Spin-valley blockade in carbon-based quantum dots

András Pályi

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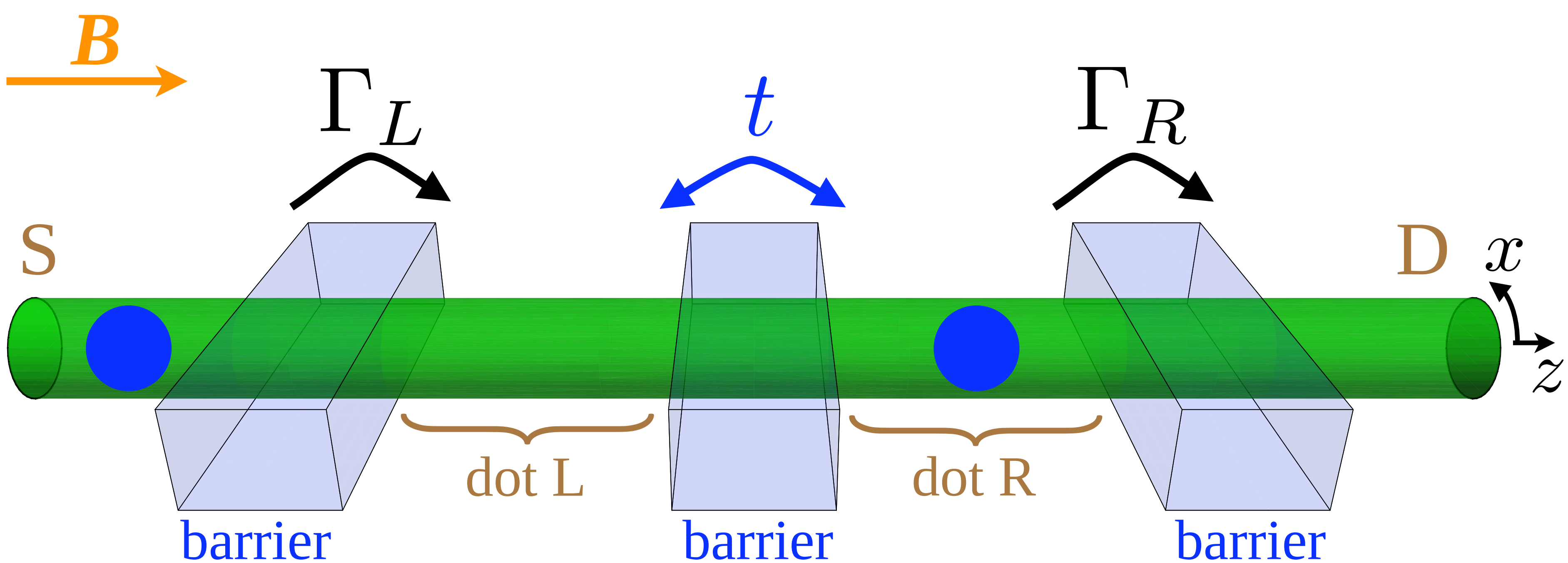
(Department of Physics, University of Konstanz, Germany)



Pályi & Burkard, Phys. Rev. B 2009, 2010
(Kiss, Pályi, ..., Dóra, Simon, Phys. Rev. Lett., to appear)

A typical GaAs double dot setup

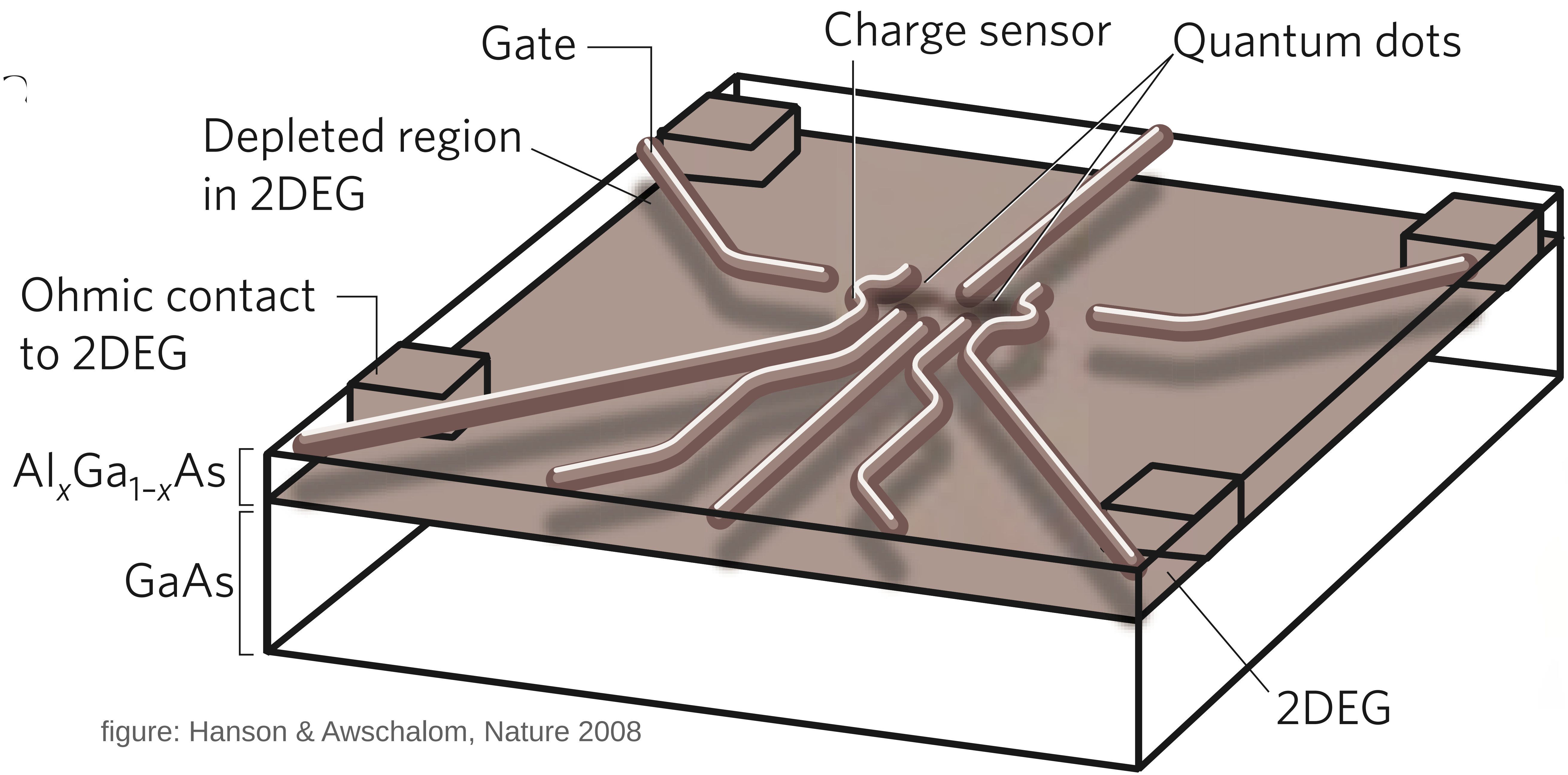


figure: Hanson & Awschalom, Nature 2008

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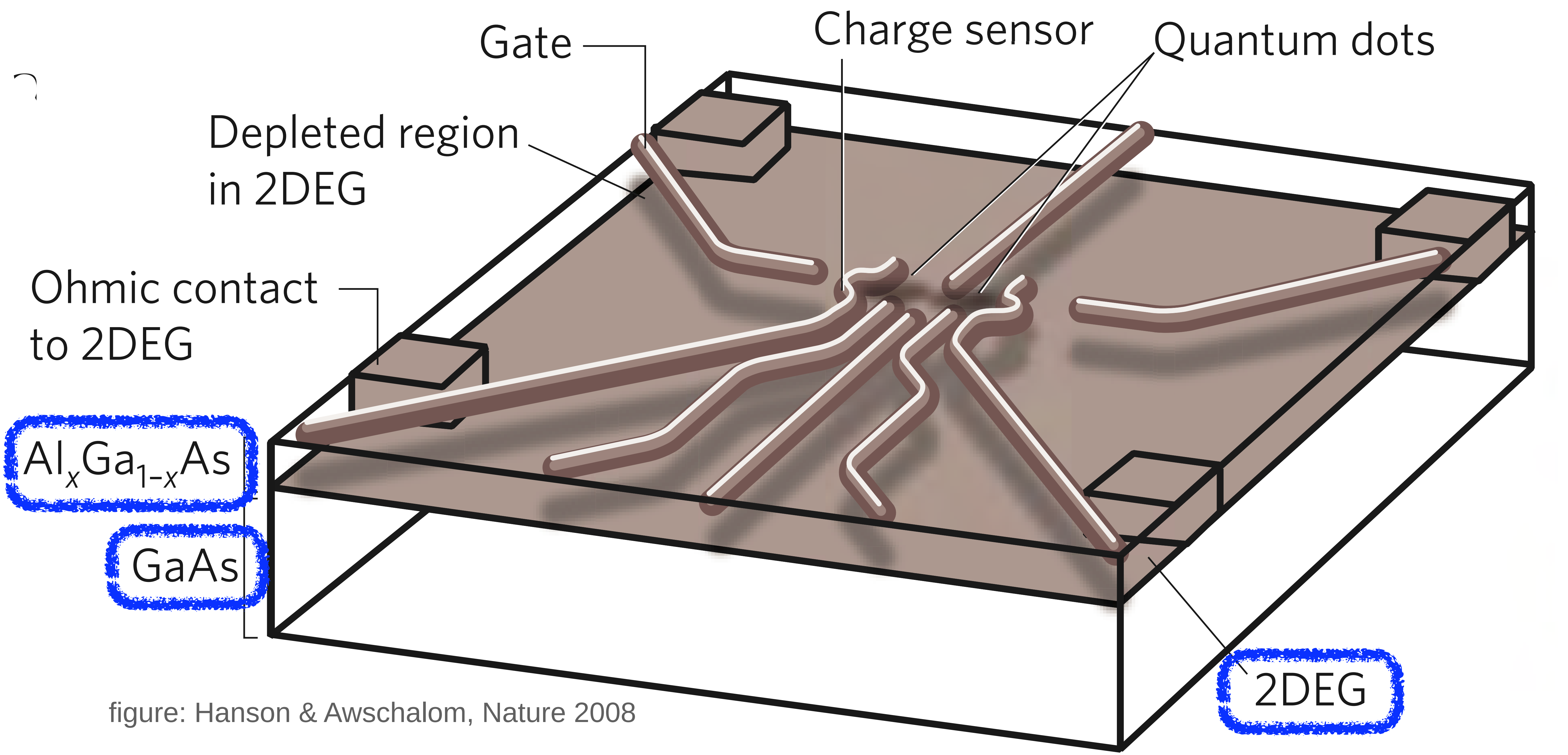

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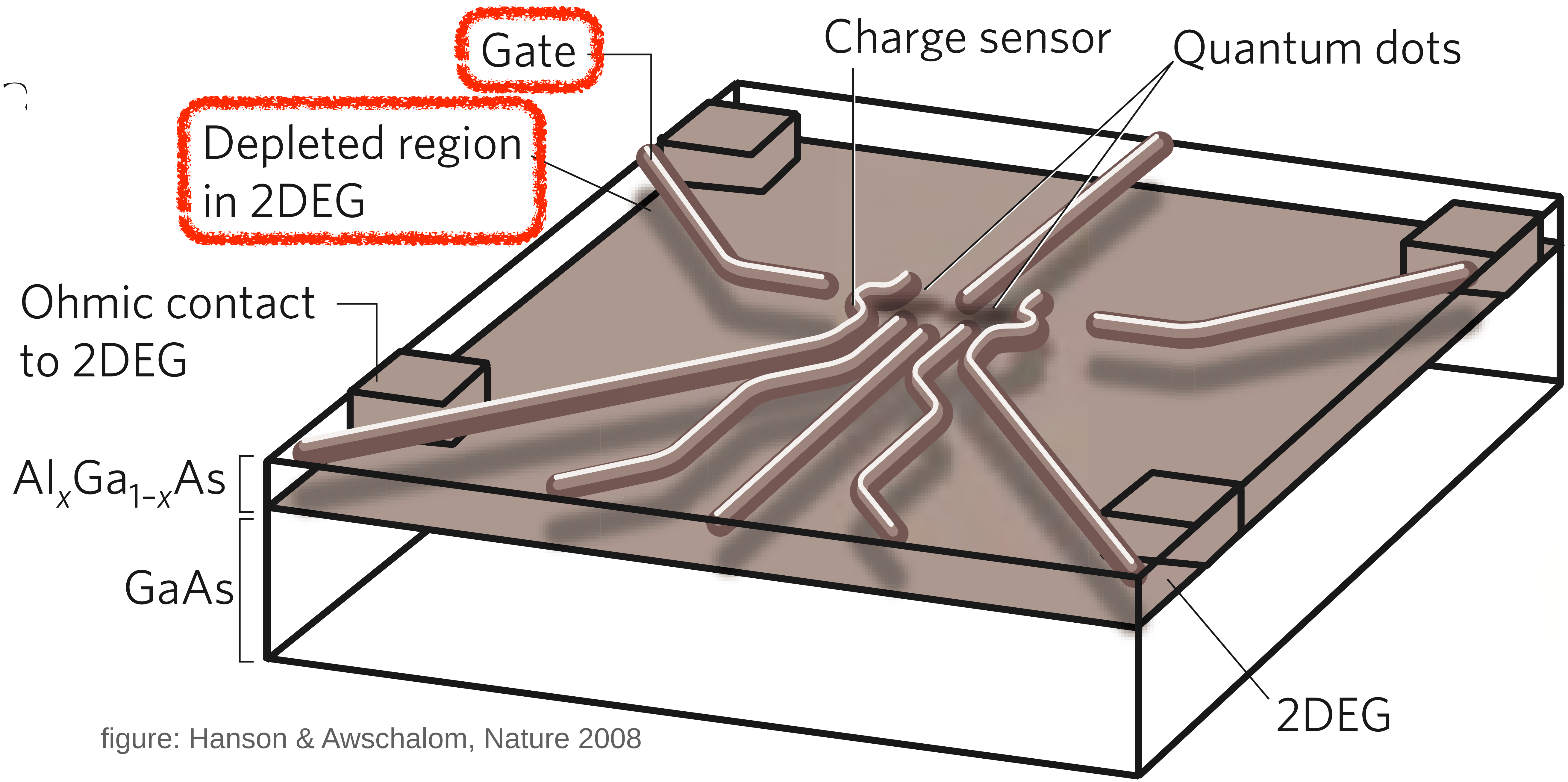

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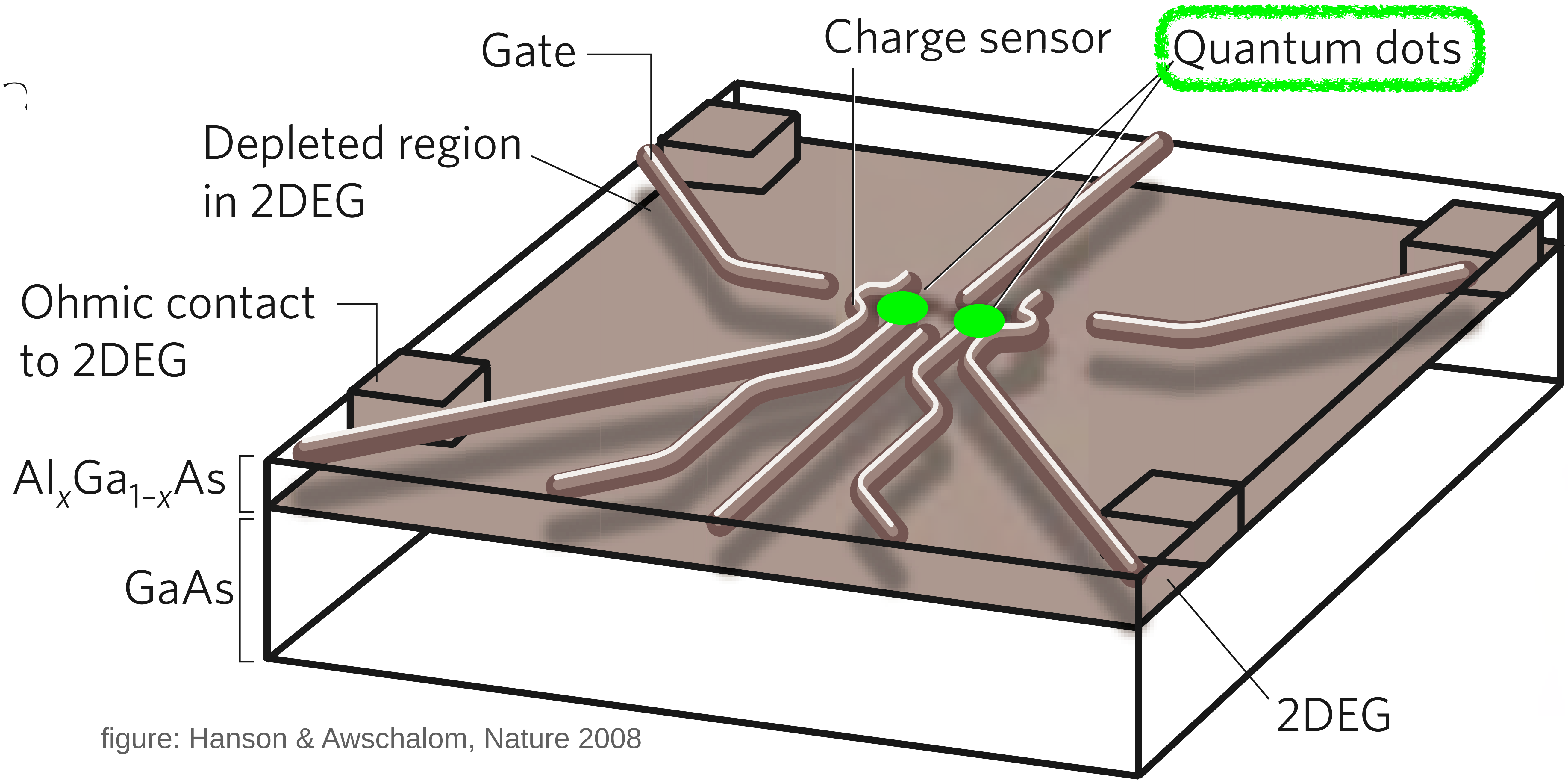

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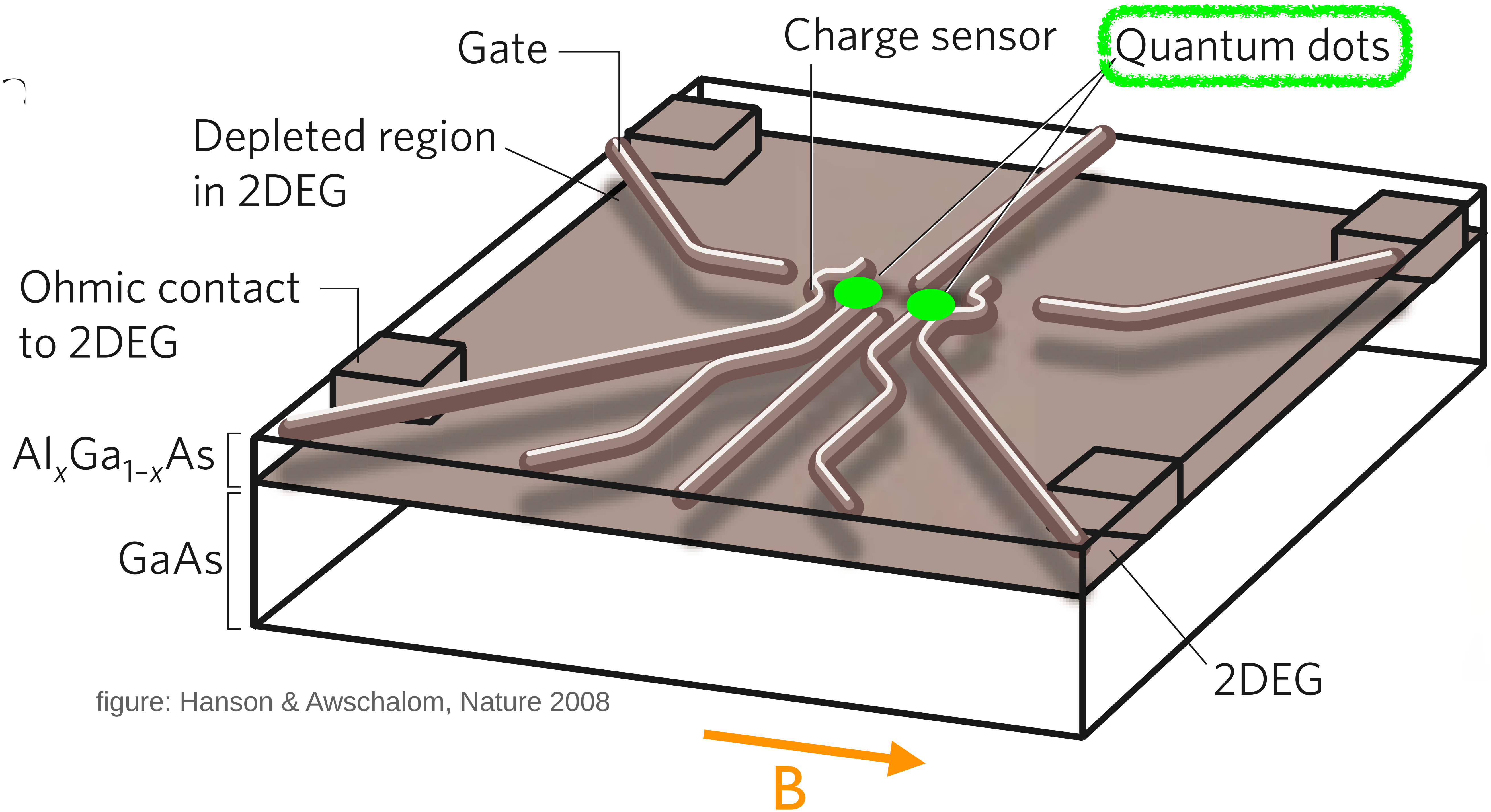

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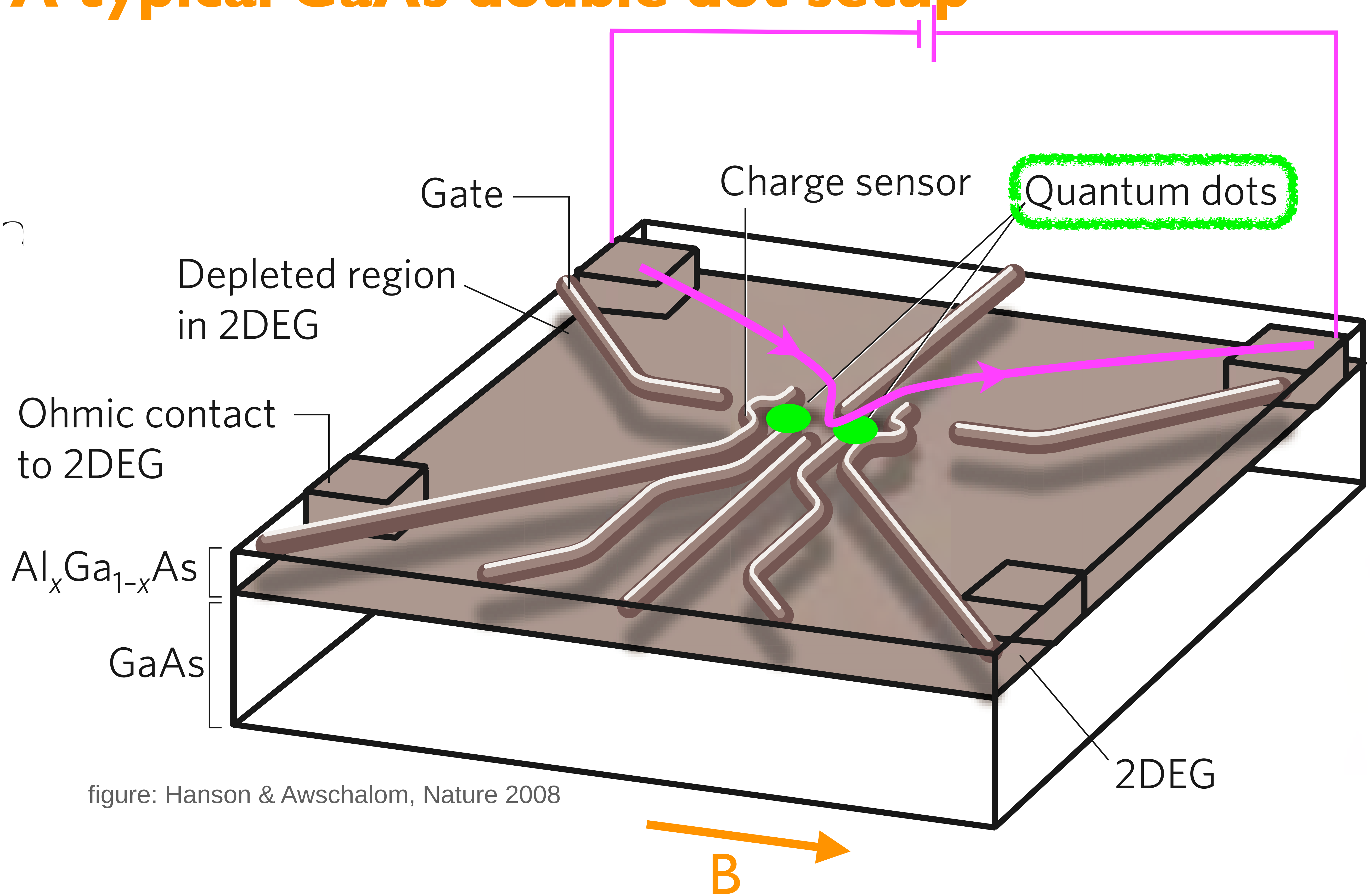

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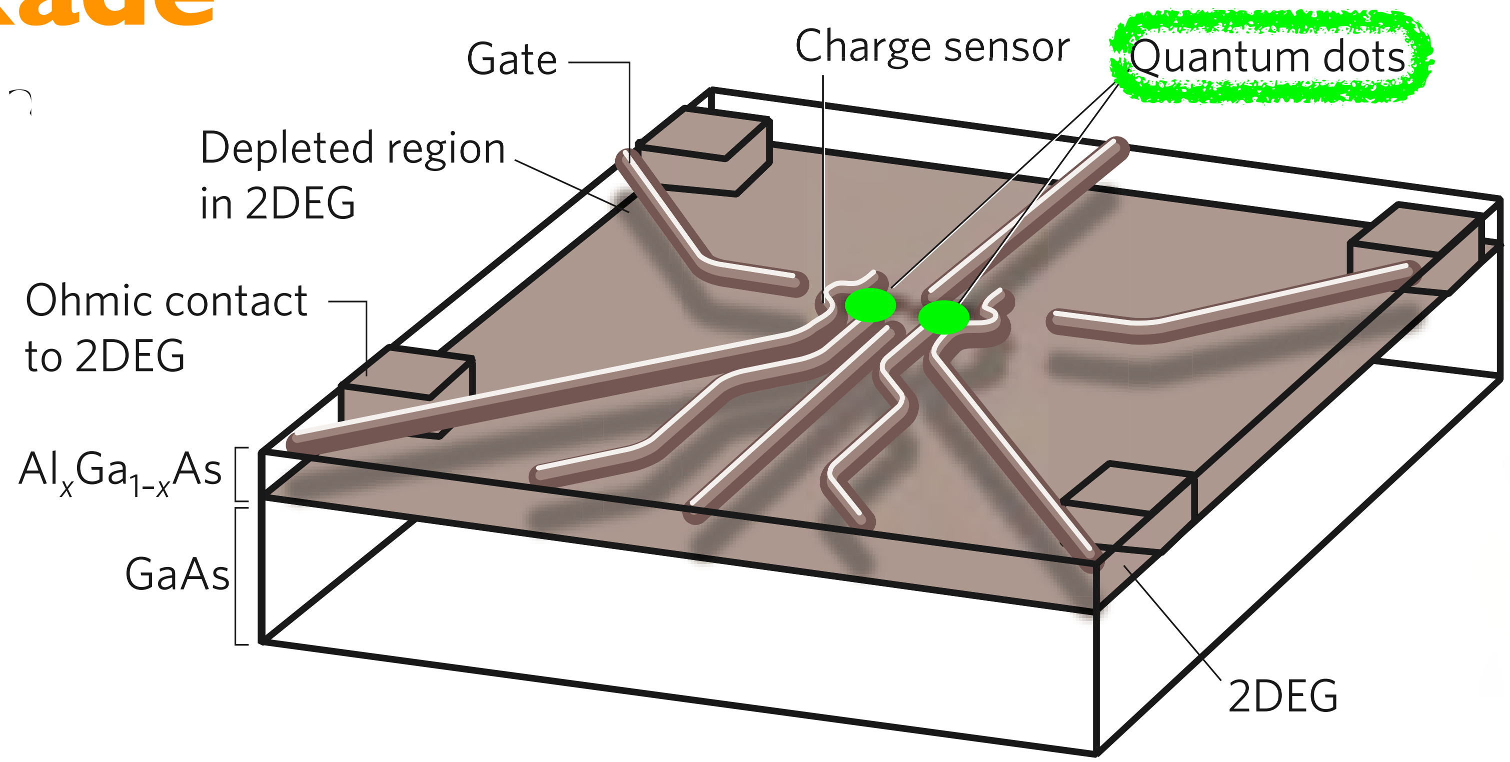
Spin blockade

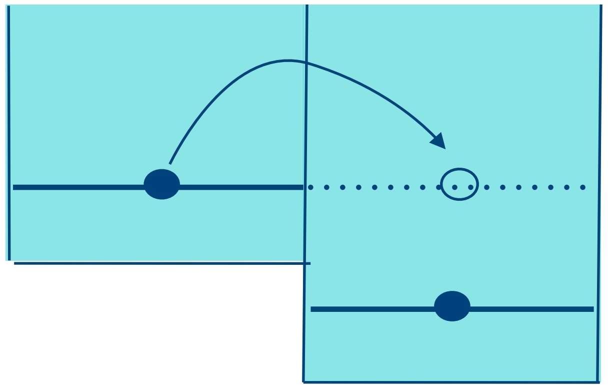


$$|s, m_s\rangle$$

1 singlet

$$|0,0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

S



3 triplets

$$|1,1\rangle = |\uparrow\uparrow\rangle$$

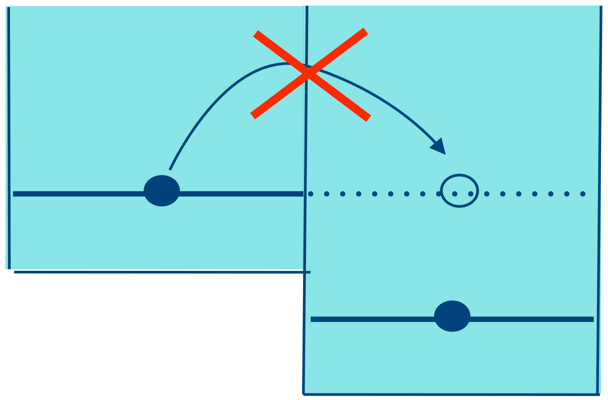
$$|1,0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$$

$$|1,-1\rangle = |\downarrow\downarrow\rangle$$

T_+

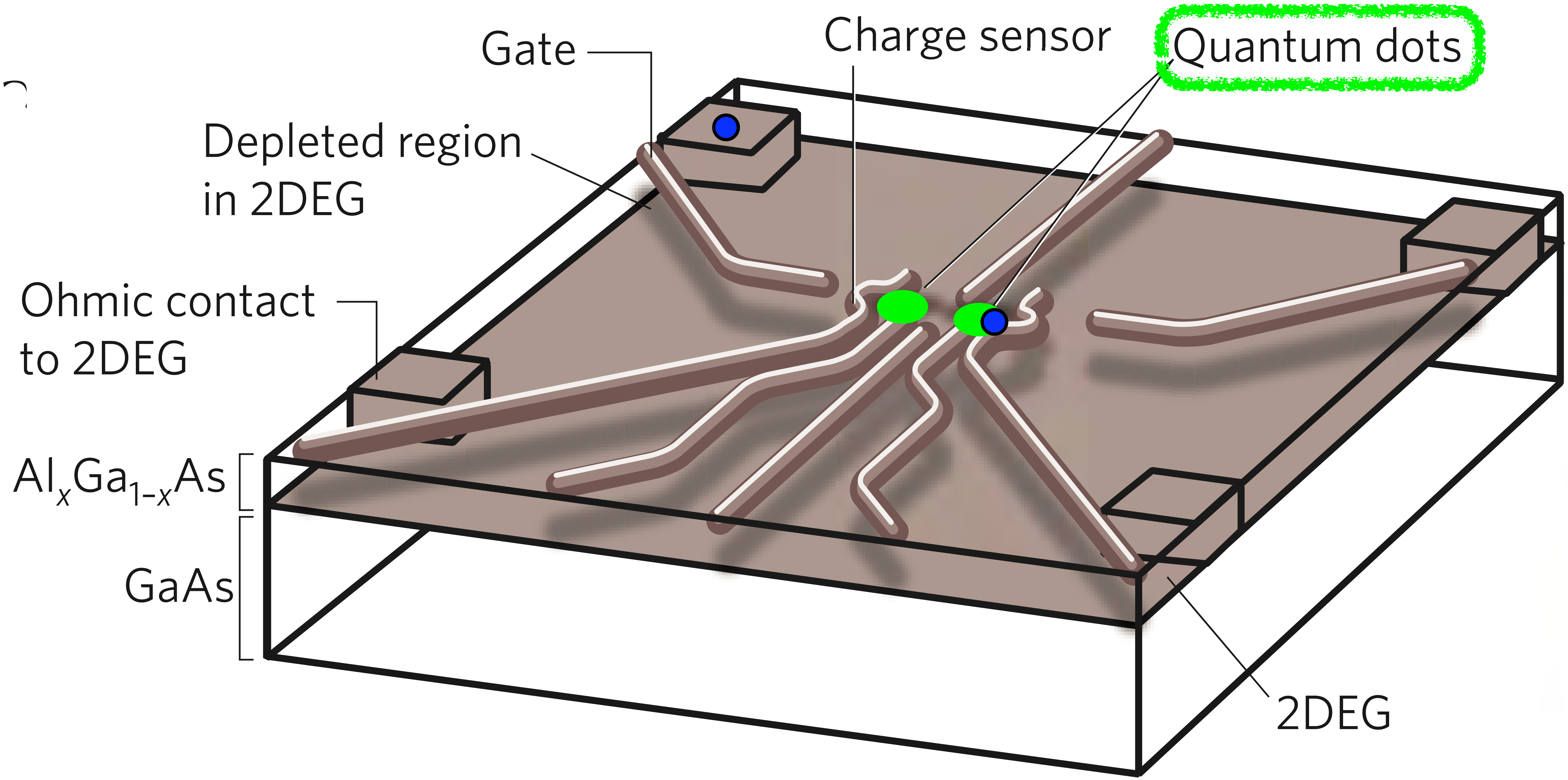
T_0

T_-



Spin blockade in transport

Ono et al., Science 2002
Koppens et al., Science 2005
Jouravlev & Nazarov, PRL 2006
Fransson & Rasander PRB 2006



