiment

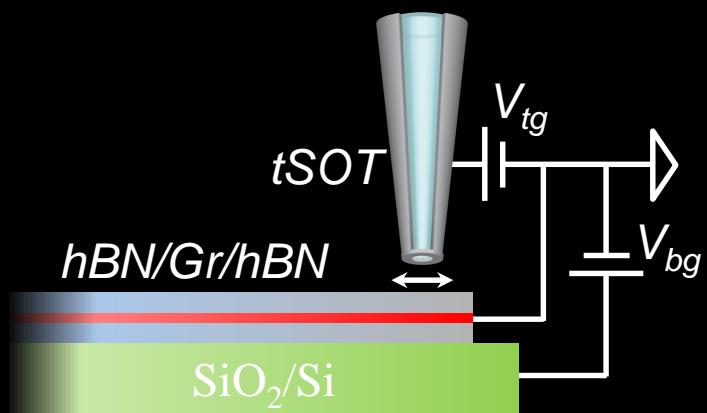




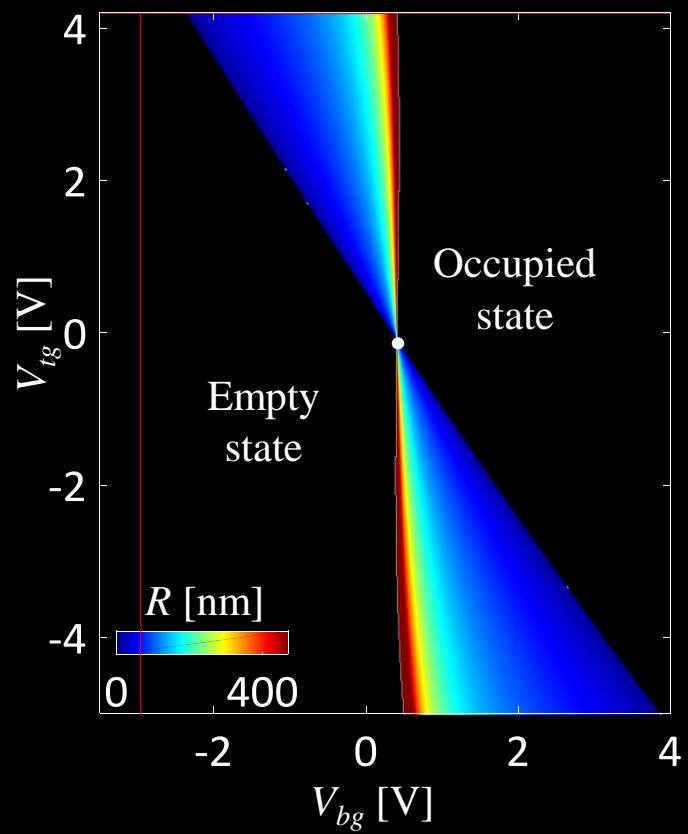
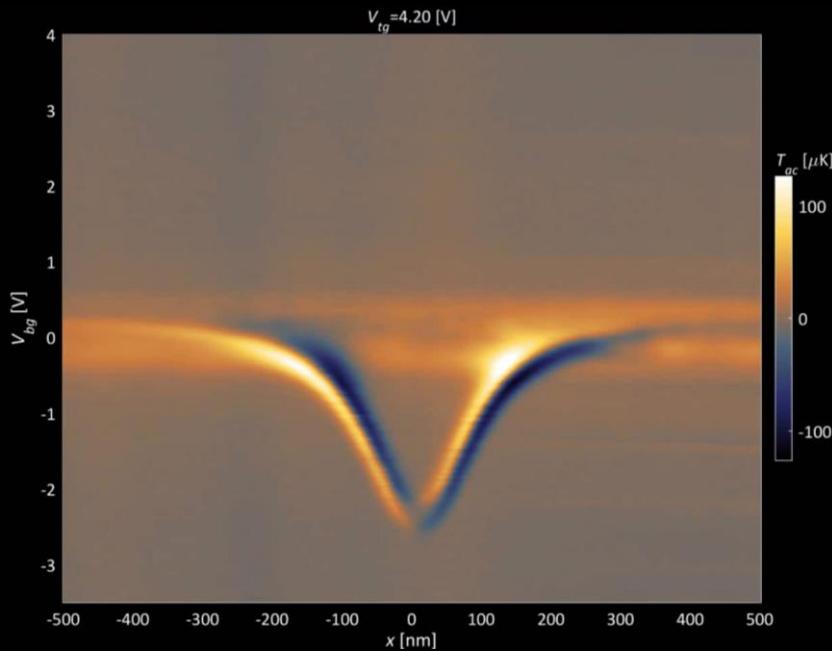
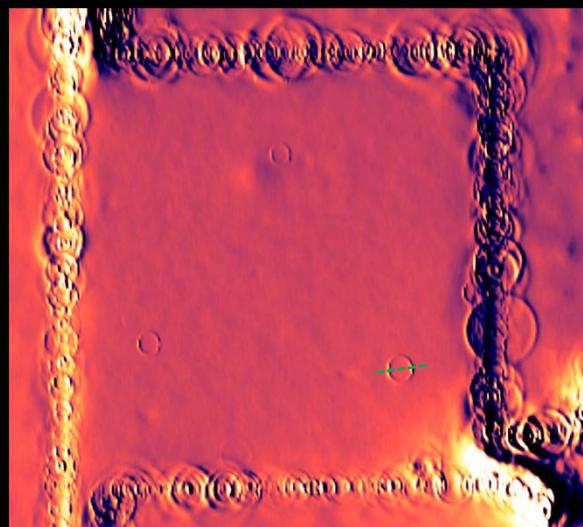
Dissipation in Graphene – evolution of rings



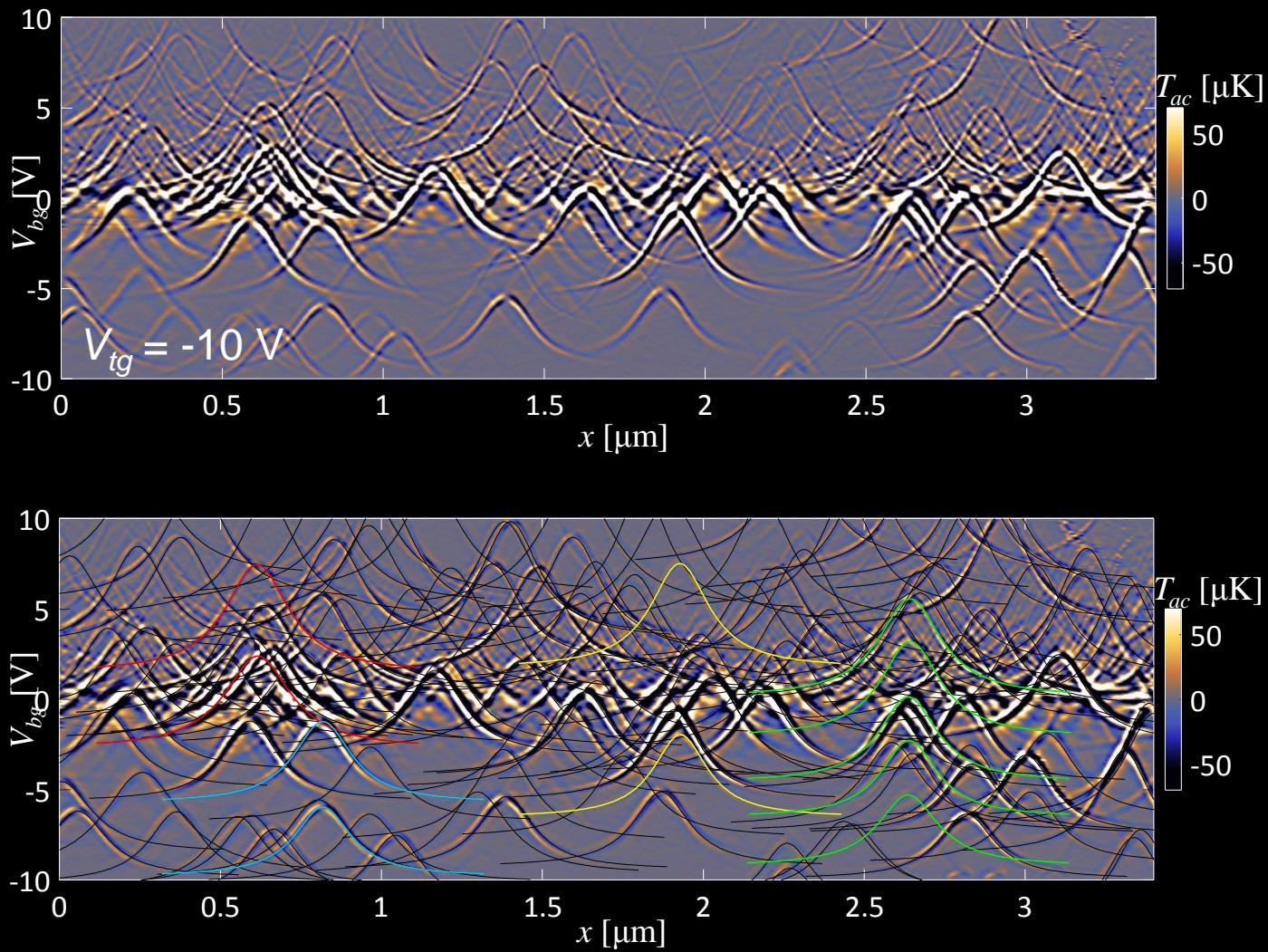
$I_{dc} = 3 \mu\text{A}$
 $h = 20 \text{ nm}$
 $V_{bg} = 2 \text{ V}$



