

# Mesoscopic valley filter in graphene Corbino disk containing a p-n junction

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[ see: [arXiv:1907.02599](https://arxiv.org/abs/1907.02599) ]



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Adam Rycerz

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Page 1 of 17

# Emergence and graphene

4 August 1972, Volume 177, Number 4047

**SCIENCE**



## More Is Different

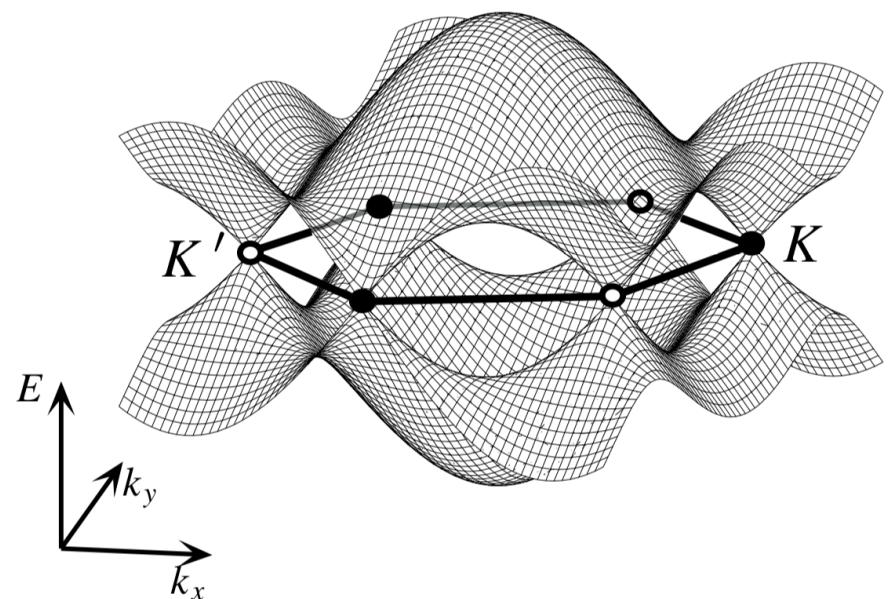
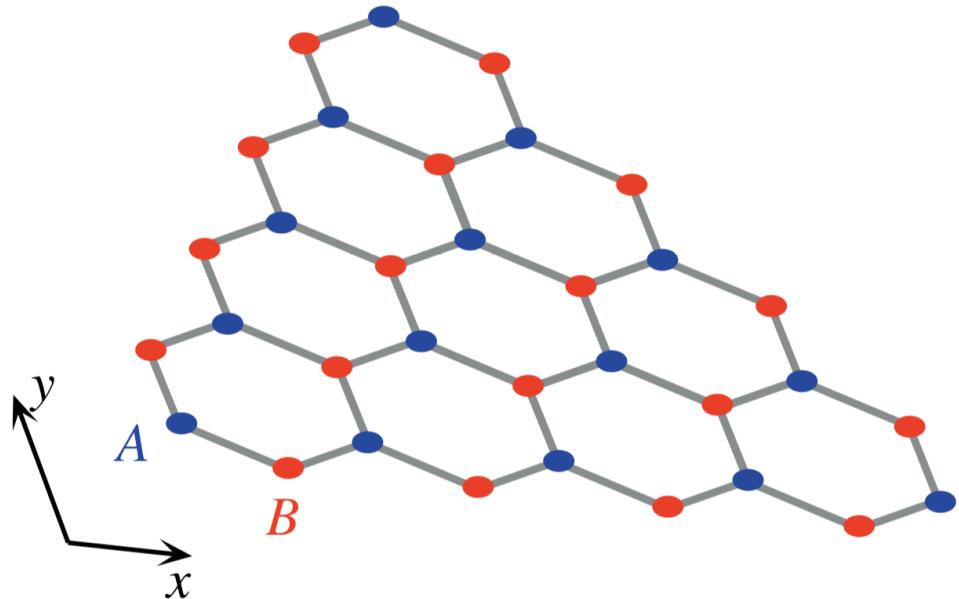
Broken symmetry and the nature of  
the hierarchical structure of science.

P. W. Anderson

### What differs graphene from a collection of carbon atoms?

- The **valley pseudospin** ( $\Rightarrow$  *fermion doubling*)
- Time-reversal symmetry breaking at zero magnetic field
- Pseudodiffusive charge transport, . . . , SC in twisted-BLG (!)

# Valleys in graphene



[ Reprinted from: AR, phys. stat. sol. (a) 205, 1281 (2008) ]

$$H_\xi = v_F (\xi p_x \sigma_x + p_y \sigma_y), \quad \xi = \pm 1 \text{ for } K/K'$$



$$J_x = \xi \sigma_x$$

$$J_y = \sigma_y$$

(!!)

# How to create valley polarization of current?

## Theoretical proposals:

A.R., J. Tworzydło, and C. W. J. Beenakker, *Valley filter and valley valve in graphene*, Nat. Phys. 3, 172 (2007).

D. Gunlycke and C. T. White, *Graphene Valley Filter Using a Line Defect*, Phys. Rev. Lett. 106, 136806 (2011).

F. Zhai, Y. Ma, and Y.-T. Zhang, *A valley-filtering switch based on strained graphene*, J. Phys.: Condens. Matter 23, 385302 (2011).

A. Pályi and G. Burkard, *Disorder-Mediated Electron Valley Resonance in Carbon Nanotube Quantum Dots*, Phys. Rev. Lett. 106, 086801 (2011).

Y. Jiang, T. Low, K. Chang, M. I. Katsnelson, and F. Guinea, *Generation of Pure Bulk Valley Current in Graphene*, Phys. Rev. Lett. 110, 046601 (2013).

M. Settnes, S. R. Power, M. Brandbyge, and A.-P. Jauho, *Graphene Nanobubbles as Valley Filters and Beam Splitters*, Phys. Rev. Lett. 117, 276801 (2016).

