High-field ground state of graphene at Dirac Point

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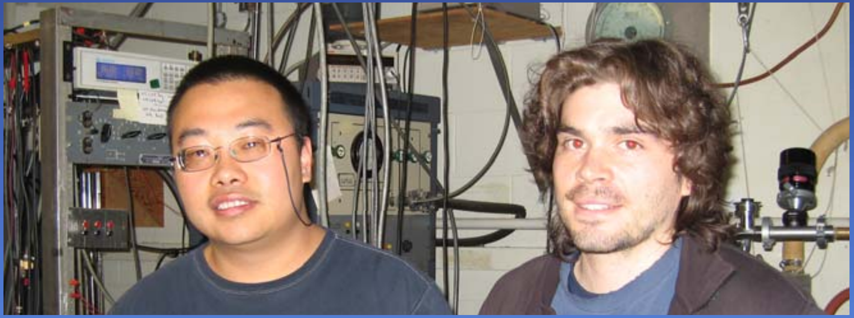


1. **Ground state of Dirac point in high fields**

2. **Thermopower at Dirac point**

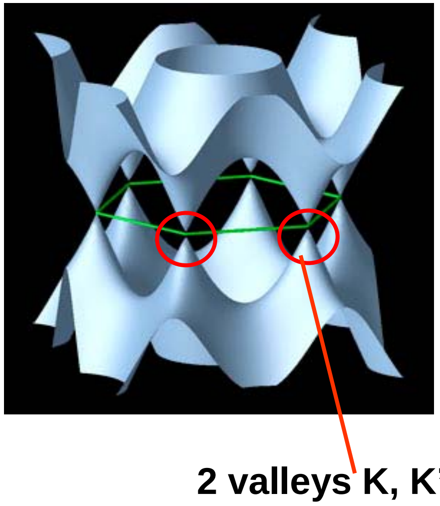
National Science Foundation
WHERE DISCOVERIES BEGIN

NSF-MRSEC DMR 084173

Zero-energy mode, *n*=0 Landau Level

For valley *K*

$$H = \mathrm{v}\begin{bmatrix} 0 & \pi_x + i\pi_y \\ \pi_x - i\pi_y & 0 \end{bmatrix} = \frac{\sqrt{2}\mathrm{v}}{\ell_B}\begin{bmatrix} 0 & a \\ a^+ & 0 \end{bmatrix}$$



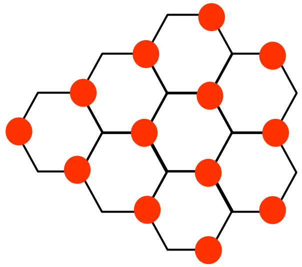
$$\boldsymbol{\pi} = \mathbf{k} - e\mathbf{A} \qquad a = \frac{(\pi_x + i\pi_y)\ell_B}{\sqrt{2}}$$

$$H^2\Psi_n = E_n^2\Psi_n$$

$$E_n = \sqrt{2n}\frac{\mathrm{v}}{\ell_B} \qquad \Psi_n = \begin{bmatrix} |n-1\rangle \\ |n\rangle \end{bmatrix}$$

$$\Psi_0 = \begin{bmatrix} 0 \\ |0\rangle \end{bmatrix}$$

For *n*=0 Landau Level



1) *K-K'* valley index same as *A-B* sublattice index
2) Electrons on *B* sites only

Broken Symmetry ground states

Coulomb interaction energy in high-field state

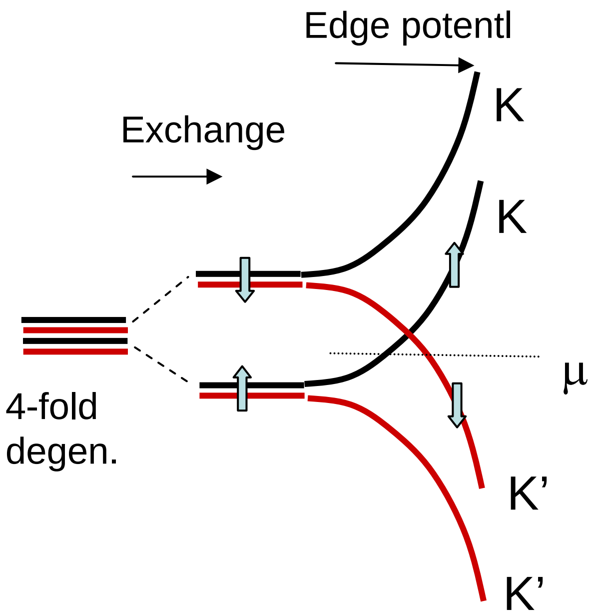
Nomura, MacDonald, PRL 06
Goerbig, Moessner, Doucot, PRB 06
Kun Yang, Das Sarma, MacDonald, PRB 06
Ezawa, JPSJ 06

Abanin, Lee, Levitov, PRL 06, 07
Fertig, Bray, PRL 06
Shimshoni, Fertig, Pai, 08

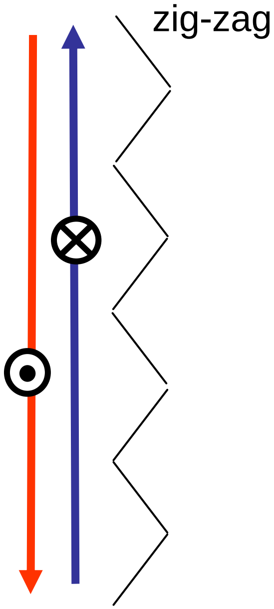
Alicea, Fisher, PRB 06

Gusynin, Miransky, Sharapov, Shovkovy, PRB 06
Khveshchenko, PRL 02

Quantum Hall Ferromagnet and CPE modes



QHF state



Counter-propg edge (CPE) modes

Abanin, Lee, Levitov

Fertig, Bray

Bernevig, Zhang

At Dirac point, CPE modes protected

R_{xx} ~ $2(h/e^2)$ at intense fields (dissipative to very large H)

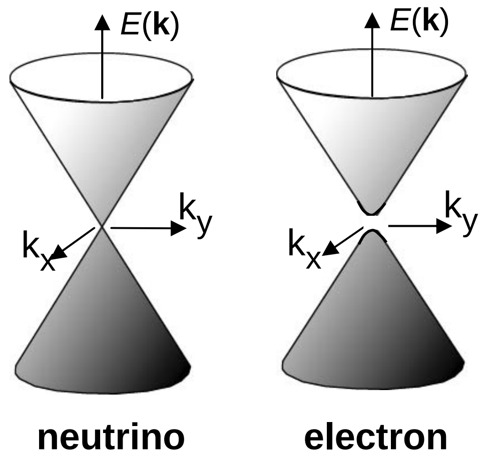
Realization of quantized spin-Hall system

Magnetic Catalysis (field induced gap)

Field *H* creates gap

Mass term $\Psi^{+}\gamma_5\Psi$

Chiral-symmetry breaking
In (2+1) QED$_3$



Applequist et al. 1986

Miransky et al.
1995, 2003, 2005, 2008

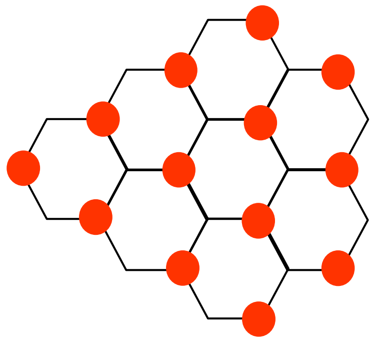
D. Khveshchenko 2002

Field-enhancement of DOS at Dirac Point
Exciton condensation of electron hole pairs

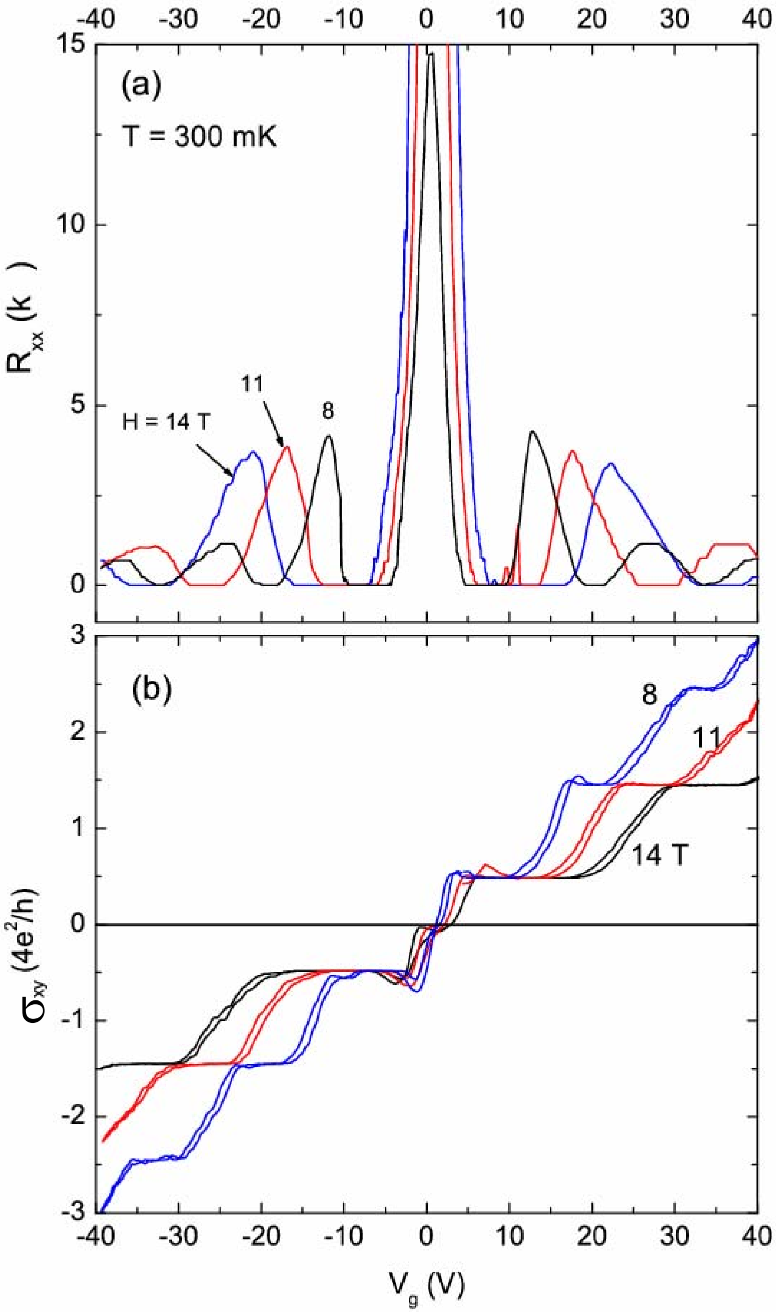
Order parameter for *H* > *H*$_c$

$$\langle \overline{\Psi}\Psi \rangle = \sum_{\sigma} |\psi_{A\sigma}|^2 - |\psi_{B\sigma}|^2$$

