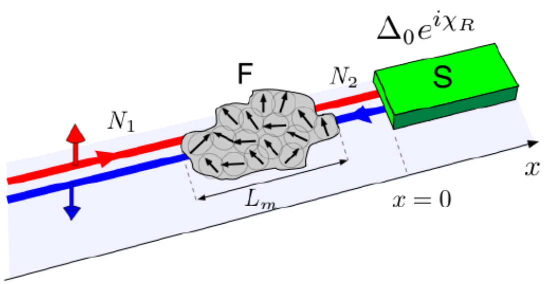
Superconducting hybrid structures based on QSH systems



New Perspectives in Spintronic and Mesoscopic Physics

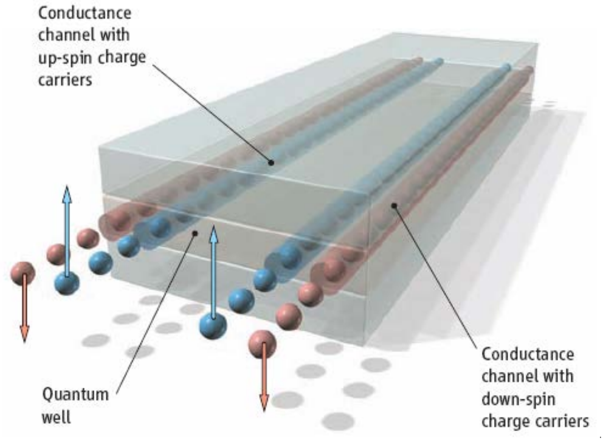
June 1-19, 2015
Kashiwa, Japan

$$F^R = G^R_{eh} i\sigma_2 = \begin{pmatrix} F^R_{\uparrow\uparrow} & F^R_{\uparrow\downarrow} \\ F^R_{\downarrow\uparrow} & F^R_{\downarrow\downarrow} \end{pmatrix}$$

Björn Trauzettel

Pablo Burset (Uni Würzburg)
François Crépin (Uni Würzburg)
Fabrizio Dolcini (PolyTech Torino)
Felix Keidel (Uni Würzburg)

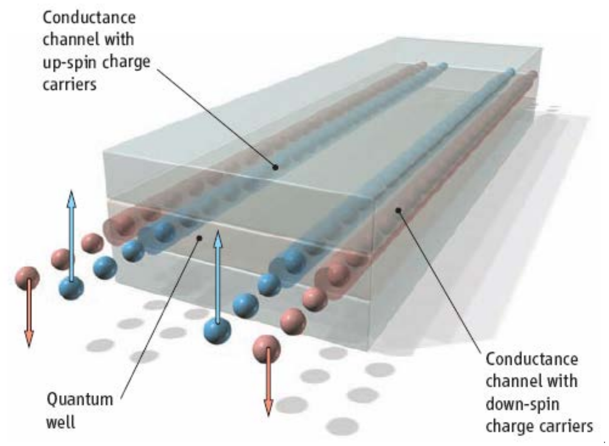
QSHE (in a nutshell)

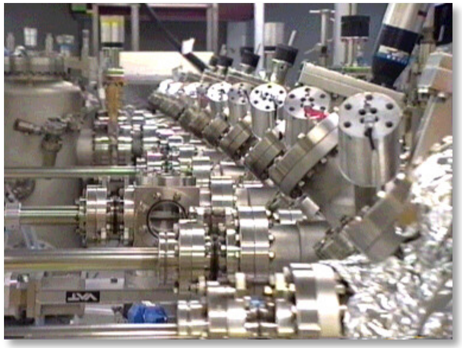


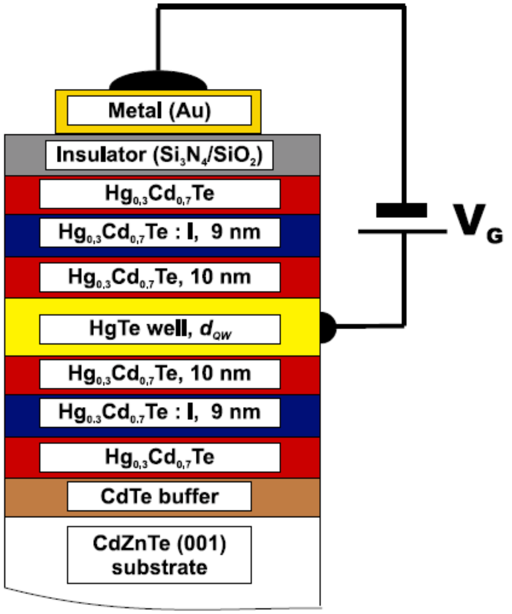
symmetry protected
topological state of matter

Kane & Mele PRL 2005
Bernevig, Hughes & Zhang Science 2006

QSHE (in a nutshell)







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König, Molenkamp et al. JPSJ 2008

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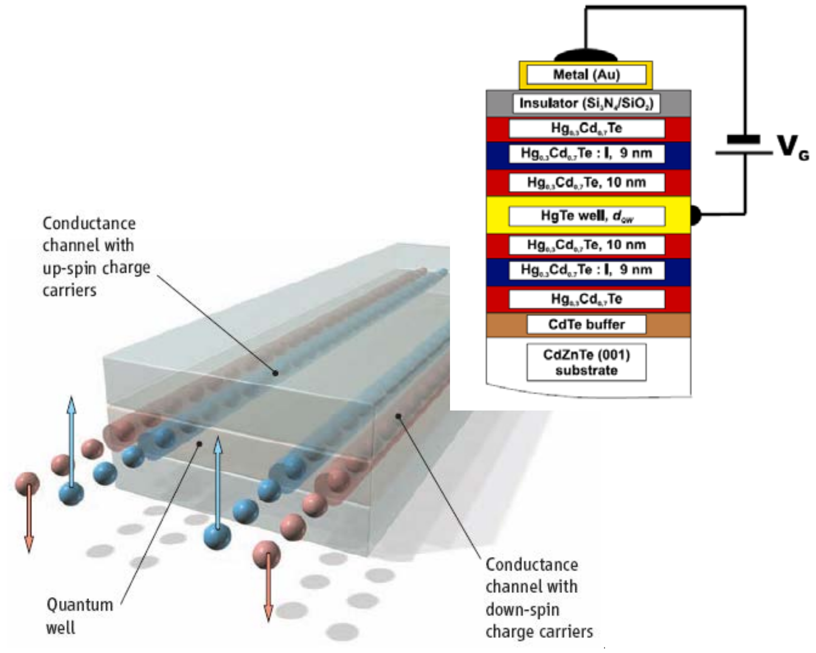

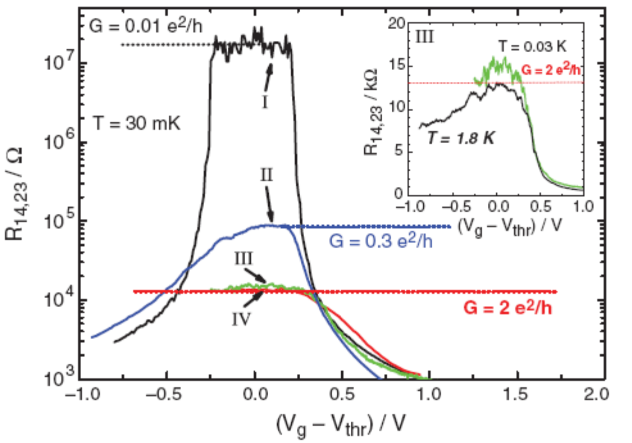

König, Molenkamp et al. Science 2007

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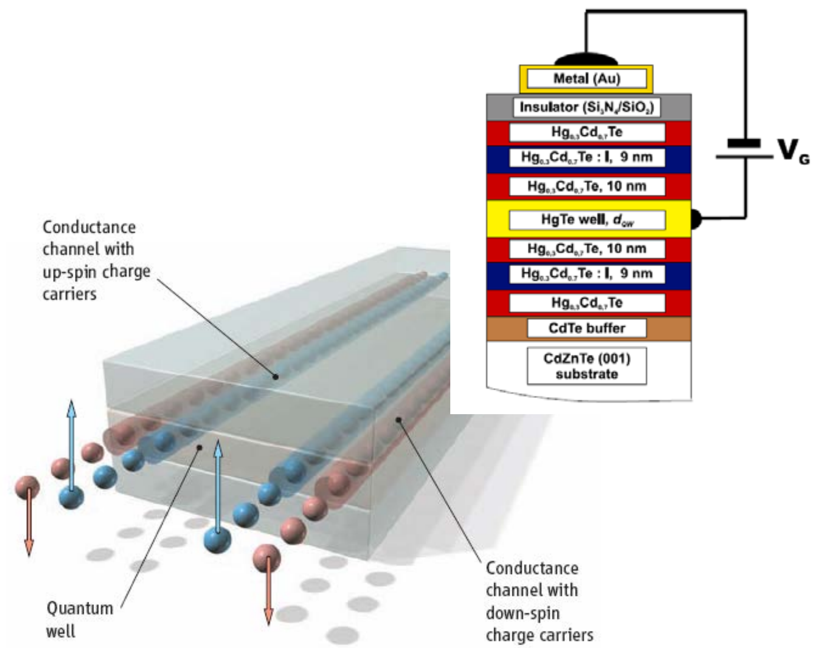

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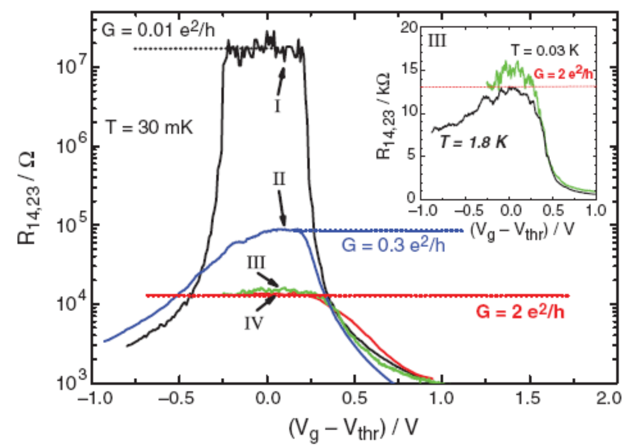
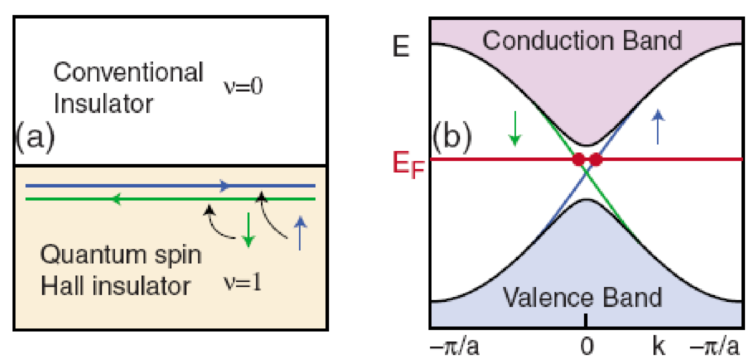
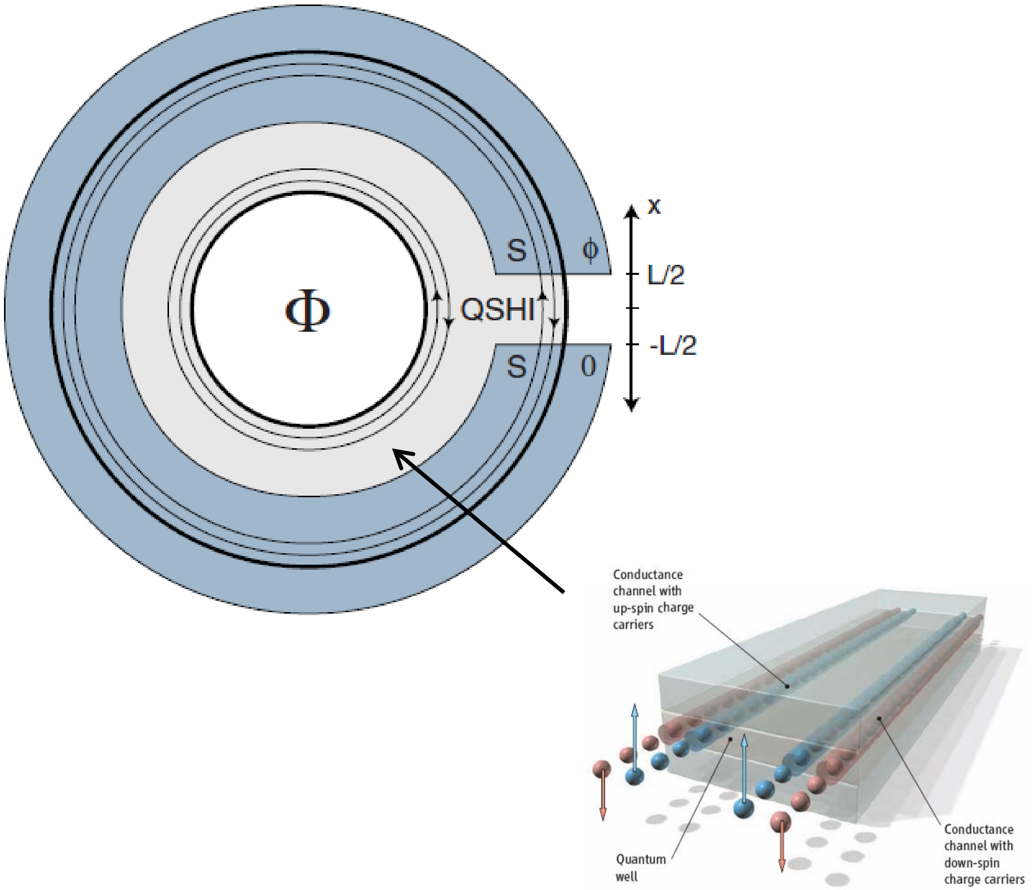


