Spin Superfluidity in the $\nu = 0$ Quantum Hall State of Graphene

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S. Takei, A. Yacoby, B. Halperin, Y. Tserkovnyak, Phys. Rev. Lett. **116**, 216801 (2016)

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contents

graphene in magnetic field

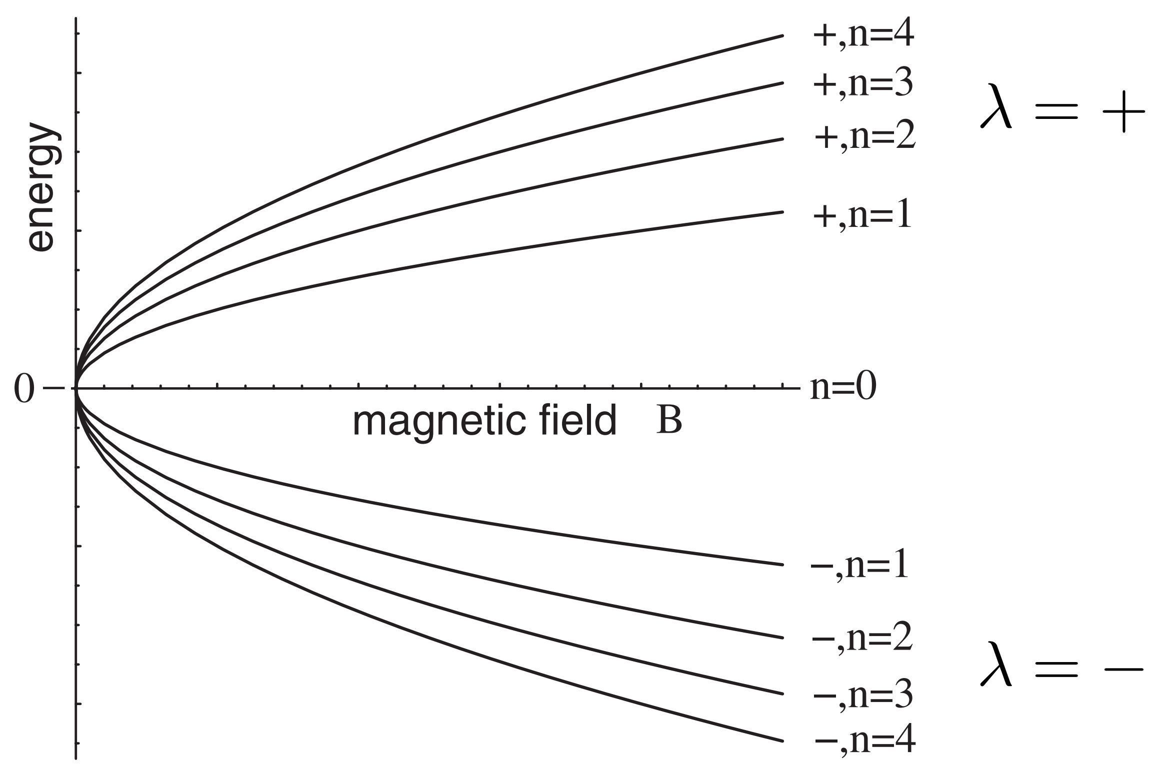
- graphene Landau levels: reflects linear dispersion and (pseudospin) chirality

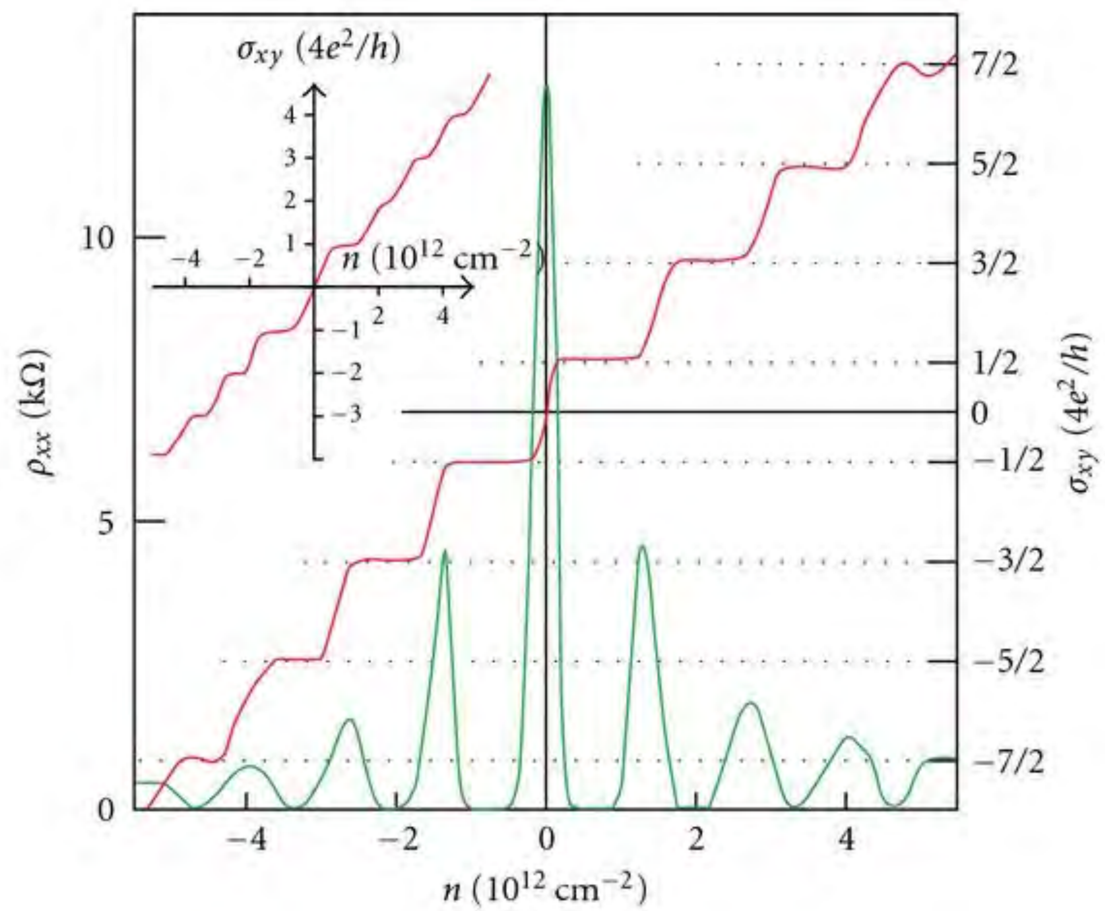
$$\epsilon_{\lambda n} = \lambda \frac{\hbar v_F}{\ell_B}\sqrt{2n}$$

$$\ell_B = \sqrt{\frac{\hbar}{eB}}, \; v_F \approx 0.01c$$

$$\nu = 4\left(n + \frac{1}{2}\right)$$

$$n = 0, \pm 1, \pm 2, \pm 3, \ldots$$





4-fold valley-spin degeneracy

M. O. Goerbig, Rev. Mod. Phys. **83**, 1193 (2011)
K. S. Novoselov *et al.*, Nature **438**, 197 (2005)

ν = 0 ground state

- leading Coulomb Hamiltonian for electrons restricted to the zLL is SU(4)-symmetric

$$\hat{H}_0 = \frac{1}{2}\sum_{\boldsymbol{q}} v_0(\boldsymbol{q})\hat{\rho}_0(-\boldsymbol{q})\hat{\rho}_0(\boldsymbol{q})$$

K. Nomura and A. H. MacDonald, Phys. Rev. Lett. **96**, 256602 (2006)
M. O. Goerbig *et al.*, Phys. Rev. B **74**, 161407 (2006)

- **SU(4) quantum Hall ferromagnetism**: at integer filling fractions, possible ground state lies on a degenerate manifold of states polarized in SU(4)-symmetric isospin space, encompassing a variety of different spin and/or valley orders

K. Nomura and A. H. MacDonald, Phys. Rev. Lett. **96**, 256602 (2006)
K. Yang *et al.*, Phys. Rev. B **84**, 075423 (2006)

SU(4) symmetry breaking can occur due to Zeeman effect and various short-ranged interactions.
Key question: how is the SU(4) symmetry broken in a real system?