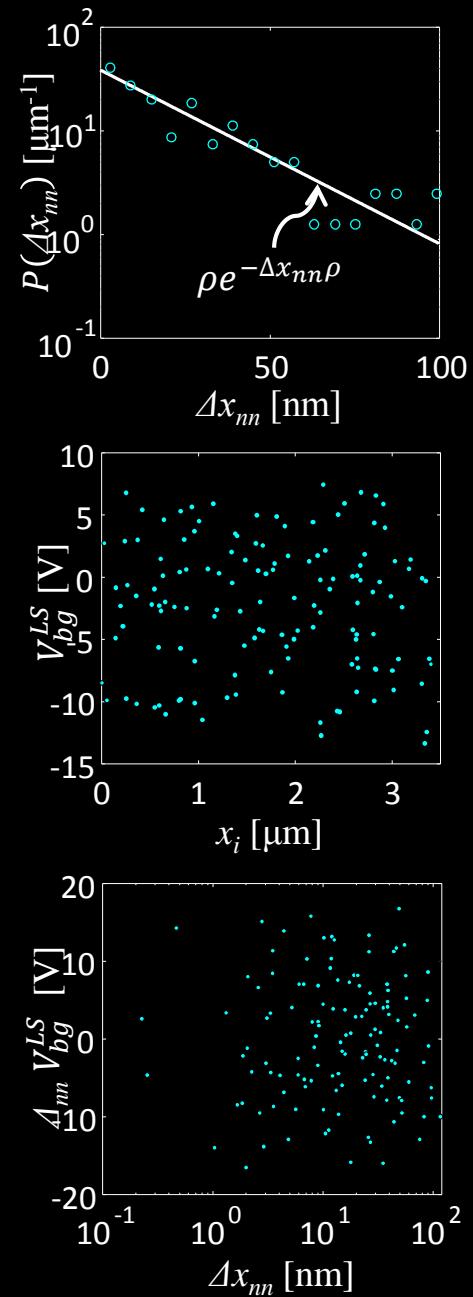
Moving tSOT spectroscopy - experiment



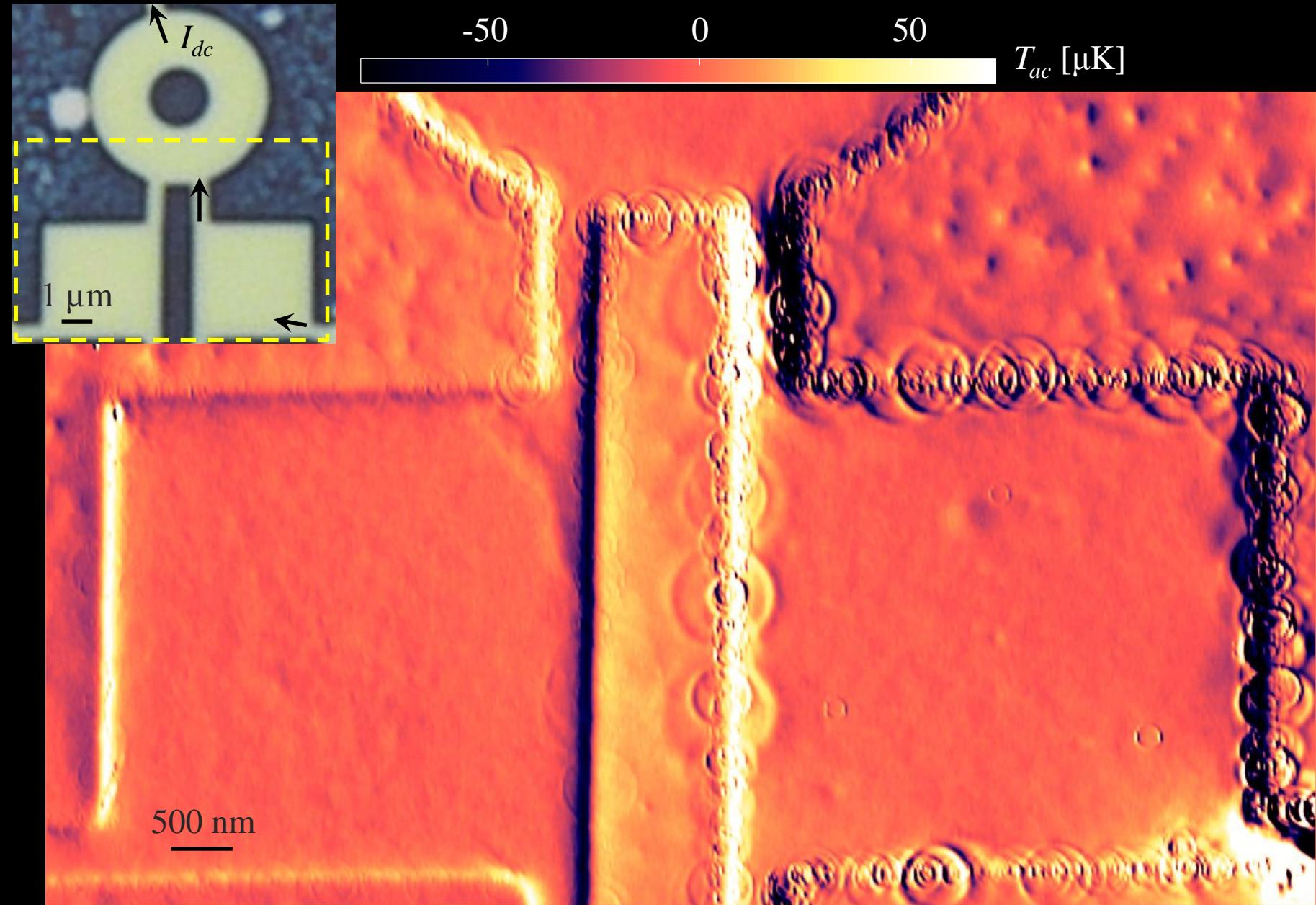
Edge defects analysis



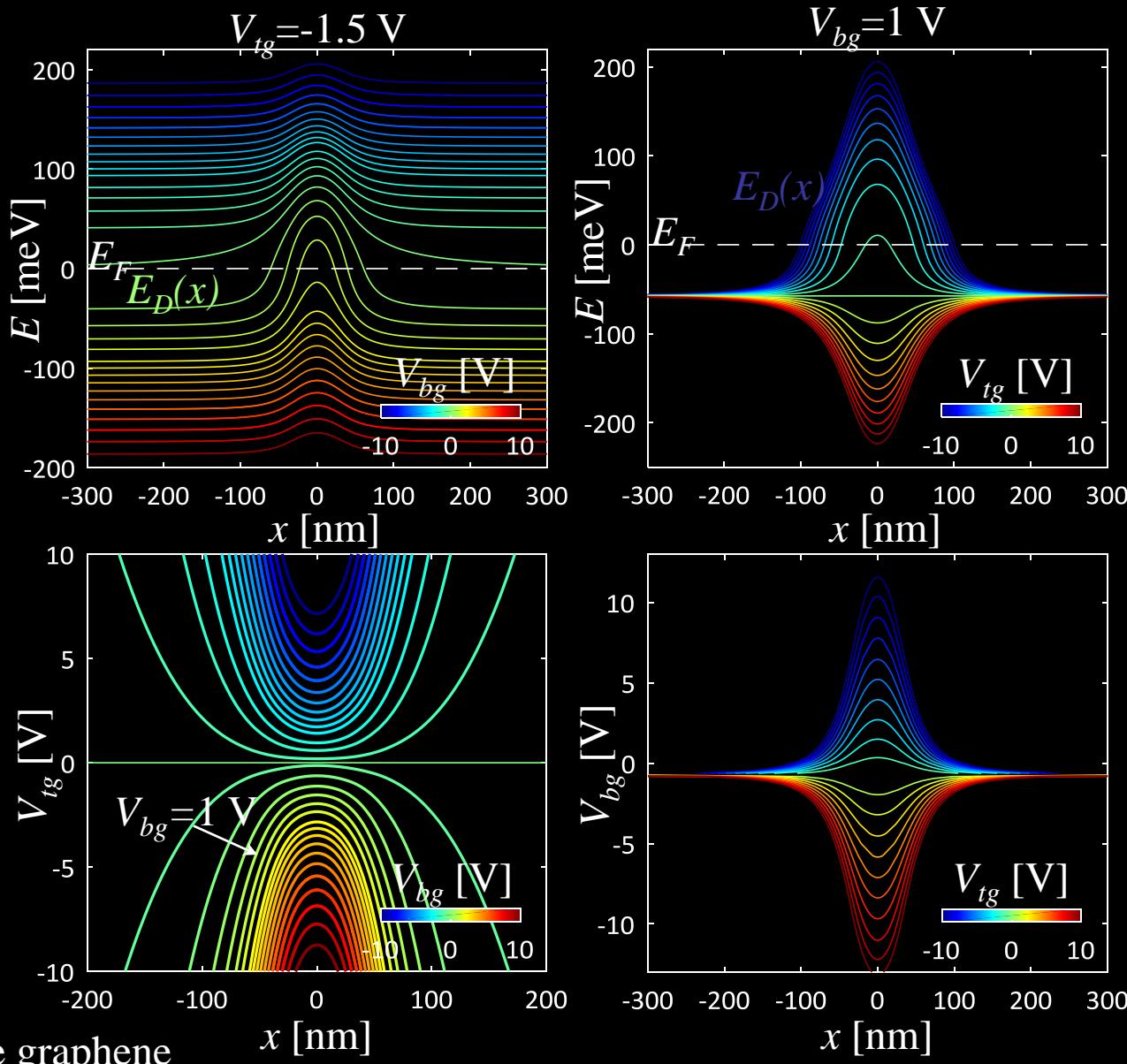
$$\rho = 135 \text{ defects}/3.5\mu\text{m} \sim 40 \text{ defects}/\mu\text{m}$$

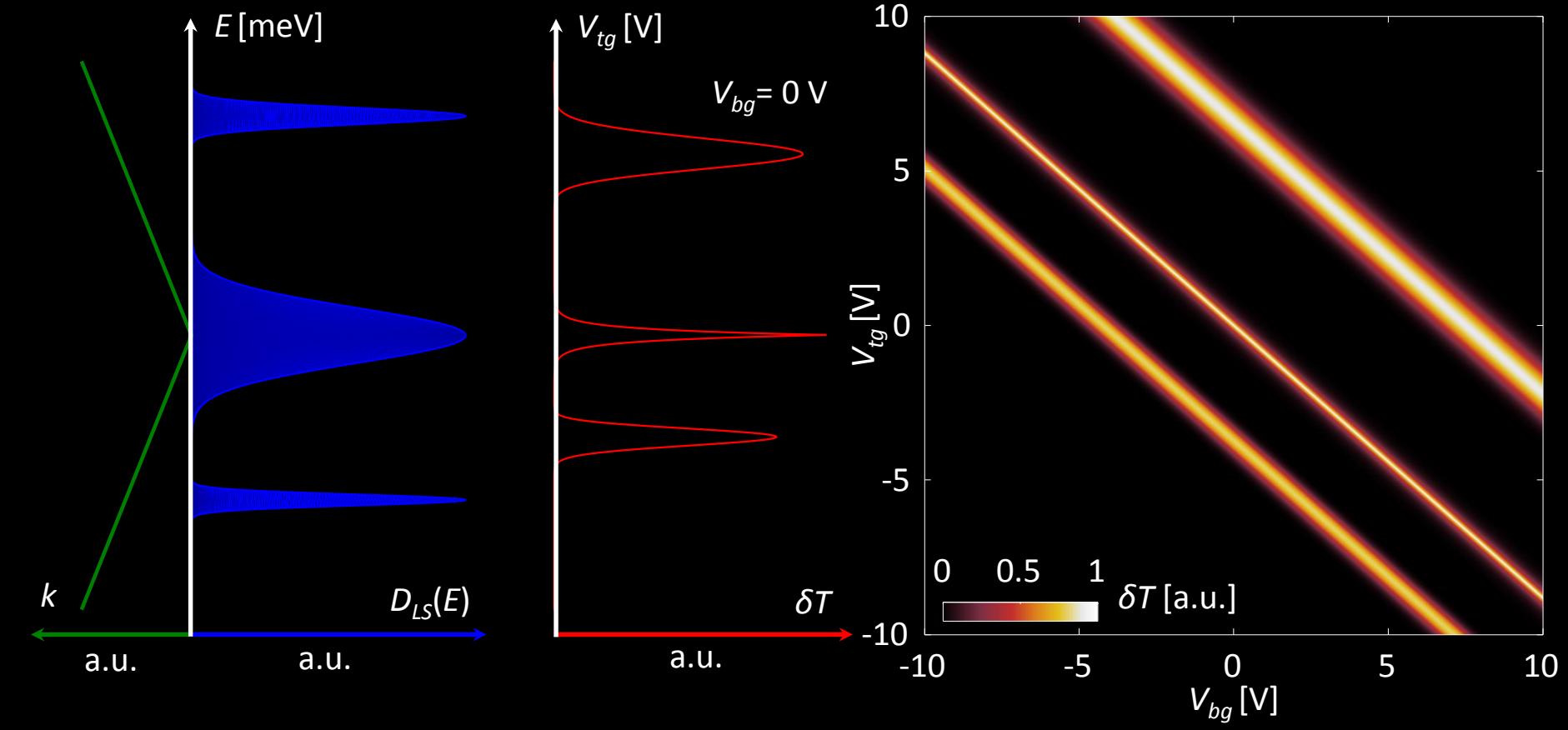


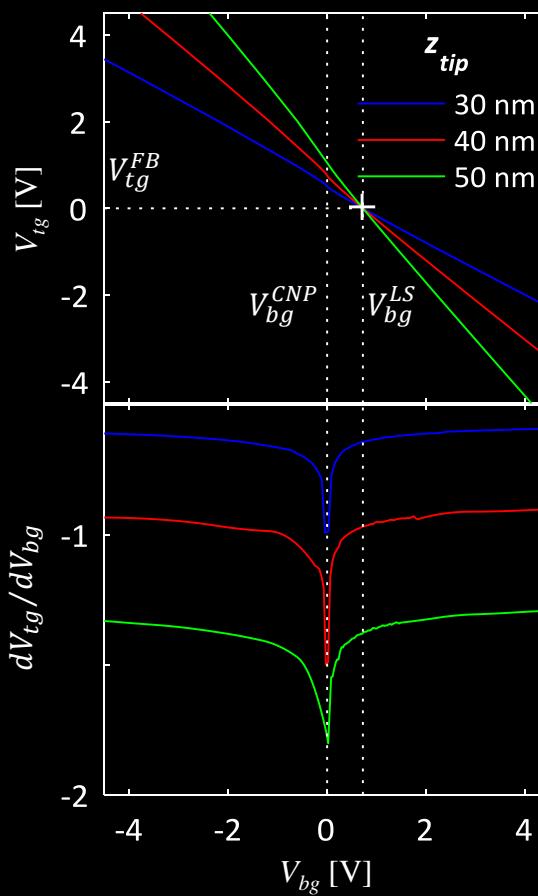
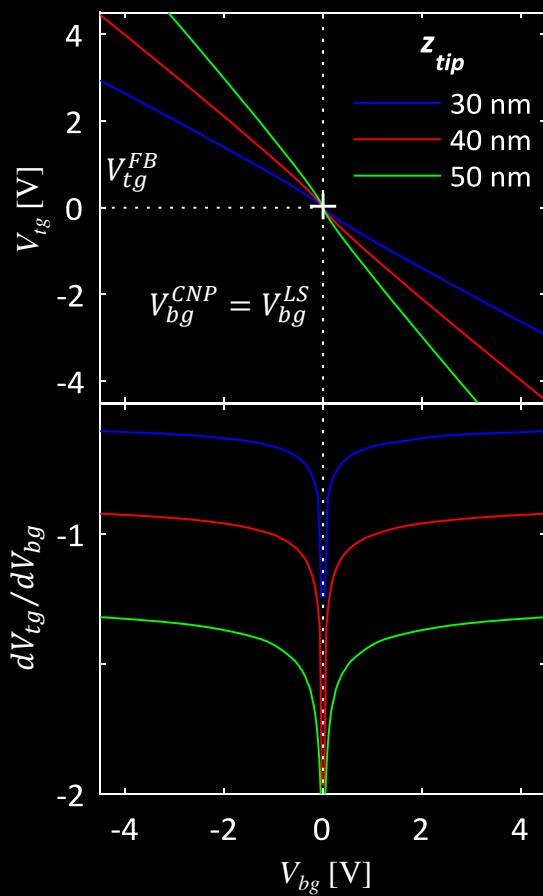
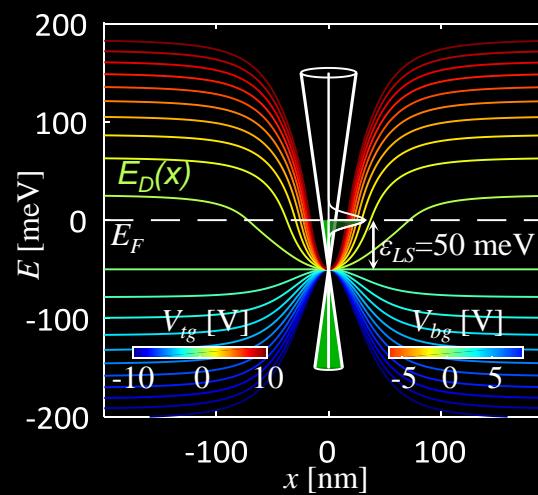
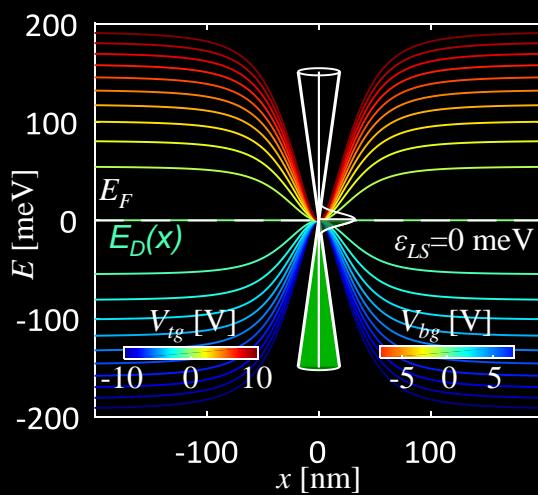
Proliferation of hot electrons