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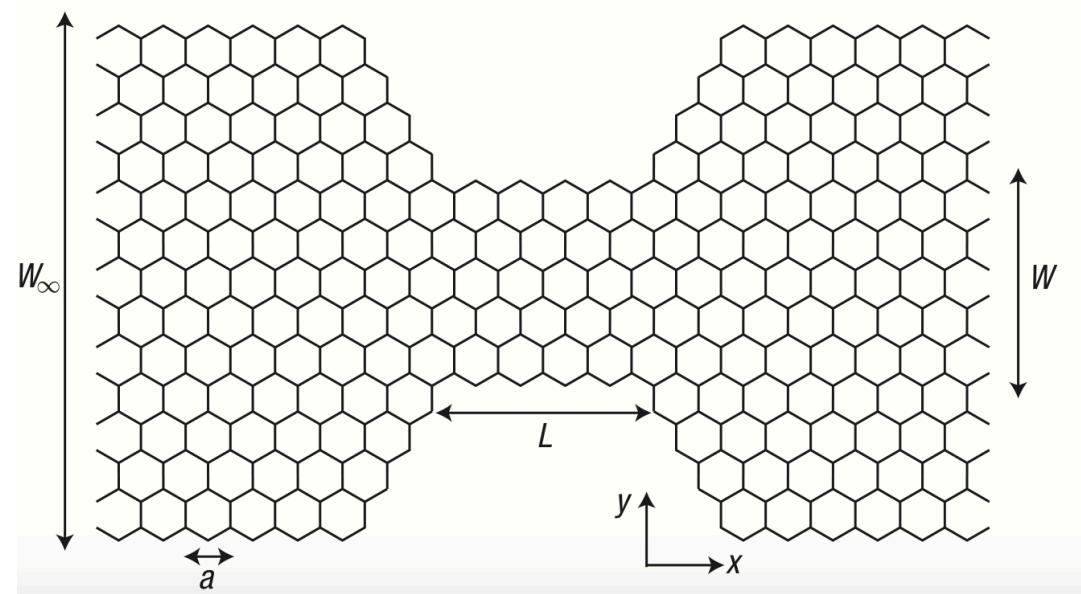
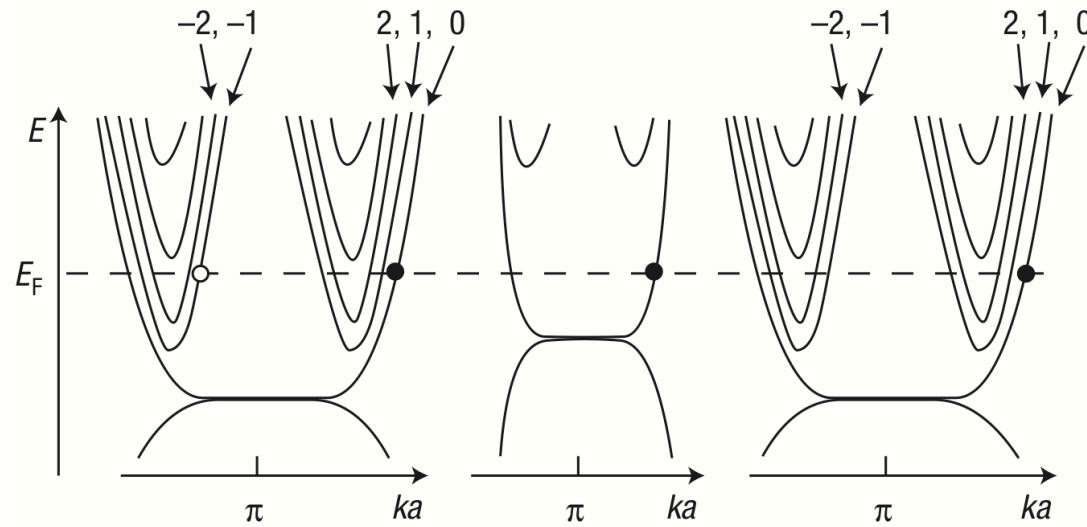
# How to create valley polarization of current?

## Experiments:

R. Gorbachev, et al., *Detecting topological currents in graphene superlattices*, Science 346, 448 (2014).

K. F. Mak, K. L. McGill, J. Park, and P. L. McEuen, *The valley Hall effect in MoS<sub>2</sub> transistors*, Science 344, 1489 (2014).

