Results on graphene in high fields and on Sr_2RuO_4 in weak fields

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Princeton University

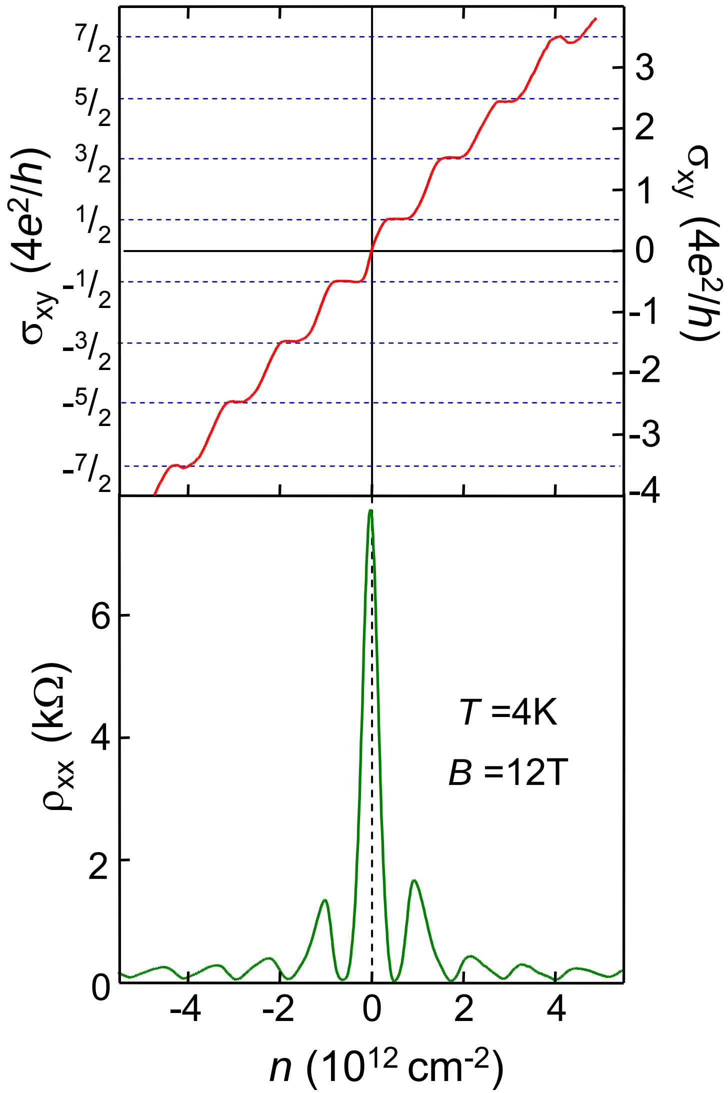
1. Introduction
2. Graphene from Kish graphite
3. The zero-energy state
4. Edge modes or QHF

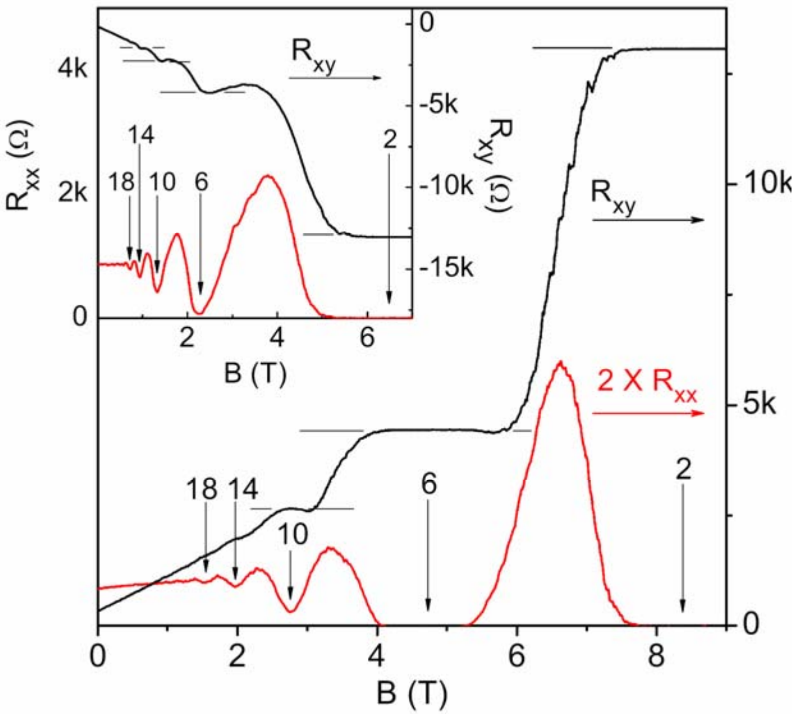
Magnetization in p-wave superconductor
L. Li, P. Casey, Y. Maeno and NPO

1. M vs H in Sr_2RuO_4 **H||c**

St. Andrews July 2007

Quantum Hall Effect in graphene





Y.Zhang, Kim et al., Nature **438**, 201 (05)

Novoselov, Geim et al., Nature **438**, 197 (05)

Single atomic-layer graphene

- Graphene sheets peeled off onto Si/SiO_2 wafers
- Single atomic-layer samples identified
- Au contacts attached by e-beam lithography

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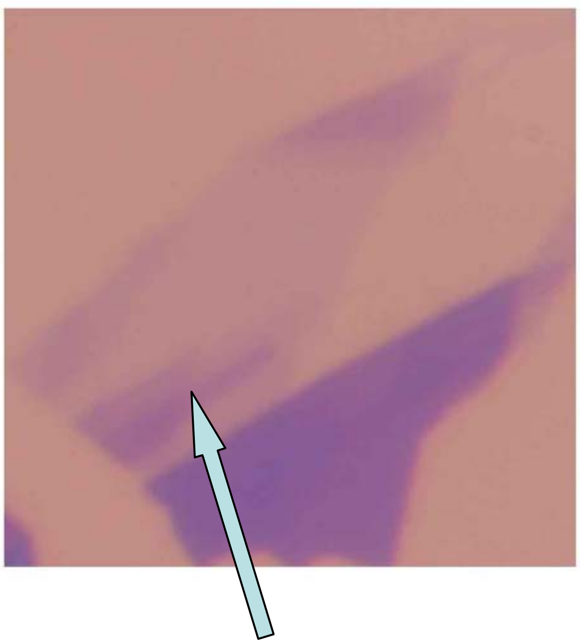
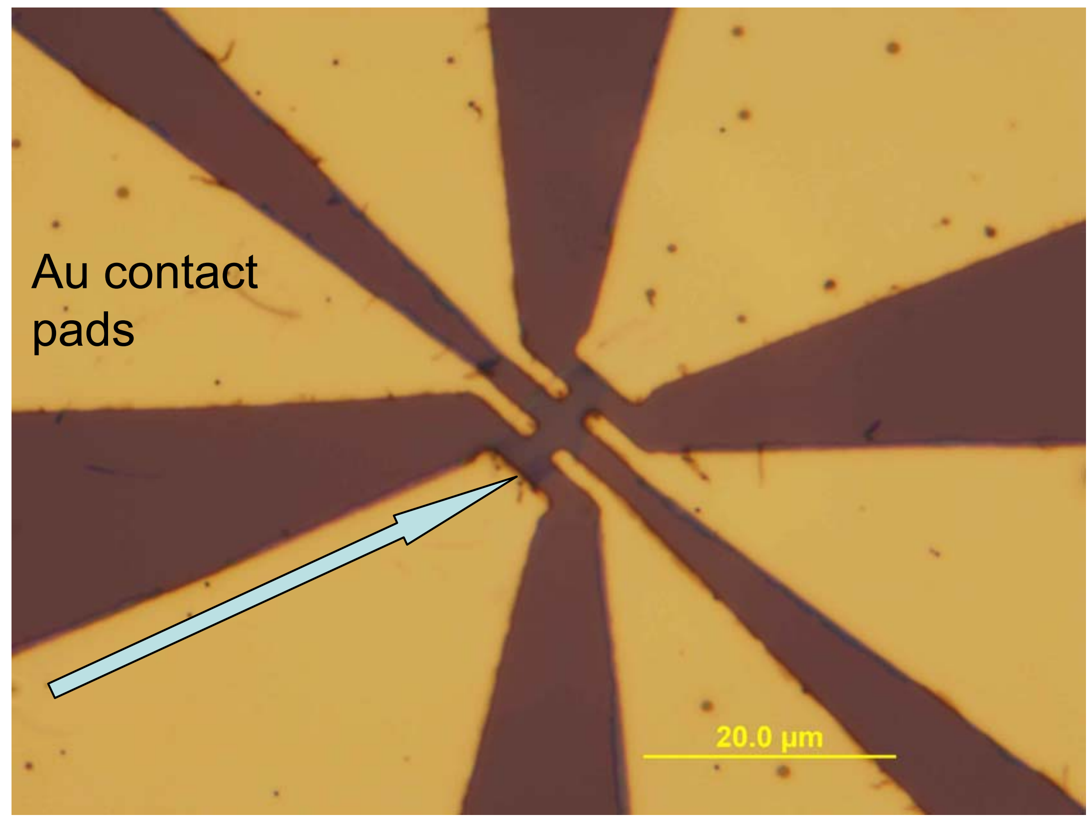
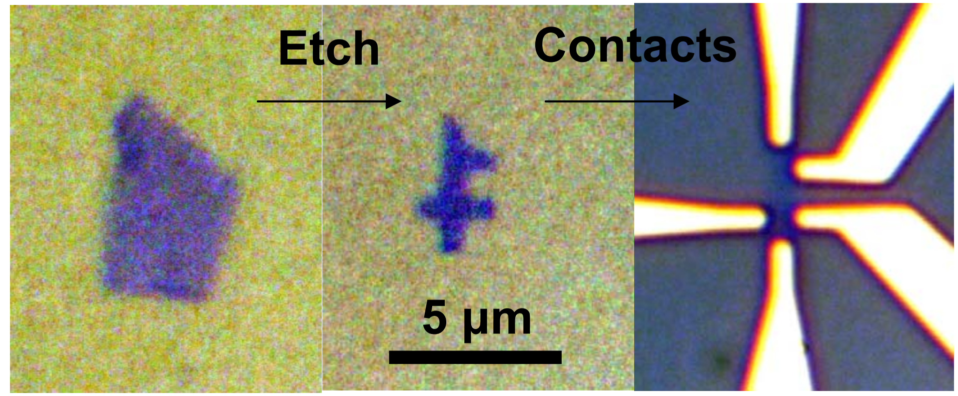
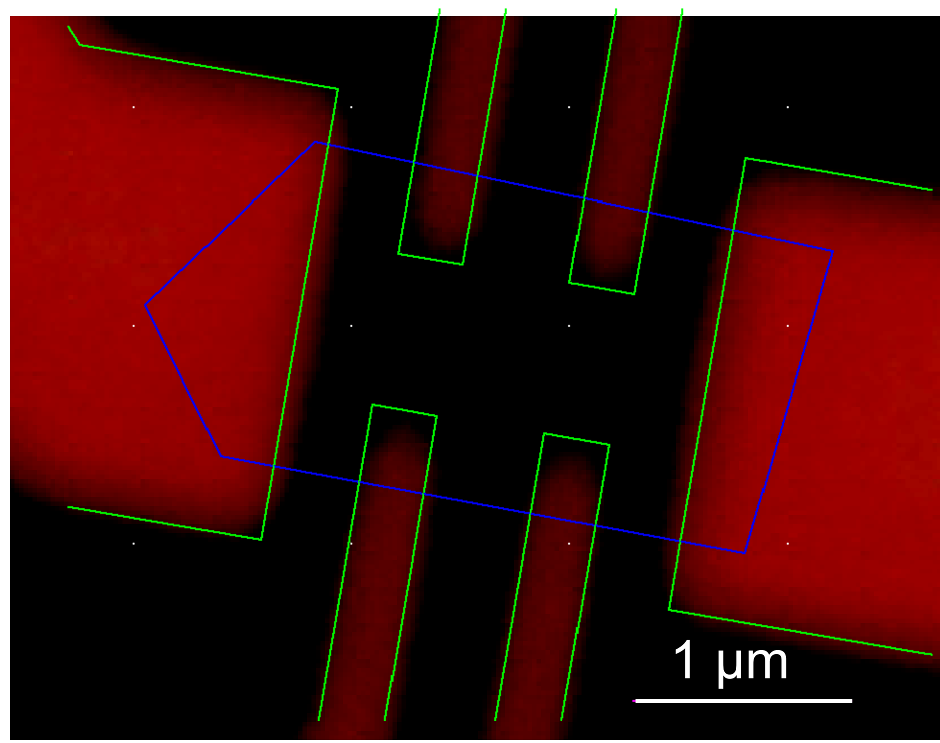