(0,1)

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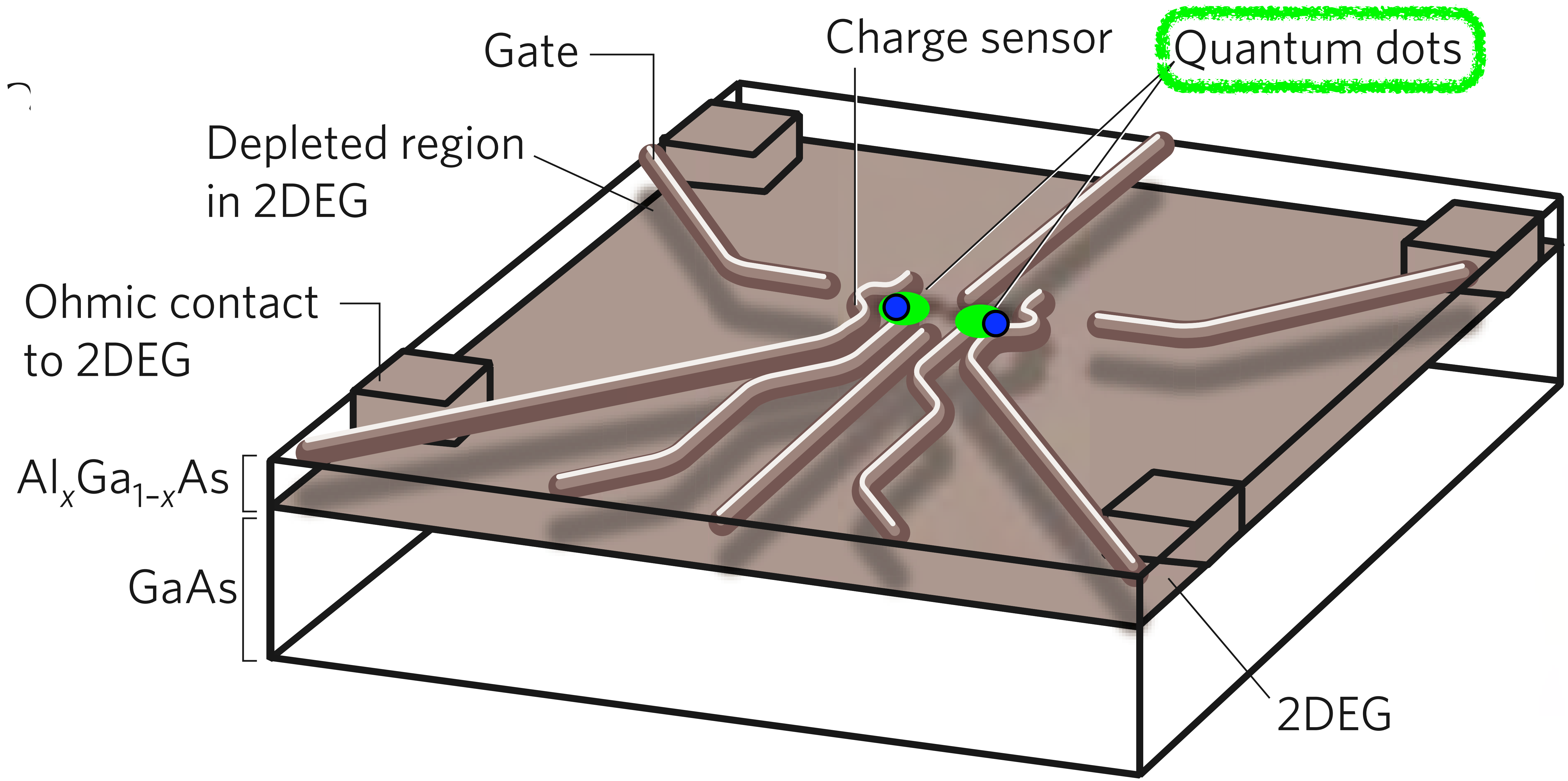

(1,1)

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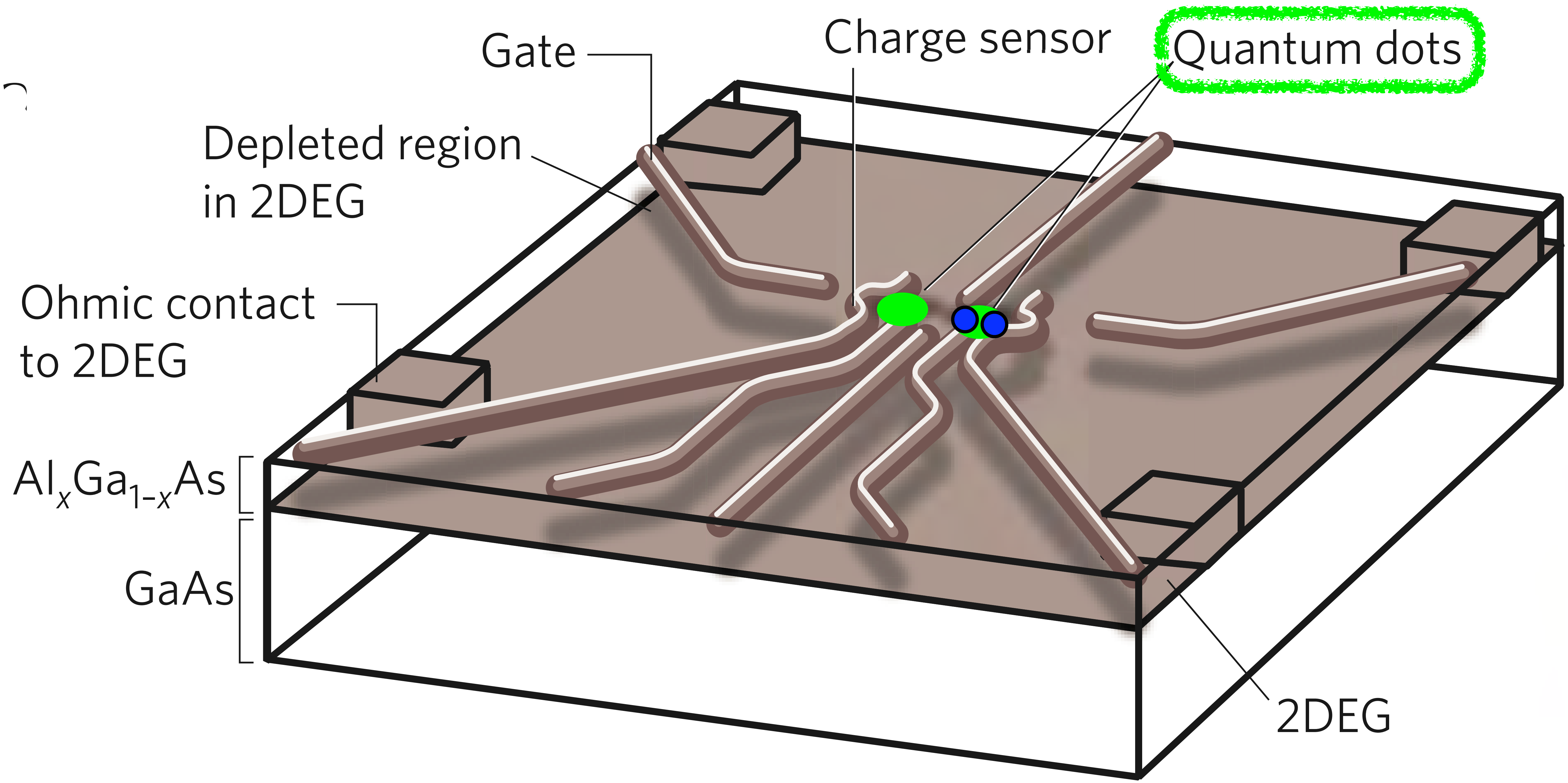
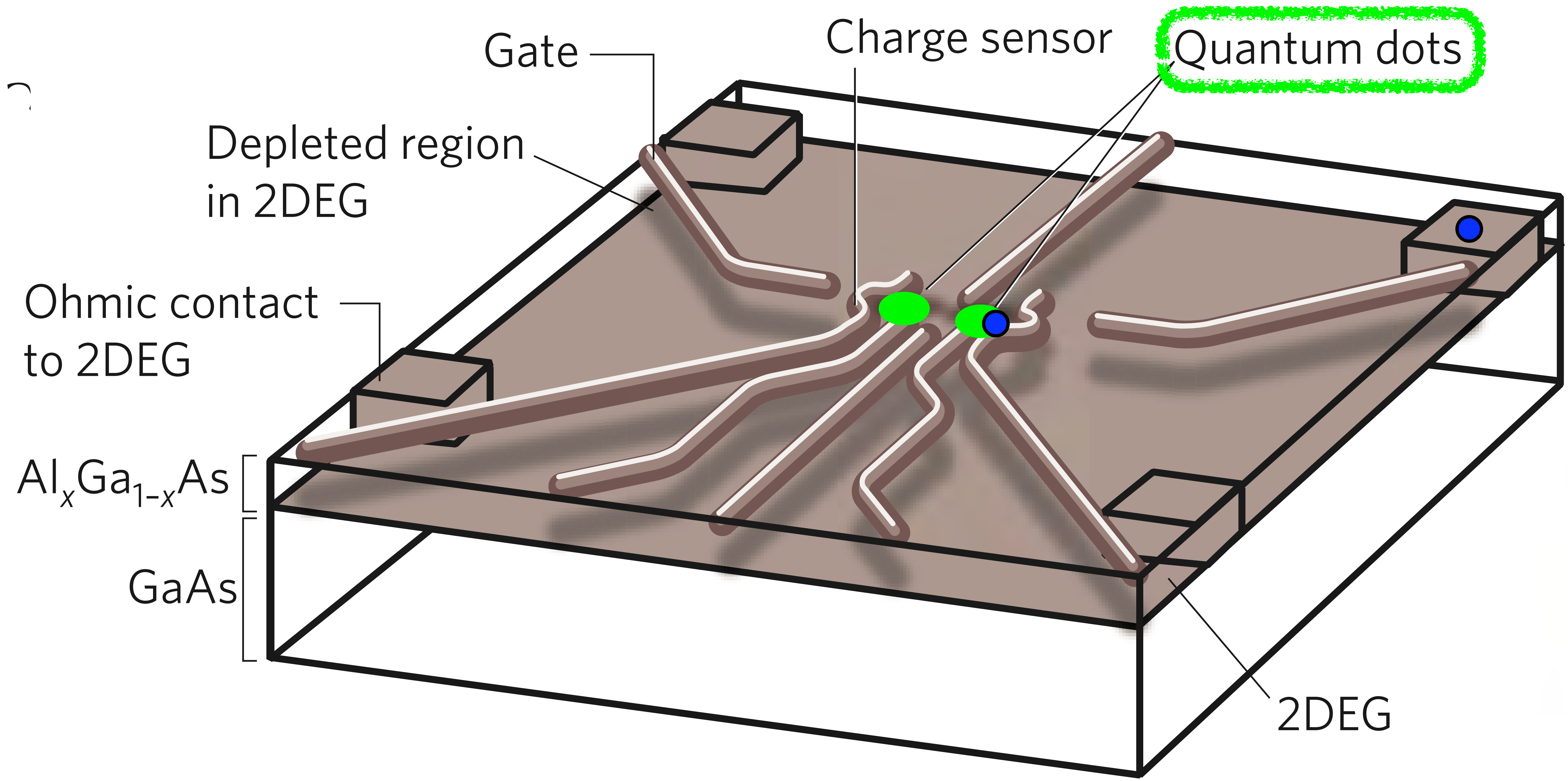


(0,2)

Spin blockade in transport

Ono et al., Science 2002
Koppens et al., Science 2005
Jouravlev & Nazarov, PRL 2006
Fransson & Rasander PRB 2006



(0,1)

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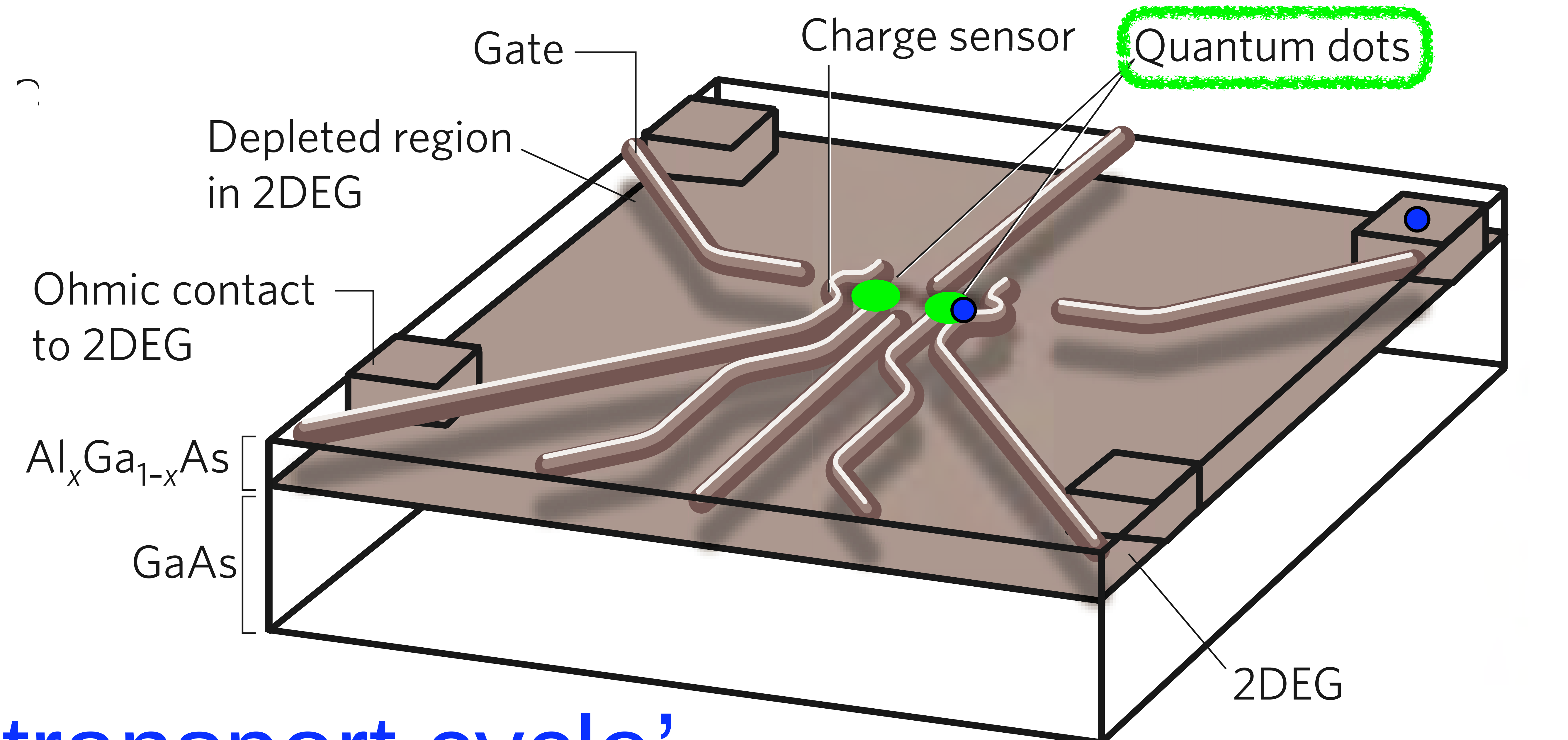

‘transport cycle’

(0,1)--(1,1)--(0,2)--(0,1)

Spin blockade in transport

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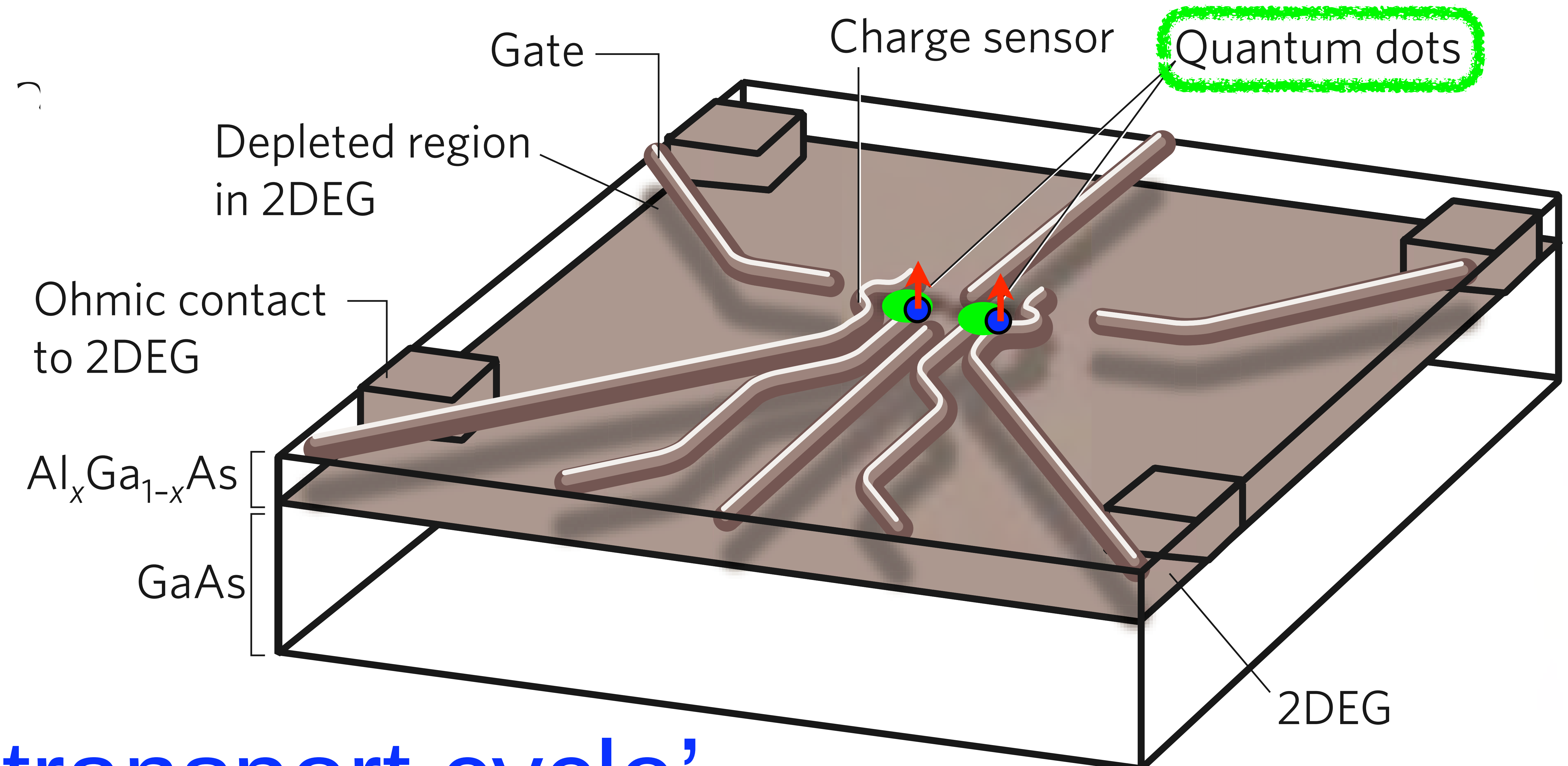


‘transport cycle’

(0,1)--(1,1)×(0,2)--(0,1)

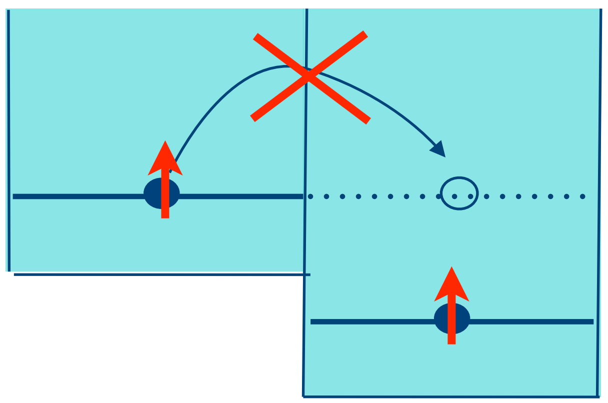
in steady-state:
current = 0

Outline

spin blockade in GaAs DQDs:

review: Hanson *et al.*, Rev. Mod. Phys. 2007

- sensitive probe of spin physics
- spin qubit initialization and readout



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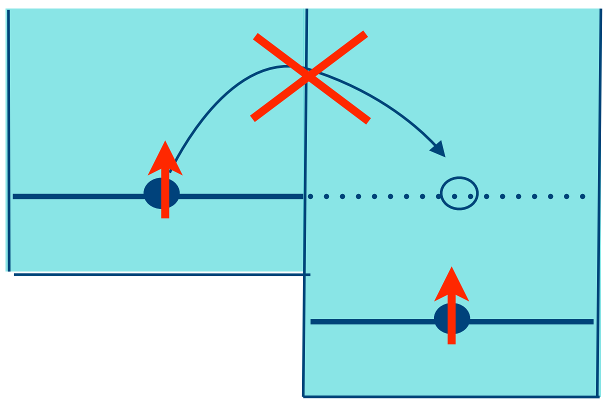

carbon-based DQDs:

- valley degeneracy
- spin-orbit interaction
- valley mixing (atomic disorder?)
- hyperfine interaction

experiment:
Mason et al., Science 2004
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Buitelaar et al., PRB 2008
Jorgensen et al. Nature Phys. 2008
Churchill et al., Nature Phys. & PRL 2009
Steele et al., Nature Nanotech. 2009
Molitor et al., APL 2009
Xing Lan Liu et al., Nano Lett. 2010
Chorley et al., arXiv:1004.4377

theory:
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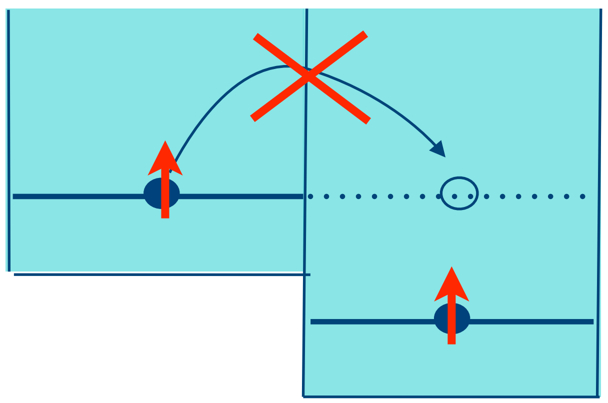

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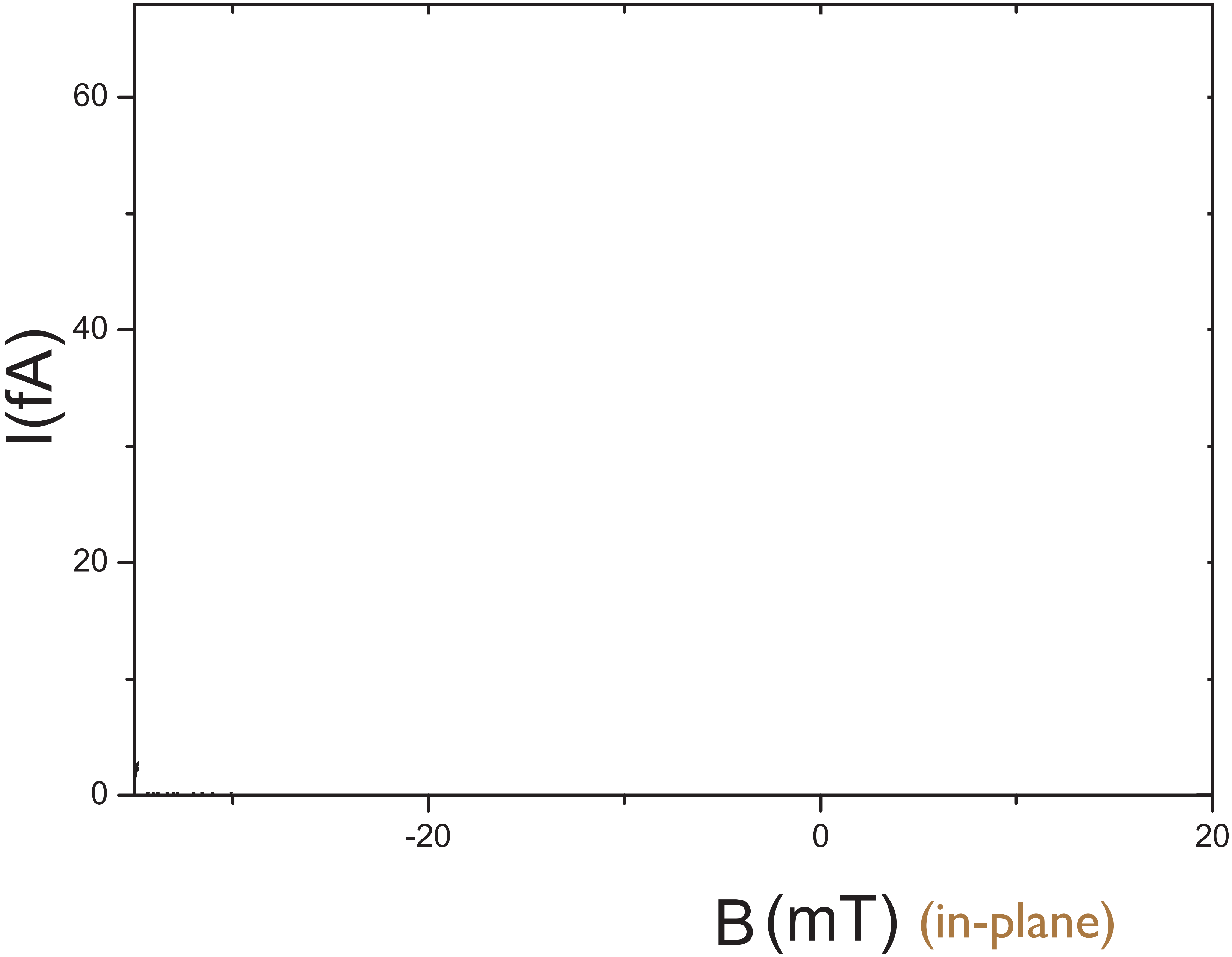
spin-valley blockade

- probing spin or valley physics

Spin blockade measurement

Koppens et al., Science 2005
Jouravlev & Nazarov, PRL 2006



Spin blockade measurement

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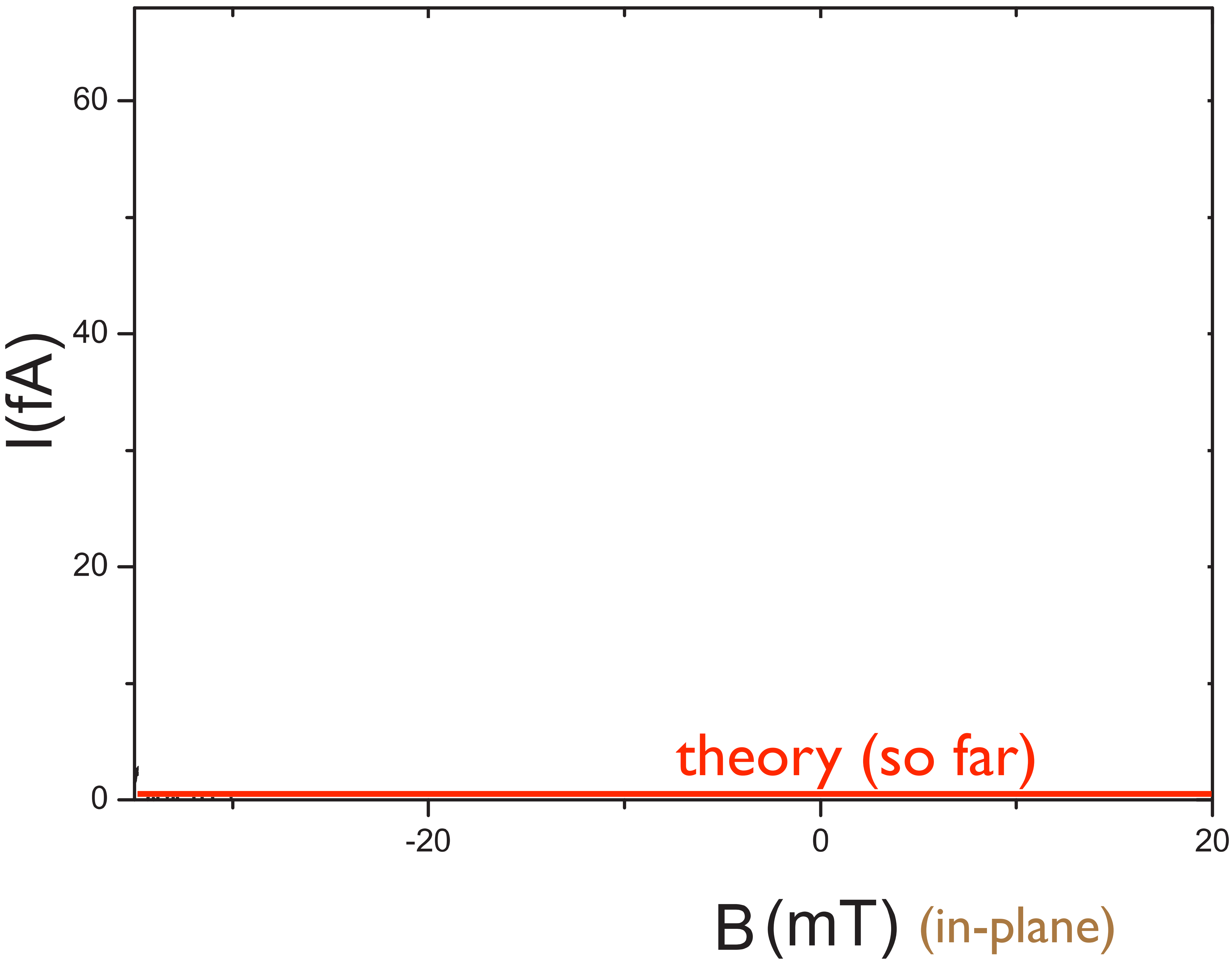

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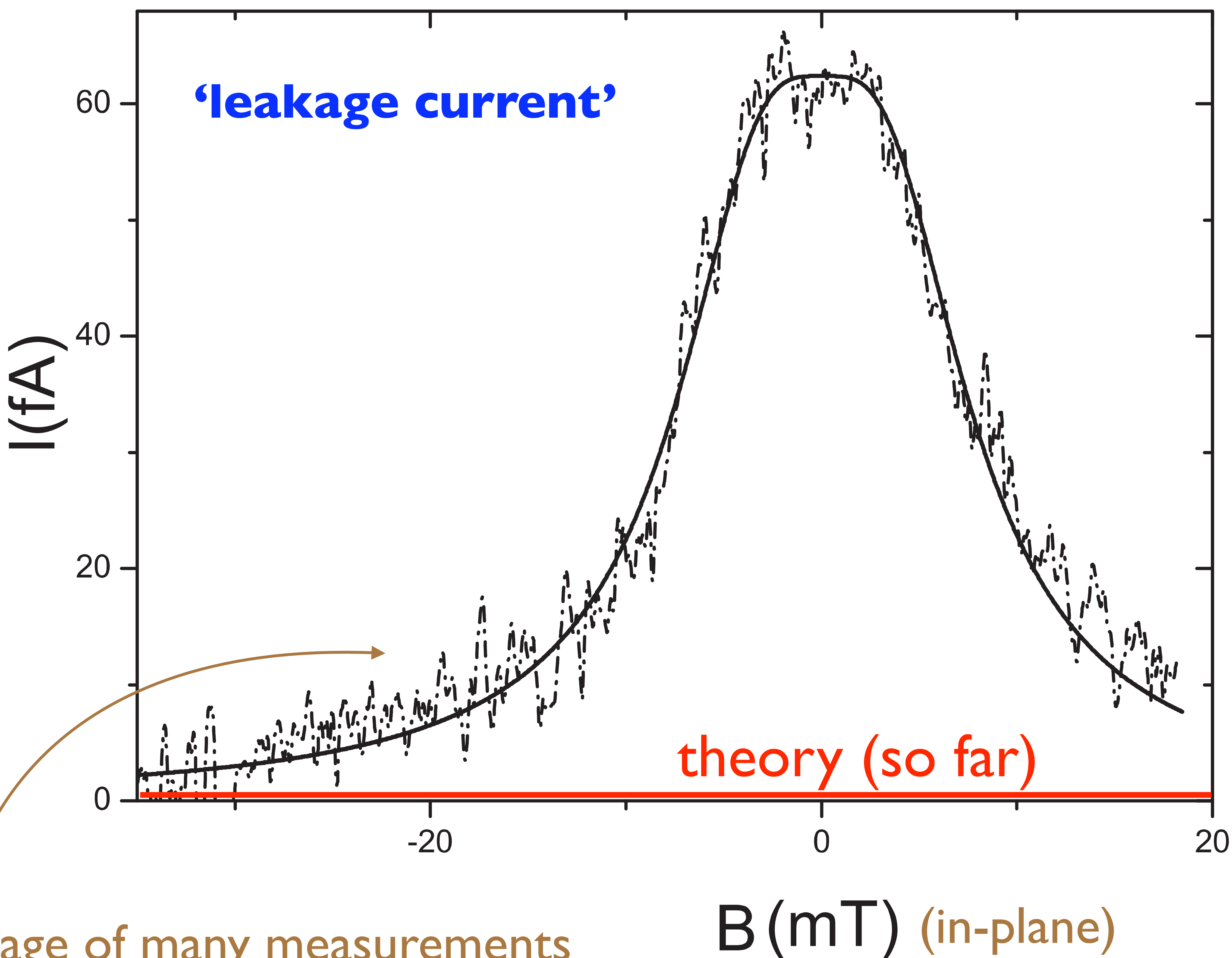