König, Molenkamp et al. Science 2007



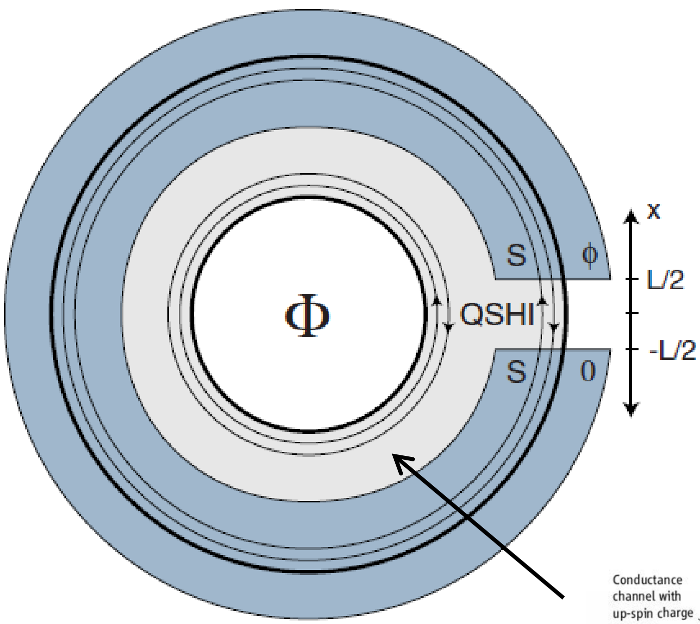
Hasan & Kane RMP 2010

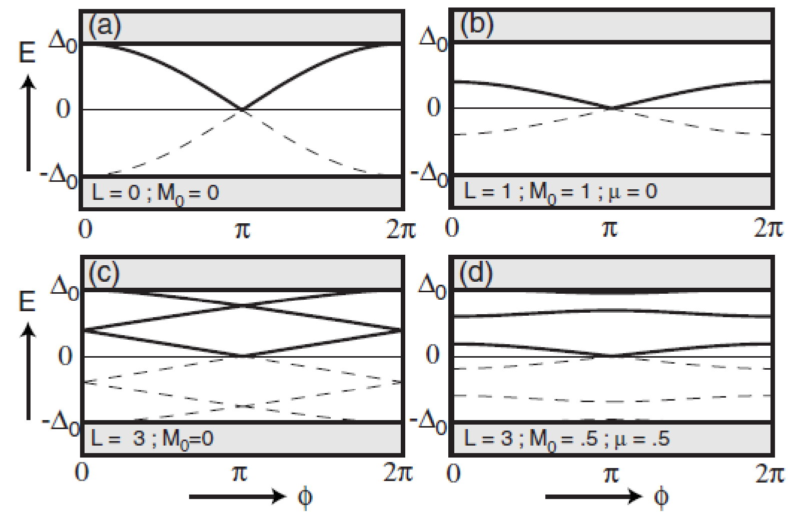
Pioneering prediction

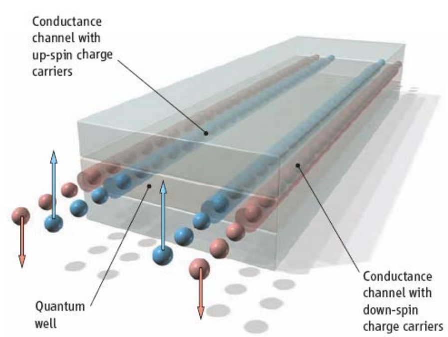


Fu & Kane PRB 2009

Pioneering prediction





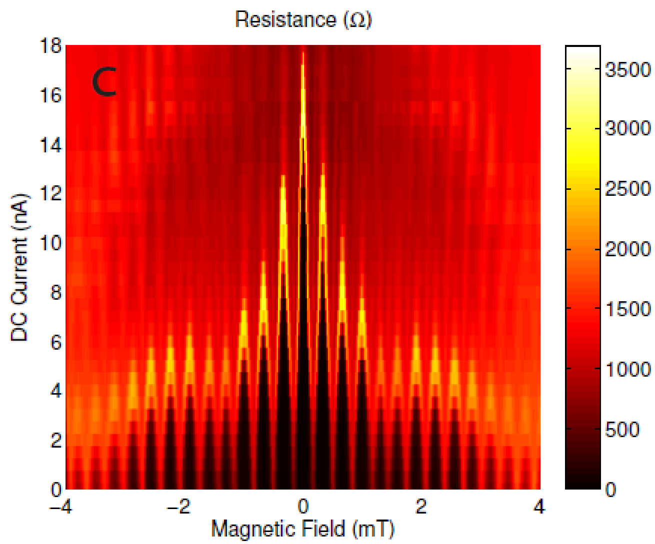


signatures of **p-wave** superconductivity?

Fu & Kane PRB 2009

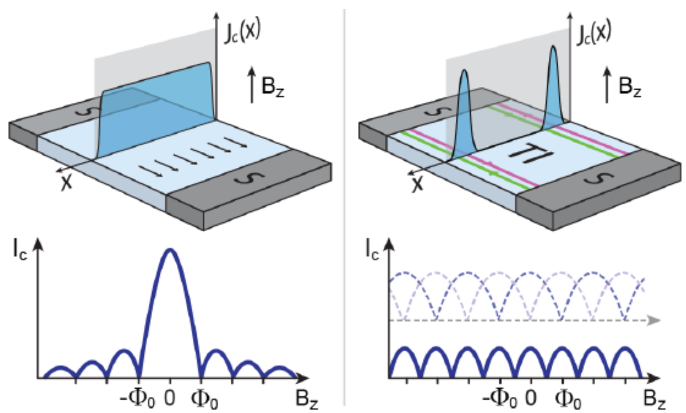
Inspiring experiments

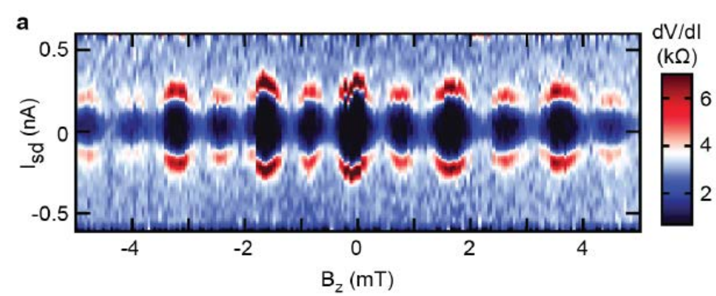
Hg(Cd)Te QWs



Hart, Molenkamp, Yacoby et al. Nature Phys 2014

InAs/GaSb QWs



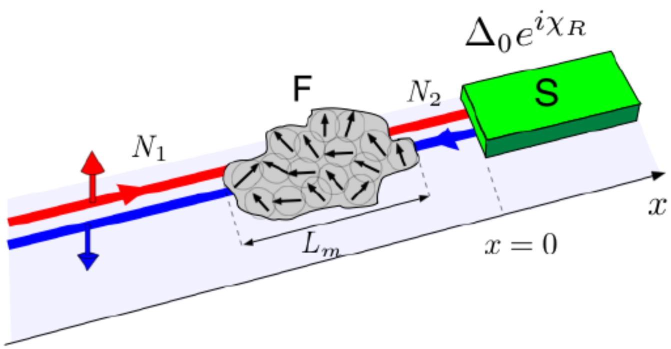


Pribiag, Kouwenhoven et al. Nature Nano 2015

Outline

- Transport signatures of NS junctions -> Majorana bound states
- Crossed Andreev reflection in NSN setups -> odd-frequency triplet superconductivity

Setup & Hamiltonian

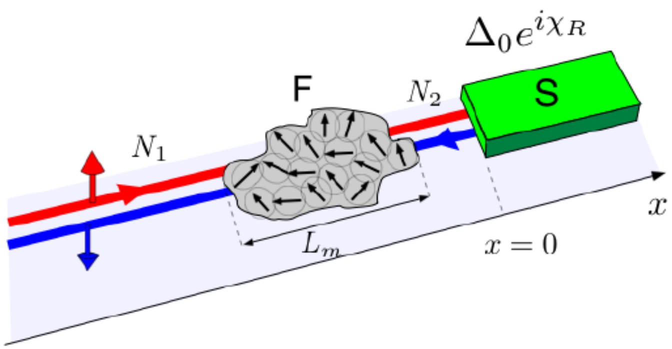


$$H = H_0 + H_{FM} + H_{SC}$$

$$H_0 = \int dx \left(\psi^\dagger_{R\uparrow}, \psi^\dagger_{L\downarrow}\right)\left[v_F p_x \sigma_z - \mu\right]\begin{pmatrix}\psi_{R\uparrow}\\ \psi_{L\downarrow}\end{pmatrix}$$

Crépin, BT & Dolcini PRB 2014

Setup & Hamiltonian



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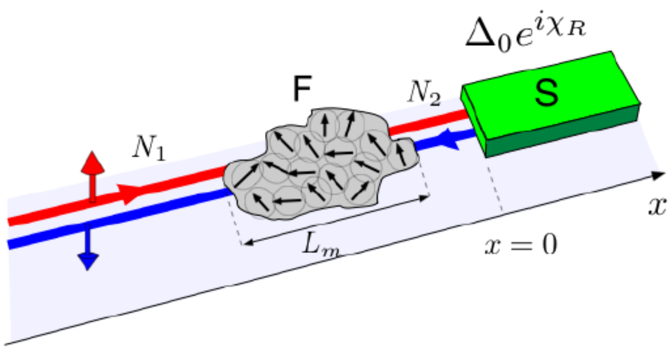
$$H_{FM} = \int dx \left(\psi^\dagger_{R\uparrow}, \psi^\dagger_{L\downarrow}\right) \vec{m}(x) \cdot \vec{\sigma} \begin{pmatrix}\psi_{R\uparrow} \\ \psi_{L\downarrow}\end{pmatrix}$$

Crépin, BT & Dolcini PRB 2014

Setup & Hamiltonian



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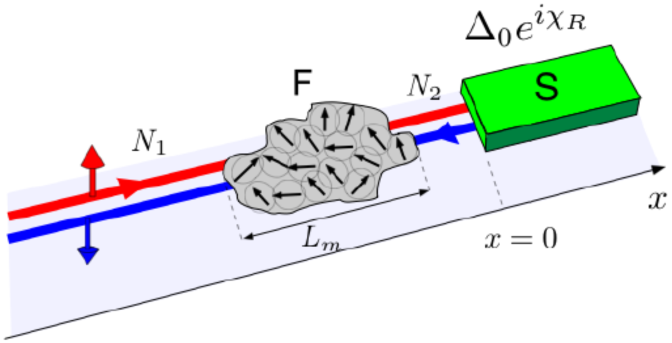
$$H_{SC} = \int dx \left[\Delta(x)\psi^\dagger_{R\uparrow}\psi^\dagger_{L\downarrow} + \Delta^*(x)\psi_{L\downarrow}\psi_{R\uparrow}\right]$$