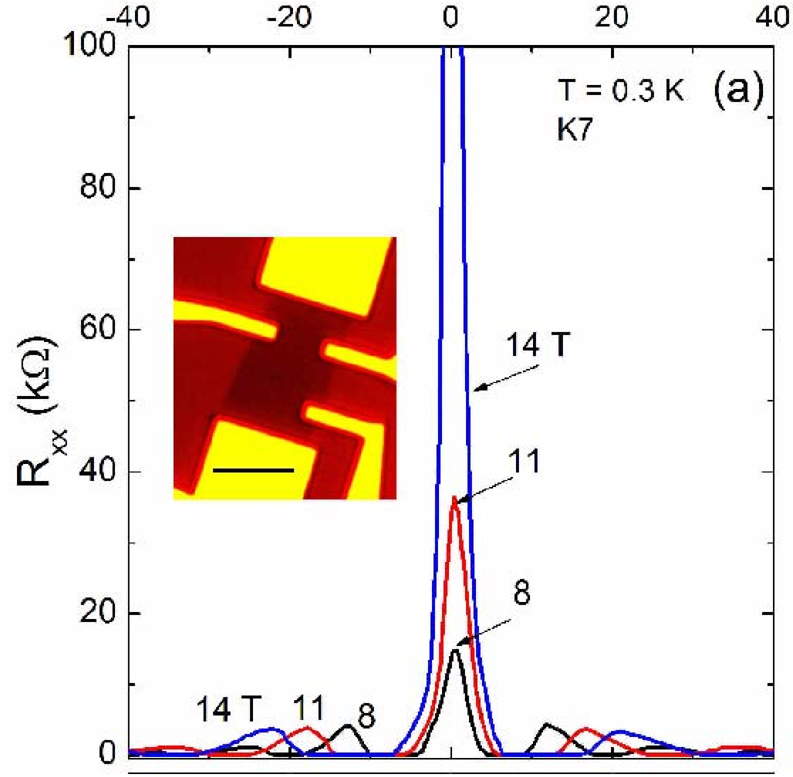
Equivalent to sublattice CDW



The resistance R_{xx} and Hall conductivity in graphene



Checkelsky, Li, Ong, PRL '08



***R*$_{xx}$ diverges with *H* at Dirac Point**

Divergent R0 and zero-Hall step

Checkelsky, Li, Ong, PRL '08

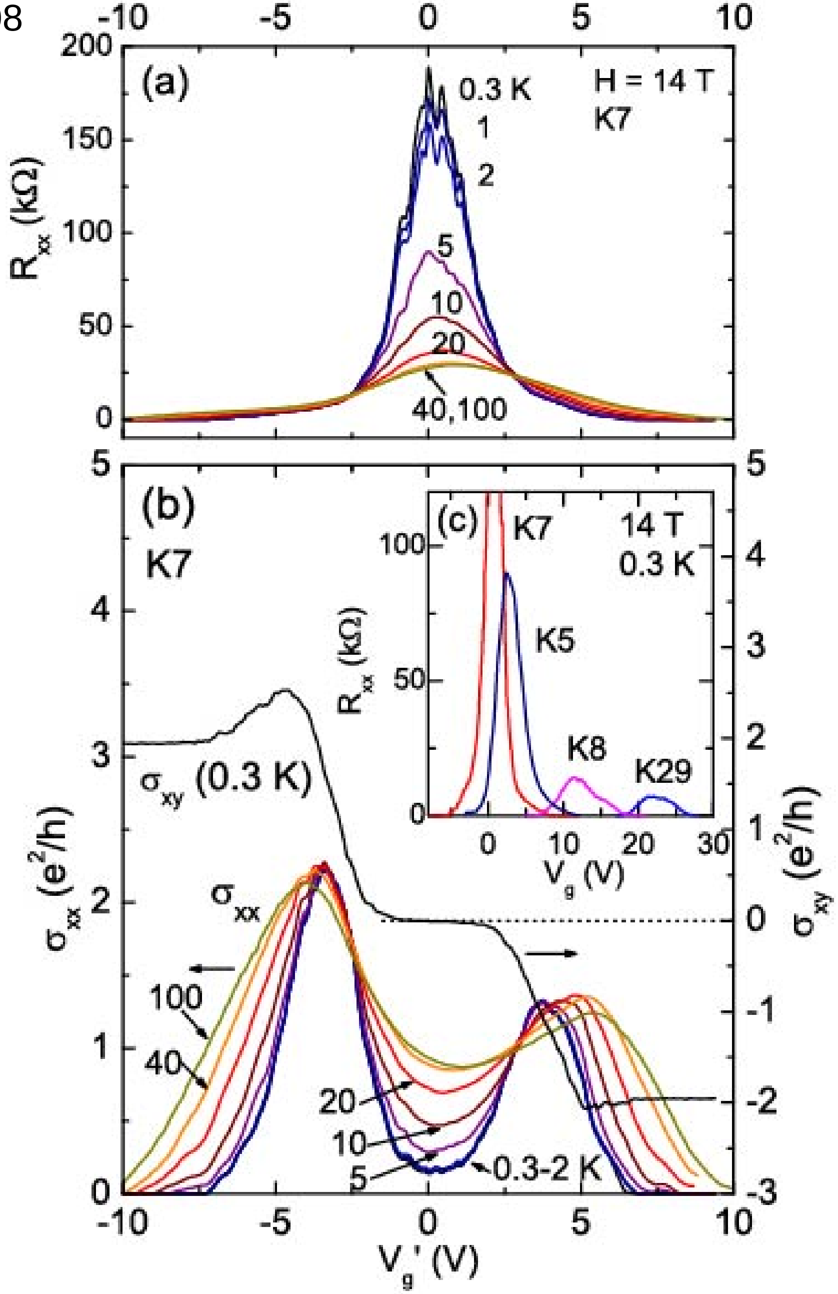
R_0 increases as T decreases

At fixed H and T, n=0 peak dependent on V_0 (offset voltage)

