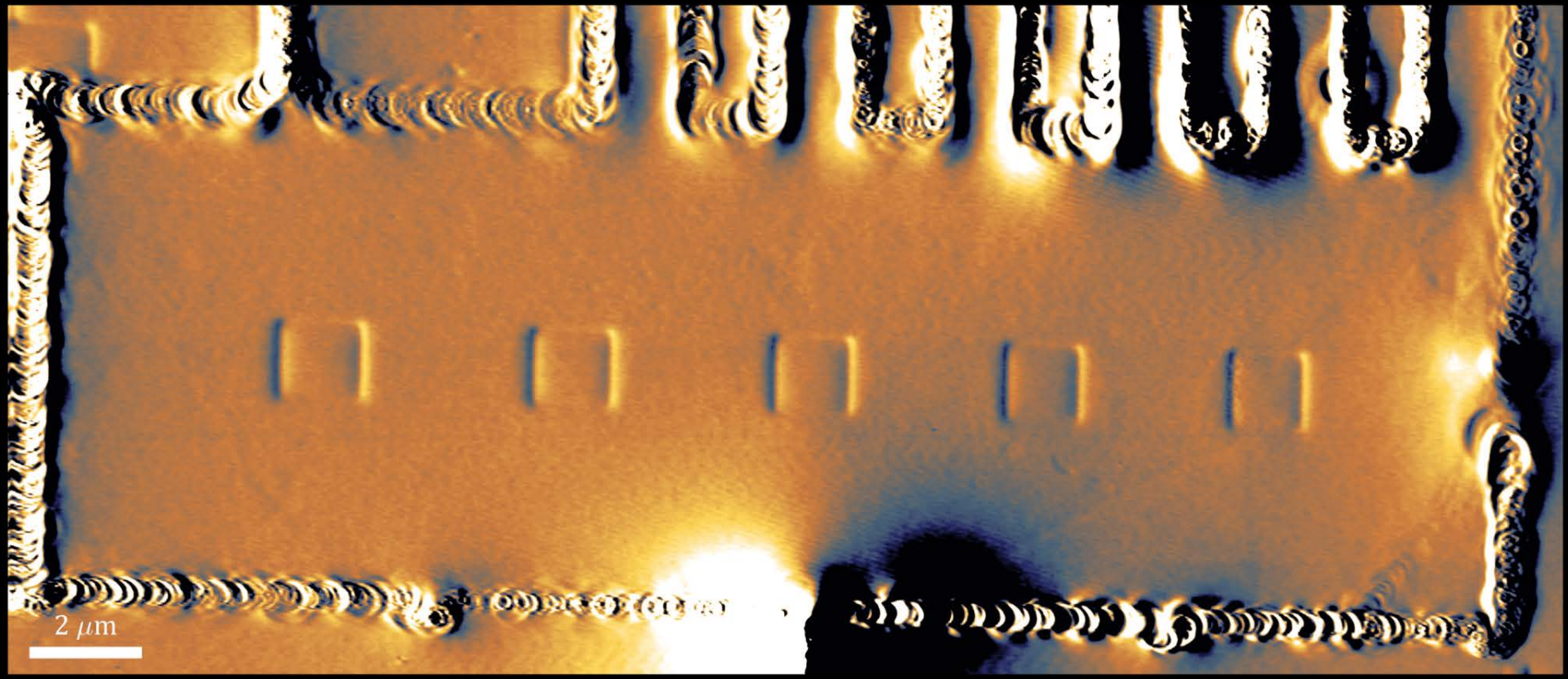
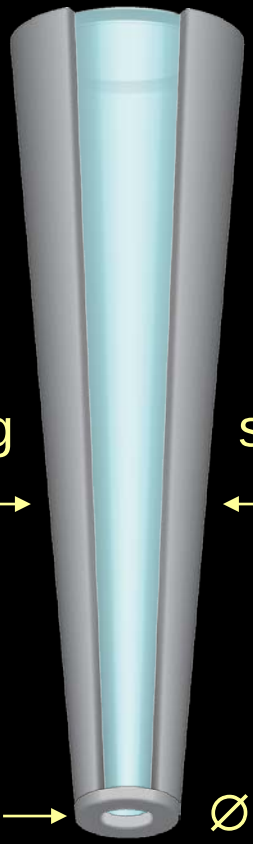
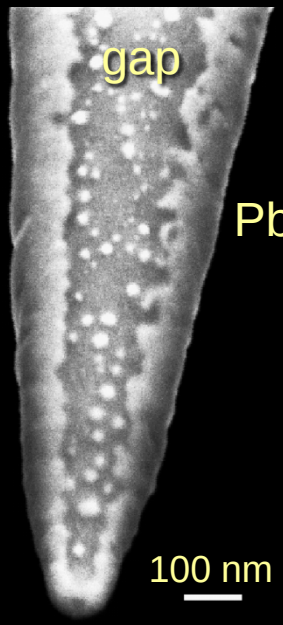
Imaging work and dissipation in quantum Hall state in graphene

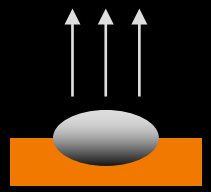


Eli Zeldov – Weizmann Institute of Science

SQUID on tip







Loop diameter < 40 nm

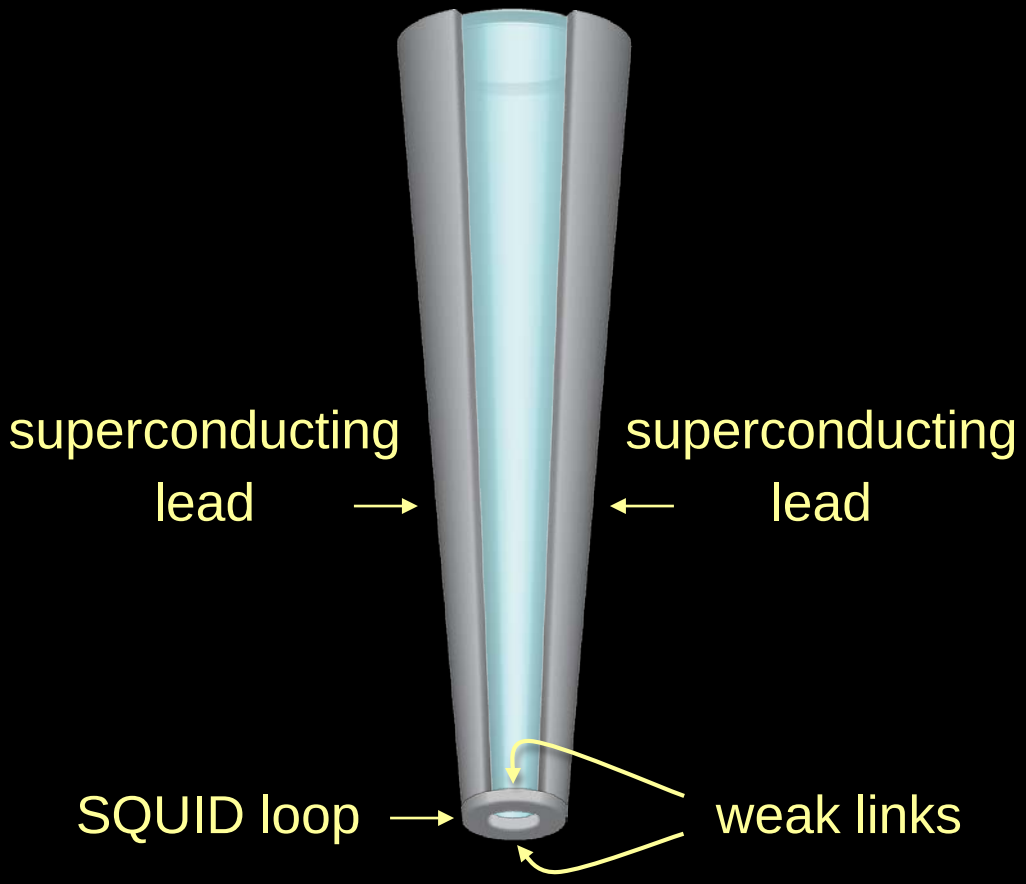
Operating field > 1 T

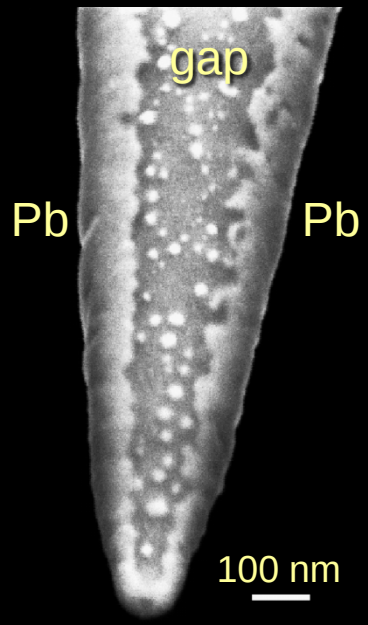
Flux noise: $\sqrt{S_\Phi}$ = 50 nΦ_0/Hz$^{1/2}$

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

D. Vasyukov *et al*., Nature Nanotech. **8**, 639 (2013)

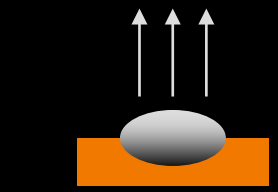
SQUID on tip





Thermal noise:

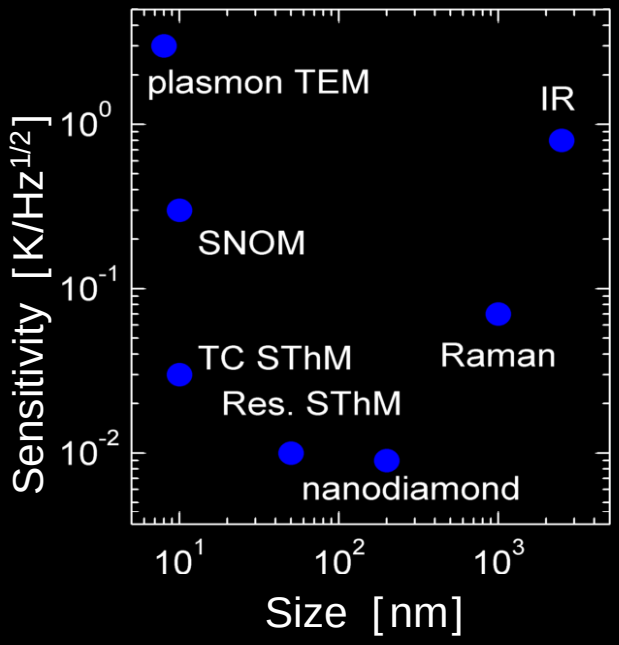
$S_T^{1/2} < 1$ μK/Hz$^{1/2}$



Al, Nb, Pb, In, Sn

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

Thermal imaging techniques



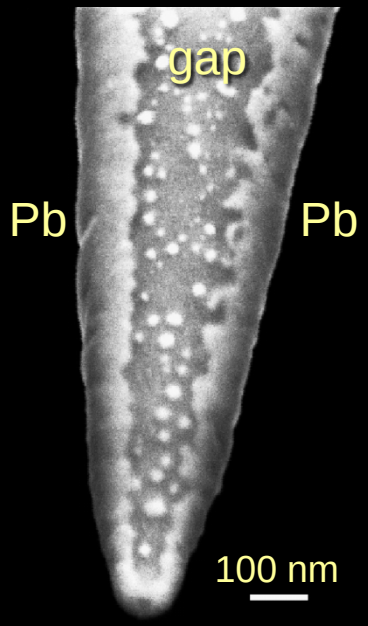
Mecklenburg *et al.,* Science (2015)