- *Zeeman effect*: ferromagnetic

K. Yang *et al.*, Phys. Rev. B **74**, 075423 (2006)
J. Alicea and M. P. A. Fisher, Phys. Rev. B **74**, 075422 (2006)
H. A. Fertig and L. Brey, Phys. Rev. Lett. **97**, 116805 (2006)

- *short-range e-e interactions*: ferromagnetic, CDW, antiferromagnetic

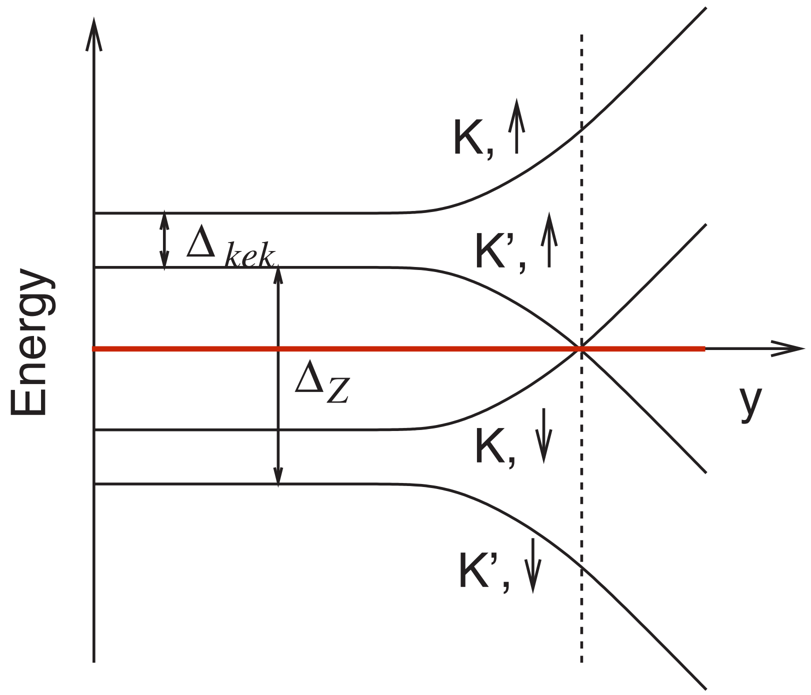
J. Alicea and M. P. A. Fisher, Phys. Rev. B **74**, 075422 (2006)
J. Jung and A. H. MacDonald, Phys. Rev. B **80**, 235417 (2009)

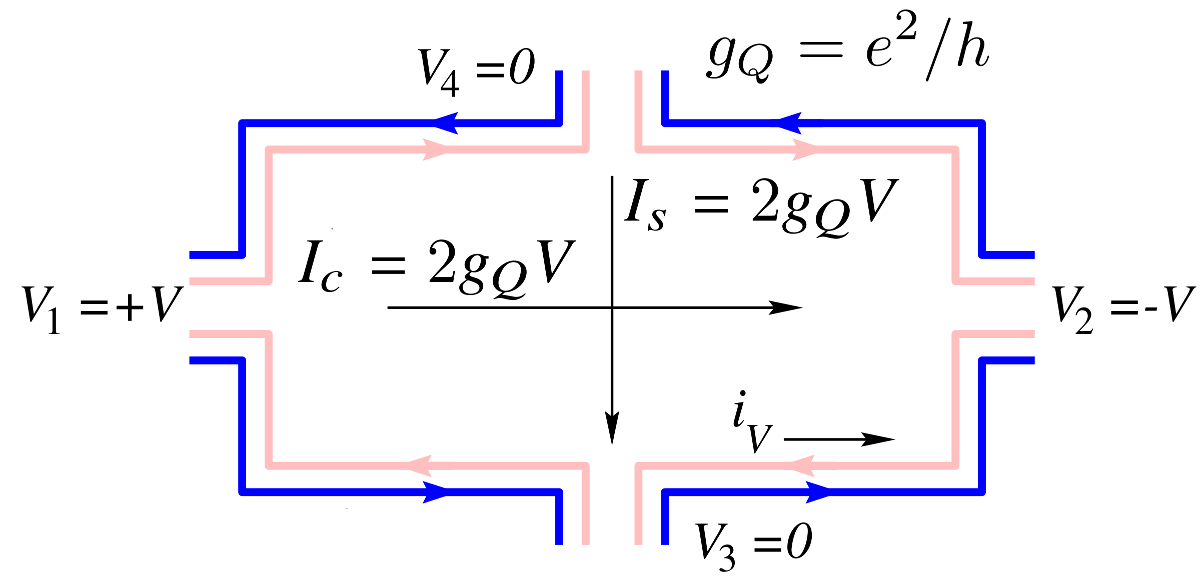
- *short-range e-ph interactions*: CDW, Kékule

J.-N. Fuchs and P. Lederer, Phys. Rev. Lett. **98**, 016803 (2007)
K. Nomura, S. Ryu, and D.-H. Lee, Phys. Rev. Lett. **103**, 216801 (2009)
C.-Yu Hou, C. Chamon, and C. Mudry, Phys. Rev. B **81**, 075427 (2010)

ν = 0 ground state

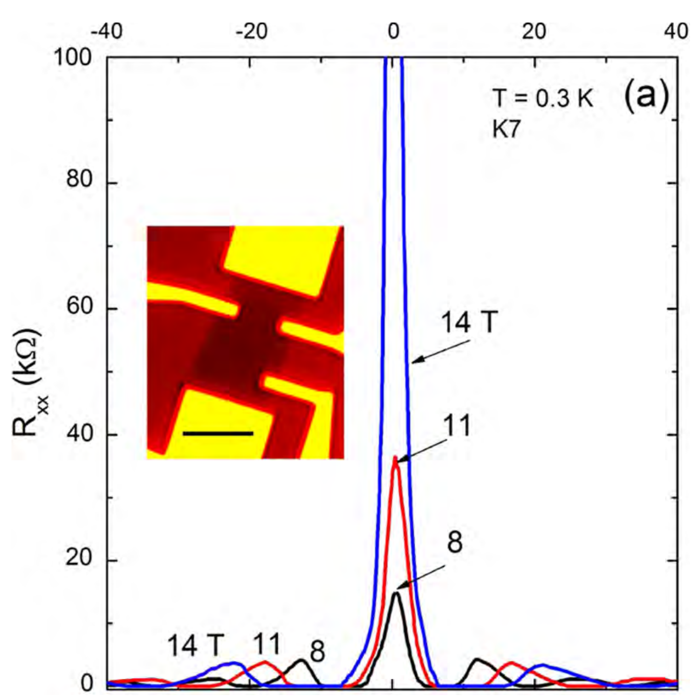
- possibility of gapless U(1) spin-symmetry protected helical edge states

