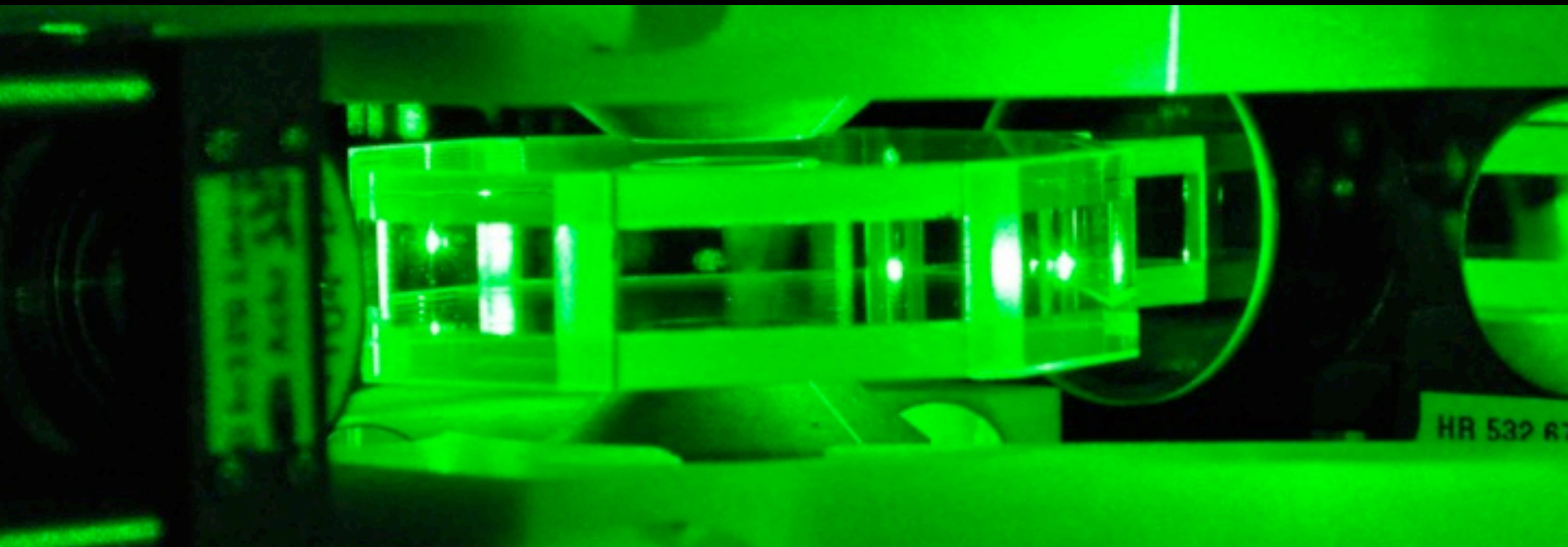
Transport experiments with ultracold Fermions



J.P. Brantut, J. Meineke, D. Stadler, S. Krinner, D. Husmann, S. Häusler, T. Esslinger

Institute for Quantum Electronics
ETH Zürich

Cold atoms and condensed matter physics

	Cold Fermionic atoms	Electrons in a solid
Density	10^{12} cm^{-3}	10^{22} cm^{-3} (Metals)

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Interparticle spacing: 1 µm

Wavelength of atomic wave functions is in the optical domain
-> optical lattices, microscopic disorder, etc

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Mass	6 (Li), 40 (K)	$5.4\ 10^{-4}$

Interparticle spacing: 1 μm

Fermi temperature: 1 μK

Requires laser cooling + evaporation

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Fermi Temperature	µK	10^4 K
Temperature	100 nK	10 mK

Temperature range : $\dfrac{T}{T_F} \sim 0.1$

Requires laser cooling + evaporation (+ new ideas ?)

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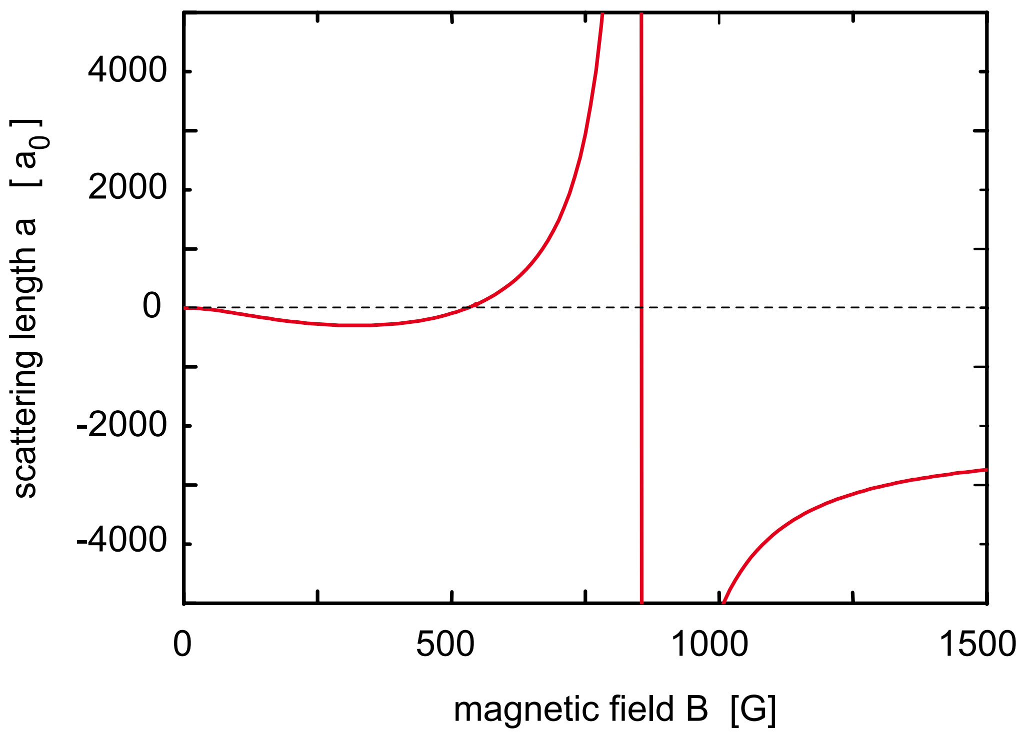
Interactions	Contact, *tunable*	Coulomb, material dep.

Feshbach resonances

Use the internal structure of atoms to manipulate scattering



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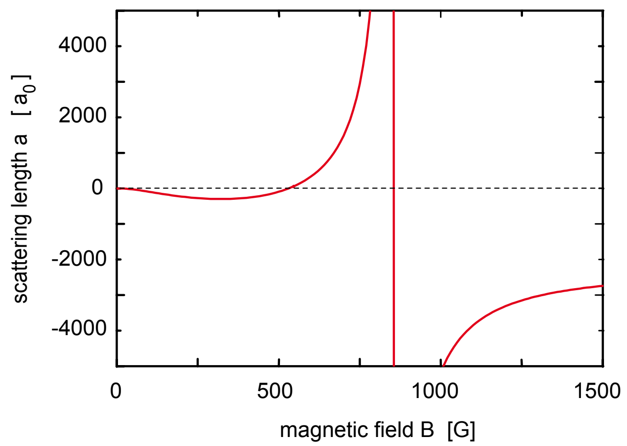
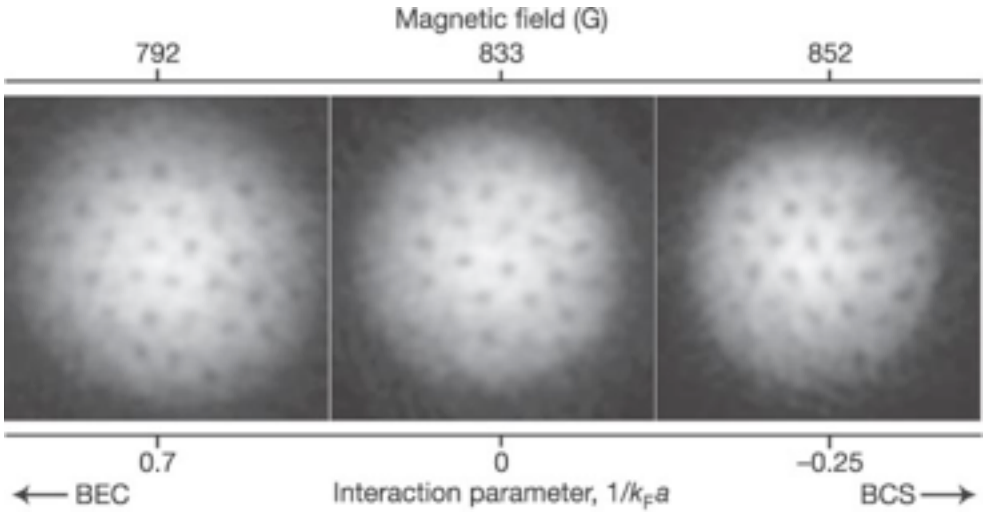
Feshbach resonances



Superfluidity emerges at low temperatures



M. Zwierlein *et al*, Nature **435**, 1047 (2005)

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K. Ensslin, ETH

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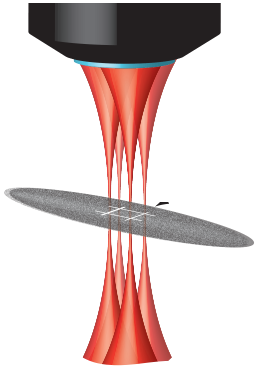

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Probing	Imaging, spectroscopy	AC/DC characteristics, response functions…

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From materials to devices

Material

e^{-} gas

atoms

From materials to devices

Material	*Device*
e^- gas →	gate pattern
atoms →	beam patterns

From materials to devices

Material	*Device*	*Measurement*	
e^- gas →	gate pattern →	terminals →	conductances
atoms →	beam patterns - - - →		

See also :
M. Inguscio (Florence), B. DeMarco (Urbana), A. Aspect (Palaiseau), I. Bloch (Munich), C. Chin (Chicago)...

- Experimental setup
  - Two terminals Landauer configuration
  - Strongly attractive interactions: superfluids
  - Disordered superfluids

- Thermoelectric transport

  Theory : Charles Grenier, Corinna Kollath and Antoine Georges

  - Ballistic channel
  - Disordered channel : ballistic to diffusive crossover
  - Efficiency of heat to work conversion

- Outlook
  - Lithography for cold atoms

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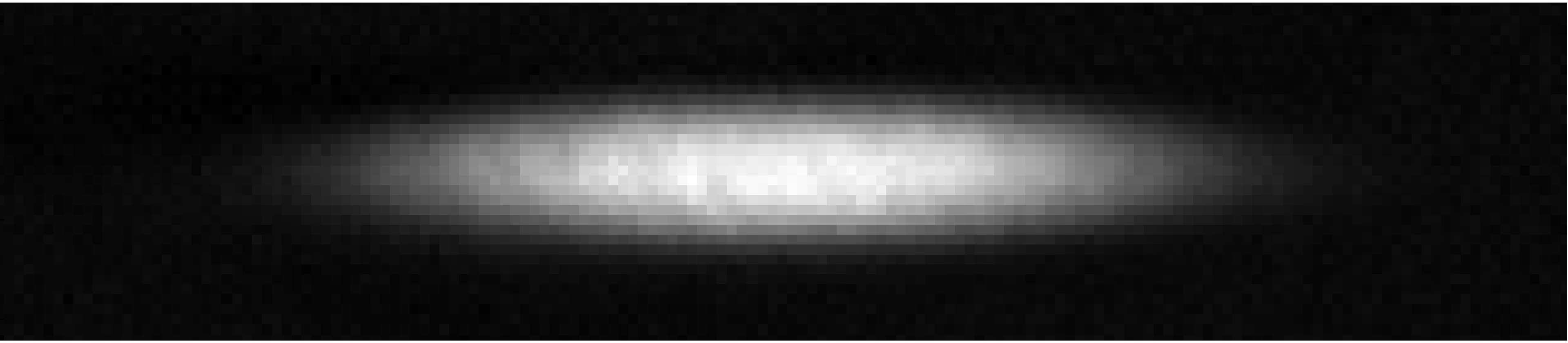
Two-terminals setup

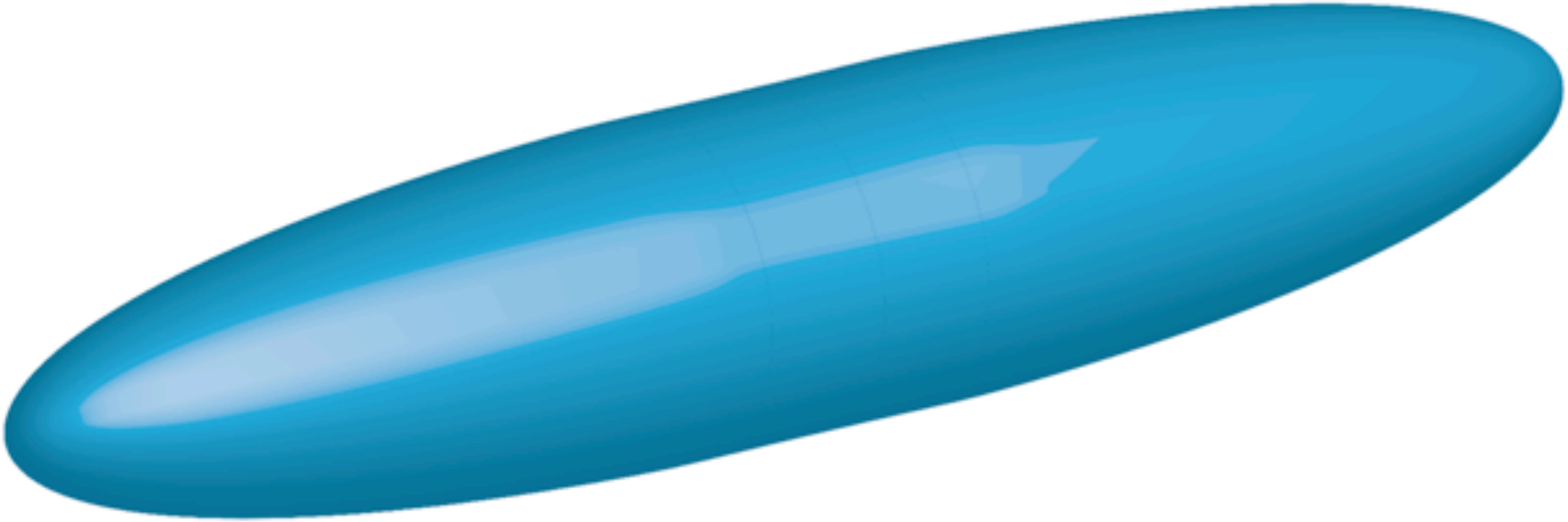


10^5 ^{6}Li atoms

$T \sim 0.2\ T_F$

$T_F = 930$ nK

Two-terminals setup



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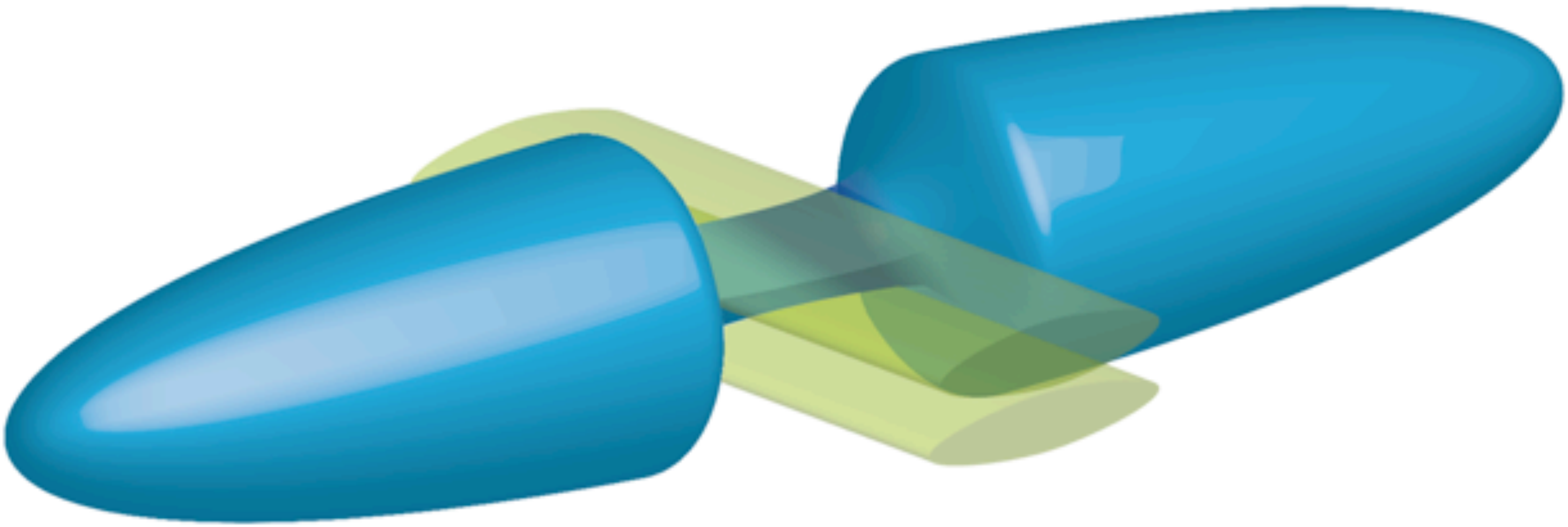

