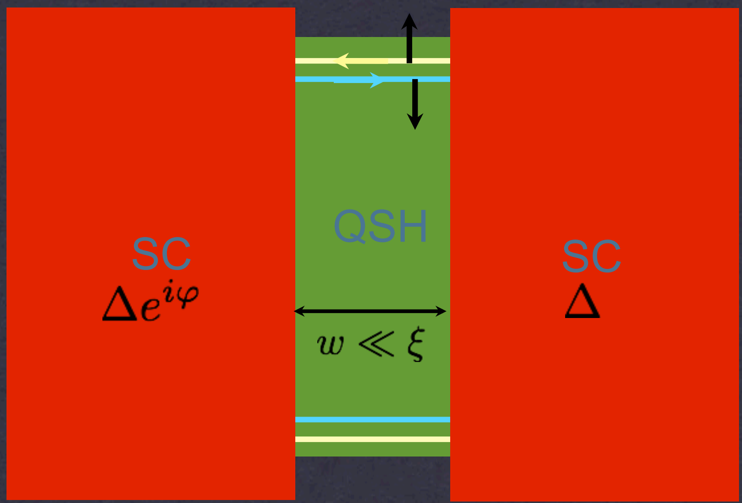
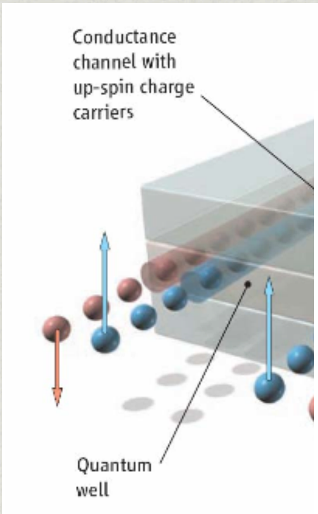
Superconductivity in Quantum Spin Hall Systems

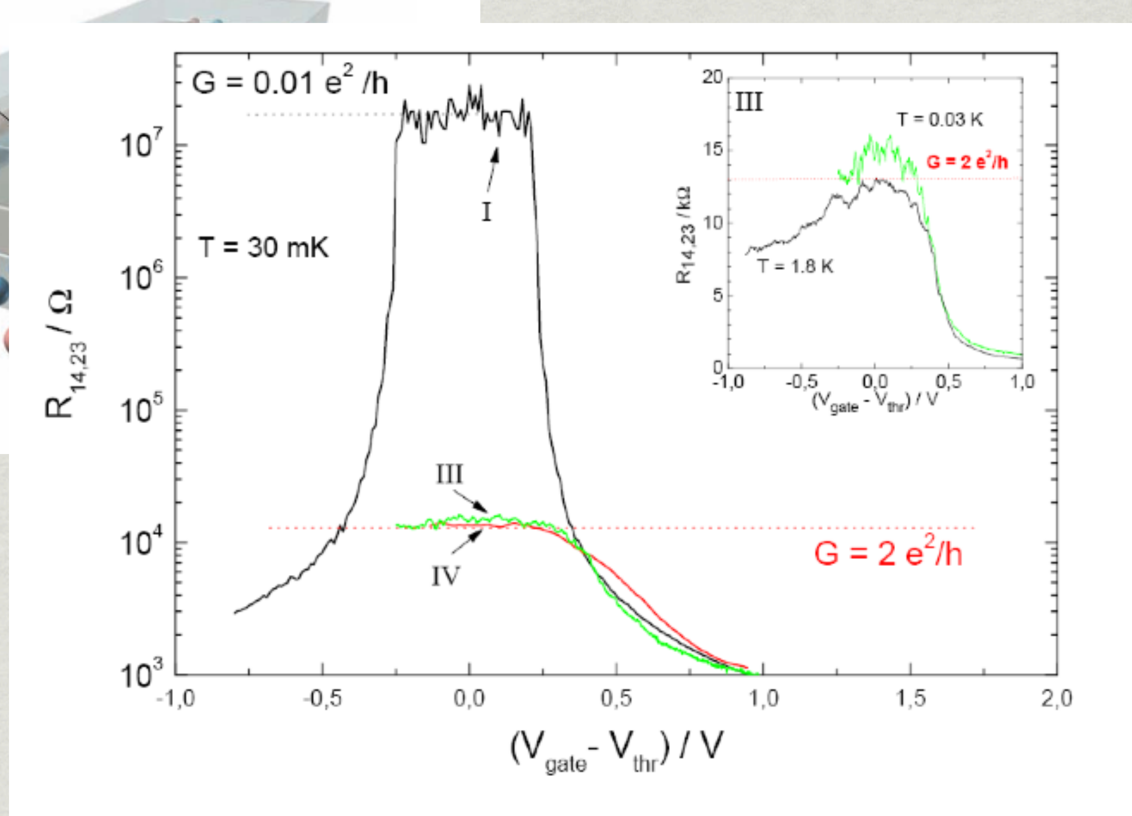
Karen Michaeli

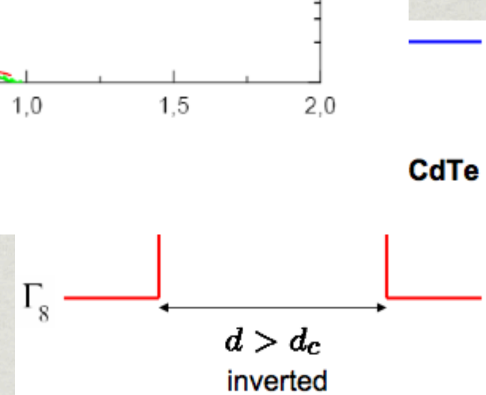


Quantum Spin Hall

B. A. Bernevig, T. L. Hughes, and S.-C. Zhang, Science, 2006.





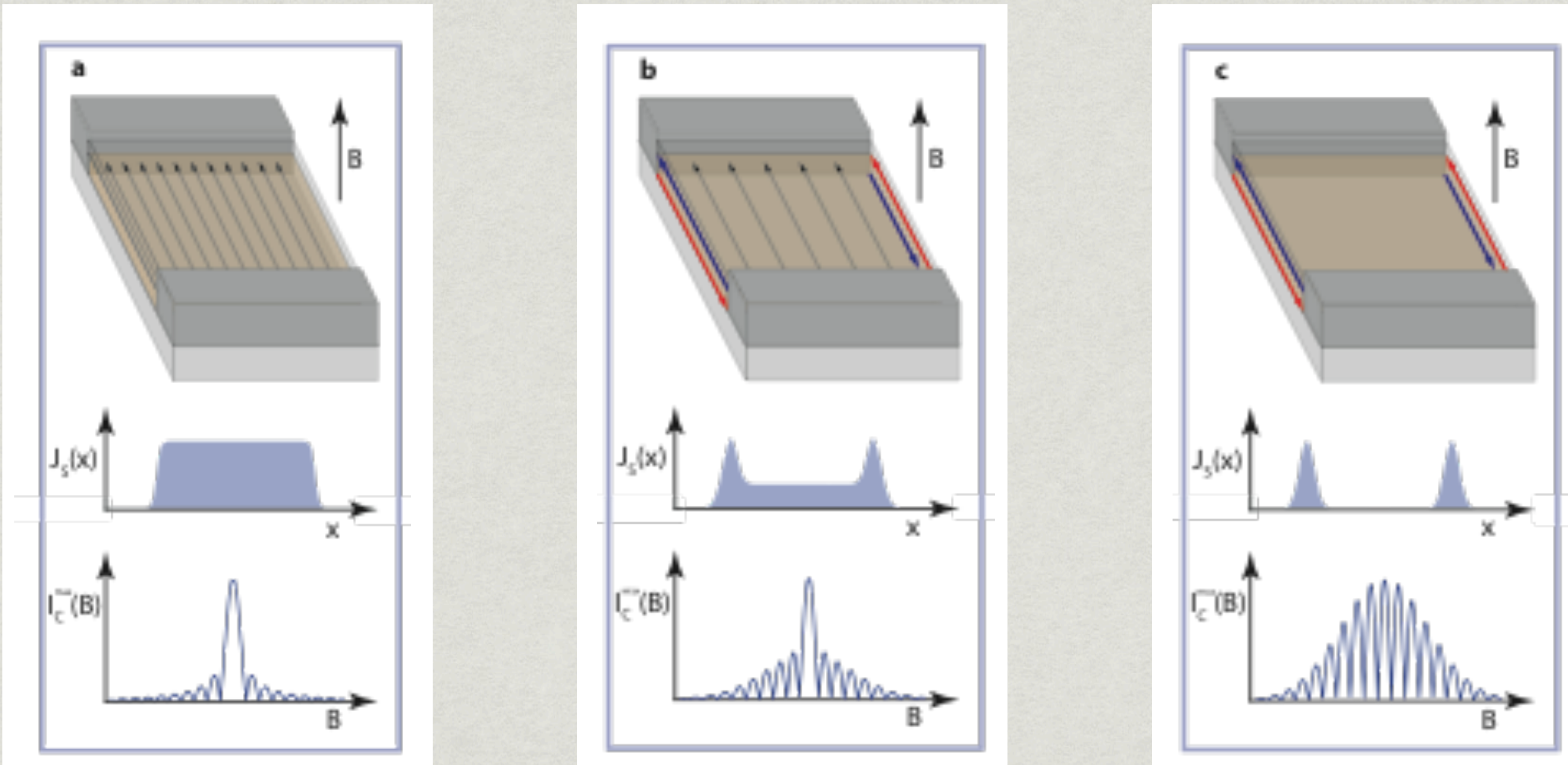


Seen also in InAs/GaSb

I. Knez, R.-R. Du, and G. Sulivan, PRL, 2012.

Induced Superconductivity in QSH

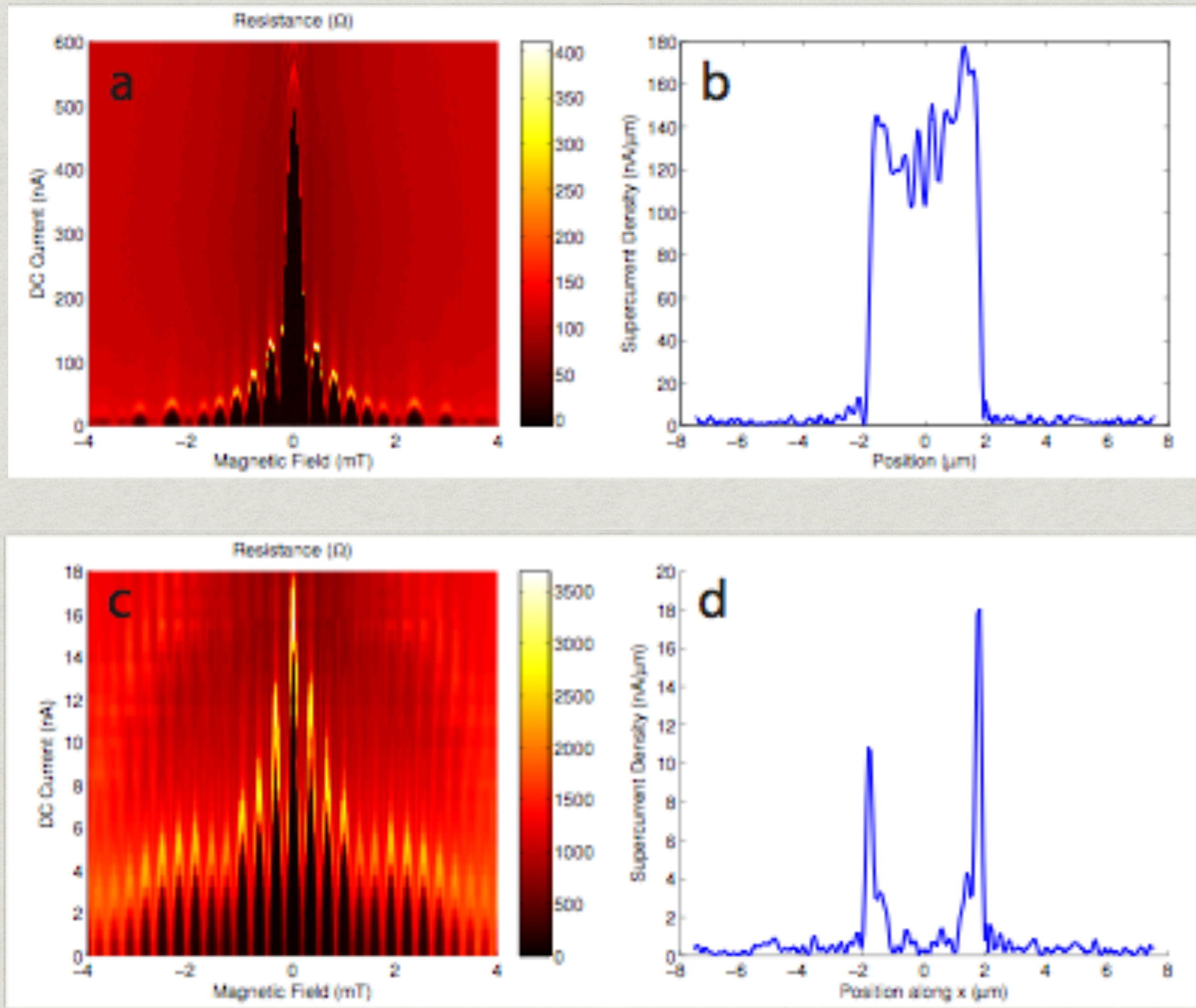
S. Hart, et al., 2013



Fraunhofer pattern

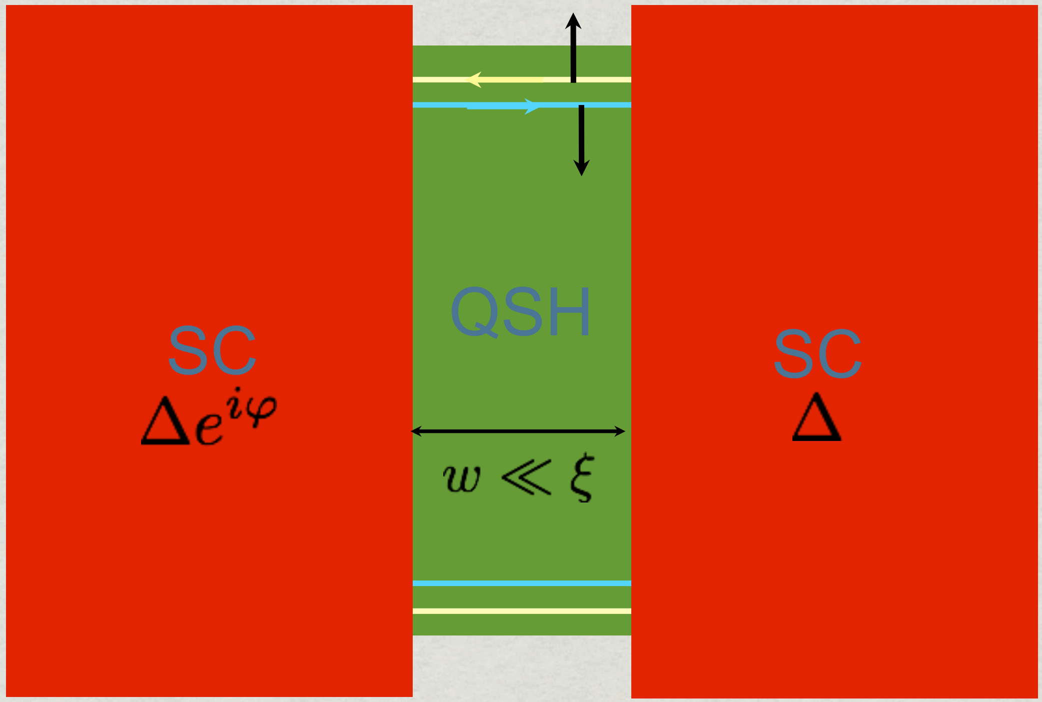
$$\frac{I_c(\phi)}{I_c} = \frac{|\sin(\pi\phi/\phi_0)|}{\pi\phi/\phi_0}$$