(in-plane)

average of many measurements

Spin blockade measurement

Koppens et al., Science 2005
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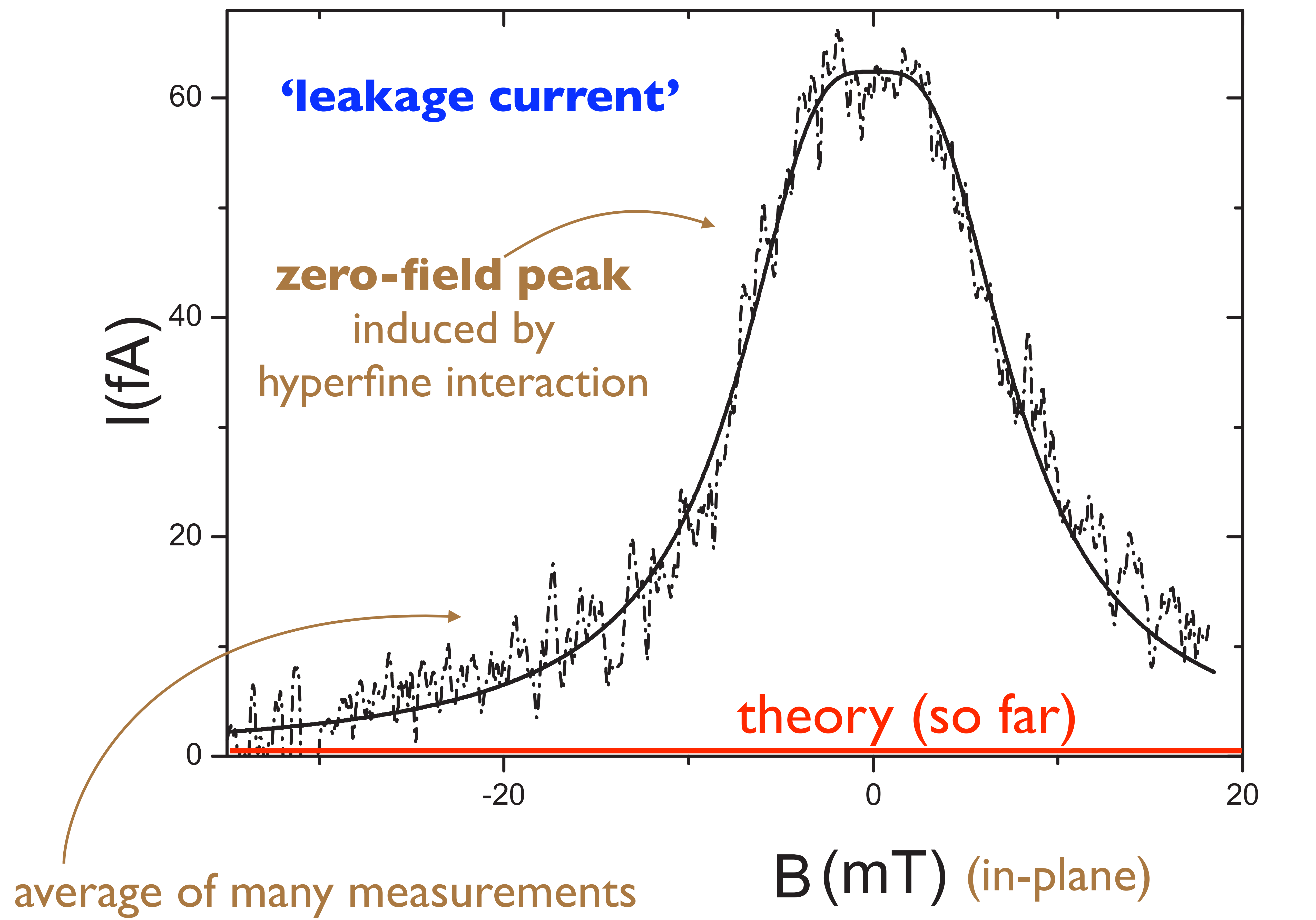

Spin blockade measurement

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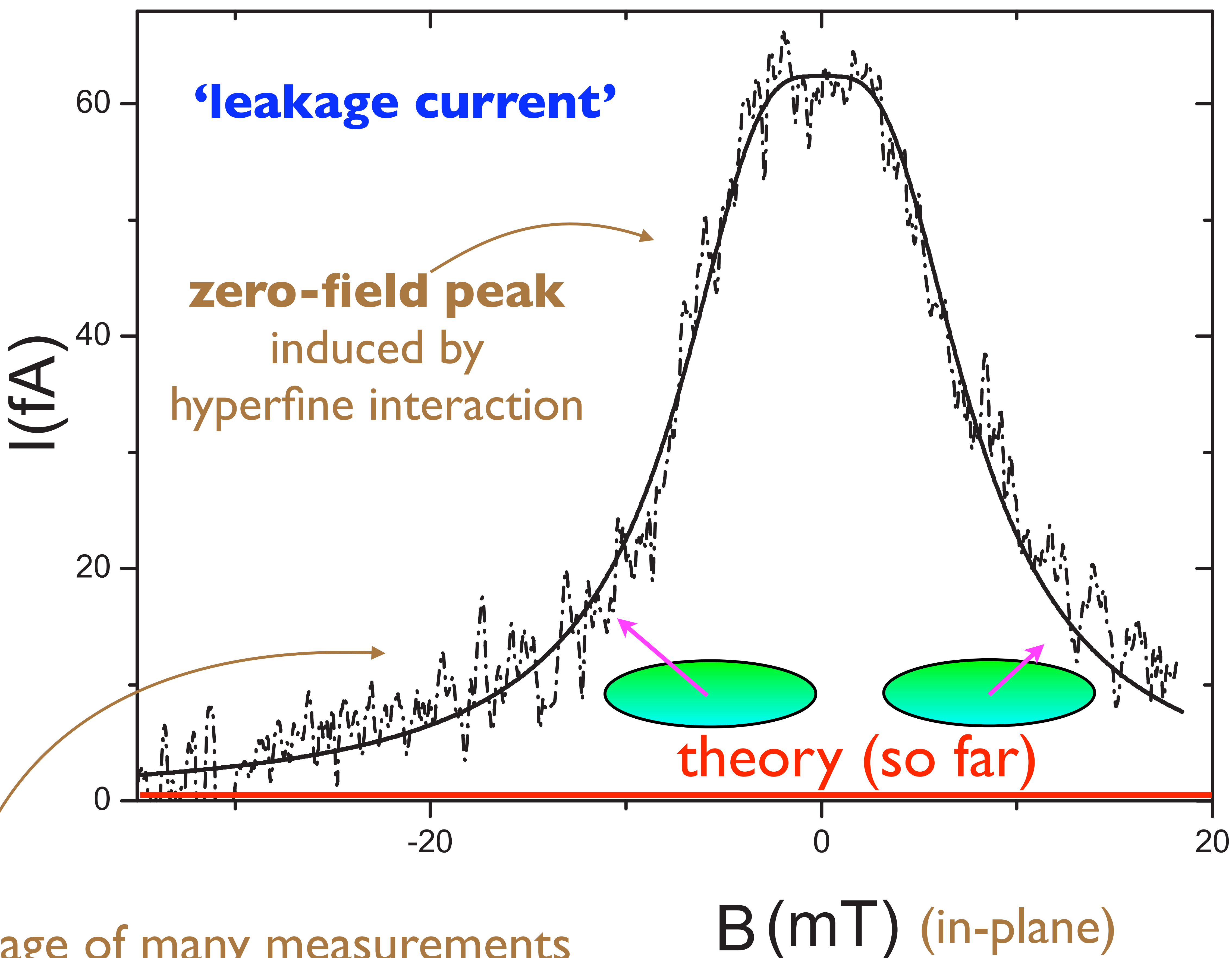

average of many measurements

Spin blockade 'application'

spin qubit **initialization** and **read-out**

Koppens *et al.*, Nature 2006

Spin blockade 'application'

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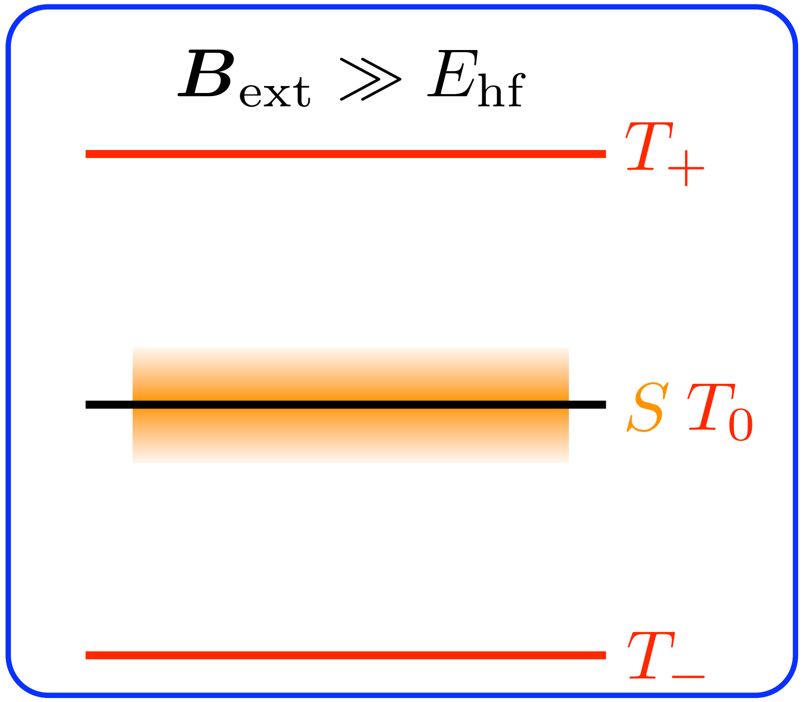
Koppens *et al.*, Nature 2006



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spin qubit **initialization** and **read-out**

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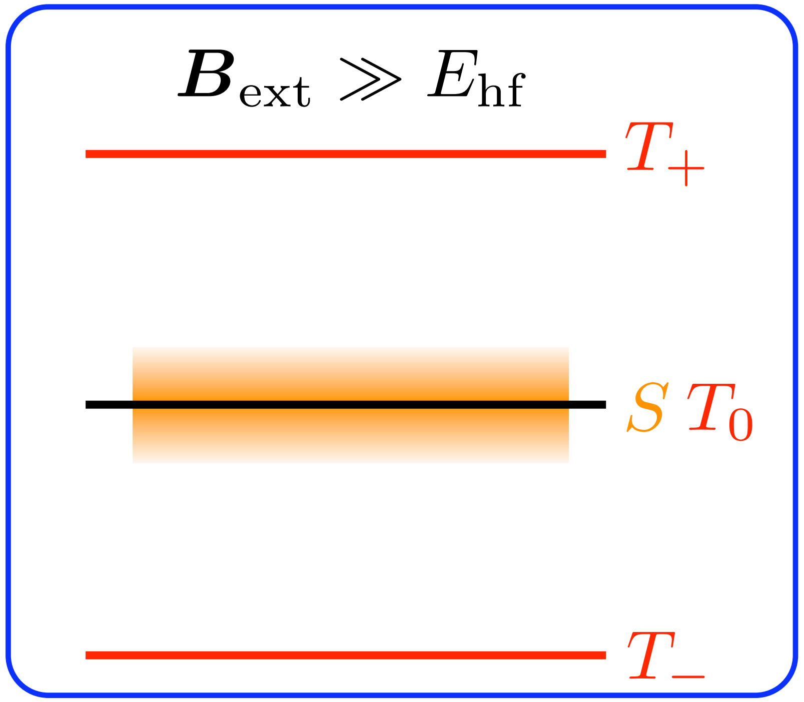

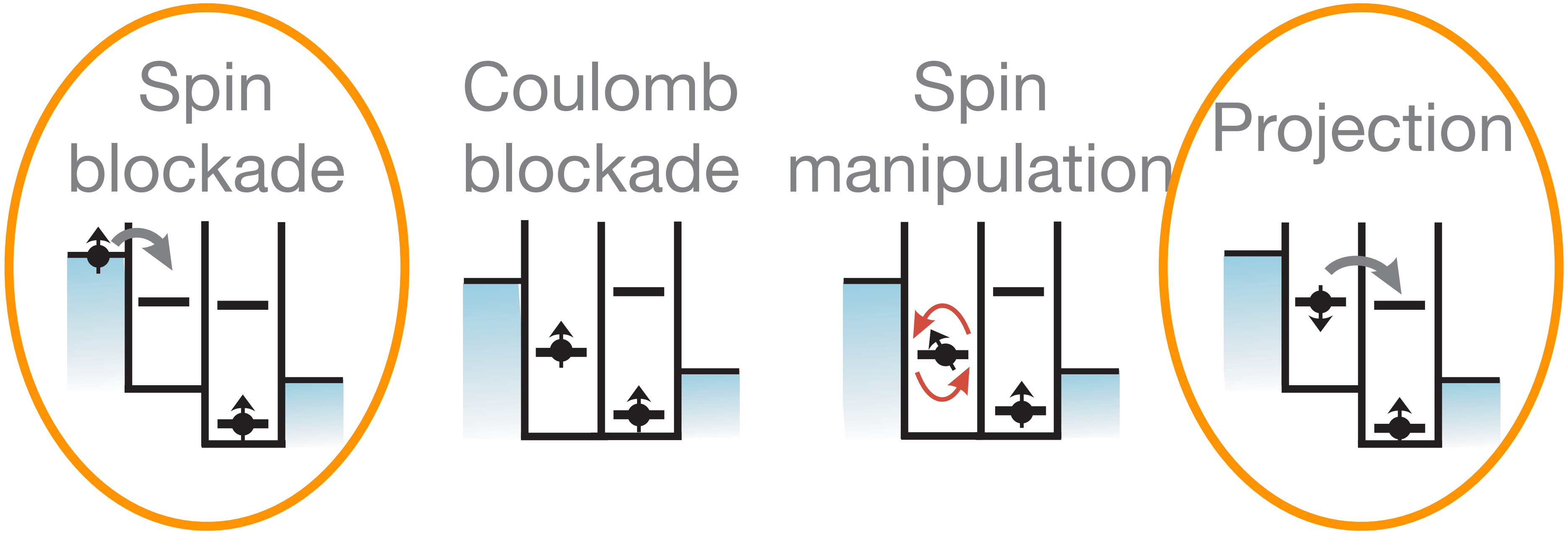

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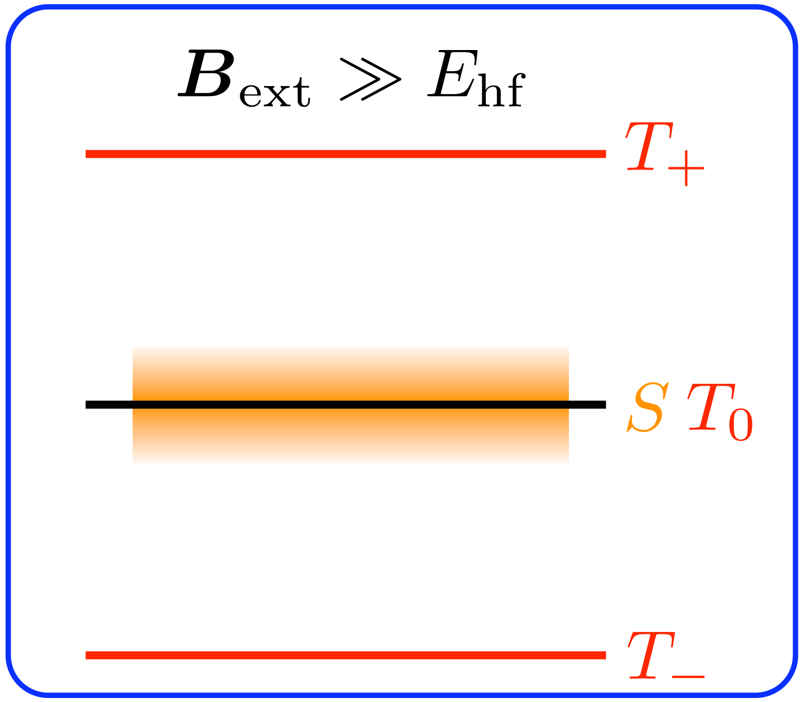
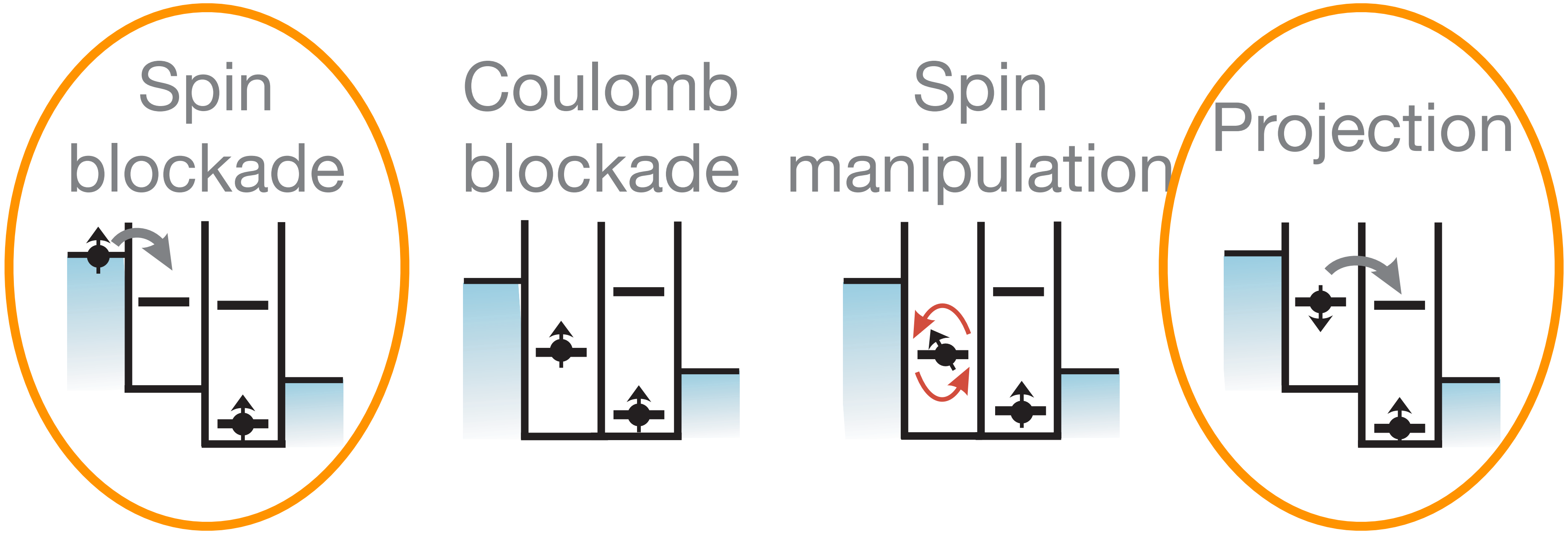
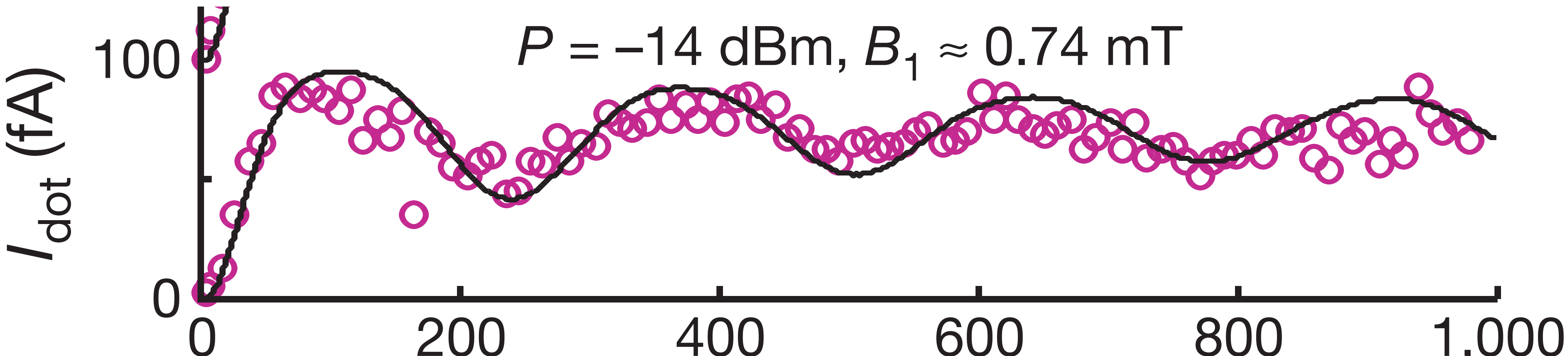




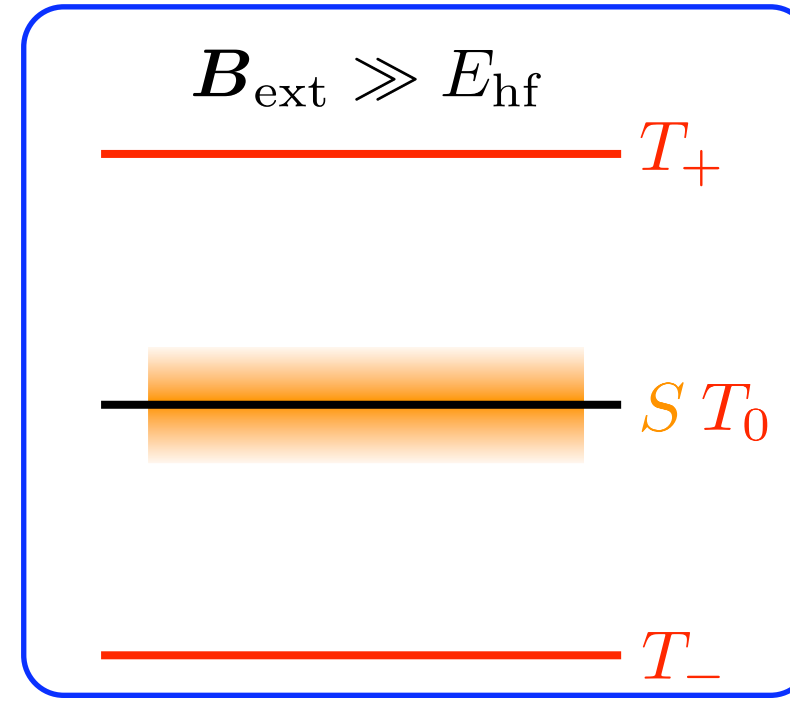


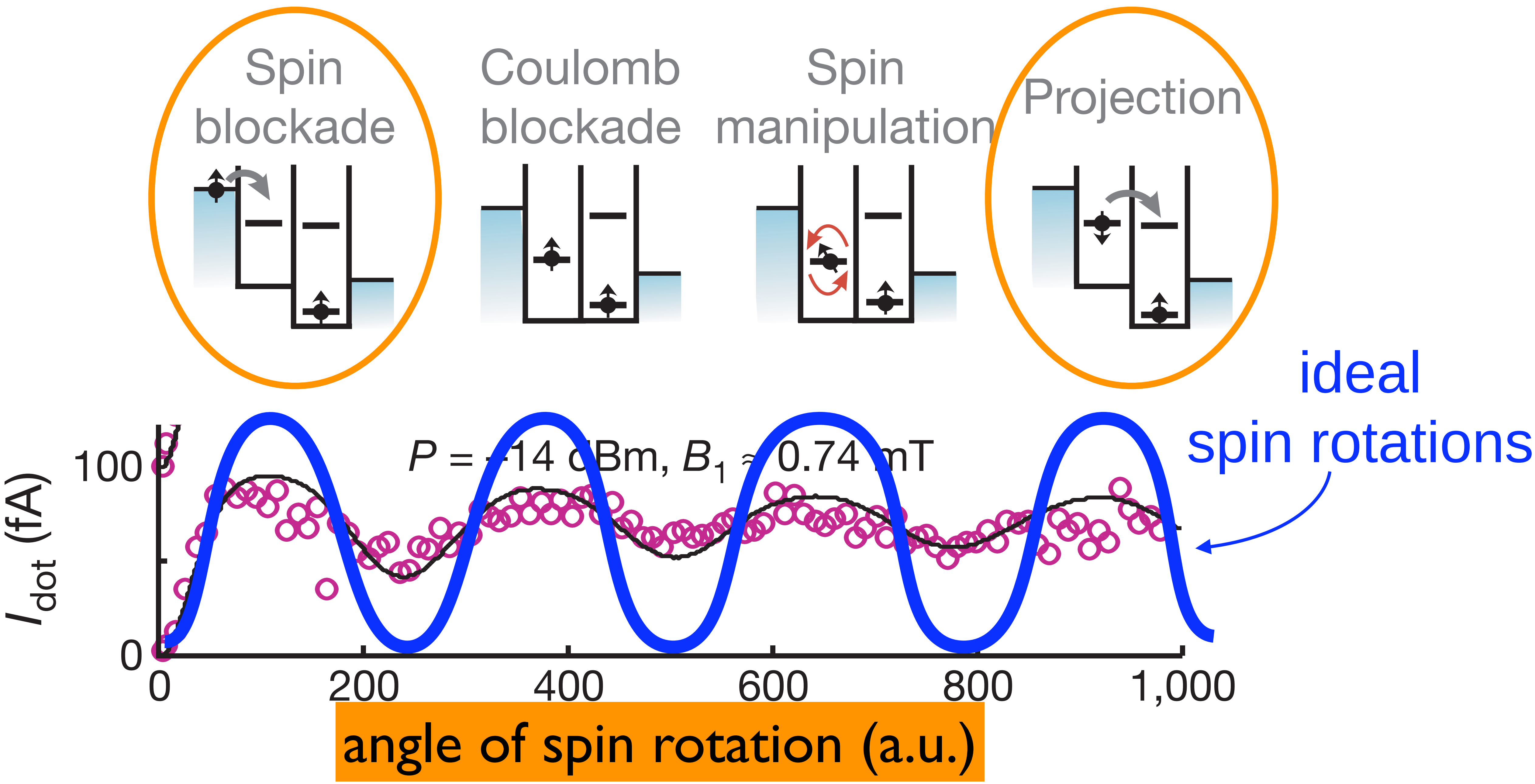
angle of spin rotation (a.u.)

Spin blockade 'application'

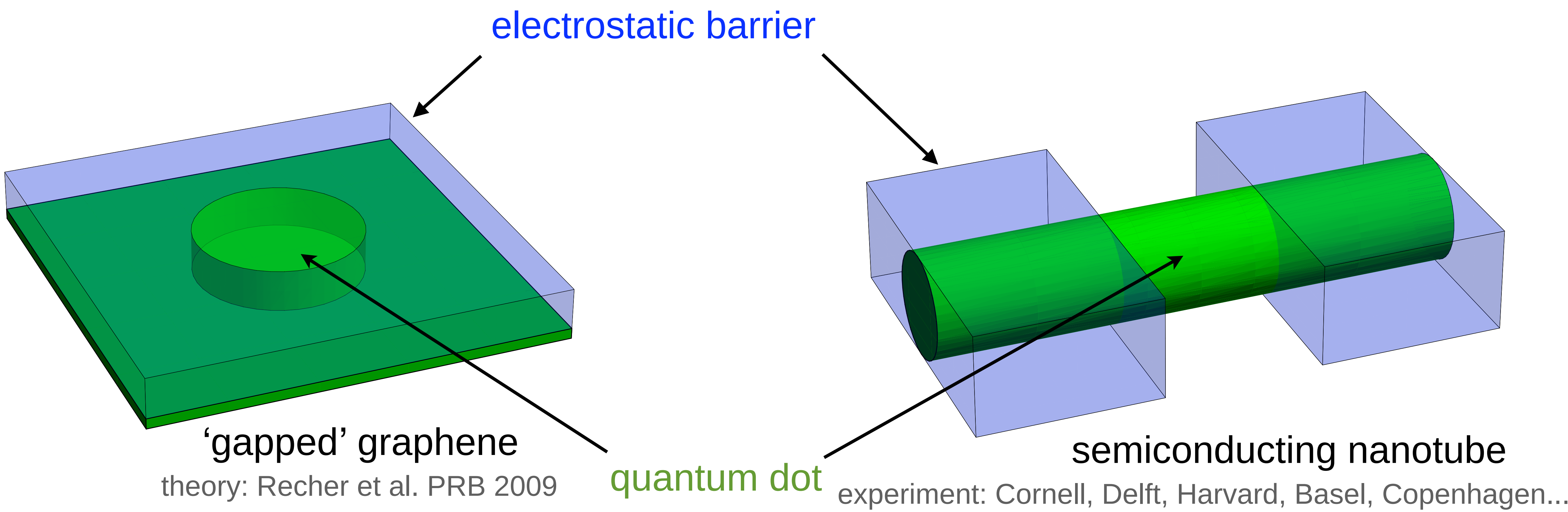
spin qubit **initialization** and **read-out**

Koppens *et al.*, Nature 2006



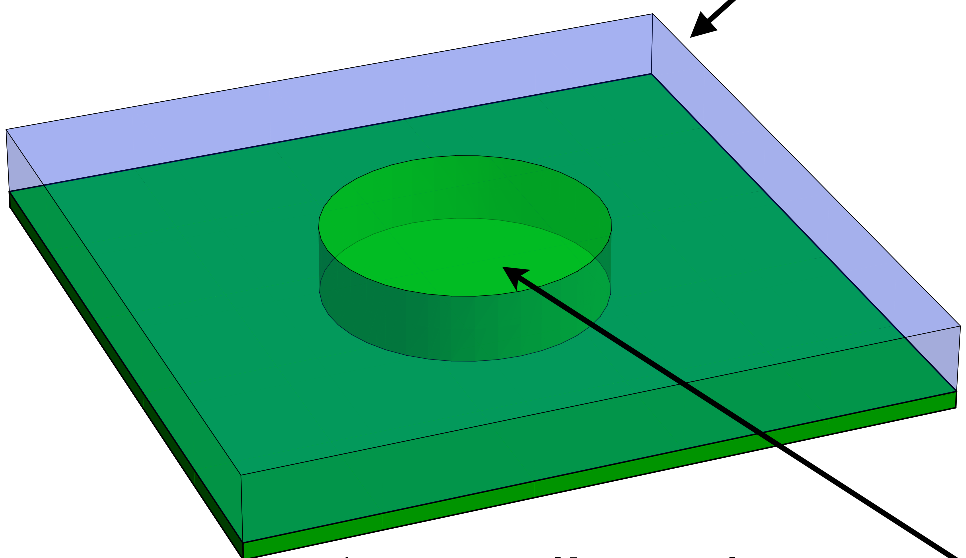


Carbon-based quantum dots



Carbon-based quantum dots

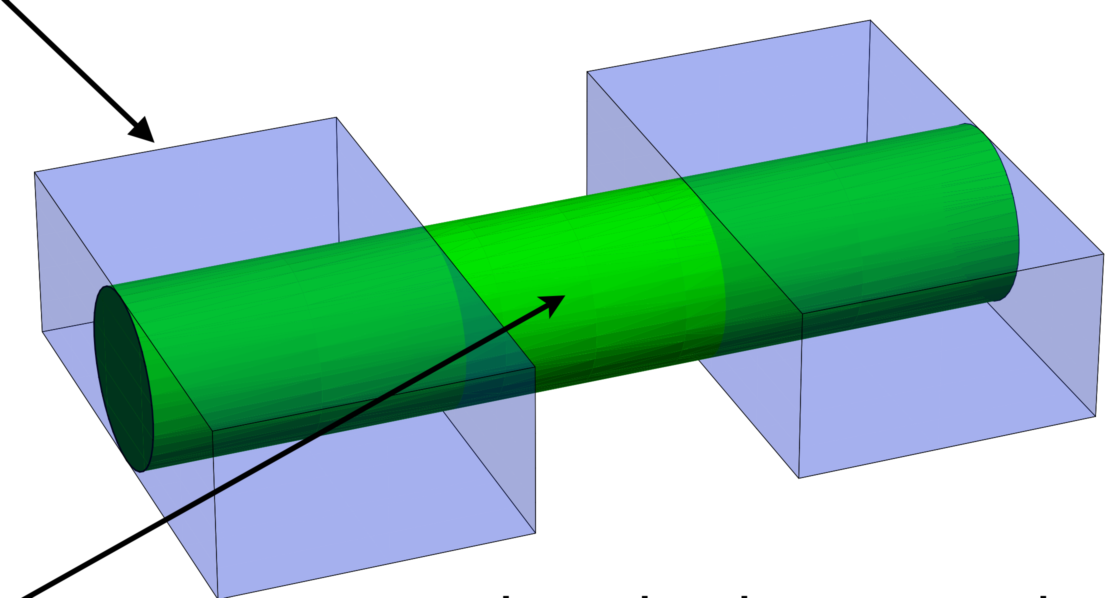
electrostatic barrier



‘gapped’ graphene

theory: Recher et al. PRB 2009

quantum dot



semiconducting nanotube

experiment: Cornell, Delft, Harvard, Basel, Copenhagen...

