Out-of-equilibrium phenomena and Quantum Transport in cold atomic gases

http://dqmp.unige.ch/giamarchi/

UNIVERSITÉ DE GENÈVE

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ARMY RESEARCH OFFICE
1951

MaNEP
SWITZERLAND
NETWORK

Equilibrium vs Non equilibrium

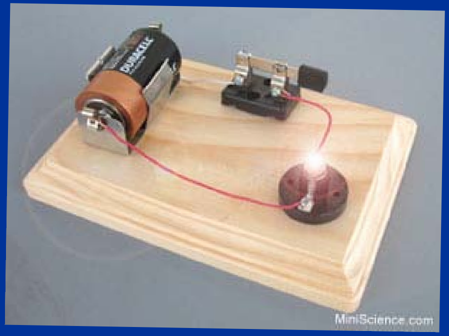
- Well equipped to deal with equilibrium

$$Z = Tr[e^{-\beta H} \ldots]$$

- Non eq: Methods ? / Concepts ?? (temperature, etc.)

- Linear response

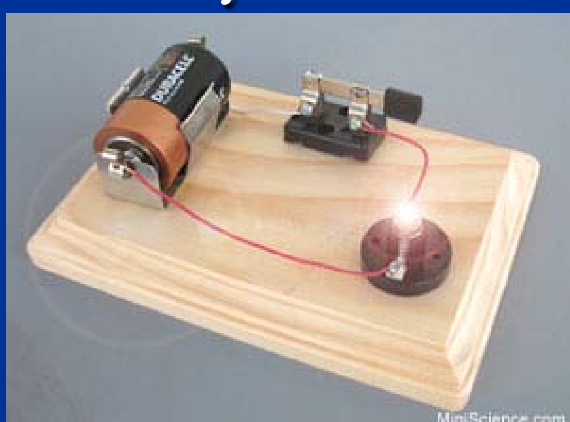
$$I = GV$$



G computed from equilibrium

Should we bother

- Condensed matter
- Rapid (?) relaxation… but pump/probe exp.
- Steady state situations, or weird systems (glasses)

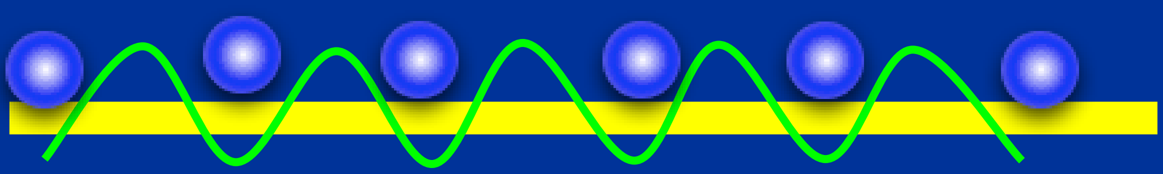


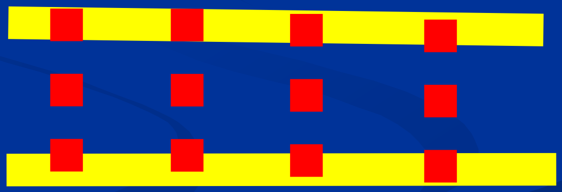
Out of equilibrium situations

- External noise

E. G. Dalla Torre, E. Demler, TG, E. Altman Nat Phys 6 806 (2010); PRB 85 184302 (2012)

- Global quench

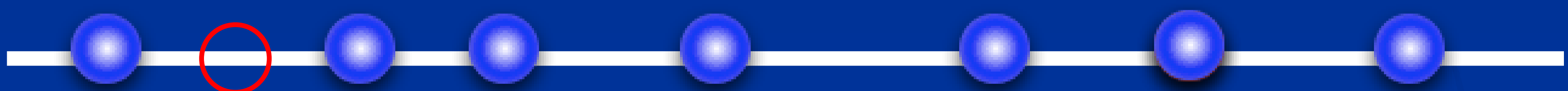




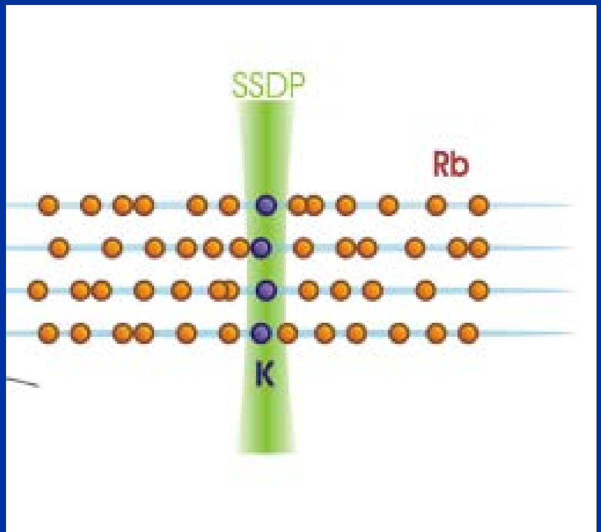
A. Mitra, TG PRL 107 150602 (2011); PRB 85 075117 (2012)
L. Foini, TG PRA 91 023627 (2015)