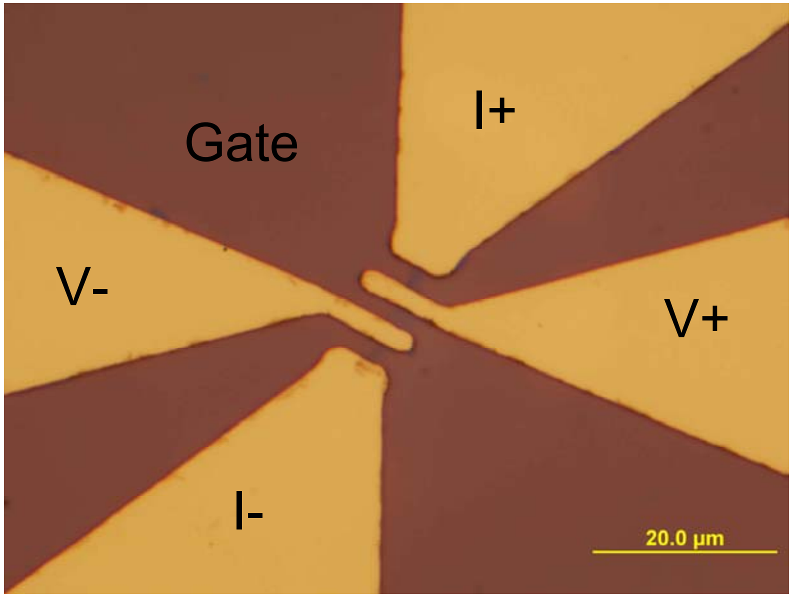
Single atomic-layers

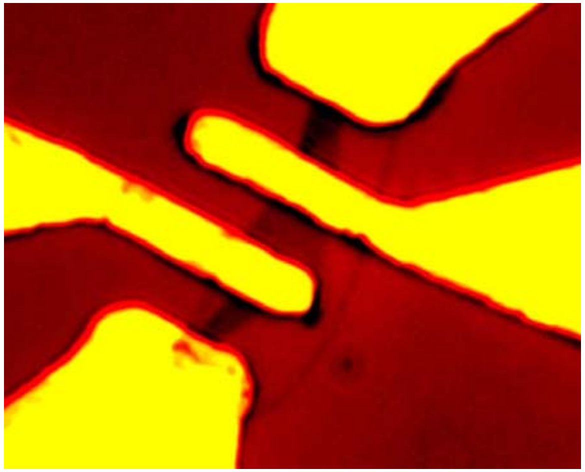
Single atomic-layer graphene





Single atomic-layer graphene





The Quantized Hall Effect in graphene

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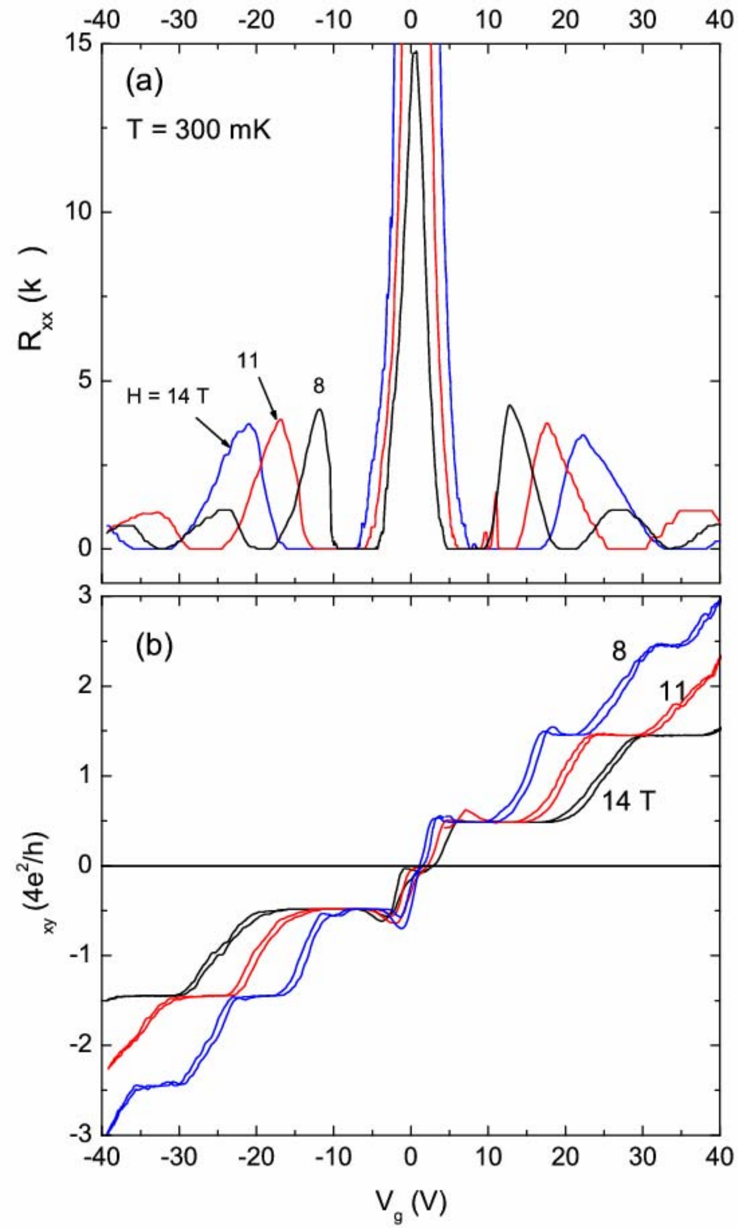
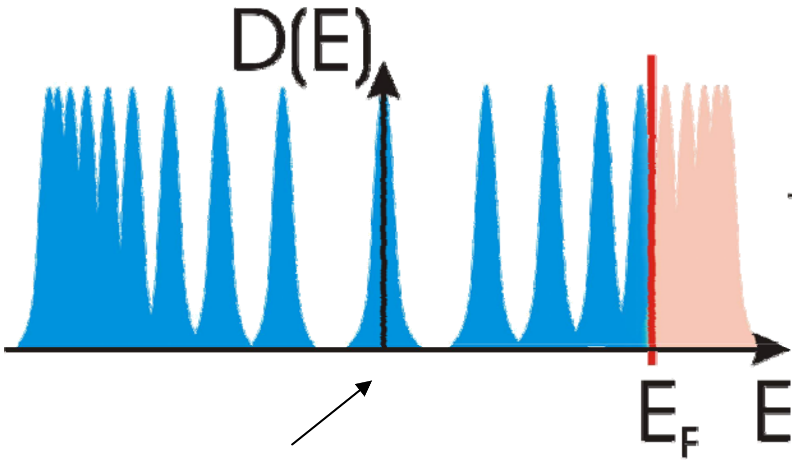
Panel (a) Resistivity R_{xx} of graphene vs gate voltage V_g at fields H = 8, 11 and 14 T. R_{xx} peaks at Landau Levels n = 0 and +1 and -1. The peak at n = 0 is singularly large. Temperature fixed at 0.3 K

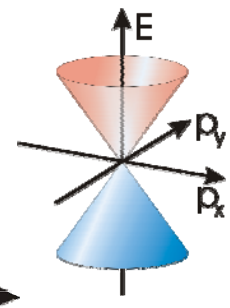
Panel (b) The Hall conductivity σ_{xy} shows step-quantization at universal values 0, $2e^2/h$, $6e^2/h$,…



Landau Levels in graphene



Zero mode

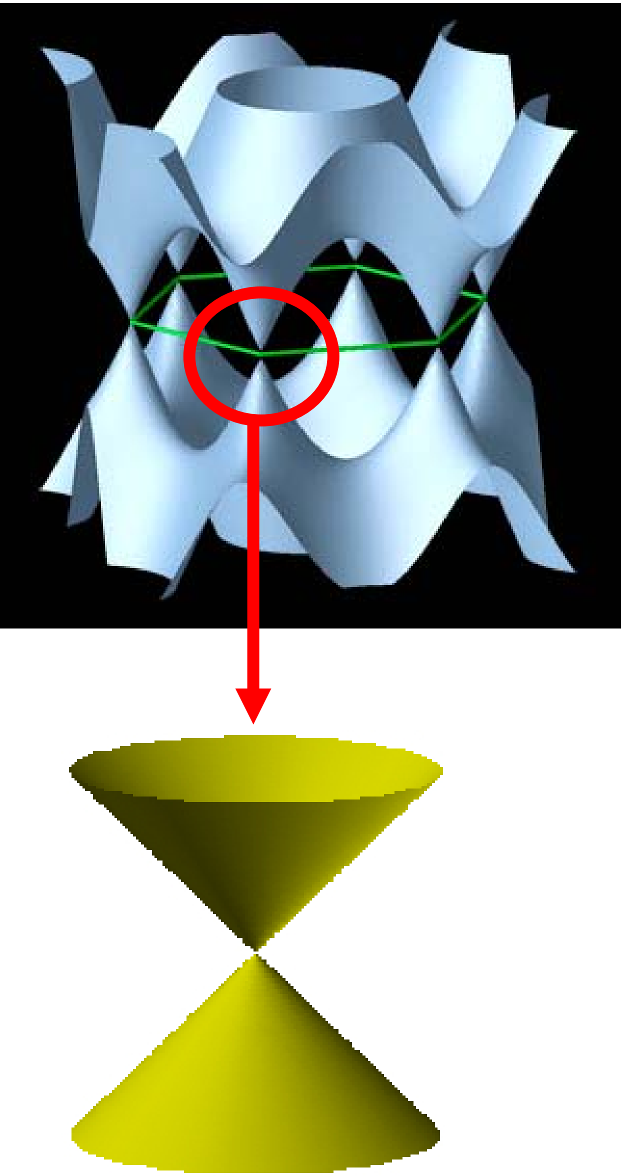


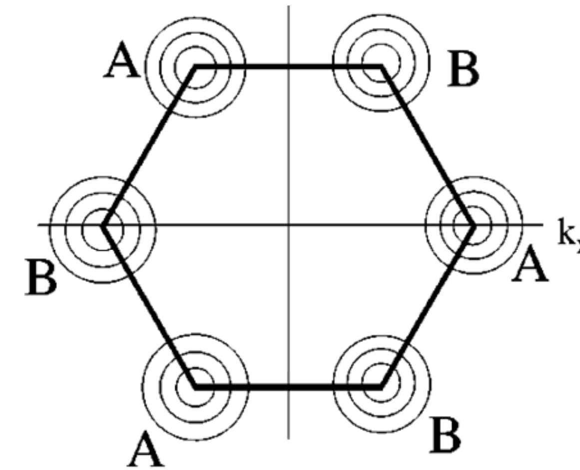
$$E_n = \mathrm{sgn}(n)|2n|^{1/2}\frac{\hbar v}{\ell_B}$$

B=10T, E_1-E_0=1500K

QHE at room temperature!

