Electronic phase control in complex oxides heterostructures

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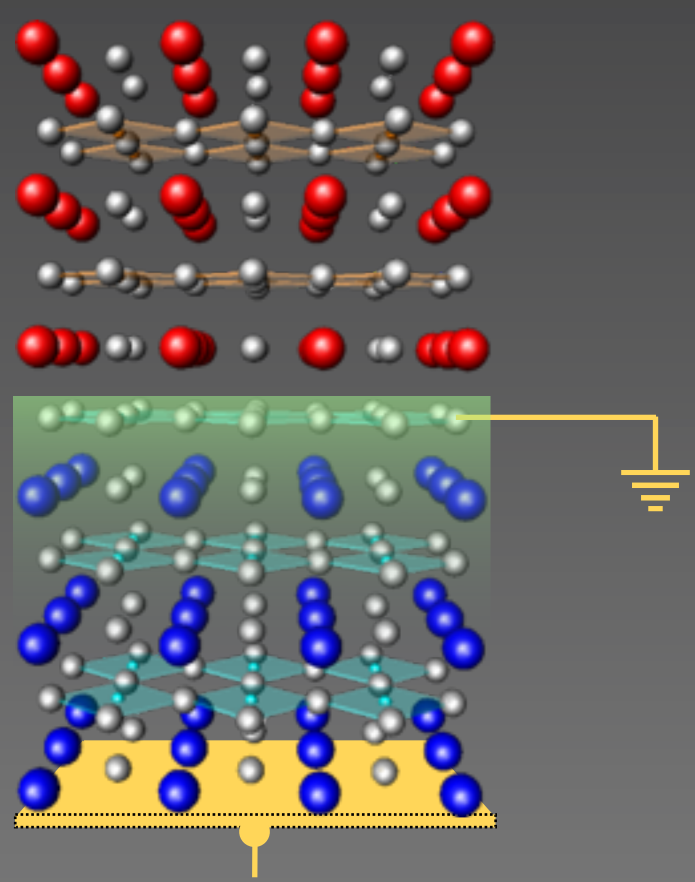
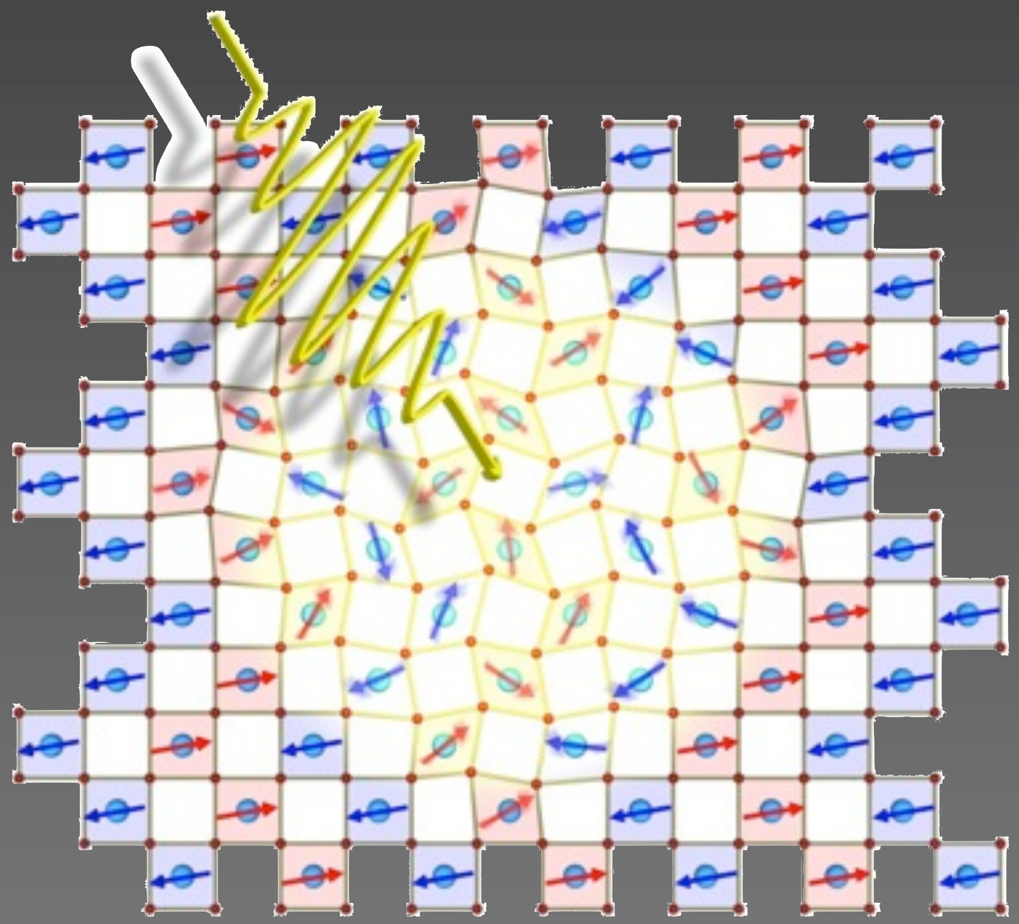
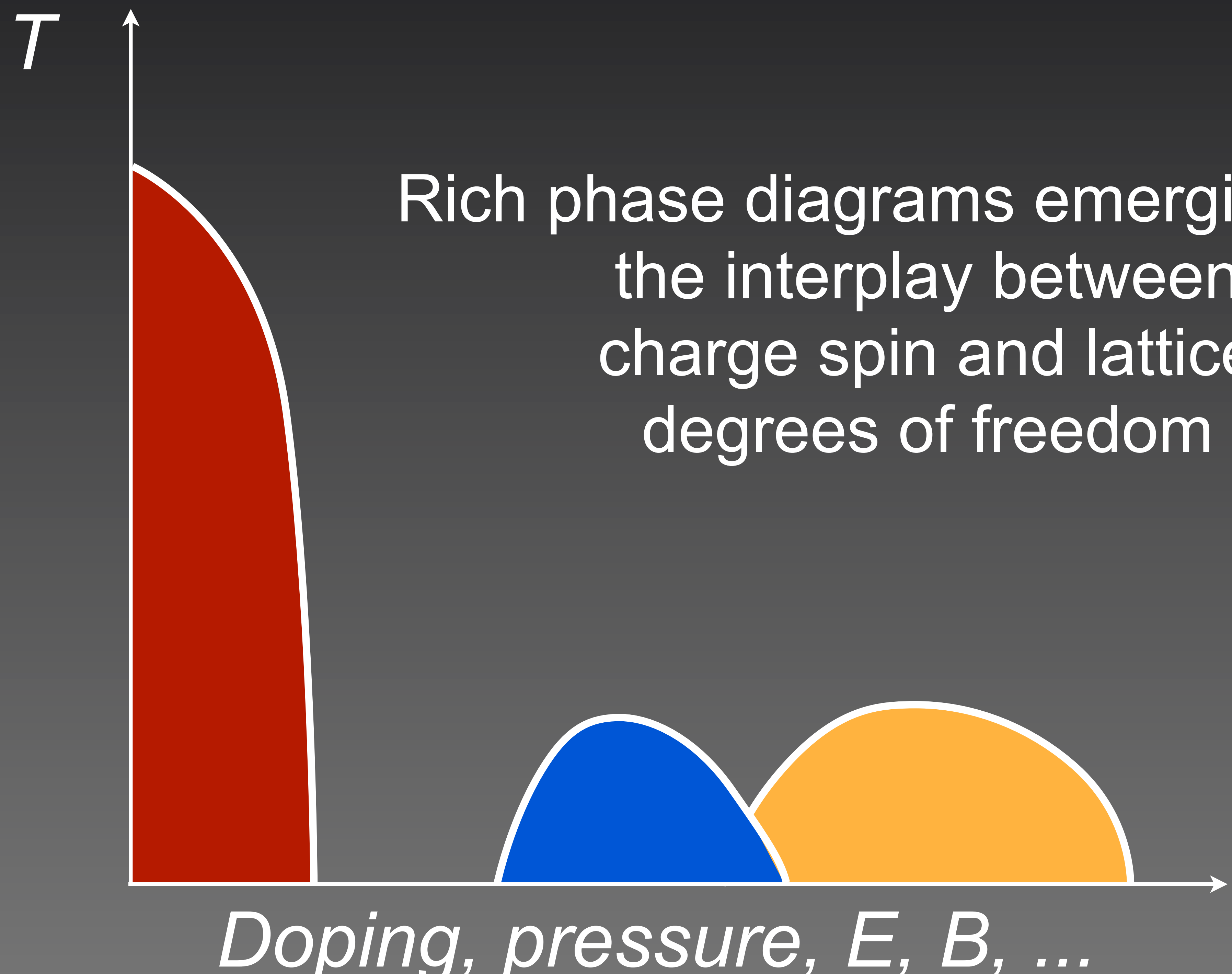
Max Planck Department for Structural Dynamics
Center for Free Electron Laser Science
University of Hamburg



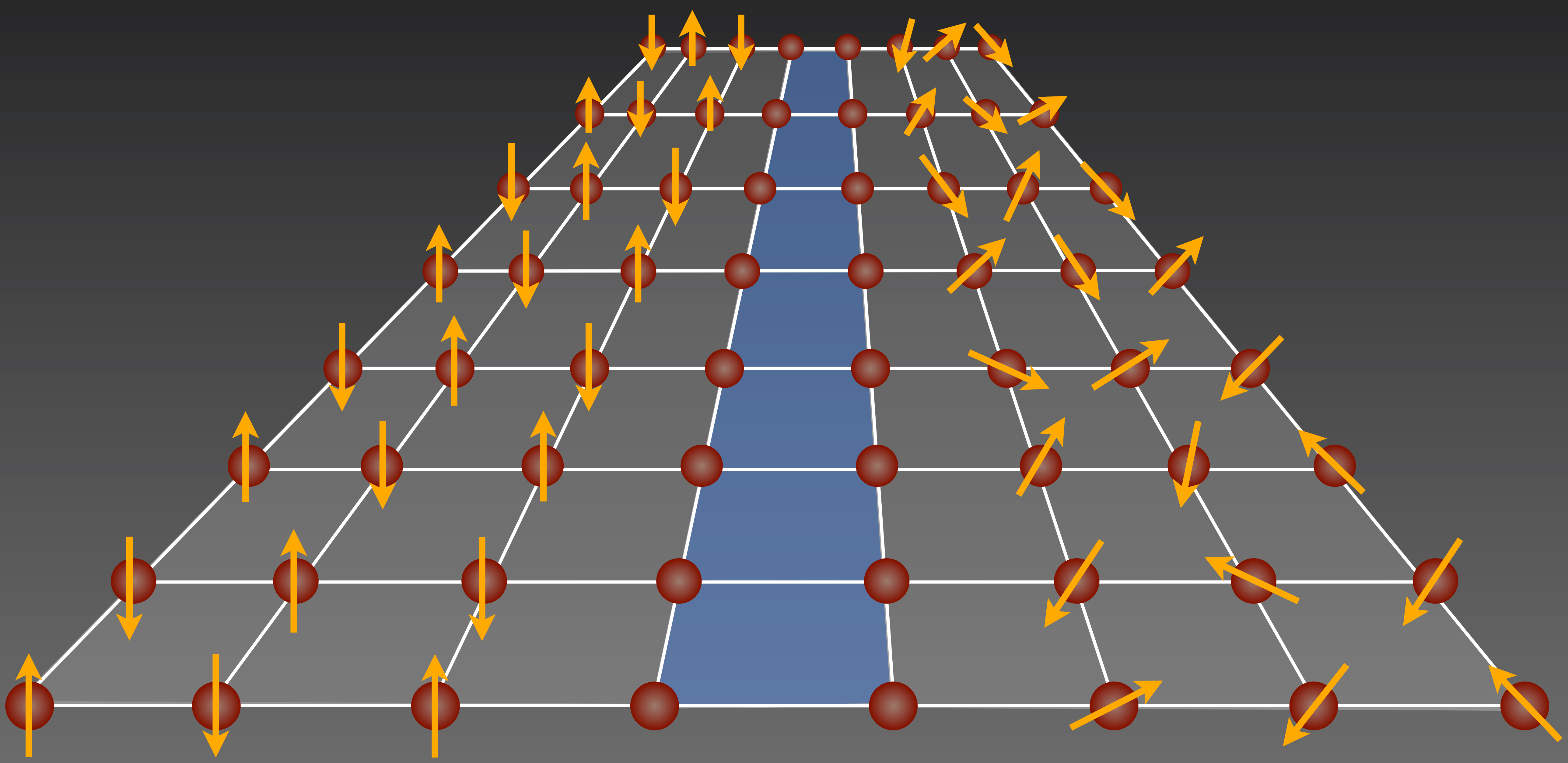


Competing ground states in quantum materials



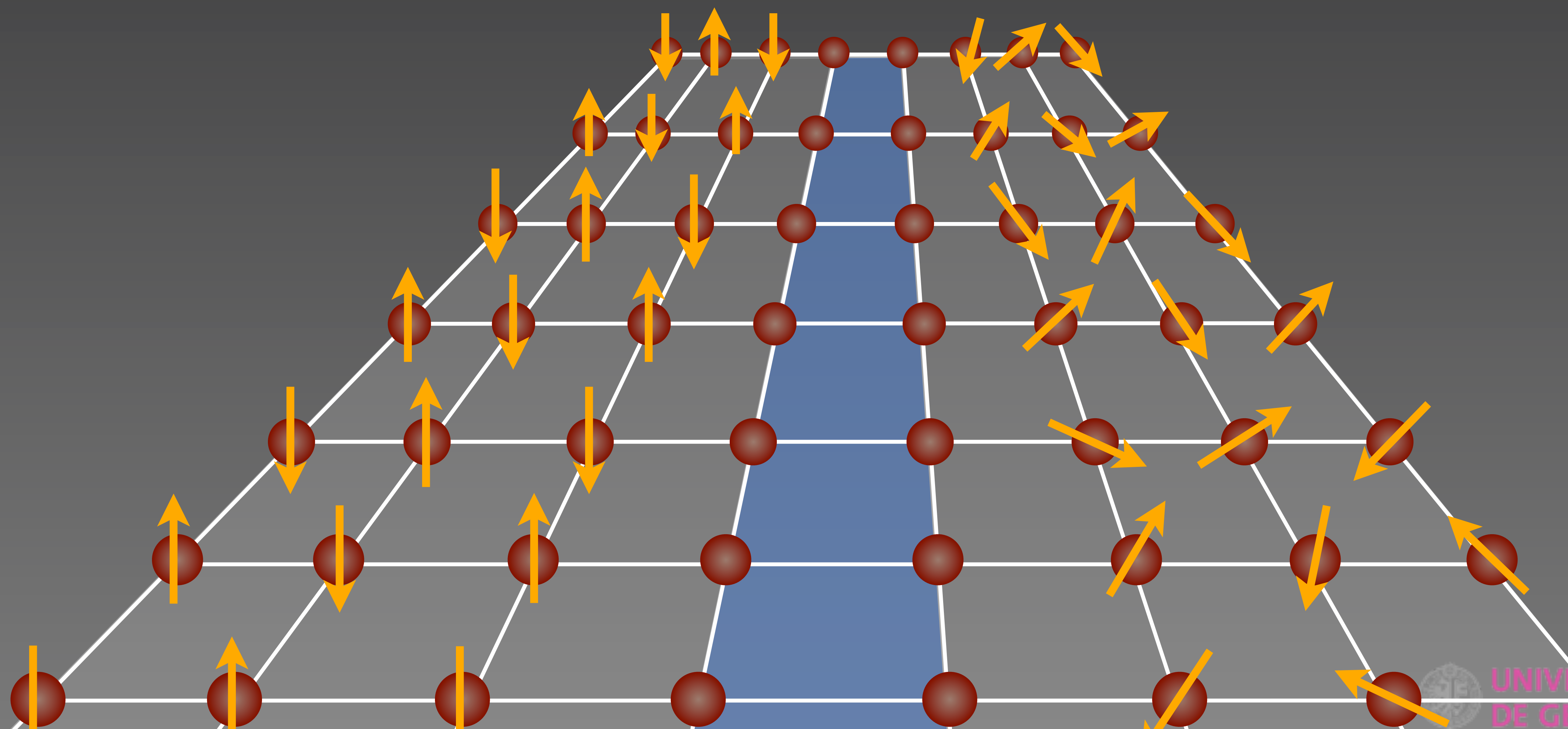
Rich phase diagrams emerging from the interplay between charge spin and lattice degrees of freedom

Novel electronic phases at their interfaces



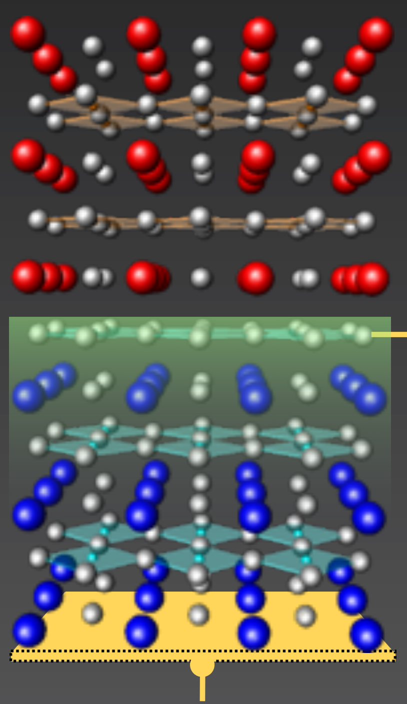
Phase control at interfaces

Breaking of inversion symmetry
Low dimensionality
Structural distortions
Modulation doping
Polar discontinuities



Two experimental approaches

Electrostatic field-effect



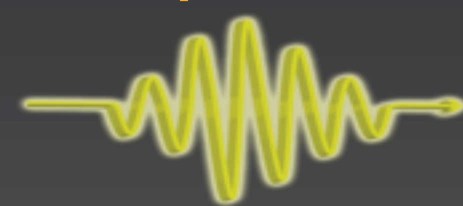
static 10 kV/cm fields
$n_{2D} \sim 10^{13} - 10^{14}$ cm^{-2}
modulation of doping and interactions

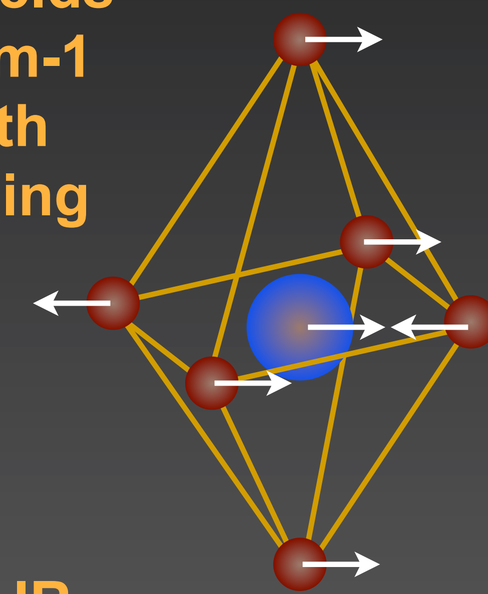
electronic properties investigated by dc transport

LaAlO$_3$/SrTiO$_3$
Superconductor - Insulator
Quantum Phase Transition

Ultrafast lattice excitation

100 fs pulsed 10 MV/cm fields
16 um wavelength, 600 cm-1
modulation of bandwidth
non-linear phonon coupling





electronic properties investigated by pump and probe THz and IR spectroscopy

NdNiO$_3$/LaAlO$_3$
Insulator - Metal
Non-equilibrium Phase Transition

Outline

$LaAlO_3/SrTiO_3$

Two-dimensional superconductivity

Superconductor to insulator quantum phase transition

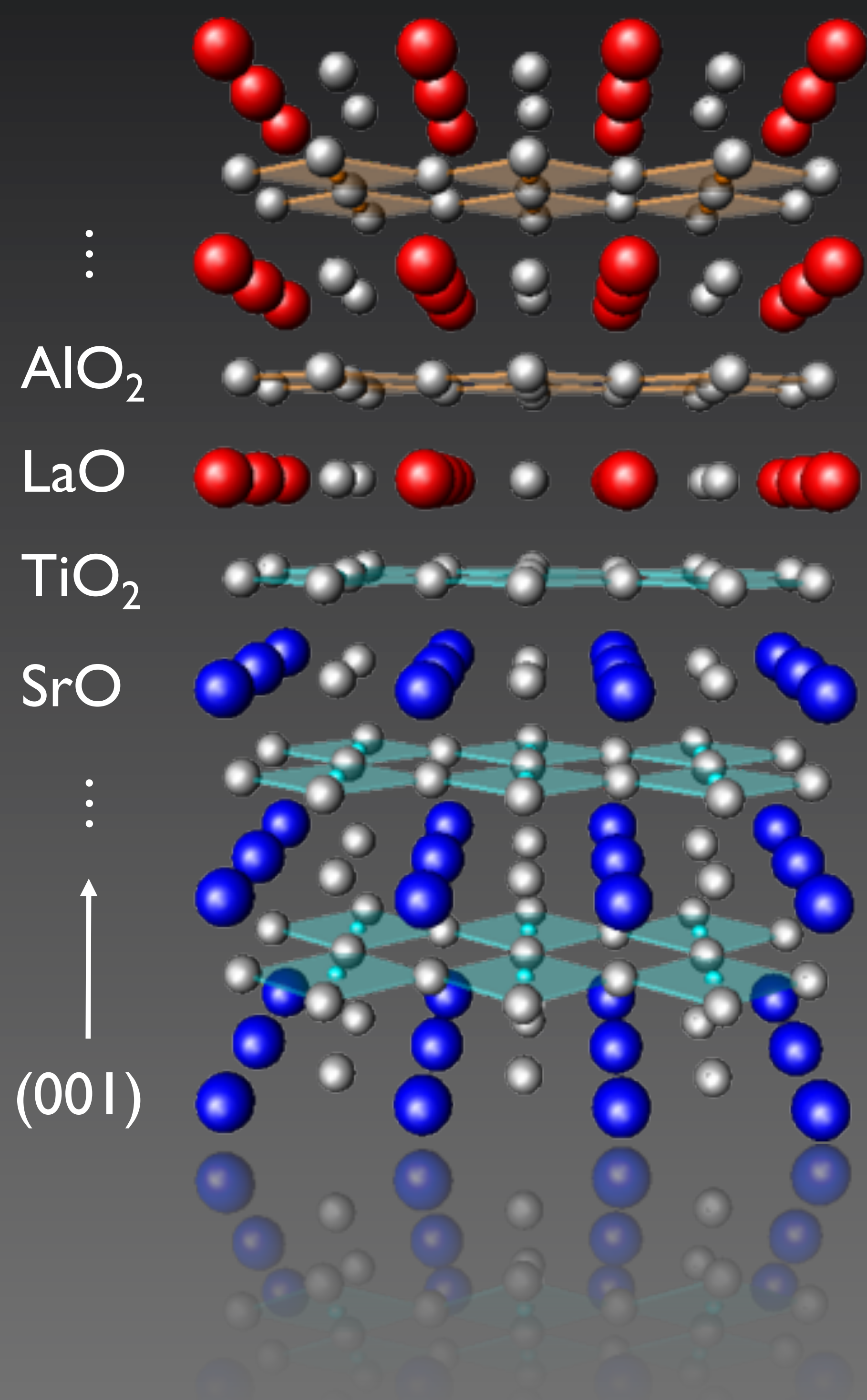
Spin-orbit interaction

$NdNiO_3/LaAlO_3$

Metal Insulator transition

Pump and probe spectroscopy

Vibrational excitation



$LaAlO_3$:

band insulator

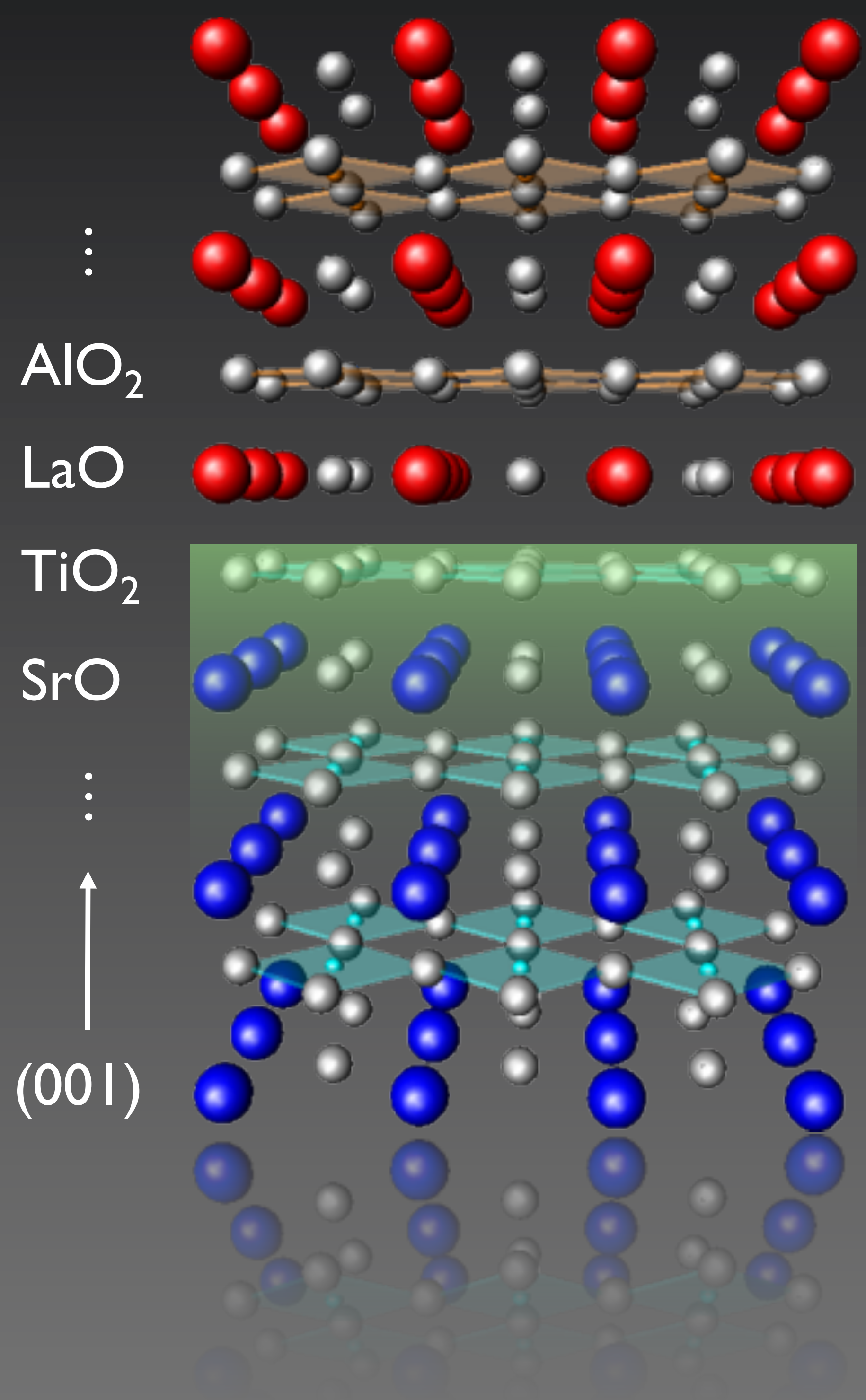
$\Delta = 5.6\,\mathrm{eV}, \quad \kappa = 24$

$SrTiO_3$:

band insulator

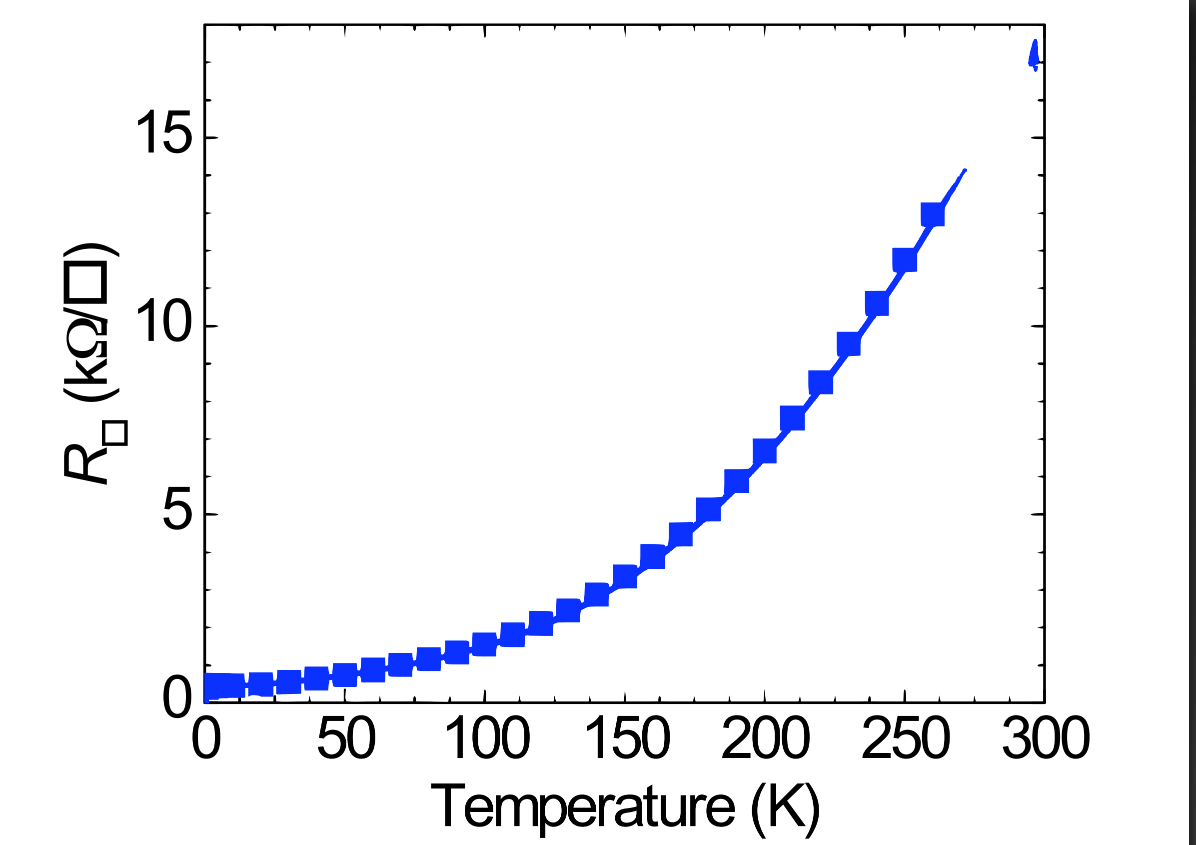
$\Delta = 3.2\,\mathrm{eV}, \quad \kappa\,(300\,\mathrm{K}) = 300$

