Physics of heterostructure interfaces as a source for quantum information processing

Martin Gmitra

Institute of Physics, P. J. Šafárik University in Košice

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Contents

- **Metallic junctions**

  semiconductor / ferromagnetic interface

  spin-orbit coupling fields in solids

  magnetic control of the fields

  semiconducting wires & Majorana bound state story

- **van der Waals heterostructures**

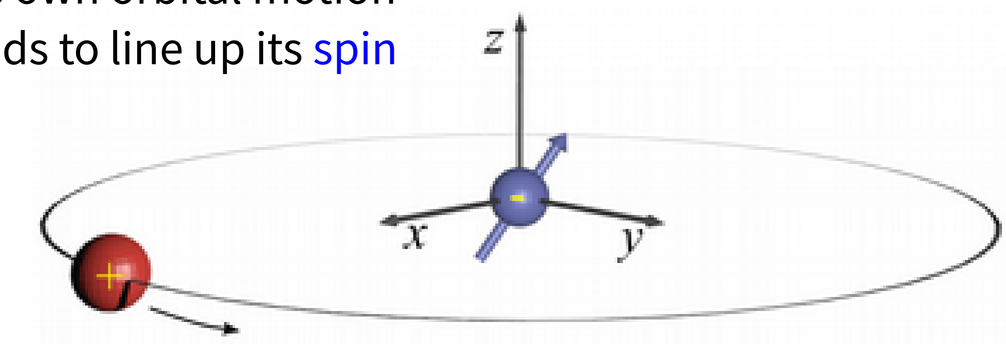
  1D semiconductor / 2D superconductor interface

  proximity induced spin-orbit coupling effects

  proposal Majorana bound states in carbon nanotubes

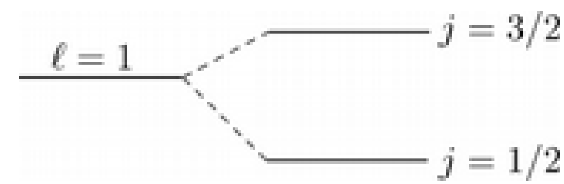
Spin-orbit coupling essentials

electron feels a magnetic field because of its own orbital motion that tends to line up its spin



$$\mathcal{H}_{\mathrm{so}} = \frac{\hbar}{4m^2c^2}(\nabla V(\mathbf{r}) \times \mathbf{p}) \cdot \sigma \quad \longrightarrow \quad \mathcal{H}_{\mathrm{so}}^{\mathrm{atom}} = \xi_\ell \mathbf{L} \cdot \mathbf{S}$$

spin-orbit coupling field



communication between charge and spin => *spintronics*

Concept of spin-orbit coupling field in solids

time reversal + space inversion symmetry

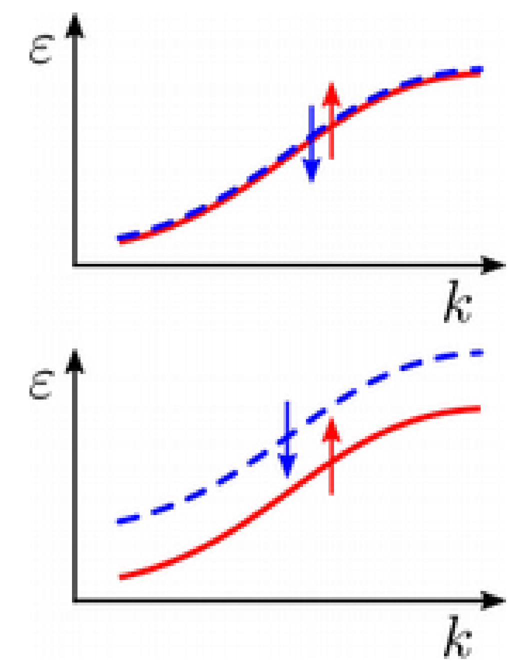
$$\varepsilon_{\mathbf{k},\uparrow} = \varepsilon_{\mathbf{k},\downarrow}$$

time reversal symmetry only

$$\varepsilon_{\mathbf{k},\uparrow} = \varepsilon_{-\mathbf{k},\downarrow}, \quad \varepsilon_{\mathbf{k},\uparrow} \neq \varepsilon_{\mathbf{k},\downarrow}$$

$$\mathbf{\Omega}(-\mathbf{k}) = -\mathbf{\Omega}(\mathbf{k})$$

effective k-dependent spin-splitting magnetic field



$$\mathcal{H}_{\rm so}(\mathbf{k}) = \frac{\hbar}{2}\mathbf{\Omega}(\mathbf{k}) \cdot \sigma$$

$$\mathcal{H}_{\rm D}(\mathbf{k}) = \gamma(\sigma_y k_y - \sigma_x k_x) \longrightarrow \mathbf{\Omega}_{\rm BIA}(\mathbf{k}) = \gamma(-k_x, k_y)$$

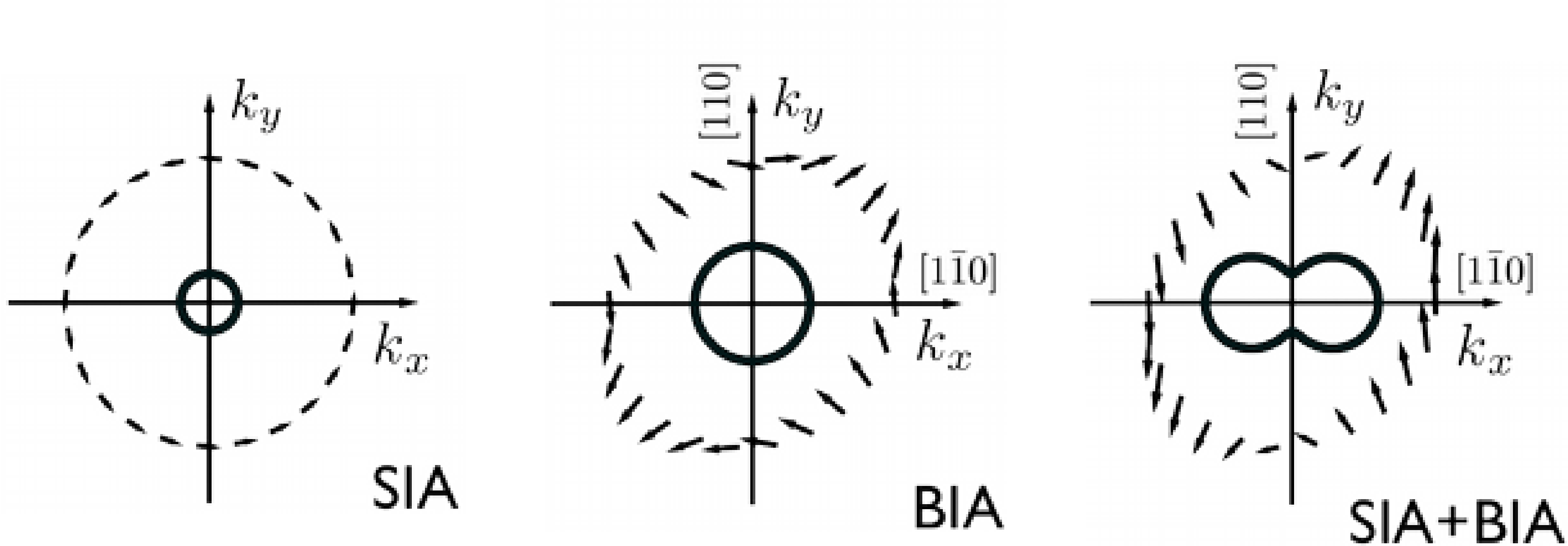
bulk inversion asymmetry (BIA)

$$\mathcal{H}_{\rm BR}(\mathbf{k}) = \alpha(\sigma_y k_x - \sigma_x k_y) \longrightarrow \mathbf{\Omega}_{\rm SIA}(\mathbf{k}) = \alpha(-k_y, k_x)$$

structure inversion asymmetry (SIA)

Combination of the linearized spin-orbit fields

symmetry lowering



$$\mathcal{H}_{\mathrm{D}}(\mathbf{k}) = \gamma(\sigma_y k_y - \sigma_x k_x) \longrightarrow \mathbf{\Omega}_{\mathrm{BIA}}(\mathbf{k}) = \gamma(-k_x, k_y)$$

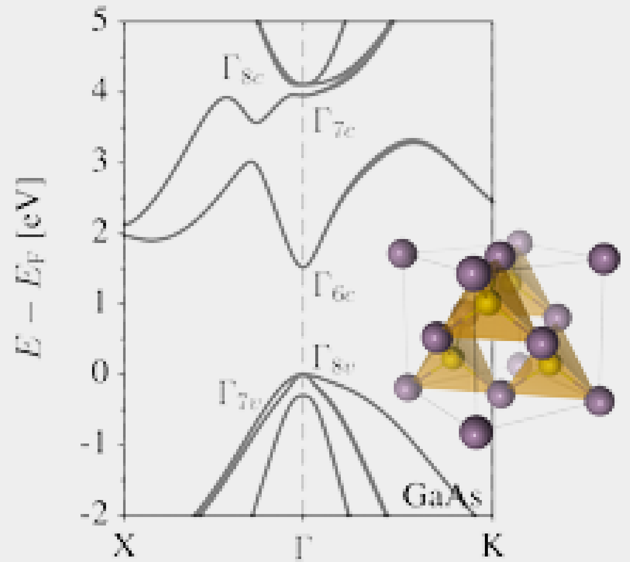
bulk inversion asymmetry (BIA)

$$\mathcal{H}_{\mathrm{BR}}(\mathbf{k}) = \alpha(\sigma_y k_x - \sigma_x k_y) \longrightarrow \mathbf{\Omega}_{\mathrm{SIA}}(\mathbf{k}) = \alpha(-k_y, k_x)$$

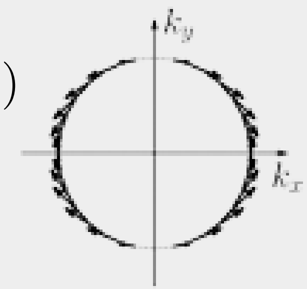
structure inversion asymmetry (SIA)

SOC fields in bulk III-V semiconductors

zinc-blende



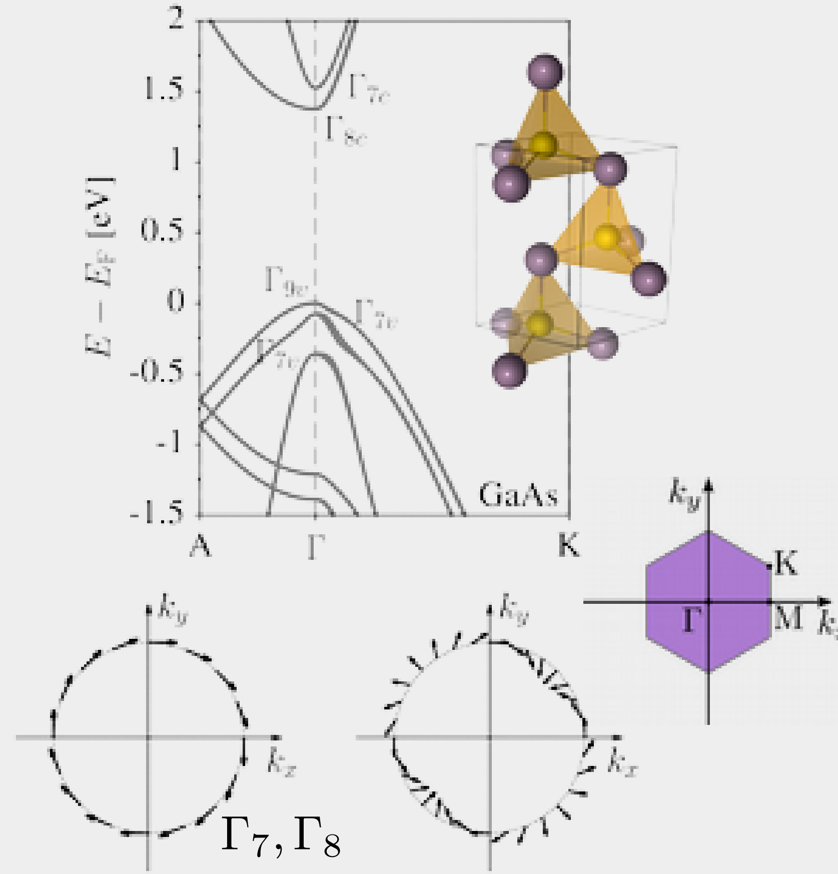
$\mathbf{\Omega}(k_x, k_y, 0)$



$$\mathbf{\Omega}(\mathbf{k})^{\Gamma_6} = \gamma[k_x(k_y^2 - k_z^2), k_y(k_z^2 - k_x^2), k_z(k_x^2 - k_y^2))]$$

G. Dresselhaus, Phys. Rev. **100**, 580 (1955)

wurtzite



$$\mathbf{\Omega}(\mathbf{k})^{\Gamma_{7/8}} = (\alpha + \gamma[bk_z^2 - k_{||}^2](k_y, -k_x, 0))$$

$$\mathbf{\Omega}(\mathbf{k})^{\Gamma_9} = \gamma(k_y(k_y^2 - 3k_x^2), k_x(k_x^2 - 3k_y^2), 0)$$

J. Y. Fu and M. W. Wu, JAP **104**, 093712 (2008)

Spin-orbit coupling parameters for bulk III-V

extracted parameters for conduction band

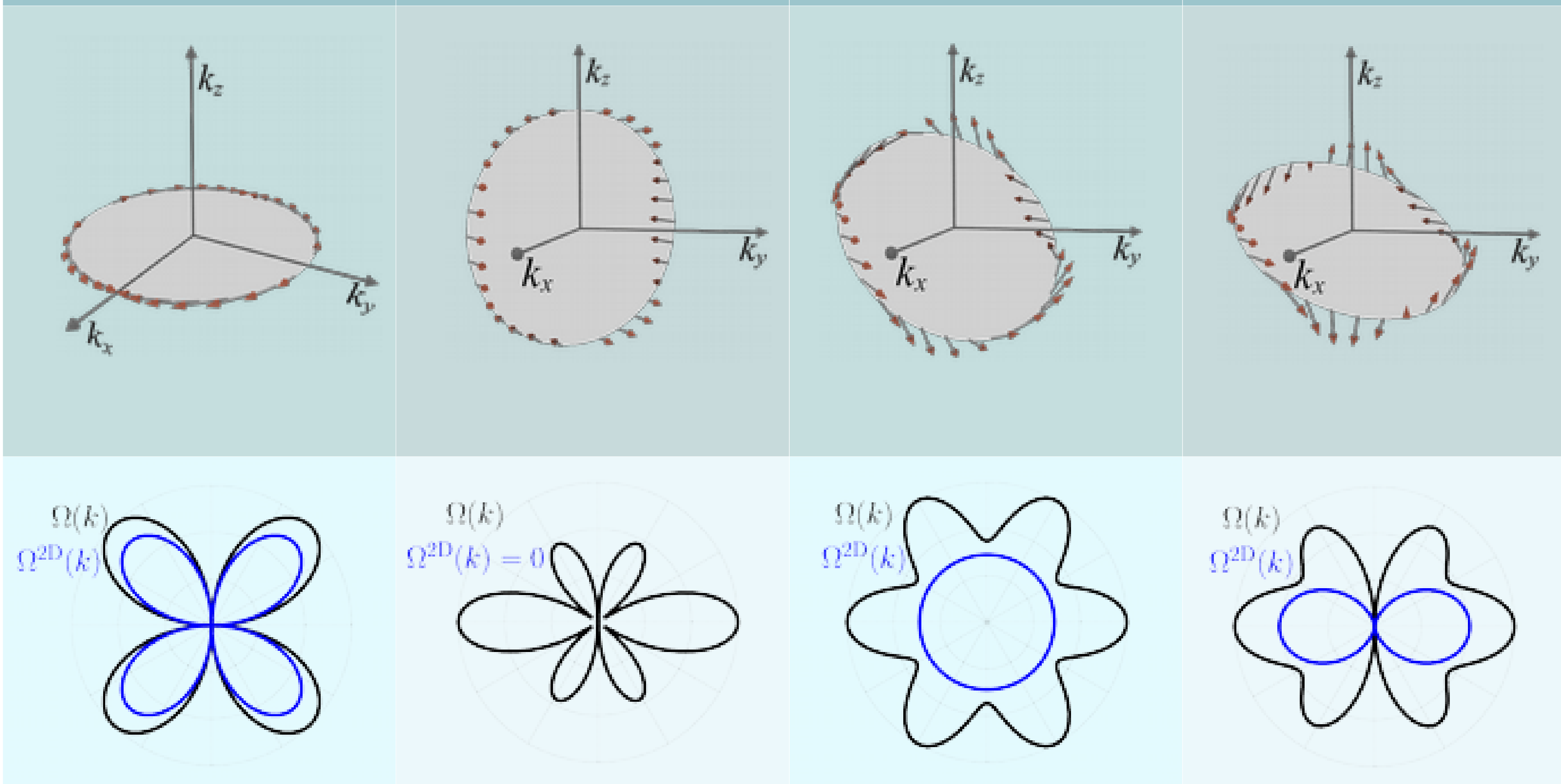
		GaAs	GaSb	InAs	InSb
zinc-blende					
Γ_{6c}	$\boldsymbol{\Omega}(\mathbf{k}) = \gamma[k_x(k_y^2 - k_z^2), k_y(k_z^2 - k_x^2), k_z(k_x^2 - k_y^2)]$				
	γ [eV Å^3]	9.13	105.3	21.4	200
	(GW calculations) [*]	(8.5)	(119)	(47)	(209)
		[a]		[b]	[b]
wurtzite					
Γ_{7c}	$\boldsymbol{\Omega}(\mathbf{k}) = (\alpha + \gamma[bk_z^2 - k_\parallel^2])(k_y, -k_x, 0)$				
	α [eV Å]	0.04	0.078	0.3	0.76
	γ [eV Å^3]	6.51	52.1	134.2	904
	b	0.54	1.29	-1.25	-0.93
Γ_{8c}	$\boldsymbol{\Omega}(\mathbf{k}) = (\alpha + \gamma[bk_z^2 - k_\parallel^2])(k_y, -k_x, 0)$				
	α [eV Å]	0.1	0.49	0.04	0.34
	γ [eV Å^3]	1.97	18.7	2.77	10.9
	b	0.03	-0.04	-0.06	-0.07

[a] M.I. McMahon, R.J. Nelmes, Phys. Rev. Lett. **95**, 215505 (2005)
[b] D. Kriegner *et al.*, Nano Lett. **11**, 1438 (2011)
[*] A.N. Chantis *et al.*, Phys. Rev. Lett. **96**, 086406 (2006)
M. Gmitra, J. Fabian, Phys. Rev. B 94, 165202 (2016)

DFT calculations
WIEN2k + mBJ

Spin-orbit fields in zinc-blende

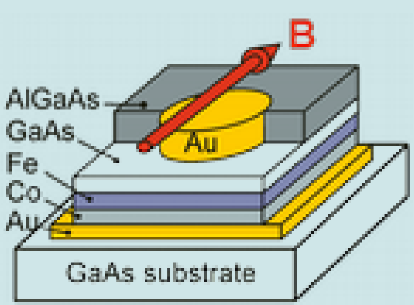
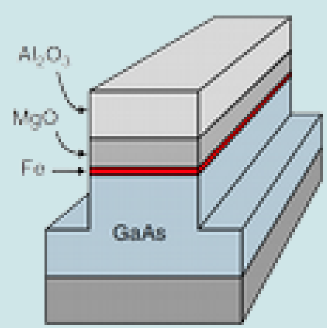
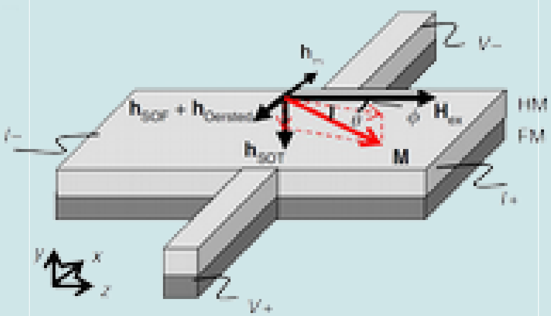
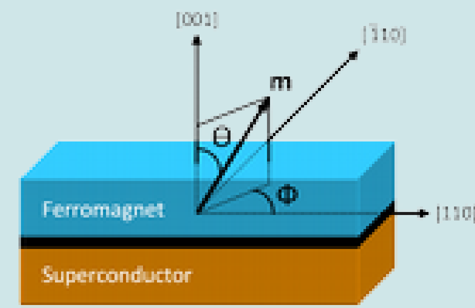
growth directions of quantum wells



