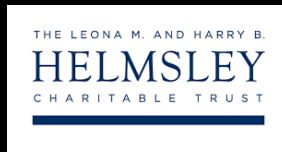
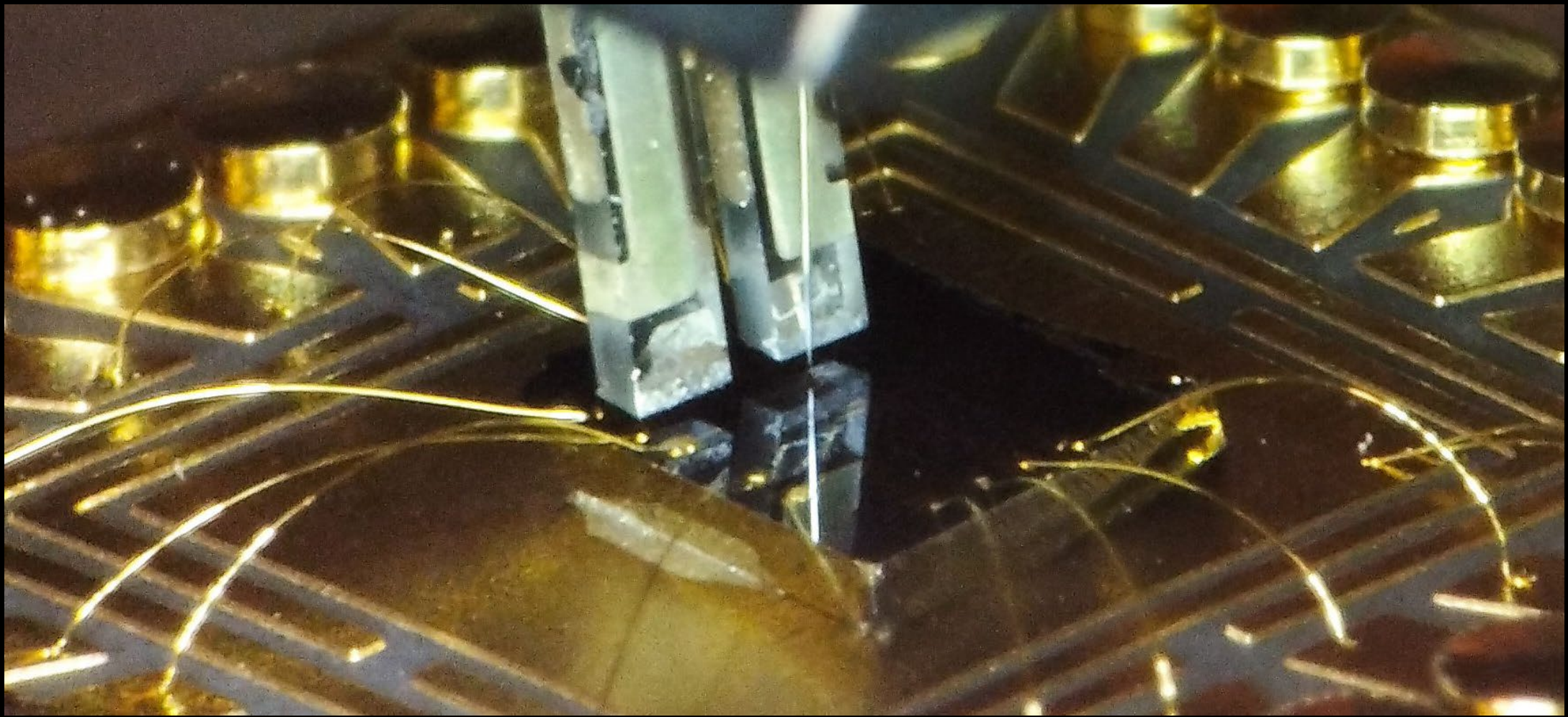




# Scanning SQUID-on-tip magnetic and thermal imaging: Nanoscale probe of superconductivity and strongly correlated electronic systems

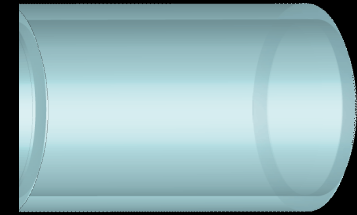


Eli Zeldov  
Weizmann Institute of Science, Israel





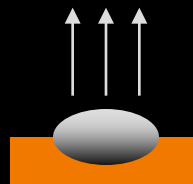
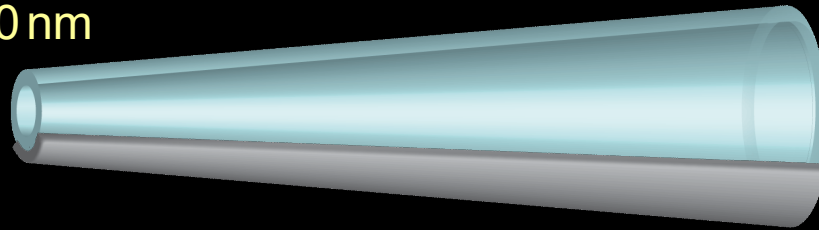
# SQUID on tip



Ø 1 mm

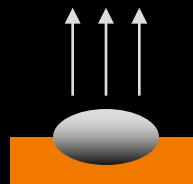
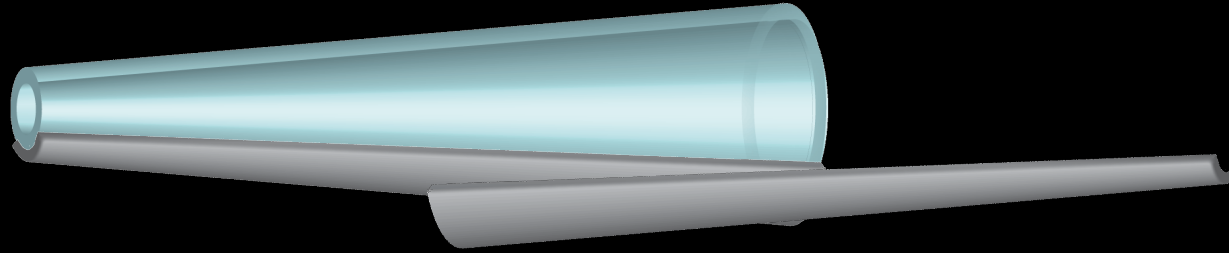
# SQUID on tip

Ø 30 ÷ 400 nm



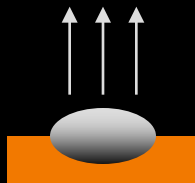
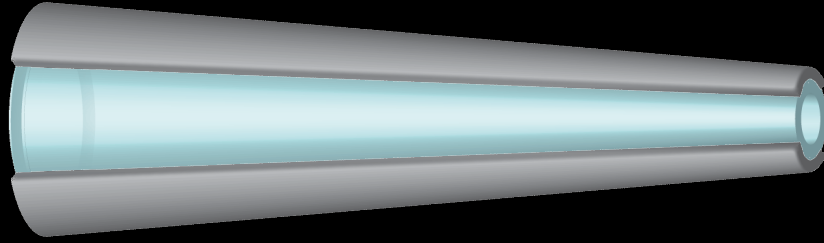
Al, Nb, Pb, In, Sn, MoRe

# SQUID on tip



Al, Nb, Pb, In, Sn, MoRe

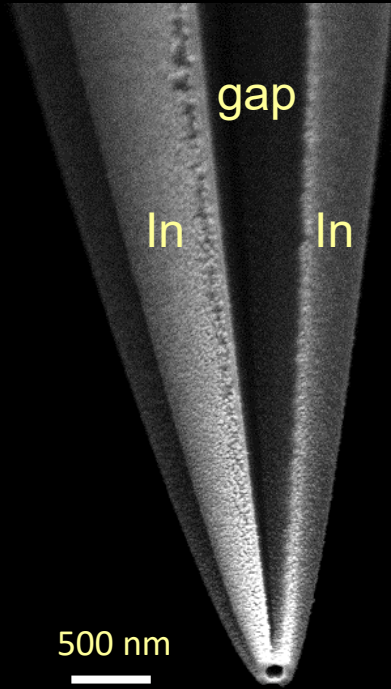
# SQUID on tip



Al, Nb, Pb, In, Sn, MoRe

# SQUID on tip

SEM image



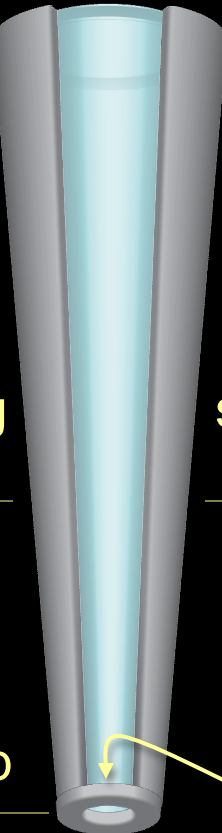
- Loop diameter  $< 40$  nm
- Operating magnetic field  $> 5$  T
- Field sensitivity  $< 10$  nT/Hz<sup>1/2</sup>
- Flux sensitivity  $< 50$  n $\Phi_0$ /Hz<sup>1/2</sup>
- Spin sensitivity  $< 0.3$   $\mu_B$ /Hz<sup>1/2</sup>
- Thermal sensitivity  $< 1$   $\mu$ K/Hz<sup>1/2</sup>

superconducting  
lead

superconducting  
lead

SQUID loop

weak links



Al, Nb, Pb, In, Sn, MoRe

Quartz tuning fork



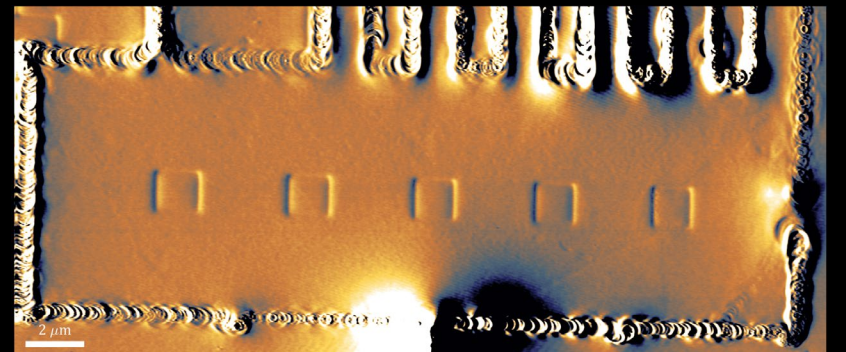
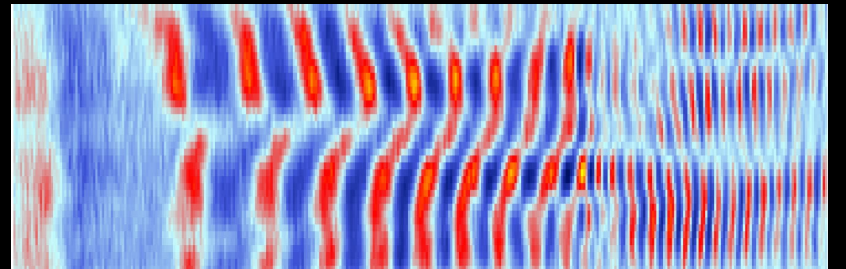
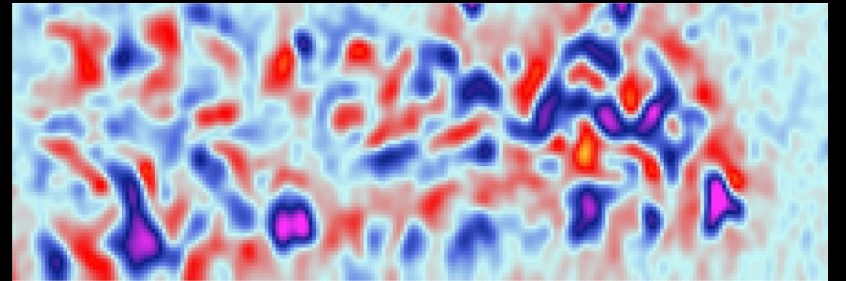
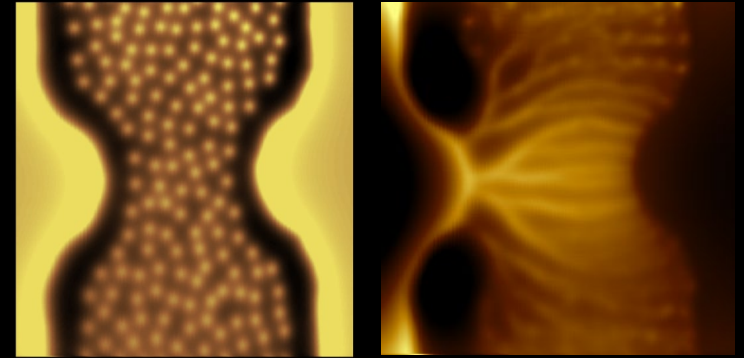
SQUID-on-tip attached to  
tuning fork for force sensing

Scan height:  $\sim 10$  nm

- D. Vasyukov *et al.*, Nature Nano. **8**, 639 (2013)
- K. Bagani *et al.*, PR Applied **12**, 044062 (2019)
- D. Halbertal *et al.*, Nature **539**, 407 (2016)

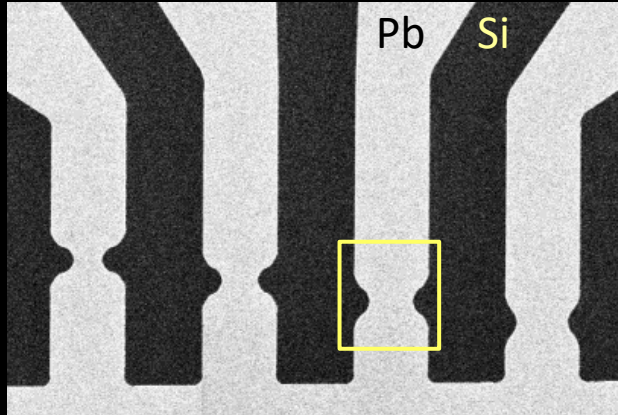
## Outline

- Vortices in superconductors and electron fluids
- Magnetism in graphene
- Thermodynamic quantum oscillations
- Thermal nanoscale imaging



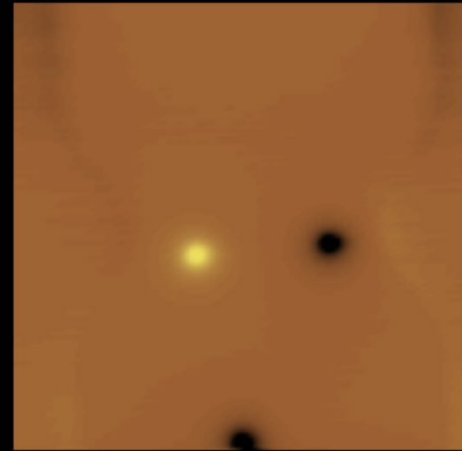
# Vortices in Pb film

Patterned Pb film 50 nm



10  $\mu\text{m}$

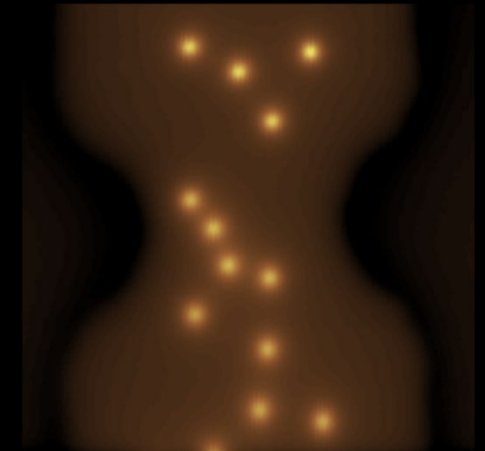
SQUID diameter: 225 nm  
Scan area:  $12 \times 12 \mu\text{m}^2$   
Scan time: 2 min  
Pixel size: 100 nm  
T = 4.2 K