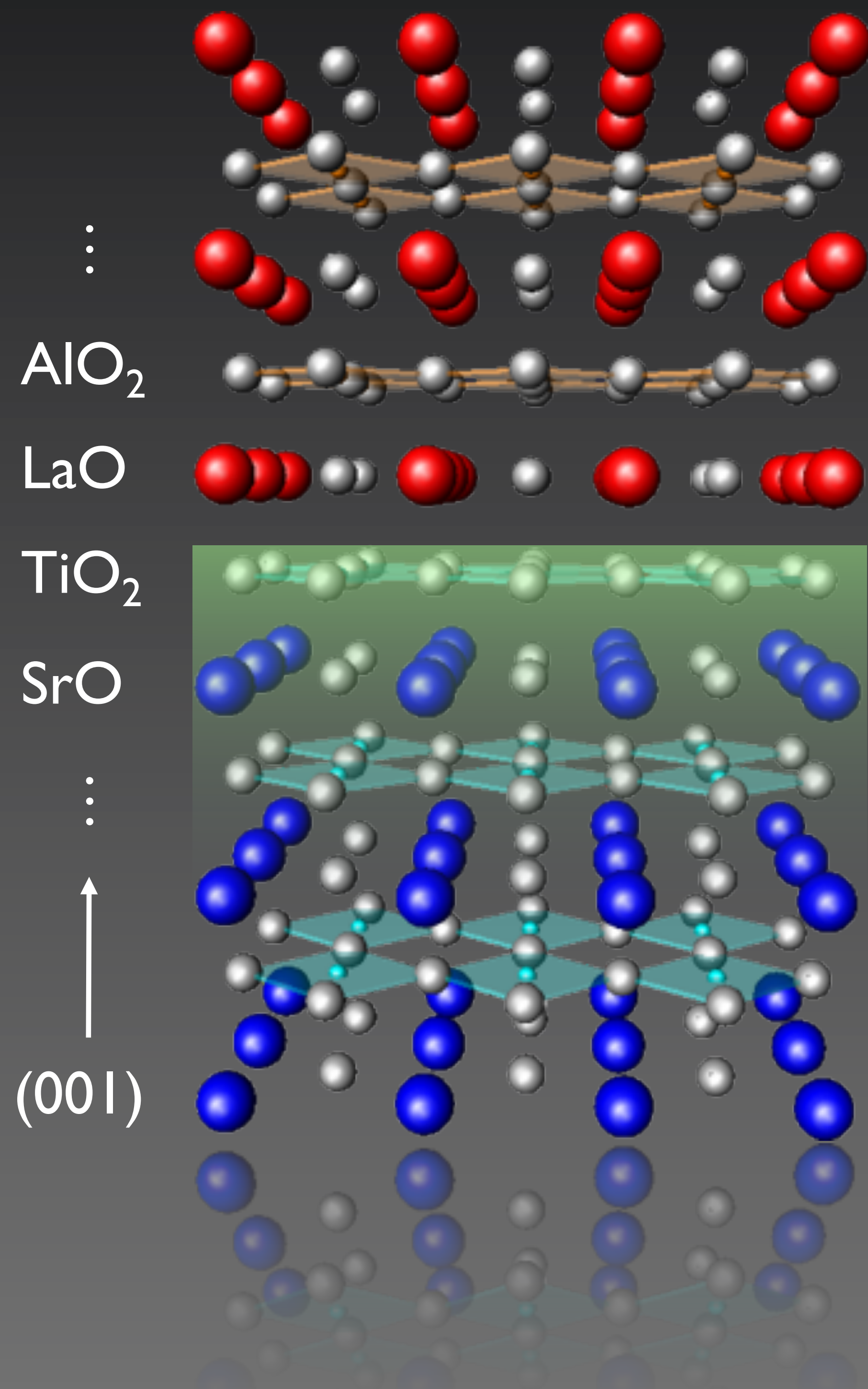
quantum paraelectric

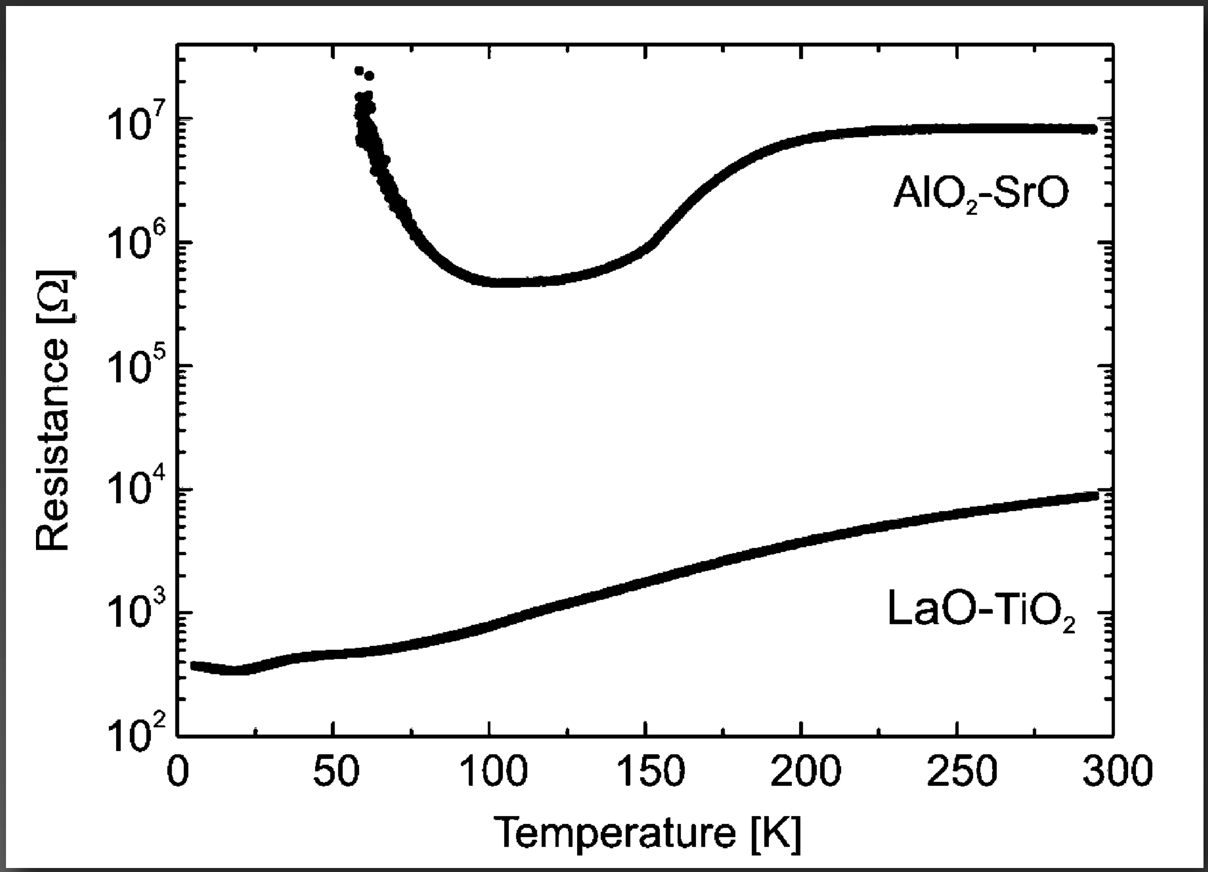


A high-mobility electron gas at the $LaAlO_3/SrTiO_3$ heterointerface

A. Ohtomo[1,2,3] & H. Y. Hwang[1,3,4] *Nature* **427**, 423 (2004)

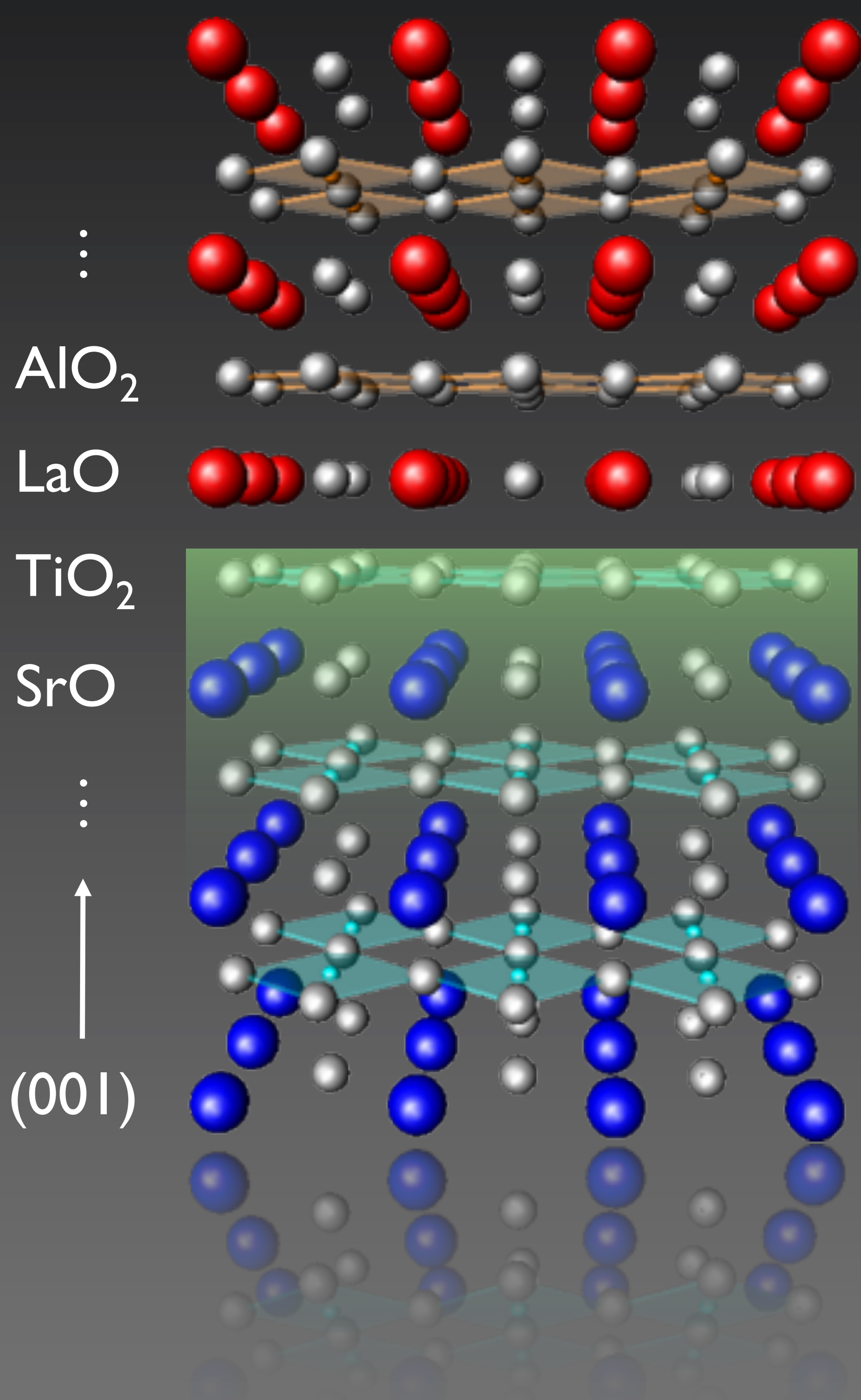






A. Ohtomo and H.Y. Hwang Nature **427**, 423 (2004)
M. Huijben *et al. Advanced materials* **21**, 1665 (2009)

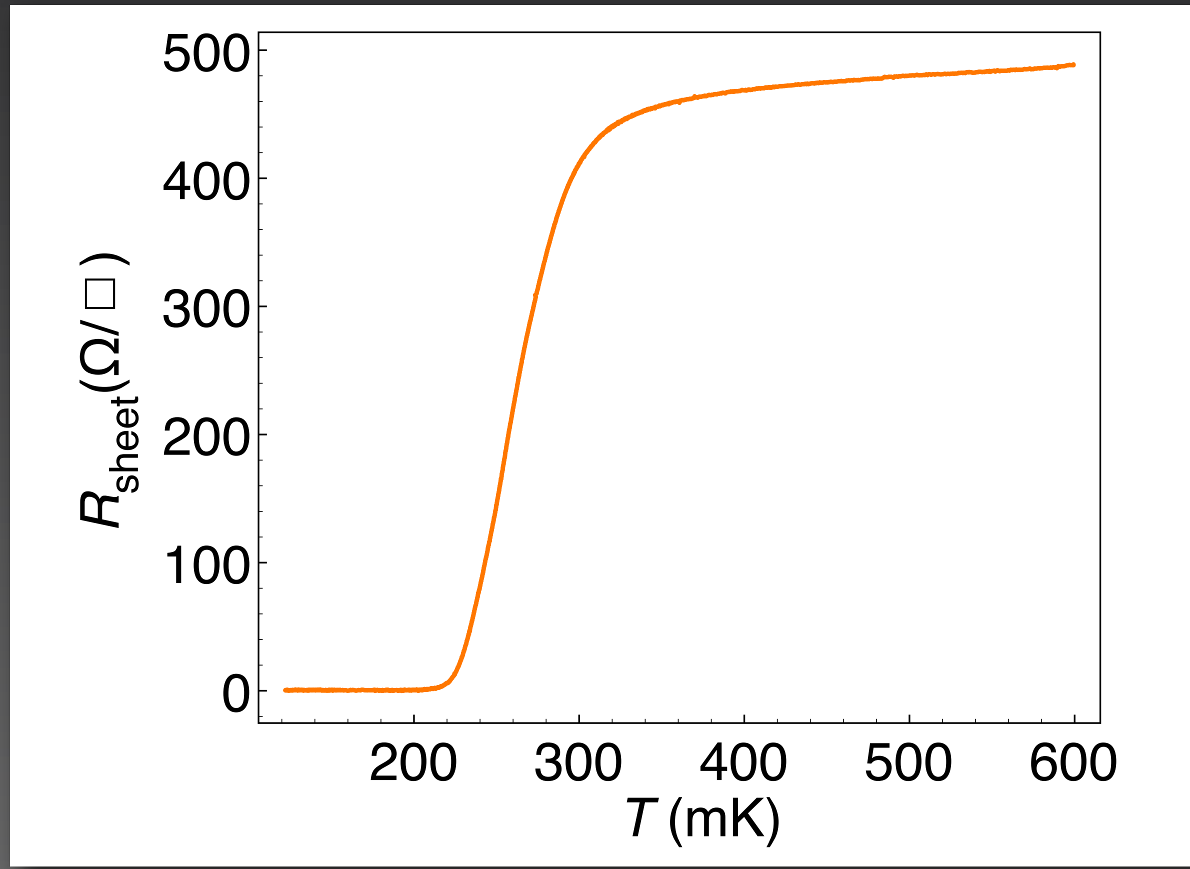
SC in LAO/STO



Superconducting Interfaces Between Insulating Oxides

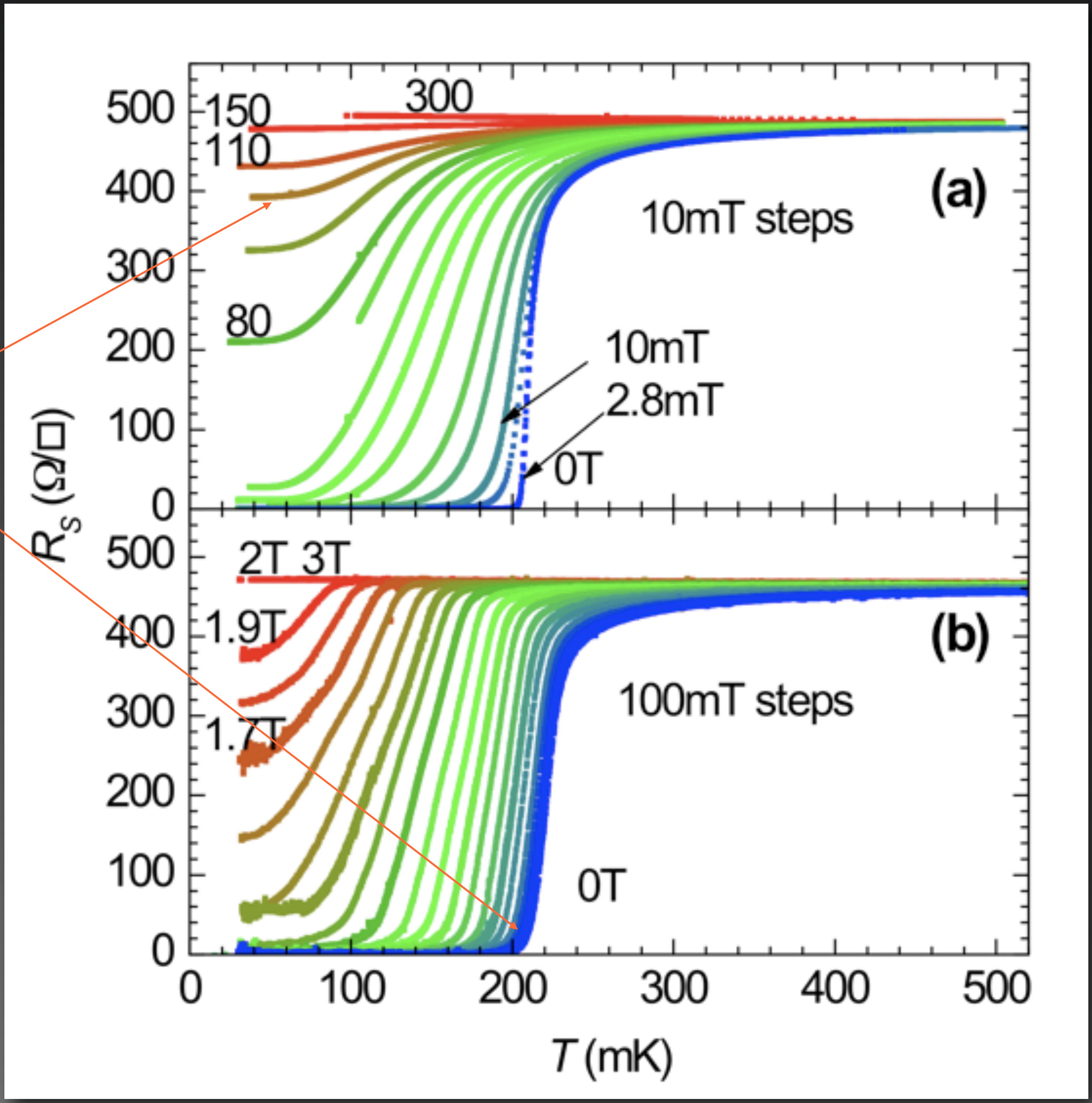
N. Reyren,[1] S. Thiel,[2] A. D. Caviglia,[1] L. Fitting Kourkoutis,[3] G. Hammerl,[2] C. Richter,[2] C. W. Schneider,[2] T. Kopp,[2] A.-S. Rüetschi,[1] D. Jaccard,[1] M. Gabay,[4] D. A. Muller,[3] J.-M. Triscone,[1] J. Mannhart[2]*

Science **317**, 1196 (2007)



Transport anisotropy

100mT

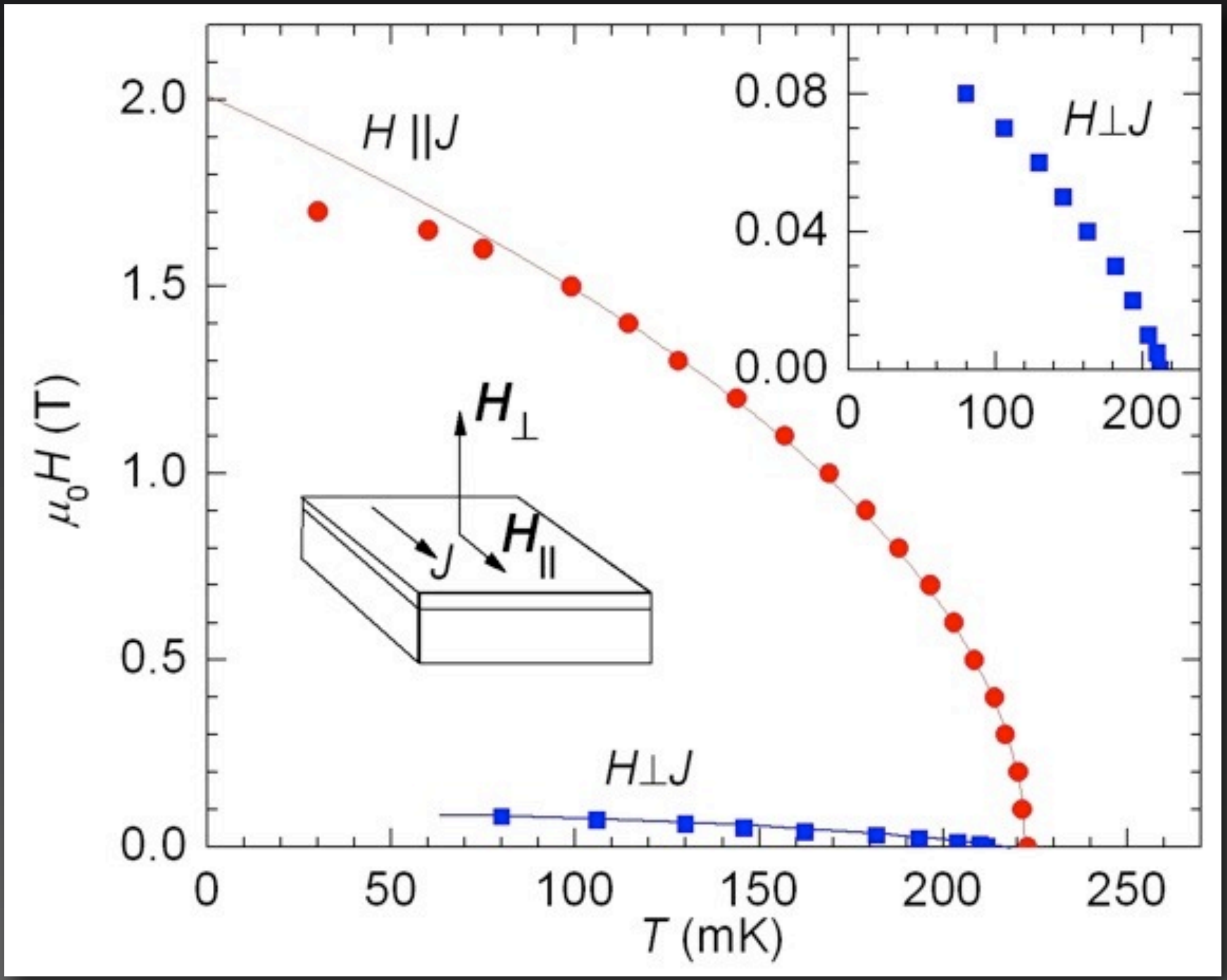


H⊥

H//

N. Reyren, AC *et al*, *APL* **94**, 112506 (2009)

Two-dimensional SC



$$\mu_0 H_\perp(T) = \frac{\Phi_0}{2\pi\xi_\|^2(T)}$$

$$\xi_\|(T=0) \sim 60 \text{ nm}$$

$$\mu_0 H_\|(T) = \frac{\sqrt{3}\Phi_0}{\pi d \xi_\|(T)}$$

$d \approx 10$ nm

consistent with

A. Dubroka *et al., PRL* **104**, 156807 (2010)
M. Basletic *et al., Nature Materials* **7**, 621 (2008)
O. Copie *et al., PRL* **102**, 216804 (2009)
M. Sing *et al., PRL* **102**, 176805 (2009)

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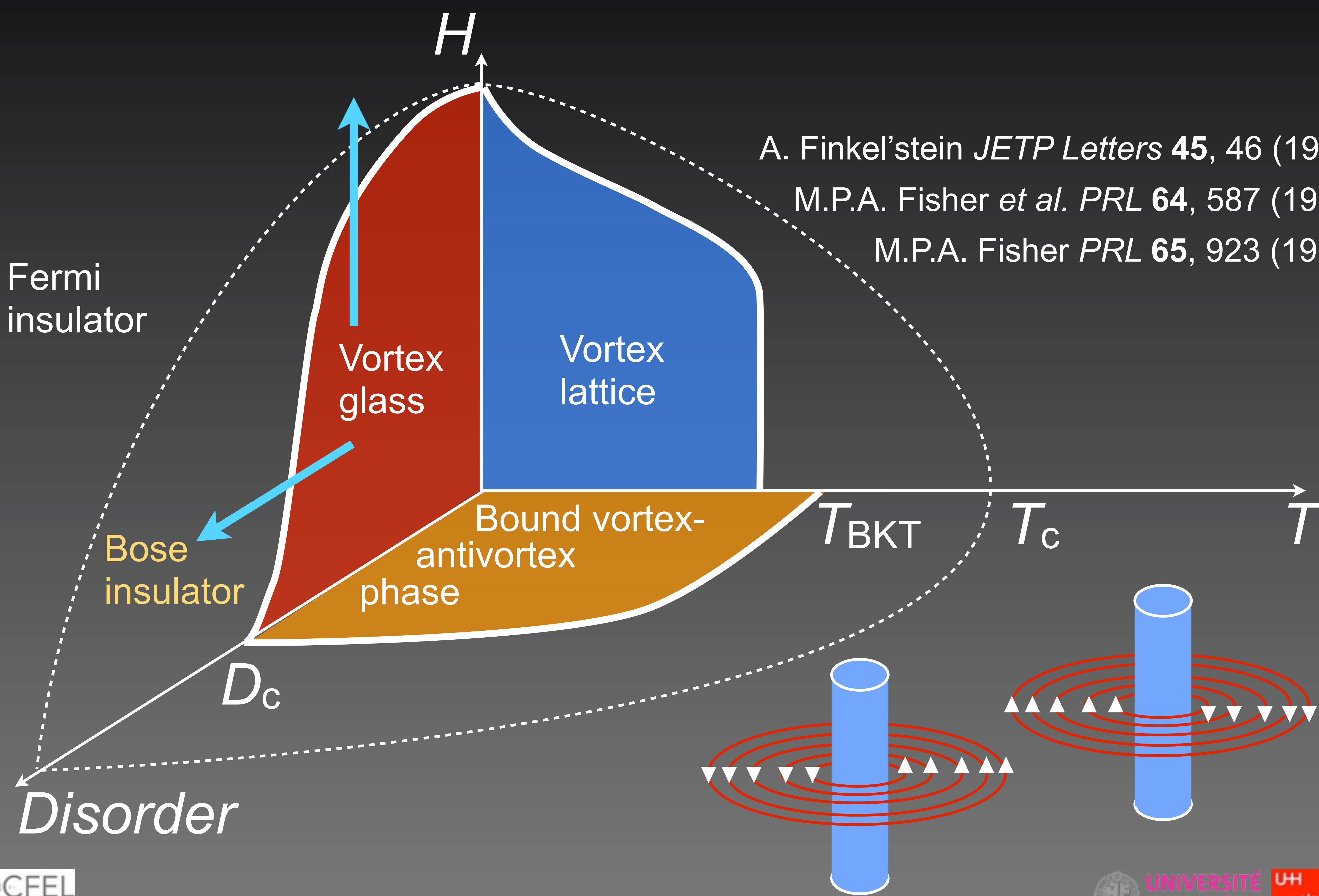
Phase diagram

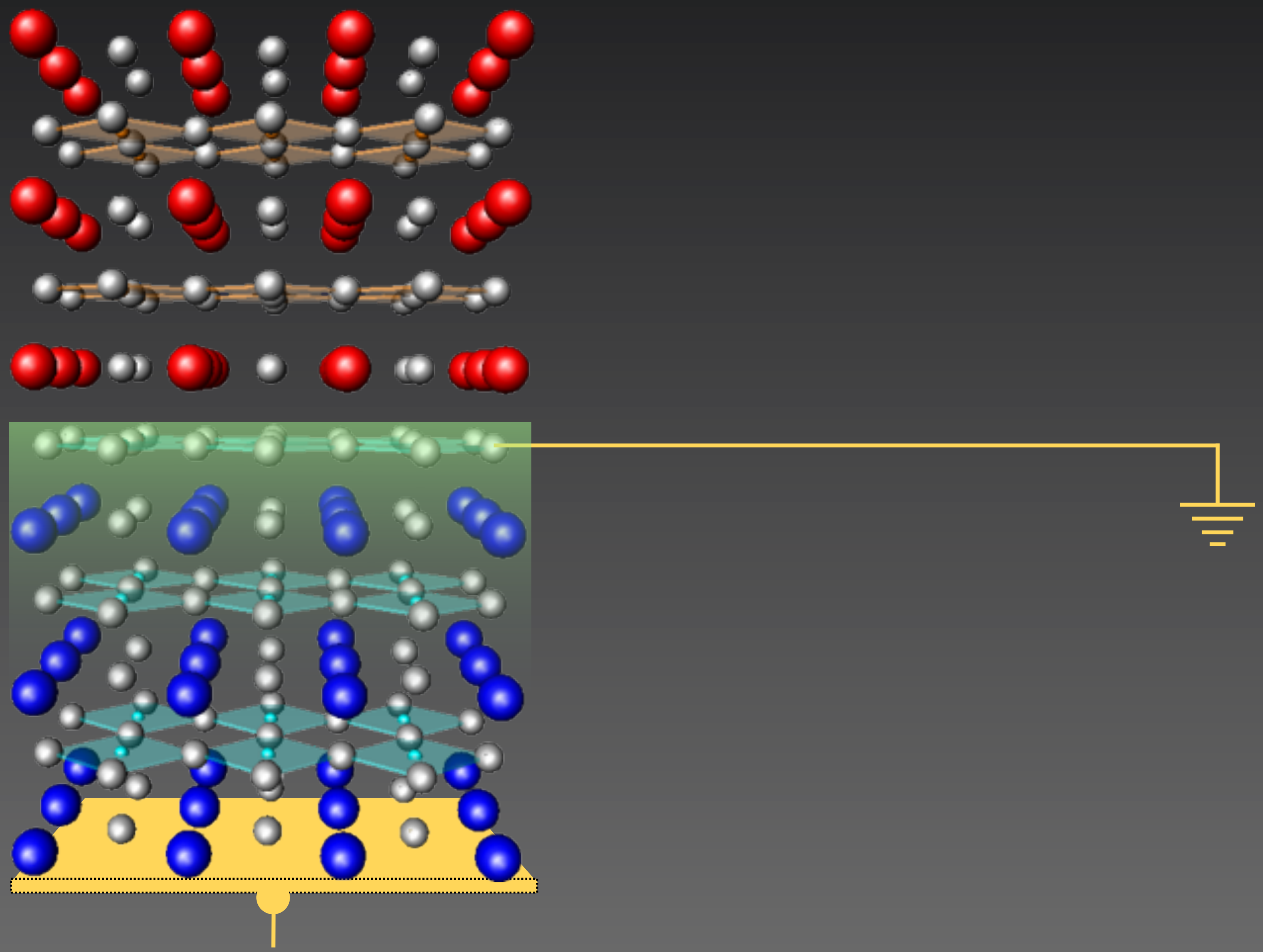
A. Finkel'stein *JETP Letters* **45**, 46 (1987)