$\langle 001 \rangle$	$\langle 110 \rangle$	$\langle 111 \rangle$	$\langle 112 \rangle$
$\mathbf{\Omega}(\mathbf{k}_{\parallel}) \propto (-k_x, k_y, 0)$	$\mathbf{\Omega}(\mathbf{k}_{\parallel}) \propto (0, 0, k_x)$	$\mathbf{\Omega}(\mathbf{k}_{\parallel}) \propto (k_y, -k_x, 0)$	$\mathbf{\Omega}(\mathbf{k}_{\parallel}) \propto (\sqrt{6}k_y, -6k_x, -k_x)$
$k_x \parallel [100]; k_y \parallel [010]$	$k_x \parallel [\bar{1}10]; k_y \parallel [001]$	$k_x \parallel [11\bar{2}]; k_y \parallel [\bar{1}10]$	$k_x \parallel [\bar{1}10]; k_y \parallel [\bar{1}\bar{1}1]$

Manifestation of spin-orbit fields

magnetoresistive effects

<table>
<tr><th>GMR/TMR
(giant magnetoresistance)</th><th>GMR/TMR
(giant magnetoresistance)</th><th>Hall effect</th><th>SPAR
(spin polarized Andreev reflection)</th></tr>
<tr><td>TAMR
(tunneling anisotropic magnetoresistance)</td><td>CAMR
(crystalline anisotropic magnetoresistance)</td><td>PHE
(planar Hall effect)</td><td>MAAR
(magnetoanisotropic Andreev reflection)</td></tr>
<tr><td>
</td><td>
</td><td>
</td><td>
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<tr><td>J. Moser *et al.*, PRL **99**, 056601 (2007)</td><td>T. Hupfauer *et al.*, Nat. Comm. **6**, 7374 (2015)</td><td>X. Fan *et al.*, Nat. Comm. **4**, 1799 (2013)</td><td>P. Högl *et al.*, PRL **115**, 116601 (2015)</td></tr>
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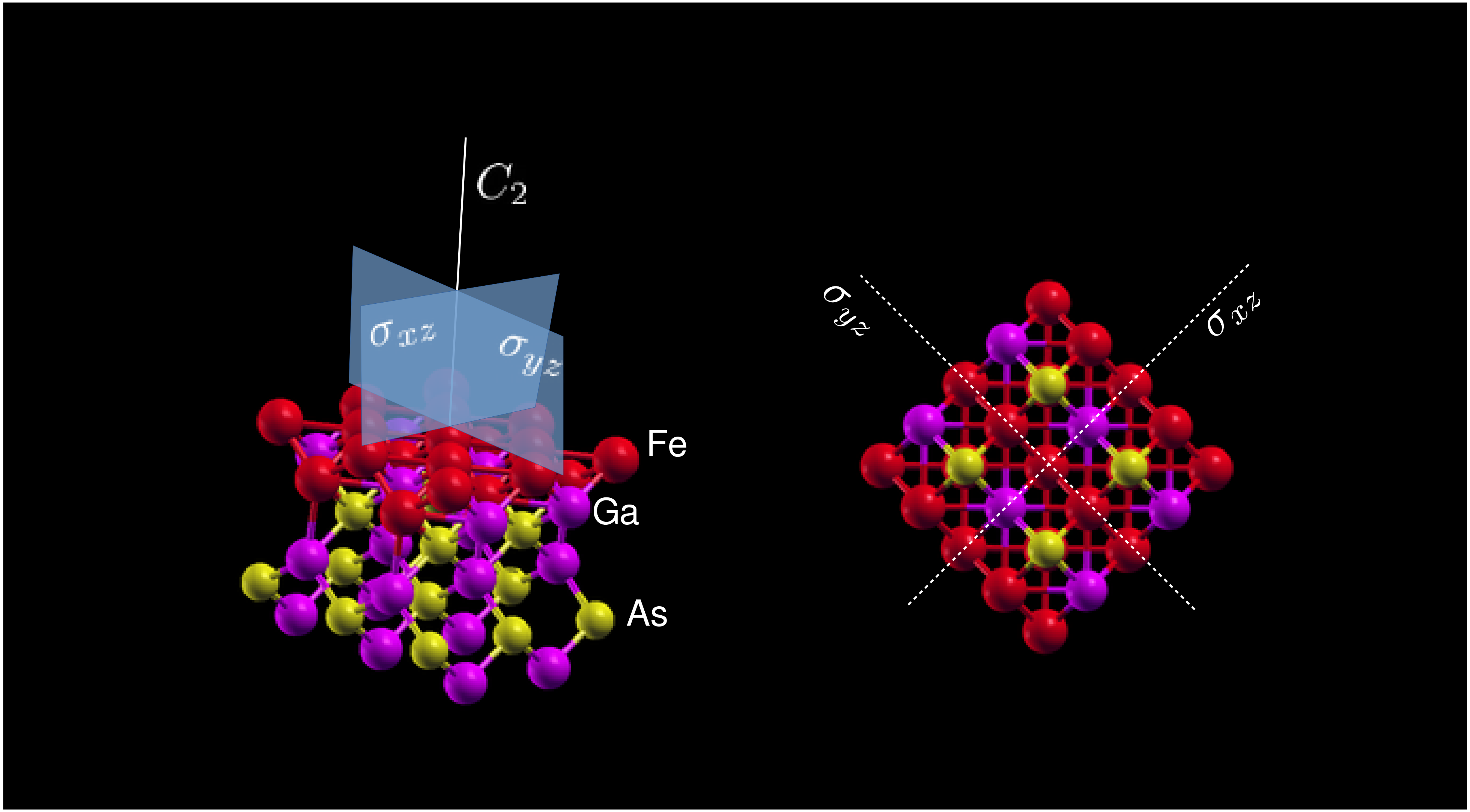
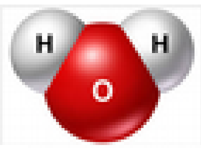
Symmetry of Fe/GaAs (001) interface

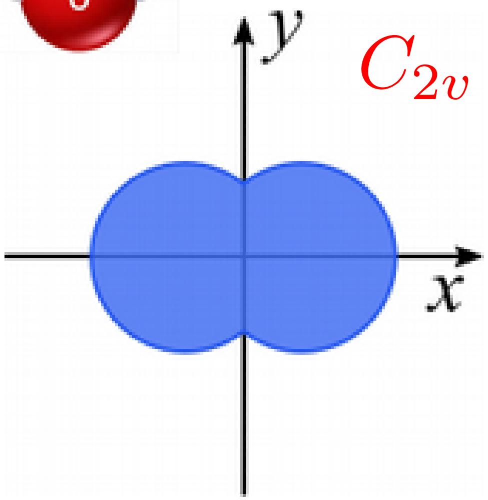
advances of epitaxial growth



Exploring symmetry

a path to the effective Hamiltonian





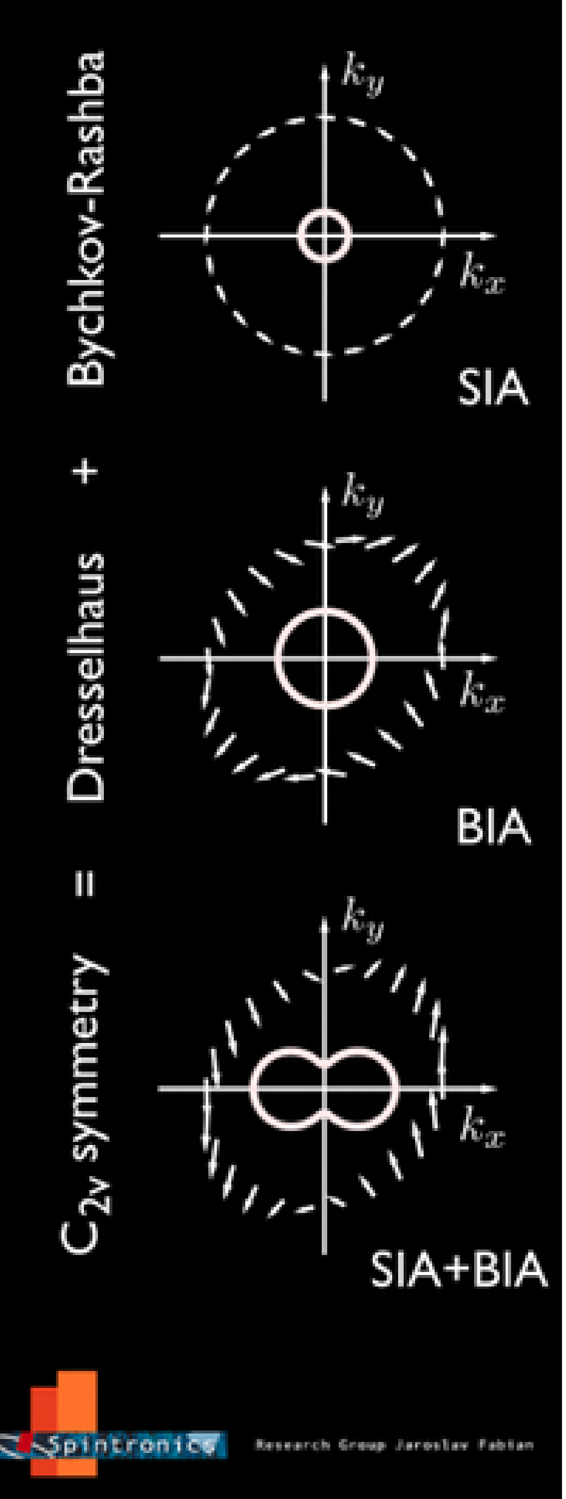
C_{2v} : $E, C_2, \sigma_{xz}, \sigma_{yz}$

$$H_{\text{plane}} \sim \left(\alpha x^2 + \beta y^2\right) \times z$$

$$k_x \sim x, \quad k_y \sim y, \qquad \sigma_x \sim yz, \quad \sigma_y \sim -xz$$

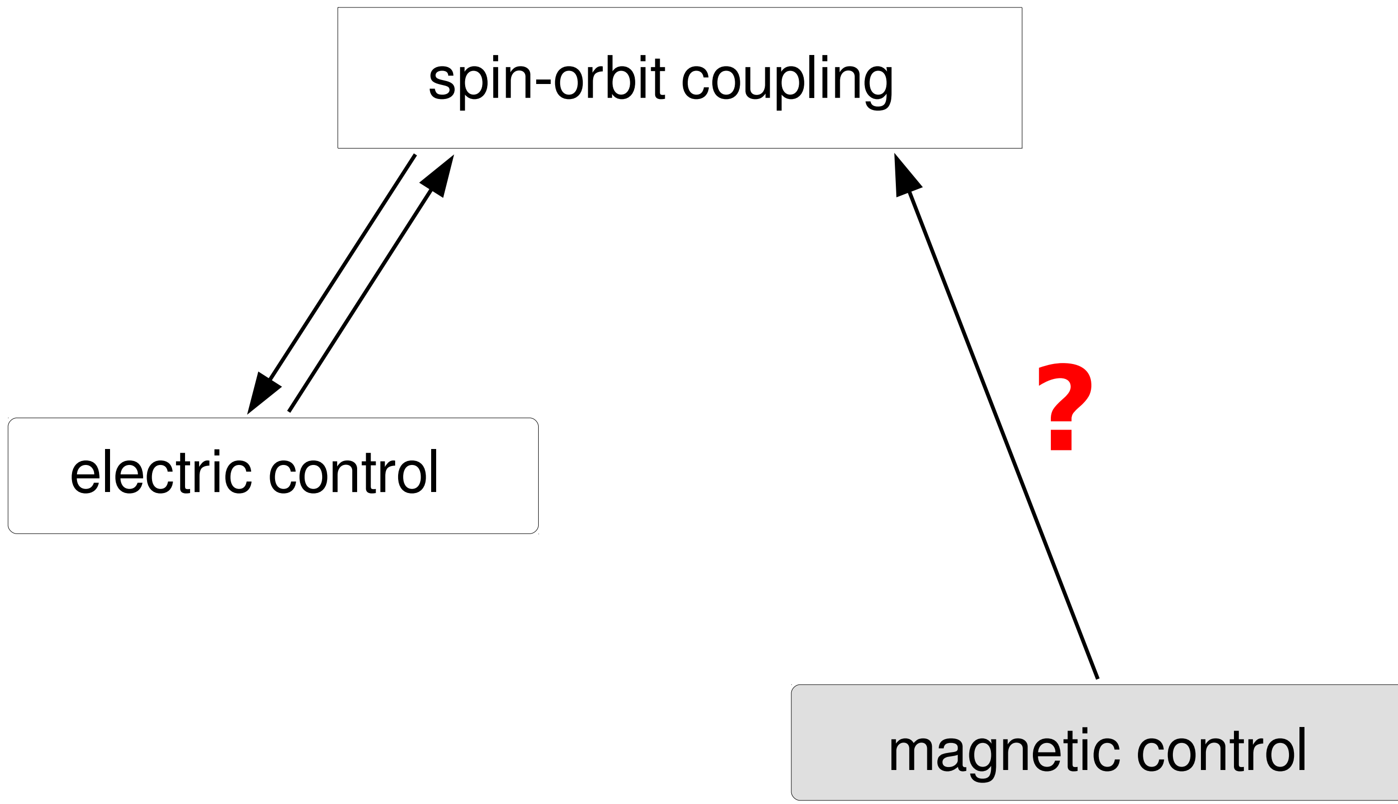
$$H_{so} \sim \alpha\, k_x \sigma_y + \beta\, k_y \sigma_x$$

generic linear in *k* spin-orbit coupling of C_{2v}



Fe/GaAs (001) interface

change of the paradigm



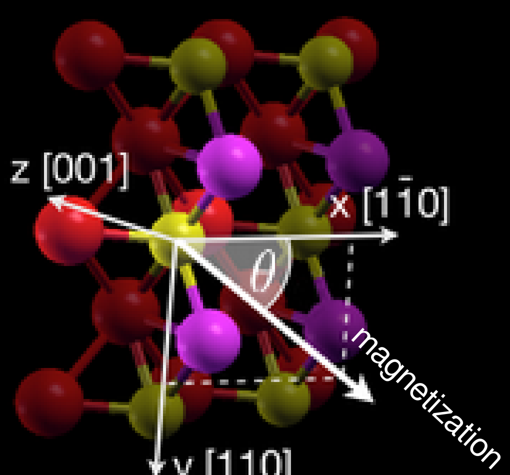
Parameters depend on magnetization

most general Hamiltonian for C_{2v}

$$\mathcal{H}_{\rm so} = \mu_n(k_x, k_y, \theta) k_x \sigma_y + \eta_n(k_x, k_y, \theta) k_y \sigma_x$$

$$\mu_n(k_x, k_y, \theta) = \mu_n^{(0)}(\theta) + \mu_n^{(1)}(\theta) k_x^2 + \mu_n^{(2)}(\theta) k_y^2 + \dots$$

$$\eta_n(k_x, k_y, \theta) = \eta_n^{(0)}(\theta) + \eta_n^{(1)}(\theta) k_x^2 + \eta_n^{(2)}(\theta) k_y^2 + \dots$$

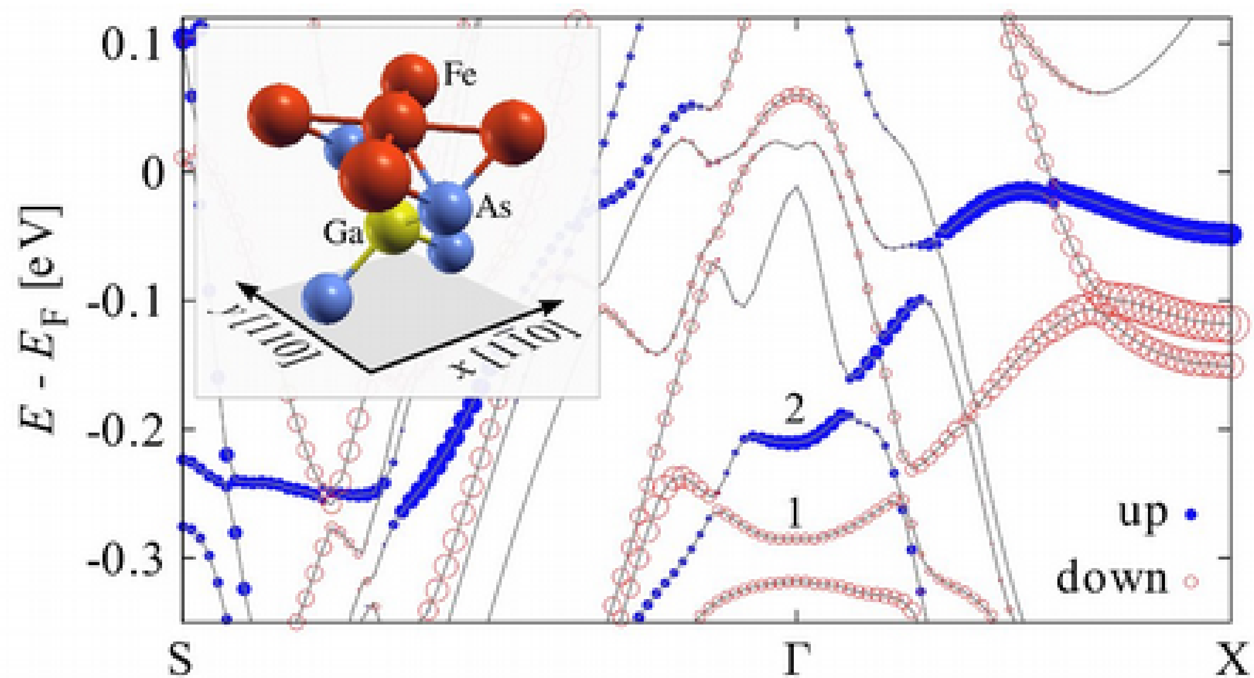


$$\Omega(k_x, k_y, \theta) = \begin{pmatrix} \eta_n(k_x, k_y, \theta) \\ \mu_n(k_x, k_y, \theta) \\ 0 \end{pmatrix}$$

Spin-orbit field obtained from bands

$$\Omega_{nx}(k_x, k_y, \theta) = \sigma \left[\frac{E_n(\mathbf{k}, \theta) - E_n(-\mathbf{k}, \theta) + E_n(-k_x, k_y, \theta) - E_n(k_x, -k_y, \theta)}{4\cos\theta} \right]$$

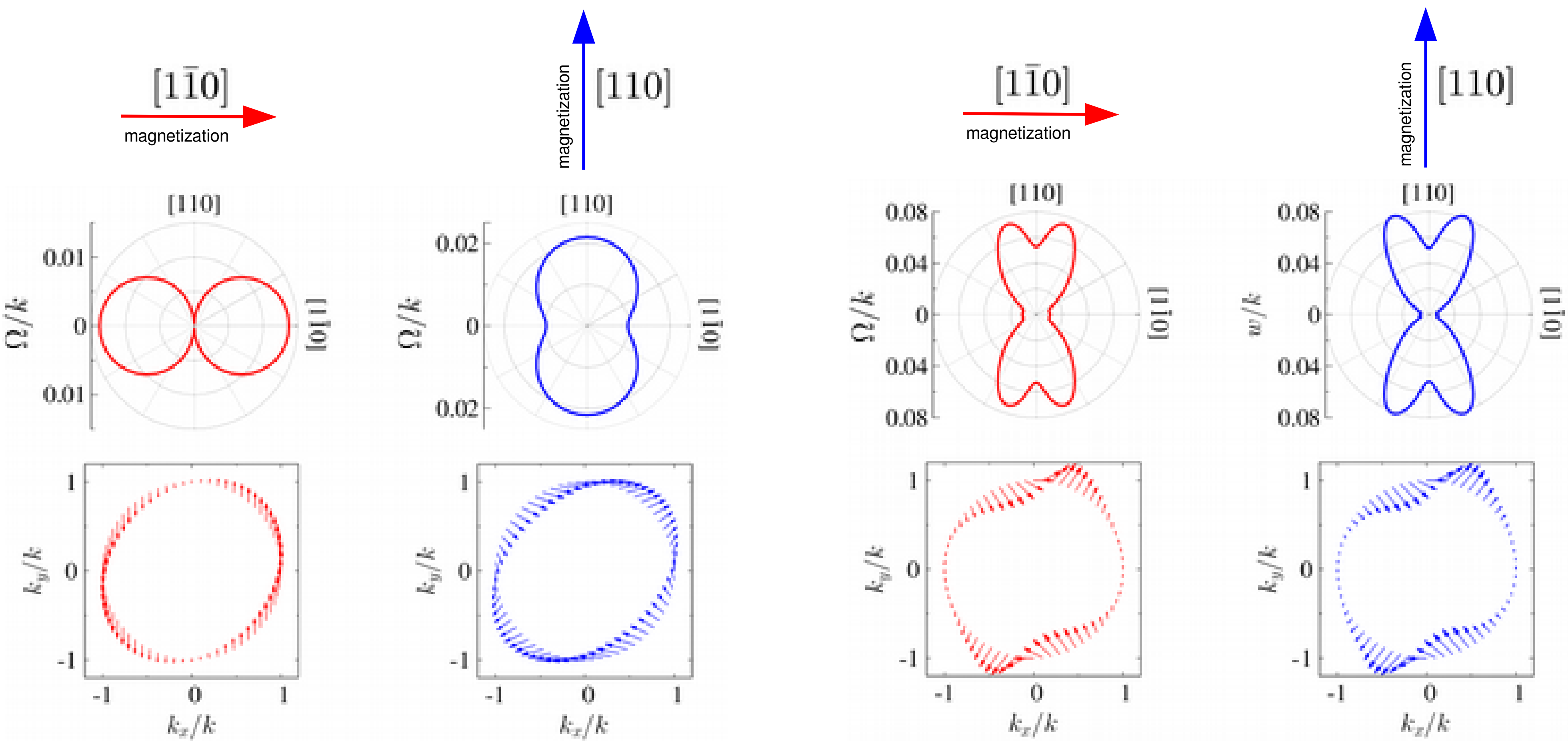
$$\Omega_{ny}(k_x, k_y, \theta) = \sigma \left[\frac{E_n(\mathbf{k}, \theta) - E_n(-\mathbf{k}, \theta) - E_n(-k_x, k_y, \theta) + E_n(k_x, -k_y, \theta)}{4\sin\theta} \right]$$



