Bogoliubov-Majorana Gun:
An On-demand Single Bogoliubov Quasiparticle Source

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$\underbrace{\text{Fellow gunsmiths}}_{\text{theoretical}}$: B. Tarasinski, D. Chevallier, B. Baxevanis and C. W. J. Beenakker

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Electronic quantum "optics"

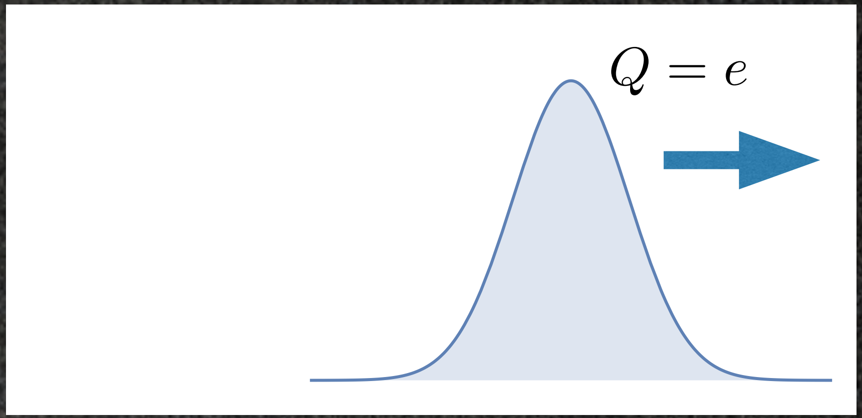
Goal: coherent manipulation of a single electronic quantum

- applying ideas from quantum optics in mesoscopic systems
- potential applications in quantum information/communication

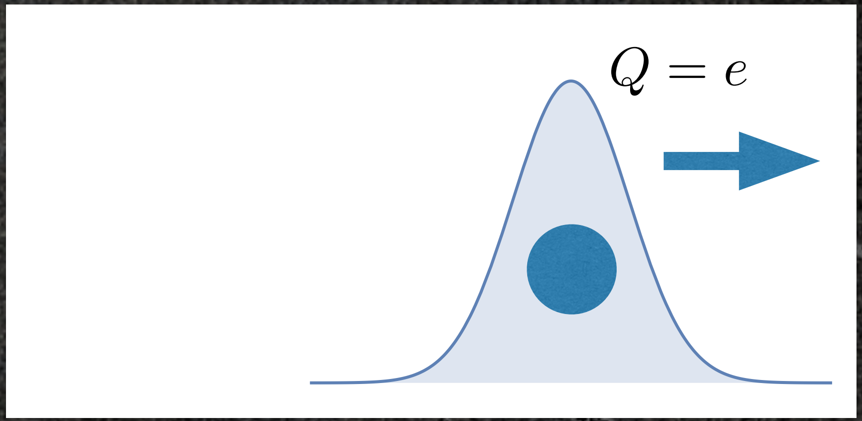
The analog of photon gun:	Current status:
electron/hole gun	realized
Bogoliubov-Majorana gun	in progress
Abelian anyon gun	in progress
non-Abelian anyon gun	science fiction
???	

Electron gun

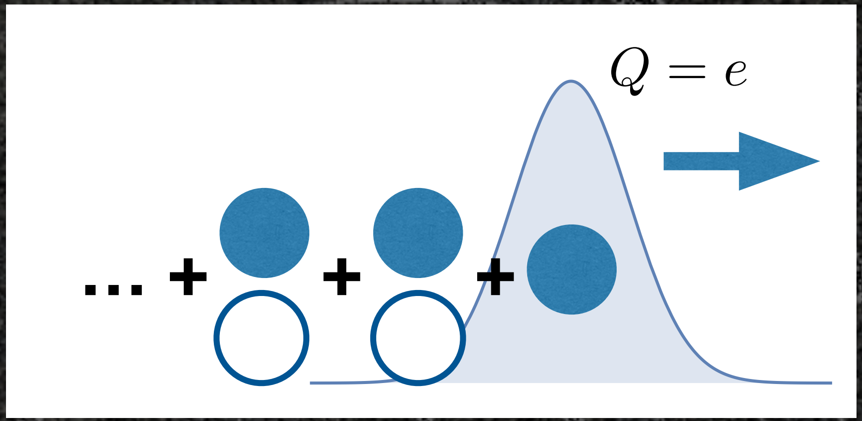
Difficulty: the ground state is a many-body ground state