Crépin, BT & Dolcini PRB 2014

BdG Hamiltonian



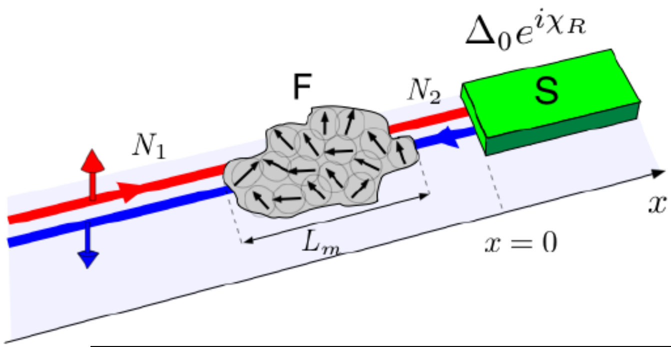
$$H = \frac{1}{2}\int dx \Psi^\dagger H_{BdG} \Psi$$

$$\Psi^\dagger = \left(\psi^\dagger_{R\uparrow}, \psi^\dagger_{L\downarrow}, \psi_{L\downarrow}, -\psi_{R\uparrow}\right)$$

$$H_{BdG} = \begin{pmatrix} H^e_{0+FM} & \Delta(x)\sigma_0 \\ \Delta^*(x)\sigma_0 & H^h_{0+FM} \end{pmatrix}$$

Crépin, BT & Dolcini PRB 2014

BdG Hamiltonian



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$$\Psi^\dagger = \left(\psi^\dagger_{R\uparrow}, \psi^\dagger_{L\downarrow}, \psi_{L\downarrow}, -\psi_{R\uparrow}\right)$$

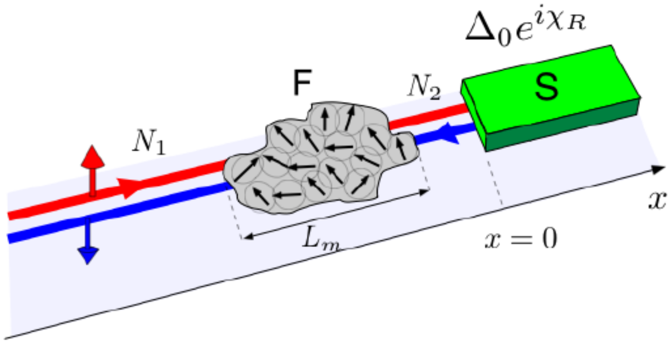
$$H^e_{0+FM} = v_F \sigma_z p_x - \mu\sigma_0 + \vec{m}\left(x\right)\cdot\vec{\sigma}$$

$$H_{BdG} = \begin{pmatrix} H^e_{0+FM} & \Delta\left(x\right)\sigma_0 \\ \Delta^*\left(x\right)\sigma_0 & H^h_{0+FM} \end{pmatrix}$$

$$H^h_{0+FM} = -TH^e_{0+FM}T^{-1}$$

Crépin, BT & Dolcini PRB 2014

BdG Hamiltonian



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$$H_{BdG} = \begin{pmatrix} H^e_{0+FM} & \Delta(x)\sigma_0 \\ \Delta^*(x)\sigma_0 & H^h_{0+FM} \end{pmatrix}$$

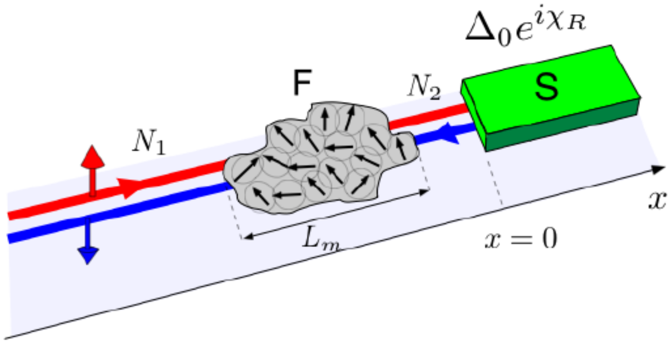
$$H = \sum_{\varepsilon_n \geq 0, j} \varepsilon_n \gamma^\dagger_{\varepsilon_n, j} \gamma_{\varepsilon_n, j}$$

$$\Psi(x) = \sum_{\varepsilon_n \geq 0, j} \left\{ \varphi_{\varepsilon_n, j}(x)\gamma_{\varepsilon_n, j} + \left[C\varphi_{\varepsilon_n, j}\right](x)\gamma^\dagger_{\varepsilon_n, j} \right\}$$

charge conjugated wave function

Crépin, BT & Dolcini PRB 2014

Symmetries & Majoranas



Particle-hole symmetry

$$C H_{BdG} C^{-1} = -H_{BdG}$$

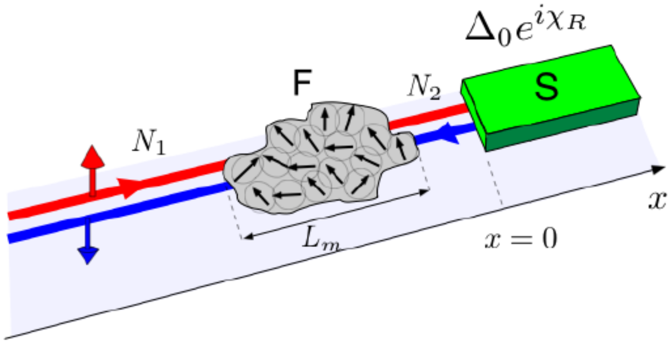
$$C = K\tau_y \otimes \sigma_y = K U_C$$

$$\gamma^\dagger_{\varepsilon_n, j} = \gamma_{-\varepsilon_n, j}$$

Chamon, Jackiw, Nishida, Pi & Santos PRB 2010

Crépin, BT & Dolcini PRB 2014

Symmetries & Majoranas



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Majorana fermion

Chamon, Jackiw, Nishida, Pi & Santos PRB 2010

Crépin, BT & Dolcini PRB 2014

Majorana fermions *vs.* anyons

Majorana fermions

$$\Psi(x) = \sum_{\varepsilon_n \geq 0, j} \left\{ \varphi_{\varepsilon_n, j}(x)\, \gamma_{\varepsilon_n, j} + \left[C \varphi_{\varepsilon_n, j} \right](x)\, \gamma^{\dagger}_{\varepsilon_n, j} \right\}$$

fermions

$$\Psi^{\dagger}(x) = U_C \Psi(x)$$

$$\gamma^{\dagger}_{\varepsilon_n, j} = \gamma_{-\varepsilon_n, j}$$

Chamon, Jackiw, Nishida, Pi & Santos PRB 2010

Majorana fermions *vs.* anyons

Majorana fermions

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fermions

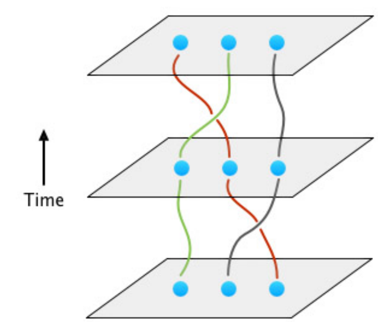
$$\Psi^{\dagger}(x) = U_C \Psi(x)$$

$$\gamma^{\dagger}_{\varepsilon_n, j} = \gamma_{-\varepsilon_n, j}$$

Majorana bound states

$$\gamma^{\dagger}_{0, j} = \gamma_{0, j}$$

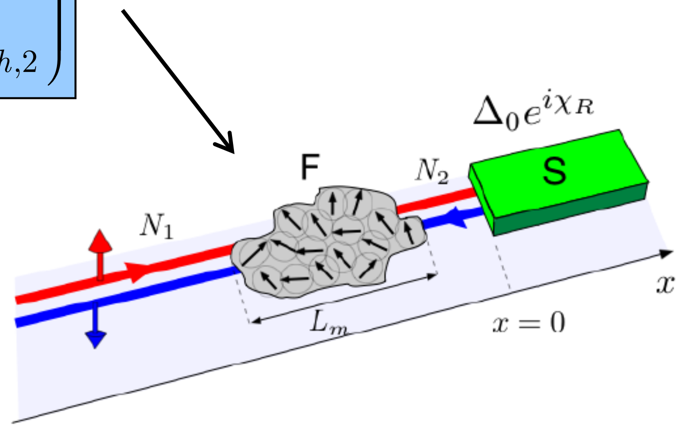
anyons



Chamon, Jackiw, Nishida, Pi & Santos PRB 2010

S-matrix construction

$$\begin{pmatrix} b_{e,1} \\ b_{e,2} \\ b_{h,1} \\ b_{h,2} \end{pmatrix} = \begin{pmatrix} S_0^e(\varepsilon) & 0 \\ 0 & S_0^h(\varepsilon) \end{pmatrix} \begin{pmatrix} a_{e,1} \\ a_{e,2} \\ a_{h,1} \\ a_{h,2} \end{pmatrix}$$



Crépin, BT & Dolcini PRB 2014

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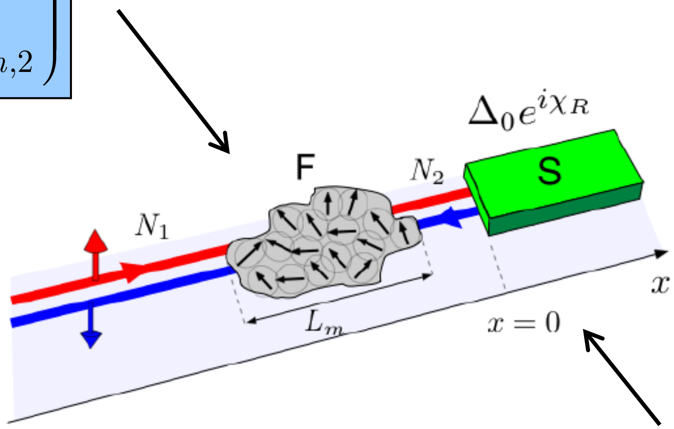


perfect AR

$$\begin{pmatrix} a_{e,2} \\ a_{h,2} \end{pmatrix} = \exp\left(-i \arccos\left(\frac{\varepsilon}{\Delta_0}\right)\right) \begin{pmatrix} 0 & e^{i\chi_R} \\ e^{-i\chi_R} & 0 \end{pmatrix} \begin{pmatrix} b_{e,2} \\ b_{h,2} \end{pmatrix}$$

Crépin, BT & Dolcini PRB 2014

S-matrix of FM domain

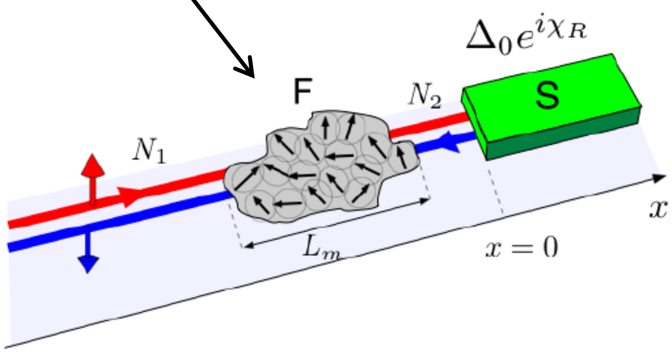
$$\Gamma_m(\varepsilon) \sim k_F L_m$$

$$\Phi_m(\varepsilon) \sim k_F x_0$$

$$S_0^e(\varepsilon) = e^{i\Gamma_m(\varepsilon)} \begin{pmatrix} -ie^{i\Phi_m(\varepsilon)}\sqrt{1-T_\varepsilon} & e^{i\chi_m(\varepsilon)}\sqrt{T_\varepsilon} \\ e^{-i\chi_m(\varepsilon)}\sqrt{T_\varepsilon} & -ie^{-i\Phi_m(\varepsilon)}\sqrt{1-T_\varepsilon} \end{pmatrix}$$