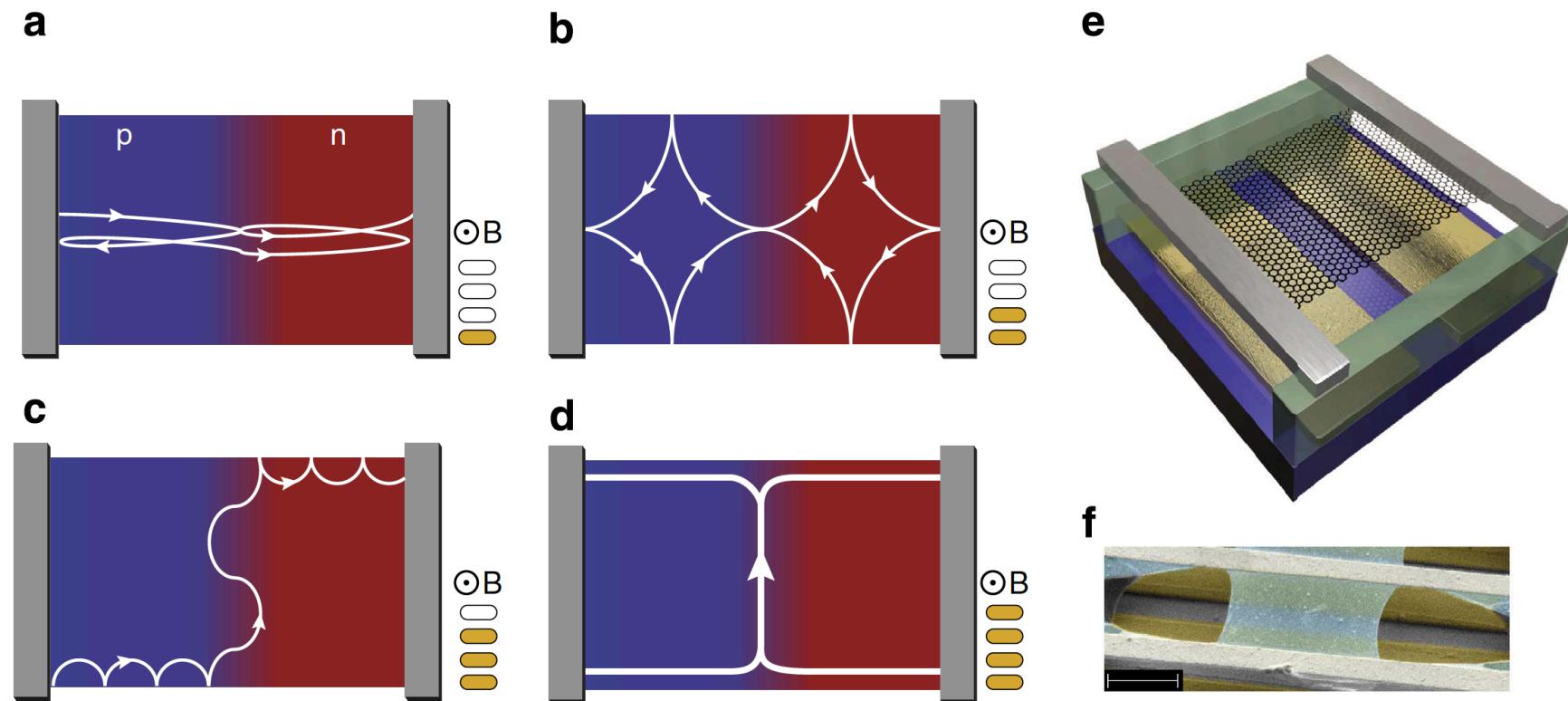
Y. Shimazaki, M. Yamamoto, I. V. Borzenets, K. Watanabe, T. Taniguchi, and S. Tarucha, *Generation and detection of pure valley current by electrically induced Berry curvature in bilayer graphene*, Nat. Phys. 11, 1032 (2015).



[ Reprinted from: AR, J.Tworzydło, C.W.J. Beenakker, Nat. Phys. (2007) ]

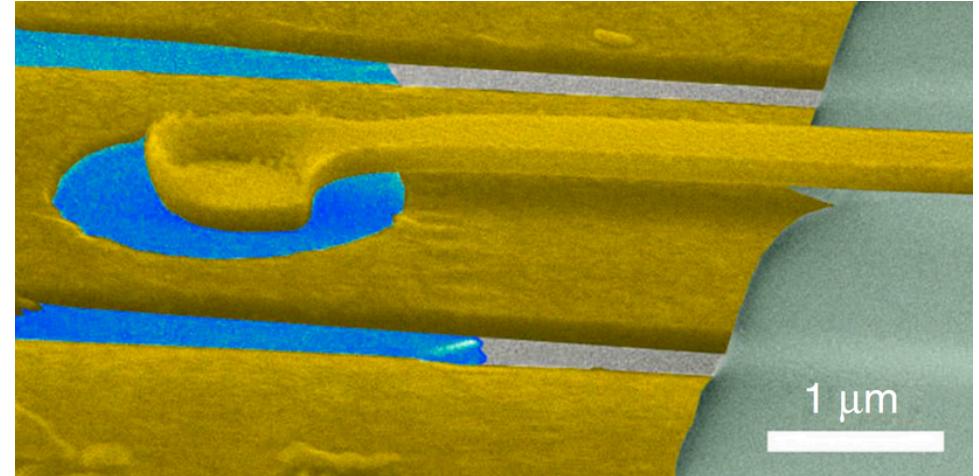
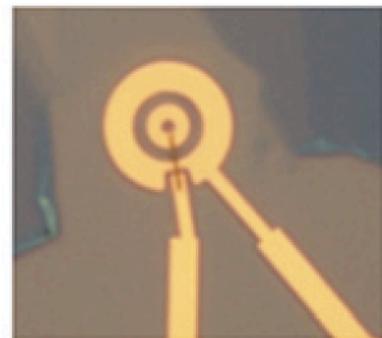
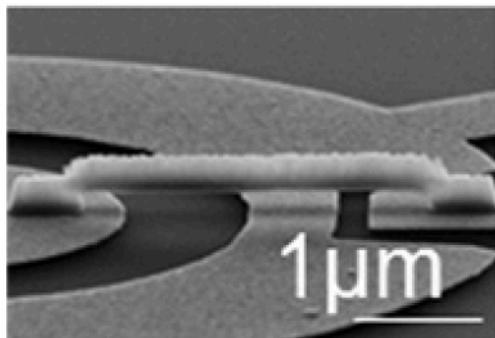
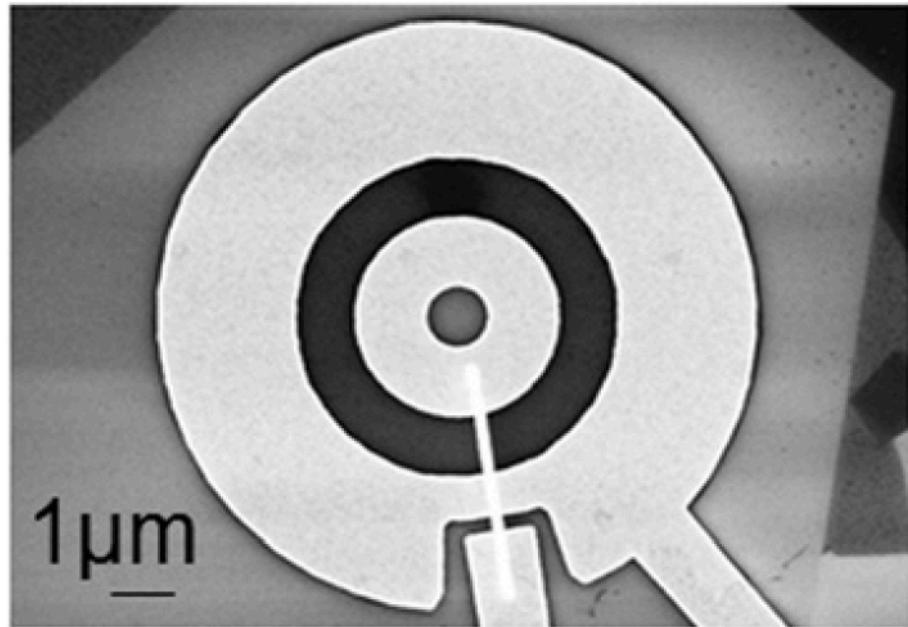
# Mesoscopic valley filter: Motivation (1)