so, instead of

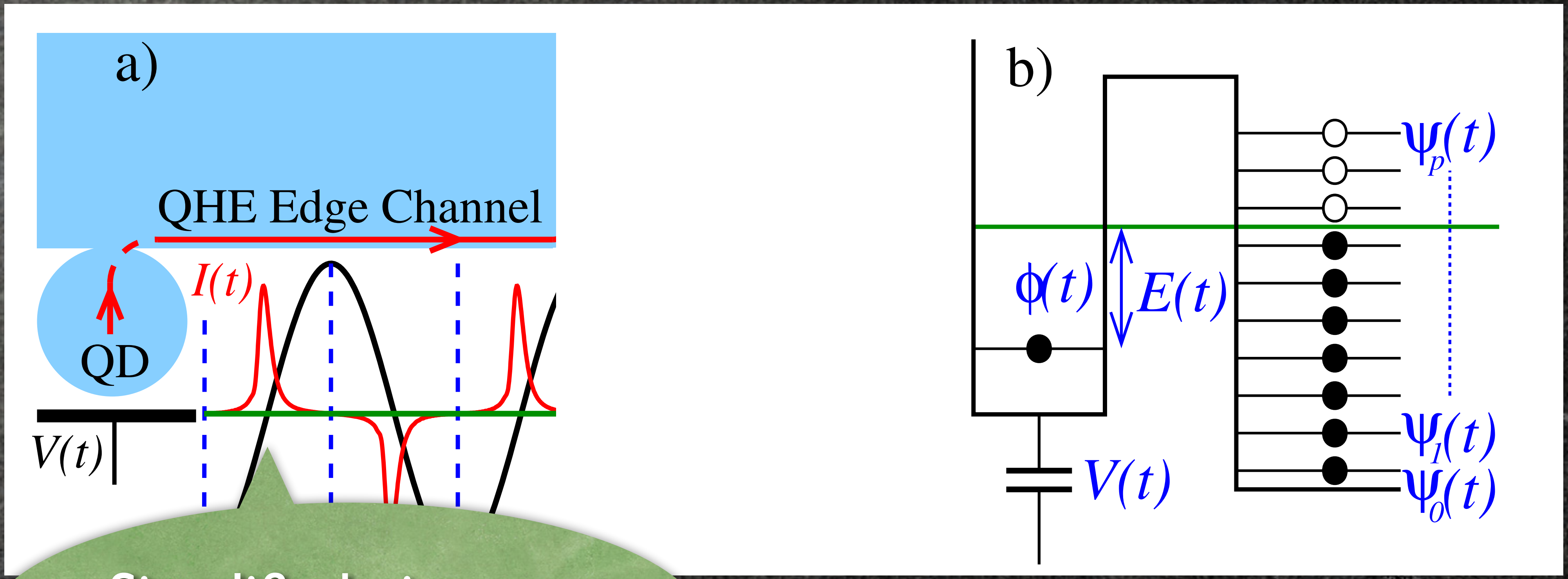


in general, you have



Mesoscopic capacitor

Couple a localized state to the lead and drive it periodically



Simplified picture:
a linear drive

Feve, *et. al.*, Science (2007)

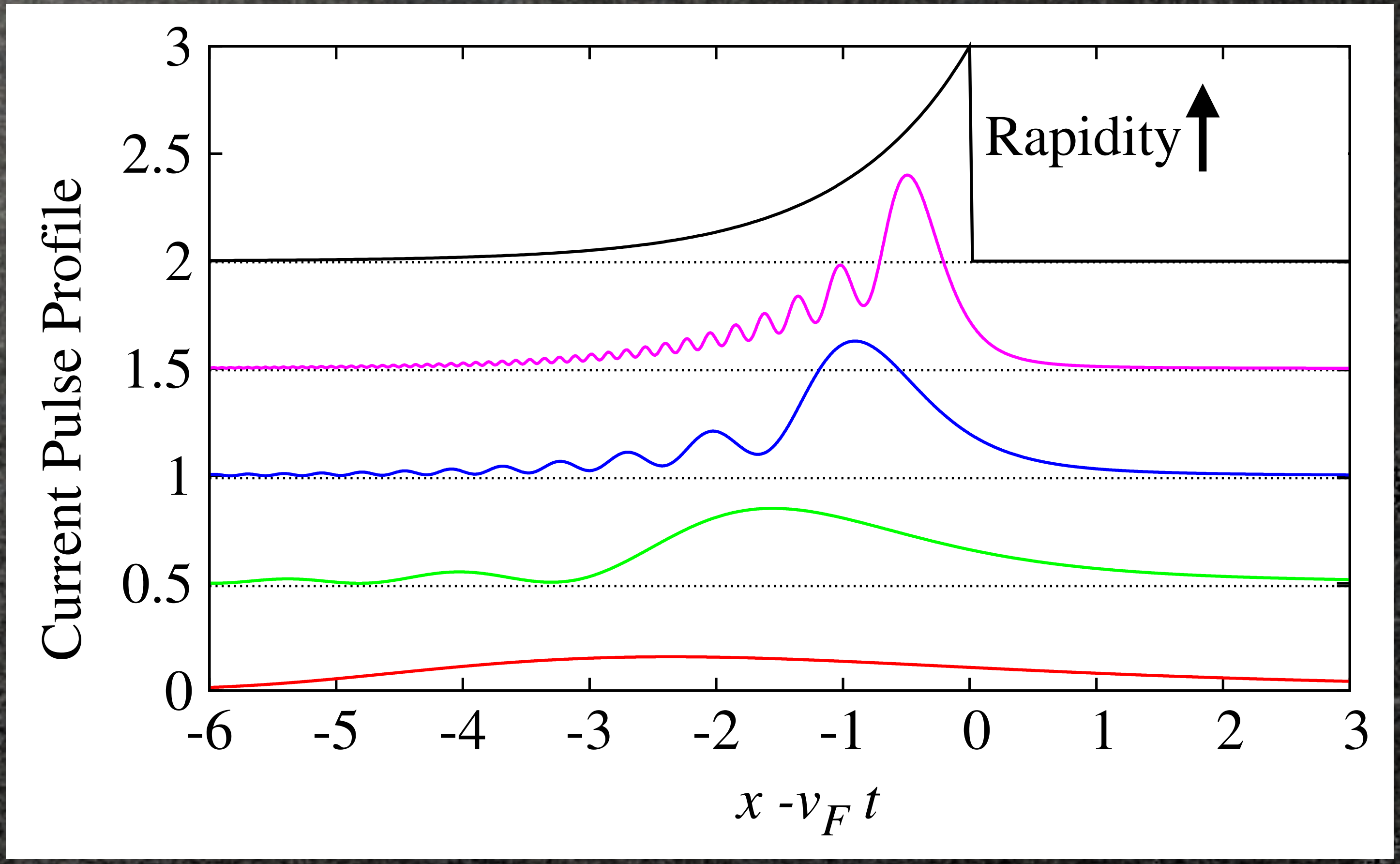
Parmentier, *et. al.*, PRB (2012)