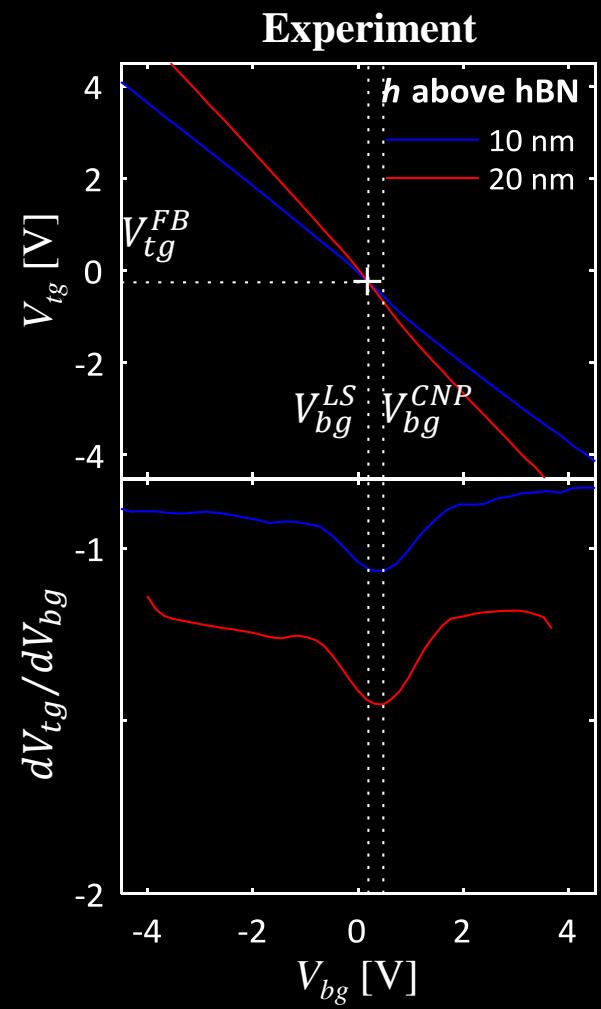
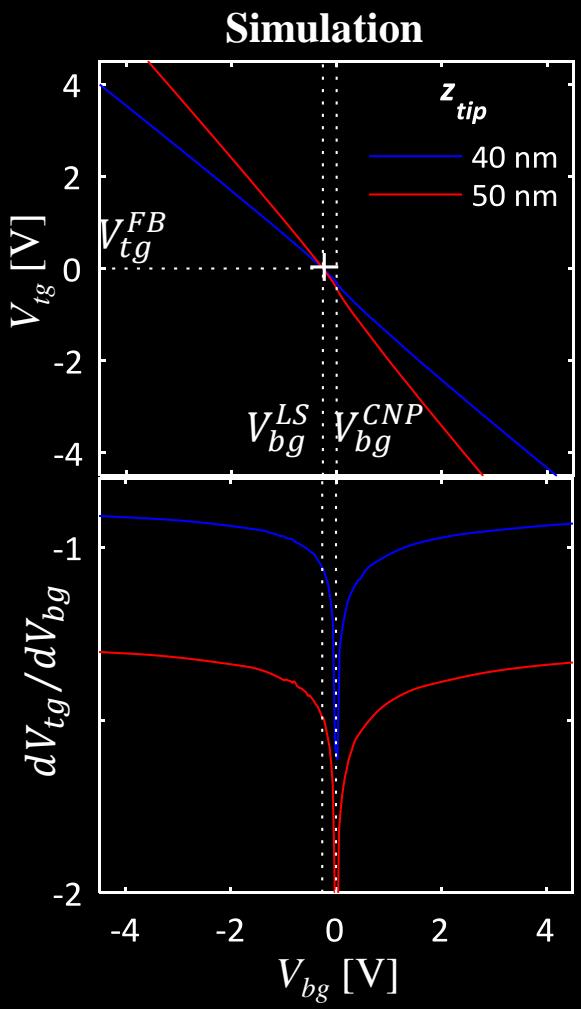
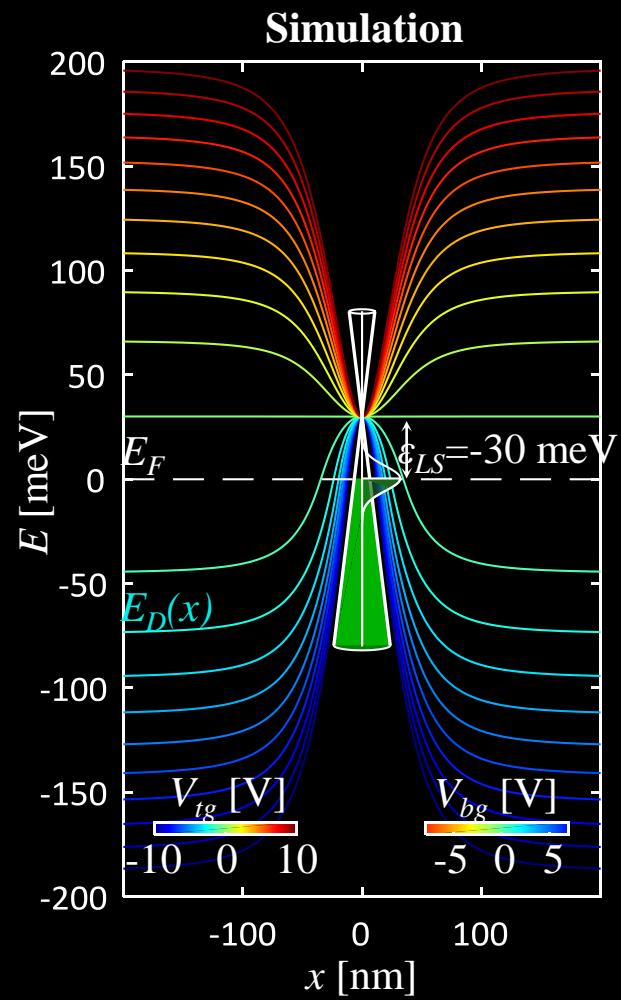


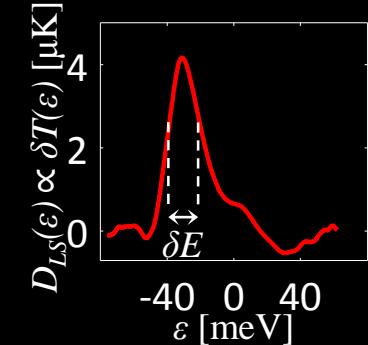
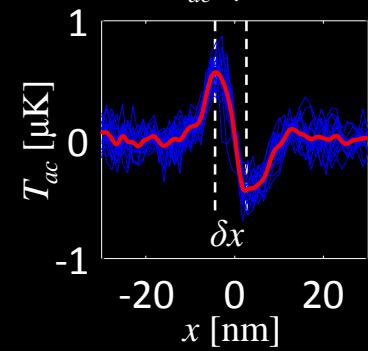
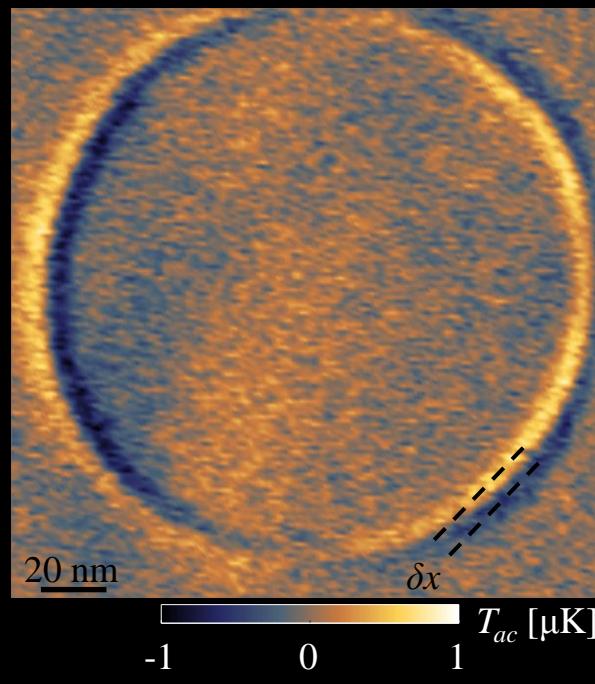
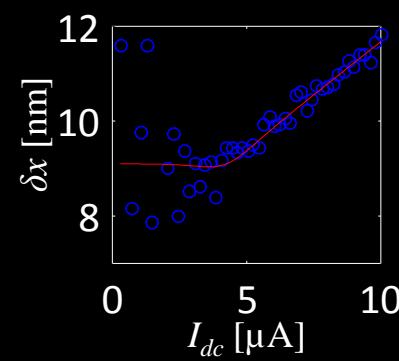
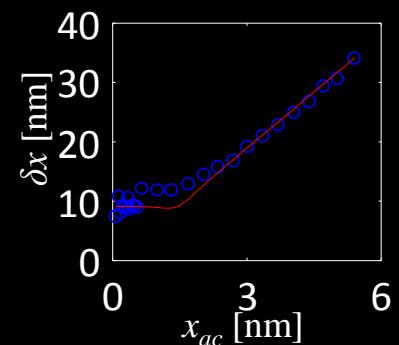
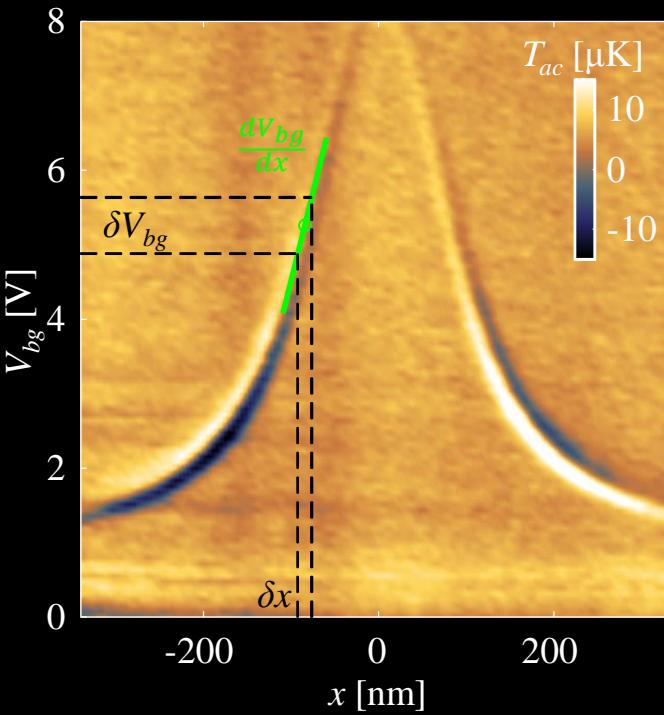
Single defect spectroscopy – band bending simulation



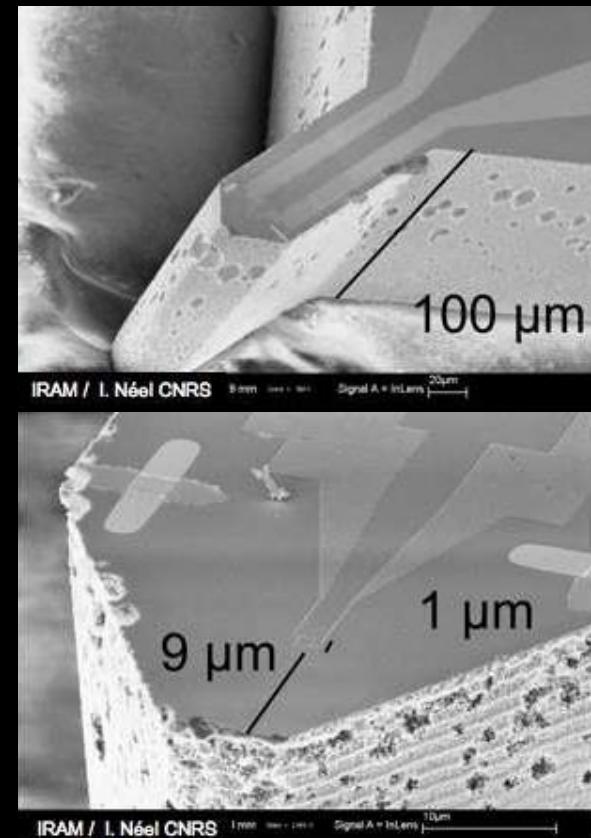
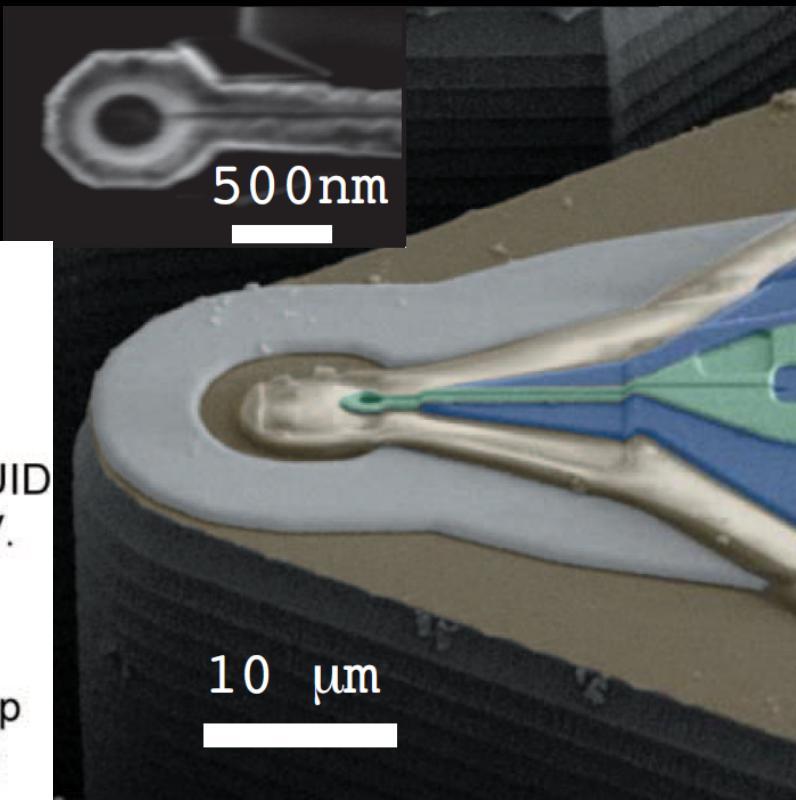
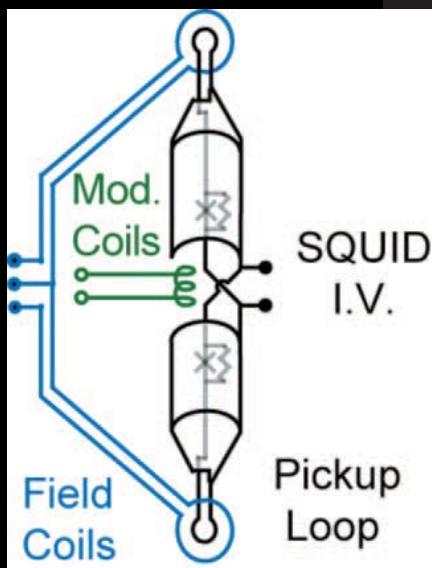