Momentum Space

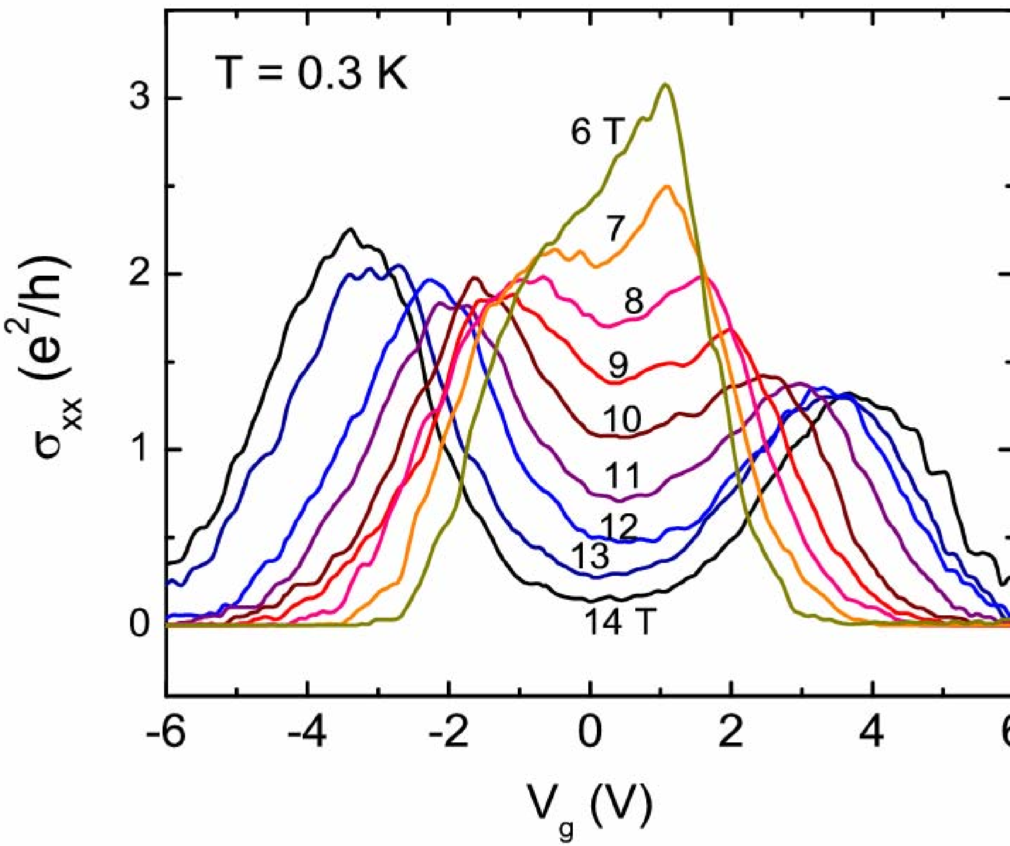




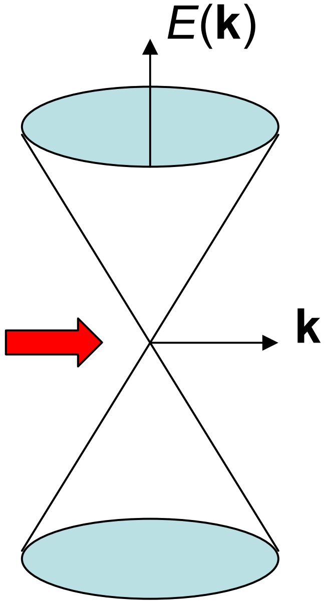
$E = v_0 |\, p \,|$ massless Dirac spectrum

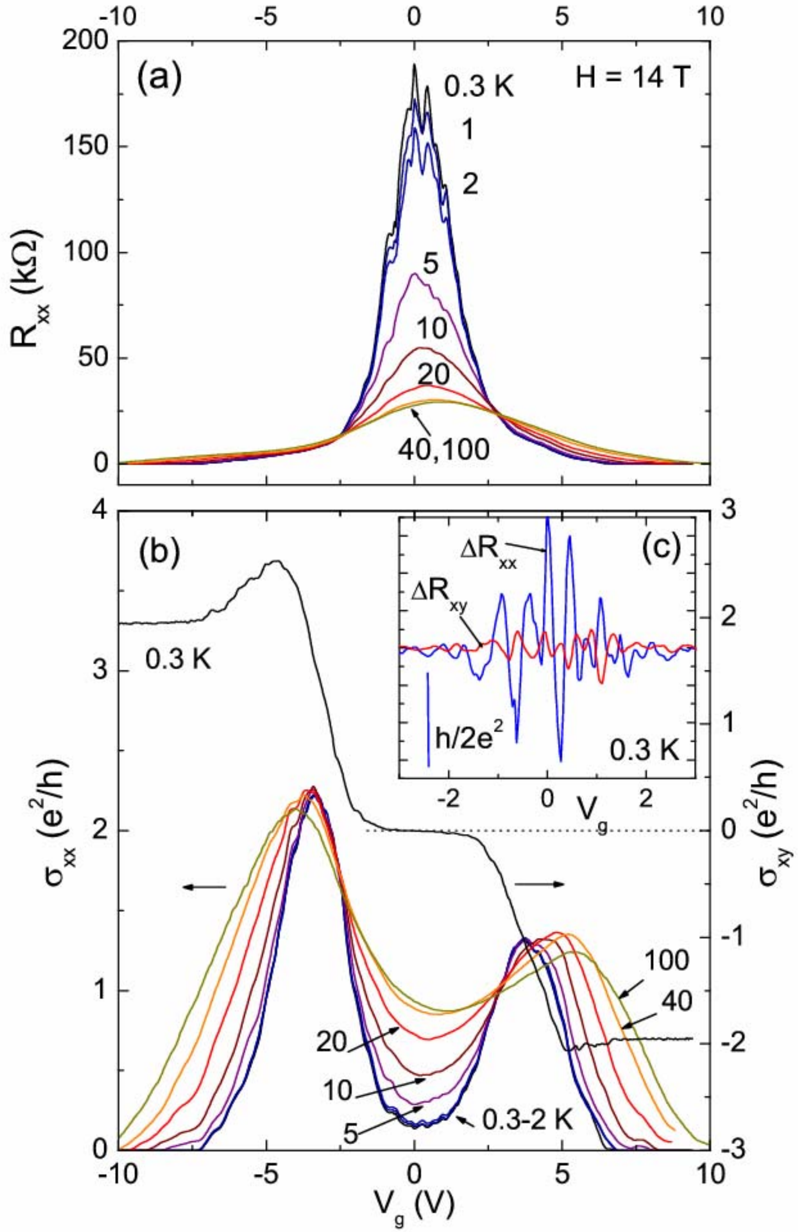
$v_0 = 10^6$ m/s $= c/300$

Opening of gap with field



Physics at the Dirac Point (*n* = 0 Landau Level)





(a) R_{xx} in n = 0 Landau Level increases steeply as $T \rightarrow 0$.

(b) Conductivity shows sublevel split. Hall conductivity displays plateau.

(c) Quantum oscillations in conductance at 0.3 K

Conductance G_0 at Dirac point $\mu = 0$

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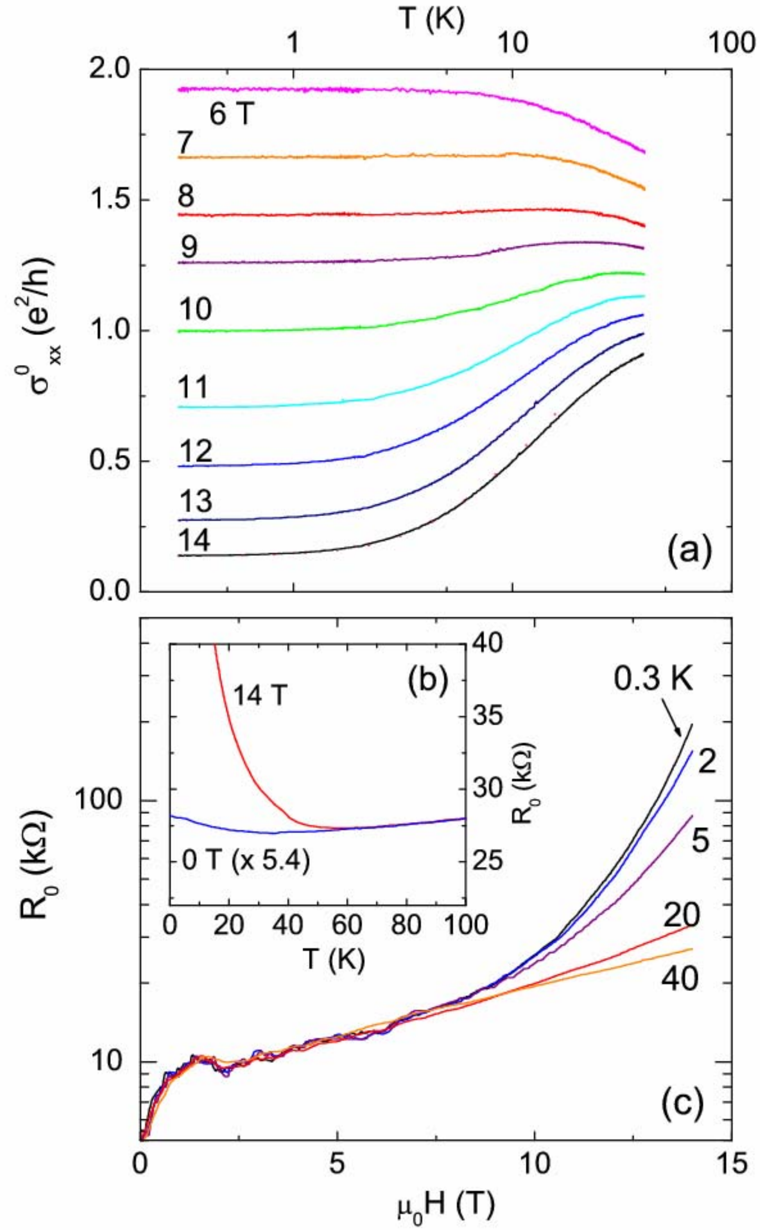
1. At large *H*, G_0 falls as T → 2 K revealing gap

2. G_0 saturates to G_{res} below 2 K *Gapless* excitations

3. G_{res} strongly suppressed by *H* *Faster* than Gaussian *exp(-H²)*

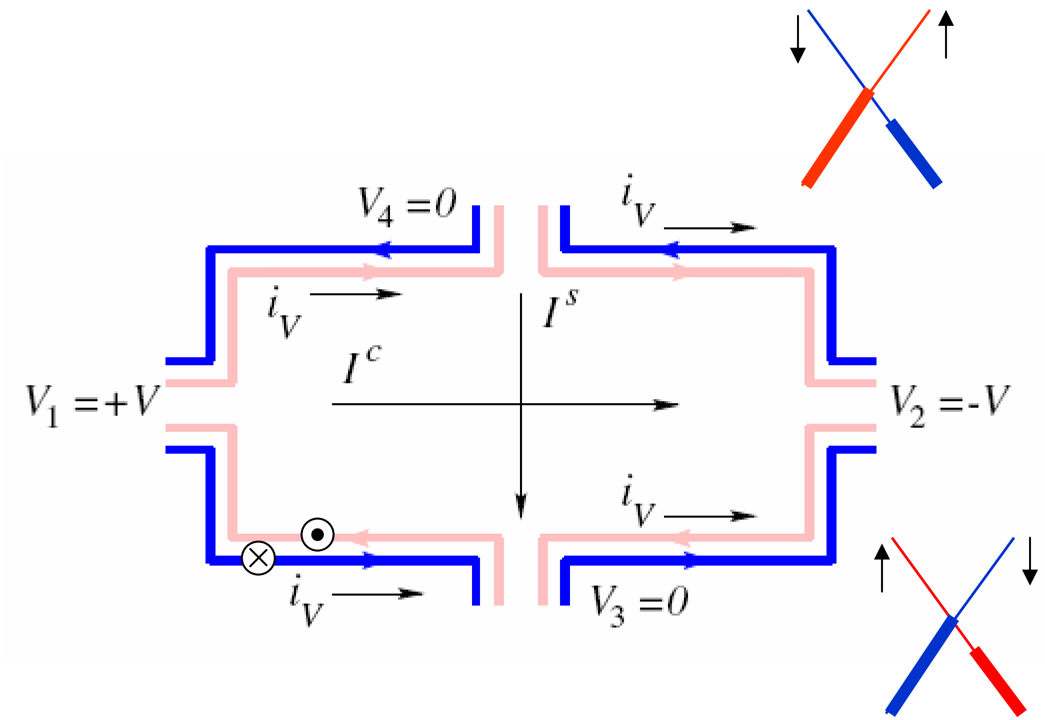
4. Phase diagram reveals unusual approach to insulating state

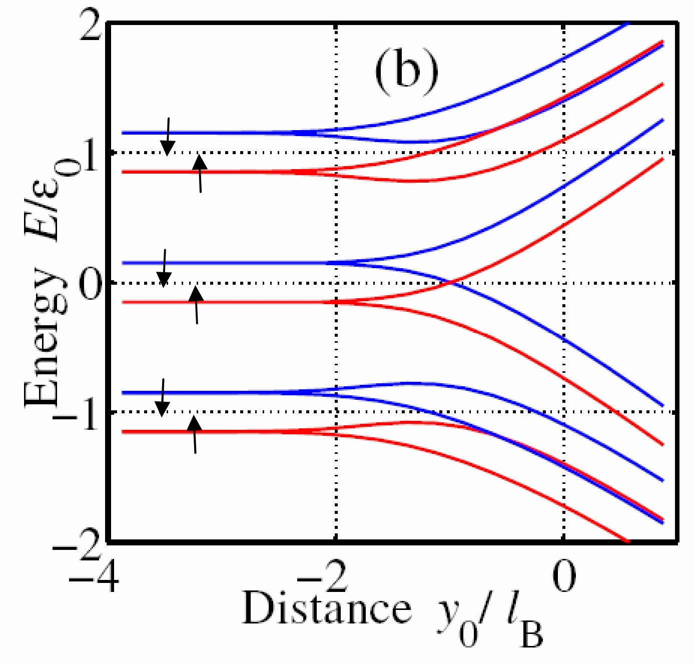
   a) Fixed H, gapless conductance
   b) Fixed T, insulating limit at large H