Keeling, Shytov and Levitov, PRL (2008)

Linear drive (I)

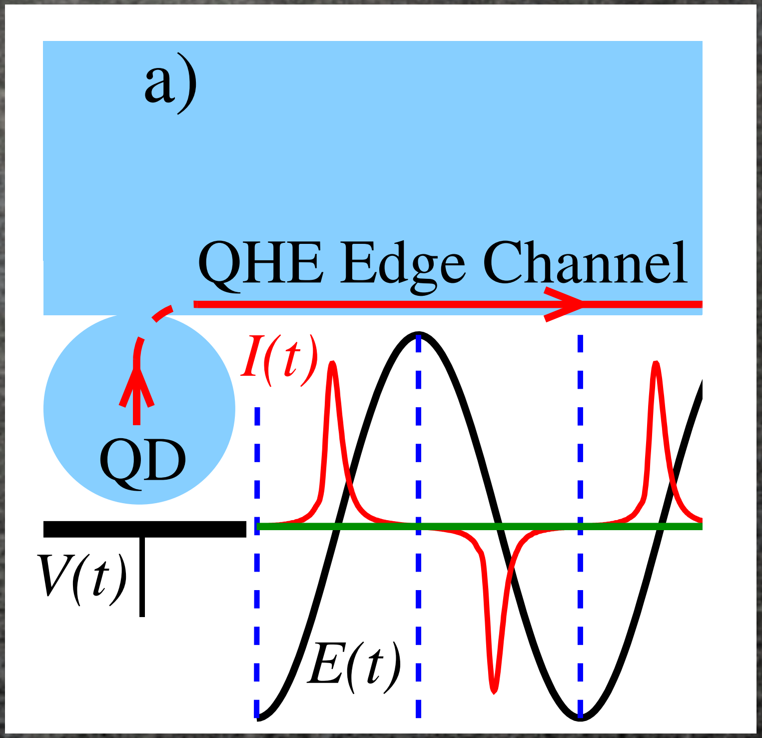
Couple a localized state to the lead and drive it linearly

Keeling, Shytov and Levitov, PRL (2008)



particle current = charge current

Linear drive (2)

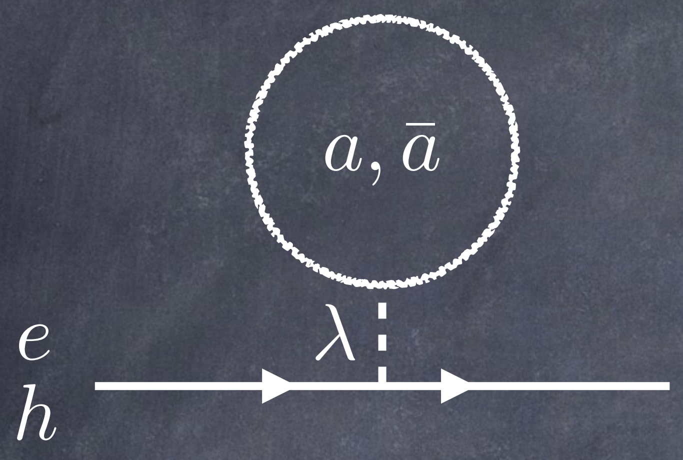


electron gun = hole gun

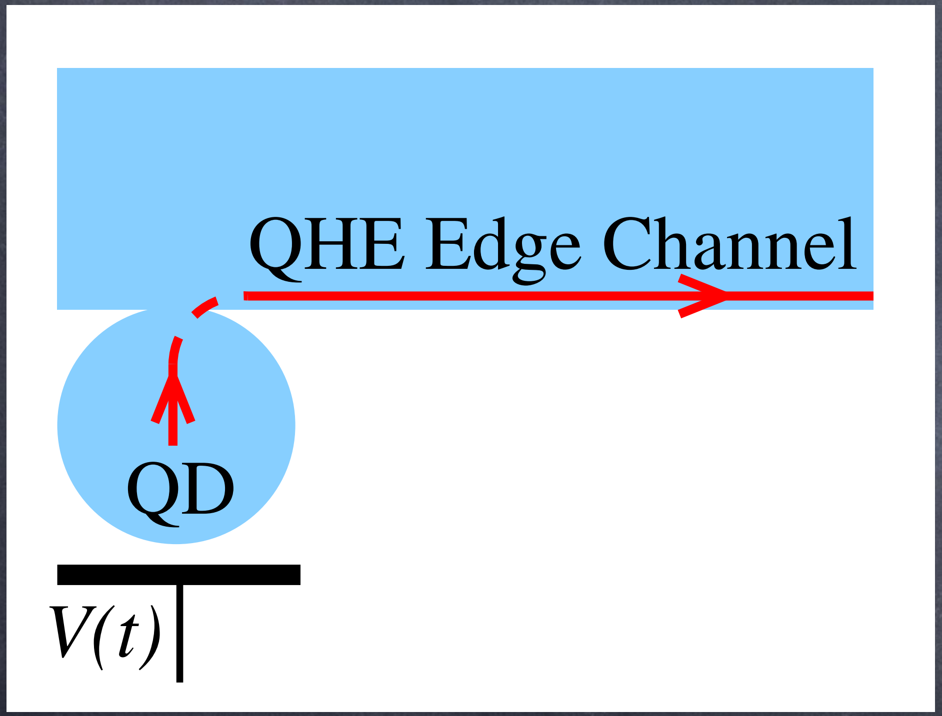
electron + hole gun?

Majorana gun?