M. Gmitra *et al.*, PRL **111**, 036603 (2013)

Magnetic control of spin-orbit symmetry

spin-orbit field for general k-point



$k = 1\%BZ$

$k = 12.5\%BZ$

M. Gmitra *et al.*, PRL **111**, 036603 (2013)

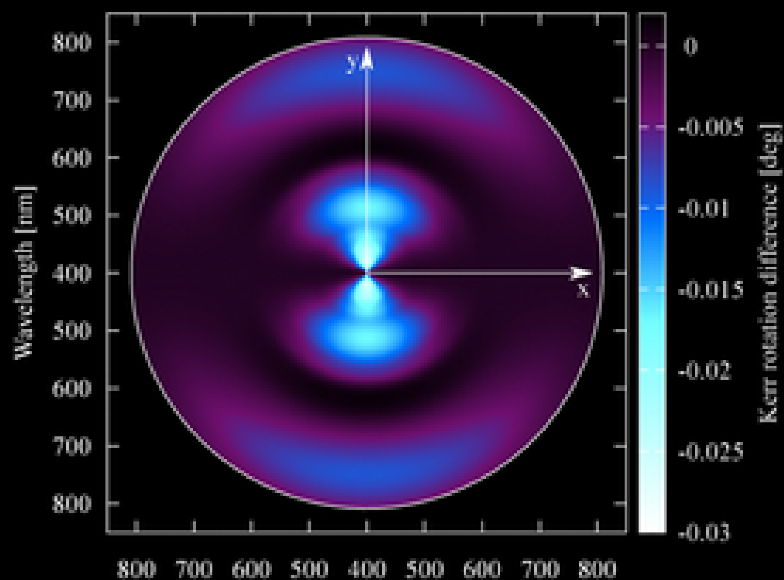
Symmetry of Fe/GaAs (001) interface

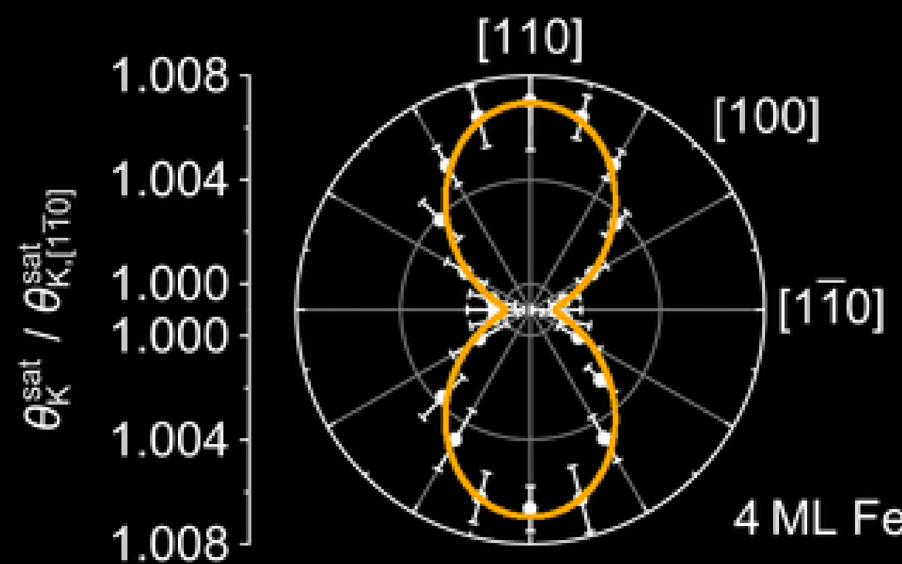
addressing the spin-orbit field by optics

anisotropic polar MOKE – Kerr rotation

$$C_{2v}: \quad E, C_2, \sigma_{xz}, \sigma_{yz}$$

$$\frac{\theta_K^{\mathrm{sat}}(\phi)}{\theta_{K,[1\bar{1}0]}^{\mathrm{sat}}} - 1 \sim \langle a_2^{(2)}(\boldsymbol{k}) w_x(\boldsymbol{k}) w_y(\boldsymbol{k}) \rangle [1 - \cos(2\phi)]$$

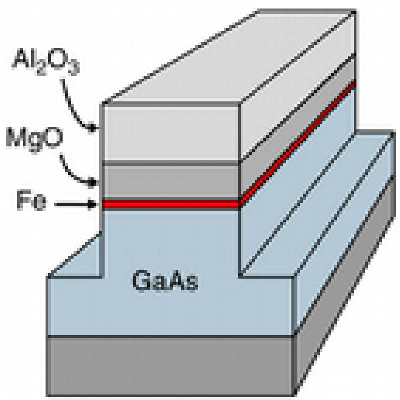


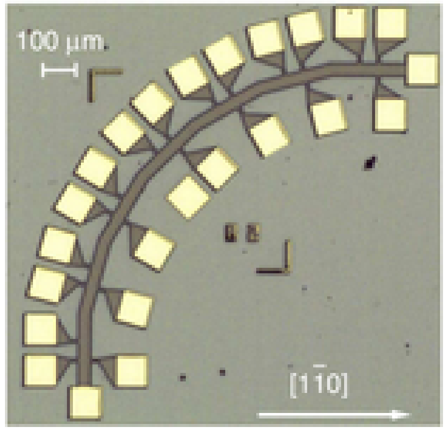


S. Putz *et al.*, Phys. Rev. B **90**, 045315 (2014)

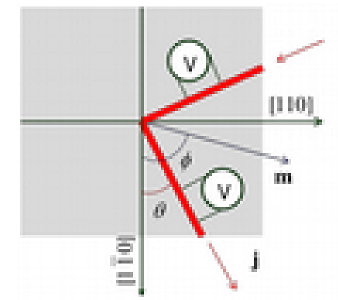
M. Buchner *et al.*, Phys. Rev. Lett. **117**, 157202 (2016)

Crystalline anisotropic magnetoresistance

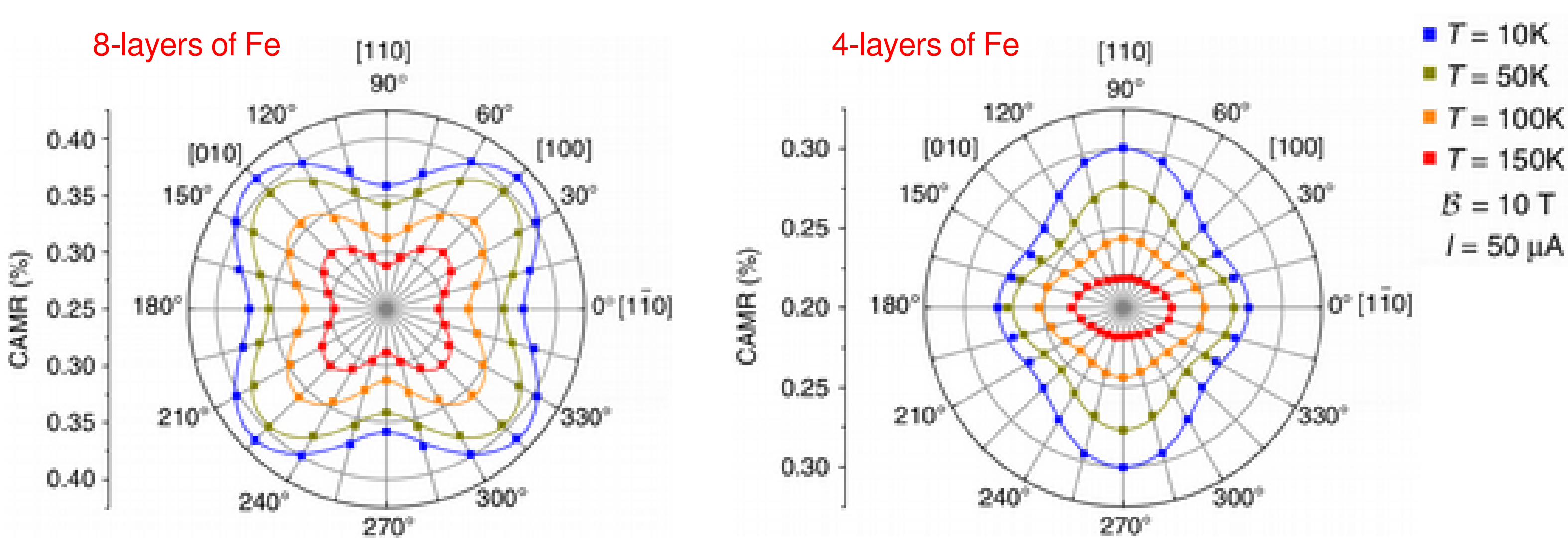




$$\mathrm{CAMR}(\theta) = \frac{U_{\max}(\theta) - U_{\min}(\theta)}{U_{\max}(\theta) + U_{\min}(\theta)}$$



$$\mathrm{CAMR}(\theta) \approx \frac{B + C + (C - B)\cos(4\theta) - 4F\cos(2\theta)}{4A}$$



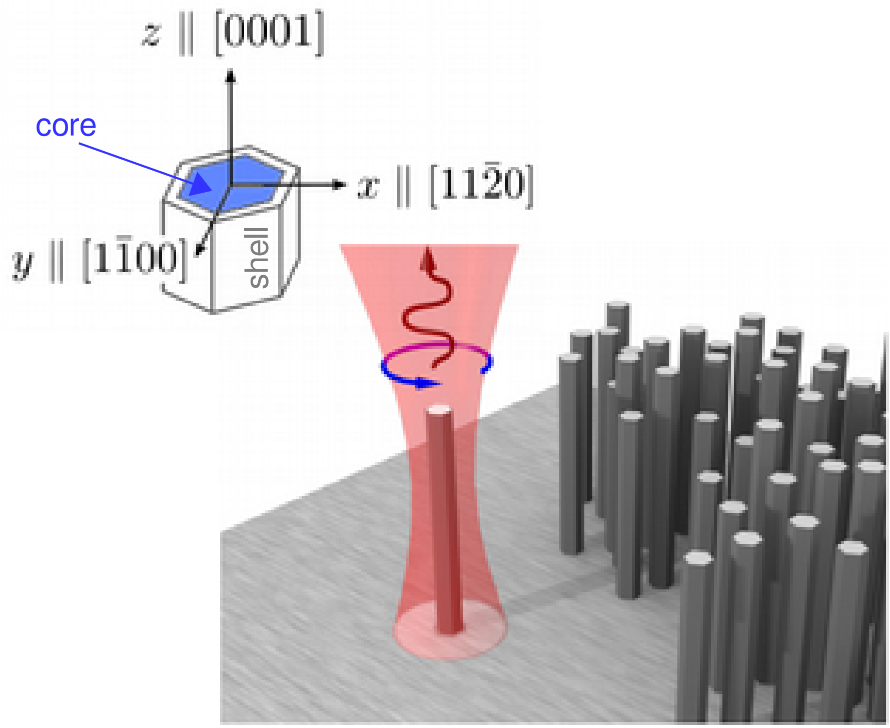
reduction of symmetry

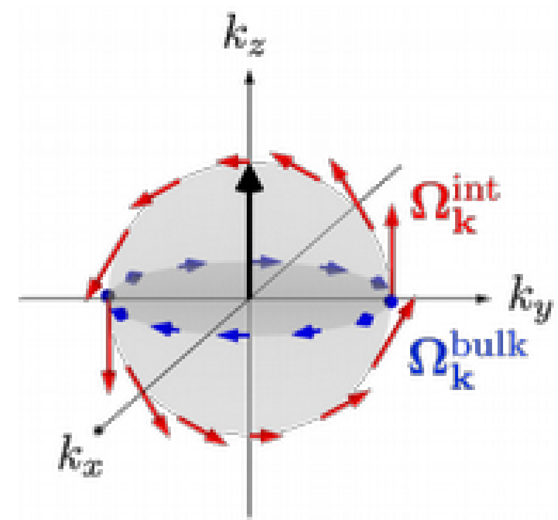
reduction of Fe thickness

T. Hupfauer *et al.*, Nat. Comm. **6**, 7374 (2015)

Spin-orbit field in core/shell wurtzite nanowires

role of GaAs/AlGaAs interface





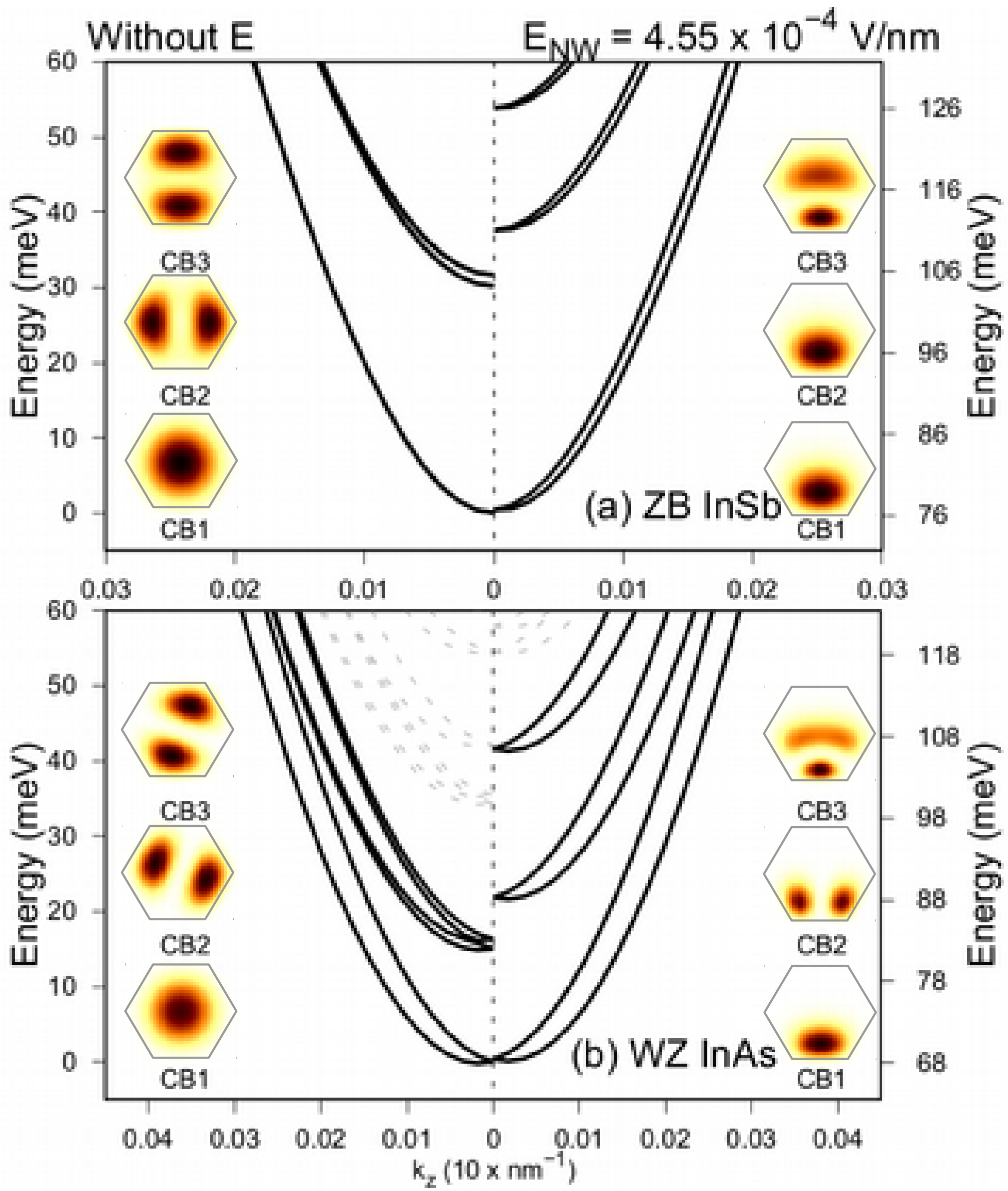
$$\mathbf{\Omega_k} = \mathbf{\Omega_k^{bulk}} + \mathbf{\Omega_k^{int}} = \beta \begin{pmatrix} k_y \\ -k_x \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ -\alpha_\perp k_z \\ \alpha_{||} k_y \end{pmatrix}$$

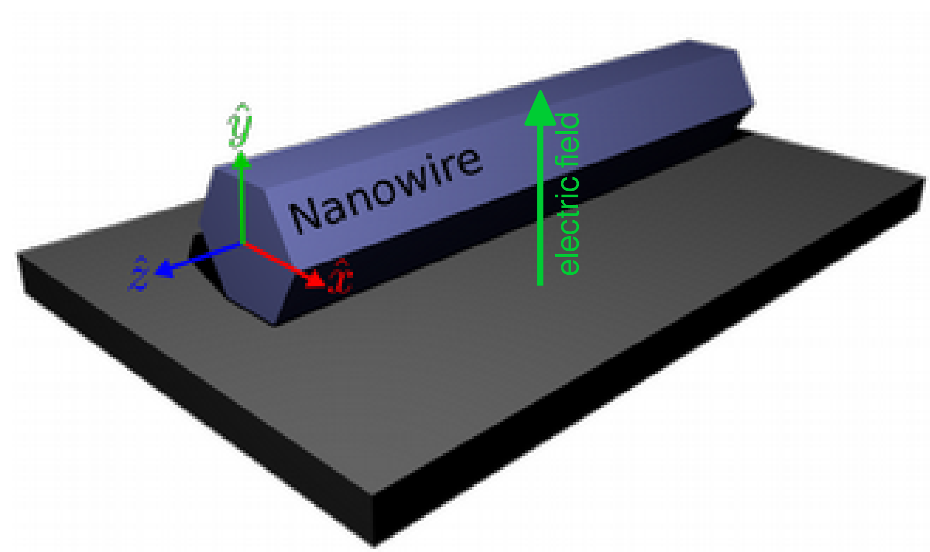
- pioneering optical spin injection into a single free-standing nanowire
- *g*-factor significantly different than in the cubic zinc-blende phase
- highly anisotropic spin relaxation due to SOC at core/shell interface