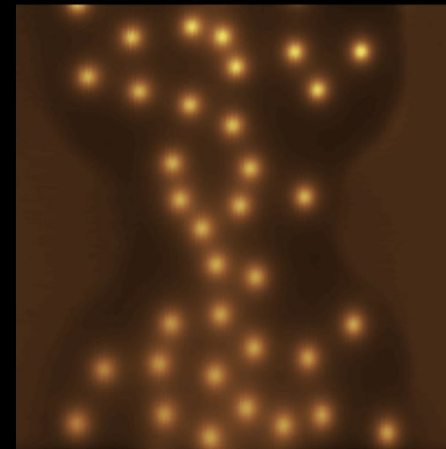
0 G



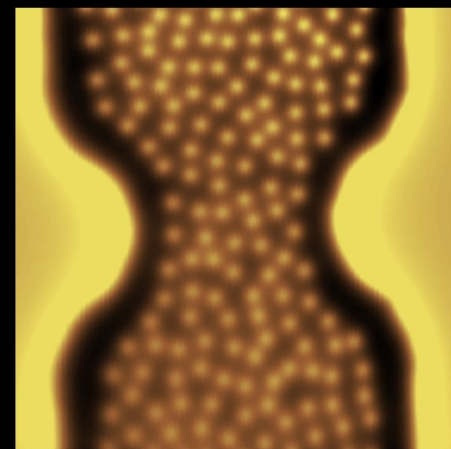
3 G



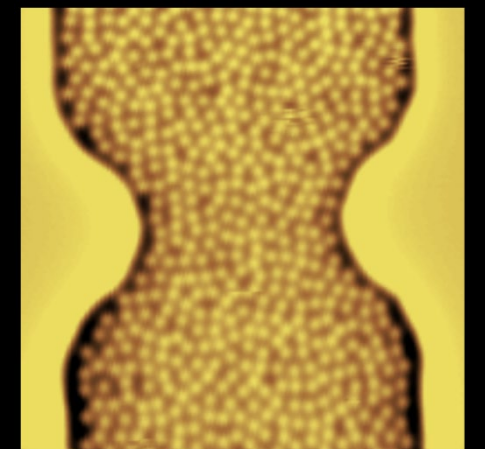
6 G



15 G



54 G



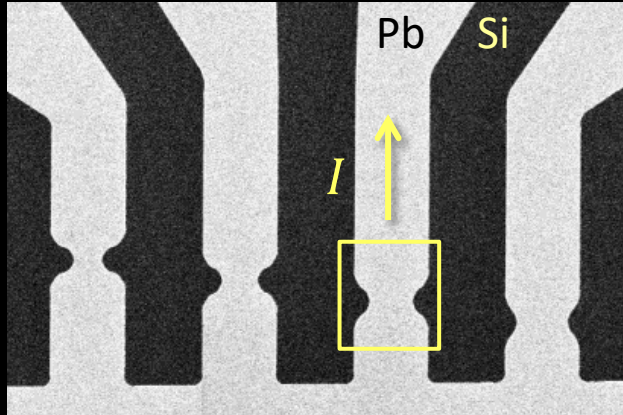
120 G

Embon *et al.*, Scientific Reports **5**, 7598 (2015)

Embon *et al.*, Nature Commun. **8**, 85 (2017)

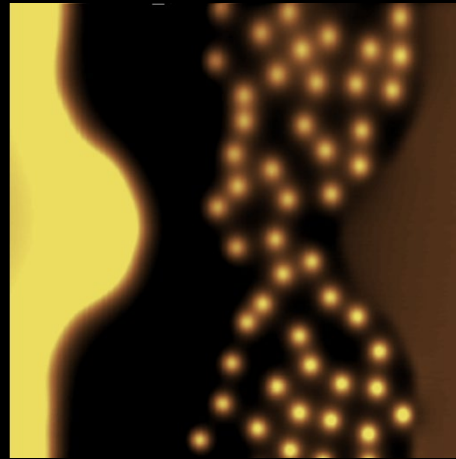
# Vortices in presence of current

Patterned Pb film 50 nm

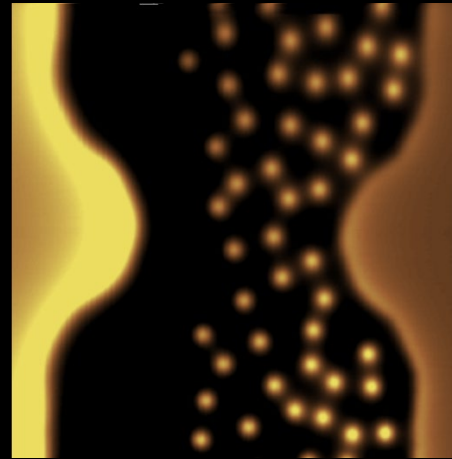


$10\ \mu\text{m}$

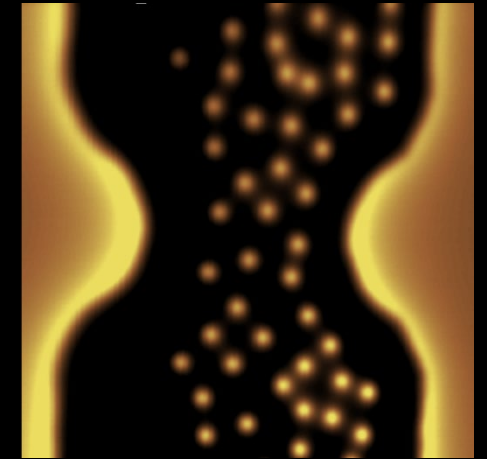
SQUID diameter: 225 nm  
Scan area:  $12 \times 12\ \mu\text{m}^2$   
Scan time: 2 min  
Pixel size: 100 nm  
 $T = 4.2\ \text{K}$   
 $B_a = 27\ \text{G}$



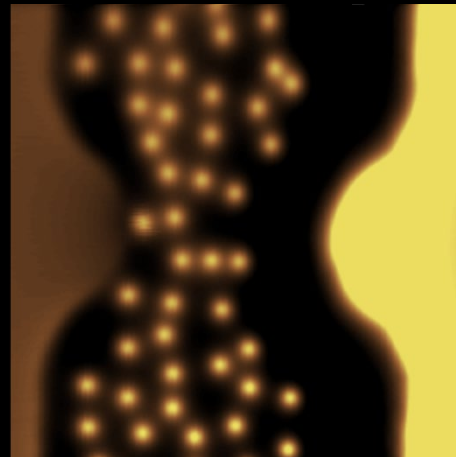
16 mA



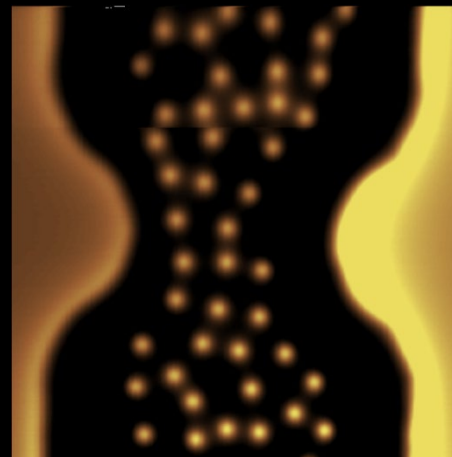
8 mA



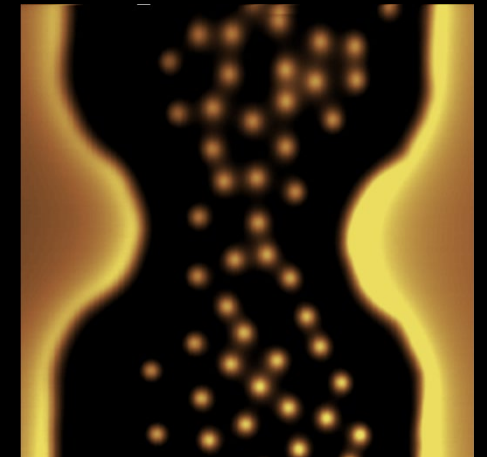
0 mA



-16 mA



-8 mA



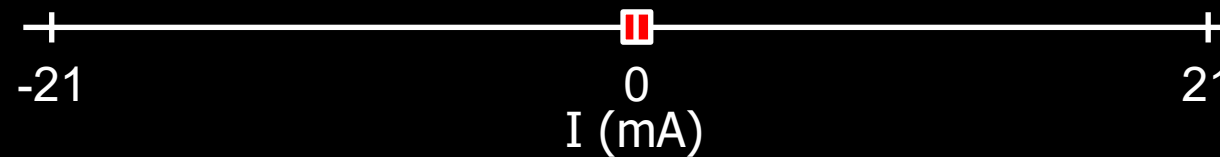
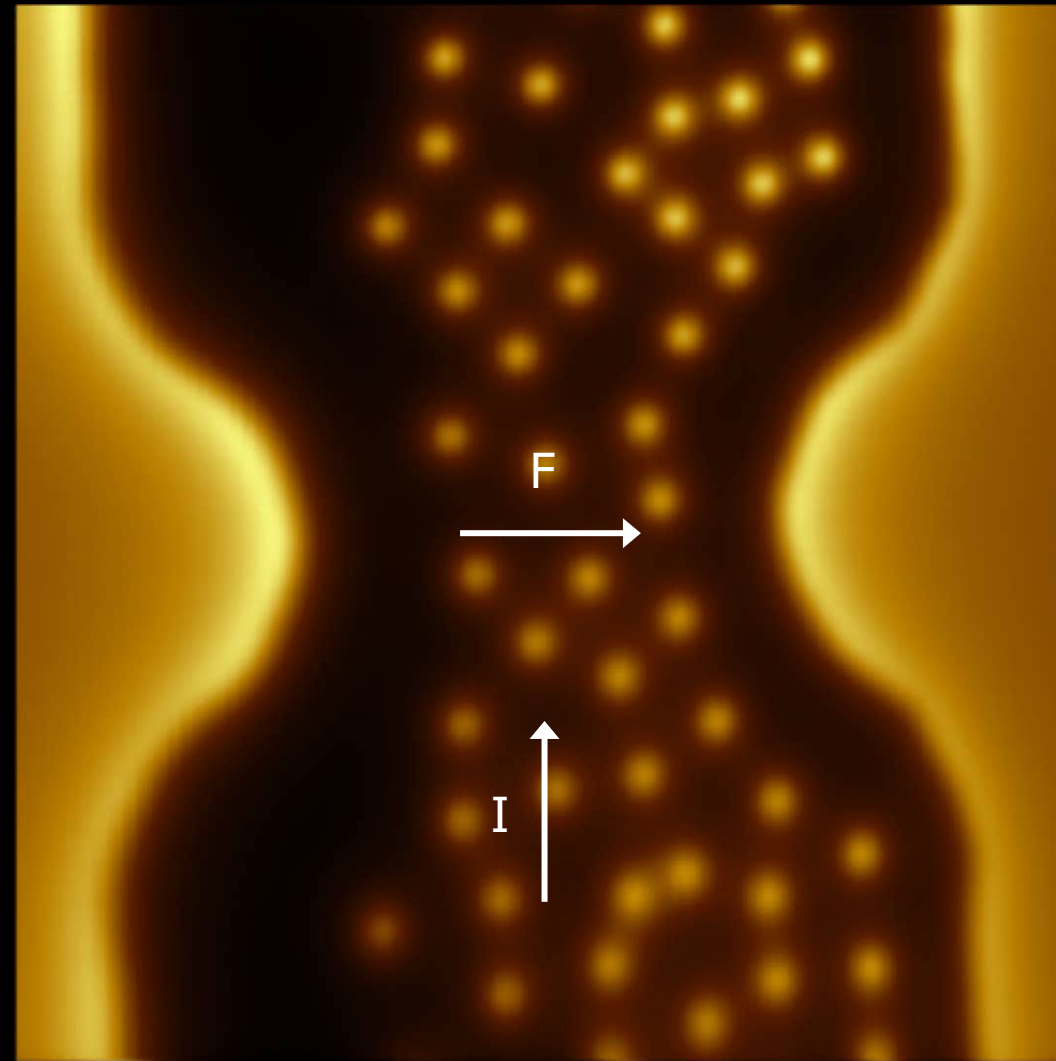
-4 mA

Embon *et al.*, Scientific Reports **5**, 7598 (2015)

Embon *et al.*, Nature Commun. **8**, 85 (2017)

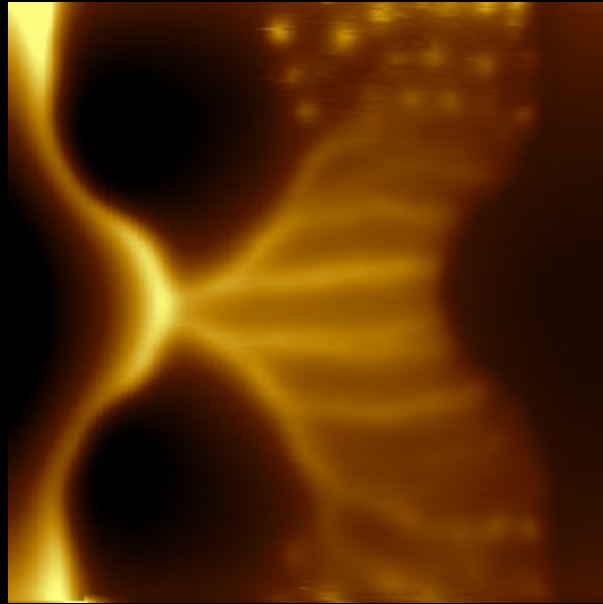
# Vortex dynamics

$B_a = 27$  G  
SOT diameter: 225 nm  
Scan area:  $12 \times 12 \mu\text{m}^2$   
Pixel size: 40 nm  
Scan time: 4 min/frame  
 $T = 4.2$  K