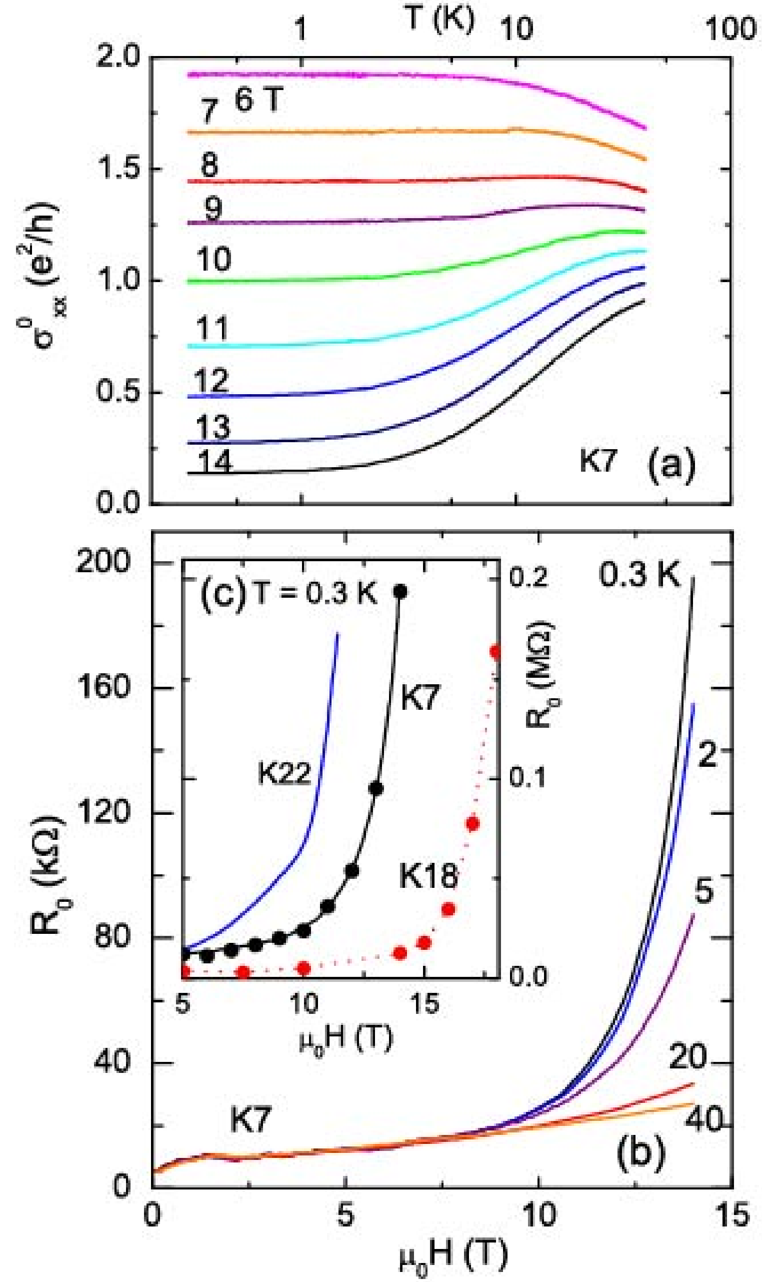
σ_{xy} = 0 at n=0

At 14 T, n=0 LL split into 2 subbands

Split resolved at 100 K



R_0 saturates below 2 K

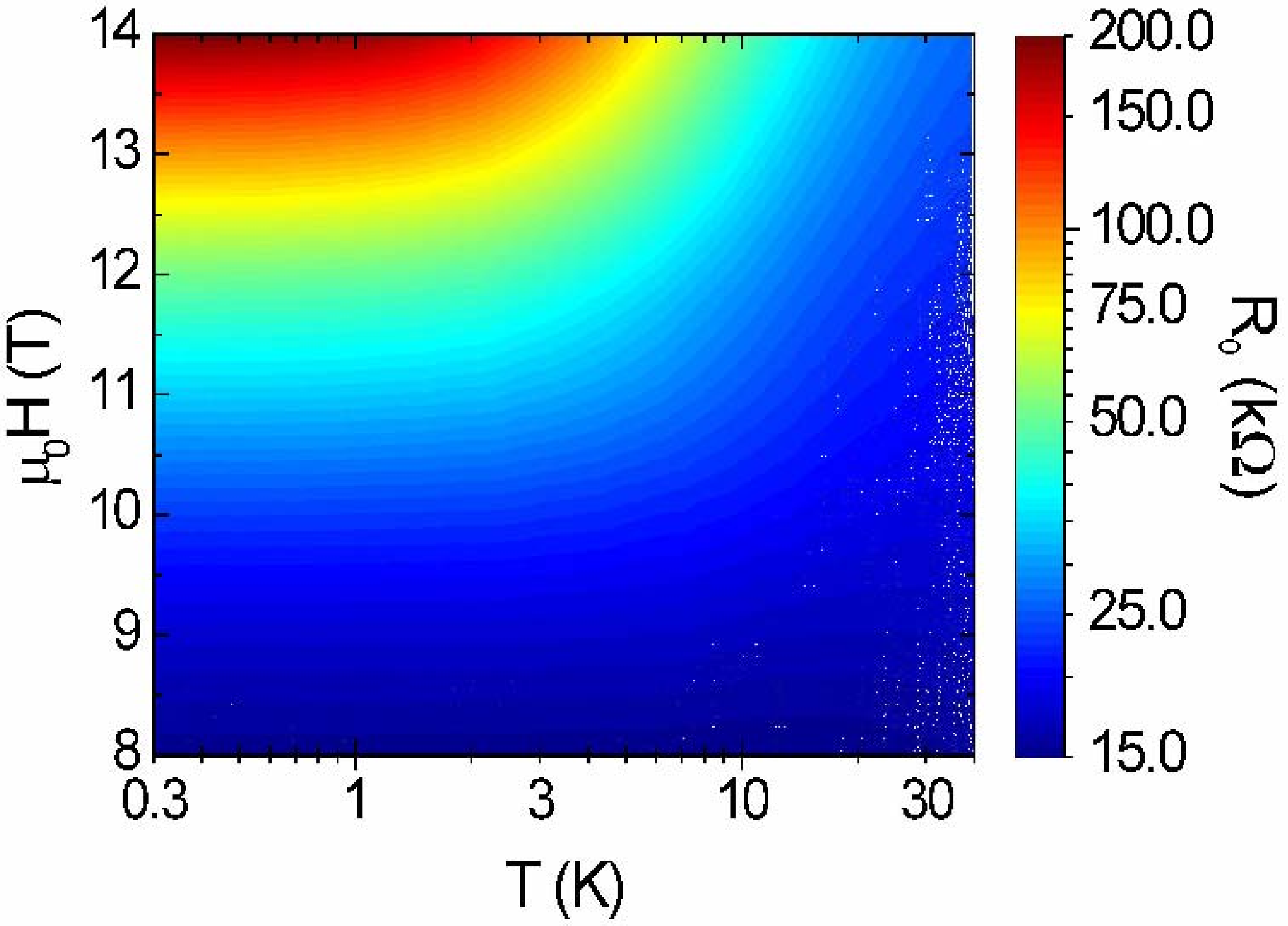


Conductance saturates
T below 2 K

Divergence in R_0 steepest
At 0.3 K

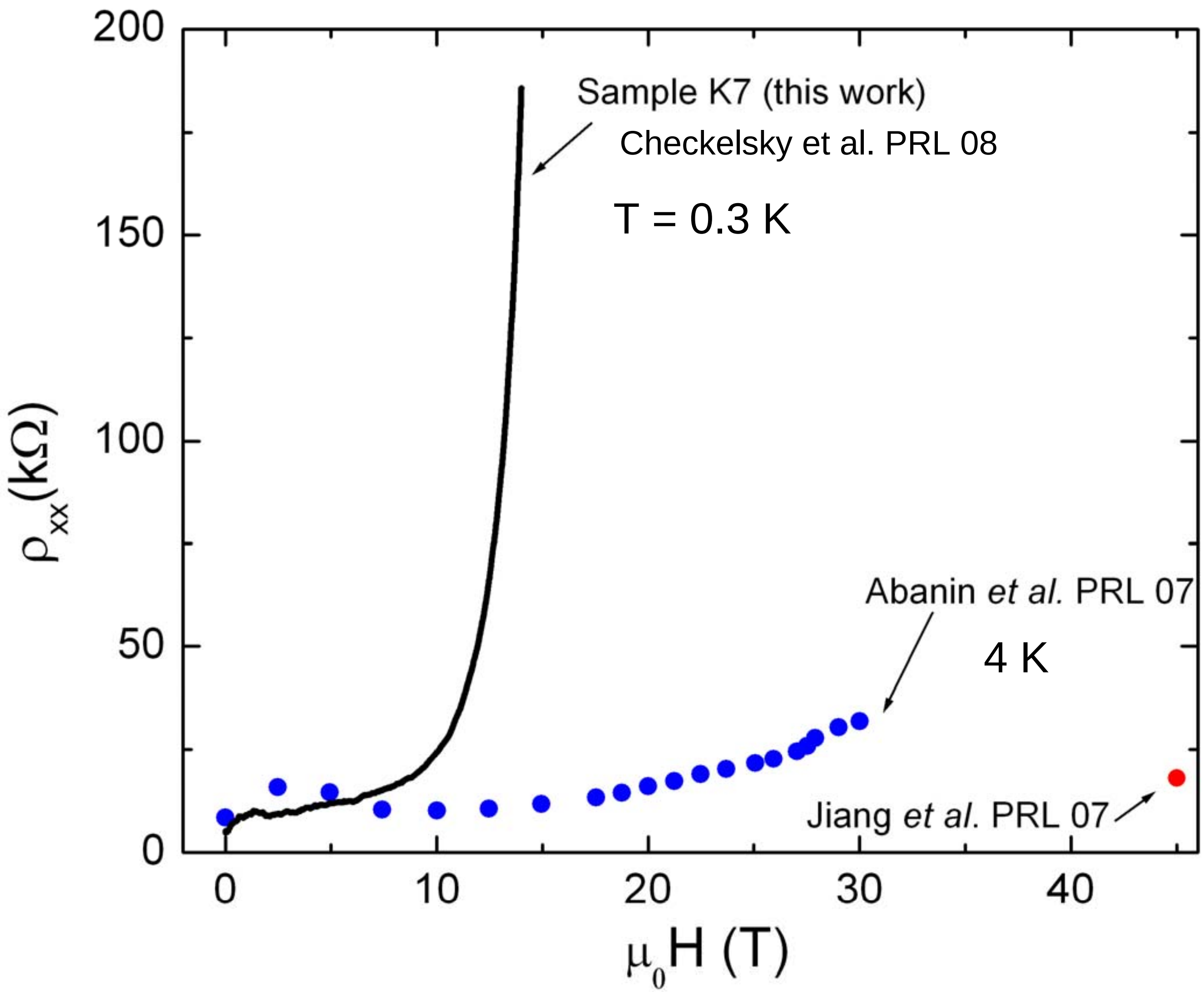
Sample dependent

Contour map of R_0 at Dirac point in *H-T* plane

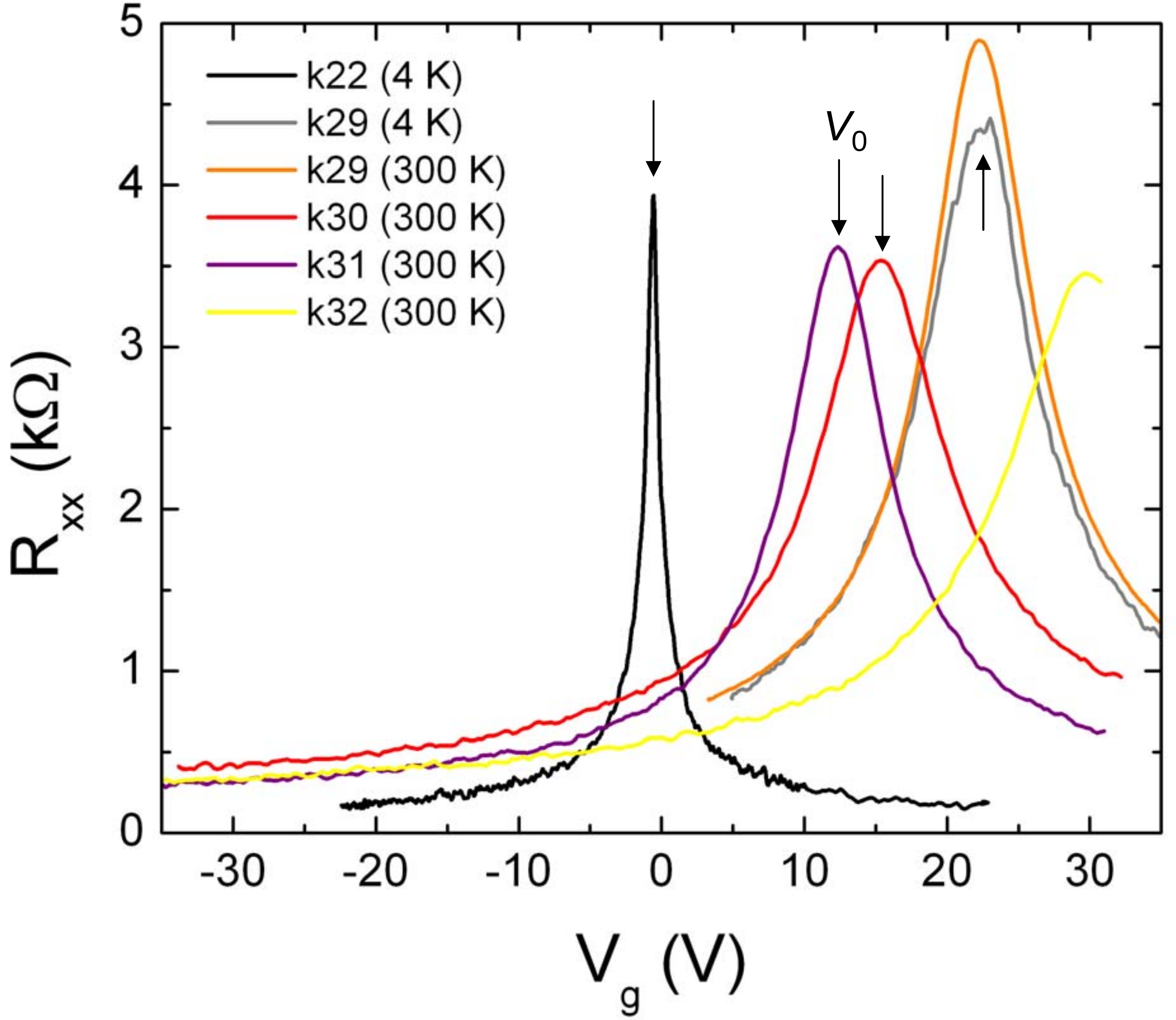


R_0* is exponentially sensitive to *H
but *T*-independent below 2 K

Comparison of divergent R_0 with previous reports



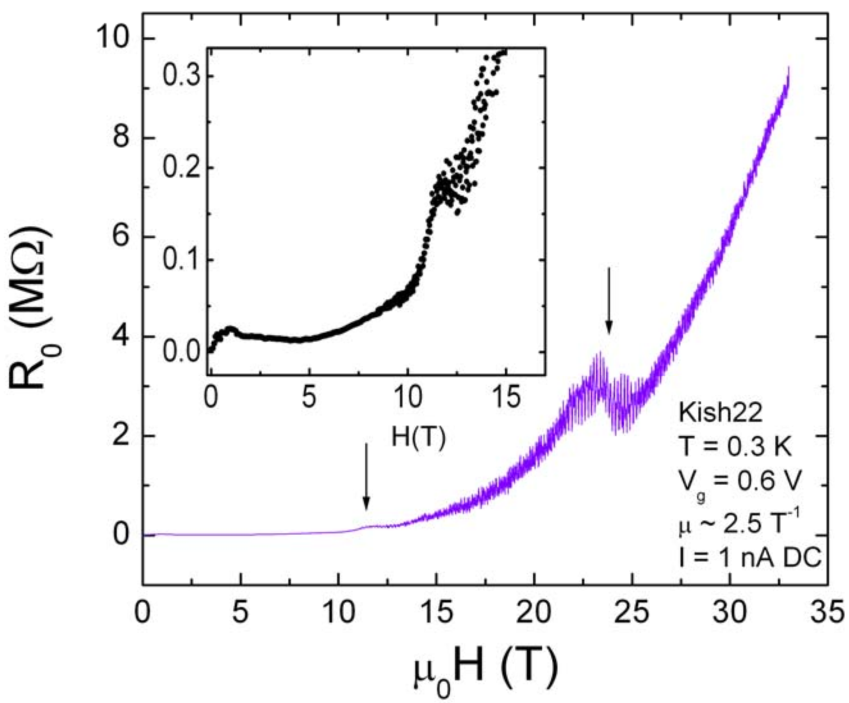
Offset Gate voltage V_0 -- an important parameter

