From Perfect Conductor to Perfect Insulator: the Zero-Plateau QH State in Graphene

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(arXiv:0807.2867)

Acknowledgements:

L. Brey, R. Berkovits, M. Goldstein, K. Novoselov, P. Ong

NSF, GIF

KITP Low Dimensions Conference, Feb 26, 2009

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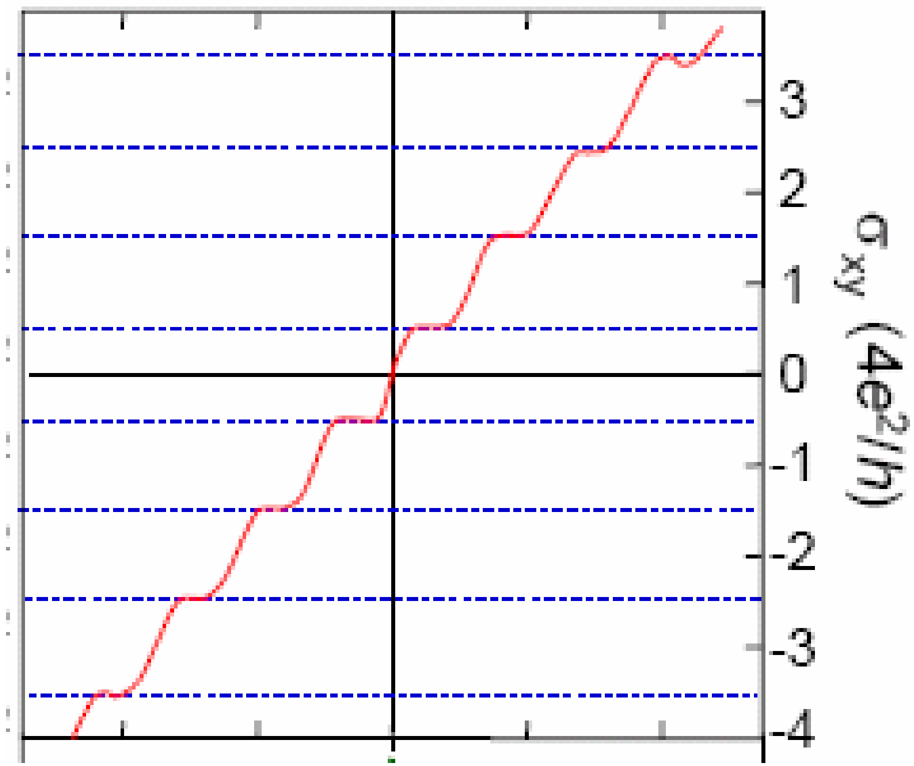
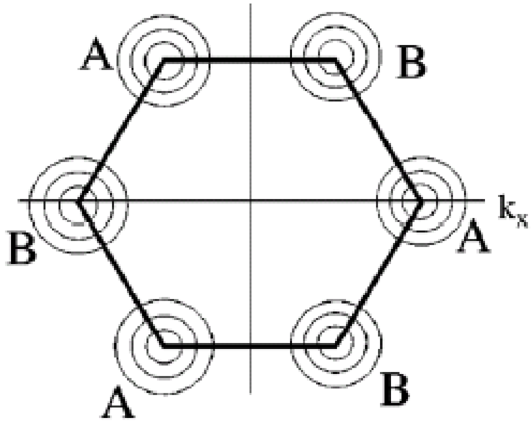
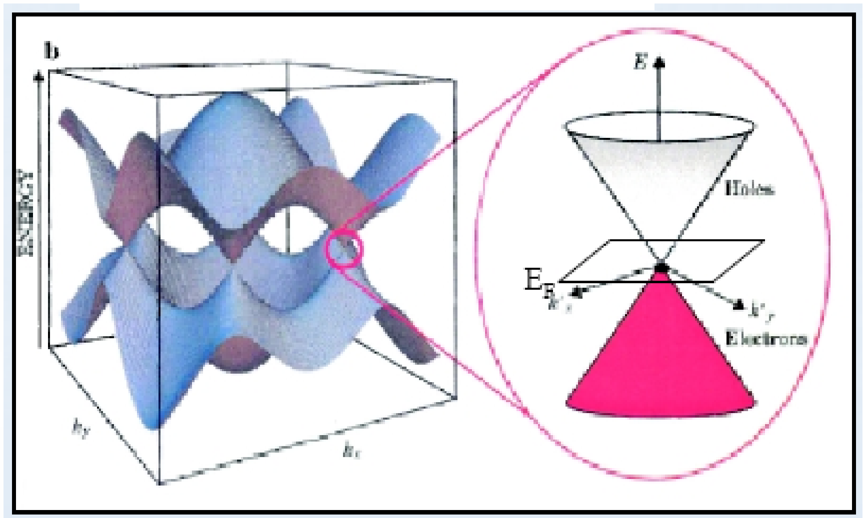
"…*Now,* ***here****, you see, it takes all the running* ***you*** *can do, to keep in the same place…* " (L. Carroll, from "Alice's Adventures through the Looking Glass")