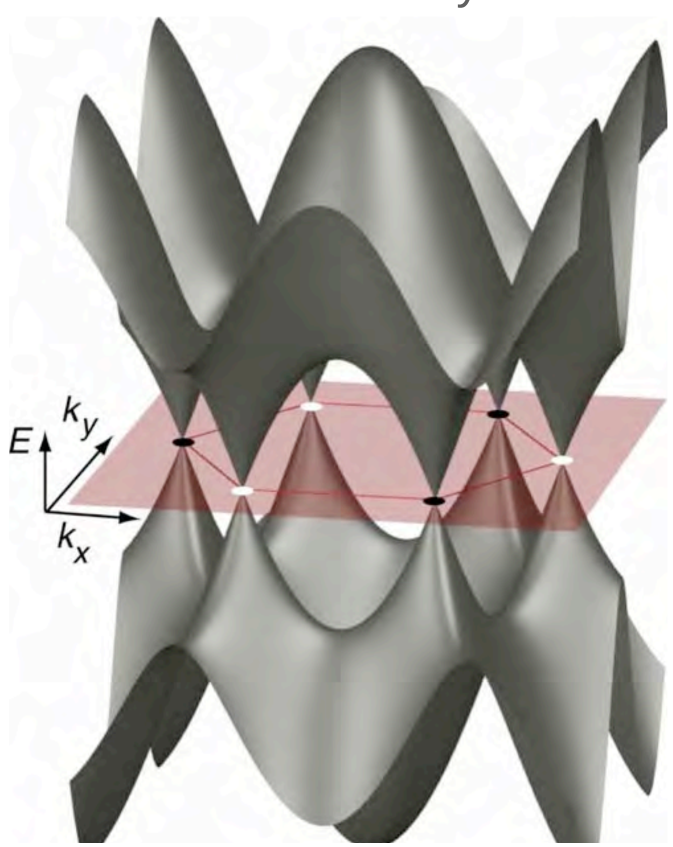
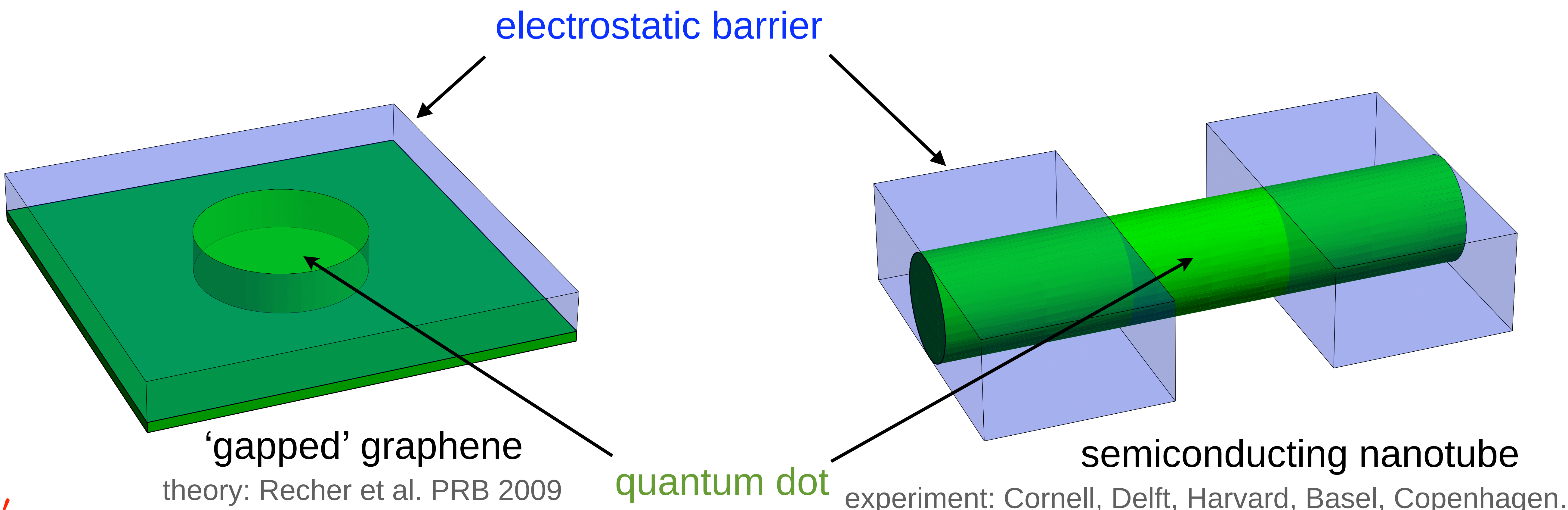
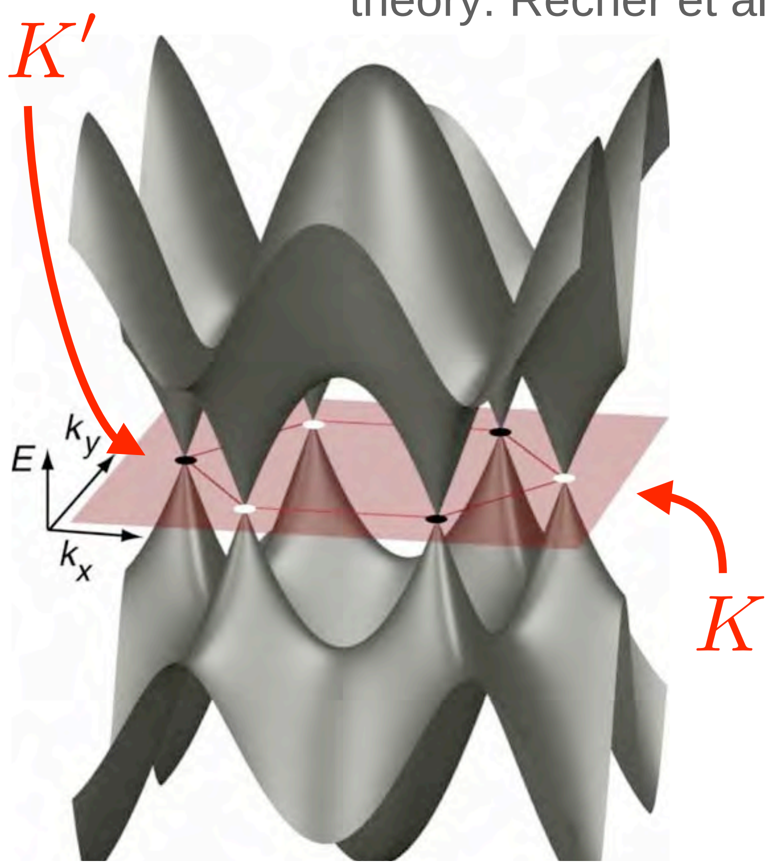


figure: Beenakker RMP 2008

Carbon-based quantum dots





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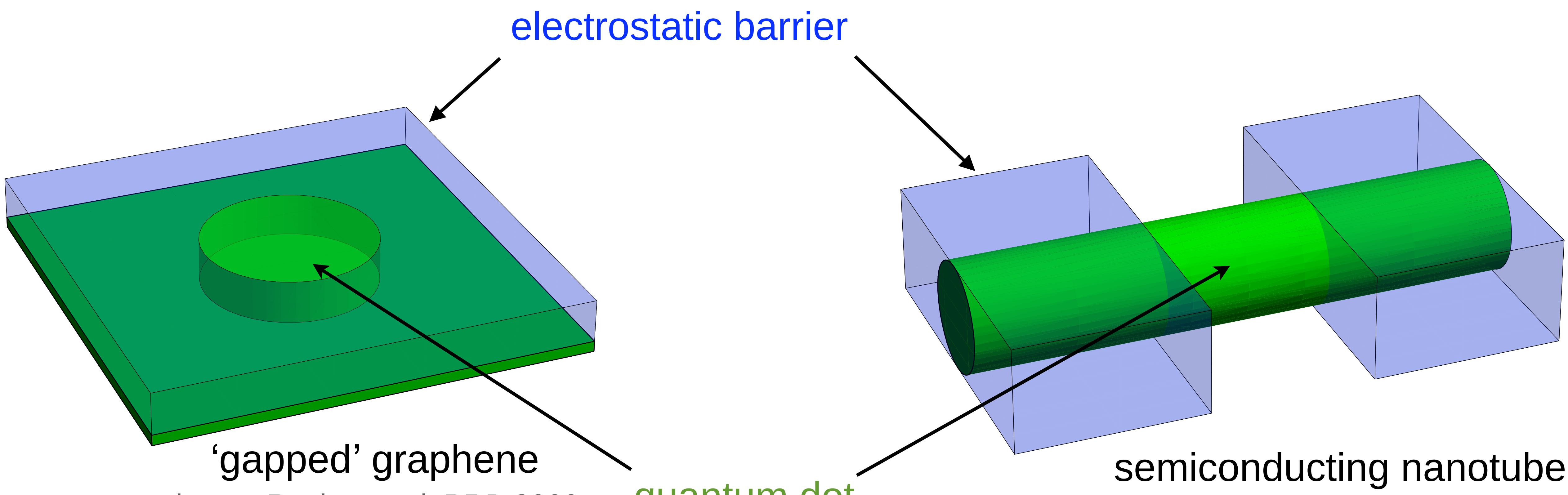
Carbon-based quantum dots



theory: Recher et al. PRB 2009

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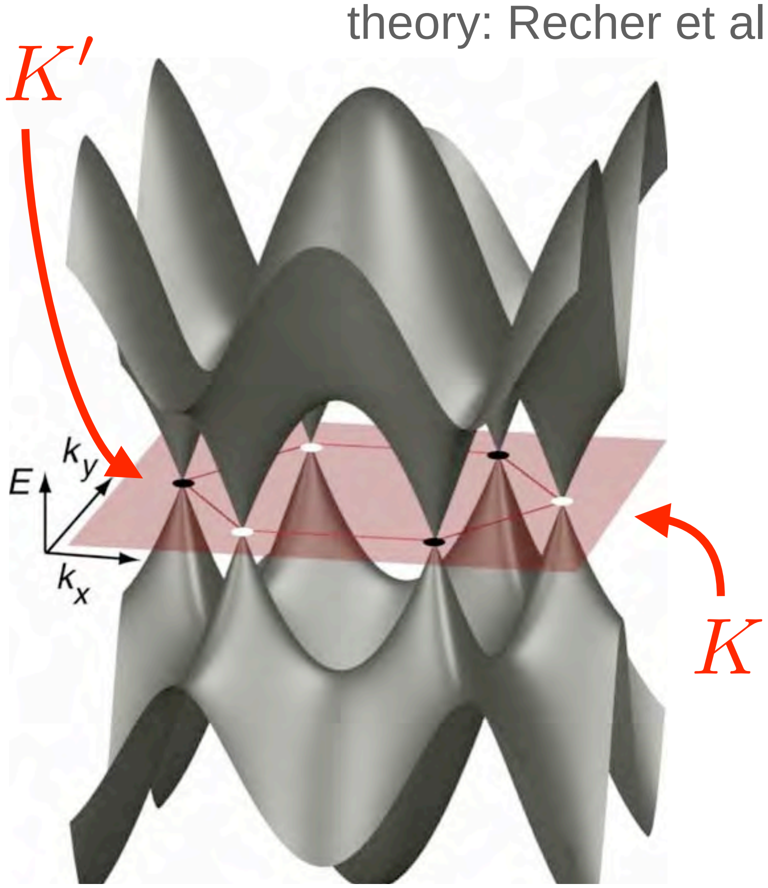
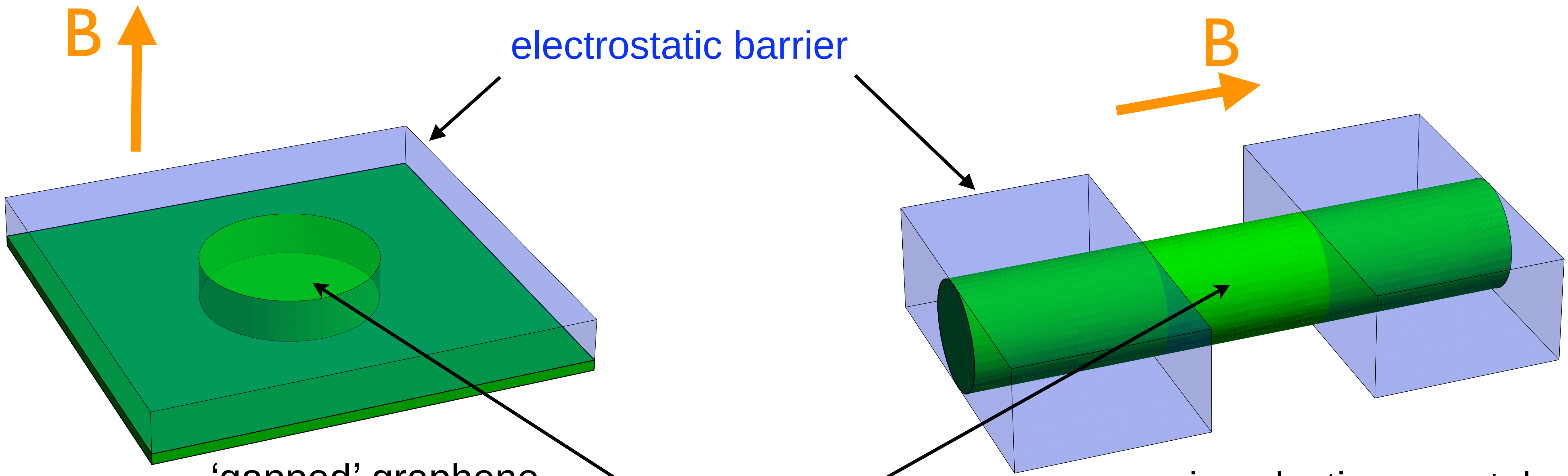


figure: Beenakker RMP 2008

- energy levels: spin & valley degeneracy
- spin and valley splittings (Δ_s, Δ_v)

  controllable by magnetic field

Carbon-based quantum dots



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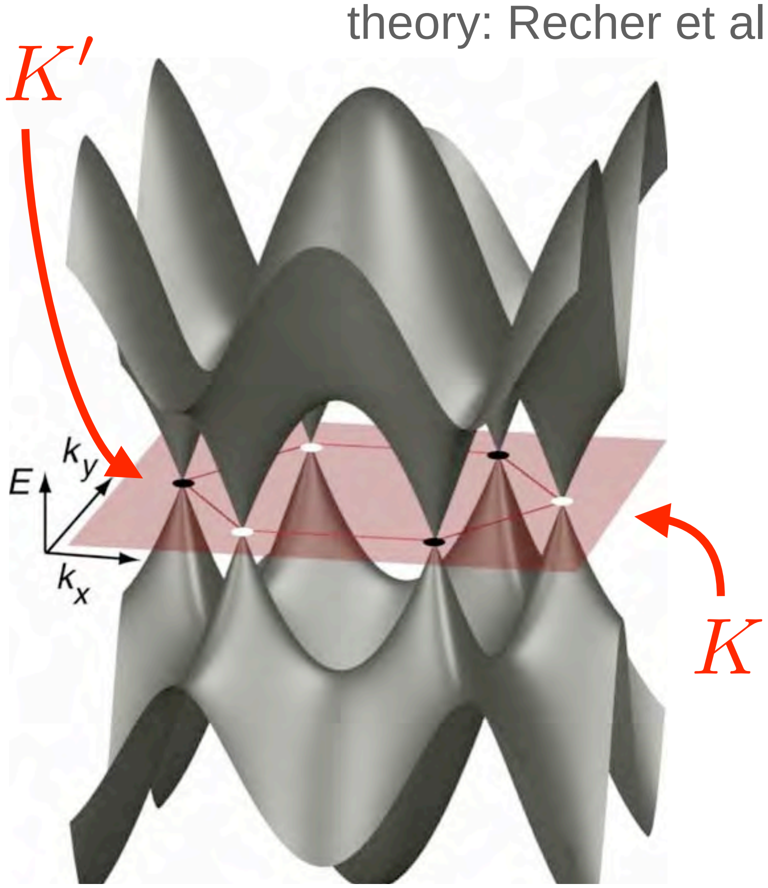

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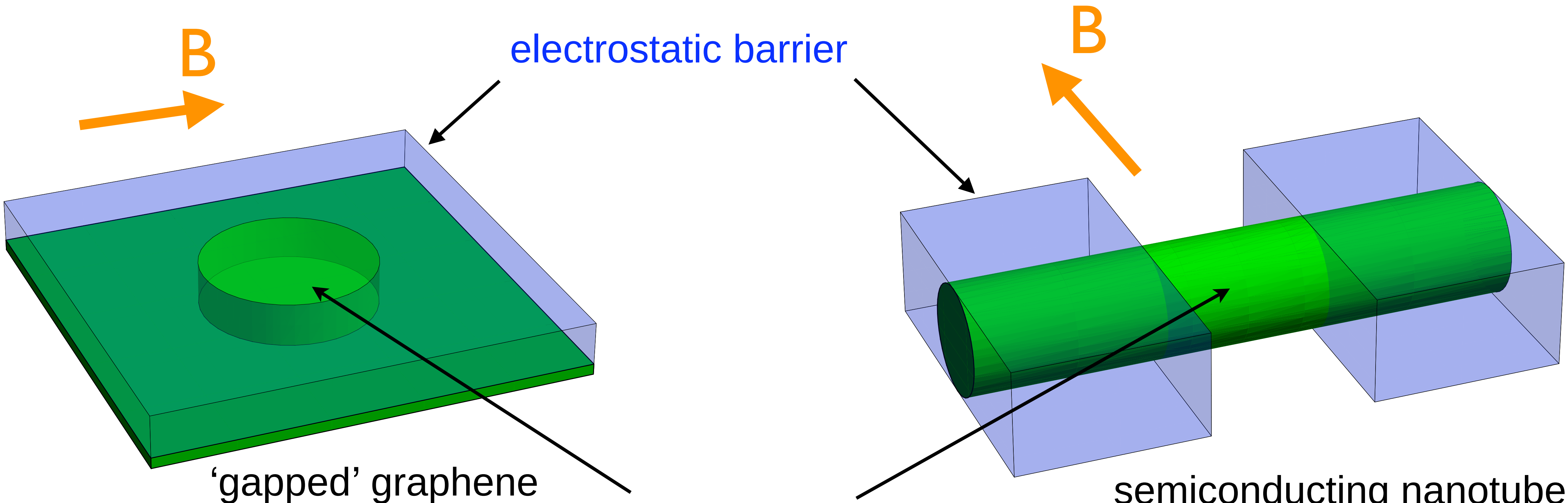

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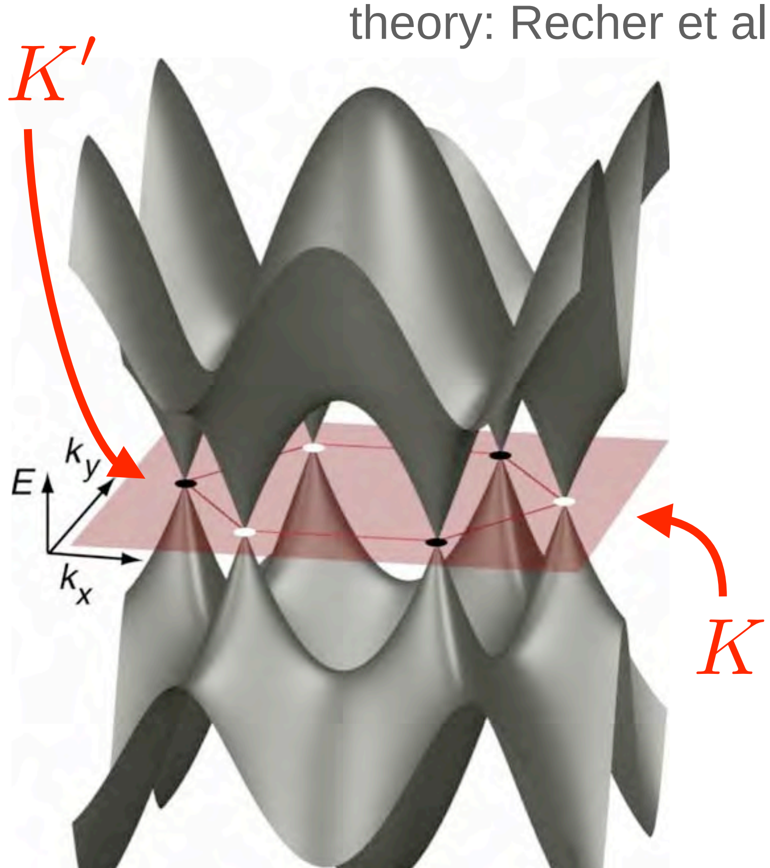

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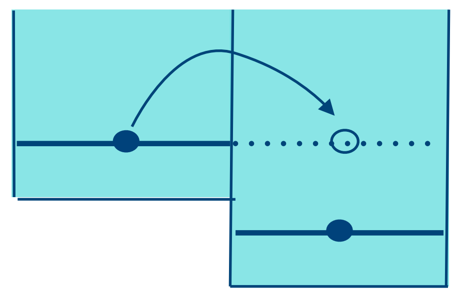
Spin-valley blockade in double dots

spin blockade (GaAs)

Ono et al., Science 2002
Koppens et al., Science 2005
Jouravlev & Nazarov, PRL 2006

$|s, m_s\rangle$

1 singlet $|0,0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$



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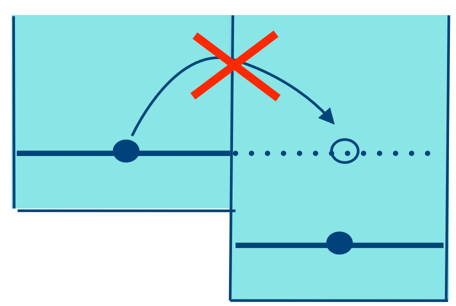

current = 0

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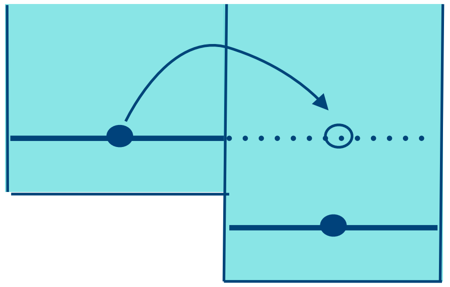

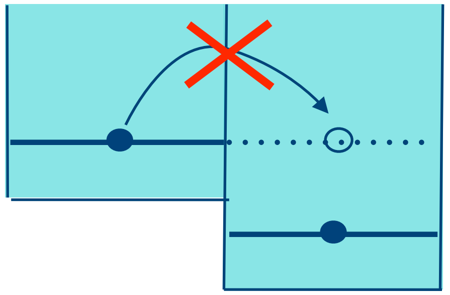

spin-valley blockade (C)

Churchill et al., Nature Phys. 2009
Pályi & Burkard, PRB 2009

6 supersinglets

$|0,0\rangle_{\text{sp}}|1,m_v\rangle_{\text{val}}$

$|1,m_s\rangle_{\text{sp}}|0,0\rangle_{\text{val}}$

10 supertriplets

$|0,0\rangle_{\text{sp}}|0,0\rangle_{\text{val}}$

$|1,m_s\rangle_{\text{sp}}|1,m_v\rangle_{\text{val}}$

$m_s, m_v \in \{1, 0, -1\}$

Spin-valley blockade in double dots

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Koppens et al., Science 2005
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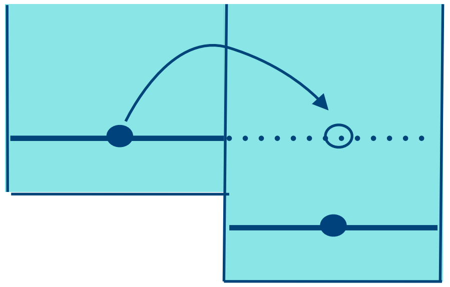

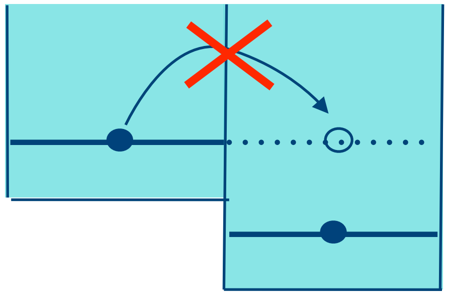

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Jouravlev & Nazarov, PRL 2006

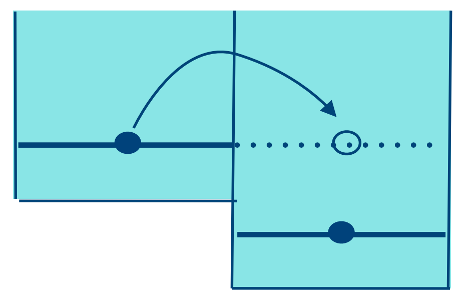
$|s, m_s\rangle$

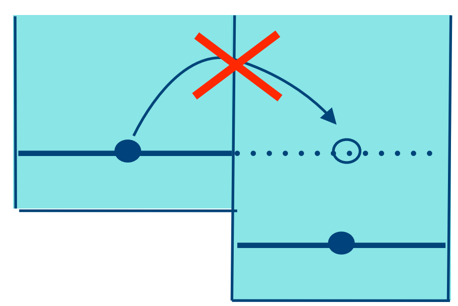
1 singlet $\quad |0,0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$

3 triplets

$$|1,1\rangle = |\uparrow\uparrow\rangle$$
$$|1,0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$$
$$|1,-1\rangle = |\downarrow\downarrow\rangle$$

current = 0





spin-valley blockade (C)

Churchill et al., Nature Phys. 2009
Pályi & Burkard, PRB 2009

6 supersinglets

$$|0,0\rangle_{\mathrm{sp}}|1,m_v\rangle_{\mathrm{val}}$$
$$|1,m_s\rangle_{\mathrm{sp}}|0,0\rangle_{\mathrm{val}}$$

10 supertriplets

$$|0,0\rangle_{\mathrm{sp}}|0,0\rangle_{\mathrm{val}}$$
$$|1,m_s\rangle_{\mathrm{sp}}|1,m_v\rangle_{\mathrm{val}}$$

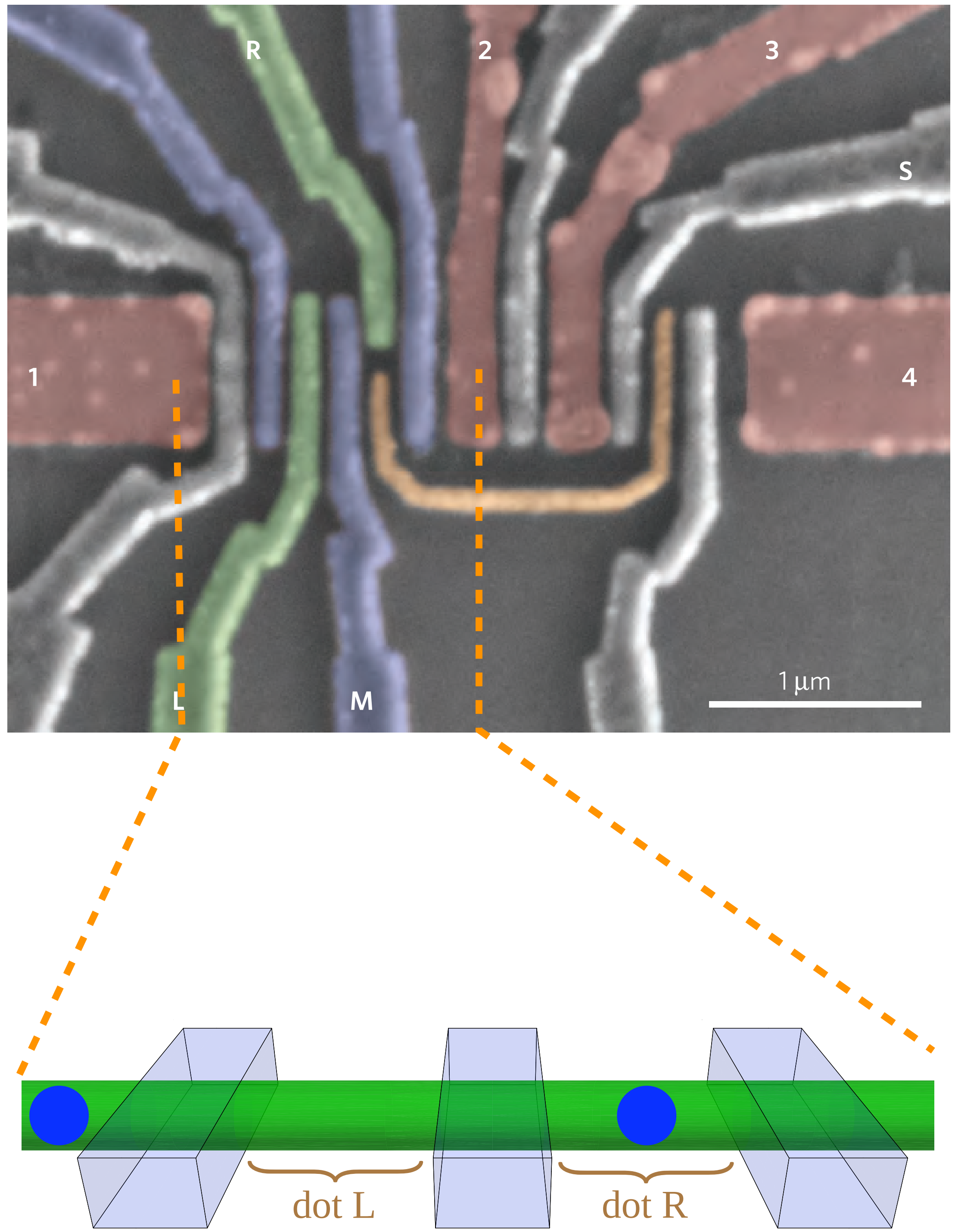
$$m_s, m_v \in \{1, 0, -1\}$$

current = 0

spin/valley-mixing → leakage current

Leakage current in the spin-valley blockade

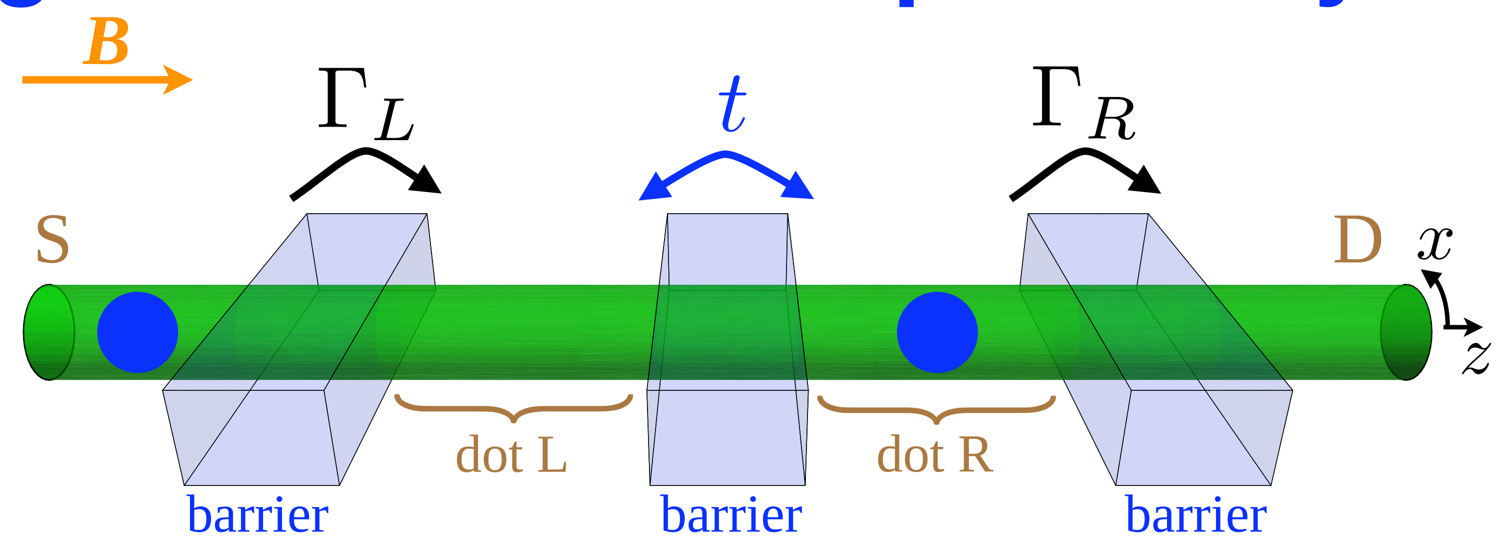
experiments:
Churchill *et al.*,
Nature Phys. 2009
PRL 2009



carbon nanotube underneath

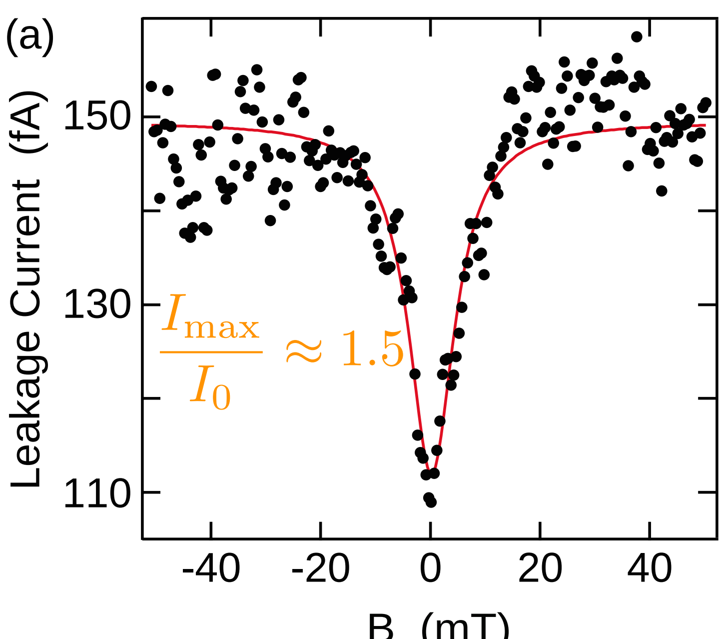
theory:
Palyi & Burkard, PRB 2009-2010
von Stecher *et al.*, PRB 2010

Leakage current in the spin-valley blockade



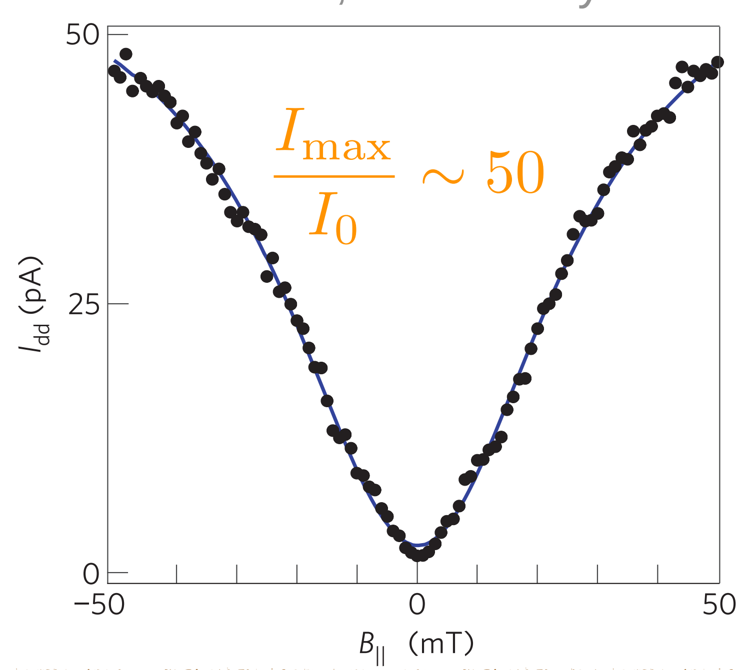
experiment #1

Churchill *et al.*, PRL 2009



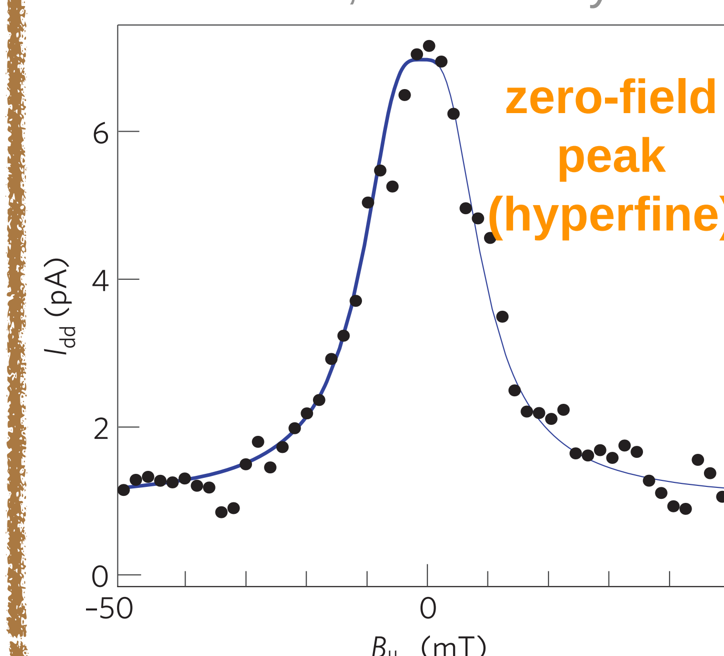
experiment #2

Churchill *et al.*, Nature Phys. 2009



experiment #3

Churchill *et al.*, Nature Phys. 2009

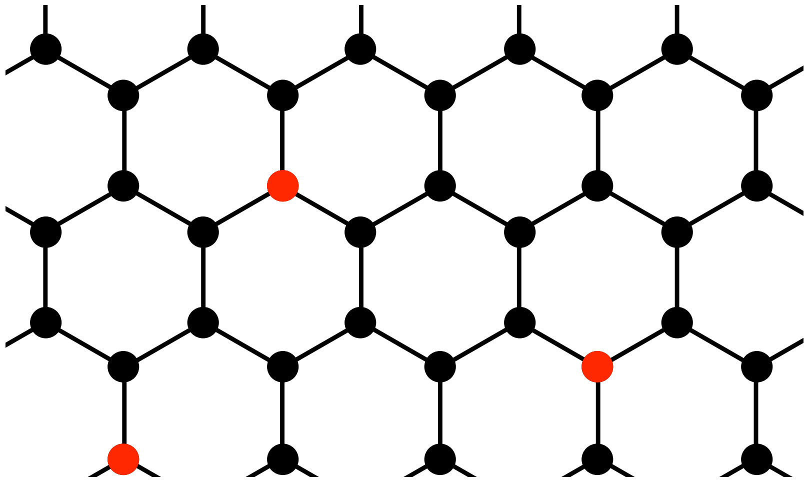


99% 13C
2 electrons

1% 13C
many electrons

99% 13C
many electrons

Atomic disorder couples the valleys K and K'

