Superfluid transport through a dissipative quantum point contact

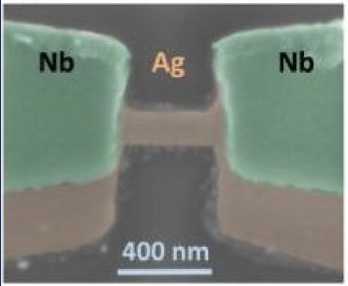
Anne-Maria Visuri

UNIVERSITÄT BONN



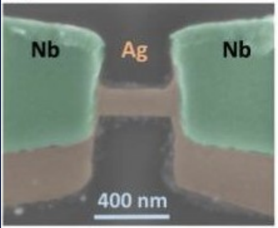



Superconducting contact



Basset *et al.*, Phys. Rev. Research **1**, 032009(R) (2019)

Superconducting contact



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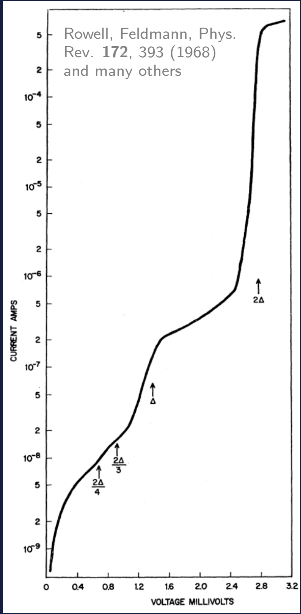

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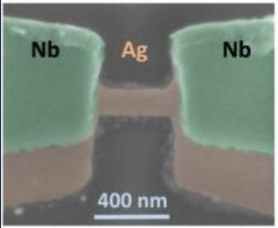
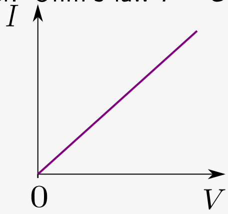
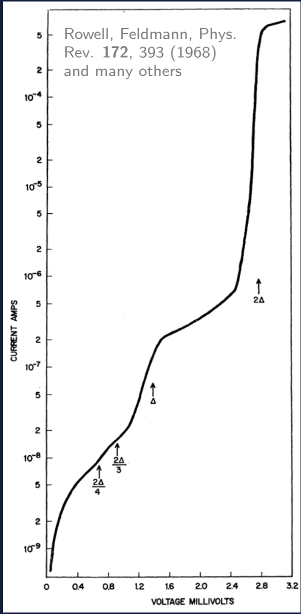


Basset *et al.*, Phys. Rev. Research **1**, 032009(R) (2019)

Cf. Ohm's law $I = GV$





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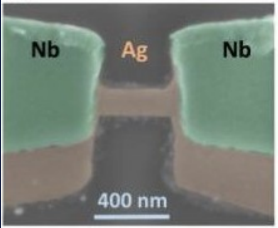

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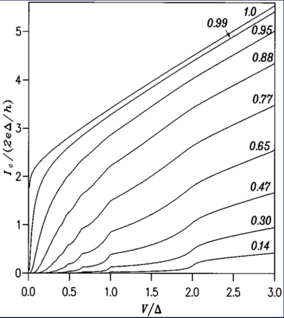
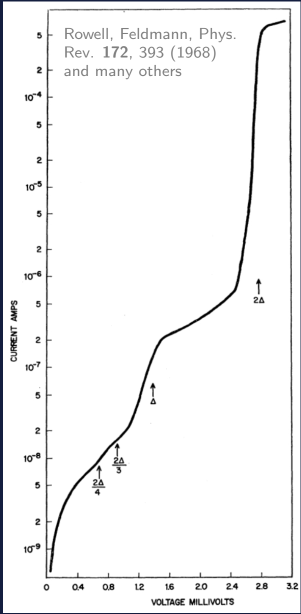


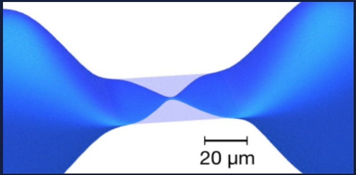
Cuevas *et al.*, Phys. Rev. B **54**, 7366 (1996)

Klapwijk, Blonder Tinkham, Physica **109**, 1657 (1982)
Blonder, Tinkham, Klapwijk, Phys. Rev. B **25**, 4515 (1982)
Averin, Bardas, Phs. Rev. Lett. **75, 1831 (1995)**

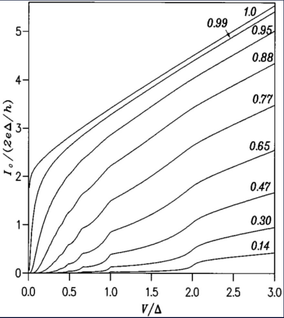


Rowell, Feldmann, Phys. Rev. **172**, 393 (1968) and many others

Connected superfluids



modied from Krinner et al., PNAS **113, 8144 (2016)**



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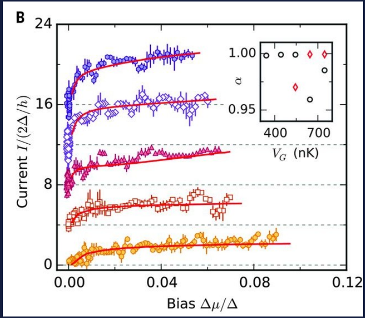
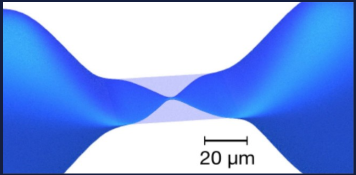