Induced Superconductivity in QSHE



S. Hart, et al., 2013

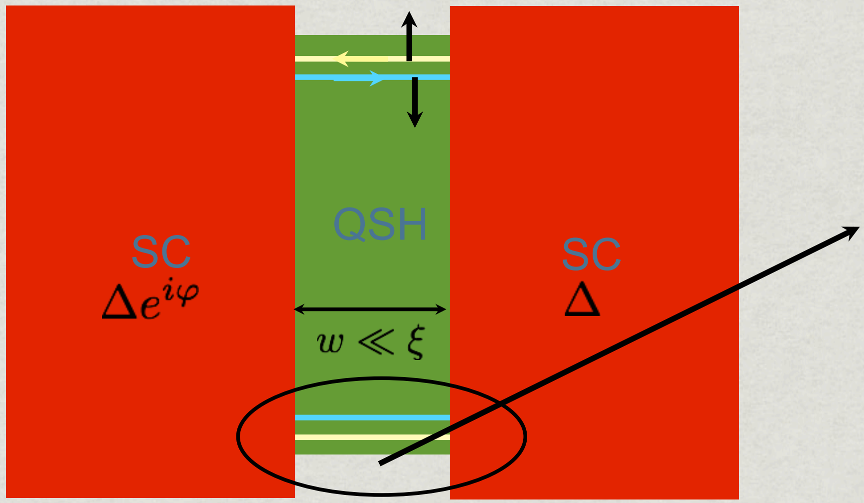
Josephson Junctions



S.-P. Lee, KM, J. Alicea, and A. Yacoby

Josephson Junctions

L. Fu and C. L. Kane, PRB, 2009.



$$E(\varphi) = -2(\Gamma^{\dagger}\Gamma - 1/2)\Delta\cos(\varphi/2)$$

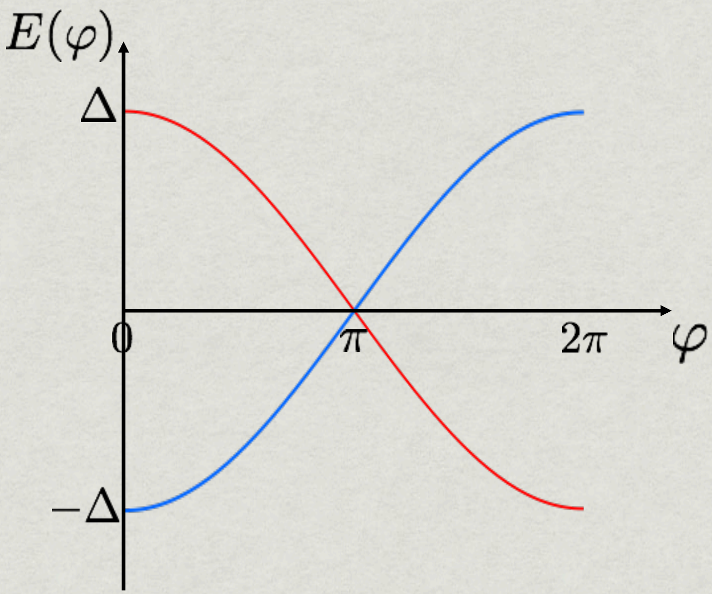
$\Gamma^{\dagger}\Gamma$ - occupation of the bound state

No backscattering

↓

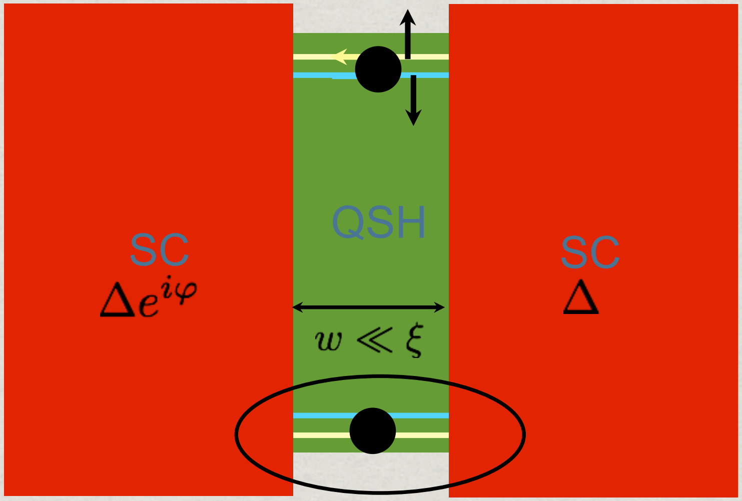
Behaves as a ballistic junction

$$E(\varphi) \sim \Delta\cos(\varphi/2)$$



C. W. J. Beenakker and H. van Houten, PRL, 1991.

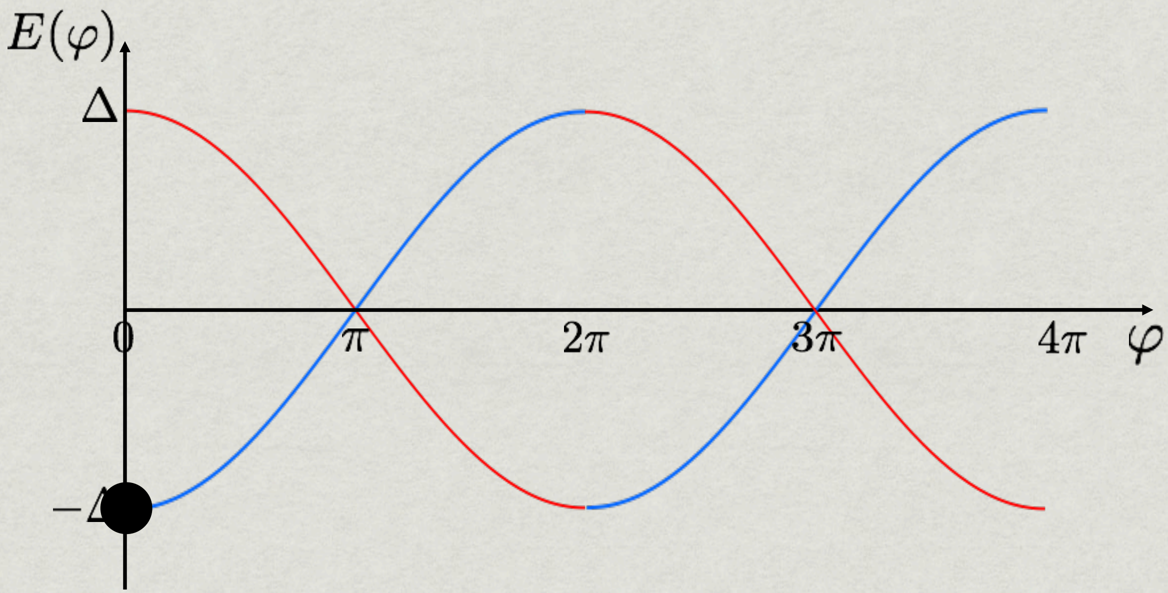
Josephson Junctions



Liang Fu and C. L. Kane, PRB, 2009.

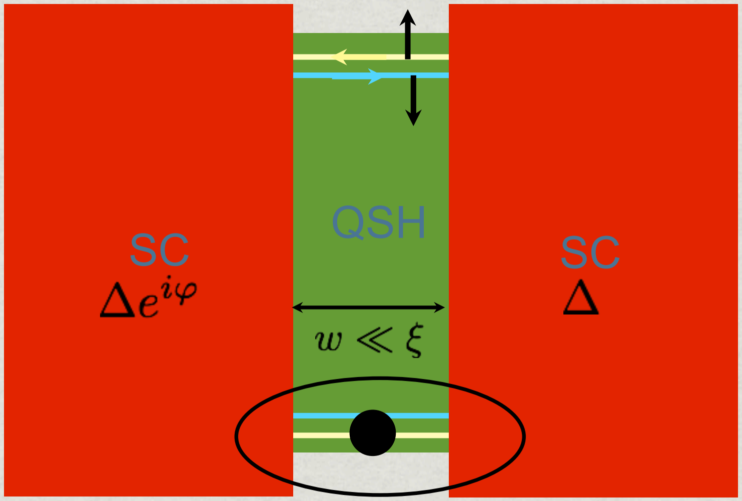
$$E(\varphi) = -2(\Gamma^\dagger\Gamma - 1/2)\Delta\cos(\varphi/2)$$

$\Gamma^\dagger\Gamma$ - occupation of the bound state



4π - periodic in φ

Josephson Junctions

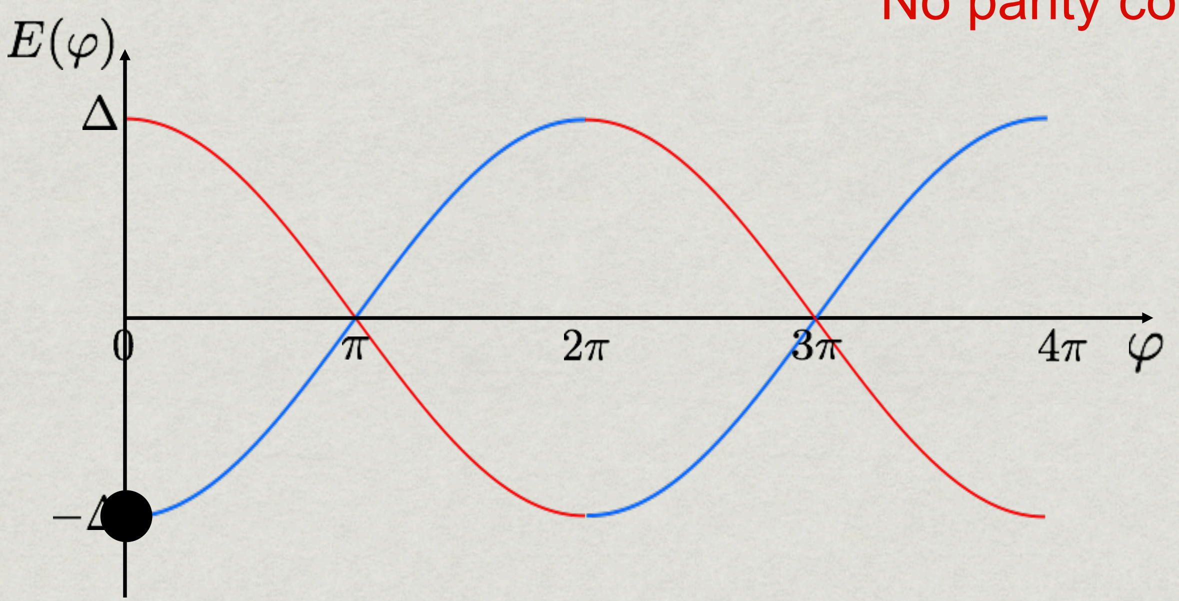


Liang Fu and C. L. Kane, PRB, 2009.

$$E(\varphi) = -2(\Gamma^\dagger \Gamma - 1/2)\Delta \cos(\varphi/2)$$

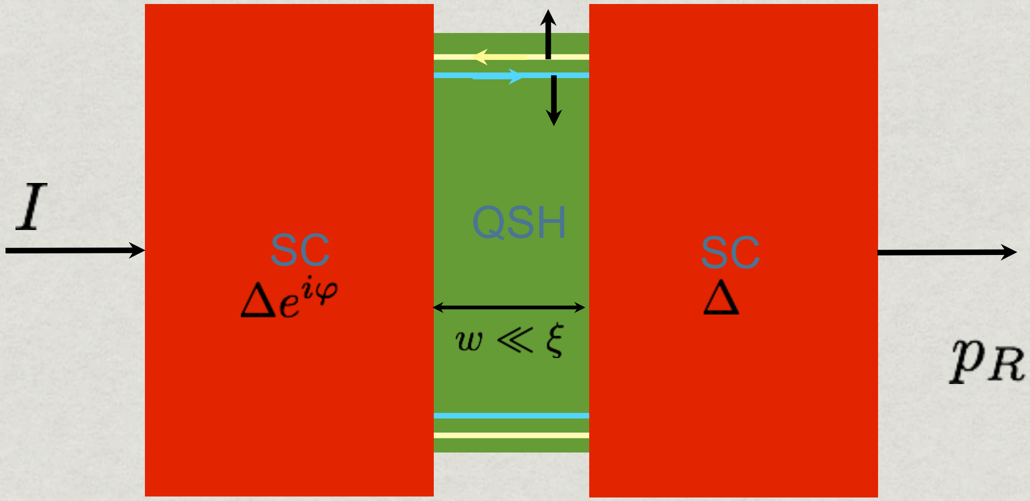
$\Gamma^\dagger \Gamma$ - occupation of the bound state