The Quantum Hall Effect in Graphene

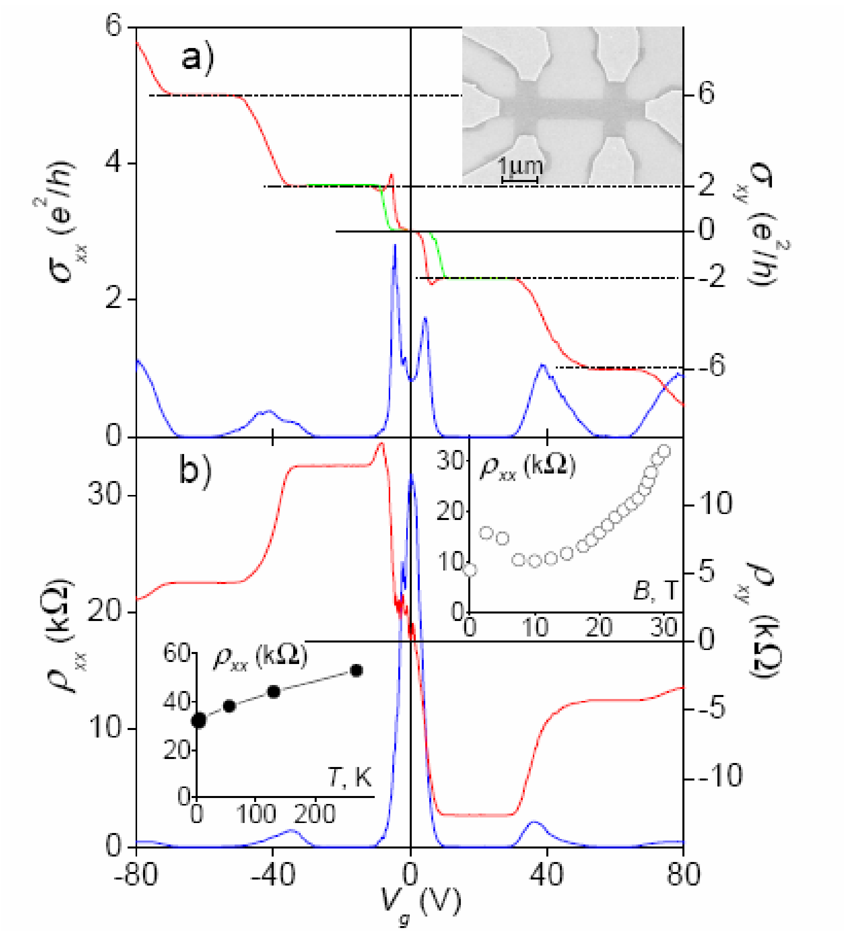


Novoselov, Geim et al., Nature **438**, 197 (05)





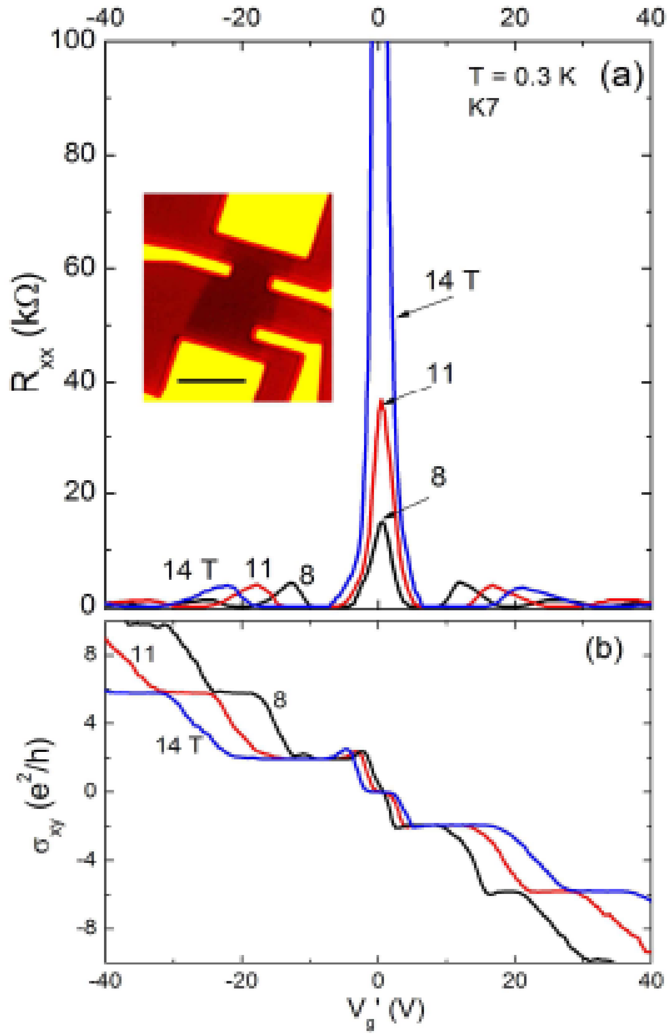
Stronger B: Dissipative QHE at the Dirac Point

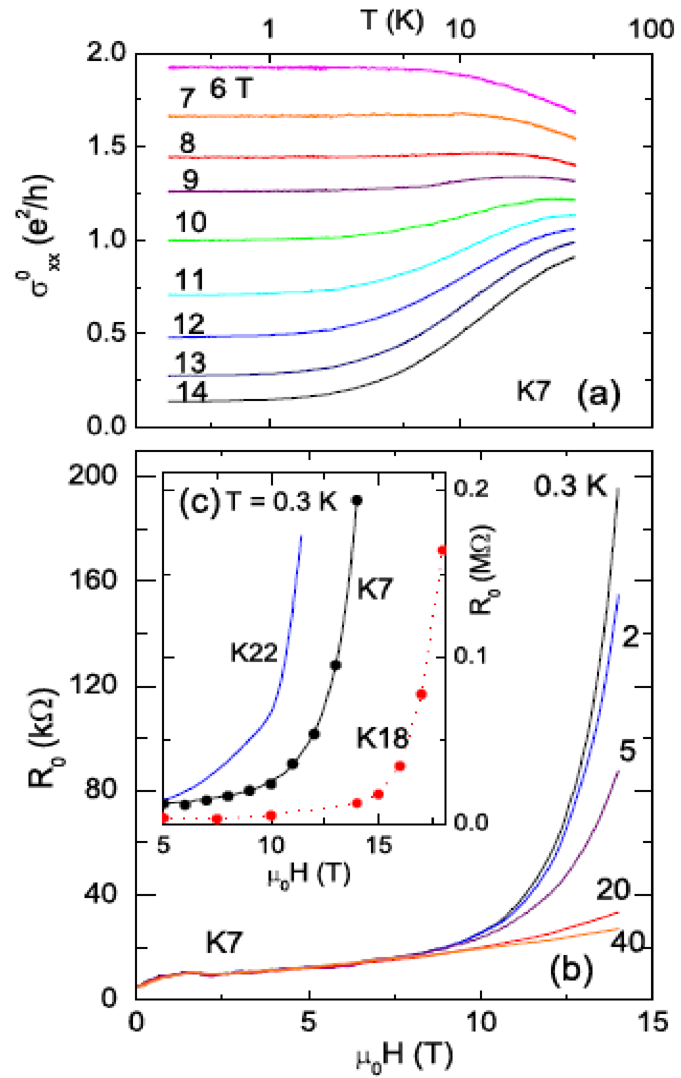


Abanin *et al.* (2007)

- Plateau at ν=0, but $\rho_{xx} \neq 0$!
- ρ_{xx} increases with T $\Rightarrow$ Metal
- ρ_{xx} increases with B