S. Furthmeier *et al.*, Nat. Comm. **7**, 12413 (2016)

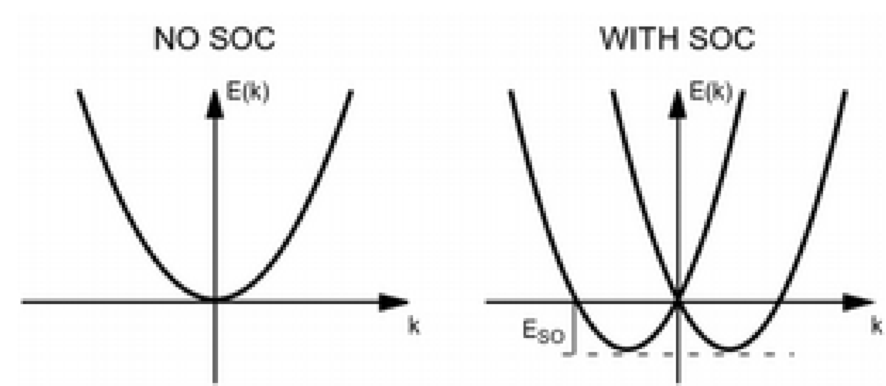
Conduction subbands in nanowires (50 nm)

an element for Topological Quantum Computation



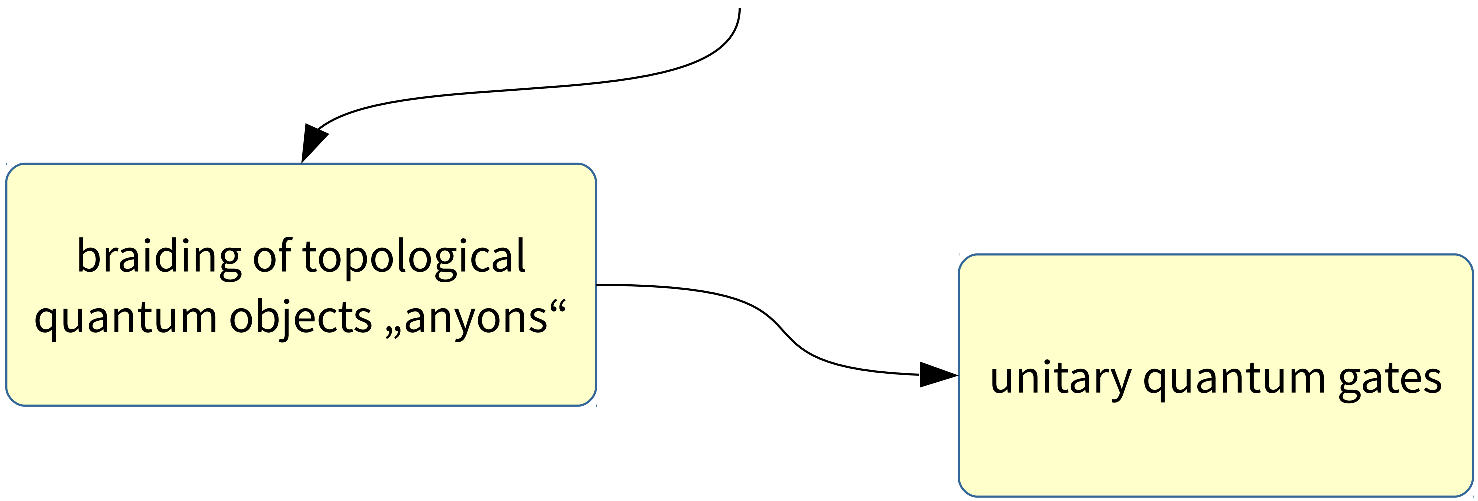


T. Campos *et al.*, arXiv: 1802.06734



Topological Quantum Computation

approach to fault-tolerant quantum computation



- **Localized excitations on an interacting Hamiltonian**
  (Laughlin fractional Quantum Hall liquid)
- **Defects in an ordered system**
  (Abrikosov vortices in topological superconductor / domain wall in 1D system)

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simplest realization of non-Abelian anyons (no anionic excitations) is a quasiparticle or defect supporting a **Majorana zero mode** (zero energy mid-gap excitation)

What is the Majorana zero mode?

zeroth order crash course

- **is a fermionic operator** γ
- **squares to unity** $\gamma^2 = 1$

(Majorana fermion)

- **commutes with the Hamiltonian of a system** $[\gamma, H] = 0$
- **degenerate ground state / non-local entanglement** $\{\gamma_i, \gamma_j\} = 2\delta_{ij}$
- **decomposition to conventional fermions** $c_j = \frac{1}{2}(\gamma_{2j-1} + i\gamma_{2j})$

To realize Majorana excitations $\gamma = \gamma^\dagger$ we seek for, e. g., $\gamma = uc + vc^\dagger$ with energy dependent coefficients of Bogoliubov quasiparticle excitations

BCS **spinless** fermion pairing → Cooper pair wave function must be **antisymmetric** therefore Majorana zero-energy excitations should exist in ***p*-wave superconductors**

Spinless *p*-wave superconductors

continuum mean-field many-particle Hamiltonian

$$\mathcal{H} = \int dx \left\{ \psi^\dagger(x) \left(\frac{p^2}{2m} - \mu \right) \psi(x) + \Delta' [\psi^\dagger(x) \partial_x \psi^\dagger(x) + \text{h.c.}] \right\}$$

associated Bogoliubov—de Gennes Hamiltonian

$$H = \begin{pmatrix} \xi_p & -i\Delta' p \\ i\Delta' p & -\xi_p \end{pmatrix} = \xi_p \tau_z + \Delta' p \tau_y$$ where $$\xi_p = p^2/2m - \mu$$

excitation spectrum for an infinite system

$$E_k = \pm(\xi_k^2 + \Delta'^2 k^2)^{1/2}$$

effective BdG field in particle-hole space

$$H_k = \mathbf{b}_k \cdot \boldsymbol{\tau}$$

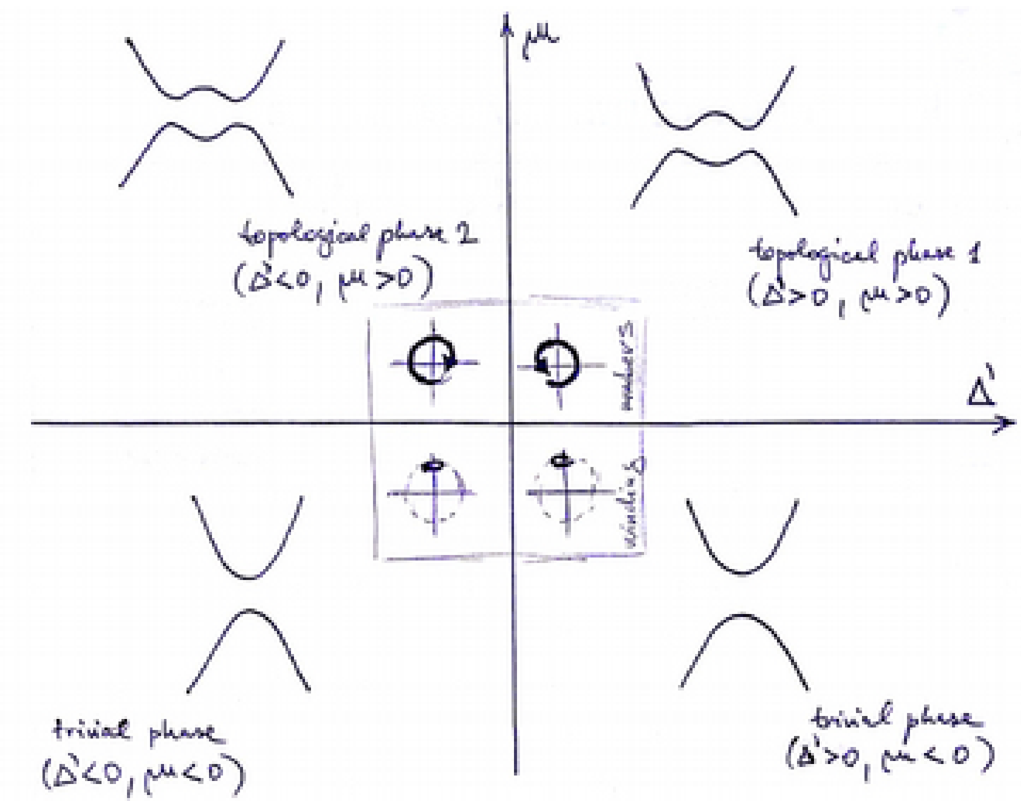
Pauli matrices in particle-hole space

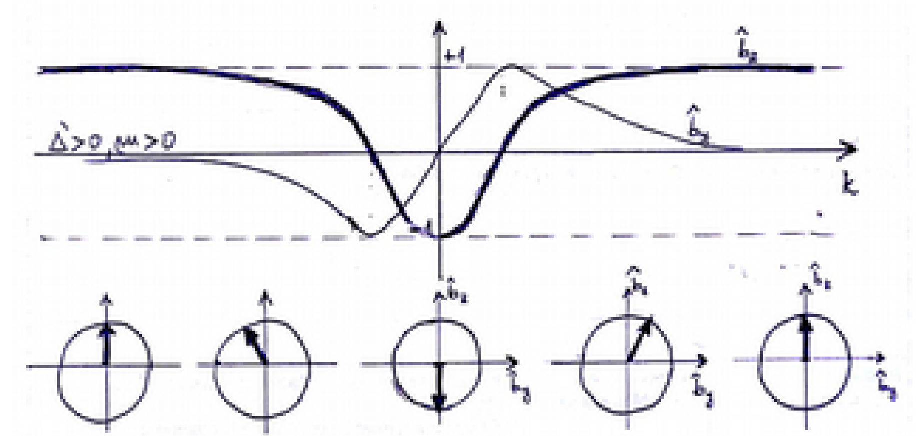
$$\hat{\mathbf{b}}_k = \mathbf{b}_k / ||\mathbf{b}_k|| = \begin{pmatrix} 0 \\ \Delta' k / \sqrt{(\Delta' k)^2 + \xi_k^2} \\ \xi_k / \sqrt{(\Delta' k)^2 + \xi_k^2} \end{pmatrix}$$

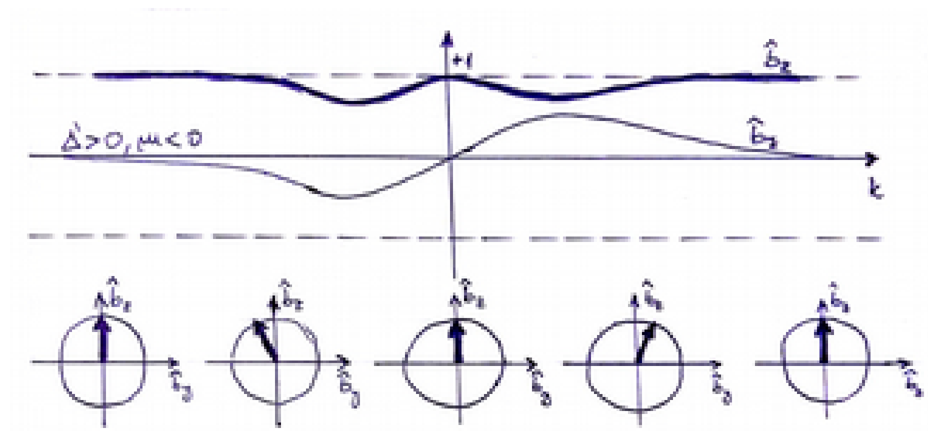
Spinless *p*-wave superconductors

$$E_k = \pm((k^2/2m - \mu)^2 + \Delta'^2 k^2)^{1/2}$$

$$\hat{\mathbf{b}}_k = \begin{pmatrix} 0 \\ \Delta' k/\sqrt{(\Delta' k)^2 + \xi_k^2} \\ \xi_k/\sqrt{(\Delta' k)^2 + \xi_k^2} \end{pmatrix}$$







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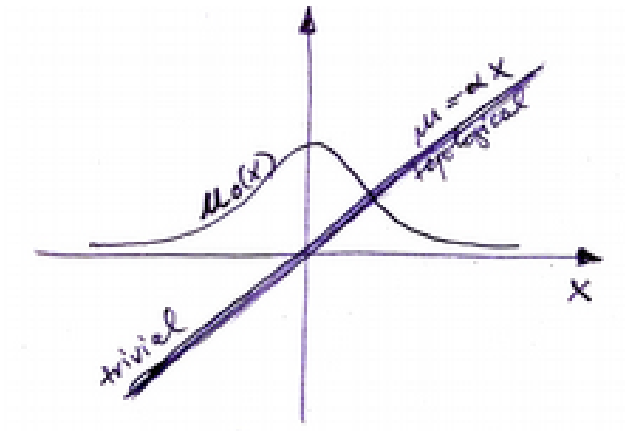
Domain wall Majorana excitations

$$\mu(x) = \alpha x$$

$$p^2/2m \ll 1$$



$$H = -\alpha x \tau_z + \Delta' p \tau_y$$

$$H^2 = (\alpha x)^2 + (\Delta' p)^2 - \Delta' \alpha [x, p] \tau_z \tau_y$$

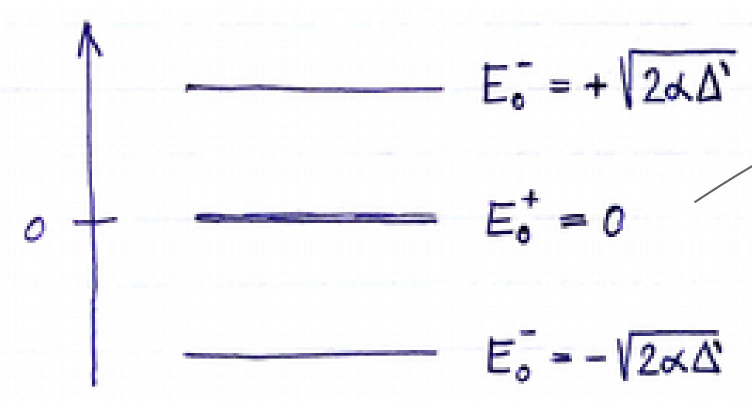
$$\{\tau_i, \tau_j\} = 2\delta_{ij}$$

$$[x, p] = i$$

$$\tau_z \tau_y = -i\tau_x$$

$$H^2 = (\alpha x)^2 + (\Delta' p)^2 - \Delta' \alpha \tau_x$$

$$(E_n^{\pm})^2 = 2\Delta' \alpha \left(n + \tfrac{1}{2}\right) \mp \Delta' \alpha$$



BdG eigenspinor

$$\langle x | n = 0, + \rangle = u_0(x) \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

$$\gamma = \int dx\, u_0(x) [\psi(x) + \psi^\dagger(x)] \longrightarrow \gamma = \gamma^\dagger$$

“Synthetic” realization of Majorana excitations

experimentally accessible system

Basic ingredients:

1. proximity coupling to s-wave superconductor
2. spin polarization
3. spin-orbit coupling

$$g\mu_{\mathrm{B}} B > \sqrt{\Delta^2 + \mu^2}$$

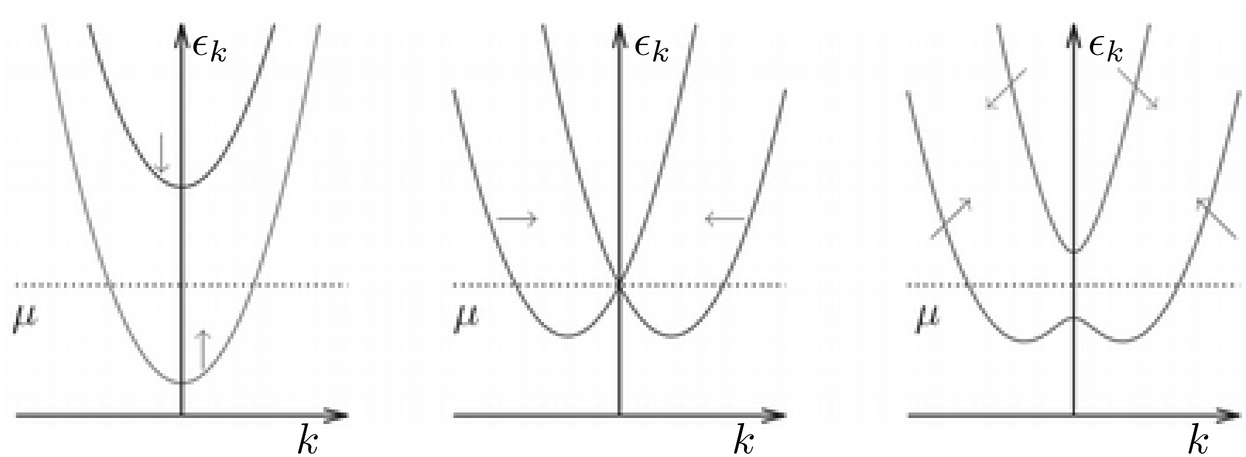
$$H = \left(\frac{p^2}{2m} + up\sigma_x - \mu\right)\tau_z - B\sigma_z + \Delta\tau_x$$

Kitev limit (*p*-wave SC)

strong Zeeman+perturbative SOC

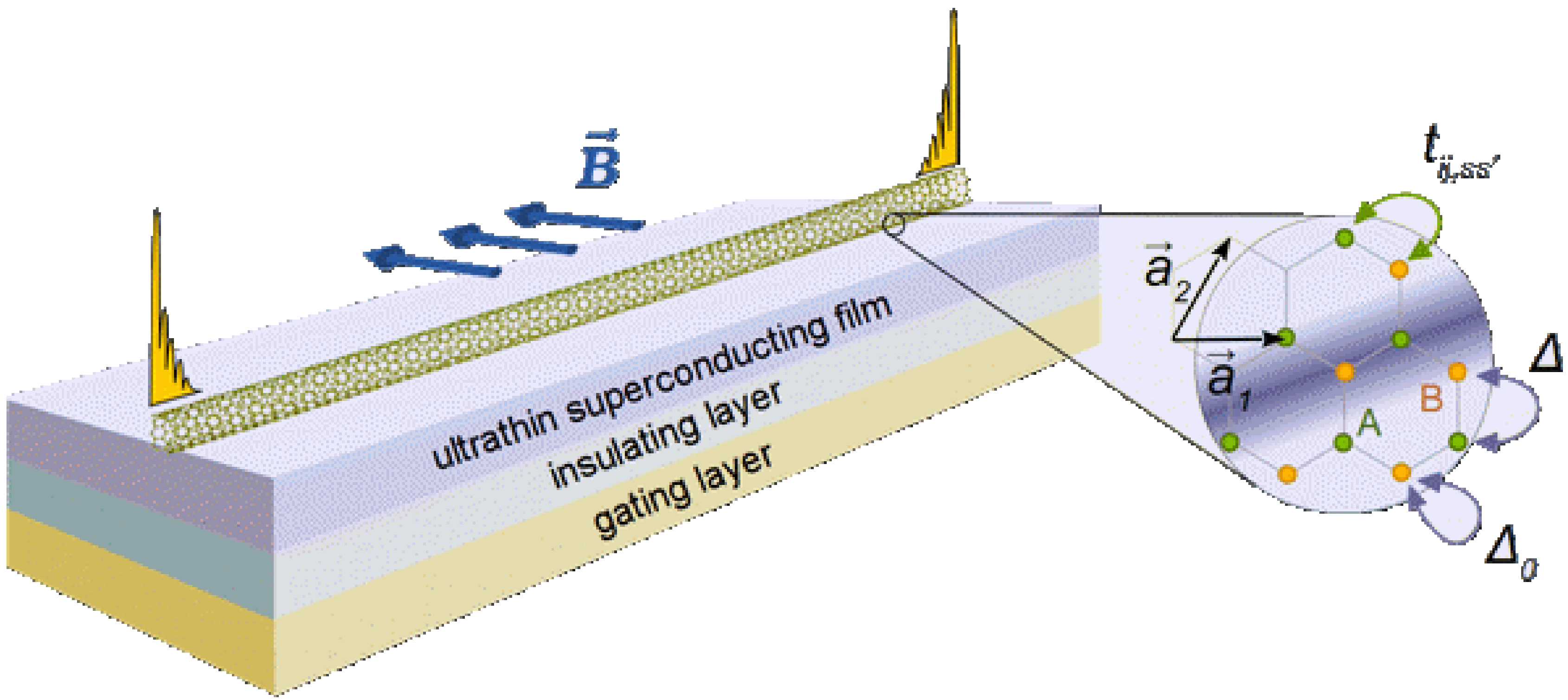
$$H \simeq \left(\frac{p^2}{2m} - \mu\right)\tau_z - \frac{up}{B}\Delta\tau_x$$

effective *p*-wave pairing strength of the proximity-coupled quantum wire



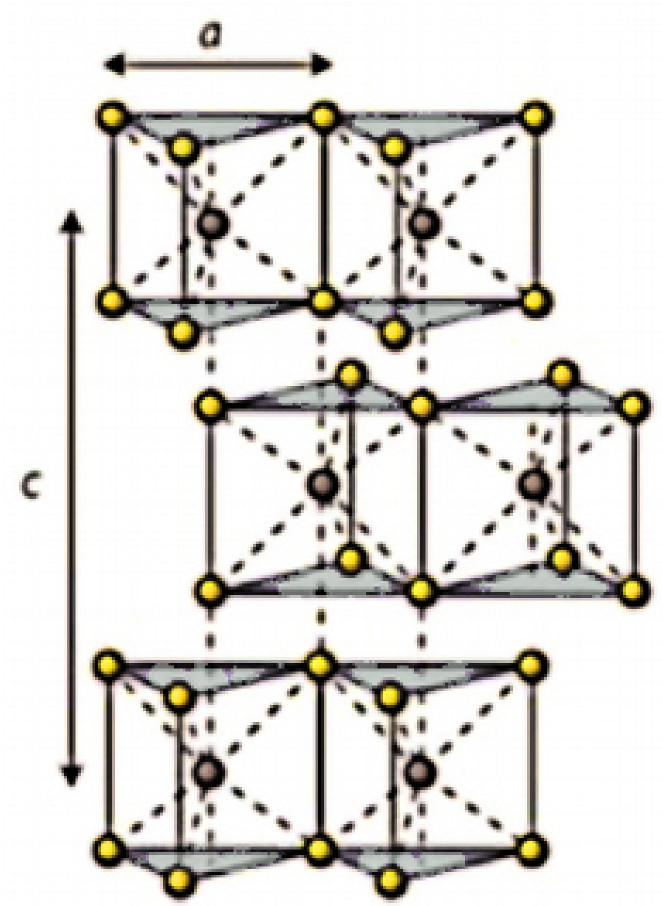
Carbon nanotube hosts Majorana zero mode

novel proposal



[*]M. Marganska et al., arXiv: 1711.03616v1

2H polytype of $NbSe_2$



SG: #194 ($P6_3/mmc$)