M.P.A. Fisher *et al. PRL* **64**, 587 (1990)

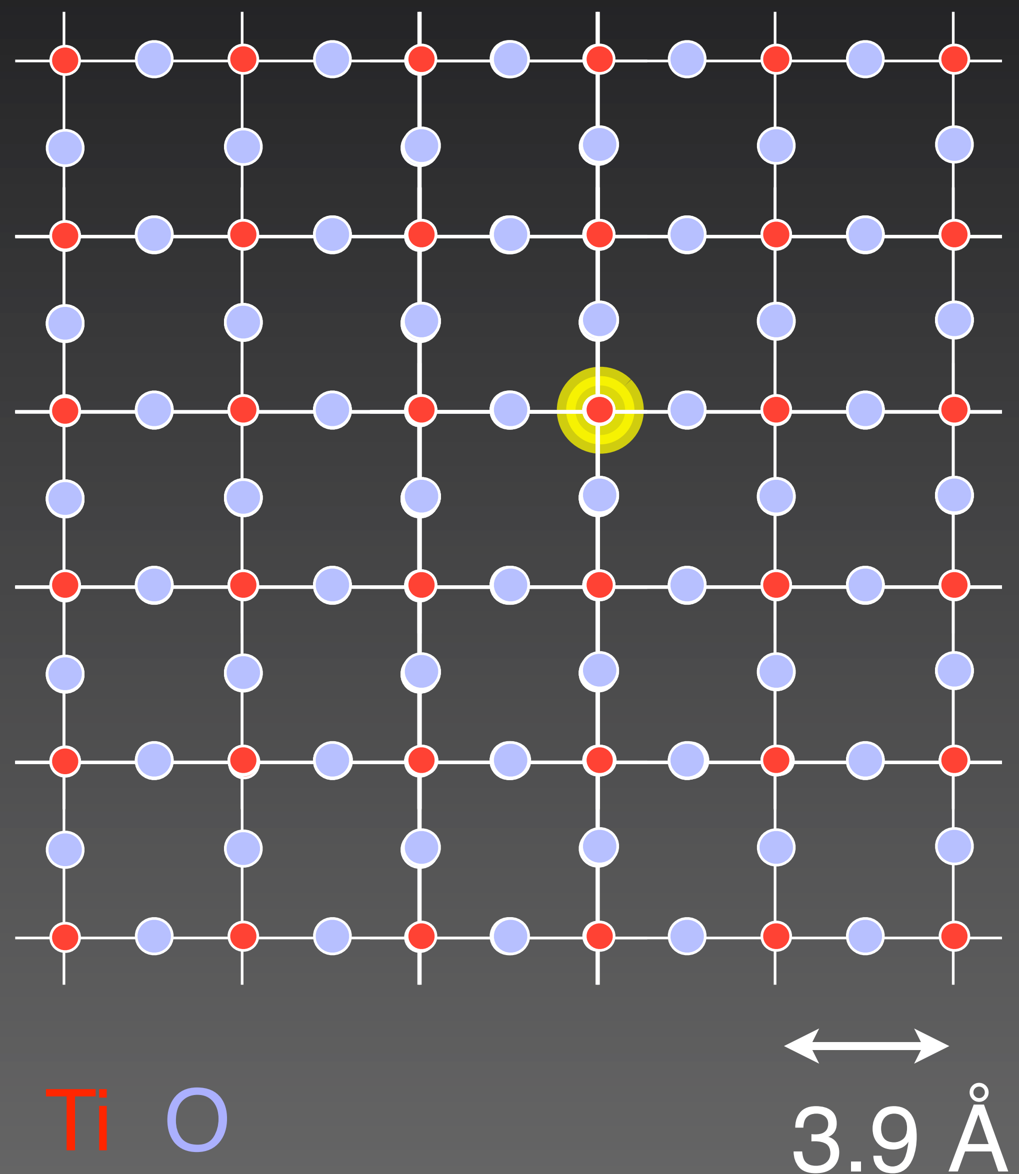
M.P.A. Fisher *PRL* **65**, 923 (1990)



Field effect experiments

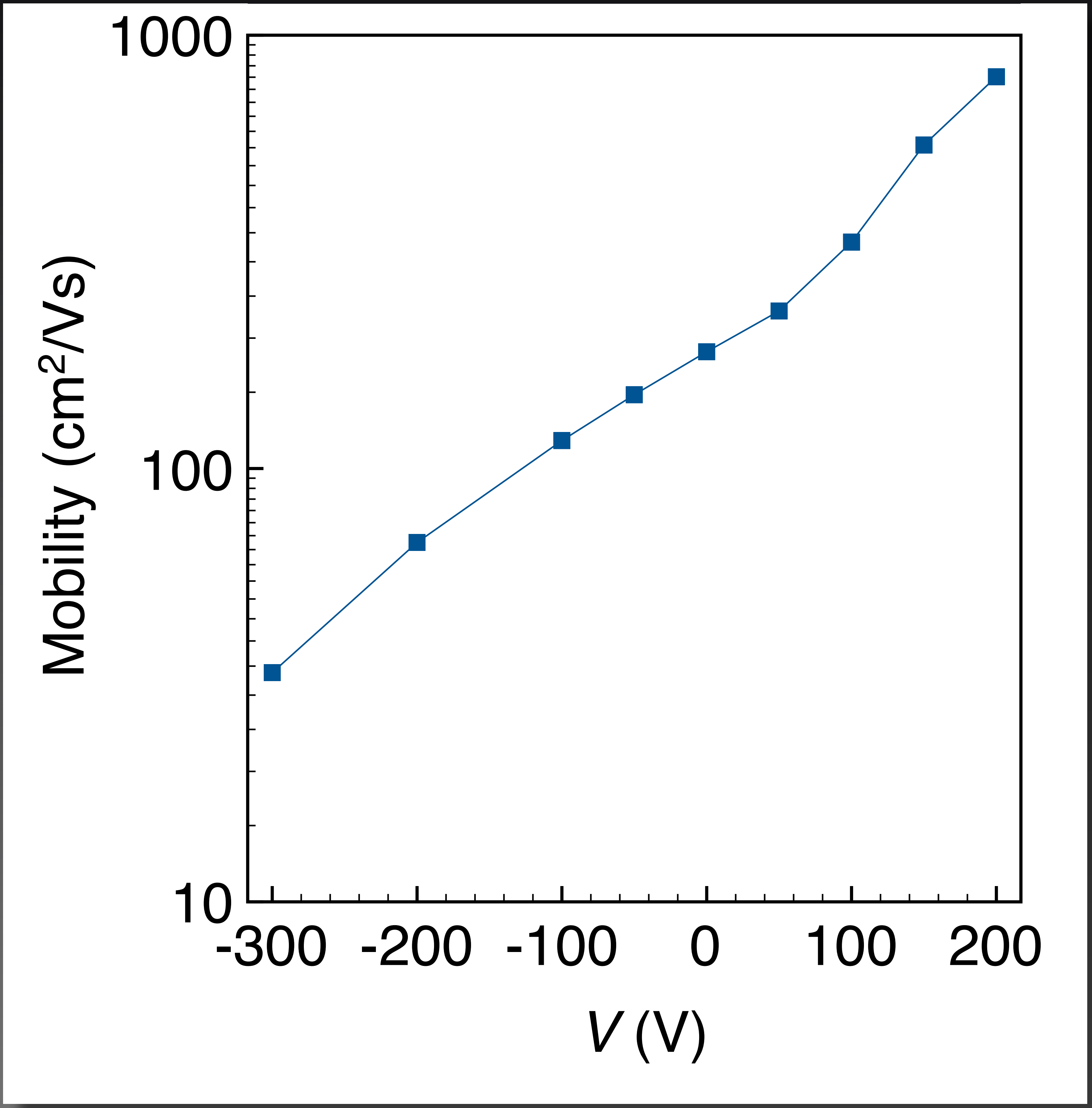


Low carrier density



~2-4×10^{13}/cm^{2}

TiO_2-plane



C. Bell *et al.*, *PRL* **103**, 226802 (2009)
A.D. Caviglia *et al.*, *PRL* **104**, 126803 (2010)

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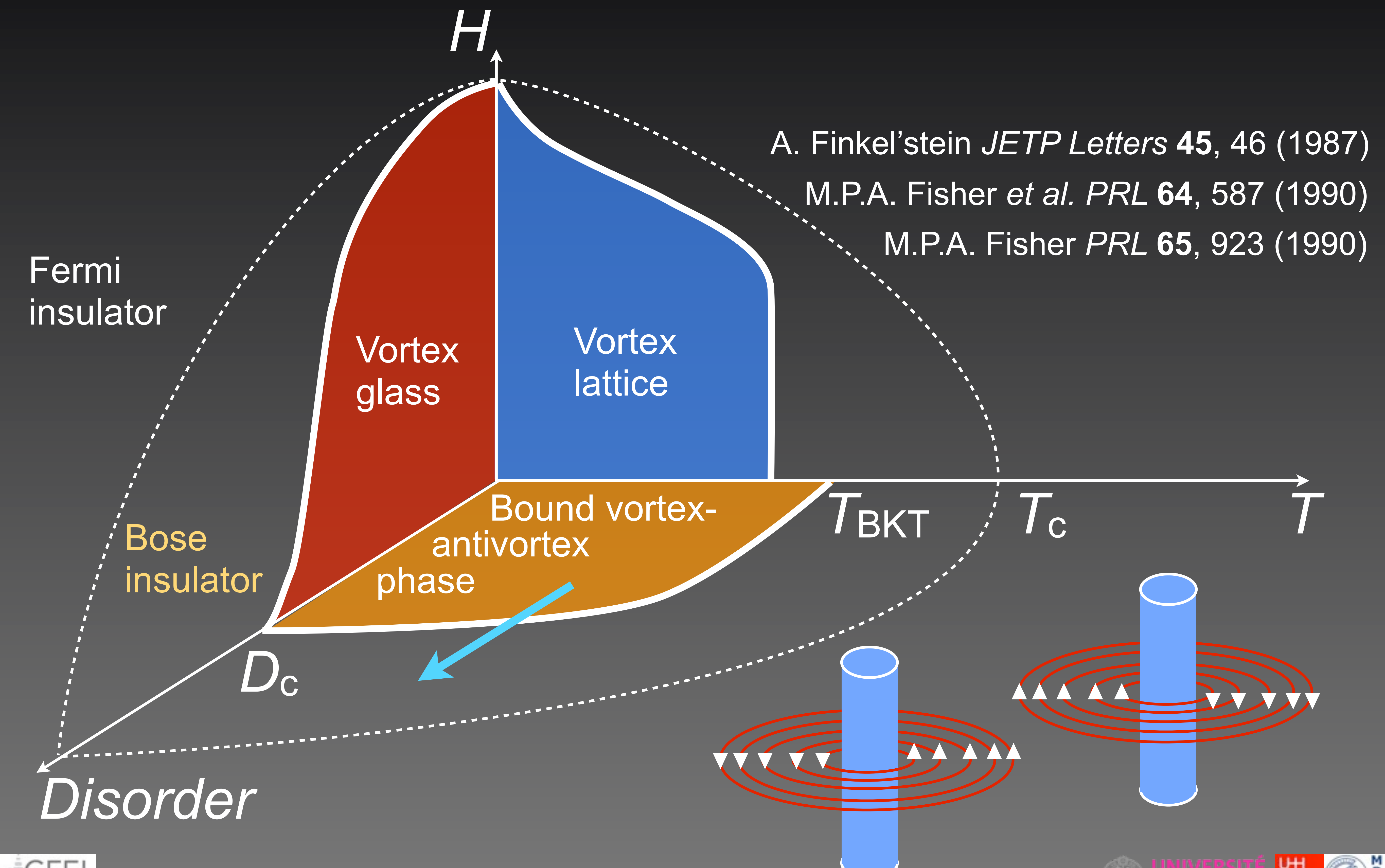
Phase diagram

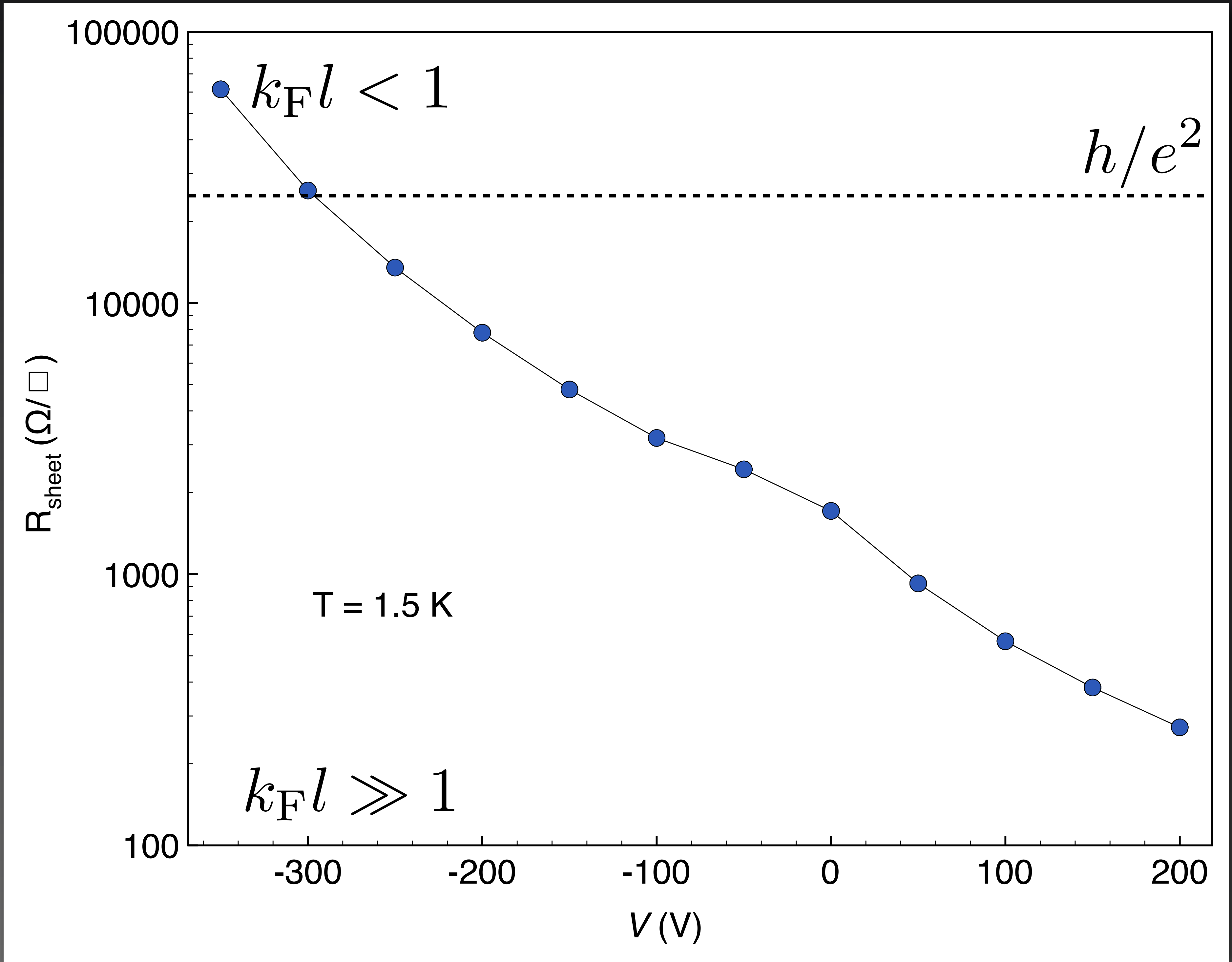
A. Finkel'stein *JETP Letters* **45**, 46 (1987)

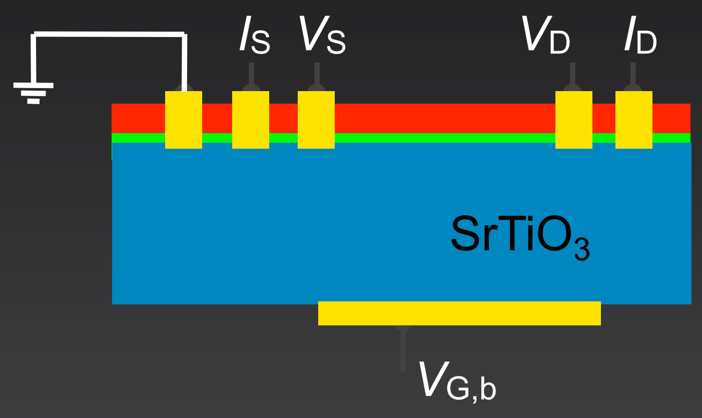
M.P.A. Fisher *et al. PRL* **64**, 587 (1990)

M.P.A. Fisher *PRL* **65**, 923 (1990)

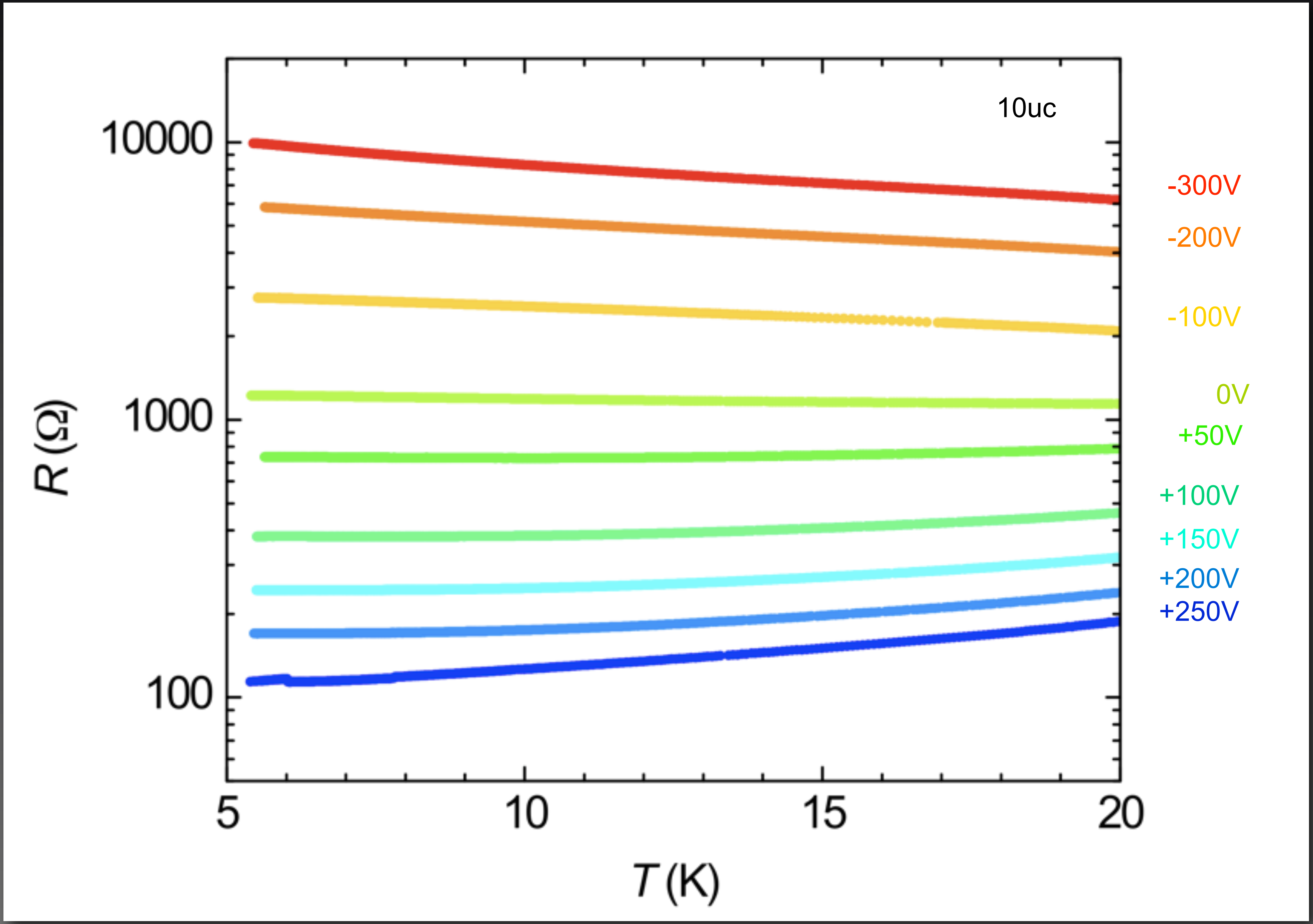


R_{sheet} modulation





5 mm



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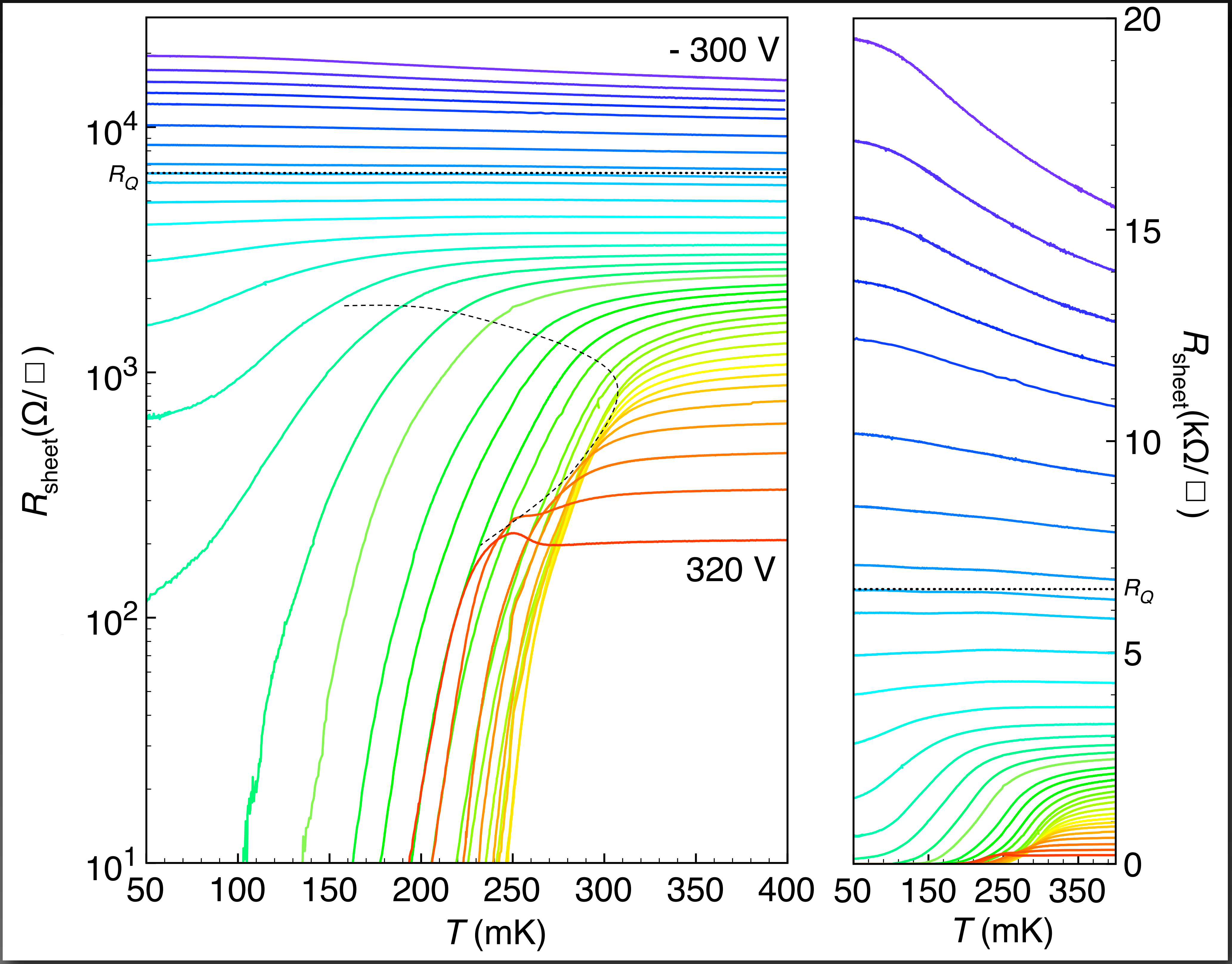
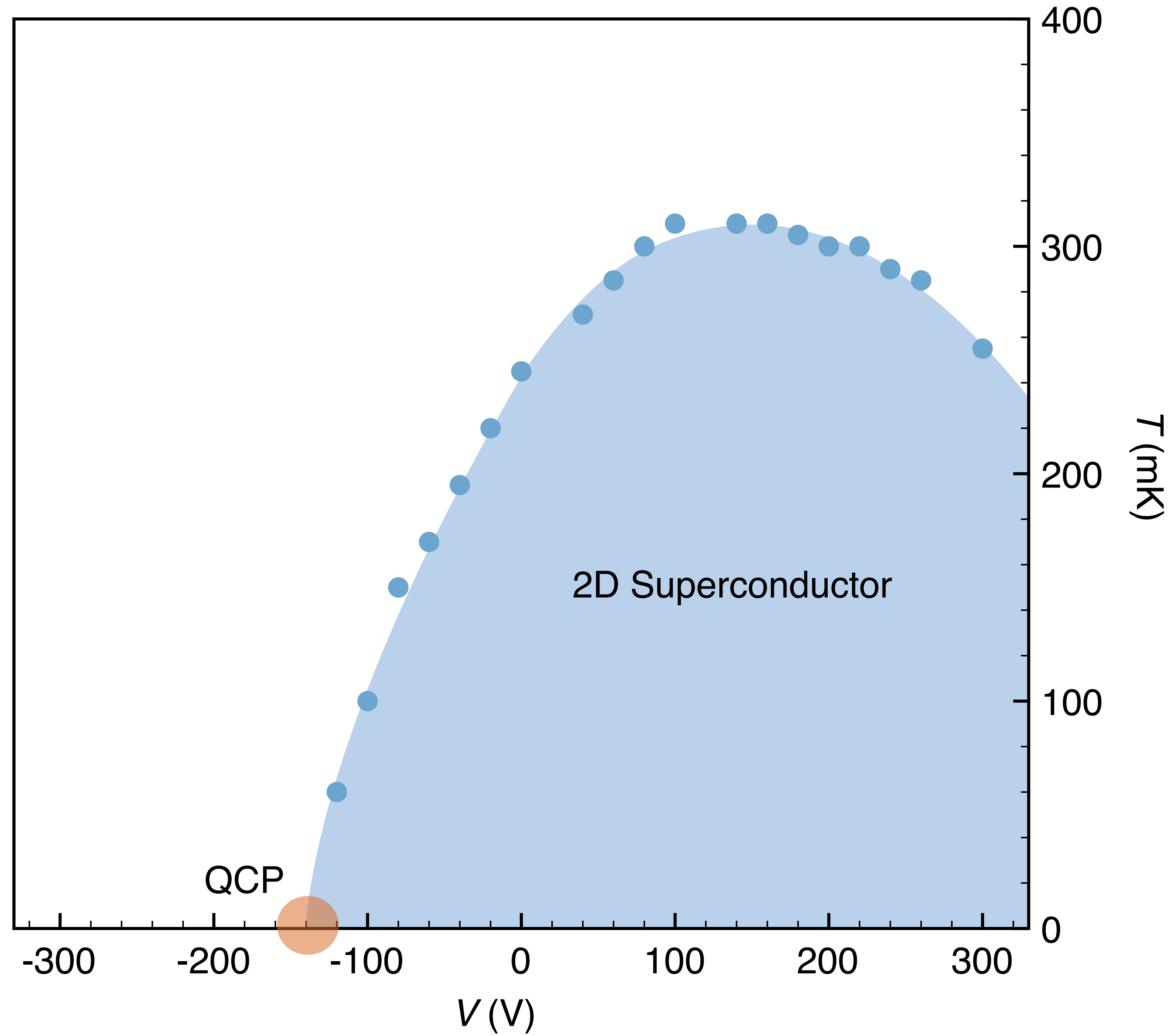
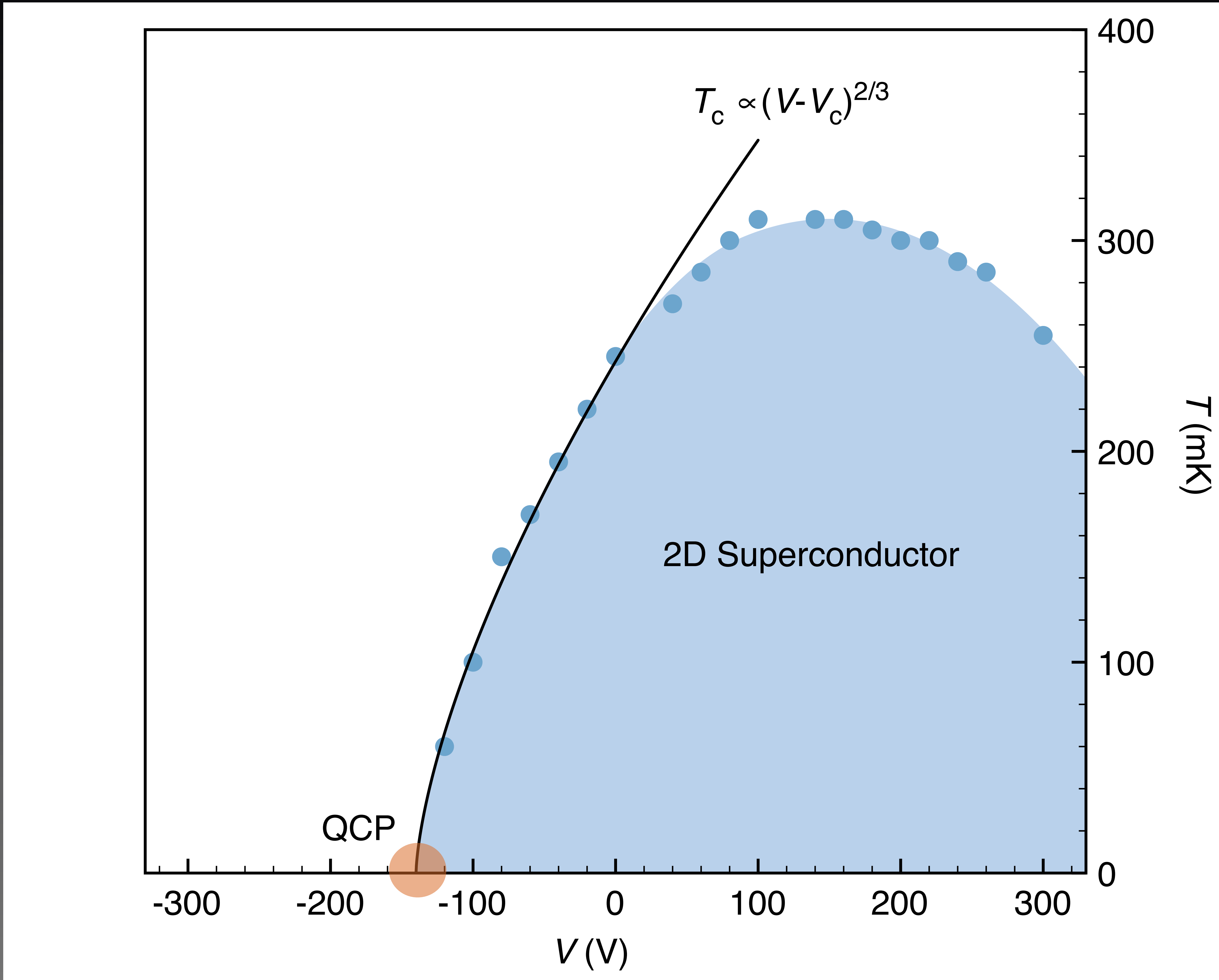
Modulation of SC