Husmann *et al.*, Science **18**, 1498 (2015)

Transport with cold atoms



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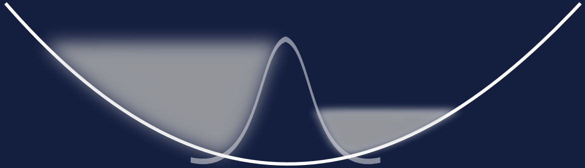

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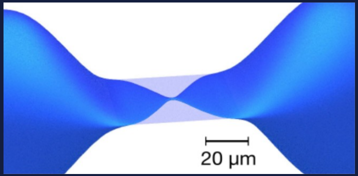

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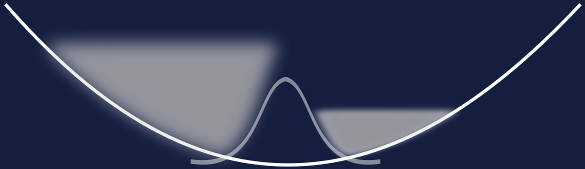

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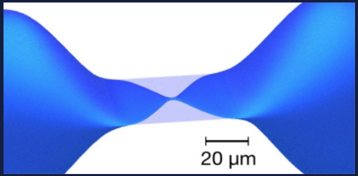

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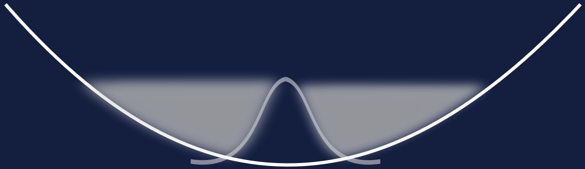
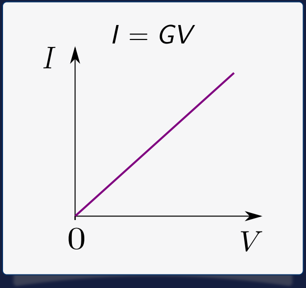
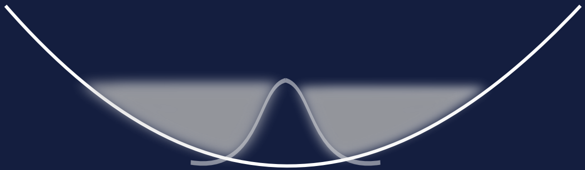
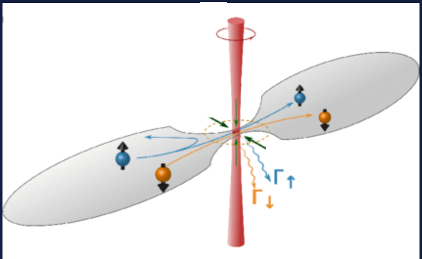


Transport of noninteracting fermions

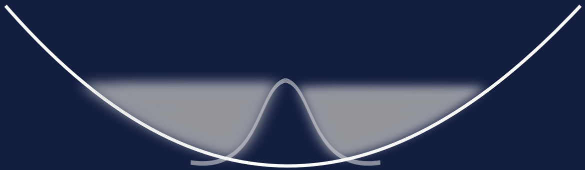




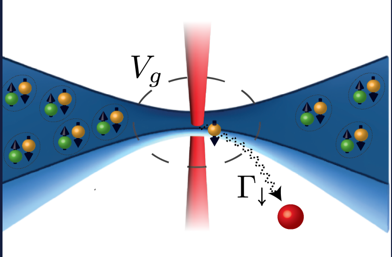
Transport of noninteracting fermions in the presence of dissipation



Corman *et al.*, Phys. Rev. A **100**, 053605 (2019)



Superfluid transport in the presence of dissipation?



M.-Z. Huang, et al., arXiv:2210.03371

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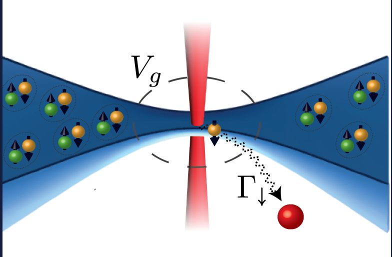

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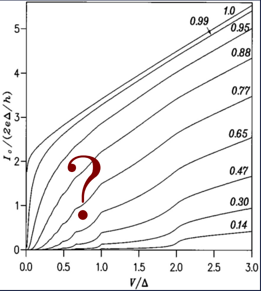