No parity conservation



2π - periodic in φ

Critical Current



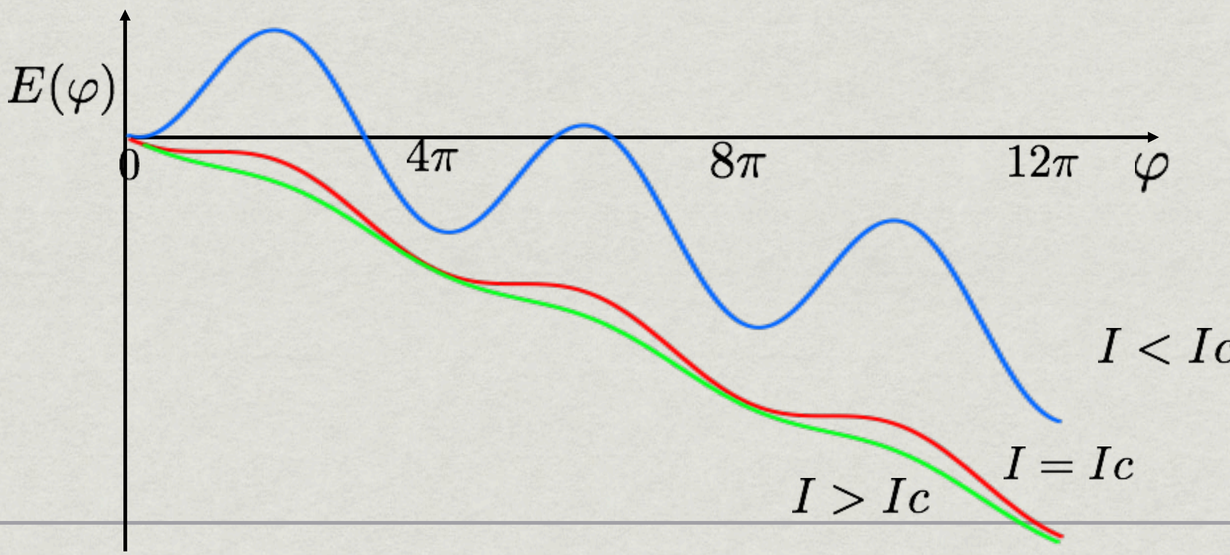
Josephson relation

$$\frac{d\varphi}{dt} = \frac{2eV}{\hbar}$$

p_R, p_L - parity of the right/left junction

$$\varphi_R = \varphi_L = \varphi$$

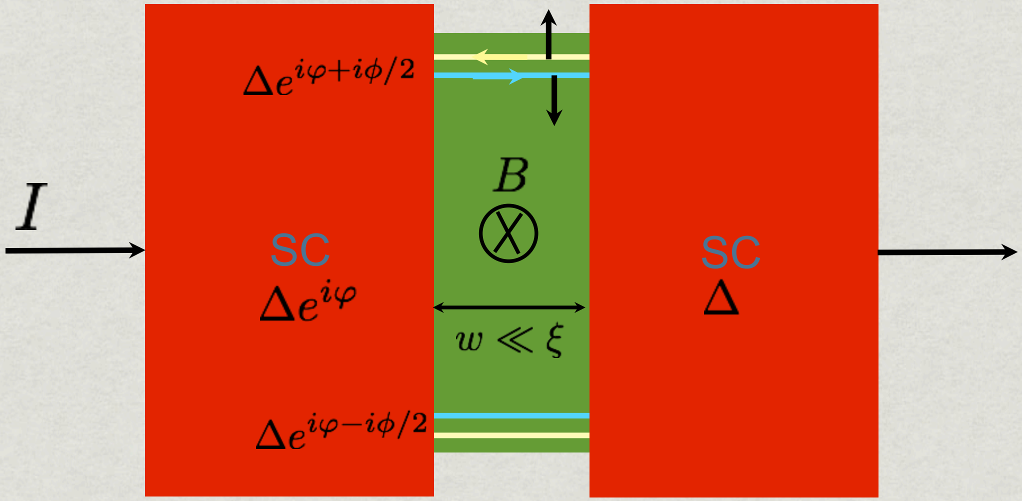
$$E(\varphi_R, \varphi_L) = -(-1)^{p_R}\Delta\cos(\varphi_R/2) - (-1)^{p_L}\Delta\cos(\varphi_L/2) - \frac{\hbar}{2e}I(\varphi_R + \varphi_L)$$



$$0 = \frac{\partial E(\varphi)}{\partial \varphi}$$

$$I_c = \frac{e\Delta}{\hbar}$$

Critical Current



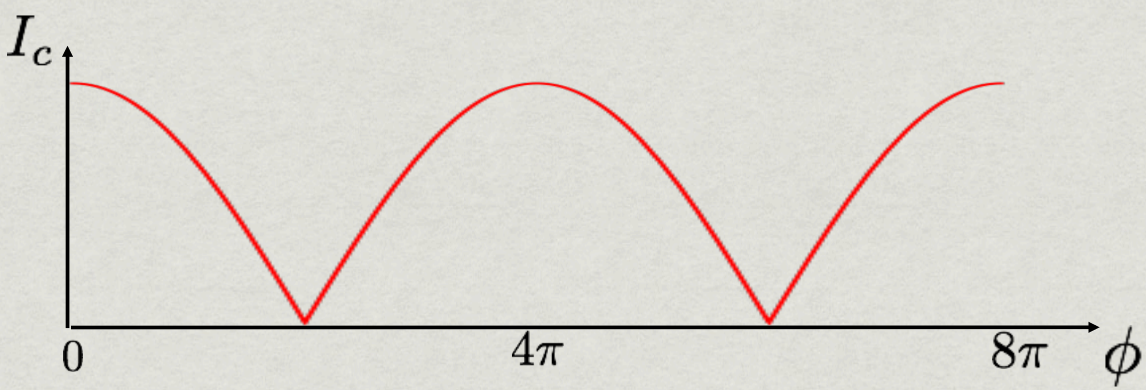
Josephson relation

$$\frac{d\varphi}{dt} = \frac{2eV}{\hbar}$$

$$\varphi_R = \varphi + \phi/2$$
$$\varphi_L = \varphi - \phi/2$$

$$E(\varphi_R,\varphi_L) = (-1)^{n_R}\Delta\cos(\varphi_R/2) + (-1)^{n_L}\Delta\cos(\varphi_L/2) - \frac{\hbar}{2e}I(\varphi_R+\varphi_L)$$

$$E(\varphi,\phi) = -2\Delta\cos(\phi/4)\cos(\varphi/2) - \frac{\hbar}{e}I\varphi$$



$$I_c = \frac{e\Delta}{\hbar}|\cos(\phi/4)|$$

Parity Relaxation

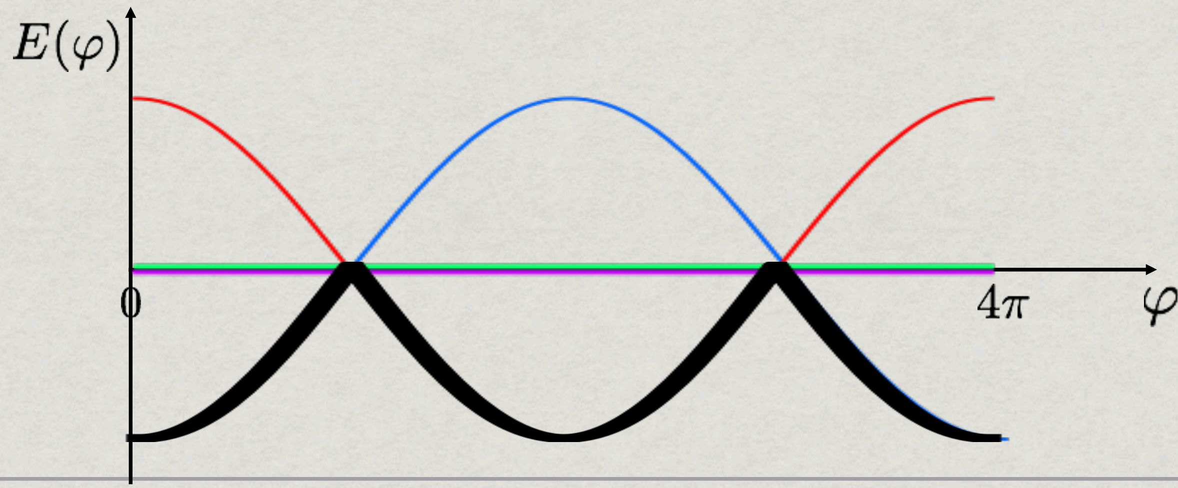
$$E(\varphi,\phi) = -(-1)^{p_R}\Delta\cos(\varphi/2+\phi/4) - (-1)^{p_L}\Delta\cos(\varphi/2-\phi/4) - \frac{\hbar}{e}I\varphi$$

$$E_1(\varphi,\phi) = -2\Delta\cos(\phi/4)\cos(\varphi/2) - \frac{\hbar}{e}I\varphi \qquad p_R = p_L = even$$

$$E_2(\varphi,\phi) = -2\Delta\sin(\phi/4)\sin(\varphi/2) - \frac{\hbar}{e}I\varphi \qquad p_R \neq p_L = odd$$

$$E_3(\varphi,\phi) = 2\Delta\sin(\phi/4)\sin(\varphi/2) - \frac{\hbar}{e}I\varphi \qquad p_R = p_L = odd$$

$$E_4(\varphi,\phi) = 2\Delta\cos(\phi/4)\cos(\varphi/2) - \frac{\hbar}{e}I\varphi \qquad p_R \neq p_L = even$$



$$\phi = 0$$

$$I_c = \frac{e\Delta}{\hbar}$$

Parity Relaxation

$$E(\varphi,\phi) = -(-1)^{p_R}\Delta\cos(\varphi/2+\phi/4) - (-1)^{p_L}\Delta\cos(\varphi/2-\phi/4) - \frac{\hbar}{e}I\varphi$$

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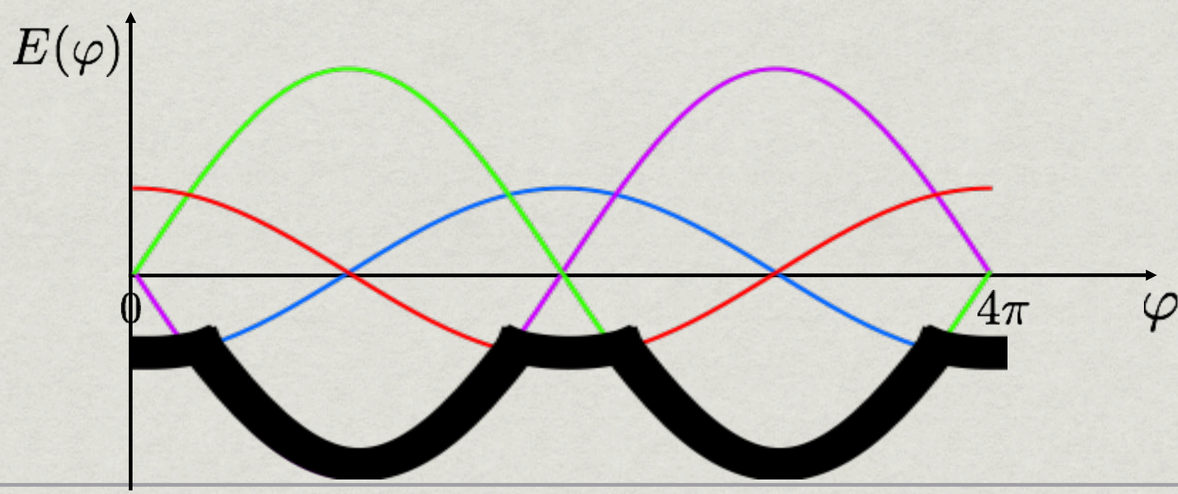
$$E_4(\varphi,\phi) = 2\Delta\cos(\phi/4)\cos(\varphi/2) - \frac{\hbar}{e}I\varphi \qquad p_R \neq p_L = even$$



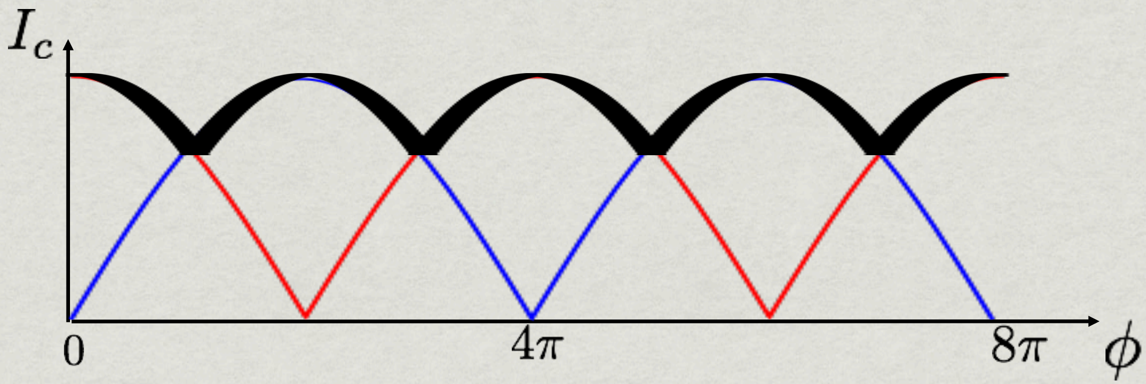
$$\phi = 3\pi/2$$

$$I_c = \frac{e\Delta}{\hbar}\sin(3\pi/8)$$

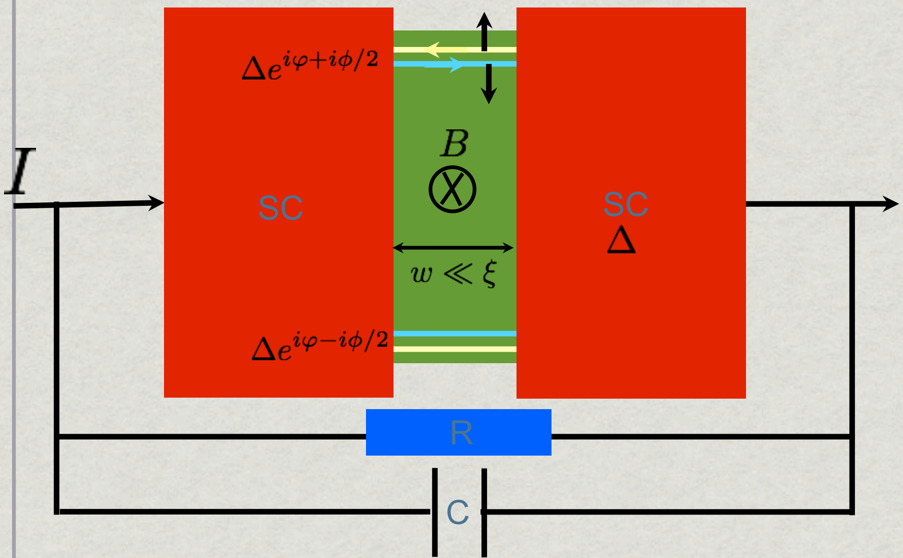
Parity Relaxation

$$E(\varphi, \phi) = -(-1)^{p_R}\Delta\cos(\varphi/2 + \phi/4) - (-1)^{p_L}\Delta\cos(\varphi/2 - \phi/4) - \frac{\hbar}{e}I\varphi$$

$$I_c = \frac{e\Delta}{\hbar}\max\{\cos(\phi/4), \sin(\phi/4)\}$$



Parity Relaxation



$$I = \frac{\partial E(\varphi,\phi)}{\partial \varphi} + \frac{V}{R} + C\frac{\partial V}{\partial t}$$

$$\frac{d\varphi}{dt} = \frac{2eV}{\hbar}$$

$$I = \frac{\partial E(\varphi,\phi)}{\partial \varphi} + \frac{\hbar}{2eR}\frac{\partial \varphi}{\partial t} + C\frac{\hbar}{2eR}\frac{\partial^2 \varphi}{\partial t^2} + \zeta(t)$$