$$\chi_m(\varepsilon) \sim m_z L_m$$

all symmetries broken

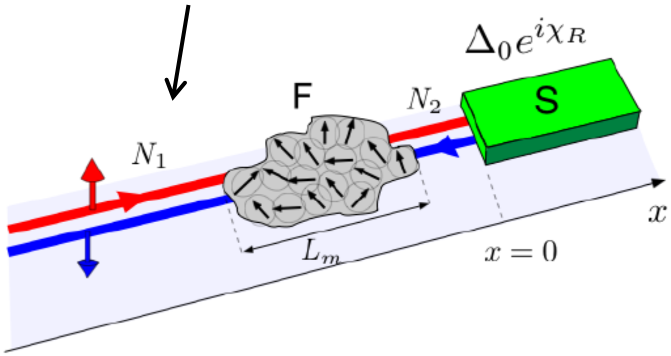


Crépin, BT & Dolcini PRB 2014

Andreev reflection

$$\begin{pmatrix} b_{e,1} \\ b_{h,1} \end{pmatrix} = \begin{pmatrix} r_{ee} & r_{eh} \\ r_{he} & r_{hh} \end{pmatrix} \begin{pmatrix} a_{e,1} \\ a_{h,1} \end{pmatrix}$$

$$R_A = \left| r_{eh} \right|^2 = \left| r_{he} \right|^2$$



Crépin, BT & Dolcini PRB 2014

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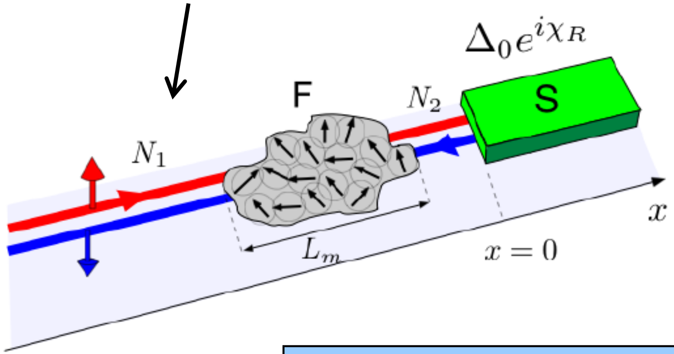
$$R_A = |r_{eh}|^2 = |r_{he}|^2$$



$$\Phi_m^A(\varepsilon) = \frac{1}{2}\left(\Phi_m(\varepsilon) - \Phi_m(-\varepsilon)\right)$$

$$R_A = \frac{T_\varepsilon T_{-\varepsilon}}{\left(1 - \sqrt{R_\varepsilon R_{-\varepsilon}}\right)^2 + 4\cos^2\left[\arccos\left(\frac{\varepsilon}{\Delta_0}\right) + \Phi_m^A(\varepsilon)\right]\sqrt{R_\varepsilon R_{-\varepsilon}}}$$

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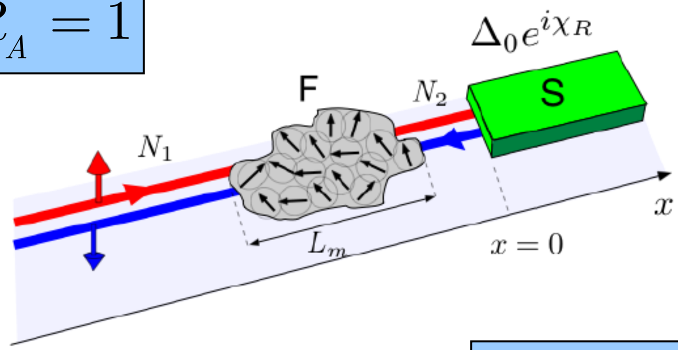
Resonance condition

$$R_A = 1$$



$$\left(\sqrt{R_\varepsilon} - \sqrt{R_{-\varepsilon}}\right)^2 + 4\cos^2\left[\arccos\left(\frac{\varepsilon}{\Delta_0}\right) + \Phi_m^A(\varepsilon)\right]\sqrt{R_\varepsilon R_{-\varepsilon}} = 0$$

Crépin, BT & Dolcini PRB 2014

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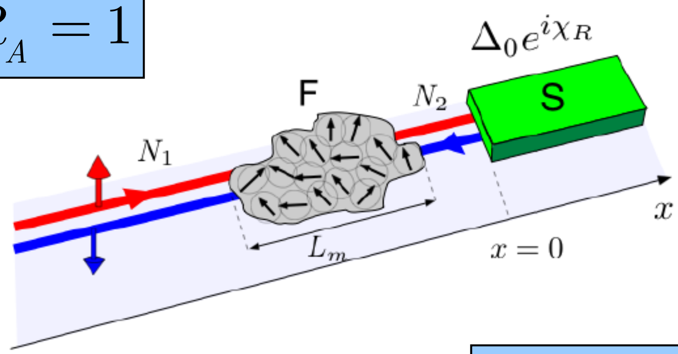

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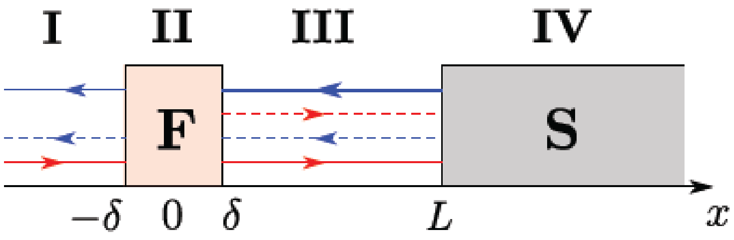
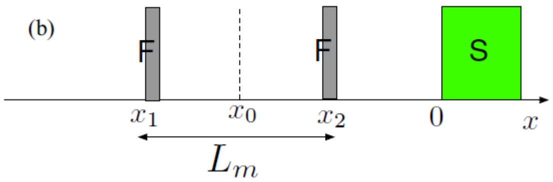
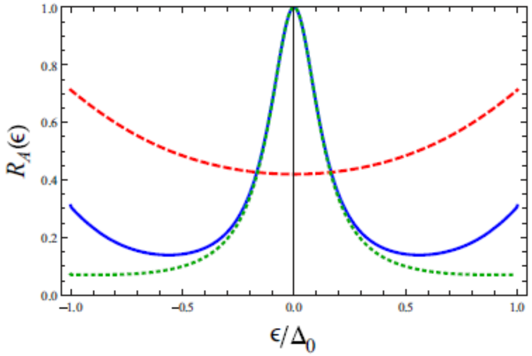
Fabry-Perot resonator
for electrons/holes



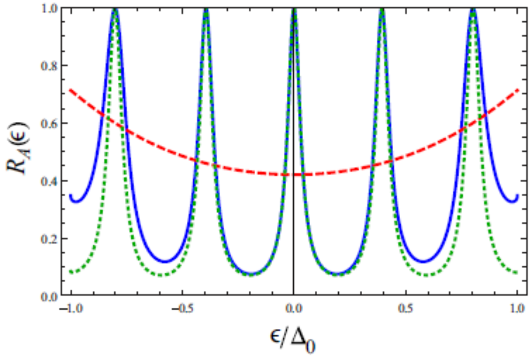
Crépin, BT & Dolcini PRB 2014

Detection of MBS





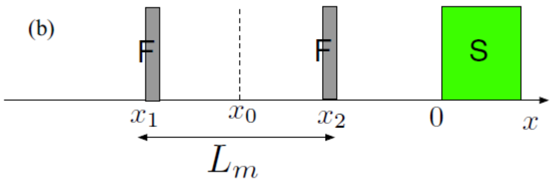
(a) $\mu_0 = 0.5, \mu = 0, L_m = 1, x_0 = 1.5, \Delta\phi = 0$

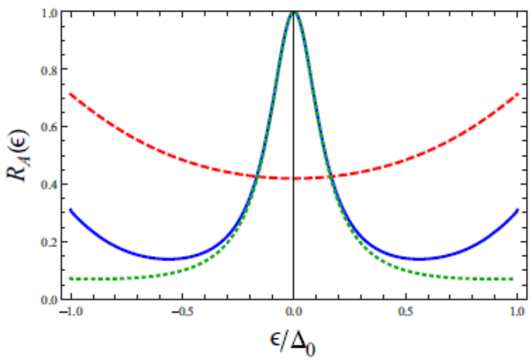


(b) $\mu_0 = 0.5, \mu = 0, L_m = 1, x_0 = 4.5, \Delta\phi = 0$

Crépin, BT & Dolcini PRB 2014

Detection of MBS





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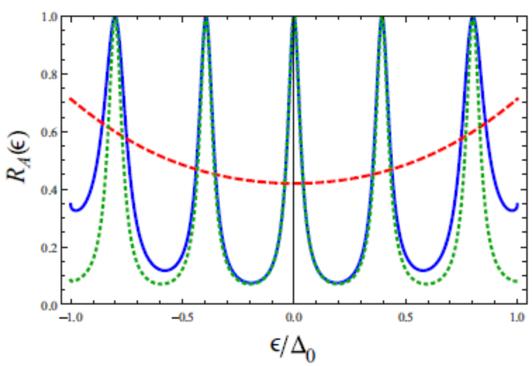
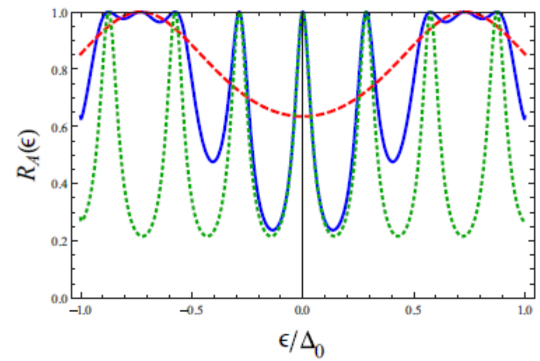
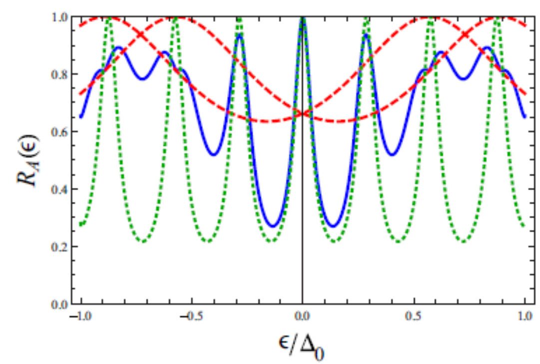


(b) $\mu_0 = 0.5, \mu = 0, L_m = 1, x_0 = 4.5, \Delta\phi = 0$



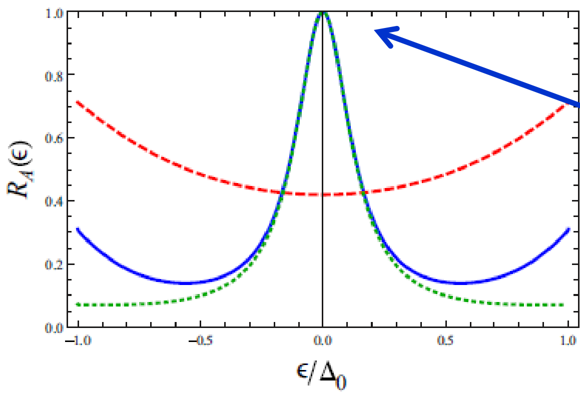
(a) $\mu_0 = 0.35, \mu = 0, L_m = 2.15, x_0 = 6$