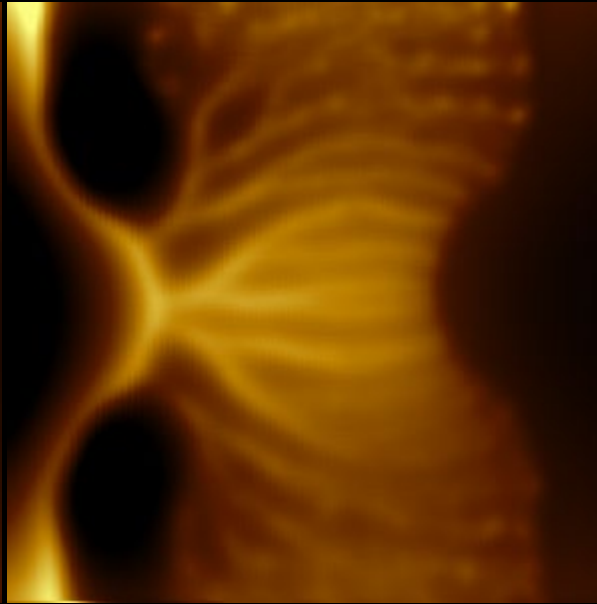


# Vortex flow patterns

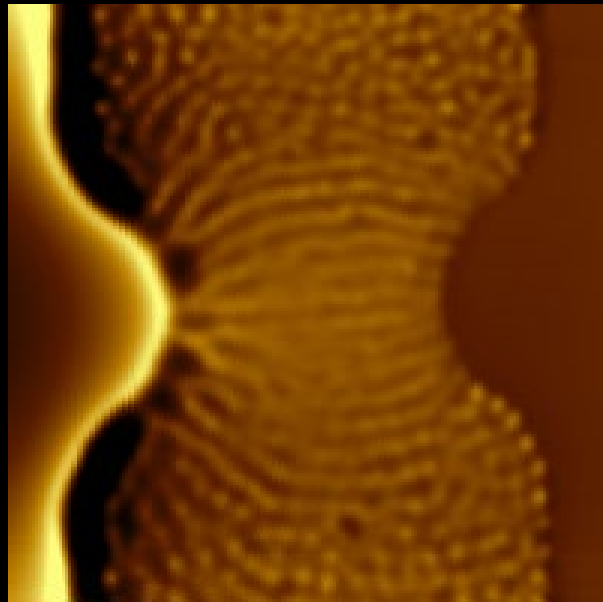
27 G



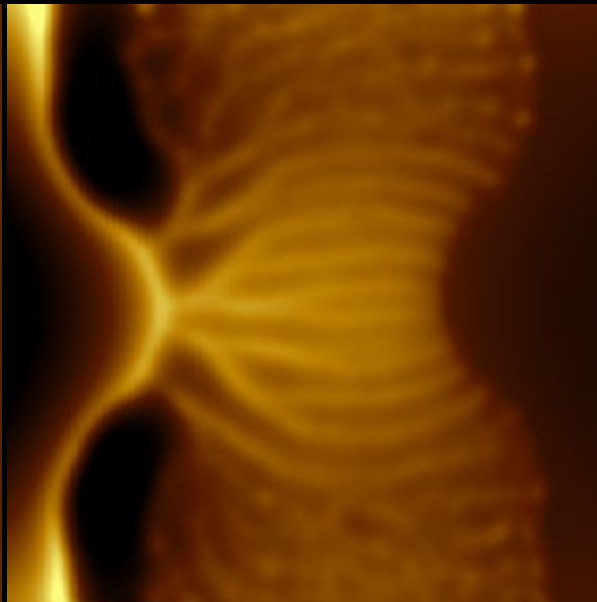
42 G



90 G

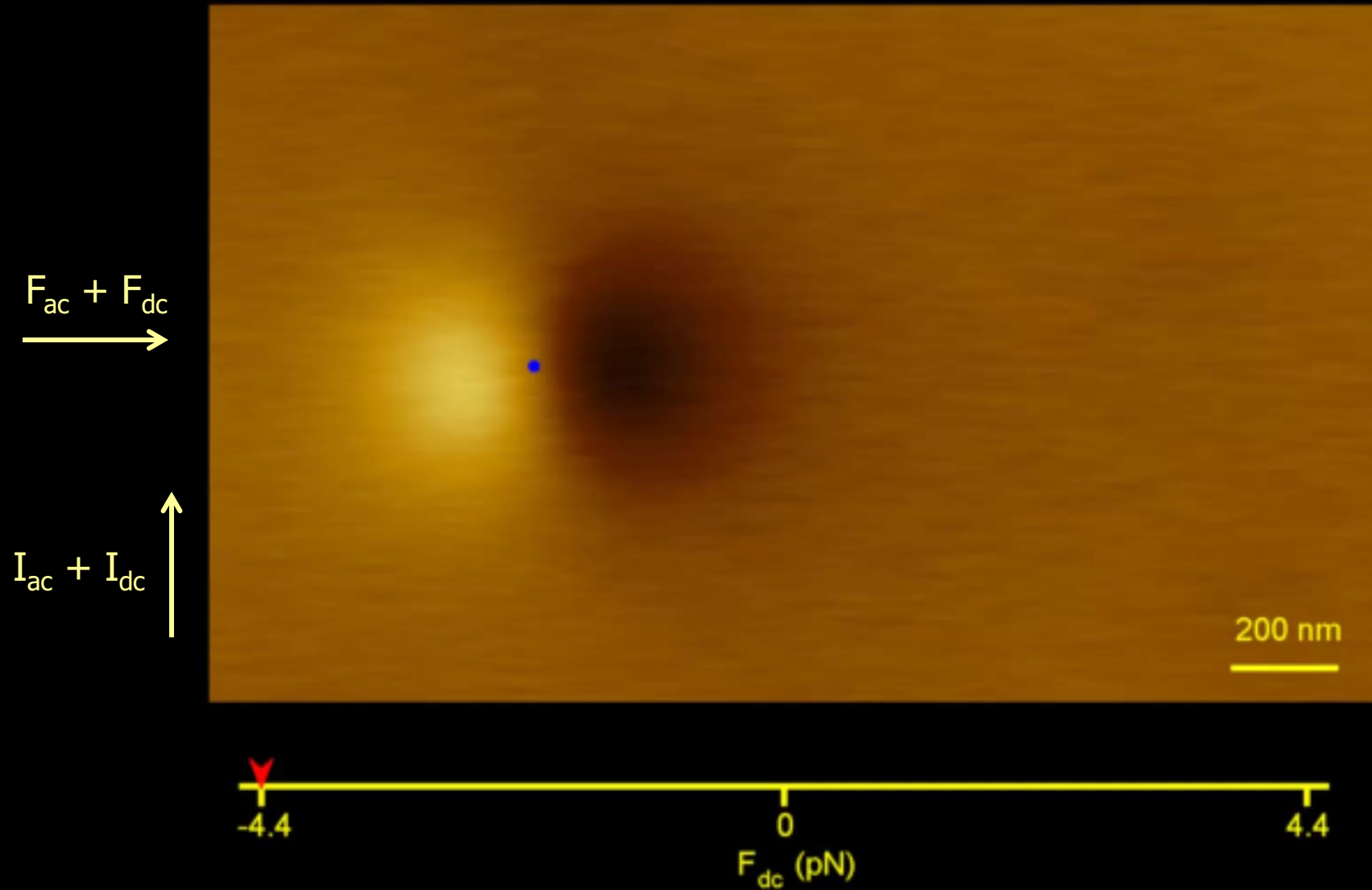


54 G



Cars on highway at night

# Single vortex dynamics

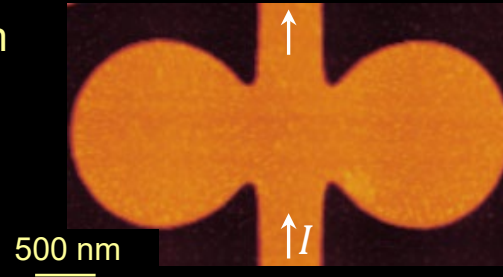


Embon *et al.*, Scientific Reports **5**, 7598 (2015)

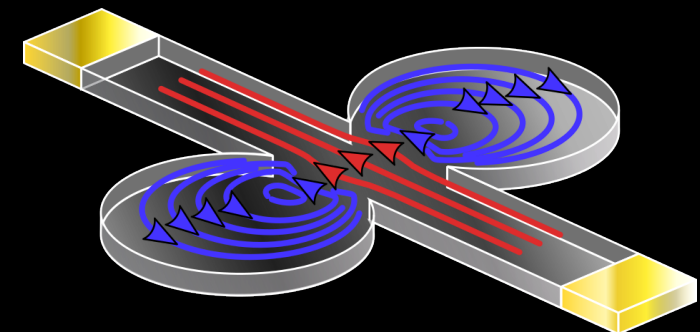
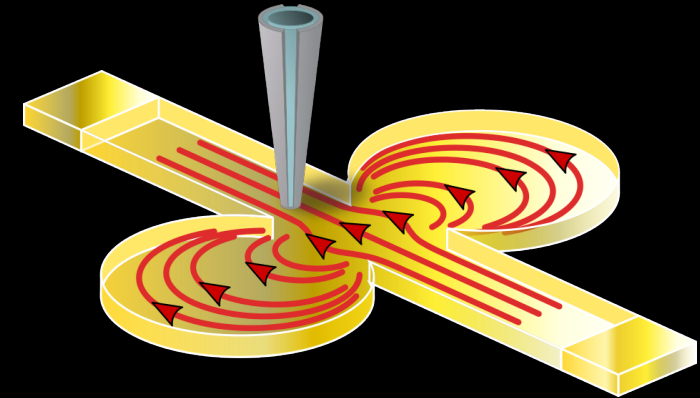
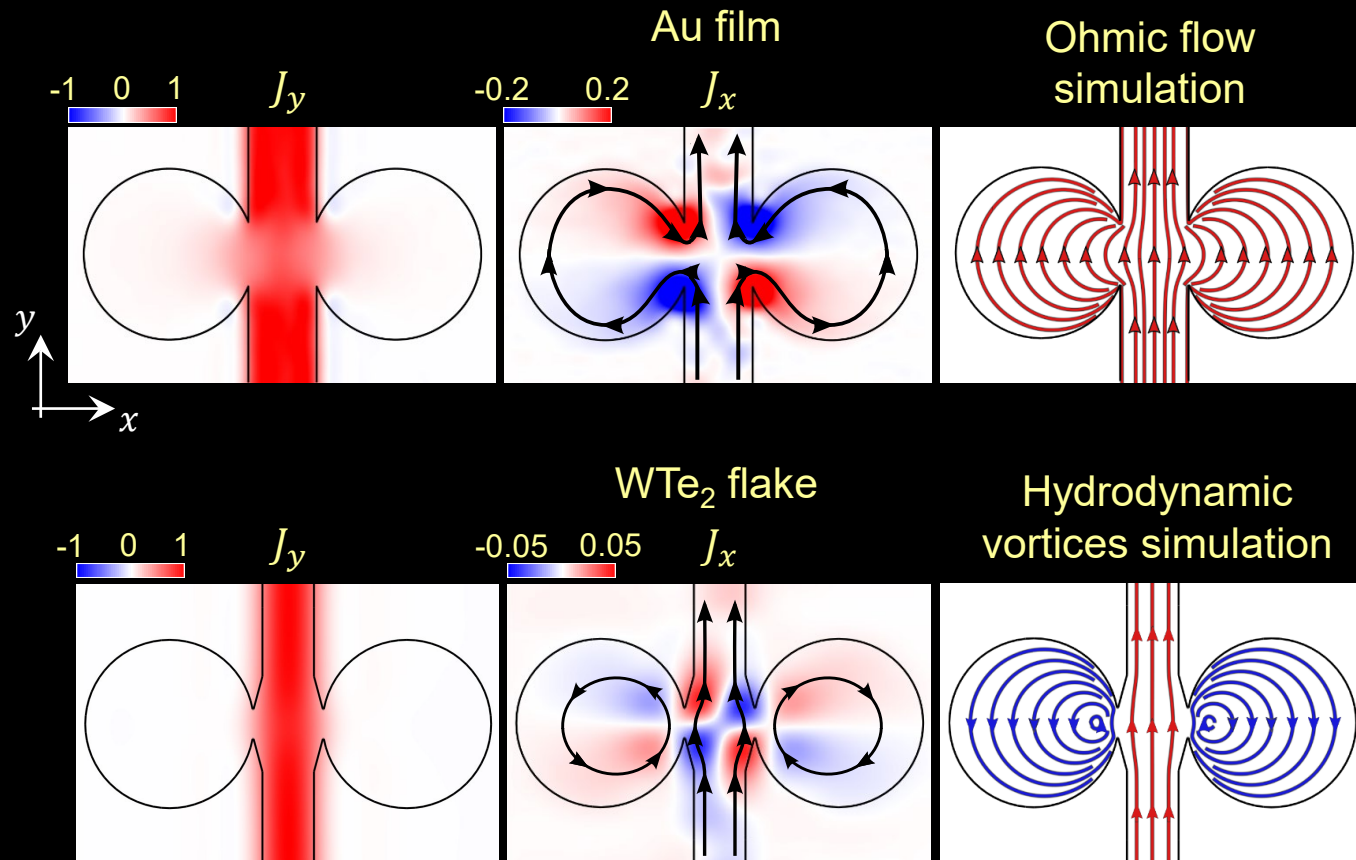
Embon *et al.*, Nature Commun. **8**, 85 (2017)

# Observation of hydrodynamic vortices in electron fluid

Thin Au film



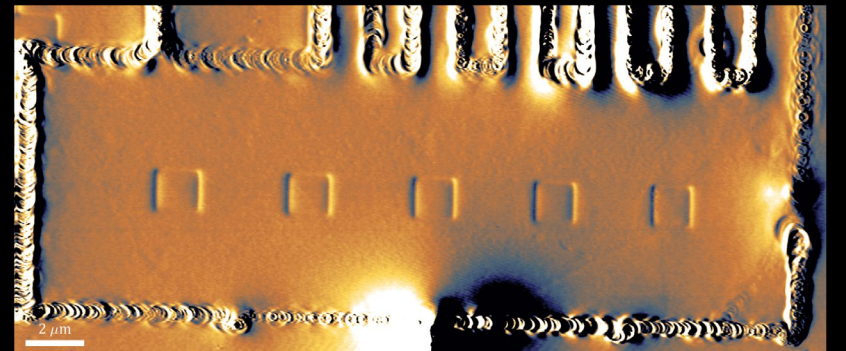
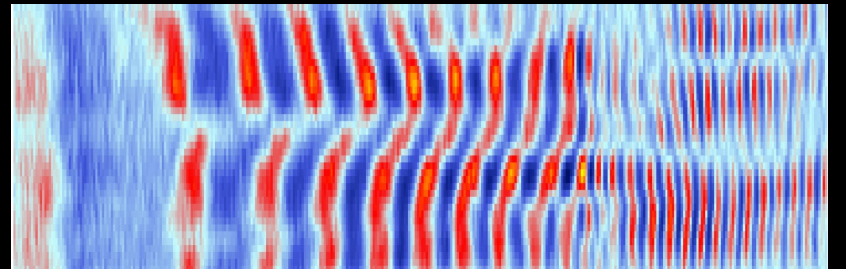
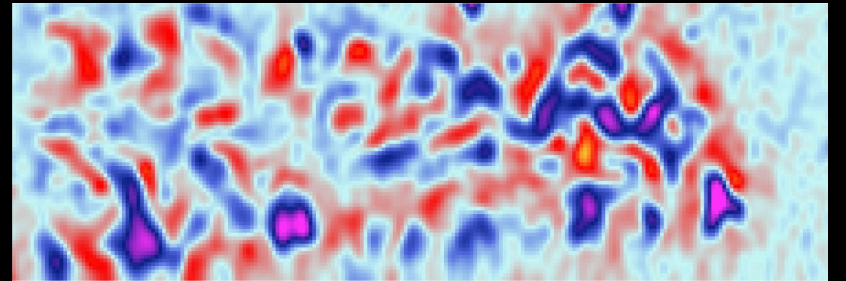
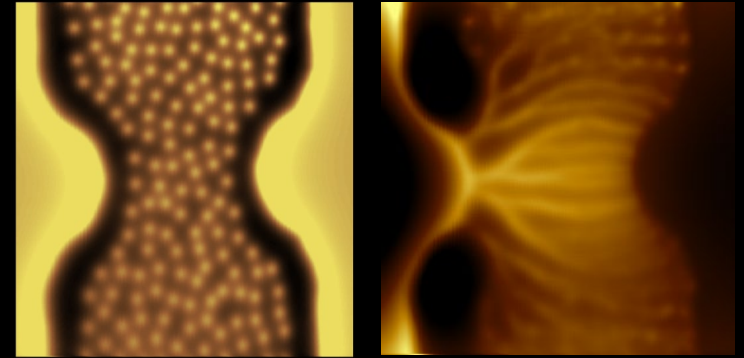
Thin WTe<sub>2</sub> flake