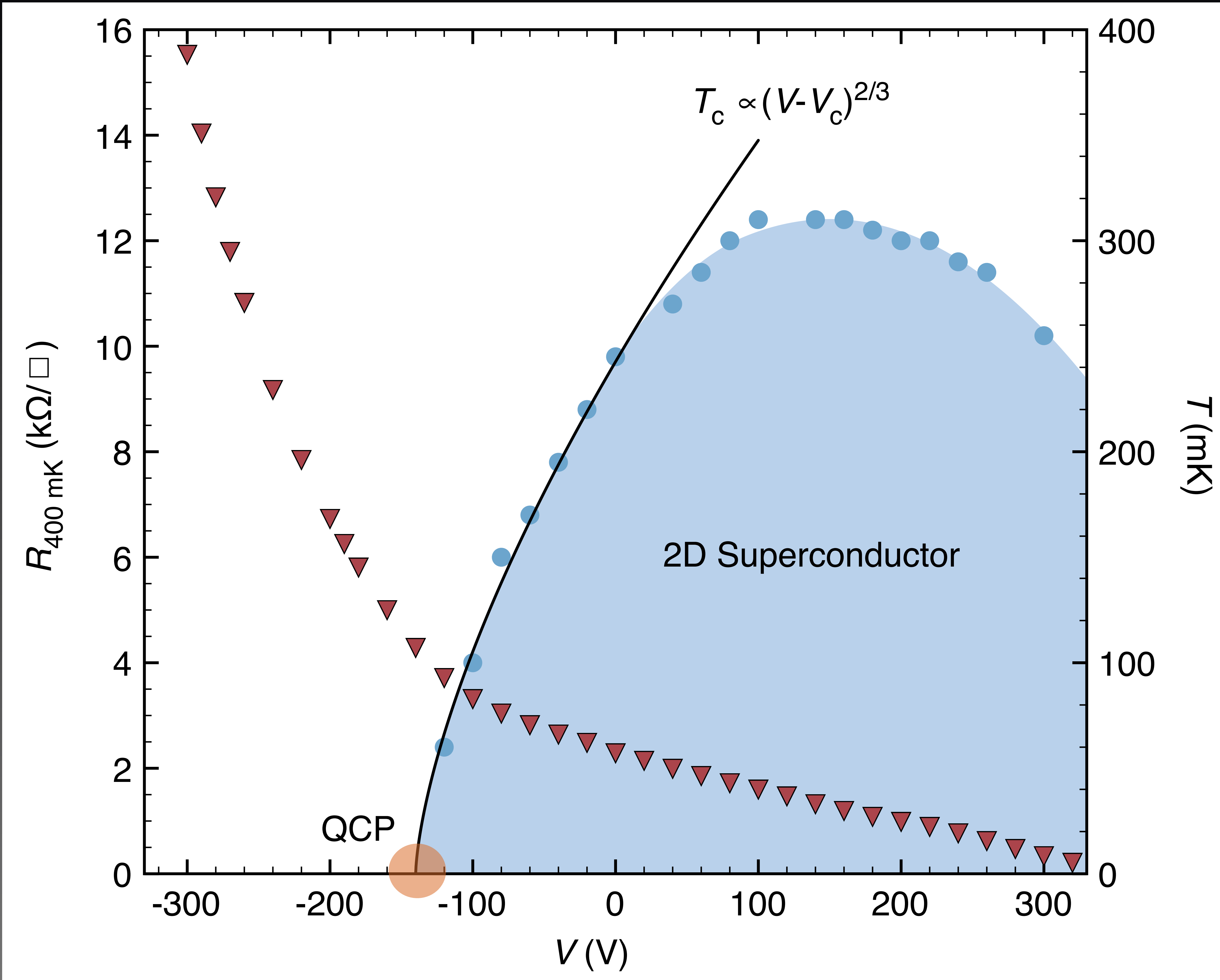
A.D. Caviglia *et al*, *Nature* **456**, 625 (2008)



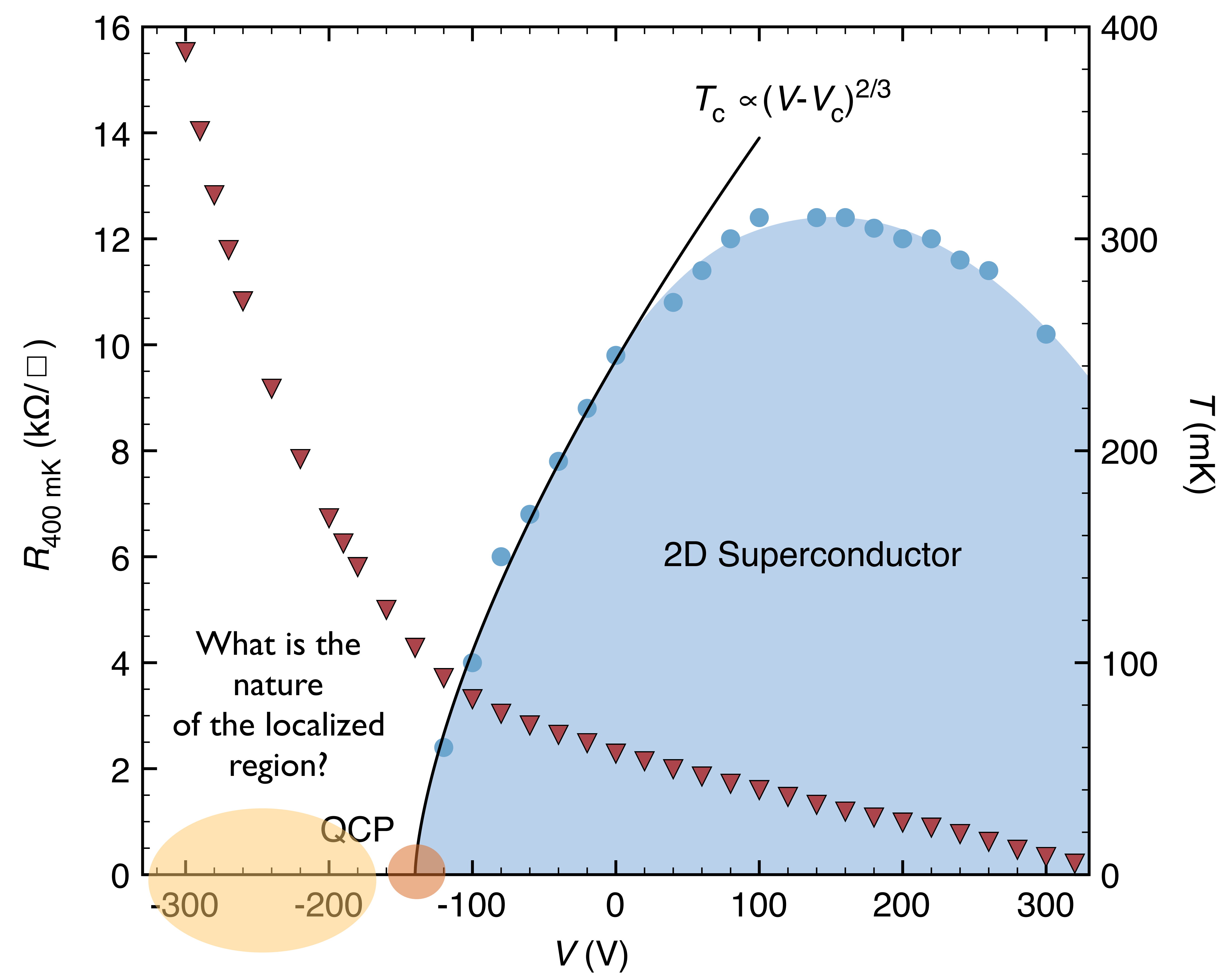
400
300
200
100
0
T (mK)
2D Superconductor
QCP
-300
-200
-100
0
100
200
300
V (V)



T. Schneider, AC et al. *PRB* **79**, 184502 (2009)



A.D. Caviglia *et al*, *Nature* **456**, 625 (2008)



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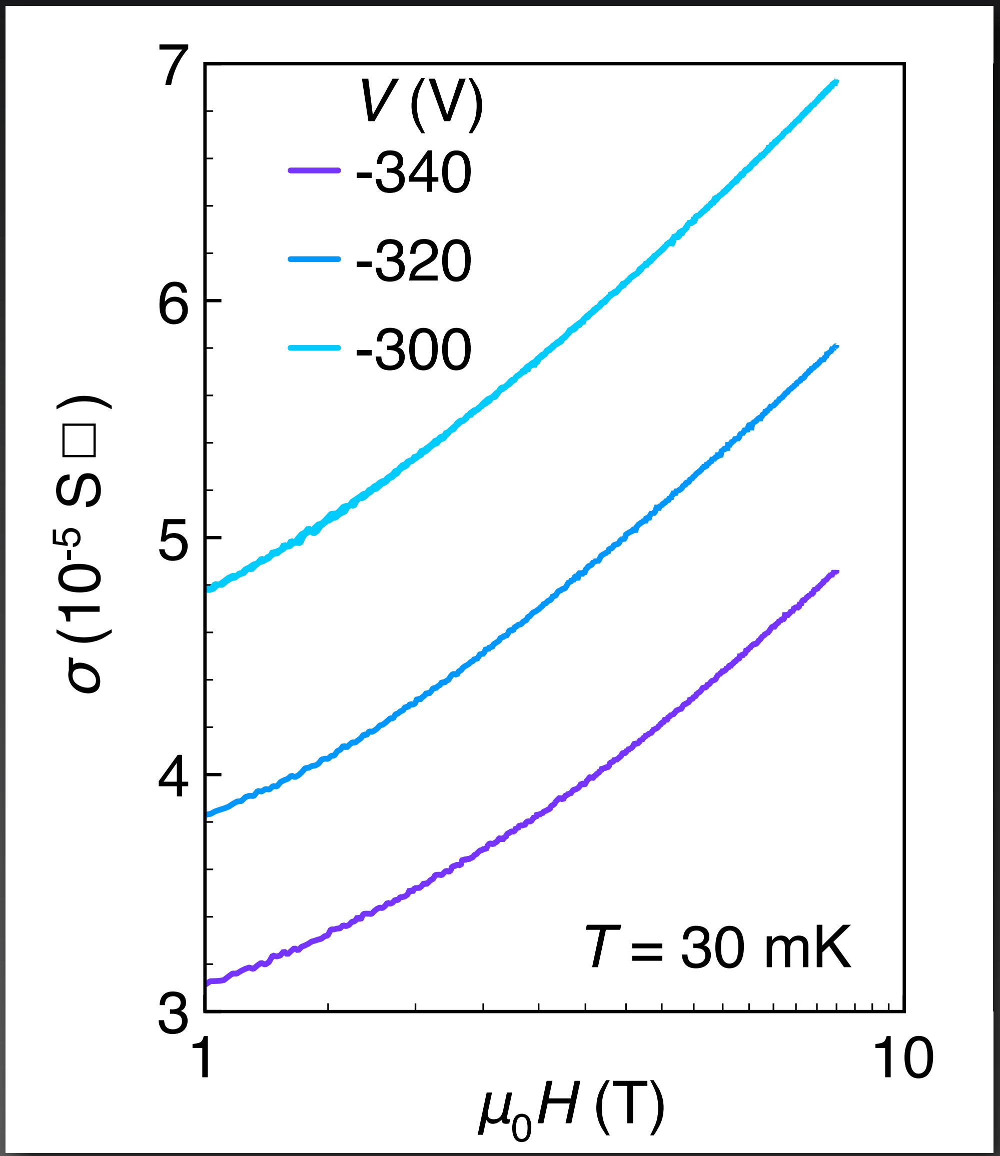
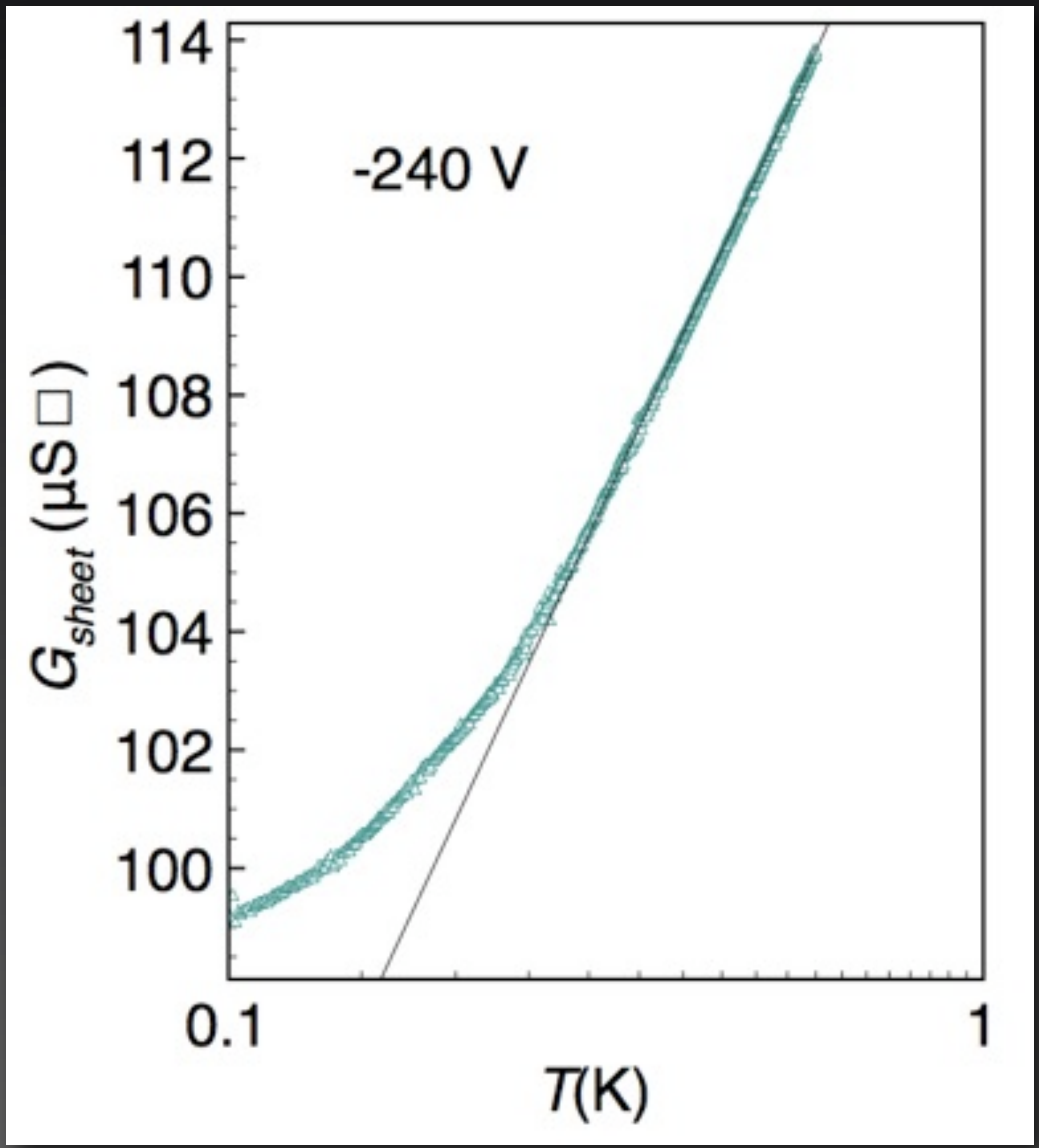
2D Weak localization





$$\frac{d\sigma}{d\ln H} = \frac{e^2}{\pi h} = 1.23\times10^{-5}\,S$$

$$\frac{d\sigma}{d\ln T} = \frac{e^2}{\pi h} = 1.23\times10^{-5}\,S$$

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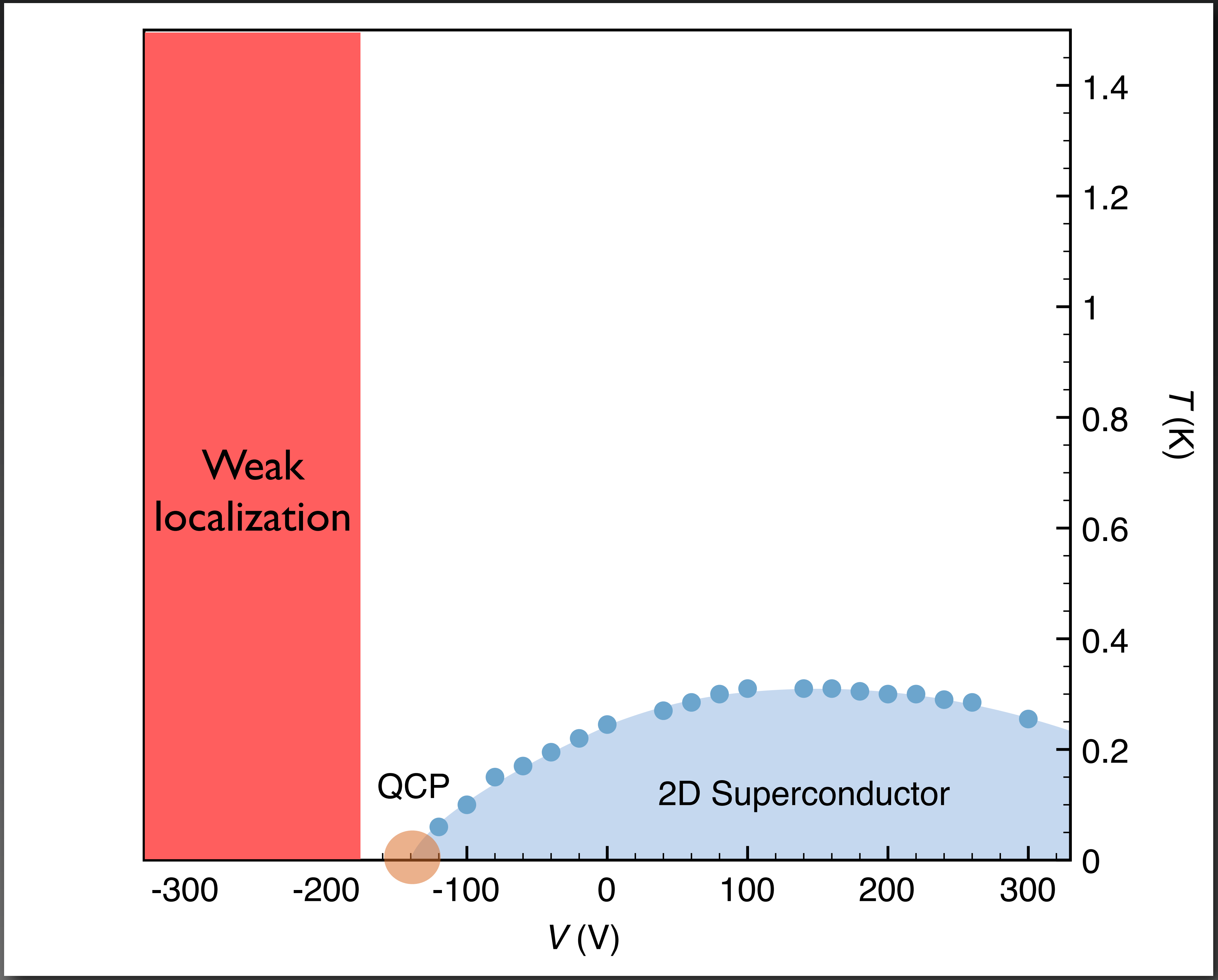
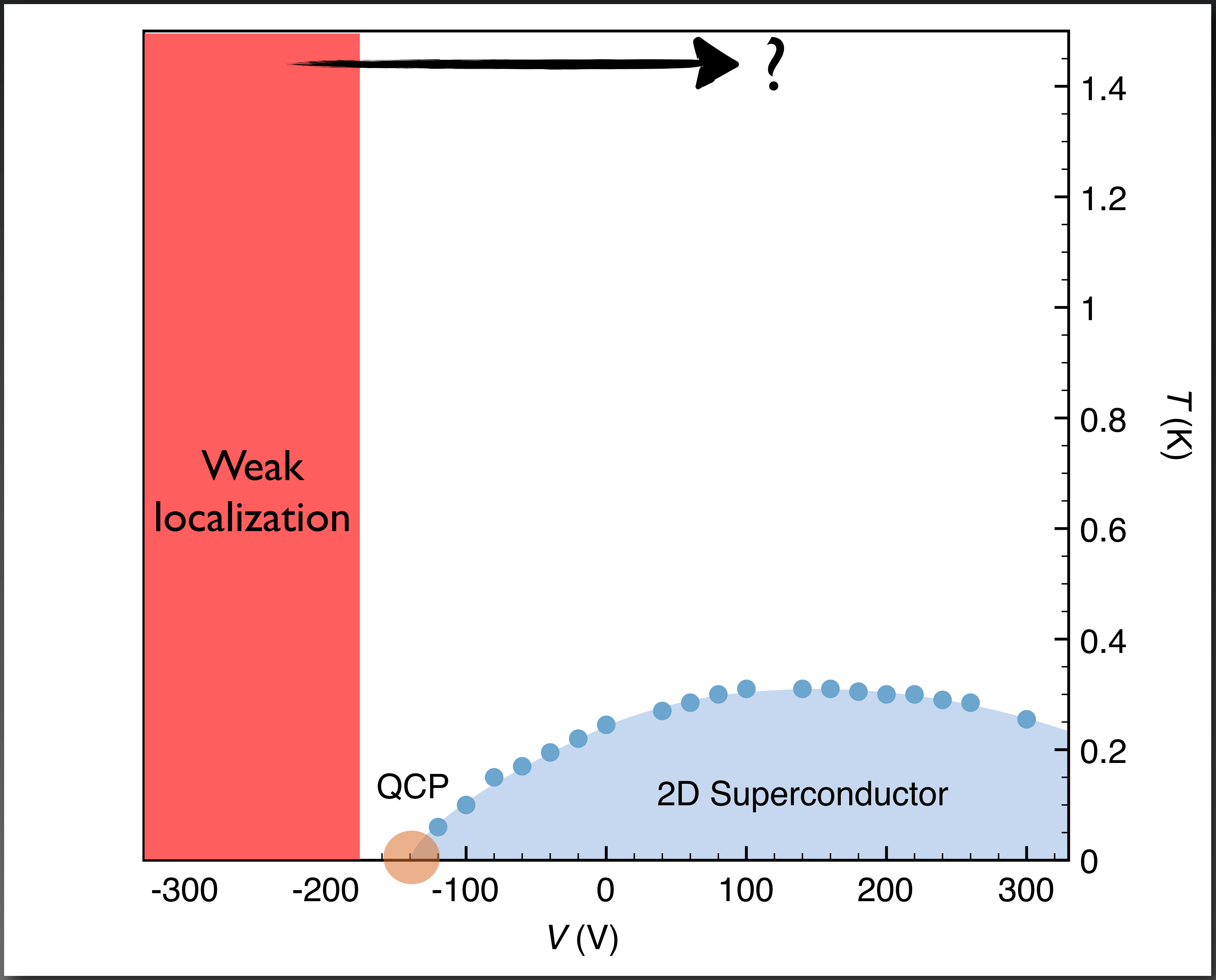
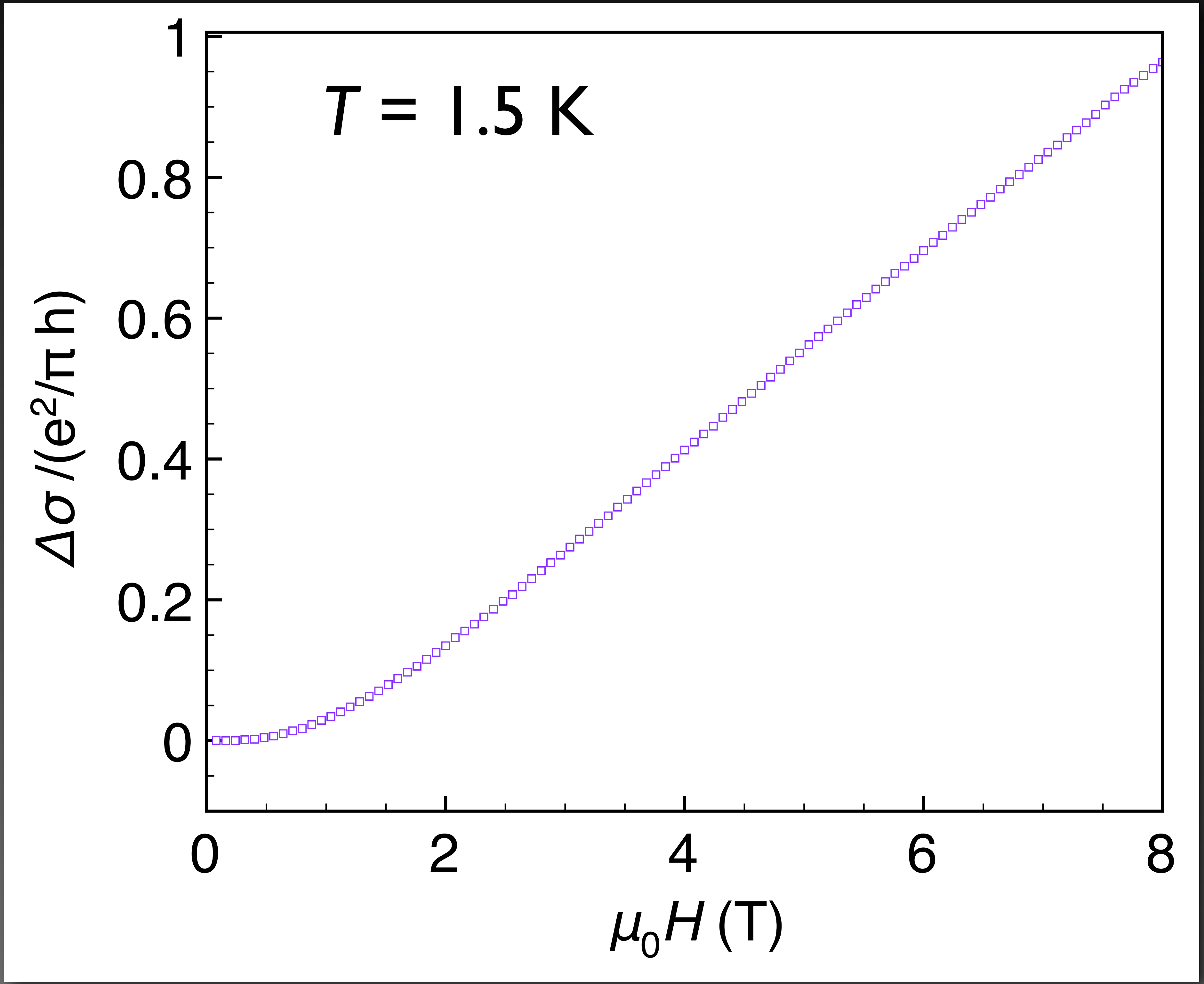
Phase diagram