(b) $\mu_0 = 0.35, \mu = 0.16, L_m = 2.15, x_0 = 6$

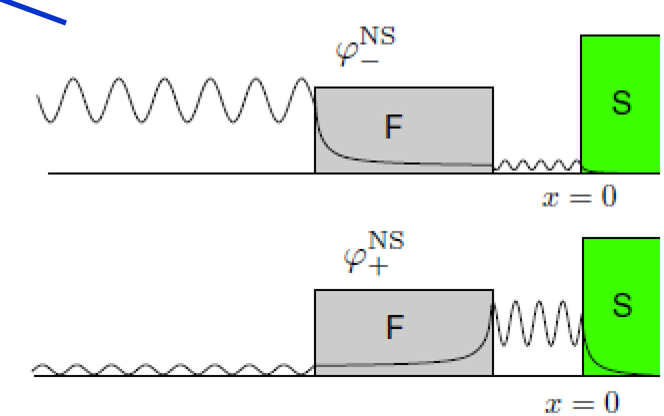
Crépin, BT & Dolcini PRB 2014

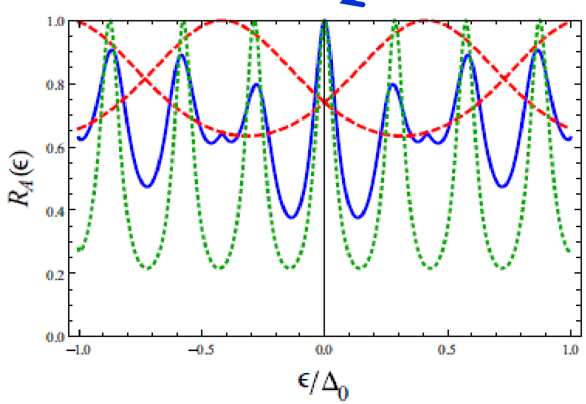
Robust MBS signature



(a) $\mu_0 = 0.5, \mu = 0, L_m = 1, x_0 = 1.5, \Delta\phi = 0$

$$C\varphi_{\pm}^{NS} = \varphi_{\pm}^{NS}$$





(c) $\mu_0 = 0.35, \mu = 0.3, L_m = 2.15, x_0 = 6$

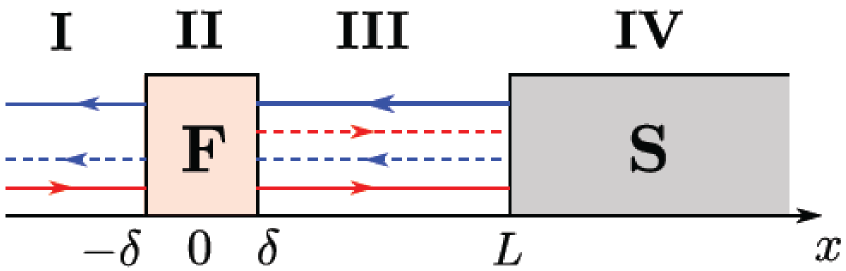
Majorana bound states $\varepsilon = 0$

Crépin, BT & Dolcini PRB 2014

Outline

- Transport signatures of NS junctions -> Majorana bound states
- Crossed Andreev reflection in NSN setups ->
  odd-frequency triplet superconductivity

Model and setup



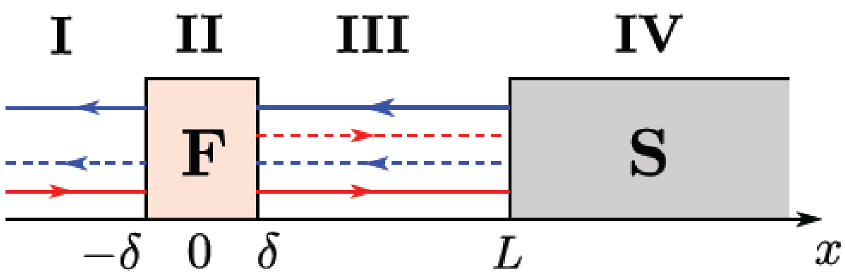
BdG Hamiltonian

$$H = \frac{1}{2}\int dx \Psi^\dagger H_{BdG} \Psi$$

$$\Psi^\dagger = \left(\psi^\dagger_{R\uparrow}, \psi^\dagger_{L\downarrow}, \psi_{L\downarrow}, -\psi_{R\uparrow}\right)$$

Crépin, Burset & BT arXiv 2015

Model and setup



BdG Hamiltonian

$$H = \frac{1}{2}\int dx \Psi^\dagger H_{BdG} \Psi$$

$$\Psi^\dagger = \left(\psi^\dagger_{R\uparrow}, \psi^\dagger_{L\downarrow}, \psi_{L\downarrow}, -\psi_{R\uparrow}\right)$$

spin space

$$H_{BdG} = \left(-iv_F \partial_x \sigma_z - \mu\right)\tau_z + \vec{m}(x)\cdot\vec{\sigma} + \Delta_1(x)\tau_x + \Delta_2(x)\tau_y$$

particle-hole space

Crépin, Burset & BT arXiv 2015

Julius-Maximilians-
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Green's functions

$$r = (x, t)$$

$$G^R\left(r, r'\right) = -i\theta\left(t - t'\right)\left\langle\left\{\Psi\left(r\right), \Psi^\dagger\left(r'\right)\right\}\right\rangle$$

$$G^A\left(r, r'\right) = i\theta\left(t - t'\right)\left\langle\left\{\Psi\left(r\right), \Psi^\dagger\left(r'\right)\right\}\right\rangle$$

$$G^M\left(x, \tau, x', \tau'\right) = -\left\langle T_\tau \Psi\left(x, \tau\right)\Psi^\dagger\left(x', \tau'\right)\right\rangle$$

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Green's functions

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$$G^R(r, r') = -i\theta(t - t')\left\langle\left\{\Psi(r), \Psi^\dagger(r')\right\}\right\rangle$$

$$G^A(r, r') = i\theta(t - t')\left\langle\left\{\Psi(r), \Psi^\dagger(r')\right\}\right\rangle$$

$$G^M(x, \tau, x', \tau') = -\left\langle T_\tau \Psi(x, \tau) \Psi^\dagger(x', \tau')\right\rangle$$

$$G^X = \begin{pmatrix} G^X_{ee} & G^X_{eh} \\ G^X_{he} & G^X_{hh} \end{pmatrix}$$

4x4 matrix

$$G^X_{eh} = \begin{pmatrix} \left[G^X_{eh}\right]_{\uparrow\downarrow} & \left[G^X_{eh}\right]_{\uparrow\uparrow} \\ \left[G^X_{eh}\right]_{\downarrow\downarrow} & \left[G^X_{eh}\right]_{\downarrow\uparrow} \end{pmatrix}$$

Scattering states: N side

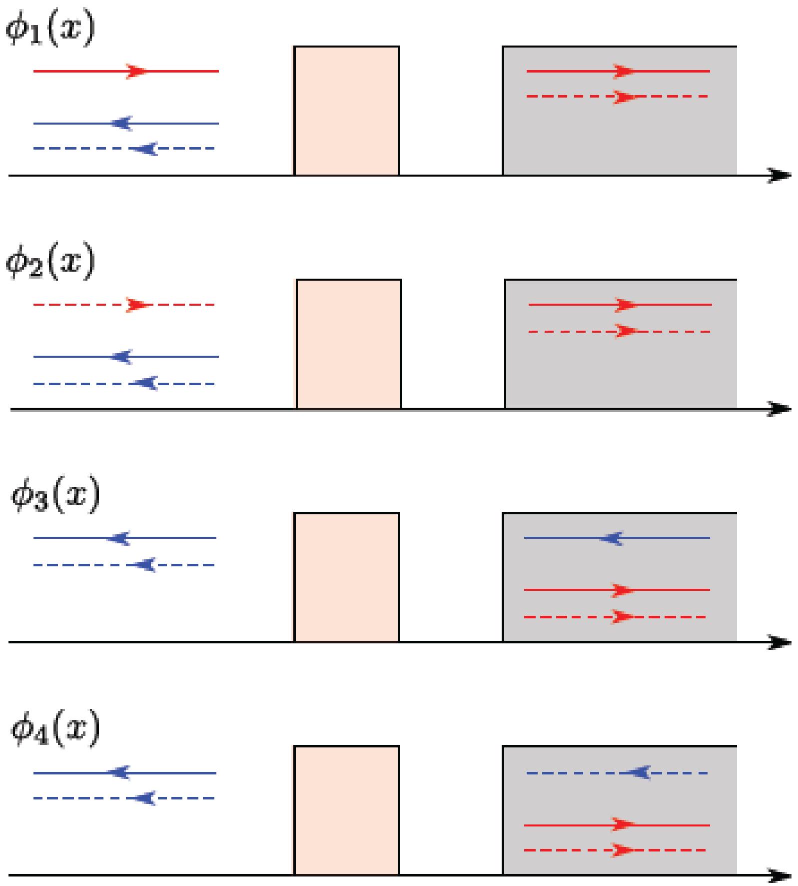
$$\phi_1(x) = \phi_e^{(+)} e^{ik_e x} + a_1 \phi_h^{(-)} e^{ik_h x} + b_1 \phi_e^{(-)} e^{-ik_e x}$$

$$\phi_2(x) = \phi_h^{(+)} e^{-ik_h x} + b_2 \phi_h^{(-)} e^{ik_h x} + a_2 \phi_e^{(-)} e^{-ik_e x}$$

$$\phi_3(x) = c_3 \phi_e^{(-)} e^{-ik_e x} + d_3 \phi_h^{(-)} e^{ik_h x}$$

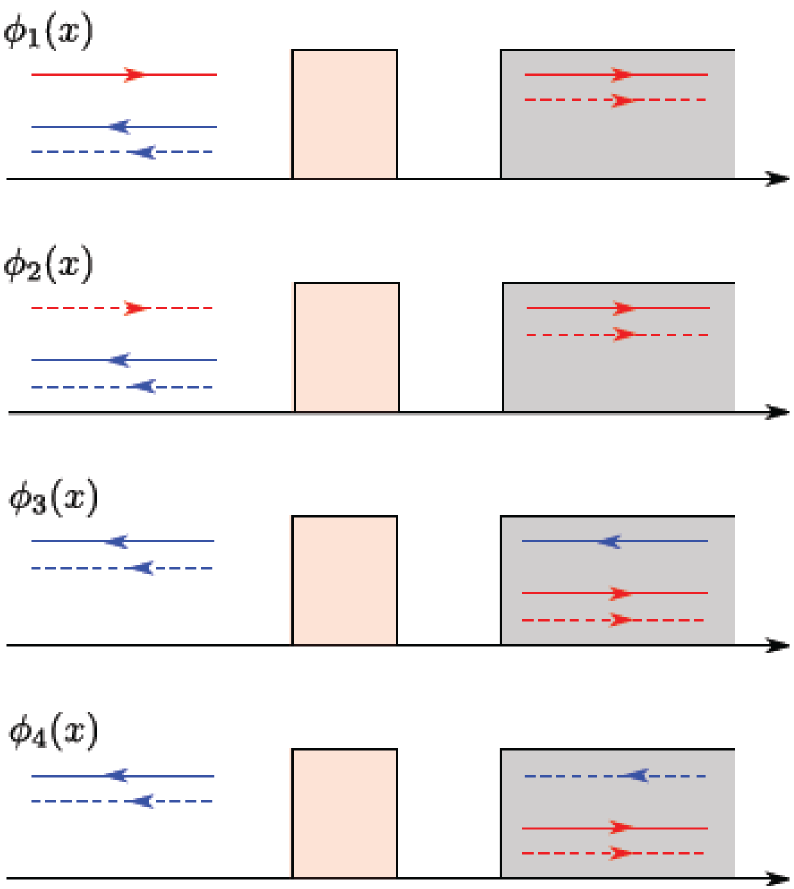
$$\phi_4(x) = d_4 \phi_e^{(-)} e^{-ik_e x} + c_4 \phi_h^{(-)} e^{ik_h x}$$

$$k_e = \mu + \varepsilon \qquad k_h = \mu - \varepsilon$$



McMillan Phys. Rev. 1968

Scattering states: S side



$$\phi_1(x) = c_1 \chi_e^{(+)} e^{ik_e^S x} + d_1 \chi_h^{(+)} e^{-ik_h^S x}$$

$$\phi_2(x) = d_2 \chi_e^{(+)} e^{ik_e^S x} + c_2 \chi_h^{(+)} e^{-ik_h^S x}$$

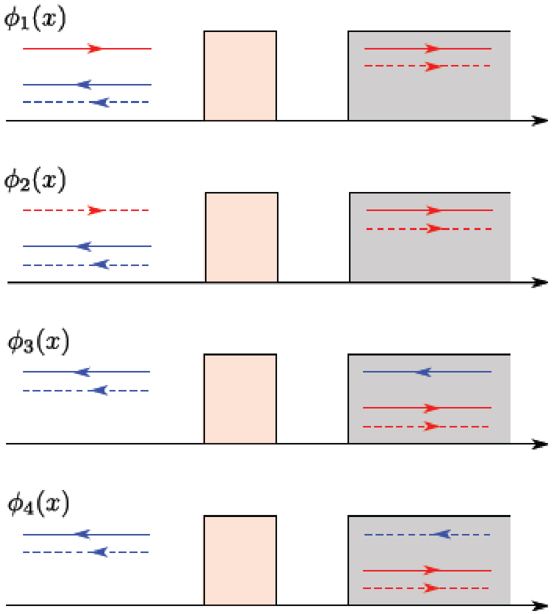
$$\phi_3(x) = \chi_e^{(-)} e^{-ik_e^S x} + a_3 \chi_h^{(+)} e^{-ik_e^S x} + b_3 \chi_h^{(+)} e^{ik_e^S x}$$

$$\phi_4(x) = \chi_h^{(-)} e^{ik_h^S x} + b_4 \chi_h^{(+)} e^{-ik_h^S x} + a_4 \chi_e^{(+)} e^{ik_e^S x}$$

$$k_e^S = \mu + \sqrt{\varepsilon^2 - \Delta^2} \qquad k_h^S = \mu - \sqrt{\varepsilon^2 - \Delta^2}$$