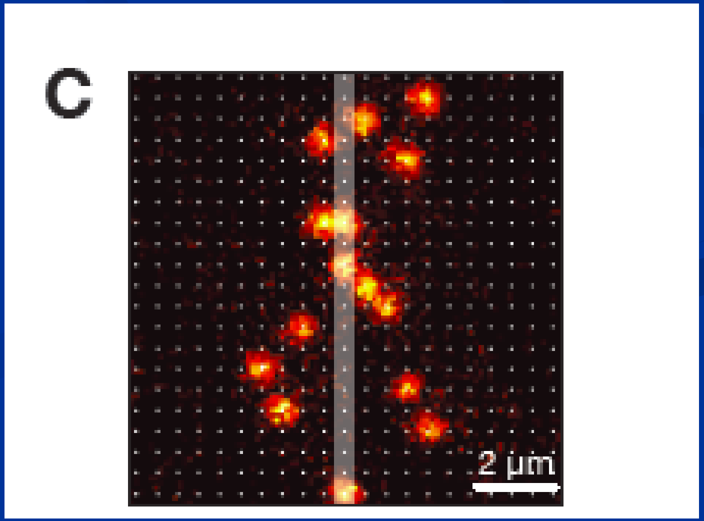
Out of equilibrium situations

- Local quench (impurity)

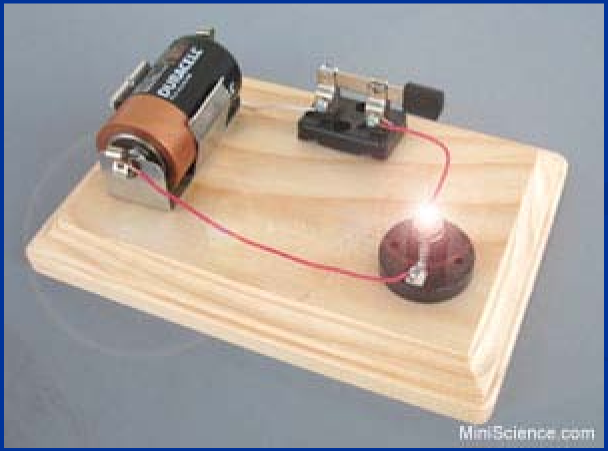


M. Zvonarev, V. Cheianov, TG PRL (2007);
J. Catani et al, PRA 85 023623 (2012) ; T. Fukuhara, A. Kantian et al. Nat Phys. (2013)
A. Kantian, U. Schollwoeck, TG PRL 113 070601 (2015)





Steady state Out-of-Equilibrium: Transport

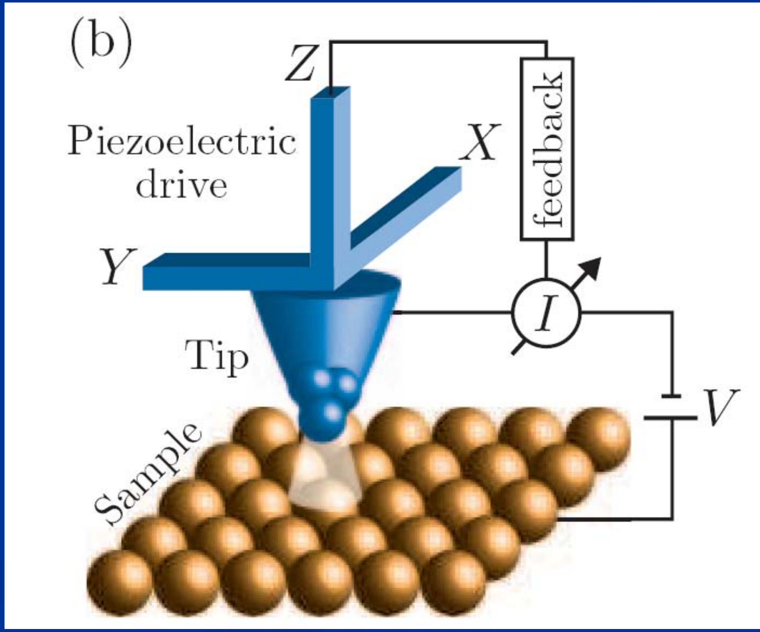


- Be happy with linear response ?

Often… but not always..

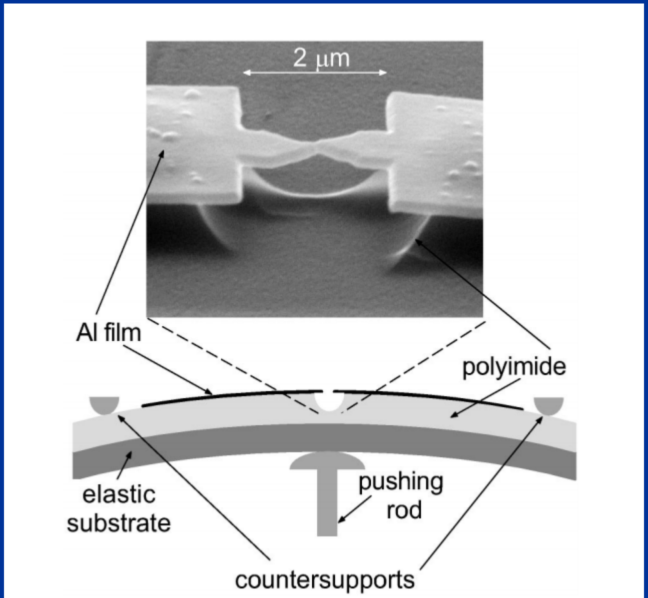
- Non linear I-V characteristics I(V)
- Quantum point contact