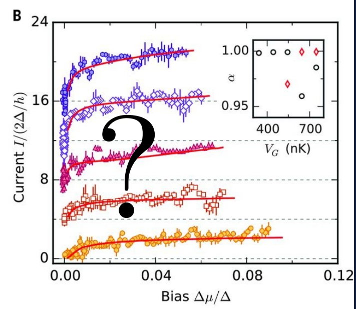

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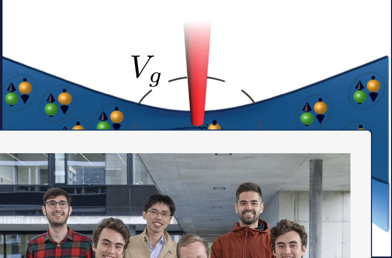
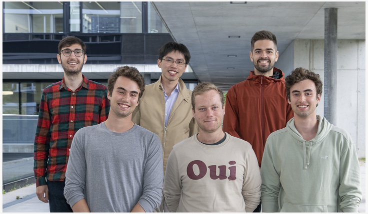
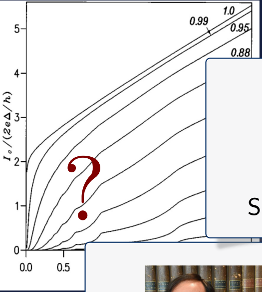
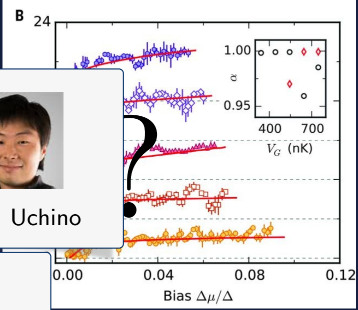




Lithium team, ETH



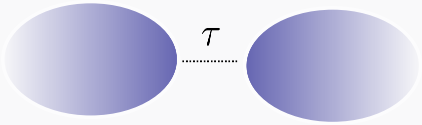


Shun Uchino

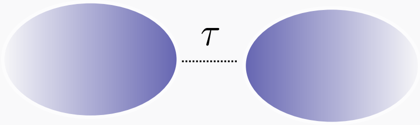
Thierry Giamarchi

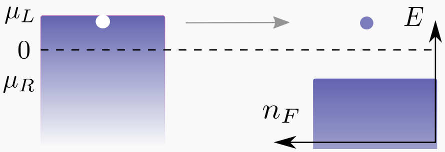
Outline

Quantum transport: tunneling Hamiltonian



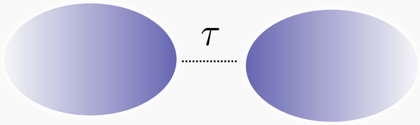
Quantum transport: tunneling Hamiltonian

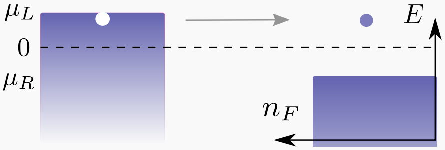




$$n_F(E-\mu) = \frac{1}{e^{\frac{E-\mu}{k_B T}} + 1}$$

Quantum transport: tunneling Hamiltonian

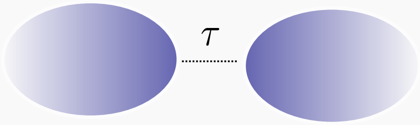


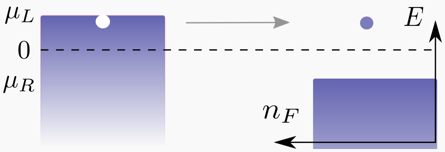


current

$$I = \frac{1}{h} \int_{-\infty}^{\infty} dE \mathcal{T}(E) \left[n_F(E - \mu_L) - n_F(E - \mu_R) \right]$$

Quantum transport: tunneling Hamiltonian



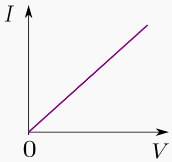


current

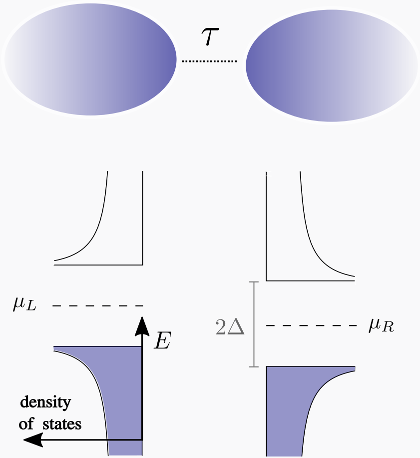
$$I = \frac{1}{h}\int_{-\infty}^{\infty} dE\mathcal{T}(E)\left[n_F(E-\mu_L) - n_F(E-\mu_R)\right]$$

$$= G(\mu_L - \mu_R) = GV$$

G: conductance
V: voltage



Connected superfluids – tunneling Hamiltonian

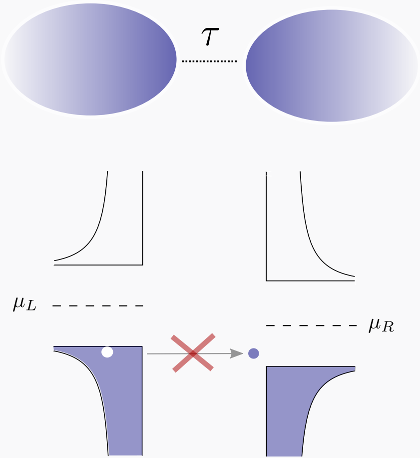


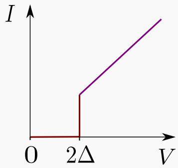
$$H = \sum_{i=L,R} H_i + H_{\text{tun}},$$