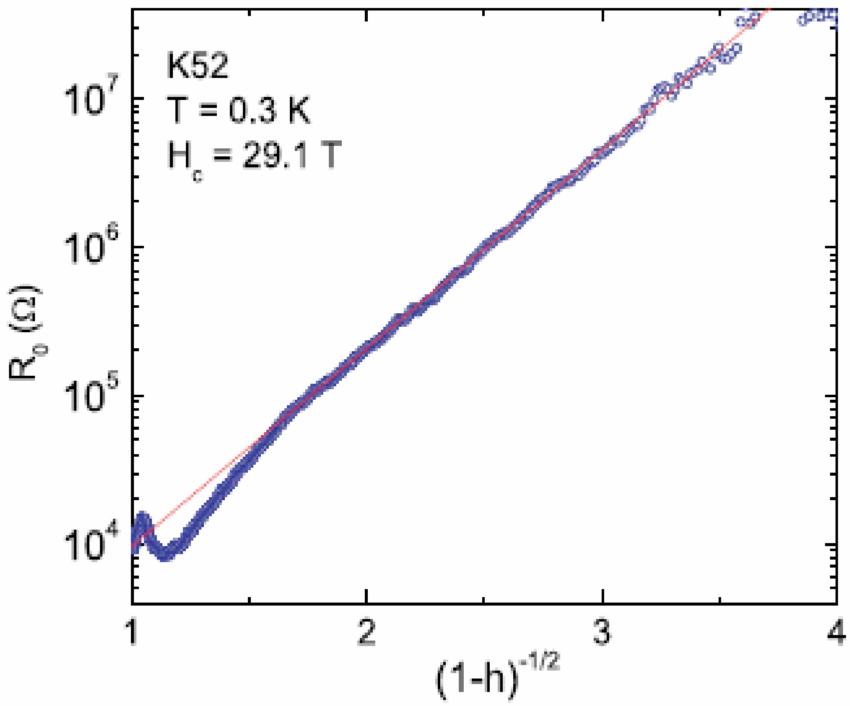
Checkelsky, Li and Ong (2007):





Checkelsky, Li and Ong (2008): more on the “Insulator” -

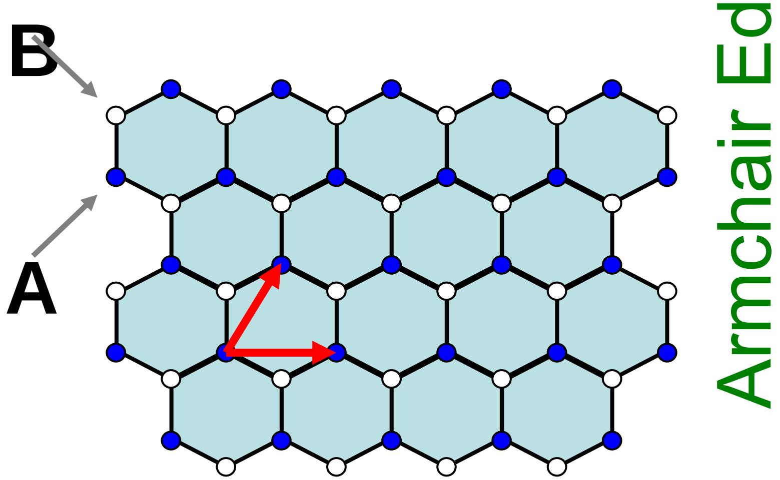
Divergence of R_0 at high H

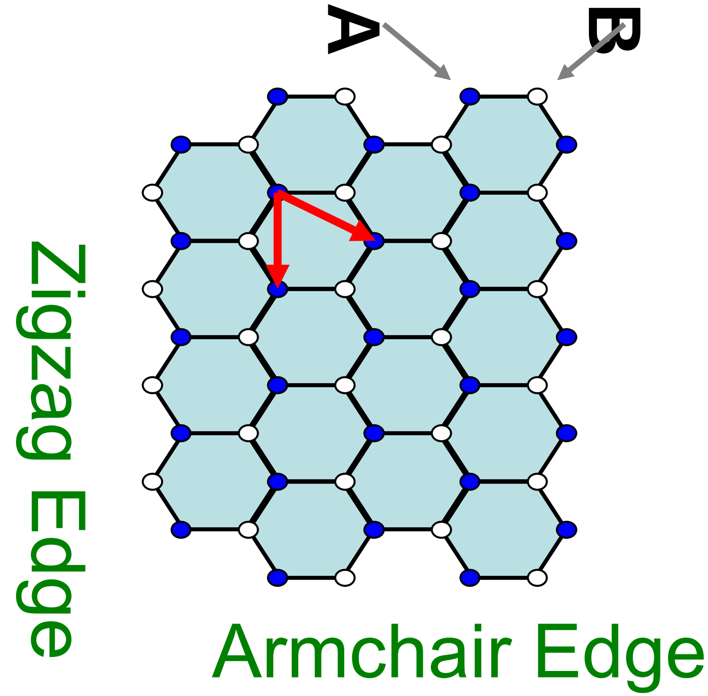


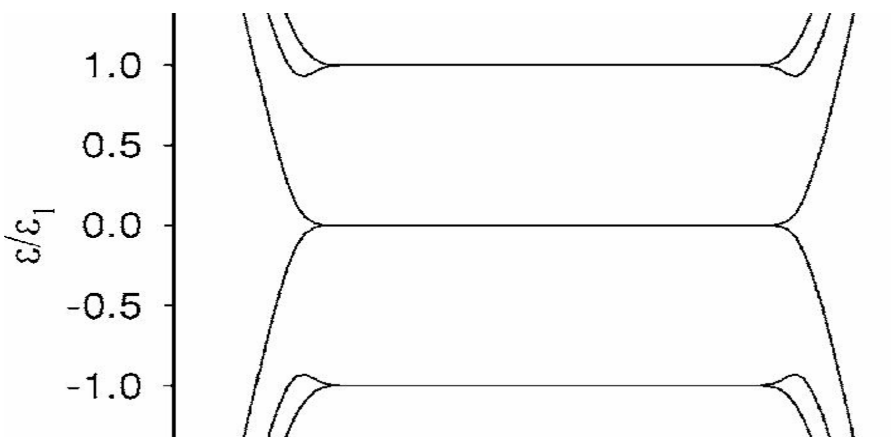
$$R_0 \sim \exp\left\{ \underbrace{\frac{2C}{\sqrt{(H_c - H)}}}_{\xi_{KT}^2 \;!!} \right\}$$

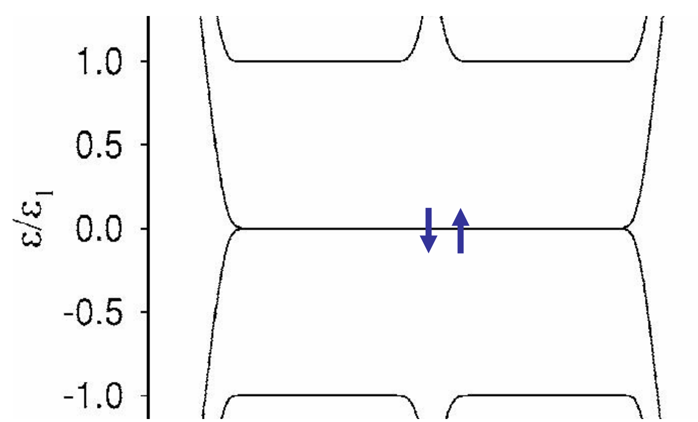
QH Edge-States in Graphene Ribbons

Brey and Fertig (2006):