Experiments on ultraclean p-n junctions [  $\Rightarrow$  BUT no edges needed ... ]



[Reprinted from: Rickhaus et al., Nat. Comm. **6**, 6470 (2015)]

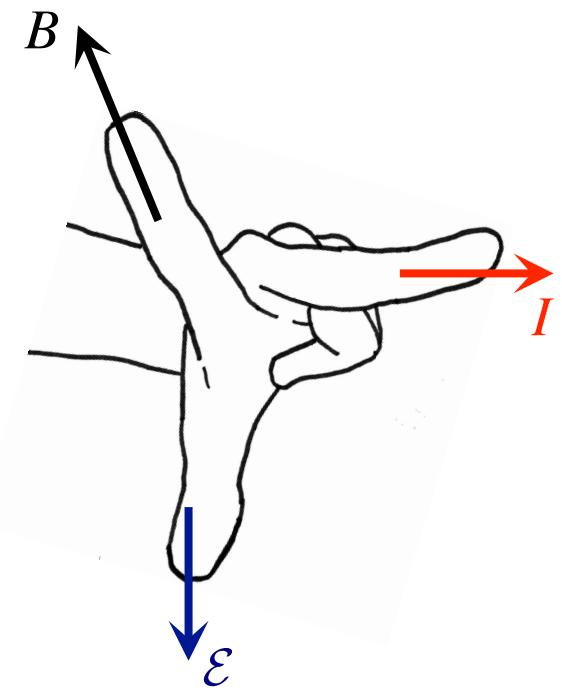
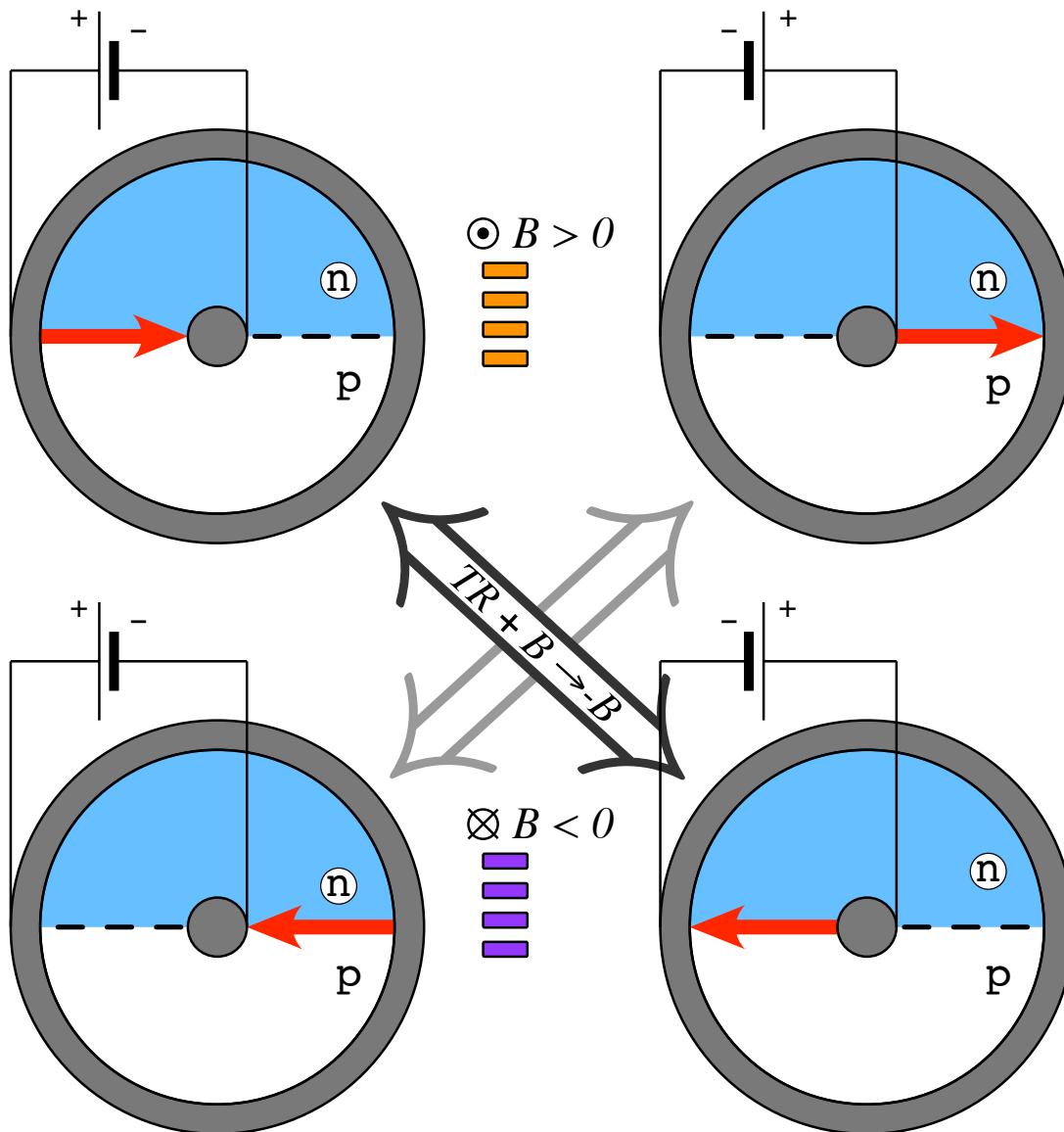
# Mesoscopic valley filter: Motivation (2)