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

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

Kucsko *et al.,* Nature (2013)

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



Thermal noise:

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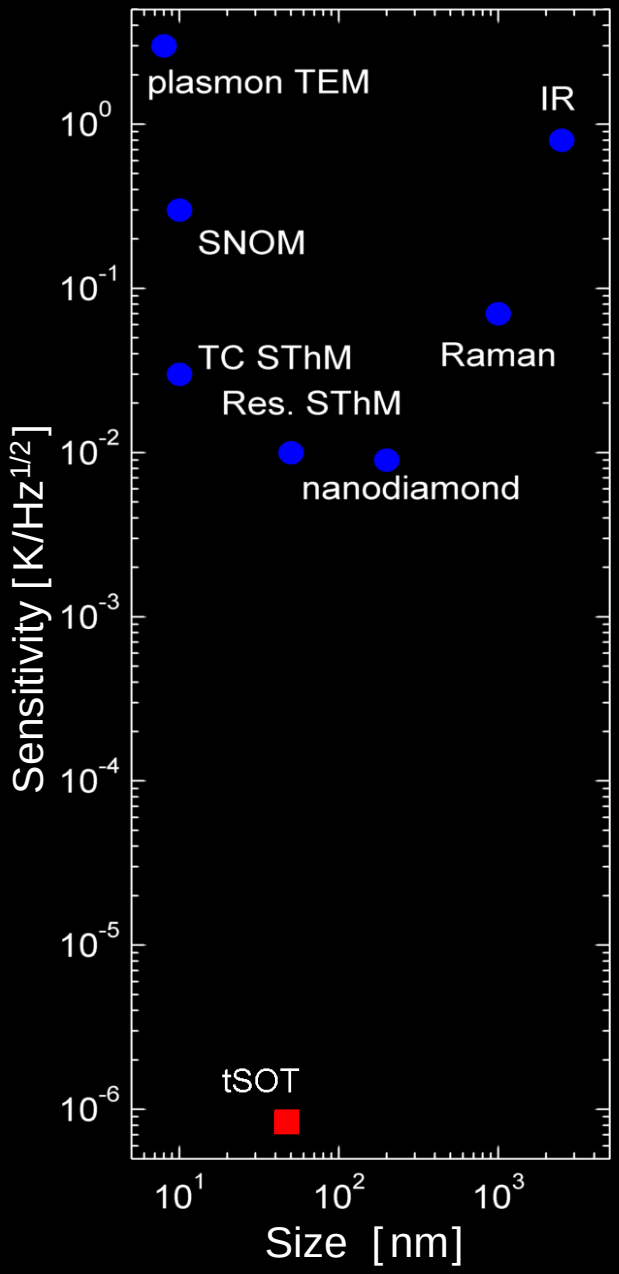
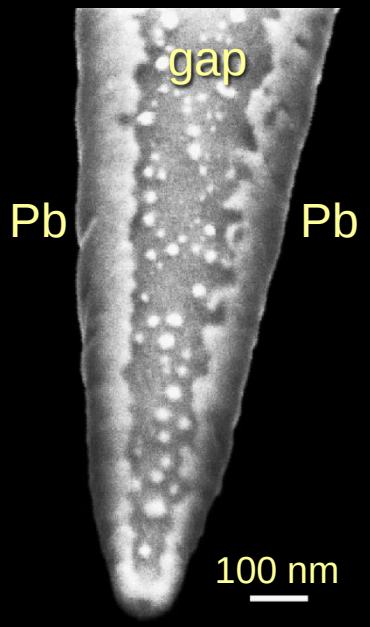
D. Halbertal *et al*., Nature **539**, 407 (2016)

Thermal imaging techniques



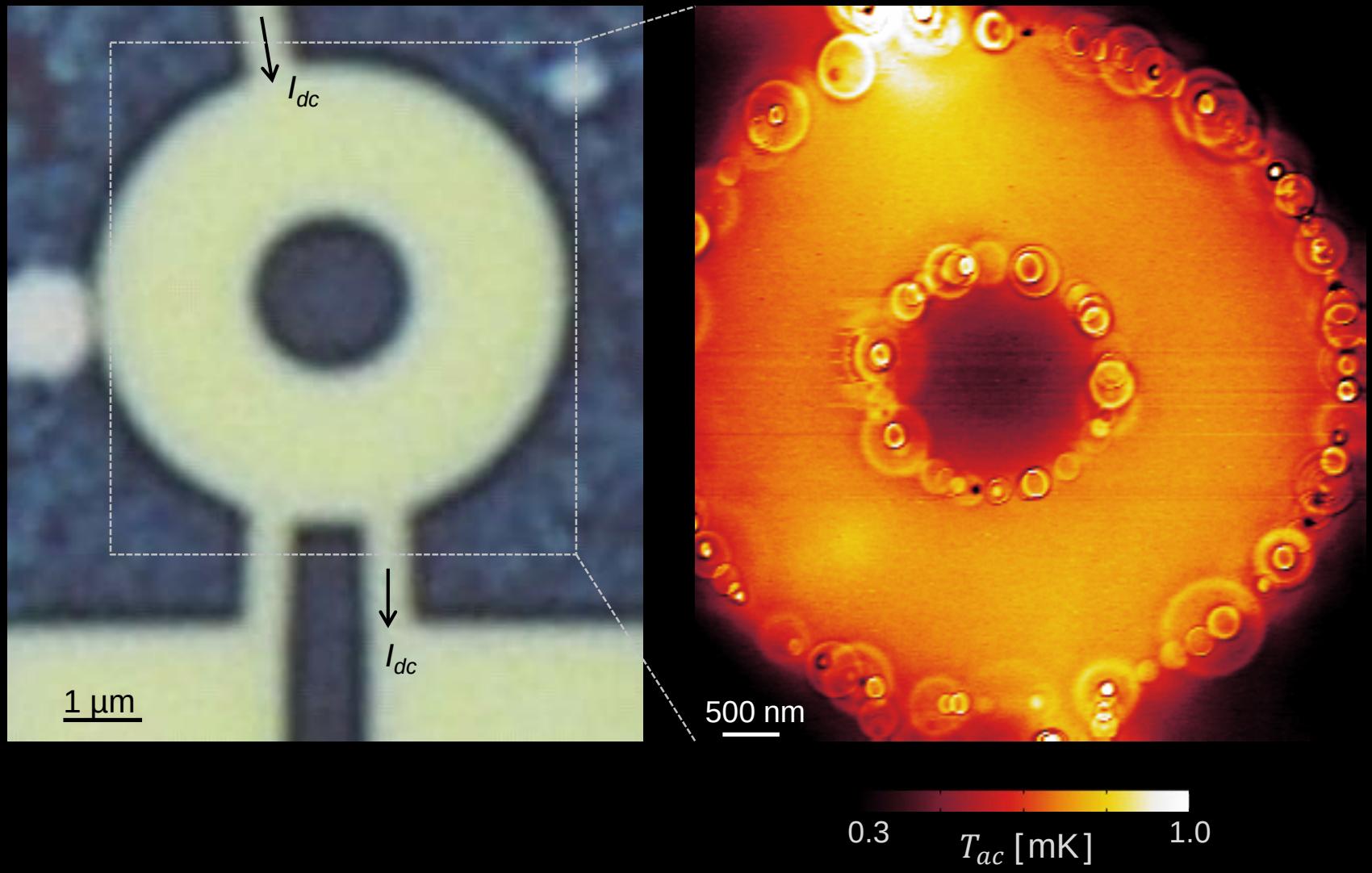


Thermal noise:

$S_T^{1/2} < 1$ μK/Hz$^{1/2}$

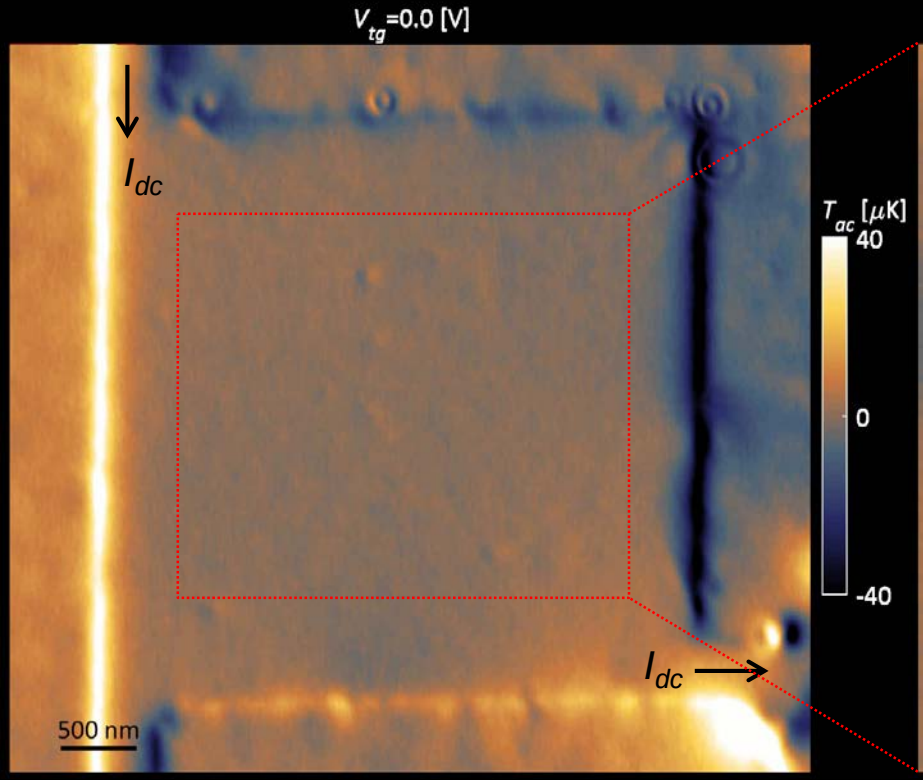
D. Halbertal *et al*., Nature 539, 407 (2016)