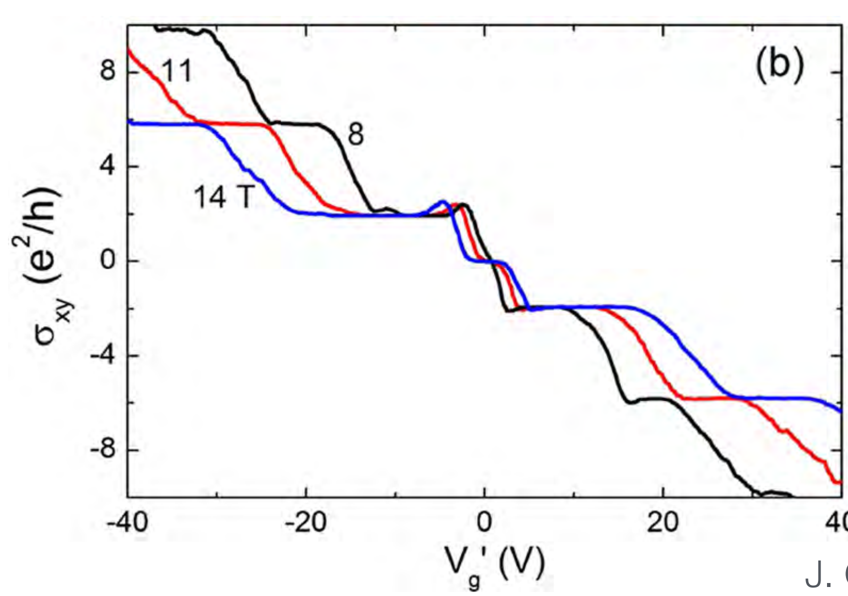




D. Abanin *et al.*, Phys. Rev. Lett. **96**, 176803 (2006)

- experiments support an insulating ground state, and inconsistency with a spin-polarized ground state



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nature physics

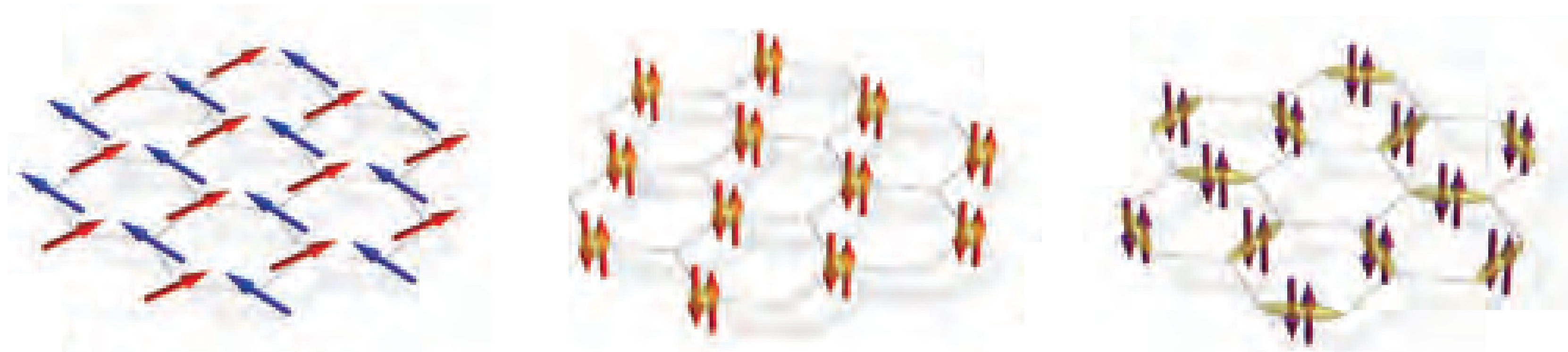
Spin and valley quantum Hall ferromagnetism in graphene

A. F. Young[1*†], C. R. Dean[2,3†], L. Wang[3], H. Ren[1], P. Cadden-Zimansky[1], K. Watanabe[4], T. Taniguchi[4], J. Hone[3], K. L. Shepard[2] and P. Kim[1*]

J. G. Checkelsky et al., Phys. Rev. Lett. **100**, 206801 (2008)
X. Du *et al.*, Nature **462**, 192–195 (2009)
A. F. Young *et al.*, Nature Phys. **8**, 550 (2012)

canted antiferromagnetic scenario

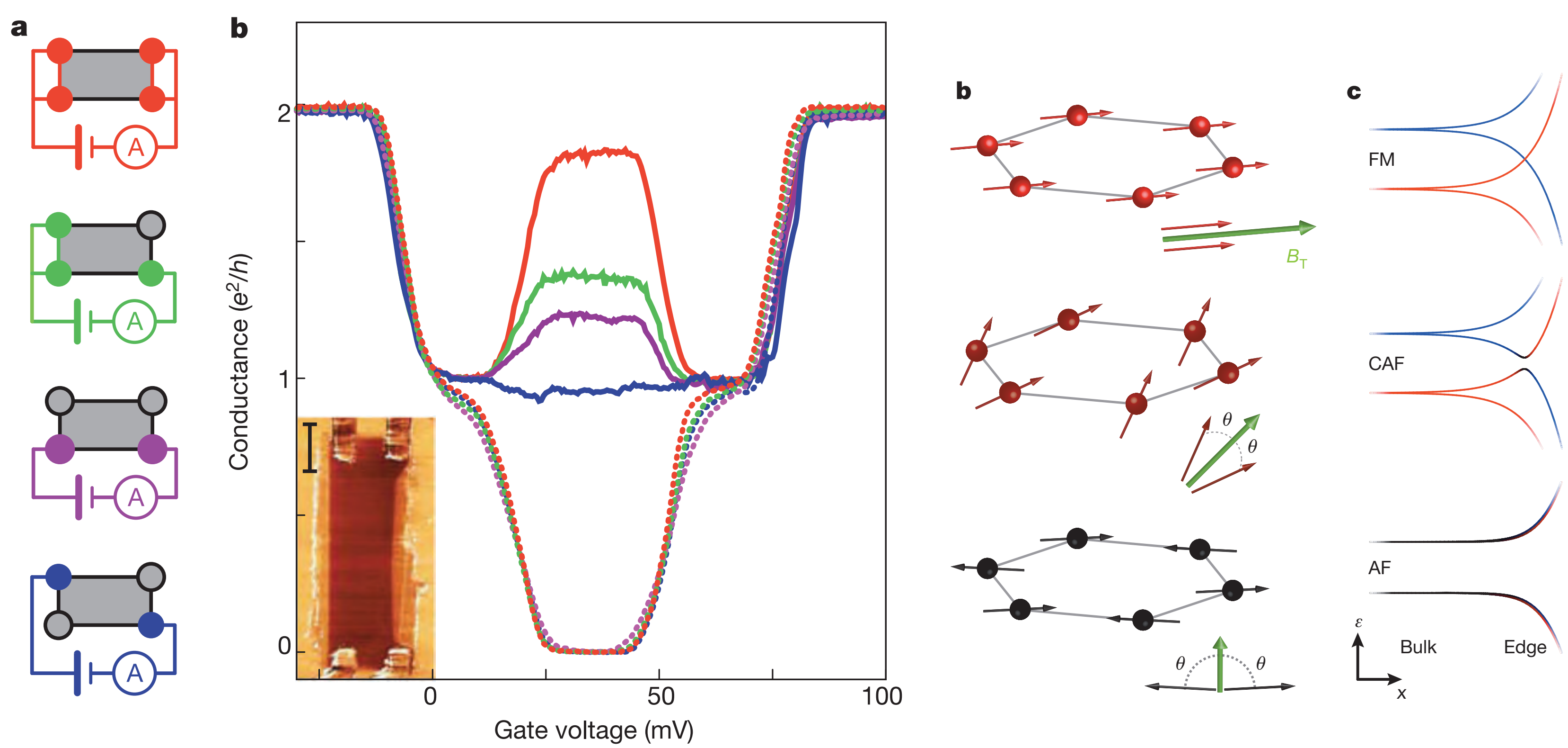
- possible spin unpolarized scenarios:



canted antiferromagnet | charge density wave | Kekulé

J.-N. Fuchs and P. Lederer, Phys. Rev. Lett. **98**, 016803 (2007)
K. Nomura, S. Ryu, and D.-H. Lee, Phys. Rev. Lett. **103**, 216801 (2009)
C.-Yu Hou, C. Chamon, and C. Mudry, Phys. Rev. B **81**, 075427 (2010)

- edge reconstruction in tilted magnetic field shows consistency with the canted antiferromagnetic (CAF) ground state scenario



U(1) symmetry-protected helical edge states

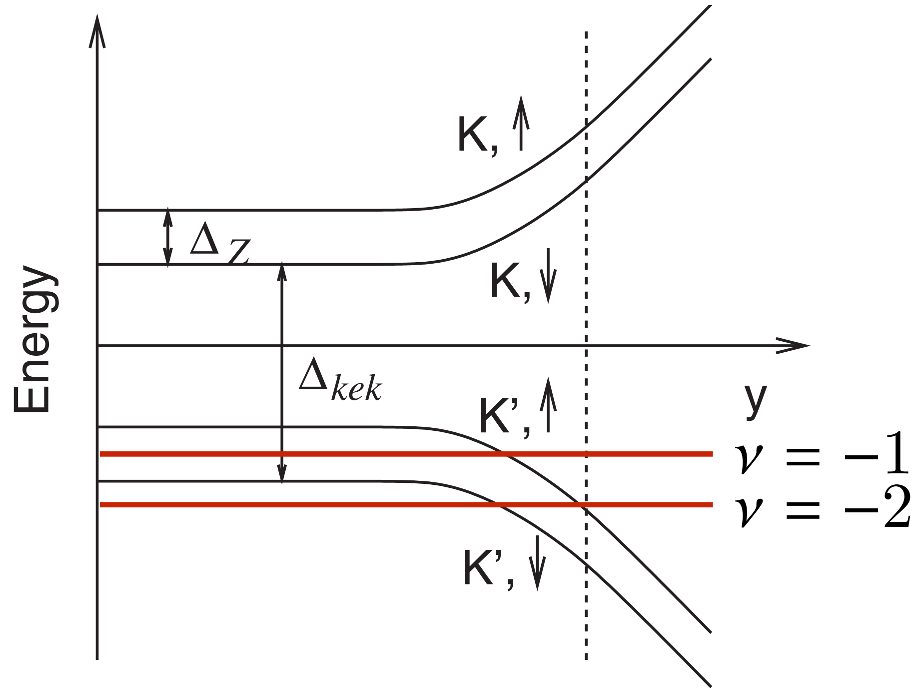
Antiferromagnetic order breaks U(1) symmetry and edge opens a gap

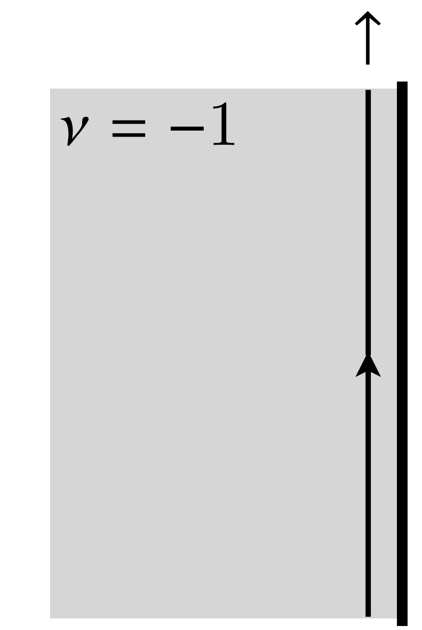
M. Kharitonov, Phys. Rev. B **86**, 075450 (2012)
A. F. Young et al., Nature **505**, 528 (2014)

ν = −2 / ν = −1 edges

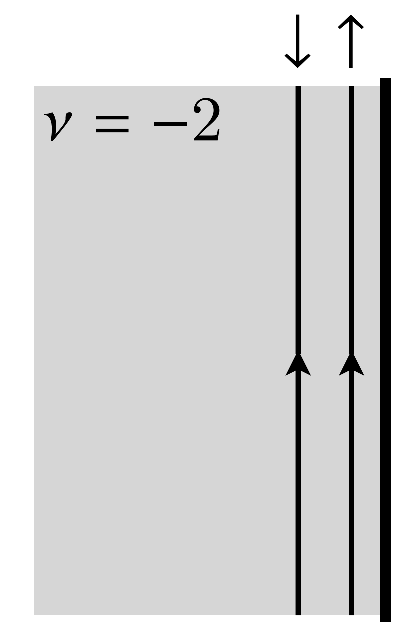
- degeneracy lifting of zLL in the bulk and at an edge

H. A. Fertig and L. Brey, Phys. Rev. B **73**, 195408 (2006)

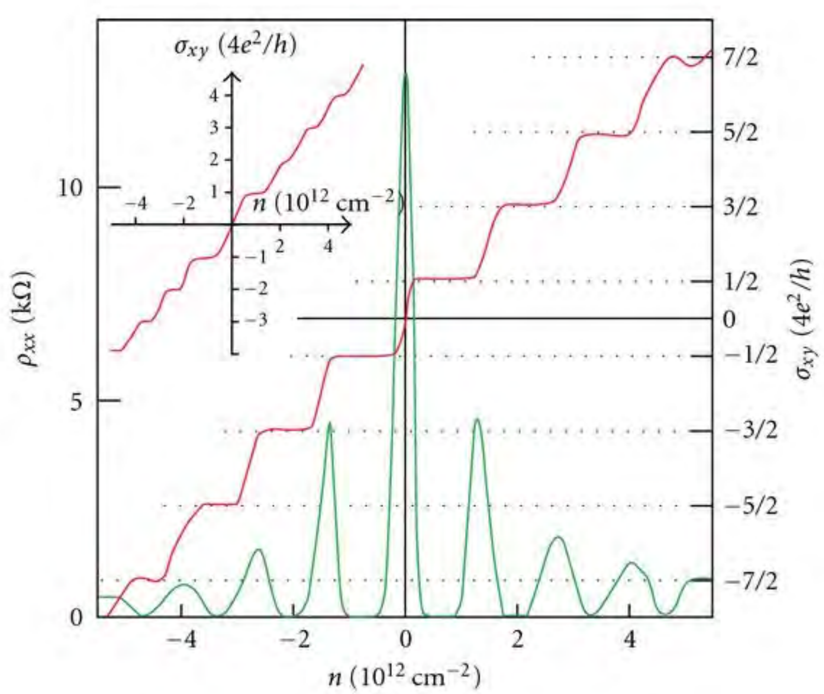




one spin-polarized hole-like edge



two co-propagating spin-polarized hole-like edges



PRL **112,** 196601 (2014) PHYSICAL REVIEW LETTERS week ending 16 MAY 2014

Selective Equilibration of Spin-Polarized Quantum Hall Edge States in Graphene

F. Amet,[1] J. R. Williams,[2] K. Watanabe,[3] T. Taniguchi,[3] and D. Goldhaber-Gordon[2]
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(Received 3 July 2013; revised manuscript received 25 November 2013; published 12 May 2014)