Particle-hole symmetric version

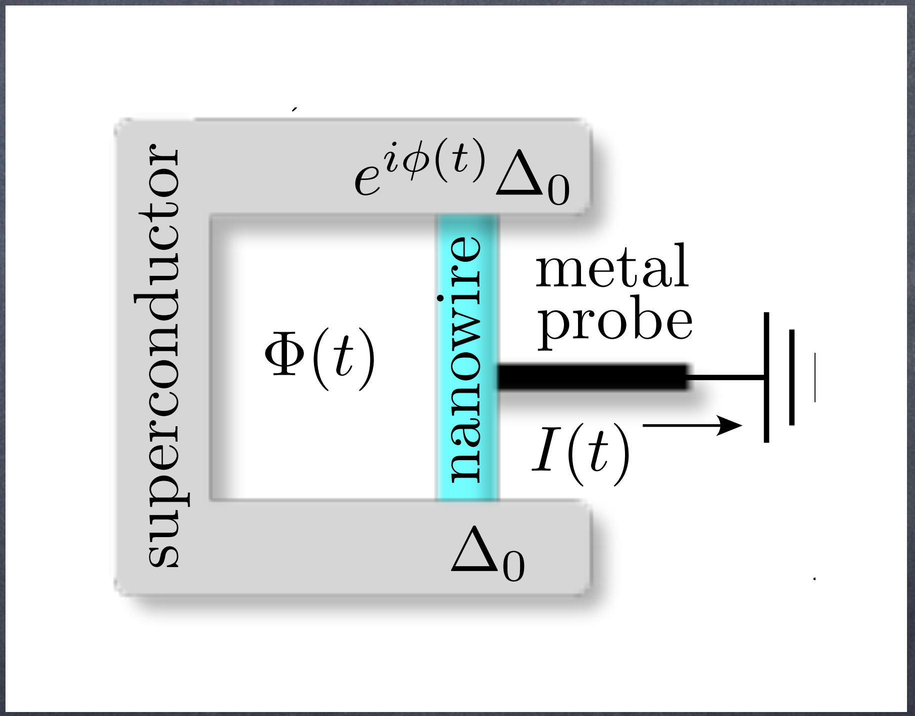


Couple an Andreev quasi bound state to the lead and drive it linearly



superconducting quantum dot

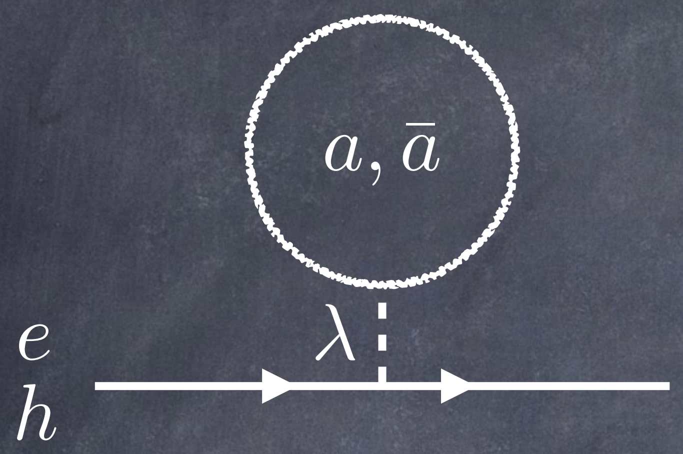
Lee, et. al, Nat. Nanotech. (2014); Wan et al; Goswami et al; Kumaradivel and Du; Amet et al (2015)



Josephson junction

Chang, et. al, PRL (2013)

Particle-hole symmetric version



Couple an Andreev quasi bound state to the lead and drive it linearly

$$H = \left(\begin{array}{cc|cc} H_a & 0 & \multicolumn{2}{c}{\multirow{2}{*}{λ}} \\ 0 & H_{\bar{a}} & & \\ \hline \multicolumn{2}{c|}{\multirow{2}{*}{$\lambda^\dagger$}} & H_e & 0 \\ & & 0 & H_h \end{array}\right)$$

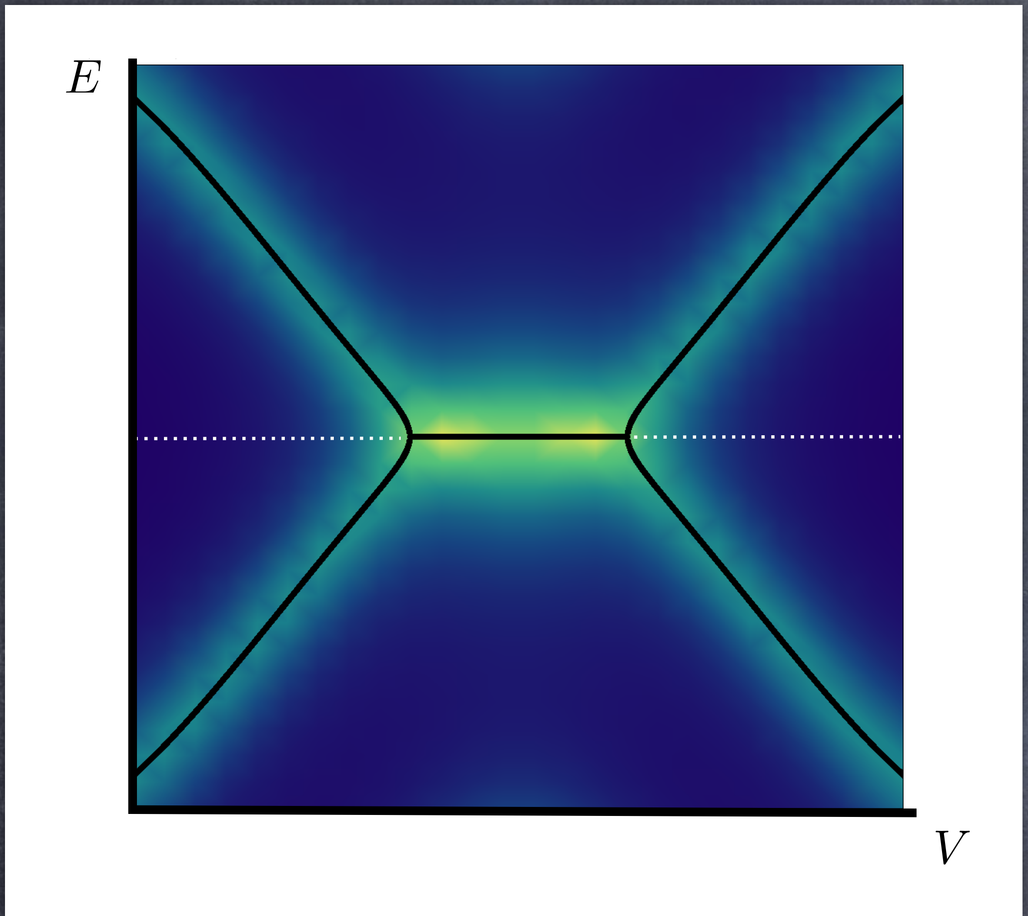
$$\lambda = i\sqrt{\gamma}\begin{pmatrix} \cos\theta & \sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