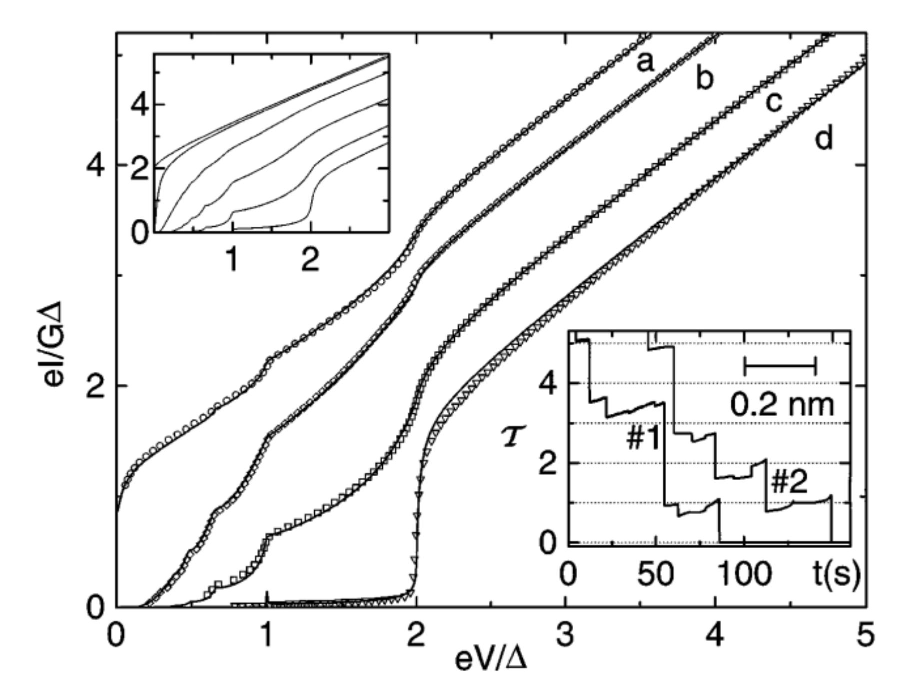
STM



S-S Quantum point contact

- Theory: Blonder, Tinkham, Klapwijk (1982); Averin, Bardas (1995); Cueva, Martin-Rodero, Yetati (1996)





E. Scheer et al. PRL 78 3535 (1997)

But…

- Difficult to control the junction
- Reservoirs: BCS (supra) or Fermi liquids (normal)
- Small gaps only
- Can one transpose Experiment/Theory to a cold atom realization

Non-linear transport with cold atoms

- Dominik Husmann, Shun Uchino, Sebastian Krinner, Martin Lebrat, Thierry Giamarchi, Tilman Esslinger, Jean-Philippe Brantut, arXiv:1508.00578
  Science 350 62667 (2015).

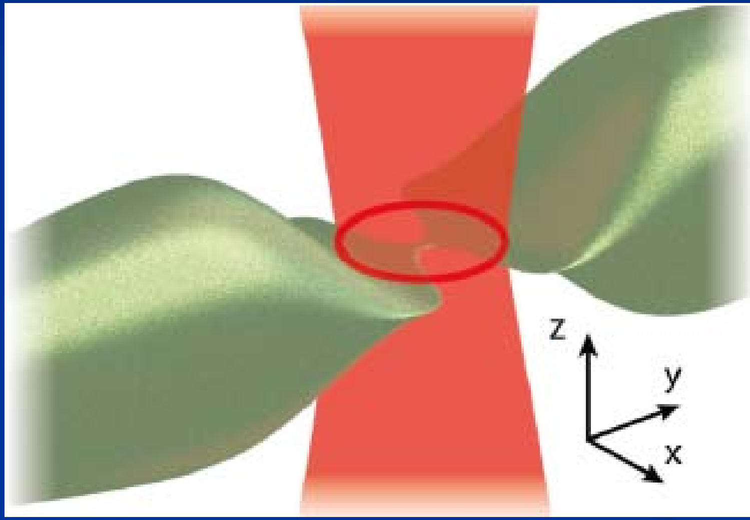
Shun Uchino
(Unige)

Coll.: T. Esslinger's group (ETHZ)