Thermal noise $\langle \zeta(t)\zeta(t')\rangle = \frac{2T}{R}\delta(t-t')$

Parity Relaxation

$$I - \frac{\partial E(\varphi,\phi)}{\partial \varphi} - \zeta(t) = \frac{\hbar}{2eR}\frac{\partial \varphi}{\partial t} + \cancel{C\frac{\hbar}{2eR}\frac{\partial^2 \varphi}{\partial t^2}}$$

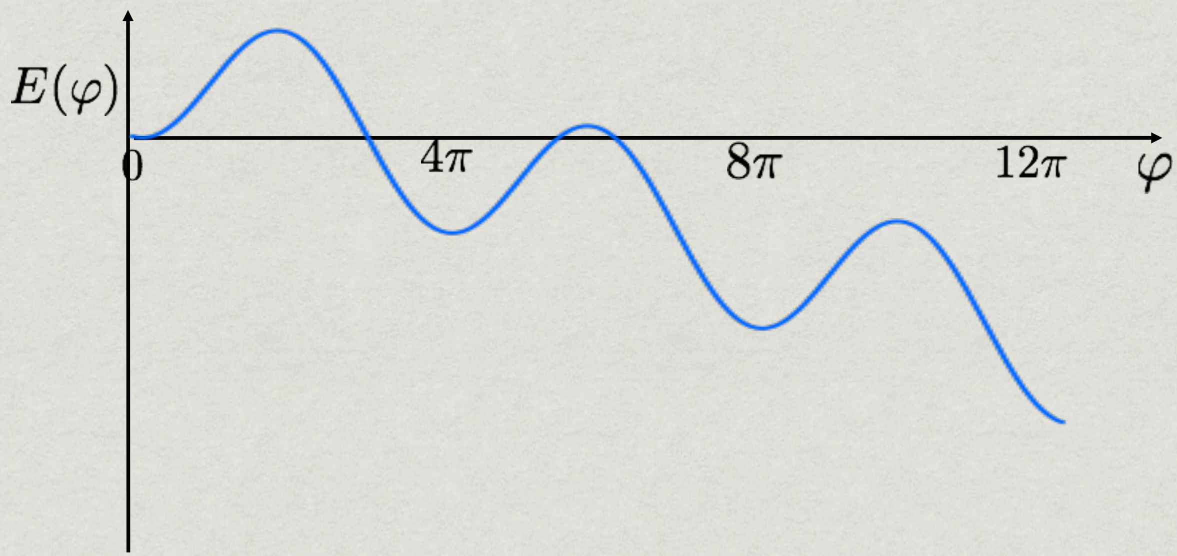
force due to the tilted washboard potential

random force

friction

inertial term

Overdamped junction



Parity Relaxation

$$I - \underbrace{\frac{\partial E(\varphi,\phi)}{\partial \varphi}}_{\text{force due to the tilted washboard potential}} - \underbrace{\zeta(t)}_{\text{random force}} = \underbrace{\frac{\hbar}{2eR}\frac{\partial \varphi}{\partial t}}_{\text{friction}} + \underbrace{\cancel{C\frac{\hbar}{2eR}\frac{\partial^2 \varphi}{\partial t^2}}}_{\text{kinetic term}}$$

Overdamped junction

$P_i(\varphi, t)$ - the distribution function for the parity and phase

$$\frac{\partial P_i(\varphi,t)}{\partial t} = \frac{2eR}{\hbar}\frac{\partial}{\partial \varphi}\left[I - \frac{\partial E(\varphi,\phi)}{\partial \varphi} + T\frac{\partial}{\partial \varphi}\right]P_i(\varphi,t) + \sum_{i\neq j}\left[W_{j\to i}P_j(\varphi,t) - W_{i\to j}P_i(\varphi,t)\right]$$

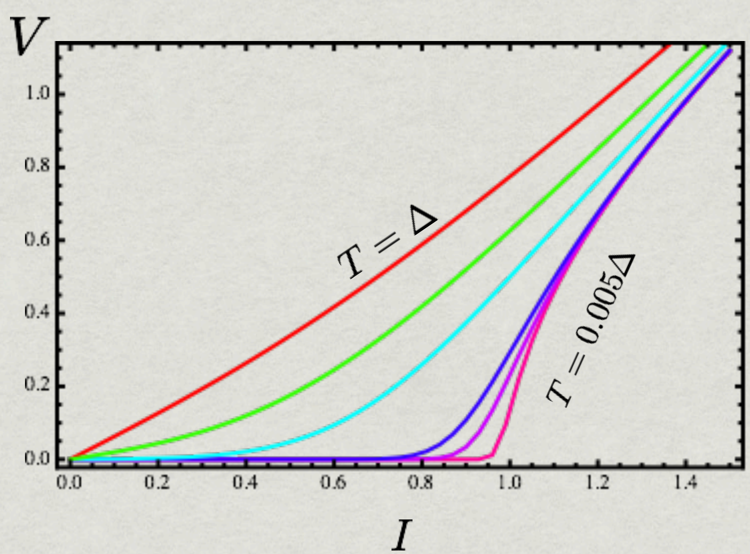
$$W_{i\to j} = \frac{\exp[(E_i(\phi) - E_j(\phi))/\underbrace{\tilde{T}}_{\text{temperature of the particle bath}}]}{\tau}$$

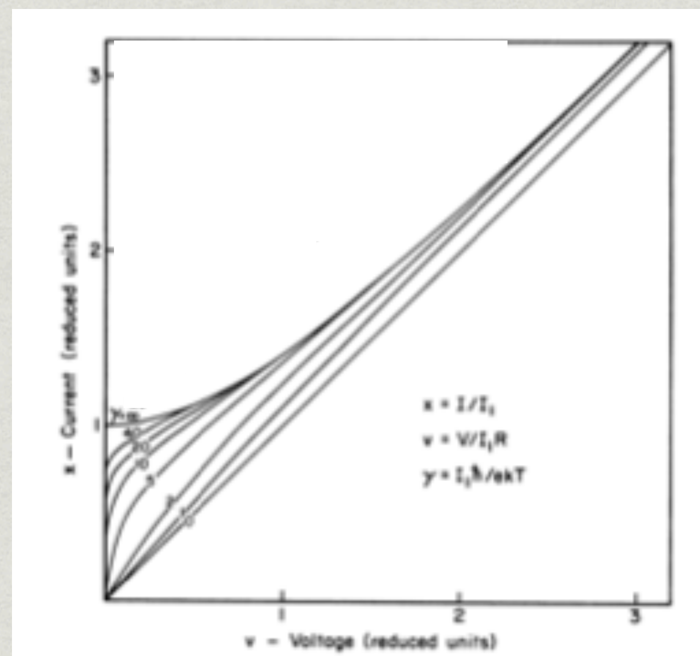
I-V Characteristics

$$\frac{\partial P_i(\varphi,t)}{\partial t} = \frac{2eR}{\hbar}\frac{\partial}{\partial\varphi}\left[I - \frac{\partial E(\varphi,\phi)}{\partial\varphi} + T\frac{\partial}{\partial\varphi}\right]P_i(\varphi,t) + \sum_{i\neq j}\left[W_{j\to i}P_j(\varphi,t) - W_{i\to j}P_i(\varphi,t)\right]$$

$$W_{i\to j} = \frac{\exp[(E_i(\phi) - E_j(\phi))/\tilde{T}]}{\tau}$$

$\tau \to \infty$ no parity relaxation, reproduces the known Ambegaokar-Halperin I-V curves





V. Ambegaokar, and B.I. Halperin, PRL,1969.

I-V Characteristics

$$\frac{\partial P_i(\varphi,t)}{\partial t} = \frac{2eR}{\hbar}\frac{\partial}{\partial\varphi}\left[I - \frac{\partial E(\varphi,\phi)}{\partial\varphi} + T\frac{\partial}{\partial\varphi}\right]P_i(\varphi,t) + \sum_{i\neq j}\left[W_{j\to i}P_j(\varphi,t) - W_{i\to j}P_i(\varphi,t)\right]$$

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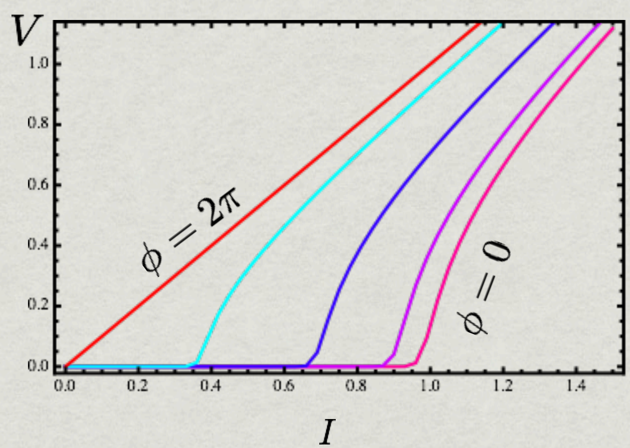

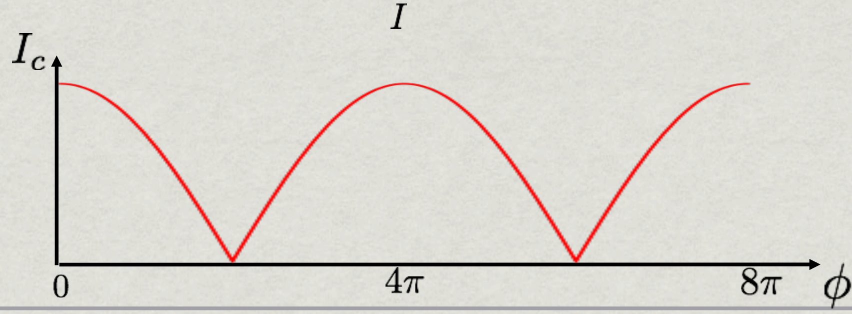

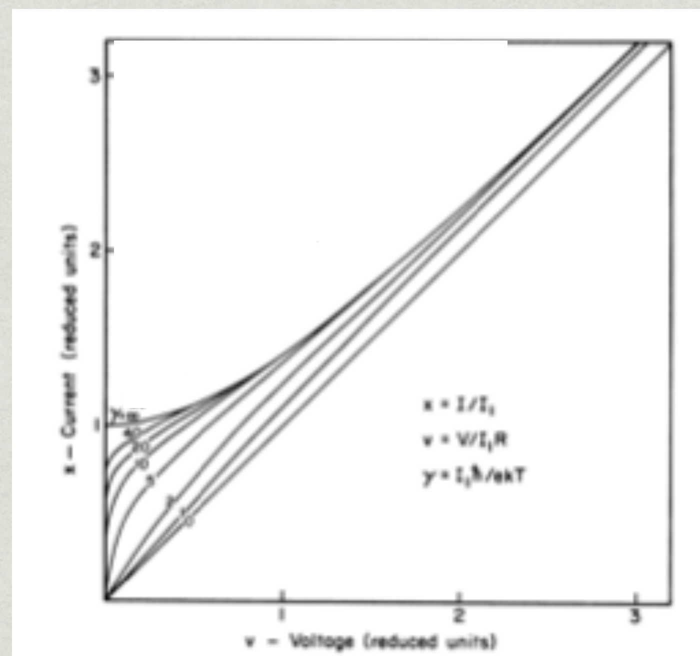

V. Ambegaokar, and B.I. Halperin, PRL,1969.

I-V Characteristics

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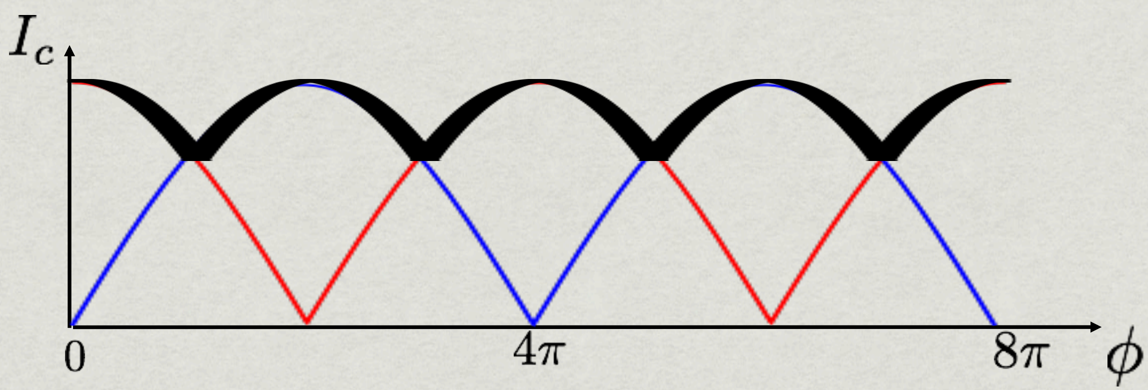
$$W_{i\to j} = \frac{\exp[(E_i(\phi) - E_j(\phi))/\tilde{T}]}{\tau}$$

$\tilde{T} \to 0$ the parity can change only at the degeneracy points of the energies.