$$H_i = \sum_k \begin{pmatrix} \psi^\dagger_{i\uparrow k} & \psi_{i\downarrow -k} \end{pmatrix} \begin{pmatrix} \epsilon_k - \mu_i & \Delta \\ \Delta & -(\epsilon_{-k} - \mu_i) \end{pmatrix} \begin{pmatrix} \psi_{i\uparrow k} \\ \psi^\dagger_{i\downarrow -k} \end{pmatrix}$$

$$H_{\text{tun}} = -\tau \sum_{\sigma=\uparrow,\downarrow} [\psi^\dagger_{R\sigma}(\mathbf{r} = \mathbf{0})\psi_{L\sigma}(\mathbf{r} = \mathbf{0}) + \text{H.c.}]$$

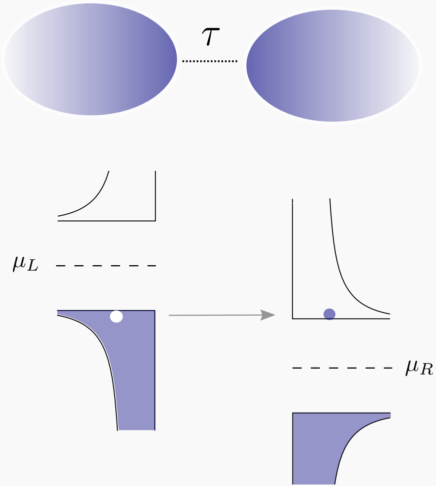
Single-particle tunneling





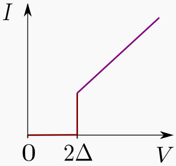
first-order tunneling, $V = \mu_L - \mu_R$

Single-particle tunneling



$$I \propto \int_{-\infty}^{\infty} dE \, \rho(E-\mu_L)\rho(E-\mu_R)$$
$$\times \left[n_F(E-\mu_L) - n_F(E-\mu_R)\right]$$

$\rho(E)$: density of states

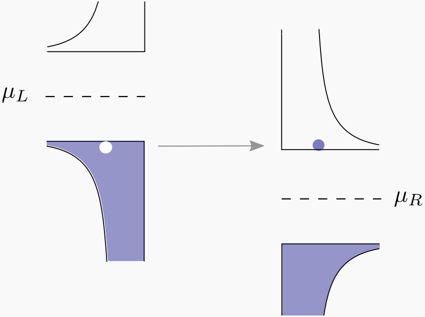


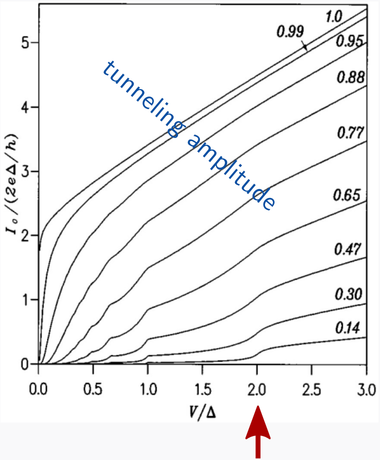
first-order tunneling, $V = \mu_L - \mu_R$

Blonder, Tinkham, Klapwijk, Phys. Rev. B **25**, 4515 (1982)

Sub-gap currents

- Multiple Andreev reflections lead to a nonzero current at $V < 2\Delta$.





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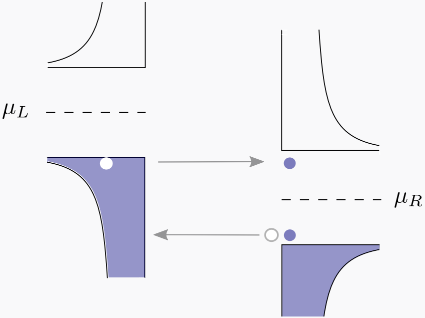

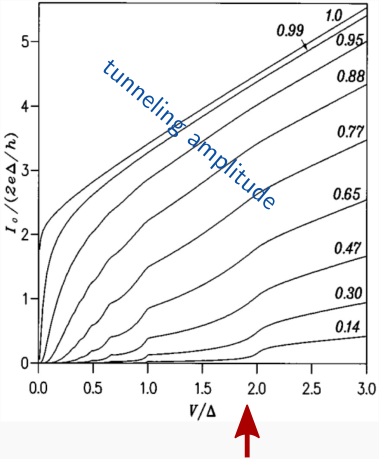

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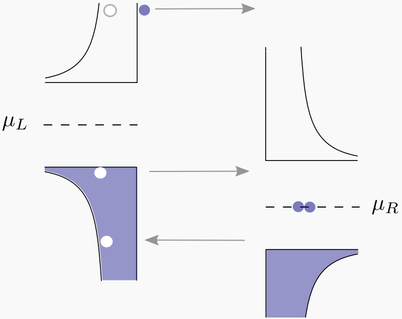