Spin-filtered chiral edge states

Abanin, Lee and Levitov, PRL (2006)

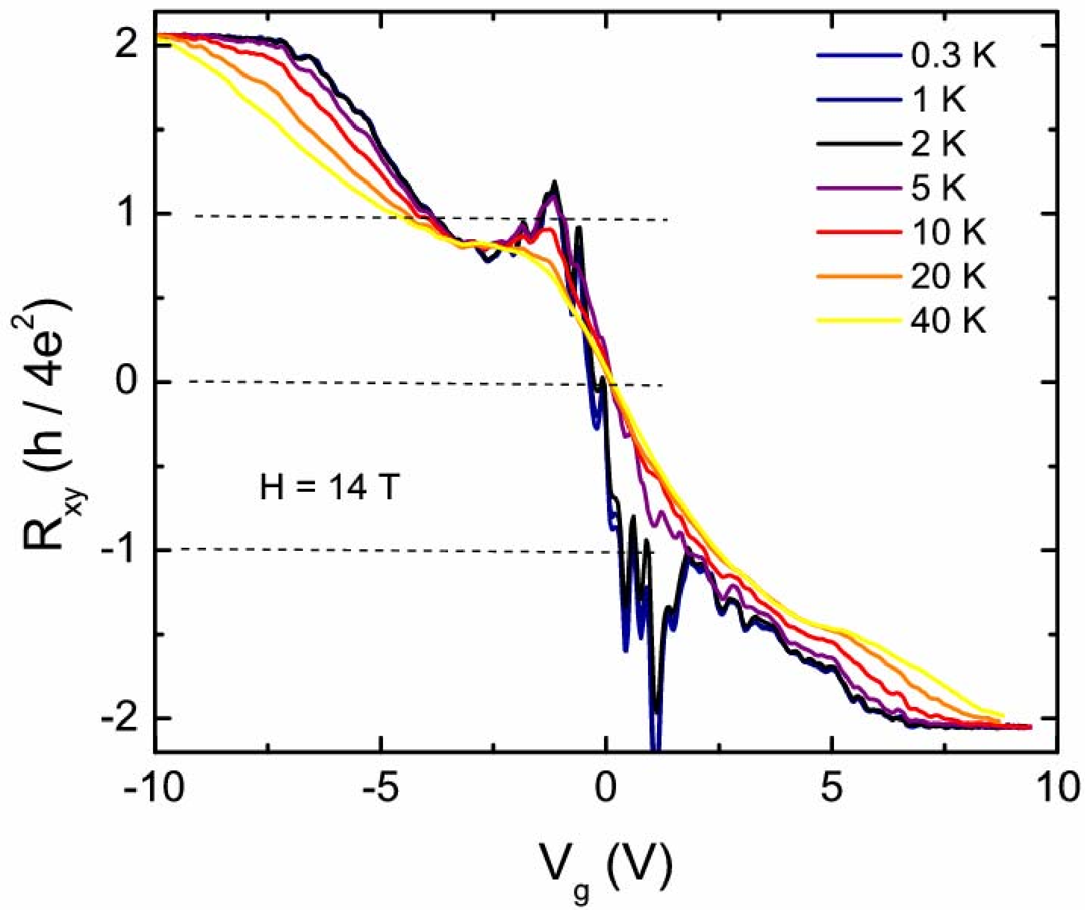




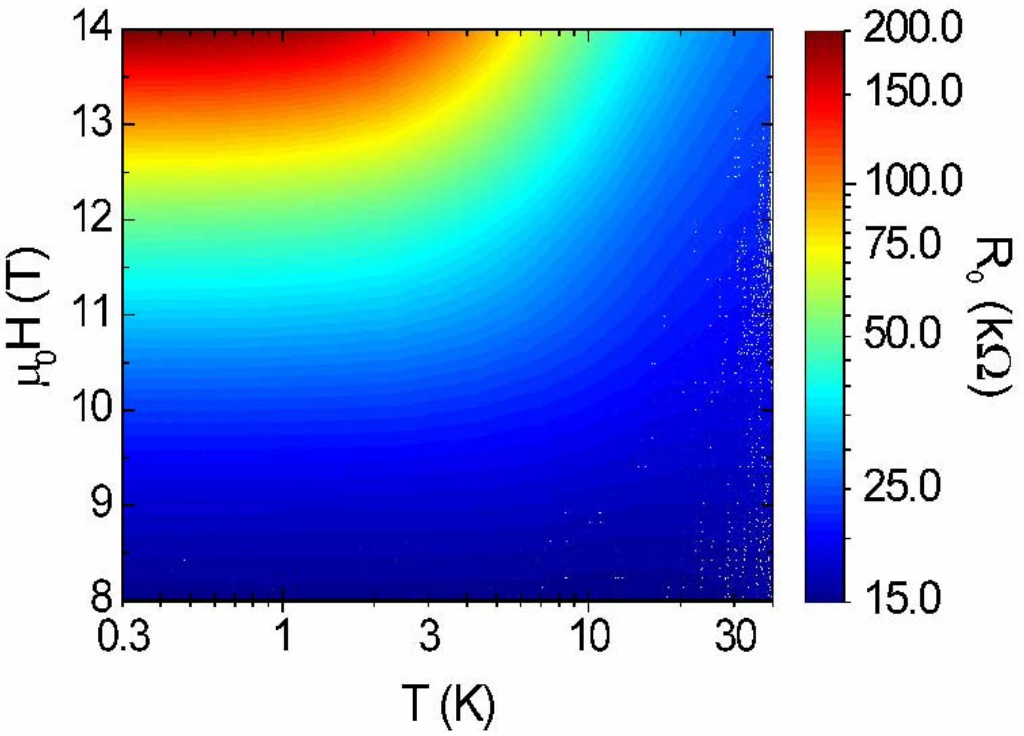
Edge →

No Hall current $R_{xy}=0$, but ideal spin current: $I_s=2e^2V/h$.
Also predicts longitudinal charge current, i.e.
$R_{xx}=h/2e^2$. (13 kOhms)

Incipient $\nu = 1$ Hall steps



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

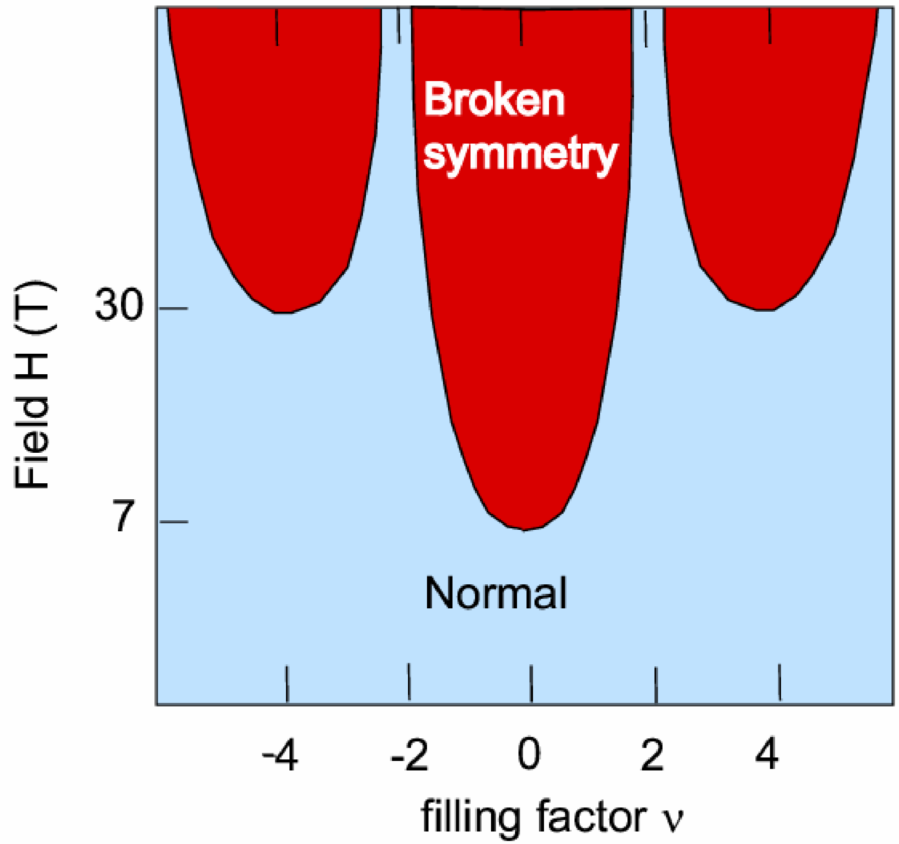
Quantum Hall ferromagnet?

Nomura, MacDonald, PRL06
Goerbig, Moessner, Ducot, PRB06
Alicia, Fisher PRB 06

Layer index → Valley index *K, K'*

1. Coulomb exchange
Splits 4-fold degeneracy
Of n = 0 Landau Level

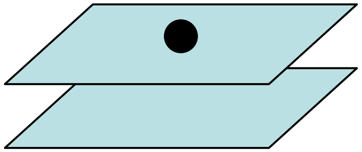
2. In high fields (and
low disorder), have QHF
state.



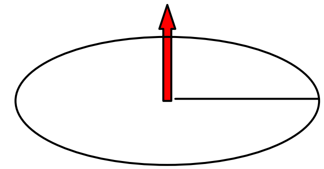
Role of Coulomb Interaction -- quantum Hall ferromagnet

Pseudospin in Bilayer QHE systems

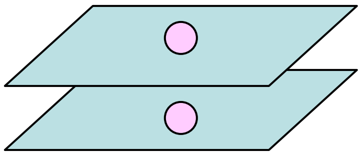
Moon, Yang, Girvin, MacDonald… 1995



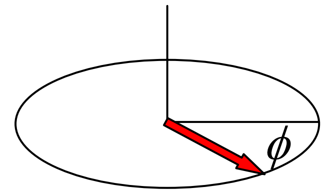
$$\begin{bmatrix}1\\0\end{bmatrix} = 1|\uparrow\rangle + 0|\downarrow\rangle$$



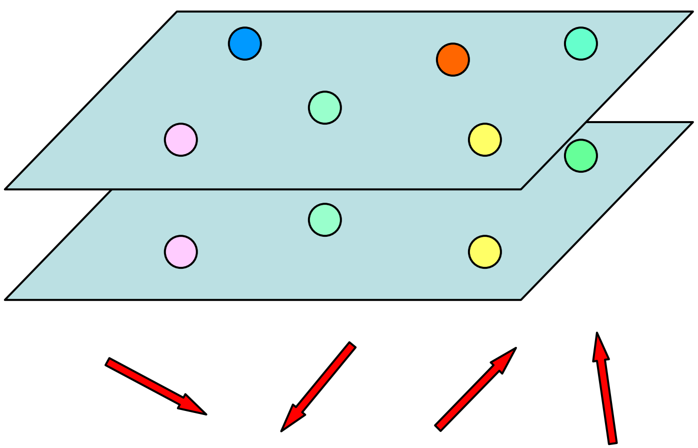
Capacitance → *U(1)* symm.



$$\begin{bmatrix}1\\e^{i\phi}\end{bmatrix} = \left(1|\uparrow\rangle + e^{i\phi}|\downarrow\rangle\right)\frac{1}{\sqrt{2}}$$

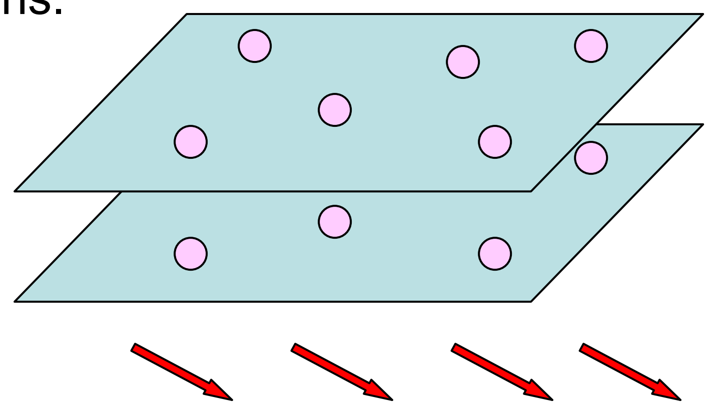


Paramagnet



KT trans.