Aharon-Steinberg *et al.*, Nature **607**, 74 (2022)

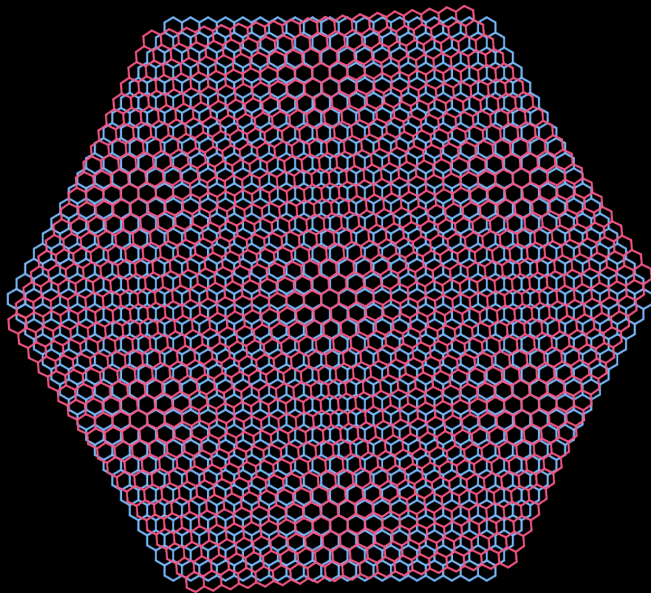
## Outline

- Vortices in superconductors and electron fluids
- Magnetism in graphene
- Thermodynamic quantum oscillations
- Thermal nanoscale imaging

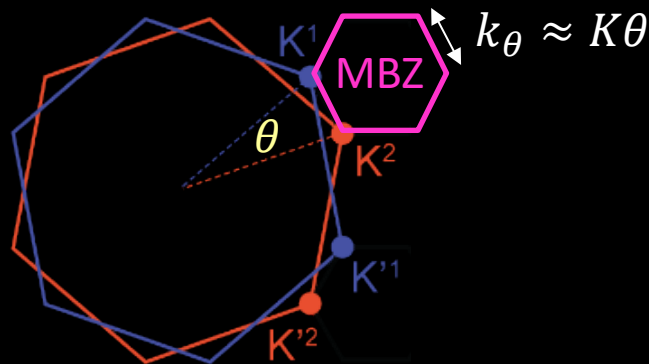


# Magic angle twisted bilayer graphene

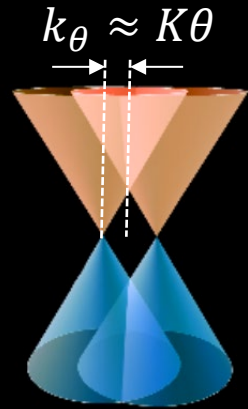
Moiré super-lattice



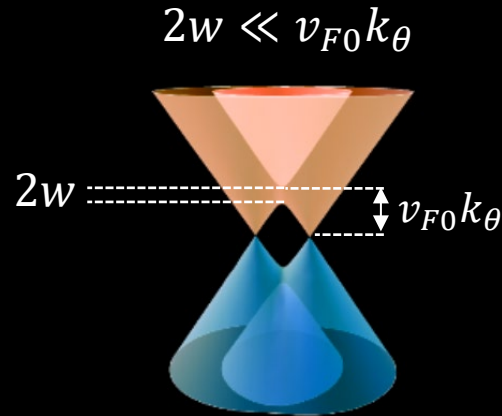
Mini Brillouin zone (MBZ)



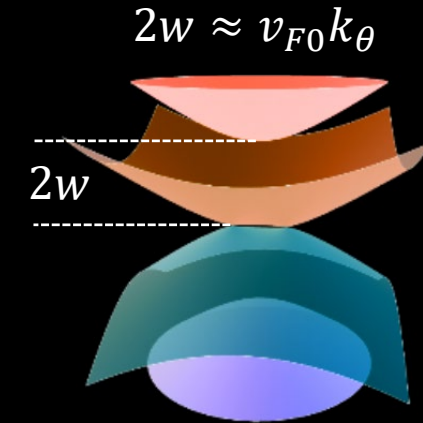
No interlayer interaction



Interlayer interaction  $w$



Magic angle  $\theta_M \approx 1.1^\circ$



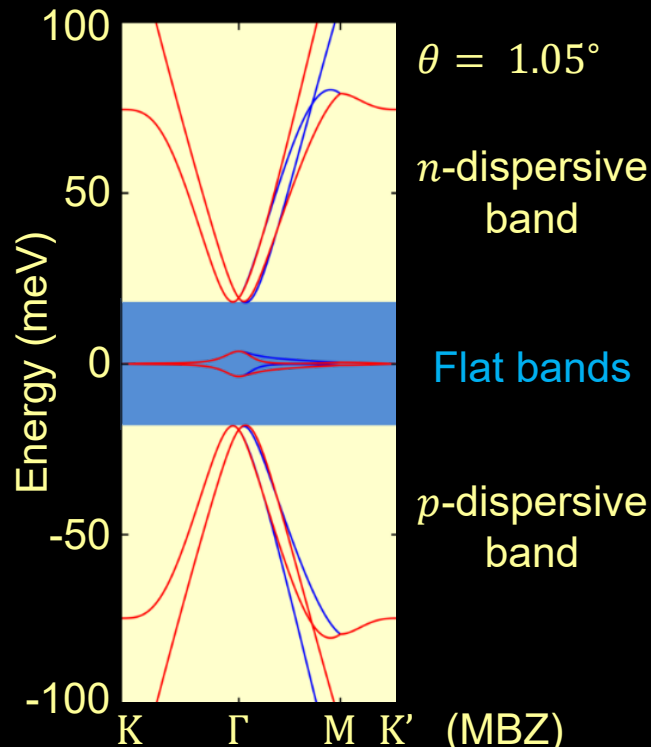
Decreasing Twist Angle



$$v_F \approx 0$$

$$\text{Coulomb } e-e \gg \epsilon_k$$

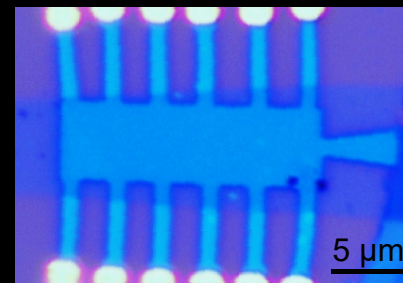
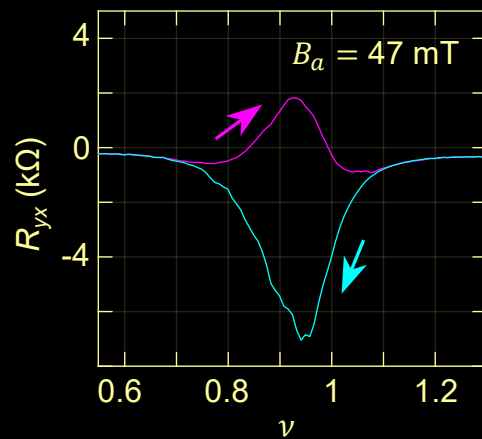
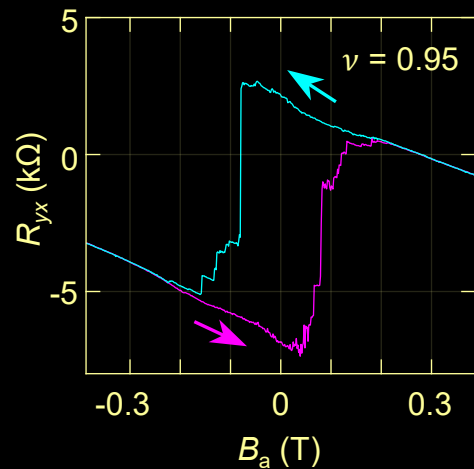
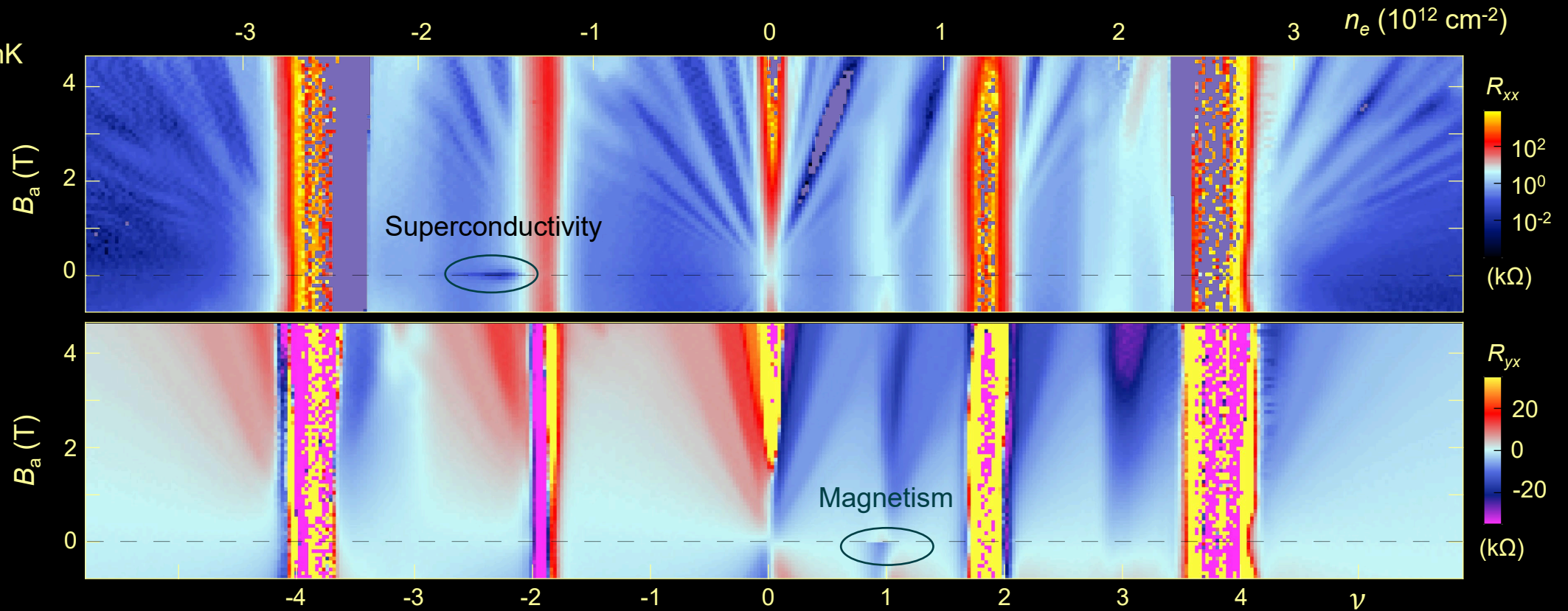
Strongly correlated states, correlated insulators, superconductivity, orbital ferromagnetism, topology, Berry curvature, Chern insulators, QAH ...



Y. Cao *et al.*, Nature **556**, 43 (2018)  
 Y. Cao *et al.*, Nature **556**, 80 (2018)  
 G. Li *et al.*, Nature Phys. **6**, 109 (2010)  
 M. Yankowitz *et al.*, Science **363**, 1059 (2019)  
 X. Lu *et al.*, Nature **574**, 653 (2019)  
 A. L. Sharpe *et al.*, Science **365**, 605 (2019)  
 E. Suarez Morell *et al.*, PRB **82**, 121407 (2010)  
 Bistritzer, MacDonald, PNAS **108**, 12233 (2011)  
 Nam, Koshino, PRB **96**, 075311 (2017)

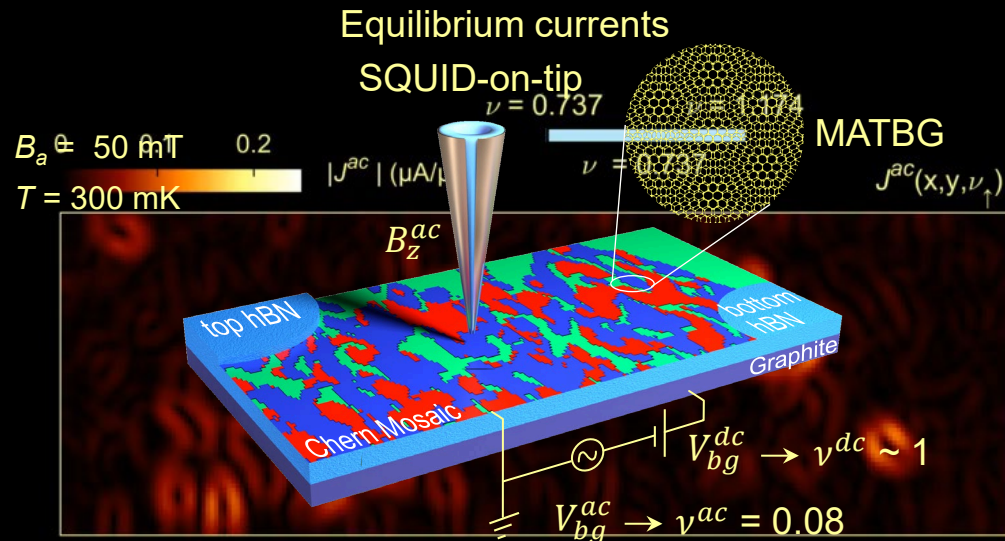
# Transport measurements in magic angle graphene

$\theta = 1.08^\circ$   
 $T = 300$  mK



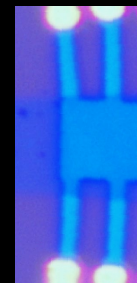
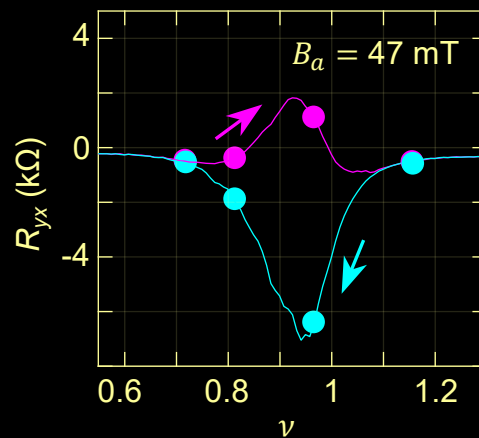
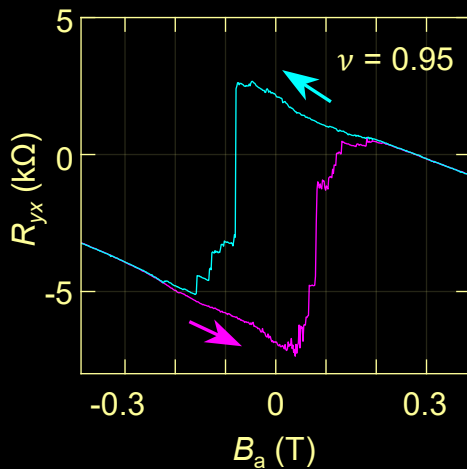
P. Stepanov *et al.*, PRL **127**, 197701 (2021)  
 A. Uri *et al.*, Nature **581**, 47 (2020)  
 S. Grover *et al.*, Nature Phys. **18**, 885 (2022)