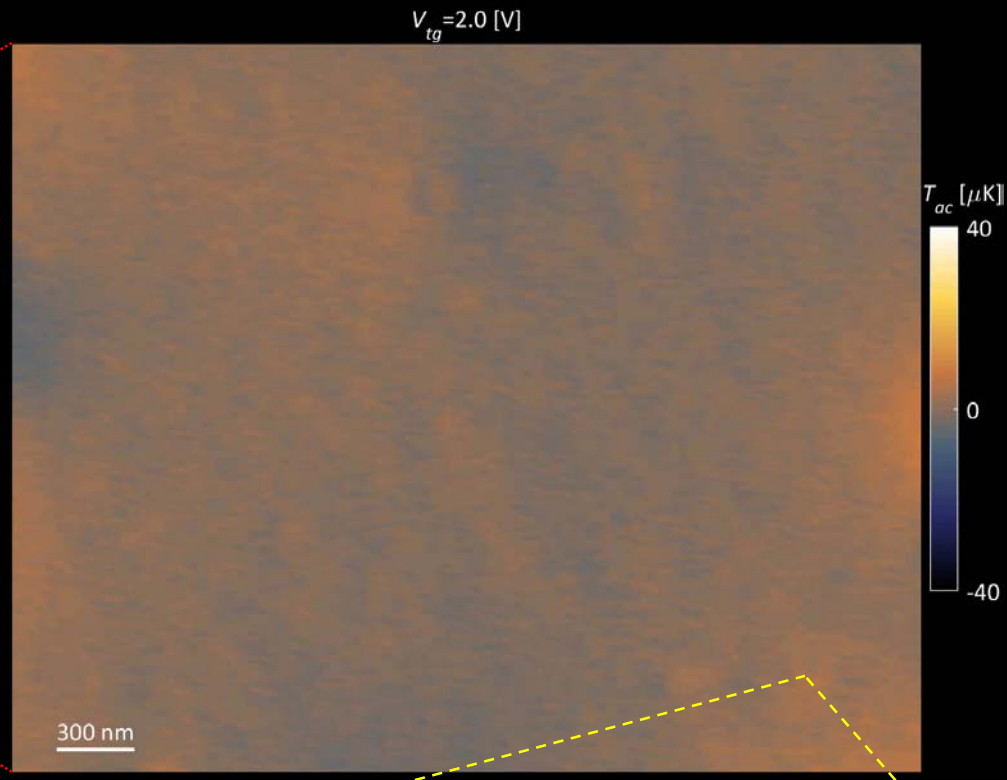
Dissipation in hBN encapsulated graphene



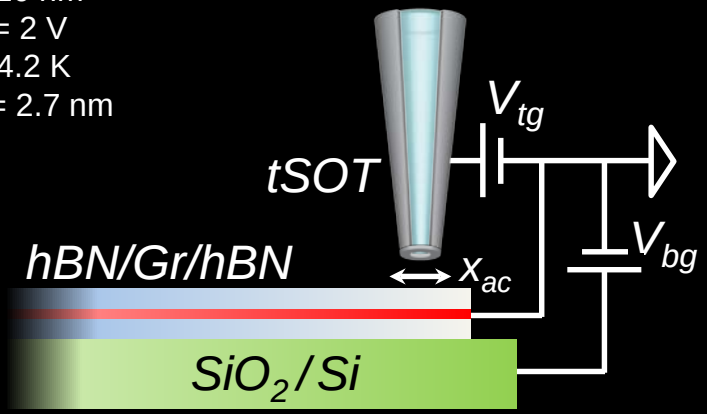
D. Halbertal *et al*., Nature **539**, 407 (2016)

Dissipation from a single atomic defect in graphene

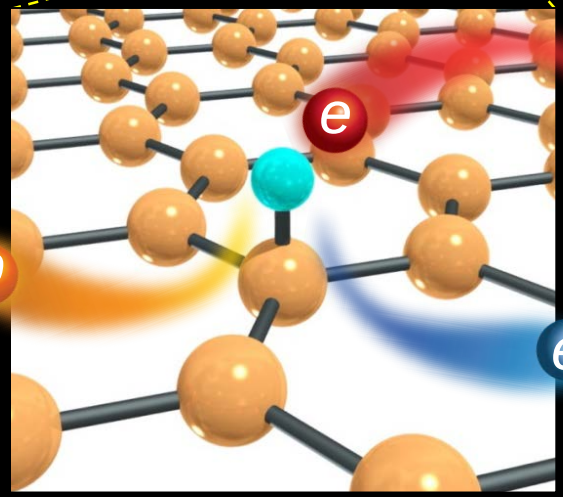




I_{dc} = 3 μA
h = 20 nm
V_{bg} = 2 V
T = 4.2 K
x_{ac} = 2.7 nm

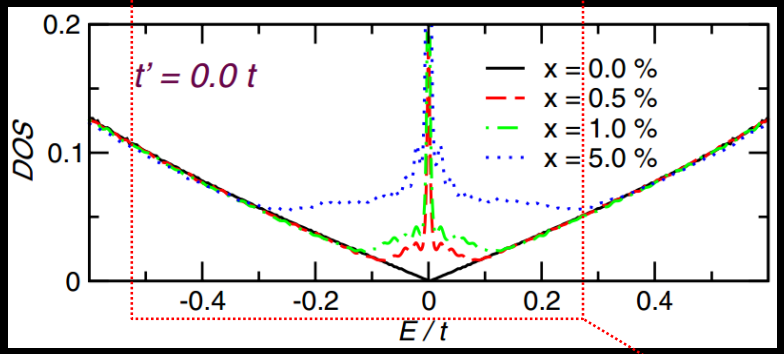


Atomic source of phonons



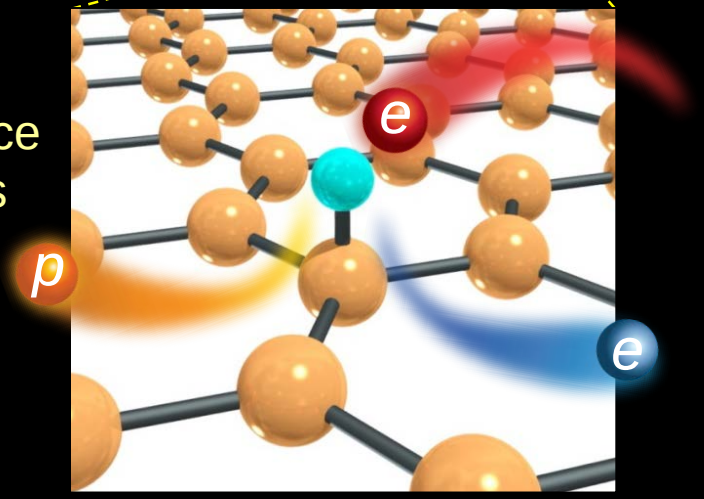
Dissipation in a single-atom defect in graphene

Vacancies and adatoms form localized states near Dirac point in graphene

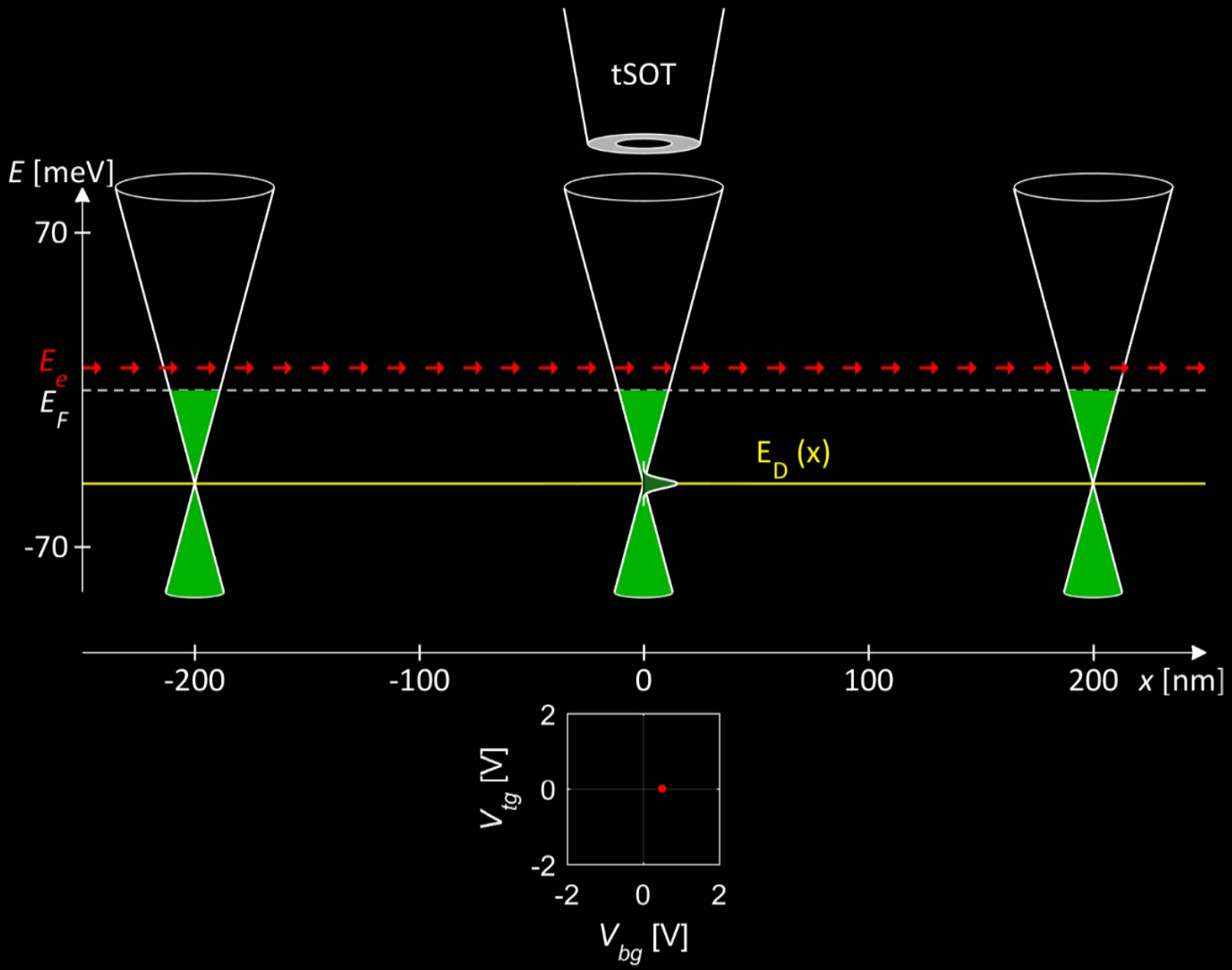


Pereira et al., PRL 96 (2006)
Bistritzer & MacDonald, PRL 102 (2009)
Song, Reizer & Levitov, PRL 109 (2012)
González-Herrero et al., Science 352 (2016)
Mao et al., Nat. Phys. 12 (2016)