2DXY Ferromagnet



Coulomb exchange leads to spontaneous alignment of pseudospins (Hund's rule)

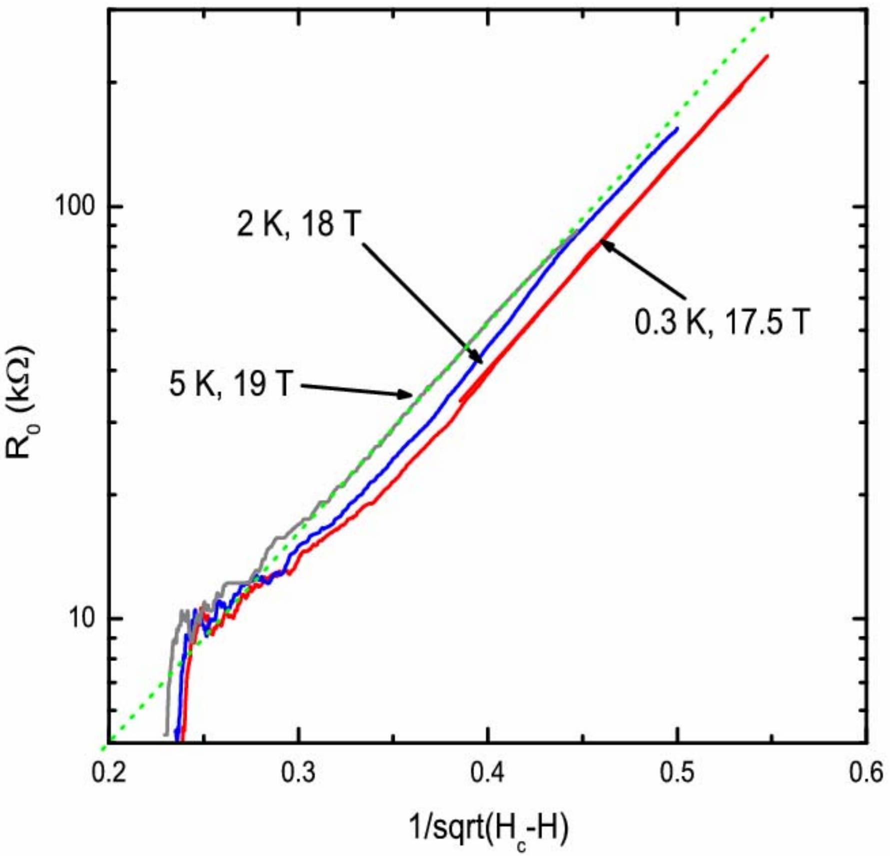
Divergent resistance in high field

Approaching KT transition?

Correlation length

$$\xi = a \exp\left[\frac{b}{\sqrt{h-1}}\right]$$

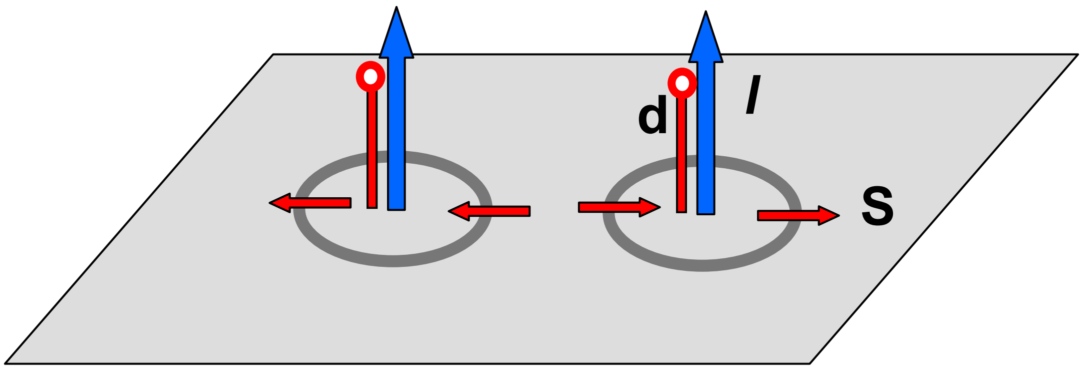
Data suggest H_c ~ 17 – 19 Tesla



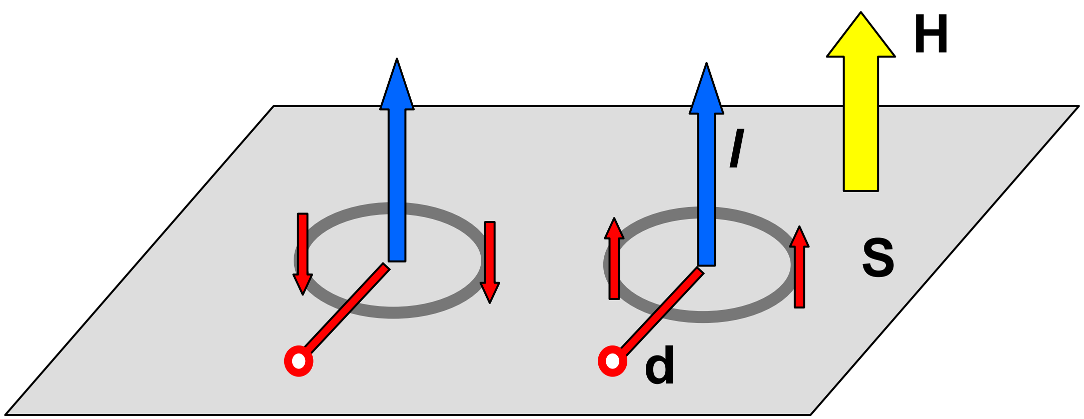
Magnetization of Sr_2RuO_4 in field H||c

Lu Li, P. Casey, Y. Maeno and N. P. Ong

Cooper pairs in p-wave superconductor (and ^{3}He A-phase)



Equal spin pairing
Dipole-locked
(***l*** || **d**)

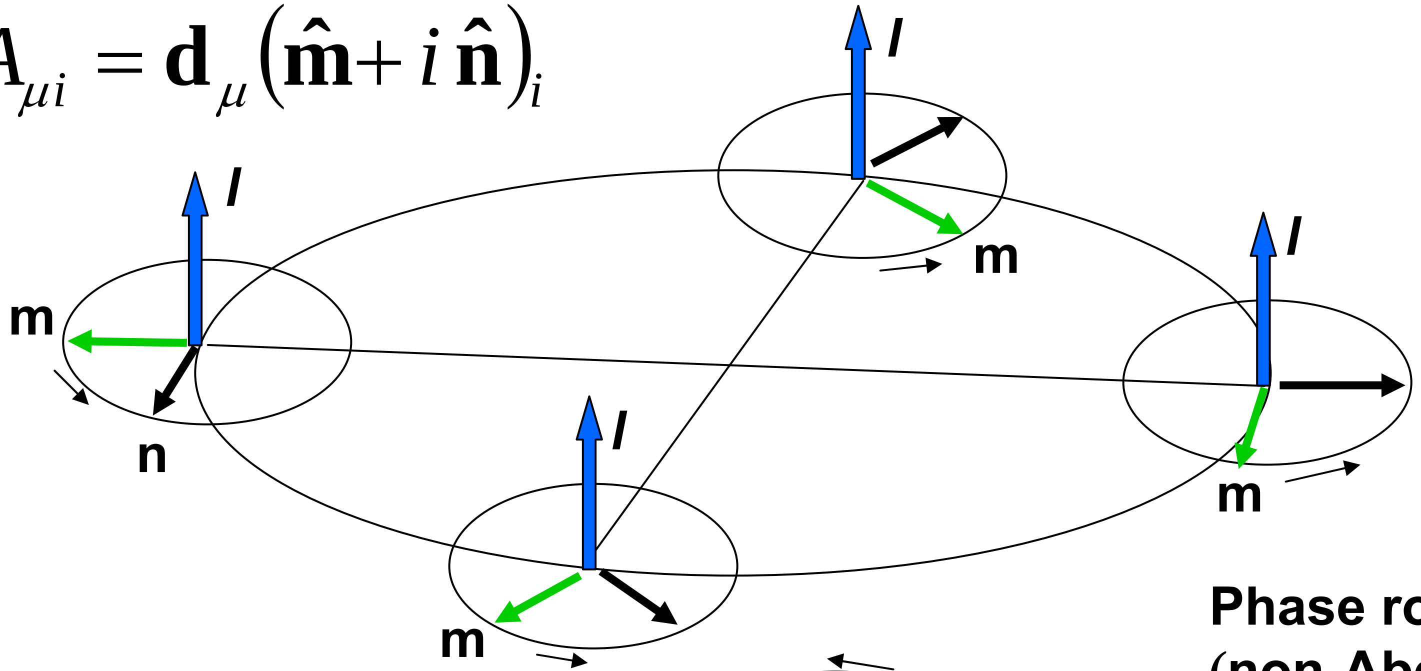


Magnetic field H
drives
dipole unlocking
transition

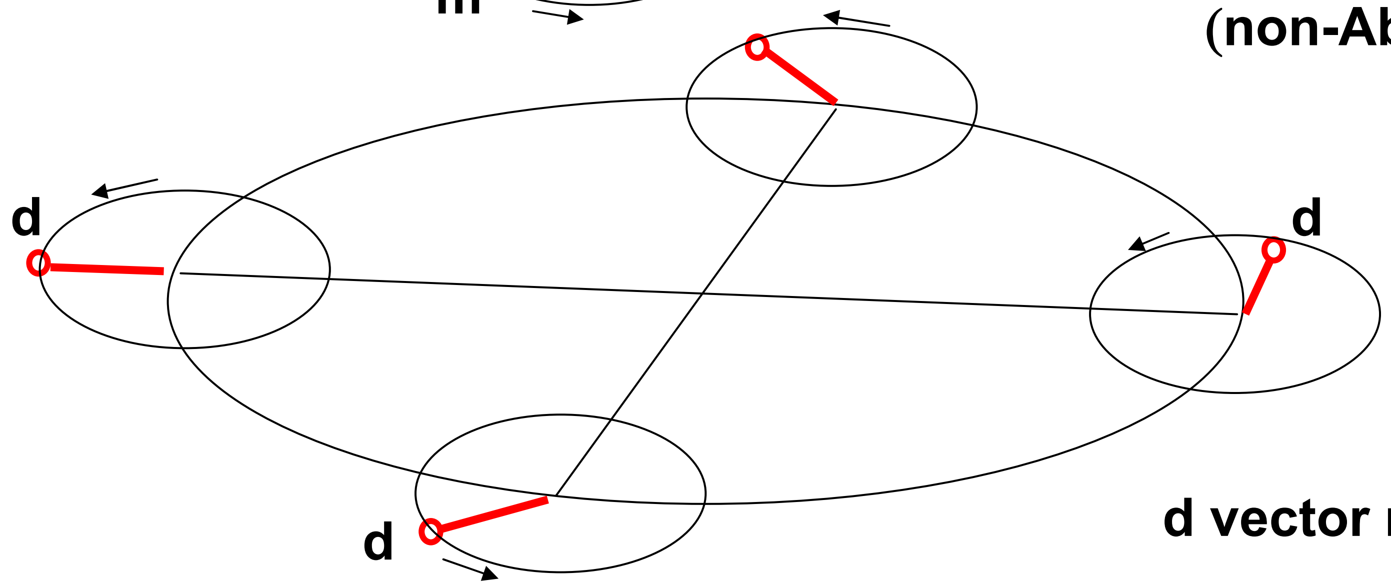
Half-vortex may be energet. favored

Circulation around a half-vortex

$$A_{\mu i} = \mathbf{d}_{\mu}\left(\hat{\mathbf{m}} + i\,\hat{\mathbf{n}}\right)_i$$