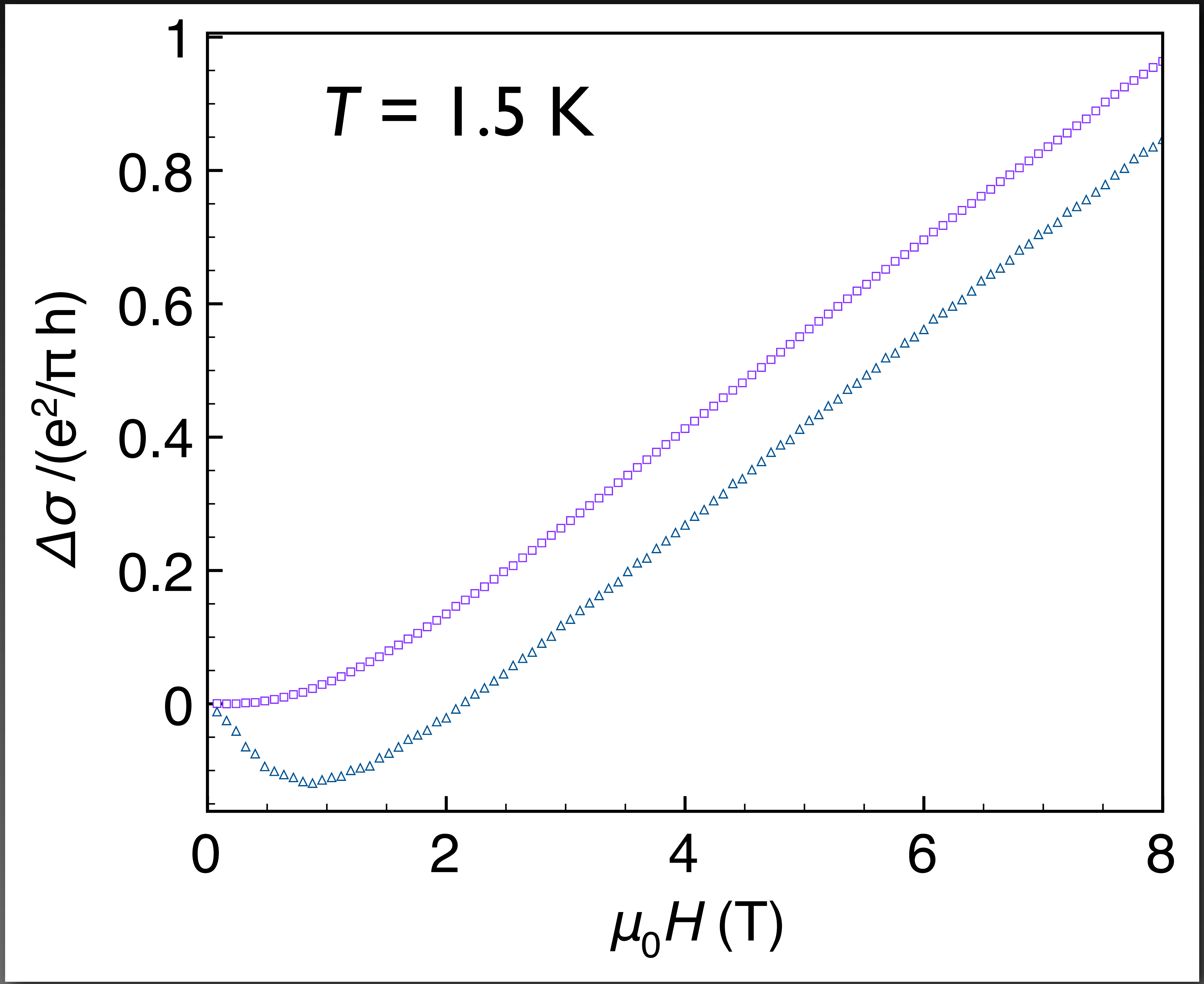


Phase diagram



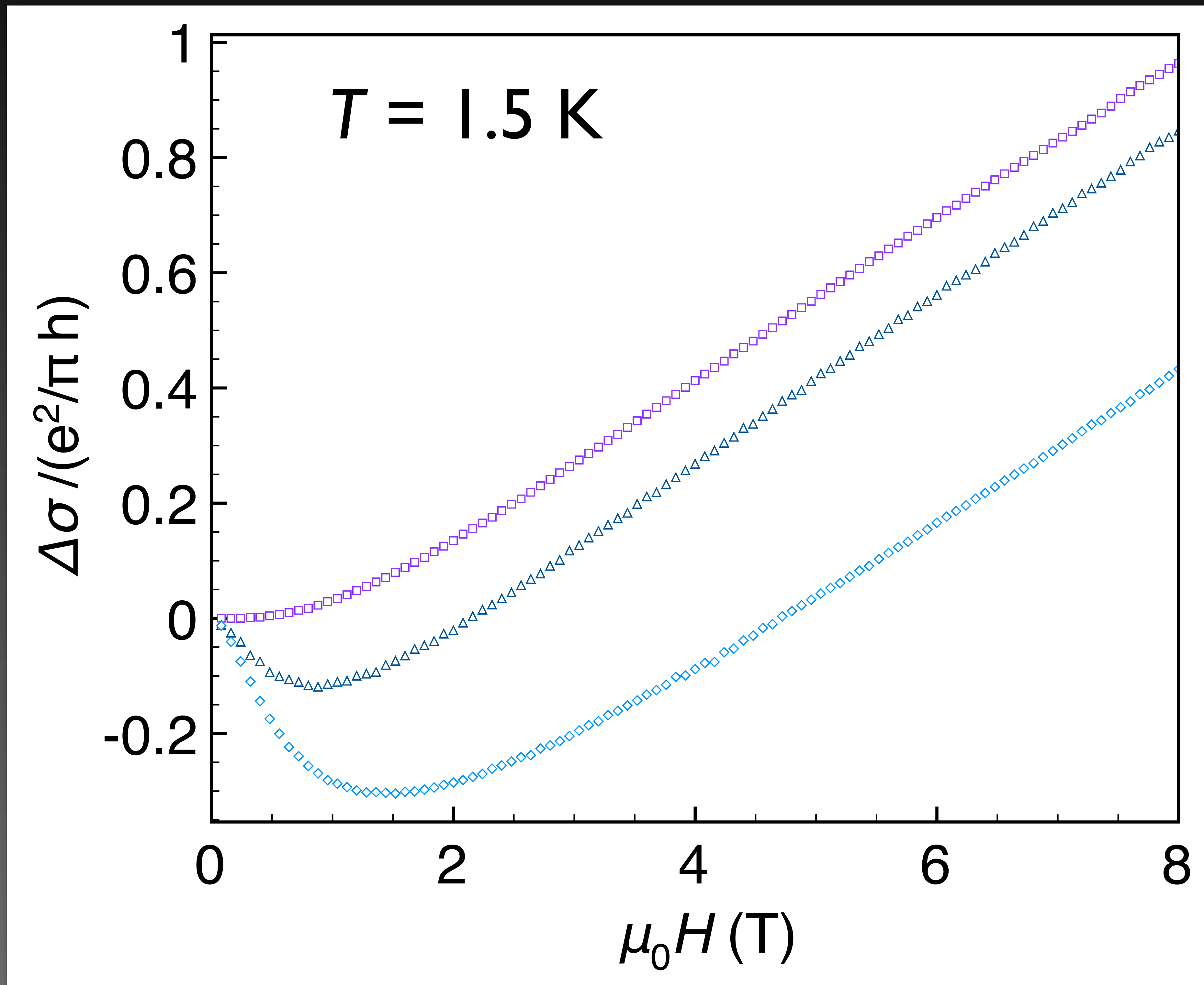


-300 V



-300 V

-100 V



-300 V

-100 V

-50 V

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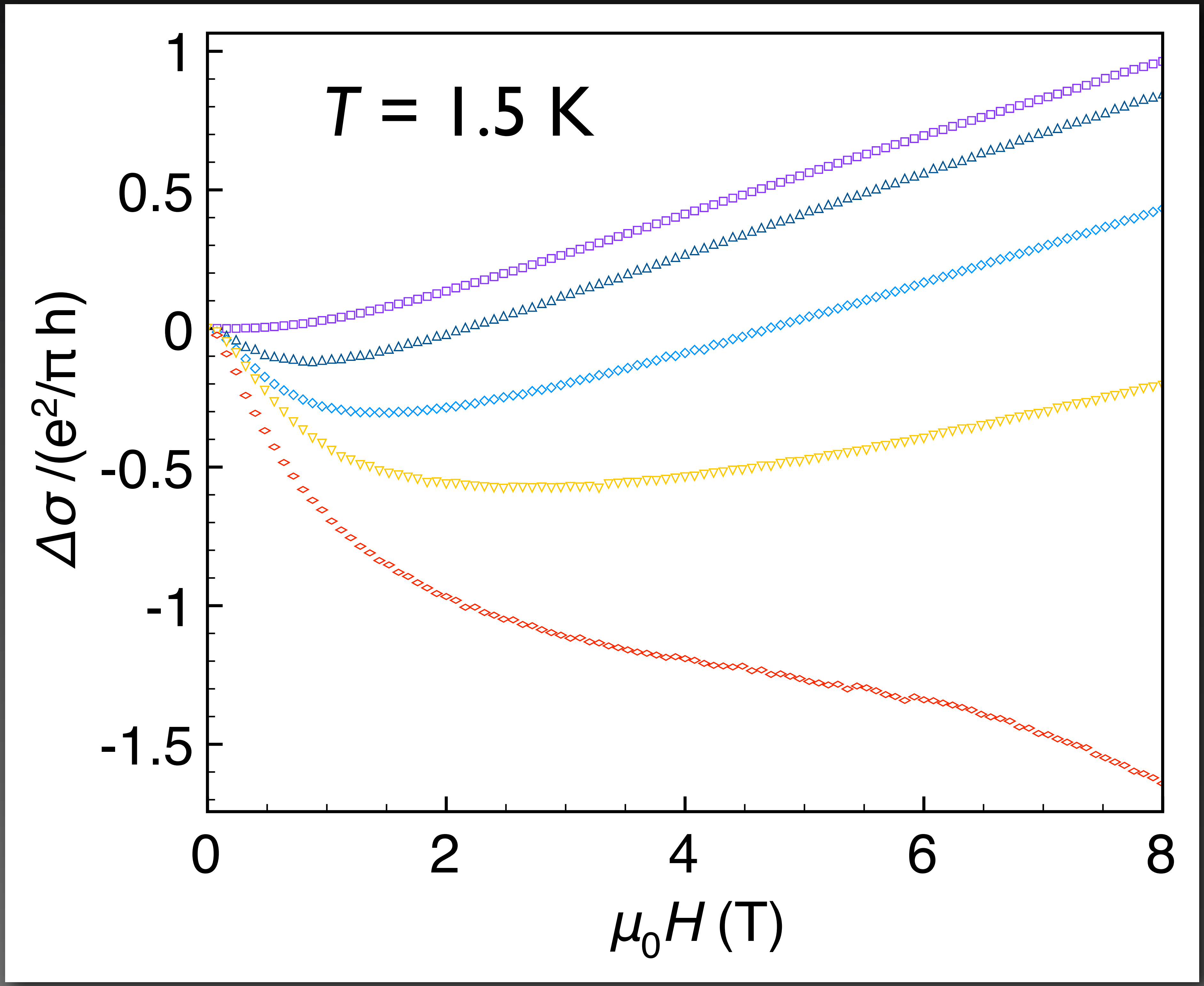


-300 V

-100 V

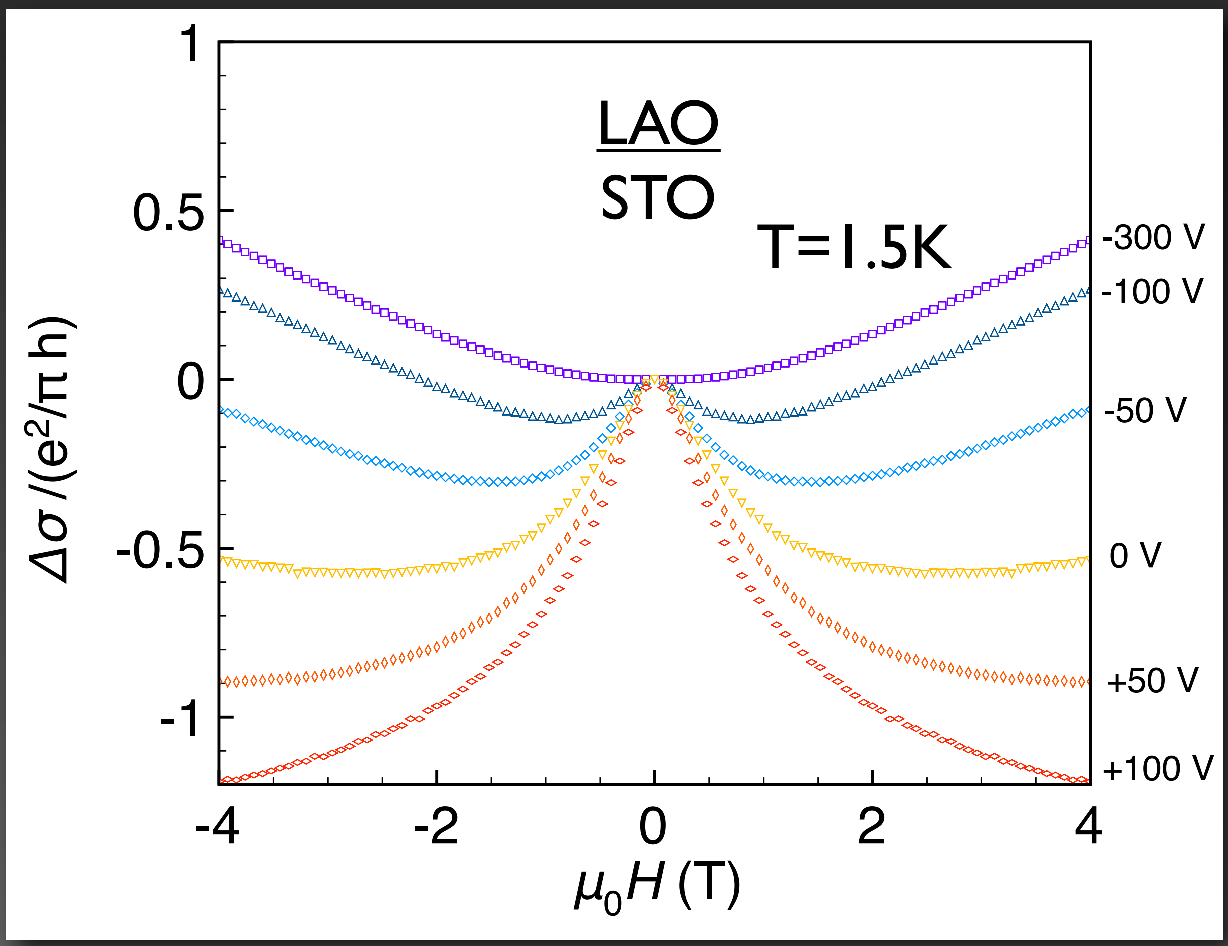
-50 V

0 V

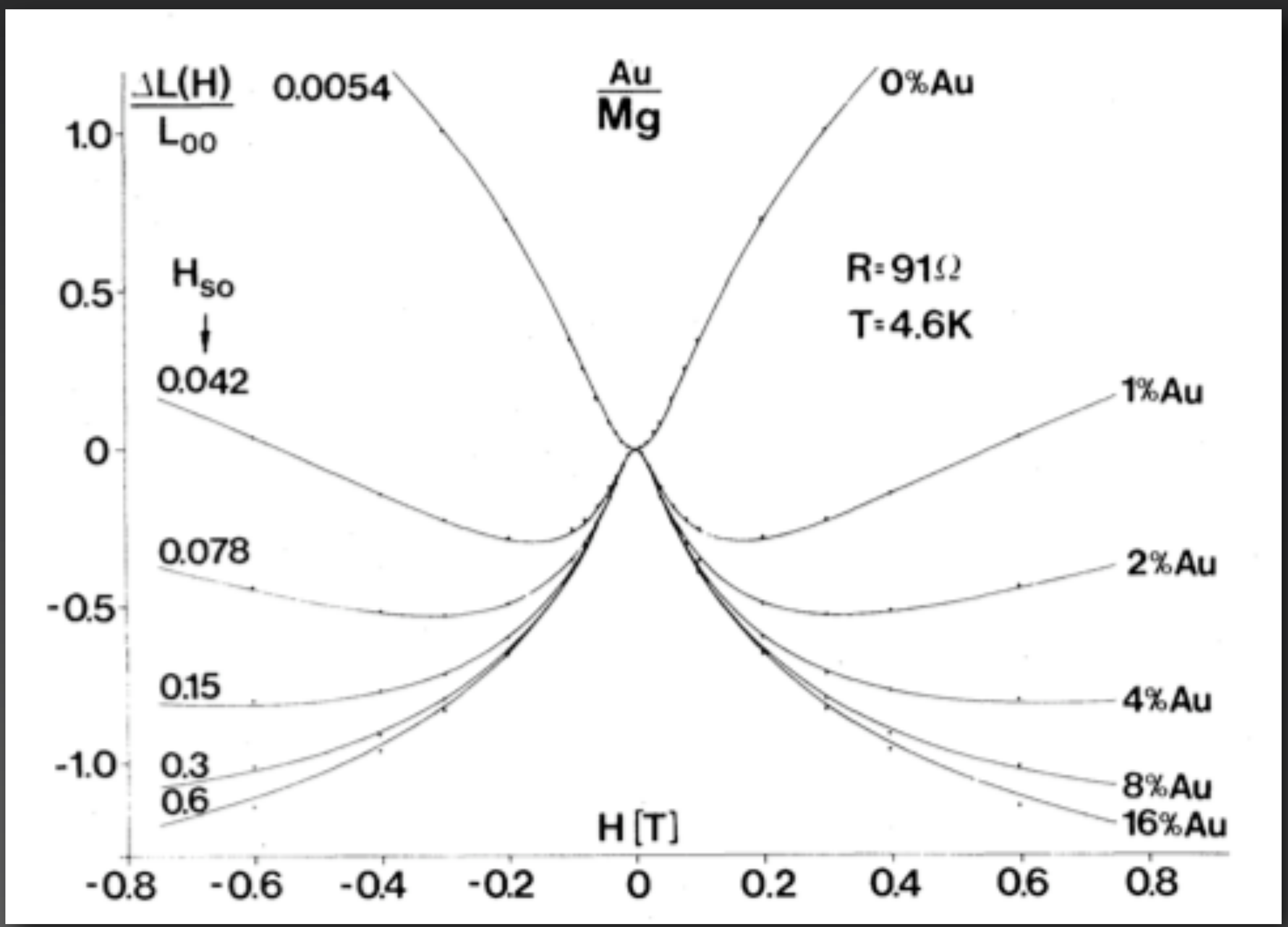
100 V

Weak antilocalization

Strong spin-orbit interaction



A.D. Caviglia et al., *PRL* **104**, 126803 (2010)



G. Bergman, *PRL* **48**, 1046 (1982)
in metallic thin films
J.B. Miller et al., *PRL* **90**, 076807 (2003)
in GaAs/AlGaAs 2DEG

$$\frac{\Delta\sigma(H)}{\sigma_0} = \Psi\left(\frac{H}{H_\mathrm{i}+H_\mathrm{so}}\right) + \frac{1}{2\sqrt{1-\gamma^2}}\Psi\left(\frac{H}{H_\mathrm{i}+H_\mathrm{so}\left(1+\sqrt{1-\gamma^2}\right)}\right)$$

$$-\frac{1}{2\sqrt{1-\gamma^2}}\Psi\left(\frac{H}{H_\mathrm{i}+H_\mathrm{so}\left(1-\sqrt{1-\gamma^2}\right)}\right)$$

Digamma function

$$\Psi(x) = \ln(x) + \psi\left(\frac{1}{2}+\frac{1}{x}\right)$$

$$\sigma_0 = e^2/\pi h = 1.2\cdot 10^{-5}\ \mathrm{S}$$

Sadamichi Maekawa and Hidetoshi Fukuyama, *Journal of the Physical Society of Japan* **50**, 2516 (1981)

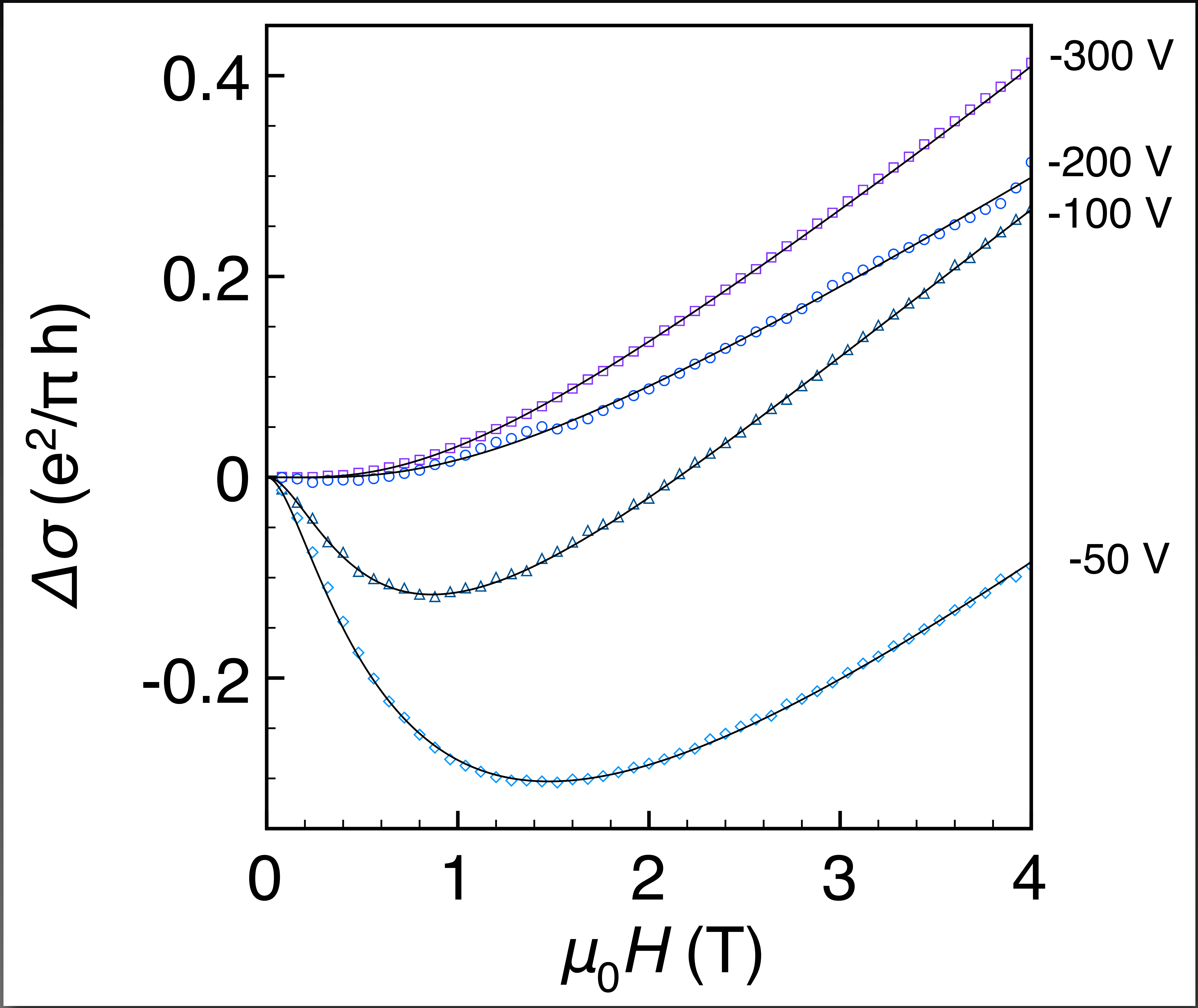
fitting parameters

$$H_\mathrm{i} = \hbar/4eD\tau_\mathrm{i}$$

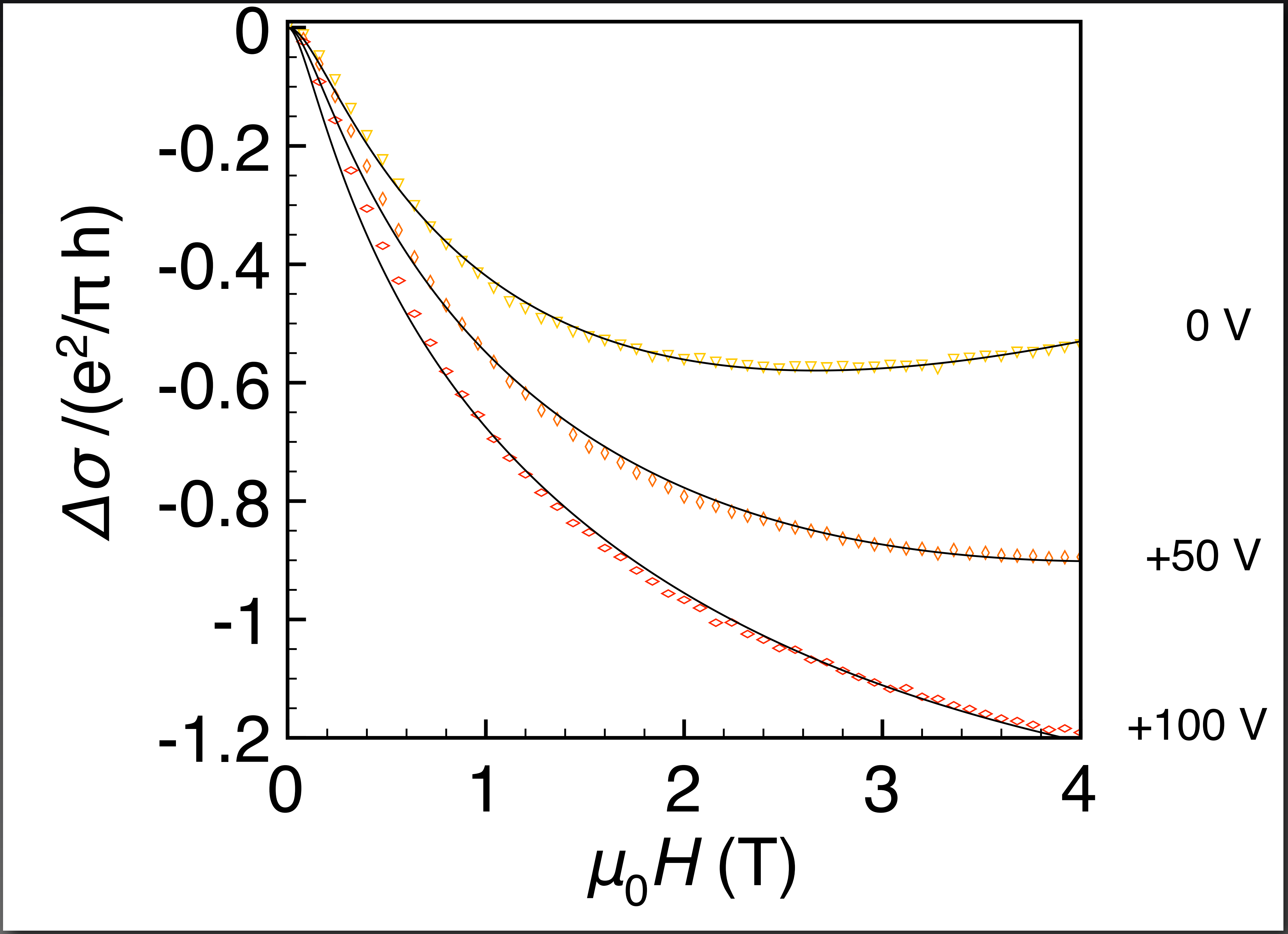
$$H_\mathrm{so} = \hbar/4eD\tau_\mathrm{so} \propto m^2$$

$$\gamma = g\mu_B H/4eDH_\mathrm{so}$$

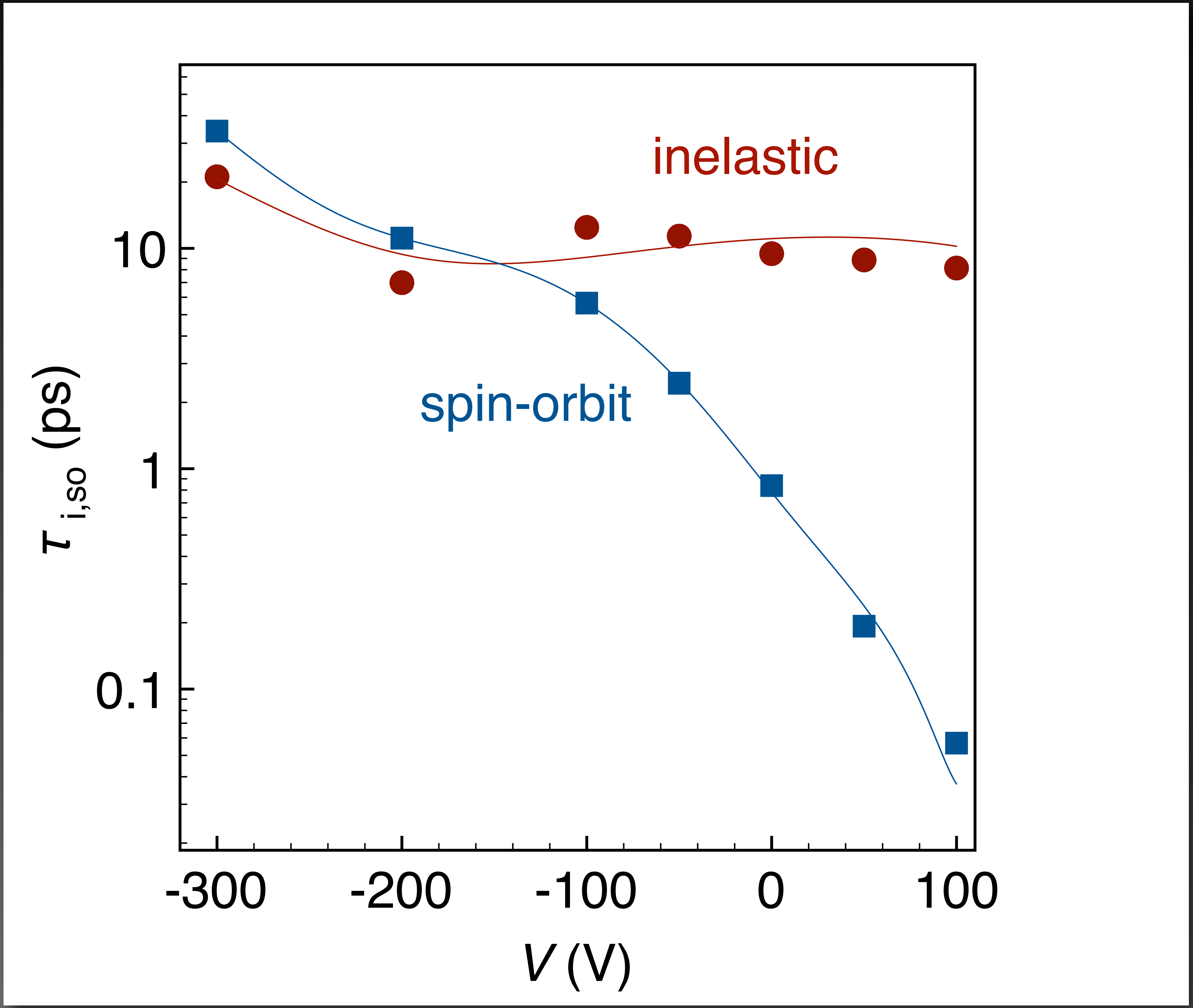
Nota bene: there is no scale parameter.
It's a variation of conductance on a universal scale