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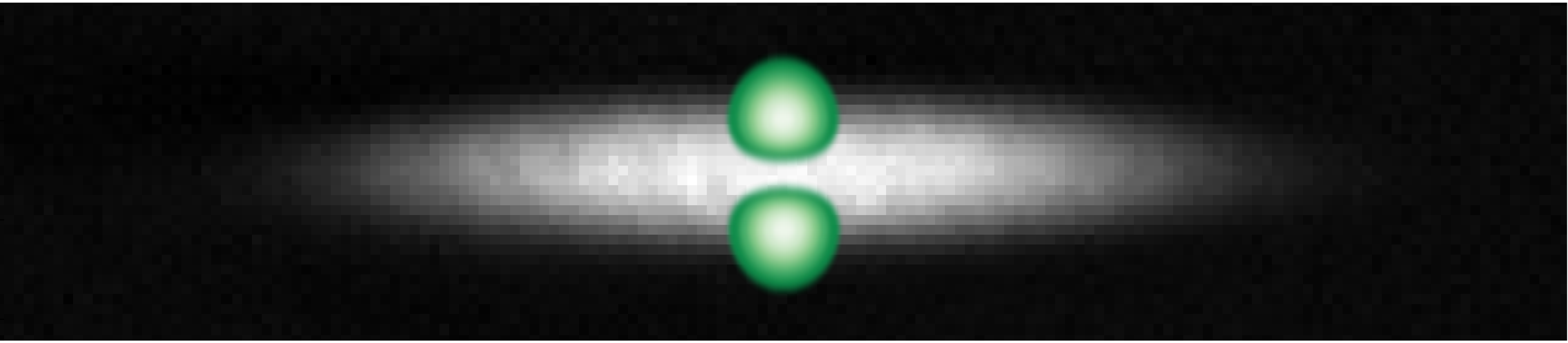
Two-terminals setup

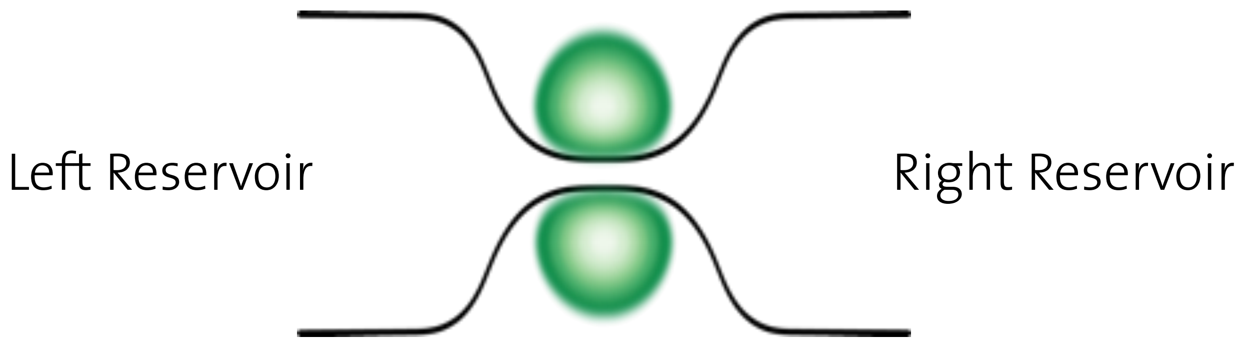


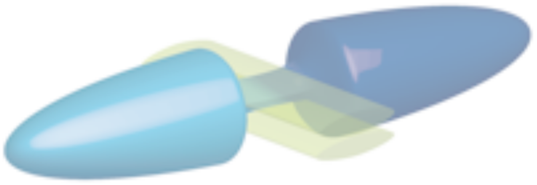
Repulsive TEM_{01} laser beam on the center of the cloud

Trap frequency up to 11 kHz

Creates a narrow multimode, *ballistic* channel

Two-terminals setup





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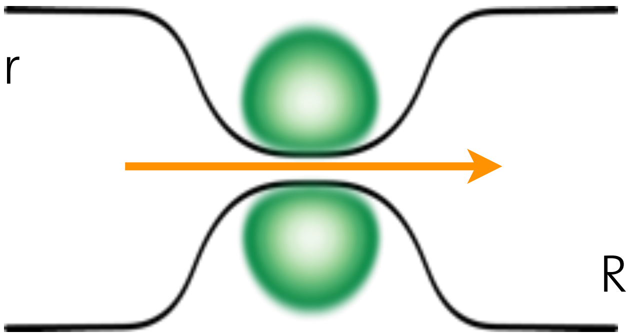
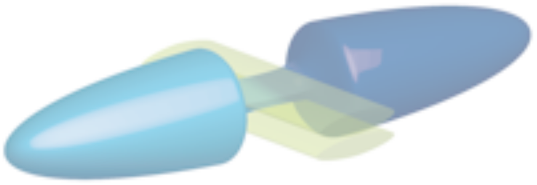


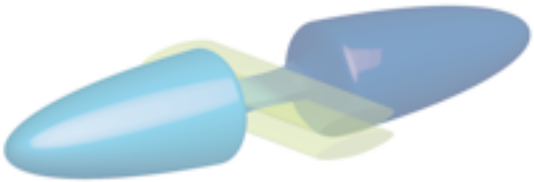
$$N_{\text{Left}} > N_{\text{Right}}$$



Linear response

Ohm's Law
channel

$$\boxed{I_{\mathrm{N}} \quad = \quad G \cdot \Delta\mu}$$



Linear response

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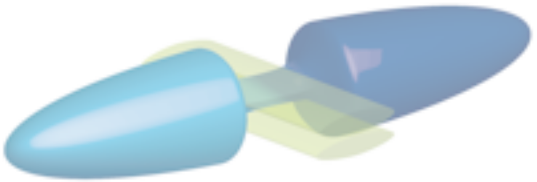
$$\boxed{I_{\mathrm{N}} = G \cdot \Delta\mu}$$

Thermodynamic relations
Reservoirs

$$\boxed{\Delta\mu = \frac{1}{\kappa}\,\Delta N}$$



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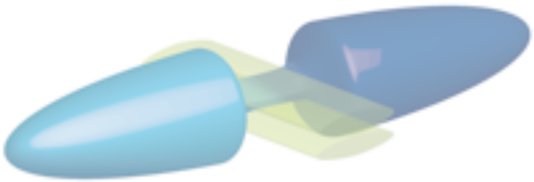
Thermodynamic relations
Reservoirs

$$\boxed{\Delta\mu \quad = \quad \frac{1}{\kappa} \; \Delta N}$$

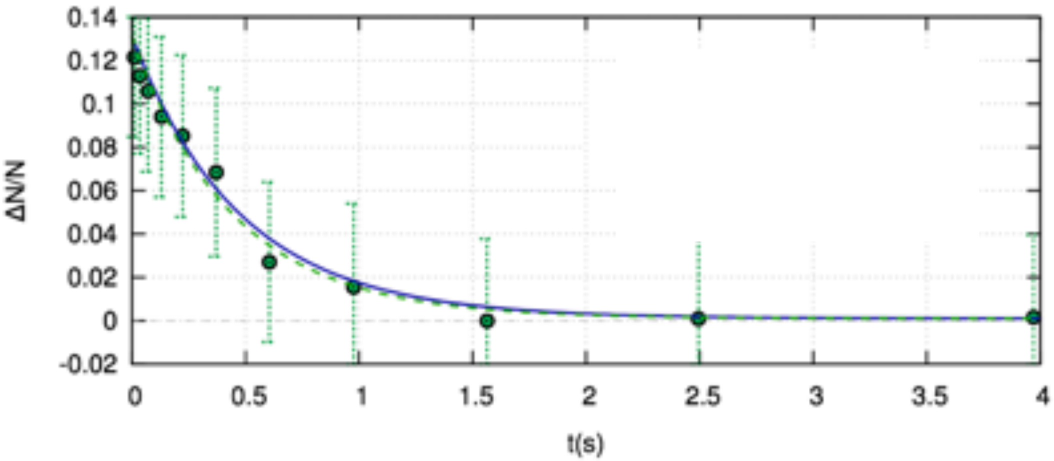
Continuity equation

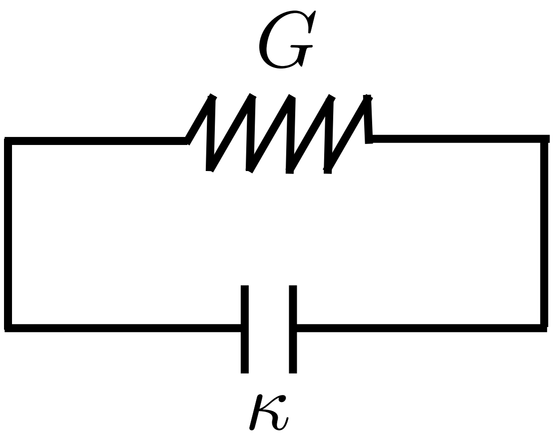
$$I_{\mathrm{N}} \quad = \quad \Delta\dot{N}$$

$$\Delta\dot{N} = \frac{G}{\kappa}\Delta N$$



Atomic flow through the channel





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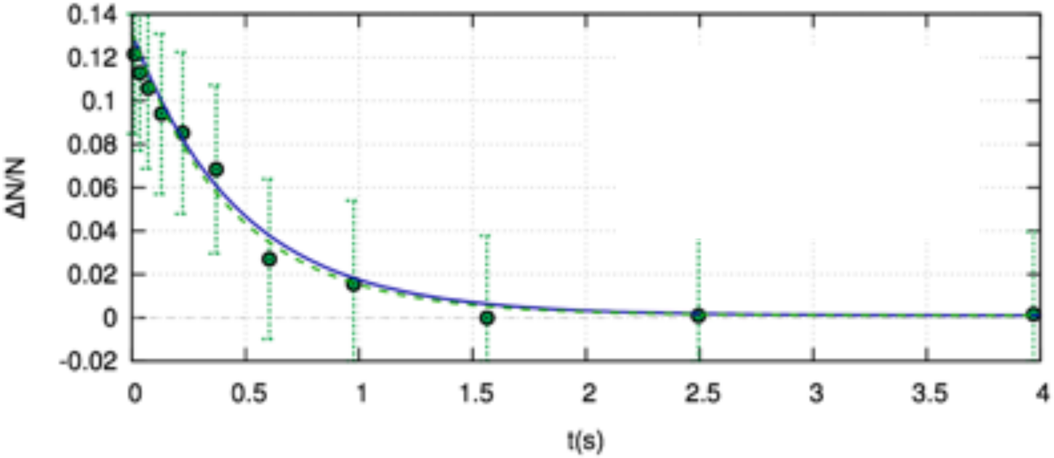
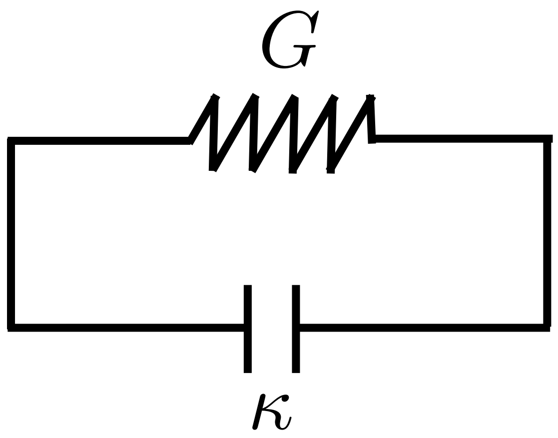
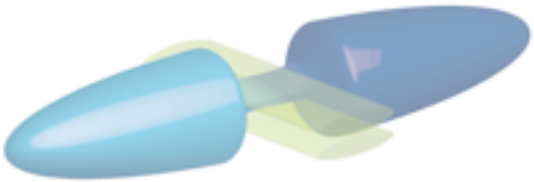




Ballistic channel :

$$\kappa/G = 481(30)\,\mathrm{ms}$$ *Experimental fit*



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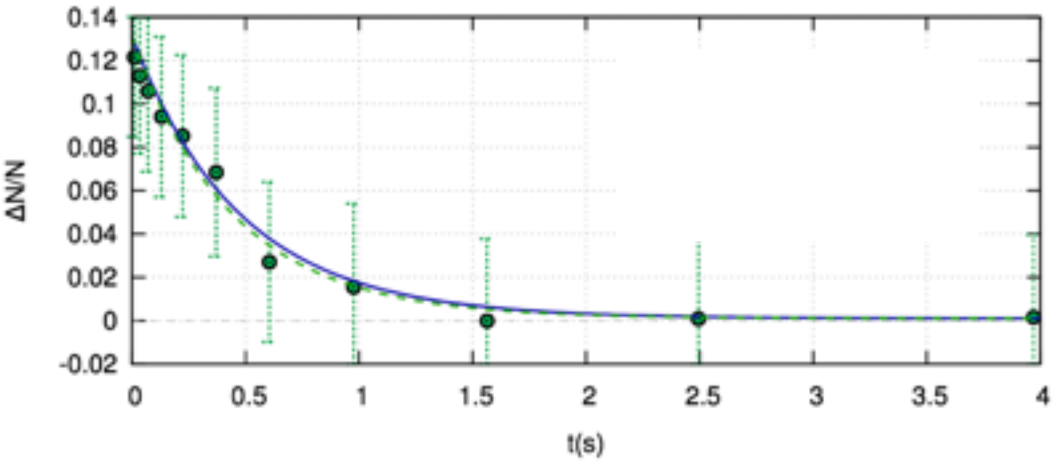

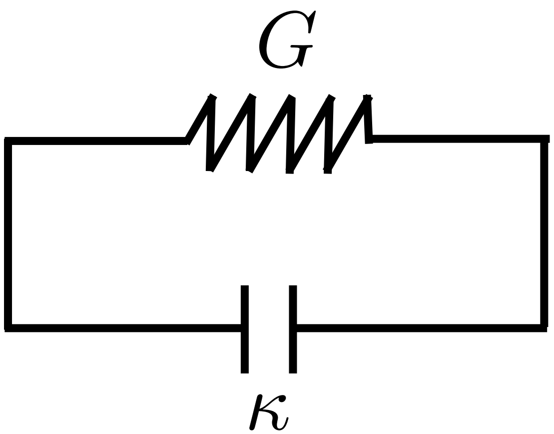

Ballistic channel :

$$\kappa/G = 481(30)\ \mathrm{ms}$$ *Experimental fit*

$$\kappa/G = 450(30)\ \mathrm{ms}$$ *Landauer-Büttiker + ideal reservoirs*

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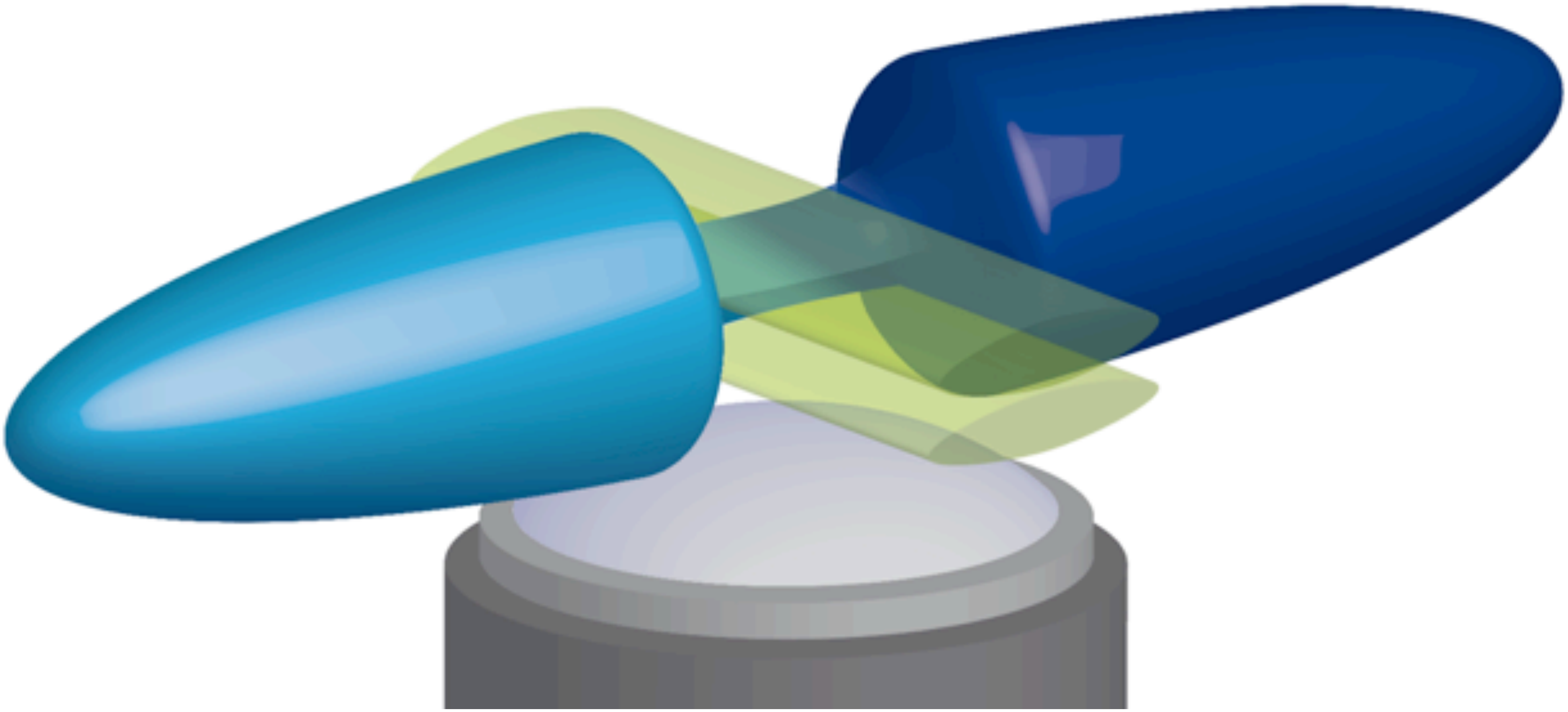
Where does the voltage drop ?