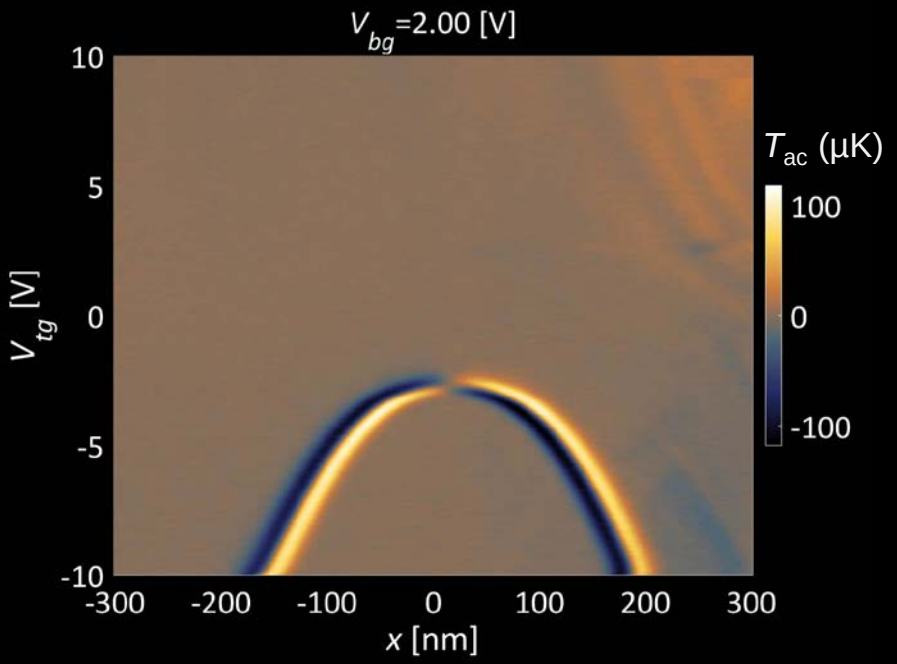
Atomic source of phonons

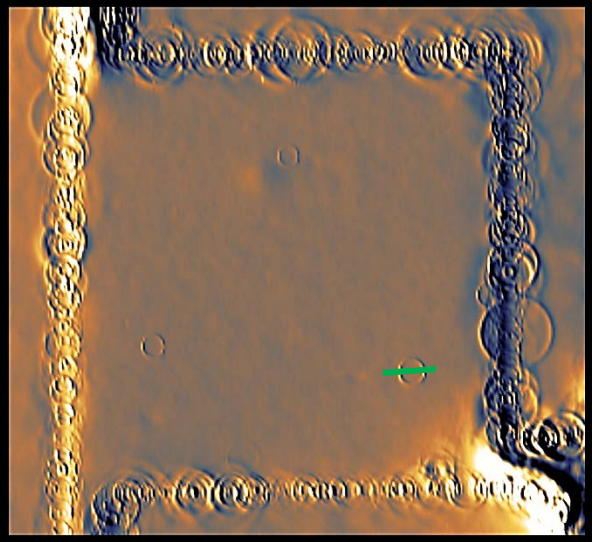


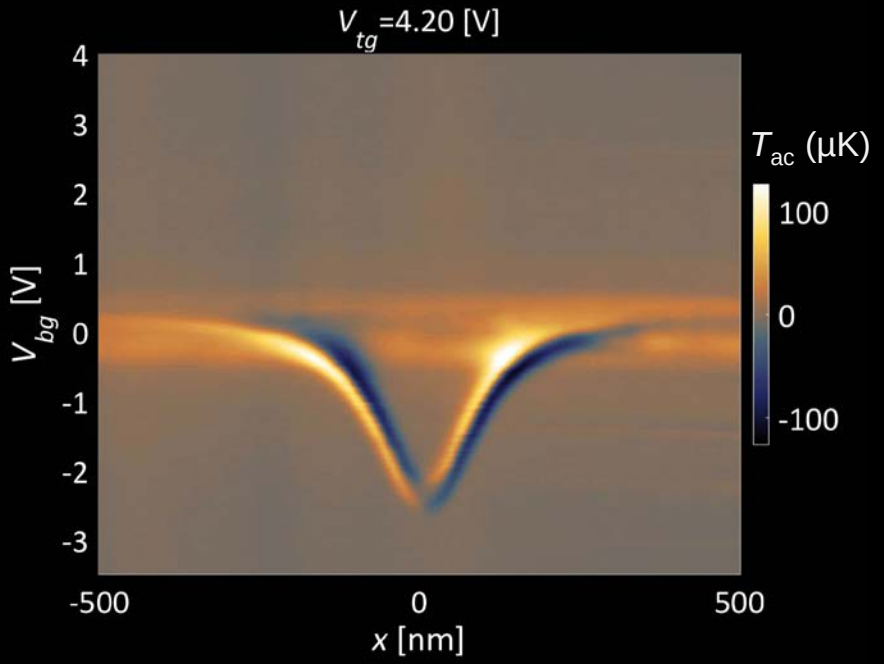
Resonant inelastic scattering by a single localized state



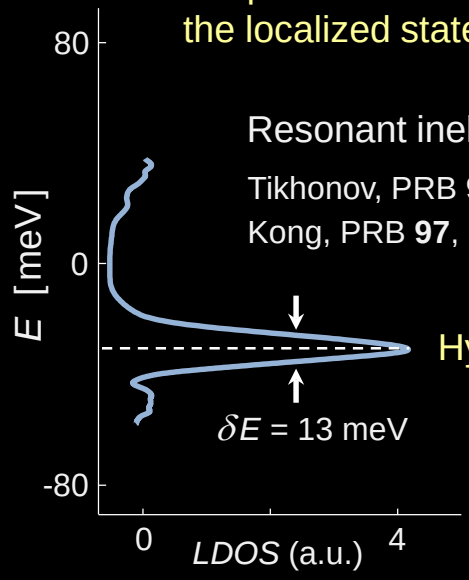
Spectroscopy of bulk defects







Dissipative LDOS of the localized state



Resonant inelastic scattering

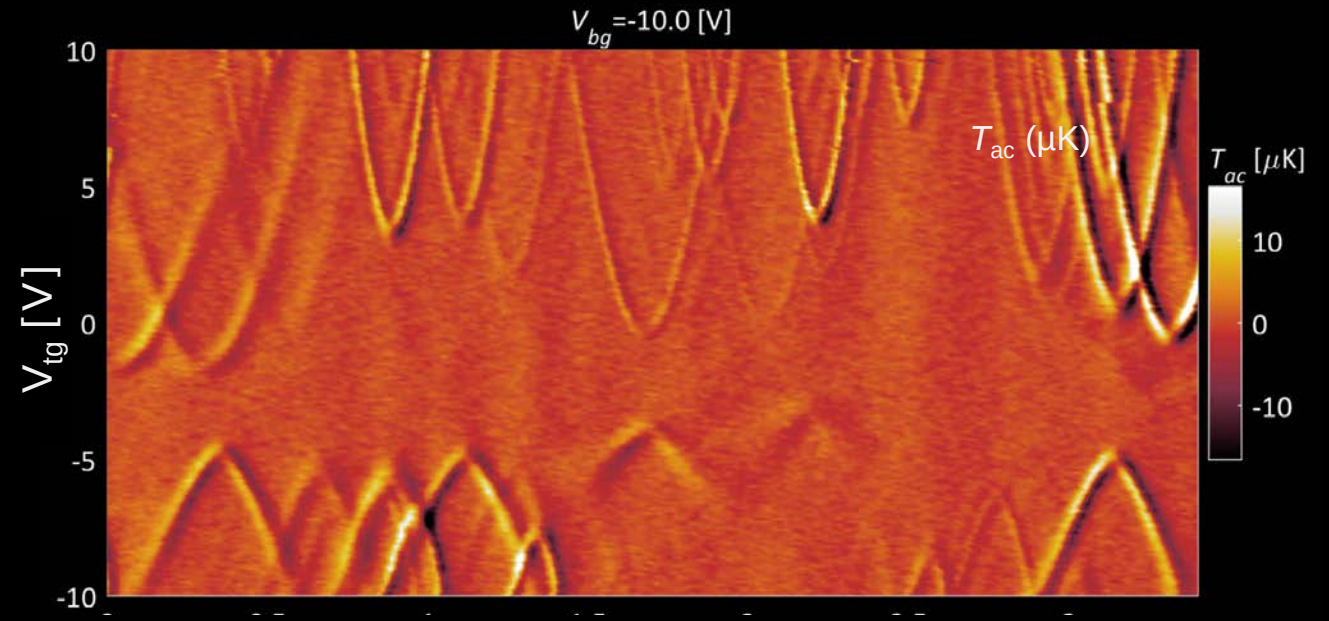
Tikhonov, PRB **97**, 085415 (2018)

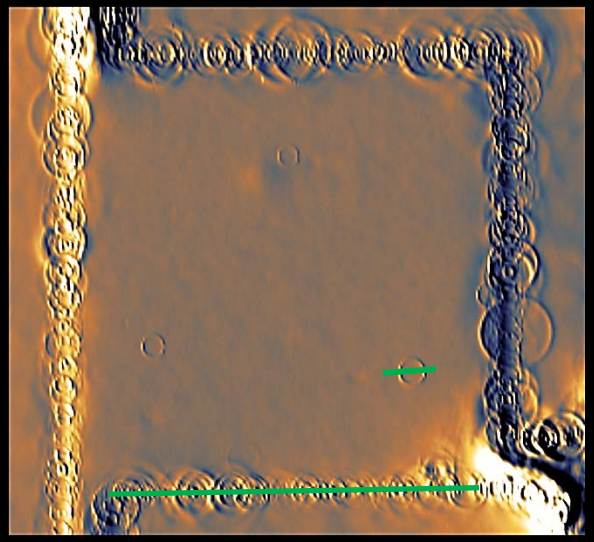
Kong, PRB **97**, 245416 (2018)