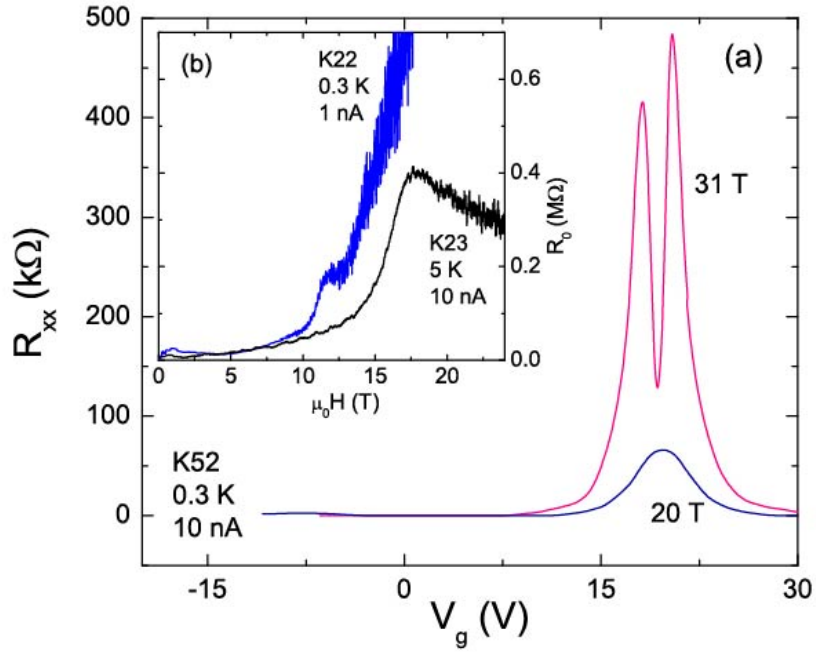


Small offset V_0 correlates with low disorder

Spurious features from self-heating

Power dissip *P* > 10 pW leads to thermal runaway at Dirac point

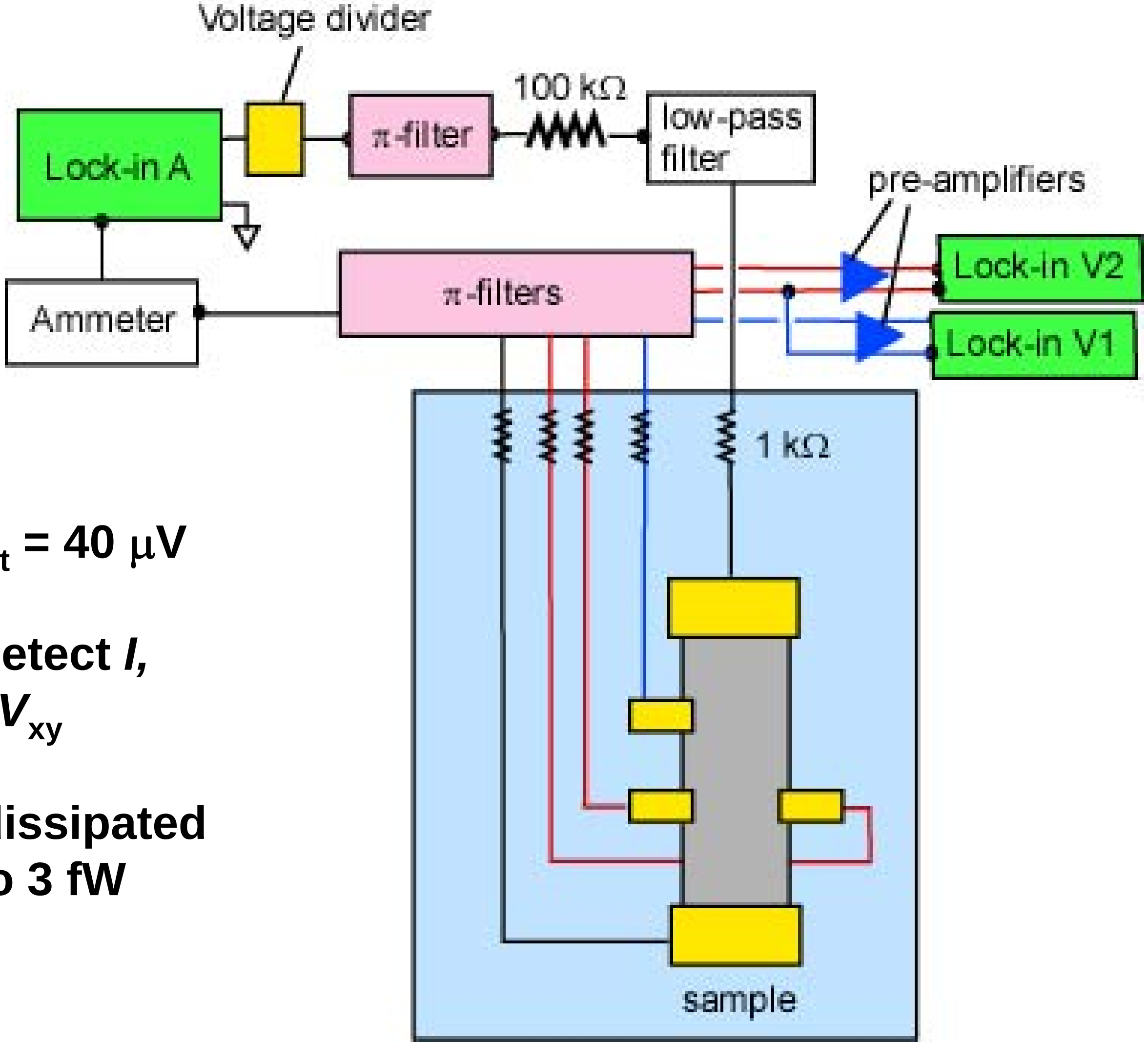




A major experimental obstacle

Adopt ultralow dissipation measurement circuit

Checkelsky, Li, NPO, PRB ‘09



Hold V_{tot} = 40 μV

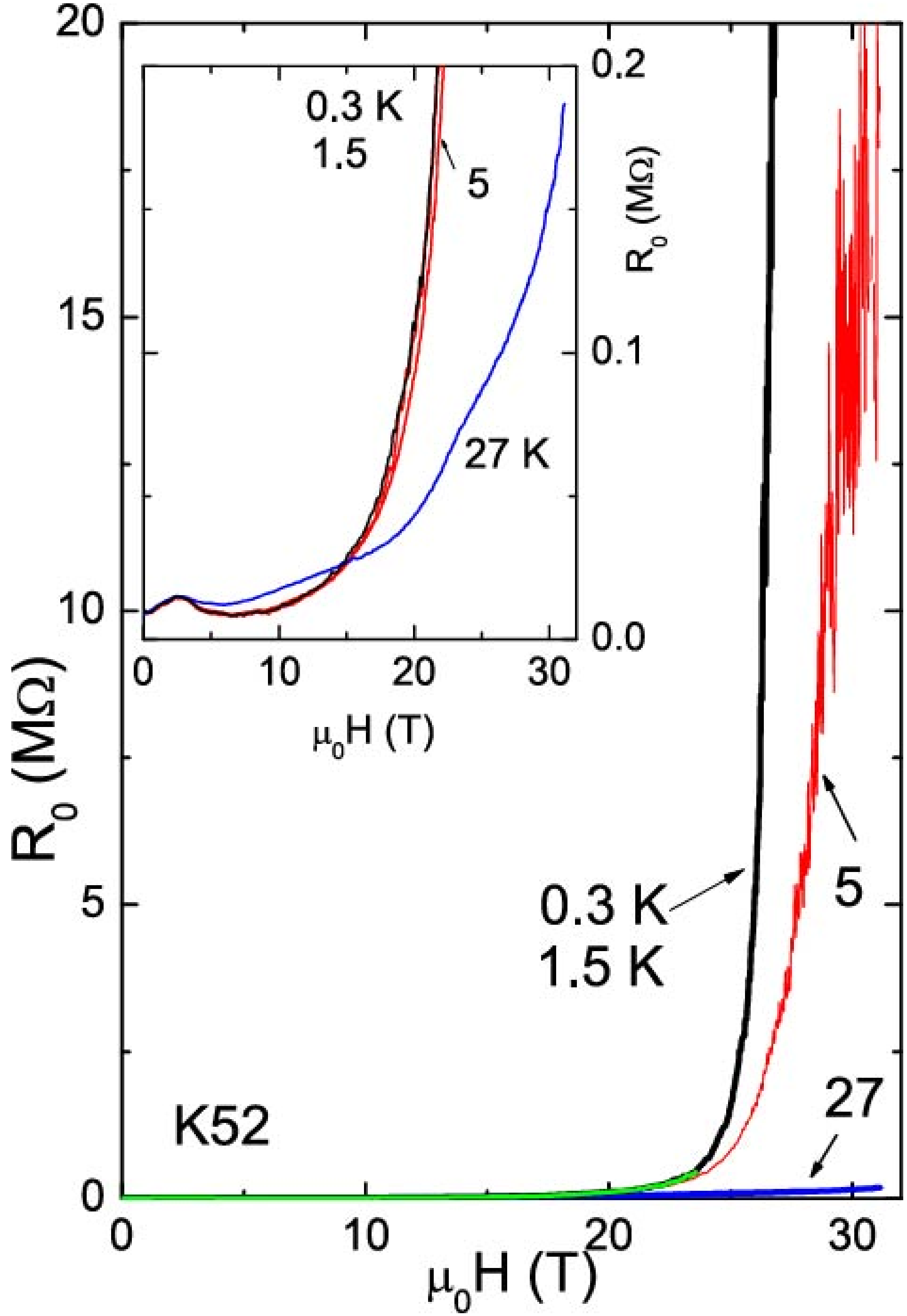
Phase detect *I*, V_{xx} and V_{xy}

Power dissipated 10 aW to 3 fW

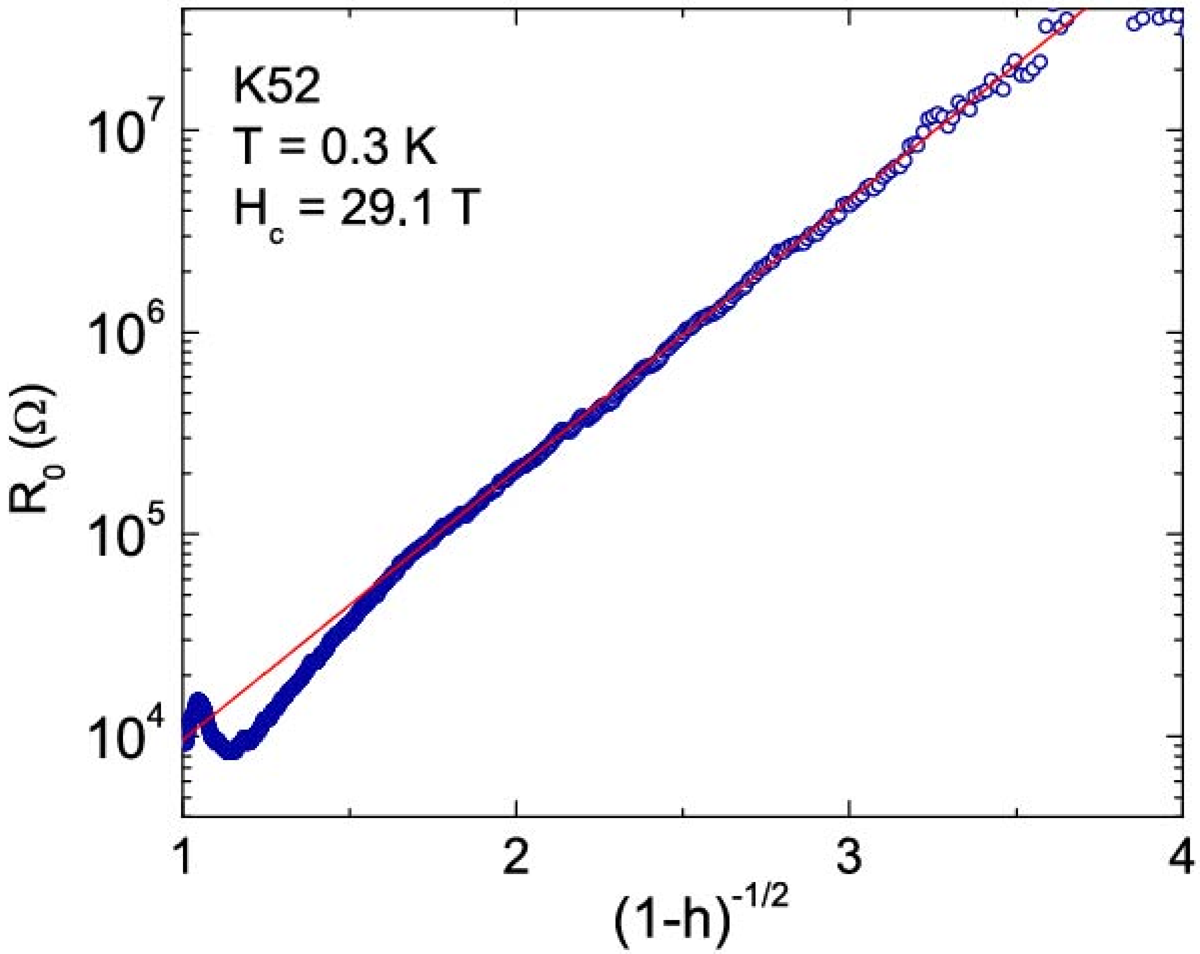
Checkelsky, Li, NPO, PRB '09

At 0.3 K, R_0 diverges to 40 MΩ

Divergence in R_0 seems *singular*



Fits to Kosterlitz-Thouless correlation length over 3 decades



3-decade fit to
KT correlation ξ

$$R_0 = 440 \exp\left[\frac{2b}{\sqrt{1-h}}\right]$$

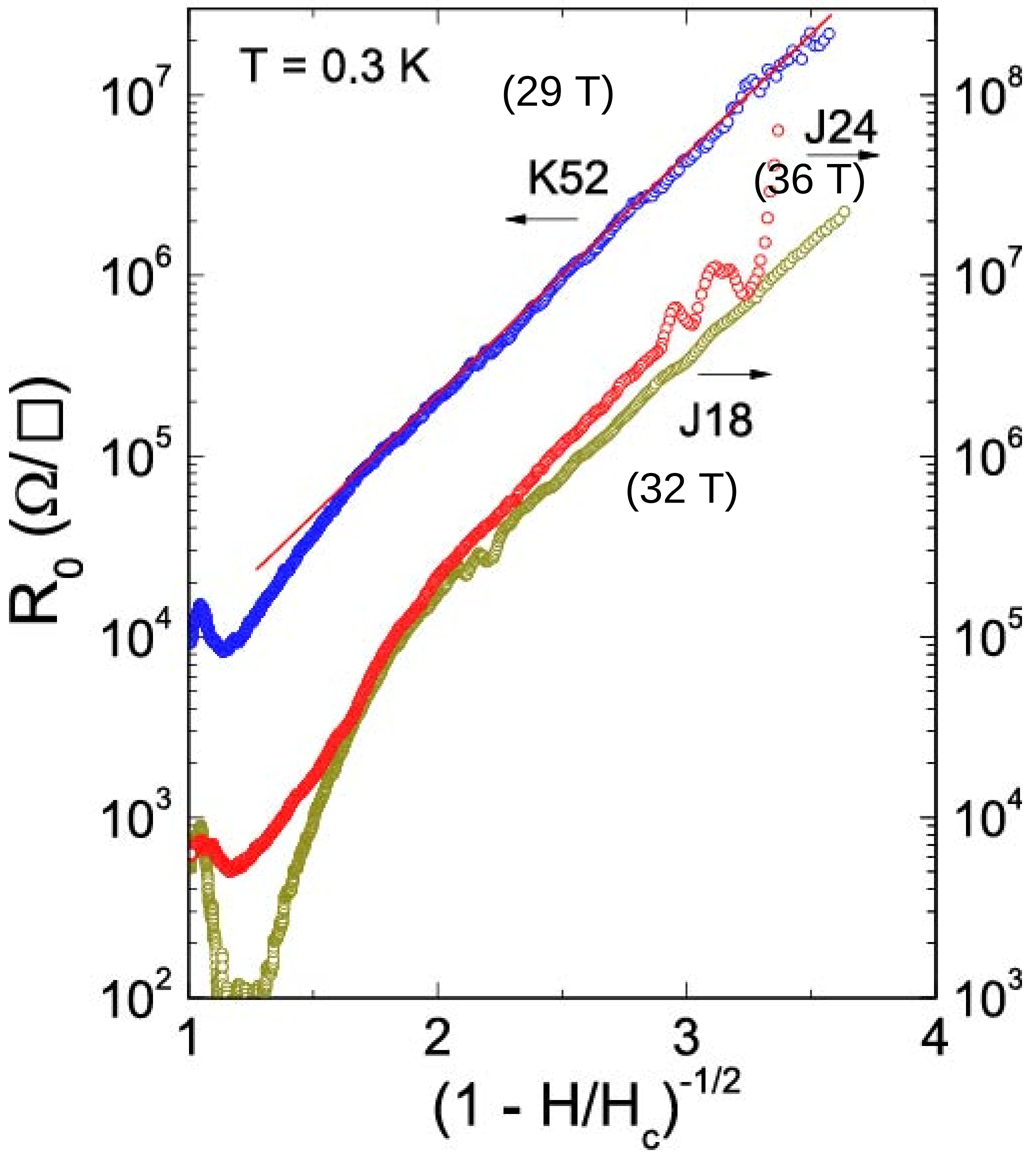
Kosterlitz Thouless fit in Samples K52, J18 and J24