McMillan Phys. Rev. 1968

Green's functions from scattering states



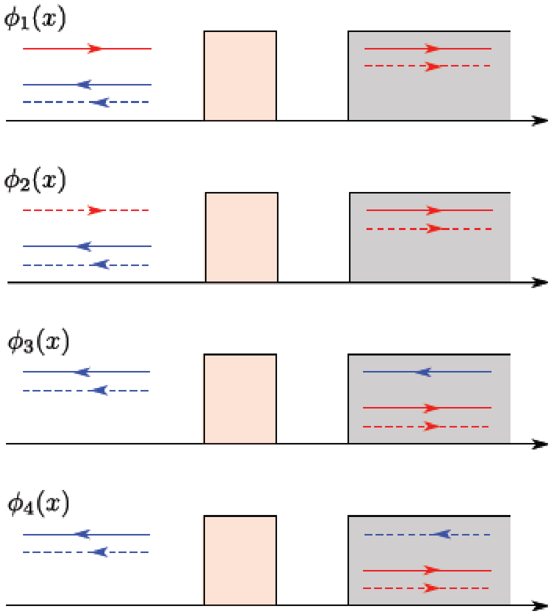
$$G^R_\omega\left(x,x'\right)=\int dt e^{i\left(\omega+i\eta\right)\left(t-t'\right)}G^R\left(x,t,x',t'\right)$$

$$\left[w-H_{BdG}\left(x\right)\right]G^R_\omega\left(x,x'\right)=\delta\left(x-x'\right)$$

$$\lim_{\varepsilon\to 0}\left[G^R_\omega\left(x+\varepsilon,x\right)-G^R_\omega\left(x-\varepsilon,x\right)\right]=\frac{1}{iv_F}\sigma_z\tau_z$$

McMillan Phys. Rev. 1968

Green's functions from scattering states



$$G^R_\omega(x,x') = \int dt e^{i(\omega+i\eta)(t-t')} G^R(x,t,x',t')$$

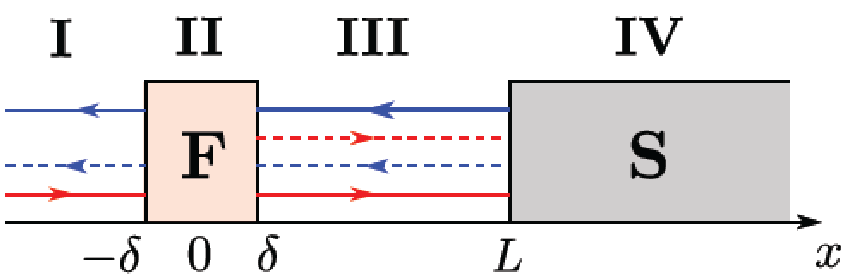
$$\left[w - H_{BdG}(x)\right] G^R_\omega(x,x') = \delta(x-x')$$

$$\lim_{\varepsilon\to 0}\left[G^R_\omega(x+\varepsilon,x) - G^R_\omega(x-\varepsilon,x)\right] = \frac{1}{iv_F}\sigma_z\tau_z$$

$$G^R_\omega(x,x') = \begin{cases} \phi_3(x)A_3(x')^T + \phi_4(x)A_4(x')^T & \text{if } x < x' \\ \phi_1(x)A_1(x')^T + \phi_2(x)A_2(x')^T & \text{if } x > x' \end{cases}$$

McMillan Phys. Rev. 1968

Pairing amplitude



Green‘s function

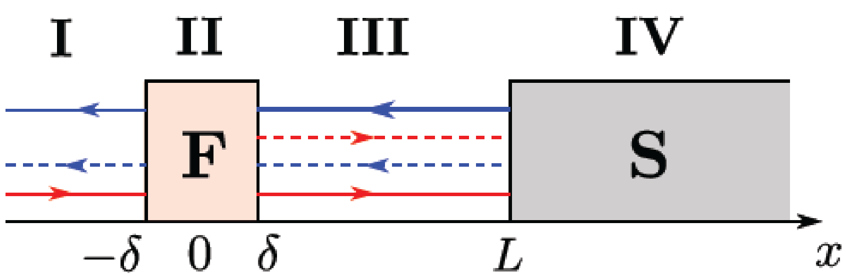
$$G^R = \begin{pmatrix} G^R_{ee} & G^R_{eh} \\ G^R_{he} & G^R_{hh} \end{pmatrix}$$

Pairing amplitude

$$F^R = G^R_{eh} i\sigma_2 = \begin{pmatrix} F^R_{\uparrow\uparrow} & F^R_{\uparrow\downarrow} \\ F^R_{\downarrow\uparrow} & F^R_{\downarrow\downarrow} \end{pmatrix}$$

Crépin, Burset & BT arXiv 2015

Pairing amplitude



Green's function

$$G^R = \begin{pmatrix} G^R_{ee} & G^R_{eh} \\ G^R_{he} & G^R_{hh} \end{pmatrix}$$

Pairing amplitude

$$F^R = G^R_{eh} i\sigma_2 = \begin{pmatrix} F^R_{\uparrow\uparrow} & F^R_{\uparrow\downarrow} \\ F^R_{\downarrow\uparrow} & F^R_{\downarrow\downarrow} \end{pmatrix}$$

singlet

triplet

$$F^R(x,x',\omega) = \left[f^R_0(x,x',\omega)\sigma_0 + f^R_i(x,x',\omega)\sigma_i \right] i\sigma_2$$

Crépin, Burset & BT arXiv 2015

Antisymmetry of pairing amplitude

singlet

triplet

$$F^R(x,x',\omega) = \left[f_0^R(x,x',\omega)\sigma_0 + f_i^R(x,x',\omega)\sigma_i\right] i\sigma_2$$

$$f_0^R(x,x',\omega) = f_0^A(x',x,-\omega)$$
$$f_i^R(x,x',\omega) = -f_i^A(x',x,-\omega)$$

Crépin, Burset & BT arXiv 2015

Classification of pairing amplitude

$$F^R(x,x',\omega) = \left[f_0^R(x,x',\omega)\sigma_0 + f_i^R(x,x',\omega)\sigma_i\right] i\sigma_2$$

orbital

$$f_0^R(x,x',\omega) = \pm f_0^R(x',x,\omega)$$
$$f_i^R(x,x',\omega) = \pm f_i^R(x',x,\omega)$$

Berezinskii JETP Lett 1974

Tanaka, Sato & Nagaosa JPSJ 2012

Classification of pairing amplitude

$$F^R(x,x',\omega) = \left[f_0^R(x,x',\omega)\sigma_0 + f_i^R(x,x',\omega)\sigma_i \right] i\sigma_2$$

orbital

$$f_0^R(x,x',\omega) = \pm f_0^R(x',x,\omega)$$
$$f_i^R(x,x',\omega) = \pm f_i^R(x',x,\omega)$$

frequency

$$f_0^R(x,x',\omega) = \pm f_0^A(x,x',-\omega)$$
$$f_i^R(x,x',\omega) = \pm f_i^A(x,x',-\omega)$$

Berezinskii JETP Lett 1974

Tanaka, Sato & Nagaosa JPSJ 2012

Classification of pairing amplitude

$$F^R(x,x',\omega) = \left[f_0^R(x,x',\omega)\sigma_0 + f_i^R(x,x',\omega)\sigma_i\right]i\sigma_2$$

frequency, spin, orbital

even, singlet, even -> ESE
odd, singlet, odd -> OSO
even, triplet, odd -> ETO
odd, triplet, even -> OTE

orbital

$$f_0^R(x,x',\omega) = \pm f_0^R(x',x,\omega)$$
$$f_i^R(x,x',\omega) = \pm f_i^R(x',x,\omega)$$

frequency

$$f_0^R(x,x',\omega) = \pm f_0^A(x,x',-\omega)$$
$$f_i^R(x,x',\omega) = \pm f_i^A(x,x',-\omega)$$

Berezinskii JETP Lett 1974

Tanaka, Sato & Nagaosa JPSJ 2012

Classification of pairing amplitude

$$F^R(x,x',\omega) = \left[f_0^R(x,x',\omega)\sigma_0 + f_i^R(x,x',\omega)\sigma_i \right] i\sigma_2$$

frequency, spin, orbital

even, singlet, even -> ESE
odd, singlet, odd -> OSO
even, triplet, odd -> ETO
odd, triplet, even -> OTE

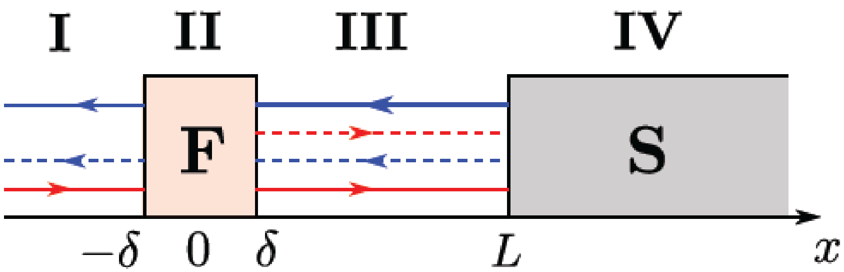
S and T mix if spin rotational symmetry is broken

(orbital) E and O mix if inversion is broken -> NS junctions

Berezinskii JETP Lett 1974

Tanaka, Sato & Nagaosa JPSJ 2012

Classification of pairing amplitude: results



frequency, spin, orbital

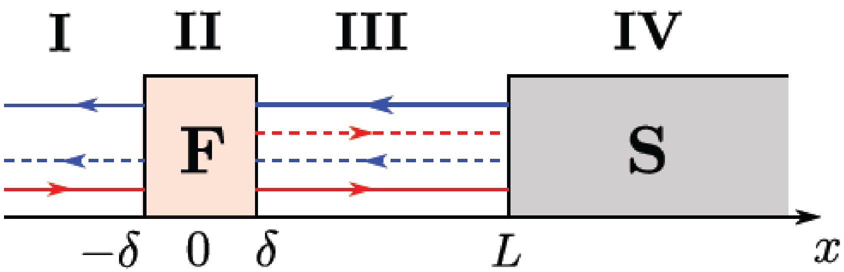
-> ESE, OSO, ETO, OTE

$$f_{\alpha}^{R}\left(x,x',\omega\right)=f_{\alpha,bulk}^{R}\left(x,x',\omega\right)+f_{\alpha,edge}^{R}\left(x,x',\omega\right)$$

	Pairing	Interface	Bulk
f_0	$\uparrow\downarrow-\downarrow\uparrow$	ESE+OSO	ESE
f_3	$\uparrow\downarrow+\downarrow\uparrow$	ETO+OTE	ETO
$f_{\pm}$	$\uparrow\uparrow,\downarrow\downarrow$	OTE	X

Crépin, Burset & BT arXiv 2015

Classification of pairing amplitude: results



frequency, spin, orbital

-> ESE, OSO, ETO, OTE

	Pairing	Interface	Bulk
f_0	$\uparrow\downarrow - \downarrow\uparrow$	ESE+OSO	ESE
f_3	$\uparrow\downarrow + \downarrow\uparrow$	ETO+OTE	ETO
$f_\pm$	$\uparrow\uparrow, \downarrow\downarrow$	OTE	X

$$f^R_\alpha\left(x,x',\omega\right) = f^R_{\alpha,bulk}\left(x,x',\omega\right) + f^R_{\alpha,edge}\left(x,x',\omega\right)$$

$$f^R_{\alpha,bulk}\left(x,x',\omega\right) \propto e^{-\kappa(\omega)|x-x'|}$$

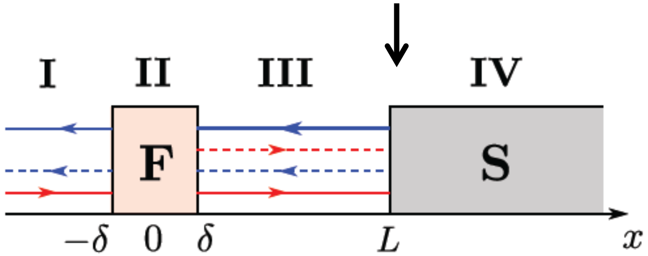
$$f^R_{\alpha,edge}\left(x,x',\omega\right) \propto e^{-\kappa(\omega)(x+x')}$$