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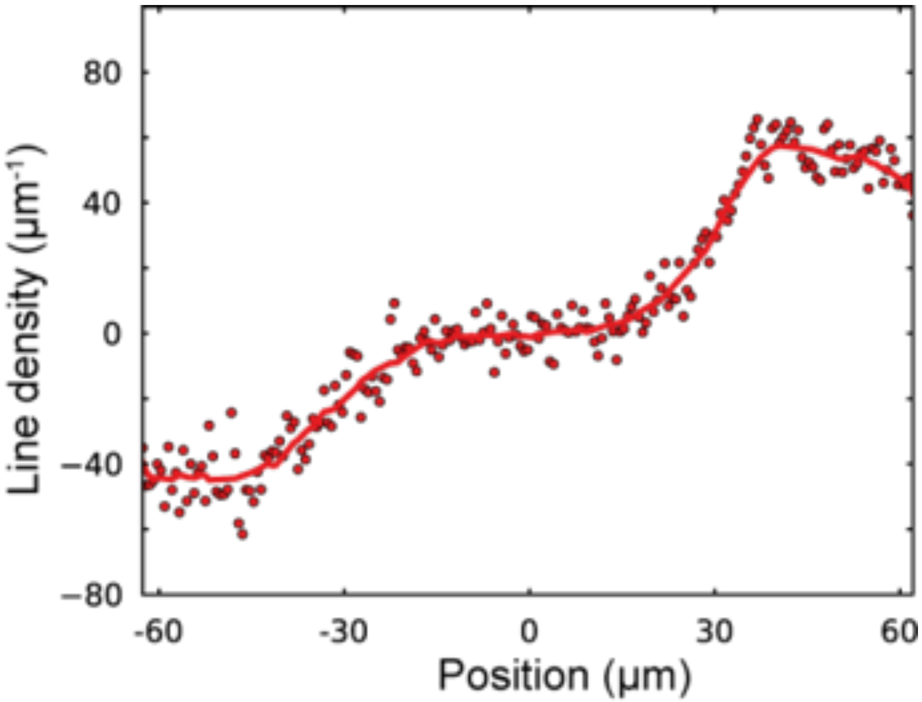

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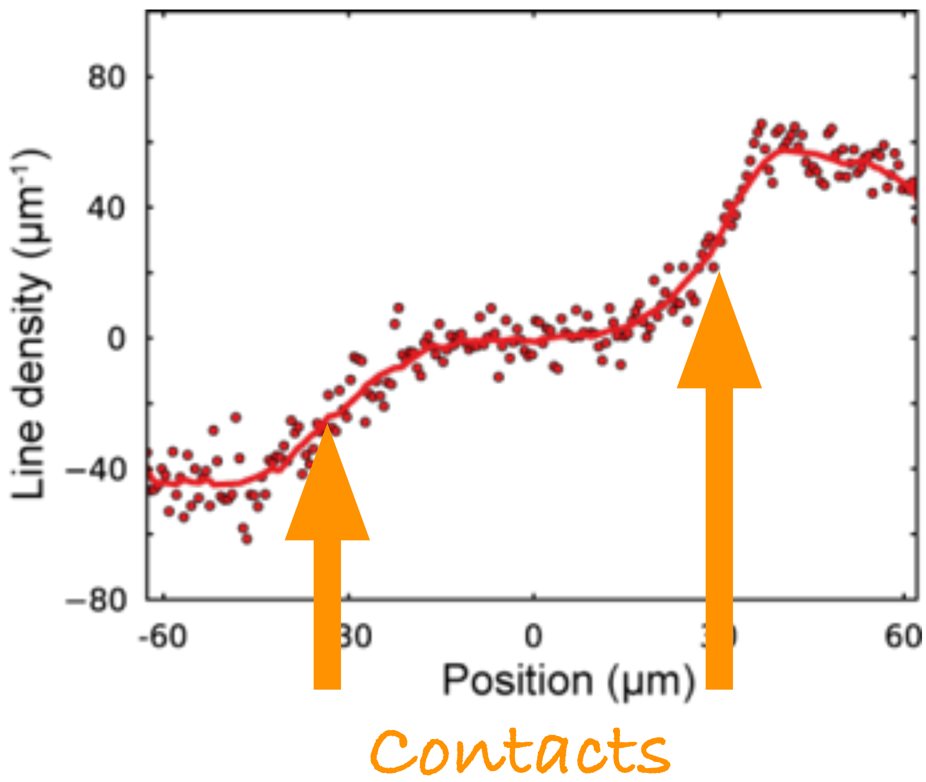
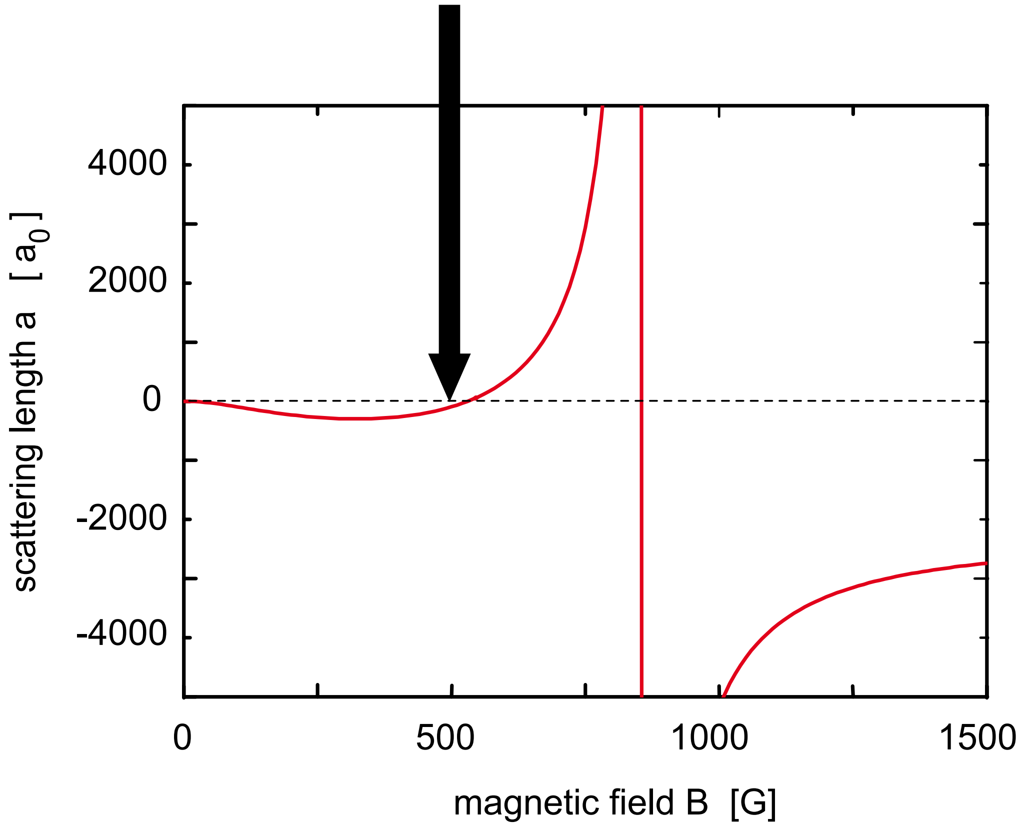


Resistance of cold atom systems : interactions



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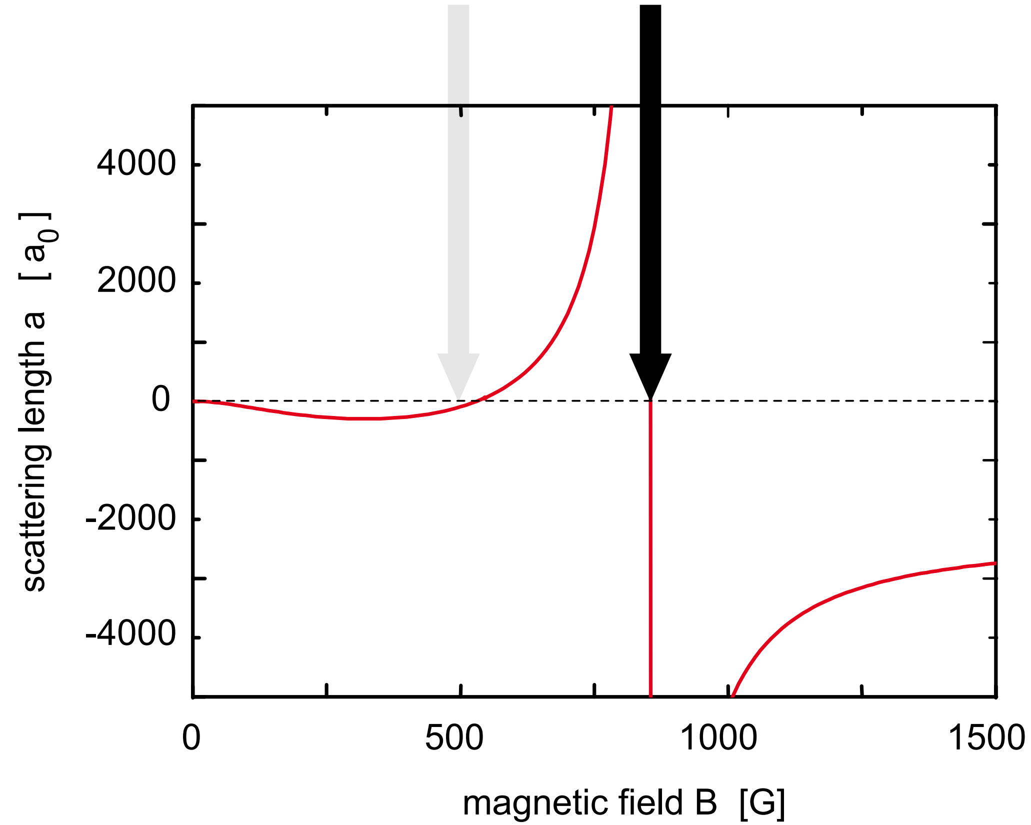
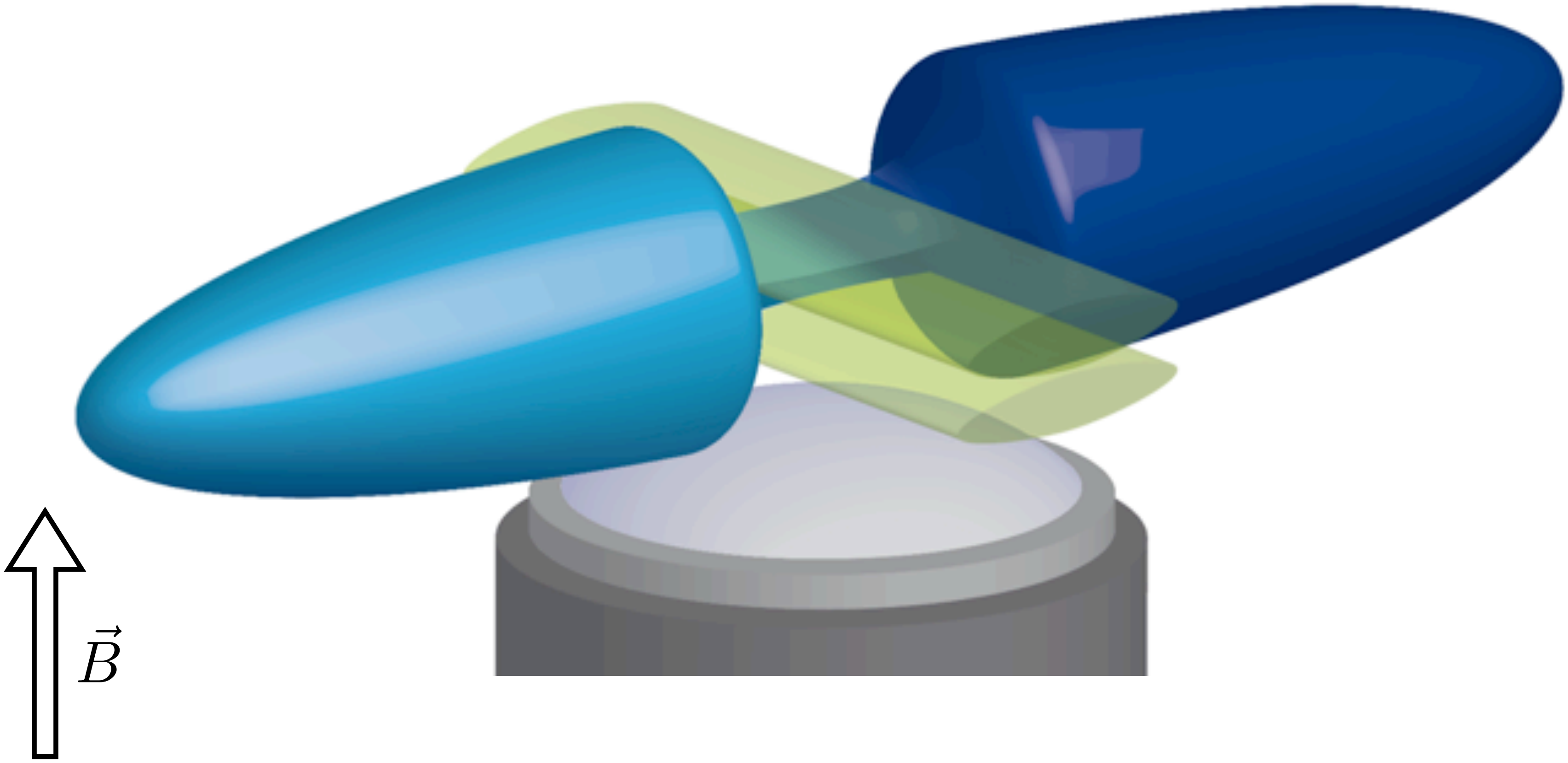


Strongly attractive Fermi gases : pairing and superfluidity

Resistance of cold atom systems : interactions



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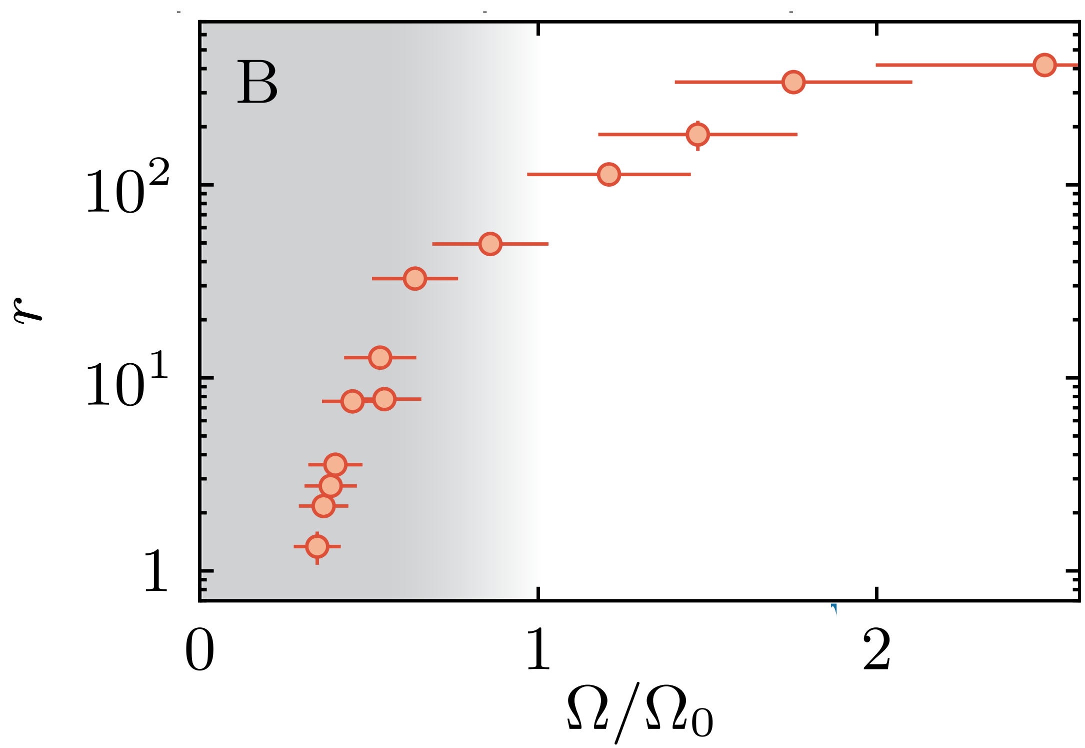