# Local magnetic imaging in magic angle graphene

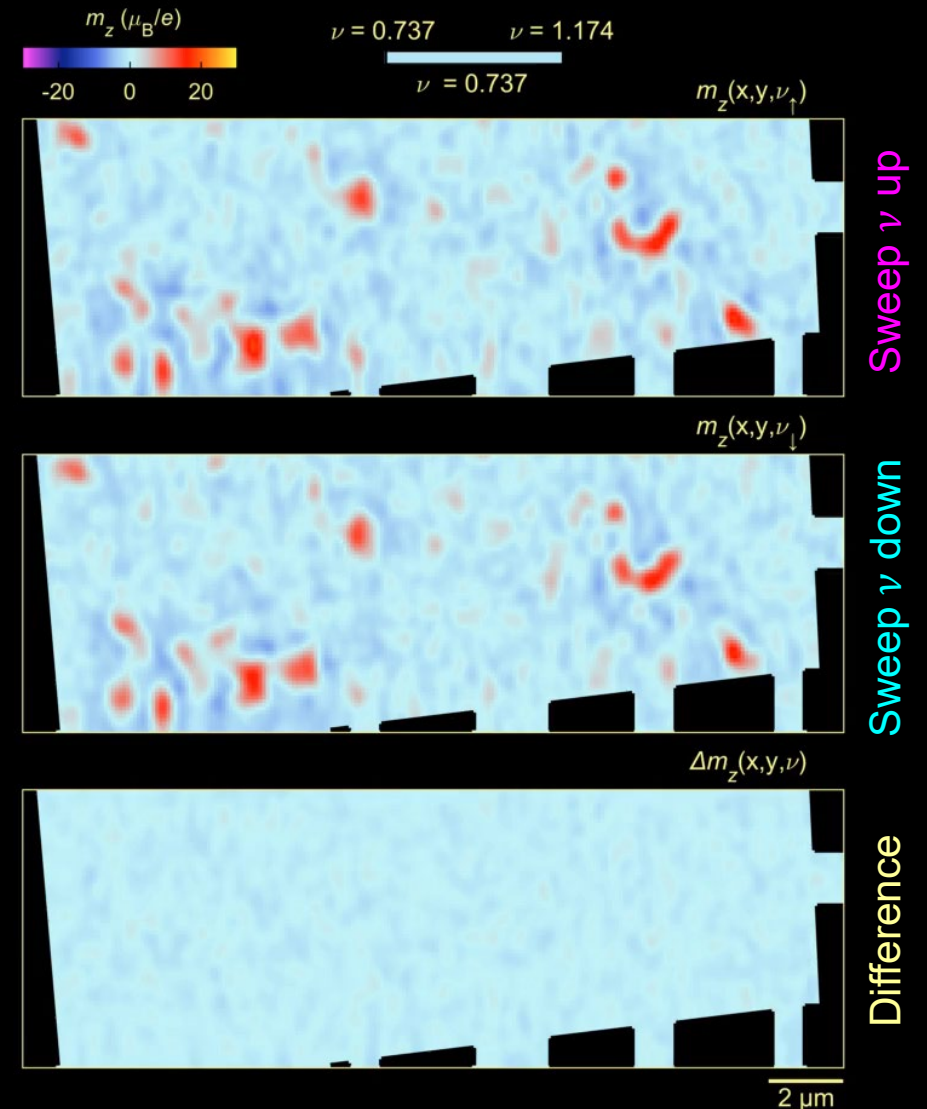


$$B_z^{ac}(x,y) = n^{ac}(dB_z/dn) \propto \nu^{ac}(dM_z/d\nu)$$

2  $\mu\text{m}$



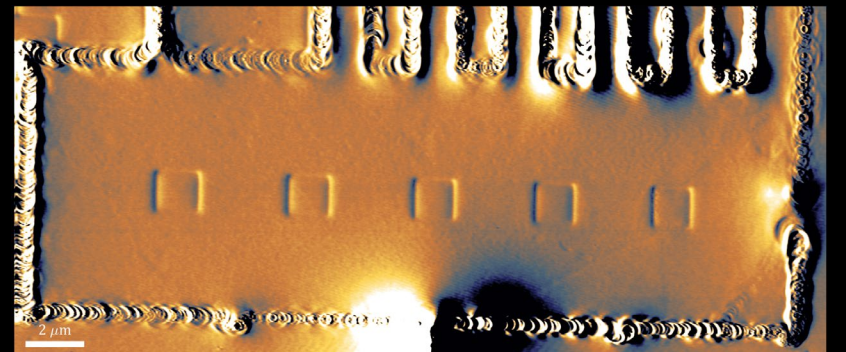
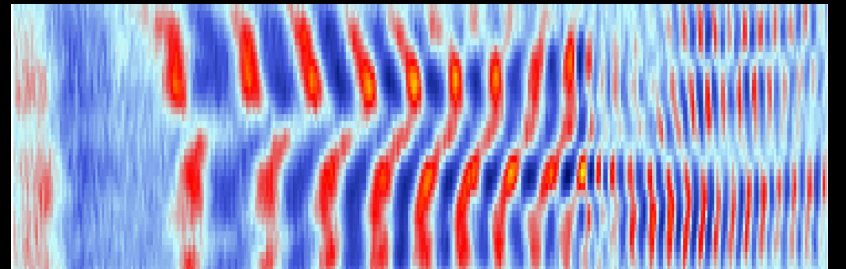
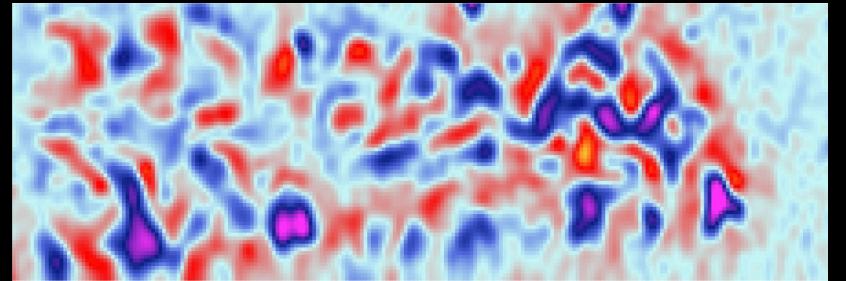
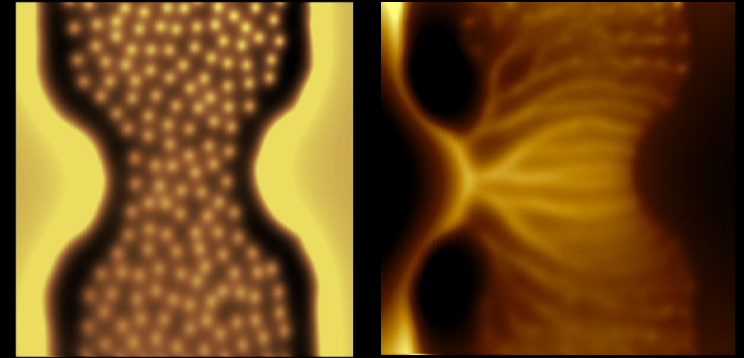
## Local differential magnetization



S. Grover *et al.*, Nature Phys. **18**, 885 (2022)

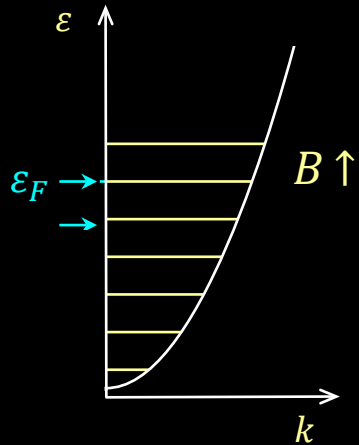
## Outline

- Vortices in superconductors and electron fluids
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- Thermodynamic quantum oscillations
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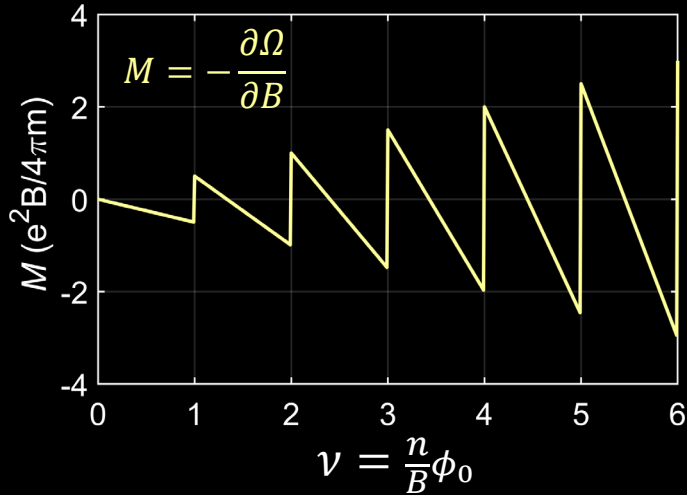


# de Haas–van Alphen (dHvA) thermodynamic quantum oscillations

Landau levels in 2DEG



Quantum oscillations in magnetization



dHvA oscillations

- Thermodynamic property of the band structure
- Does not involve scattering
- Allows quantitative analysis and band structure reconstruction
- Low magnetic fields
- Spatially resolved
- Interaction effects

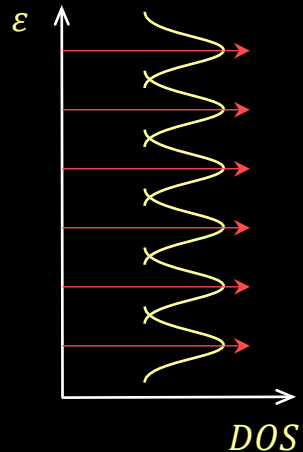
**Problem:  $M$  proportional to volume**

Bulk magnetometer sensitivity =  $1 \cdot 10^{-8}$  emu =  $10^{15} \mu_B$

Graphene of  $10 \mu\text{m}^2$  area doped to  $10^{12} \text{cm}^{-2}$   
 =  $10^5$  electrons  $\cong 10^5 \mu_B$

10 orders of magnitude below magnetometer sensitivity!

DOS and LL broadening



de Haas–van Alphen (dHvA)

oscillations  $M \sim \sin\left(2\pi \frac{\phi_0 n}{B N}\right)$   
 $\rho_{xx}$

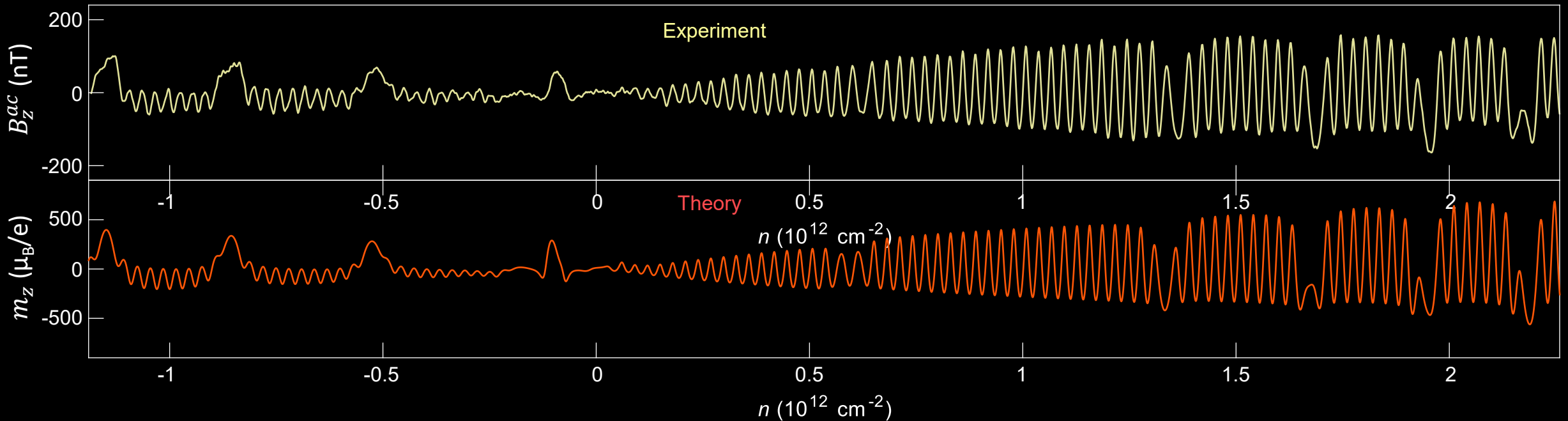
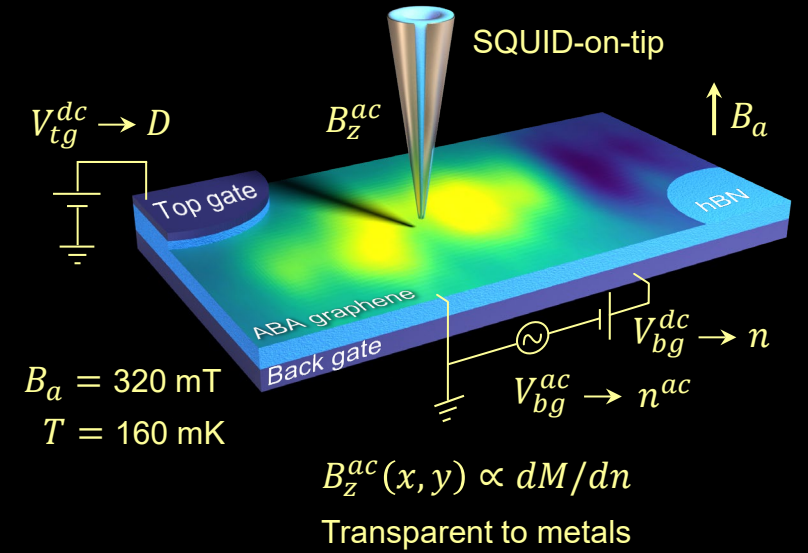
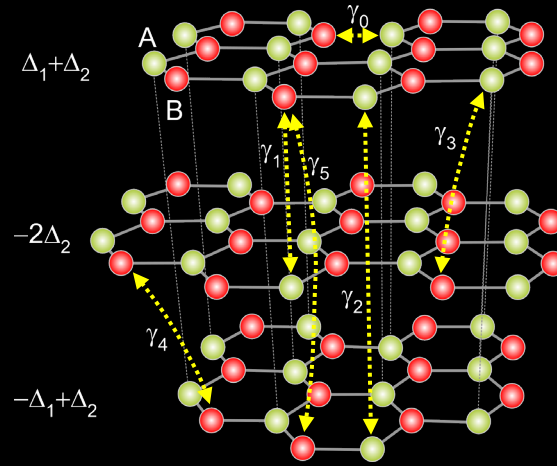
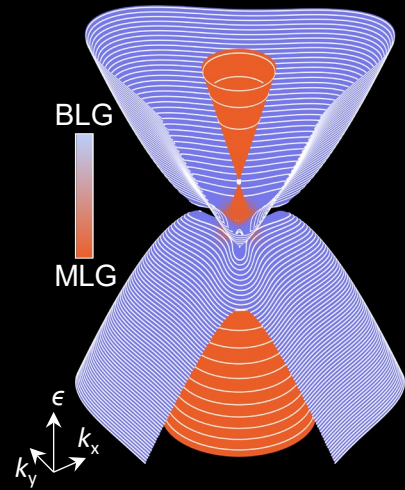
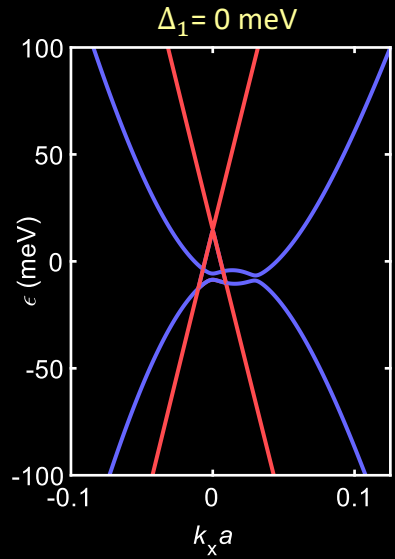
Shubnikov–de Haas (SdH)