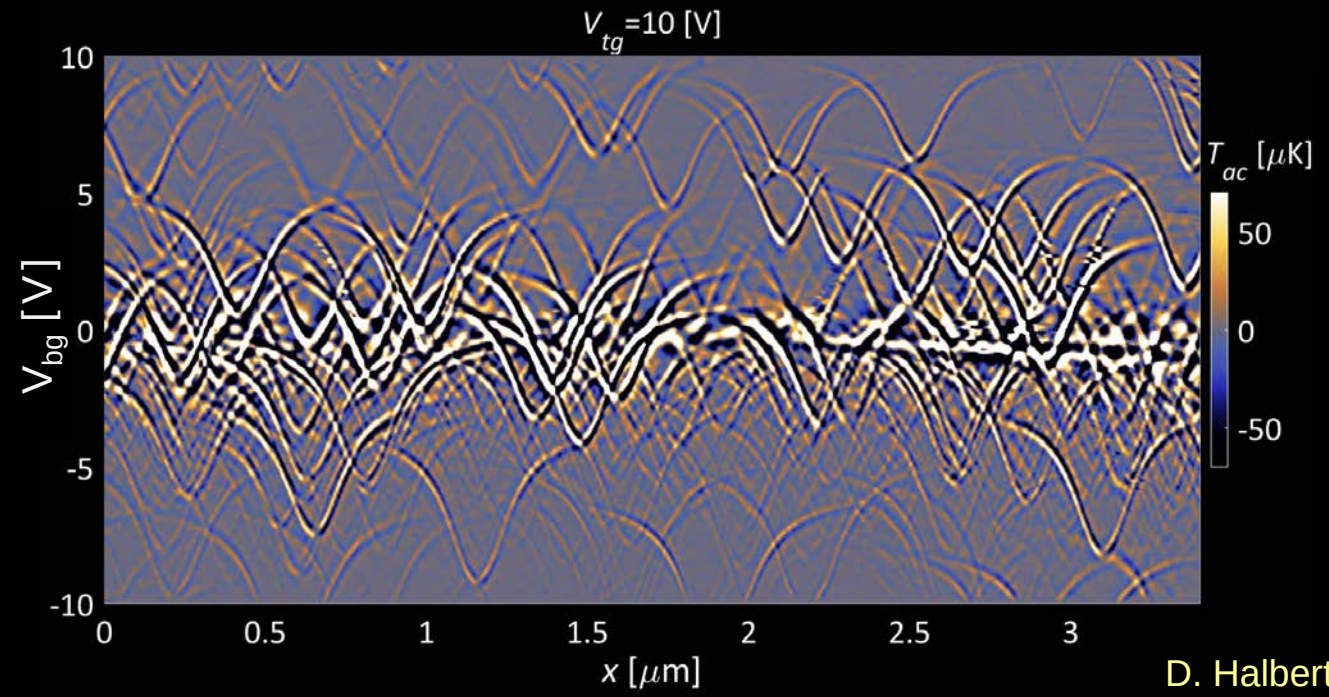
Hydrogen adatom

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

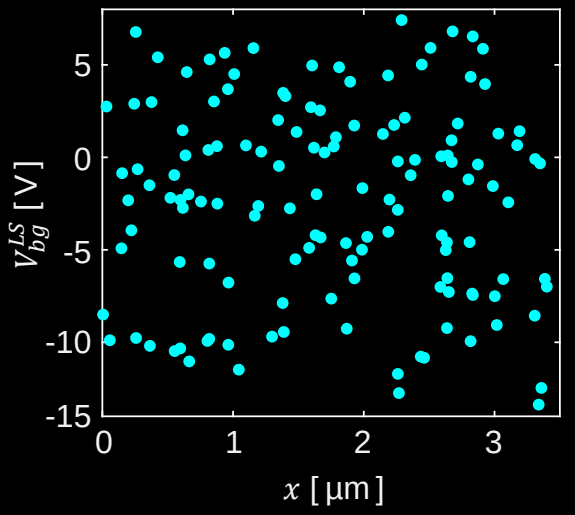
Spectroscopy of edge defects







Energy of the localized states vs. position



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

Dissipation in the quantum Hall state

Guiding principles of idealized QH

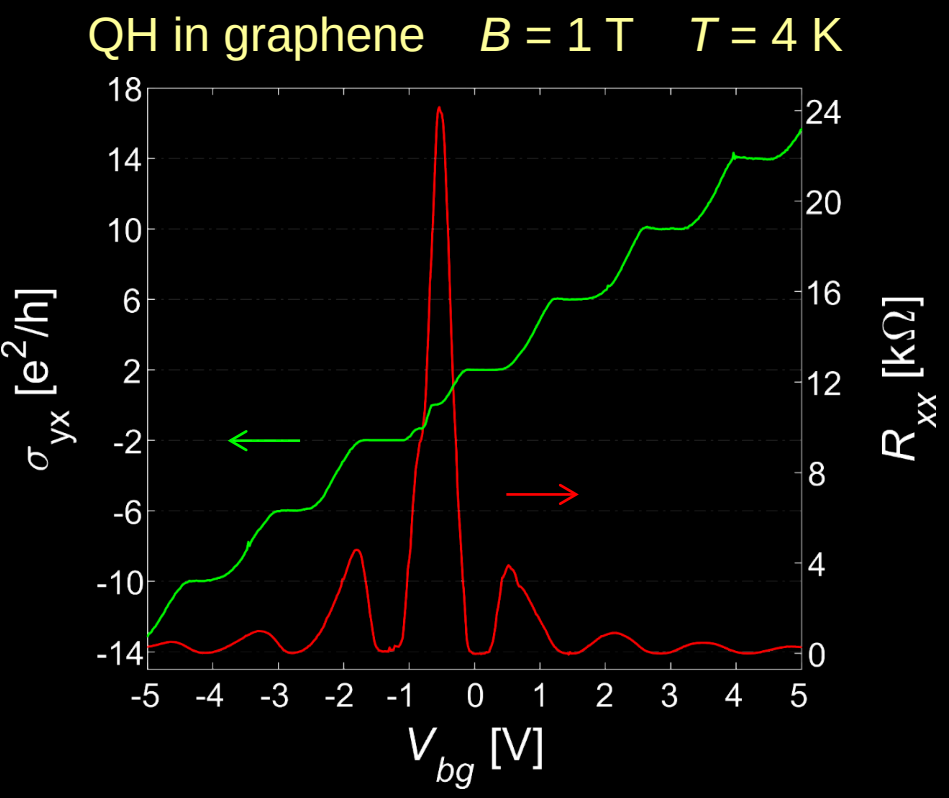
I. QH plateau

Chiral edge channels carrying current with no dissipation. Dissipation only at contacts.

II. Plateau transition

Dissipation in the bulk

III. Topological state is robust against local perturbations



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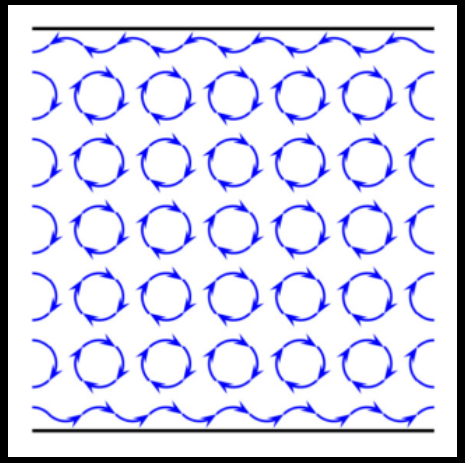

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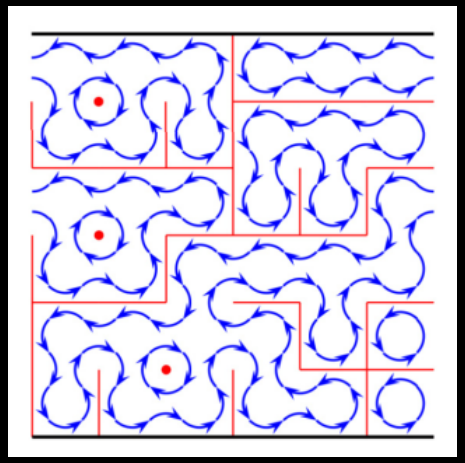

III. Topological state is robust against local perturbations

Vasseur, PRB 92 (2015)

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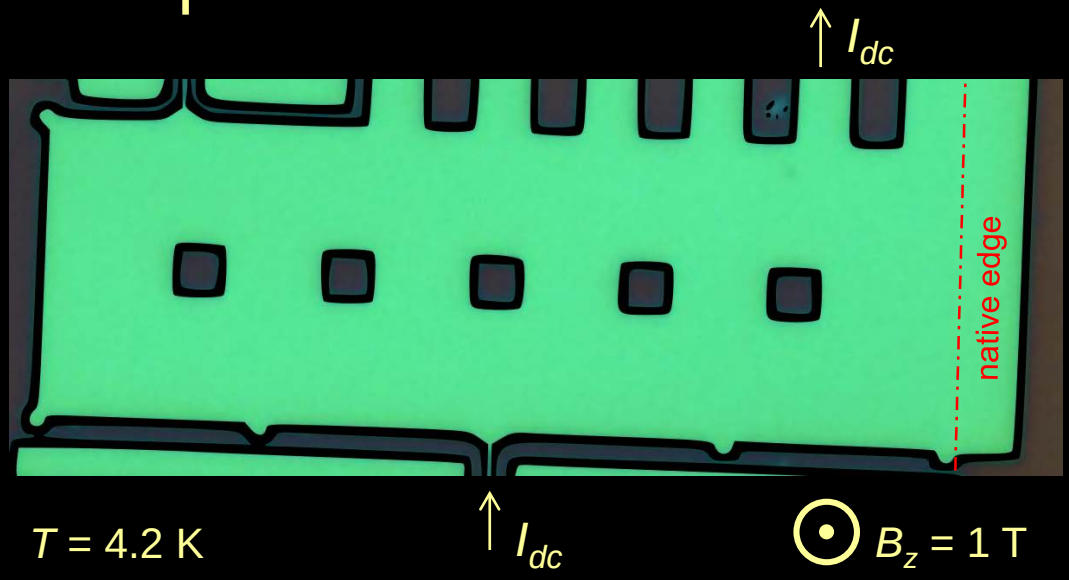