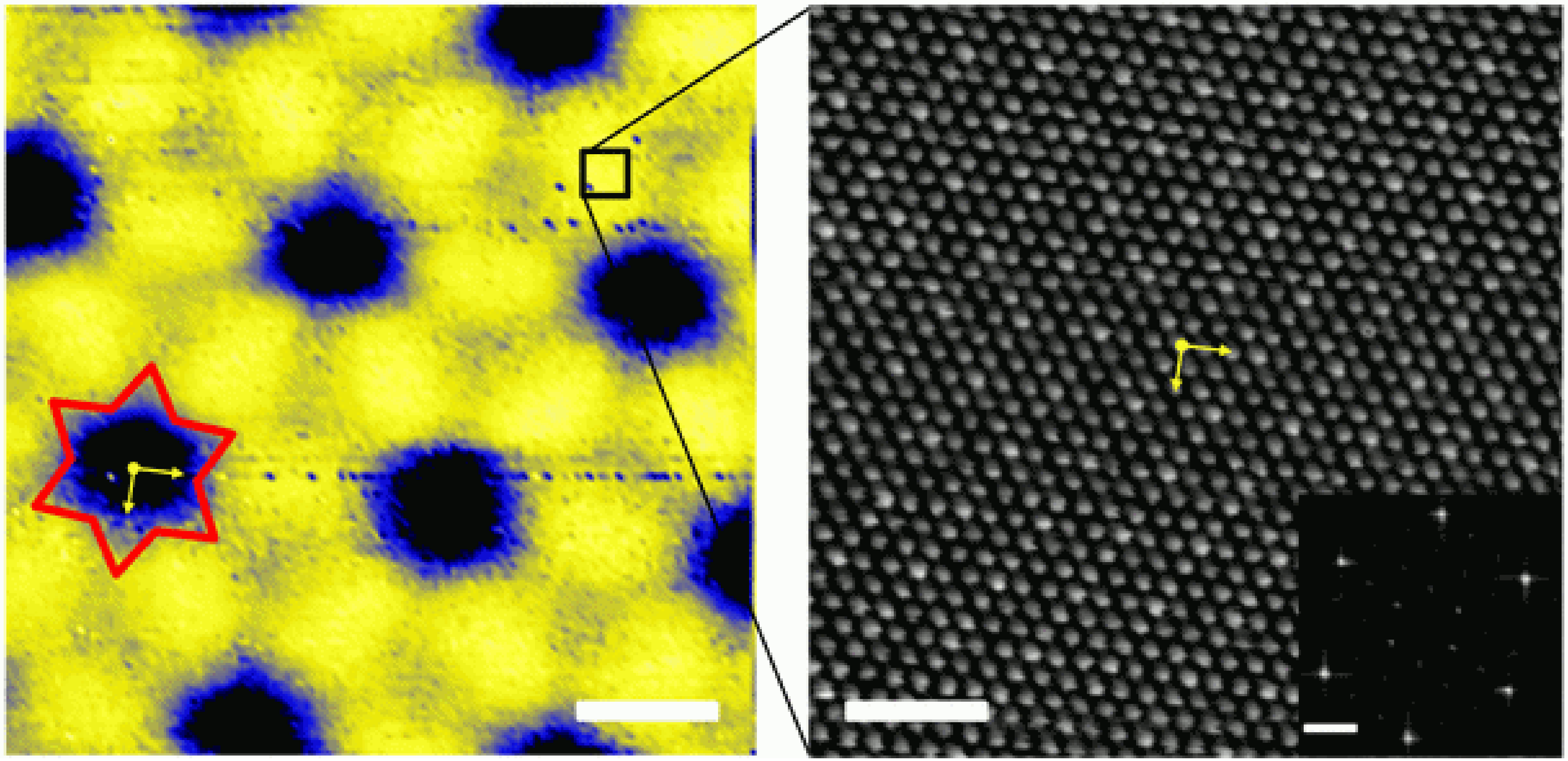
PG: D_{6h}

a = 3.445 Å [*]

c = 12.55 Å

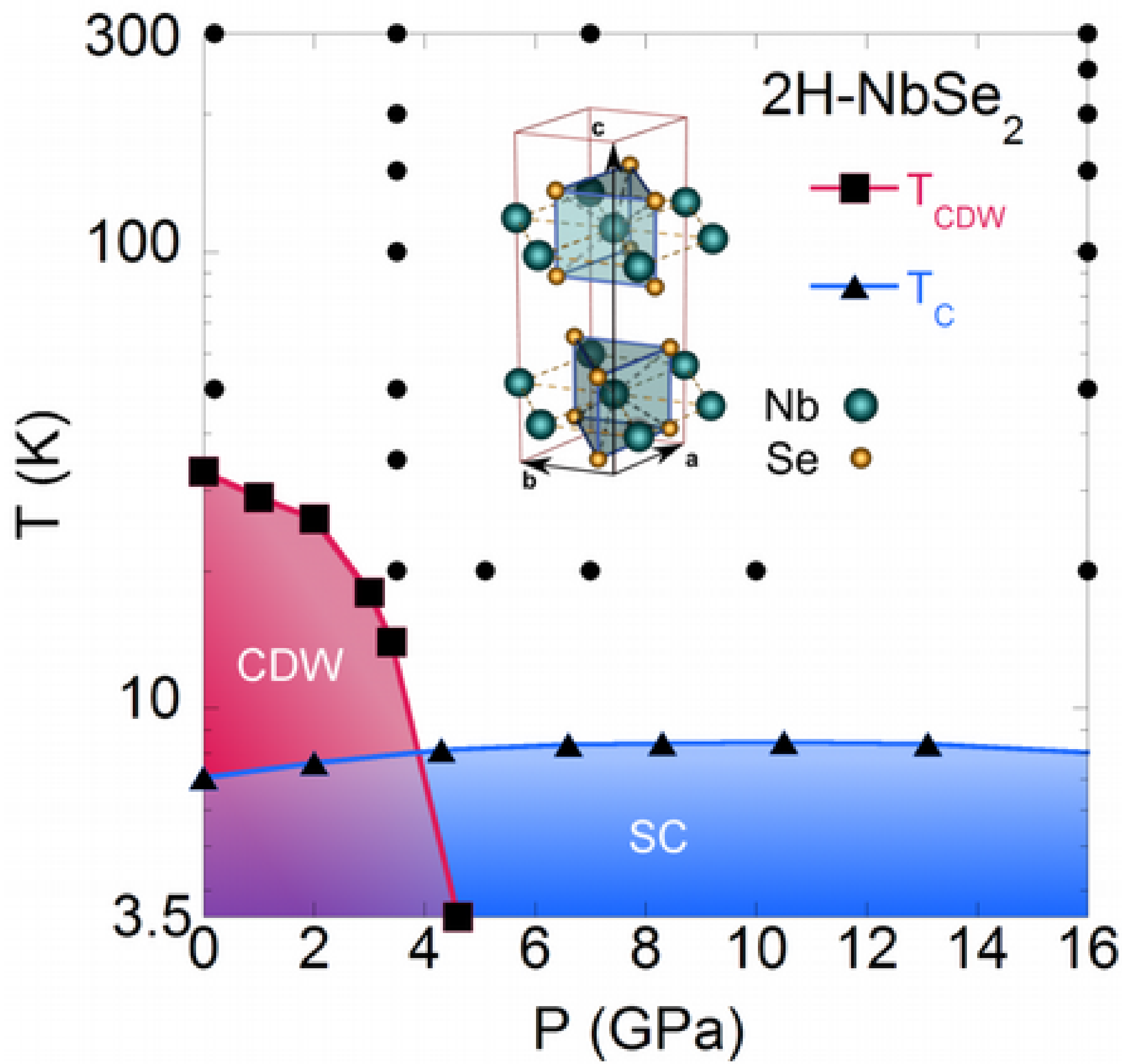
[*] J. Xu et al., Digest Journal of Nanomaterials and Biostructures **10**, 505 (2015)

Anisotropic type-II superconductor



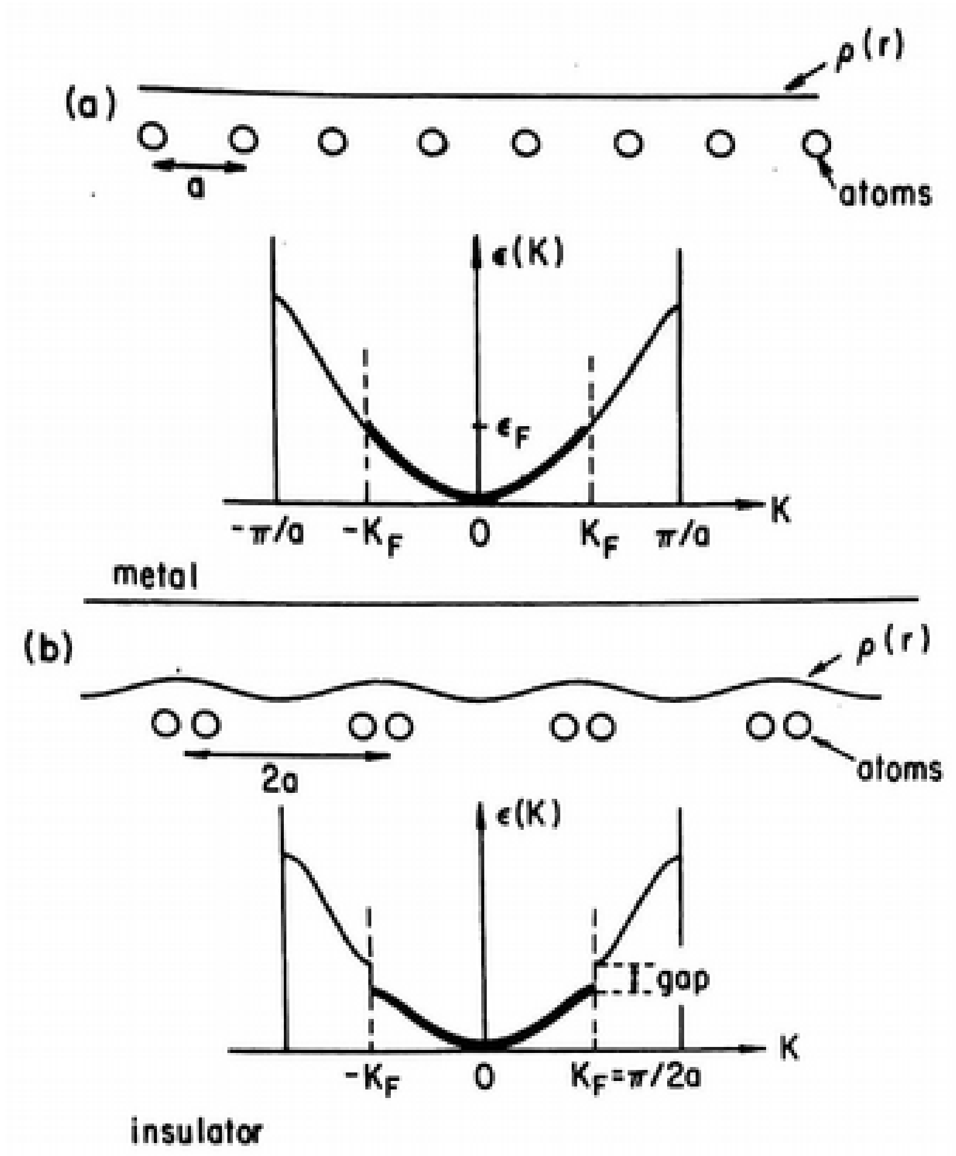
[*]J. A. Galvis et al., arXiv:1711.09269 (2017)

Phase diagram of 2H-$NbSe_2$



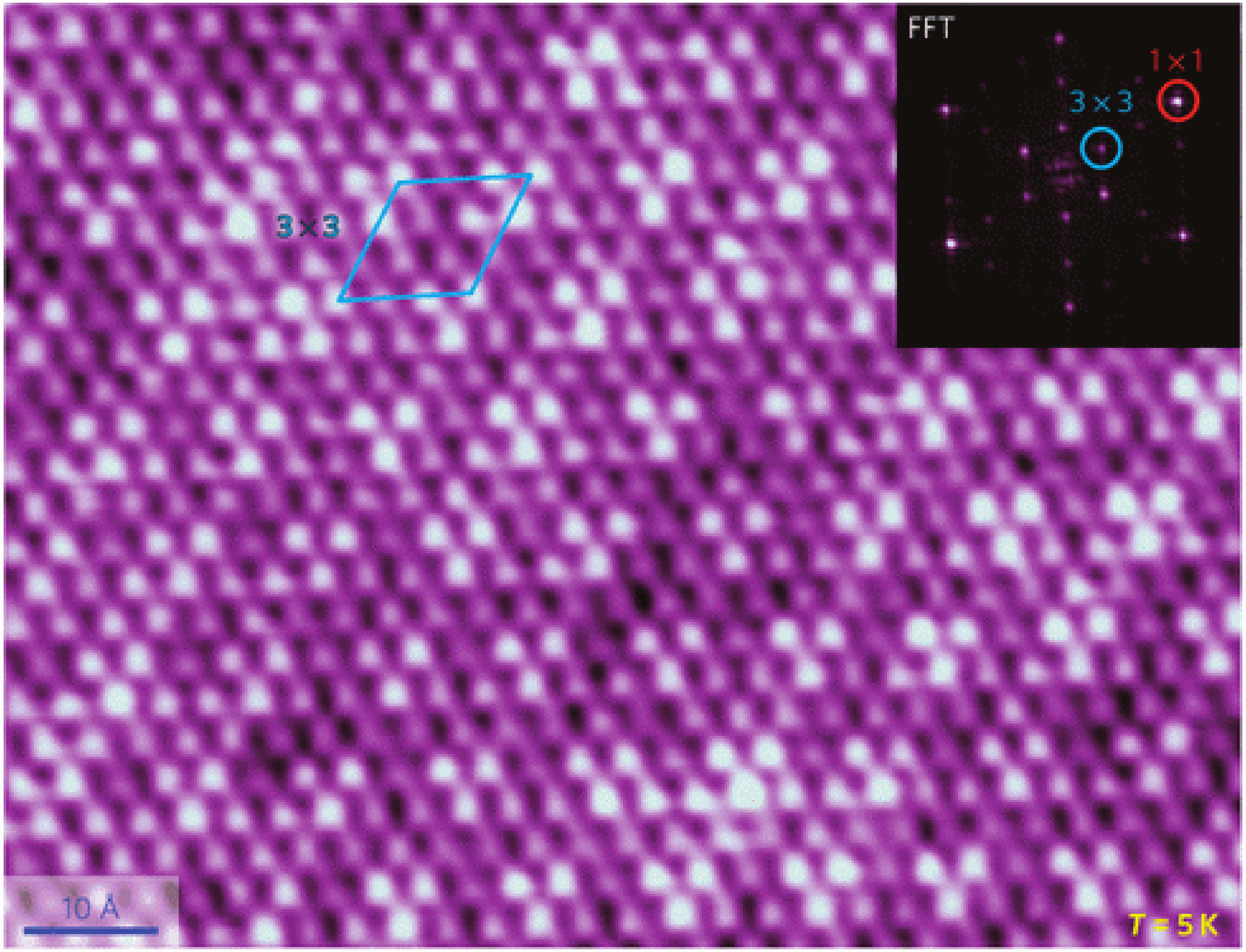
[*]M. Leuroux et al., PRB **92**, 140303 (2015)

Charge density wave (CDW)
Peierls transition



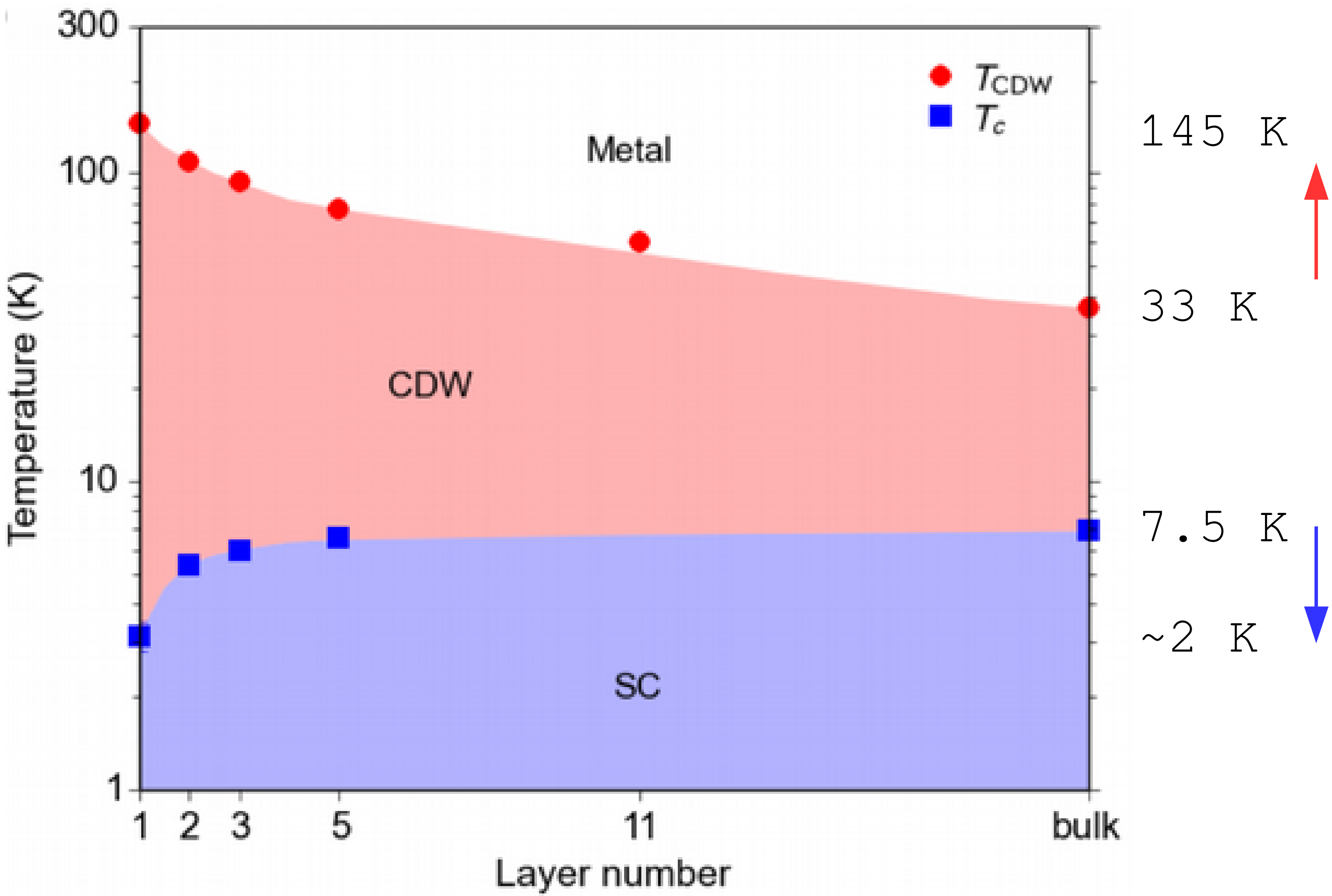
[*]G. Gruener, Rev. Mod. Phys. **60**, 1129 (1988)