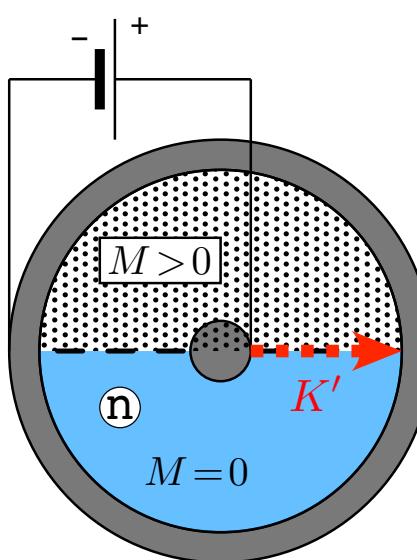
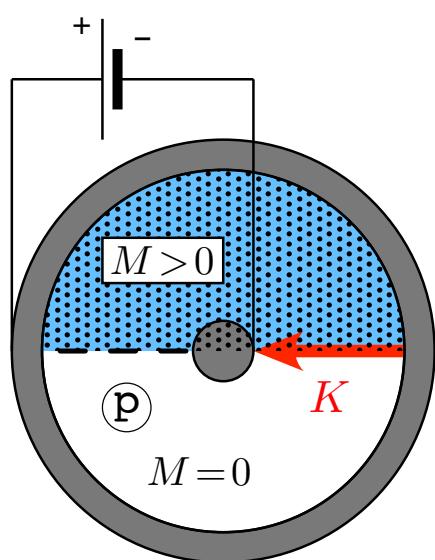
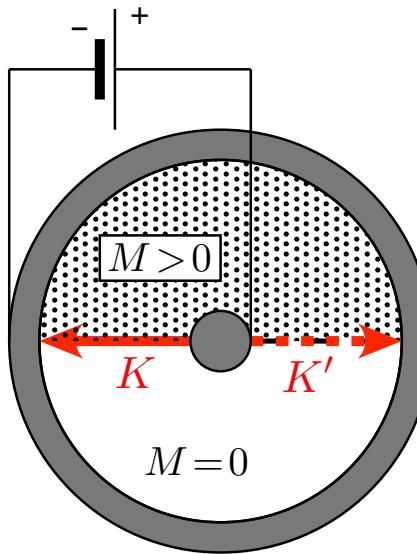
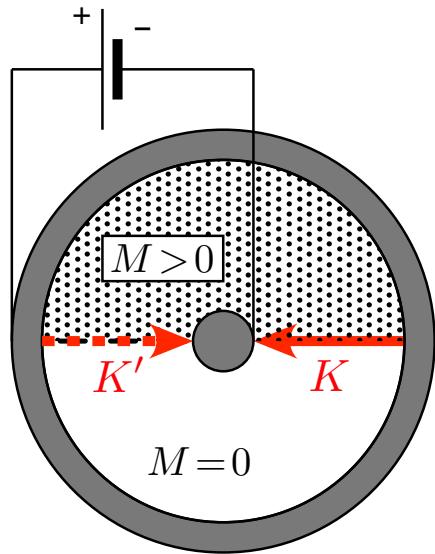
**Left:** Peters et al., APL (2014)

**Right:** Kumar, Laitinen, Hakonen, Nature Comm. (2018)

# Mesoscopic valley filter: Symmetries



# Mesoscopic valley filter: Mass term



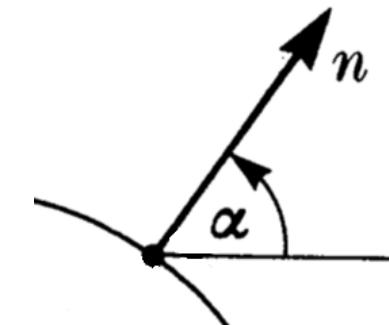
$$H_M = M(x, y) \sigma_z$$

# Why the mass term split valleys?

[ Berry & Mondragon 1987; *revisited for the TWO valleys* ]

We suppose zero outward current normal to the boundary **at each valley** ( $\xi = \pm 1$ ):

$$j_{\mathbf{n}(\alpha)} = \langle \xi \sigma_x \cos \alpha + \sigma_y \sin \alpha \rangle_{\Phi_\xi} = 0,$$



where  $\mathbf{n}(\alpha) = (\cos \alpha, \sin \alpha)$  and  $\Phi_\xi = (\Phi_{\xi,A}, \Phi_{\xi,B})^T$

The above can be rewritten as

$$\xi \cos \alpha \operatorname{Re} (\Phi_{\xi,A}^* \Phi_{\xi,B}) + \sin \alpha \operatorname{Im} (\Phi_{\xi,A}^* \Phi_{\xi,B}) = 0,$$

which is equivalent to

$$\left( \frac{\Phi_{\xi,B}}{\Phi_{\xi,A}} \right)^\xi = i \mathcal{B} \exp(i\alpha),$$

where *real*  $\mathcal{B}$  depends on physical nature of a confinement.

Infinite mass for  $x < 0$  corresponds to  $\mathcal{B} = 1$  and  $\alpha = \pi$ , leading to the condition (\*)

$$\Phi_{\xi,A}|_{x=0} = i\xi \Phi_{\xi,B}|_{x=0}.$$

The **zero-energy solution** for the Dirac equation,  $H_\xi \Phi_\xi = 0$ , is

$$\Phi_{0,k_y,\xi=1}^{[\mathcal{E}=0]}(x) = C_1 \begin{bmatrix} 0 \\ e^{-\chi^2/2} \end{bmatrix} + C_2 \begin{bmatrix} e^{\chi^2/2} \\ 0 \end{bmatrix},$$

OR

$$\Phi_{0,k_y,\xi=-1}^{[\mathcal{E}=0]}(x) = C_1 \begin{bmatrix} e^{-\chi^2/2} \\ 0 \end{bmatrix} + C_2 \begin{bmatrix} 0 \\ e^{\chi^2/2} \end{bmatrix}$$