I-V Characteristics

$$\frac{\partial P_i(\varphi,t)}{\partial t} = \frac{2eR}{\hbar}\frac{\partial}{\partial\varphi}\left[I - \frac{\partial E(\varphi,\phi)}{\partial\varphi} + T\frac{\partial}{\partial\varphi}\right]P_i(\varphi,t) + \sum_{i\neq j}\left[W_{j\to i}P_j(\varphi,t) - W_{i\to j}P_i(\varphi,t)\right]$$

$$W_{i\to j} = \frac{\exp[(E_i(\phi) - E_j(\phi))/\tilde{T}]}{\tau}$$

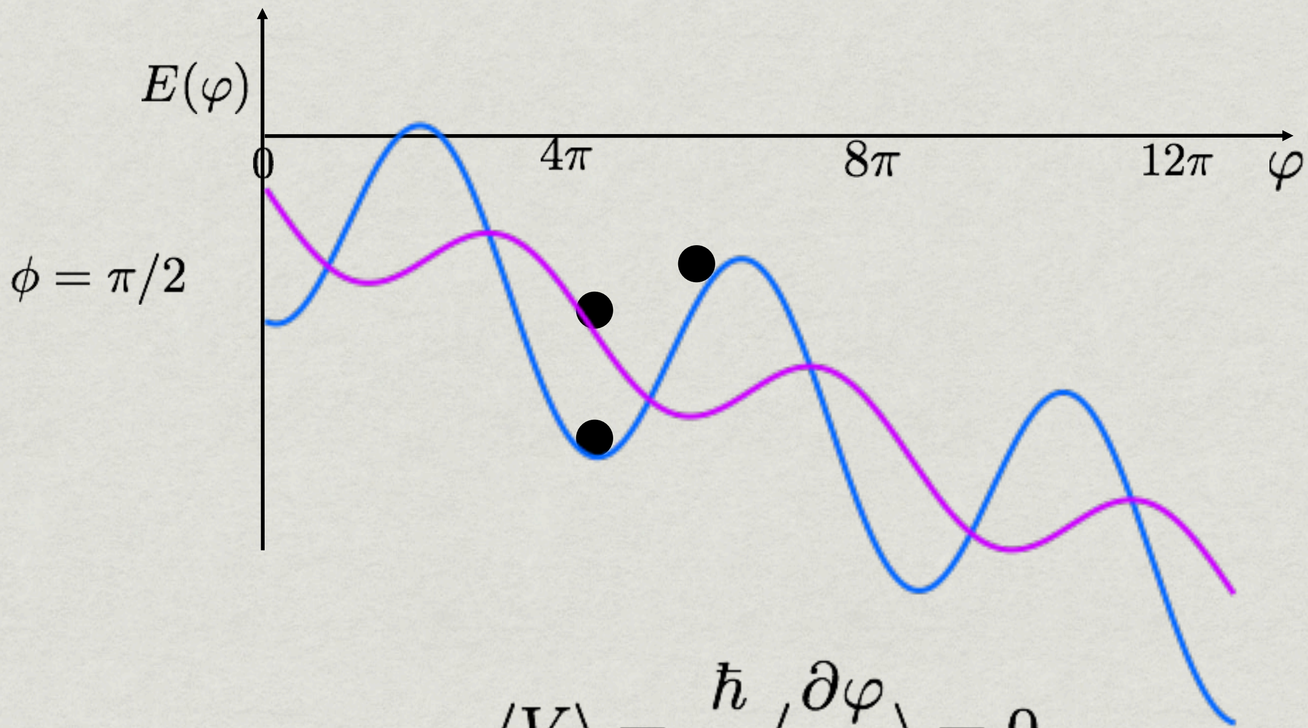
$\tilde{T} \to \infty$ the parity switching rate is independent of the energy.

Strong Parity Relaxation

$$E_1(\varphi,\phi) = -2\Delta\cos(\phi/4)\cos(\varphi/2) - \frac{\hbar}{e} I\varphi$$

$$E_2(\varphi,\phi) = -2\Delta\sin(\phi/4)\sin(\varphi/2) - \frac{\hbar}{e} I\varphi$$

$$I < I_c^{P_R=P_L}, I_c^{P_R\neq P_L}$$



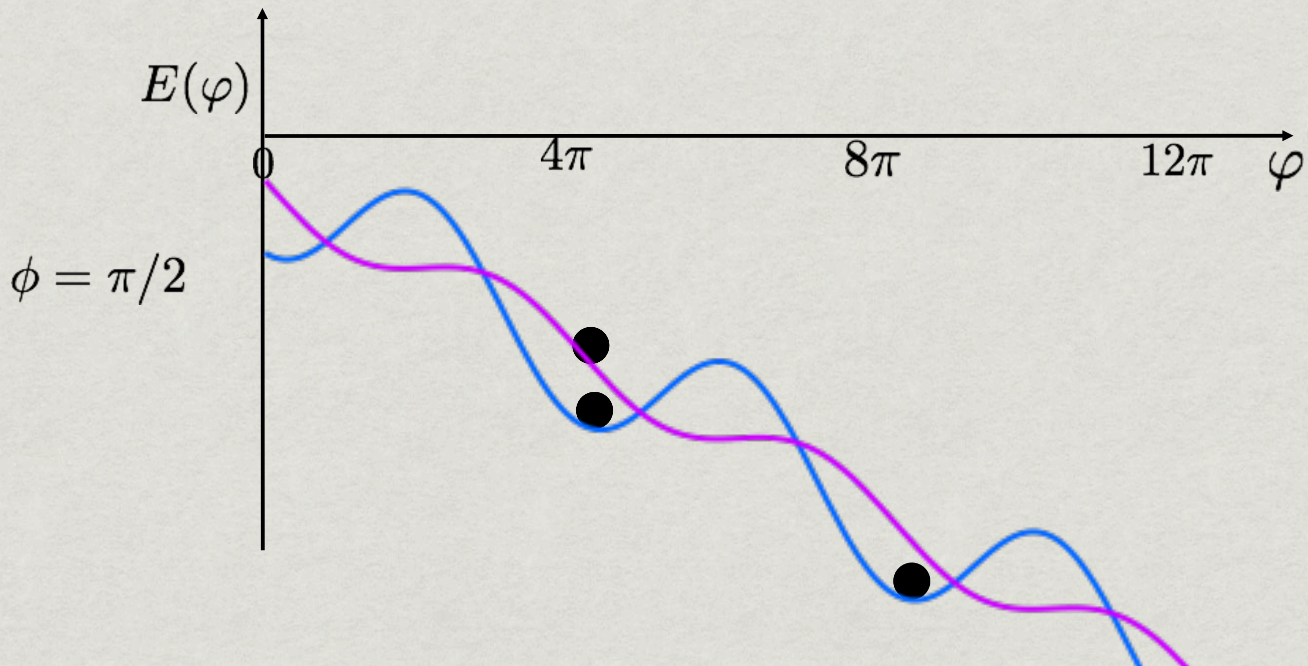
$$\langle V\rangle = \frac{\hbar}{2e}\langle\frac{\partial\varphi}{\partial t}\rangle = 0$$

Strong Parity Relaxation

$$E_1(\varphi, \phi) = -2\Delta \cos(\phi/4)\cos(\varphi/2) - \frac{\hbar}{e} I\varphi$$

$$E_2(\varphi, \phi) = -2\Delta \sin(\phi/4)\sin(\varphi/2) - \frac{\hbar}{e} I\varphi$$

$$I_c^{P_R \neq P_L} < I < I_c^{P_R = P_L}$$



$$\langle V \rangle = \frac{\hbar}{2e}\langle \frac{\partial \varphi}{\partial t} \rangle = \frac{R}{2}\sqrt{I^2 - I_{c1}^2}$$

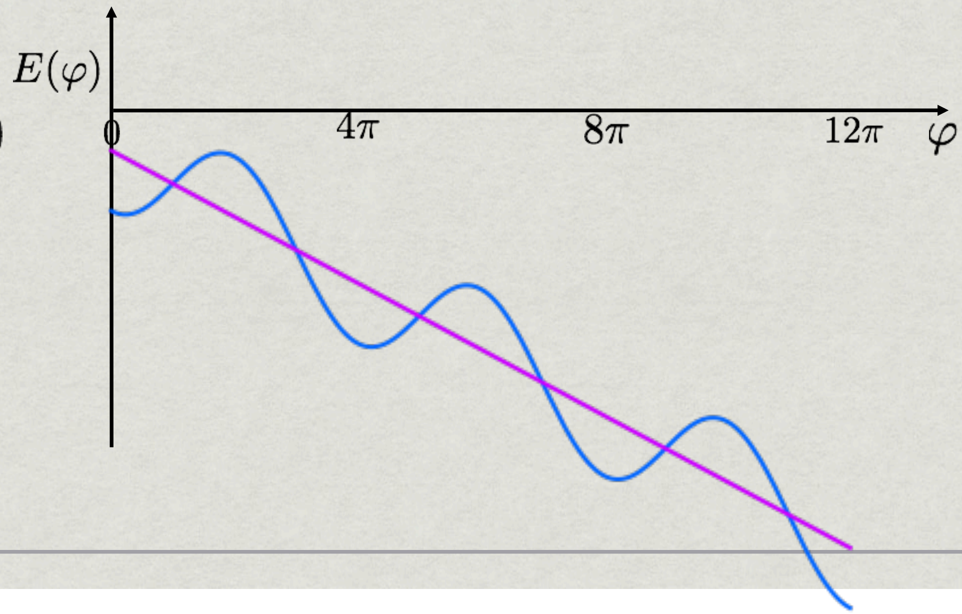
Strong Parity Relaxation

$$E_1(\varphi,\phi) = -2\Delta\cos(\phi/4)\cos(\varphi/2) - \frac{\hbar}{e}I\varphi$$

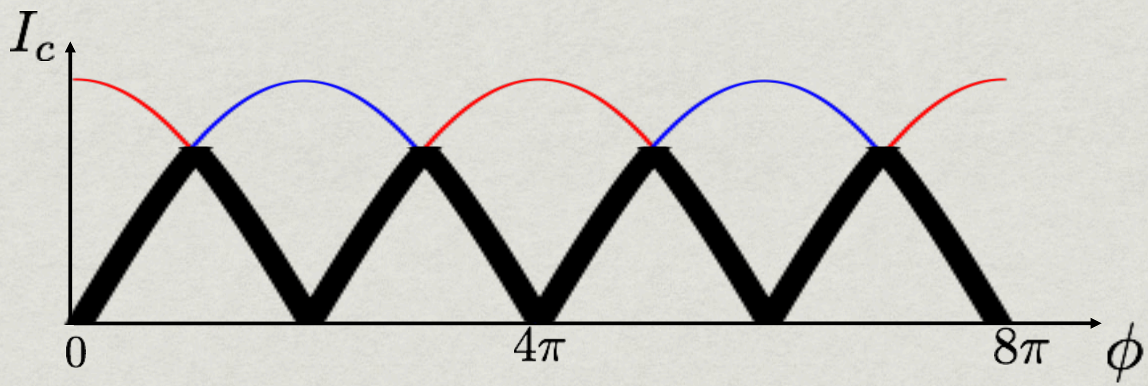
$$E_2(\varphi,\phi) = -2\Delta\sin(\phi/4)\sin(\varphi/2) - \frac{\hbar}{e}I\varphi$$

$$\langle V\rangle = \frac{\hbar}{2e}\langle\frac{\partial\varphi}{\partial t}\rangle = \frac{R}{2}\sqrt{I^2 - I_{c1}^2} + \frac{R}{2}\sqrt{I^2 - I_{c2}^2} \qquad I > I_c^{P_R\neq P_L}, I_c^{P_R=P_L}$$

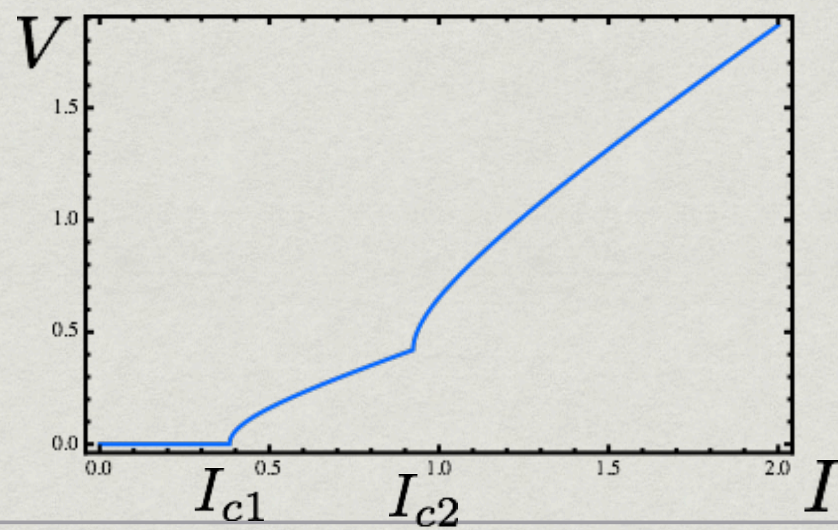
$\phi = 0$



Strong Parity Relaxation



$$I_c = \frac{e\Delta}{\hbar} \min\{\cos(\phi/4), \sin(\phi/4)\}$$



Conclusions

- The chirality of the edge states in quantum spin Hall systems is reflected in the properties of the Josephson junction.

- Parity conservation - the junction is equivalent to a ballistic one. The critical current is 4π - periodic in the flux.

- Parity relaxation - restores the 2π- periodicity in the flux.

- There is no node at π, and at strong enough parity switching a node appears at zero flux, and the junction becomes π - junction

While lifted nodes can be observed in asymmetric junctions, the transition into a π- junction is unique to the QSH state.