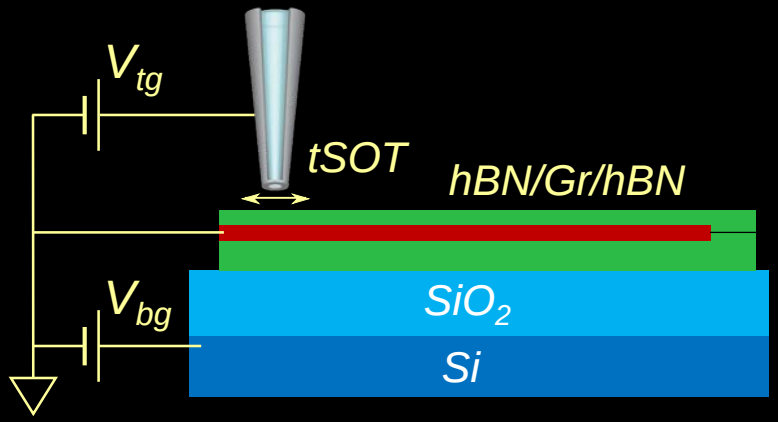

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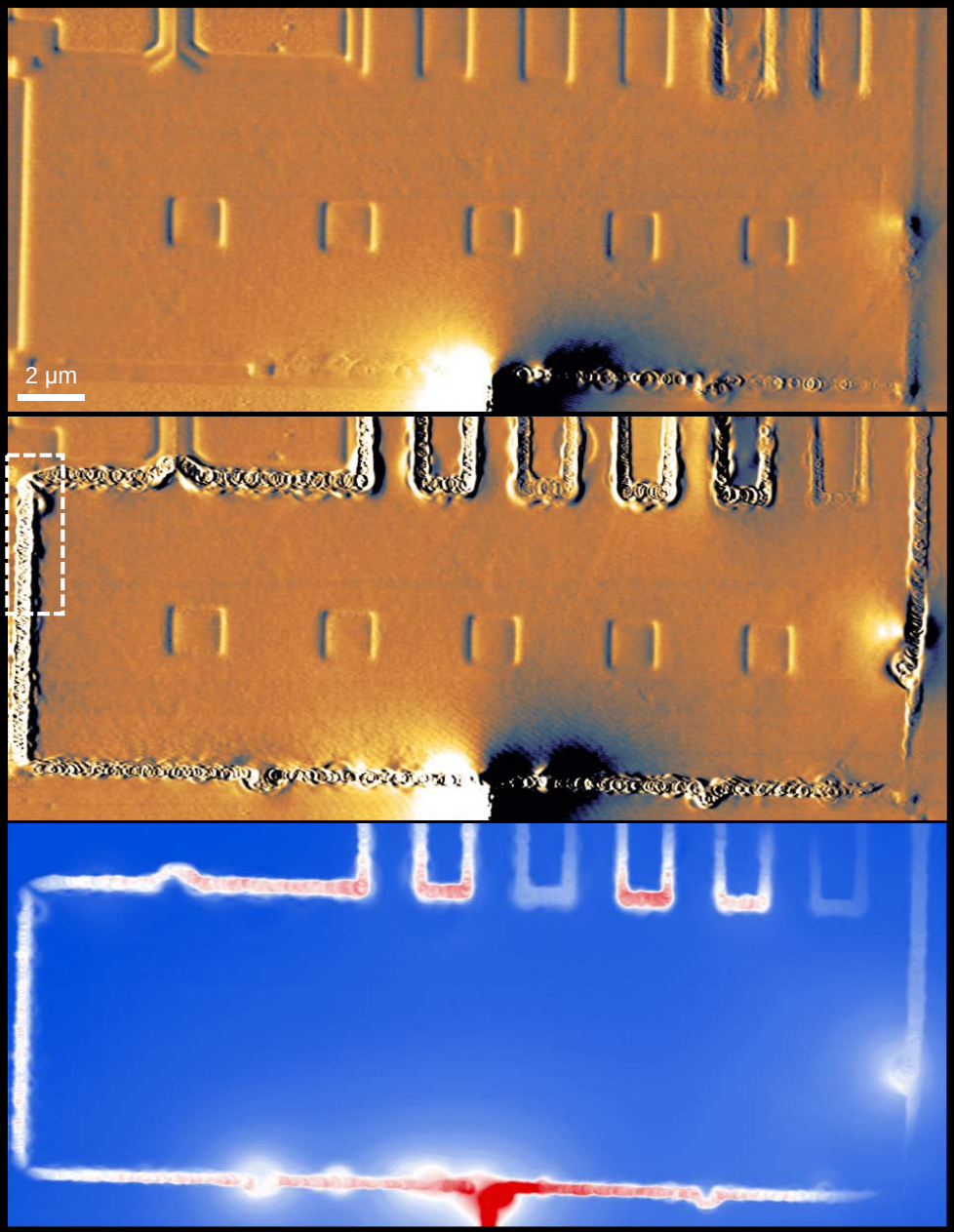
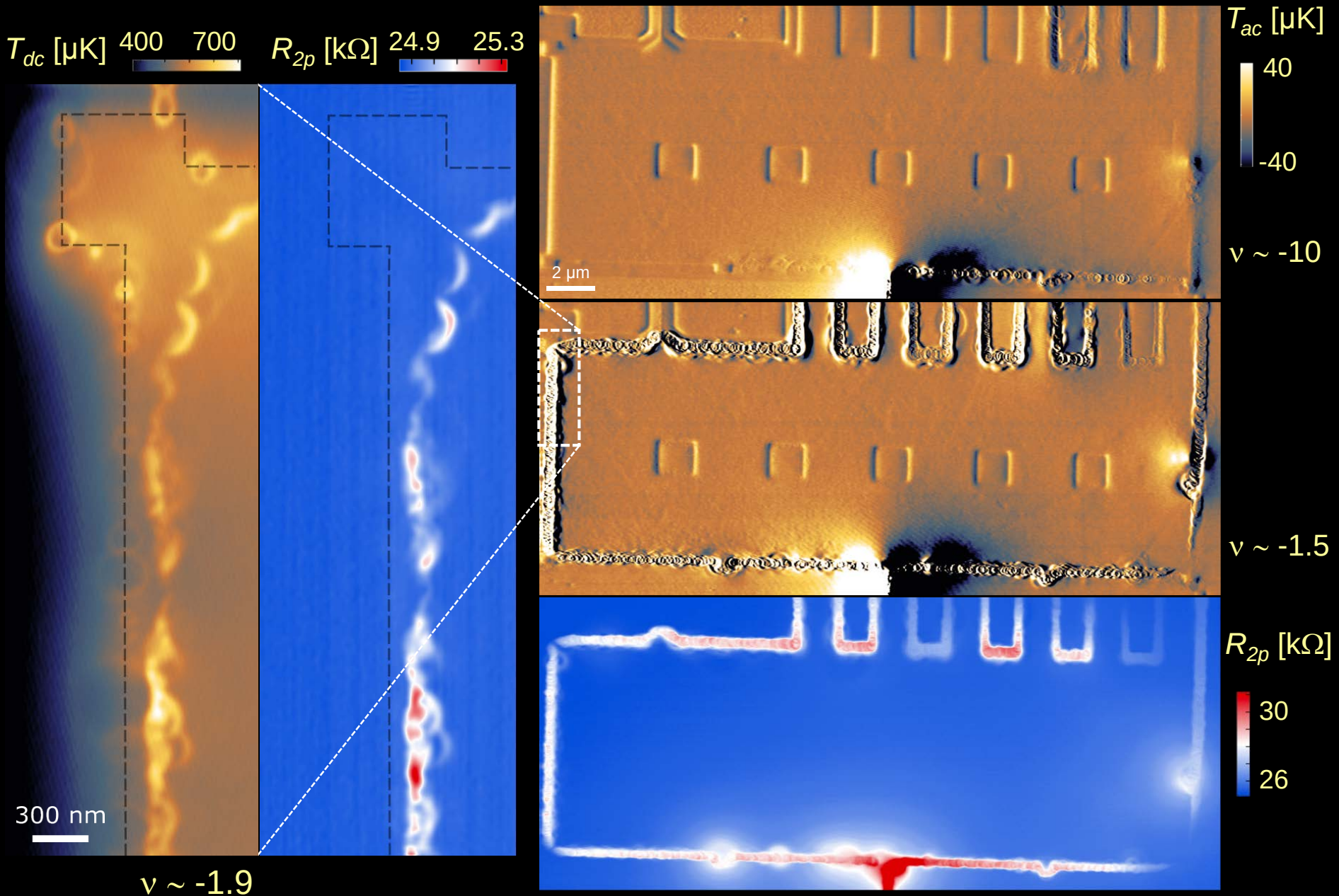
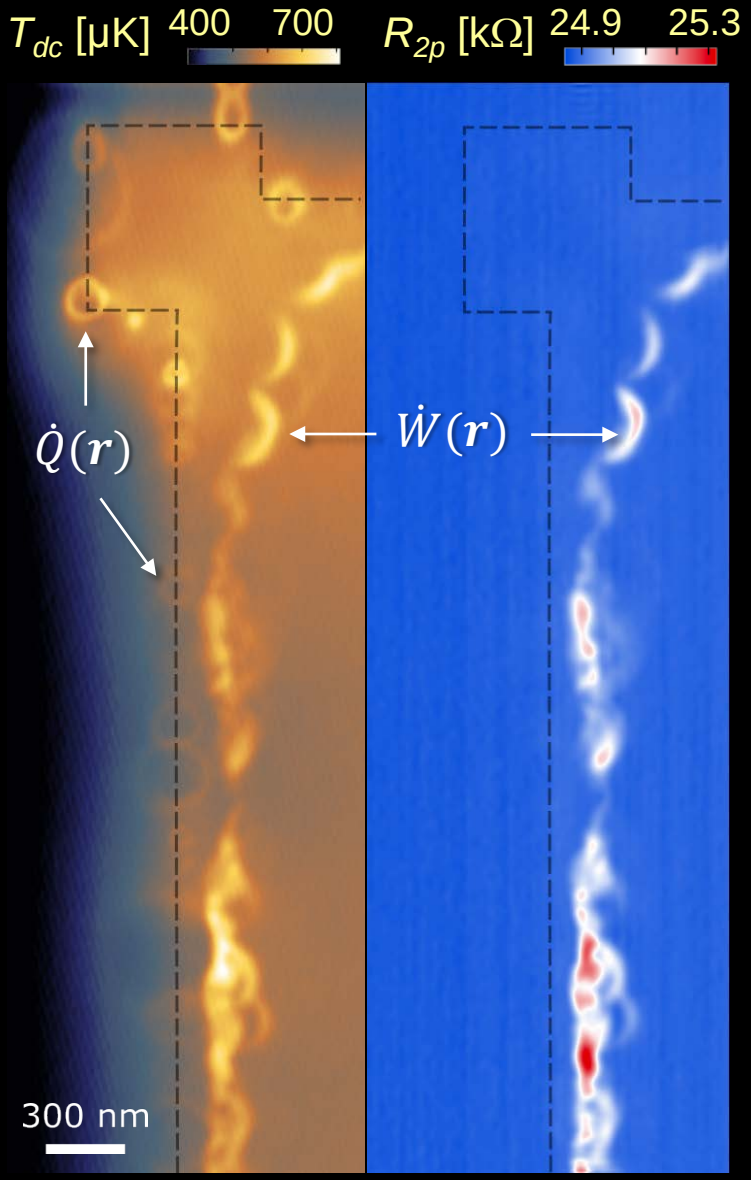