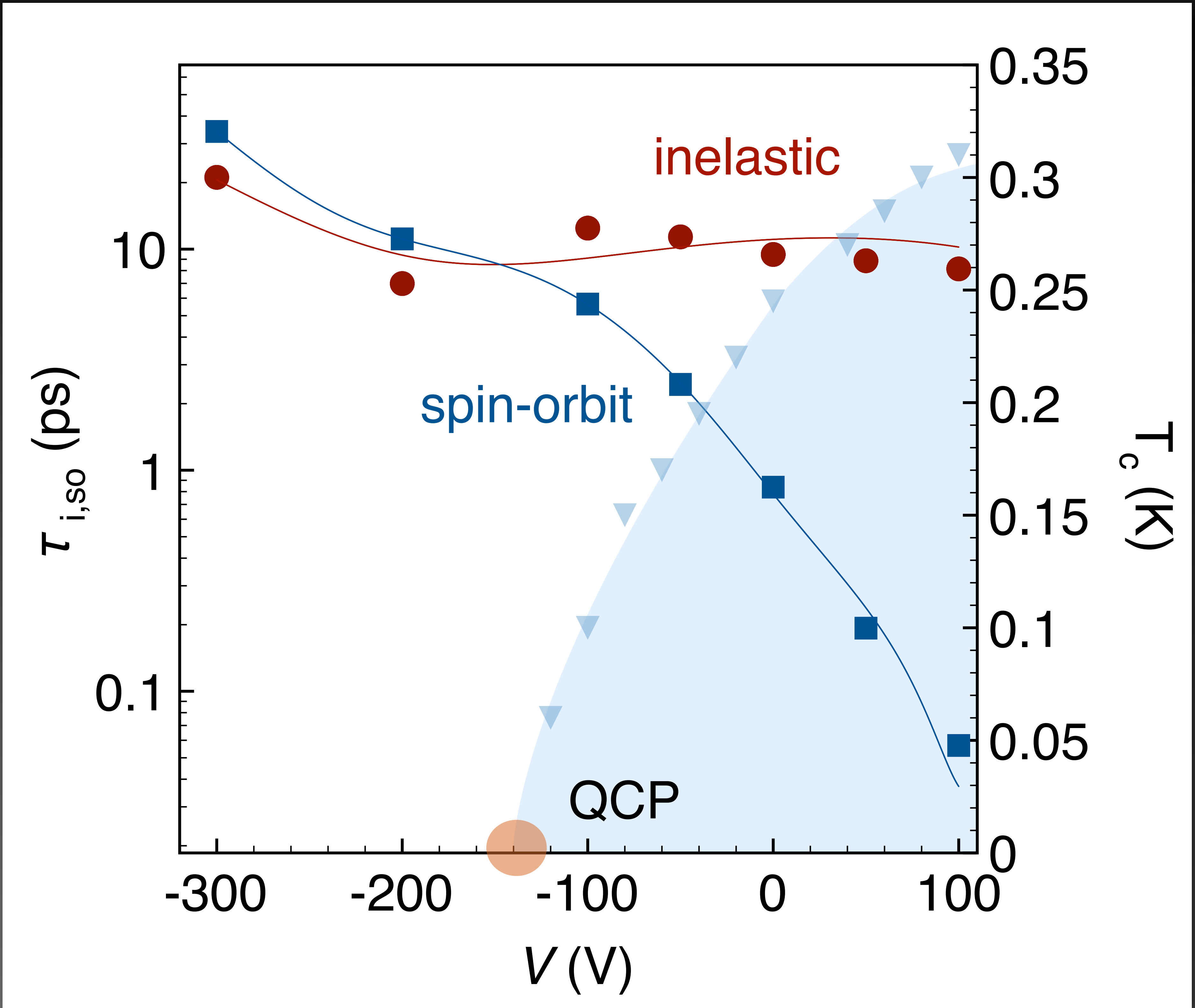
-300 V
-200 V
-100 V
-50 V
0.4
0.2
0
-0.2
0
1
2
3
4
Δσ (e²/π h)
μ₀H (T)



0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
0
1
2
3
4
$\Delta\sigma/(e^2/\pi h)$
$\mu_0 H$ (T)
0 V
+50 V
+100 V



inelastic
spin-orbit
10
1
0.1
$\tau_{i,so}$ (ps)
-300
-200
-100
0
100
V (V)



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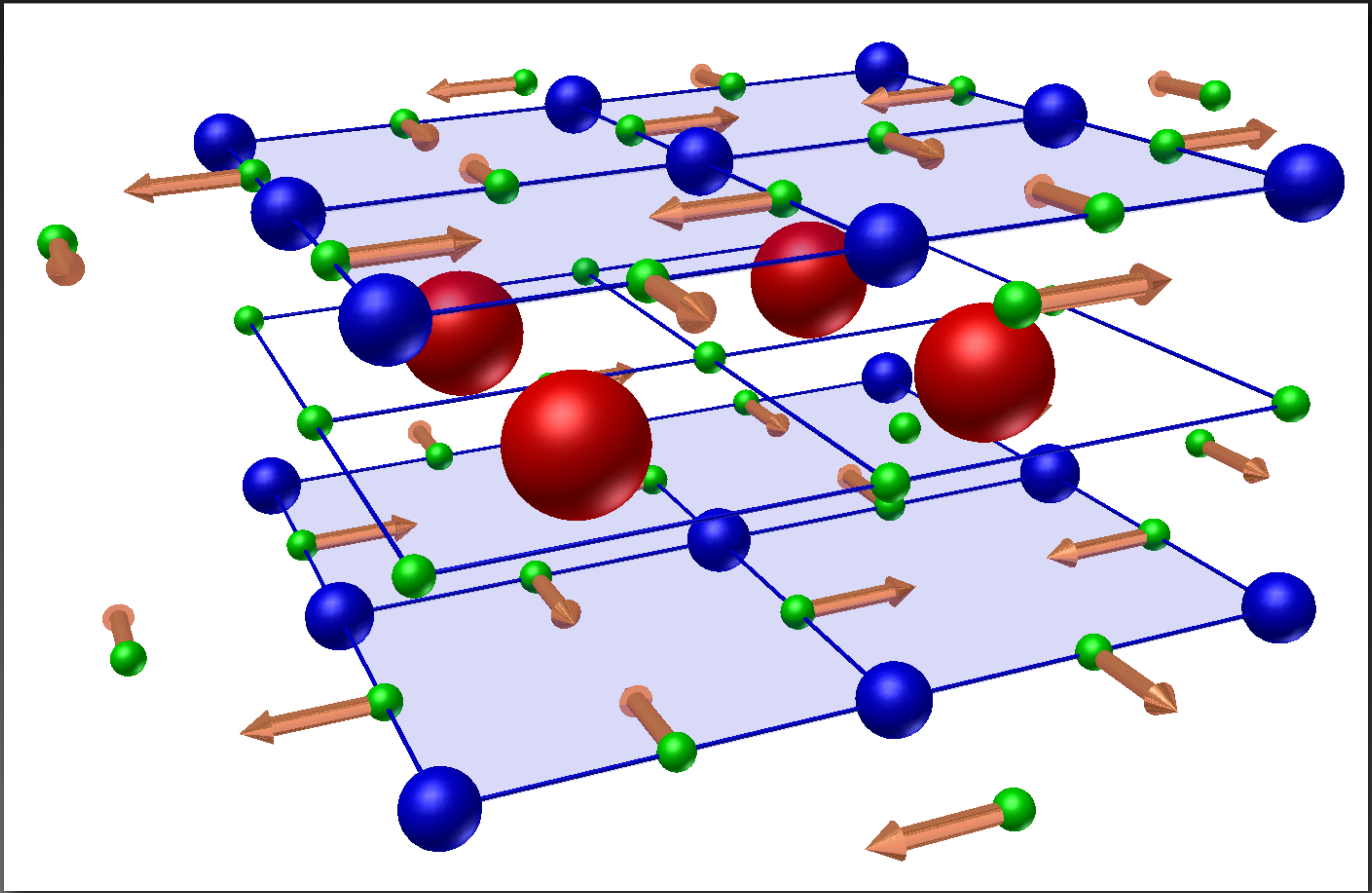
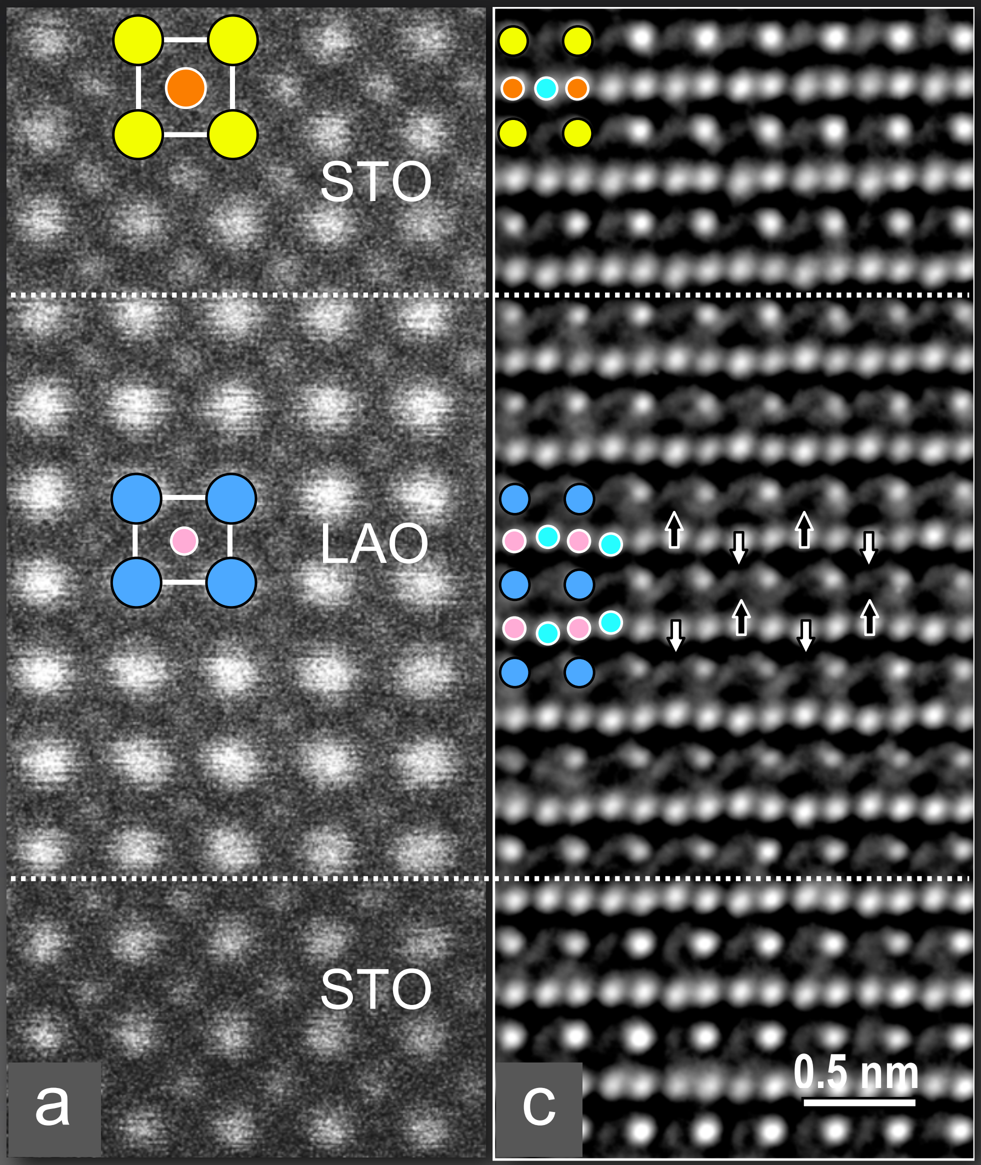
AFD mode

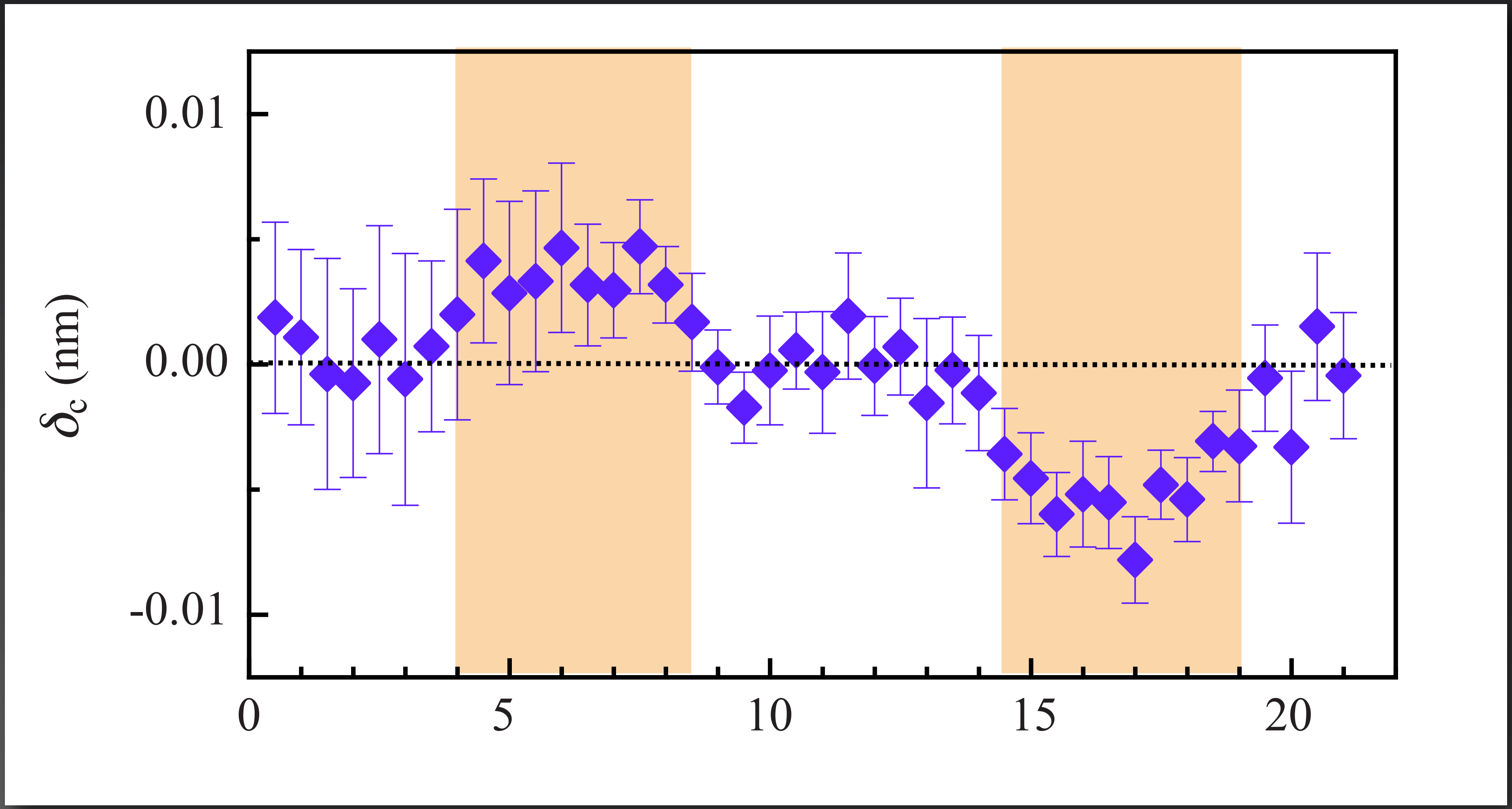




Structural distortion of LAO propagates in several layers of STO at the interface

C.L. Jia *et al.*, *PRB* **79**, 081405(R) (2009)

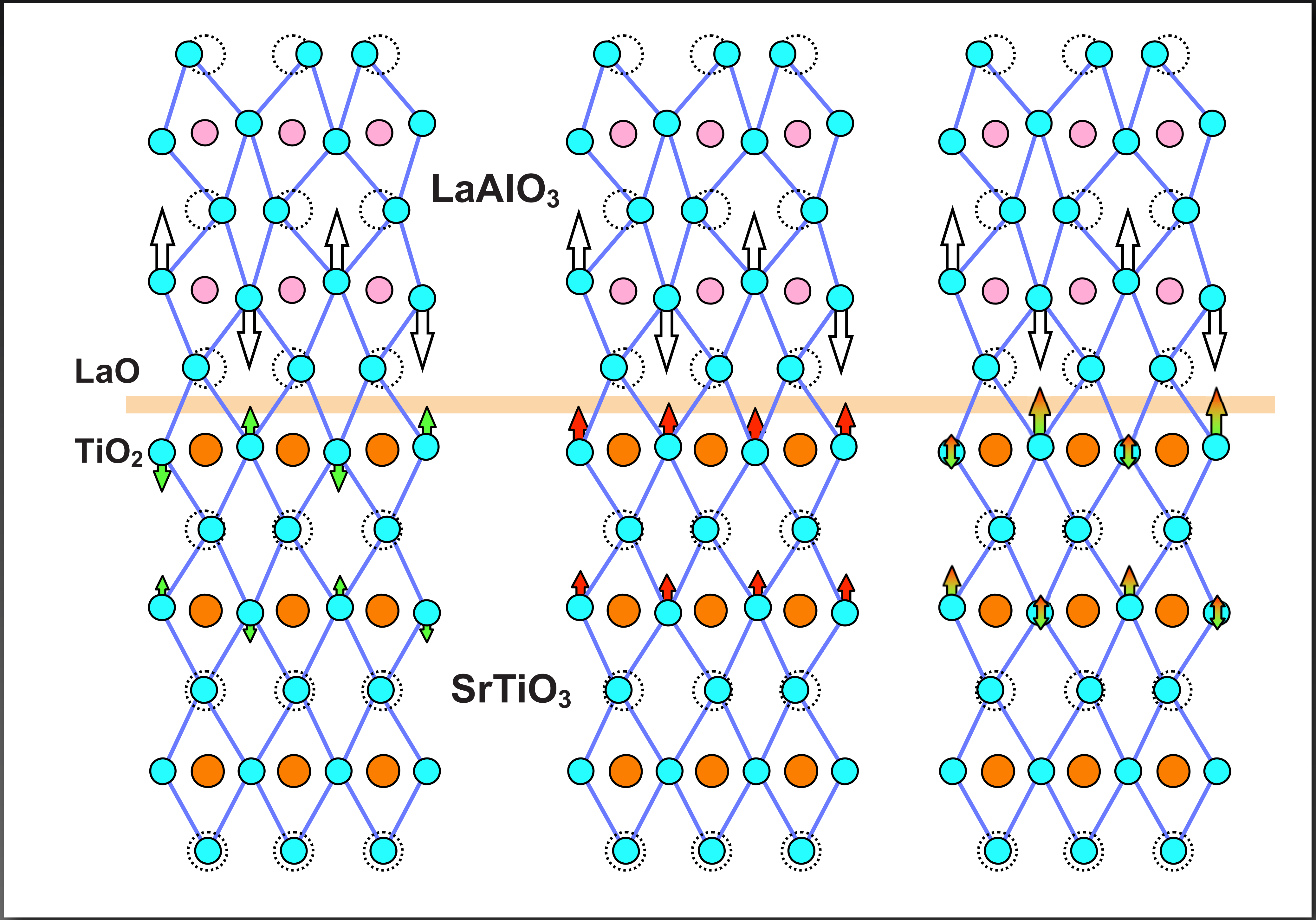
STO LAO STO



Shift of the center of the oxygen octahedron with respect to the appertaining cations

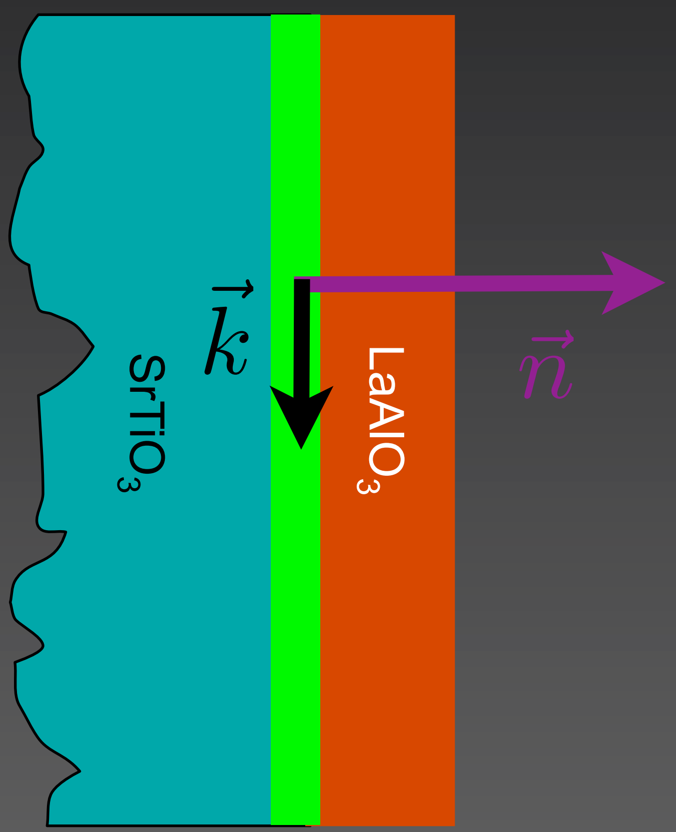
C.L. Jia *et al.*, *PRB* **79**, 081405(R) (2009)

Polarisation



Combination of AFD and FE distortions

Rashba spin-orbit coupling

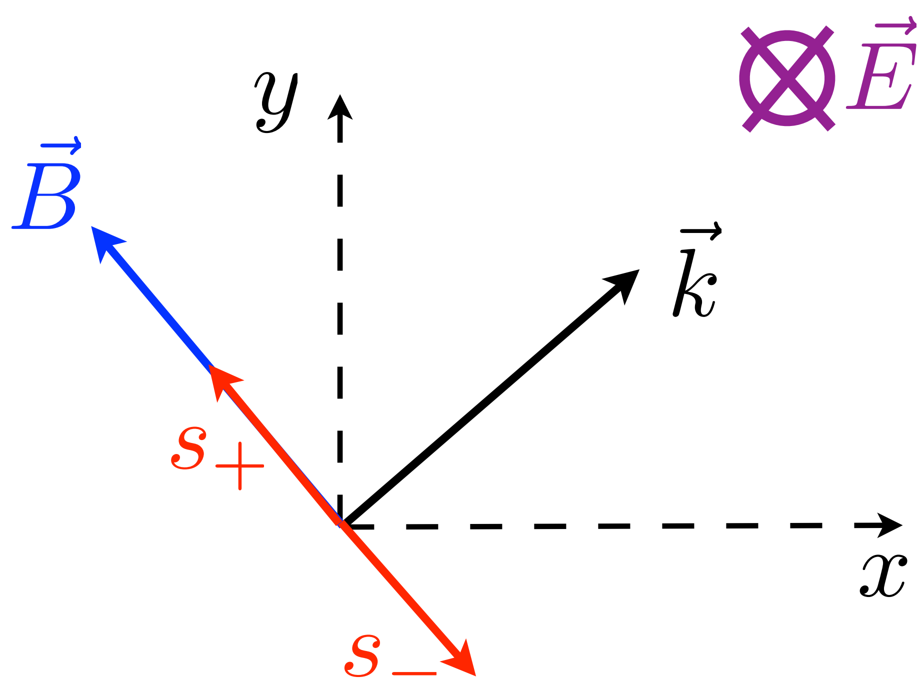


asymmetric confining potential

The electrons experience an internal magnetic field always oriented on the plane of the conduction

Rashba spin-orbit coupling

$$H_R = \alpha(\vec{k} \wedge \vec{n}) \cdot \vec{\sigma}$$

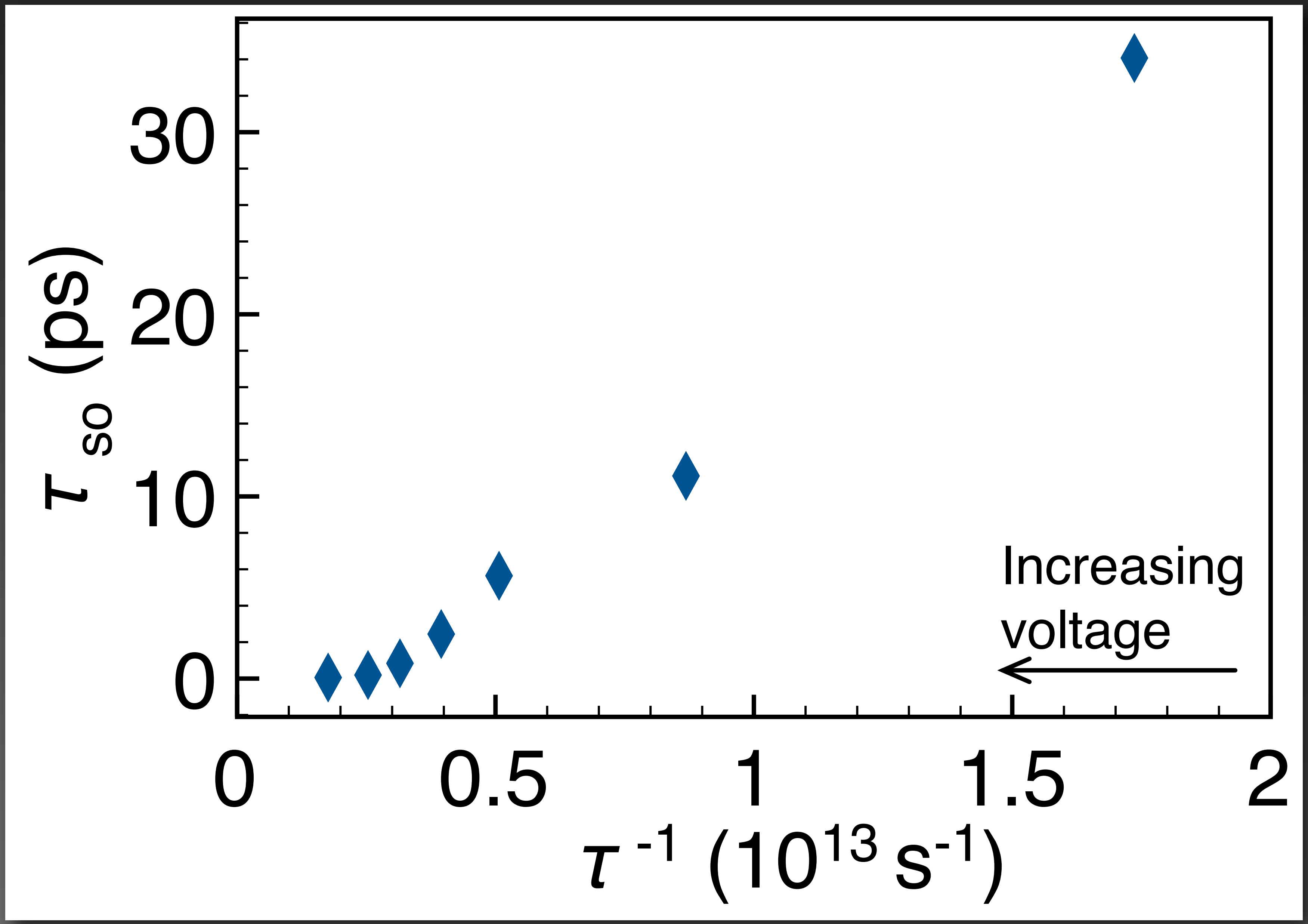


$$\tau_{\text{so}} = \hbar^4 / 4\alpha^2 m^2 2D$$

The electrons experience an internal magnetic field always oriented on the plane of the conduction