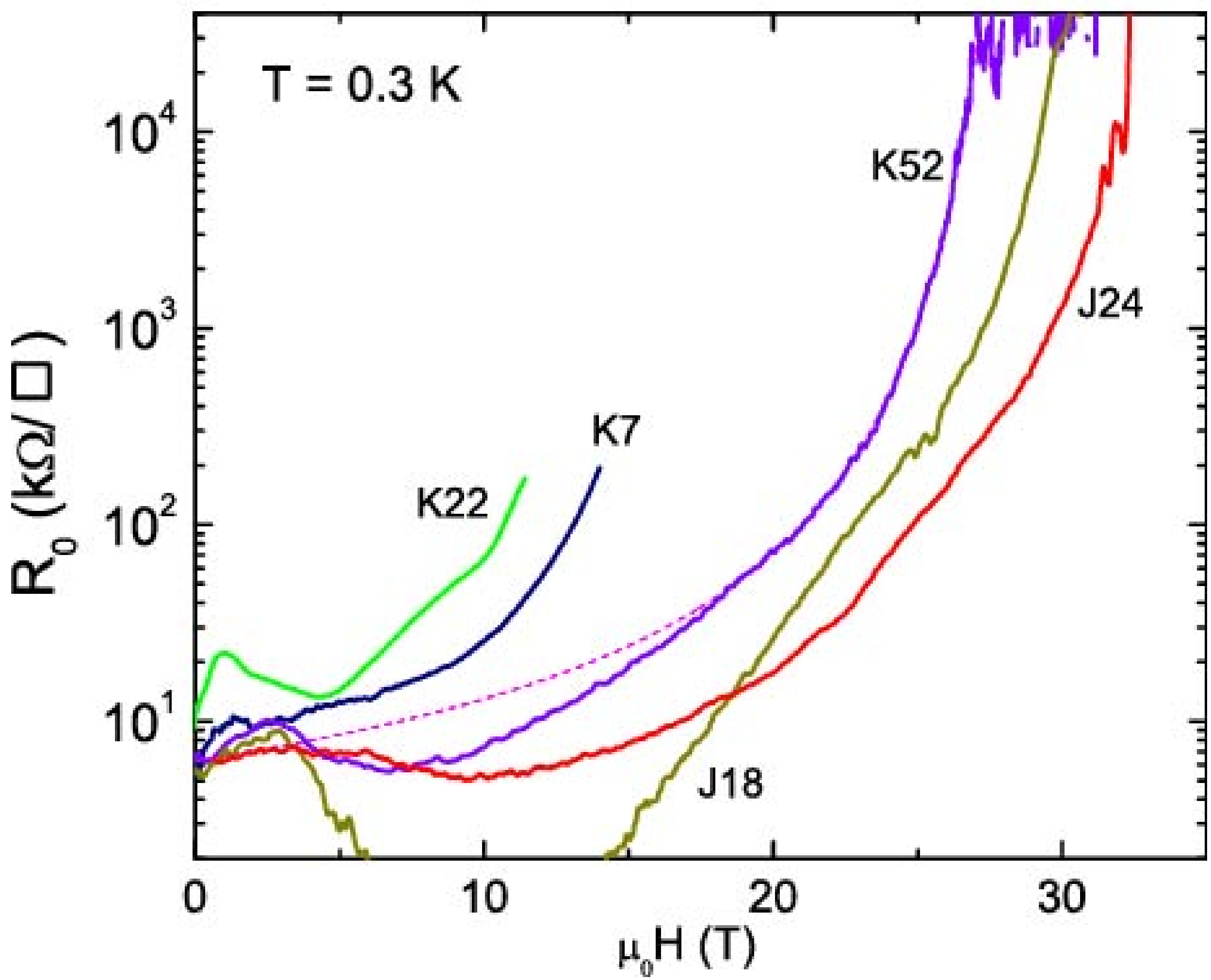
Checkelsky, Li, NPO, PRB '09

$$R_0 = A\,\mathbf{exp}\left[\frac{2b}{\sqrt{1-h}}\right]$$

Slopes *b* are similar

H_c sample dependt

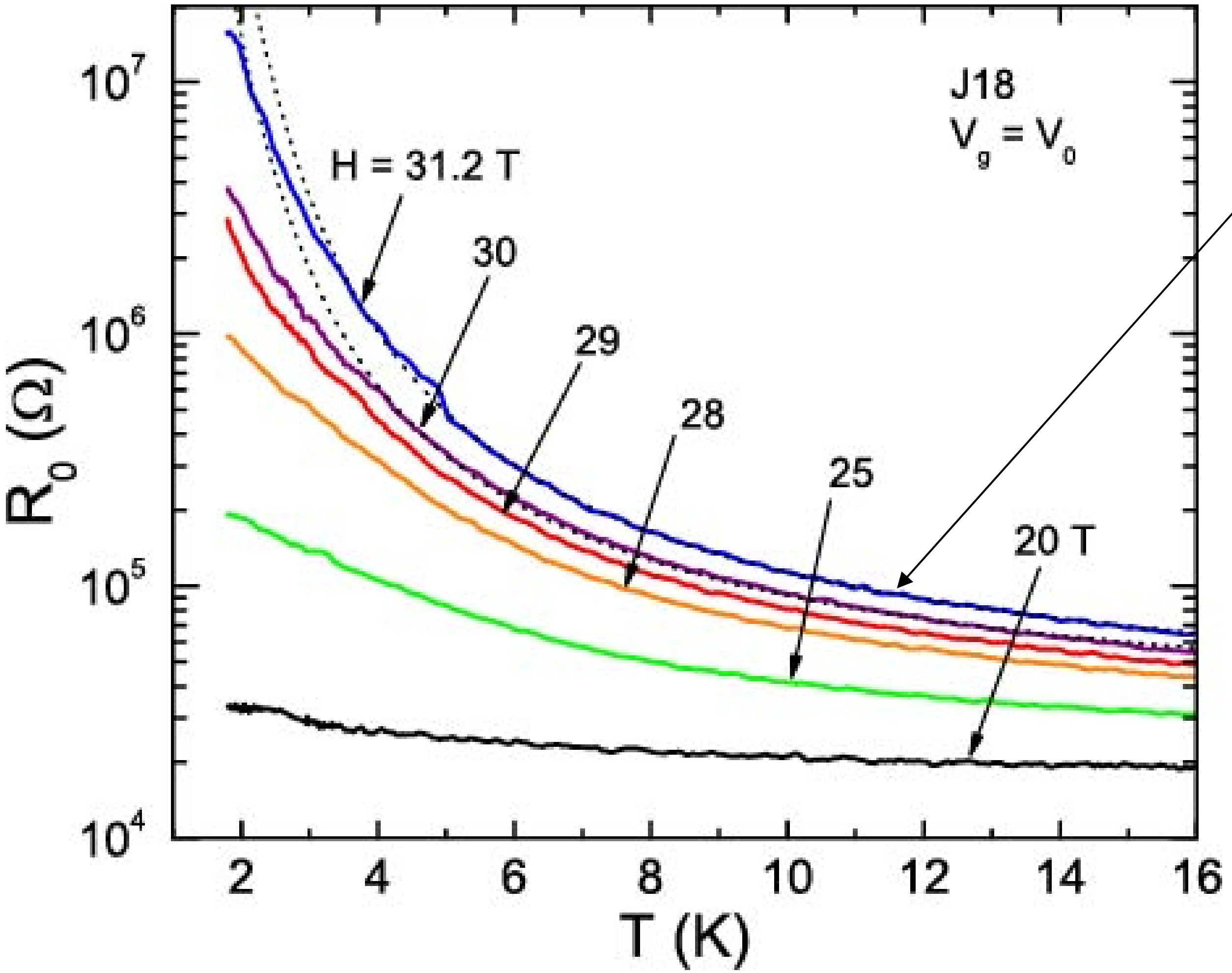




T = 0.3 K
K52
J24
K7
K22
J18
10^4
10^3
10^2
10^1
R_0 (kΩ/□)
0
10
20
30
μ_0H (T)