$n$  - Carrier density

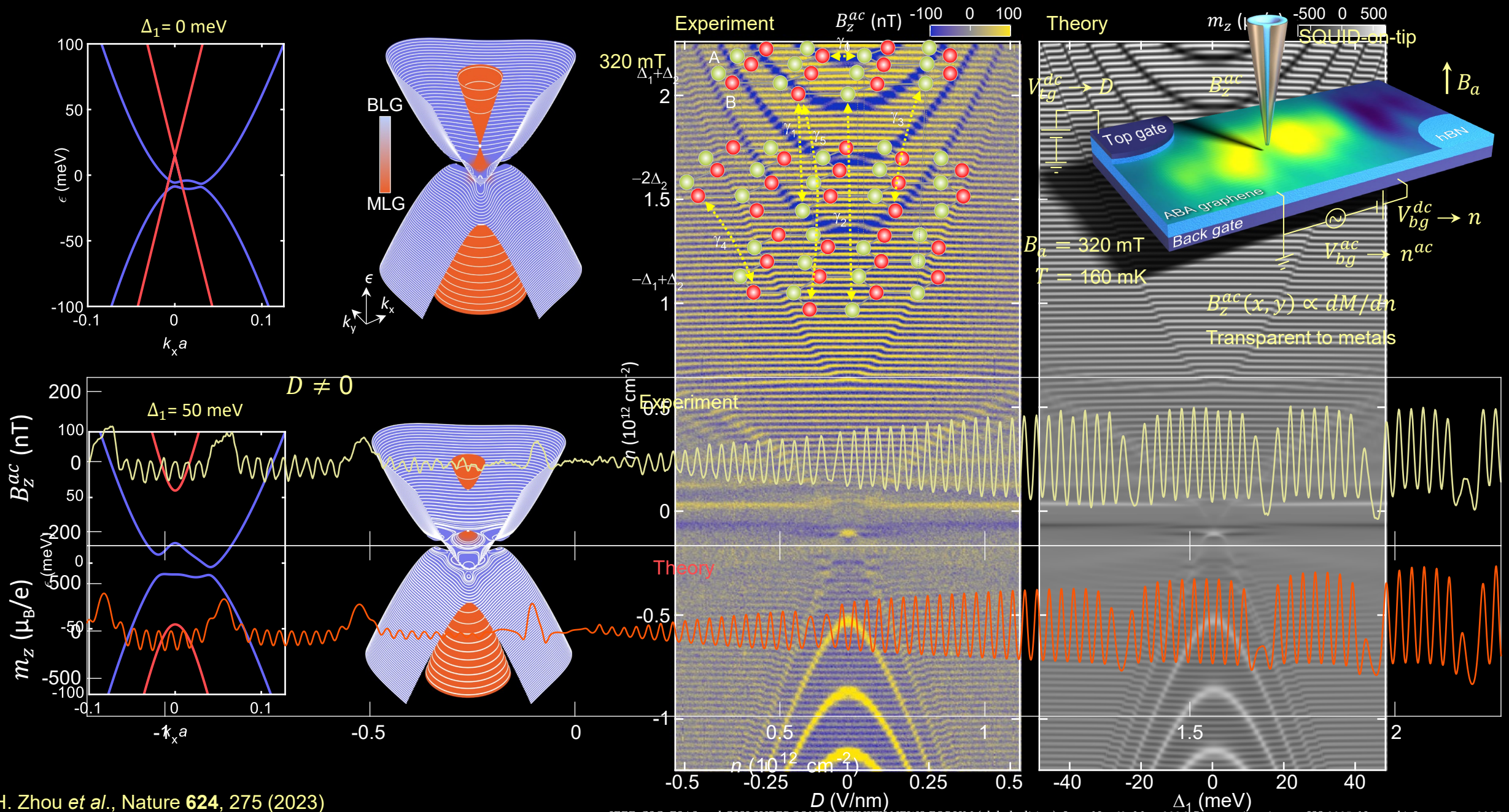
$N$  - Degeneracy

$B$  - Applied magnetic field

# De Haas–van Alphen thermodynamic quantum oscillations in ABA graphene

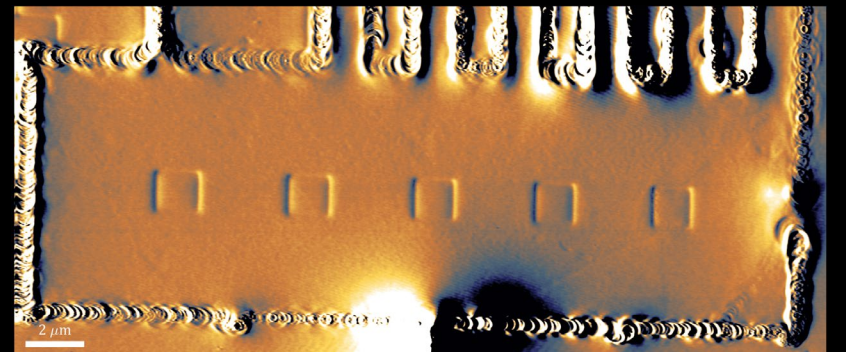
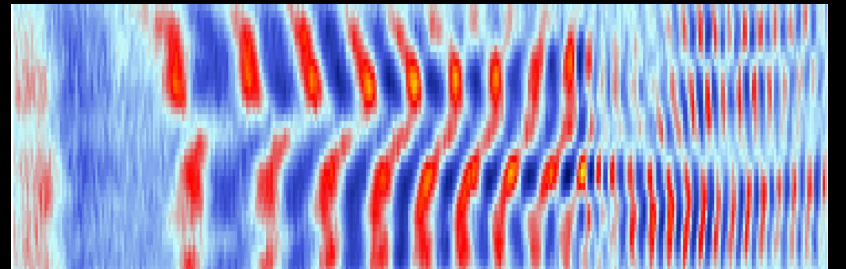
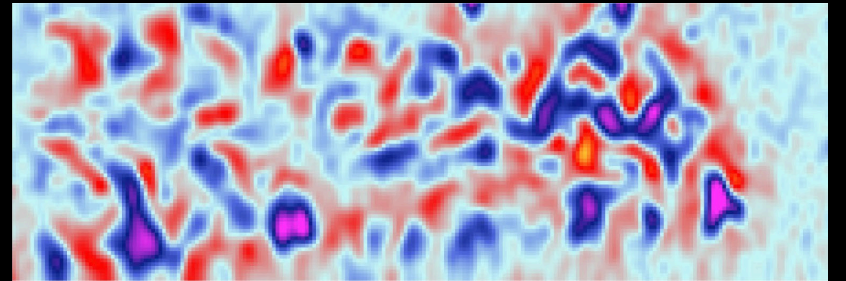
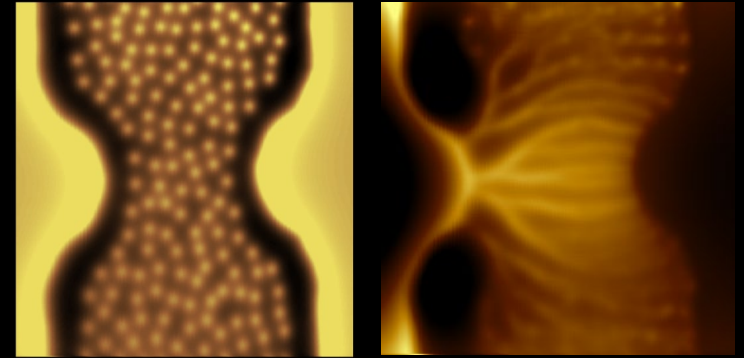


# In situ tunable band structure with displacement field $D$ in ABA graphene



## Outline

- Vortices in superconductors and electron fluids
- Magnetism in graphene
- Thermodynamic quantum oscillations
- Thermal nanoscale imaging



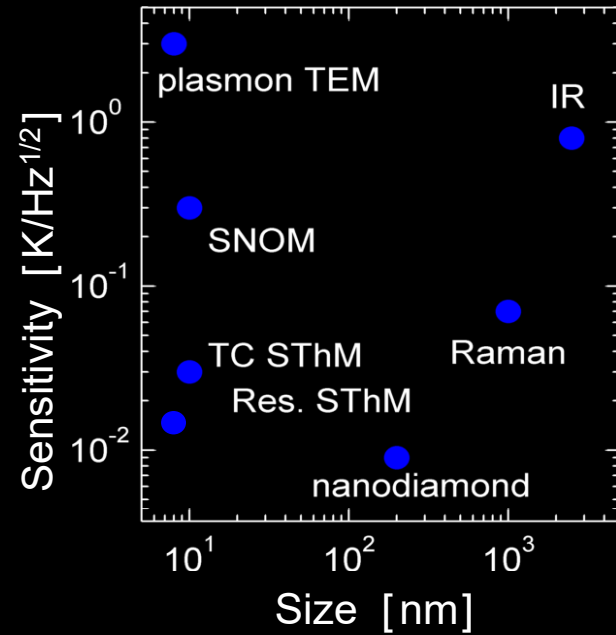


# Thermal imaging

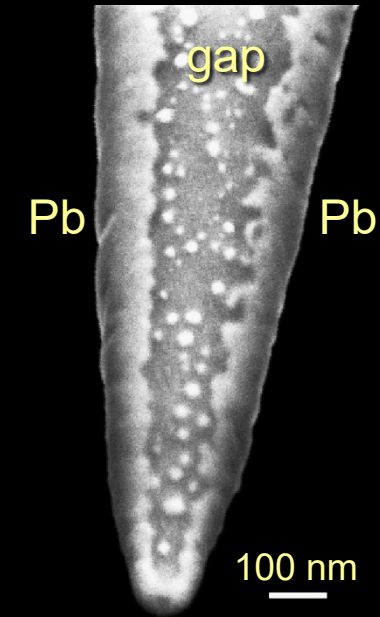


dissipation

# 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)

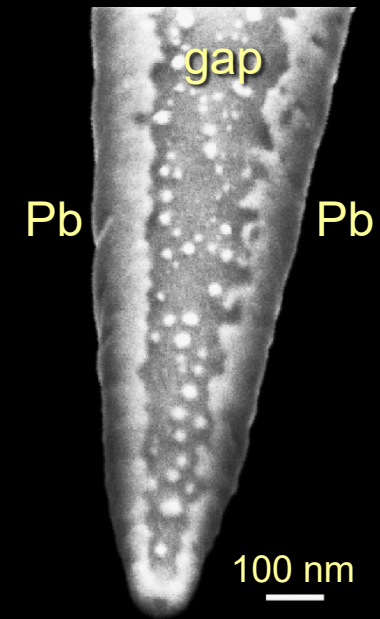
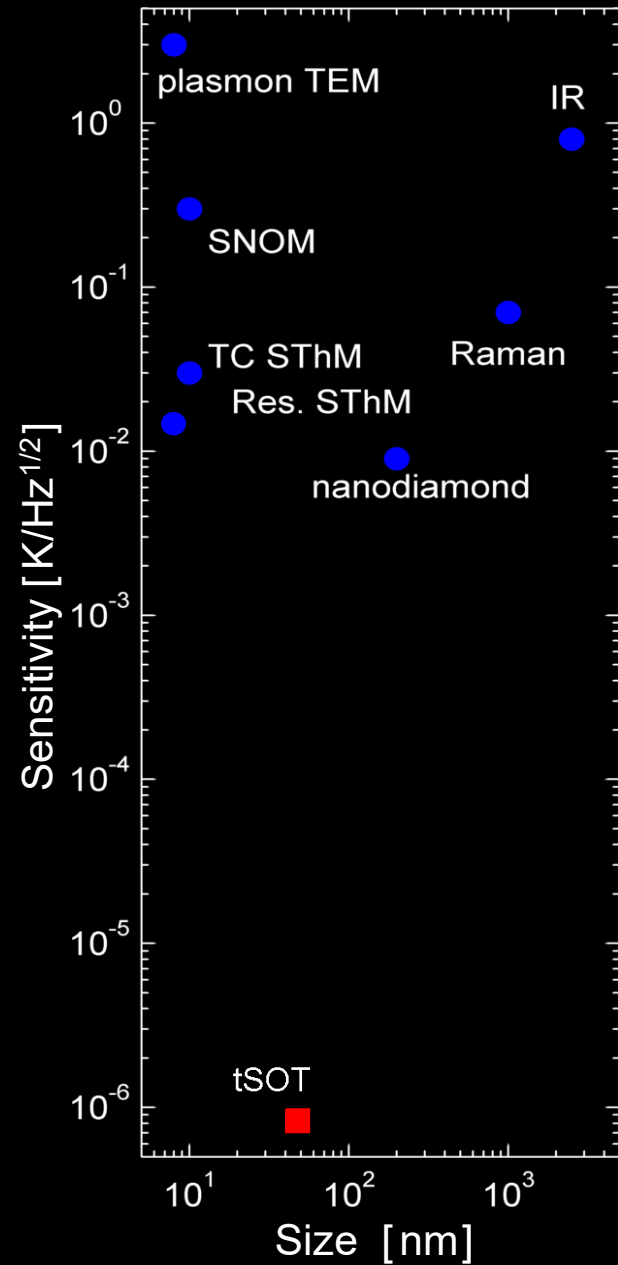