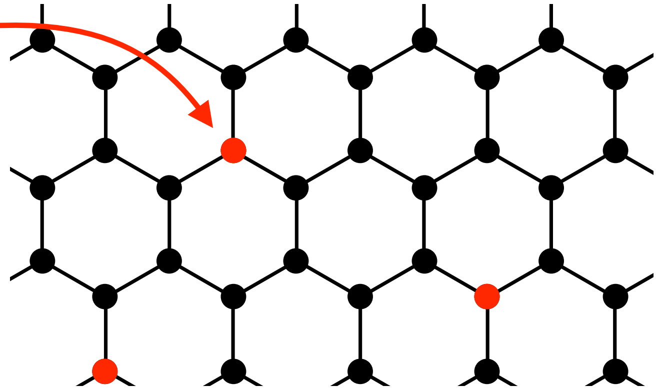


Kuemmeth, Ilani et al., Nature 2008
Churchill et al., Nature Phys. & PRL 2009
Jespersen et al., arXiv:1008.1600

Pályi & Burkard, PRB 2010, arXiv:1010.4338

substitutional atom,
adatom,
vacancy, etc.

$$(H_{\mathrm{dis,tb}})_{ij} = V_i \delta_{ij}$$



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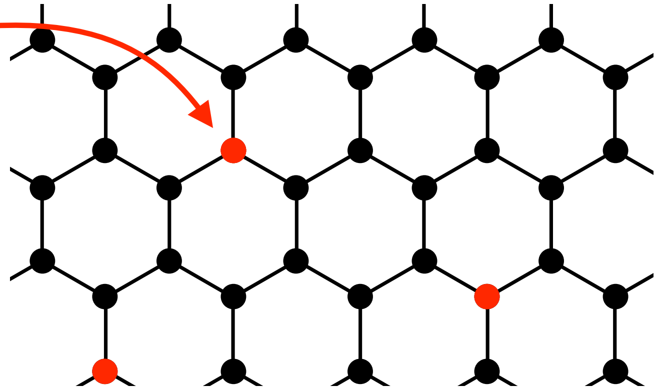

effective Hamiltonian for
a single QD level?

substitutional atom,
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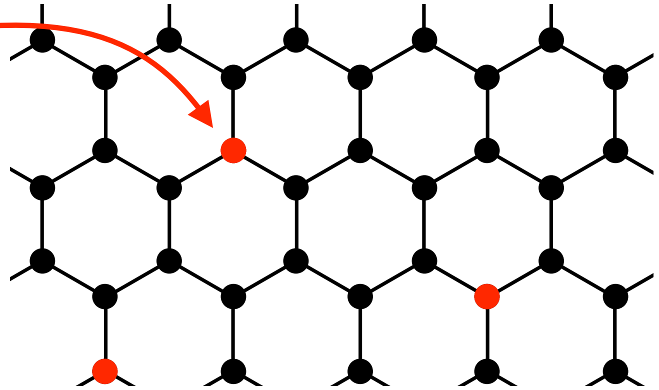

effective Hamiltonian for a single QD level?

$$v \in (K, K') \equiv (+, -)$$

step 1:

$$[v_F(\sigma_x p_x + v\sigma_y p_y) + V_{\mathrm{conf}}(x,y)] \begin{pmatrix} \Psi_A^{(v)} \\ \Psi_B^{(v)} \end{pmatrix} = E \begin{pmatrix} \Psi_A^{(v)} \\ \Psi_B^{(v)} \end{pmatrix}$$

Dirac envelope functions

unit cell index

sublattice index (A or B)

step 2:

$$(\psi_{vs})_{l\sigma} \equiv (\psi_v)_{l\sigma}\chi_s = \sqrt{\Omega_{\mathrm{cell}}}\, e^{iv\boldsymbol{K}\cdot\boldsymbol{r}_{l\sigma}} \Psi_\sigma^{(v)}(\boldsymbol{r}_{l\sigma})\chi_s,$$

$$s \in (\uparrow, \downarrow)$$

tight-binding wave function

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$$H_{\mathrm{eff}} = P H_{\mathrm{tb}} P$$

$$P = \sum_{vs} |\psi_{vs}\rangle\langle\psi_{vs}|$$

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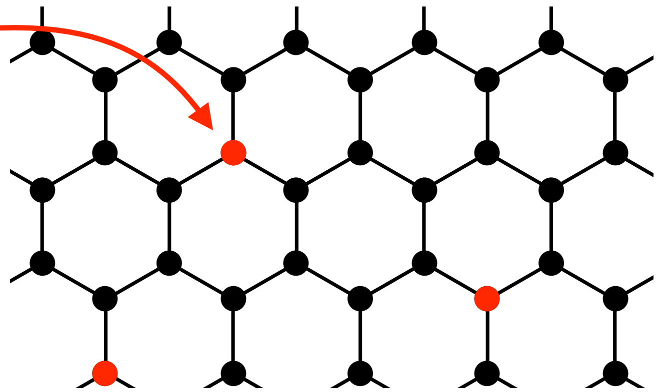

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restricted valley operators, e.g:

$$\tau_z = |\psi_K\rangle\langle\psi_K| - |\psi_{K'}\rangle\langle\psi_{K'}|$$

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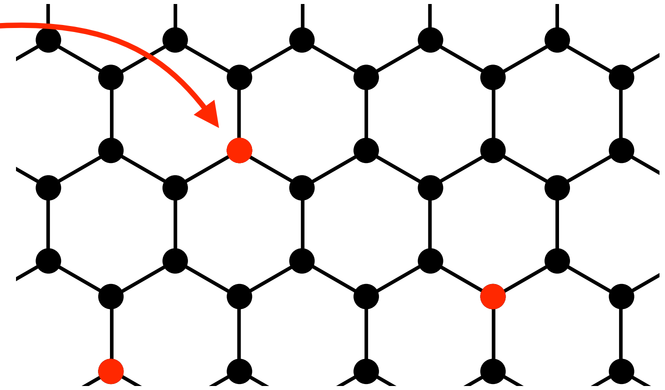

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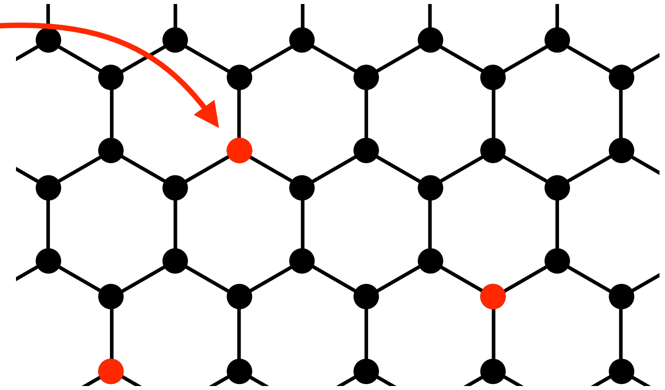

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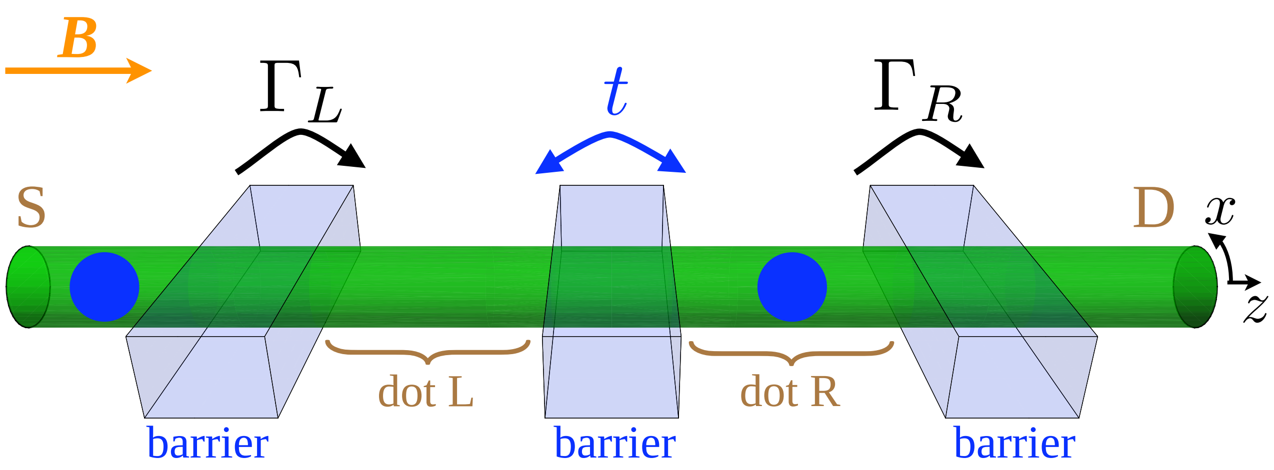
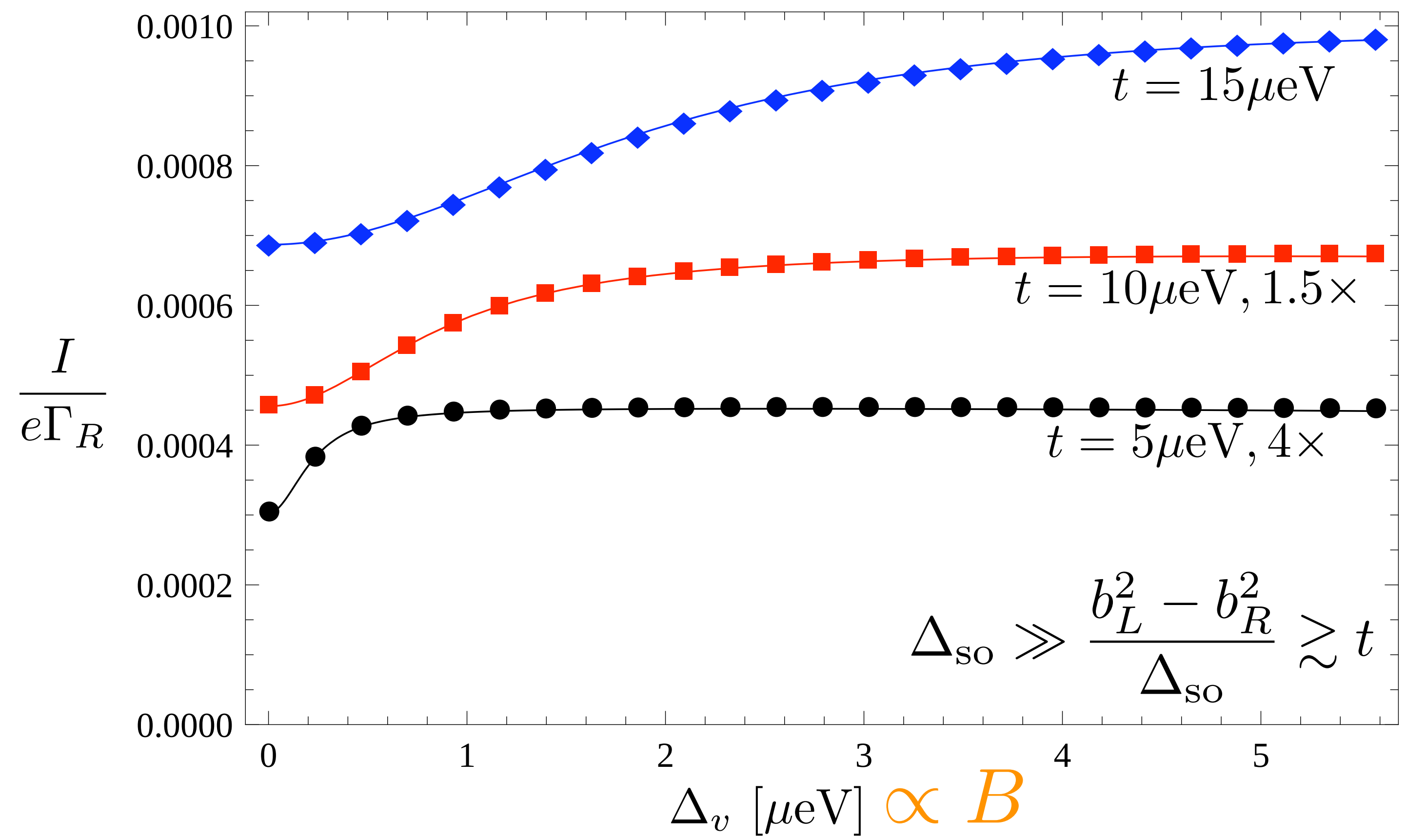
short-range perturbation = valley mixing

Leakage current - theory

Pályi & Burkard PRB 2010



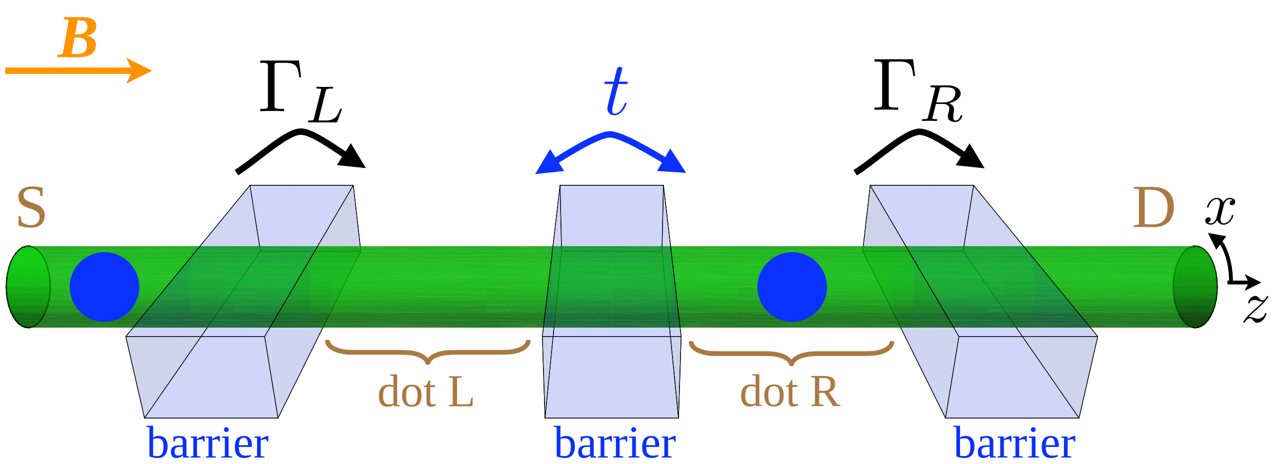
- effect of **disorder** on leakage current in CNTs?
- **spin-orbit splitting** taken into account
- coherent interdot tunneling
- no hyperfine interaction



$$\Delta_{\rm SO} = 250\mu{\rm eV},\ b_{Lx} = 20\mu{\rm eV},\ b_{Ly} = 10\mu{\rm eV},\ b_{Rx} = 80\mu{\rm eV}, b_{Ry} = 0\mu{\rm eV}$$

Leakage current - theory

Pályi & Burkard PRB 2010



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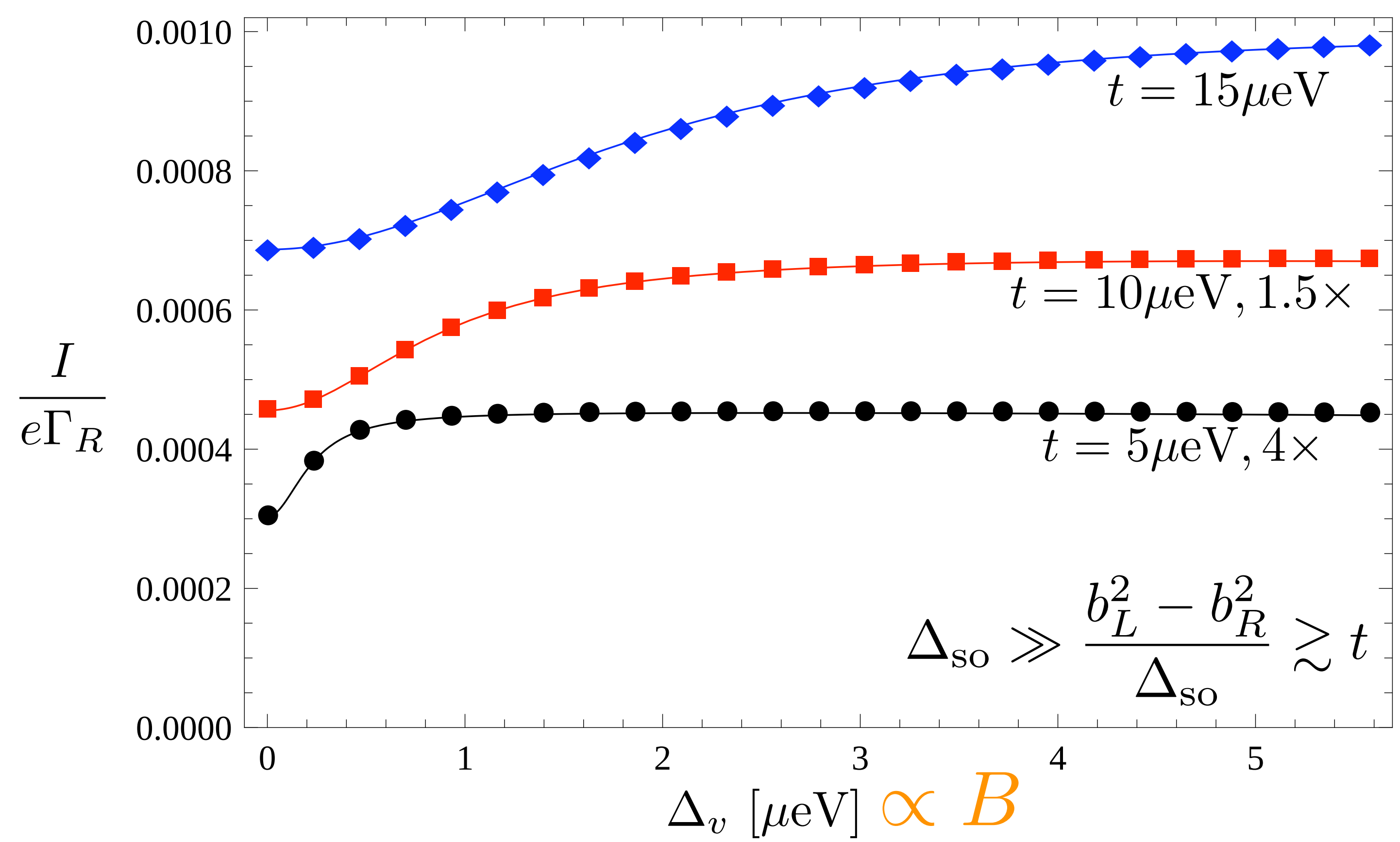
(1) finite leakage current



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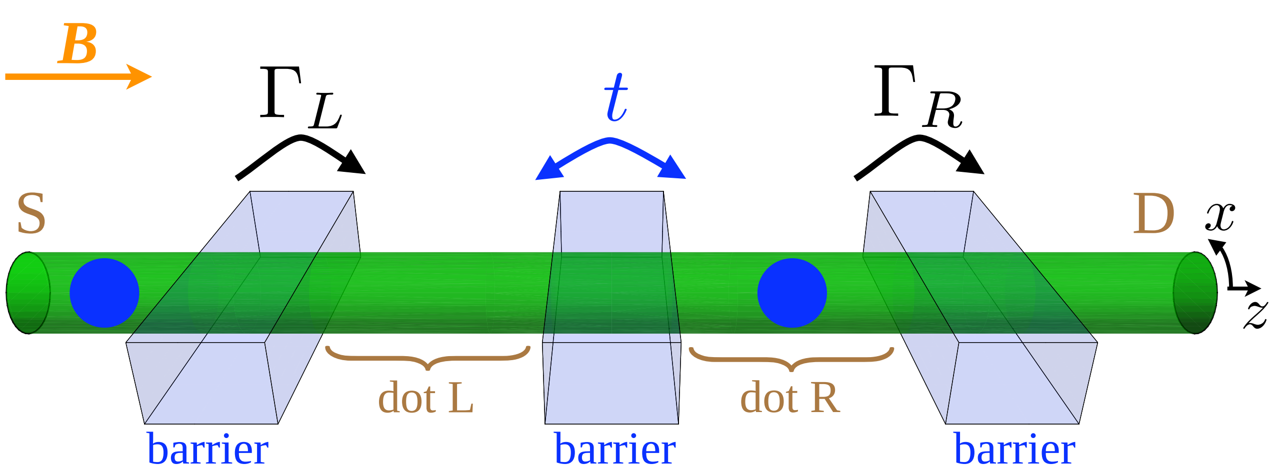
Leakage current - theory

Pályi & Burkard PRB 2010



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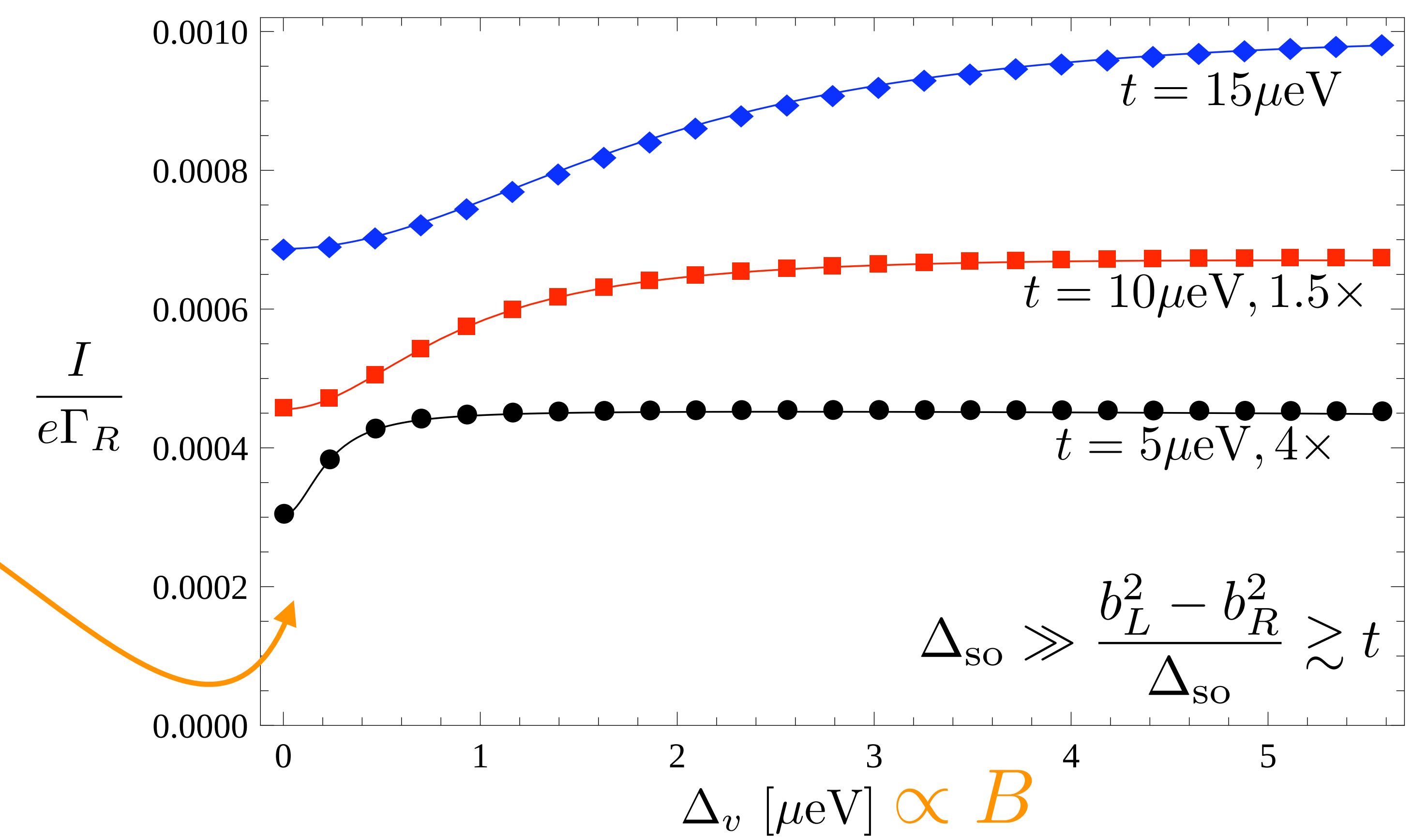
(1) finite leakage current

(2) zero-field dip



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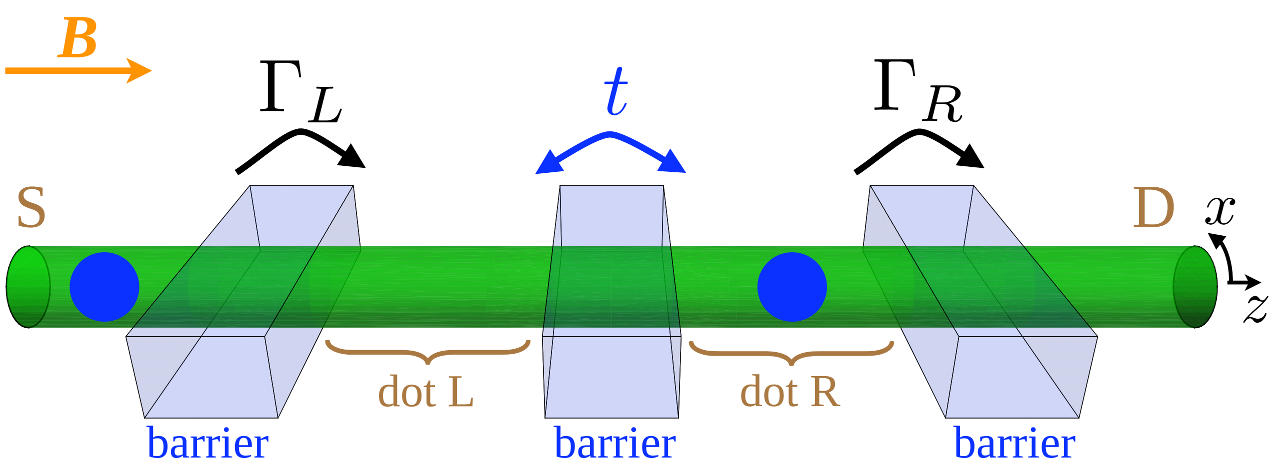
Pályi & Burkard PRB 2010



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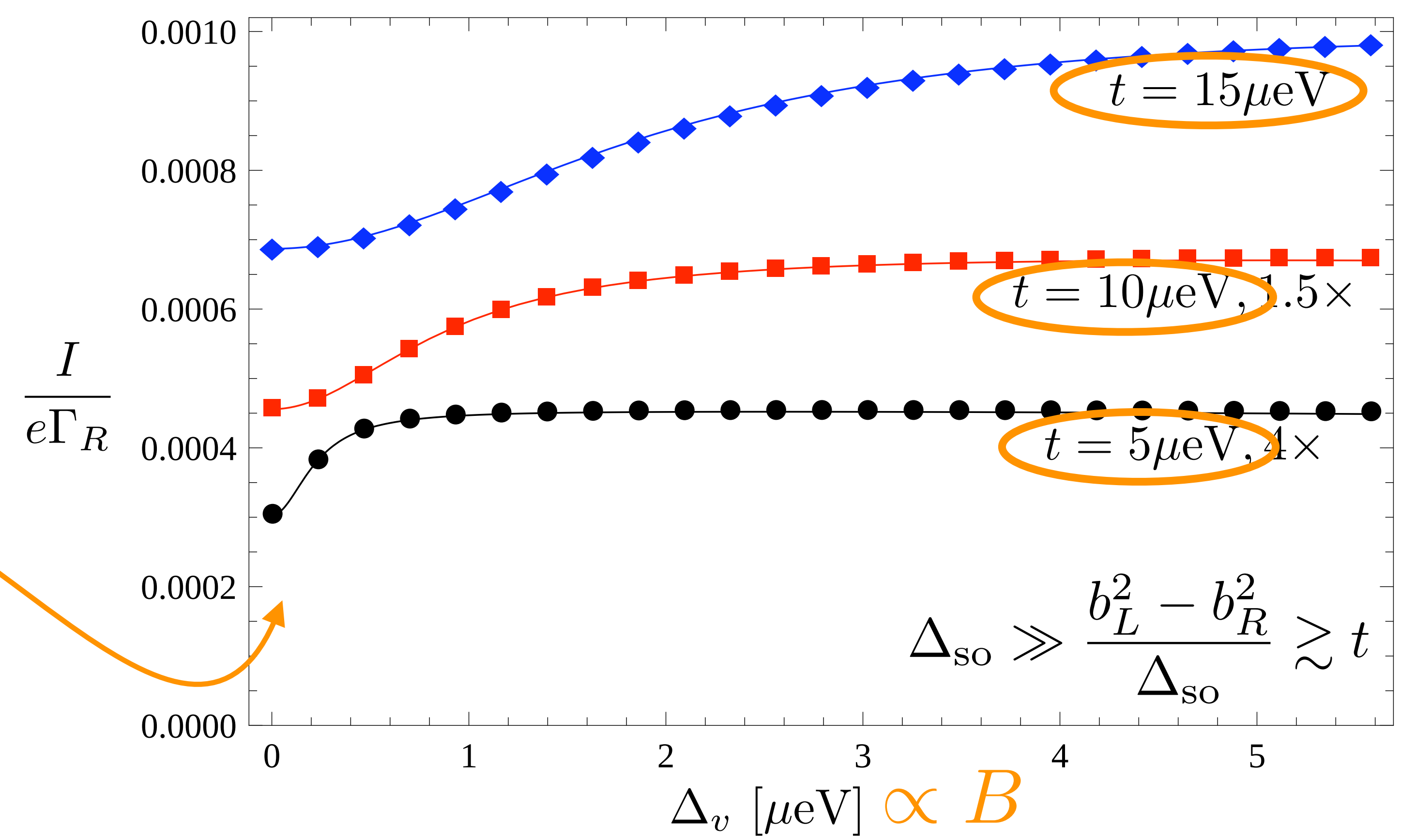
(3) dip width controlled by *t*



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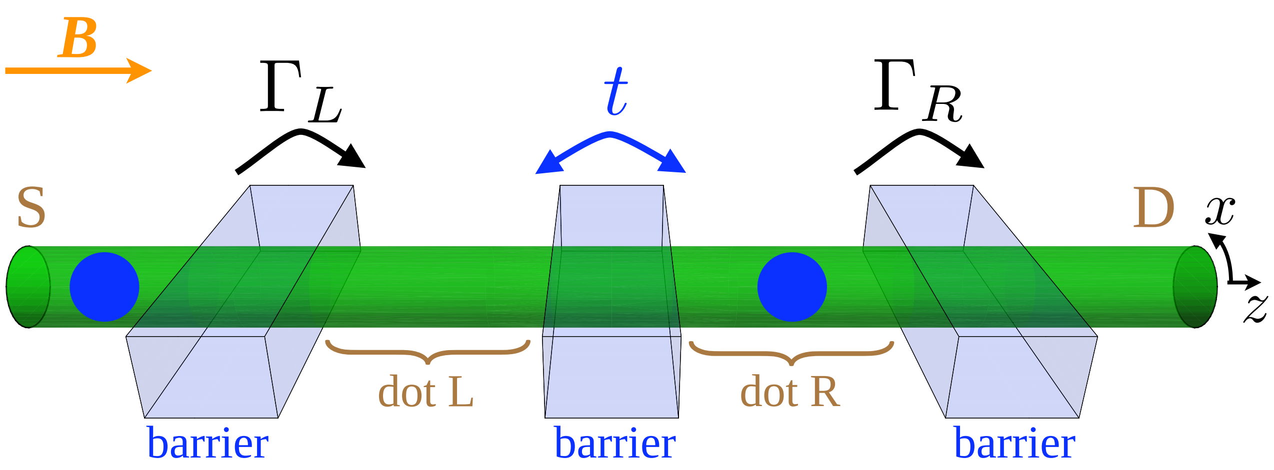
Leakage current - theory