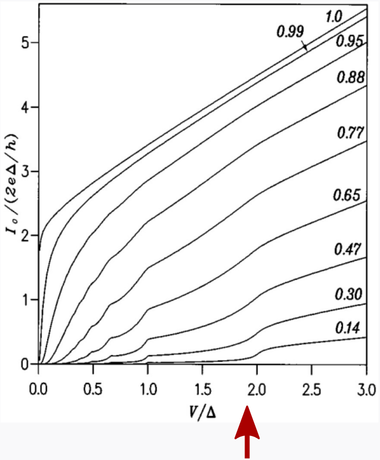

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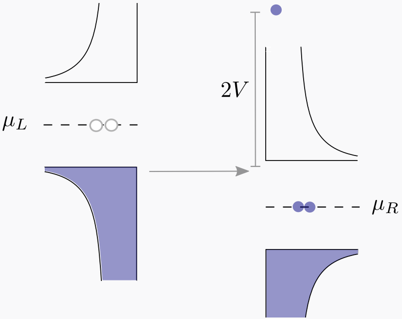

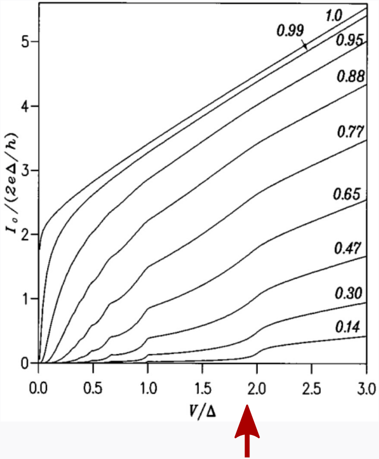

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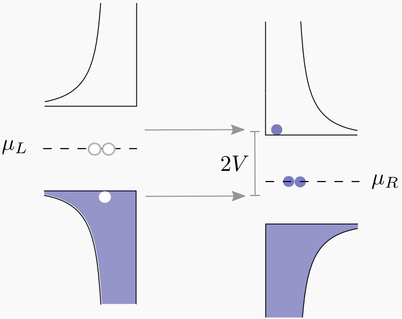
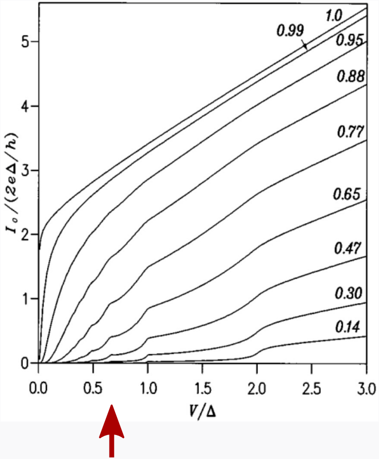
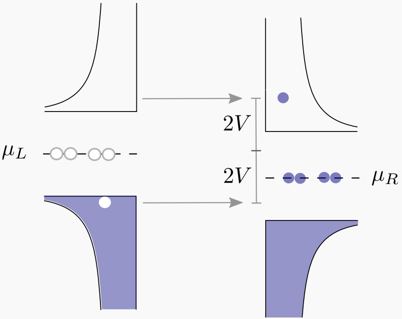
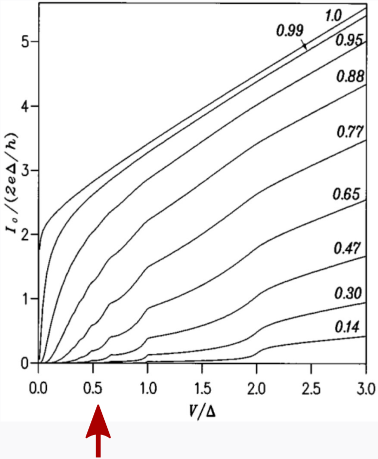




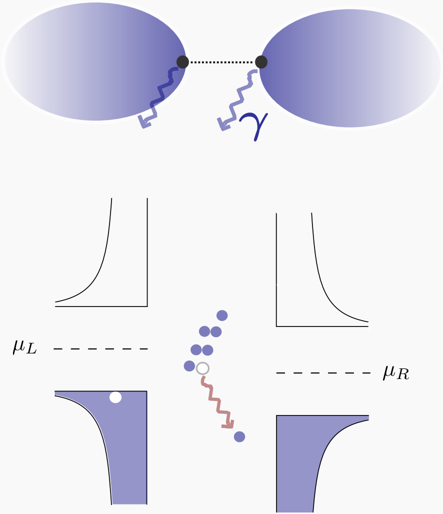
Sub-gap currents

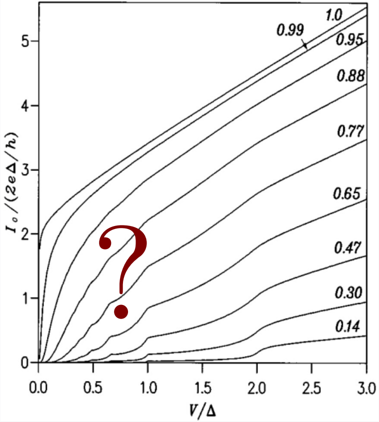
- Smaller voltage $\rightarrow$ more pairs ($n \sim \frac{2\Delta}{2V}$) required for the single quasiparticle to tunnel.
- Current proportional to τ^{2n}.