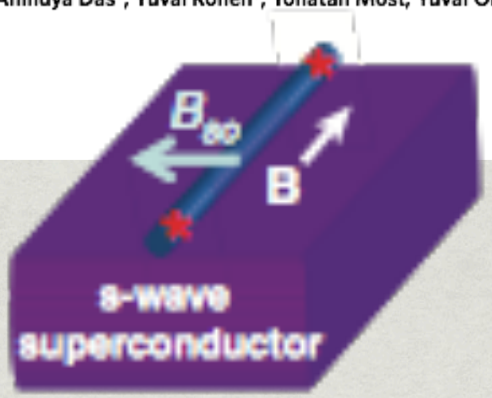
Conclusions

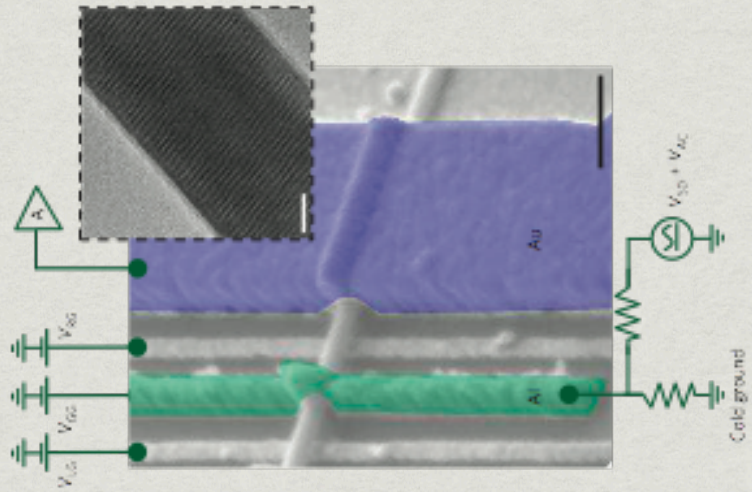
R. M. Lutchyn, J. D. Sau, and S. Das Sarma, 2010
Y. Oreg, G. Refael, and F. von Oppen, 2010

Similar physics can be observed in Josephson junctions made out of topological superconducting wires

Zero-bias peaks and splitting in an Al-InAs nanowire topological superconductor as a signature of Majorana fermions

Anindya Das†, Yuval Ronen†, Yonatan Most, Yuval Oreg, Moty Heiblum* and Hadas Shtrikman

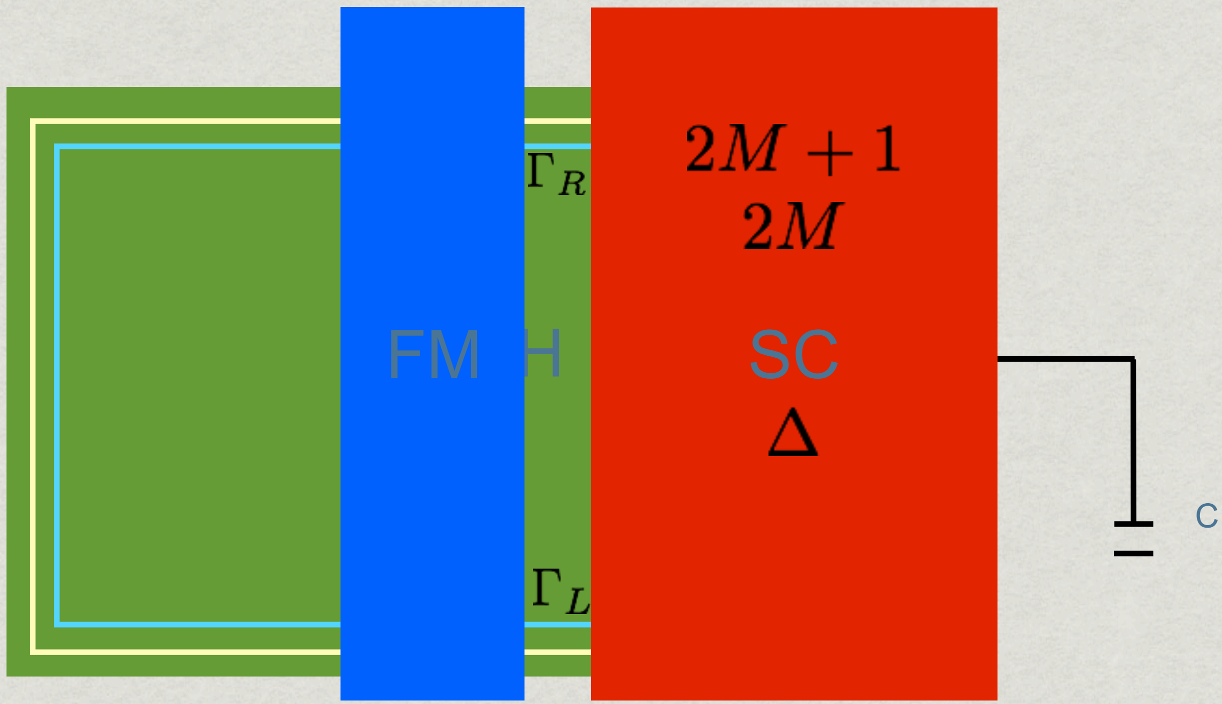




Signatures of Majorana Fermions in Hybrid Superconductor-Semiconductor Nanowire Devices

V. Mourik,[1]* K. Zuo,[1]* S. M. Frolov,[1] S. R. Plissard,[2] E. P. A. M. Bakkers,[1,2] L. P. Kouwenhoven[1]†

Superconducting Dot

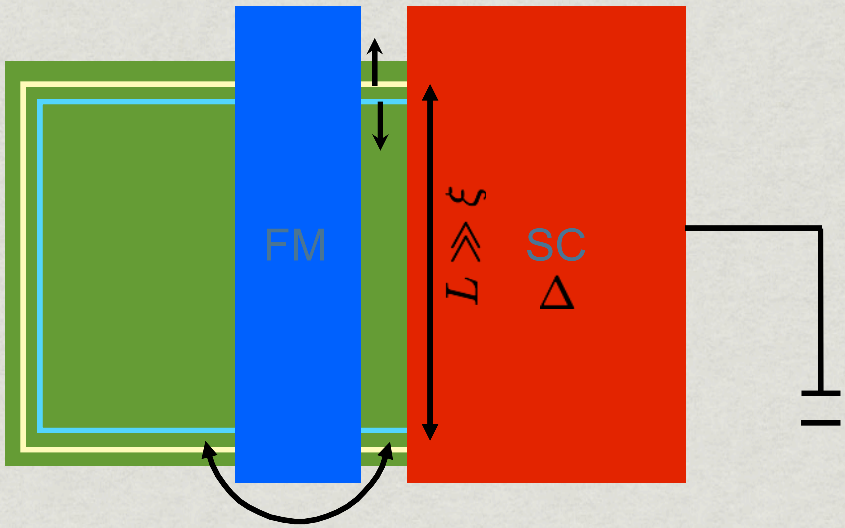


$d^\dagger = \gamma_L + i\gamma_R \quad d = \gamma_L - i\gamma_R$

KM, and L. Fu

Superconducting Dot

L. Fu, PRL, 2010.



$$U_c = \frac{(n-\bar{n})^2}{2C}$$

Tunneling to the dot = changing the occupancy of the bound state

Behaves as a quantum dot with a single level

$$H_T = tc_L^\dagger \gamma_L e^{-i\varphi/2} + t^* \gamma_L c_L e^{i\varphi/2}$$

Changes the number of electrons in the superconducting island by 1

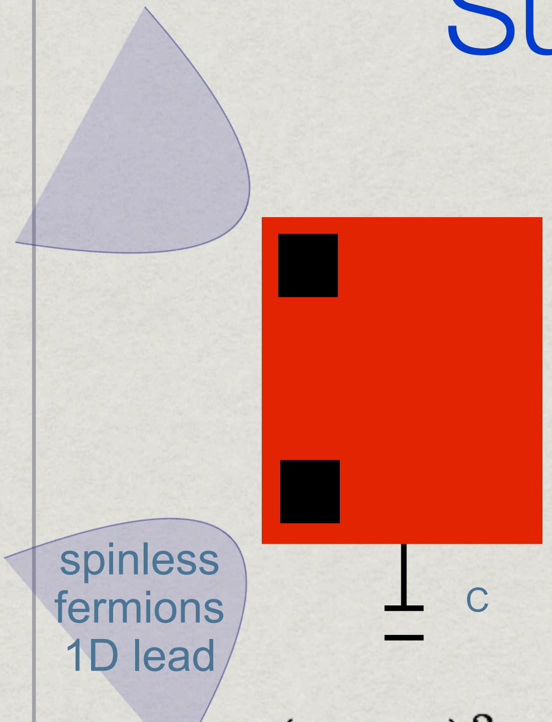
$$[n, e^{\pm i\varphi/2}] = \pm e^{\pm i\varphi/2}$$

Tunneling to the dot and out = count the number of electrons in the dot mod 2

$$\sim (d^\dagger d - 1/2) c_L^\dagger c_R$$

Coherent tunneling between the leads regardless for L

Superconducting Dot



$$U_c = \frac{(n-\bar{n})^2}{2C}$$

$\bar{n}$ - integer

Second order perturbation theory in t/U yields

$$H_{dot-leads} = \lambda_{1,2}\gamma_1\gamma_2 \left[c_2^\dagger c_1 - c_1^\dagger c_2\right]$$

$$\lambda_{1,2} = \frac{t_1 t_2}{U_c}$$

$$\downarrow$$

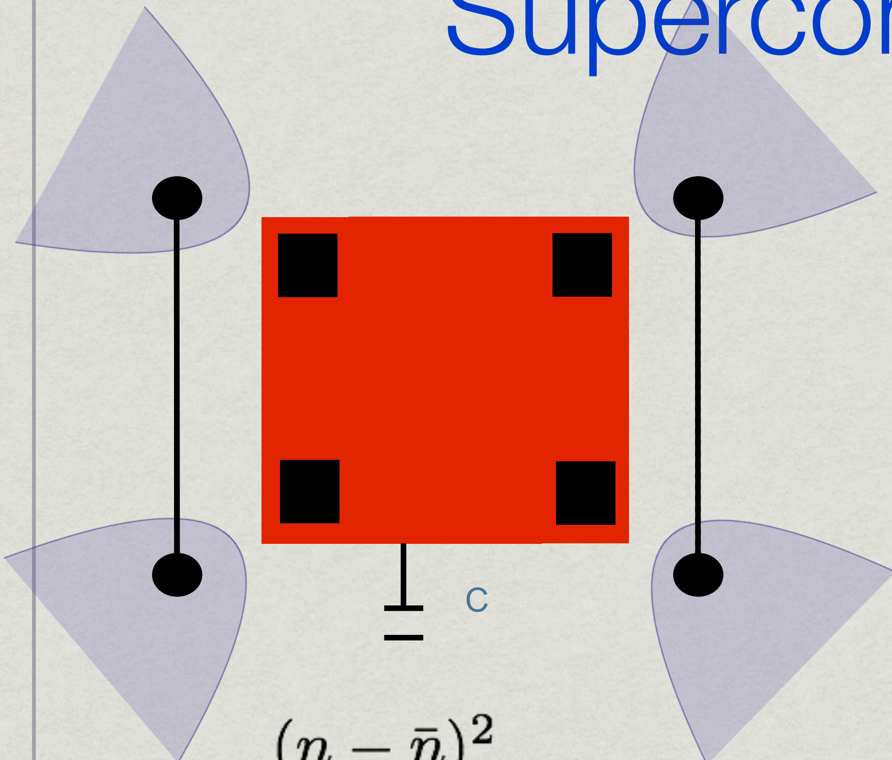
$$H_{dot-leads} = -i\lambda_{1,2}(d^\dagger d - 1/2) \left[c_2^\dagger c_1 - c_1^\dagger c_2\right]$$

Two leads coupled to a single fermion state in the dot

$$c_1 = \frac{f+g}{\sqrt{2}} \qquad c_2 = i\frac{f-g}{\sqrt{2}}$$

$$H_{dot-leads} = \lambda_{1,2}(d^\dagger d - 1/2)\left[f^\dagger f - g^\dagger g\right]$$