(in region IV)

Crépin, Burset & BT arXiv 2015

Classification of pairing amplitude: results

$x = L = 3\xi$



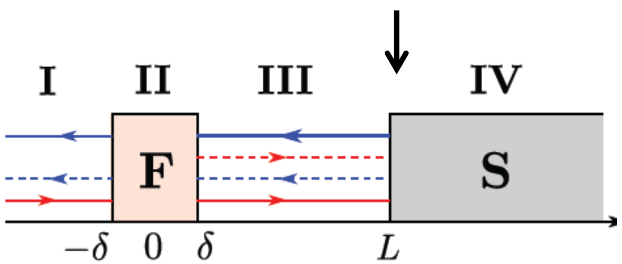
$m_0 = 0.5\Delta$

$$f_\alpha^R\left(x,x,\omega\right) = f_{\alpha,bulk}^R\left(x,x,\omega\right) + f_{\alpha,edge}^R\left(x,x,\omega\right)$$

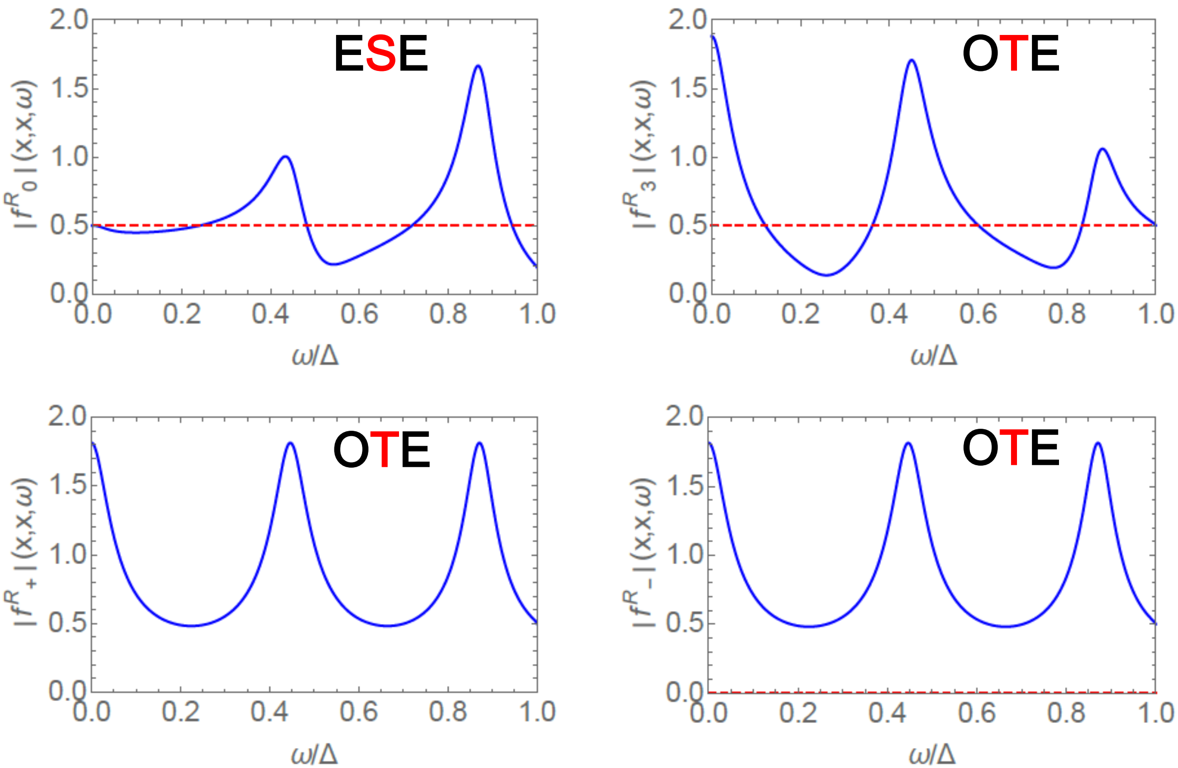
Crépin, Burset & BT arXiv 2015

Classification of pairing amplitude: results

$x = L = 3\xi$



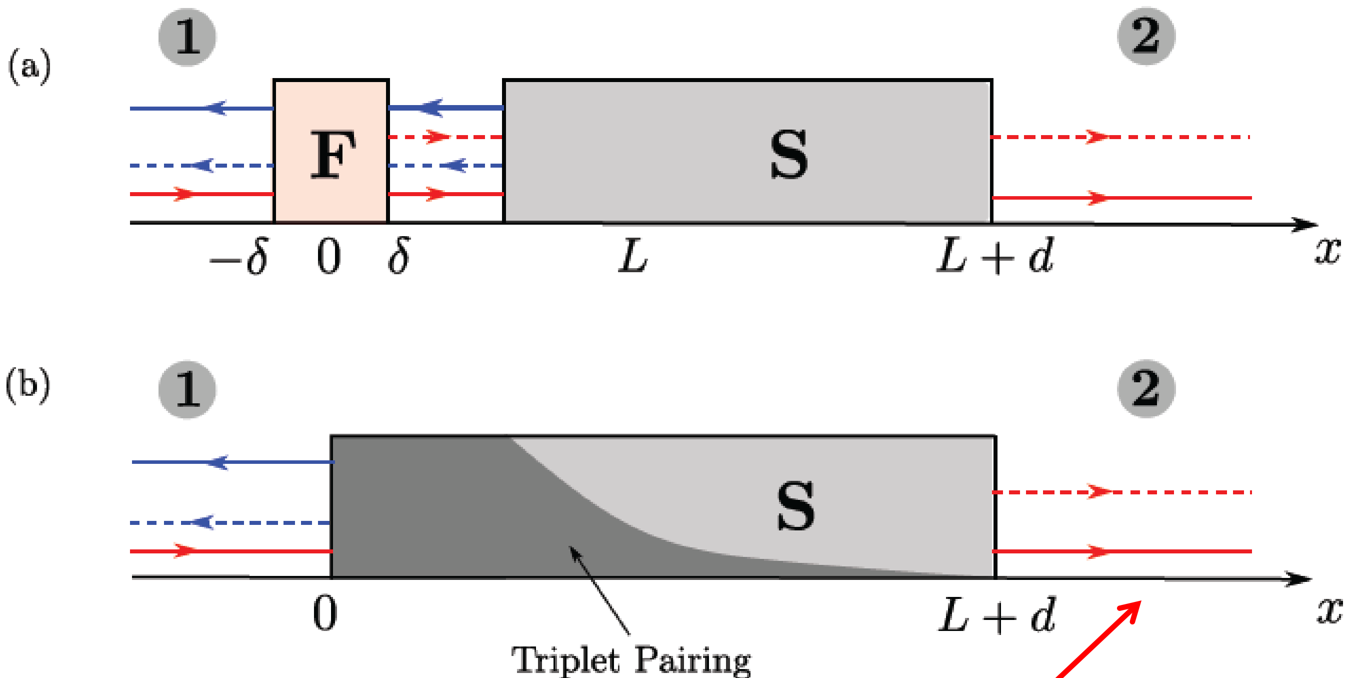
$m_0 = 0.5\Delta$



$$f^R_\alpha(x,x,\omega) = f^R_{\alpha,bulk}(x,x,\omega) + f^R_{\alpha,edge}(x,x,\omega)$$