Spin symmetry prohibits forward scattering between the two ν = – 2 edge channels superfluid spin transport using quantum Hall edge states

spin superfluidity in the canted antiferromagnet state

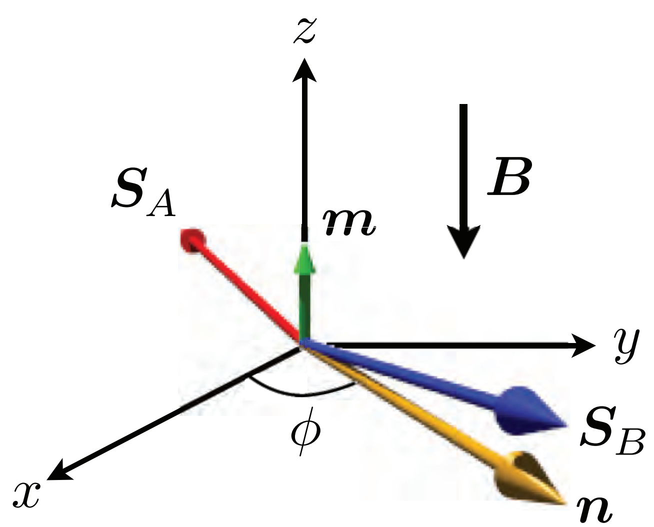
- classical dynamics for standard bipartite Heisenberg antiferromagnet in a magnetic field

A. F. Andreev and V. I. Marchenko, Sov. Phys. Uspekhi **23**, 21 (1980)

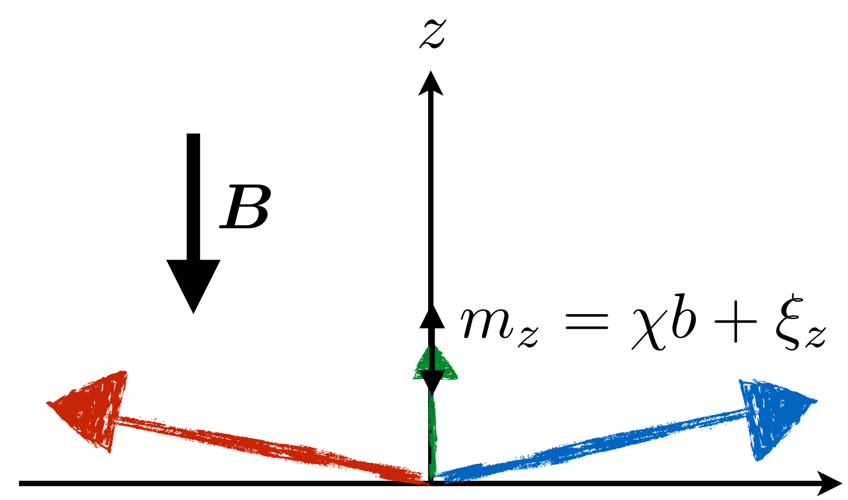
$$s\dot{\boldsymbol{n}} = \chi^{-1}\boldsymbol{m}\times\boldsymbol{n} + \boldsymbol{b}\times\boldsymbol{n}$$
$$s\dot{\boldsymbol{m}} = A\boldsymbol{n}\times\nabla^2\boldsymbol{n} + \boldsymbol{b}\times\boldsymbol{m}$$

$$|\boldsymbol{n}| = 1,\ \ |\boldsymbol{m}| \ll 1$$

- one gapless mode: (azimuthal) Néel rotations within the plane normal to the field



(ϕ, ξ_z)



- projected dynamics only in terms of the variables in the gapless sector

$$s\dot{\phi} = \chi^{-1}\xi_z, \quad s\dot{\xi}_z = A\nabla^2\phi$$

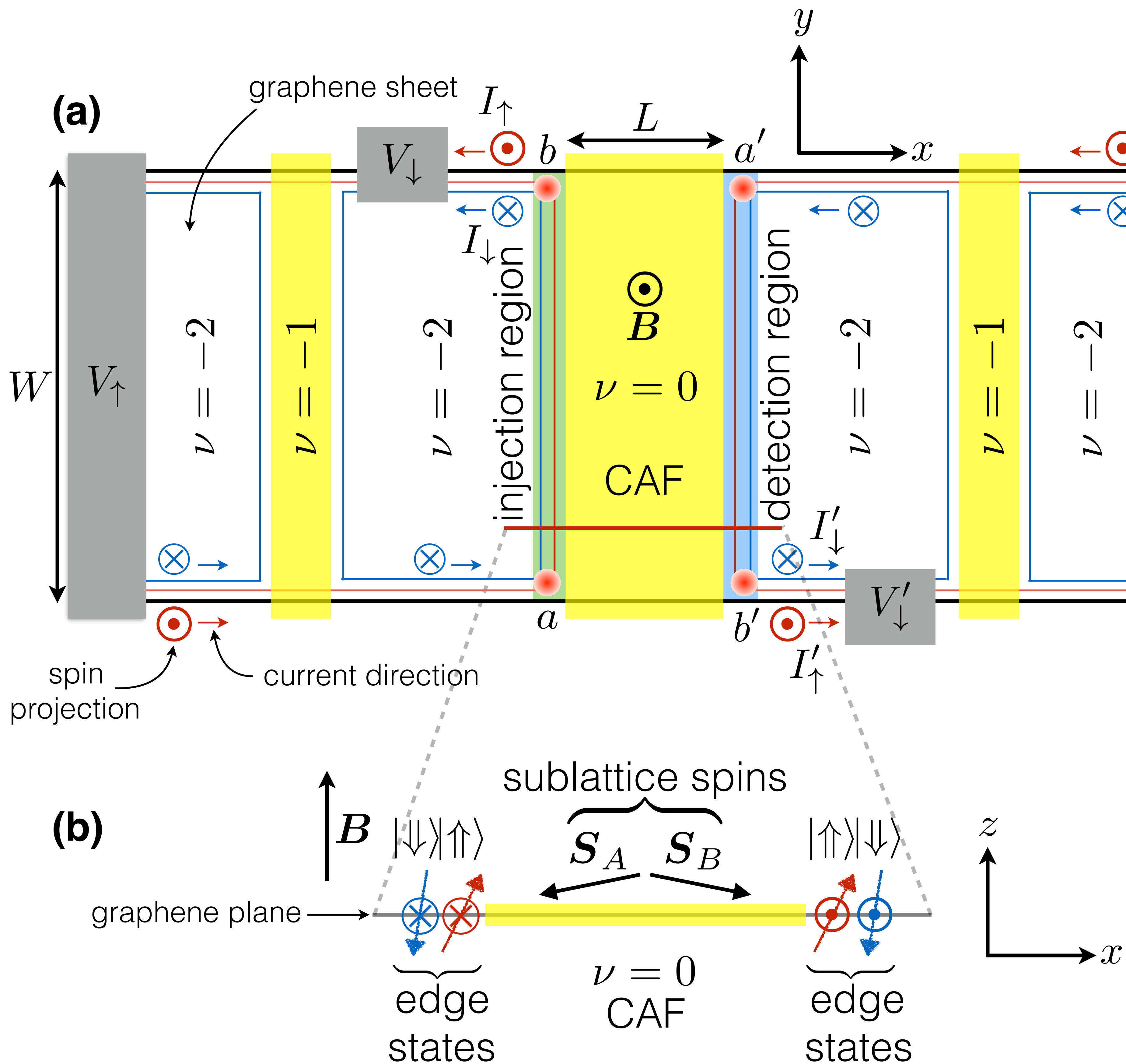
$$J_s(x,t) = -A\boldsymbol{\nabla}\phi(x,t)$$