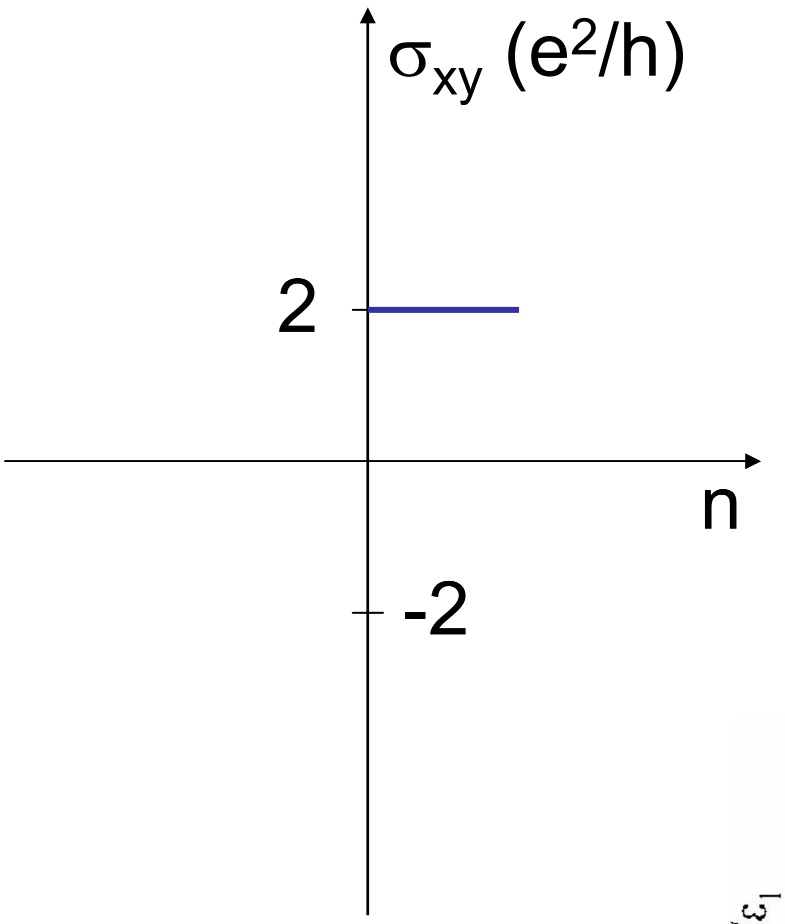


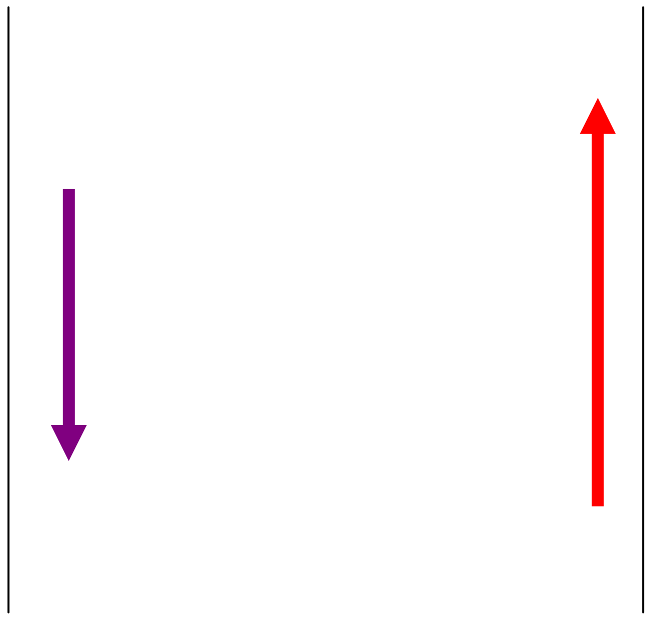


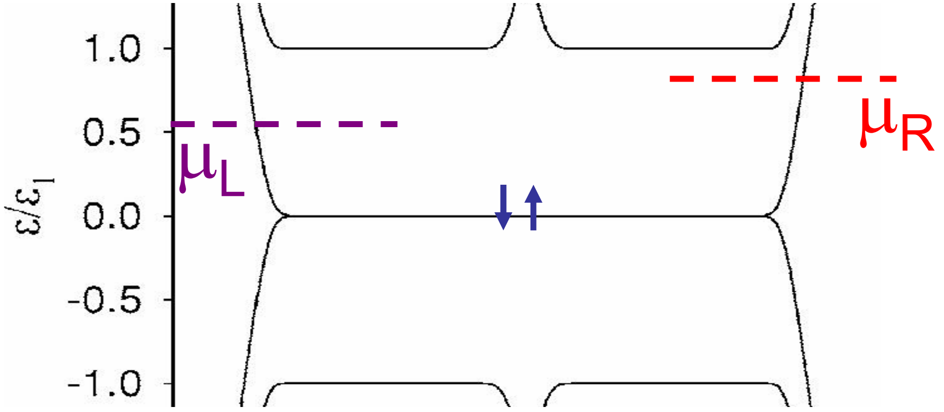




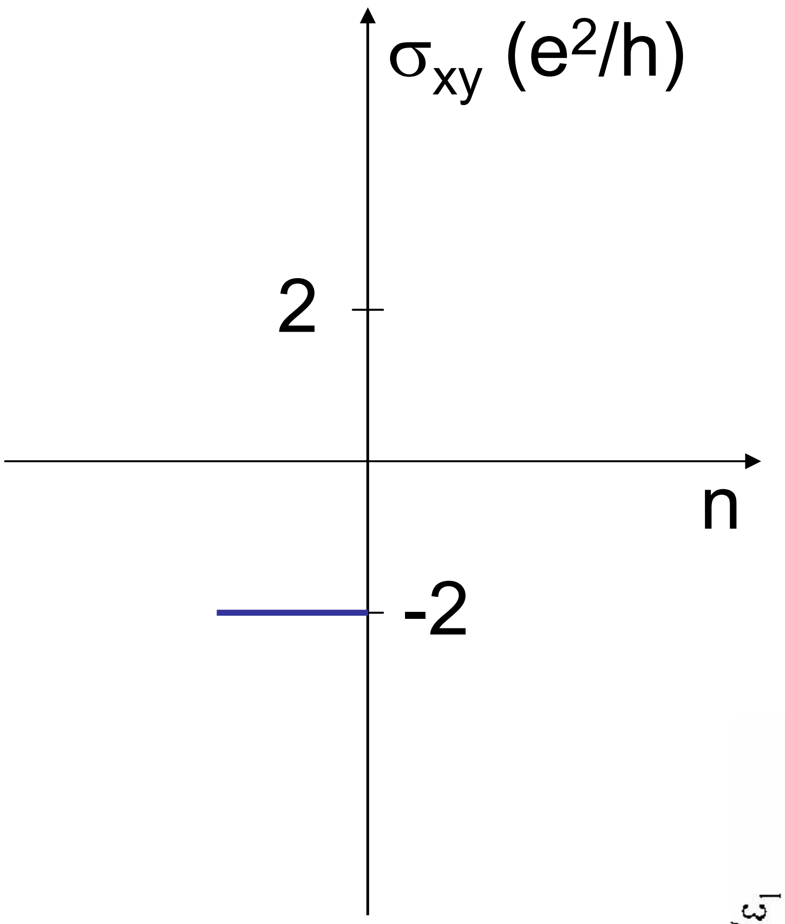
QH Edge-States in Graphene Ribbons

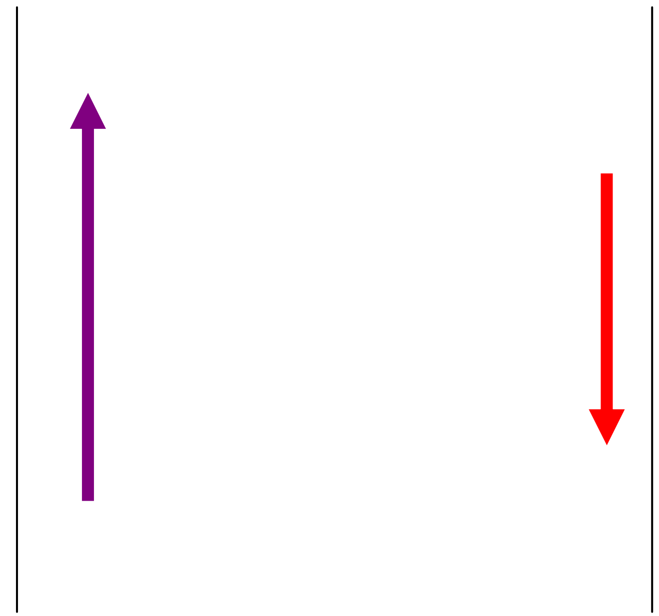


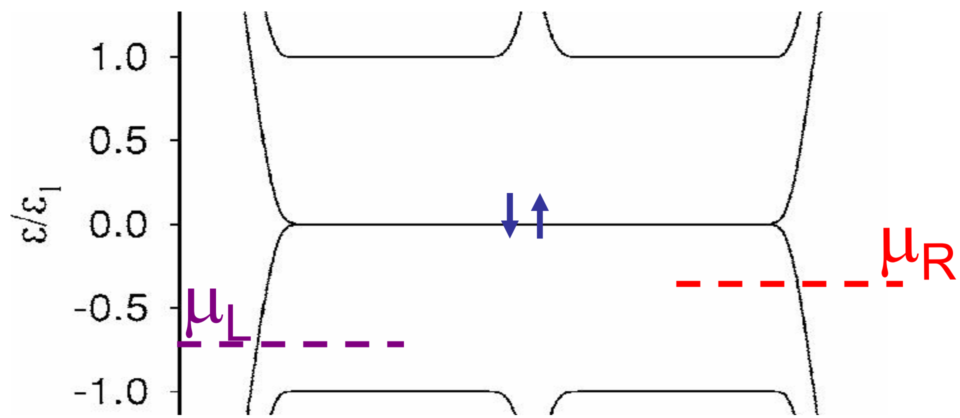




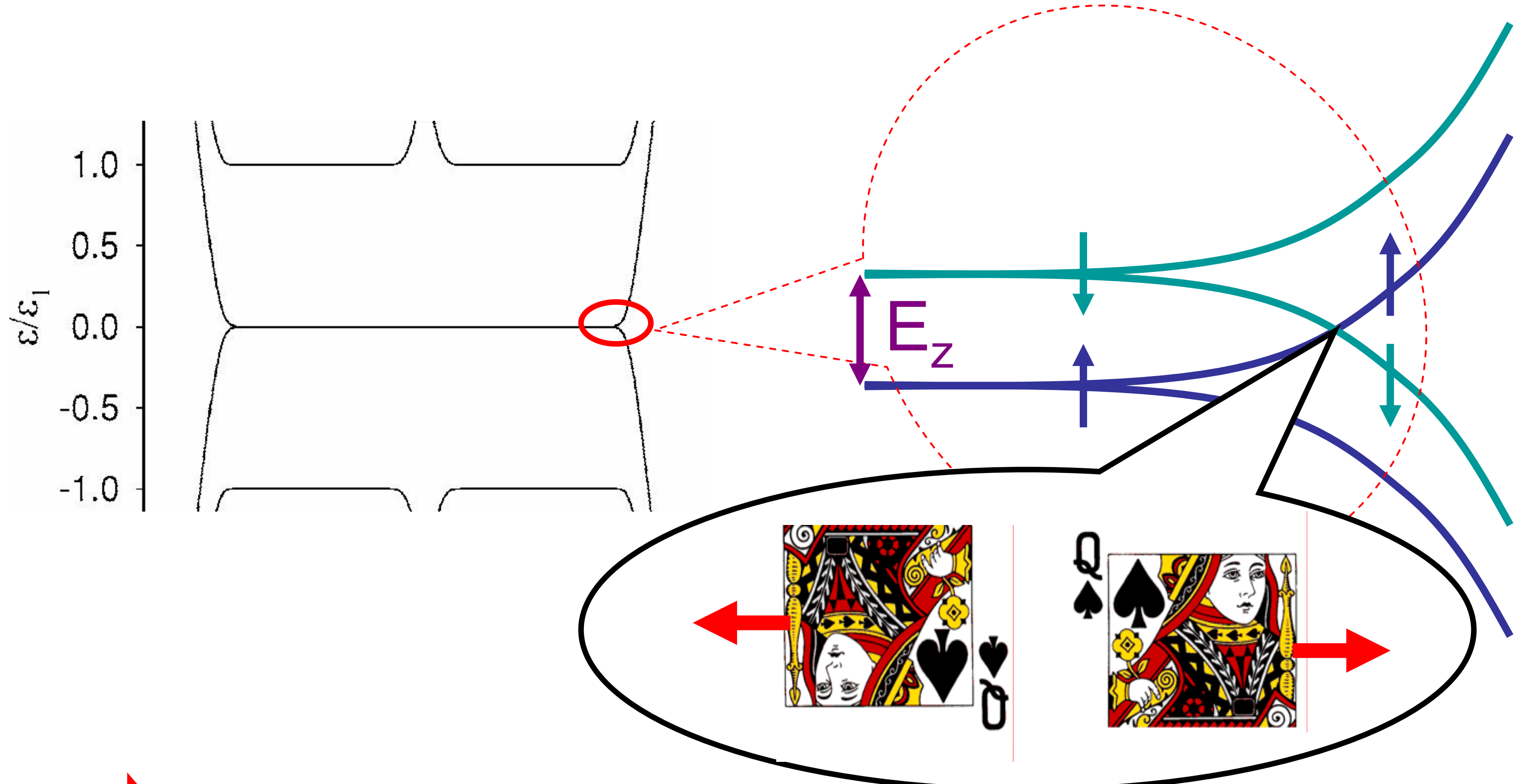