Scanning SQUID microscopy methods



N. Koshnick *et al.*
APL **93**, 243101 (2008)

K. Hasselbach *et al.*
J. Phys. **97**, 012330 (2008)

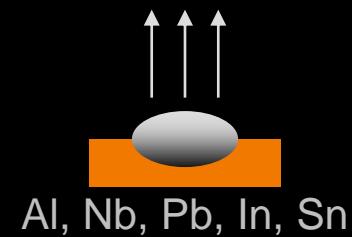
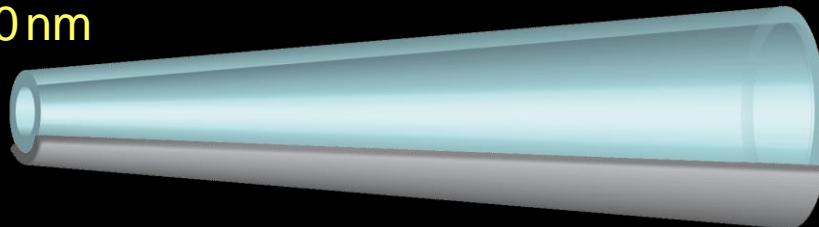
SQUID-on-tip fabrication



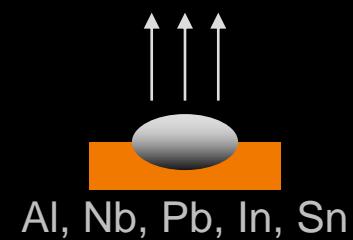
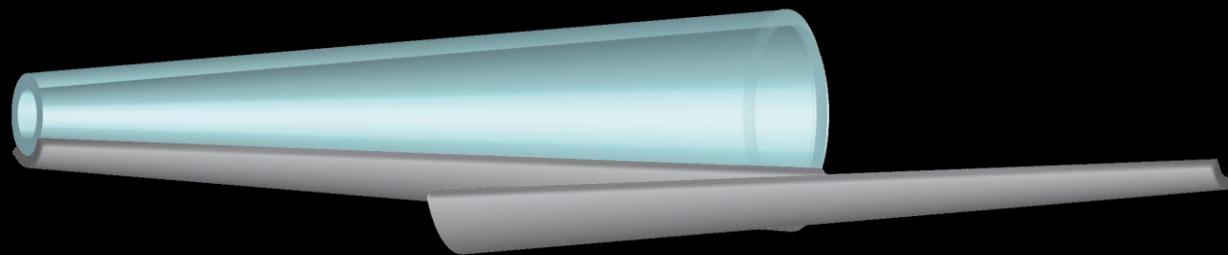
Ø1 mm

SQUID-on-tip fabrication

$\varnothing 50 \div 400 \text{ nm}$

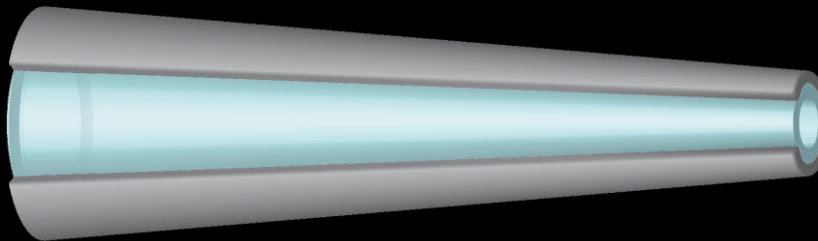


SQUID-on-tip fabrication



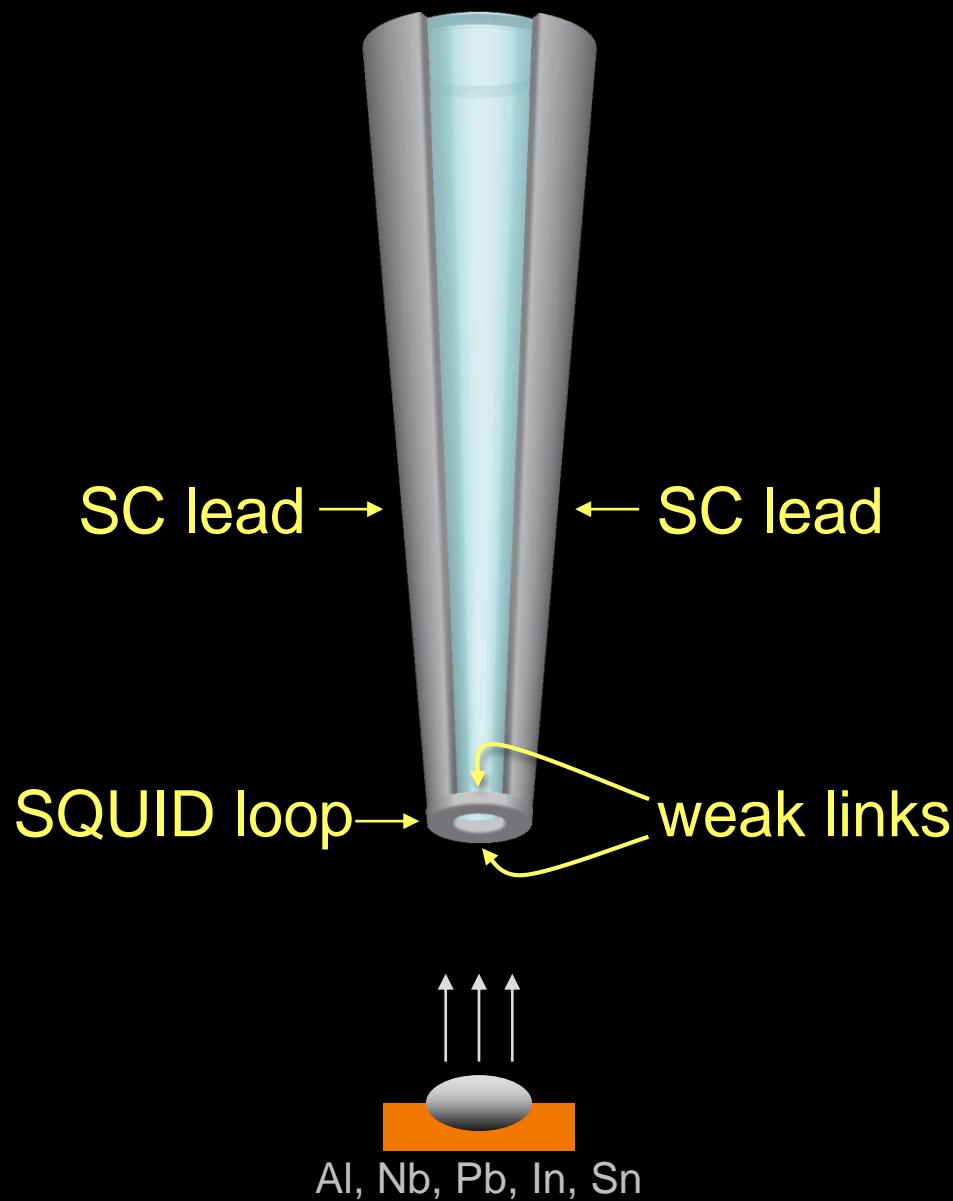
Al, Nb, Pb, In, Sn

SQUID-on-tip fabrication



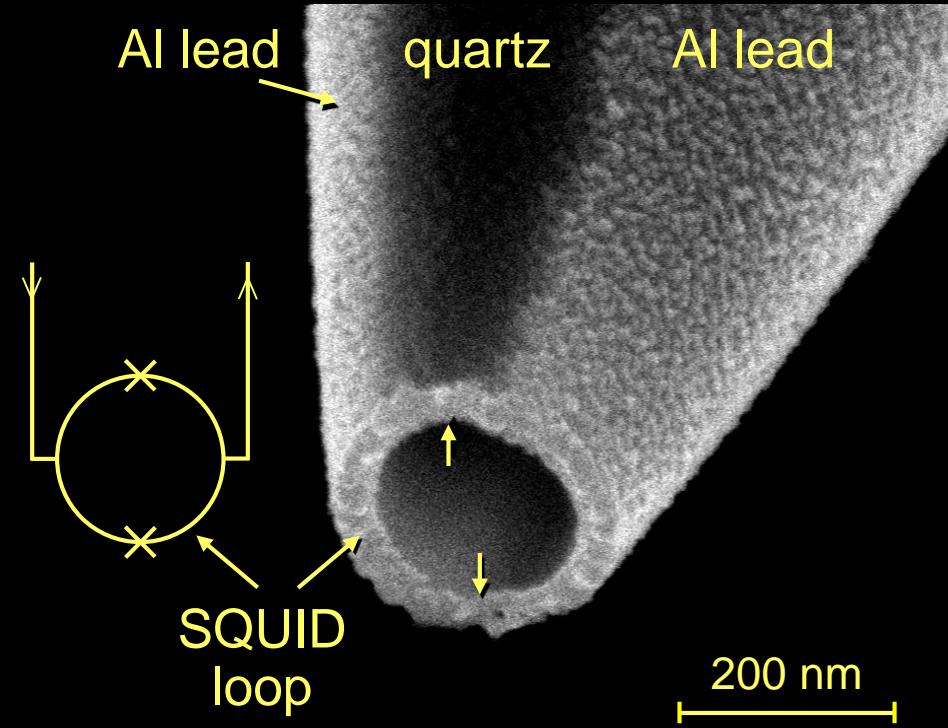
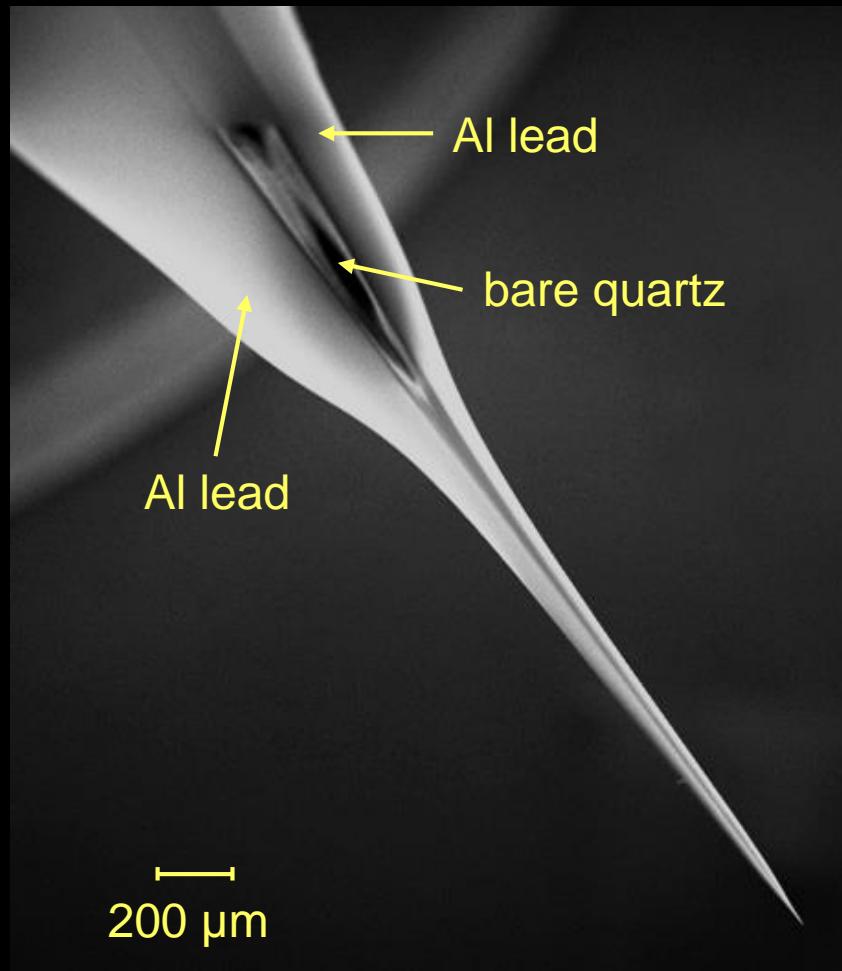
Al, Nb, Pb, In, Sn

SQUID-on-tip fabrication



Al SQUID on tip

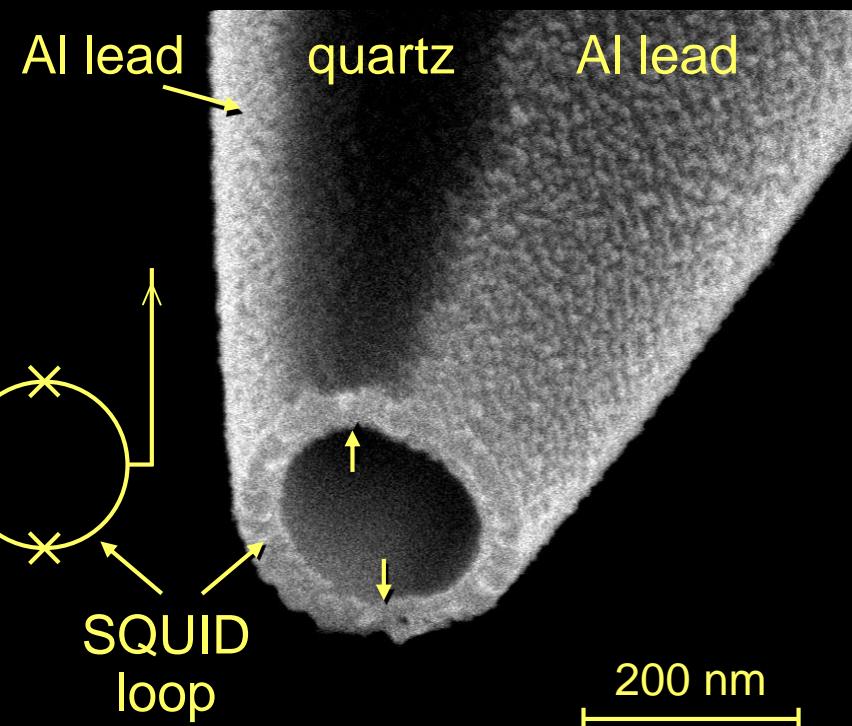
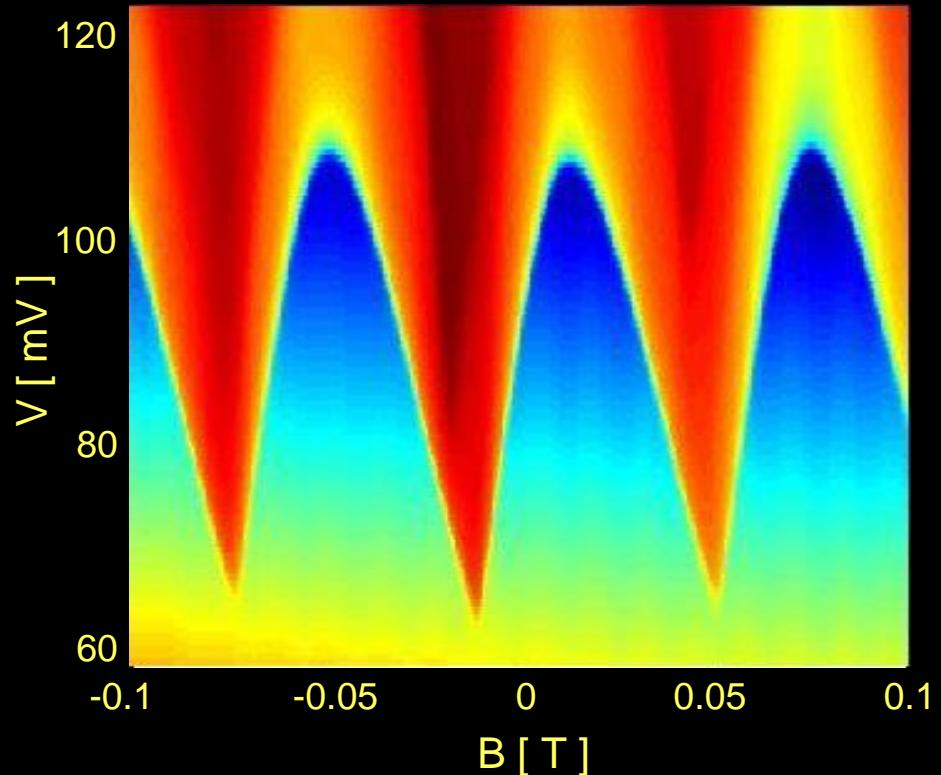
Pulled quartz tube