3x3 CDW in single layer $NbSe_2$



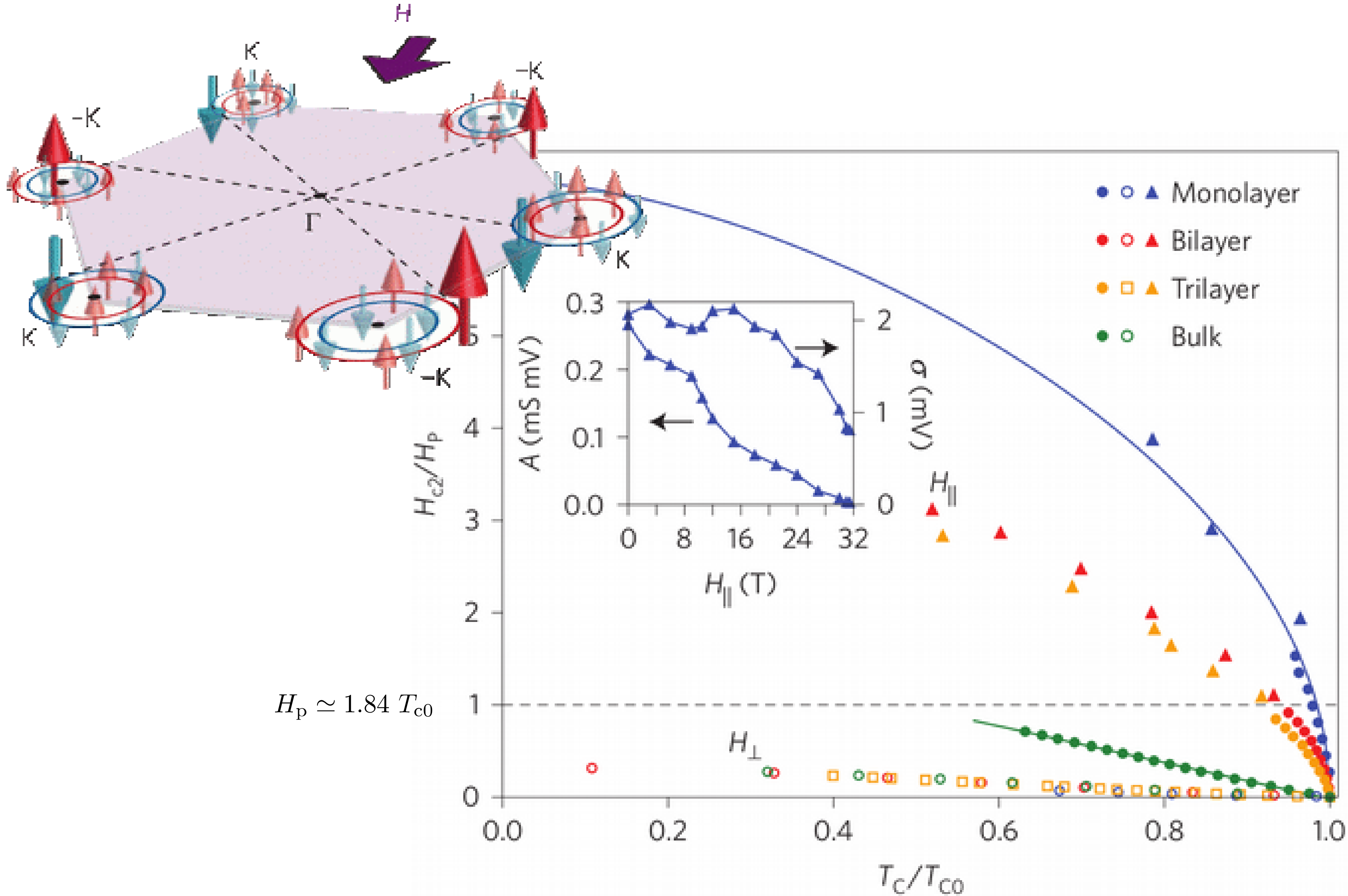
[*]M. M. Ugeda et al., Nat. Phys. **12**, 92 (2016)

Peeling-off $NbSe_2$ layer-by-layer



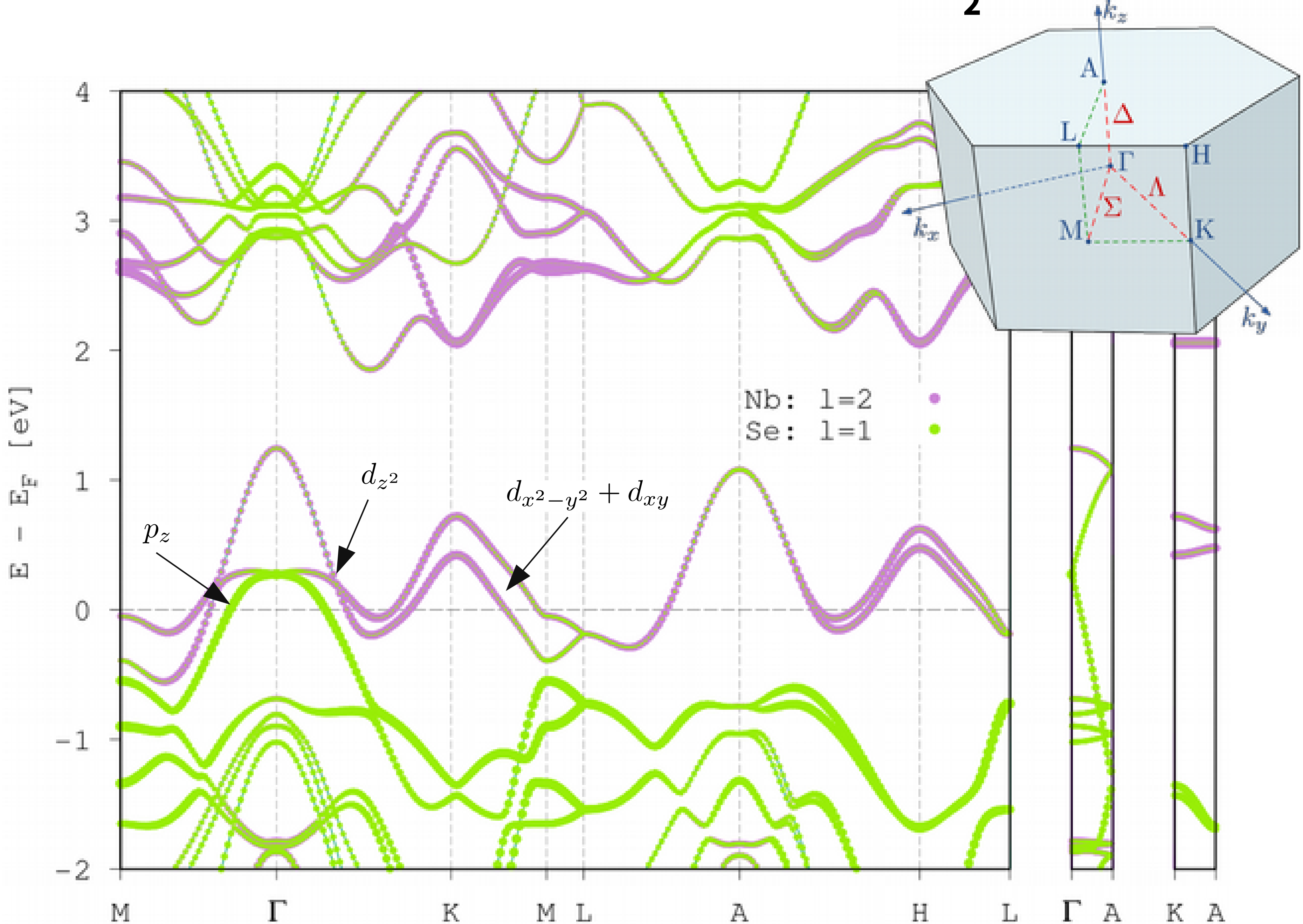
[*]X. Xi et al., Nat. Nanotech. **10**, 765 (2015)

Ising pairing by spin-momentum locking

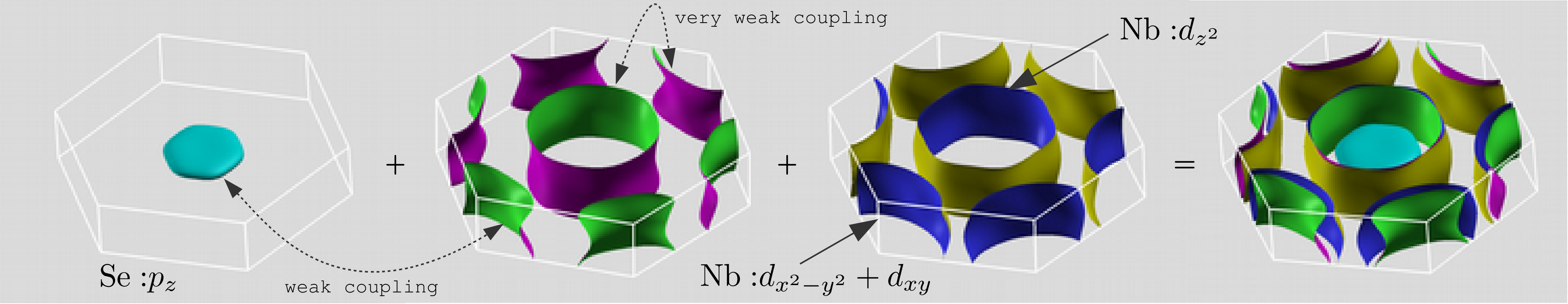


[*]X. Xi et al., Nat. Phys. **12**, 139 (2016); Y. Saito et al., ibid. **12**, 144 (2016)

Band structure of 2H-$NbSe_2$



Fermi surface/superconductivity

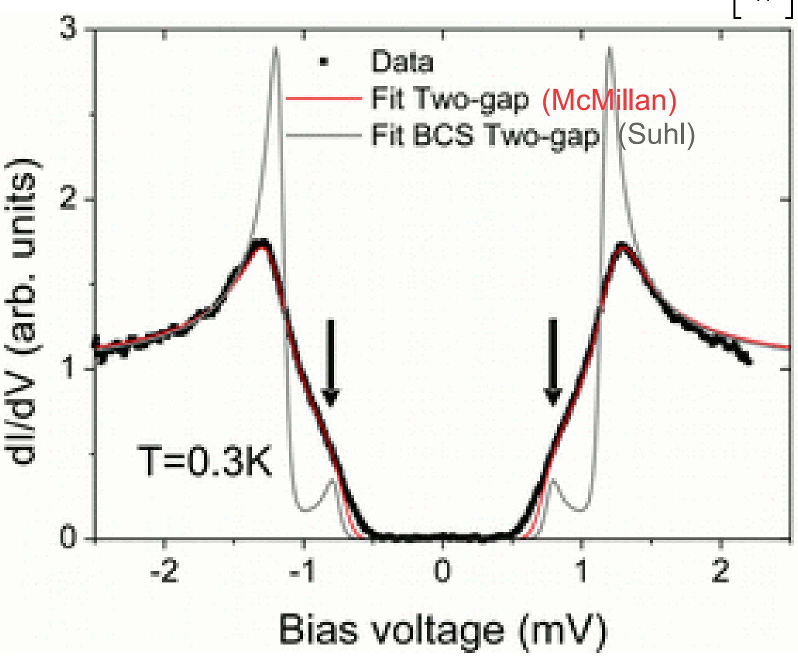


anisotropic gap

or

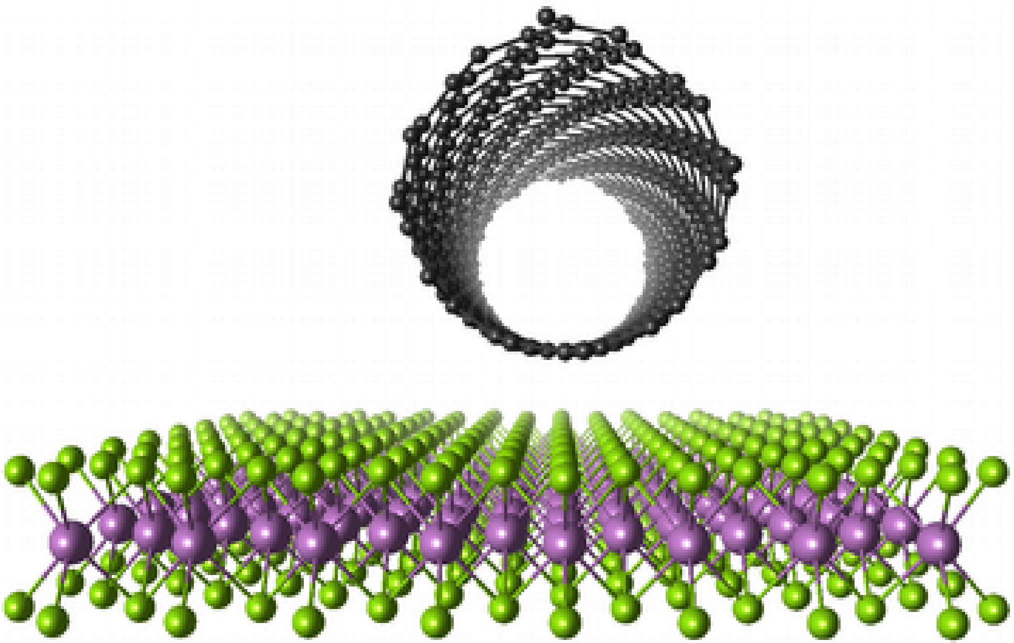
two-band superconductivity?

[*]



[*]Y. Noat et al., PRB **92**, 134510 (2015)

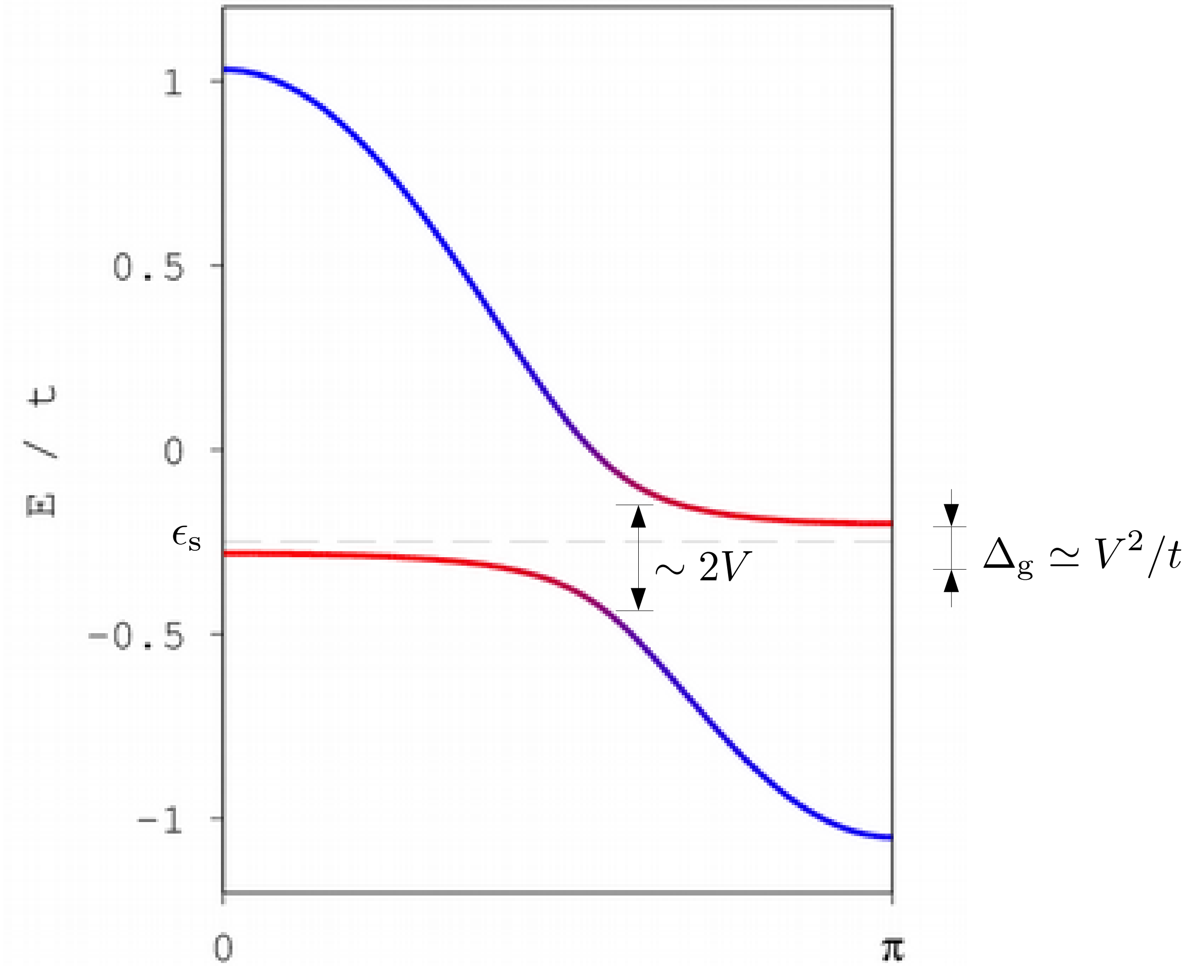
Coupling of two sub-systems



$$\mathcal{H} = \begin{pmatrix} H_0(k) & \Delta(k) \\ \Delta^\dagger(k) & H_\mathrm{s}(k) \end{pmatrix}$$

Interaction of two bands

$$\mathcal{H} = \begin{pmatrix} t\cos(k) & V \\ V^* & \epsilon_s \end{pmatrix}$$



[*]solution: $E_{1,2} = \frac{1}{2}\left[\epsilon_s + t\cos(k) \pm \sqrt{\epsilon_s^2 + 4V^2 - 2\epsilon_s t\cos(k) + t^2\cos^2(k)}\right]$

What would see ARPES?