QH Edge-States in Graphene Ribbons





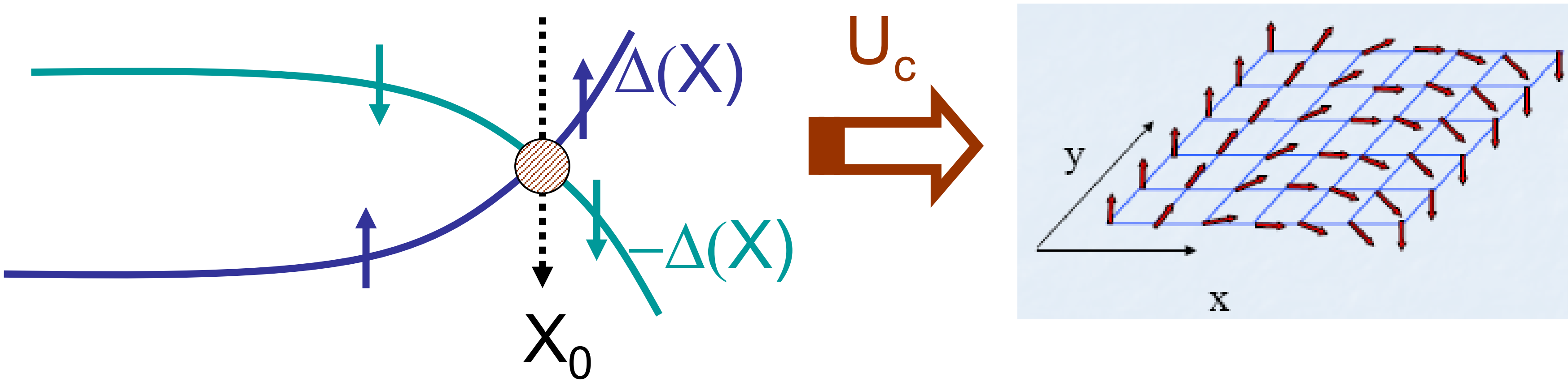


Origin of ν=0 plateau at high H: Zeeman splitting



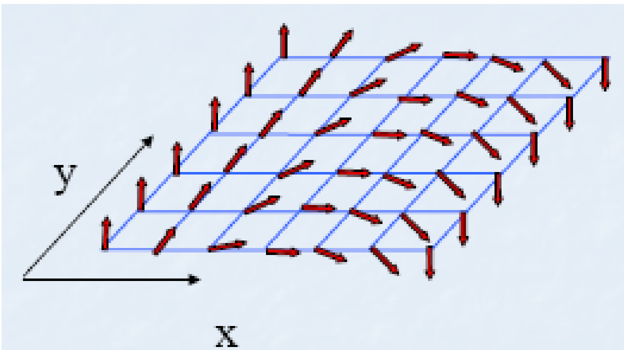
Spin-flip impurities → Finite ρ_{xx}
(Abanin, Levitov & Lee)

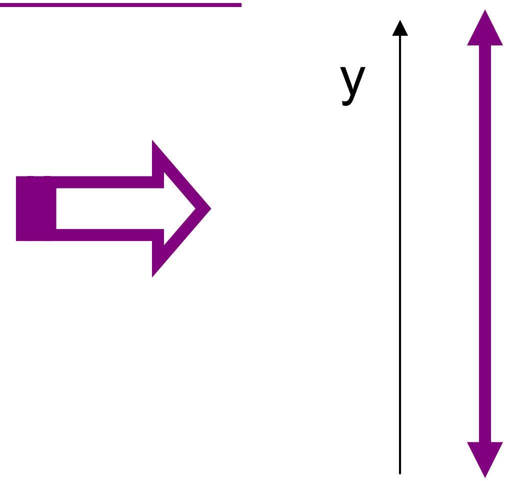
Role of Coulomb interactions (Fertig & Brey, 2007):