Pályi & Burkard PRB 2010



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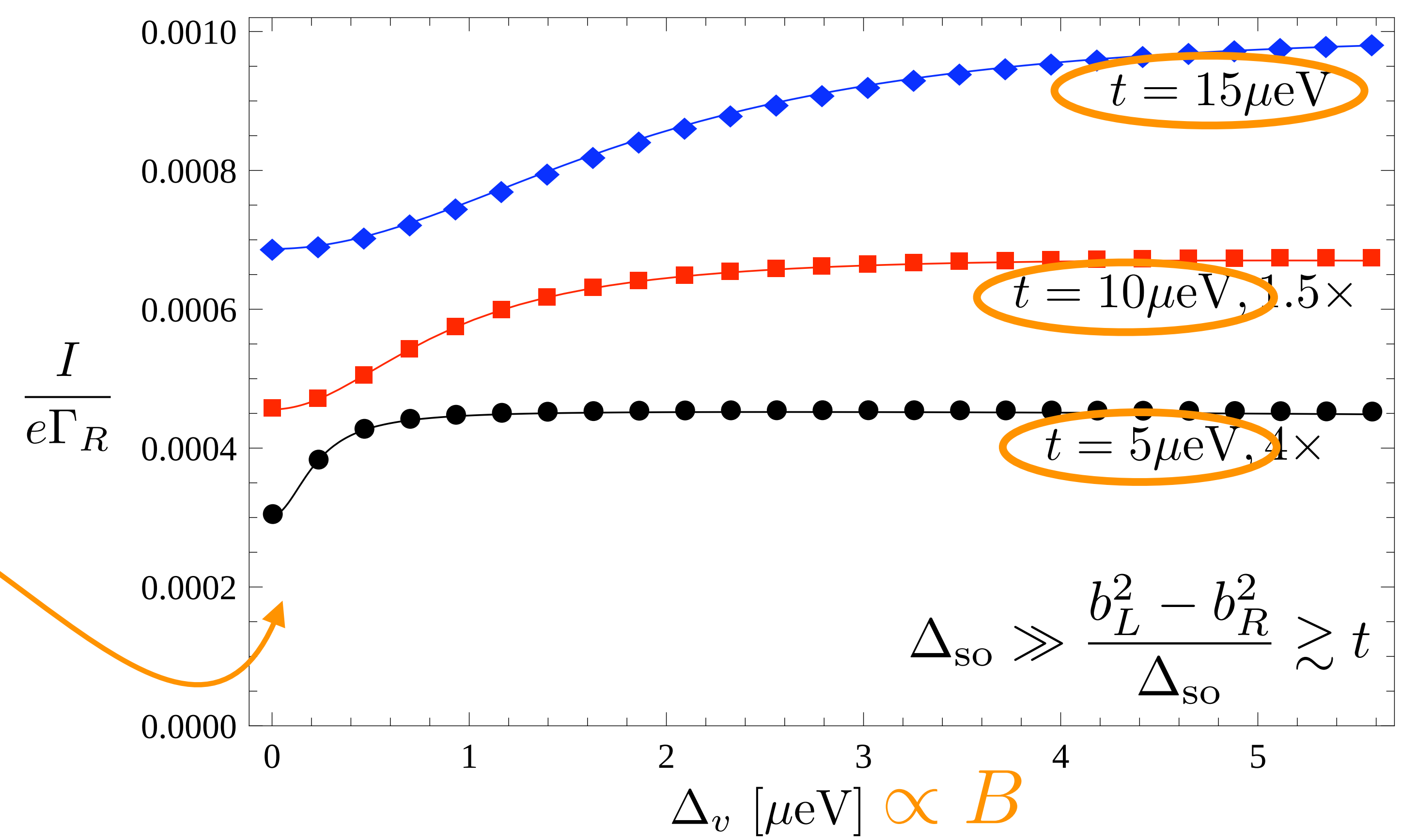
(4) $\frac{I_{\max}}{I_0} \approx 1.5$



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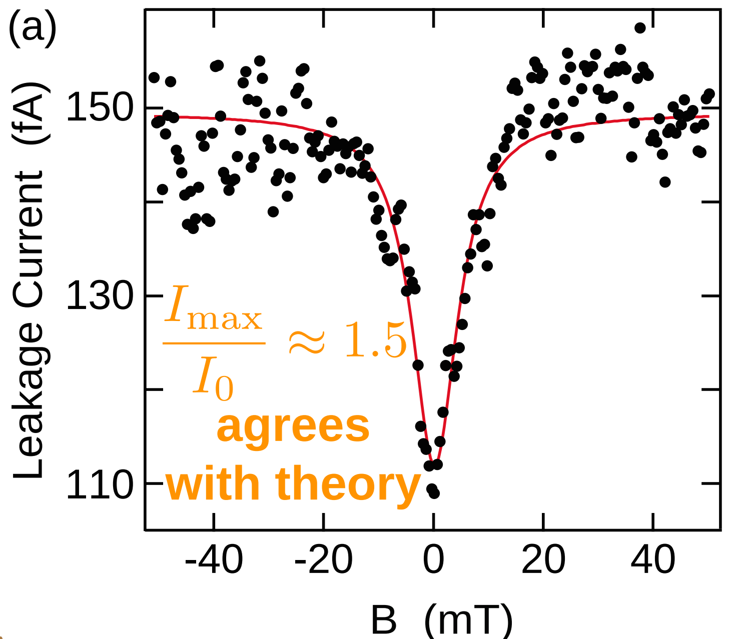
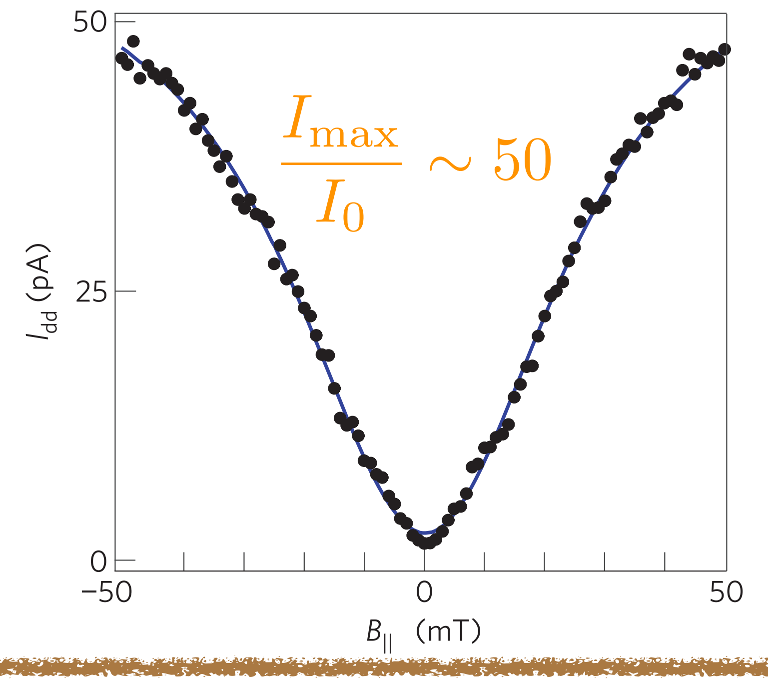
Experiment vs theory

experiment #1
Churchill *et al.*, PRL 2009



experiment #2
Churchill *et al.*, Nature Phys. 2009



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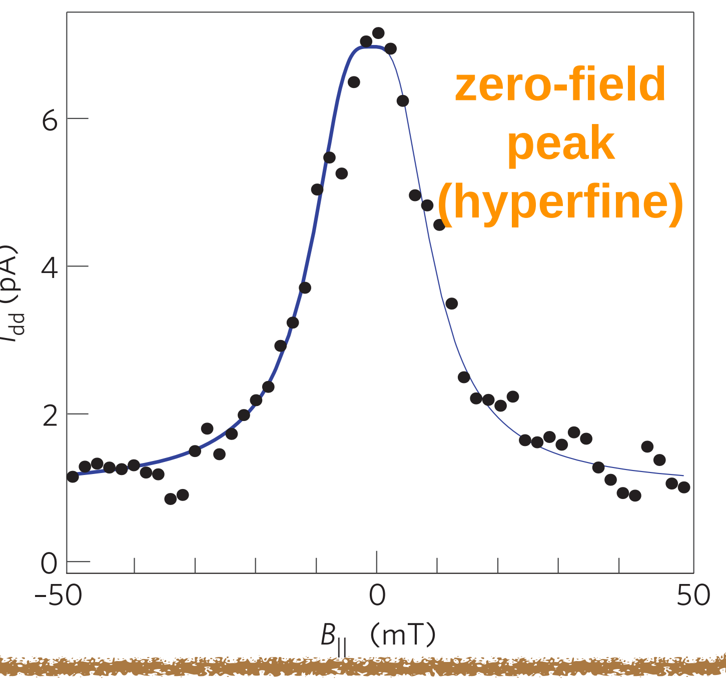

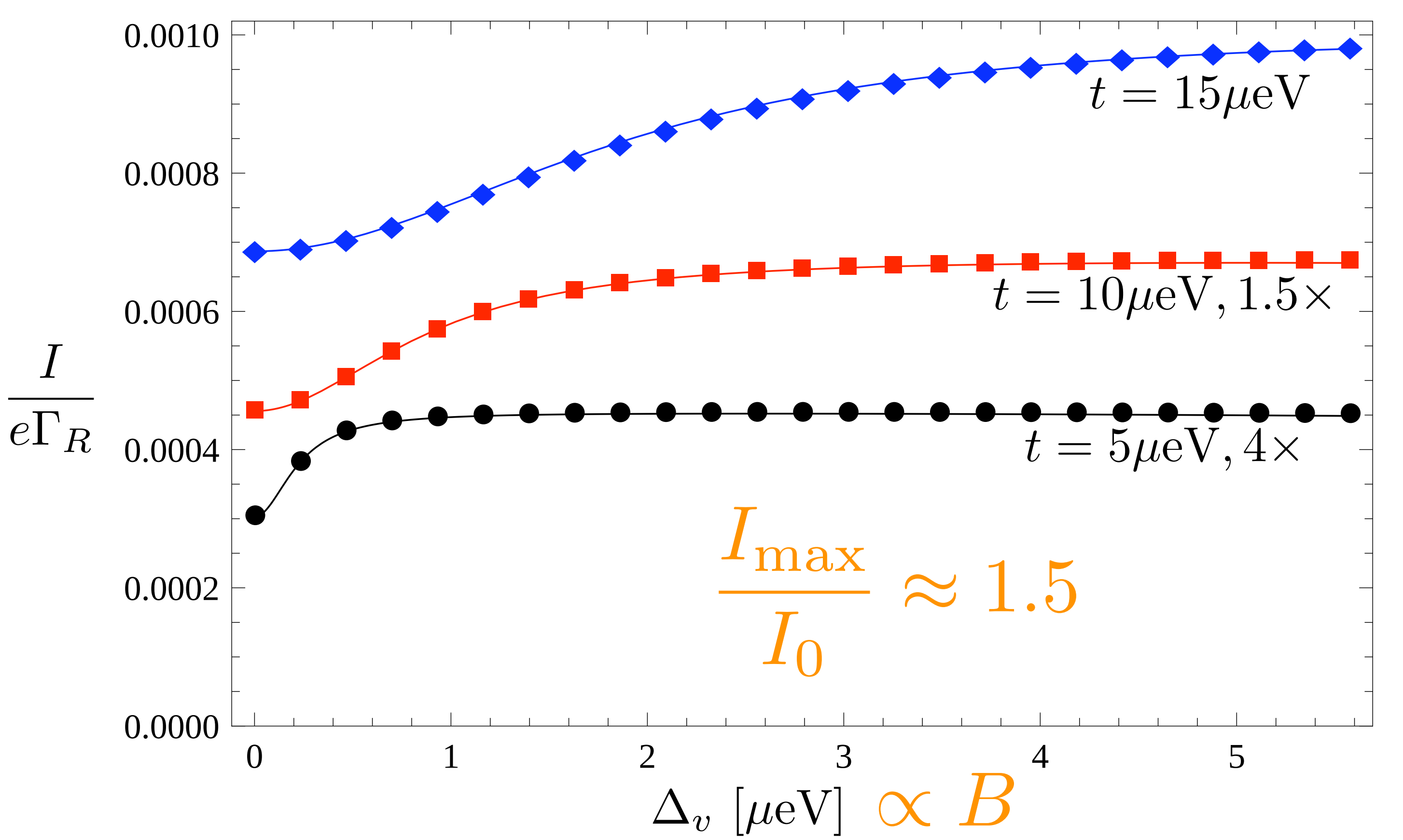

Hyperfine interaction in carbon-based QDs

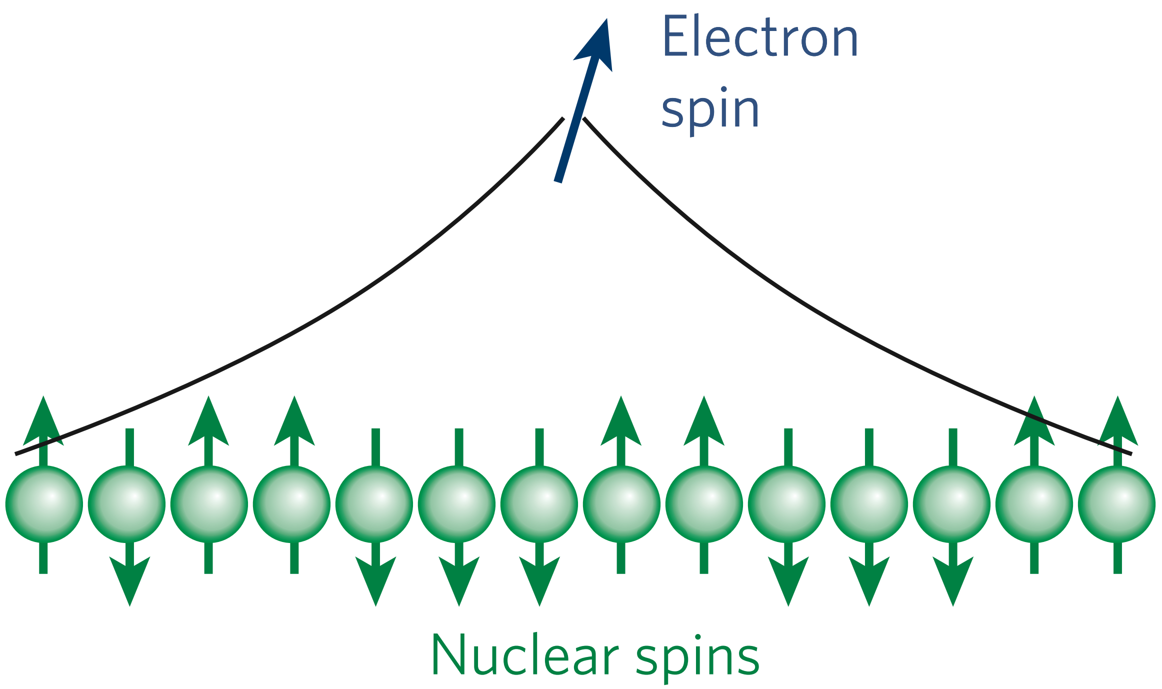

figure: Hanson & Awschalom, Nature 2008

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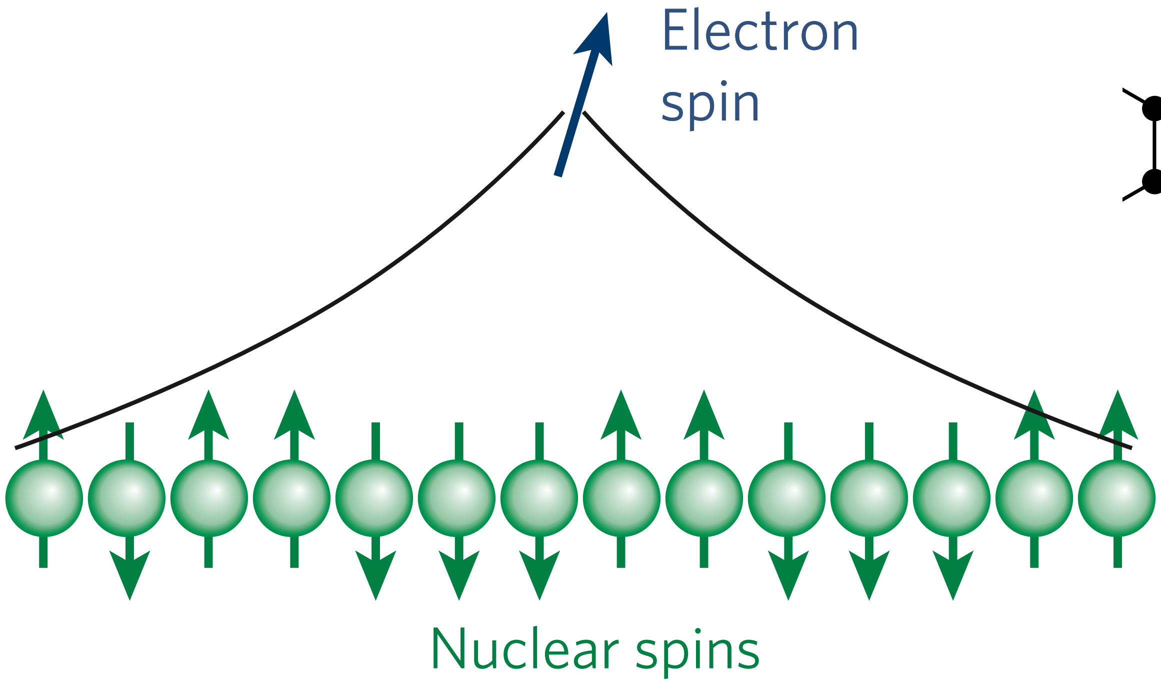

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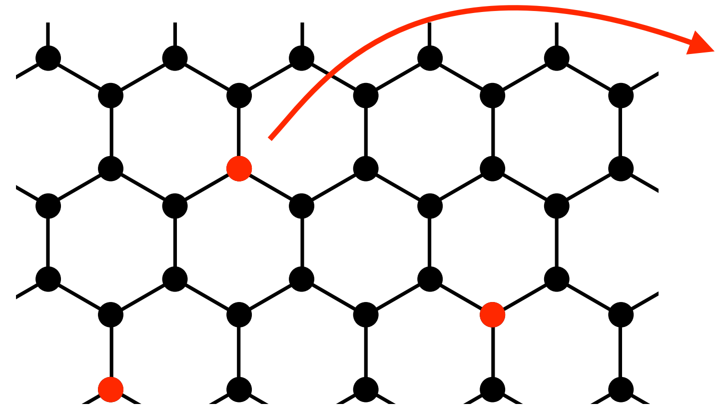

^{13}C with nuclear spin 1/2

$$(H_{\mathrm{hfi,tb}})_{ij} = \boldsymbol{S}A\boldsymbol{I}_i\delta_{ij}$$

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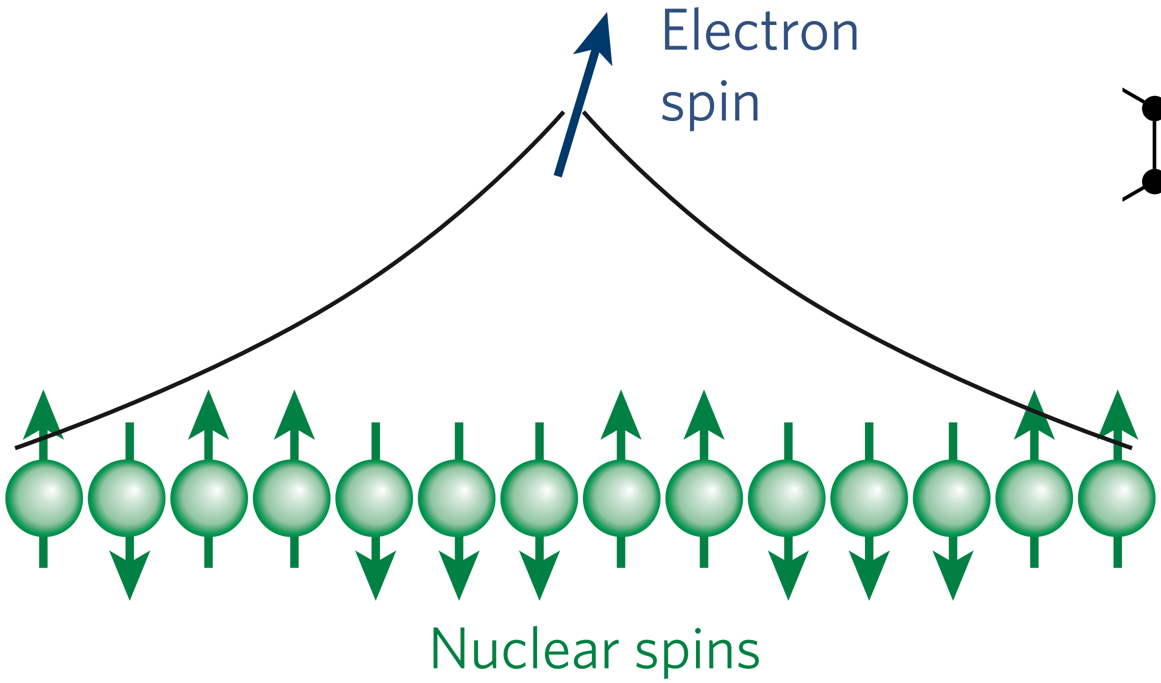

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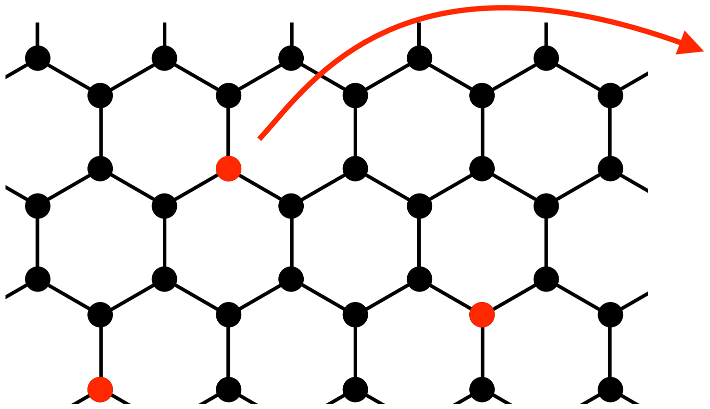

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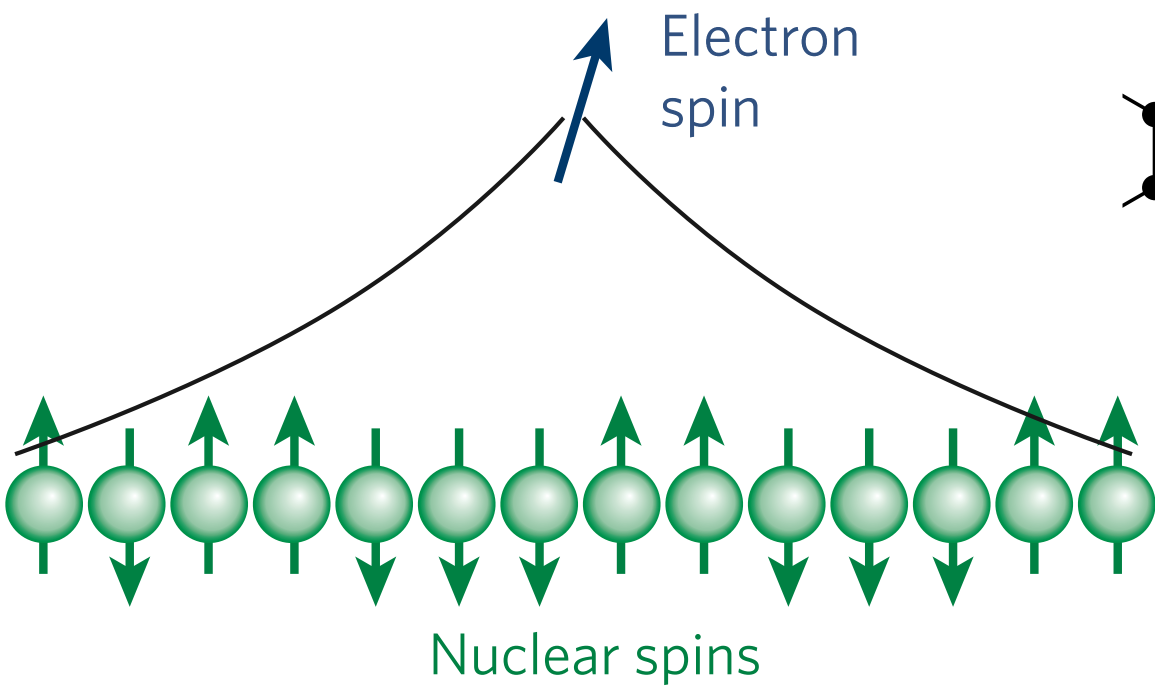

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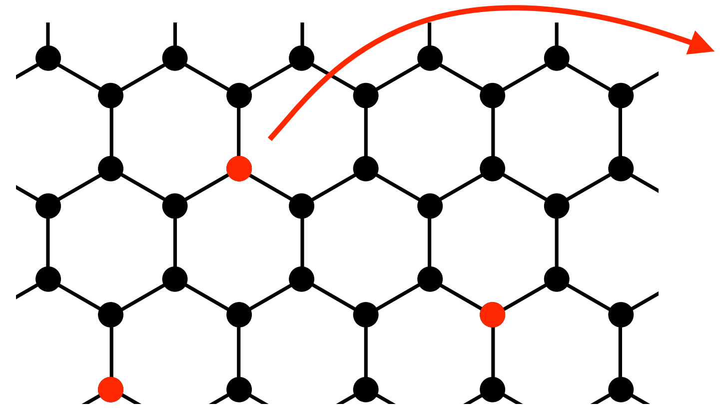

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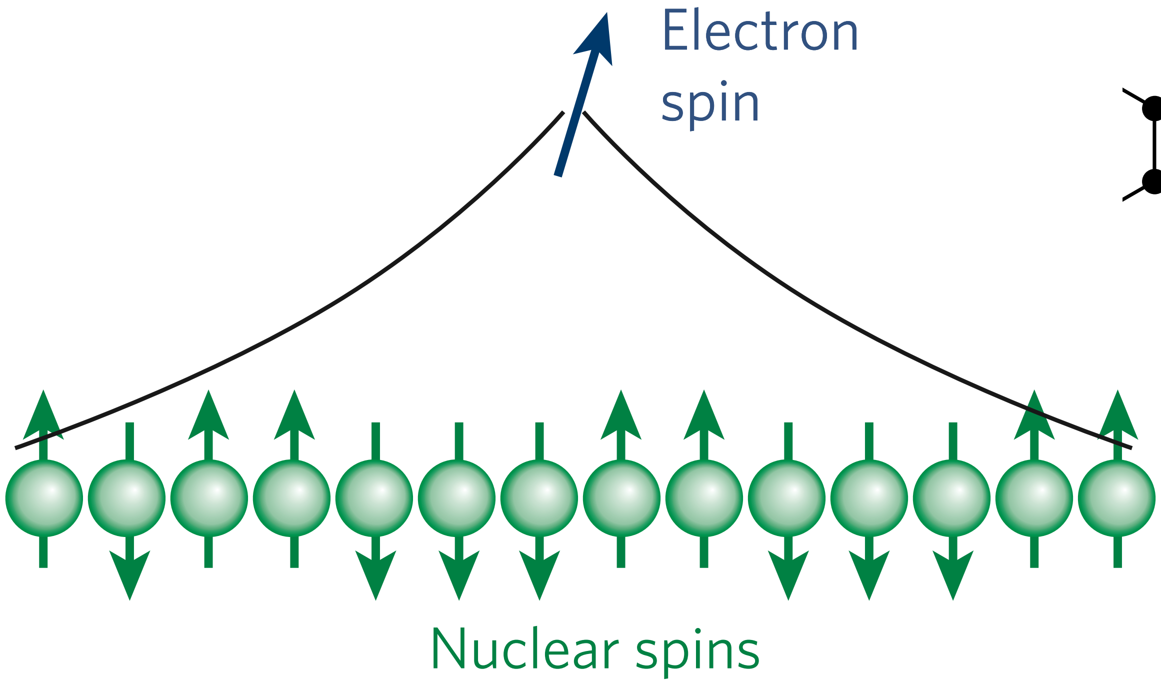

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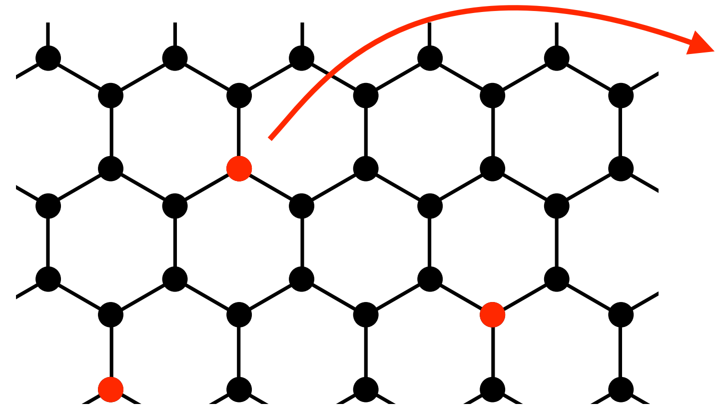

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time-reversal
symmetry

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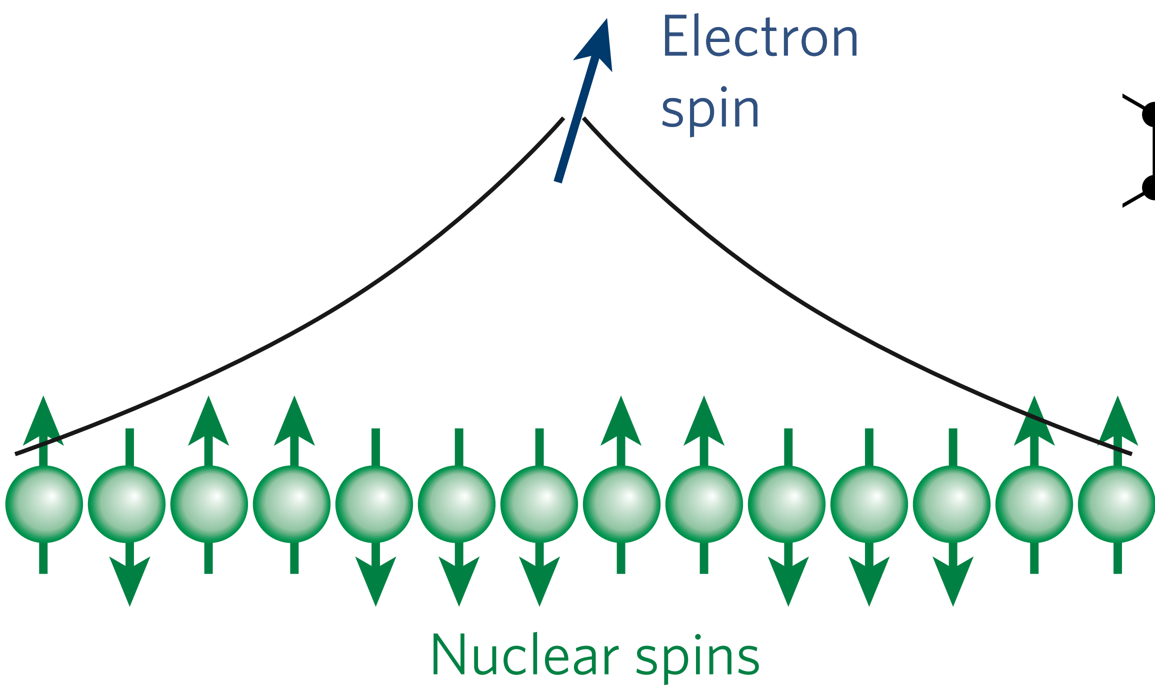

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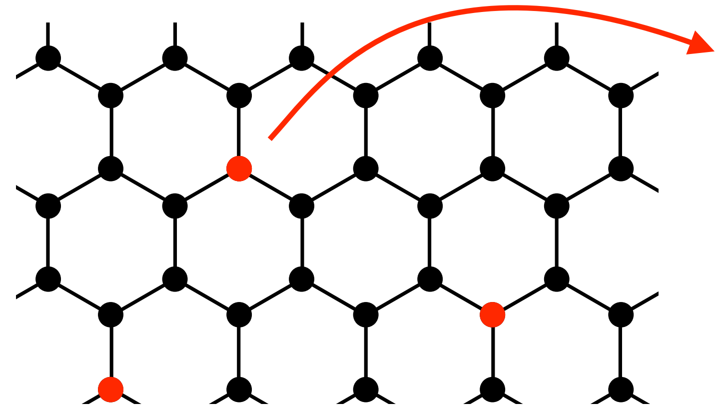

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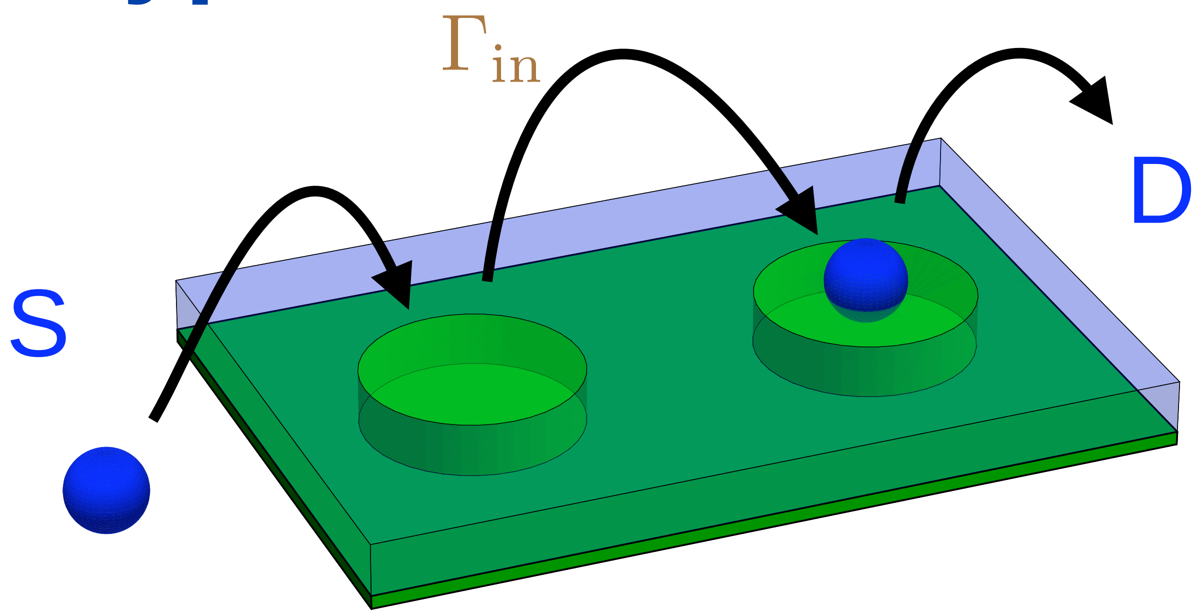
Leakage current due to hyperfine interaction

- effect of **hyperfine** interaction on leakage current?
- no disorder and no spin-orbit interaction
- incoherent interdot tunneling