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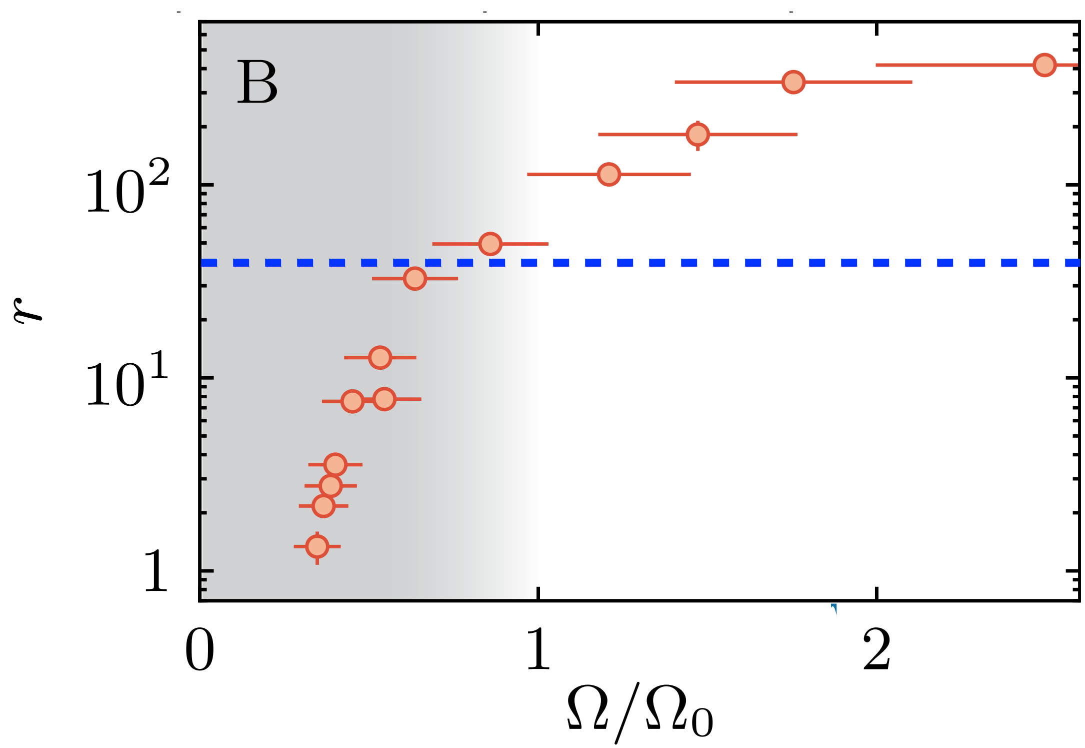
Resistance of cold atom systems : interactions



Contact resistance

Strongly attractive Fermi gases : pairing and superfluidity

Resistance of cold atom systems : disorder

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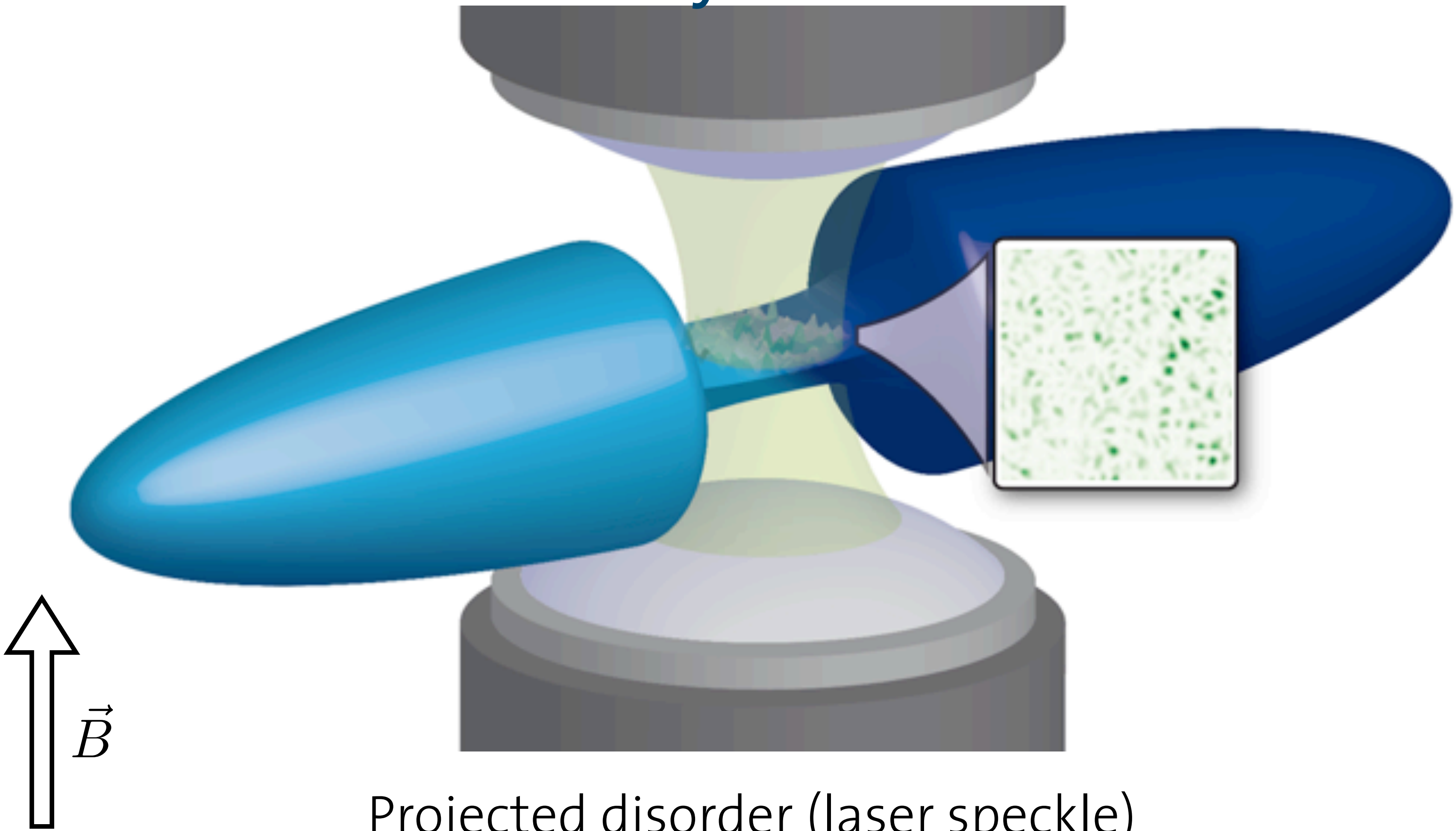
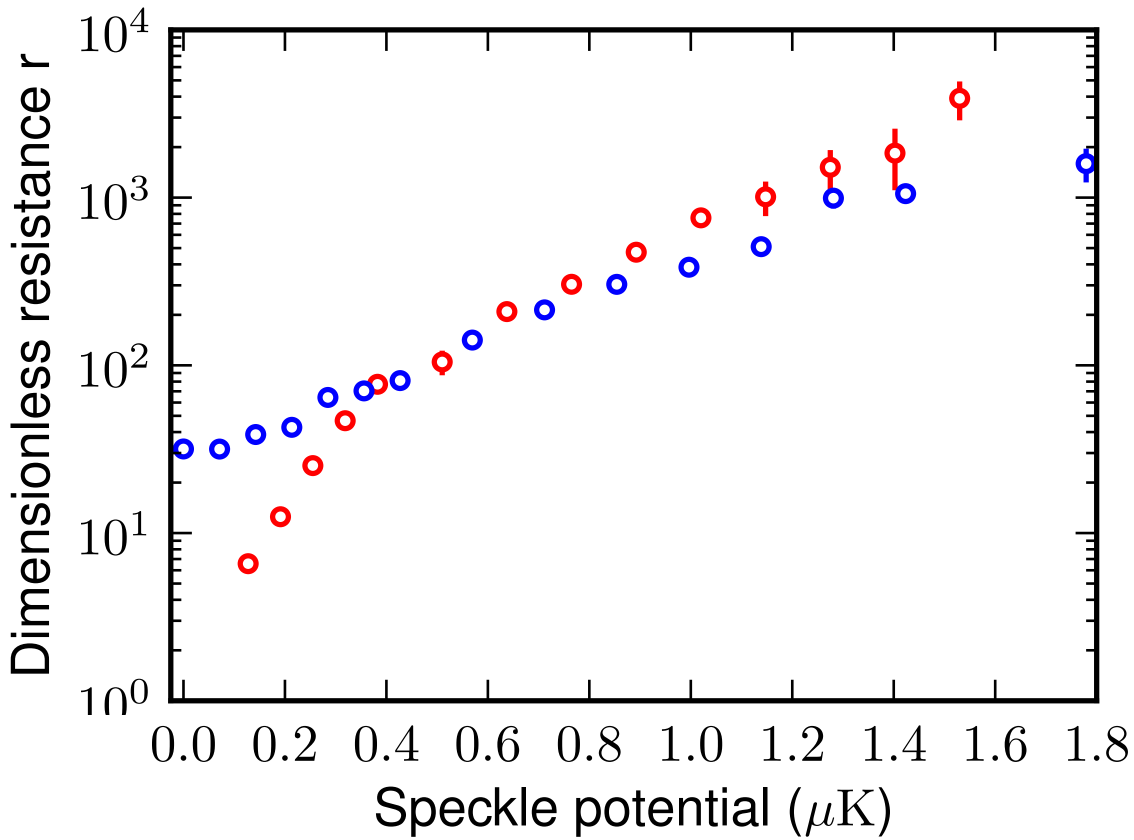


Projected disorder (laser speckle)

See also : M. Inguscio (Florence), B. DeMarco (Urbana), A. Aspect (Palaiseau), S. Rolston (NIST)

Resistance of cold atom systems : disorder



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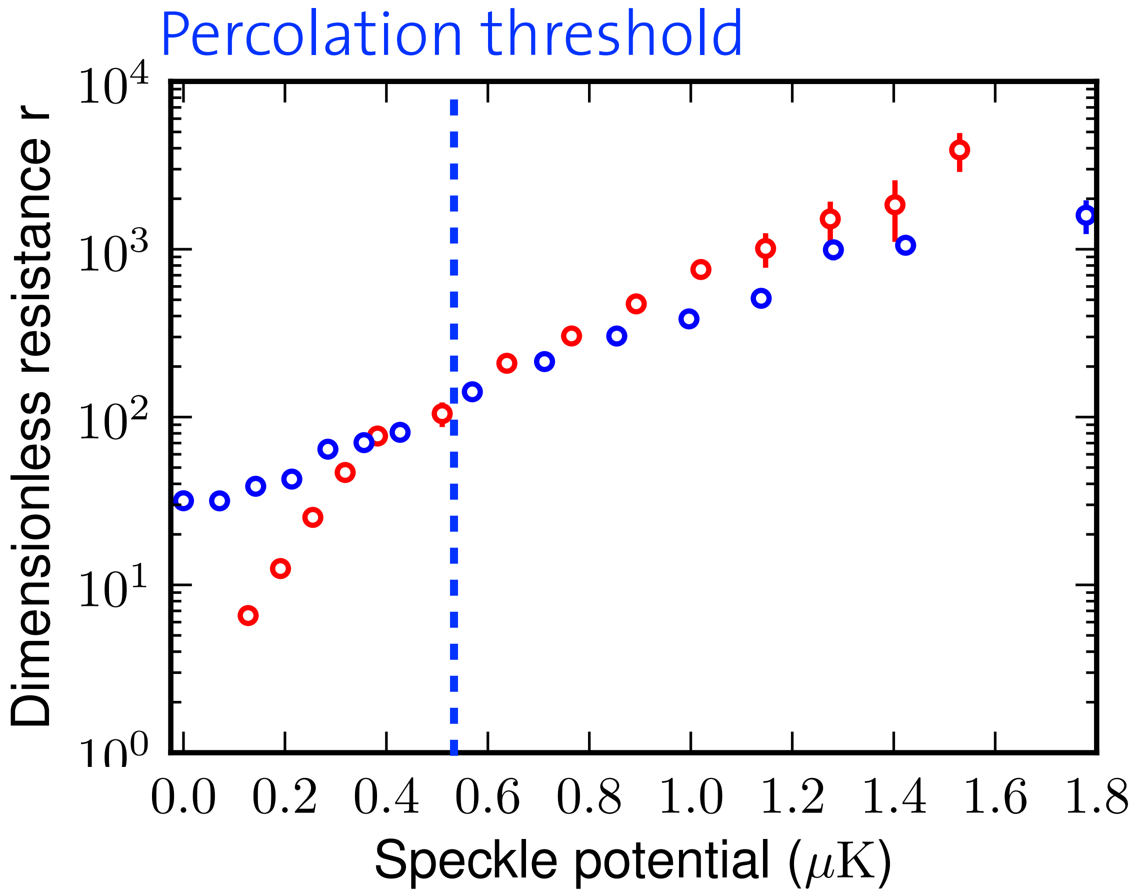

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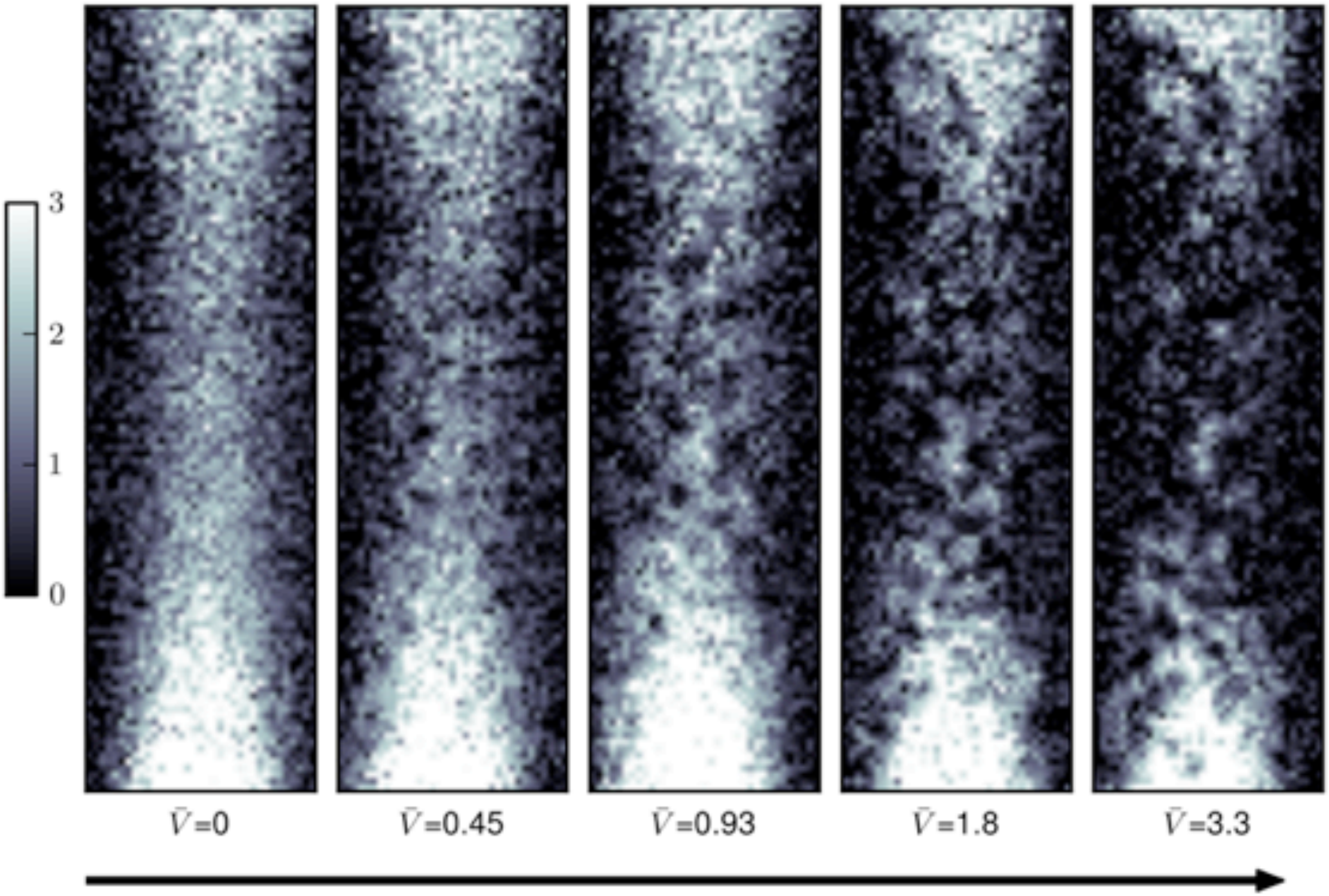