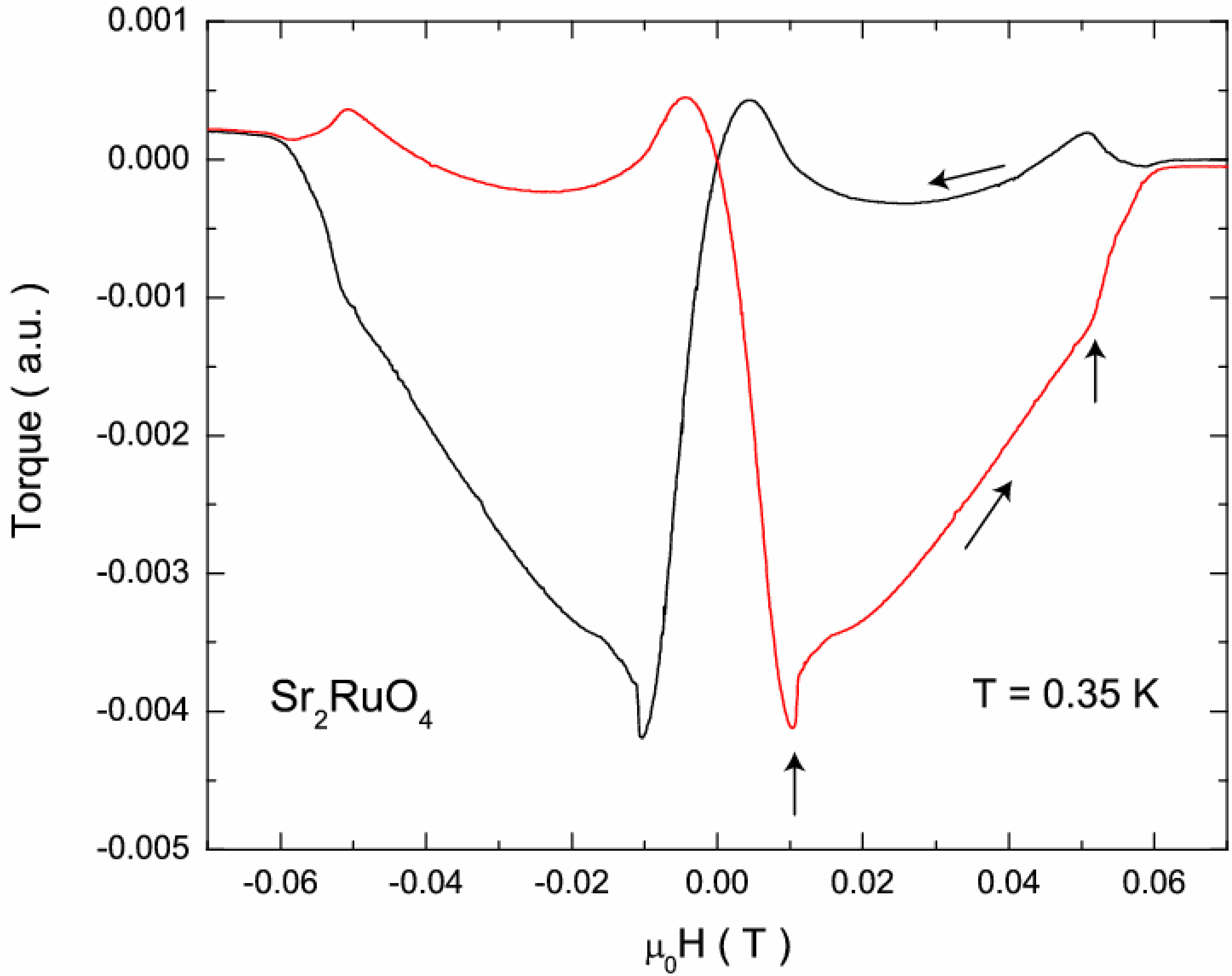


Phase rotates by π (non-Abelian)



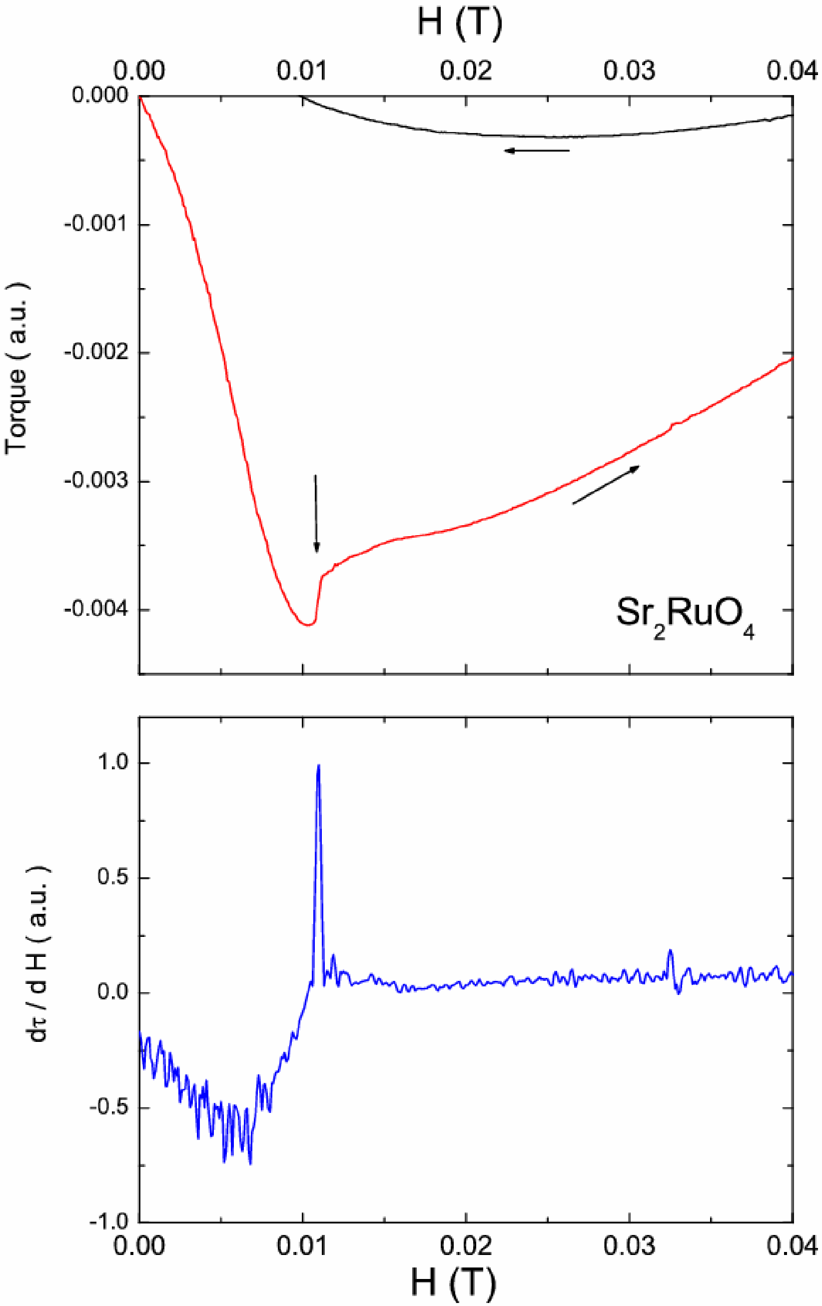
d vector rotates by π

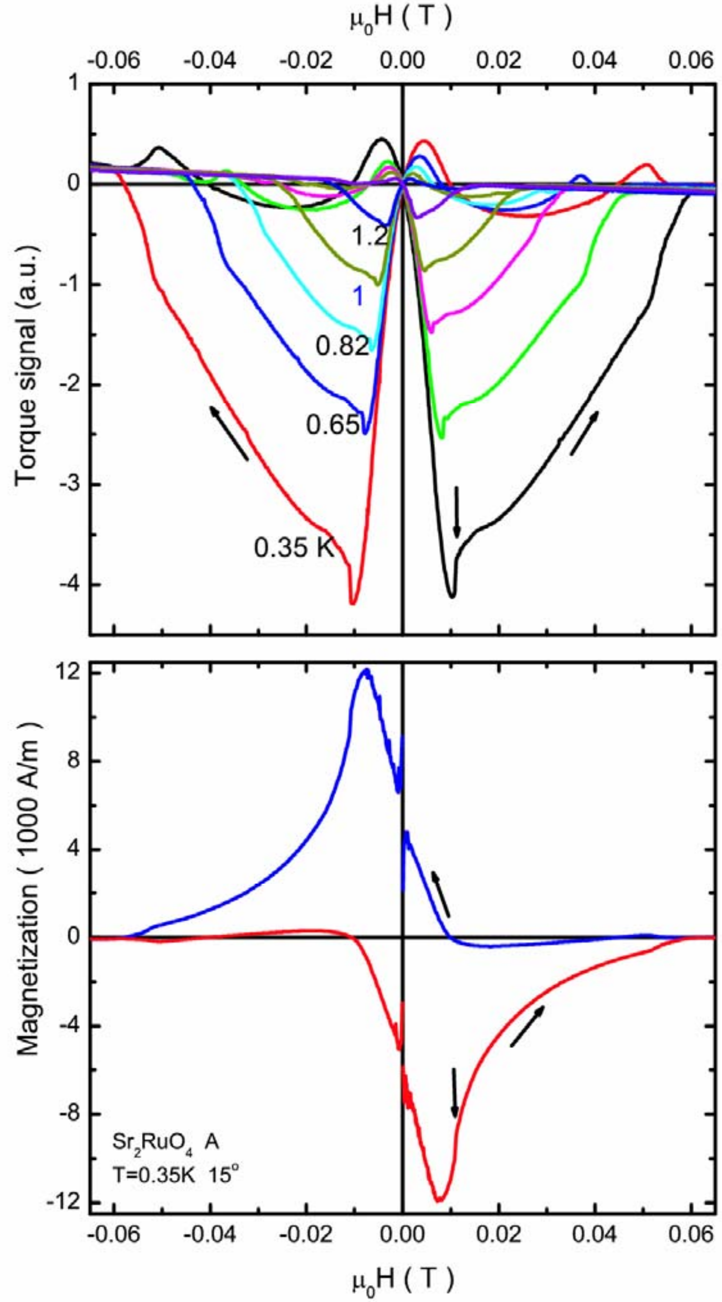
Torque signal in Sr_2RuO_4 **H || c**



Sharp transition
In magnetic fied
H ~ 120 Gauss

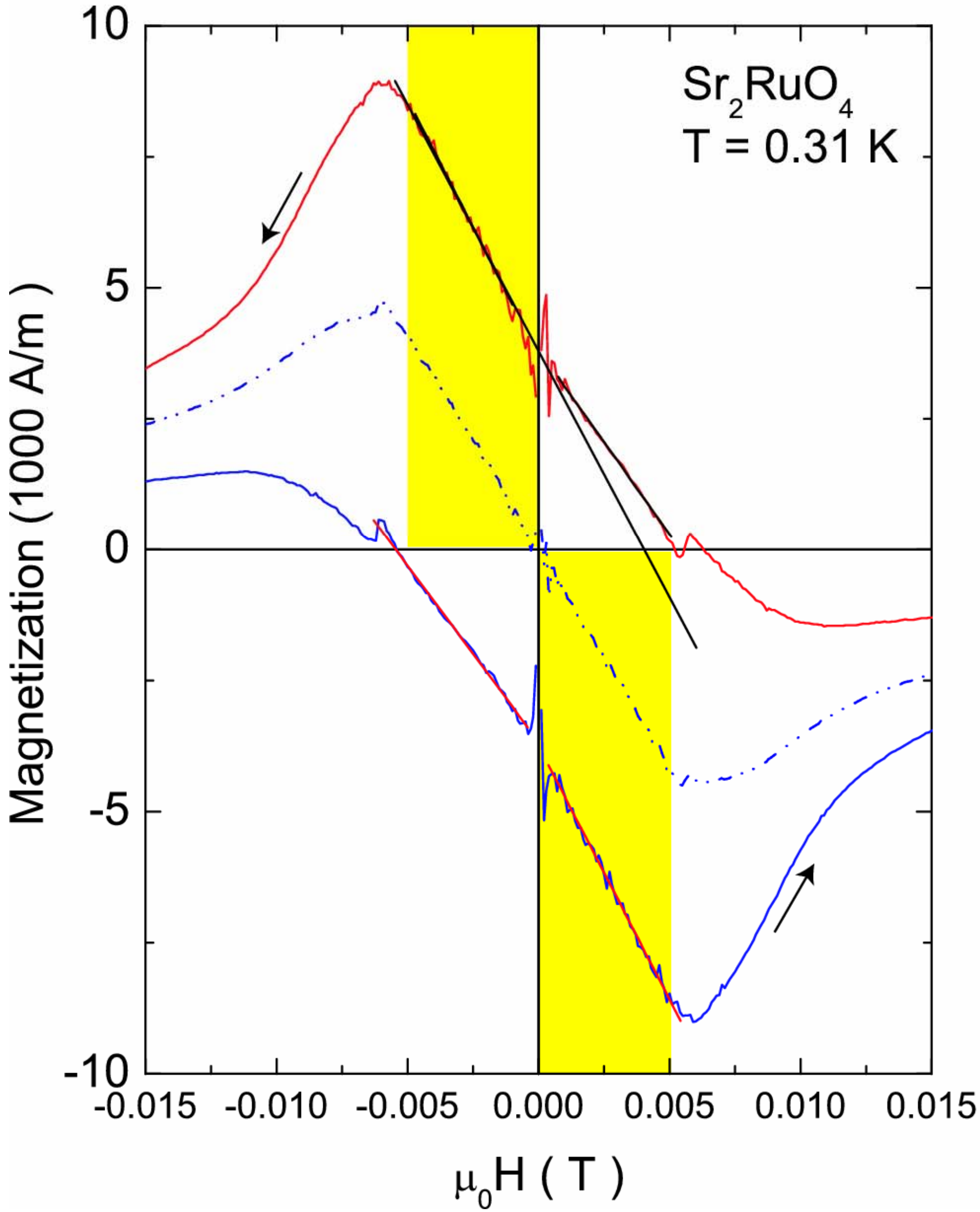
Dipole unlocking
Transition?