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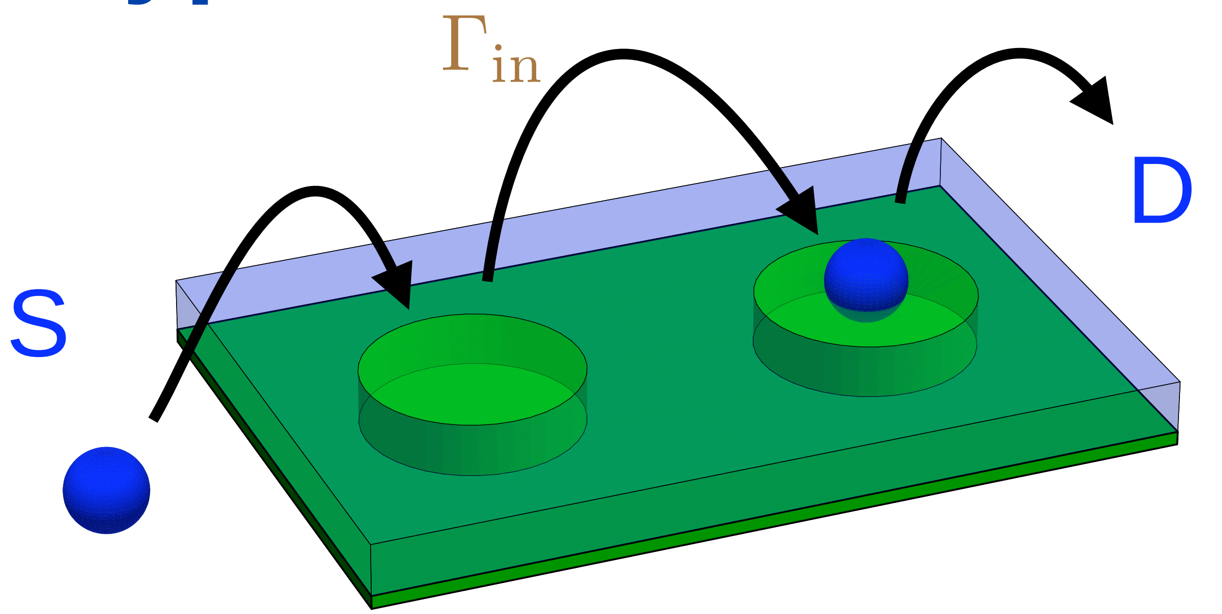
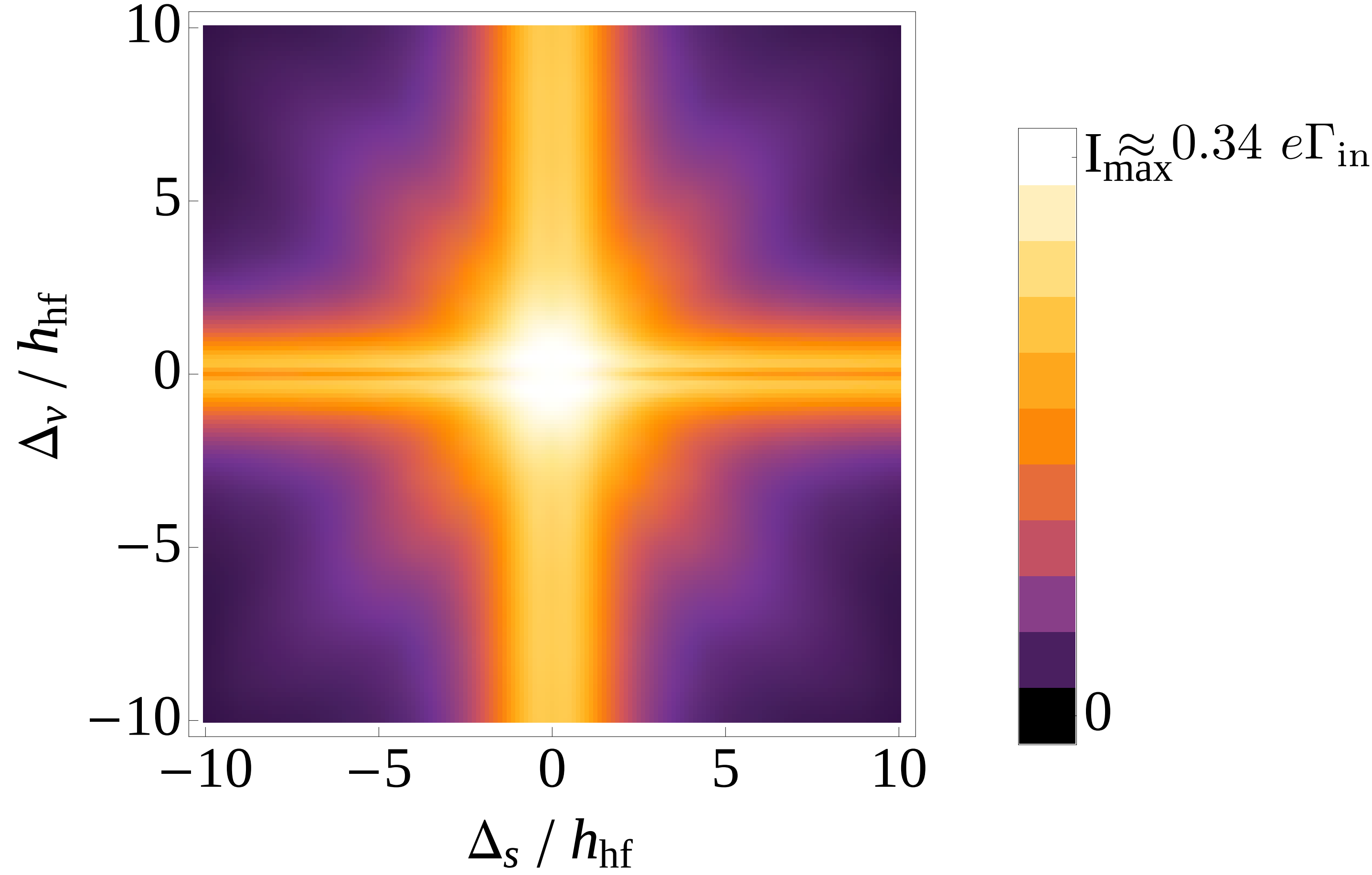
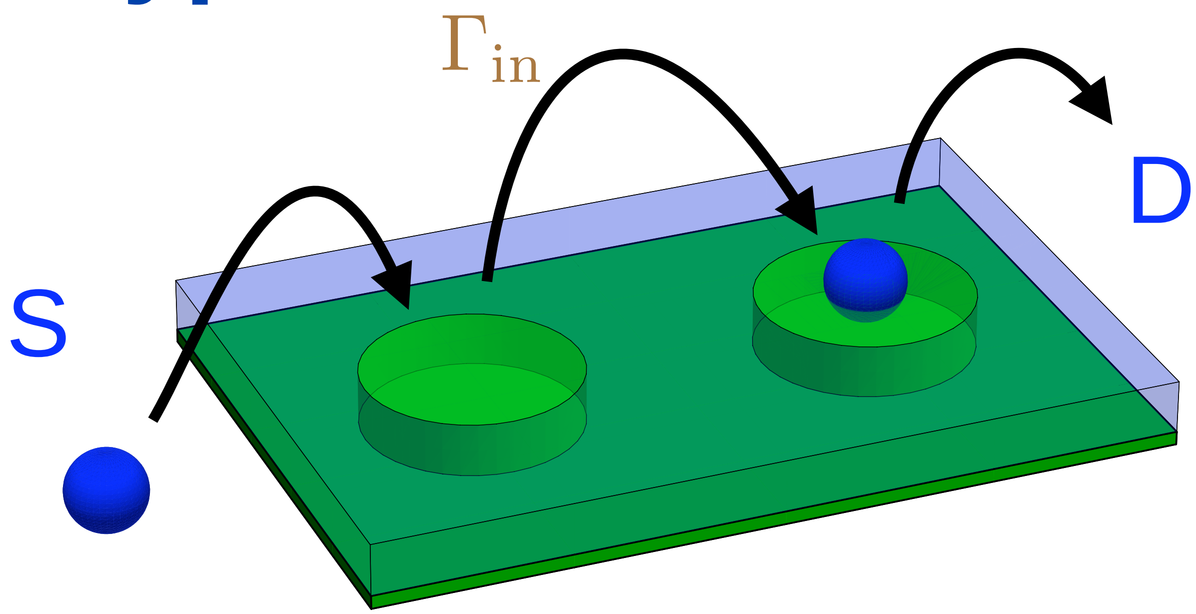
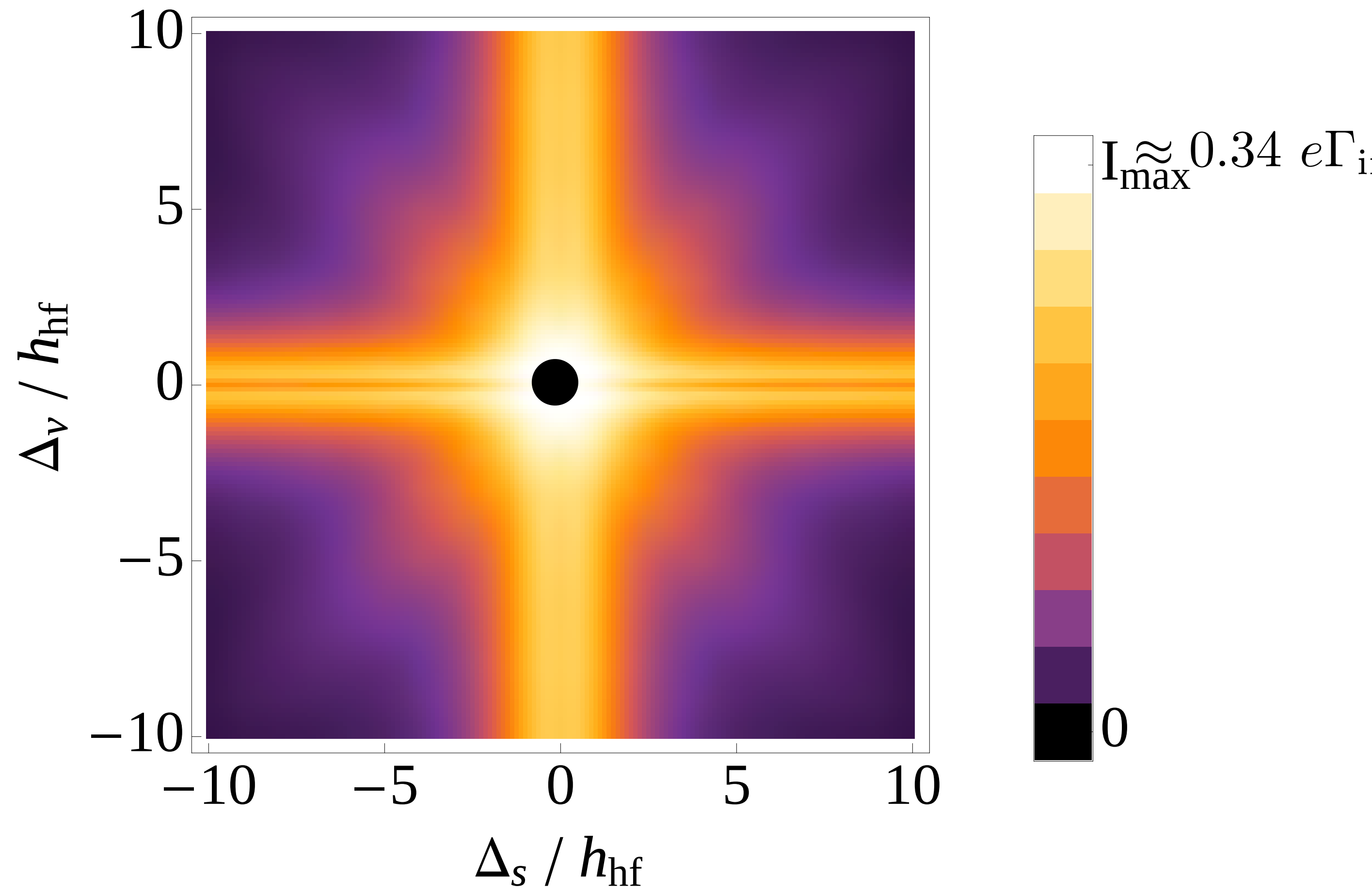




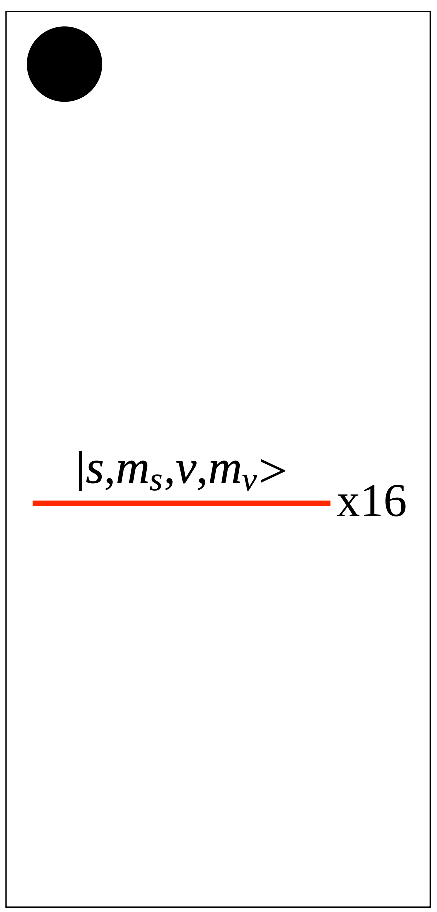
Leakage current due to hyperfine interaction

- effect of **hyperfine** interaction on leakage current?
- no disorder and no spin-orbit interaction
- incoherent interdot tunneling





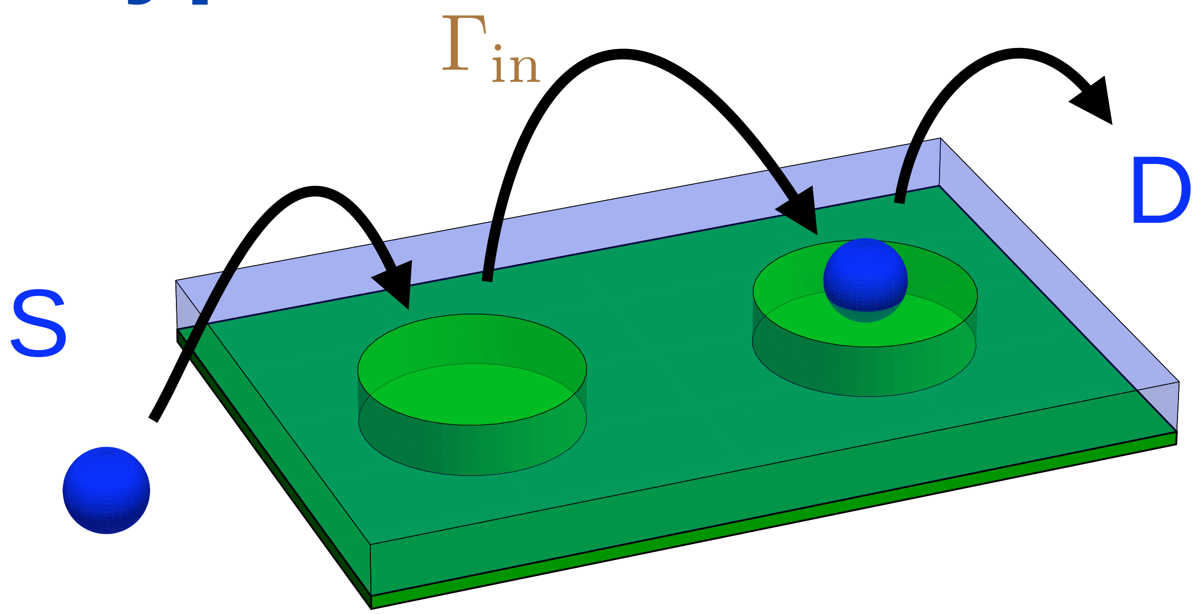
$\Delta_s = 0$ | hf-induced **spin and valley** mixing
$\Delta_v = 0$ | no pure supertriplets
blockade lifted

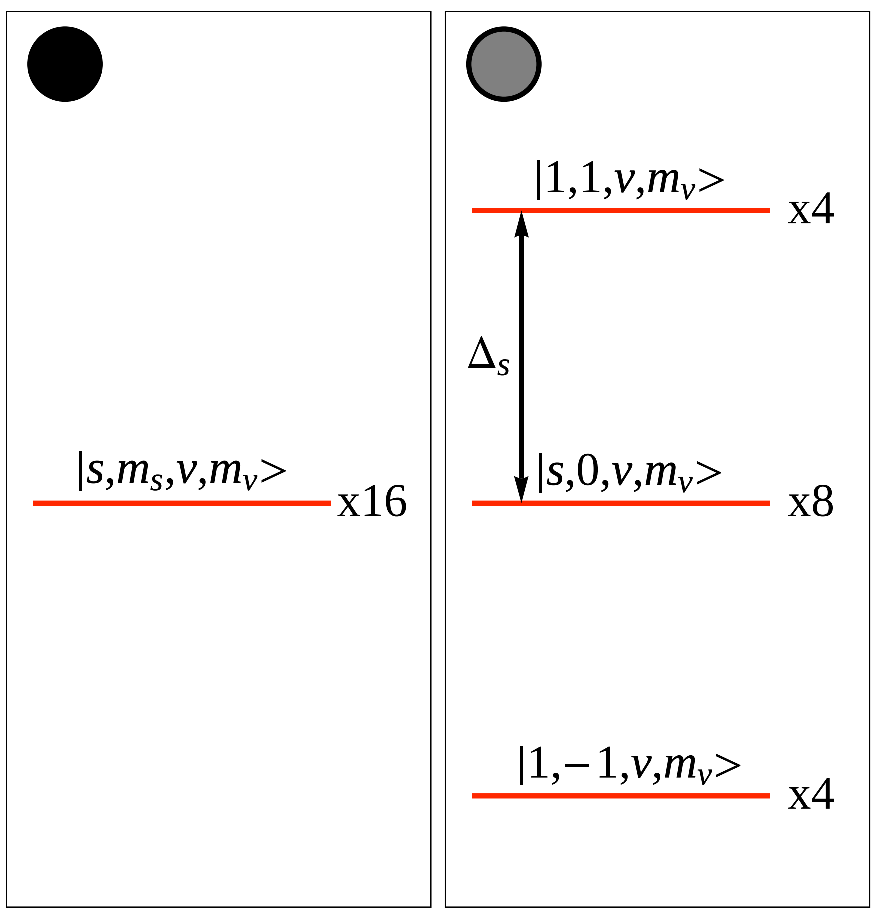


Energy level diagram in the (1,1) charge configuration

Leakage current due to hyperfine interaction

- effect of **hyperfine** interaction on leakage current?
- no disorder and no spin-orbit interaction
- incoherent interdot tunneling





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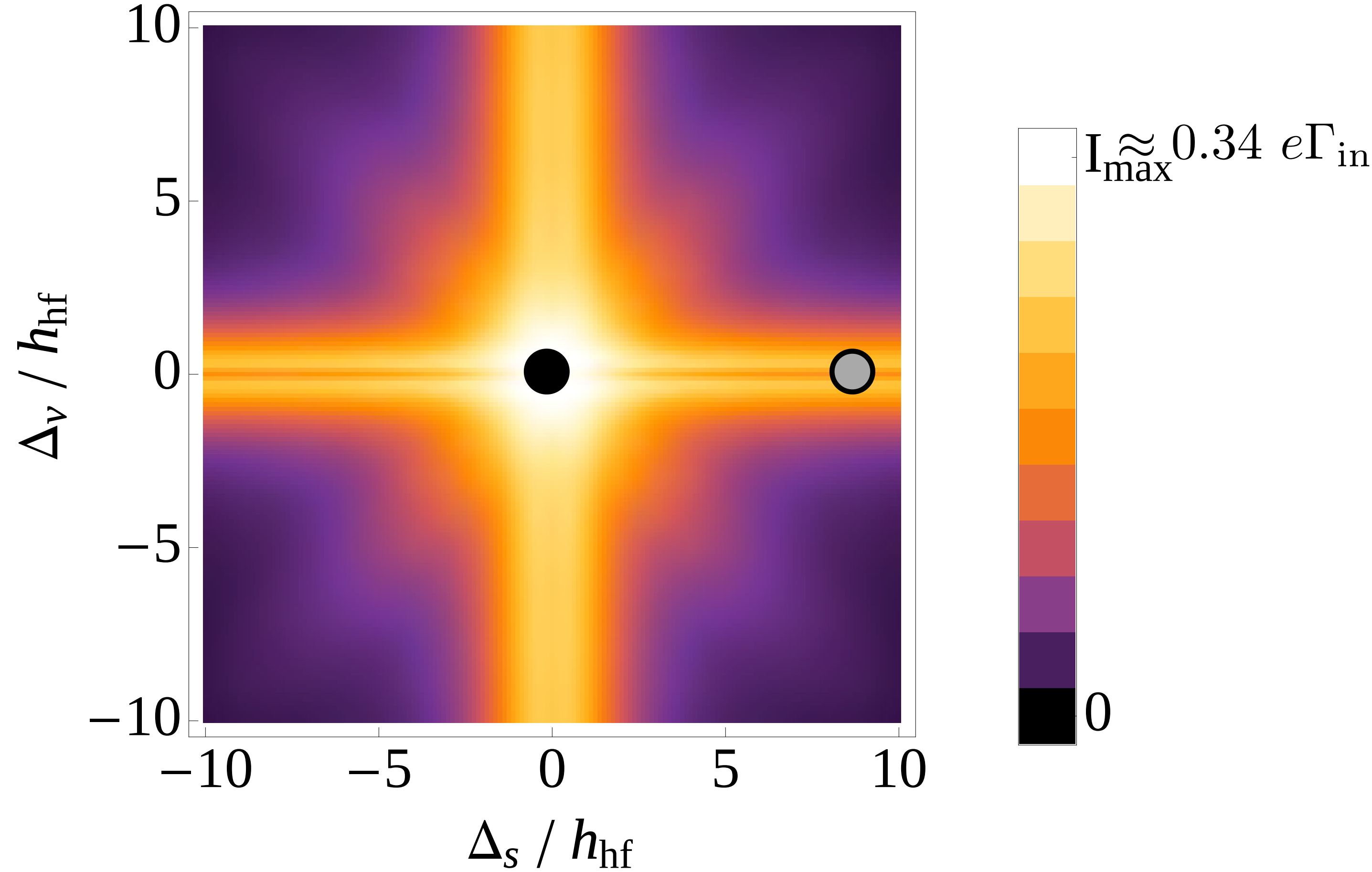


$\Delta_s = 0$, $\Delta_v = 0$

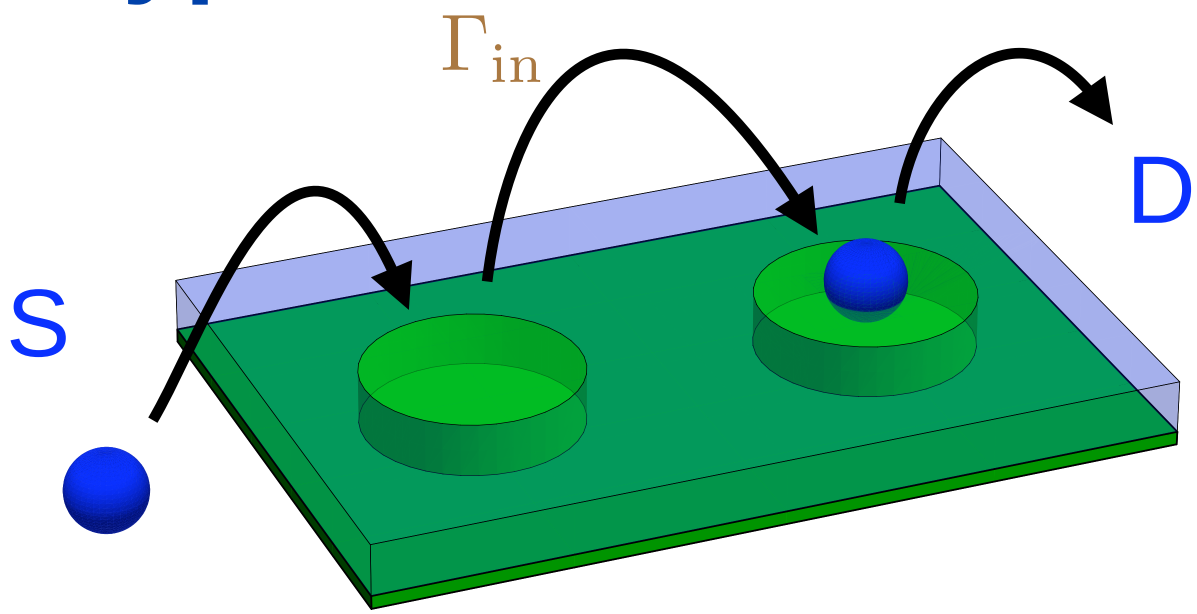
hf-induced **spin and valley** mixing
no pure supertriplets
blockade lifted

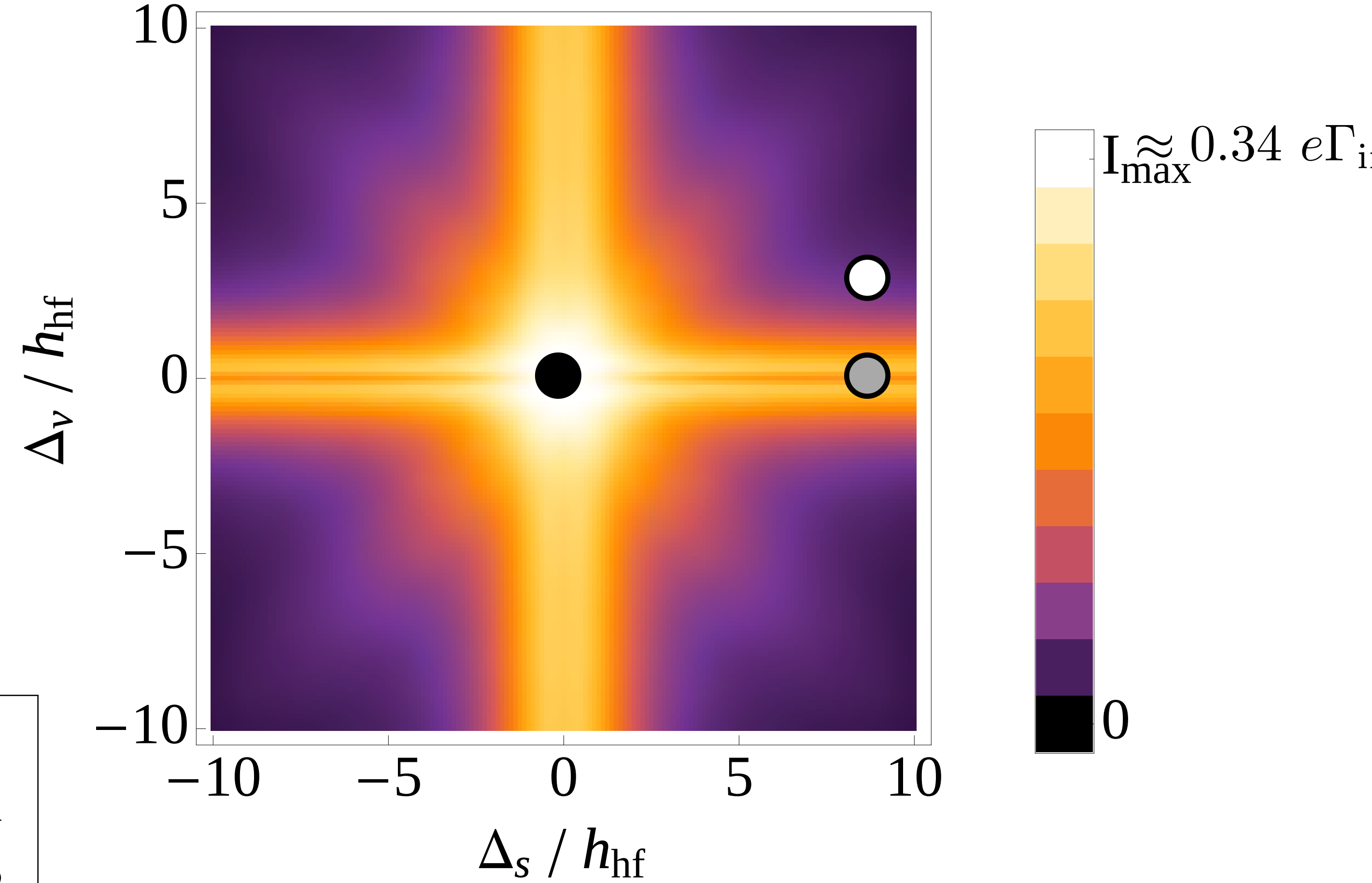
$\Delta_s \gg h_{\mathrm{hf}}$, $\Delta_v = 0$

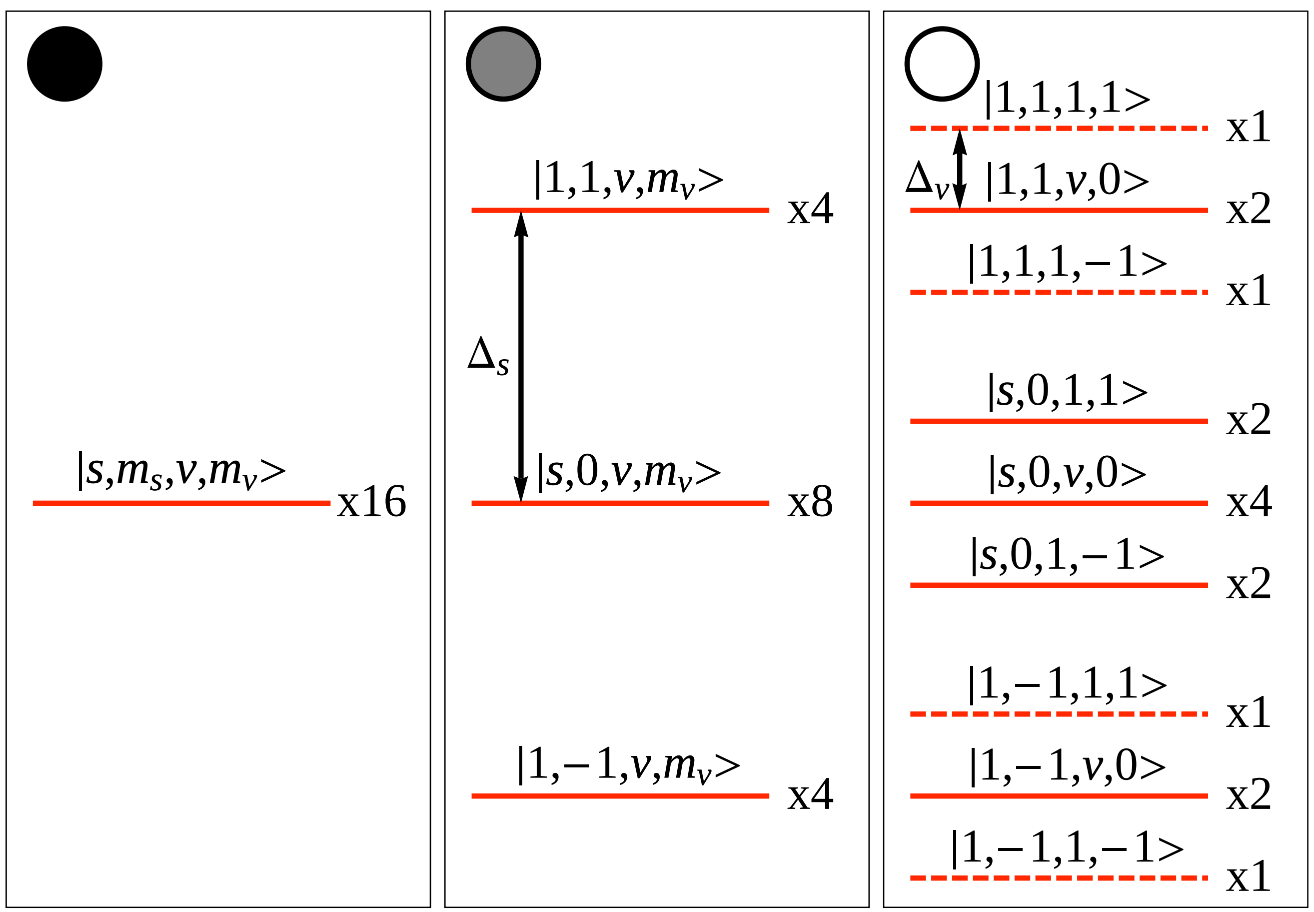
hf-induced **valley** mixing
no pure supertriplets
blockade lifted

Leakage current due to hyperfine interaction

- effect of **hyperfine** interaction on leakage current?
- no disorder and no spin-orbit interaction
- incoherent interdot tunneling







Energy level diagram in the (1,1) charge configuration

$\Delta_s = 0$, $\Delta_v = 0$: hf-induced spin and valley mixing; no pure supertriplets; **blockade lifted**

$\Delta_s \gg h_{hf}$, $\Delta_v = 0$: hf-induced valley mixing; no pure supertriplets; **blockade lifted**

$\Delta_s \gg h_{hf}$, $\Delta_v \gg h_{hf}$: 4 pure supertriplets (- - - - - - - -); **transport blocked**

Summary

Pályi & Burkard, Phys. Rev. B 80, 201404(R) (2009)
Pályi & Burkard, Phys. Rev. B 82, 155424 (2010)

Acknowledgments:

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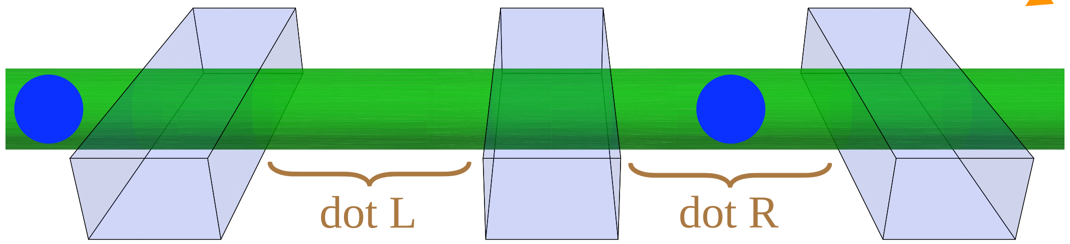

spin-valley blockade in carbon-based double dots

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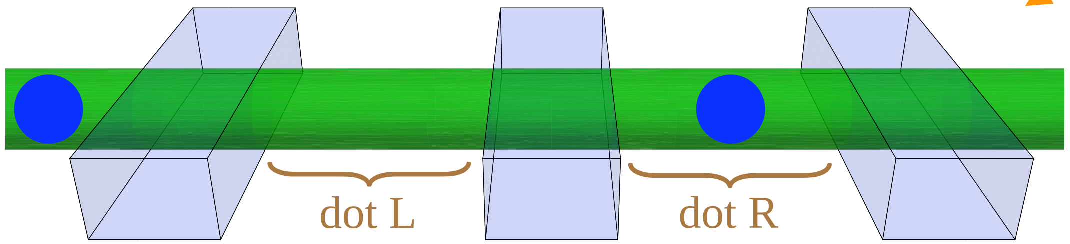

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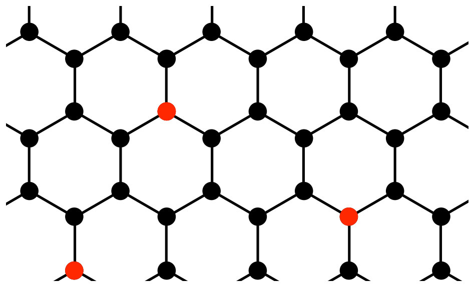