Superconducting Dot



$$U_c = \frac{(n-\bar{n})^2}{2C}$$

$\bar{n}$ - integer

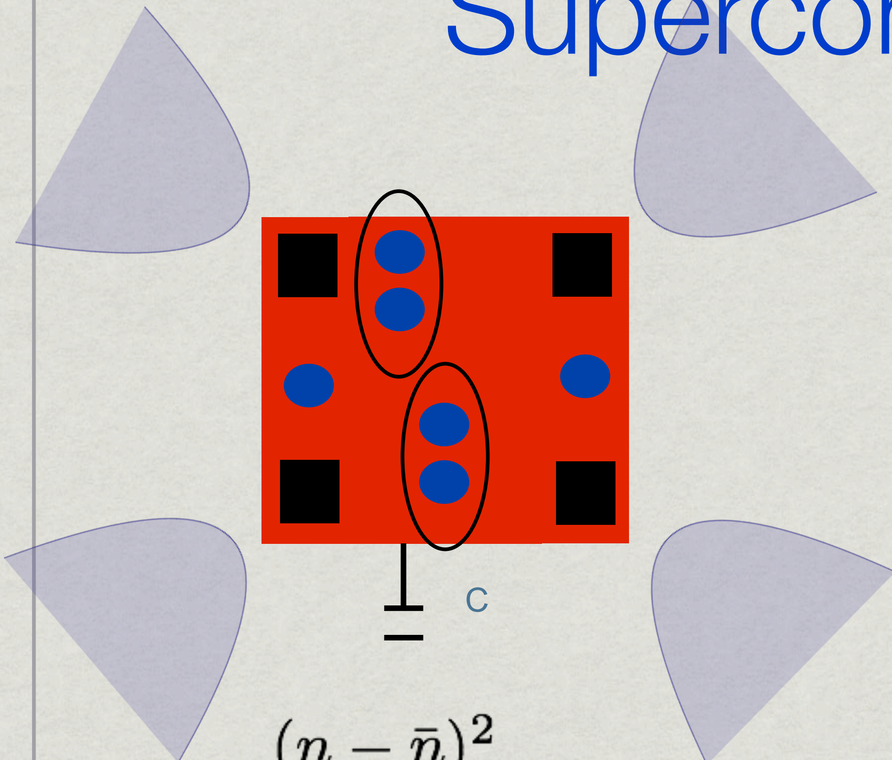
$$H_{dot-leads} = \lambda_{1,2}(d_1^\dagger d_1 - 1/2)\left[f_1^\dagger f_1 - g_1^\dagger g_1\right]$$
$$+\lambda_{3,4}(d_2^\dagger d_2 - 1/2)\left[f_2^\dagger f_2 - g_2^\dagger g_2\right]$$

$$\bar{n} = 2M$$

$$f_1^\dagger f_2$$

$$f_1^\dagger g_2$$

Superconducting Dot



$$U_c = \frac{(n-\bar{n})^2}{2C}$$

$\bar{n}$ - integer

$$H_{dot-leads} = \lambda_{1,2}(d_1^\dagger d_1 - 1/2)\left[f_1^\dagger f_1 - g_1^\dagger g_1\right]$$
$$+\lambda_{3,4}(d_2^\dagger d_2 - 1/2)\left[f_2^\dagger f_2 - g_2^\dagger g_2\right]$$

$$\bar{n} = 2M$$

$$f_1^\dagger f_2 \quad d_1^\dagger d_2^\dagger \qquad |2M;0,0\rangle \downarrow$$

$$f_1^\dagger g_2 \quad d_1 d_2 \qquad |2M-2;1,1\rangle \uparrow$$

Superconducting Dot

$su_2(2)$

$$\sigma_z = f_1^\dagger f_1 - f_2^\dagger f_2 - g_1^\dagger g_1 + g_2^\dagger g_2$$
$$\sigma_+ = f_1^\dagger f_2 - g_2^\dagger g_1$$
$$\sigma_- = f_2^\dagger f_1 - g_1^\dagger g_2$$

$$H_{dot-leads} = \lambda_{1,2}(d_1^\dagger d_1 - 1/2)\left[f_1^\dagger f_1 - g_1^\dagger g_1\right]$$
$$+\lambda_{3,4}(d_2^\dagger d_2 - 1/2)\left[f_2^\dagger f_2 - g_2^\dagger g_2\right]$$

$su_2(2)$

$$\tau_z = f_1^\dagger f_1 + f_2^\dagger f_2 - g_1^\dagger g_1 - g_2^\dagger g_2$$
$$\tau_+ = f_2^\dagger g_1 - f_1^\dagger g_2$$
$$\tau_- = g_1^\dagger f_2 - g_2^\dagger f_1$$

$$\bar{n} = 2M$$

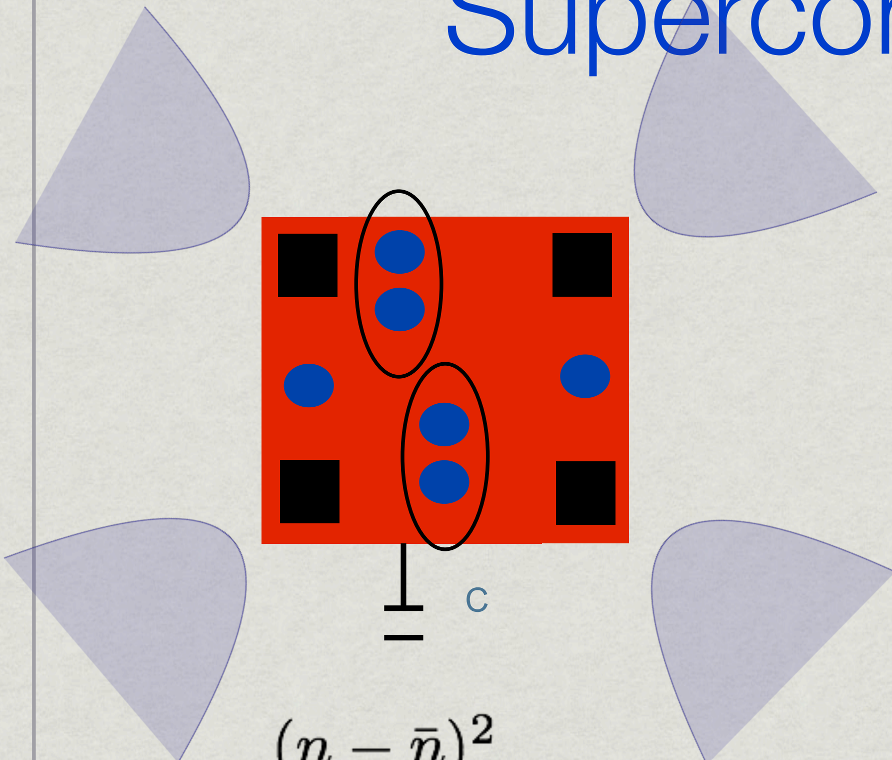
$$f_1^\dagger f_2 \quad d_1^\dagger d_2^\dagger \quad |2M;0,0\rangle \quad \downarrow$$

$$f_1^\dagger g_2 \quad d_1 d_2 \quad |2M-2;1,1\rangle \quad \uparrow$$

$$H_{dot-leads} = \lambda \vec{S} \cdot \vec{\tau}$$

Two channel Kondo problem - non Fermi liquid fixed point

Superconducting Dot



$$U_c = \frac{(n-\bar{n})^2}{2C}$$

$\bar{n}$ - integer

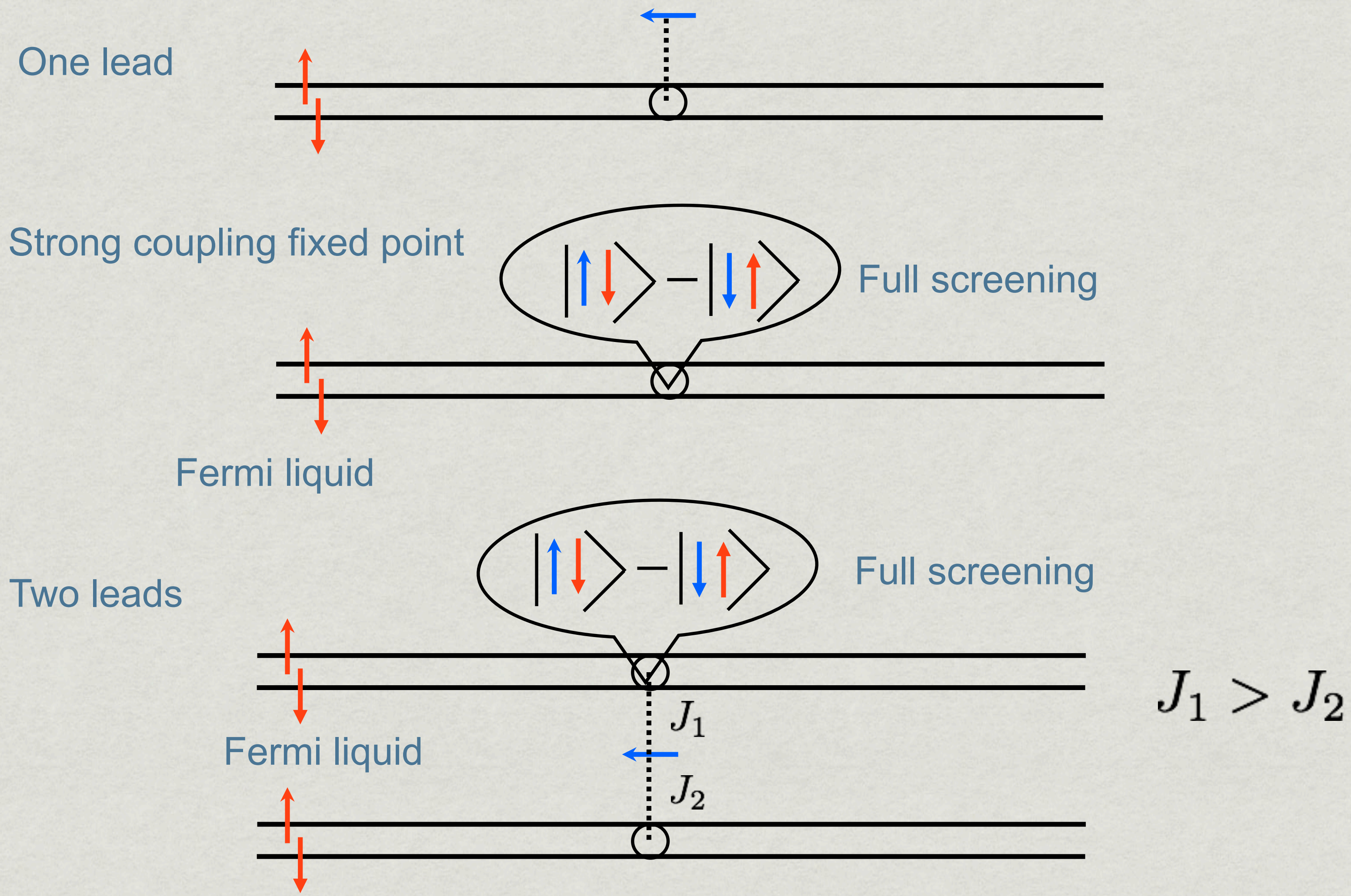
$$H_{dot-leads} = \lambda \vec{I} \cdot \vec{\sigma}$$

$$H_{dot-leads} = \lambda_{1,2}(d_1^\dagger d_1 - 1/2)\left[f_1^\dagger f_1 - g_1^\dagger g_1\right]$$
$$+\lambda_{3,4}(d_2^\dagger d_2 - 1/2)\left[f_2^\dagger f_2 - g_2^\dagger g_2\right]$$

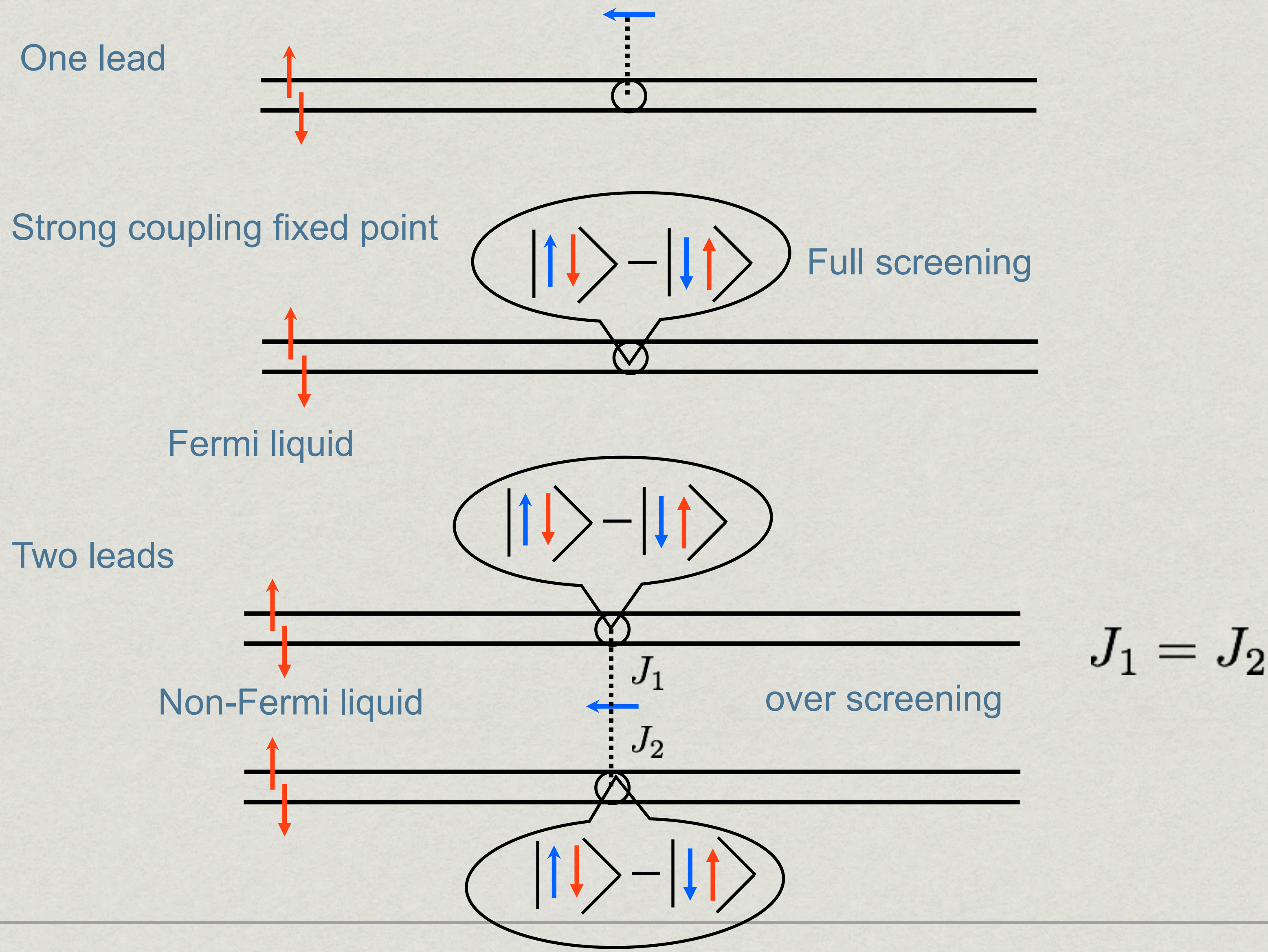
$$\bar{n} = 2M+1$$

$f_1^\dagger f_2$	$d_1^\dagger d_2$	$\vert 2M;0,1\rangle$	$\downarrow$
$f_1^\dagger g_2$	$d_2^\dagger d_1$	$\vert 2M;1,0\rangle$	$\uparrow$