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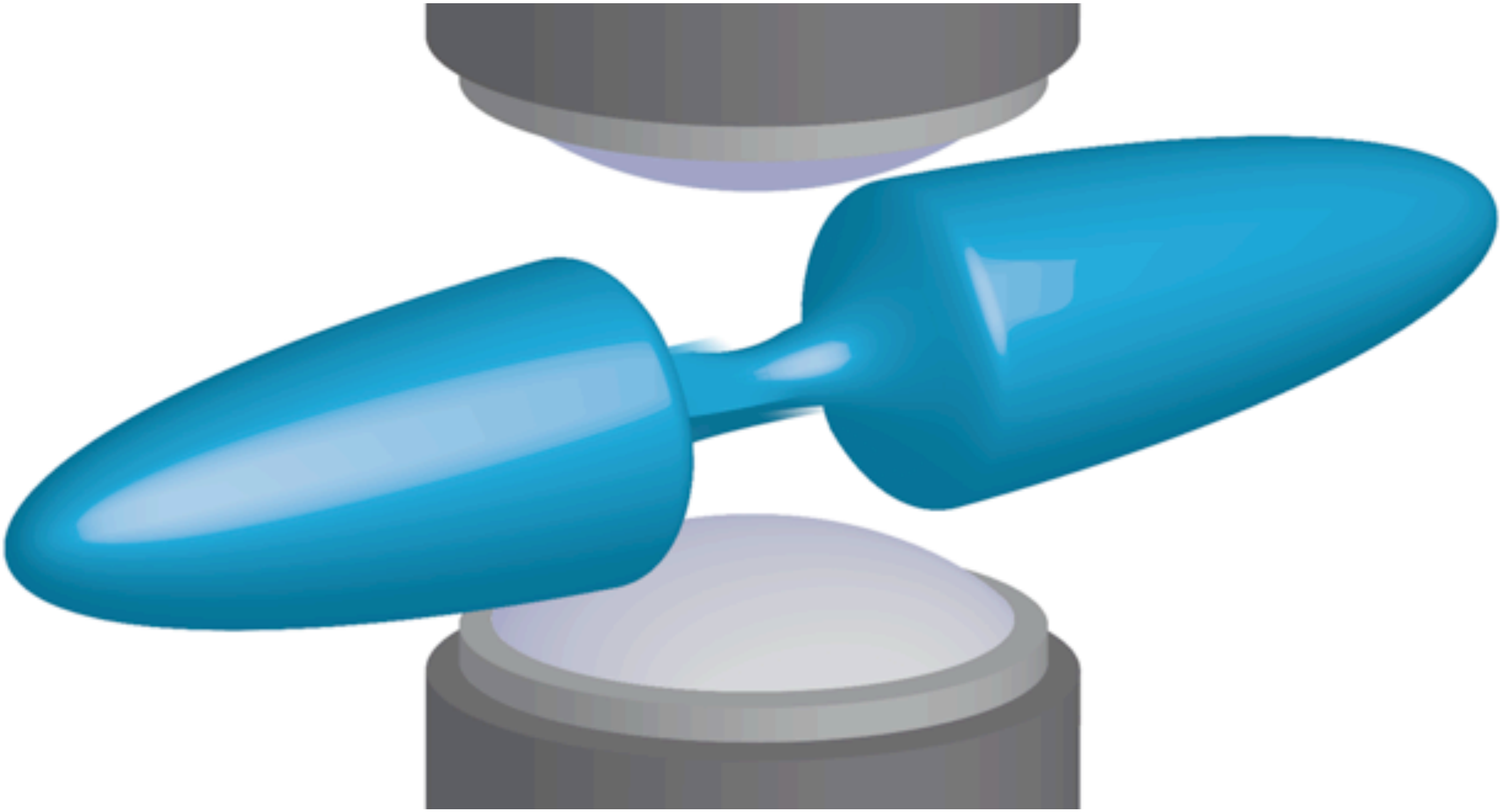
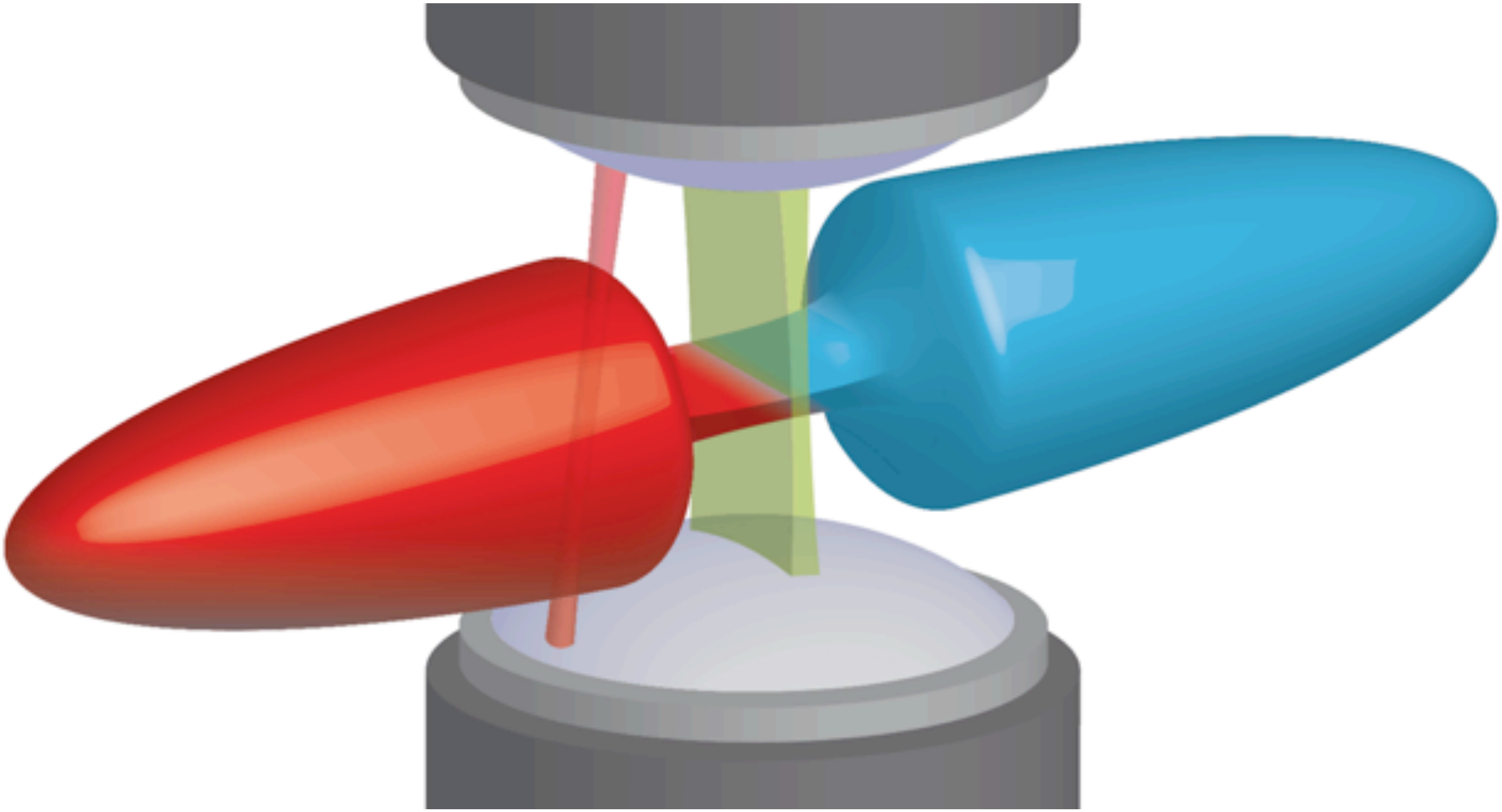
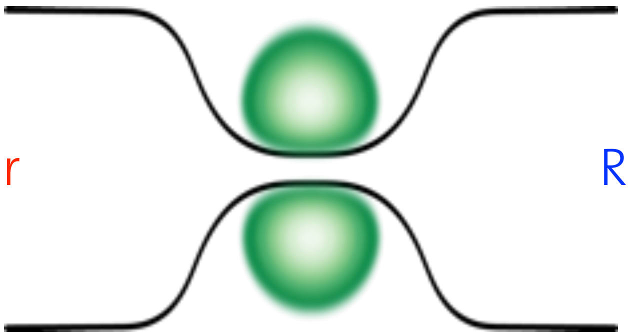




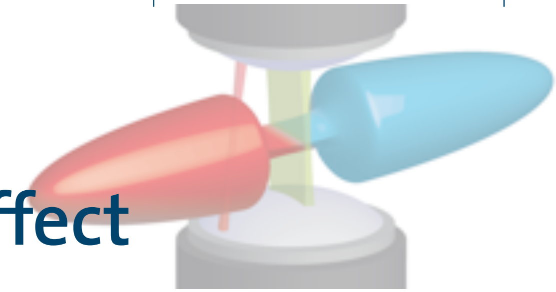
Temperature bias

Left Reservoir

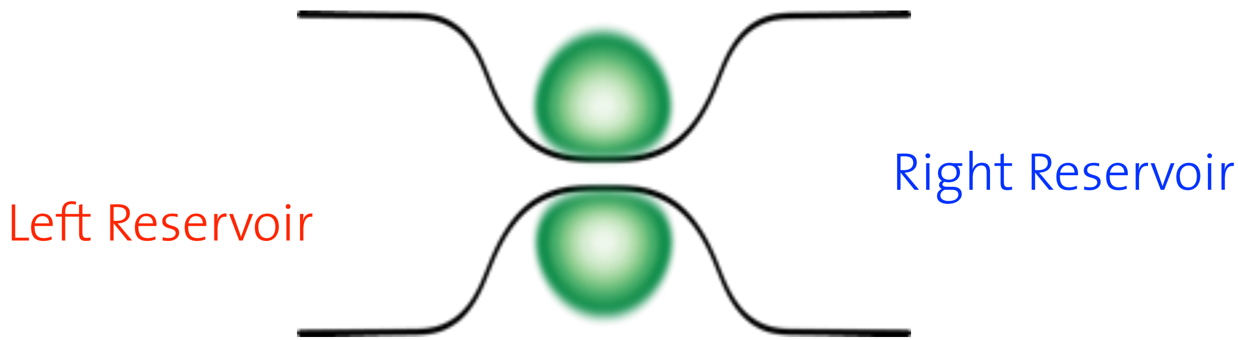


Right Reservoir

$$T_{\mathrm{Left}} > T_{\mathrm{Right}}$$



Temperature bias : a thermodynamic effect



$$T_{\text{Left}} > T_{\text{Right}}$$

$$\boxed{\mu_{\text{Left}} < \mu_{\text{Right}}}$$

negative potential bias

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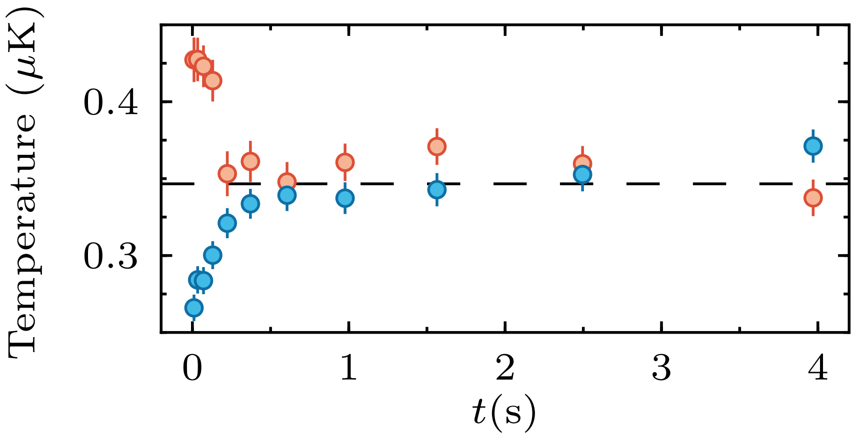
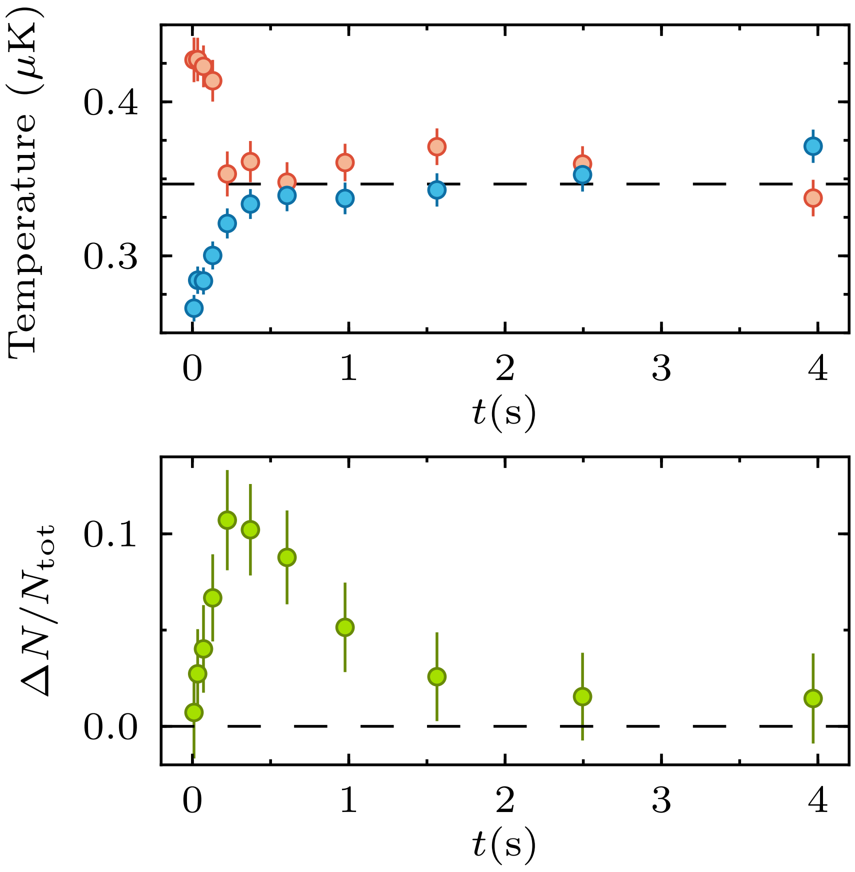
Temperature bias



Entropy flow from hot to cold

Temperature bias



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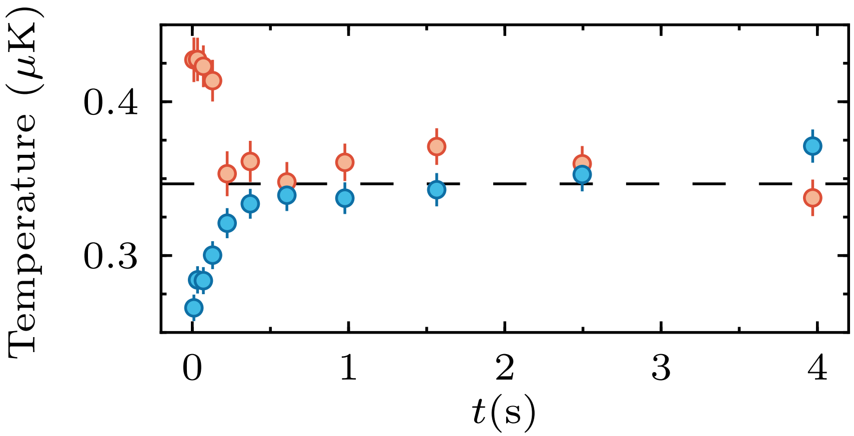
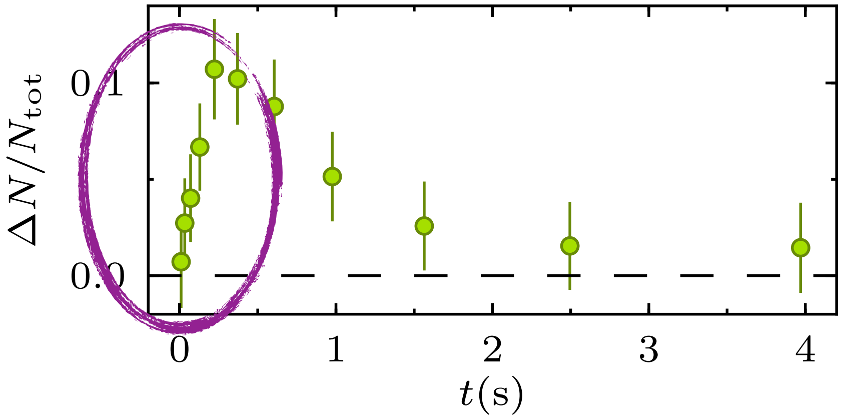