Thermal noise:

$$S_T^{1/2} < 1 \mu\text{K}/\text{Hz}^{1/2}$$

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

# Thermal imaging techniques

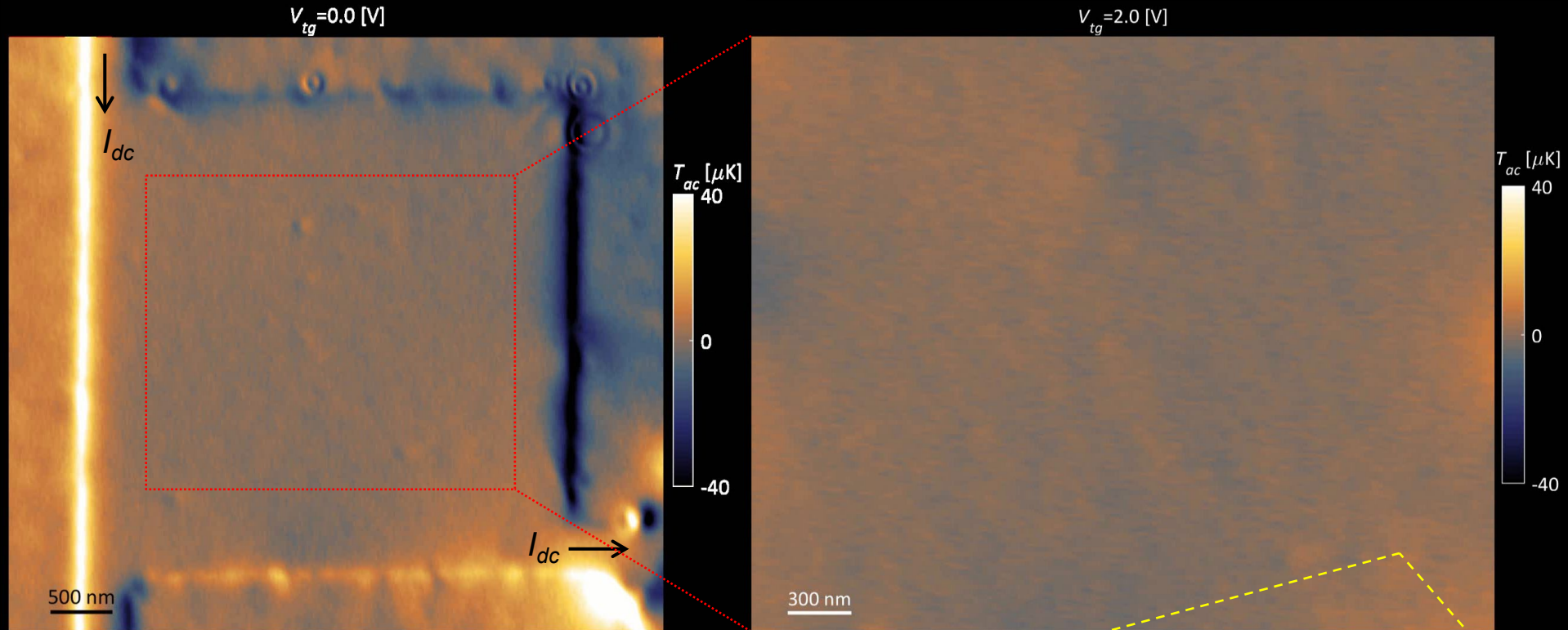


Thermal noise:

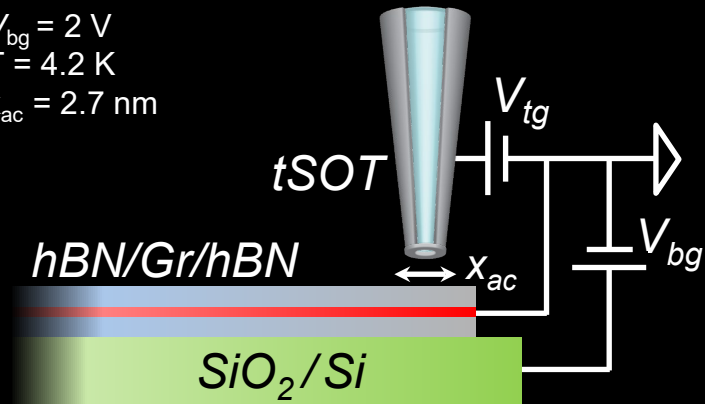
$$S_T^{1/2} < 1 \mu\text{K}/\text{Hz}^{1/2}$$

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

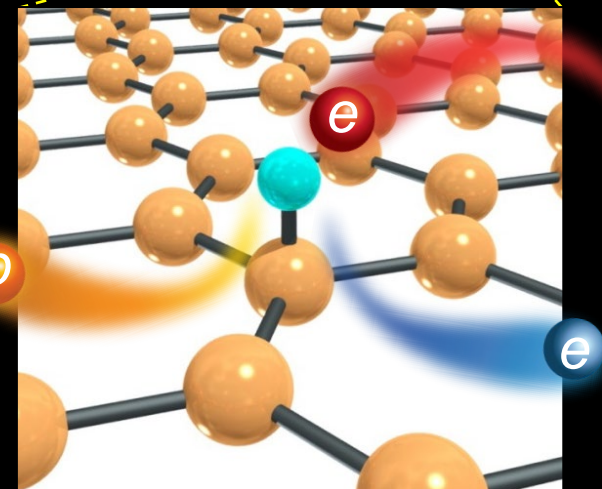
# Dissipation from Dissipative atomic defect in graphene



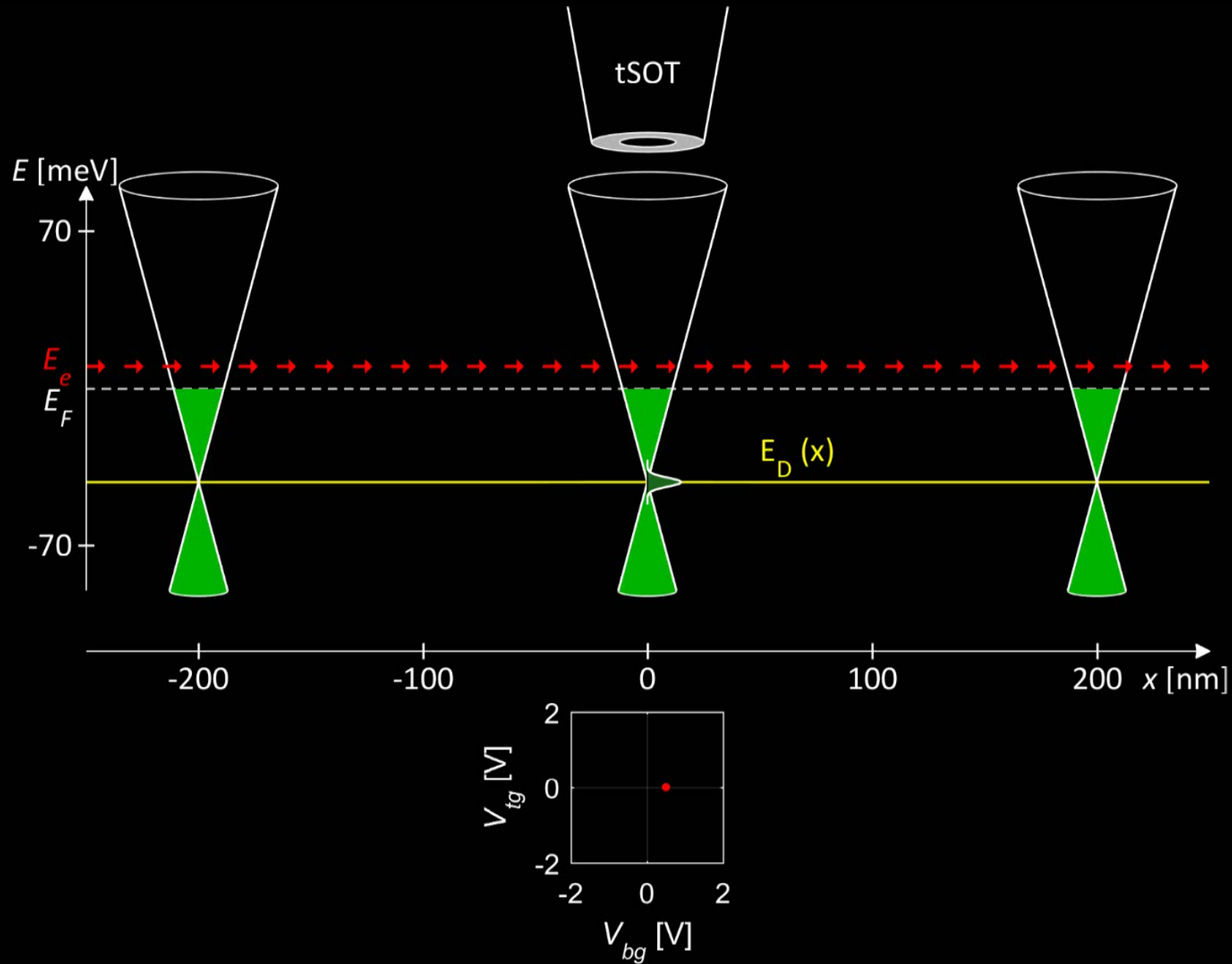
$I_{dc} = 3 \mu\text{A}$   
 $h = 20 \text{ nm}$   
 $V_{bg} = 2 \text{ V}$   
 $T = 4.2 \text{ K}$   
 $x_{ac} = 2.7 \text{ nm}$



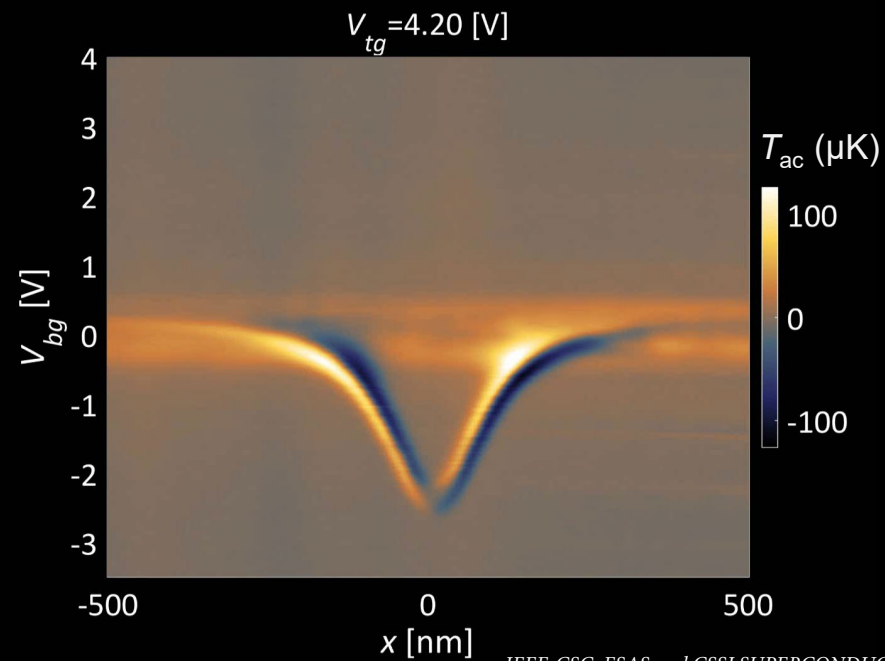
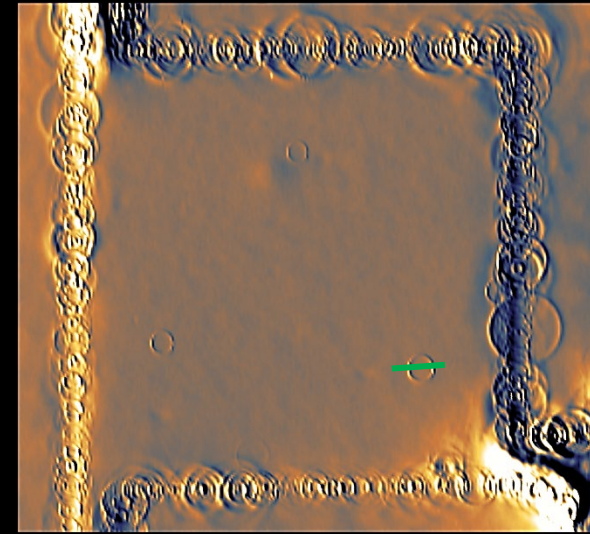
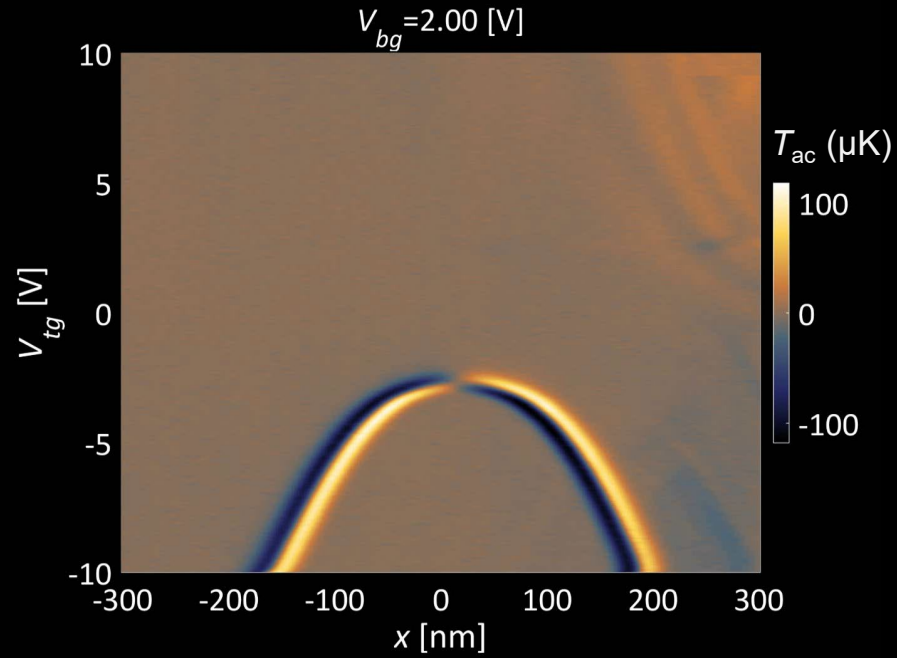
Inelastic resonant electron scattering off a single atomic defect