J.P. Brantut

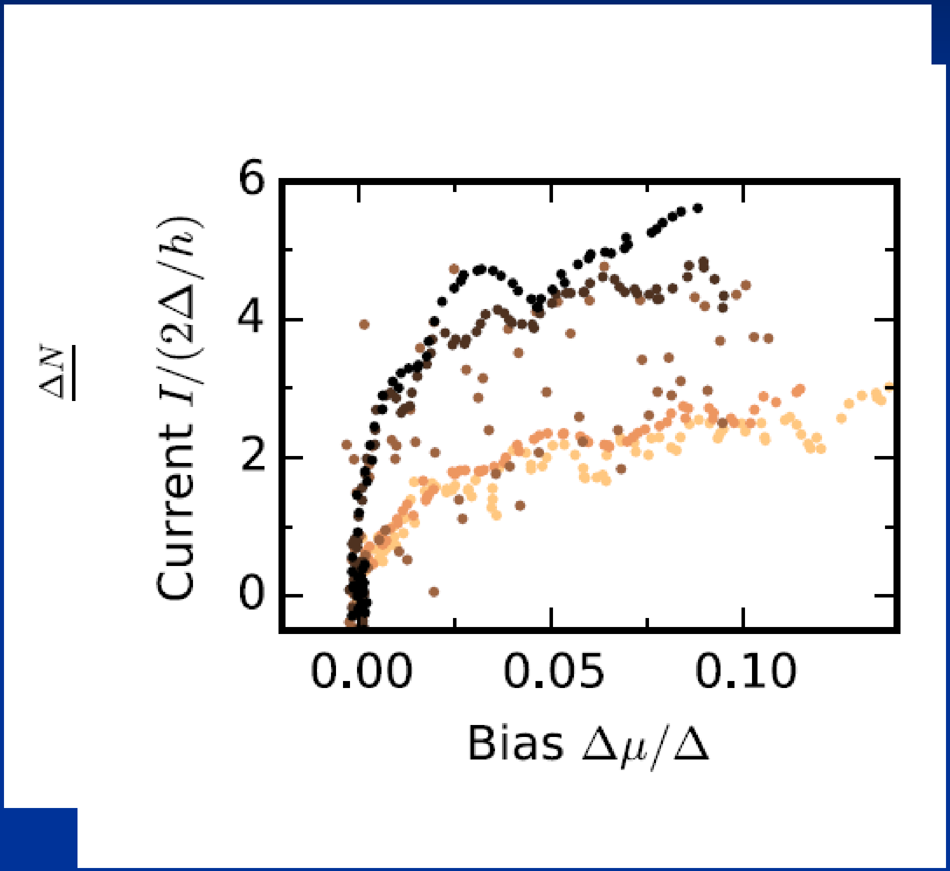
D. Husmann

Non-linear transport with cold atoms



- Strongly interacting superconductors (unitarity)
- Totally balistic system (no impurities)
- Good/better control on the barrier

Measurements: decay curves



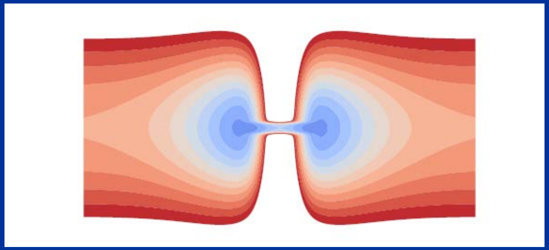
$$\frac{dN}{dt} = I = \frac{V}{R} = \frac{N}{RC}$$

$$\frac{dN}{dt} = I(V) = I(N/C)$$

Non-linear (non Ohmic) I-V curves

Modelization

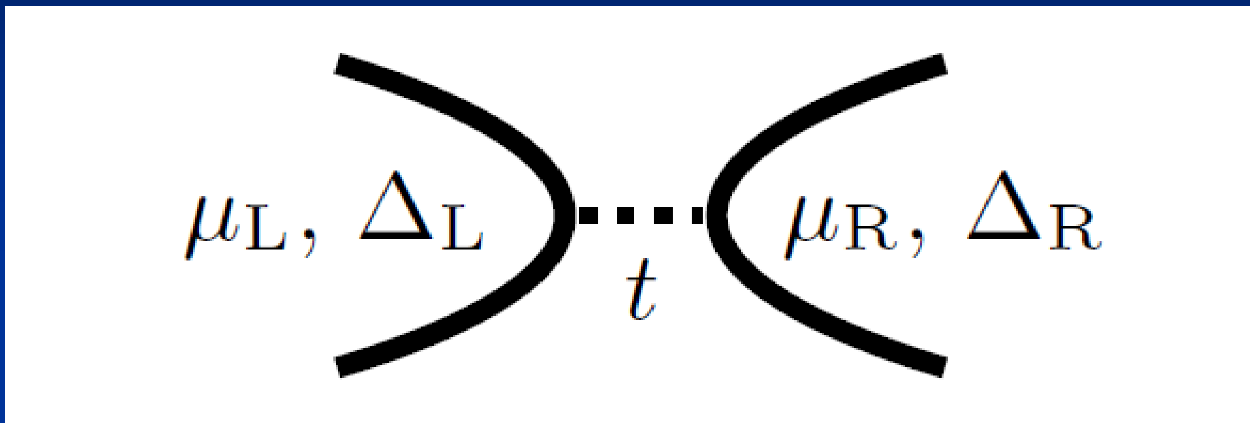
- Reservoirs: fermions with attractive interaction
- Structure between the two reservoirs: ?



- Short structure; Details of the structure not essentials (S-N, N-N, N-S barrier etc.)
- Quantum point contact

$$-t_{LR}(\psi_R^\dagger(x=0)\psi_L(x=0)+\text{h.c.})$$

Theory



$$H = H_L + H_R - t[\psi_R^\dagger(x=0)\psi_L(x=0) + \mathrm{h.c.}]$$

Mean field approximation for reservoirs

$$H_{L,R} = \sum_{k,\sigma}(\epsilon_k - \mu_{L,R})\psi_{k,\sigma}^\dagger\psi_{k,\sigma} + [\Delta\psi_{k,\uparrow}^\dagger\psi_{-k,\downarrow}^\dagger + \mathrm{h.c.}]$$

Keldysh technique to treat t

$$S = \sum_{j=L,R} \int \frac{d\omega}{2\pi} \psi_j^\dagger g_j^{-1} \psi_j + S_t,$$