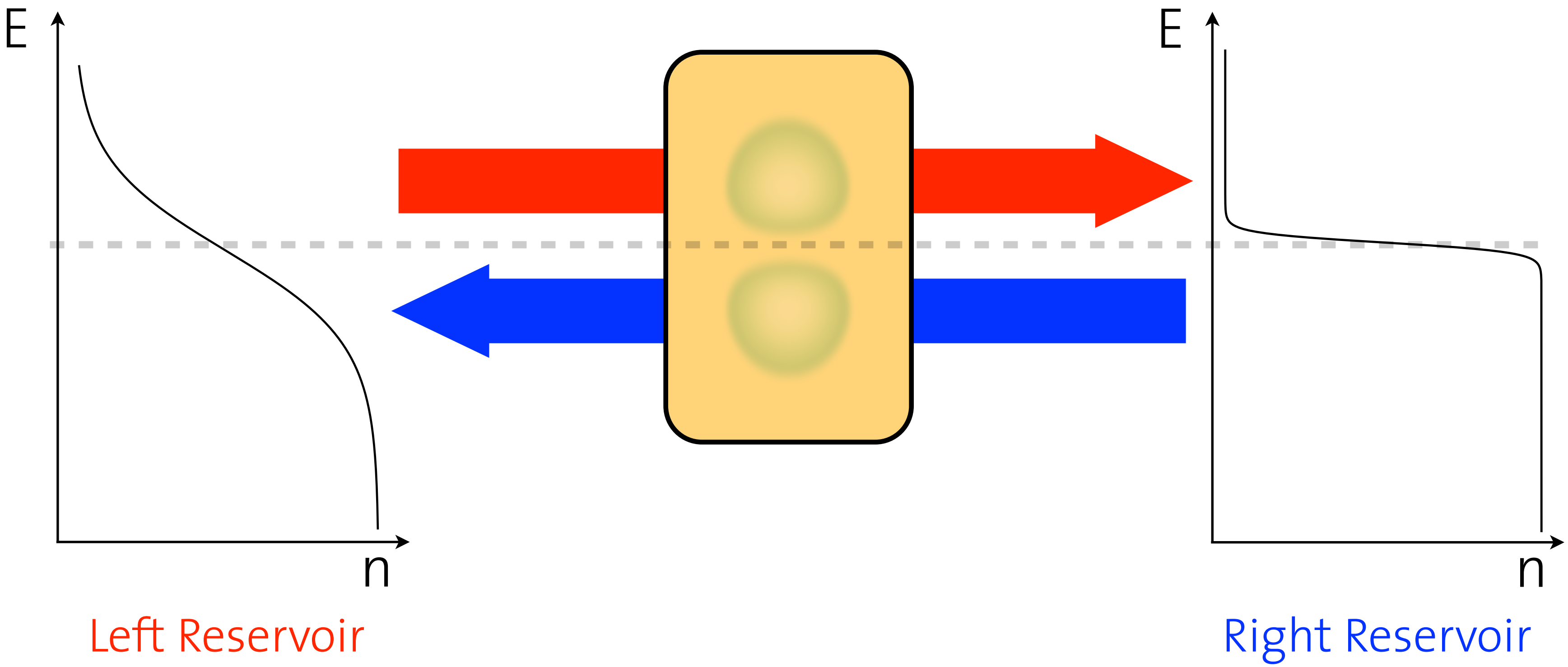
Entropy flow from hot to cold



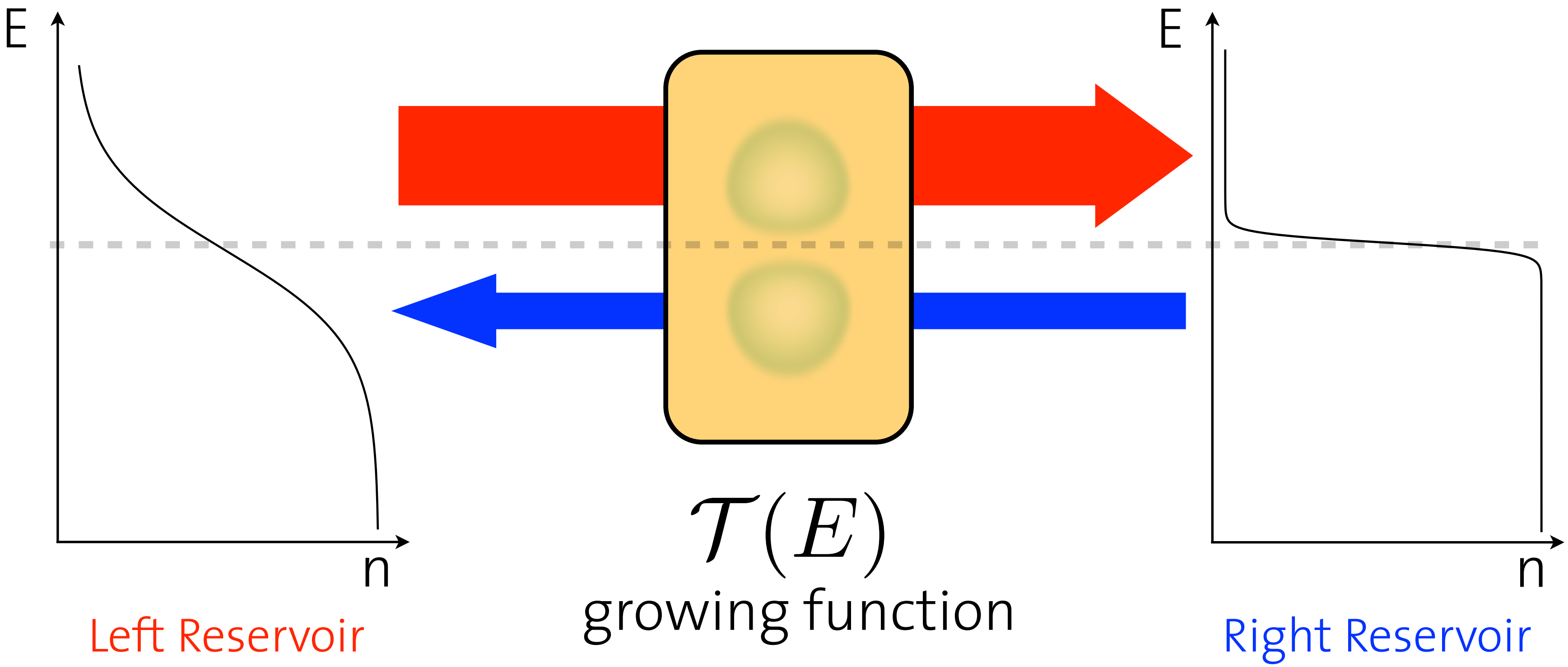
Particle flow from hot to cold

...flows against the potential bias...

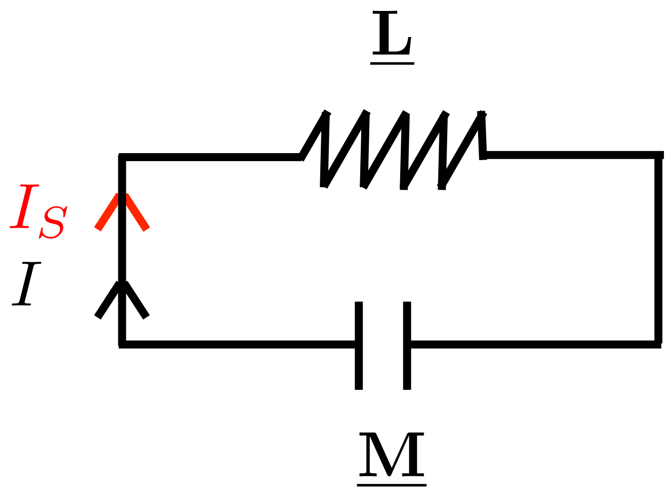
Intrinsic thermoelectric effect



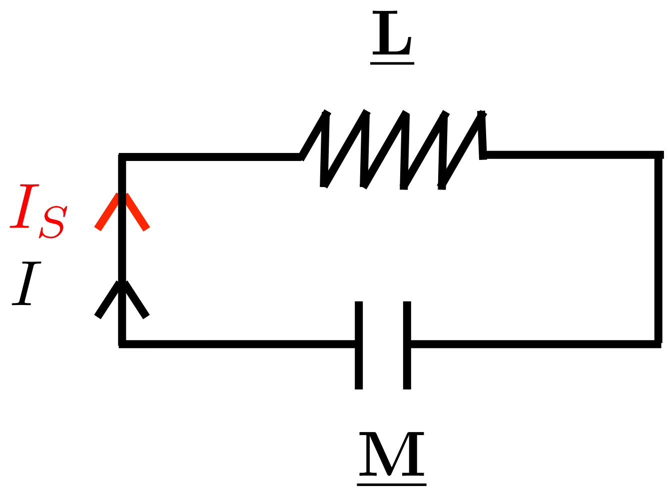
Intrinsic thermoelectric effect



Thermoelectric capacitor description



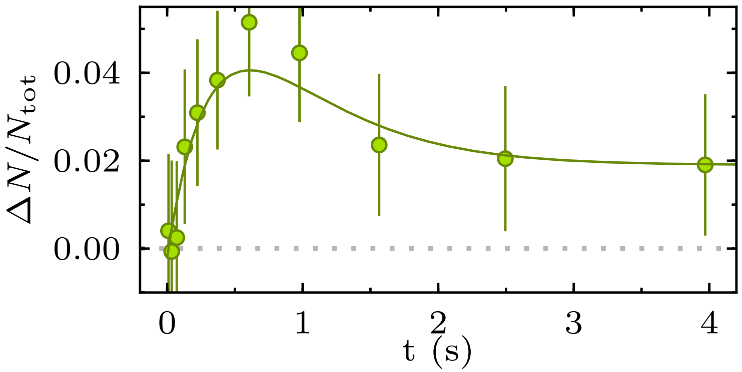
Thermoelectric capacitor description



$$\boxed{\tau_0 \frac{d}{dt}\begin{pmatrix} \Delta N \\ \Delta T \end{pmatrix} = -\underline{\Lambda}\begin{pmatrix} \Delta N \\ \Delta T \end{pmatrix}}$$

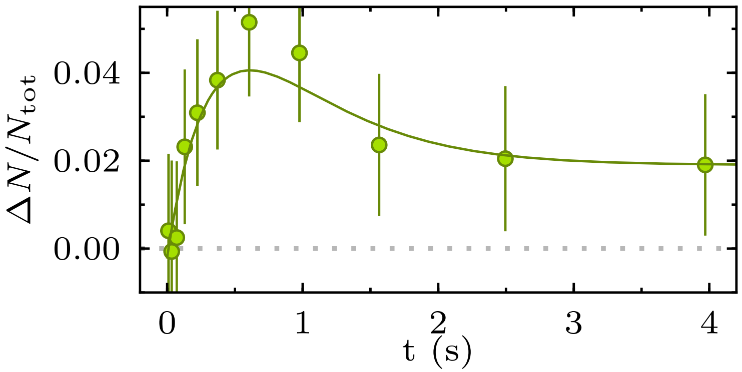
Provides a fitting procedure to extract resistance and thermopower

Ballistic channels



Trap frequency in the channel : 9.3 kHz

Ballistic channels



Trap frequency in the channel : 9.3 kHz

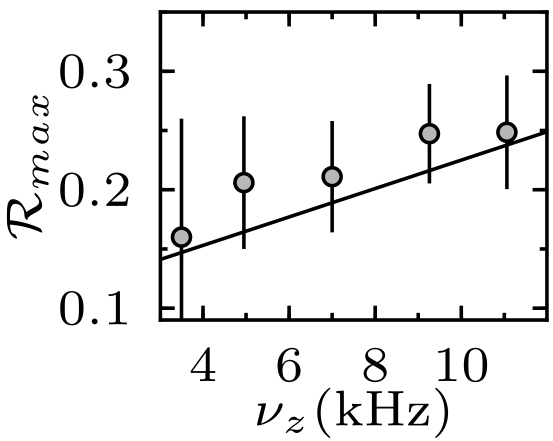
Trapped ideal Fermi gas

+

Landauer-Büttiker formula

No adjustable parameter

Ballistic channels : thermoelectric response



Normalized atom number difference as a response to the temperature bias

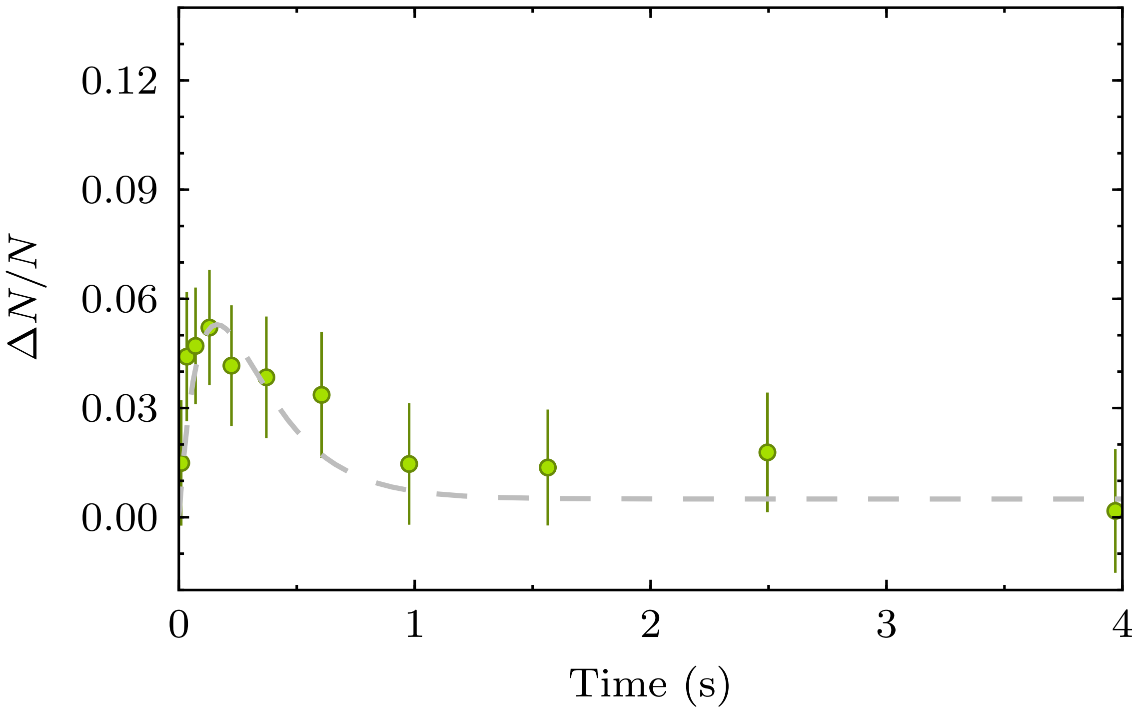
$$\mathcal{R} = \frac{(\Delta N / N_{\mathrm{tot}})}{(\Delta T_0 / T_F)}$$

Increasing confinement:

- decreases the conductance
- increases the thermoelectric response

Ballistic to diffusive crossover

Ballistic to diffusive crossover



Disorder strength = 0.13 μK

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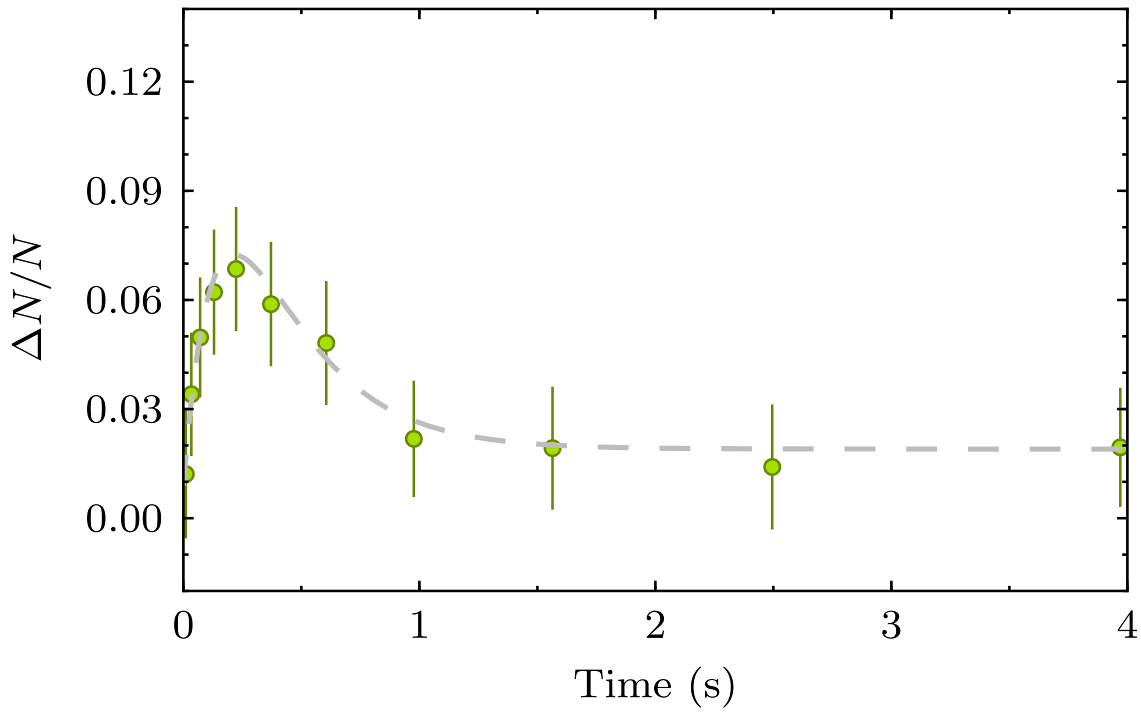
Ballistic to diffusive crossover