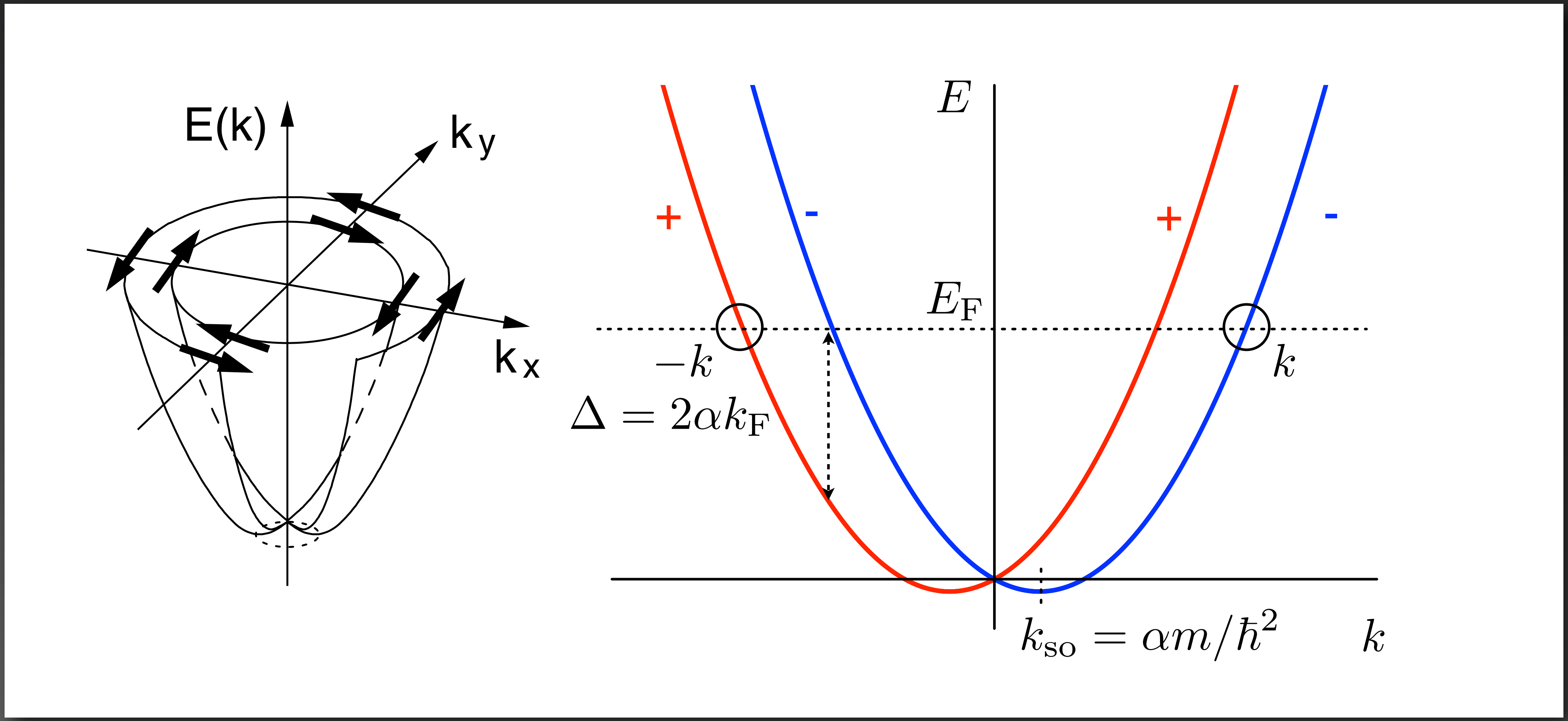
Rashba spin-orbit coupling

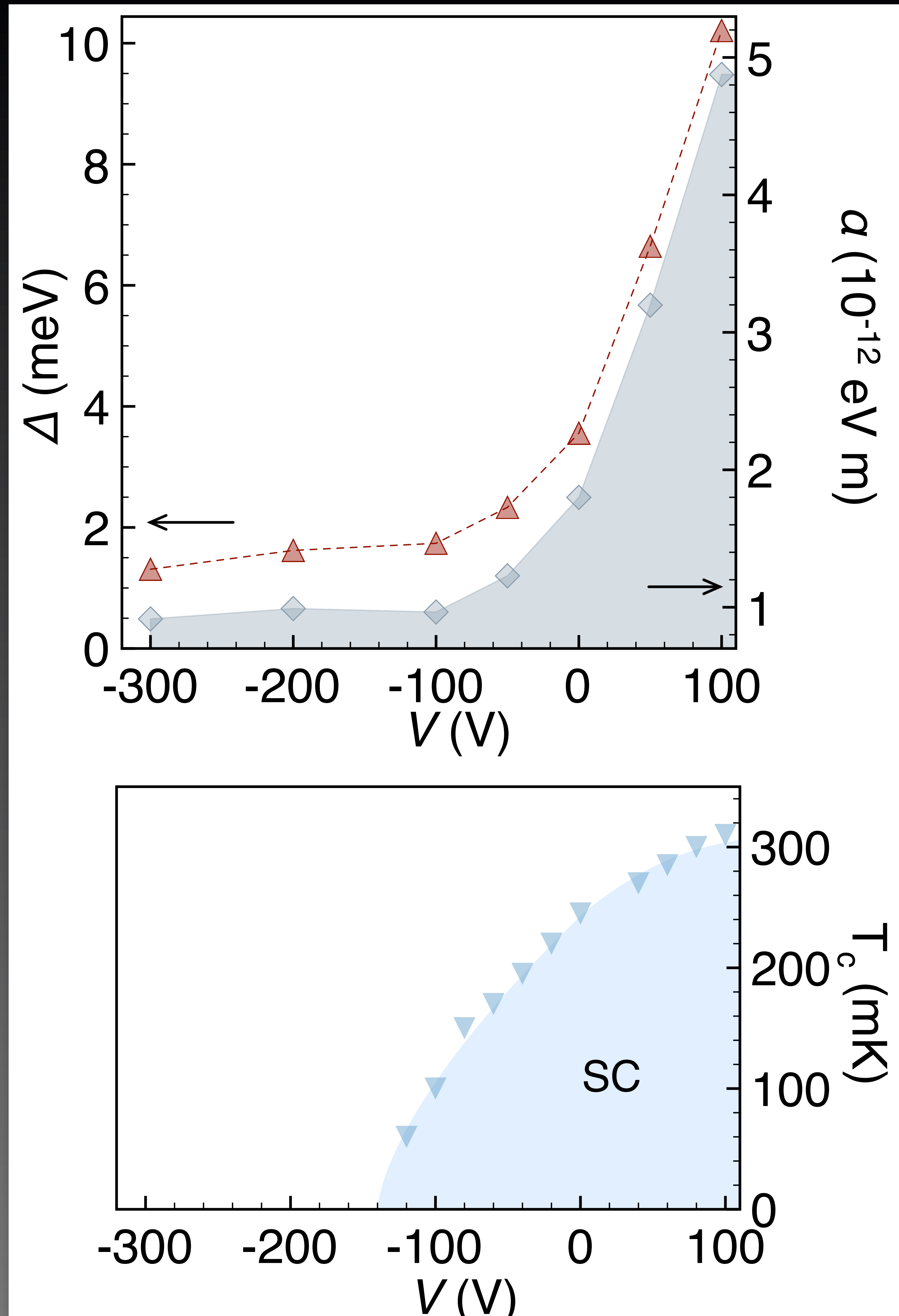
D'yakonov - Perel'



$$\tau_{\mathrm{so}} \propto \tau^{-1}$$

Spin-splitting





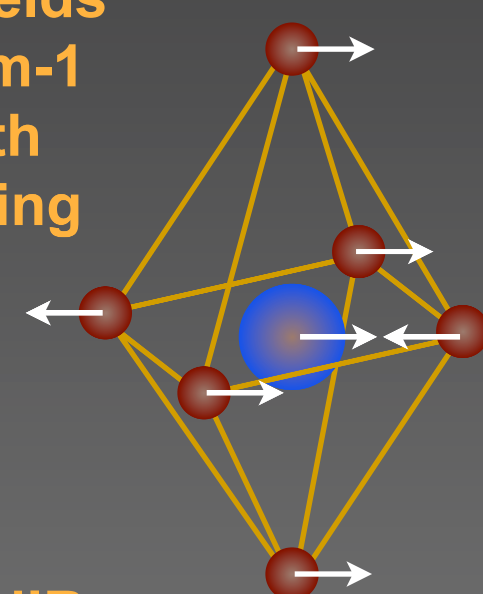
$$\Delta = 2\, k_F \alpha$$

Limitations of the field effect approach

Need for a good gate dielectric
Limited to dc breakdown fields
Slow process

Ultrafast lattice excitation using light pulses

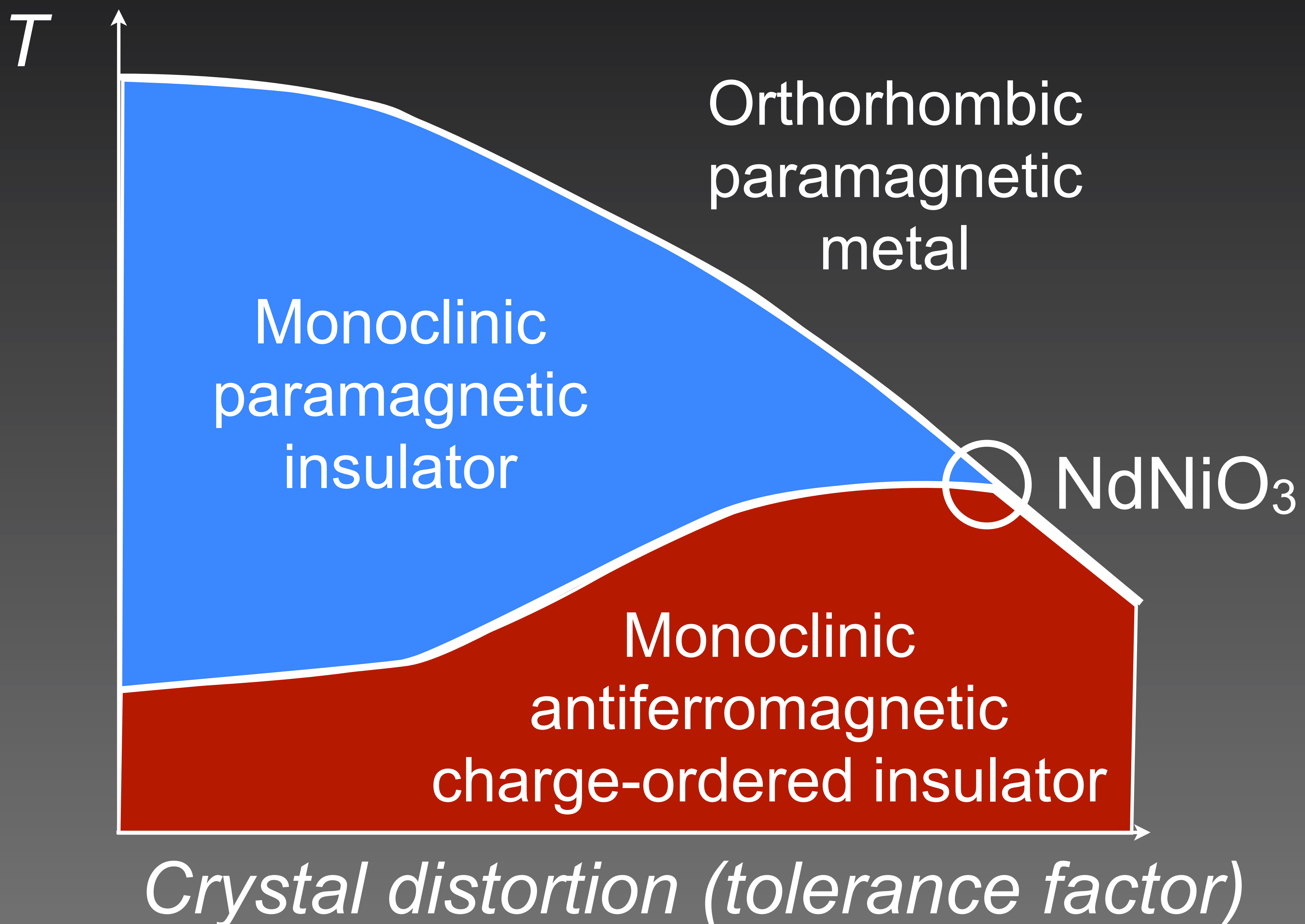
100 fs pulsed 10 MV/cm fields
16 um wavelength, 600 cm-1
modulation of bandwidth
non-linear phonon coupling

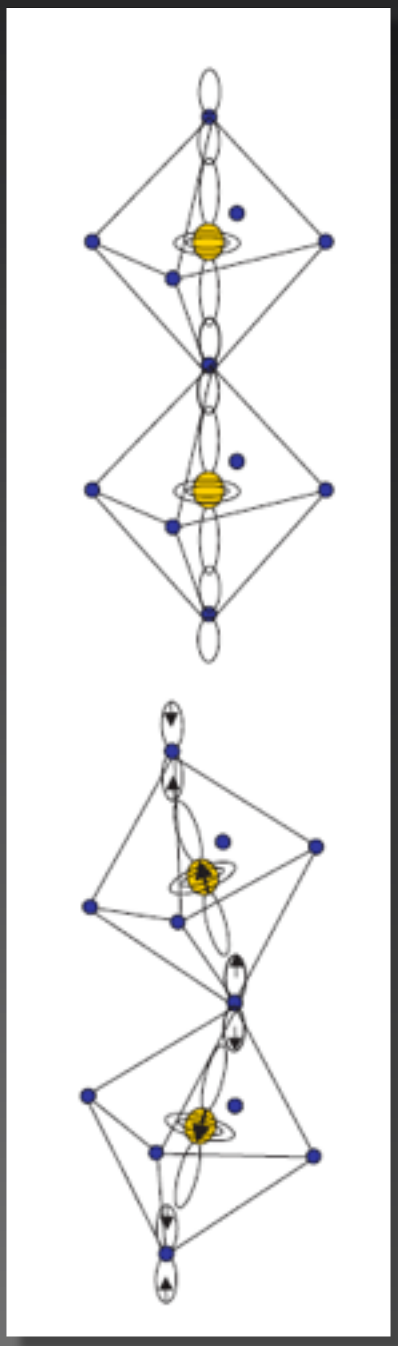


electronic properties
investigated by
pump and probe THz and NIR
spectroscopy

Nickelates phase diagram

A story of coupling between electrons and lattice





M.L. Medarde, *J Phys Cond Matt* **9**, 1679 (1997)
G. Catalan, *Phase transitions* **81**, 729 (2008)

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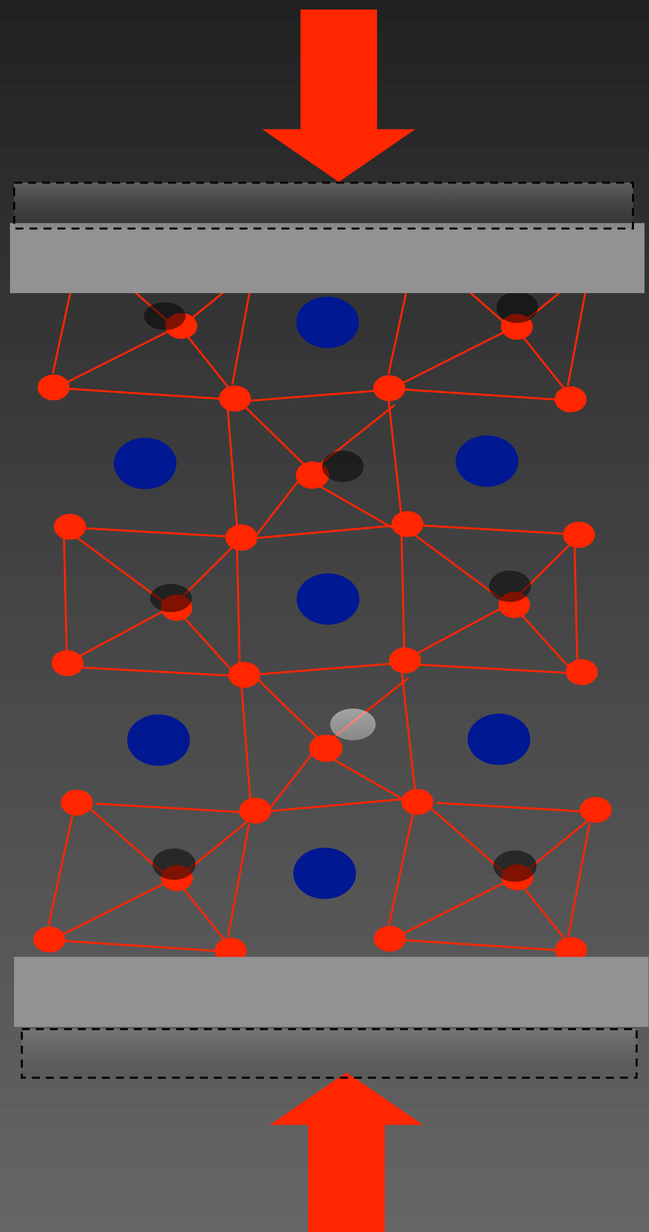
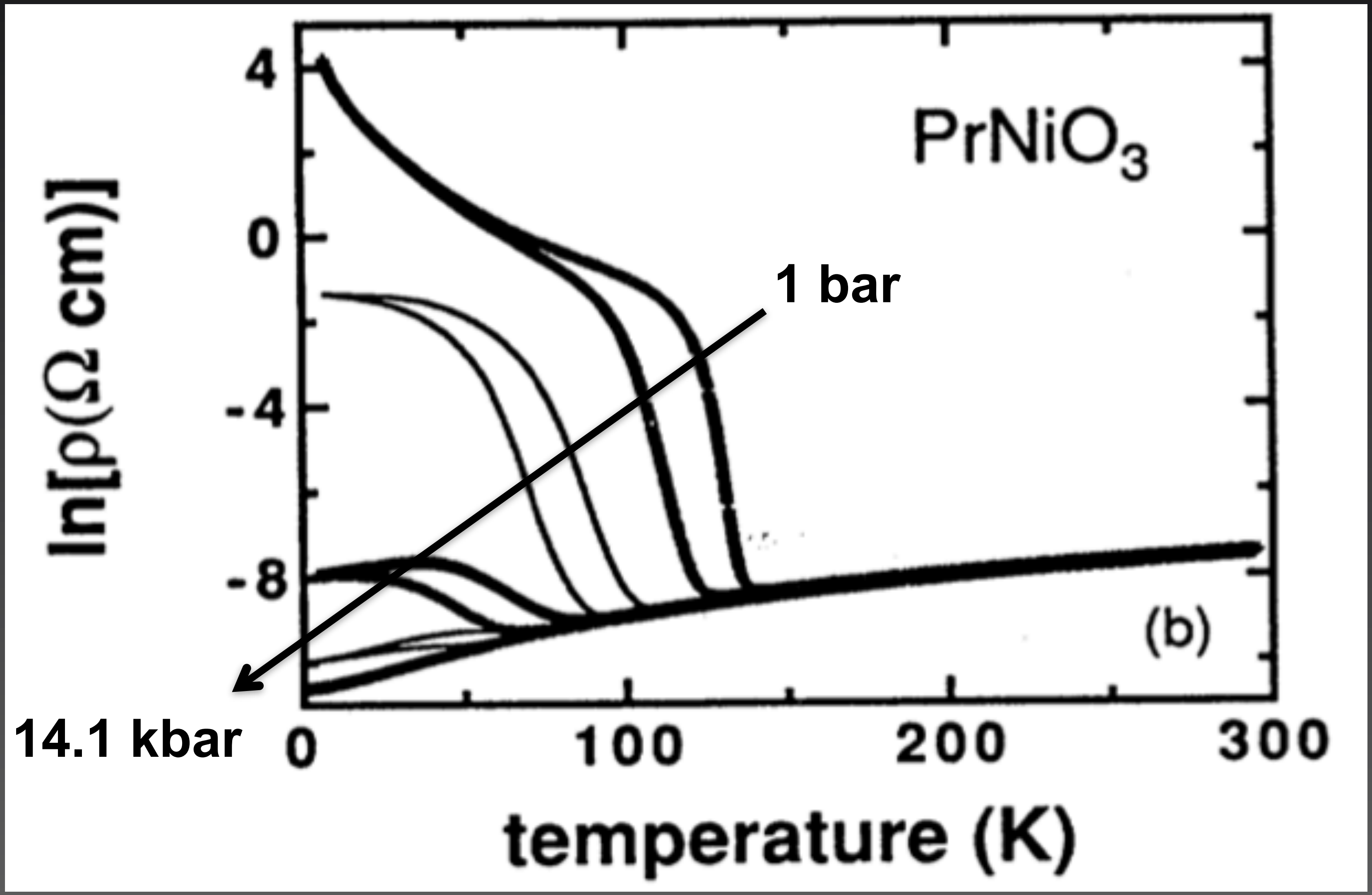
Static lattice control

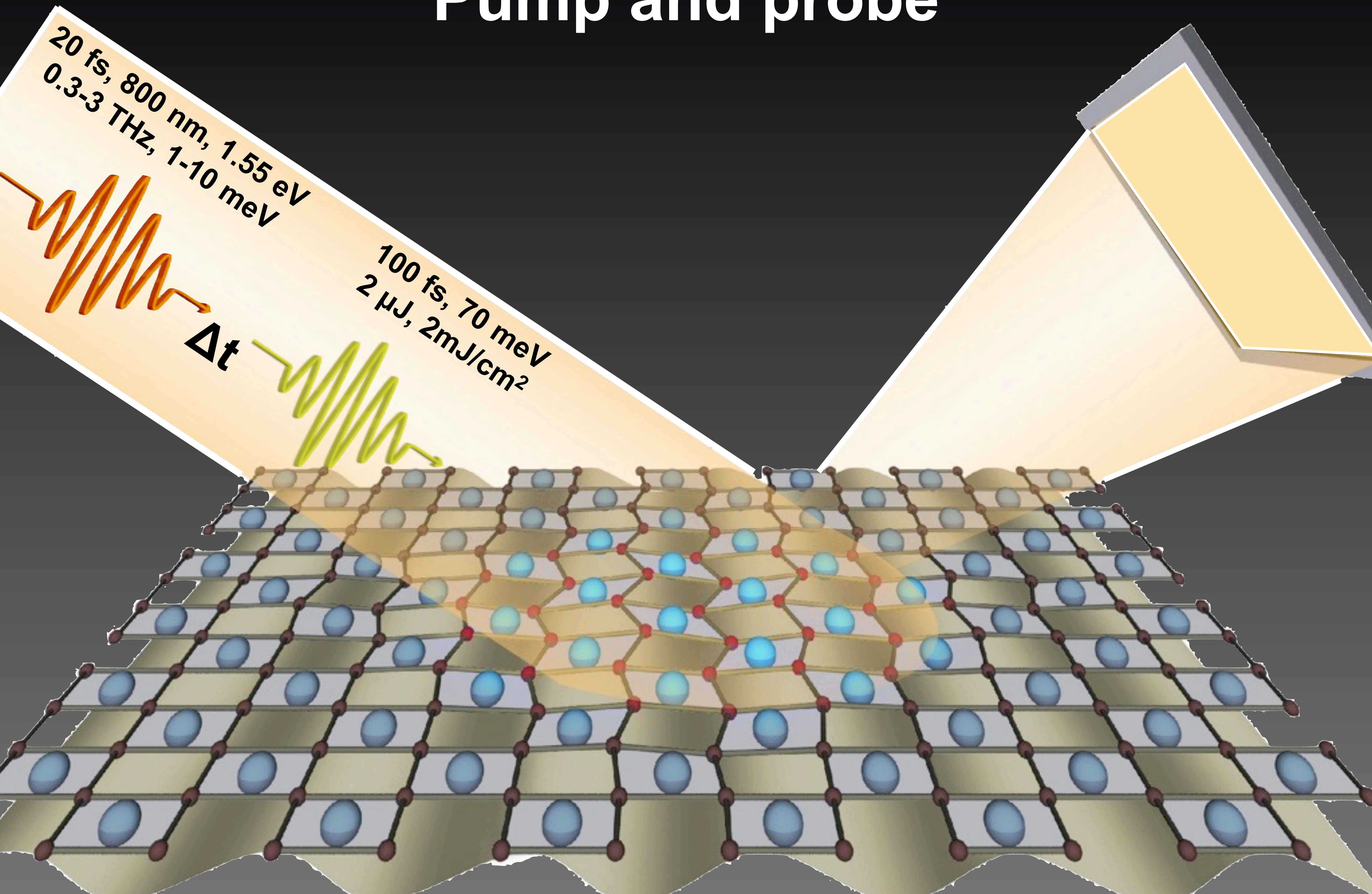




P.C. Canfield et al. *PRB* **47**, 12357 (1993)

Can we drive this phase transition on the ultrafast time scale by exciting the lattice with light?

Pump and probe



Rini et al., *Nature* **449**, 72 (2007)

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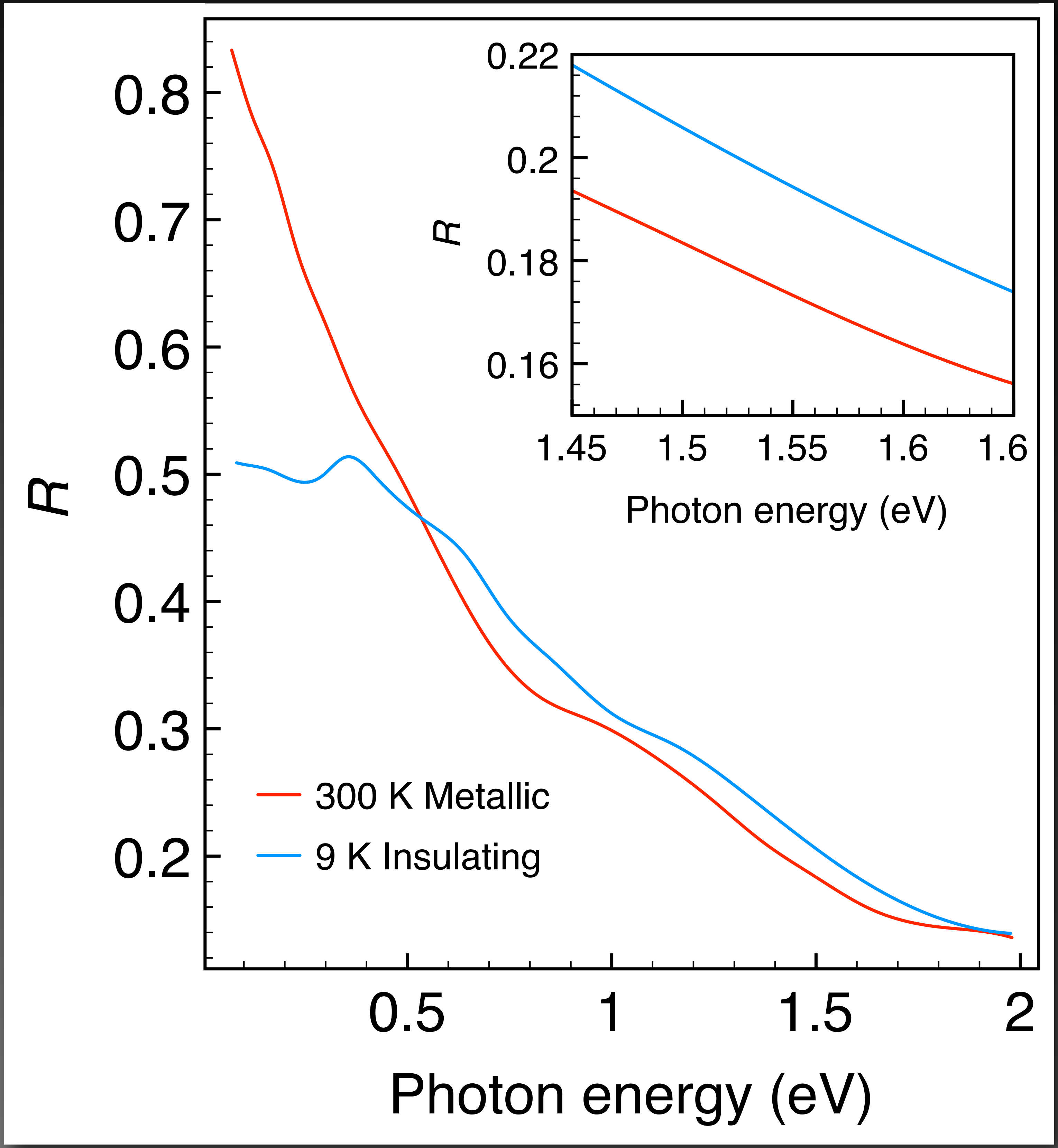
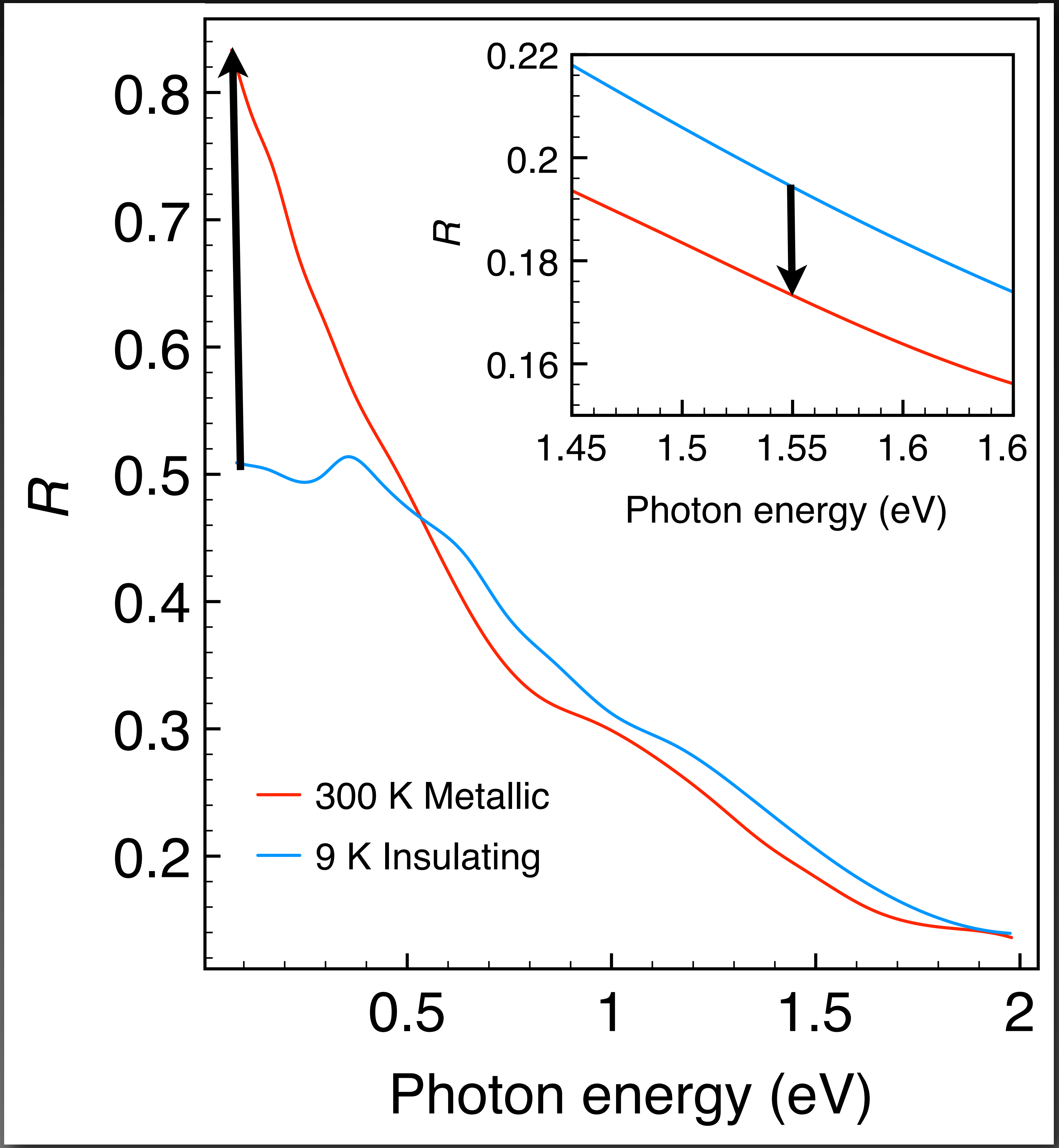
Static reflectivity