Finite width Domain Wall

Our Theory: Effective 1D Model for the Domain Wall



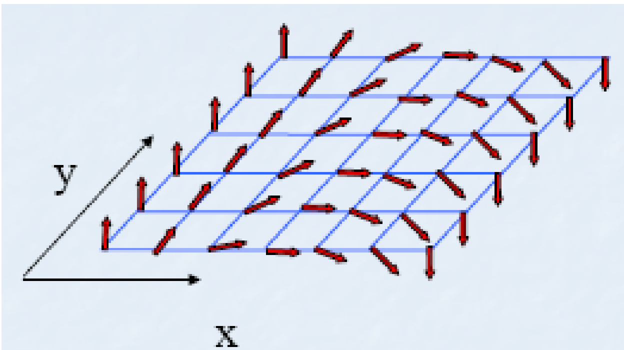


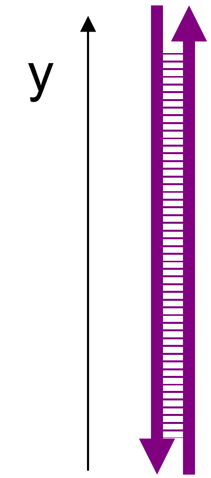
$(j_e \sim S_z)$

$$H_{DW} = \int \frac{dy}{2\pi}\left(uK\left(\partial_y \theta\right)^2 + \frac{u}{K}\left(\partial_y \phi\right)^2 - g\cos[4\phi] \right)$$