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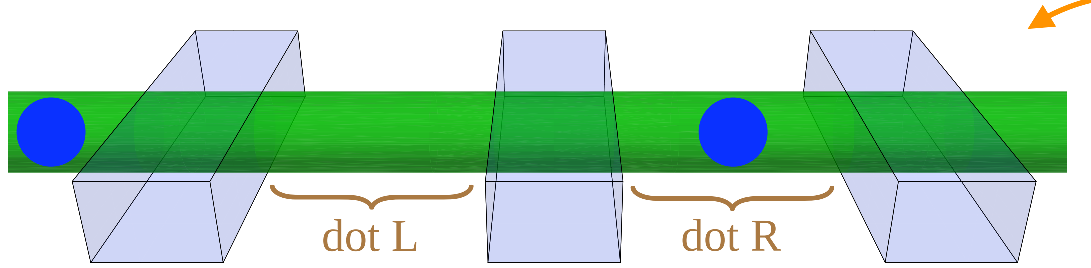

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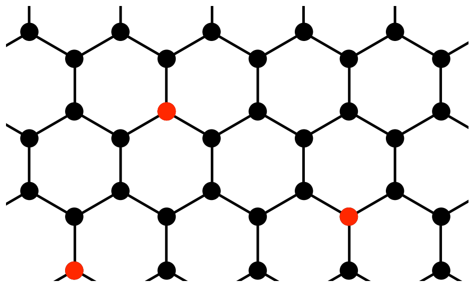
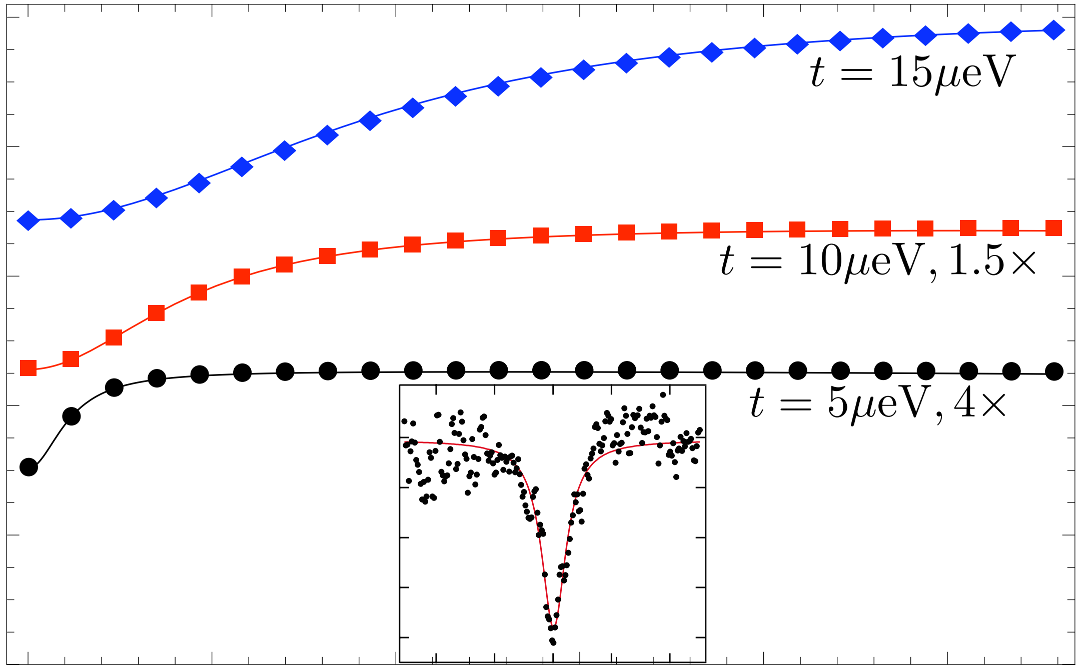


disorder-induced leakage current in nanotubes



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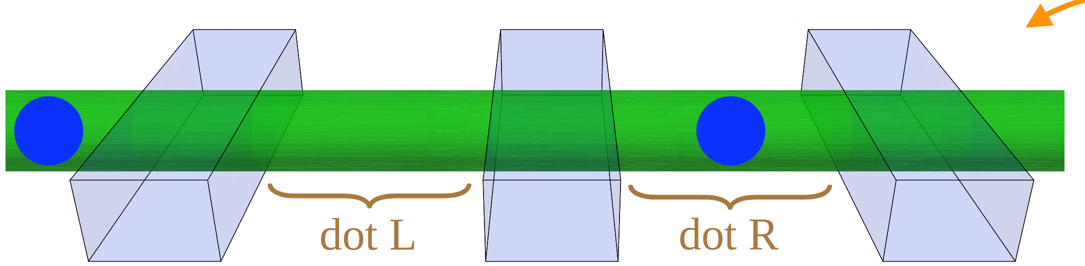

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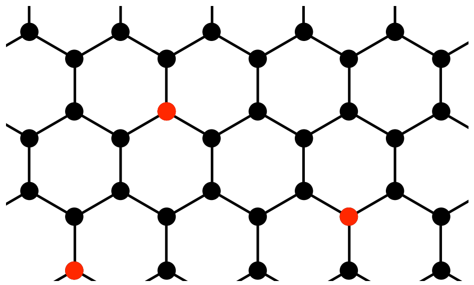

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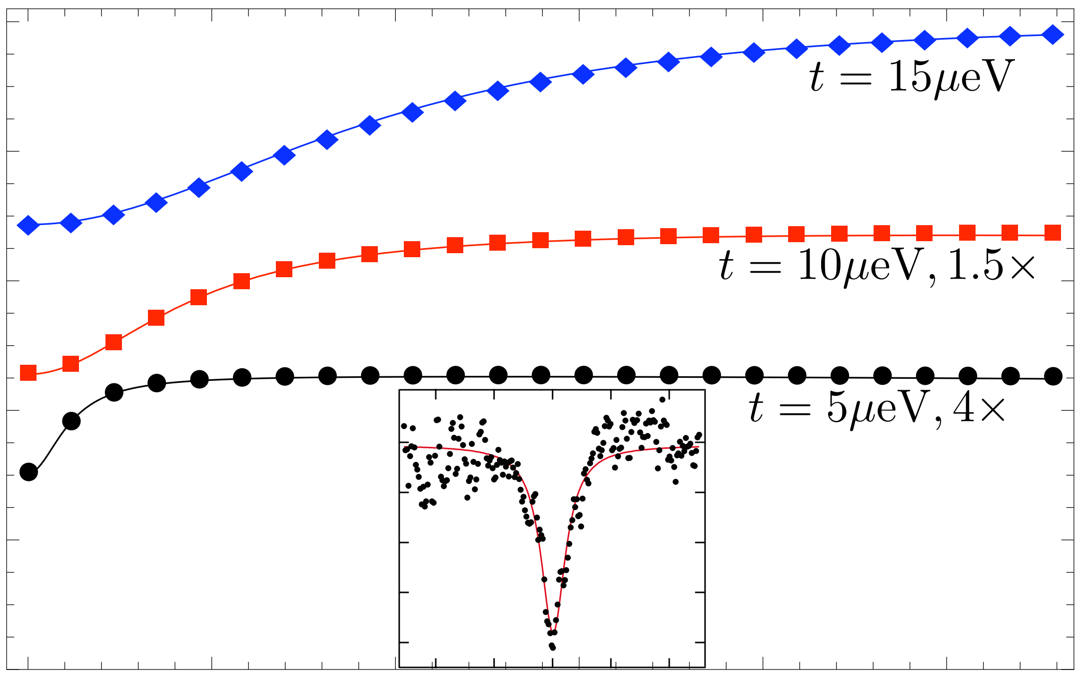
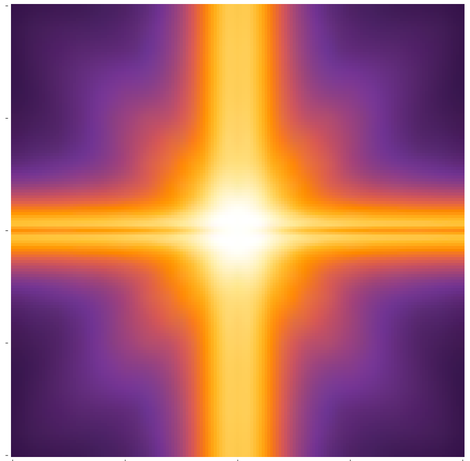




hyperfine-induced leakage current

Acknowledgments: Deutsche Forschungsgemeinschaft DFG, SFB 767, Universität Konstanz nature physics

ARTICLES

PUBLISHED ONLINE: 16 OCTOBER 2011 | DOI: 10.1038/NPHYS2111

Field-induced polarization of Dirac valleys in bismuth

Zengwei Zhu[1], Aurélie Collaudin[1], Benoît Fauqué[1], Woun Kang[2] and Kamran Behnia[1]*

The electronic structure of certain crystal lattices can contain multiple degenerate 'valleys' for their charge carriers to occupy. This valley degree of freedom could be useful in the development of electronic devices. The principal challenge in the development of 'valleytronics' is to lift the valley degeneracy of charge carriers in a controlled way. Here we show that in semi-metallic bismuth the flow of Dirac fermions along the trigonal axis is extremely sensitive to the orientation of in-plane magnetic field. Thus, a rotatable magnetic field can be used as a valley valve to tune the contribution of each valley to the total conductivity. At high temperature and low magnetic field, bismuth's three valleys are interchangeable and the three-fold symmetry of its lattice is maintained. As the temperature is decreased or the magnetic field increased, this symmetry is spontaneously lost. This loss may be an experimental manifestation of the recently proposed valley-nematic Fermi liquid state.

[1]LPEM (UPMC-CNRS), Ecole Supérieure de Physique et de Chimie Industrielles, 75005 Paris, France, [2]Department of Physics, Ewha Womans University, Seoul 120-750, Korea. *e-mail: kamran.behnia@espci.fr.

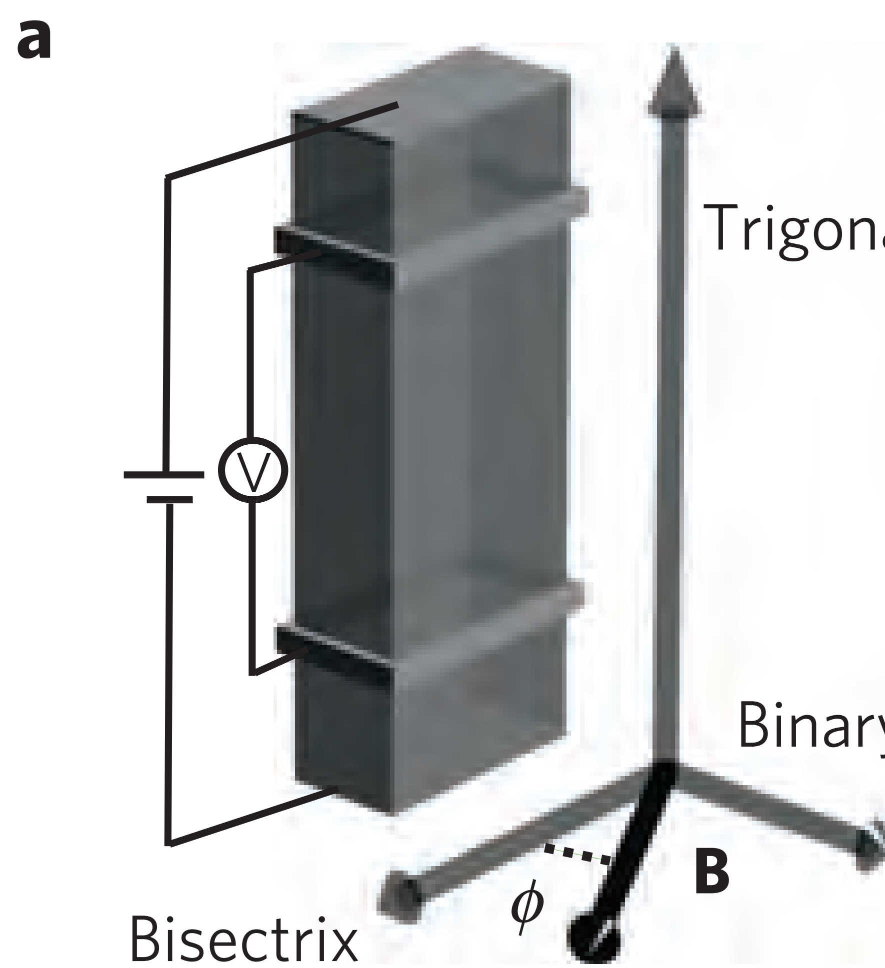
Pályi András

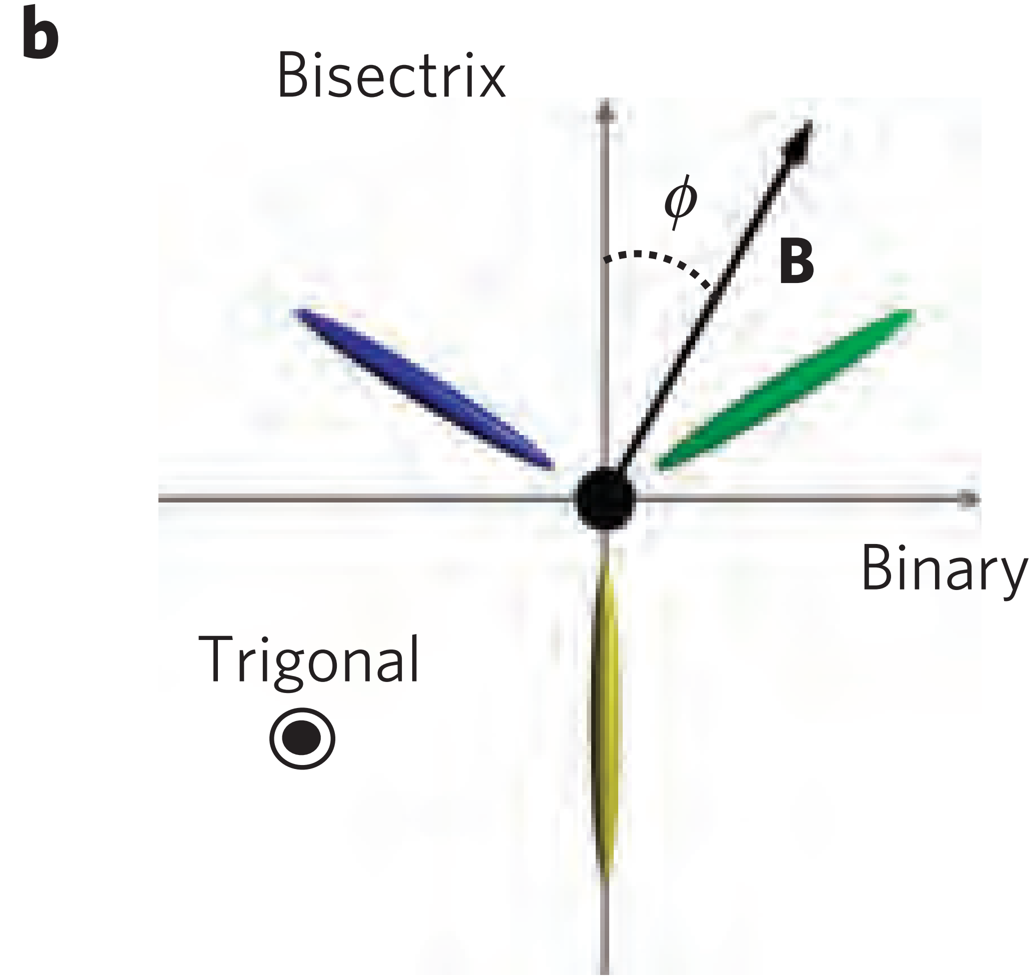
BME Nanoszeminárium JC, 2011.10.27.

Transzverzális mágneses ellenállás mérése

ellenállás mérése
a trigonális irányban

Bi: semi-metal





B-tér: trigonális irányra merőleges, forgatható

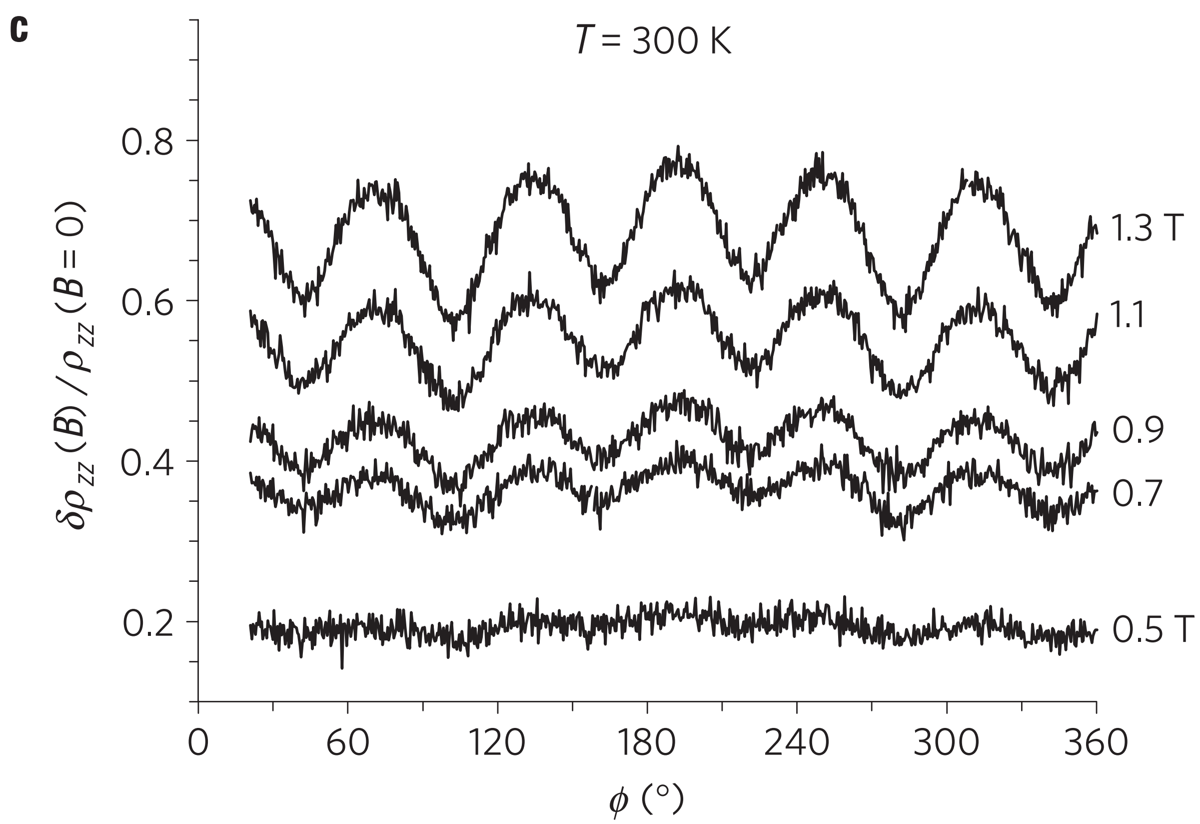
további paraméter: T

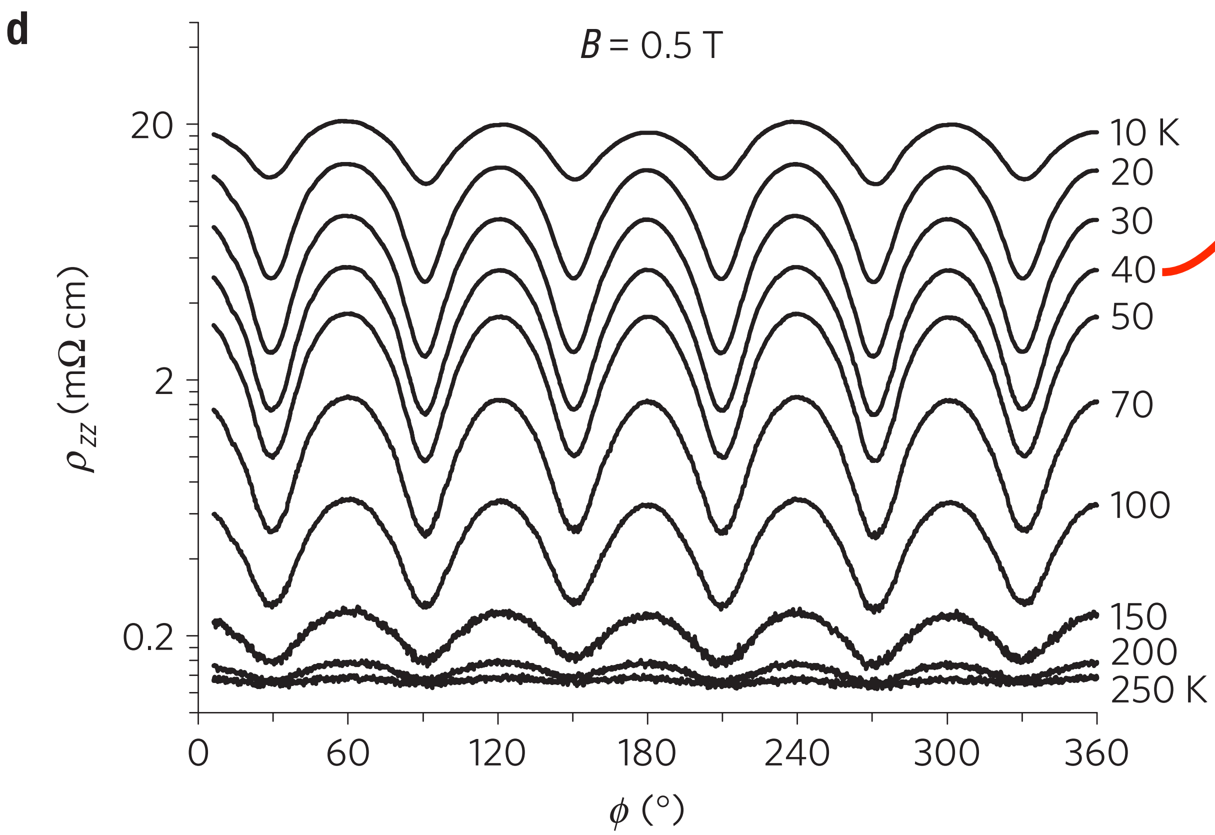
3 völgy a vezetési sávban

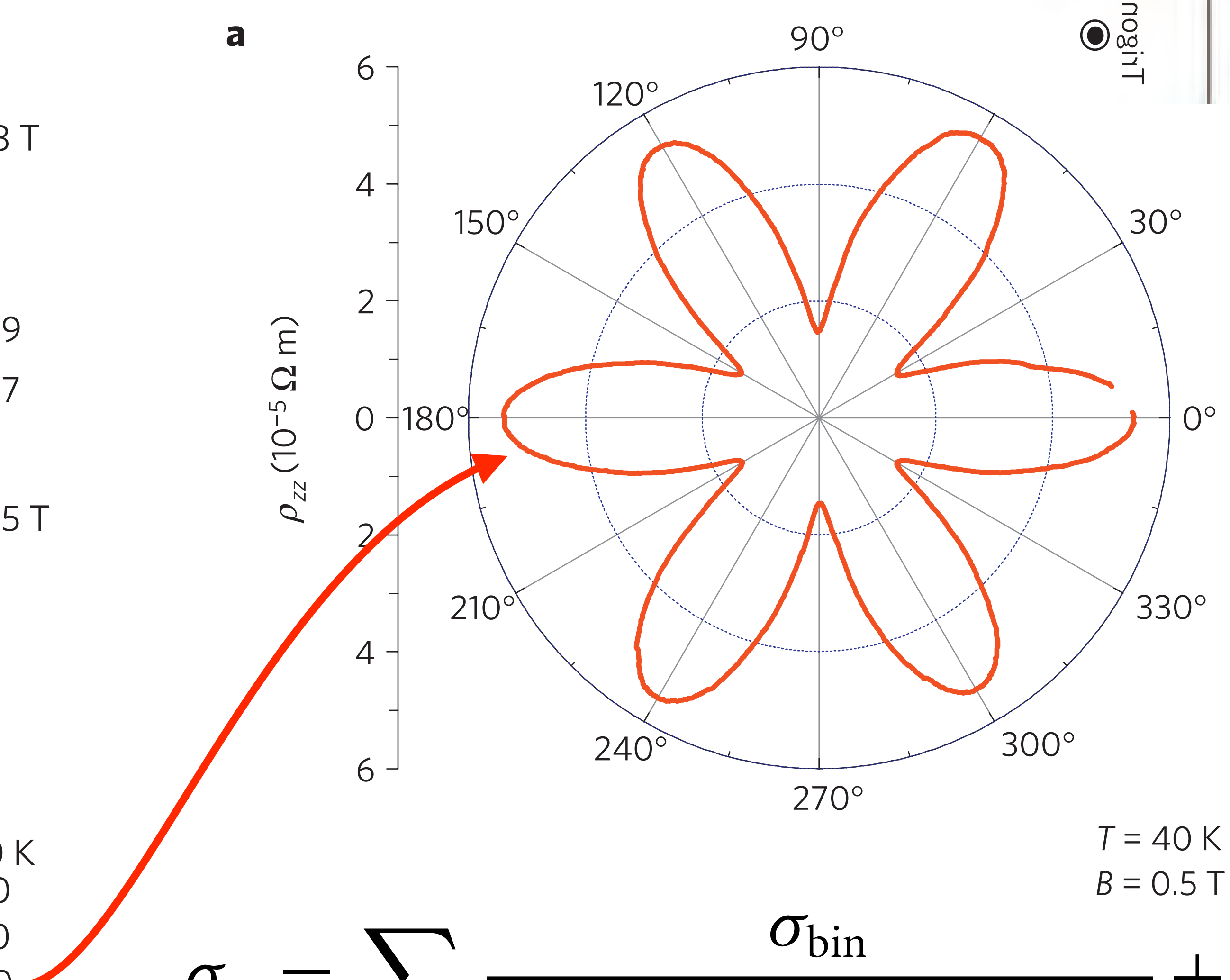
Fermi-felület a vezetési sávban: 3 ellipszoid

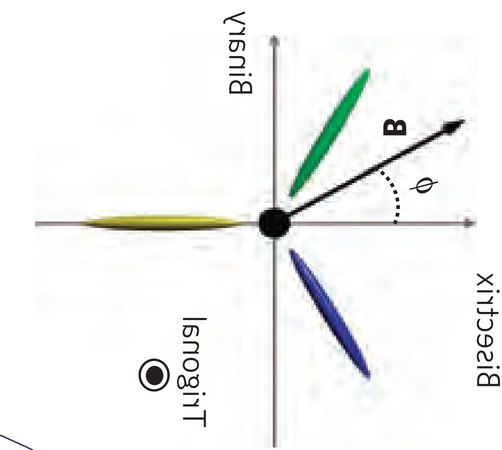
$m_1 = 0.0011 m_e$, $m_2 = 0.26 m_e$ and $m_3 = 0.0044 m_e$

Eredmények







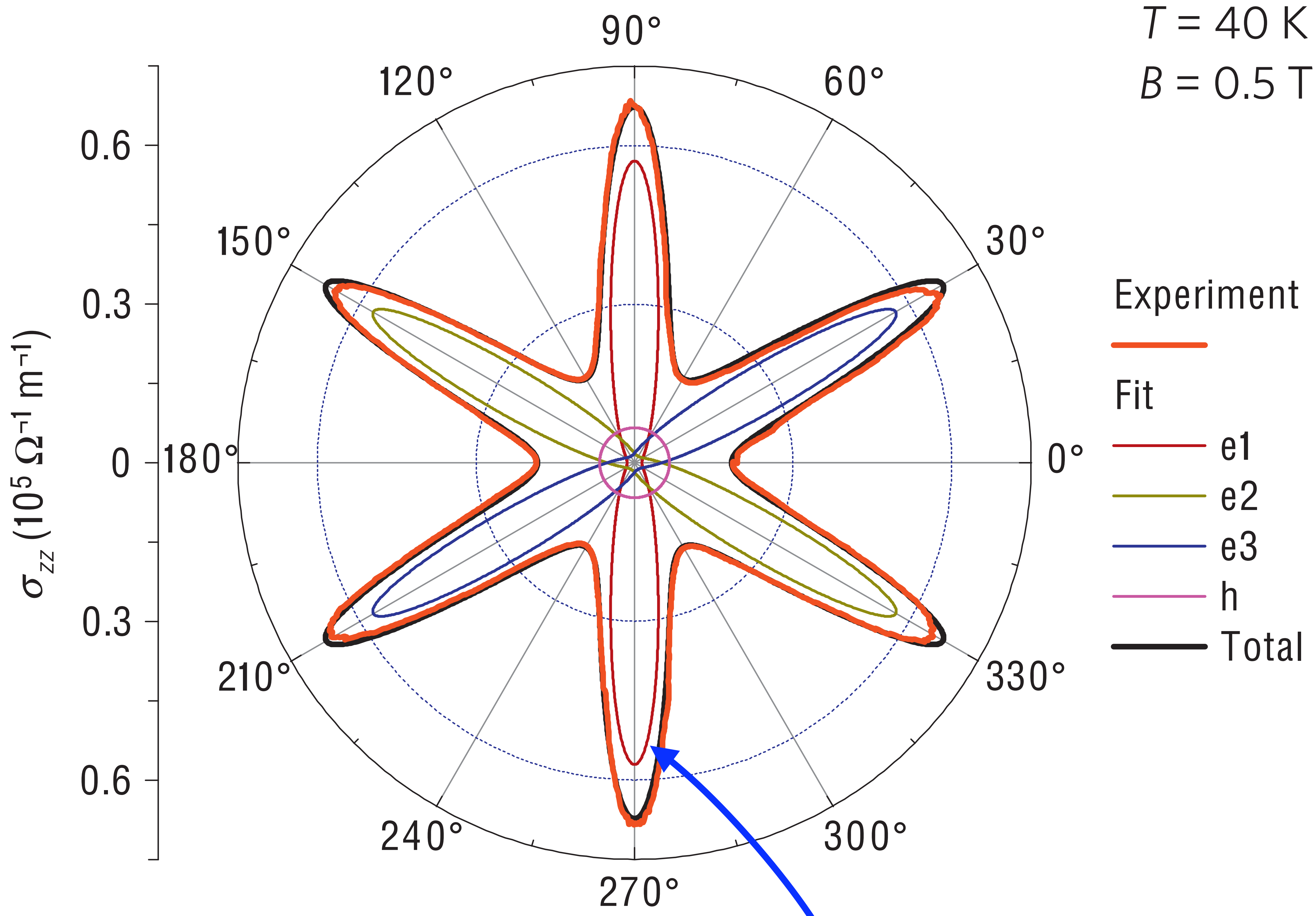


$$\sigma_{zz} = \sum_{i=1-3} \frac{\sigma_{\text{bin}}}{1 + r\cos^2\left(\phi + (i-1)\frac{2\pi}{3}\right)} + \sigma^{\text{h}}$$

illesztési paraméterek:

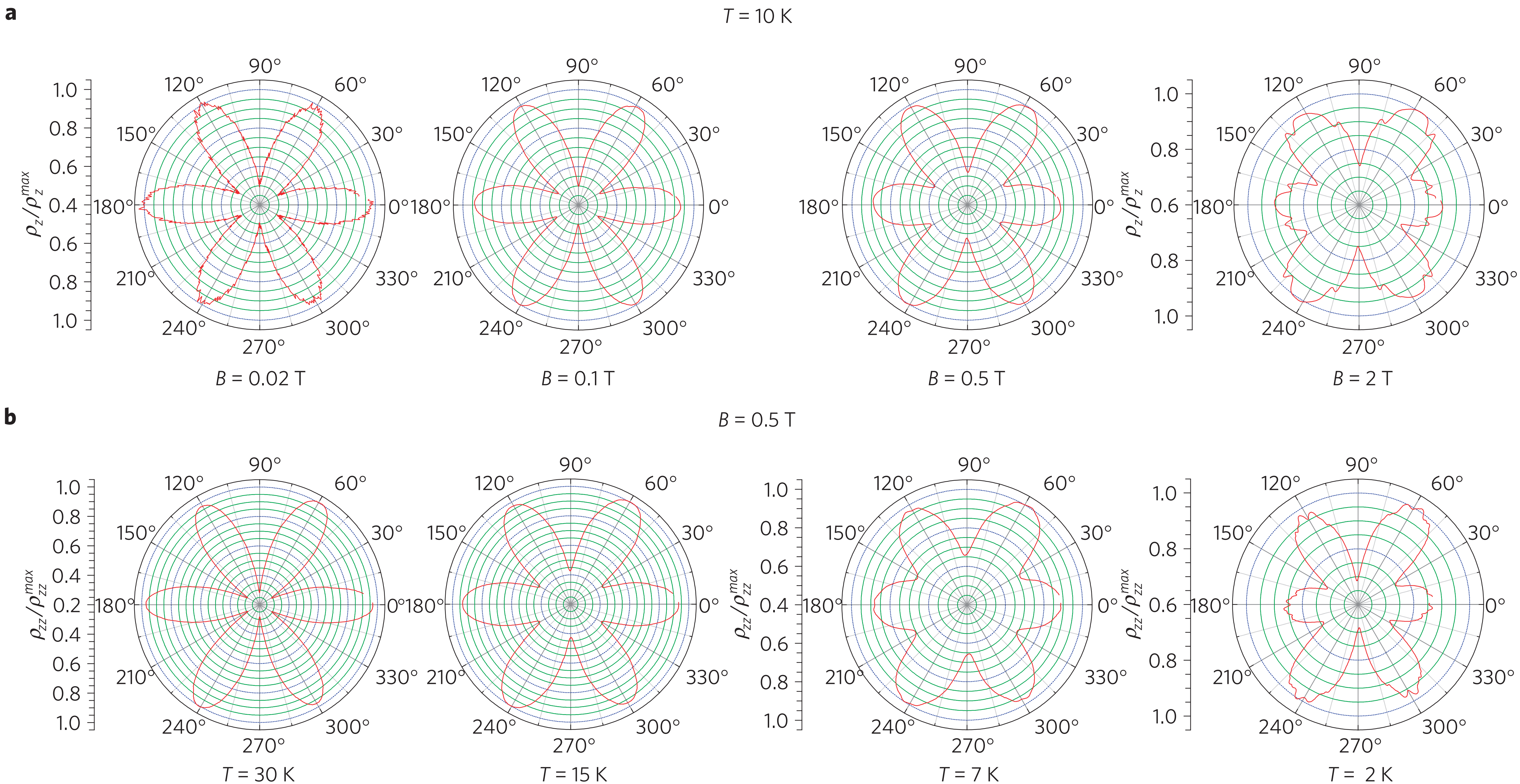
$$\sigma_{\text{bin}},\ r,\ \sigma^{\text{h}}$$

Illesztés: völgyek járuléka a vezetőképességhez



“~80% valley-polarizáció”

Spontán (?) szimmetriasértés kis T-n / nagy B-nél



tipp: **valley-nematic ordering**

#valley > 1,

anizotrop diszperzió,

Coulomb-kcsh

[Abanin et al., PRB 82 035428, (2010)]

DE:

nem látszik kritikus T

nem látszik hiszterézis

adott mintán az átalakulás “fix”