Disorder strength = 0.26 μK

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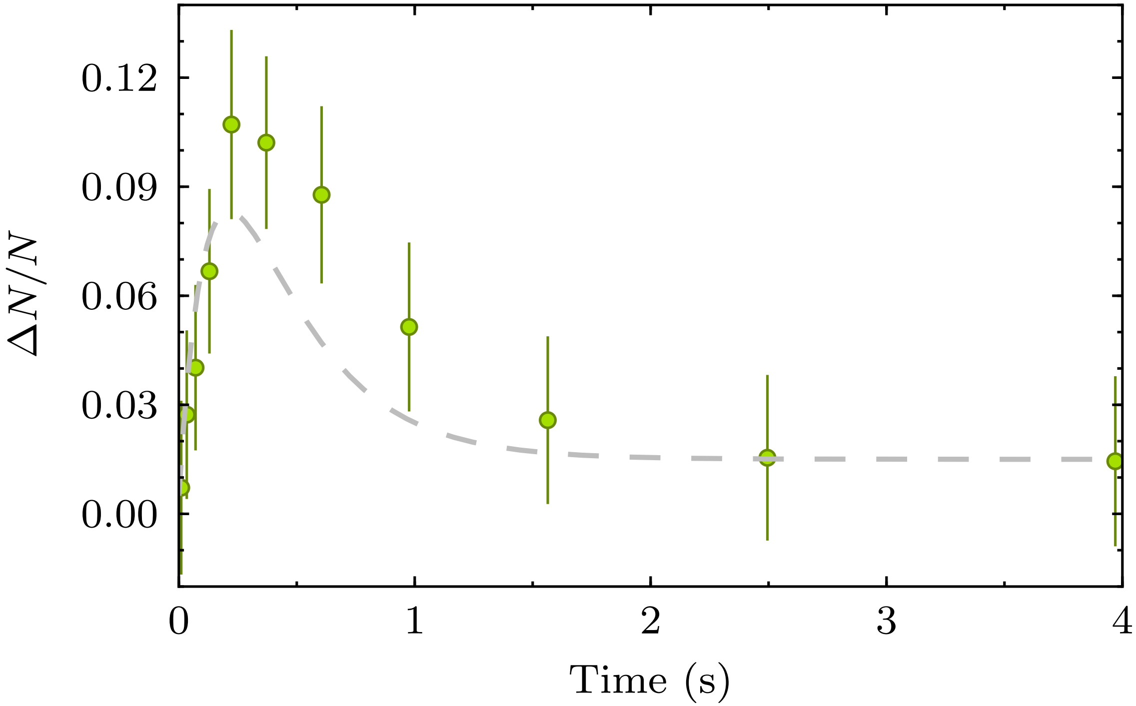
Ballistic to diffusive crossover



Disorder strength = 0.54 μK

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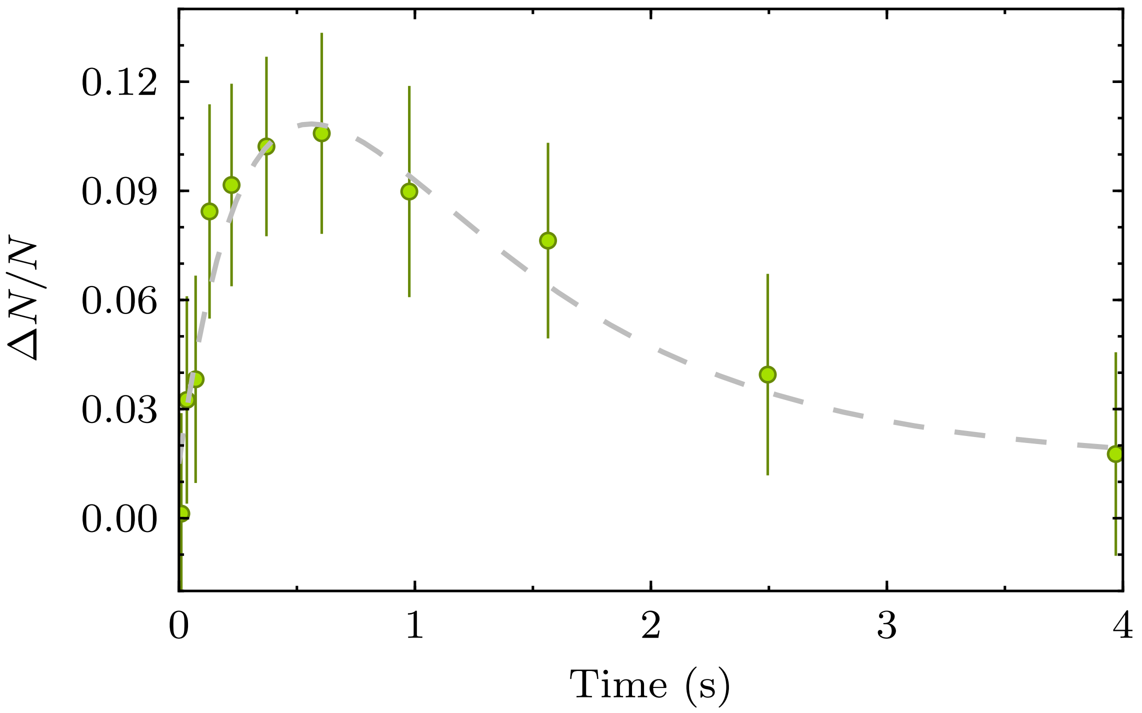
Ballistic to diffusive crossover



Disorder strength = 0.81 µK

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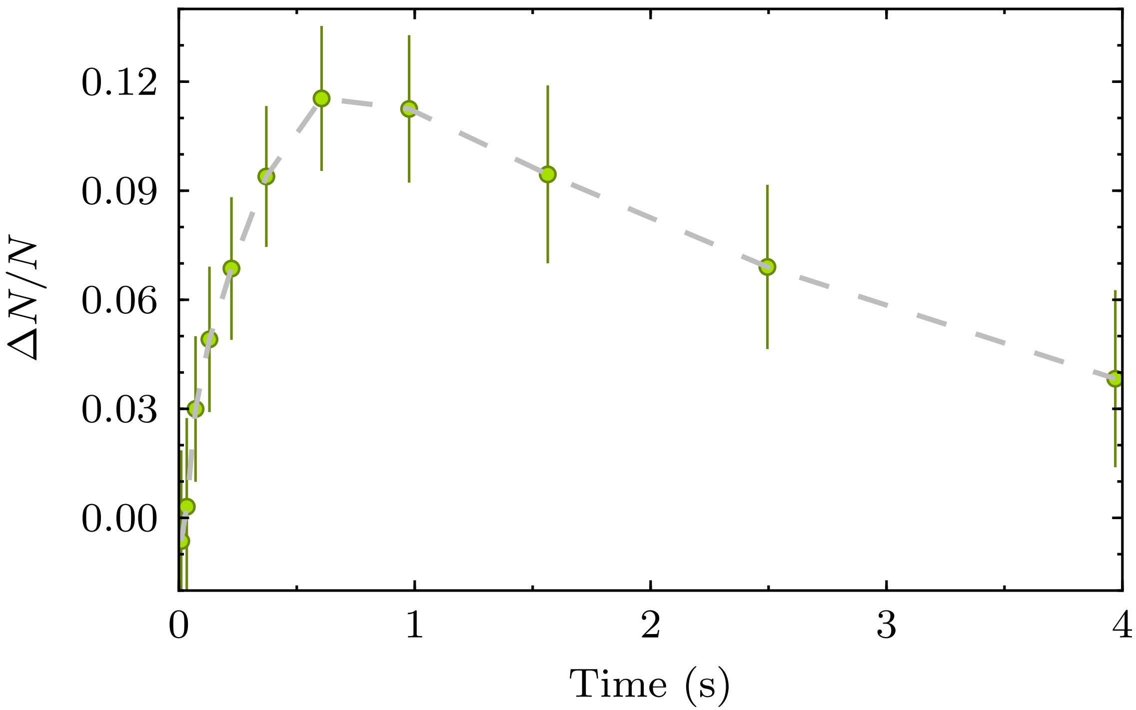
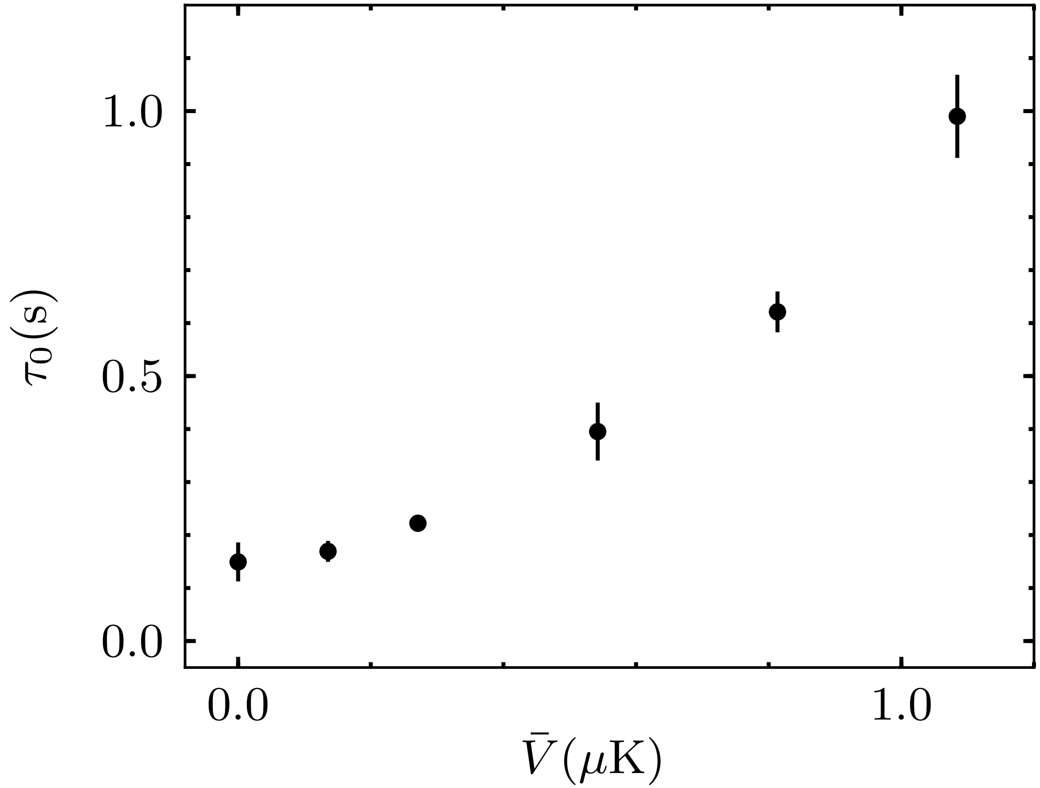
Ballistic to diffusive crossover