$K[H, U_c, \Delta'(X_0)]$, $u[H, U_c, \Delta'(X_0)]$, $g[H, U_c, \Delta'(X_0)]$

Our Theory: Effective 1D Model for the Domain Wall





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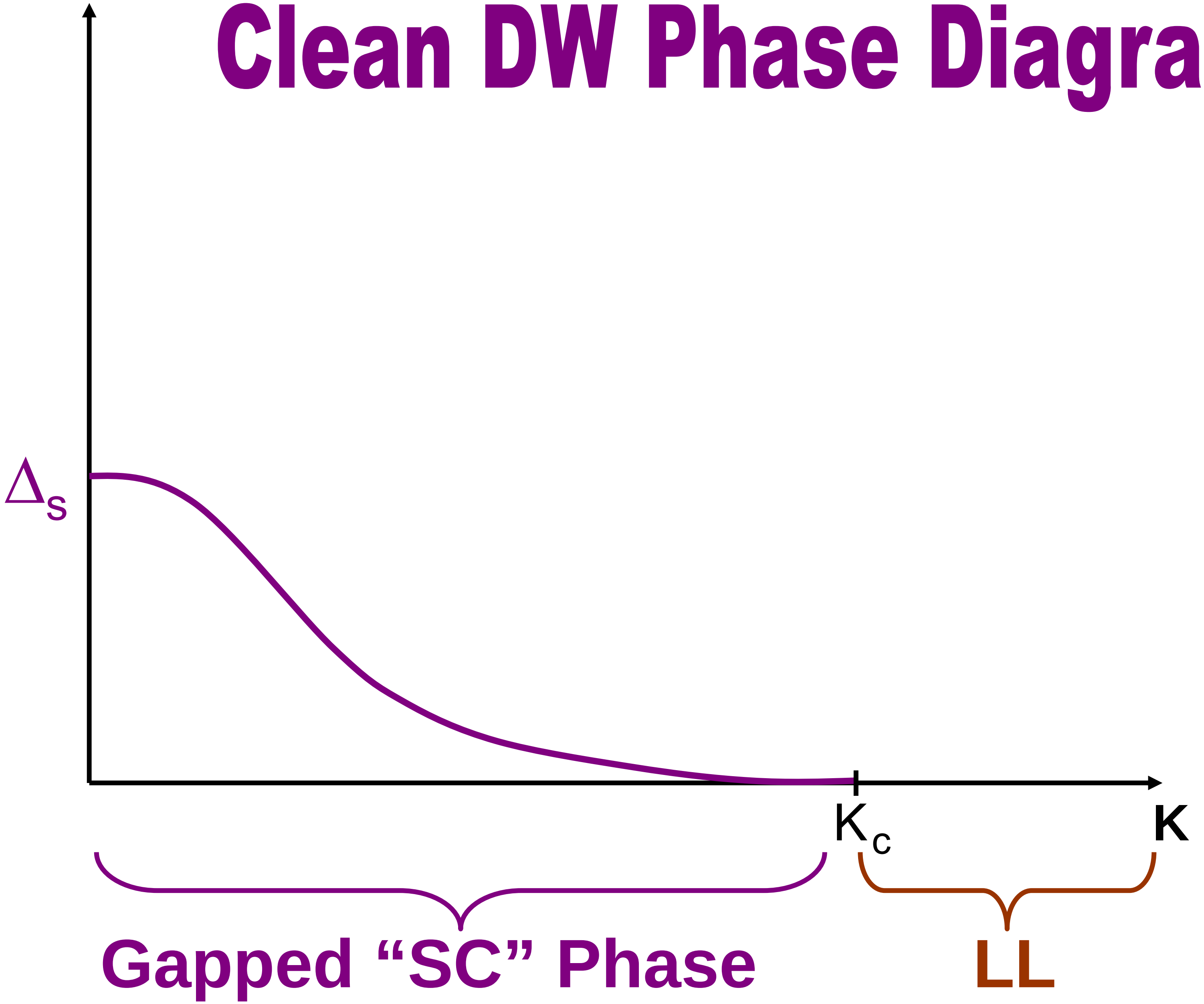
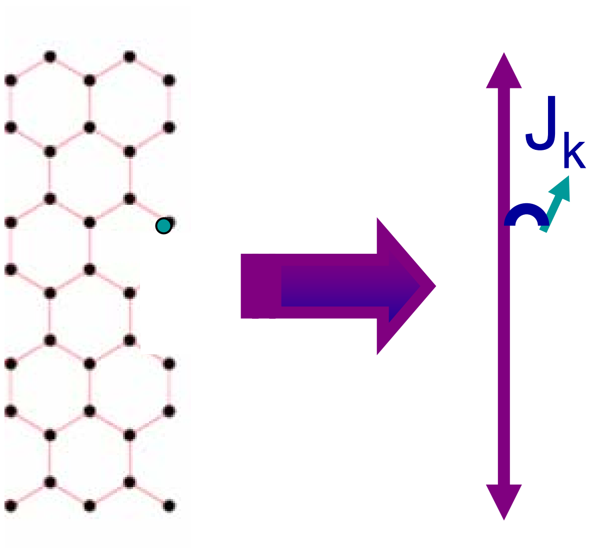
"charging energy" — "SC stiffness" — "Josephson Coupling"