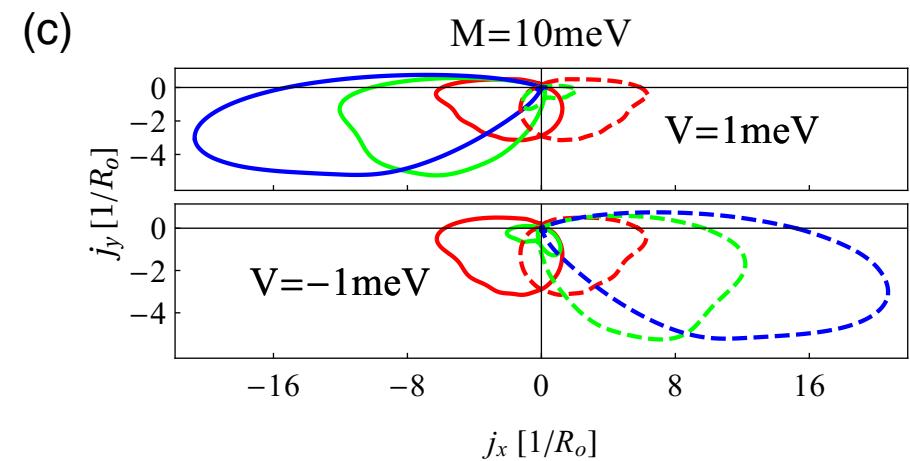
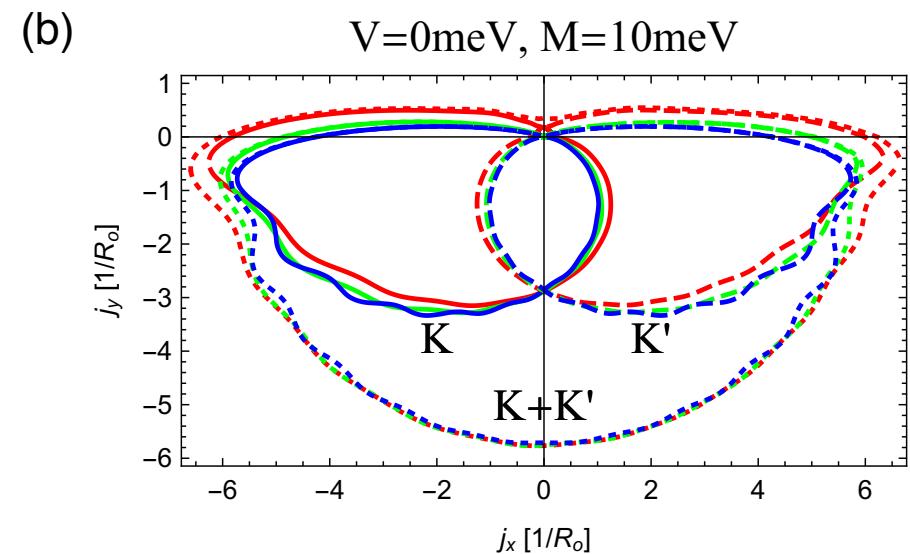
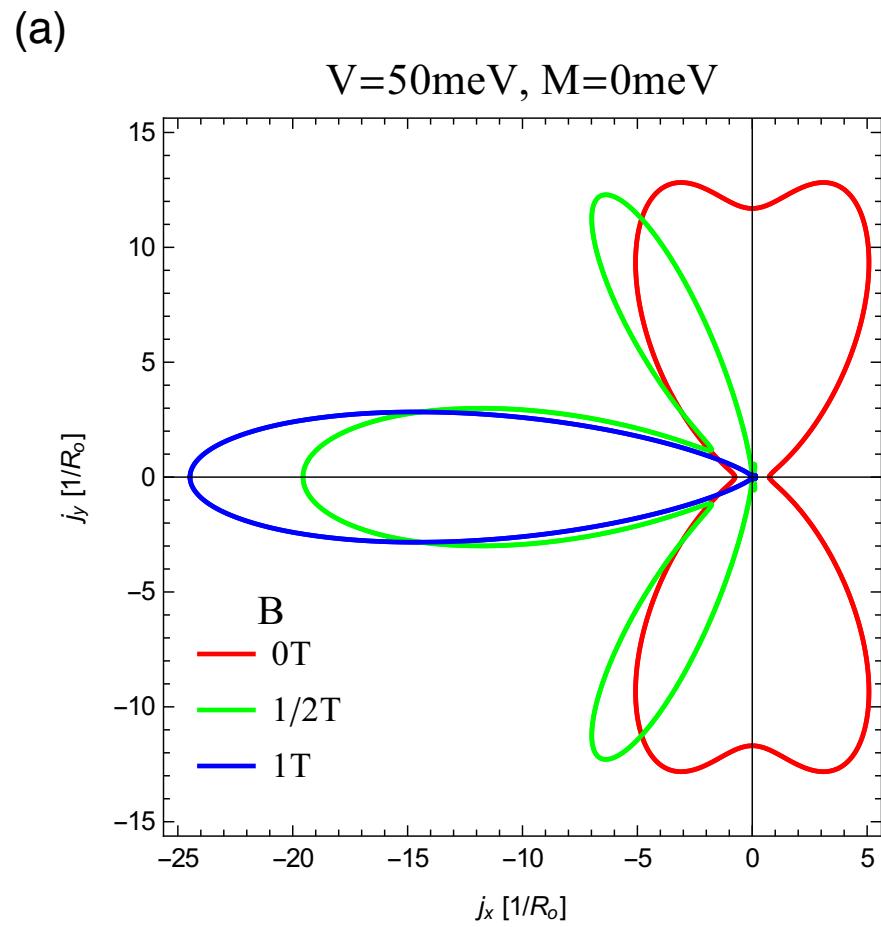
with arb. constants  $C_1, C_2$ , and  $\chi = l_B^{-1}x + l_B k_y$  ( $l_B = \sqrt{\hbar/e|B|}$ ).