spin supercurrent

Superfluid of spin component antiparallel to the field

B. I. Halperin and P. Hohenberg, Phys. Rev. **188**, 898 (1969)

two-terminal spin transport setup



ST, A. Yacoby, B. Halperin, Y. Tserkovnyak, Phys. Rev. Lett. **116**, 216801 (2016)

linear response theory for spin injection/detection

- inter-channel scattering can occur at the vertices and along the line junction
- spin current lost on the injection edge should be absorbed by CAF (neglecting external sources of spin loss, e.g., spin-orbit coupling, magnetic impurities, etc.)

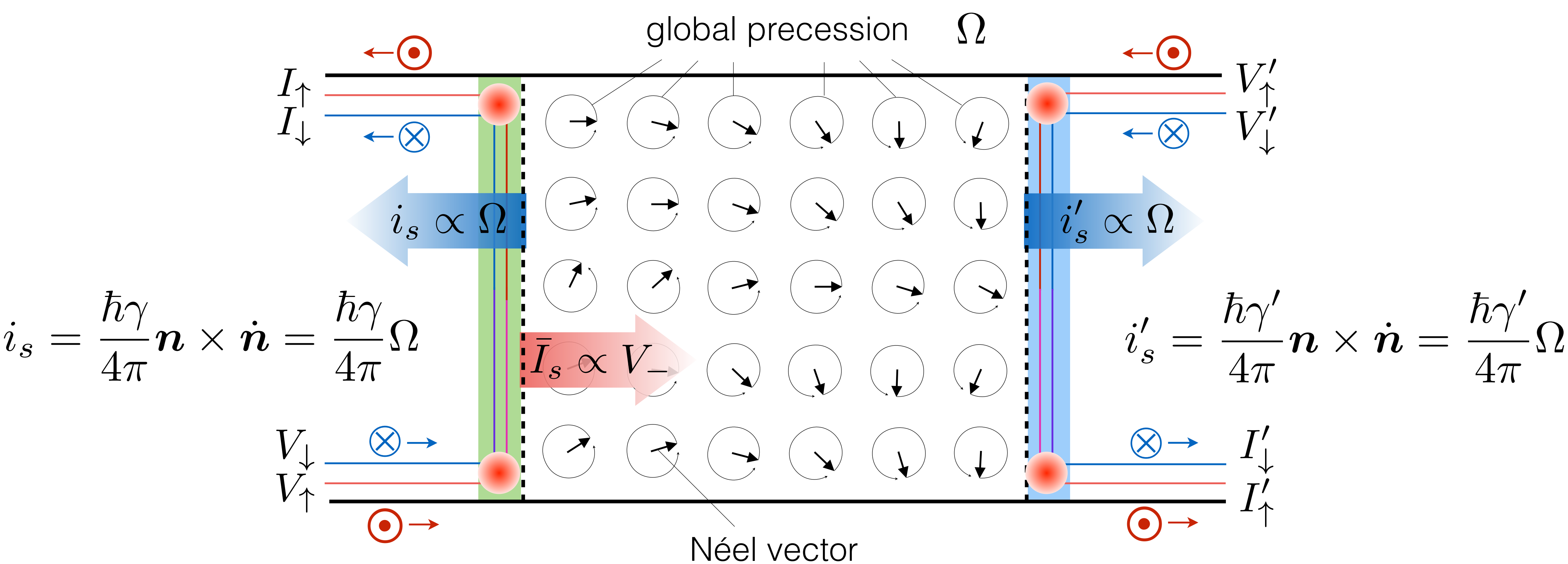
$$\bar{I}_s = \gamma \left[\frac{\hbar}{2e} \frac{e^2}{h} (V_\uparrow - V_\downarrow) \right]$$

$\gamma = 0$ no inter-channel mixing

$\gamma = 1$ full inter-channel mixing

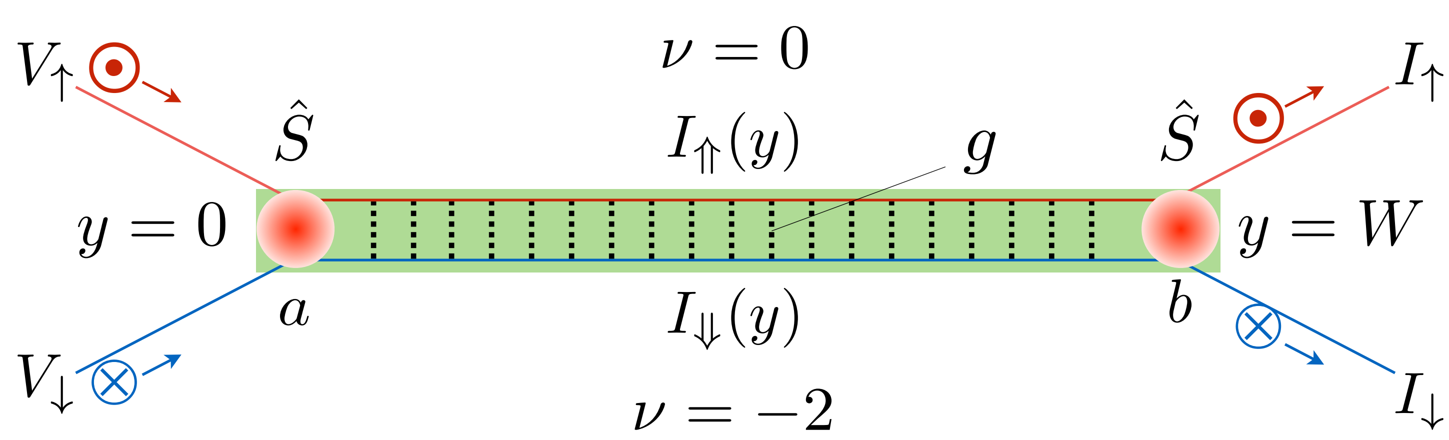
- injected spin current is carried by dynamically precessing Néel texture within graphene plane, i.e., spin superfluid.
- spin current ejected into edges by a collinear antiferromagnet with Néel vector rotating within the xy plane