Dissipation in the quantum Hall state



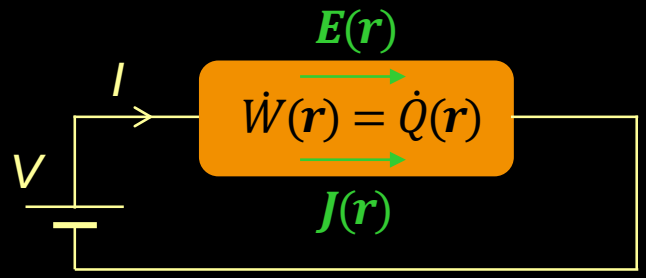
Work and dissipation



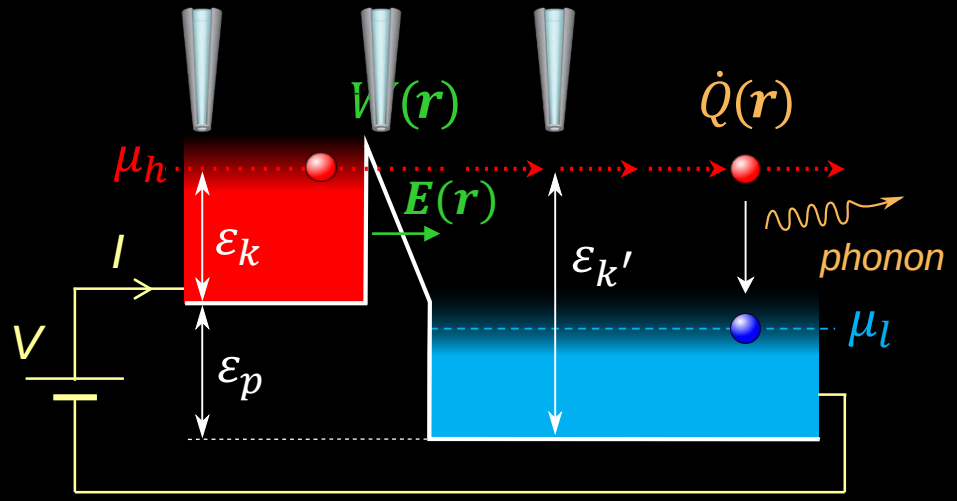
ν ~ -1.9

Diffusive system Joule heating

$$P(\boldsymbol{r}) = \dot{W}(\boldsymbol{r}) = \boldsymbol{J}(\boldsymbol{r}) \cdot \boldsymbol{E}(\boldsymbol{r}) = \dot{Q}(\boldsymbol{r})$$

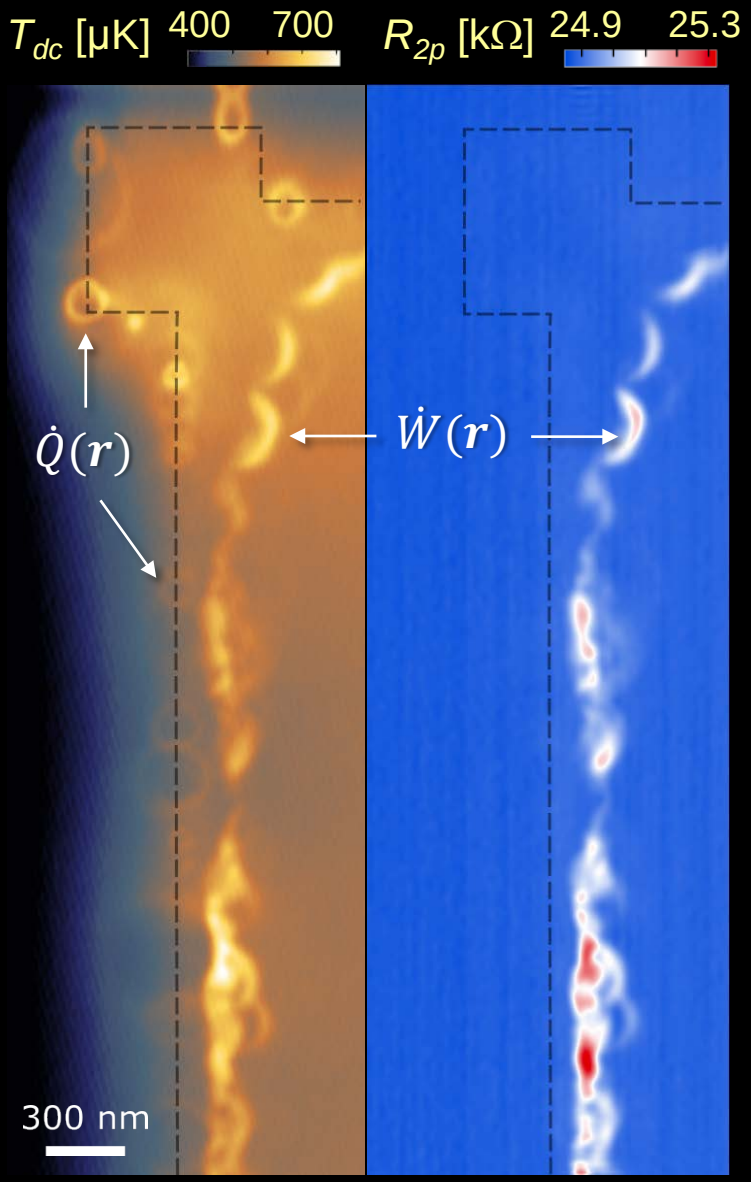


Ballistic system $\dot{W}(\boldsymbol{r}) = \boldsymbol{J}(\boldsymbol{r}) \cdot \boldsymbol{E}(\boldsymbol{r}) \neq \dot{Q}(\boldsymbol{r})$



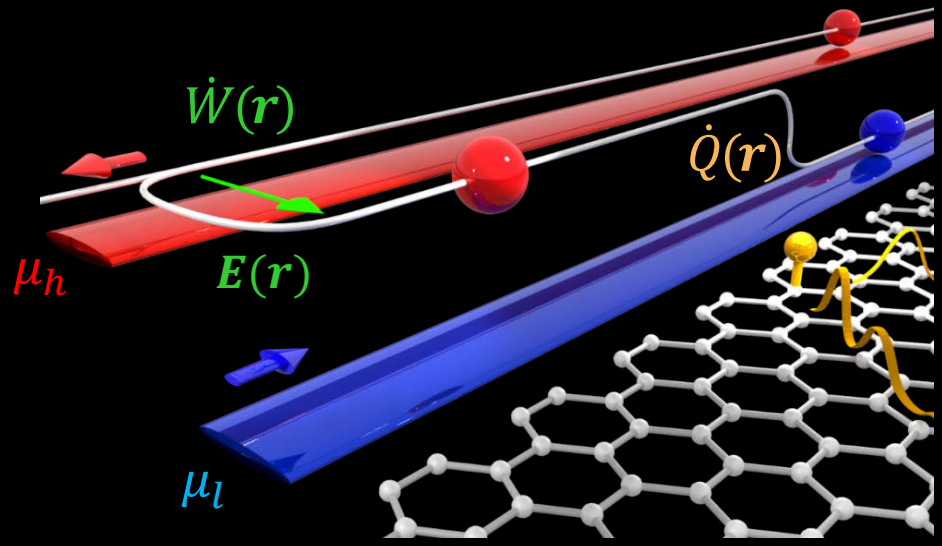
Rokni and Levinson, PRB 52, 1882 (1995)