Temperature dependences of R_0 at fields $H < H_c$

Checkelsky, Li, NPO, PRB '09

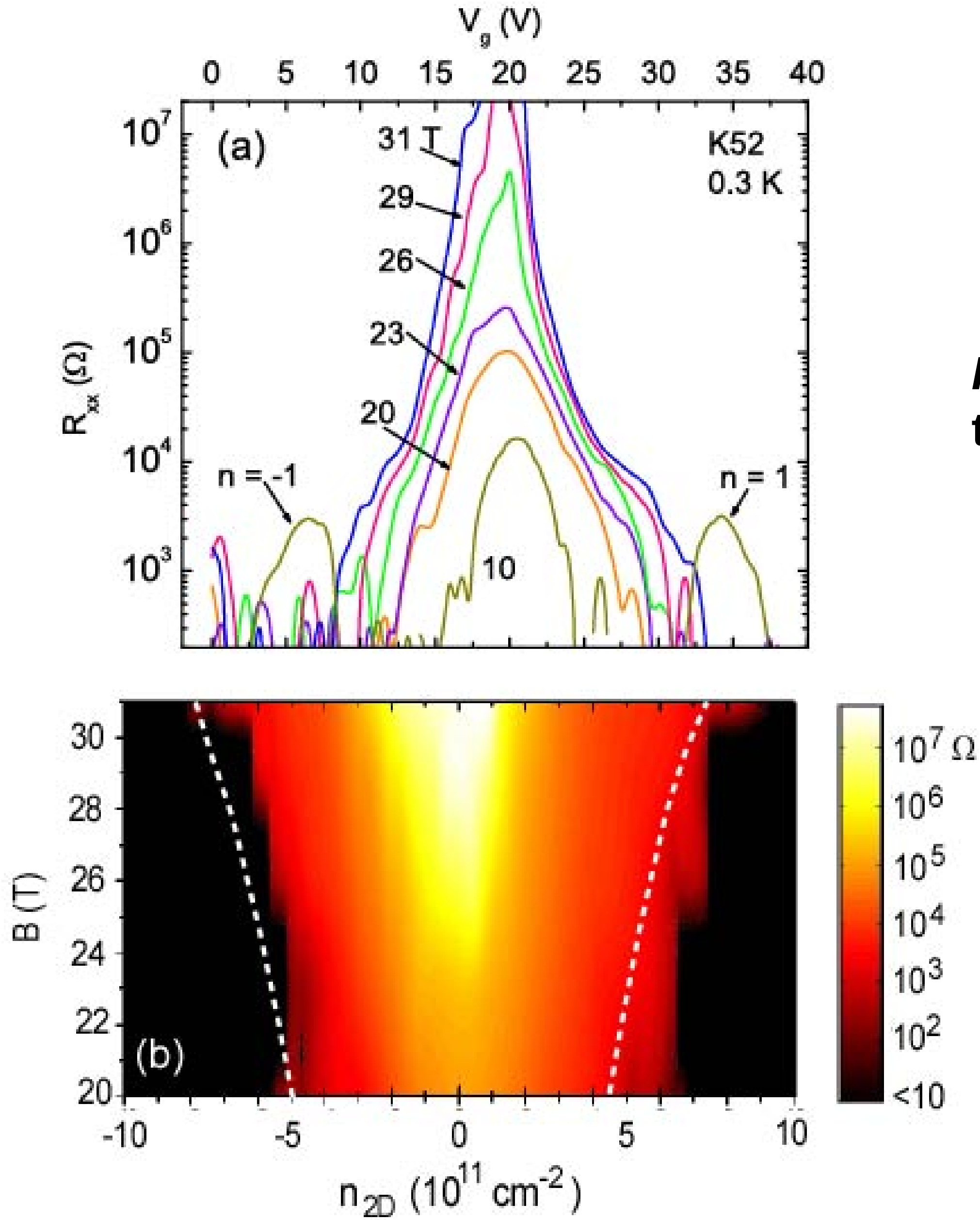


Thermally activated

$R_0 = A \exp(\beta\Delta)$
Δ = 14 K

At "low" H, R_0
Saturates below 2 K

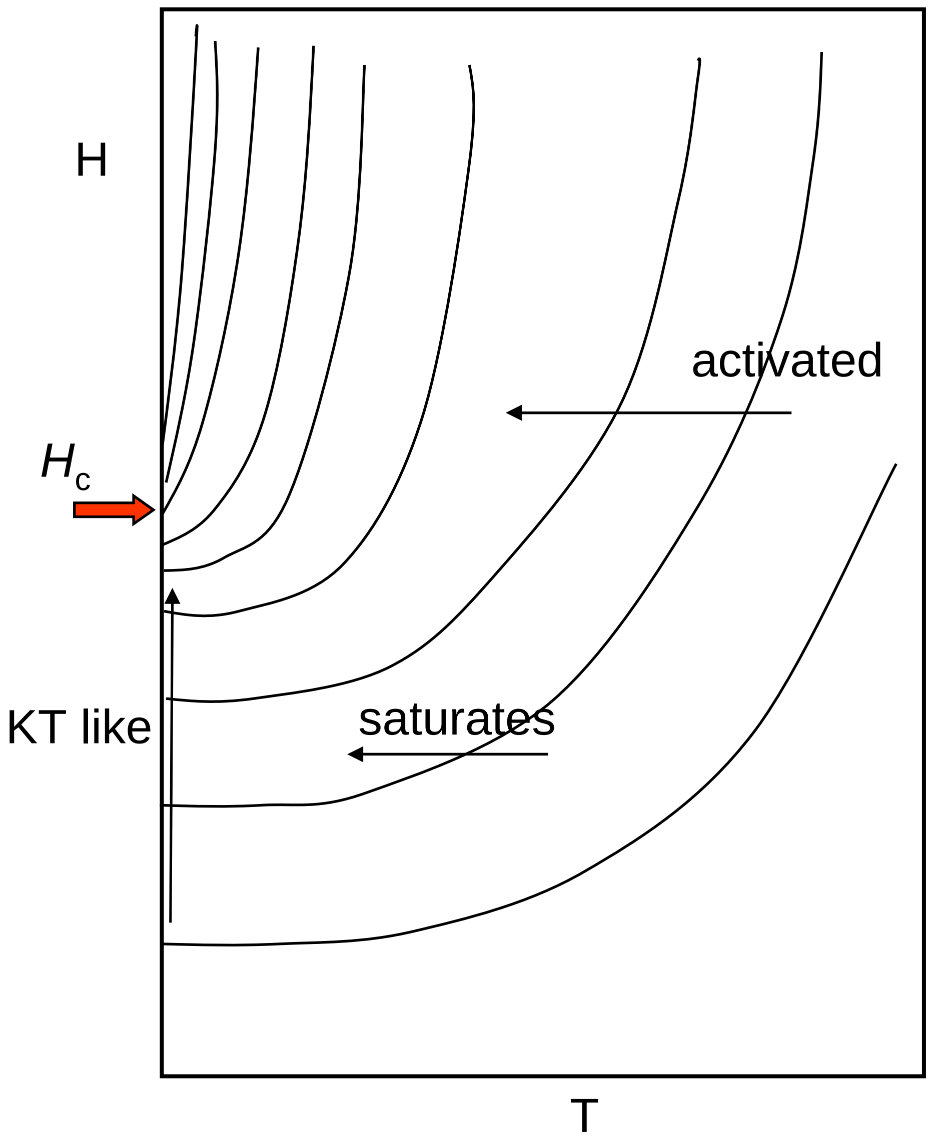
Divergence confined to n = 0 LL

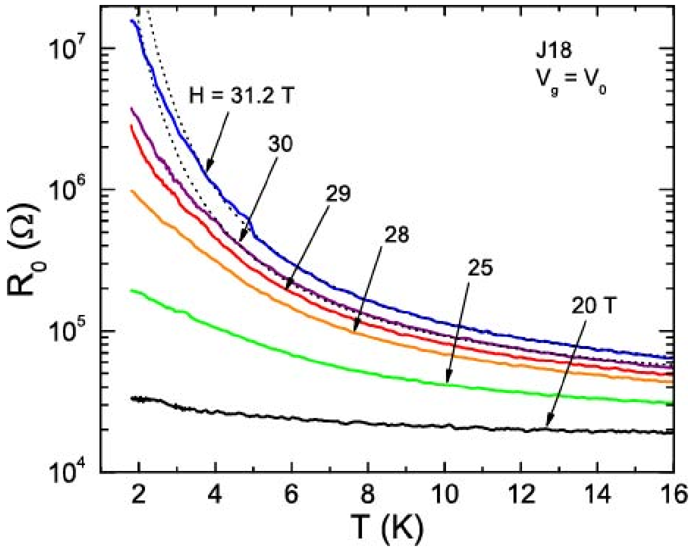


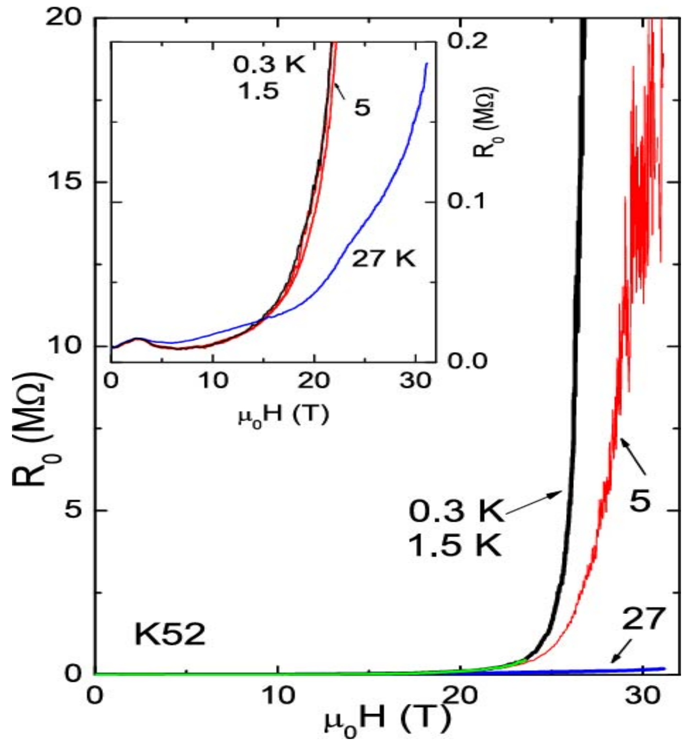
R_0 ~ 10^4 larger than R_{xx} n=1

Phase diagram in *T-H* plane at Dirac point

Constant-R_0 contours

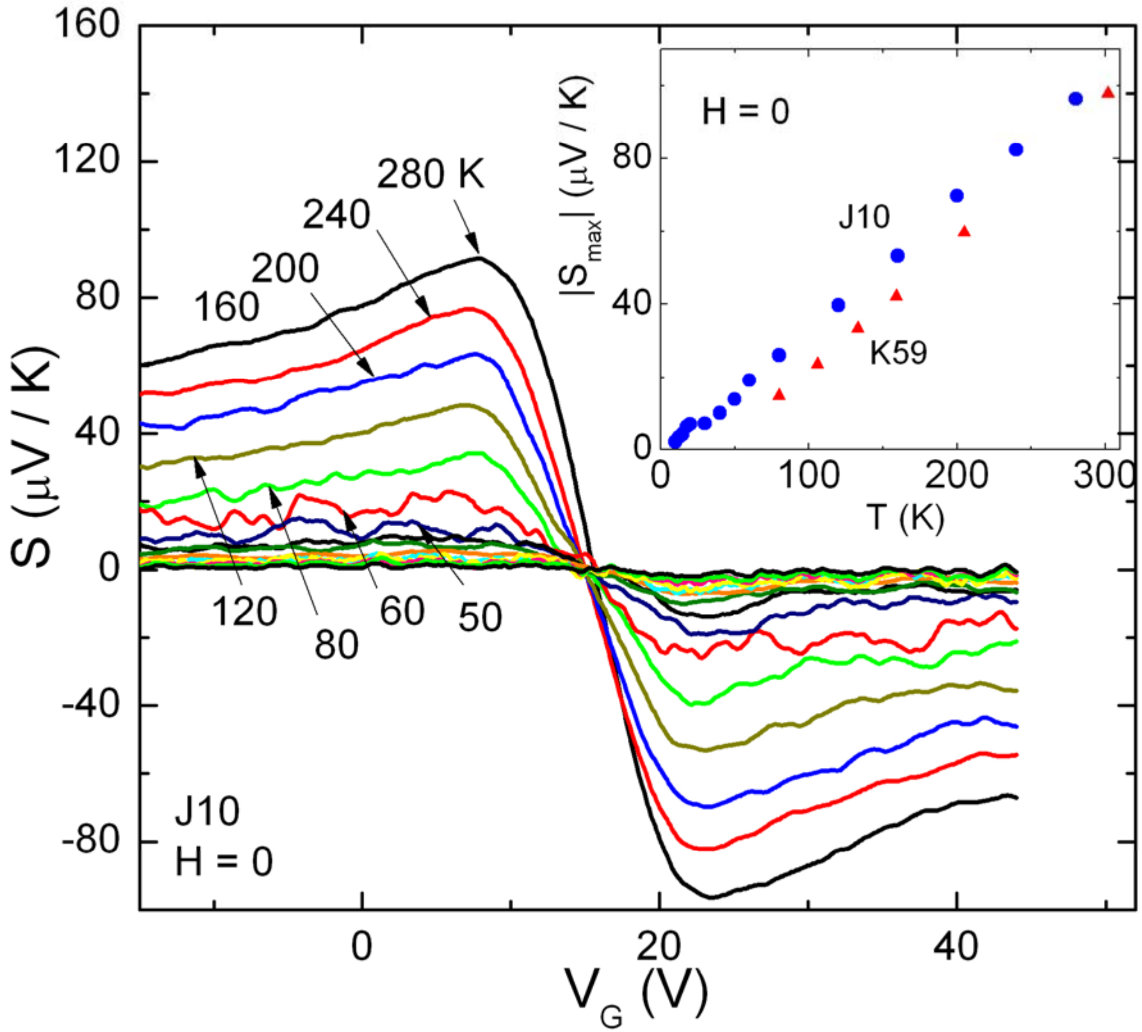


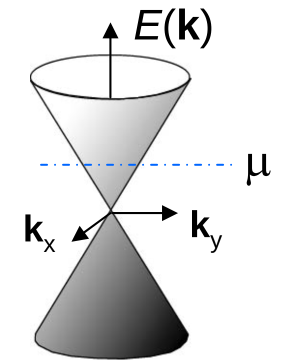




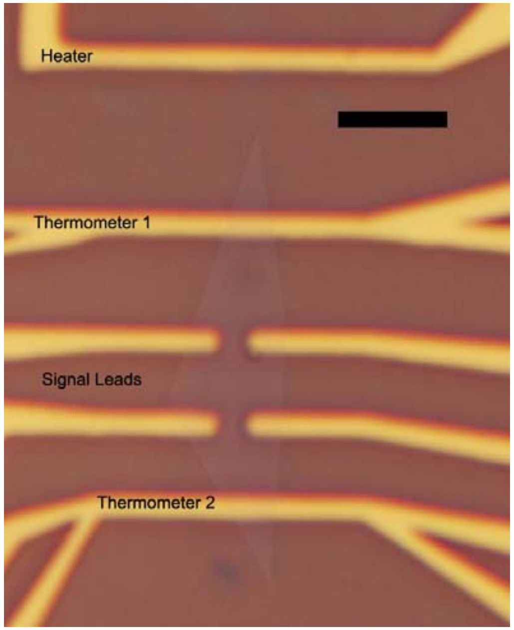
Thermopower in zero field

S is *T*-linear and large





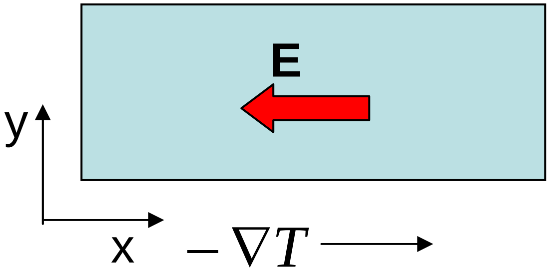
$$S = C\frac{k_B}{e}\frac{1}{\sigma}\frac{\partial\sigma}{\partial\mu}$$



Thermoelectric response functions

Current response $\mathbf{J} = \overleftrightarrow{\boldsymbol{\alpha}} . (-\vec{\nabla} T)$