The condition (\*) implies that  $C_{\xi,2} = i\xi C_{\xi,1} \exp(-k_y^2 l_B^2)$

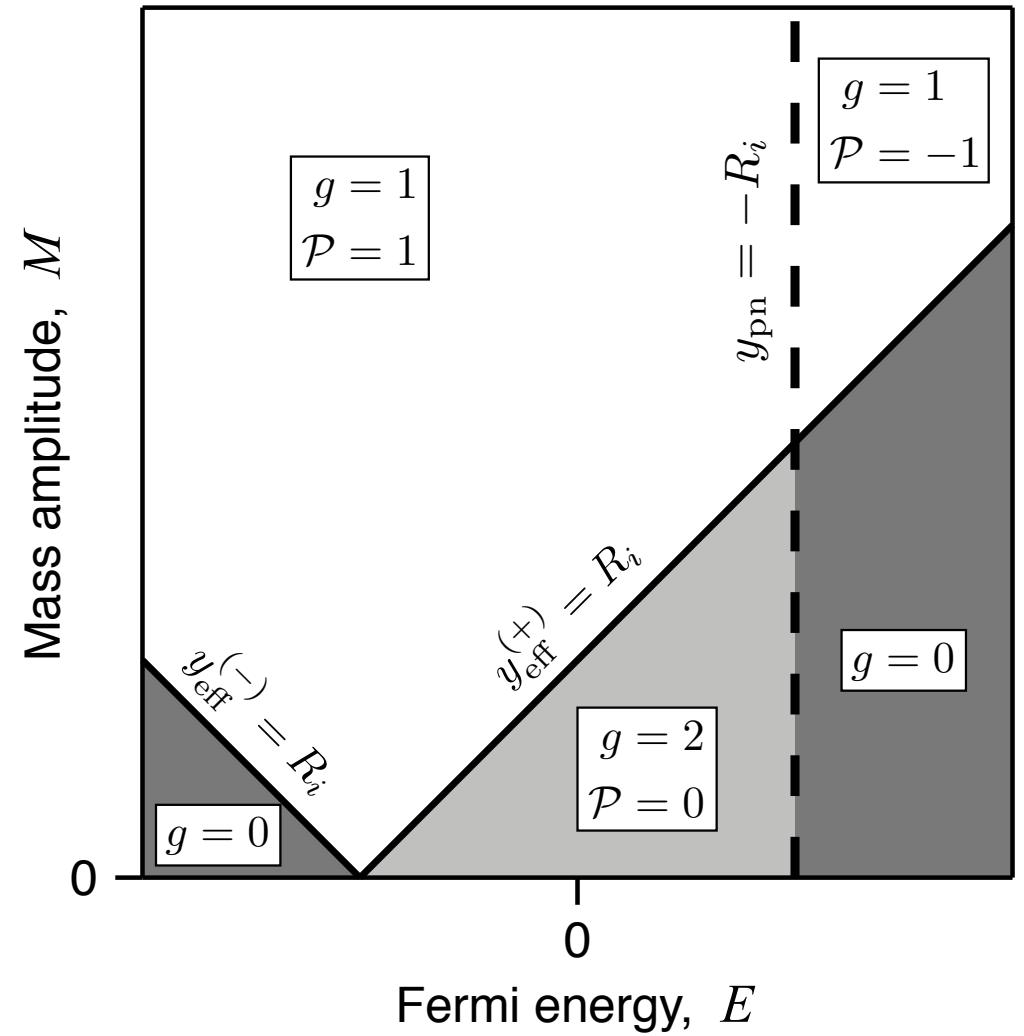
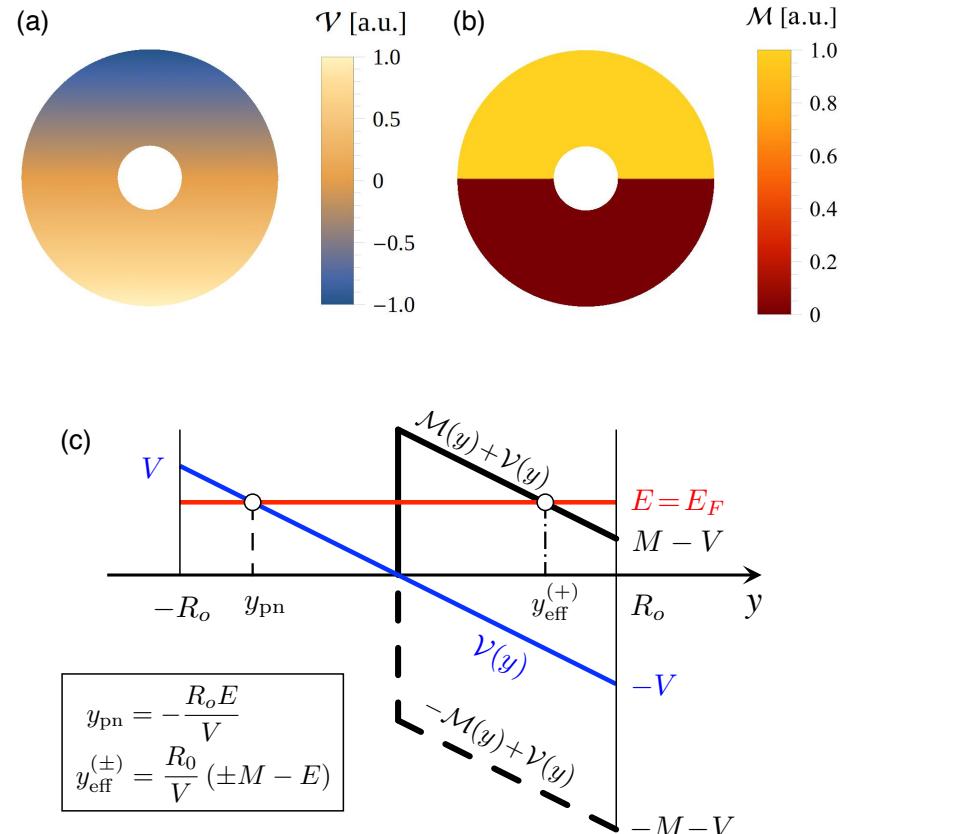
and

$$j_y = \langle \sigma_y \rangle_{\Phi_{0,k_y,\xi}^{[\mathcal{E}=0]}} = -2\xi |C_{\xi,1}|^2 \exp(-k_y^2 l_B^2)$$