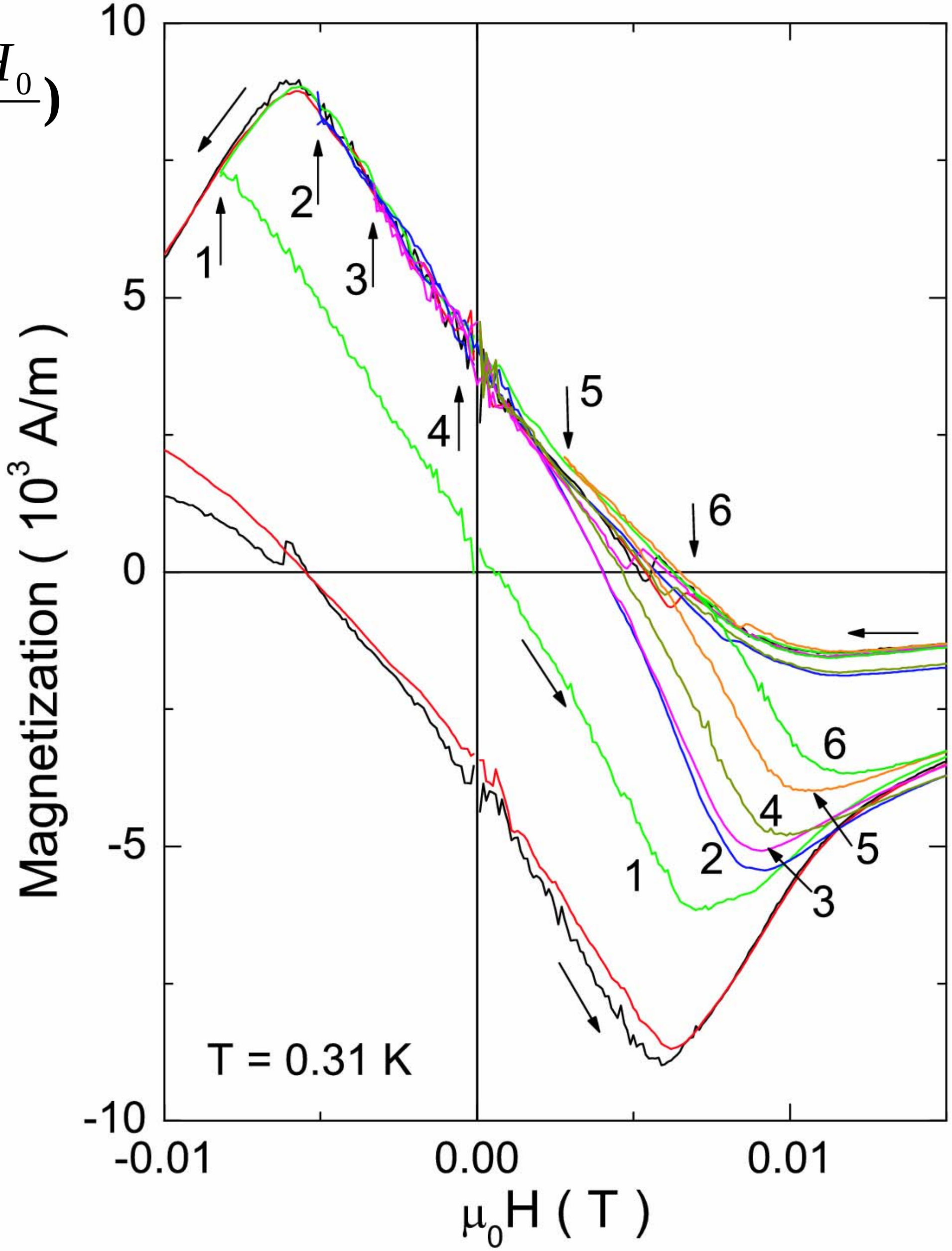


μ0H (T)
Torque signal (a.u.)
1.2
1
0.82
0.65
0.35 K
Magnetization (1000 A/m)
Sr2RuO4 A
T=0.35K 15°
μ0H (T)

Break in slope at H = 0

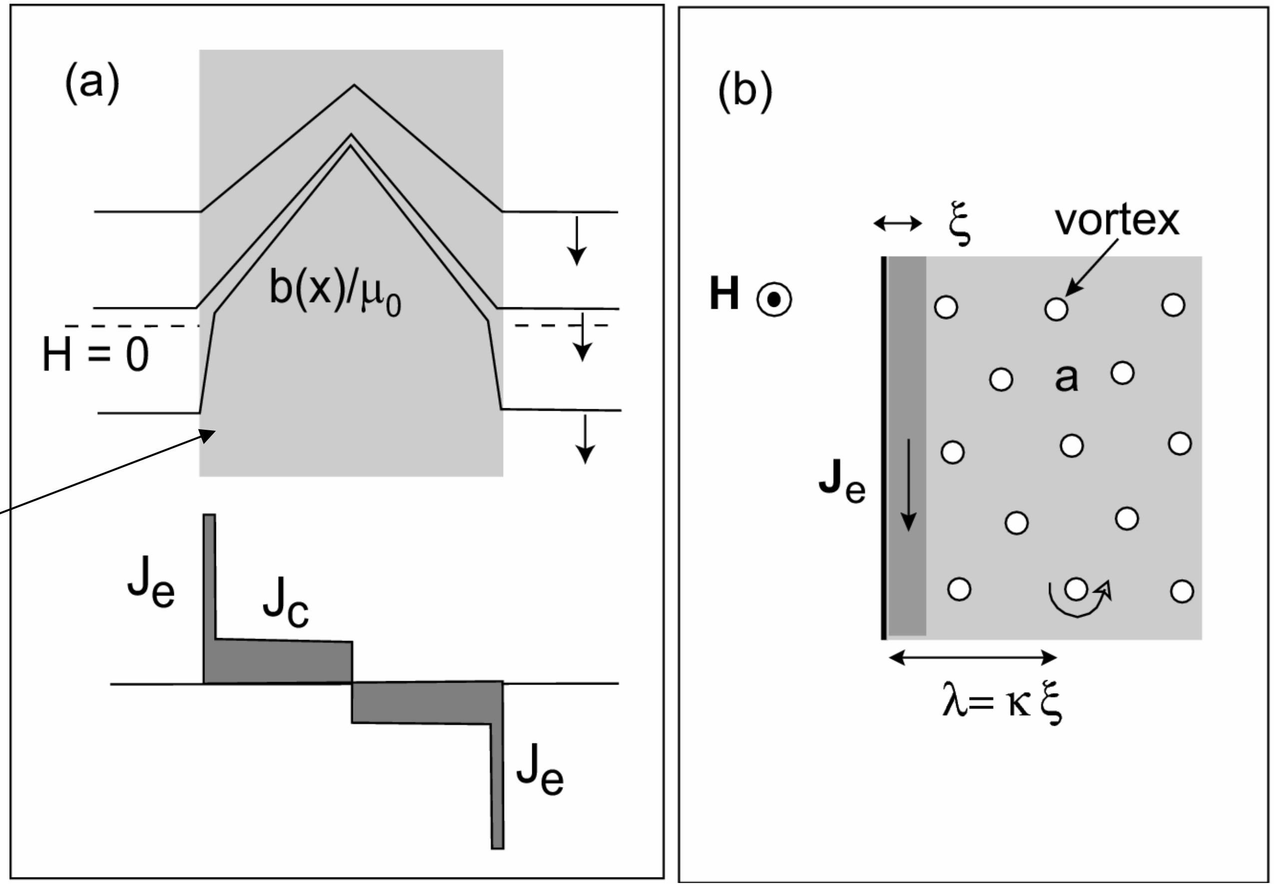


$$\frac{\partial M}{\partial H} = -1 + \frac{h}{2} + \ldots \quad \left(h = \frac{H - H_0}{J_c d}\right)$$



Critical state model

Reversible behavior



$$\mathbf{J}_{\ell} = \nabla \times \left(\rho_s \vec{\ell} \right)$$

$$\hat{\Psi} = \Psi_{\uparrow\uparrow} \left|\uparrow\uparrow\right\rangle + \Psi_{\downarrow\downarrow} \left|\downarrow\downarrow\right\rangle$$

$$\delta M = {\mu_0}^{-1} \delta B - \delta H$$

$$\frac{\partial M}{\partial H} = -1 + \frac{h}{2} + \ldots \quad \left(h = \frac{H - H_0}{J_c d}\right)$$

$$\hat{\Delta} = \begin{bmatrix} -d_1 + id_2 & d_3 \\ d_3 & d_1 + id_2 \end{bmatrix}$$

$$\mathbf{J}_\ell = \nabla \times \left(\rho_s \vec{\ell}\right)$$

Conclusions

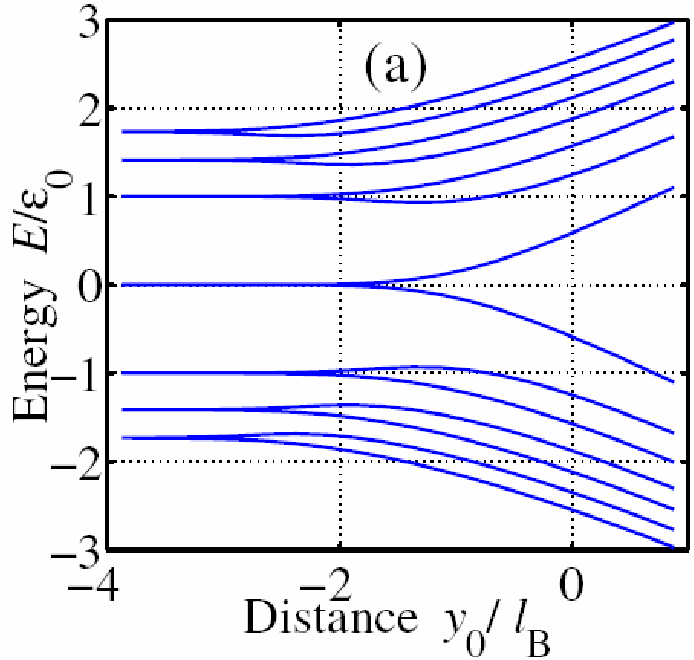
1. The n=0 *LL* splits into 2 sublevels (σ_{xy} = 0, $2e^2/h$)
   Incipient step visible at $\rho_{xy} \sim h/e^2$

2. Observation of gapless excitations inside gap at μ = 0

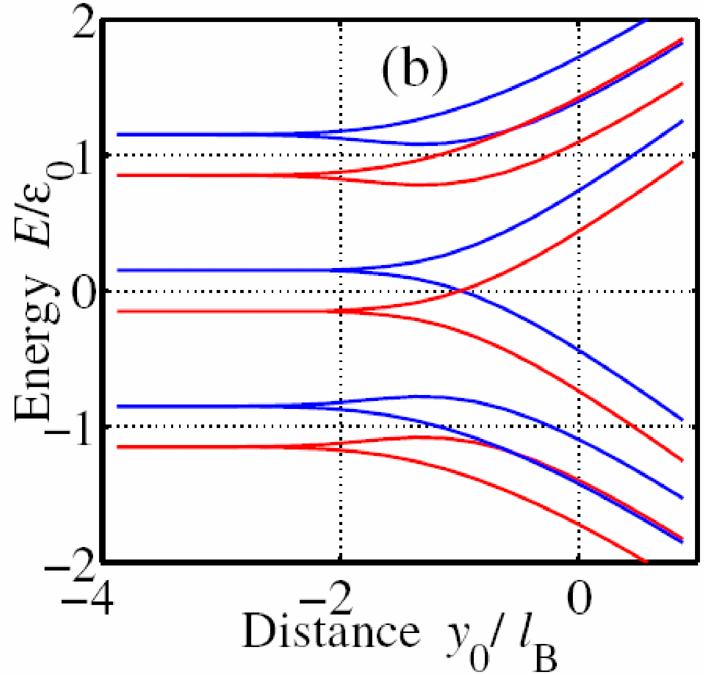
3. Residual conductance G_{res} decreases with incr. H
   Faster than Gaussian ~exp($-H^2$)