Al SQUID on tip

Quantum interference patterns

SQUID current (T=300 mK)



Loop diameter = 208 nm

Period = 60.8 mT

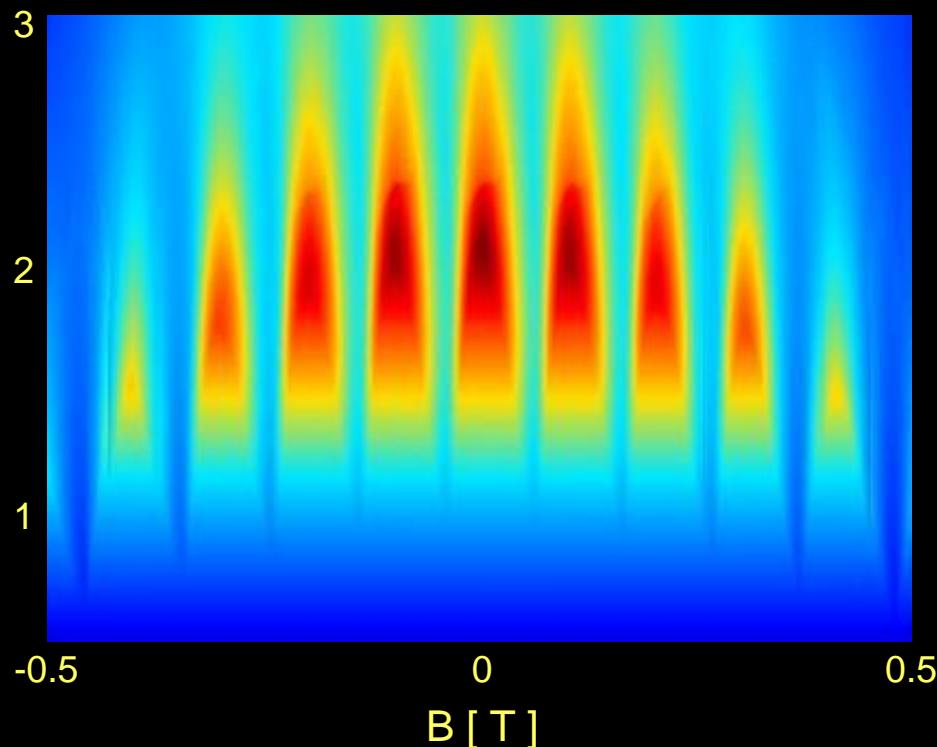
$$\text{Flux noise: } \sqrt{S_\Phi} = 2 \mu\Phi_0/\text{Hz}^{1/2}$$

$$\text{Spin noise: } \sqrt{S_n} = \sqrt{S_\Phi} R/r_e = 65 \mu_B/\text{Hz}^{1/2}$$

Pb SQUID on tip

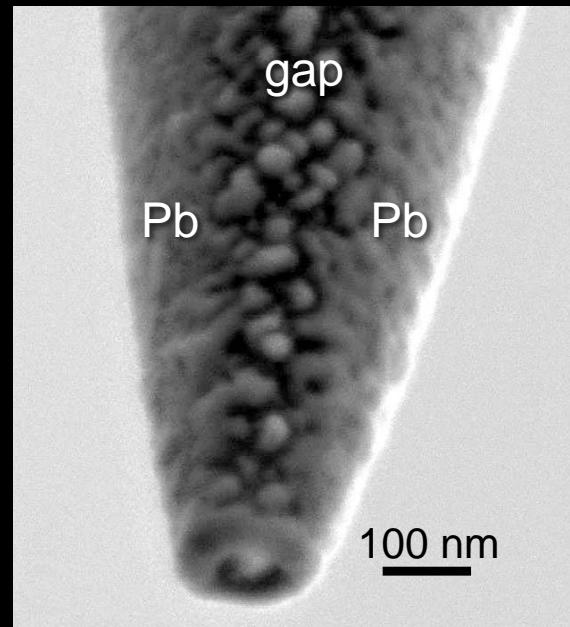
Quantum interference patterns

SQUID current ($T = 4.2 \text{ K}$)



Period = 103 mT

Loop diameter = 160 nm



Flux noise: $\sqrt{S_\Phi} = 50 \text{ n}\Phi_0/\text{Hz}^{1/2}$

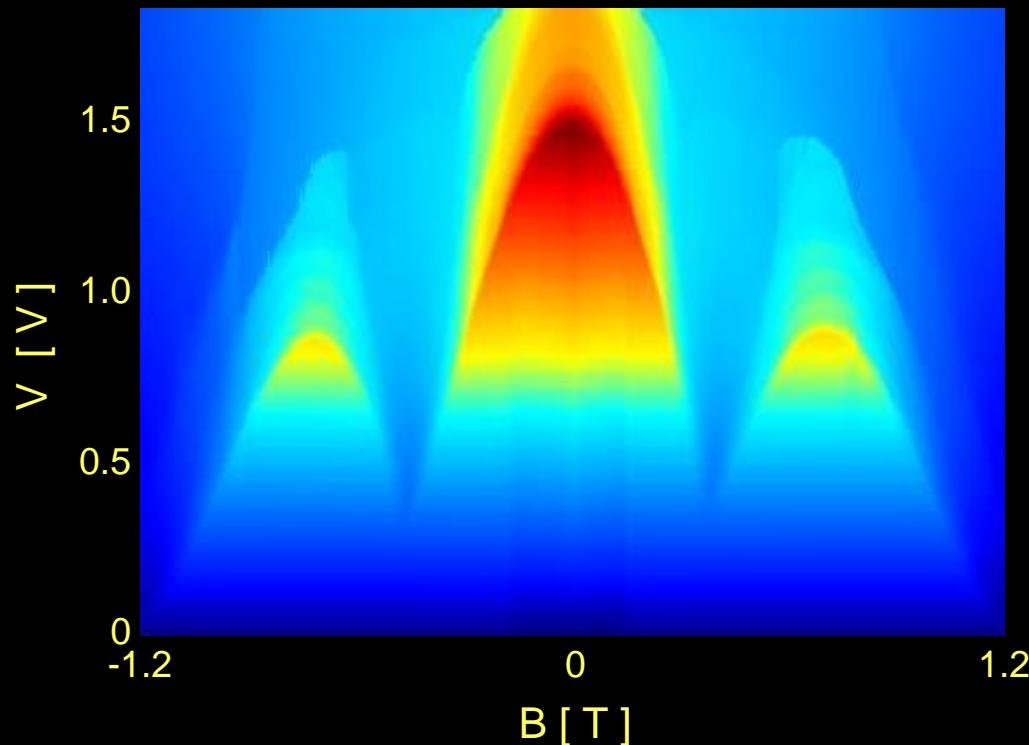
Field noise: $\sqrt{S_B} = 5.1 \text{ nT}/\text{Hz}^{1/2}$

Spin noise: $\sqrt{S_n} = 1.4 \mu_B/\text{Hz}^{1/2}$

Pb SQUID on tip

Quantum interference patterns

SQUID current (T = 4.2 K)

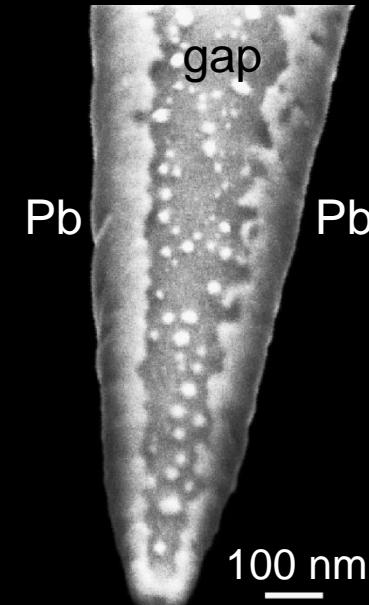


Period = 0.84 T

Loop diameter = 56 nm

Kinetic inductance: $L_k \cong 6$ pH

Quantum noise: $\sqrt{S_\Phi} = \sqrt{\hbar L_k} = 12$ n Φ_0 /Hz $^{1/2}$



Flux noise: $\sqrt{S_\Phi} = 50$ n Φ_0 /Hz $^{1/2}$

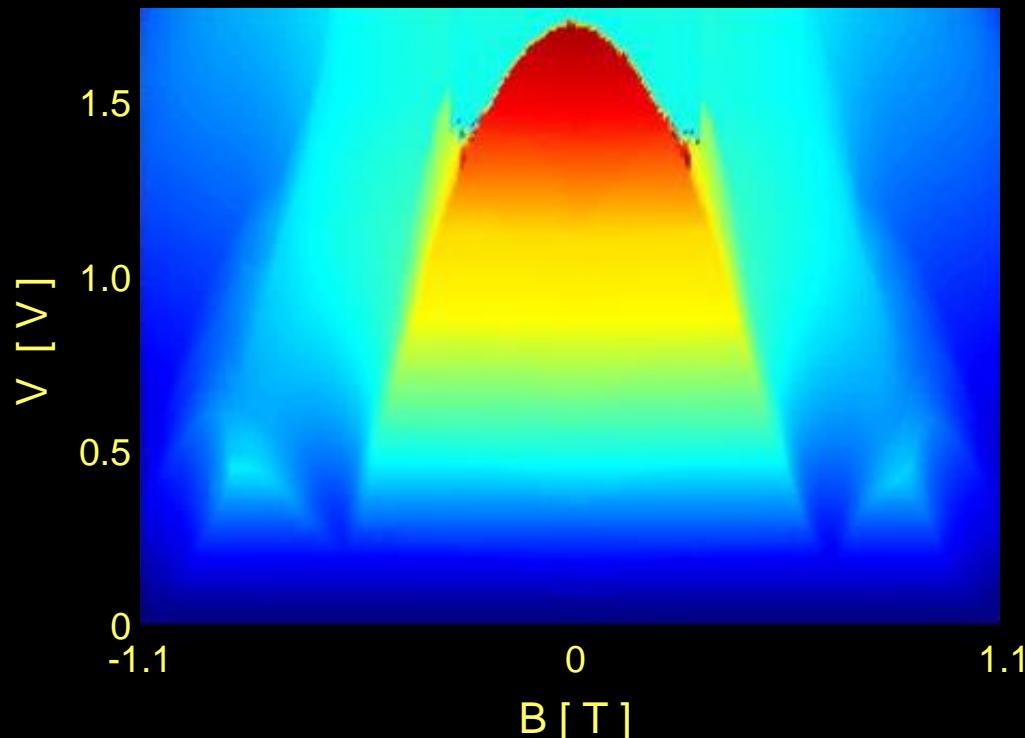
Field noise: $\sqrt{S_B} = 42$ nT/Hz $^{1/2}$

Spin noise: $\sqrt{S_n} = 0.5$ μ_B /Hz $^{1/2}$

Pb SQUID on tip

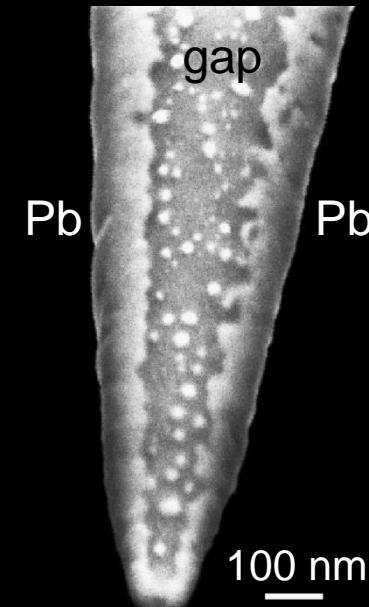
Quantum interference patterns

SQUID current ($T = 4.2 \text{ K}$)