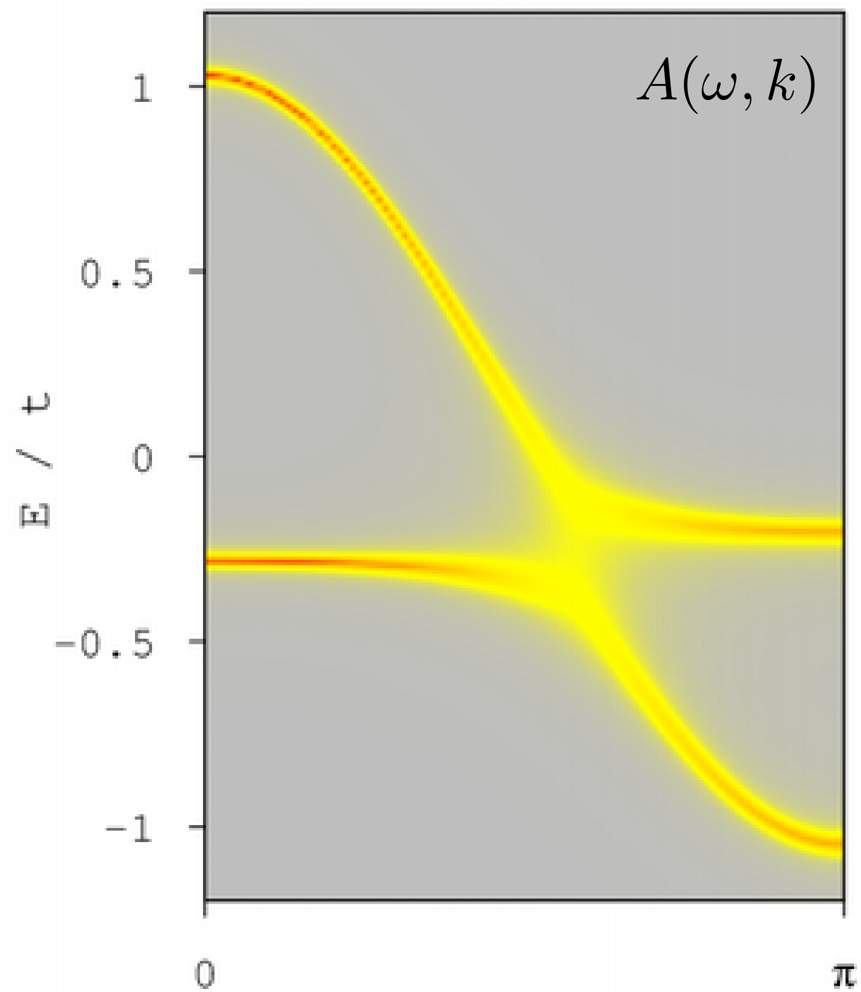
$$G^{\mathrm{R}}_{11}(\omega,k)=\frac{1}{\omega-t\cos(k)+i\eta-V^2g^{\mathrm{R}}_2}$$

$$G^{\mathrm{R}}_{22}(\omega,k)=\frac{1}{\omega-\epsilon_{\mathrm{s}}+i\eta-V^2g^{\mathrm{R}}_1}$$

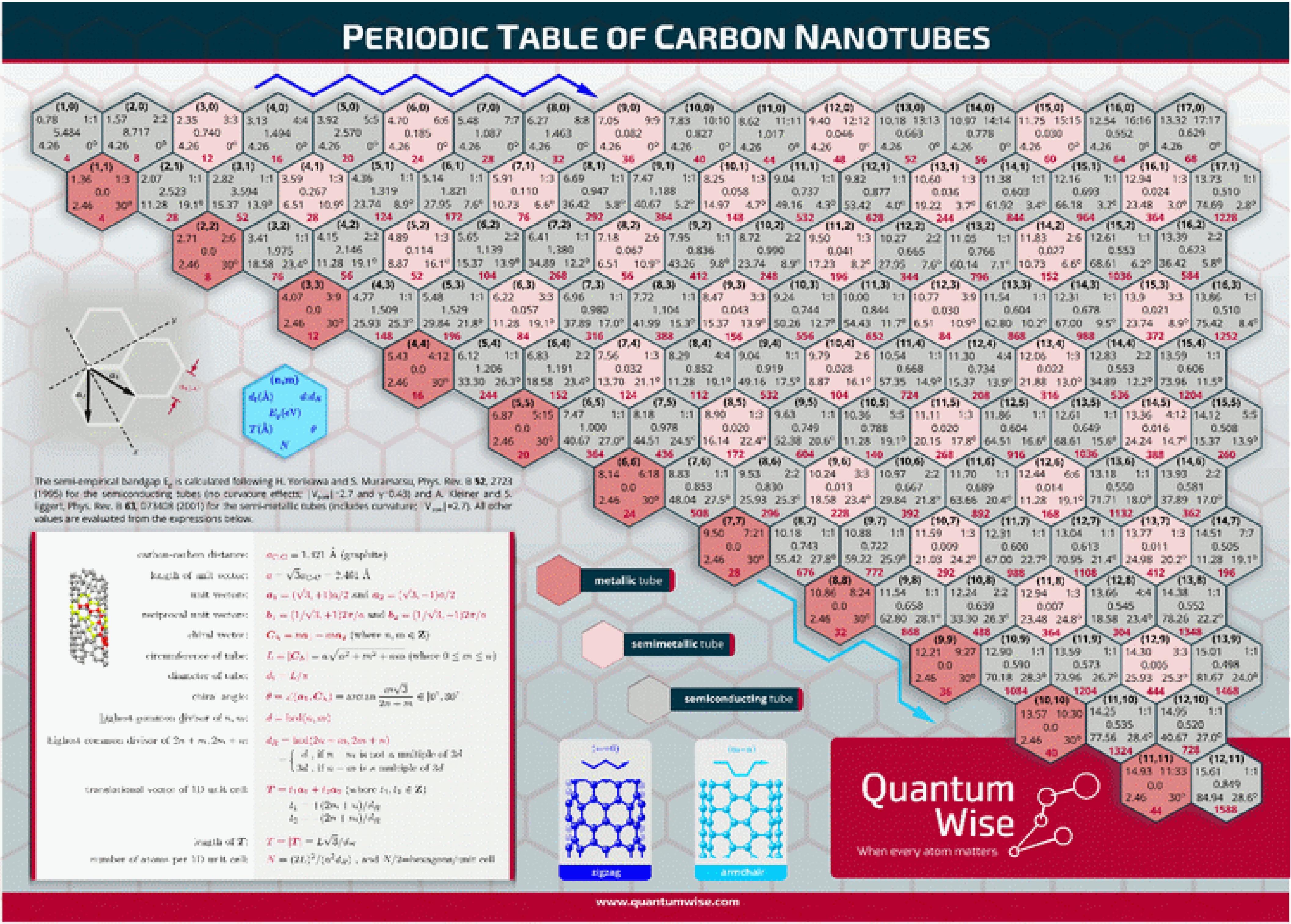
$$\Sigma_{11}(\omega,k)=V^2g^{\mathrm{R}}_2$$

$$\Sigma_{22}(\omega,k)=V^2g^{\mathrm{R}}_1$$

$$A(\omega,k)=\sum_i A_i(\omega,k)$$

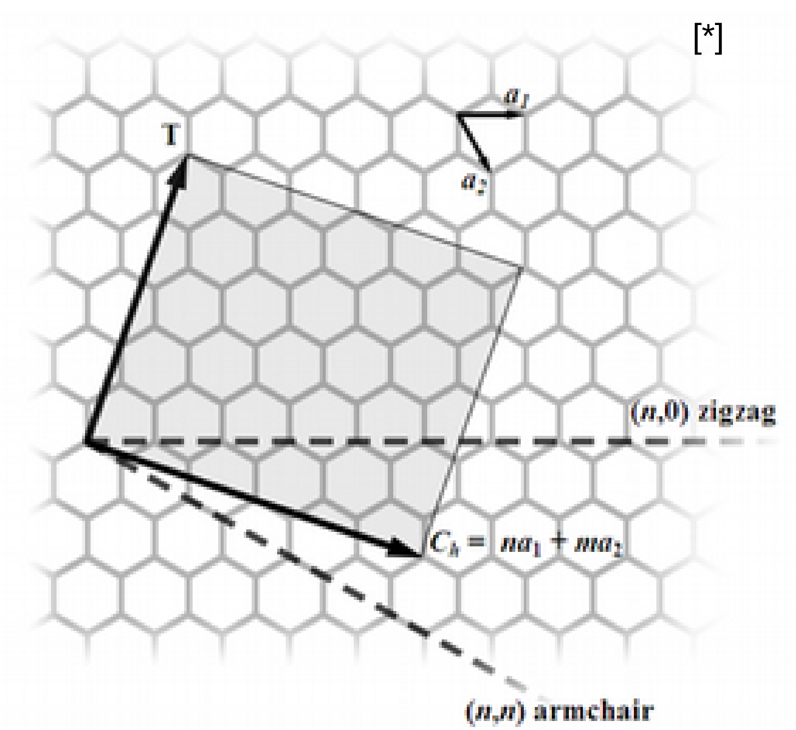


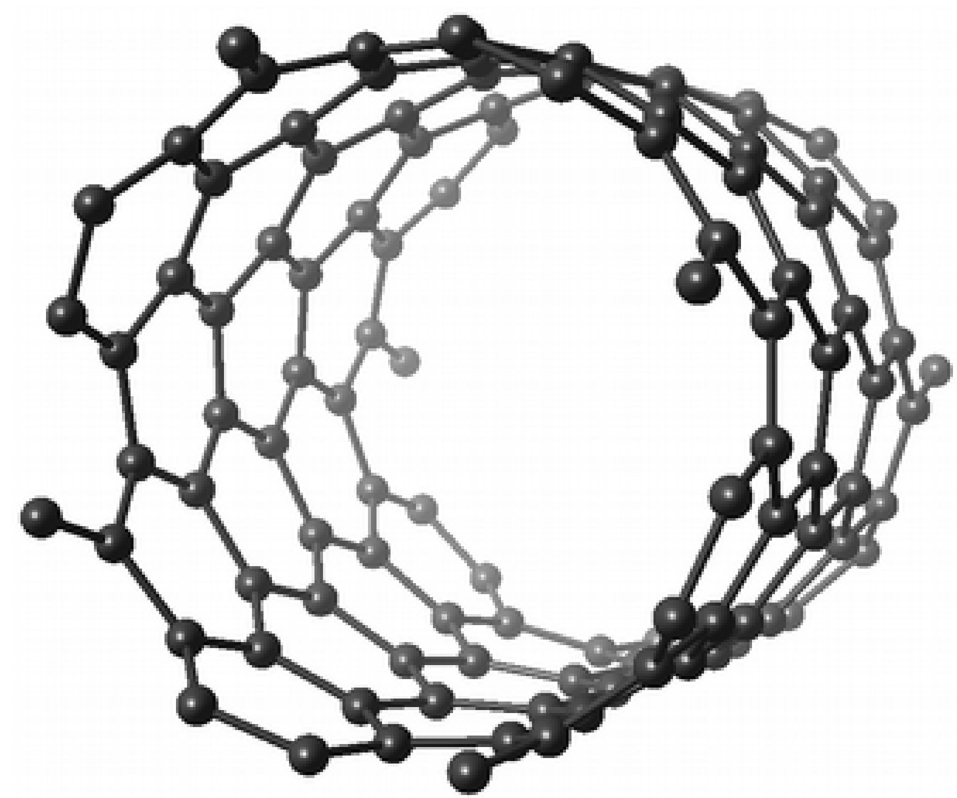
$$A_i(\omega,k)=\frac{-2\mathrm{Im}[\Sigma_{ii}(\omega,k)]}{(\omega-\epsilon_i(k)-\mathrm{Re}[\Sigma_{ii}(\omega,k)])^2+(\mathrm{Im}[\Sigma_{ii}(\omega,k)])^2}$$


PERIODIC TABLE OF CARBON NANOTUBES
(n,m)
d_t(Å)
E_g(eV)
T(Å)
N
The semi-empirical bandgap E_g is calculated following H. Yorikawa and S. Muramatsu, Phys. Rev. B 52, 2723 (1995) for the semiconducting tubes (no curvature effects; |$V_{pp\pi}$|=2.7 and γ=0.43) and A. Kleiner and S. Eggert, Phys. Rev. B 63, 073408 (2001) for the semi-metallic tubes (includes curvature; |$V_{pp\pi}$|=2.7). All other values are evaluated from the expressions below.
metallic tube
semimetallic tube
semiconducting tube
zigzag
armchair
Quantum Wise
When every atom matters
www.quantumwise.com

eduQUTE

Chiral carbon (8,4) nanotube

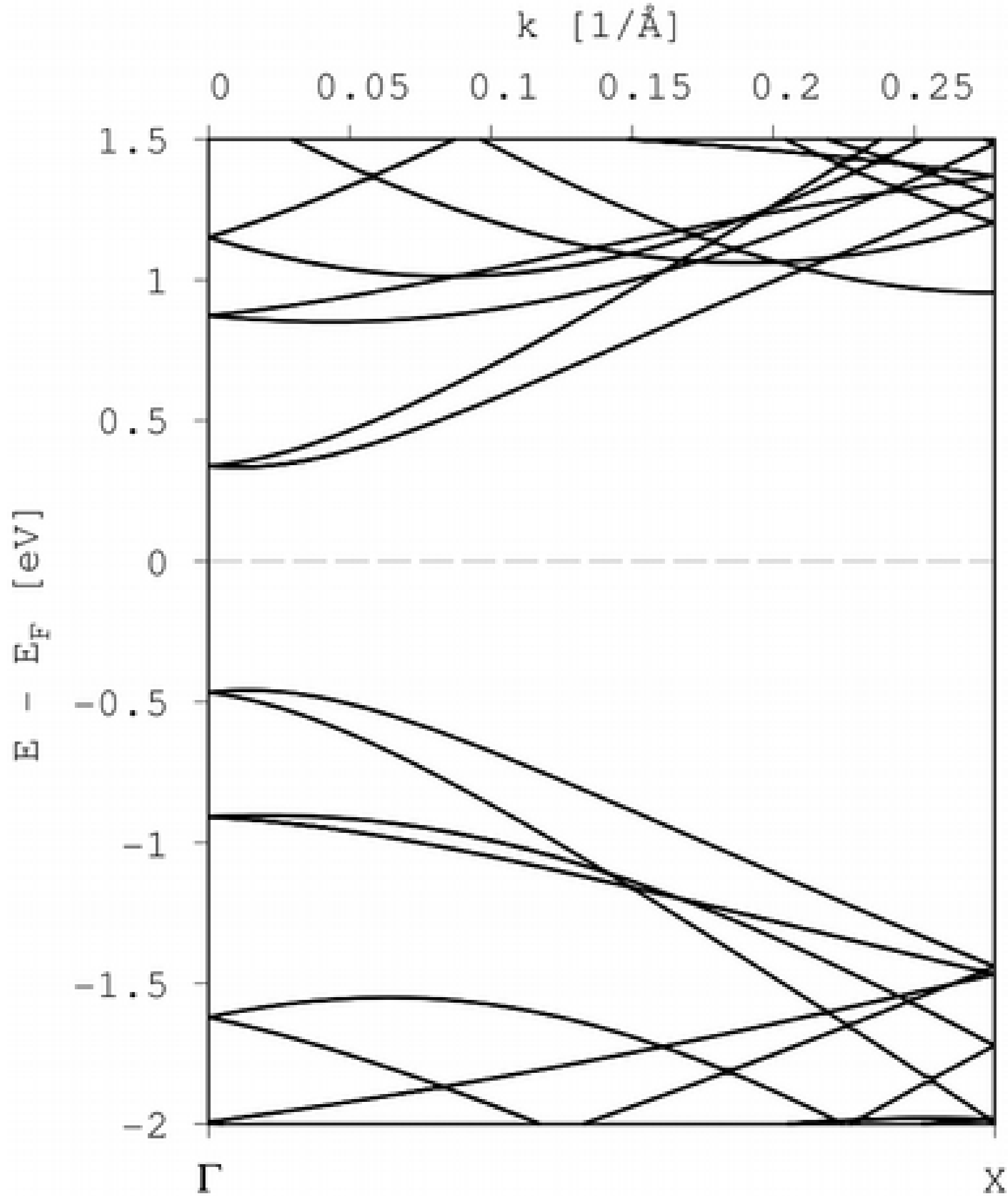


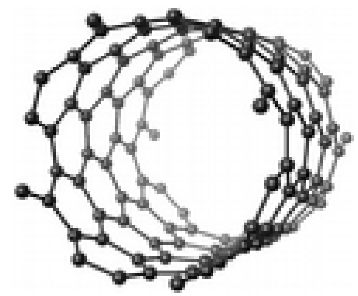


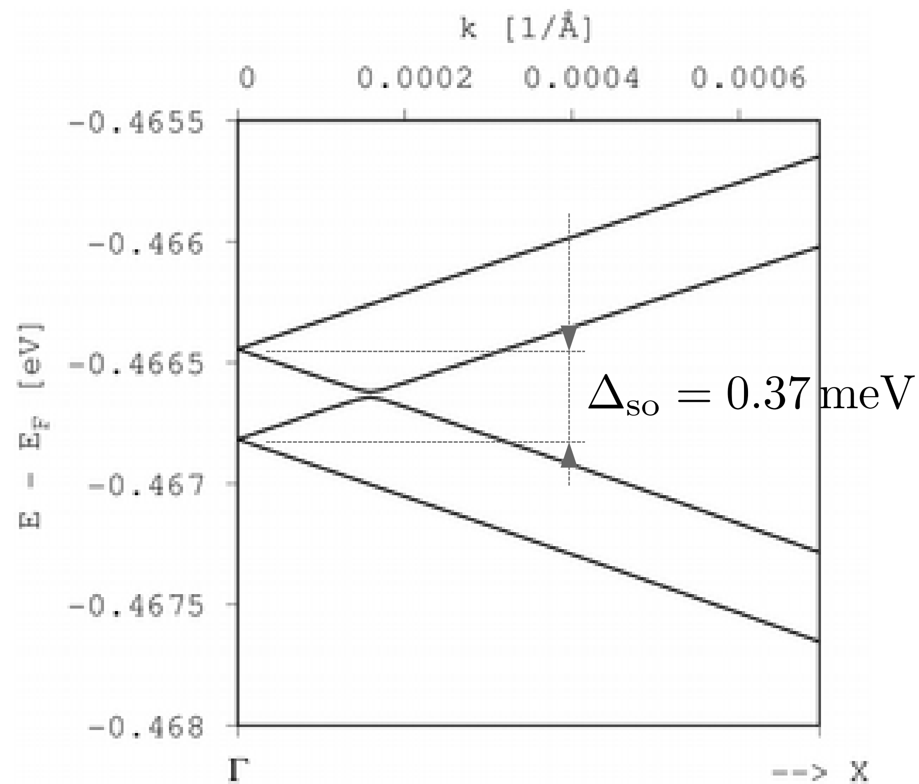
diameter of 8.3 Å
112 atoms in unit cell[**]

[*]source: https://en.wikipedia.org/wiki/Carbon_nanotube
[**]input: TubeGen3.3, J T Frey, University of Delaware

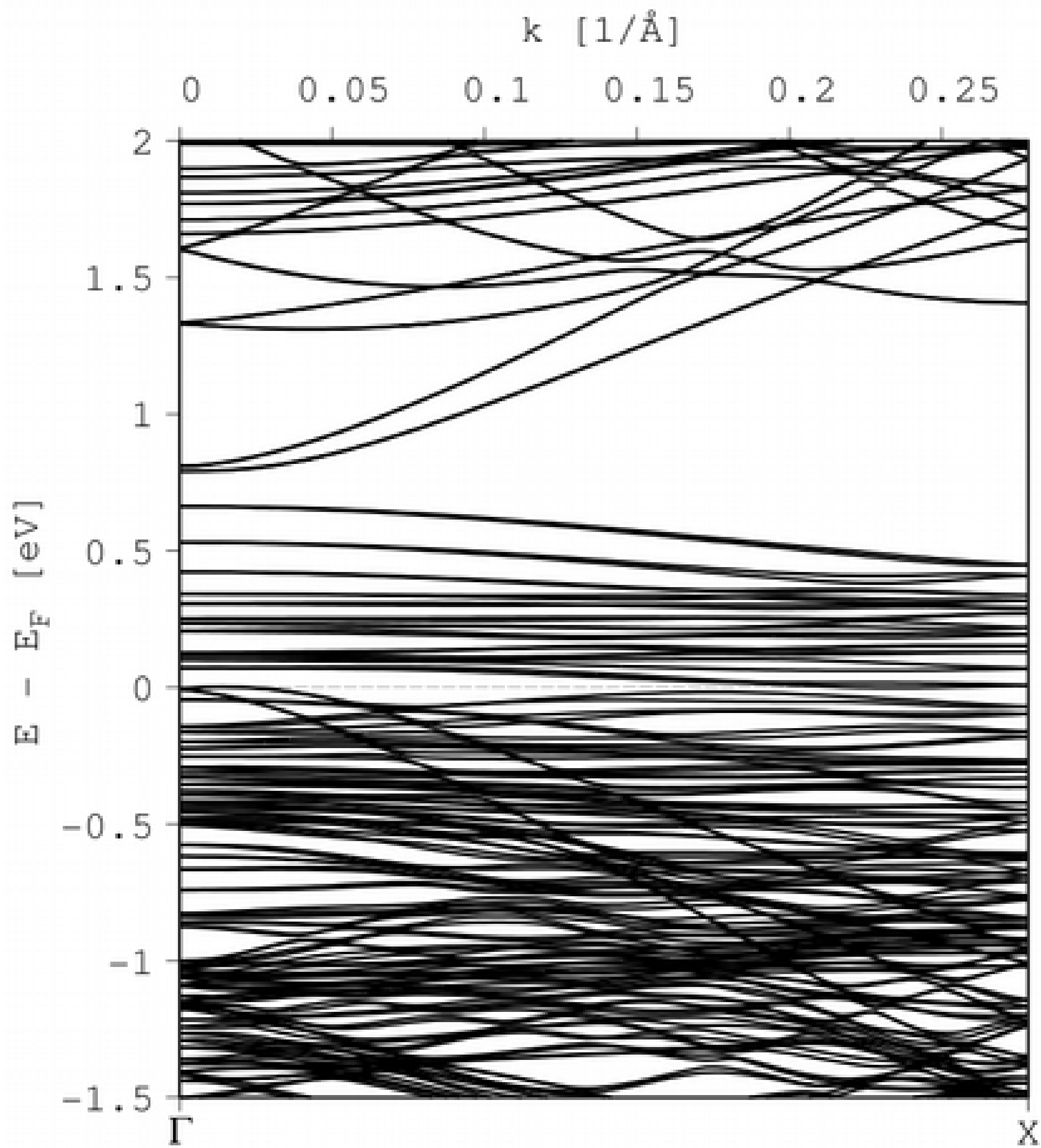
Band structure of cnt(8,4)