θ : asymmetry of the coupling between electron/hole and the Andreev states

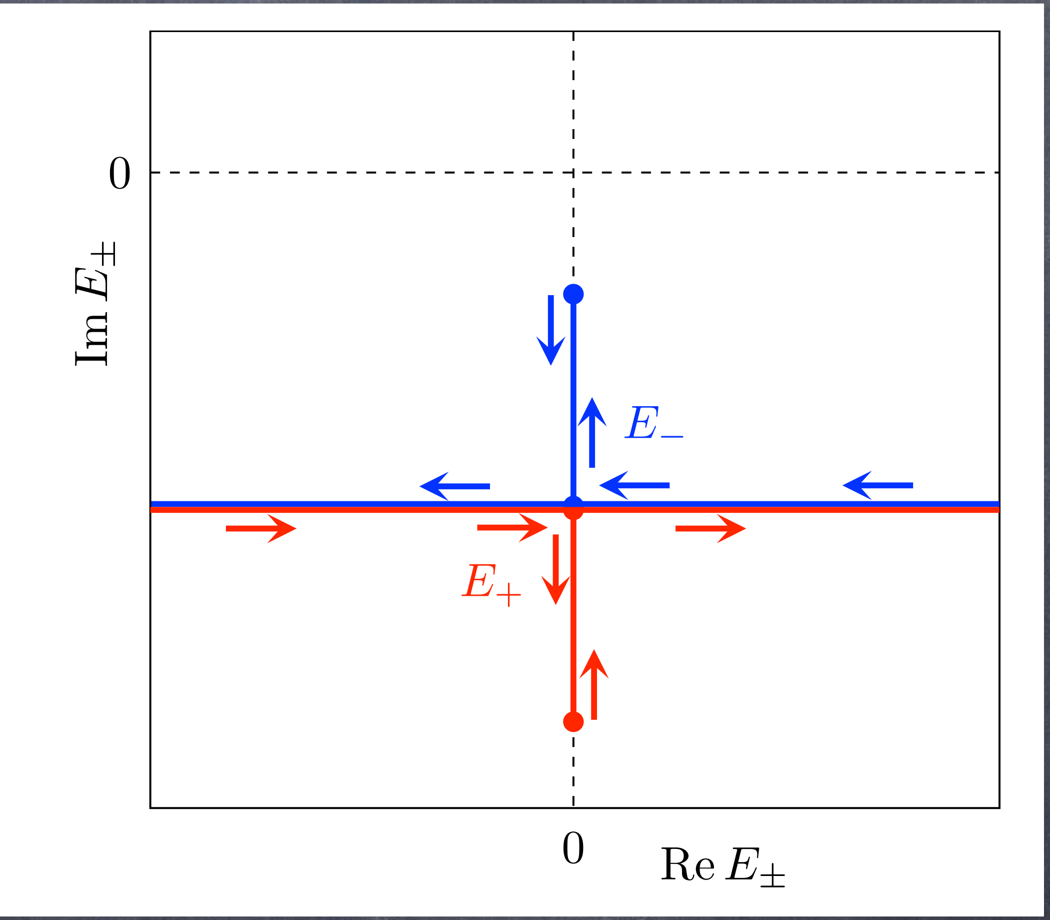
Adiabatic limit in the dot

Pikulin and Nazarov, PRB (2013)

Mi, et. al., JETP (2014)