Period = 1.27 T

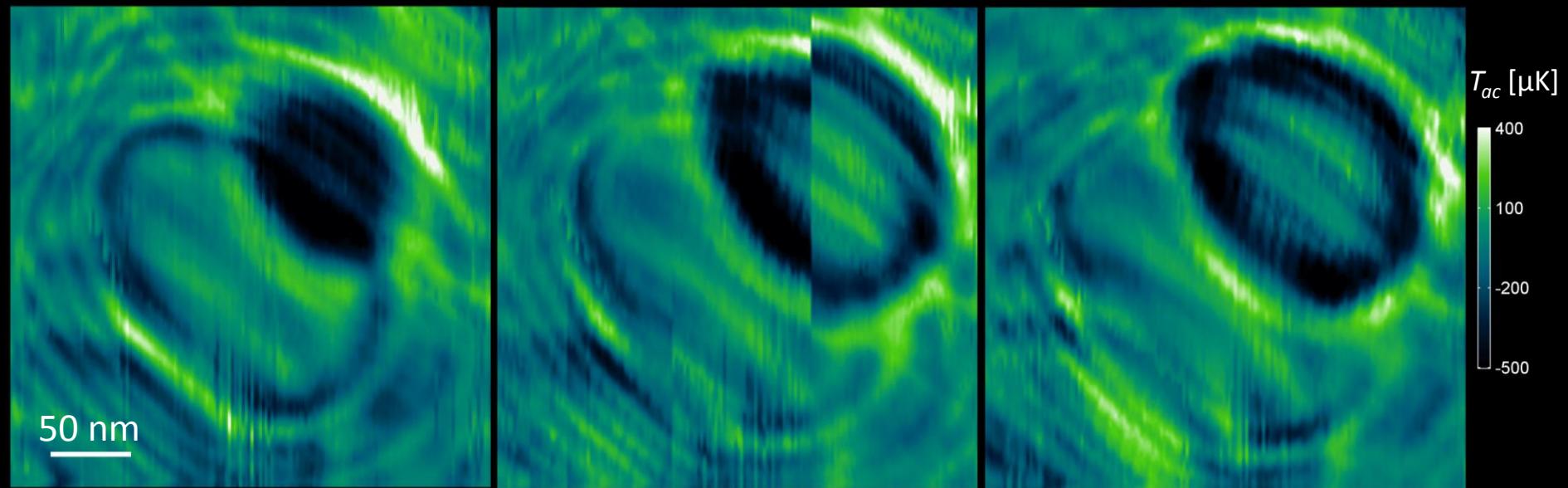
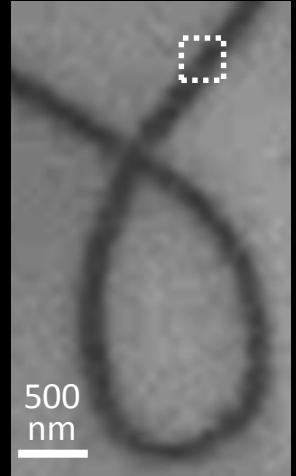
Loop diameter = 46 nm



Flux noise: $\sqrt{S_\Phi} = 50 \text{ n}\Phi_0/\text{Hz}^{1/2}$

Field noise: $\sqrt{S_B} = 62 \text{ nT}/\text{Hz}^{1/2}$

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



^3He scanning SQUID on tip microscope

Piezoelectric coarse X-Y positioners



Sample holder



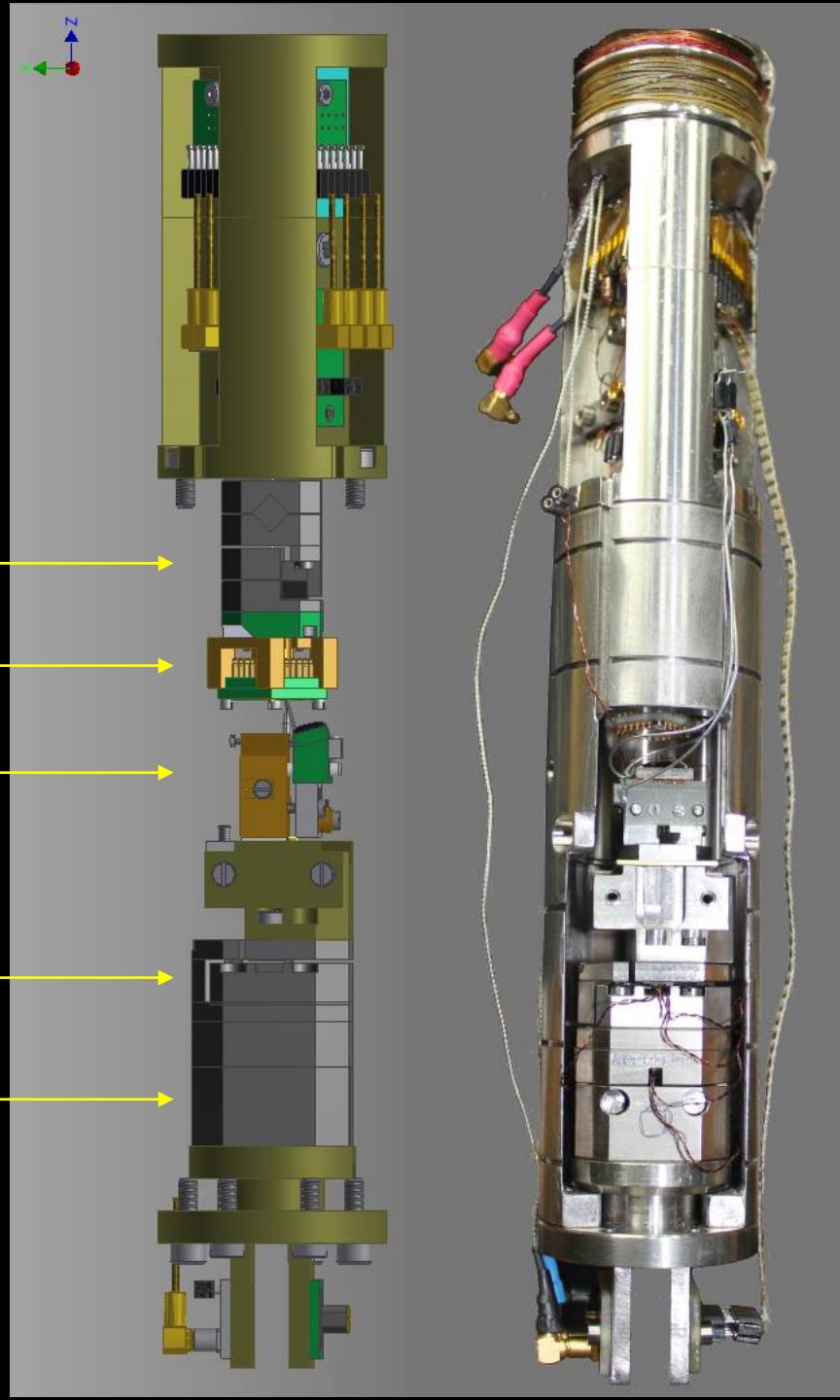
SQUID on tip and tuning fork assembly



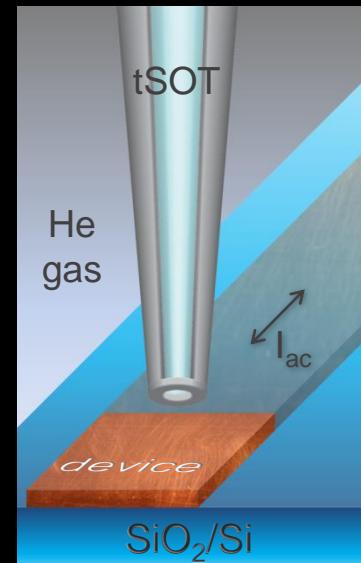
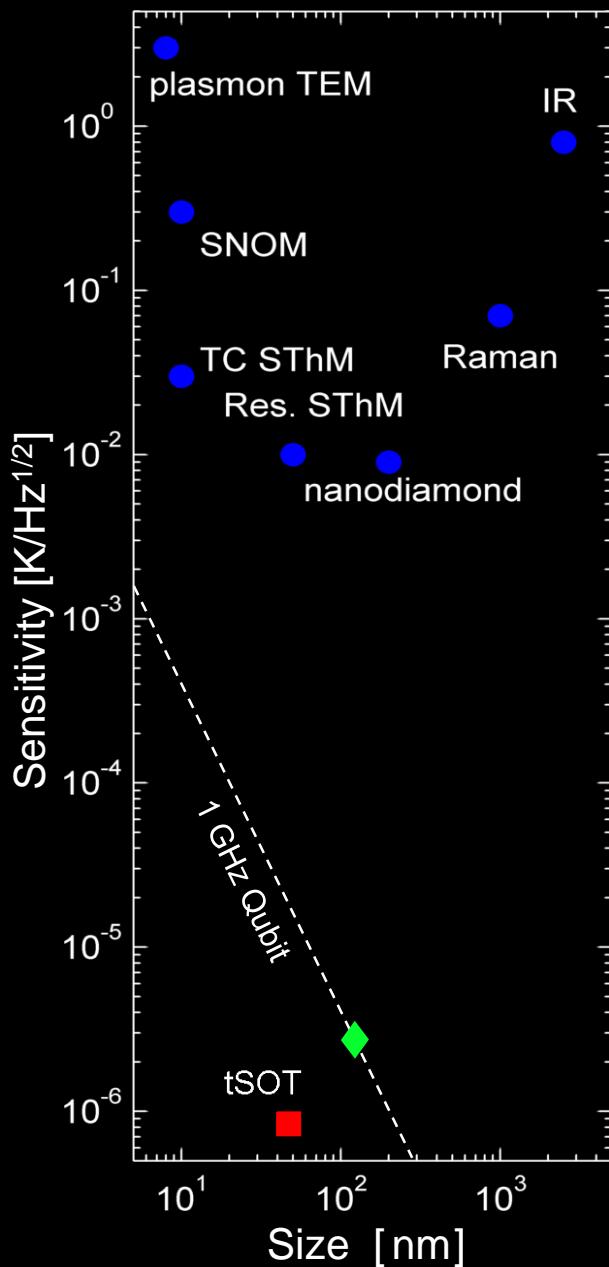
Piezoelectric coarse Z positioner



Piezoelectric X, Y and Z scanners



Thermal sensitivity



$$\begin{aligned}
 R_{ss} &\gg R_{sd} \gg R_{db} \\
 R_{ss} &\approx 10^{11} \text{ K/W} \\
 R_{sd} &\approx 10^8 - 10^{10} \text{ K/W} \\
 R_{db} &\approx 10^7 \text{ K/W}
 \end{aligned}$$

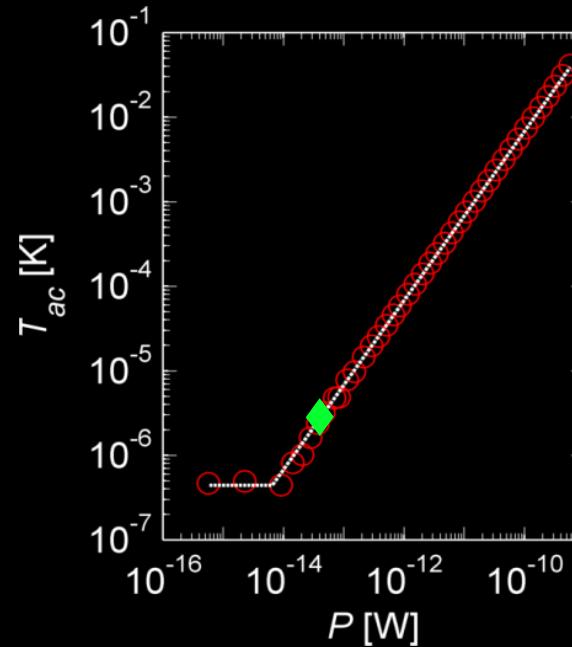


Figure of merit:
Landauer's limit of energy
dissipation for irreversible
qubit readout

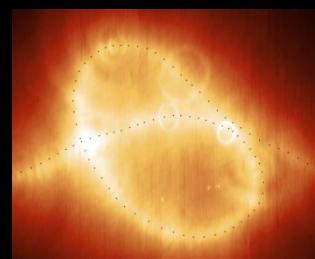
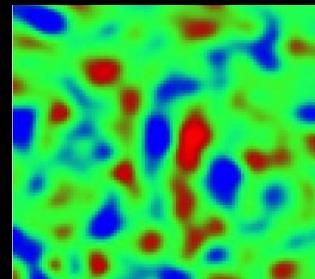
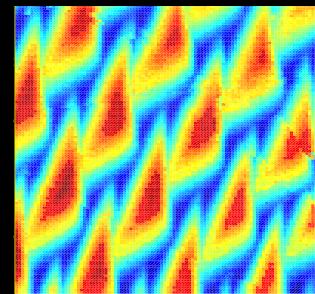
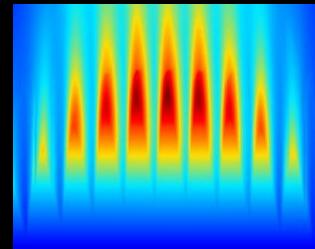
$$E = k_B T \ln 2 = 4 \times 10^{-23} \text{ J}$$

Qubit at 1 GHz:

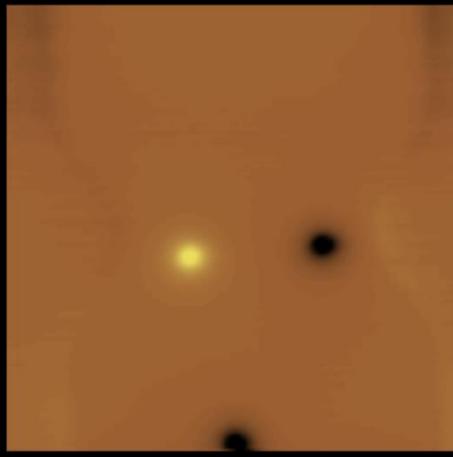
$$P = 40 \text{ fW}$$

Outline

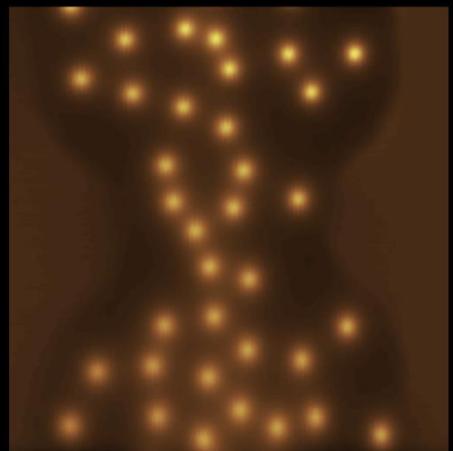
- Introduction
- SQUID-on-tip
- 3-junction SQUID-on-tip
- Superparamagnetism in TI
- Thermal nanoscale imaging