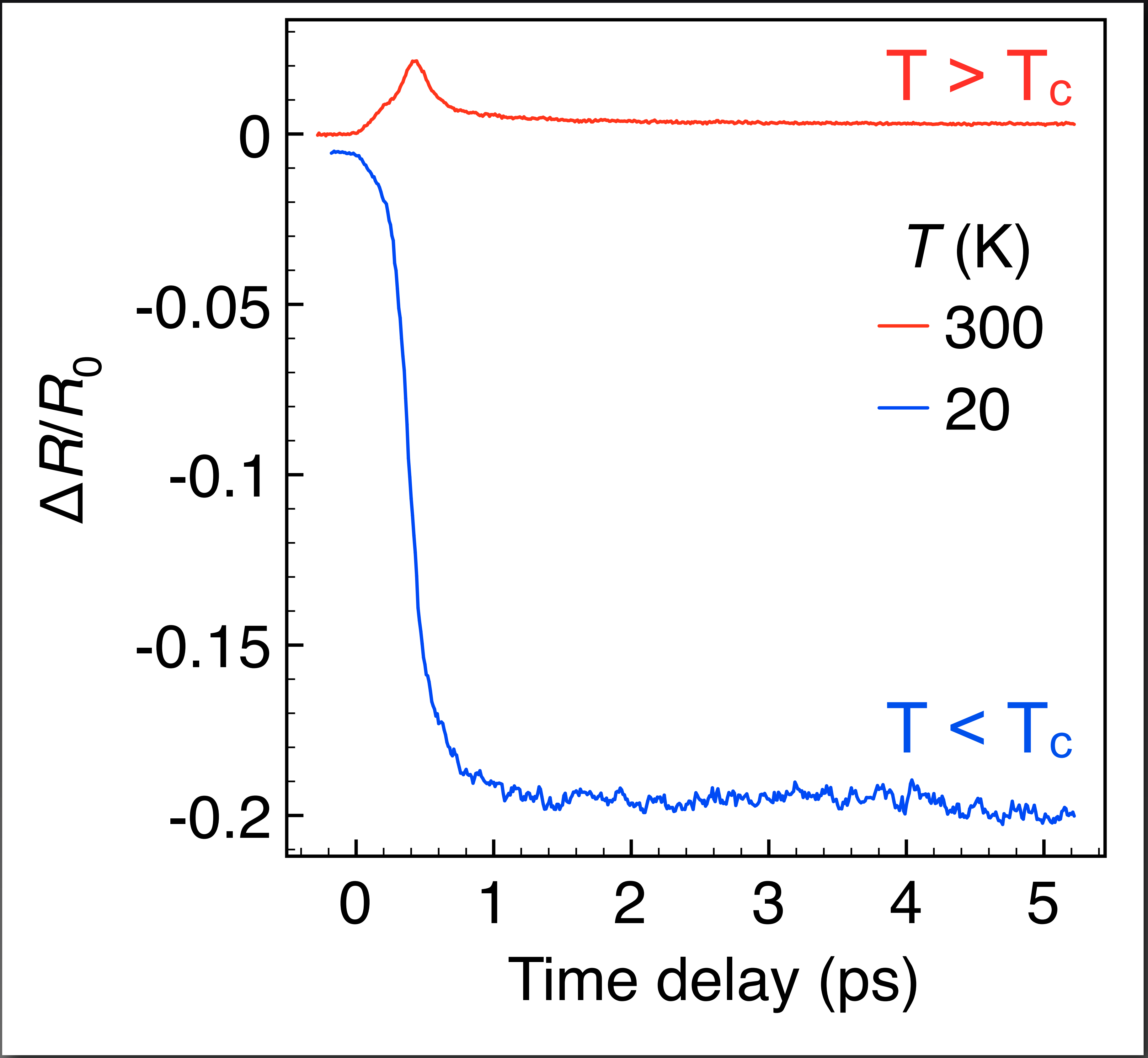
Katsufuji et al. *PRB* **51**, 4830 (1995)

Static reflectivity



Katsufuji et al. *PRB* **51**, 4830 (1995)

NIR probe



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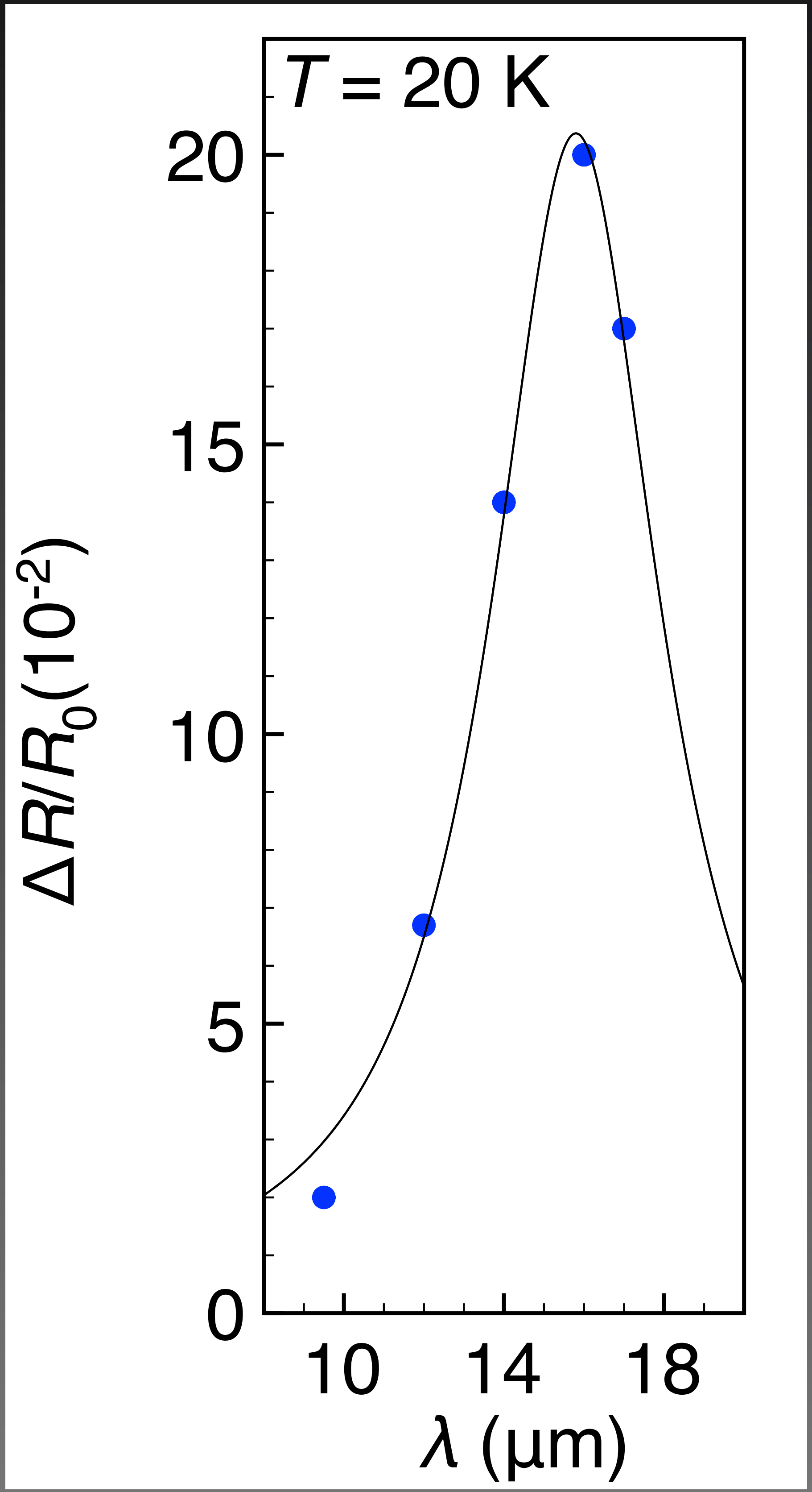
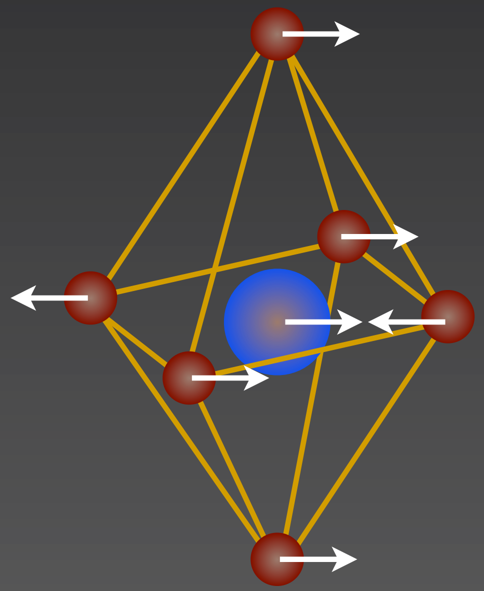
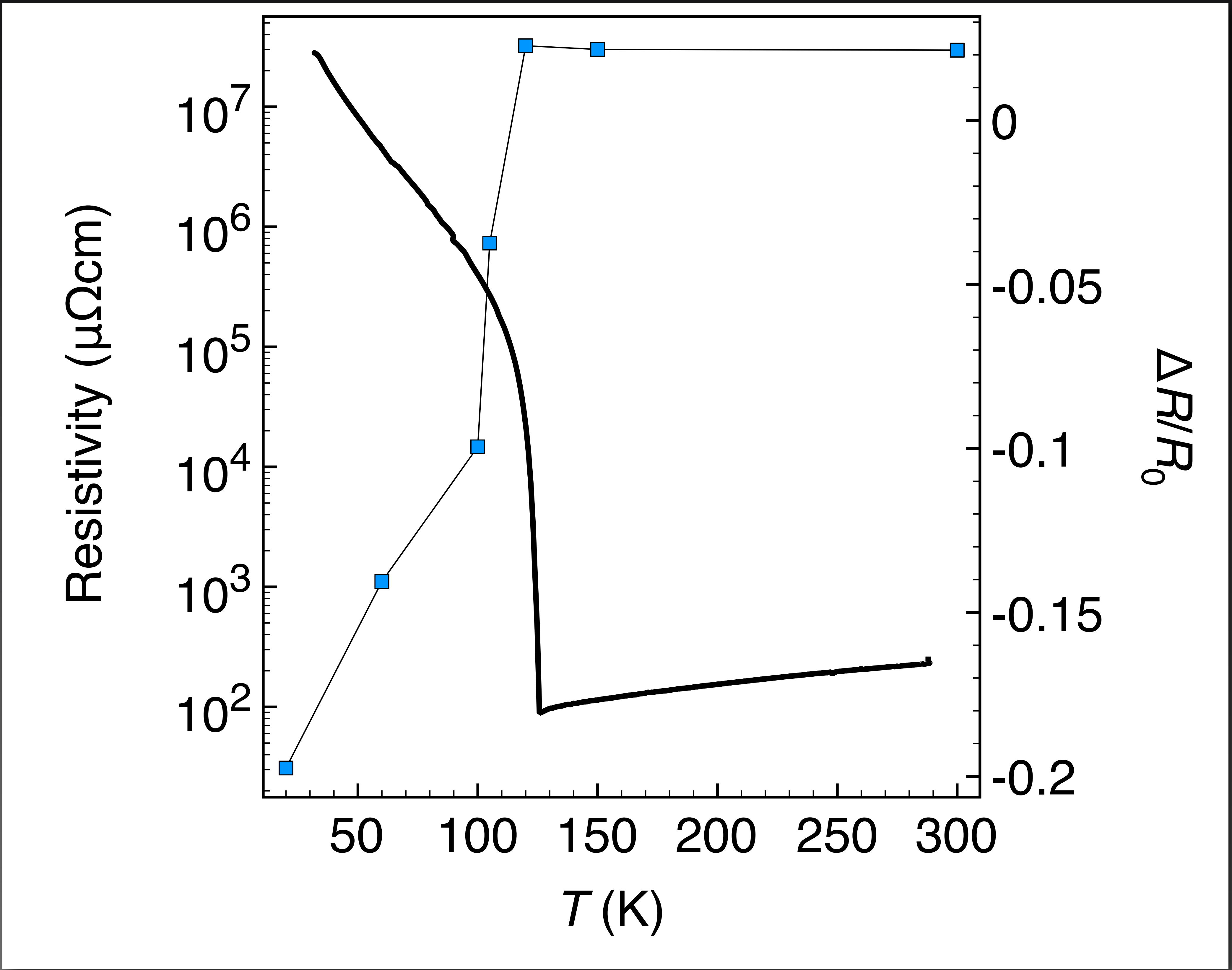
Wavelength dependence

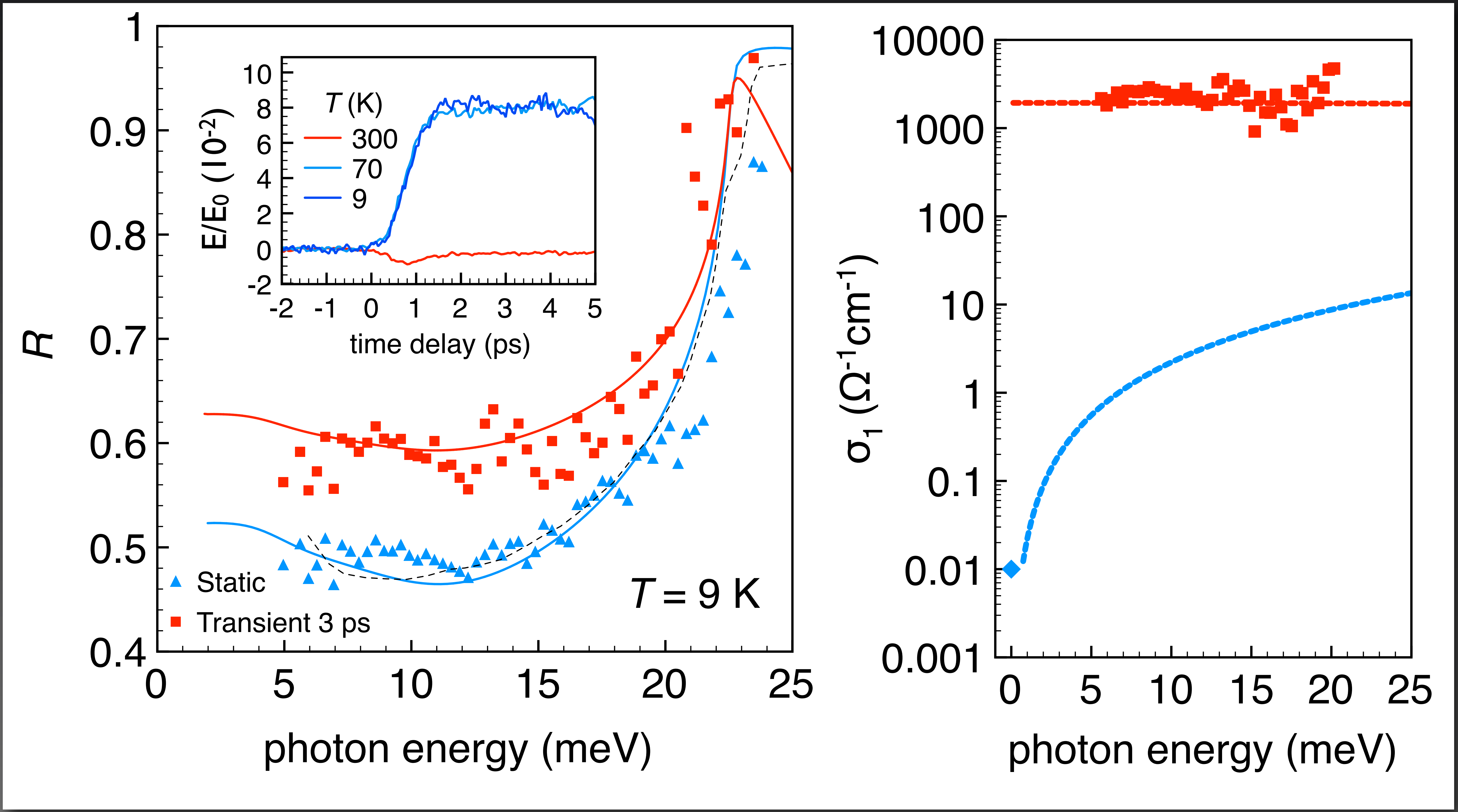




T dependence



THz probe



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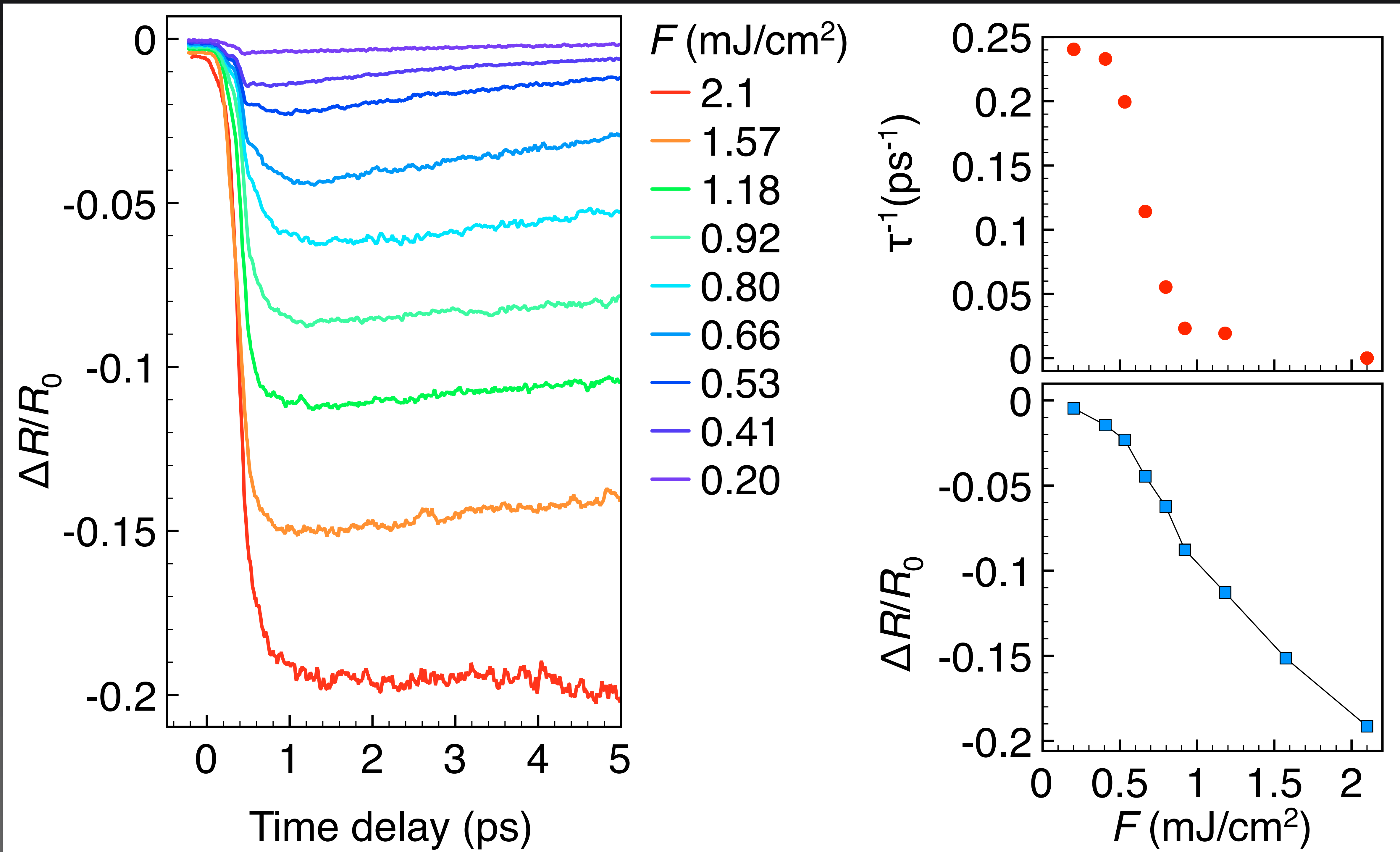
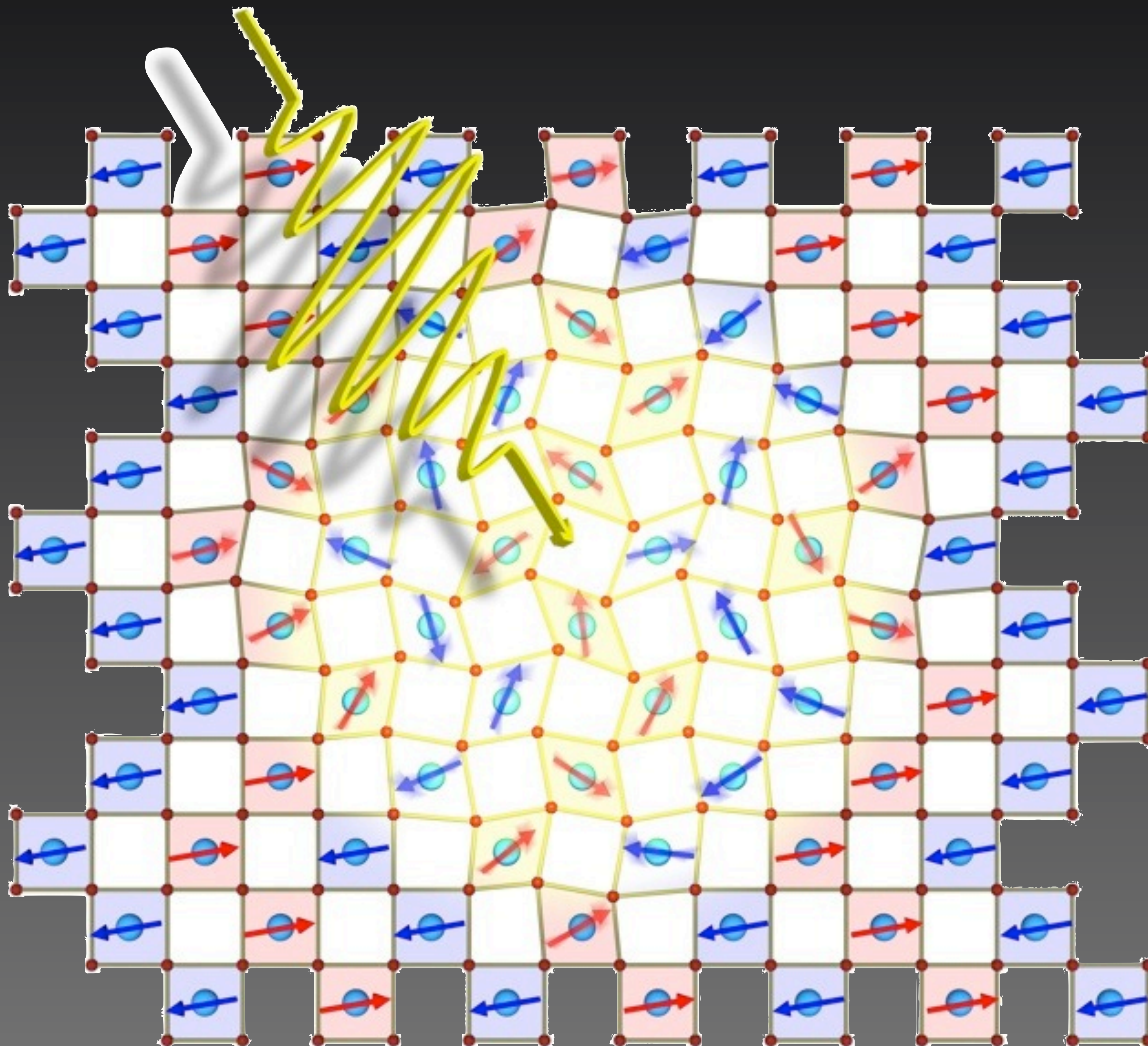
Threshold



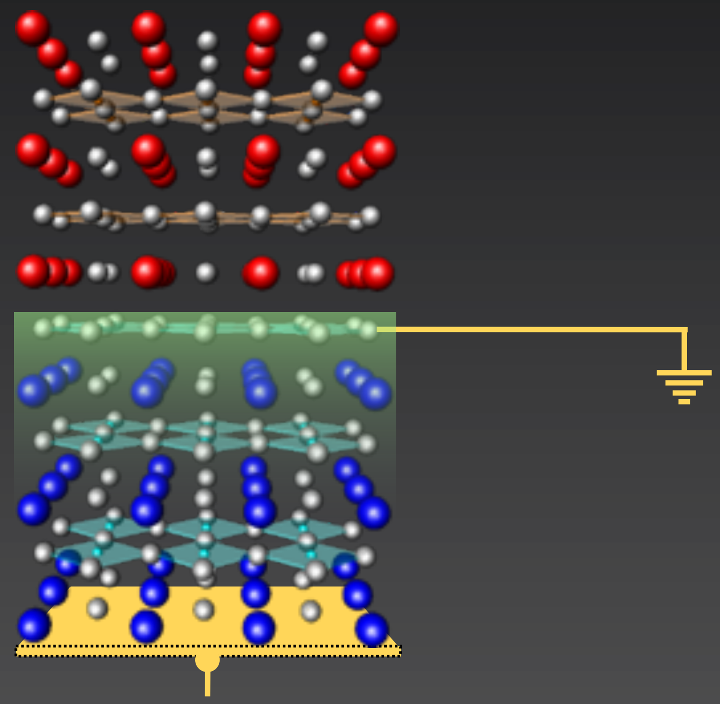
F (mJ/cm²)
2.1
1.57
1.18
0.92
0.80
0.66
0.53
0.41
0.20
ΔR/R0
Time delay (ps)
τ⁻¹(ps⁻¹)
ΔR/R0
F (mJ/cm²)

What about the electronic order?



Conclusions

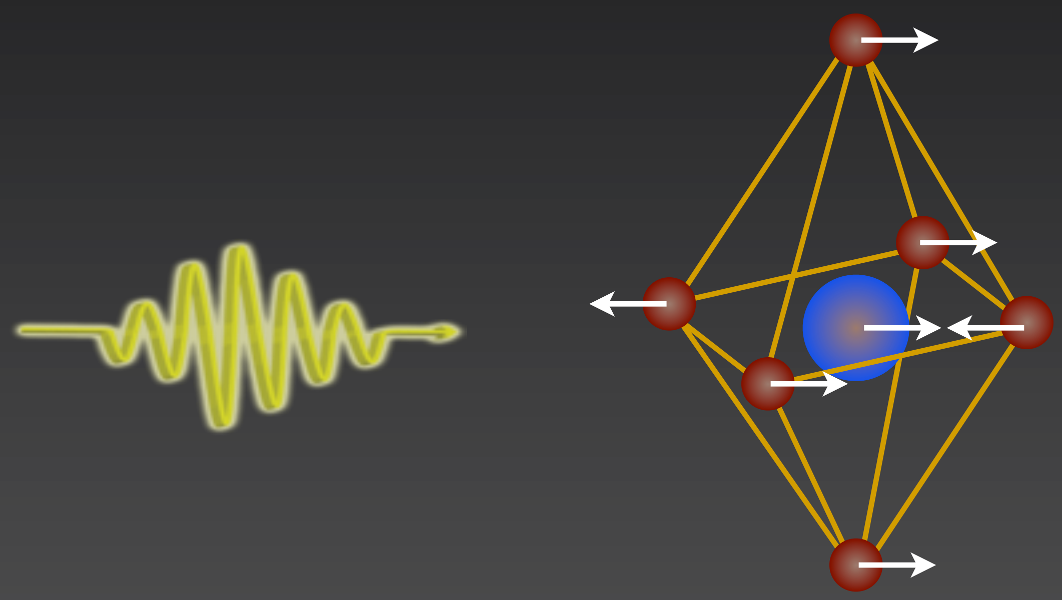
Electrostatic field-effect



$LaAlO_3/SrTiO_3$
Superconductor - Insulator
Quantum Phase Transition

Tunable spin-orbit interaction

Ultrafast lattice excitation



$NdNiO_3/LaAlO_3$
Insulator - Metal
Non-equilibrium Phase Transition

5 orders of magnitude change in dc conductivity

Collaborators

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Max Planck Departement for Structural Dynamics, Center for Free Electron Laser Science, University of Hamburg

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