R. Cheng *et al.*, Phys. Rev. Lett. **113**, 057601 (2014)



ST, A. Yacoby, B. Halperin, Y. Tserkovnyak, Phys. Rev. Lett. **116**, 216801 (2016)

edge equilibration



- scattering at vertices arises due to:
  - slight misalignment of spin states between the regions inside and outside the injection region
  - any source of momentum non-conservation, e.g., disorder, sharp change in current direction, etc.

$$\hat{S} = \begin{pmatrix} t & 1-t \\ 1-t & t \end{pmatrix}$$

$t = 0.5$ full vertex mixing

$t = 1$ no vertex mixing

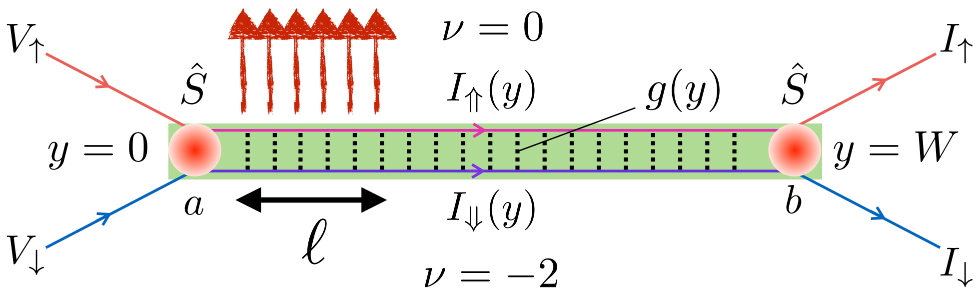
- inter-channel tunneling conductance ***g*** per unit length depends on:
  - spatial proximity of the two edge channels
  - elastic impurities: gives momentum non-conservation necessary to overcome mismatch of Fermi momenta
  - spin-flip mechanism: provided by the neighboring CAF

ST, A. Yacoby, B. Halperin, Y. Tserkovnyak, Phys. Rev. Lett. **116**, 216801 (2016)

edge equilibration

- line junction equilibration length scale

$$\ell = \frac{e^2}{2hg}$$



- current exiting the line junction

$$\begin{pmatrix} I_\Uparrow(W) \\ I_\Downarrow(W) \end{pmatrix} = \frac{1}{2} \begin{pmatrix} 1+e^{-w} & 1-e^{-w} \\ 1-e^{-w} & 1+e^{-w} \end{pmatrix} \begin{pmatrix} I_\Uparrow(0) \\ I_\Downarrow(0) \end{pmatrix} \qquad w = \frac{W}{\ell}$$

- total edge transport

$$\begin{pmatrix} I_\uparrow \\ I_\downarrow \end{pmatrix} = \hat{S}\hat{S}_{\mathrm{int}}\hat{S} \begin{pmatrix} \frac{e^2}{h} V_\uparrow \\ \frac{e^2}{h} V_\downarrow \end{pmatrix}$$

- inter-channel scattering parameter:

$$\gamma = 1 - (1-2t)^2 e^{-w}$$

- transmitted spin current

$$i'_s = \frac{1}{4\pi} \frac{\gamma\gamma'}{\gamma+\gamma'} e(V_\uparrow - V_\downarrow) \qquad i'_s = \frac{1}{4\pi} \frac{\gamma\gamma'}{\gamma+\gamma'+4\pi\alpha s W L/\hbar} e(V_\uparrow - V_\downarrow)$$

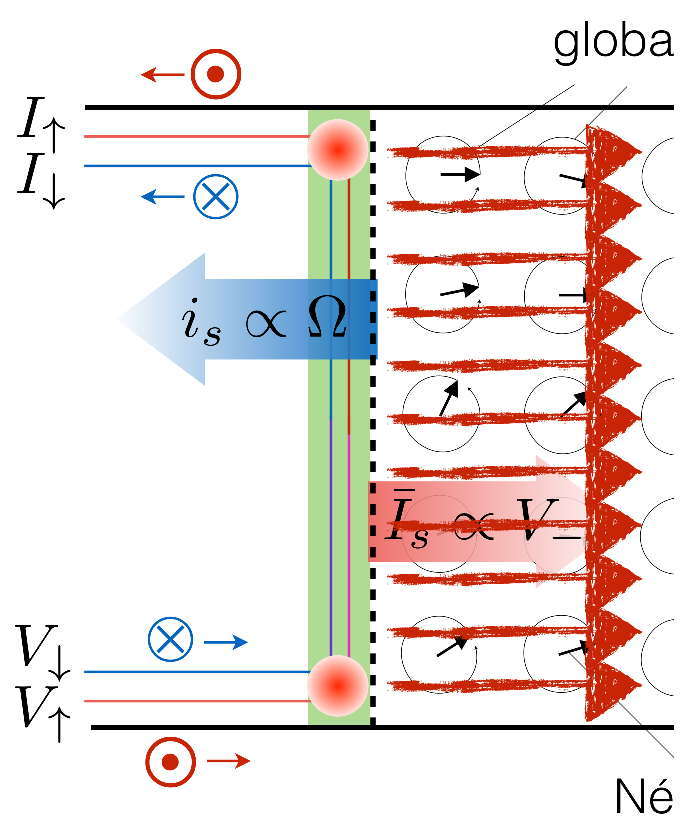
ST, A. Yacoby, B. Halperin, Y. Tserkovnyak, Phys. Rev. Lett. **116**, 216801 (2016)