Measured E field $E_i = S_{ij}(-\partial_j T)$



Total charge current is zero (open boundaries)

$$J_i = \sigma_{ij} E_j + \alpha_{ij}(-\partial_j T)$$

$$S = -S_{xx} = (\rho\alpha + \rho_{yx}\alpha_{xy})$$ (thermopower)

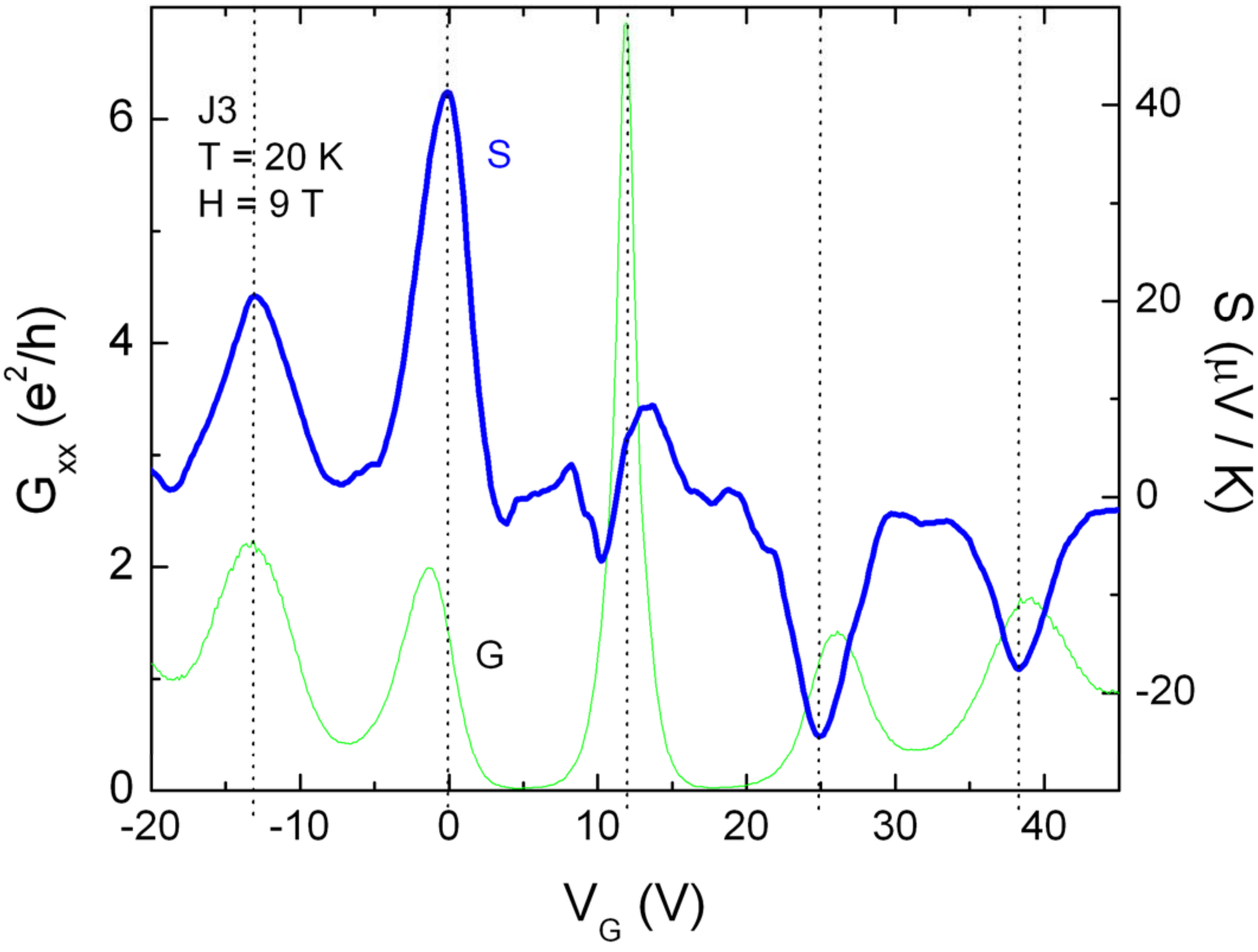
$$S_{yx} = \rho\alpha_{xy} - \alpha\rho_{yx}$$ (Nernst effect)

Can invert to find α_{ij}

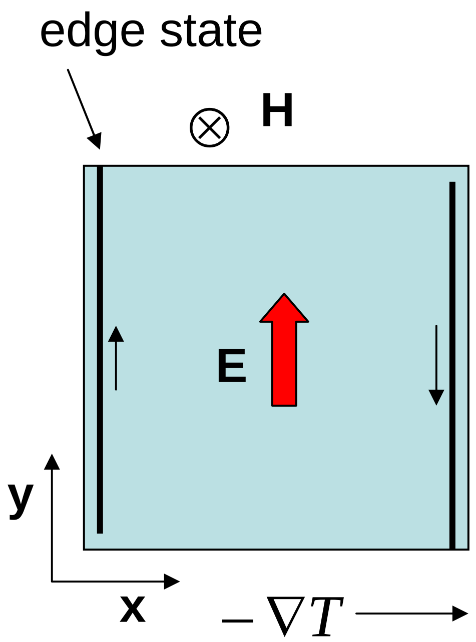
$$\alpha = -(\sigma E_x + \sigma_{xy} E_y) / |\partial T|$$

$$\alpha_{xy} = (\sigma_{yx} E_x + \sigma E_y) / |\partial T|$$

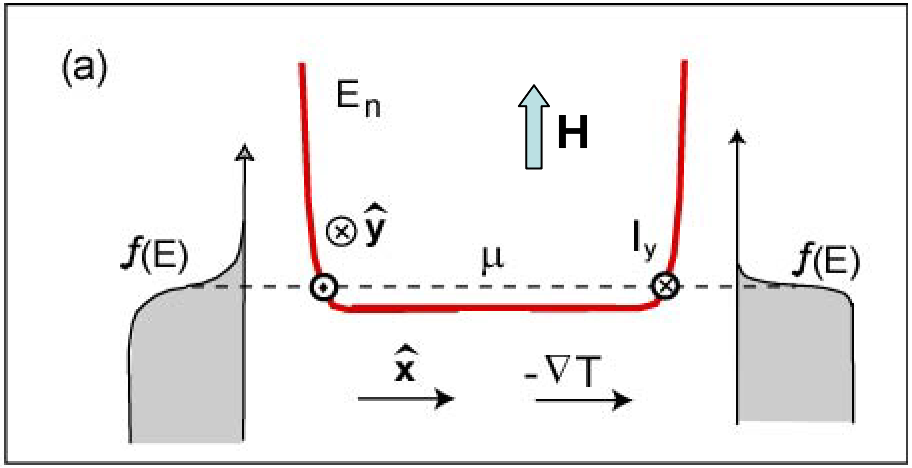
Thermopower at 9 T and 20 K



Thermopower in QHE regime (n>0)



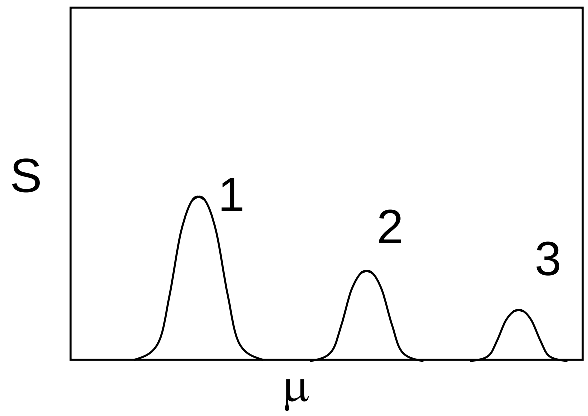
Girvin & Jonson, J Phys C 1982, PRB 1984



$$I_x = 0 \qquad I_y = \frac{L}{2\pi}\sum_n \int dk \frac{e}{\hbar L}\hbar v_k f(\varepsilon_{nk})$$

$$\alpha_{xy} = \frac{e}{hT}\sum_n \int_{E_n}^{\infty} d\varepsilon\,(\varepsilon-\mu)\left(-\frac{\partial f}{\partial \varepsilon}\right)$$

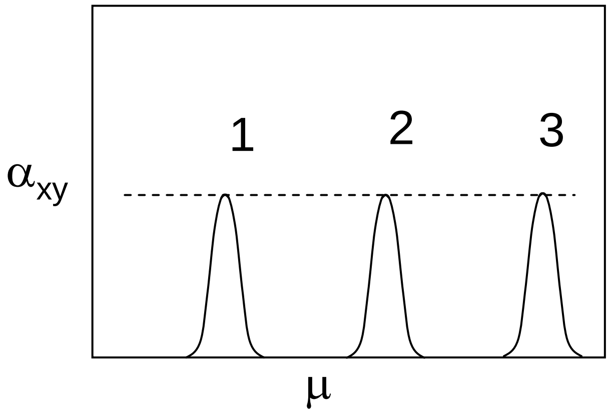
Quantization of thermoelectric current



1) Current response to ΔT is off-diagonal

$$S = \rho_{yx}\alpha_{xy} \qquad S_{\mathbf{max}}(n) = \frac{k_B \ln 2}{e(n+1/2)}$$