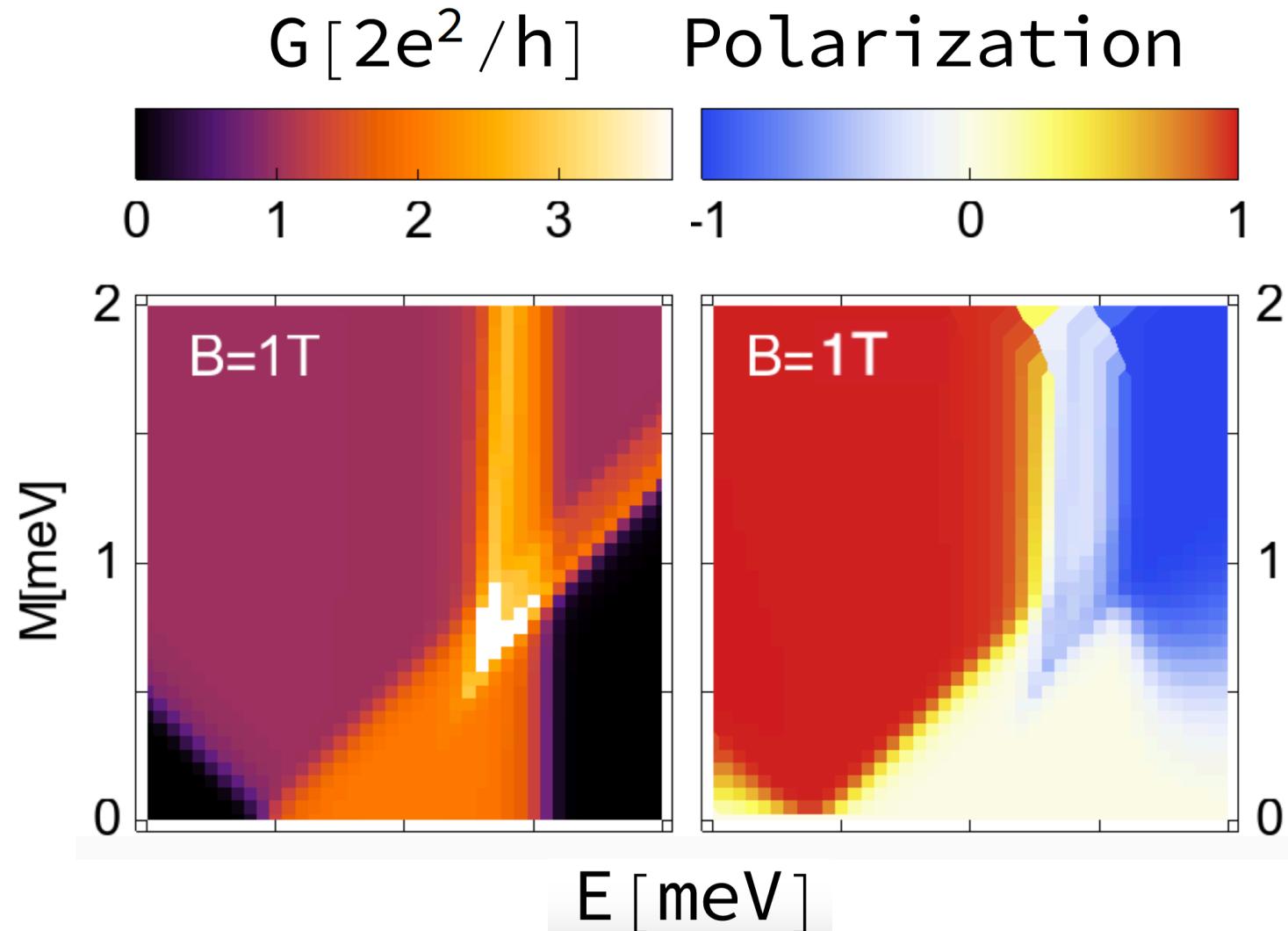
# Numerical results: *Current distribution* [ $r=R_o$ ]



# Numerical results: Phase diagram (sketch)



# Numerical results: *Phase diagram*



# Conclusions

The Corbino disk in monolayer graphene, modified such that the mass term in effective Hamiltonian is present in a half of the disk may act as a highly efficient ***valley filter***.

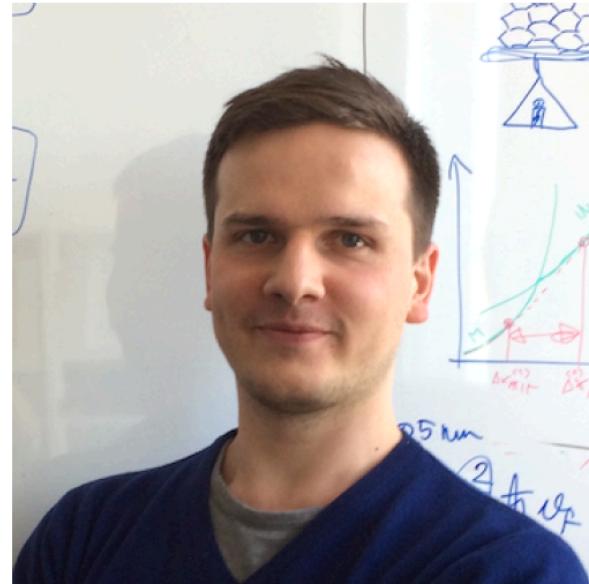
The output (valley) polarization may be ***controlled fully electrostatically*** (in constant magnetic field), alternatively by:

(1) *inverting the p-n junction polarity,*

OR

(2) *shifting the p-n line by tuning a global doping*

The magnetic field of 1T is sufficient to obtain the polarization better than 99% for the device size of 400 nm.



## Grzegorz Rut Dominik Suszalski

The work was supported by the National Science Centre of Poland (NCN)  
via Grant No. 2014/14/E/ST3/00256.

# THANK YOU!