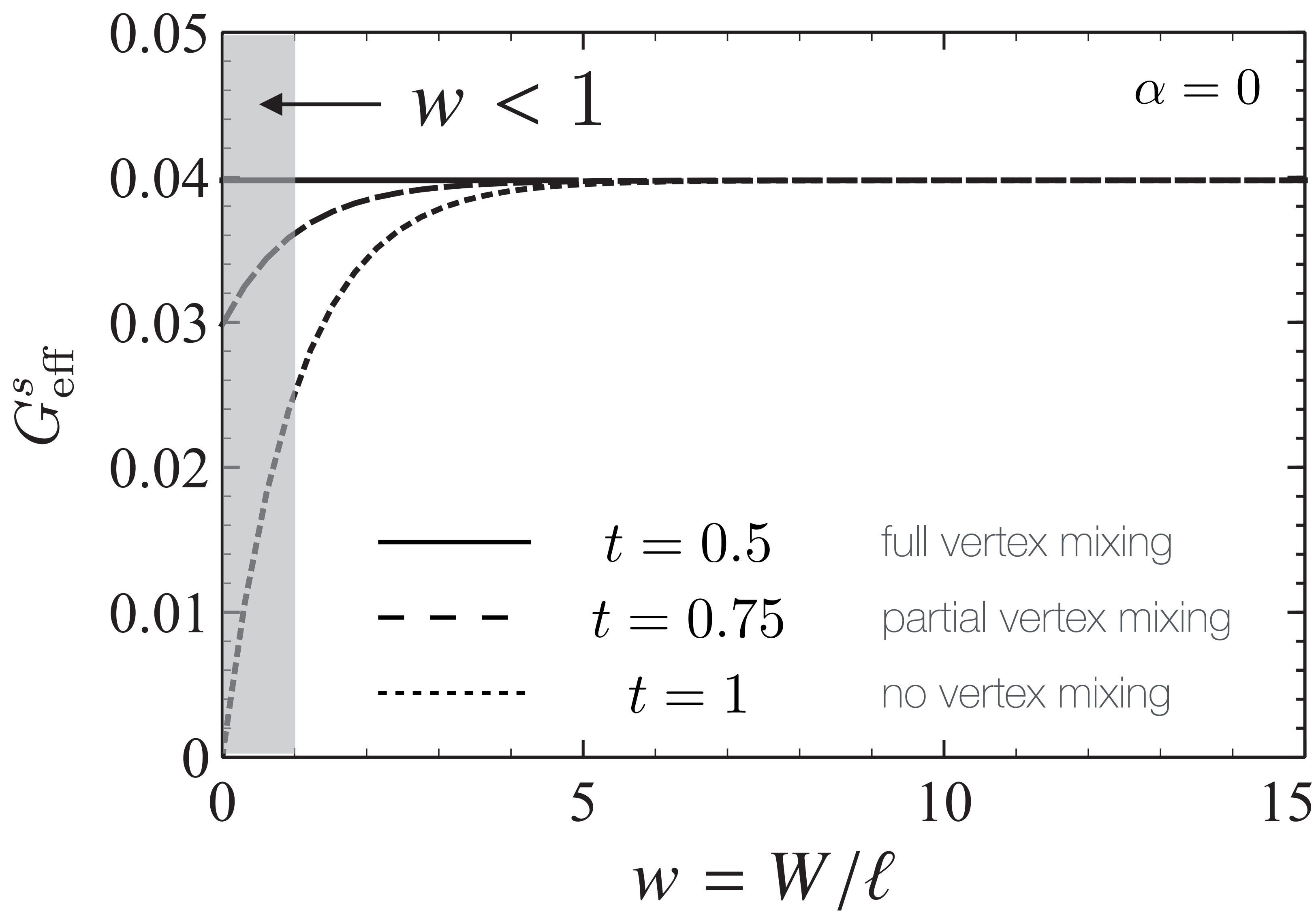
effective spin conductance

- transmitted spin current with no bulk Gilbert damping:

$$i'_s = \underbrace{\frac{1}{4\pi}\frac{\gamma\gamma'}{\gamma+\gamma'}}_{}e(V_\uparrow - V_\downarrow) \qquad \gamma = 1-(1-2t)^2 e^{-w}$$

effective spin conductance



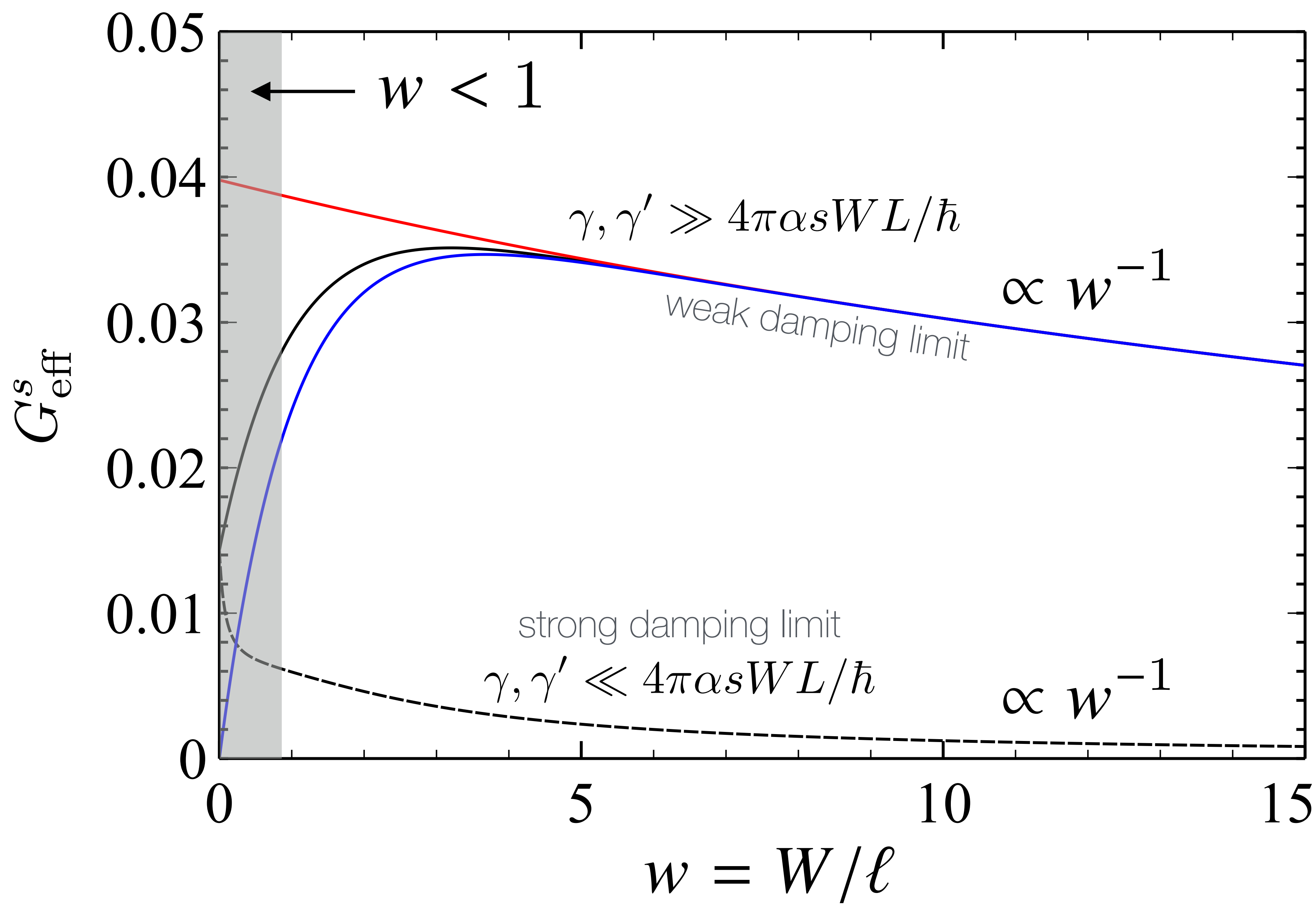


ST, A. Yacoby, B. Halperin, Y. Tserkovnyak, Phys. Rev. Lett. **116**, 216801 (2016)

effects of Gilbert damping

- transmitted spin current with Gilbert damping

$$i'_s = \frac{1}{4\pi}\frac{\gamma\gamma'}{\gamma+\gamma'+4\pi\alpha s W L/\hbar}e(V_\uparrow - V_\downarrow)$$



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summary and conclusions

- showed how (long-ranged) superfluid spin transport can be realized in the $\nu = 0$ quantum Hall state of graphene
- linear-response/Onsager reciprocity to understand spin injection/detection using quantum Hall edge states.
- superfluid spin transport will constitute a direct evidence for the canted antiferromagnetic scenario.
- microscopic approaches are necessary to determine the dependence of edge equilibration length on the disorder along the edge and on the profile of the electrostatic potential between the $\nu = 0$ and $\nu = -2$ regions
- further detailed theories of the injection and detection regions are necessary to understand the effects of external sources of spin loss along the edge on spin transport