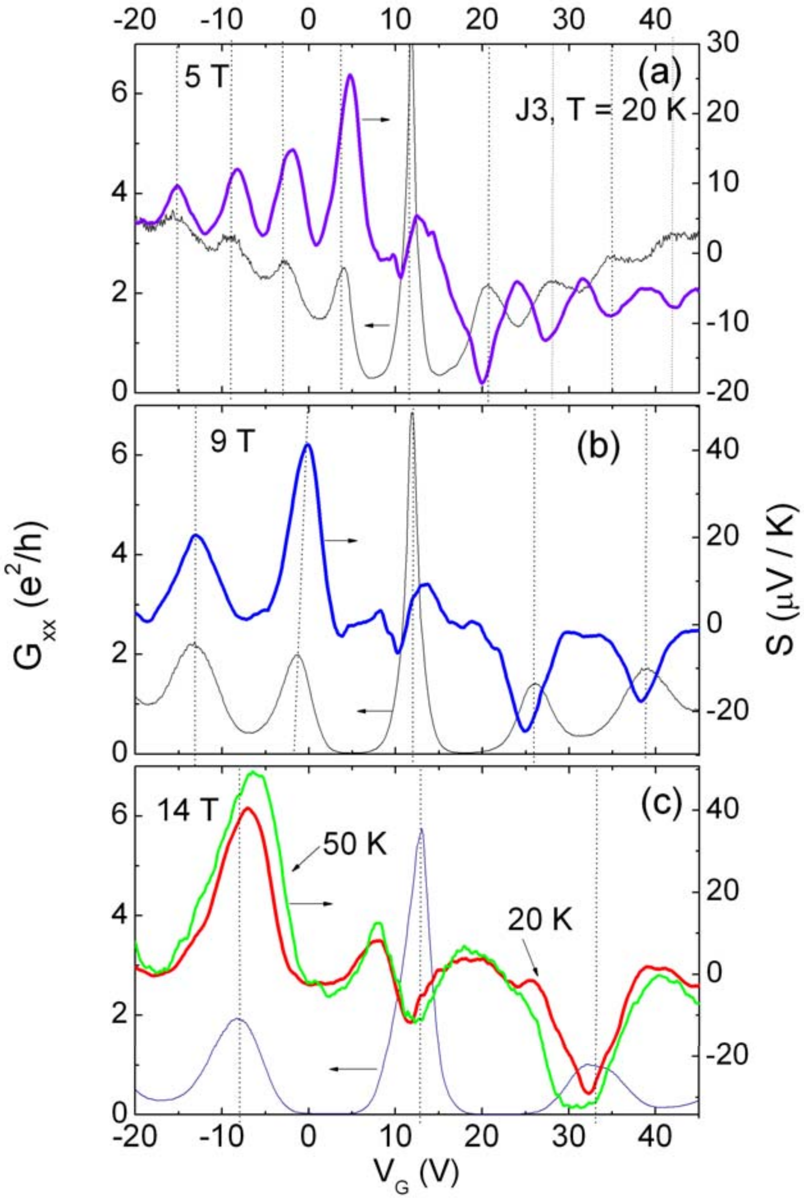
Dirac



α_{xy} is quantized indpt of *n*

$$\alpha_{xy} = \frac{k_B e}{h}\ln 2 \quad = \text{93 nA/K}$$

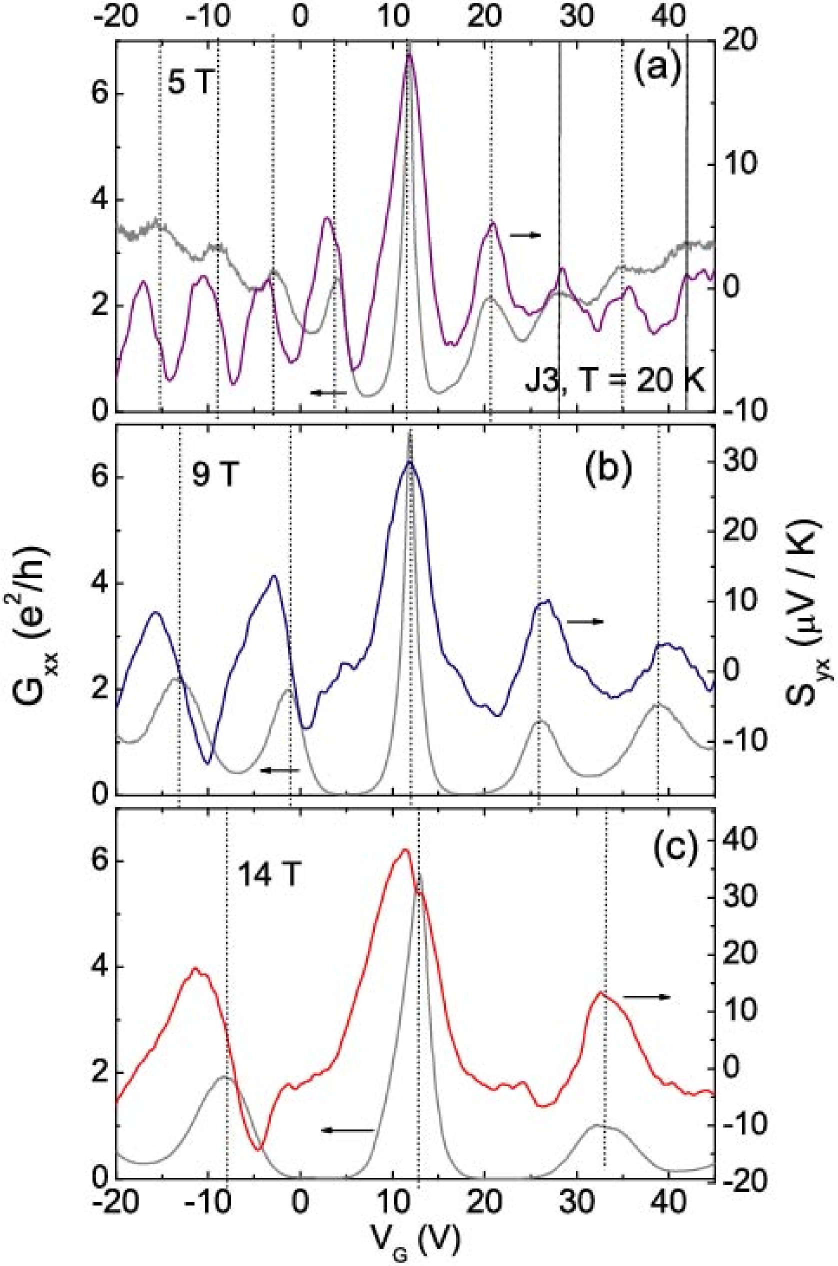
Thermopower at 5, 9 and 14 T



Features of thermopower

1. **Charge antisymmetric**
2. **Peak at n=1 nearly indpt of H**
3. **Very weak T dependence below 50 K**

Nernst Signal (off-diagonal S_{yx})



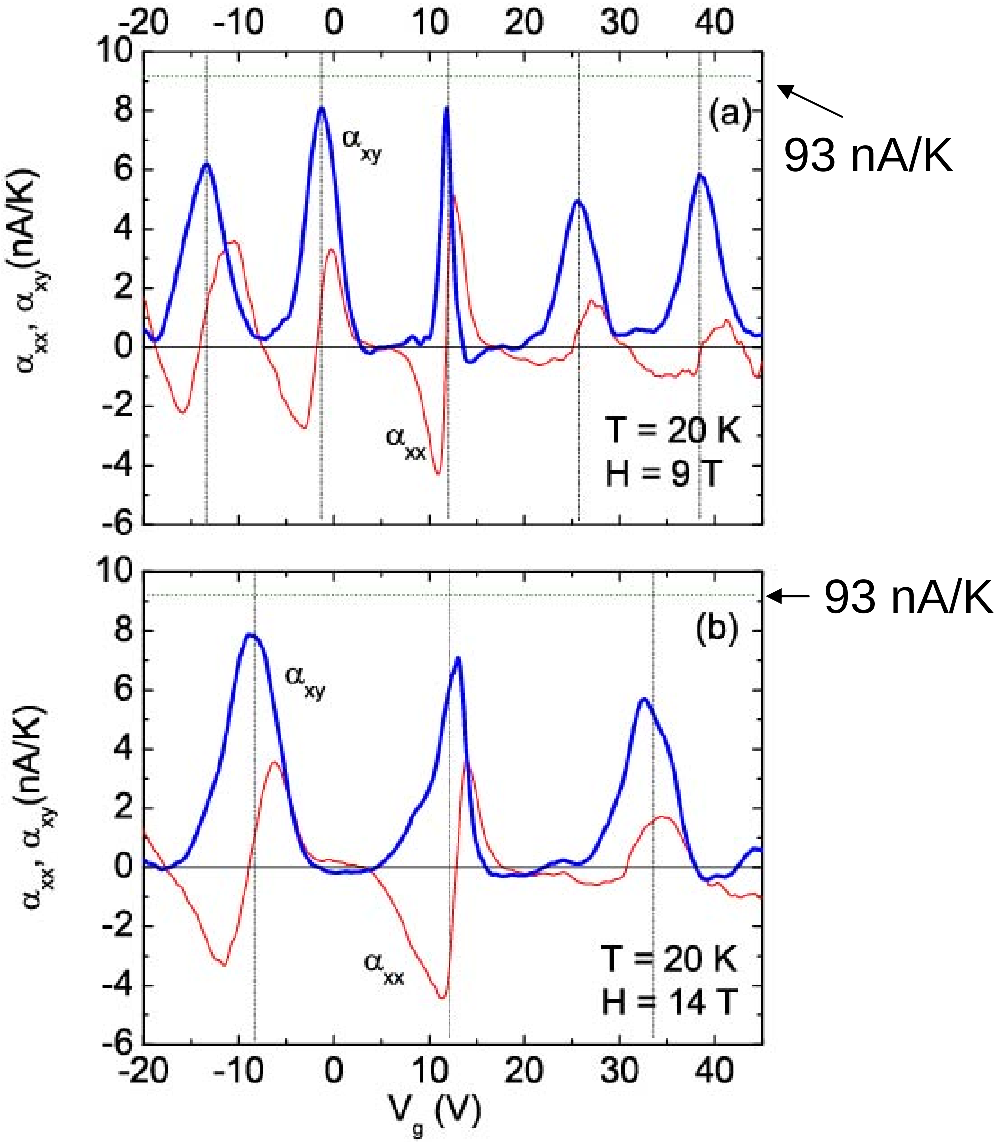
Nernst signal in graphene

- **Charge symmetric**
- **Nernst signal is anomalously large at Dirac Point**

3. Peaks at n=0, but dispersive for n=1,2,3…

4. At n=0, sign is positive (similar to vortex-Nernst signal in superconductors)

The thermoelectric tensor elements αxx and αxy



$$\alpha = -(\sigma E_x + \sigma_{xy} E_y) / |\partial T|$$

$$\alpha_{xy} = (\sigma_{yx} E_x + \sigma E_y) / |\partial T|$$

1) Peaks well defined
2) α_{xx} is antisym. In e
3) α_{xy} is symmetric

4) A surprise:

α_{xy} peak very narrow at n=0

Within 20% of quantized value
(need to estimate gradient
more accurately)

In graphene

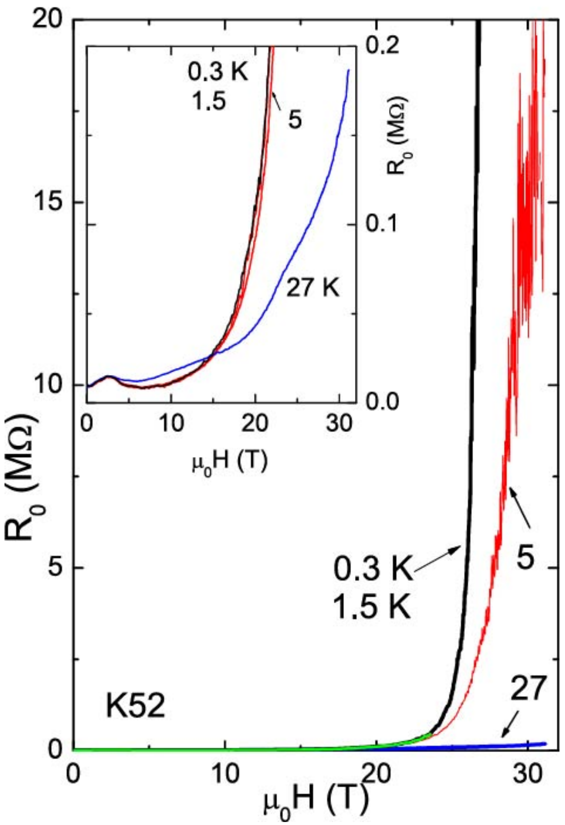
1. **Field induces transition to insulating state at H_c that correlates with V_0.**

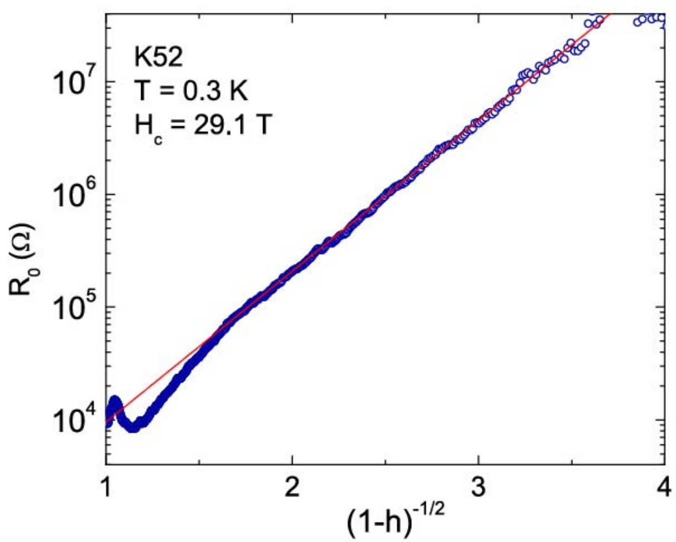
2. **For $H>H_c$, R_0 is thermally activated (Δ ~ 14 K), $H<H$c, R0 saturates below 2 K.**

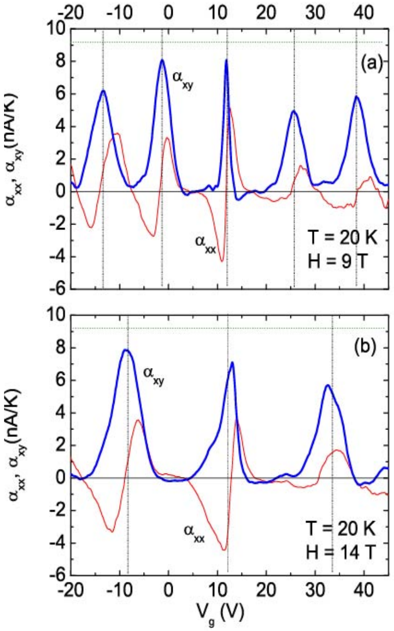
3. **$H<H_c$, divergence fits KT form $\exp[2b/(h-1)^{1/2}]$.**

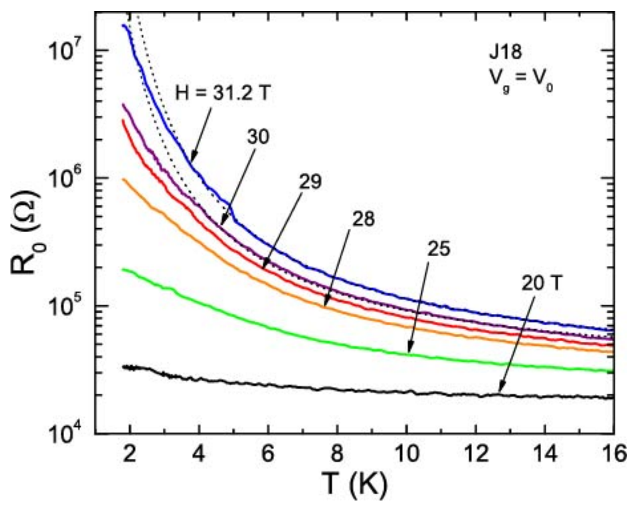
4. **Large Nernst signal at Dirac point.**

5. **α_{xy} consistent with quantization ~ 90 nA/K indpt of T, H and n.**









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