Local density of states

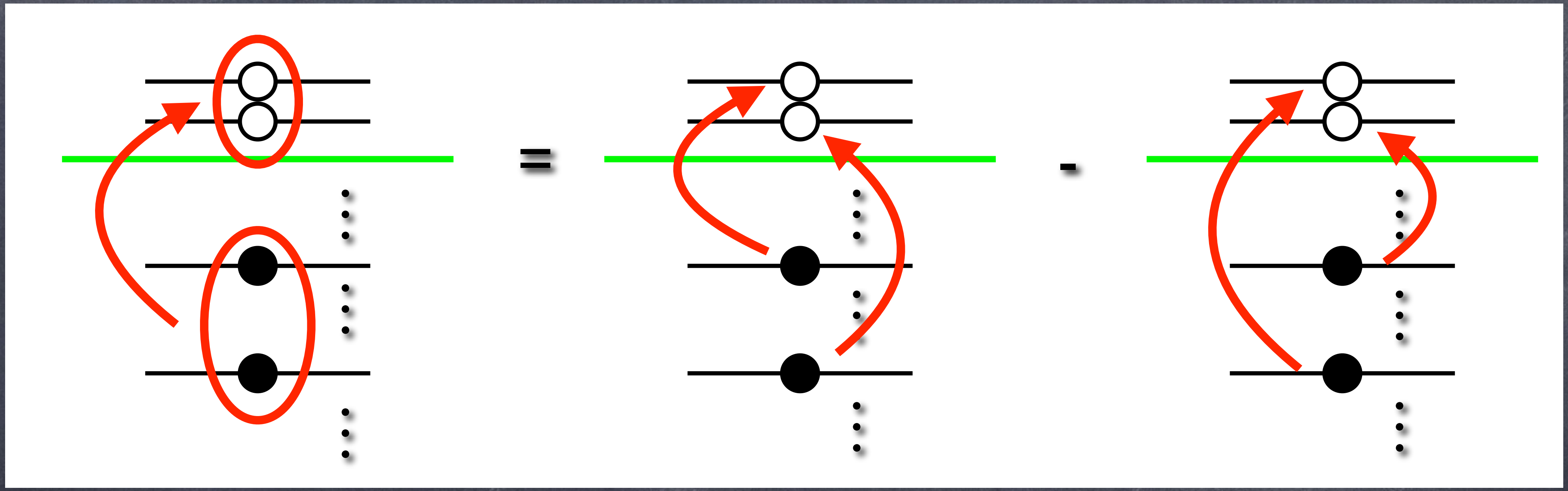


Poles of the Green's function

Emitted state (1)

$$|\Psi\rangle = c_0|0\rangle + c_1|1\text{-particle}\rangle + \cancel{\cdots}$$

Any other states will involve



$$S(\epsilon > 0, \epsilon' < 0) = \psi(\epsilon)\ \psi^\dagger(\epsilon')$$

Emitted state (2)

$$|\Psi\rangle = c_0|0\rangle + c_1|1\!-\!\text{particle}\rangle$$

but $1 = \langle\Psi|\ N\ |\Psi\rangle = |c_1|^2$

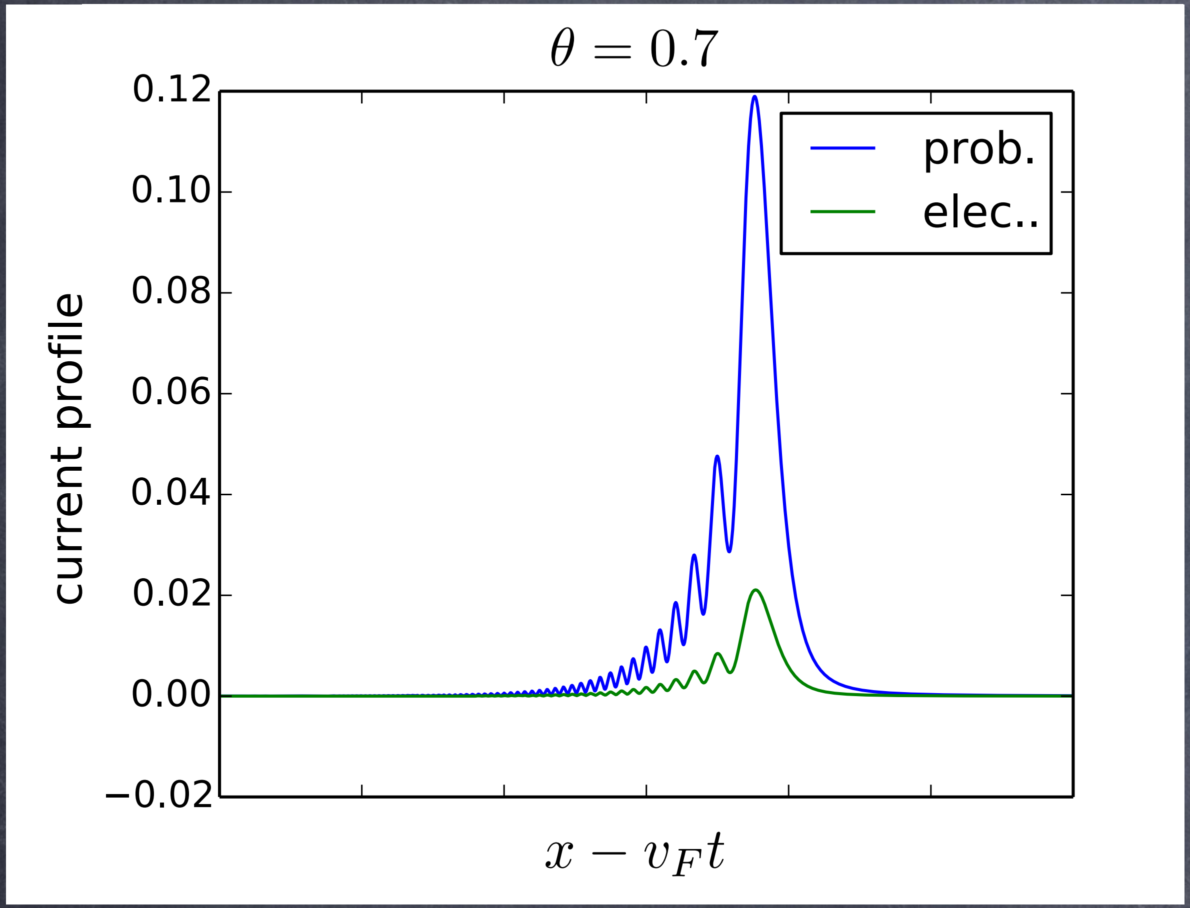
$\Rightarrow\ c_0 = 0$

Anderson orthogonality catastrophe

PRL (1967)