Clean DW Phase Diagram



Theory for Transport: adding Spin-Flip Interaction



$H = H_{DW} + H_{\sigma} + H_{int}$

$H_{\sigma} = \varepsilon_z \sigma_z$

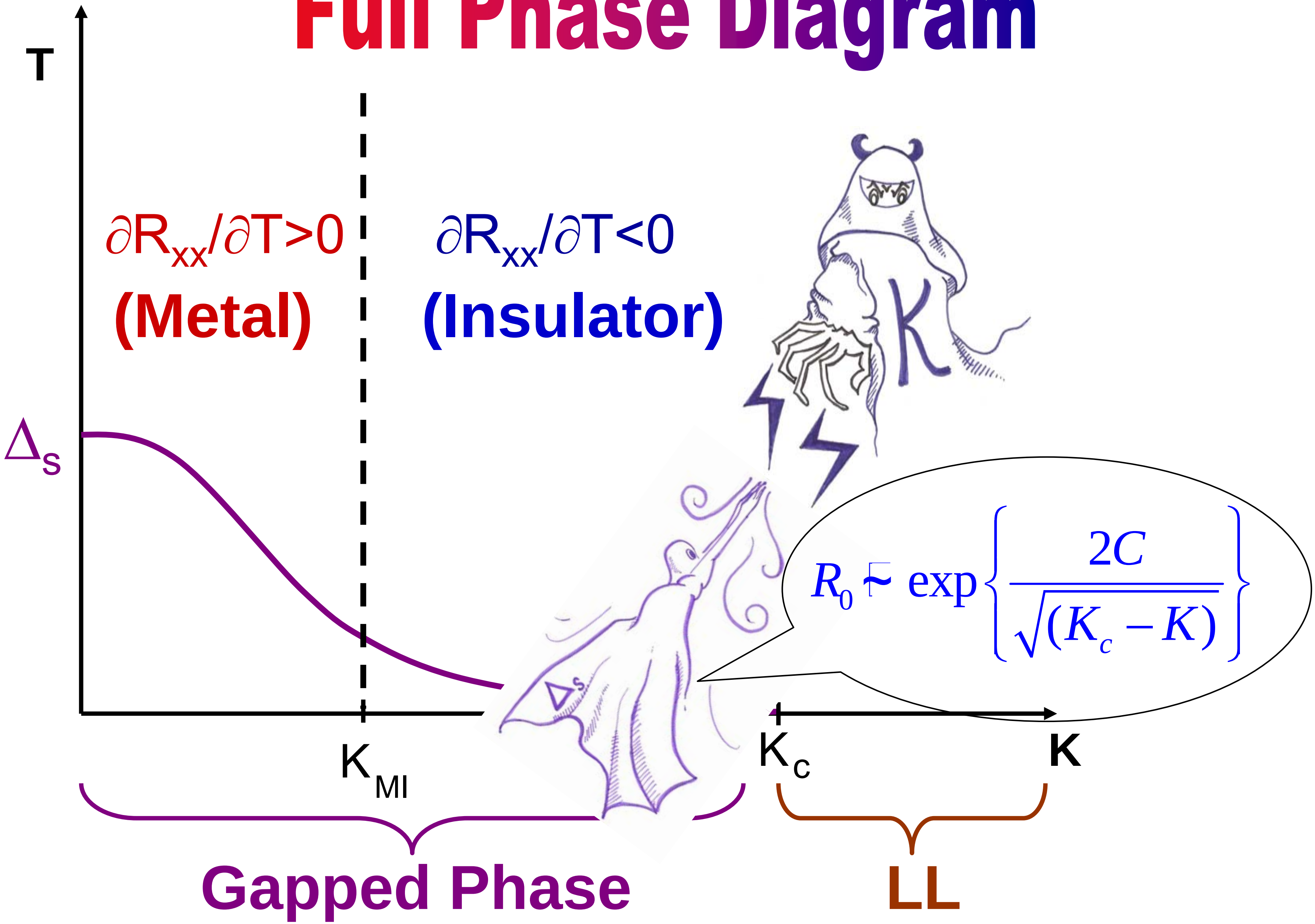
$H_{int} = J_k \mathbf{S} \bullet \boldsymbol{\sigma}$

Back-scattering induced resistance for T>Δ_s:

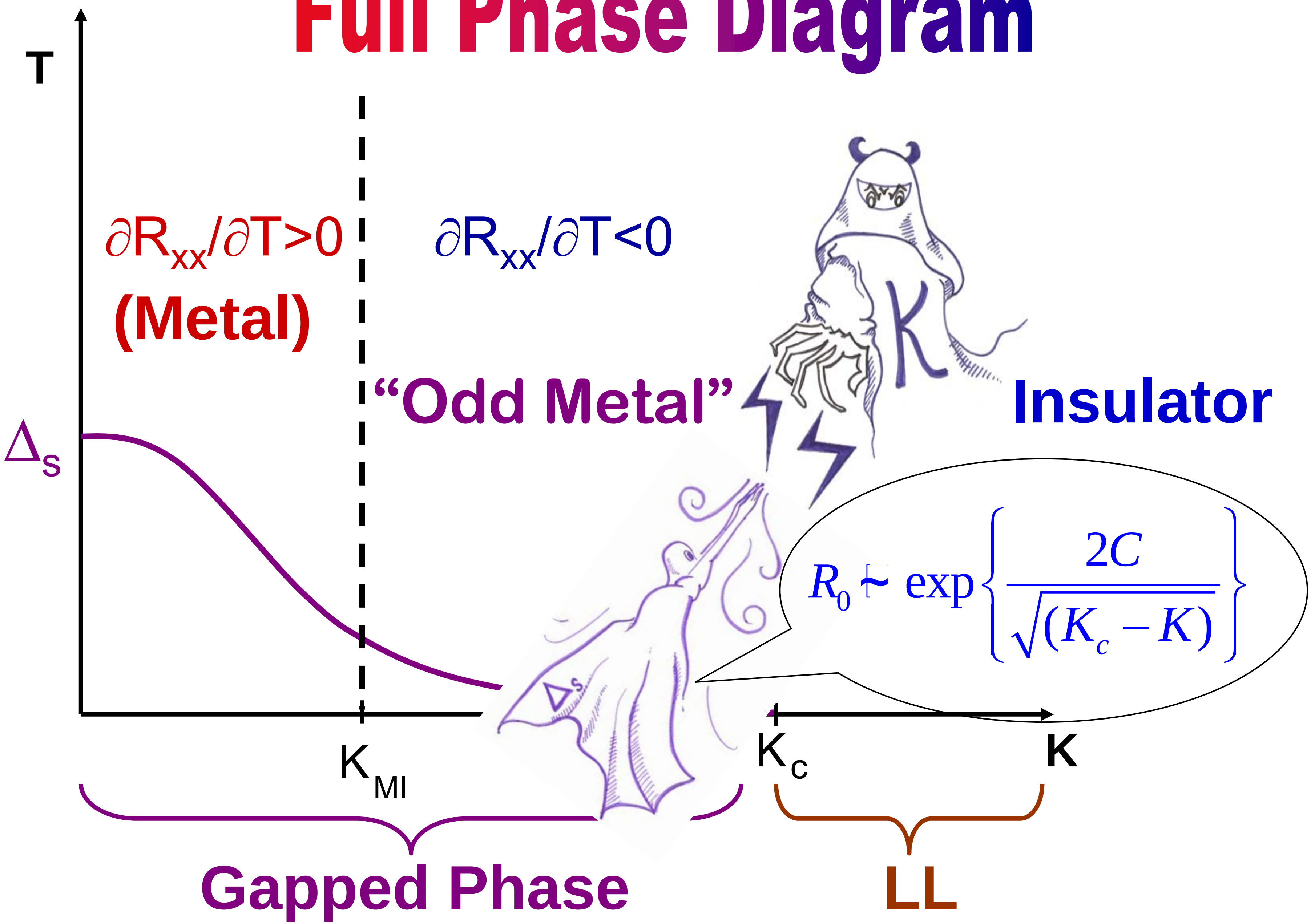
$$R_{xx} \approx g^2 T^{\nu(K)} F[\epsilon_z / T] \qquad (g \sim J_k)$$

$$\nu(K_{MI}) = 0$$

Full Phase Diagram



Full Phase Diagram



Summary

- Finite R_{xx} at the $\nu=0$ QH state induced by "chiral Kondo effect": Spin-flip = Charge backscattering
- New type of edge state: spin Domain Wall = a non-chiral perfect conducting channel
- Diverse transport phenomena: $R_{xx}(T)$ is metallic, insulating or "odd metal" depending on K.
  Divergence of R_0 => quantum KT-transition (in 1+1d)