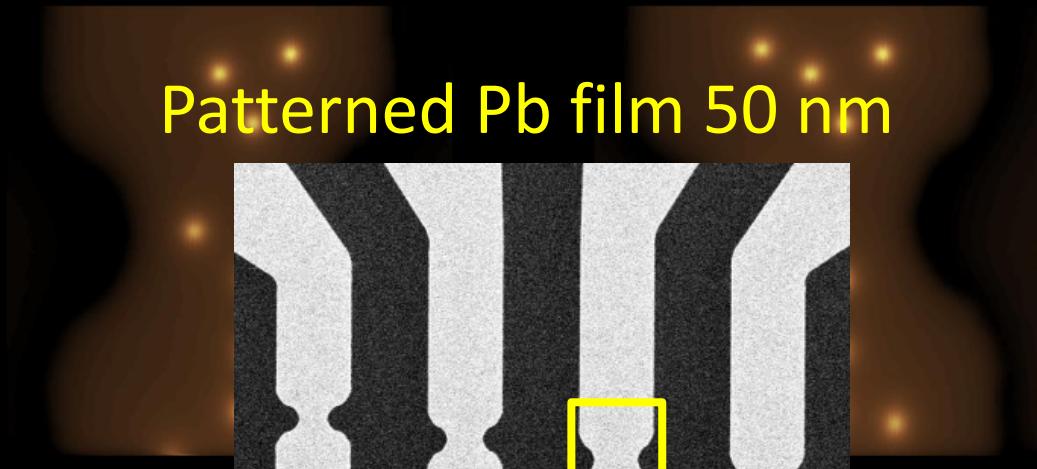
Vortices in Pb film



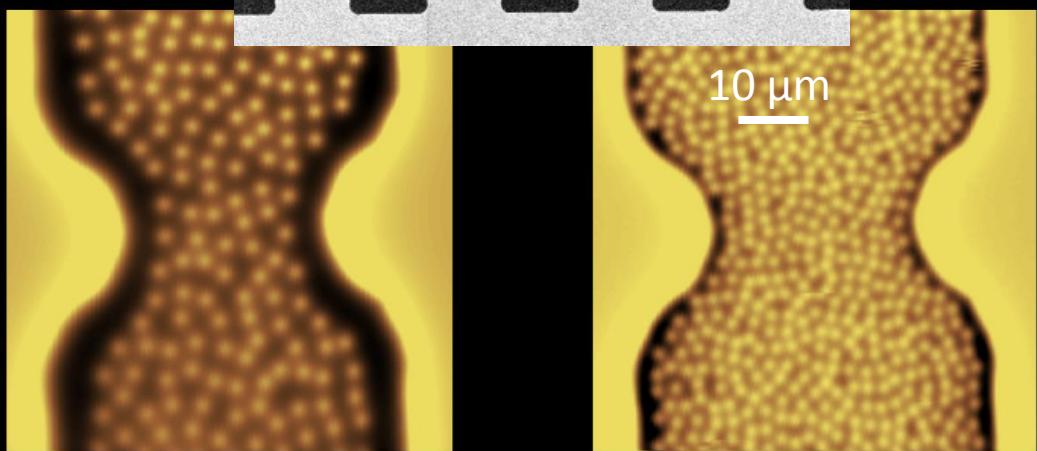
0 G



15 G



3



54 G

120 G

10 μm

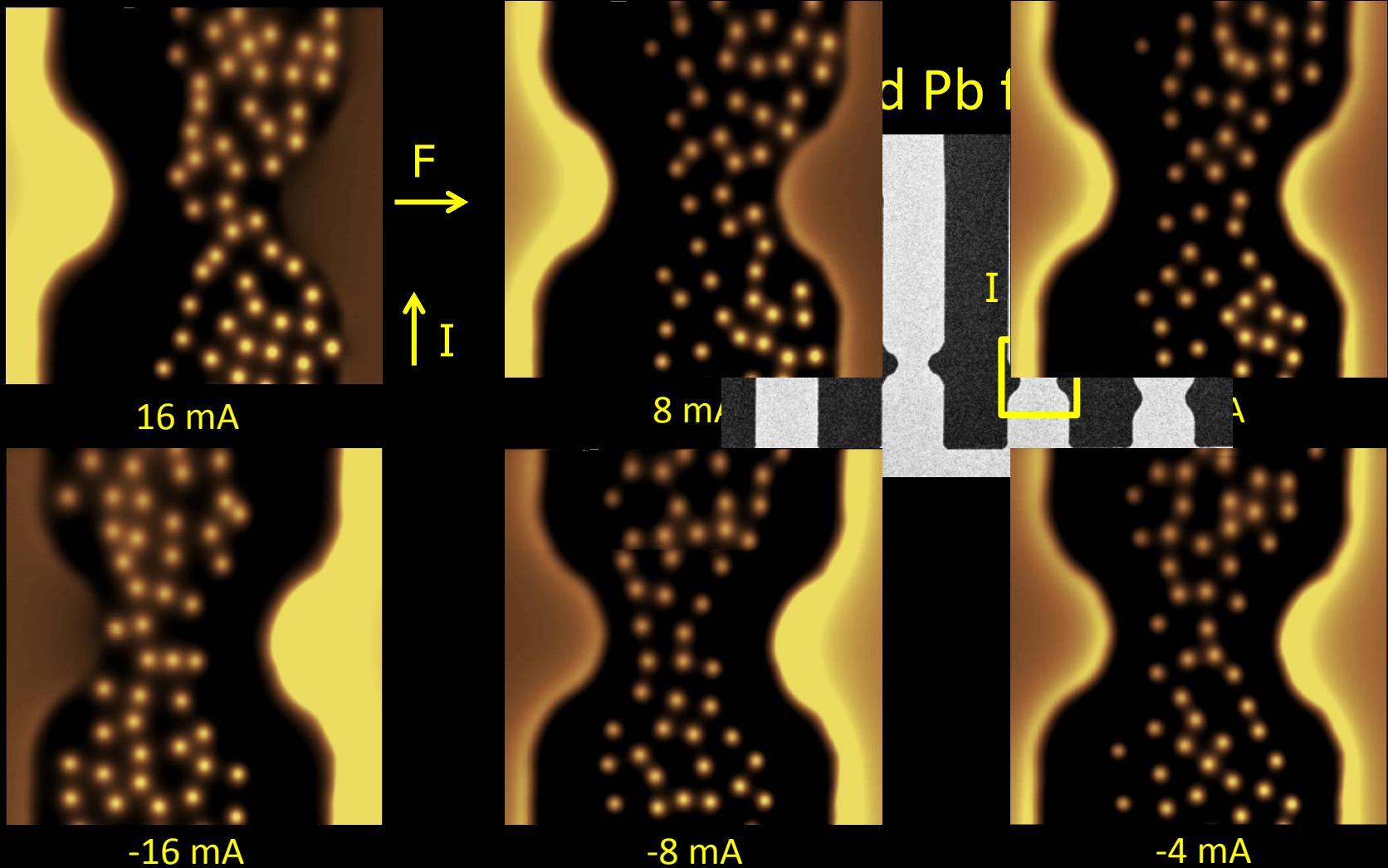
SQUID diameter: 225 nm

Scan area: $12 \times 12 \mu\text{m}^2$

Pixel size: 100nm Scan time: 2 min

T = 4.2 K

Vortices in Pb film in presence of current



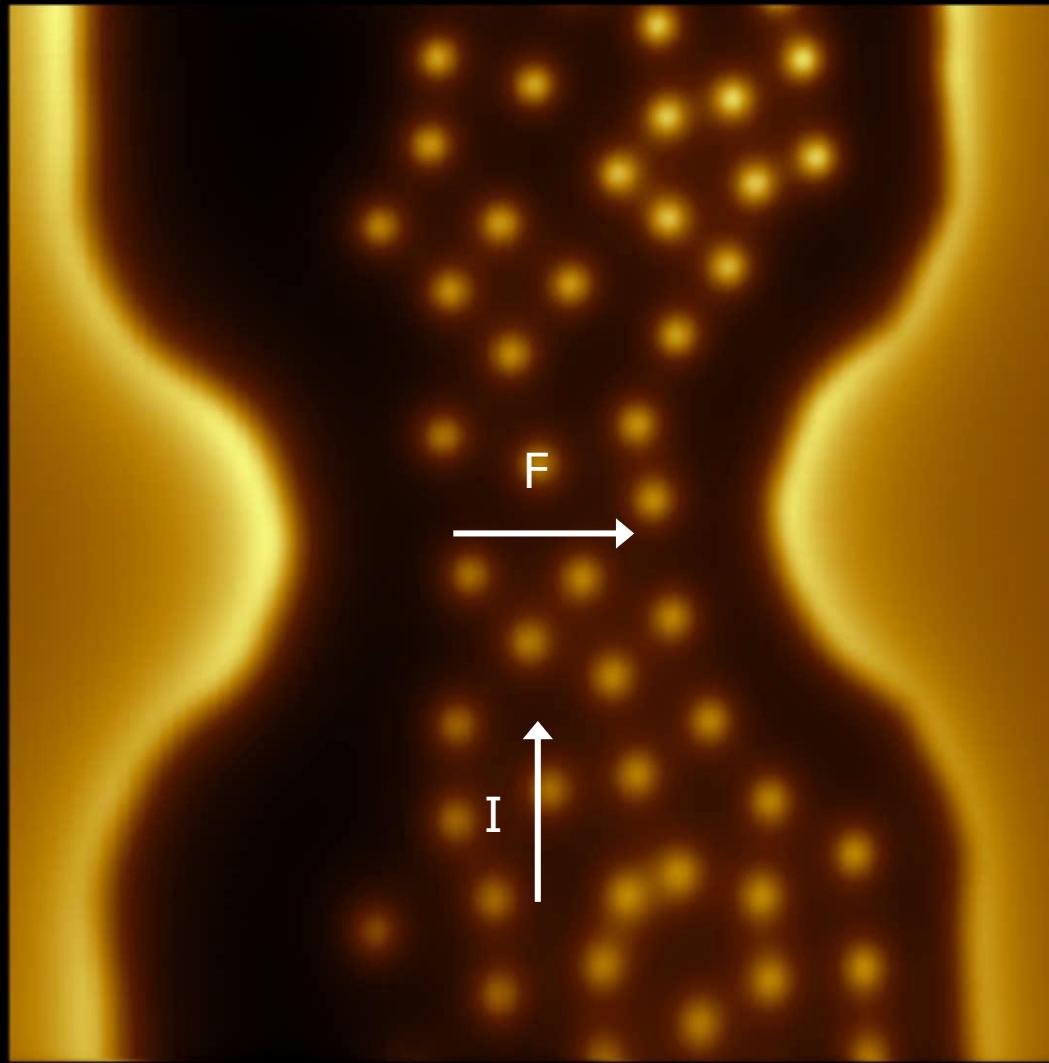
SQUID diameter: 225 nm

Scan area: $12 \times 12 \mu\text{m}^2$

Pixel size: 100 nm Scan time: 2 min

$T = 4.2 \text{ K}$ $B_a = 27 \text{ G}$

Vortex flow in Pb film



$H_a = 27$ G

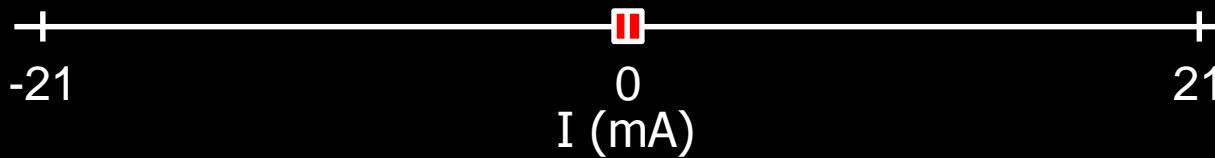
SOT diameter: 225 nm

Scan area: $12 \times 12 \mu\text{m}^2$

Pixel size: 40nm

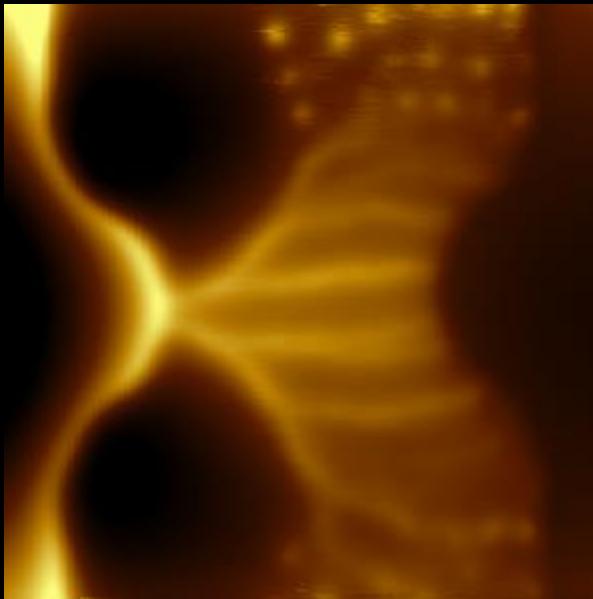