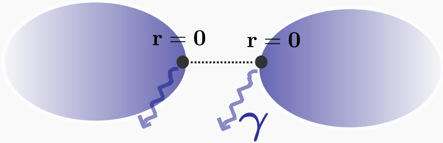


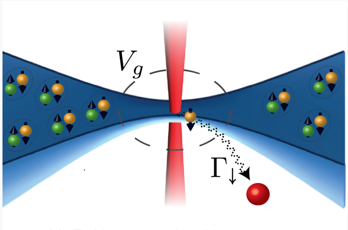
Particle loss?





Particle loss at the "contacts"





M.-Z. Huang *et al.*, arXiv:2210.03371

$$\frac{d\rho}{dt} = -i[H,\rho] + \sum_{\sigma=\uparrow,\downarrow}\sum_{i=L,R}\gamma_\sigma\left[\psi_{i\sigma}(0)\rho\psi^\dagger_{i\sigma}(0) - \frac{1}{2}\left\{\psi^\dagger_{i\sigma}(0)\psi_{i\sigma}(0),\rho\right\}\right]$$

- Conserved current $I = i\tau\sum_{\sigma=\uparrow,\downarrow}\left(\langle\psi^\dagger_{R\sigma}(0)\psi_{L\sigma}(0)\rangle - \langle\psi^\dagger_{L\sigma}(0)\psi_{R\sigma}(0)\rangle\right)$
- Nonequilibrium correlation functions $\rightarrow$ Keldysh formalism

Kamenev, *Field theory of non-equilibrium systems*, Cambridge (2011)
Sieberer, Buchhold, Diehl, Rep. Prog. Phys. **79**, 096001 (2016)

Jin, Filippone, Giamarchi, Phys. Rev. B 102, 205131 (2020)
Visuri, Giamarchi, Kollath, Phys. Rev. Lett. **129**, 056802 (2022)
Visuri, Giamarchi, Kollath, arXiv:2209.01686
M.-Z. Huang, et al., arXiv:2210.03371

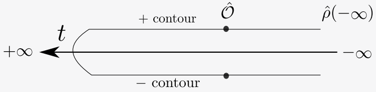
Particle loss at the "contacts"

Nonequilibrium - Keldysh formalism

- Expectation values calculated as path integrals along a closed time contour,

$$\langle \psi_a \bar{\psi}_b \rangle = \int \mathcal{D}[\psi, \bar{\psi}] \psi_a \bar{\psi}_b e^{iS[\psi,\bar{\psi}]} = iG_{ab},$$

where the action is written in matrix form as



$$S[\bar{\psi}, \psi] = \int_{-\infty}^{\infty} dt \bar{\psi}(t) G^{-1}(t) \psi(t).$$

Here, $\psi = (\psi^+, \psi^-)$: two copies of the fields for each point in time.

- The action is the sum $S = S_L + S_R + S_{\text{tun}} + S_{\text{loss}}$.

Kamenev, *Field theory of non-equilibrium systems*, Cambridge (2011)
Sieberer, Buchhold, Diehl, Rep. Prog. Phys. **79**, 096001 (2016)

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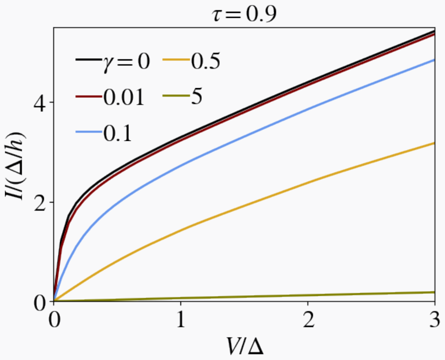
Visuri, Giamarchi, Kollath, Phys. Rev. Lett. **129**, 056802 (2022)
Visuri, Giamarchi, Kollath, arXiv:2209.01686
M.-Z. Huang, et al., arXiv:2210.03371

High transparency

- Current is reduced by the particle loss but not sharply suppressed at $V < 2\Delta$.



High transparency: compare to experimental data

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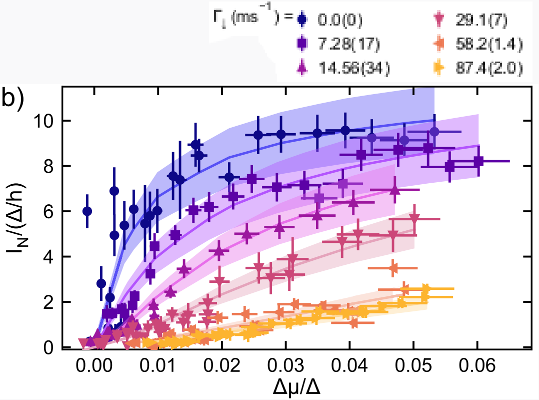
  - Results for $\tau \approx 1$ supported by experimental data.