1 & 2 Channel Kondo



1 & 2 Channel Kondo



Two channel Kondo

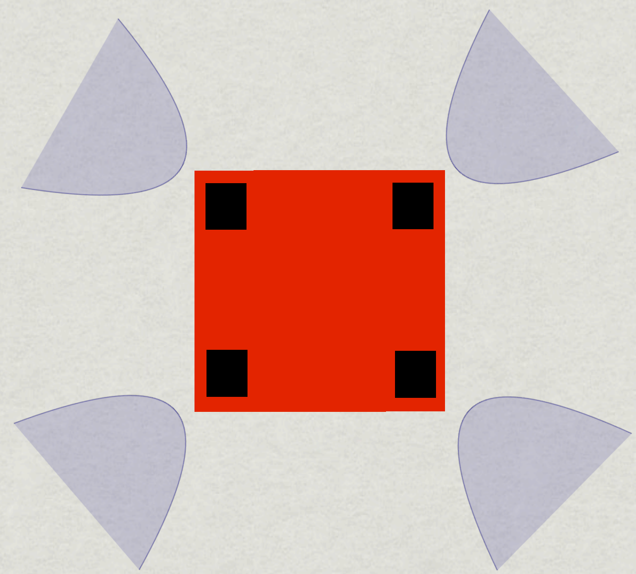
$$\frac{d\lambda}{d\ell} = 2\lambda^2 \longrightarrow$$ the coupling constant grows

The fixed point is at strong coupling

$$T_k \sim U_c e^{-\pi/2\lambda}$$

The conductance peaks below T_k

$$G = \frac{e^2}{2h} + \kappa T$$



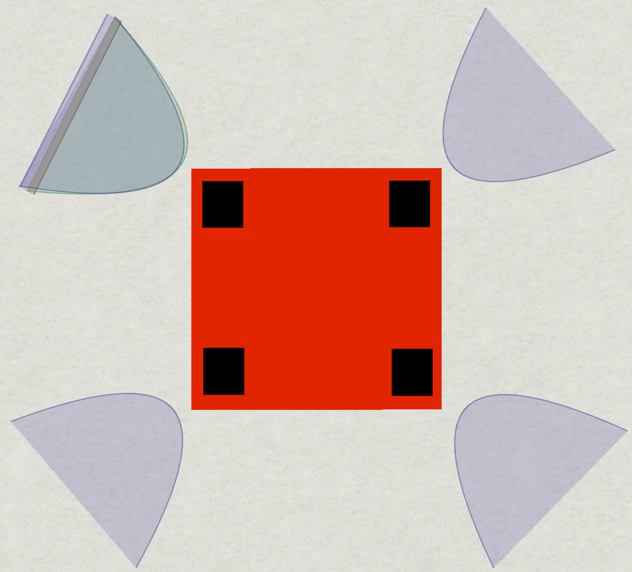
B. Beri, and N. R, Cooper, PRL, 2012.
A. Altland, and R. Egger, PRL, 2013.
M. R. Galpin, et al., 2013

Two channel Kondo

$$\frac{d\lambda}{d\ell} = 2\lambda^2 \longrightarrow$$

the coupling constant grows

$$H_{dot-leads} = \lambda \vec{S} \cdot \vec{\tau} + \delta \vec{S} \cdot \vec{\sigma}$$



$$su(2) \times su(2) \longrightarrow su(2)$$

The allowed perturbation is marginal

$$H_T = t c_L^\dagger \gamma_L e^{-i\varphi/2} + t^* \gamma_L c_L e^{i\varphi/2}$$

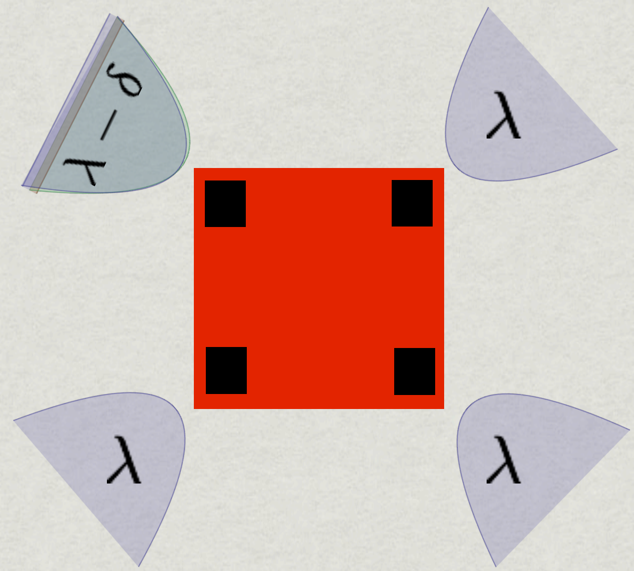
To break the symmetry between the channels we need to break the symmetry between electrons and holes $\longrightarrow$ Changing the chemical potential away from $\bar{n}$ - integer

4 leads ⟷ 3 leads

$$H_{dot-leads} = \lambda \vec{S} \cdot \vec{\tau} + \delta \vec{S} \cdot \vec{\sigma}$$

$$\frac{d\lambda}{d\ell} = \lambda^2 + (\lambda - \delta)^2$$

$$\frac{d(\lambda - \delta)}{d\ell} = 2\lambda(\lambda - \delta)$$

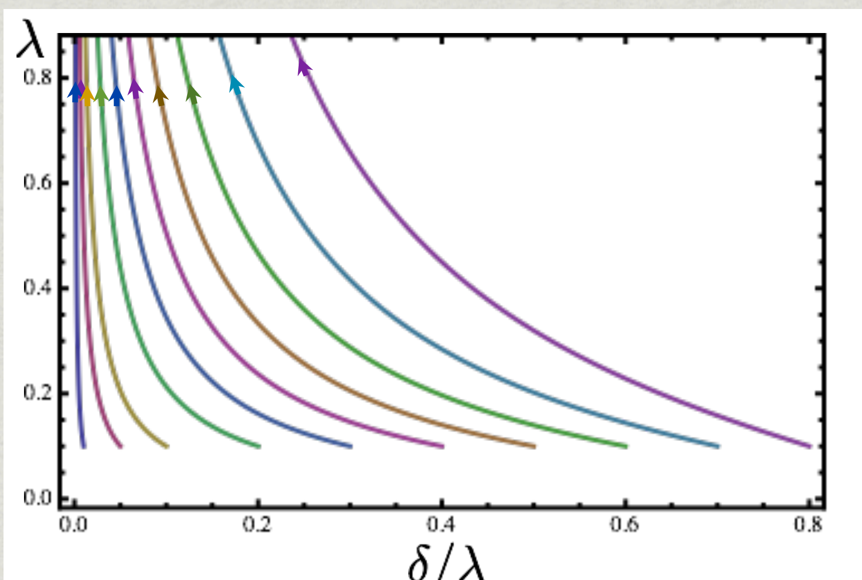


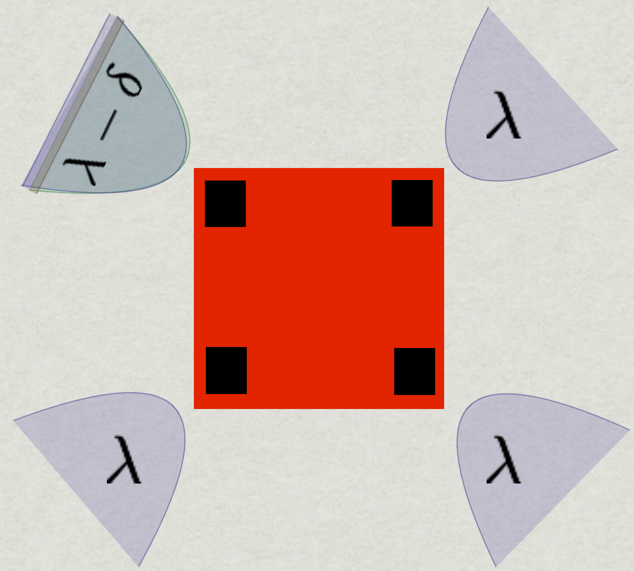
4 leads $\longleftrightarrow$ 3 leads

$$H_{dot-leads} = \lambda\vec{S}\cdot\vec{\tau} + \delta\vec{S}\cdot\vec{\sigma}$$

$$\frac{d\lambda}{d\ell} = \lambda^2 + (\lambda-\delta)^2$$

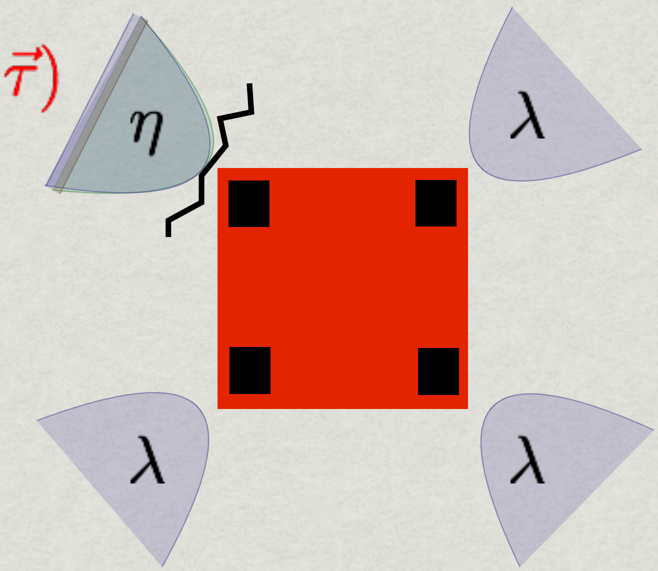
$$\frac{d(\lambda-\delta)}{d\ell} = 2\lambda(\lambda-\delta)$$





4 leads ⟷ 3 leads

$$H_{dot-leads} = \lambda \vec{S} \cdot (\vec{\tau} + \vec{\sigma}) + \eta \vec{S} \cdot (\vec{\sigma} - \vec{\tau})$$



Spin 1/2 dot coupled to spin 1 dot

The dot is over-screened by the leads

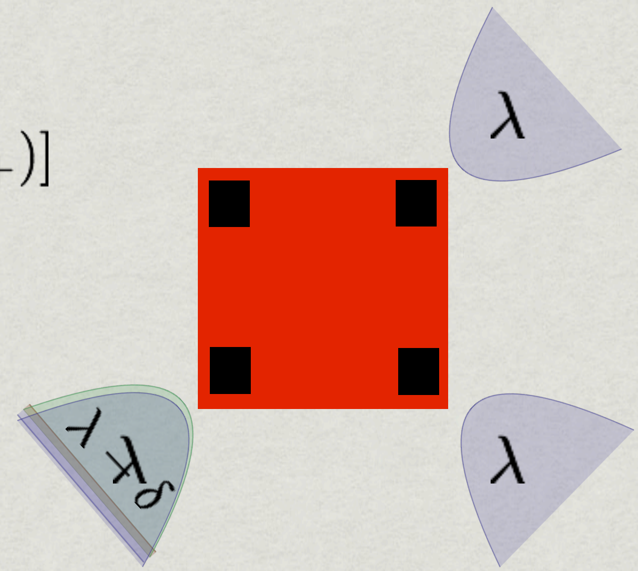
The allowed perturbation $\eta \vec{S} \cdot \vec{\phi}_{\sigma+\tau} Q_4$ has dimension of 2/3

↓

Switching on the coupling to the forth lead is relevant

3 leads $\longleftrightarrow$ 2 leads

$$H_{dot-leads} = \lambda S_z(\tau_z + \sigma_z)$$
$$+\frac{1}{2}(\lambda - \delta)\left[S_+(\tau_- + \sigma_-) + S_-(\tau_+ + \sigma_+)\right]$$

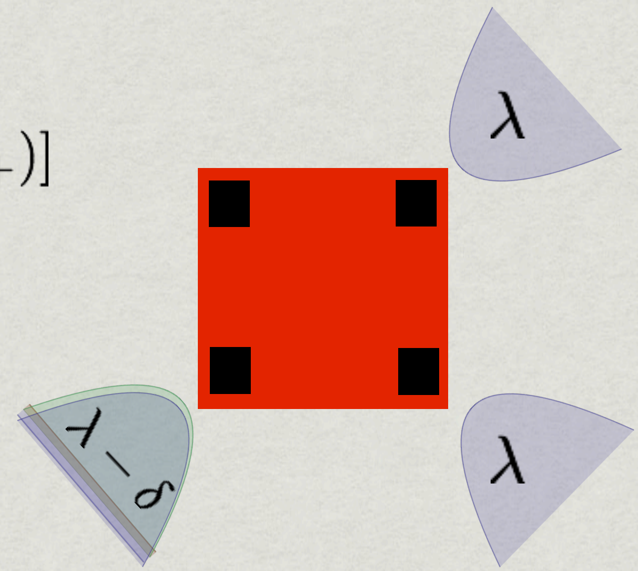


Unlike the standard overscreened su(2) Kondo problem, the anisotropic spin coupling is marginal

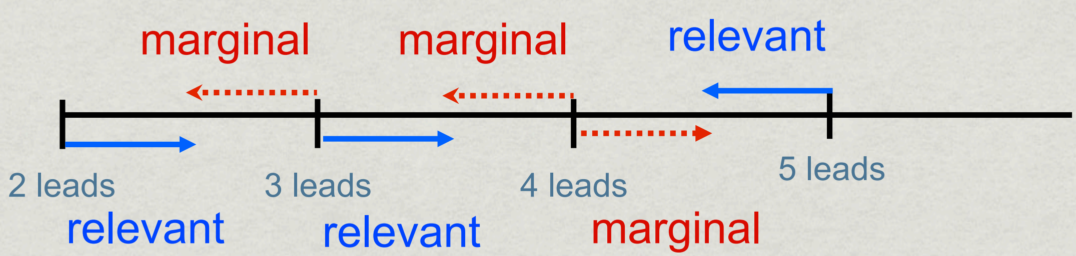
marginal

3 leads $\longleftrightarrow$ 2 leads

$$H_{dot-leads} = \lambda S_z(\tau_z + \sigma_z)$$
$$+\frac{1}{2}(\lambda - \delta)\left[S_+(\tau_- + \sigma_-) + S_-(\tau_+ + \sigma_+)\right]$$



Unlike the standard overscreened su(2) Kondo problem, the anisotropic spin coupling is marginal



marginal

Conclusions

- The superconducting dot with Majorana modes maps into an over-screened Kondo problem
- In particular for 4 Majorana modes and 4 leads the system is equivalent to the 2 channel Kondo problem. Unlike the usual 2CK, here anisotropy in the couplings of the leads to the dot does not destroy the non-Fermi liquid phase.
- The state with 4 and 3 leads coupled to the dot are connected through a line of fixed points.
- The 4 leads coupled to 4 Majorana modes is the most stable state of the system.