Crépin, Burset & BT arXiv 2015

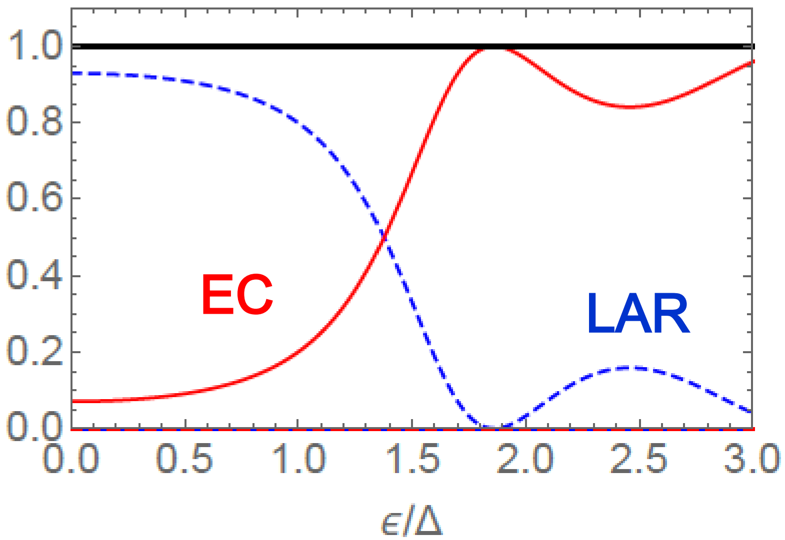
Detection of OTE: idea



use crossed Andreev reflection

Crépin, Burset & BT arXiv 2015

Detection of OTE: results

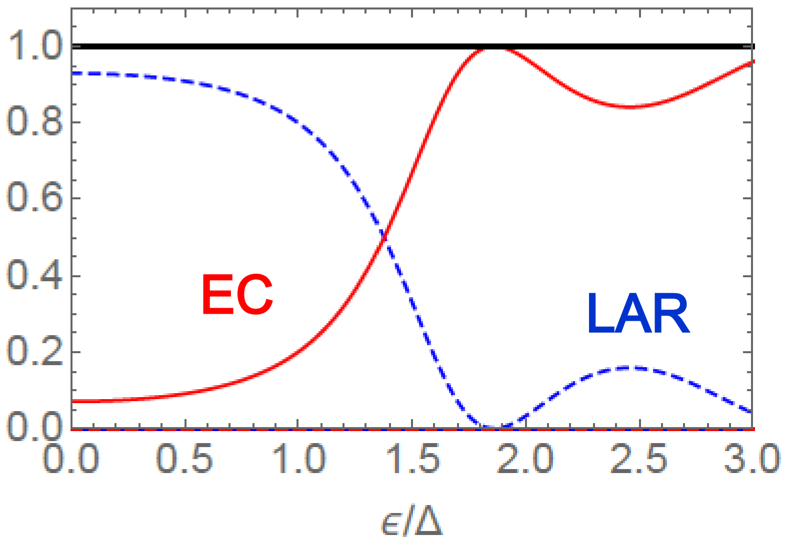


(a) $d = 2\xi$, $m_0 = 0$

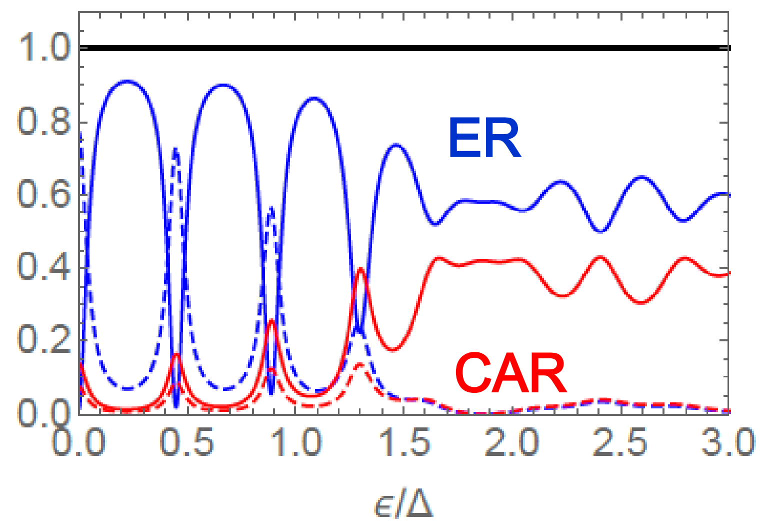
Adroguer et al. PRB 2010

Crépin, Burset & BT arXiv 2015

Detection of OTE: results



(a) $d = 2\xi,\ m_0 = 0$

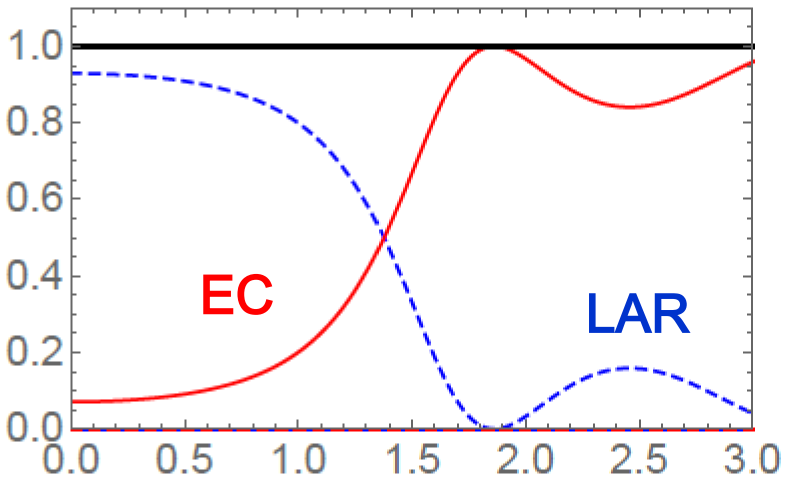


(c) $d = 2\xi,\ m_0 = 0.5,\ L = 3\xi$

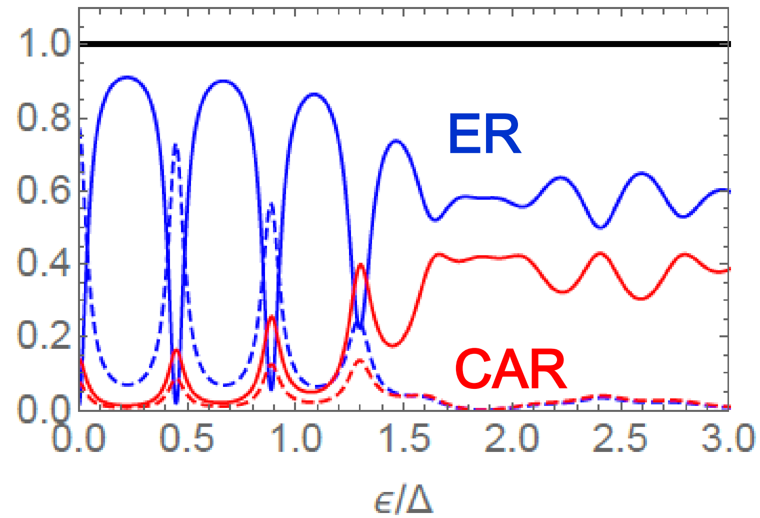
Adroguer et al. PRB 2010

Crépin, Burset & BT arXiv 2015

Detection of OTE: results



(a) $d = 2\xi,\ m_0 = 0$



(c) $d = 2\xi,\ m_0 = 0.5,\ L = 3\xi$

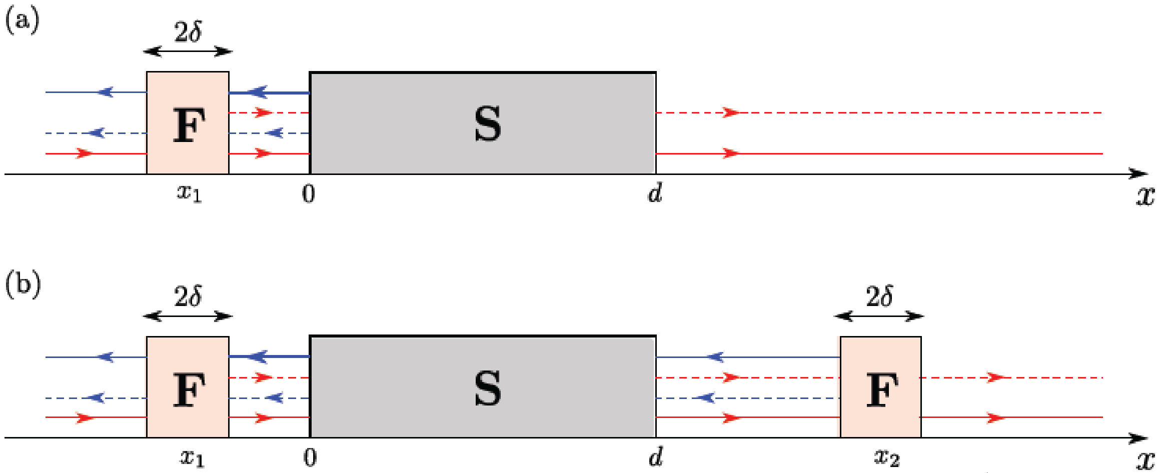
Adroguer et al. PRB 2010

-> dilemma

$$\frac{T_{CAR}}{T_{EC}} = \tanh^2\left(2m_0\right)\tanh^2\left(d/\xi\right) \leq 1$$

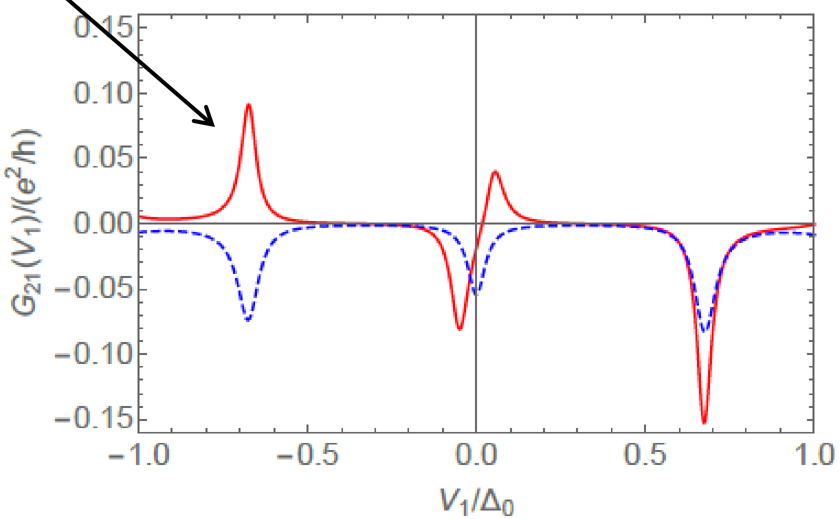
Crépin, Burset & BT arXiv 2015

Way out …

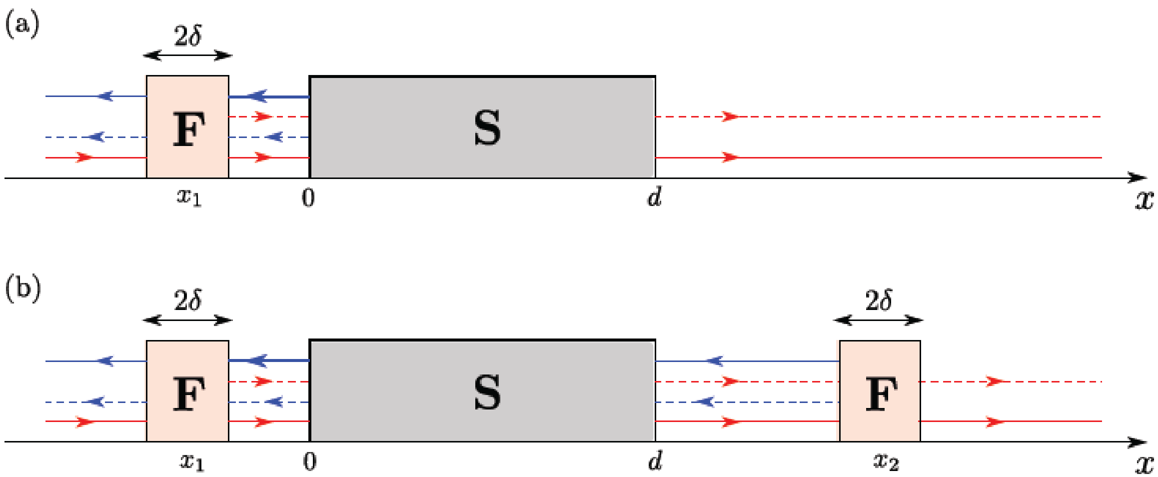


… add complexity

$$G_{21} = -\partial I_2 / \partial V_1 = T_{CAR} - T_{EC}$$



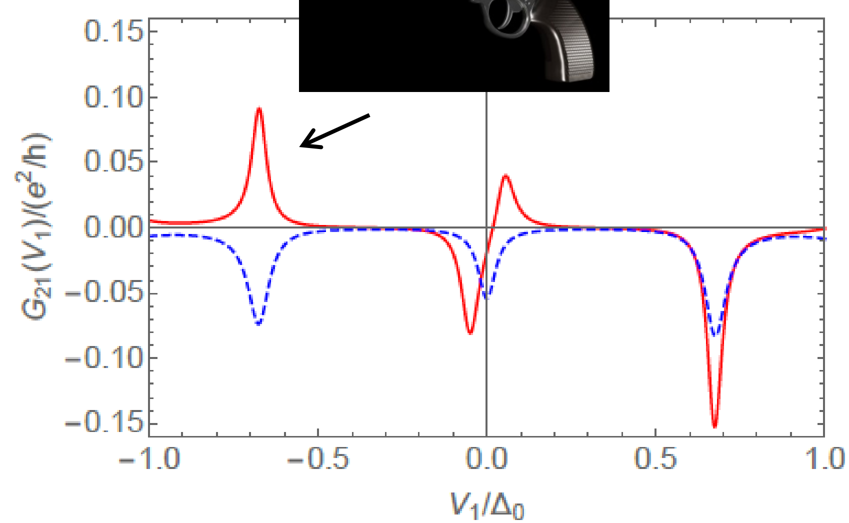
Way out …



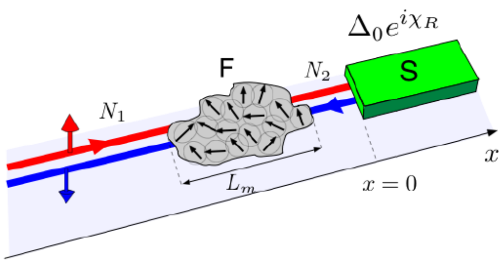
… add complexity

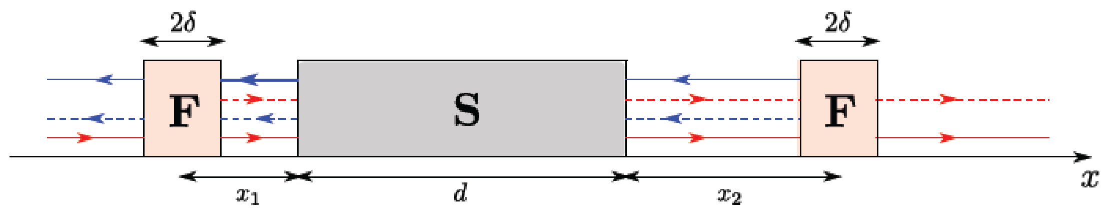
OTE

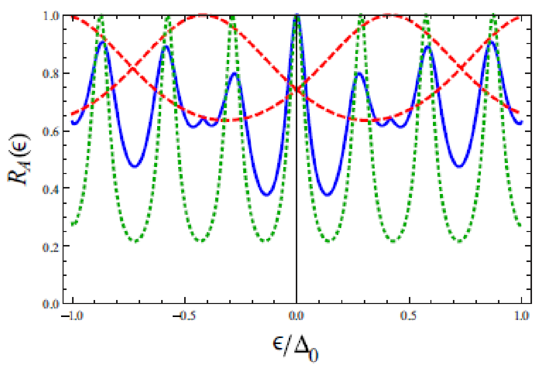
$$G_{21} = -\partial I_2 \big/ \partial V_1 = T_{CAR} - T_{EC}$$



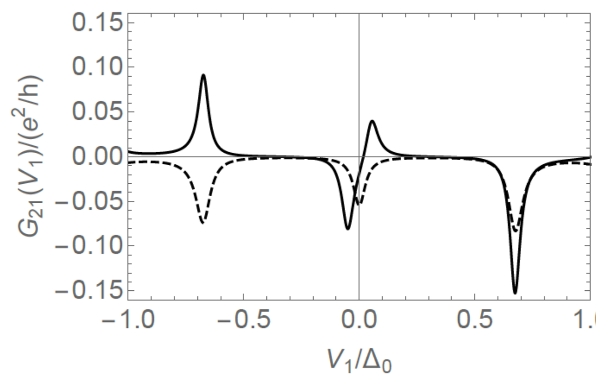
Summary







(c) $\mu_0 = 0.35, \mu = 0.3, L_m = 2.15, x_0 = 6$



Crépin, BT & Dolcini PRB **89**, 205115 (2014)

Crépin, Burset & BT arXiv:1503.07784