$$\boxed{\text{One quasiparticle emitted independent of the sweep rate}}$$

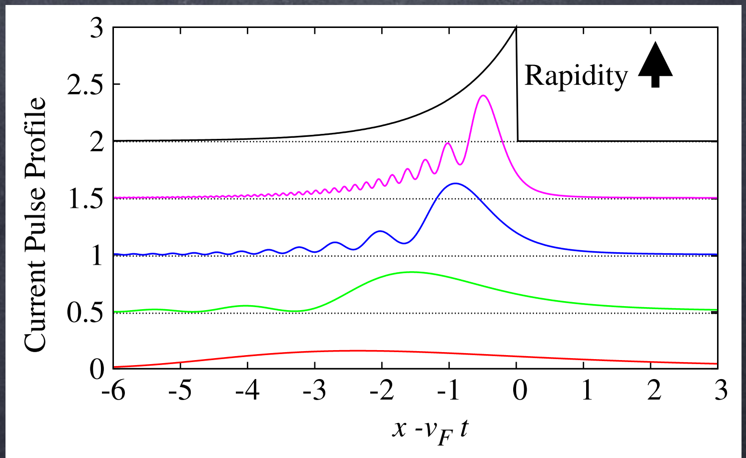
Emitted current



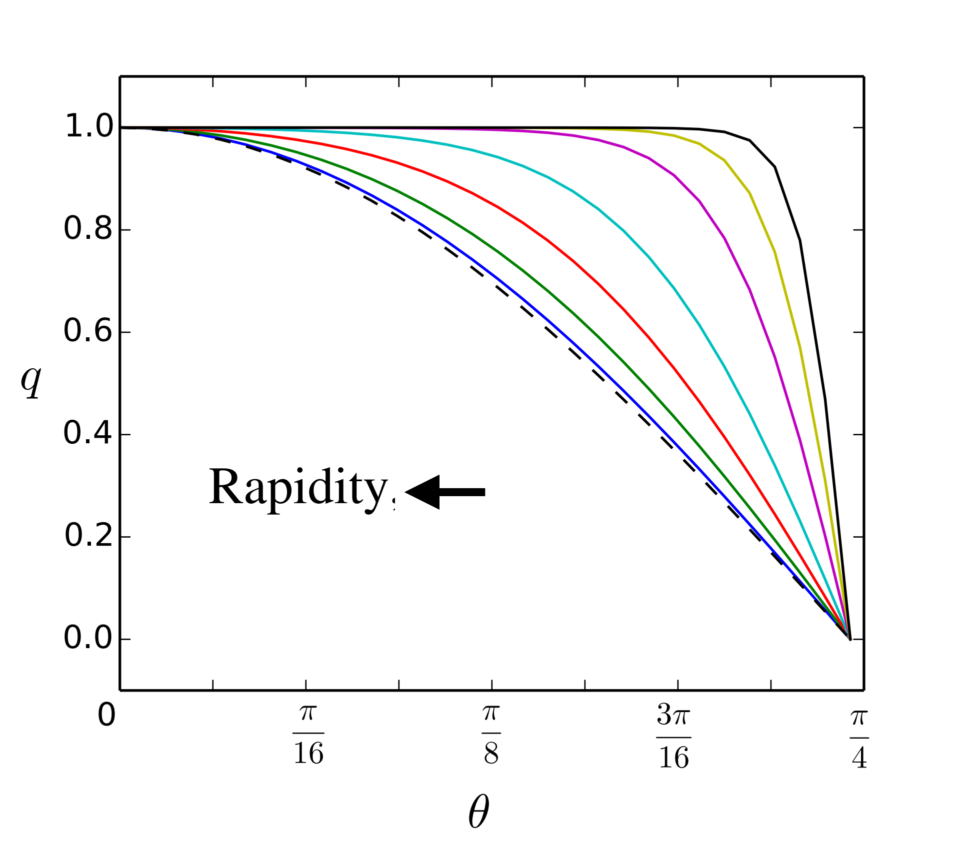
particle current $\geq$ charge current

$$\lambda = i\sqrt{\gamma}\begin{pmatrix} \cos\theta & \sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

θ : asymmetry of the coupling between electron/hole and the Andreev states



Charge of the emitted quasiparticle



- Quench limit:

$$q = \cos 2\theta$$

- Adiabatic limit:

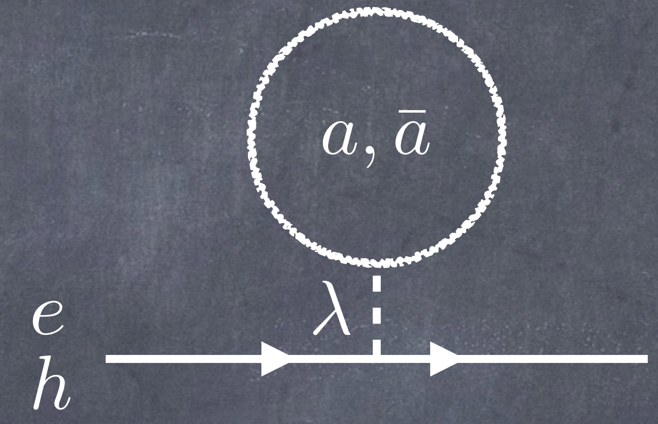
$$q = \mathrm{sign}(\cos 2\theta)$$

Electron (hole) gun is pretty robust!