M.-Z. Huang, et al., arXiv:2210.03371

High transparency: compare to experimental data

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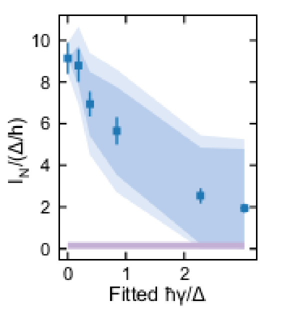
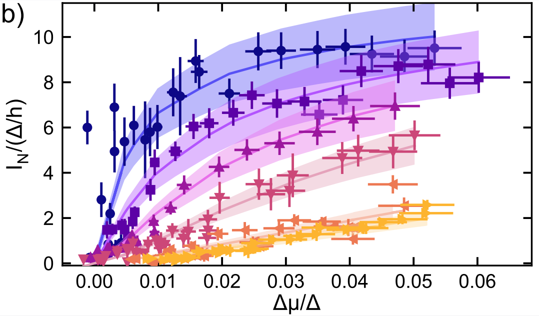
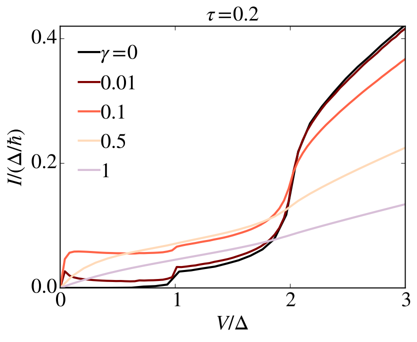
- Superfluid transport "survives" up to large dissipation strengths $\gamma \gtrsim \Delta$.





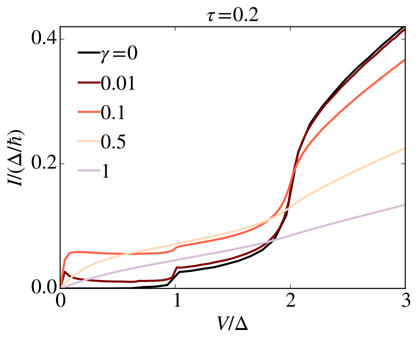
M.-Z. Huang, et al., arXiv:2210.03371

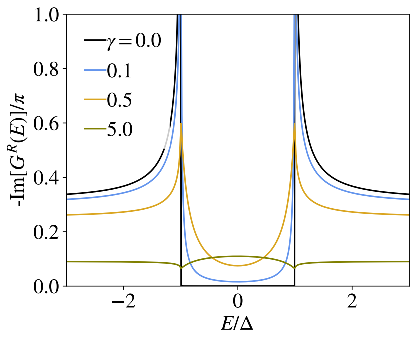
Low transparency: current enhanced at small voltage



Low transparency: current enhanced at small voltage

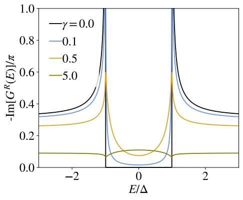
- Modified local density of states leads to an enhancement?

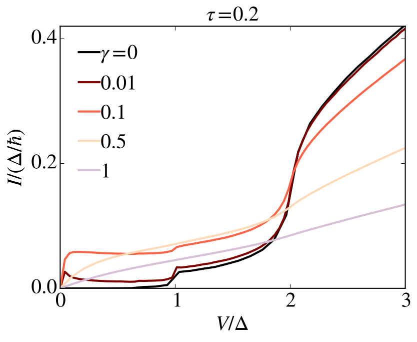


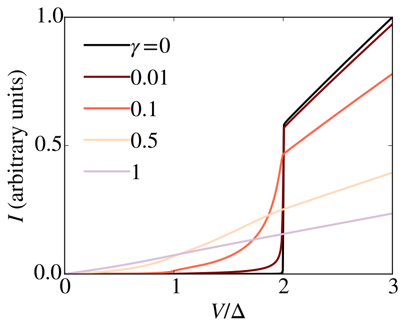


Low transparency: current enhanced at small voltage

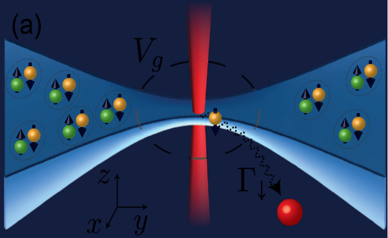
- Modified local density of states leads to an enhancement?
- Weak-tunneling approximation
  $I \propto \int_{-\infty}^{\infty} dE \rho(E-\mu_L)\rho(E-\mu_R)\left[n_F(E-\mu_L)-n_F(E-\mu_R)\right].$







Summary



Superfluid transport due to multiple Andreev reflections is surprisingly robust to local particle losses.

M.-Z. Huang, J. Mohan, A.-M. Visuri, P. Fabritius, M. Talebi, S. Wili, S. Uchino, T. Giamarchi, T. Esslinger, arXiv:2210.03371

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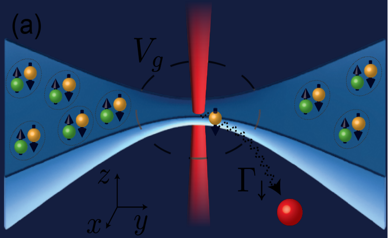

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Current is enhanced by dissipation at small voltages.