4. Suggests important role of Coulomb exchange
   in strong fields
   (approach to 2*D* transition?)

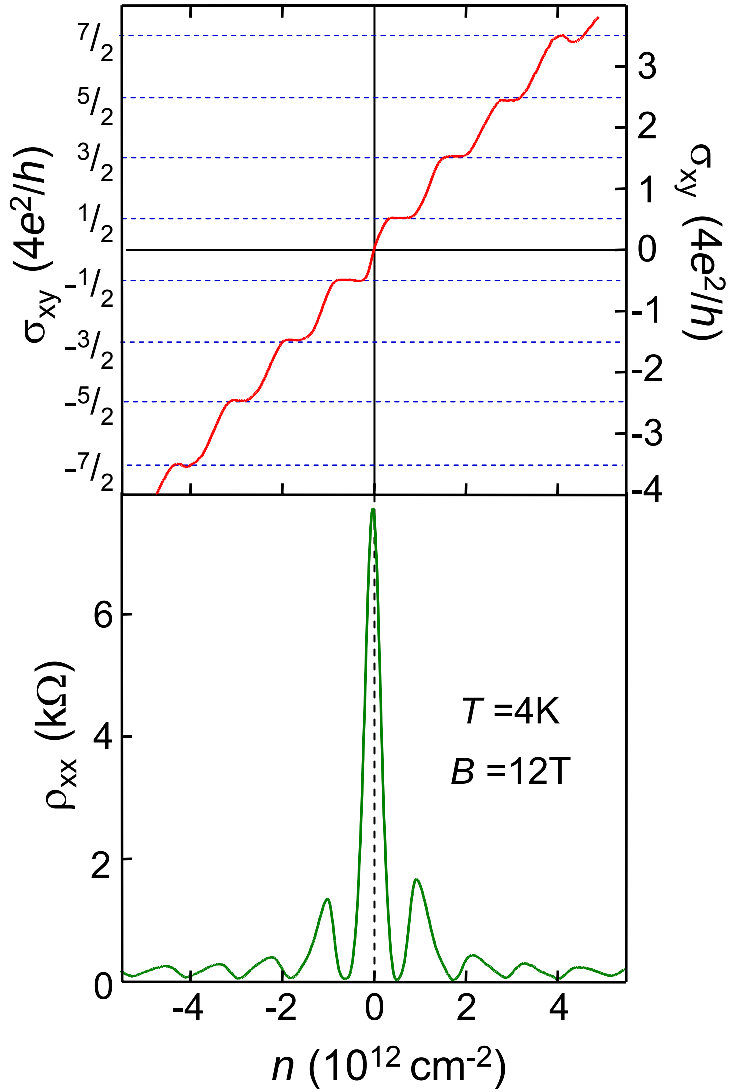
End



Spin splitting

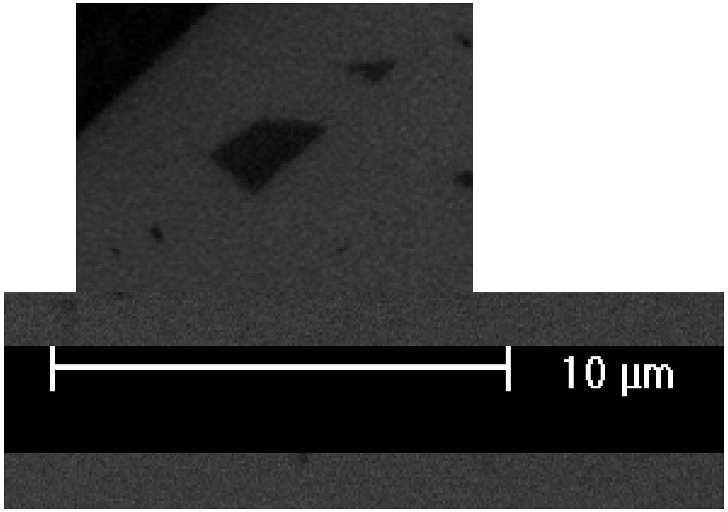


graphene

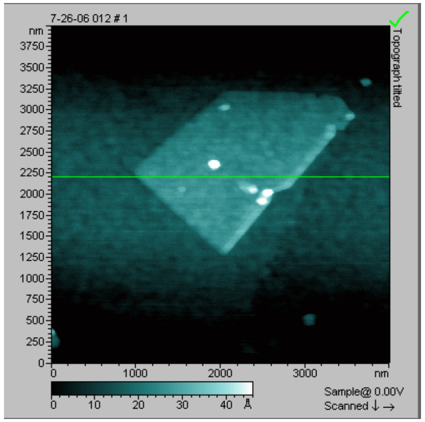


Thickness of graphene layers measured by AFM

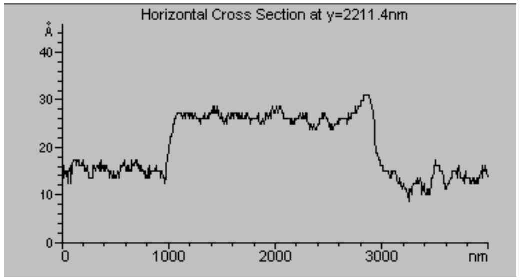
SEM



AFM

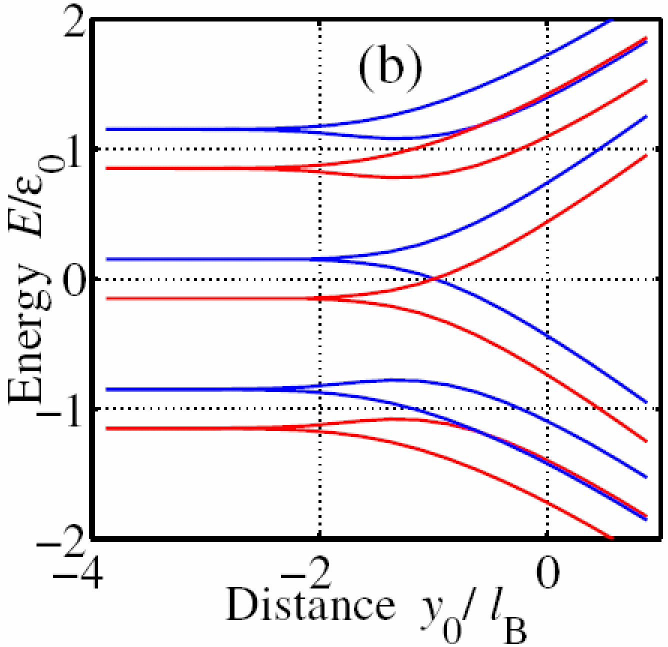


AFM



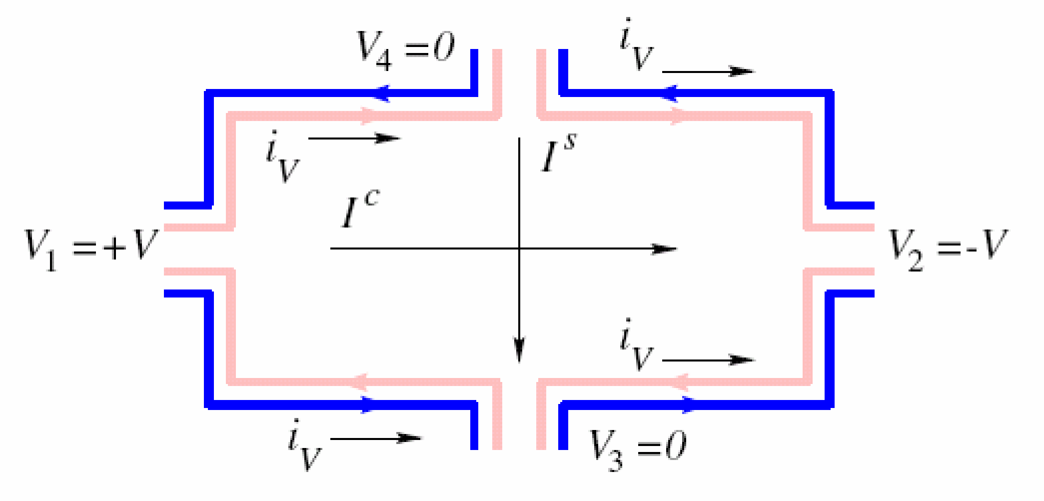
Spin filtered edge states.

Abanin, Lee and Levitov, PRL96,176803(2006)



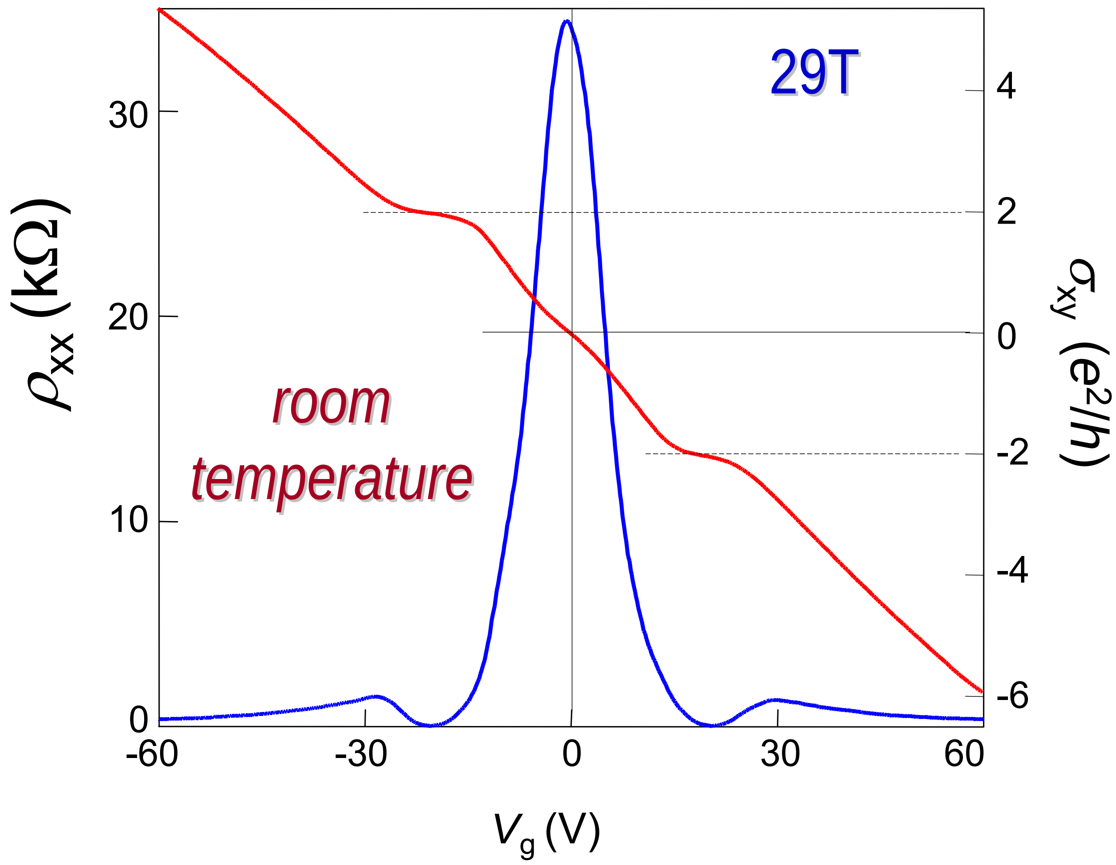
Spin up moves left

Spin down moves right



Simple example of a topological Hall insulator. (Kane and Mele,PRL2005) where gap is opened by spin-orbit effect.

No Hall current R_{xy}=0 , but ideal spin current: $I_s=2e^2V/h$.
Also predicts longitudinal charge current, ie
$R_{xx}=h/2e^2$. (13 kOhms)


29T
room temperature
ρ_{xx} (kΩ)
30
20
10
0
-60
-30
0
30
60
V_g (V)
4
2
0
-2
-4
-6
σ_{xy} (e^2/h)

Geim et al