Scan time: 4 min/frame

$T = 4.2$ K

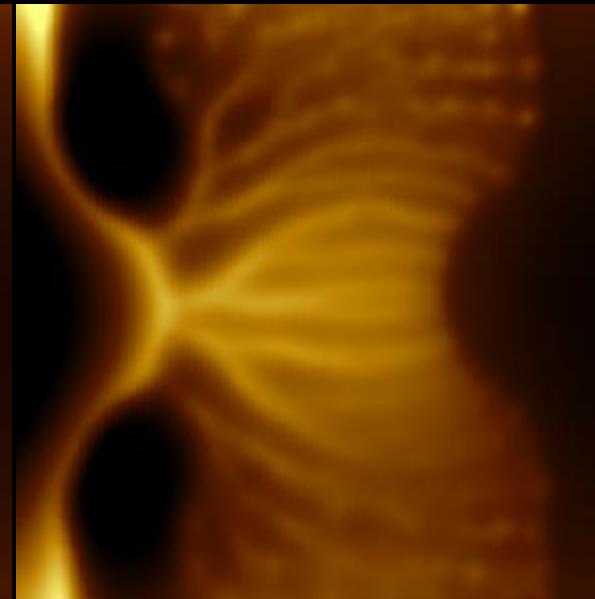


Vortex flow patterns

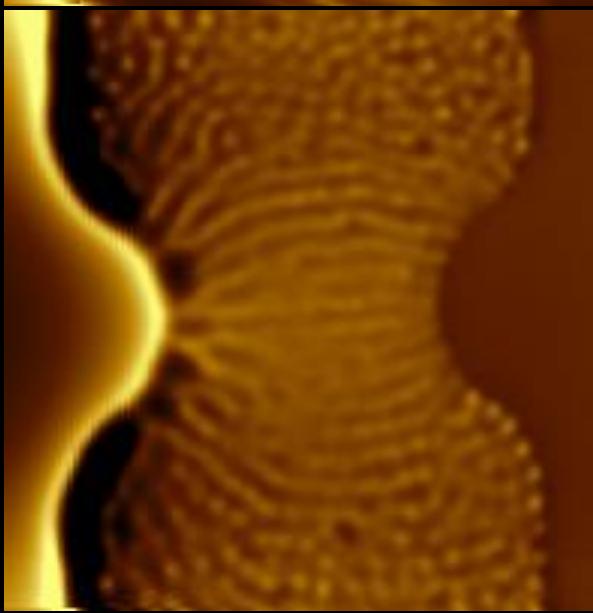
27 G



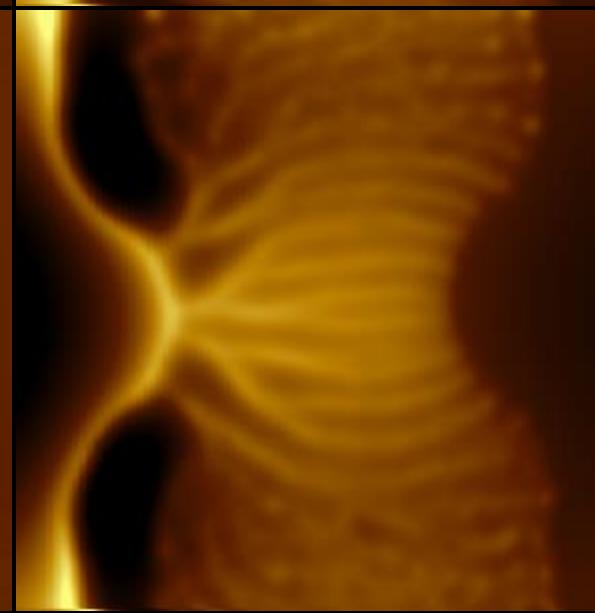
42 G



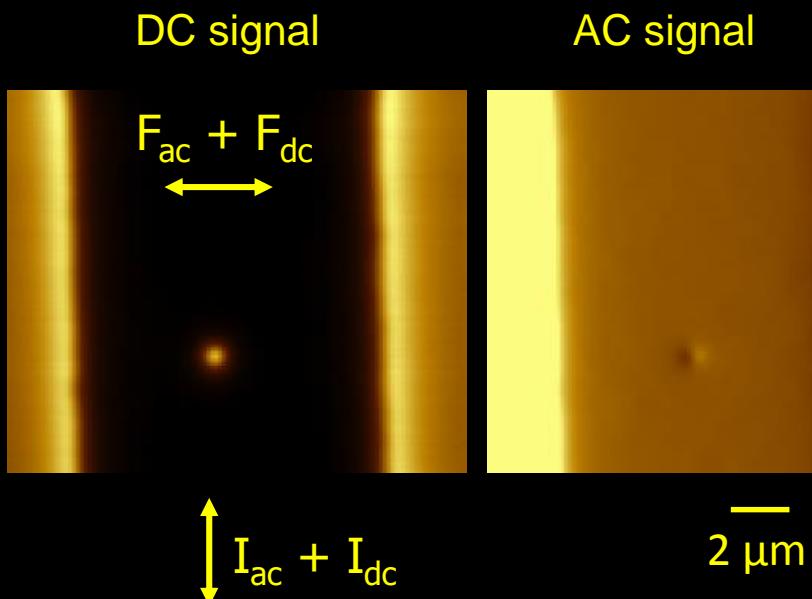
90 G



54 G



Pinning and dynamics of a single vortex



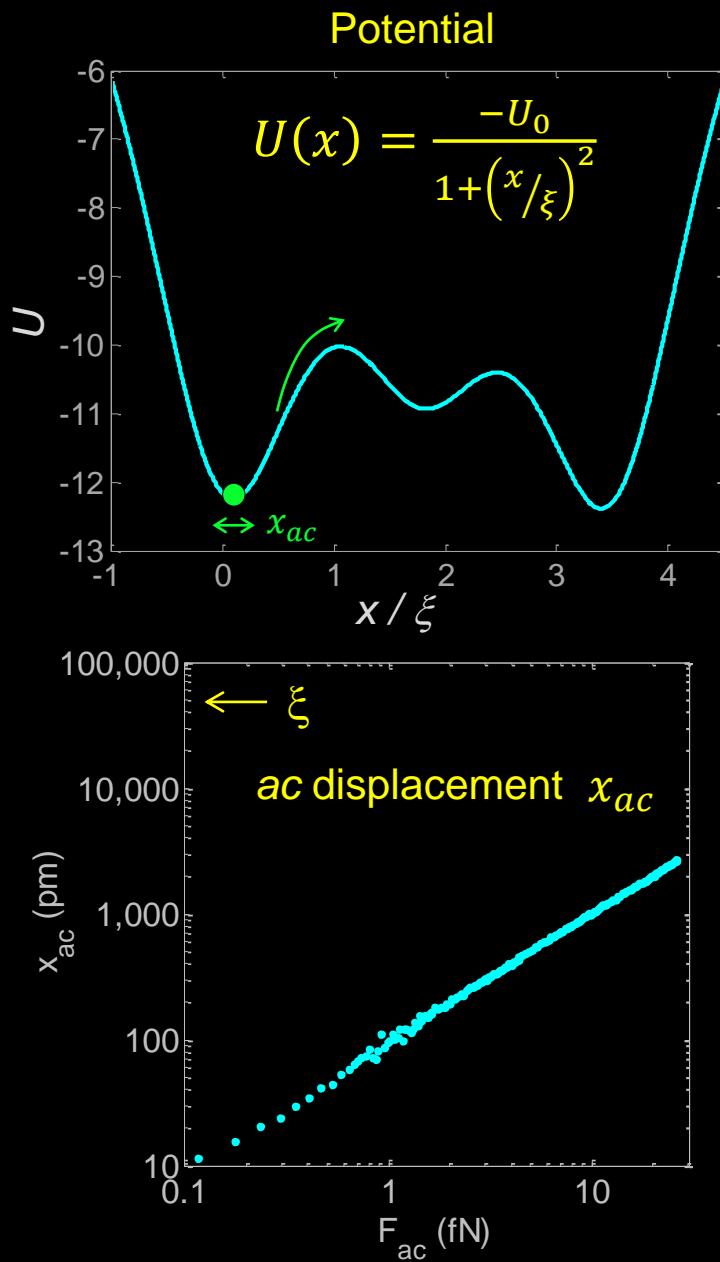
Pb film

$\xi = 46.4 \text{ nm}$

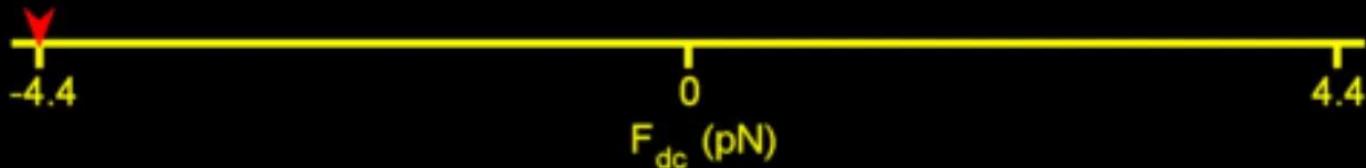
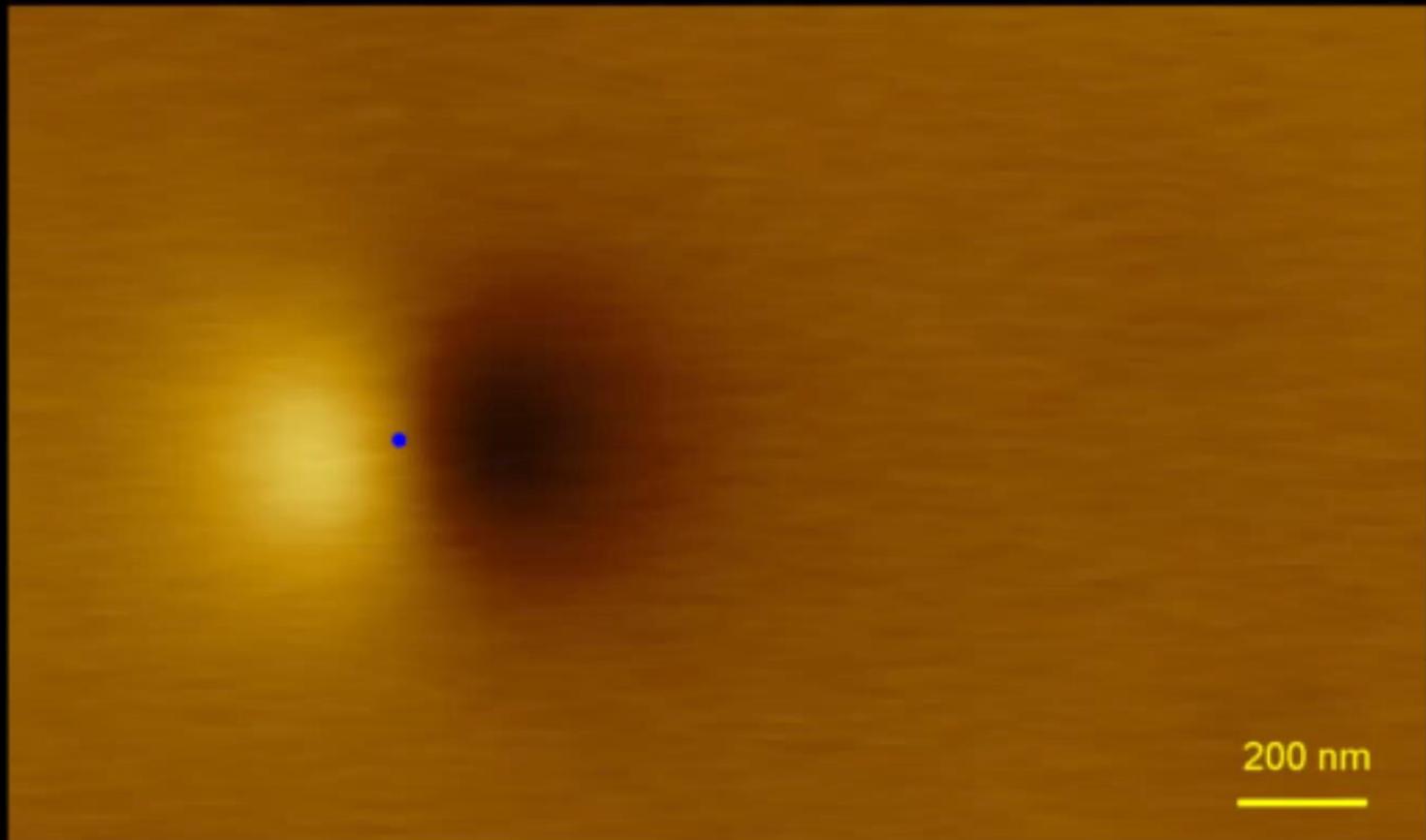
$\lambda = 90 \text{ nm}$

$d = 75 \text{ nm}$

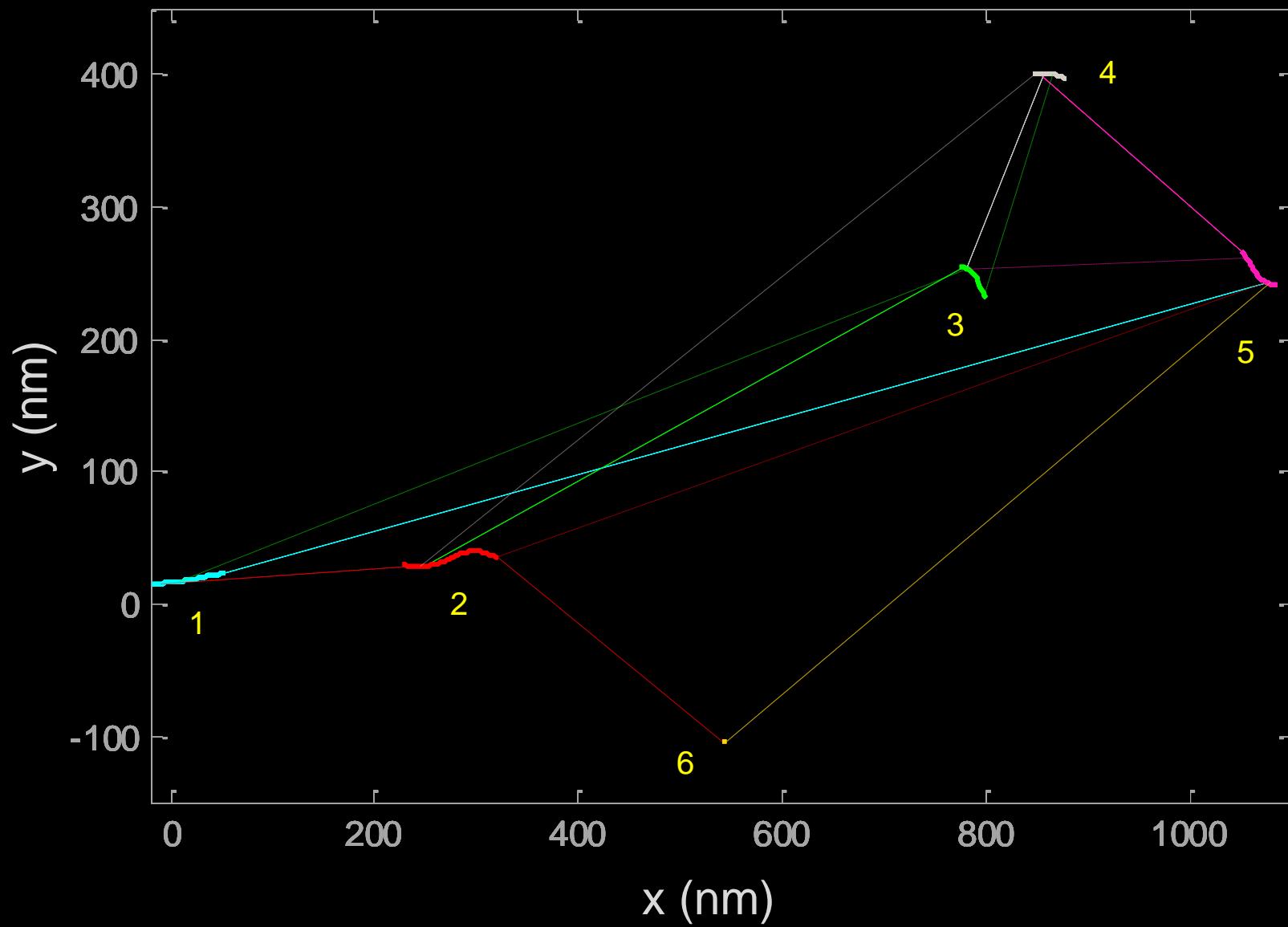
$T = 4.2 \text{ K}$



Single vortex dynamics



Vortex trajectory



Outline

- Introduction
- SQUID-on-tip
- Magnetism in topological insulators
- Thermal nanoscale imaging