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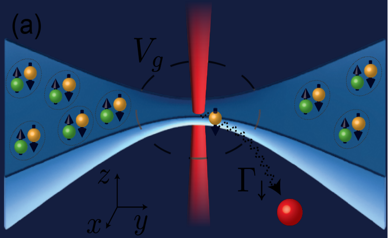

Summary and outlook

Superfluid transport due to multiple Andreev reflections is surprisingly robust to local particle losses.

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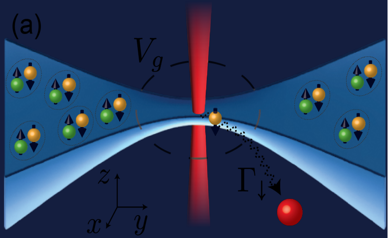
Spin bias in superfluid reservoirs, pair loss, dephasing...



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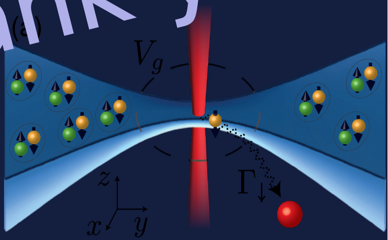
Thank you!



Fermions with spin

- Action for the reservoirs $i = L, R$ in ω basis:

$$S = \int \frac{d\omega}{2\pi} \bar{\mathbf{\Psi}}(\omega) G^{-1}(\omega) \mathbf{\Psi}(\omega),$$

where $\mathbf{\Psi} = \begin{pmatrix} \psi^1_{i\uparrow} & \bar{\psi}^1_{i\downarrow} & \psi^2_{i\uparrow} & \bar{\psi}^2_{i\downarrow} \end{pmatrix}^T$.

- The inverse Green's function G^{-1} has the structure

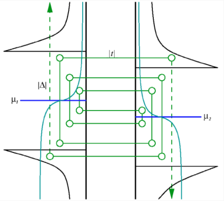
$$G^{-1} = \begin{pmatrix} 0 & [g^A]^{-1} \\ [g^R]^{-1} & [g^K]^{-1} \end{pmatrix},$$

with the elements

$$[g^{R,A}]^{-1} = \begin{pmatrix} \uparrow\uparrow & \uparrow\downarrow \\ \downarrow\uparrow & \downarrow\downarrow \end{pmatrix}.$$

- Multiple Andreev reflections described by infinite-size matrix

$$G^{-1} = \begin{pmatrix} \Omega_{L\uparrow} & \mathcal{T} & \mathbf{\Delta}_L & 0 & 0 & \cdots \\ \mathcal{T} & \Omega_{R\uparrow} & 0 & 0 & \mathbf{\Delta}_R & \\ \mathbf{\Delta}_L & 0 & \Omega_{L\downarrow} & -\mathcal{T} & 0 & \\ 0 & 0 & -\mathcal{T} & \Omega_{R\downarrow} & 0 & 0 \\ 0 & \mathbf{\Delta}_R & 0 & 0 & \Omega_{R\downarrow} & -\mathcal{T} \\ \vdots & & & 0 & -\mathcal{T} & \ddots \end{pmatrix}$$



Bolech, Giamarchi, PRB **71**, 024517 (2005)

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which can be truncated to obtain

$$\langle \psi_a \bar{\psi}_b \rangle = \int \mathcal{D}[\psi, \bar{\psi}] \psi_a \bar{\psi}_b e^{iS[\psi,\bar{\psi}]} = iG_{ab}.$$

Bolech, Giamarchi, PRL **92**, 127001 (2004)
Bolech, Giamarchi, PRB **71**, 024517 (2005)
Husmann *et al.*, Science **18**, 1498 (2015)

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$$[g^{R,A}]^{-1} = \begin{pmatrix} \frac{(\bar{\omega}\pm i\eta)}{W\sqrt{\Delta^2-(\bar{\omega}\pm i\eta)^2}} \pm \frac{i\gamma_\uparrow}{2} & \frac{\Delta}{W\sqrt{\Delta^2-(\bar{\omega}\pm i\eta)^2}} \\ \frac{\Delta}{W\sqrt{\Delta^2-(\bar{\omega}\pm i\eta)^2}} & \frac{(\bar{\omega}\pm i\eta)}{W\sqrt{\Delta^2-(\bar{\omega}\pm i\eta)^2}} \pm \frac{i\gamma_\downarrow}{2} \end{pmatrix},$$

$$[g^K(\bar{\omega})]^{-1}_{11} = -\left([g^A]^{-1}_{11} - [g^R]^{-1}_{11}\right)[1 - 2n_F(\bar{\omega})] + i\gamma_\uparrow$$

$$[g^K(\bar{\omega})]^{-1}_{22} = -\left([g^A]^{-1}_{22} - [g^R]^{-1}_{22}\right)[1 - 2n_F(\bar{\omega})] - i\gamma_\downarrow$$

$$[g^K(\bar{\omega})]^{-1}_{12} = -\left([g^A]^{-1}_{12} - [g^R]^{-1}_{12}\right)[1 - 2n_F(\bar{\omega})]$$

$$[g^K(\bar{\omega})]^{-1}_{21} = -\left([g^A]^{-1}_{21} - [g^R]^{-1}_{21}\right)[1 - 2n_F(\bar{\omega})].$$