# Resonant inelastic scattering by a single localized state

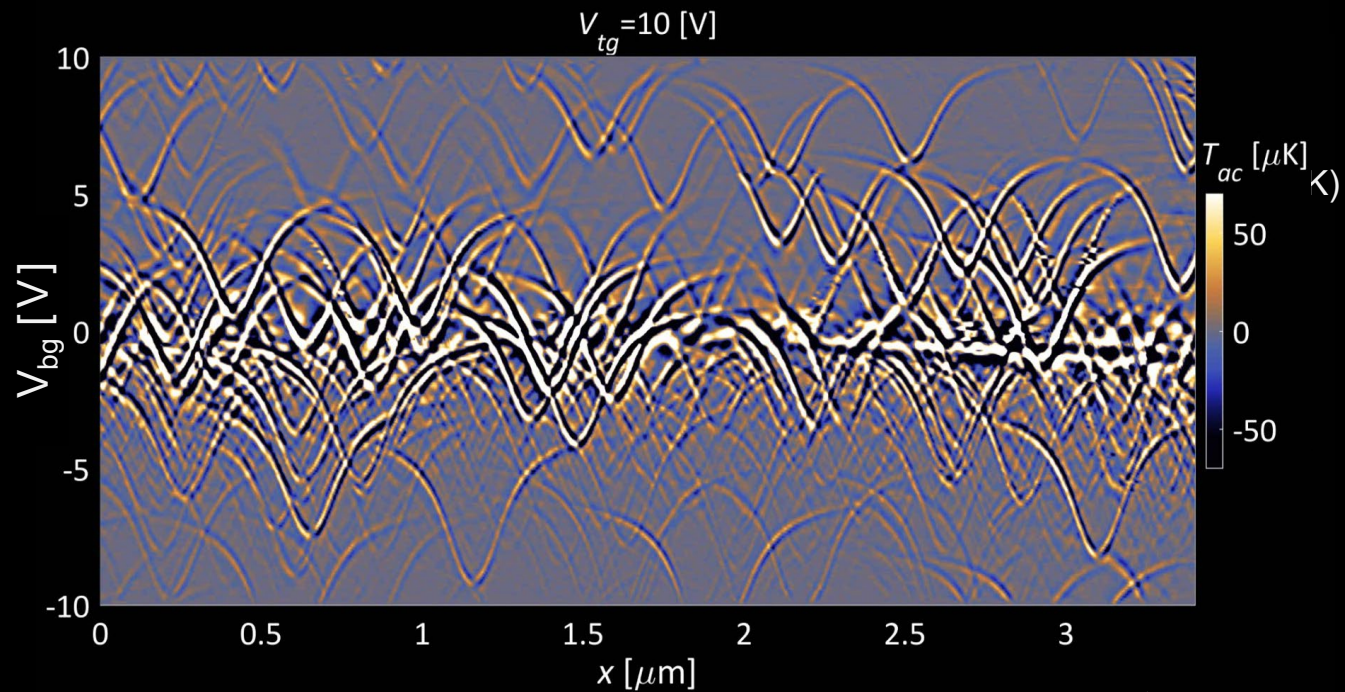
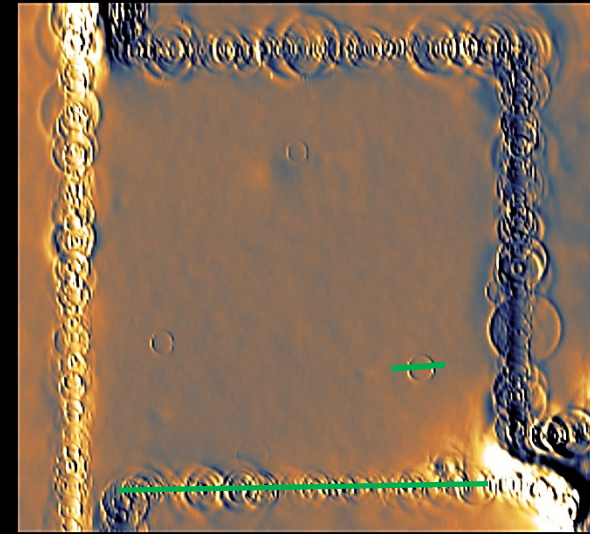
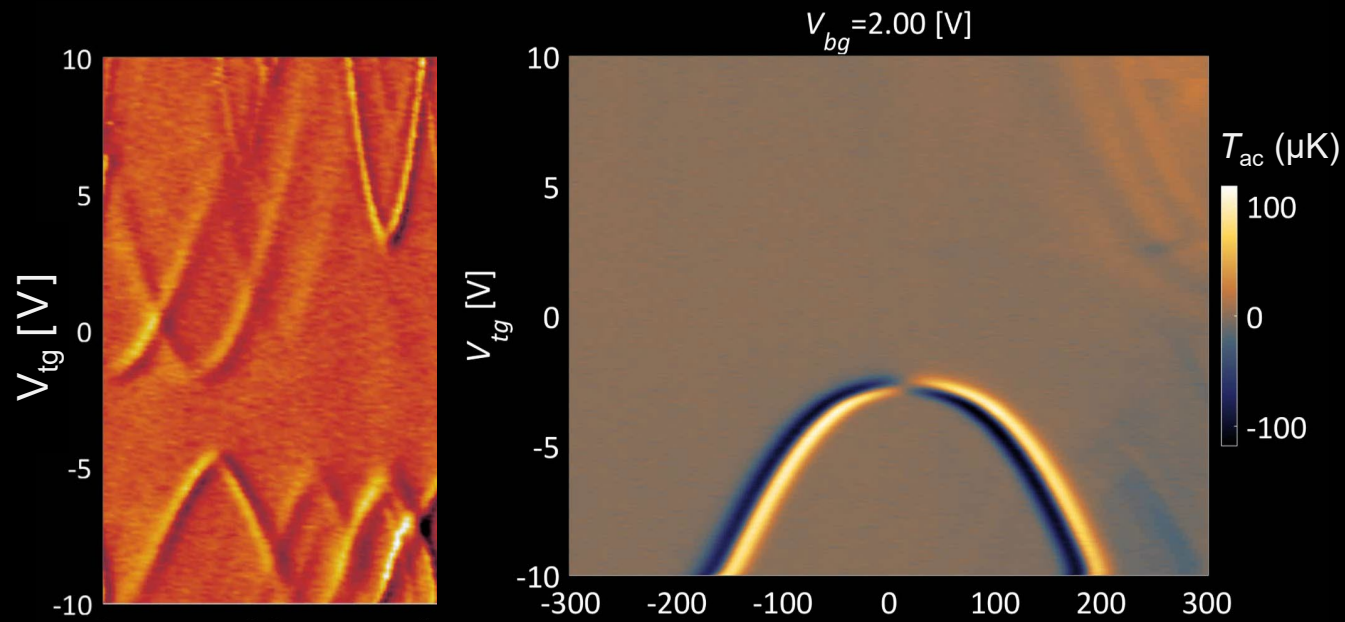


# Spectroscopy of atomic defects in the bulk

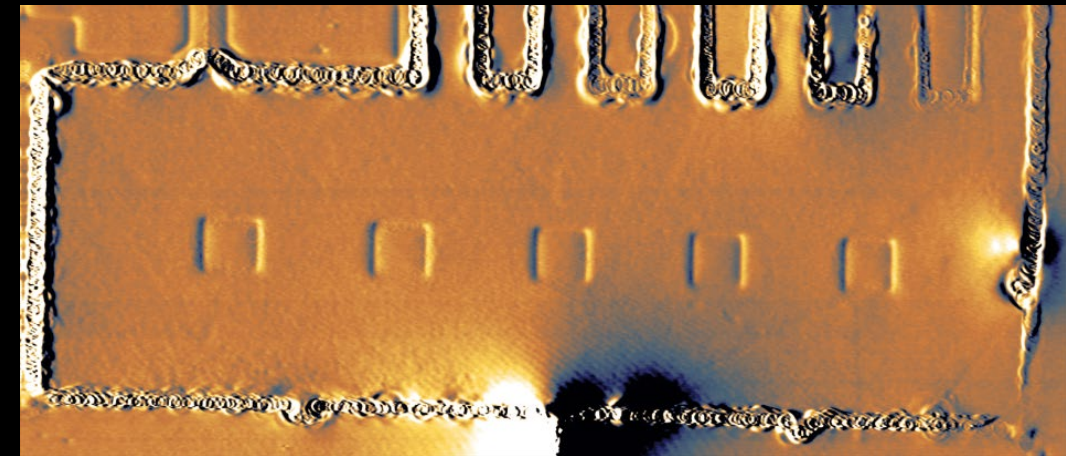


D. Halbertal *et al.*, Science **358**, 1303 (2017)

# Spectroscopy of edge defects



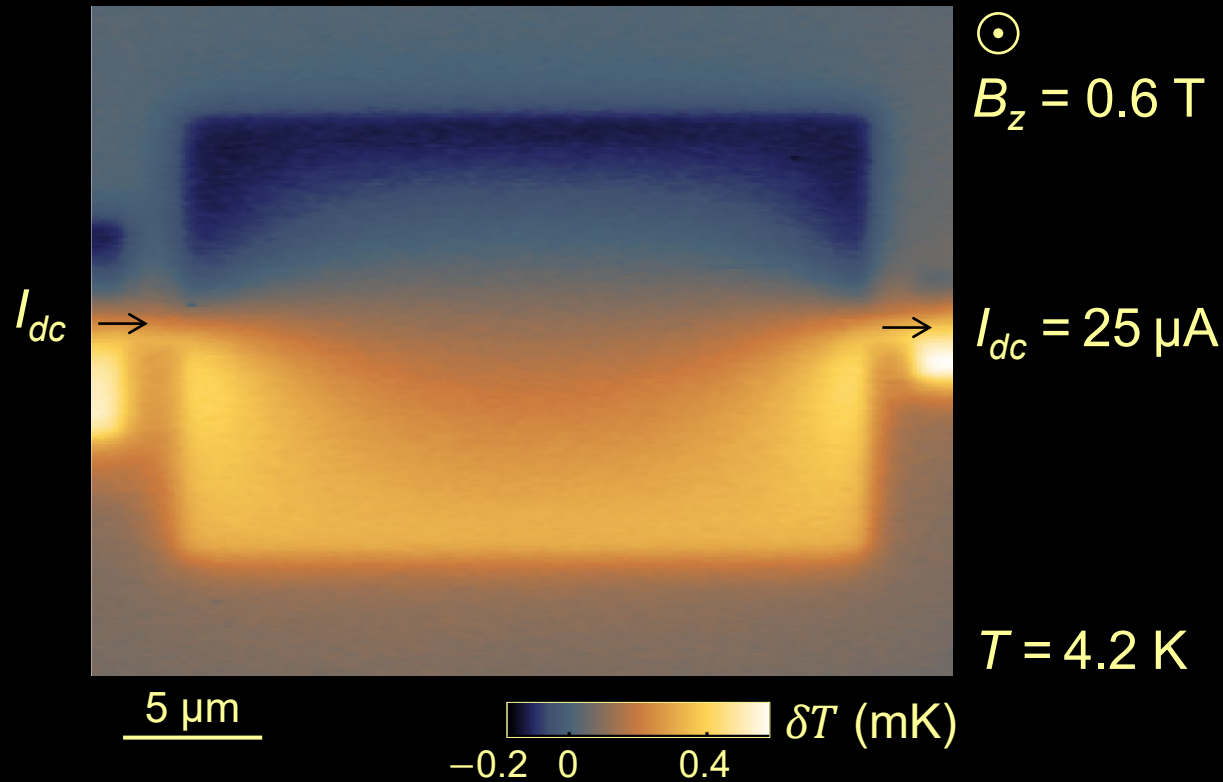
Dissipation in the quantum Hall state in graphene at 1 T



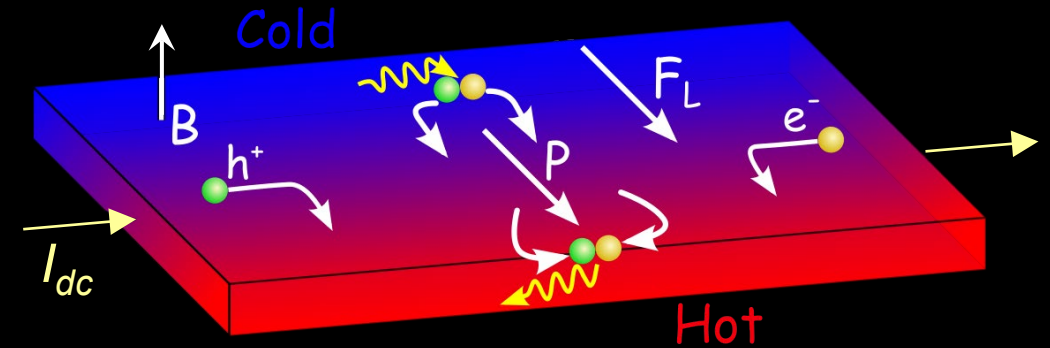
A. Marguerite *et al.*, Nature **575**, 628 (2019)  
D. Halbertal *et al.*, Science **358**, 1303 (2017)

# Thermal imaging of magneto-thermoelectric effects

## Cryogenic Ettingshausen cooling in $\text{WTe}_2$



## Ettingshausen effect in compensated semimetal

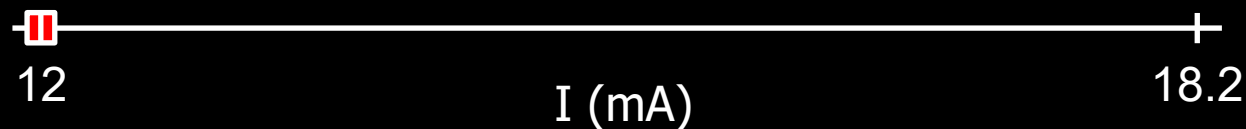
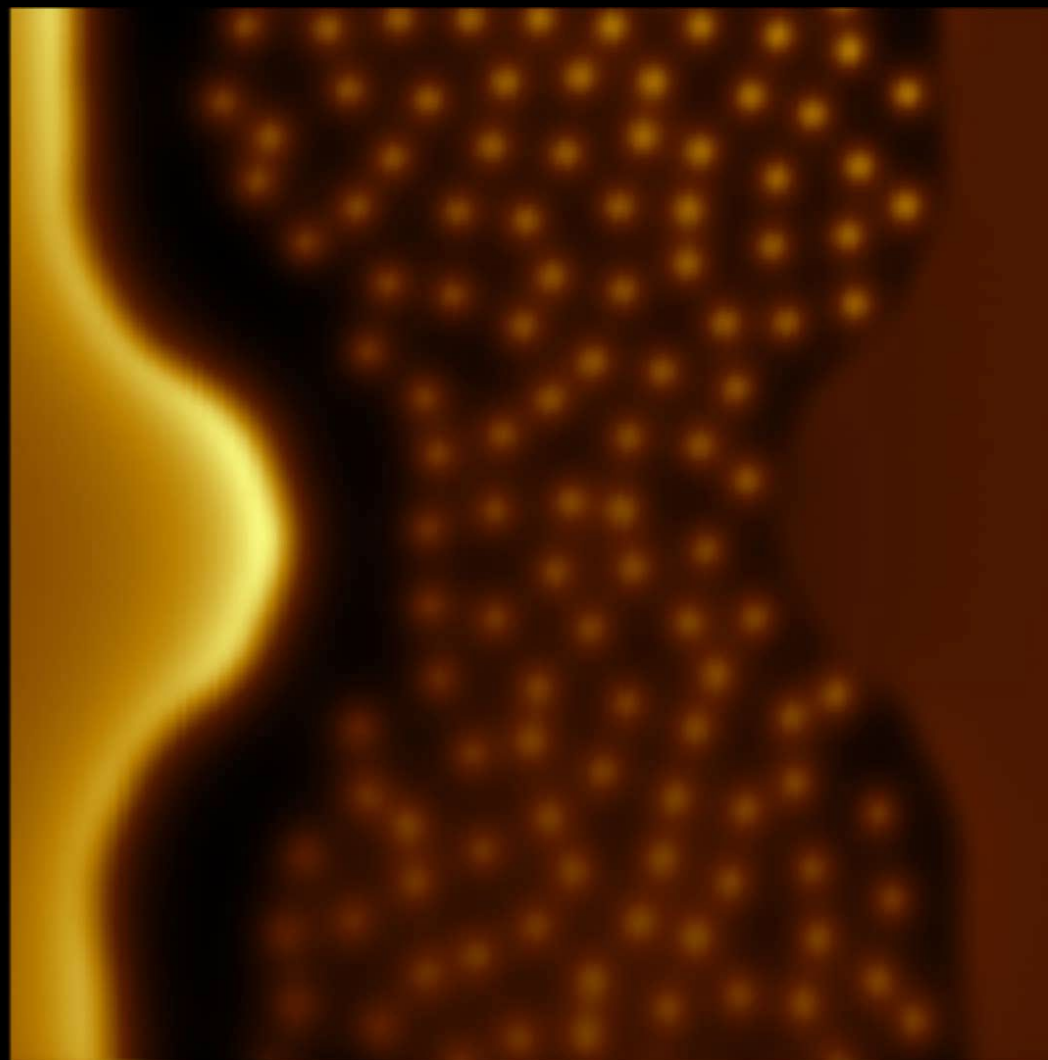


T. Völkl *et al.*, Nature Phys. **20**, 976 (2024)

# Vortex flow in Pb film

Weizmann Institute

A. Finkler  
Y. Segev  
Y. Myasoedov  
M. L. Rappaport  
D. Vasyukov  
Y. Anahory  
L. Embon  
D. Halbertal  
J. Cuppens  
J. Reiner  
A. Uri  
H. R. Naren  
K. Bagani  
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Harvard  
A. Yacoby

Denver  
M. E. Huber

MIT  
P. Jarillo-Herrero  
L. S. Levitov

Munich  
P. Stepanov  
D. K. Efetov

Manchester  
M. Ben Shalom  
J. Birkbeck  
A. K. Geim

NIMS  
T. Taniguchi  
K. Watanabe

$B_a = 42$  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