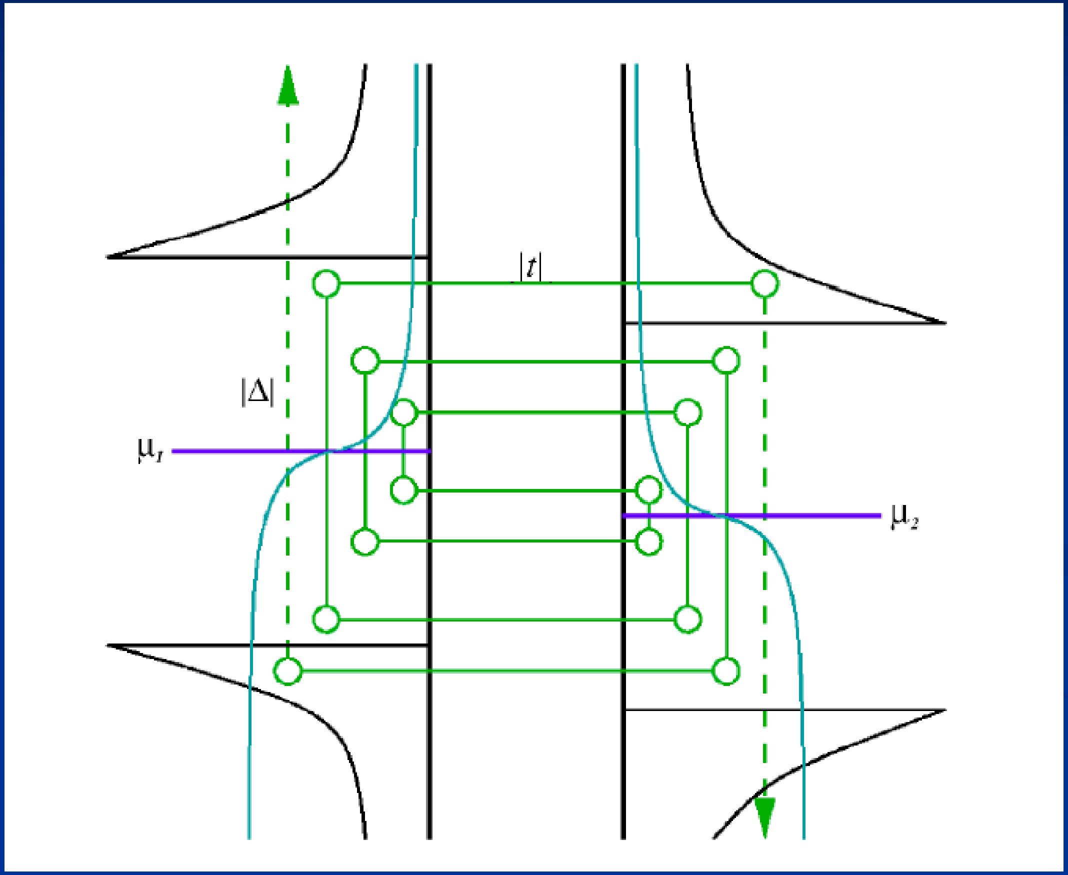
$$I = \sum_n \frac{2t_n}{h} \int d\omega \mathrm{Re} G^K,$$

$$g_j^{-1} = \quad g_j^{r,a} = \frac{1}{\sqrt{\Delta_j^2 - (\omega - \mu_i \pm i\eta)^2}} \begin{pmatrix} -(\omega - \mu_j \pm i\eta) & \Delta_j \\ \Delta_j & -(\omega - \mu_j \pm i\eta) \end{pmatrix},$$

Quadratic (but non diagonal) problem

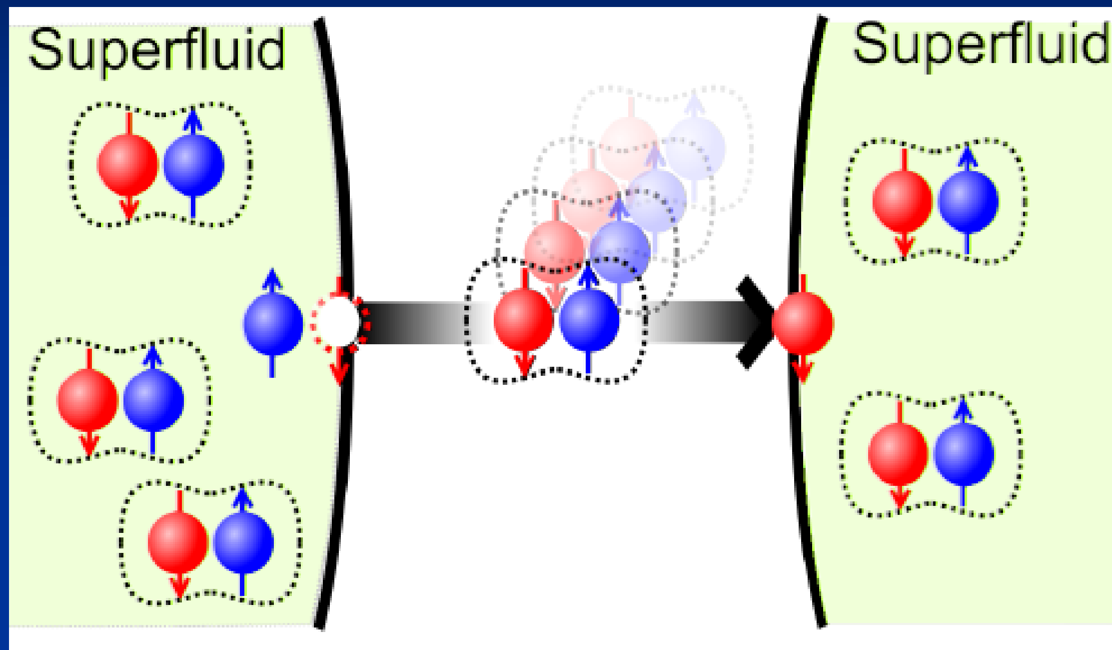
Essentially exact solution I(V,T,t,Δ)

Multiple Andreev reflections



C.J. Bolech, TG, PRB 71 024517 (05)