Work and dissipation

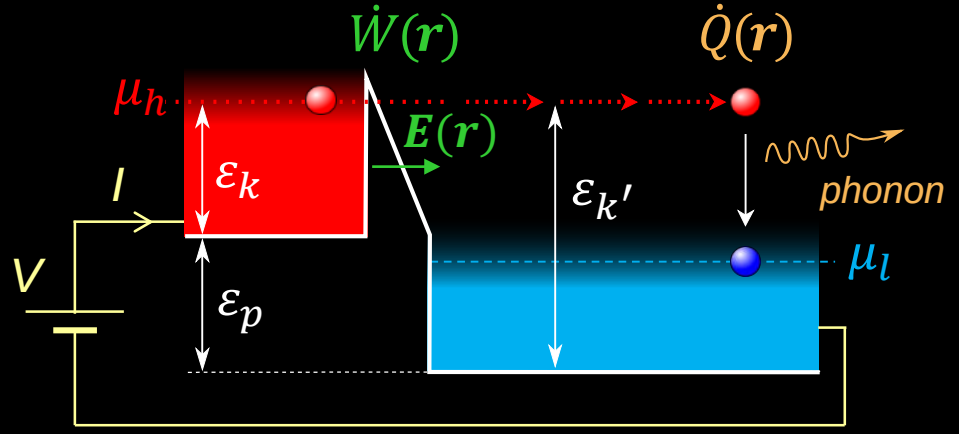


ν ~ -1.9

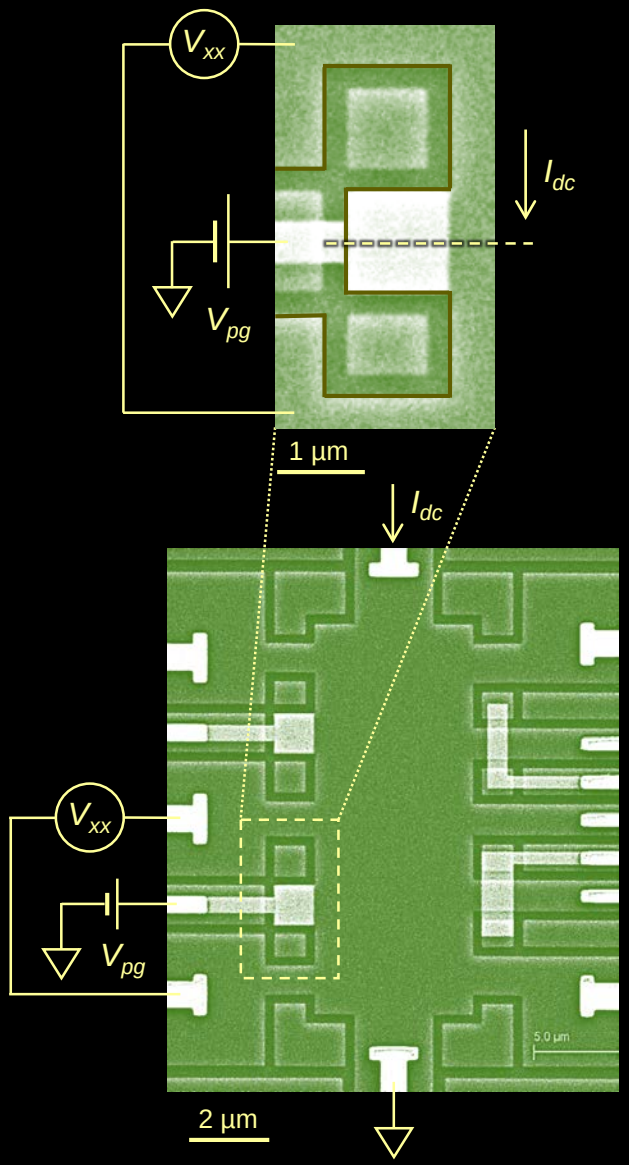
Counterpropagating QH edge states



Ballistic system $\dot{W}(r) = J(r) \cdot E(r) \neq \dot{Q}(r)$



Edge reconstruction and separation of work and dissipation



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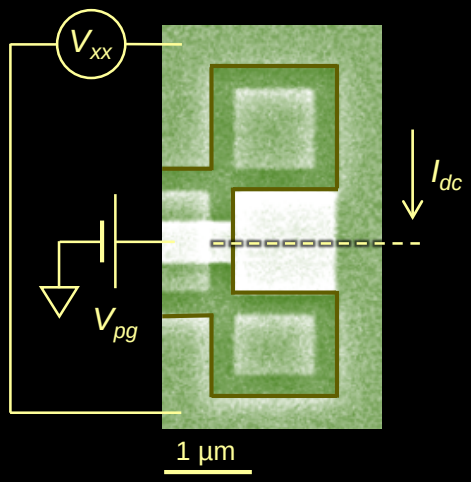

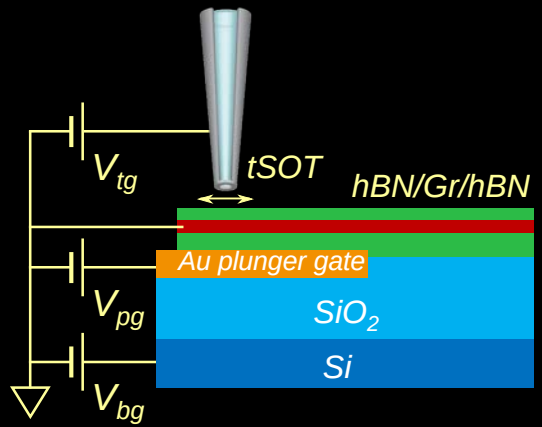

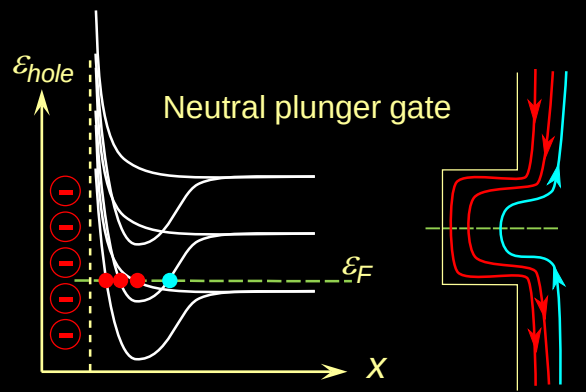

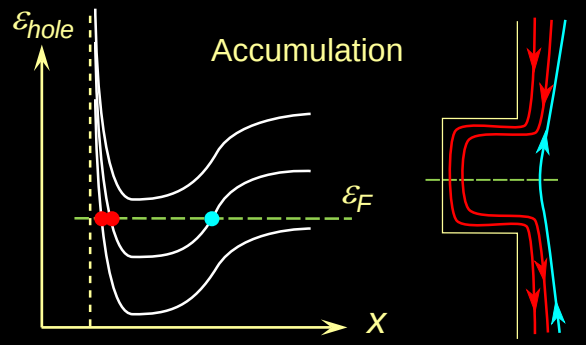

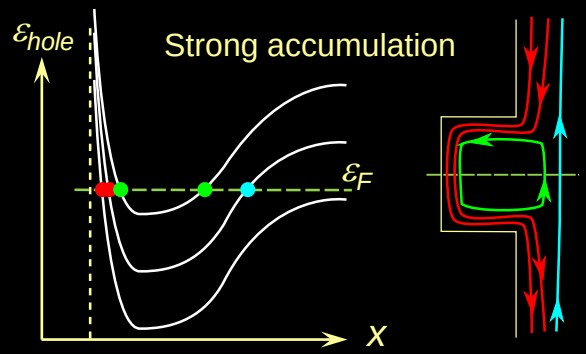

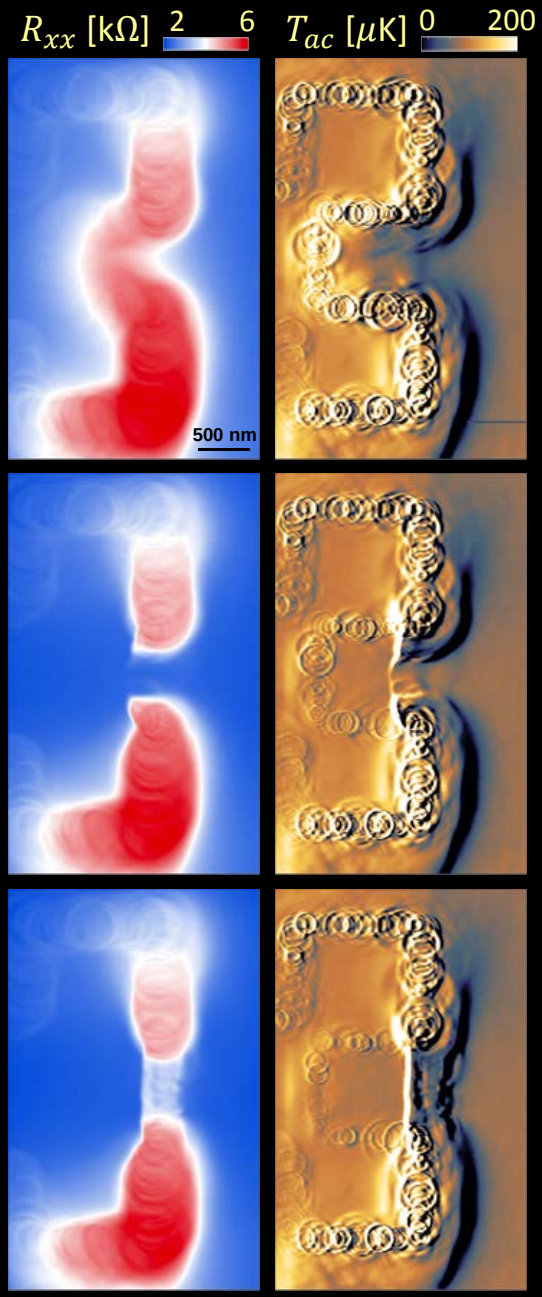

Weizmann team

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J. Cuppens
Y. Myasoedov
M. Rappaport
I. Marcus

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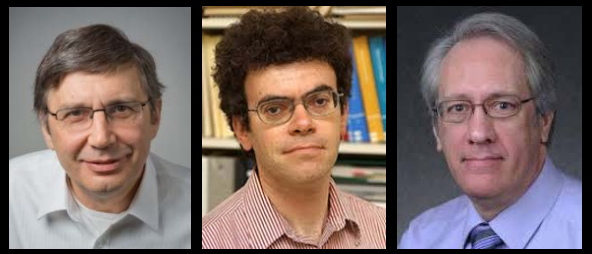
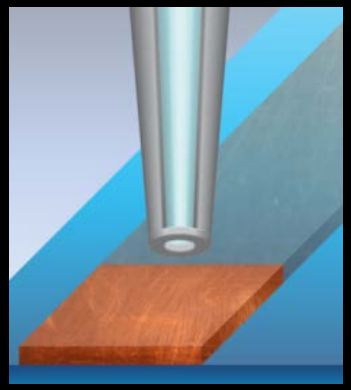
M. Ben Shalom, Manchester
A. K. Geim, Manchester
L. S. Levitov, MIT
M.E. Huber, Denver



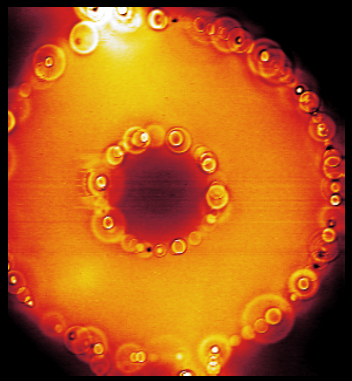
Summary

Nanoscale thermal imaging of quantum systems with sub 1 μK sensitivity

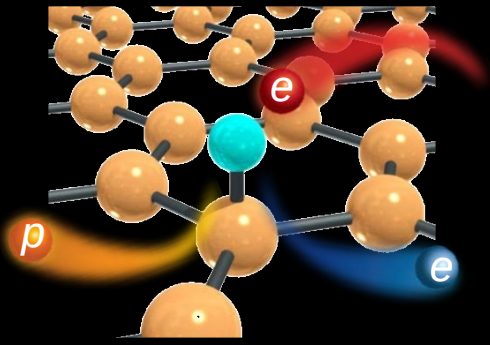


Spectroscopy of edge states in graphene

Dissipation dominated by edge detects in graphene



Detection of phonon emission from a single atomic defect



Inelastic electron scattering by a resonant localized state

Independent imaging of work and dissipation