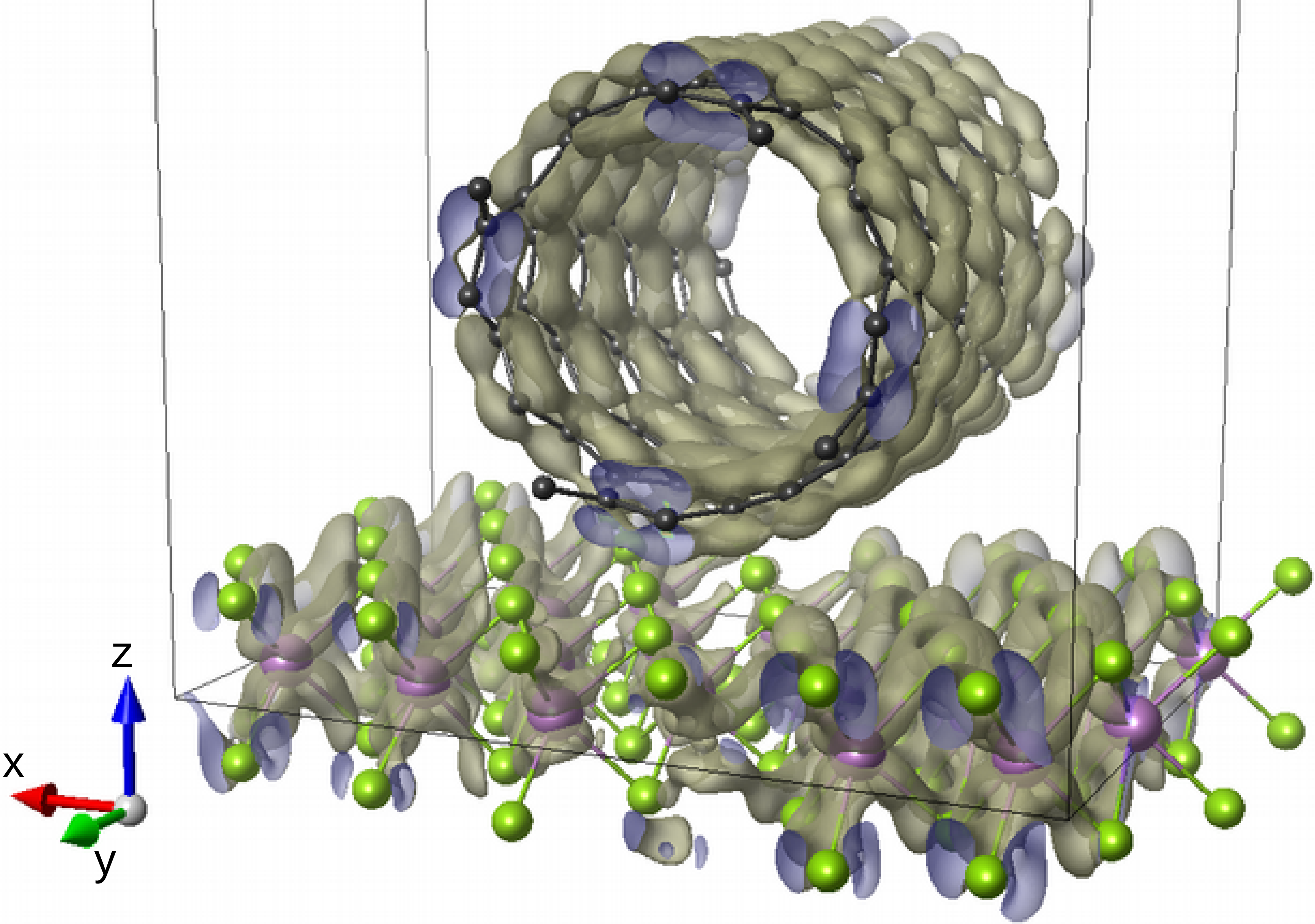




Joint spaghetti

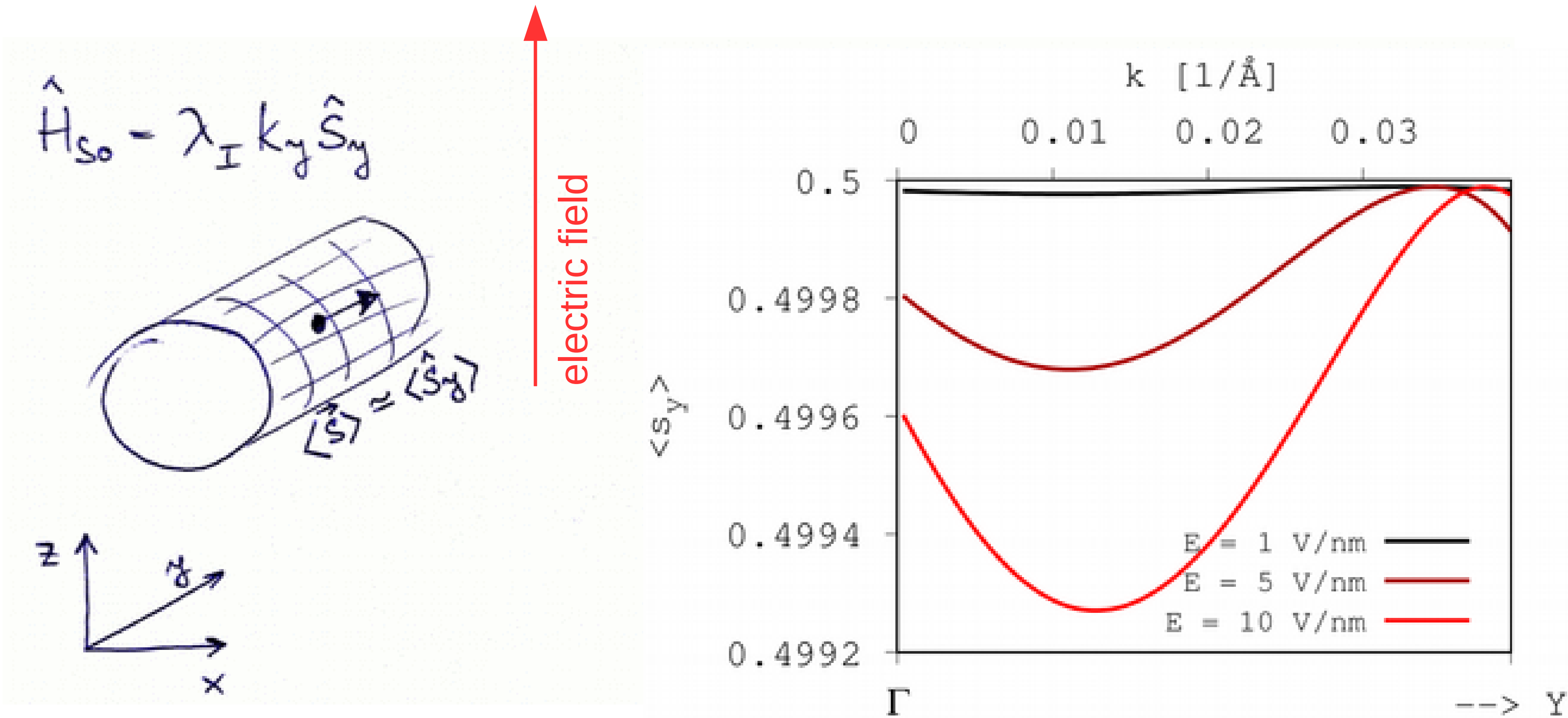


Hybridization state

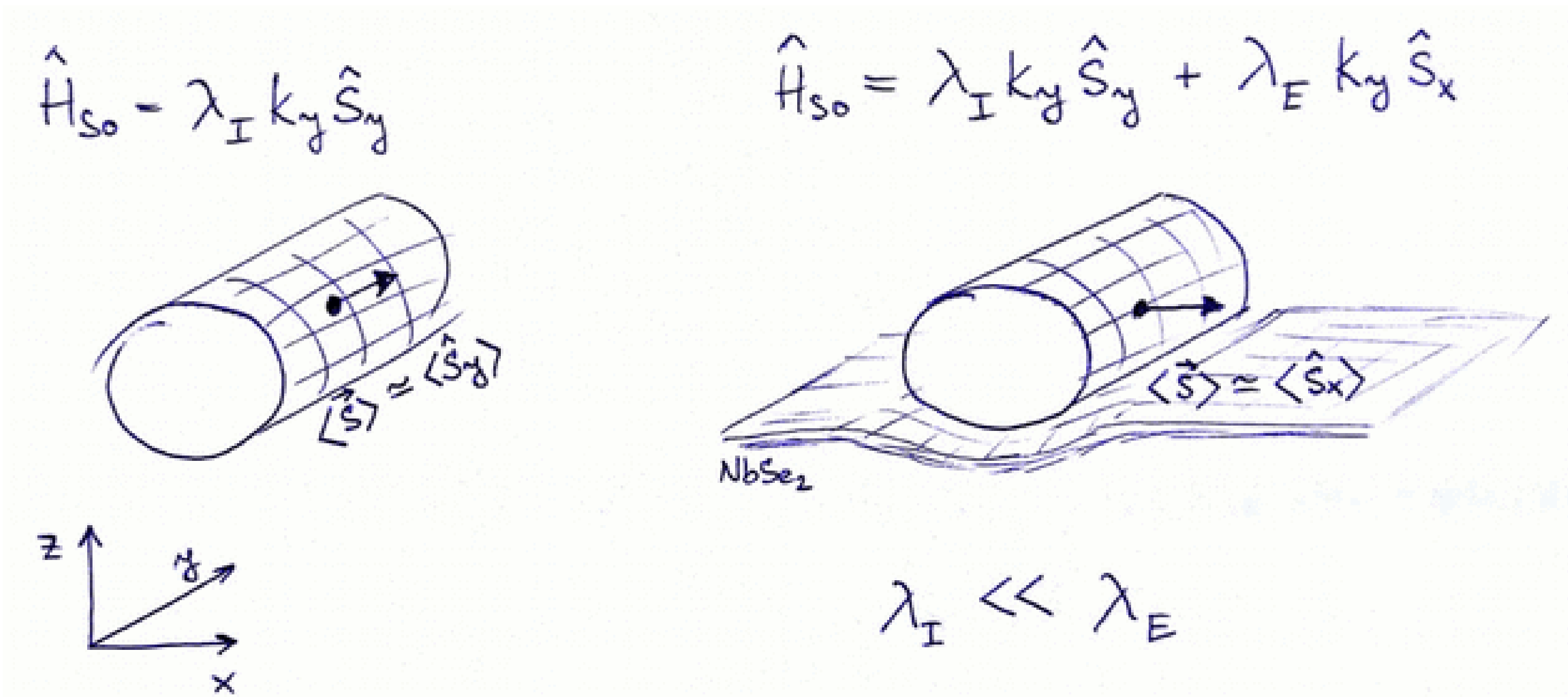


[*]k=0.0216 1/Å (path G-Y, K#9, band 1046)

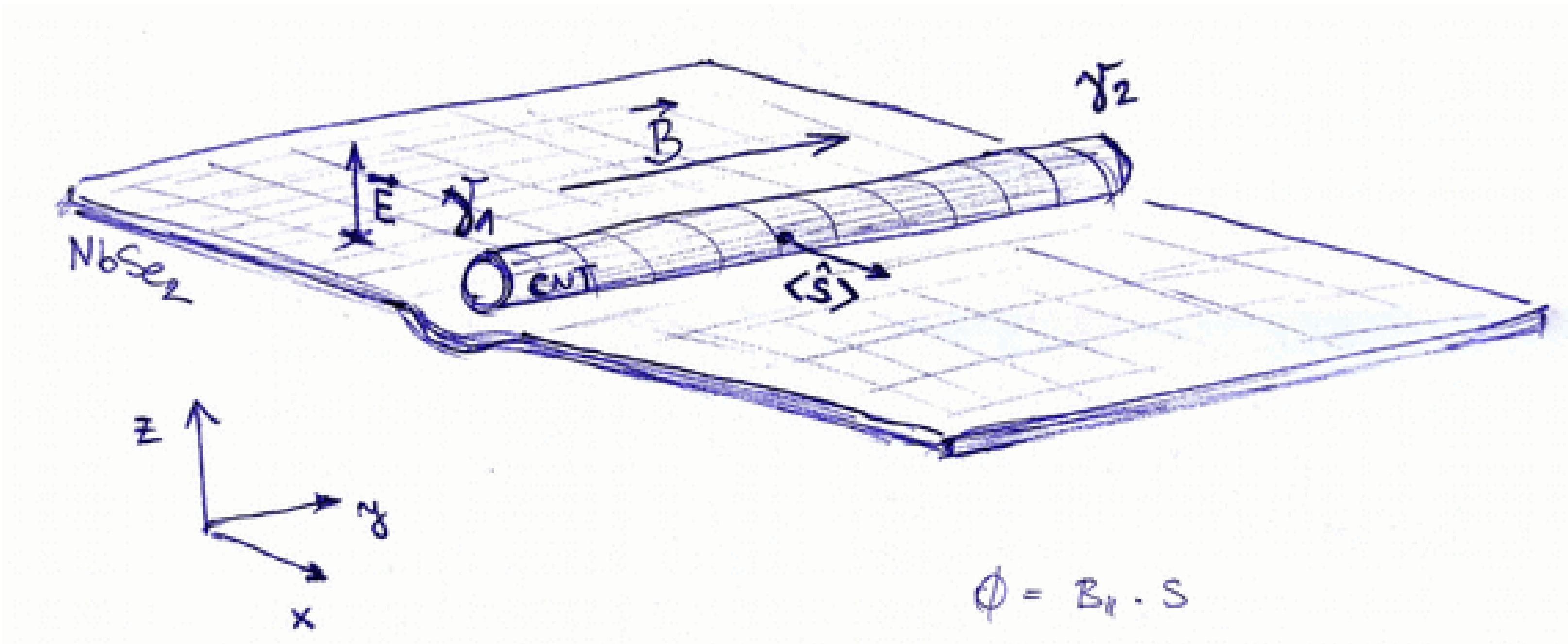
Spin-orbit coupling form



Spin-orbit coupling form



Save the Majoranas!



$$\Phi = B_\parallel \cdot S$$

$$B_\parallel = 10T$$

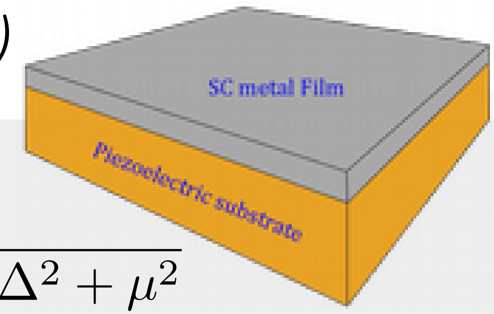
$$S = \pi R^2 = \pi \left(\frac{8.3 Å}{2}\right)^2 = 54.1 Å^2$$

$$\Phi = 1.308 \times 10^{-5} \phi_0$$

[*]Note: magnetic splitting in 10 Tesla would be 1 meV

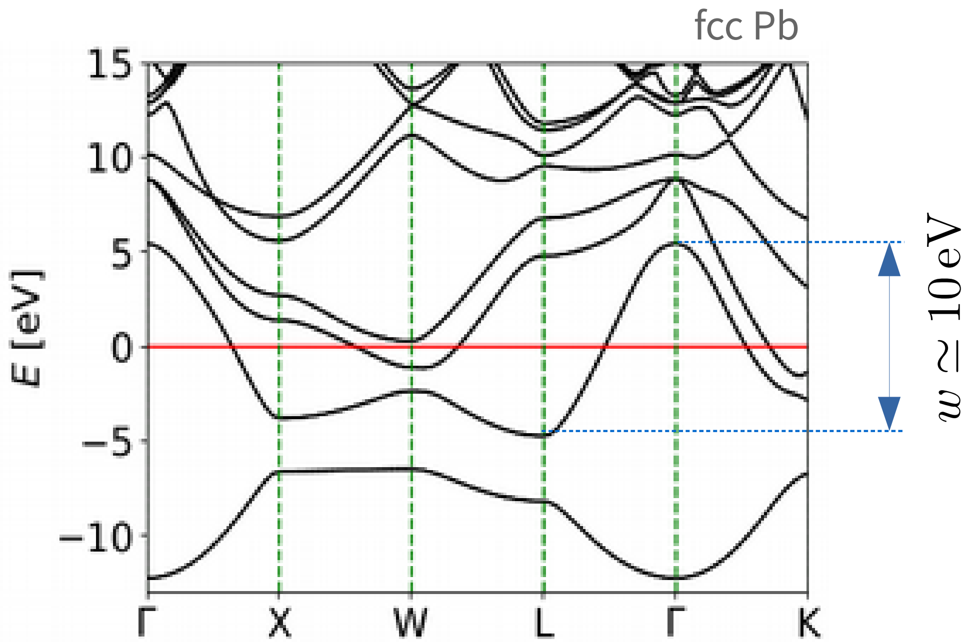
Ultrathin films of superconductors

a platform for topological superconducivity (Pb or β-Sn)



- **Cooper pairing**
- **broken inversion symmetry**
- **broken time-reversal symmetry**

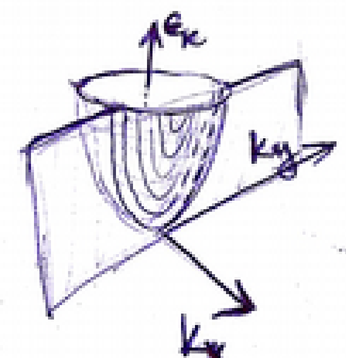
$$\Delta_z = g\mu_{\mathrm{B}}B > \sqrt{\Delta^2 + \mu^2}$$

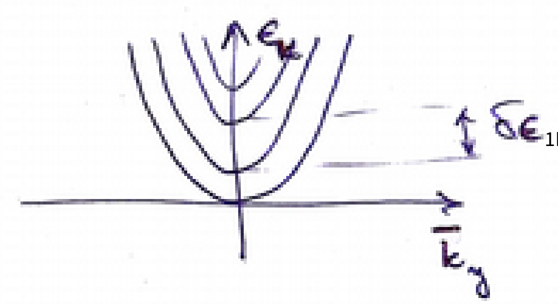


large *g*-factor	~ 100 – 350
E-field 0.1 V/nm	~ 2 meV subbands shift
strain of 1%	~ 200 meV Fermi level tunning

$$w/2N \simeq \delta\varepsilon_{2D}$$

$$H_{c,\perp} \approx 1.6\,\mathrm{T} \qquad H_{c,\parallel} \approx 55\,\mathrm{T}$$





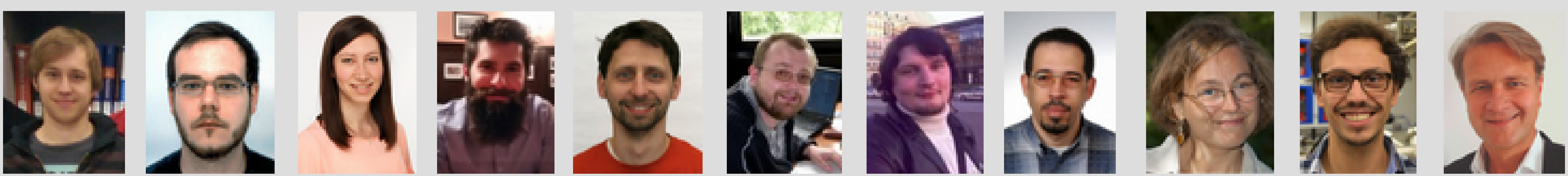
Advantage: *interface or proximity effect free* system to obtain SC in a strong SOC systems

C. Lei, H. Chen, A.H. MacDonald, arXiv:1801.05020

Conclusions

- **symmetry dictates topology** of spin-orbit coupling fields
- **appreciable proximity** induced spin-orbit coupling effects in vdW heterostructures
- **carbon nanotubes** could host **Majorana** bound states
- promising topological superconductivity in **thin films of heavy elements**

Acknowledgments



Tobias Frank, Klaus Zollner, Petra Högl, Paulo E. Faria, Marcin Kurpas, Denis Kochan, Sergej Konschuh, Alex Matos, Magda Marganska, Flo Dirnberger, Jaroslav Fabian