Multiple Andreev reflections

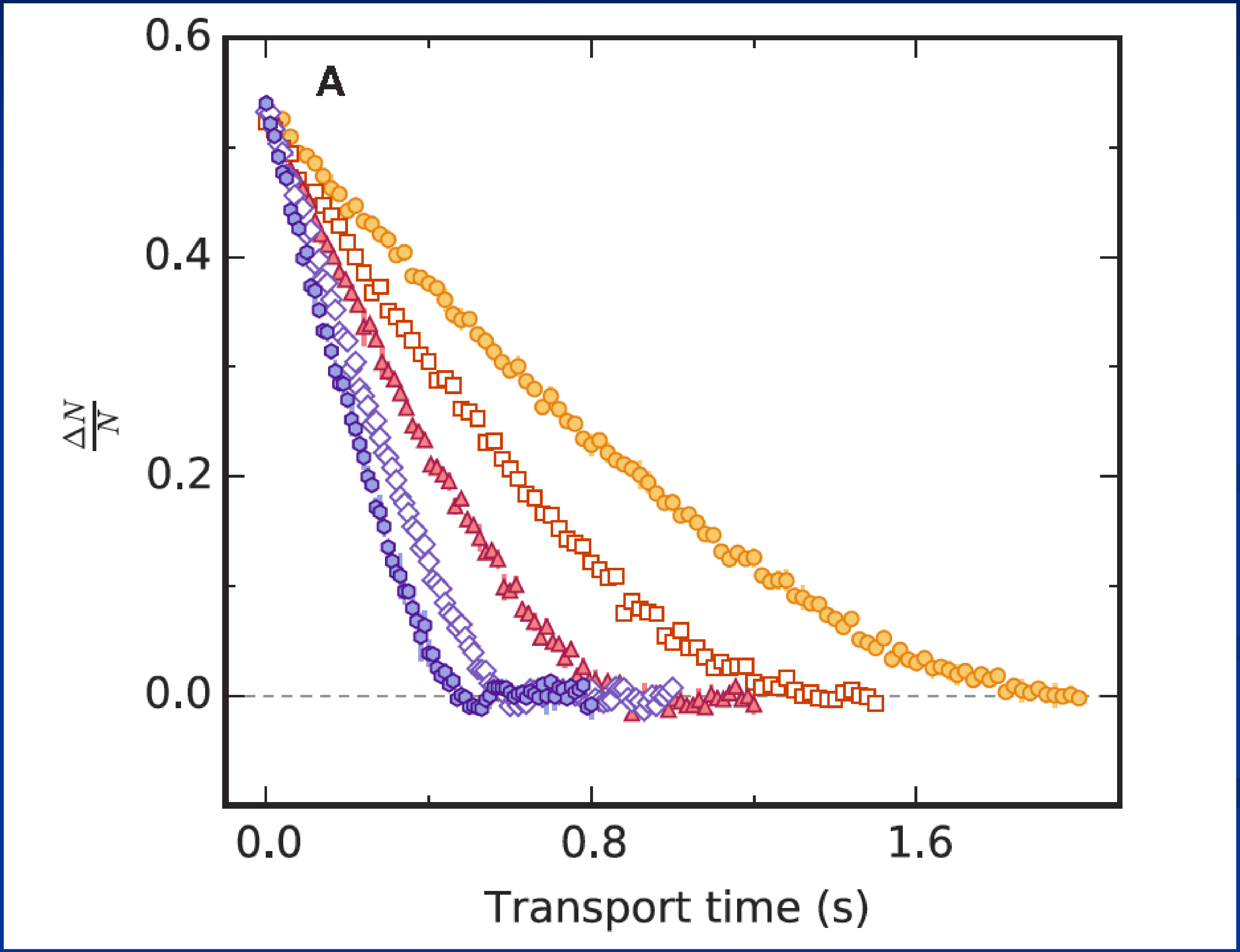


$$2nV = \Delta \qquad p = t^{2n}$$

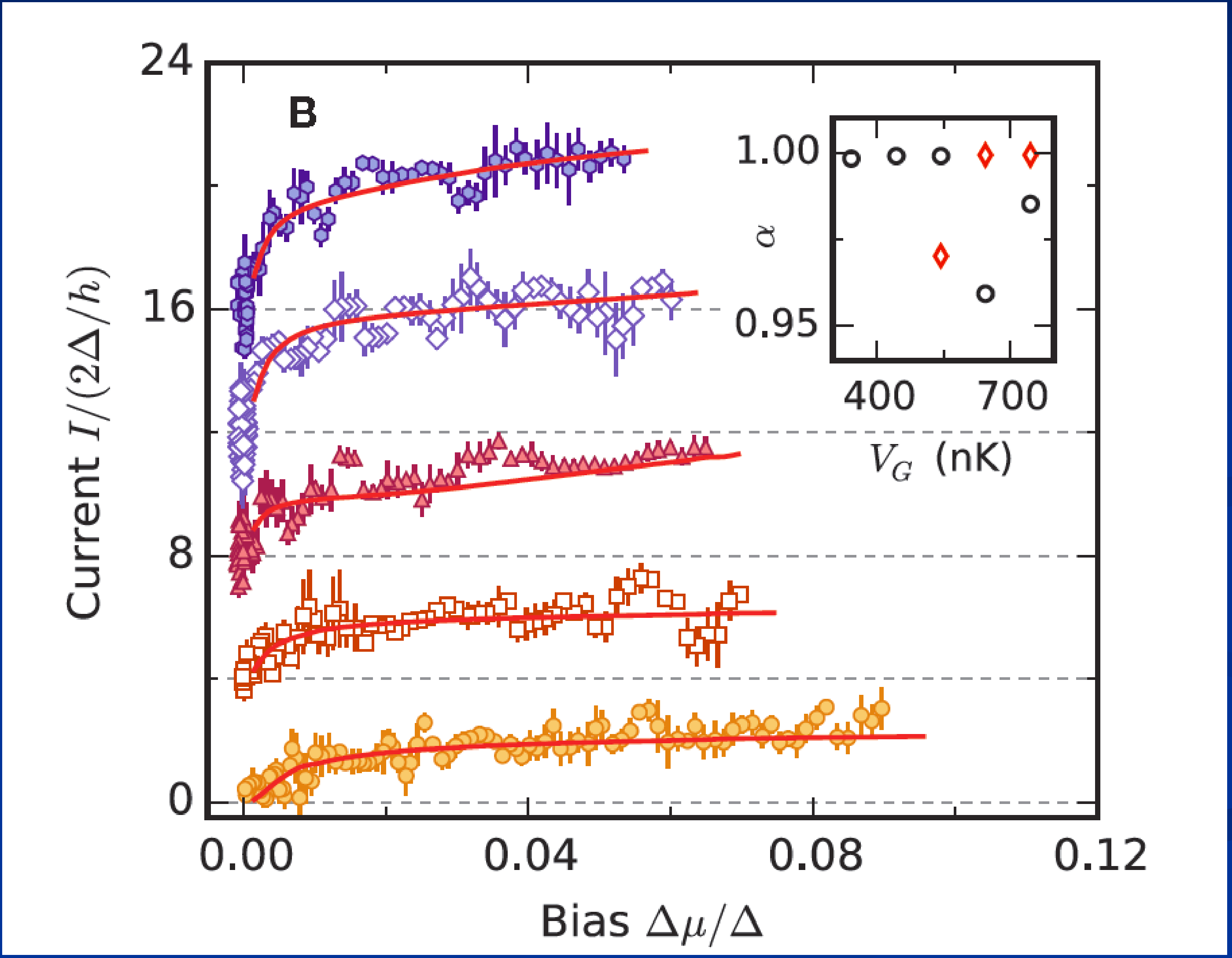
$$\frac{V_{\min}}{\Delta} = \frac{\log(t)}{\log(p_0)} = \frac{\grave{o}}{\log(p_0)}$$