- To have Majorana (neutral quasiparticle), must zoom in to $\theta = \pi/4$

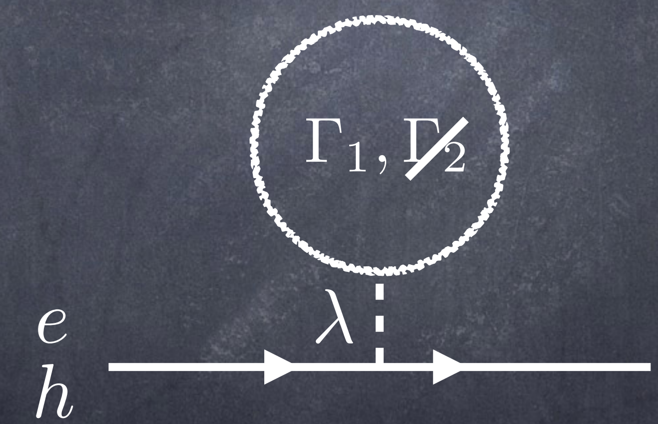
Towards Majorana gun

$$H = \left(\begin{array}{cc:cc} H_a & 0 & \multicolumn{2}{c}{\multirow{2}{*}{λ}} \\ 0 & H_{\bar{a}} & & \\ \hdashline \multicolumn{2}{c:}{\multirow{2}{*}{$\lambda^\dagger$}} & H_e & 0 \\ & & 0 & H_h \end{array}\right)$$



$$\theta = \pi/4 \Rightarrow \quad \lambda = i\sqrt{\gamma}\begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$

$$H = \left(\begin{array}{cc:cc} 0 & H_\Gamma & i\sqrt{\gamma} & i\sqrt{\gamma} \\ H_\Gamma^\dagger & 0 & 0 & 0 \\ \hdashline -i\sqrt{\gamma} & 0 & H_e & 0 \\ -i\sqrt{\gamma} & 0 & 0 & H_h \end{array}\right)$$

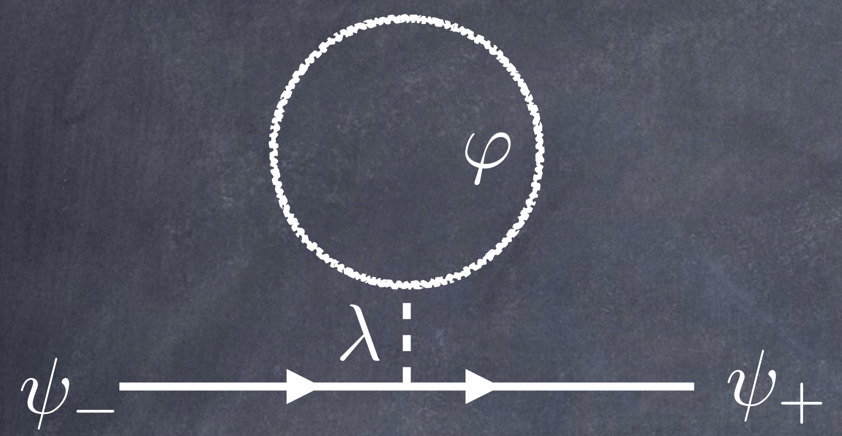


topologically non-trivial nanowire or ‘dark’ state set-up of San Jose *et. al.* (arXiv:1409.7306)

Summary

- Bogoliubov gun: an Andreev quasi-bound state driven through the Fermi sea of the lead. For linear drive:
    - one quasiparticle emitted independent of the sweep rate
    - quasiparticle charge depends on the sweep rate
- Majorana gun: filtrative coupling

Scattering problem



$$i\partial_t \varphi(t) = E(t)\tau_z \varphi(t) + \lambda\psi(0,t)$$

$$i\partial_t \psi(x,t) = \lambda^\dagger \delta(x)\varphi(t) - iv_F\partial_x\psi(x,t)$$

$$\lambda = i\sqrt{v_F\gamma}\begin{pmatrix}\cos\theta & \sin\theta \\ \sin\theta & \cos\theta\end{pmatrix}$$

$$E(t) = ct$$

$$\psi_+(t) = \int dt'\, S(t,t')\,\psi_-(t')$$

$$S = \delta(t-t') - \frac{2i}{v_F}\lambda^\dagger G(t,t')\,\lambda$$

$$\left(i\partial_t - E(t)\tau_z - \frac{i}{v_F}\lambda\lambda^\dagger\right) G(t,t') = \delta(t-t')$$

Solution (c.f. Landau-Zener and Majorana!)

$$(ic\tau_z\,\partial_\varepsilon + \varepsilon + i\gamma + i\delta\tau_x)\,G(\varepsilon,\varepsilon') = 2\pi\delta(\varepsilon-\varepsilon')$$

$$\boxed{\begin{aligned} &E(t) = ct \\ &\delta = \gamma\cos(2\theta) \end{aligned}}$$

$$G(\varepsilon,\varepsilon') = X(\varepsilon)\Theta\left(\varepsilon,\varepsilon'\right)X^{-1}\left(\varepsilon'\right)$$

$$\Theta = 2\pi i\begin{pmatrix}\theta(\varepsilon-\varepsilon') & 0 \\ 0 & \theta(\varepsilon'-\varepsilon)\end{pmatrix}$$

$$X = \begin{pmatrix}u(\varepsilon) & v^*(-\varepsilon) \\ v(\varepsilon) & u^*(-\varepsilon)\end{pmatrix}$$

$$u(\varepsilon) = e^{\frac{i(\varepsilon+i\gamma)^2}{2c}}U\left(-\tfrac{i\delta^2}{4c},\tfrac{1}{2};-\tfrac{i(\varepsilon+i\gamma)^2}{2c}\right)$$

$$v(\varepsilon) = -\sqrt{i}\delta e^{\frac{i(\varepsilon+i\gamma)^2}{2c}}U\left(-\tfrac{i\delta^2}{4c}+\frac{1}{2},\tfrac{1}{2};-\tfrac{i(\varepsilon+i\gamma)^2}{2c}\right)$$

$$\boxed{q = \cos 2\theta\int\frac{2\gamma d\varepsilon}{\det X}\left(|u|^2-|v|^2\right)}$$