Cotunnelling of a quasiparticle and n cooper pairs

Experiment

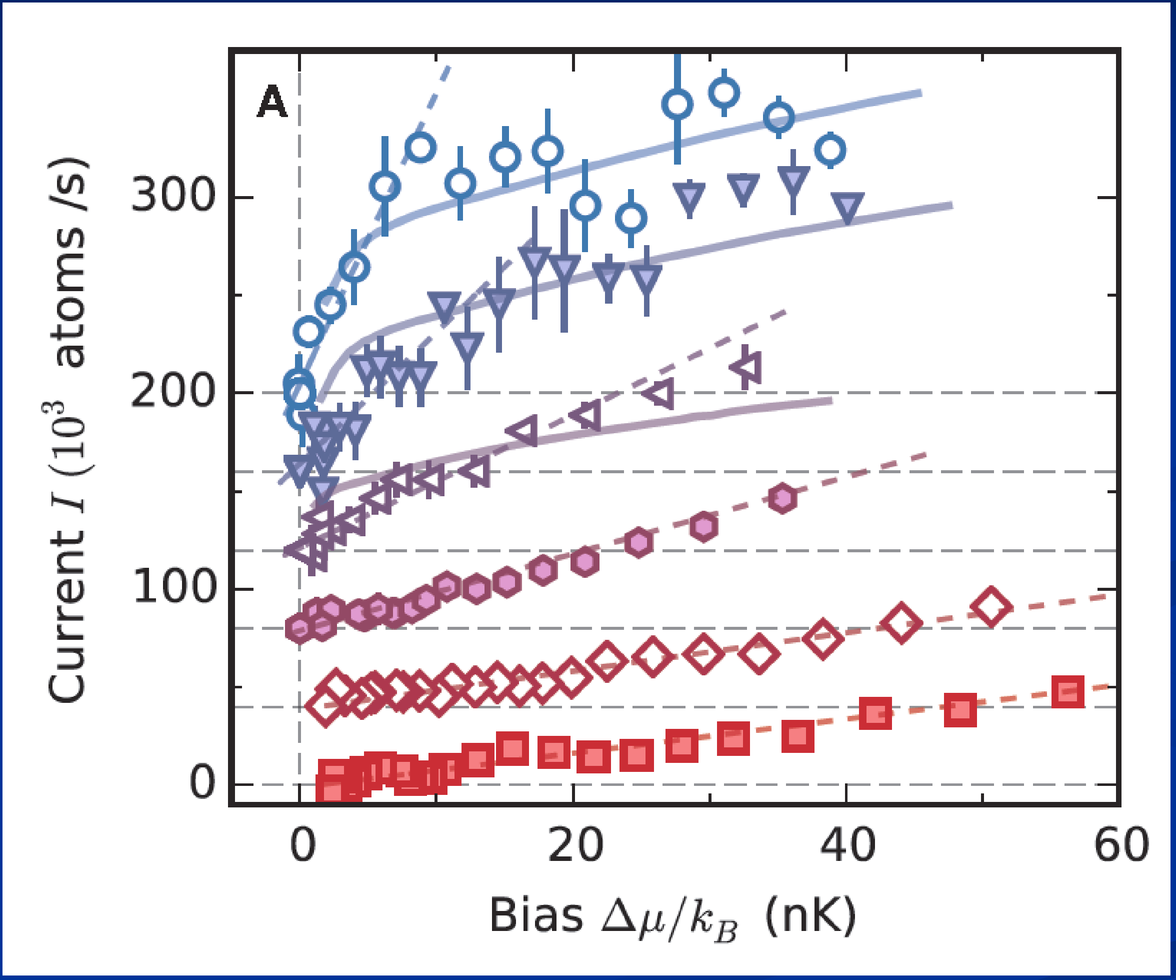


Comparison Th-Exp

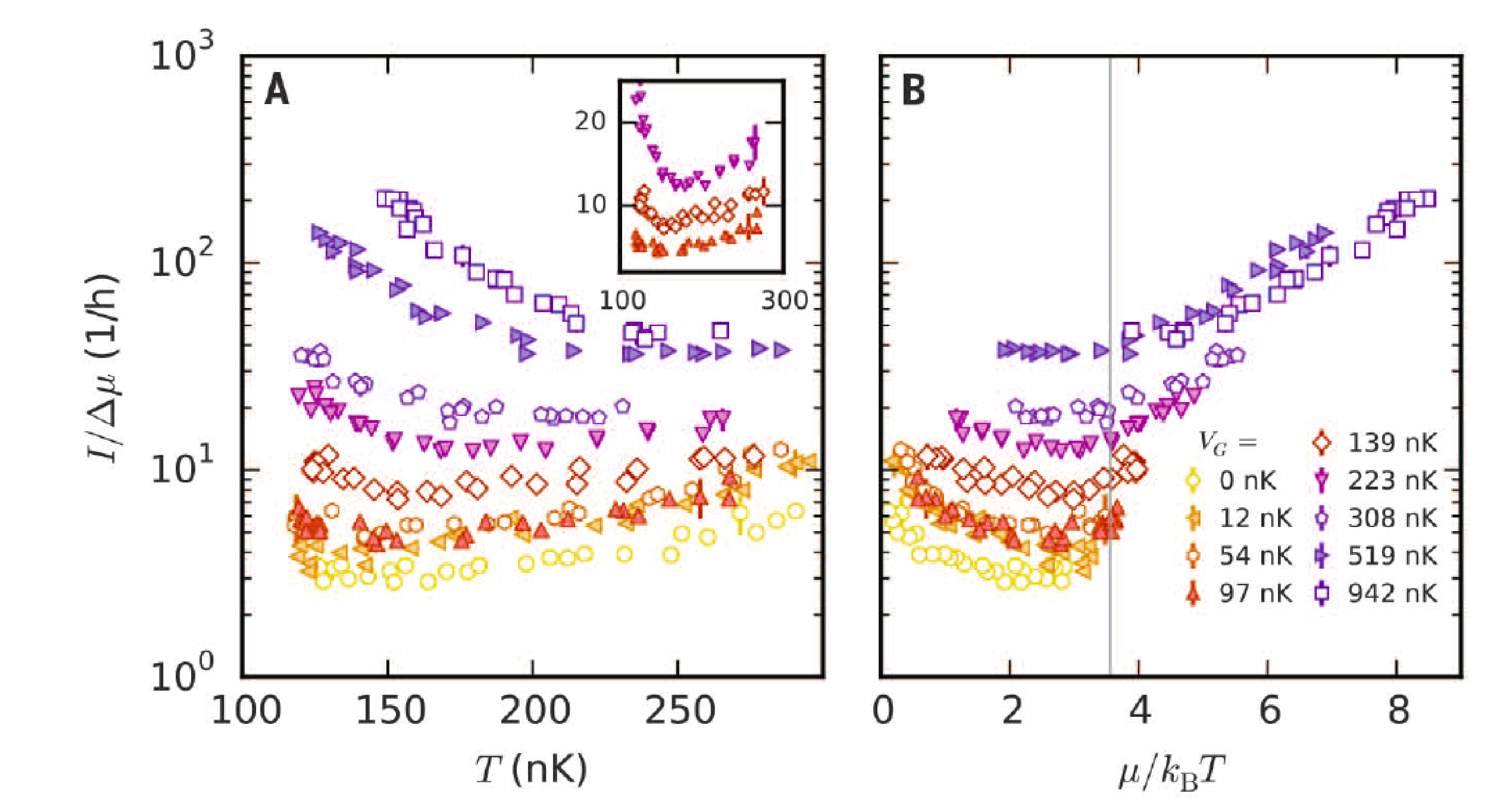


Temperature effects

Temperature effects



- Theory challenge: pseudogap in the reservoirs !


A
B
10^3
10^2
10^1
10^0
$I/\Delta\mu$ (1/h)
100
150
200
250
T (nK)
20
10
100
300
0
2
4
6
8
$\mu/k_{\mathrm{B}}T$
V_G =
0 nK
12 nK
54 nK
97 nK
139 nK
223 nK
308 nK
519 nK
942 nK

Conclusions

- First realization of a QPC in cold atomic systems
- Unitarity limit for reservoirs; control on parameters; very transparent junctions
- Excellent agreement with Keldysh based theory of the QPC
- Transport shows interplay between single particle tunnelling and Andreev tunnelling

Perspectives

- Theory: Study non-fermi liquids reservoirs; need to find theory methods in this case
- Exp: Measurements of other quantities (noise ?); other transports
- Other structure: quantum wires, periodic systems, barriers, disorder in a one dimensional structure etc.