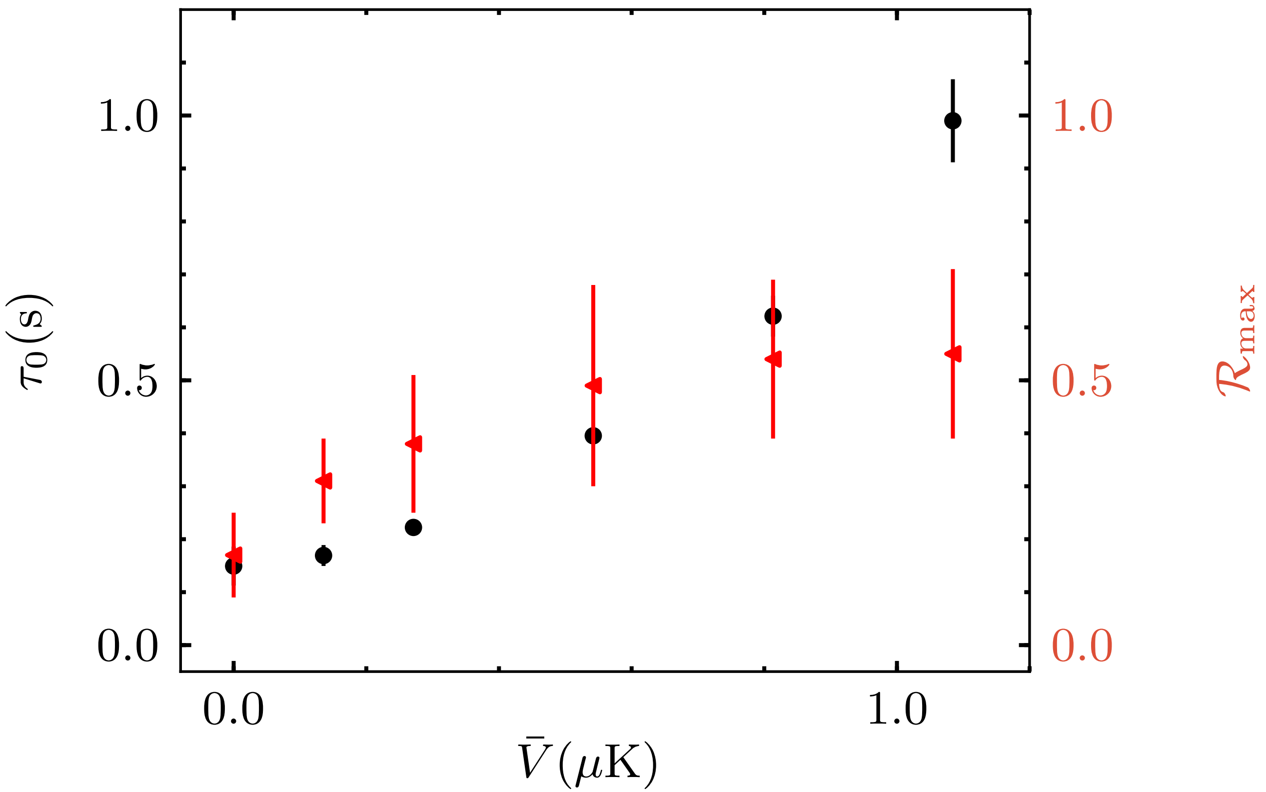


Disorder strength = 1.08 μK

Ballistic to diffusive crossover

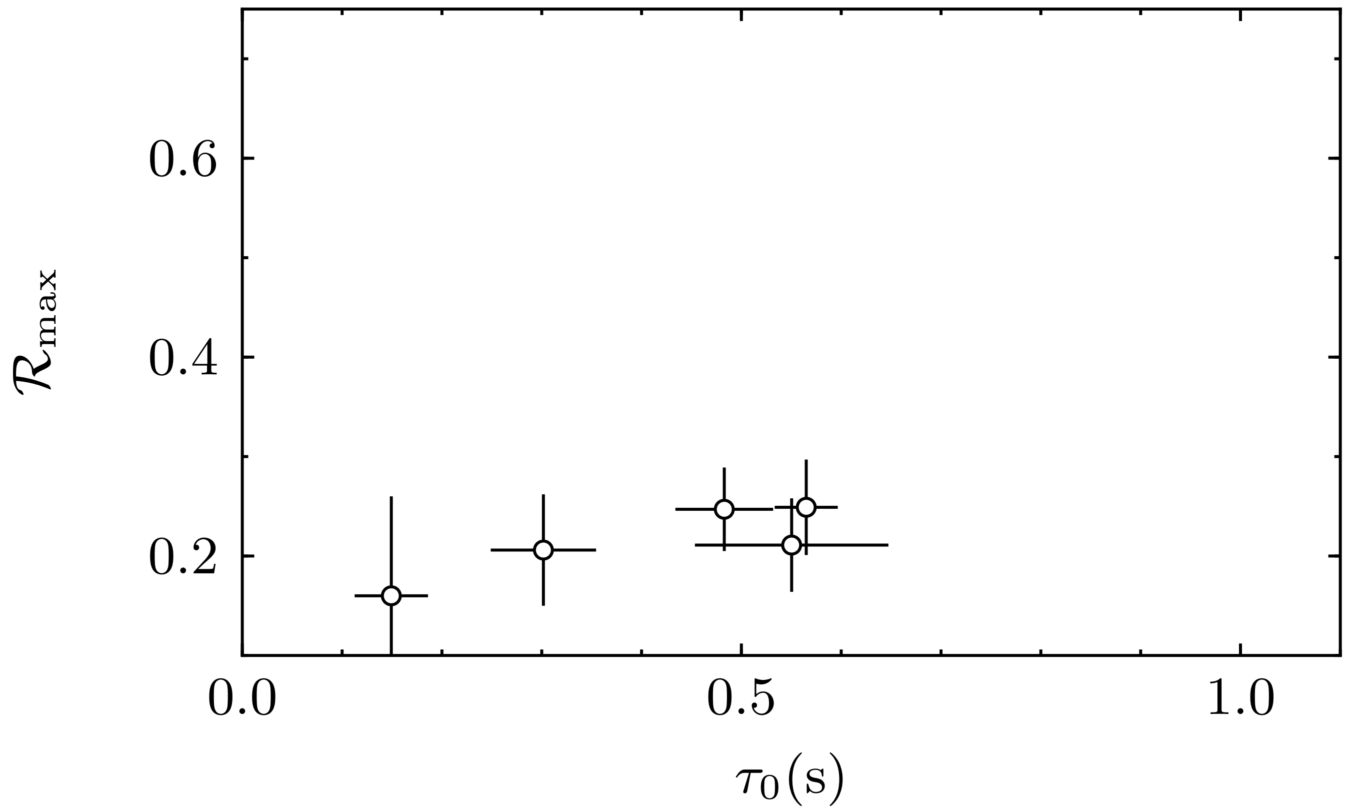


Ballistic to diffusive crossover

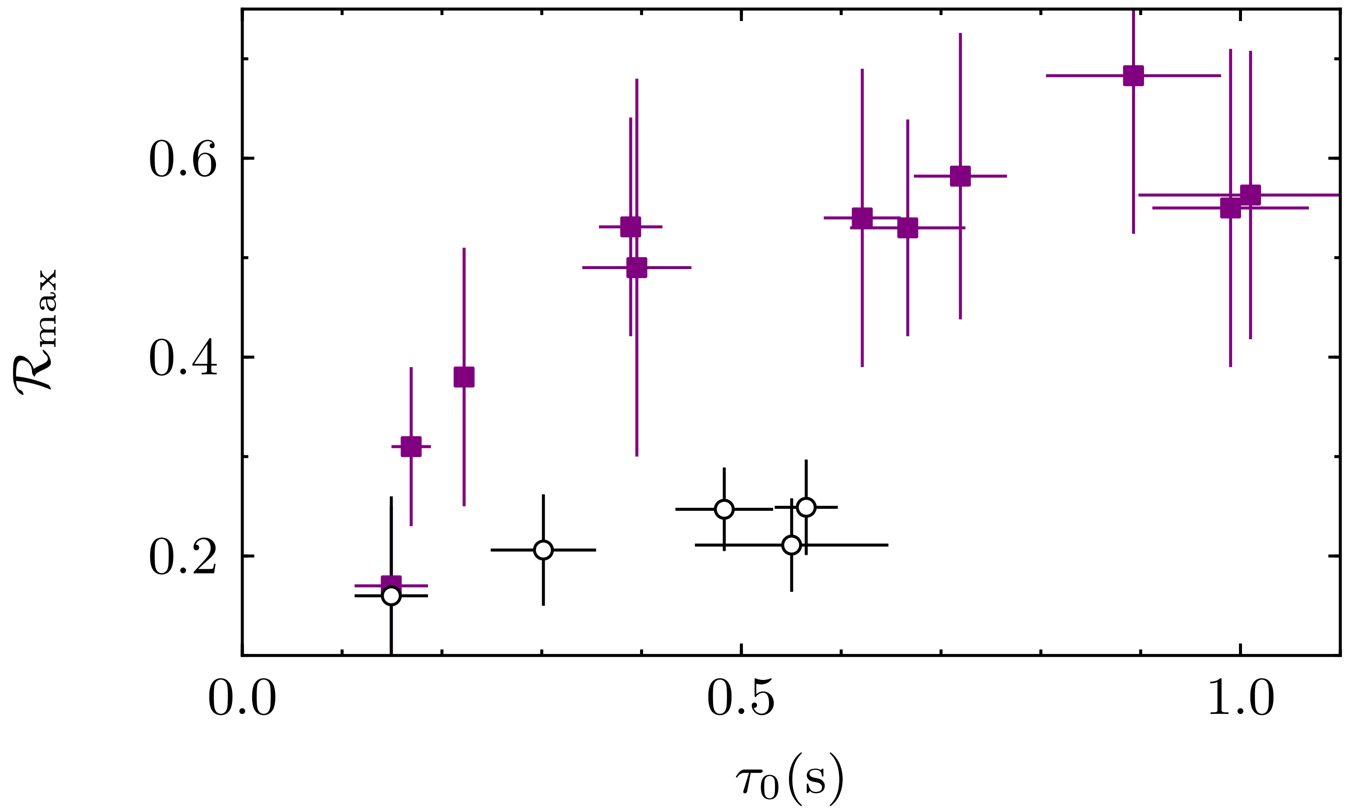


Increase thermoelectric response at the expense of a decrease of conductance

Thermopower / Resistance tradeoff



Thermopower / Resistance tradeoff



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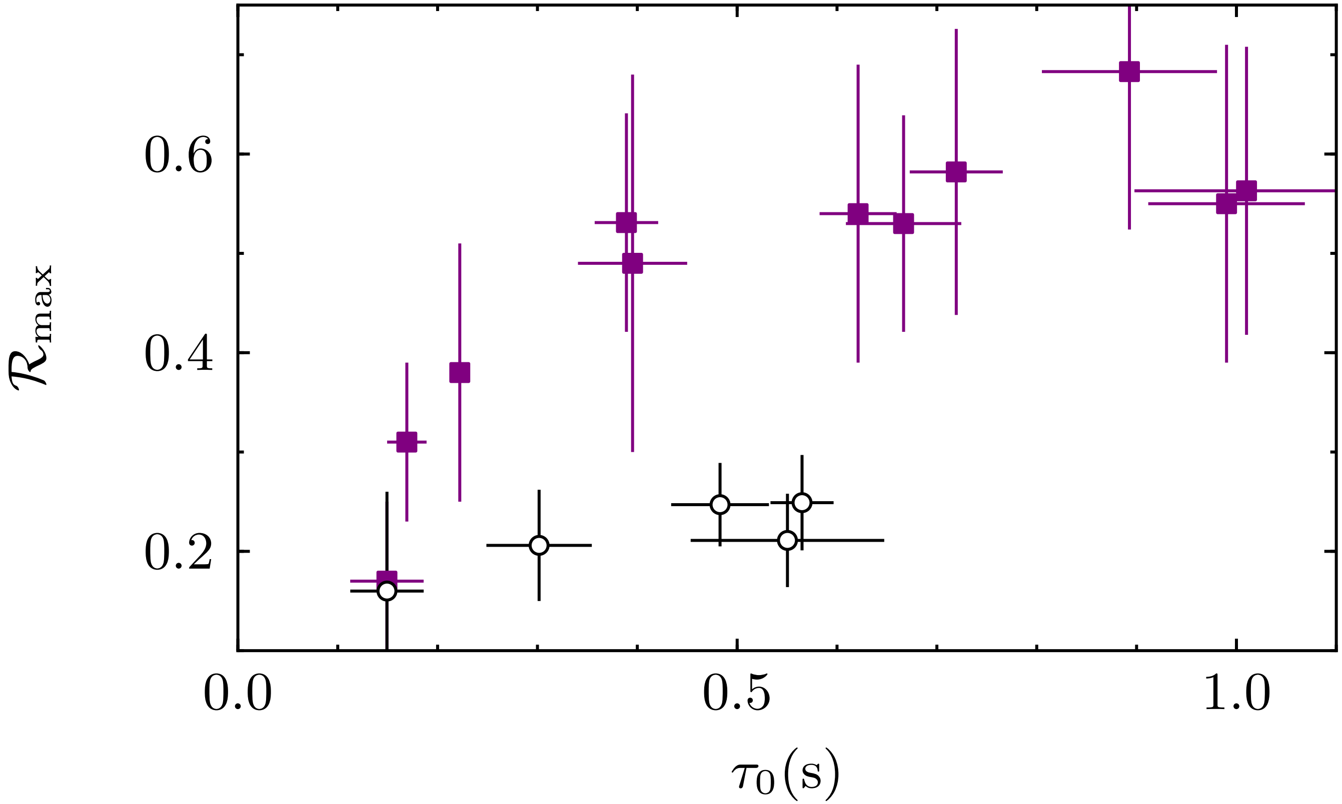
Thermopower / Resistance tradeoff



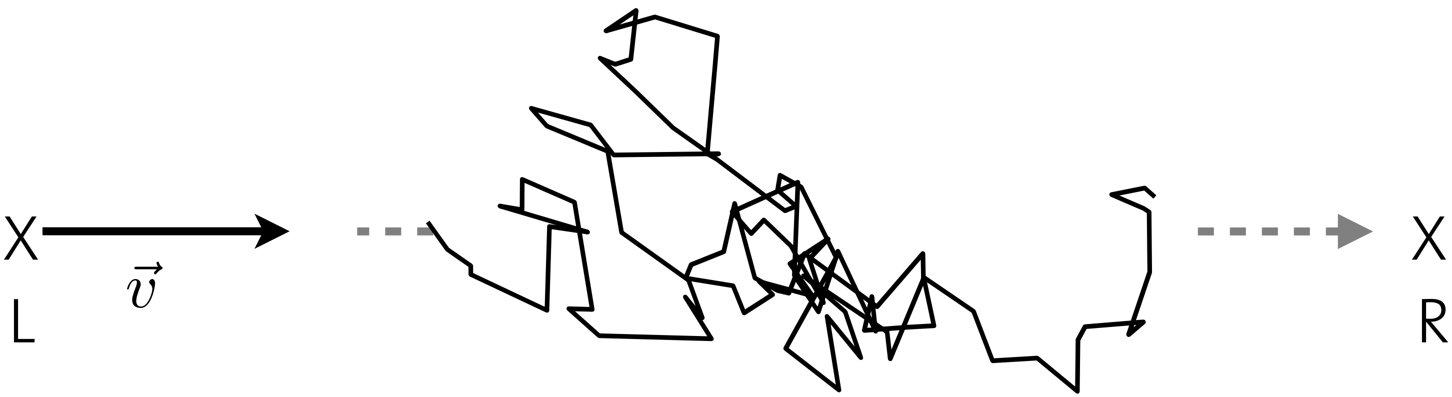
Transmission has a larger dependence on energy in the diffusive case

Energy dependance of transmission

Ballistic : $\Gamma = \dfrac{v}{d}$

Energy dependance of transmission

Ballistic : $\Gamma = \frac{v}{d}$

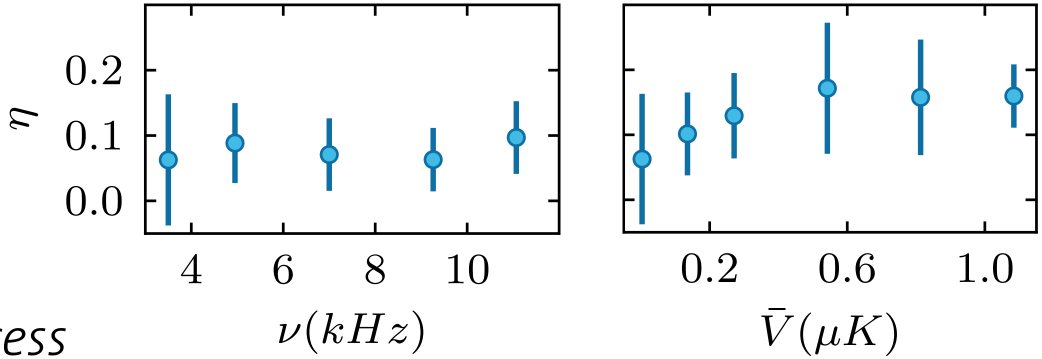


Diffusive : $\Gamma = \frac{v^2}{d^2}\tau_s$

Efficiency and Power

Thermoelectricity drives current against the potential difference

$$\eta = \frac{W}{Q_{\mathrm{irr}}} = \frac{\int I_{\mathrm{N}} \Delta\mu dt}{\int I_{\mathrm{S}} \Delta T dt}$$



efficiency relative to a reversible process

Efficiency and Power

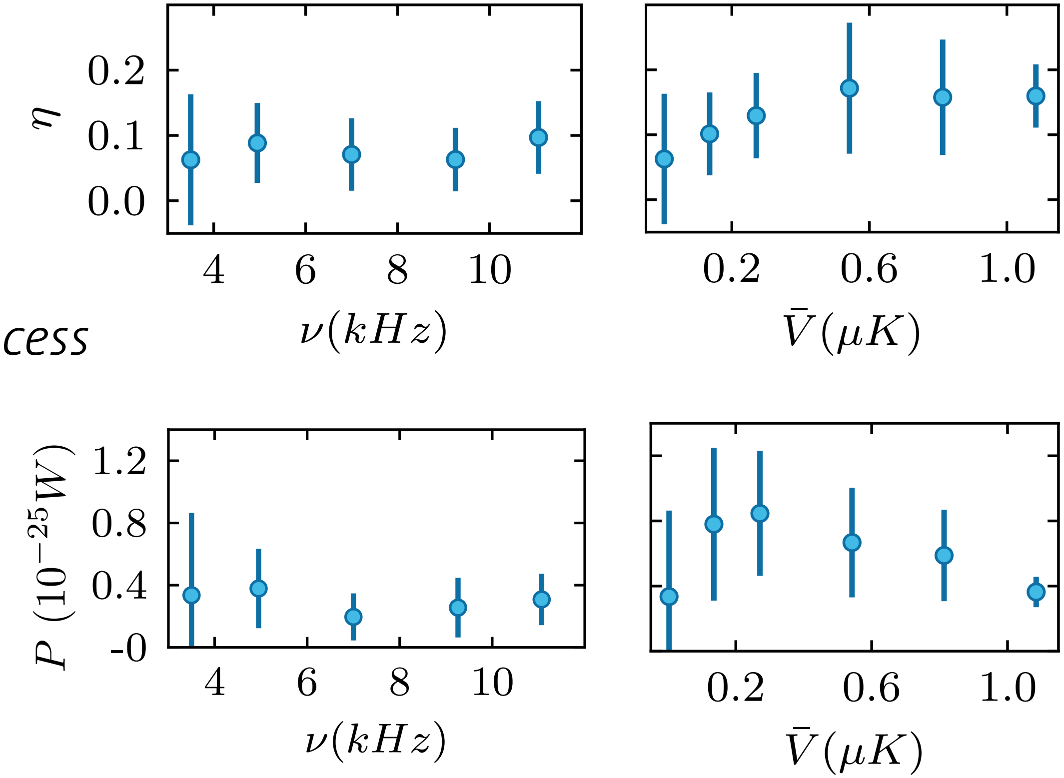
Thermoelectricity drives current against the potential difference

$$\eta = \frac{W}{Q_{\text{irr}}} = \frac{\int I_{\text{N}} \Delta\mu dt}{\int I_{\text{S}} \Delta T dt}$$

efficiency relative to a reversible process

$$P = \frac{W}{\tau_0}$$

average power for the "cycle"



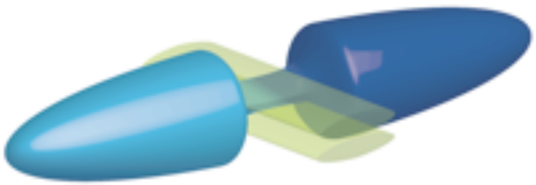
see also E.L.Hazlett *et al*, arXiv 1306.4018

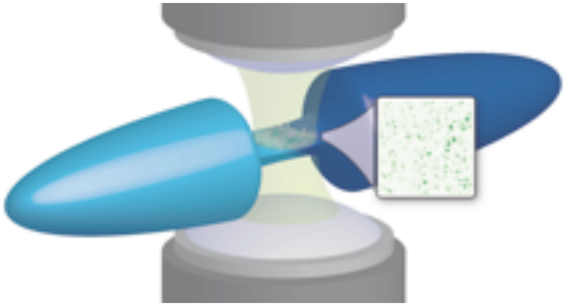
- Experimental setup
  - Two terminals Landauer configuration
  - Strongly attractive interactions: superfluids
  - Disordered superfluids

- Thermoelectric transport
  - Ballistic channel
  - Disordered channel : ballistic to diffusive crossover
  - Efficiency of heat to work conversion

- Outlook
  - Lithography for cold atoms

Conclusion





Transport properties of cold Fermions with tunable interactions / disorder / dimensionality

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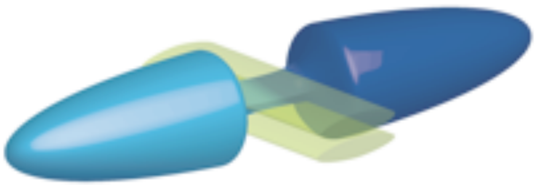
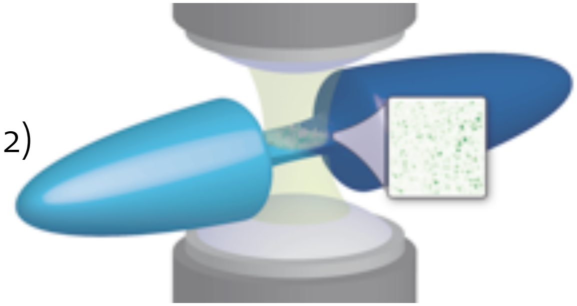
Conclusion



J.P. Brantut *et al*, Science **337**, 1069 (2012)
D. Stadler *et al*, Nature **491**, 736 (2012)

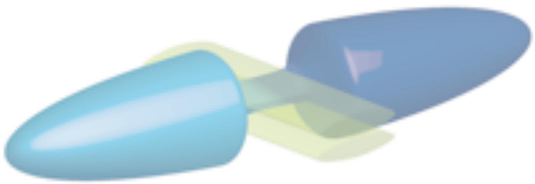


S. Krinner *et al*, PRL. **110**, 100601 (2013)
S. Krinner *et al*, arXiv:1311:5174 (2013)

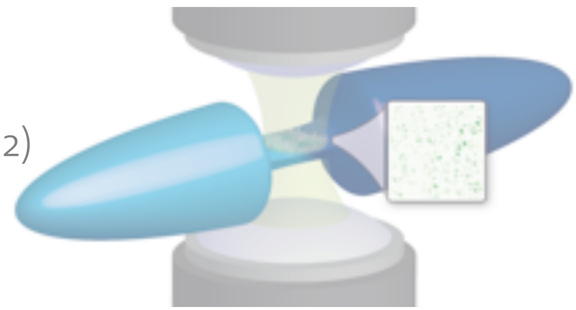
J.P. Brantut *et al*, Science **342**, 713 (2013)

Transport properties of cold Fermions with tunable interactions / disorder / dimensionality

Conclusion



J.P. Brantut *et al*, Science **337**, 1069 (2012)
D. Stadler *et al*, Nature **491**, 736 (2012)



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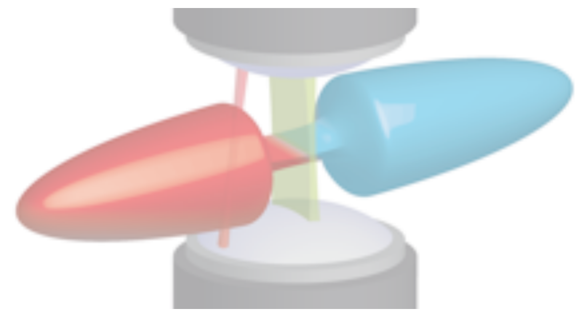
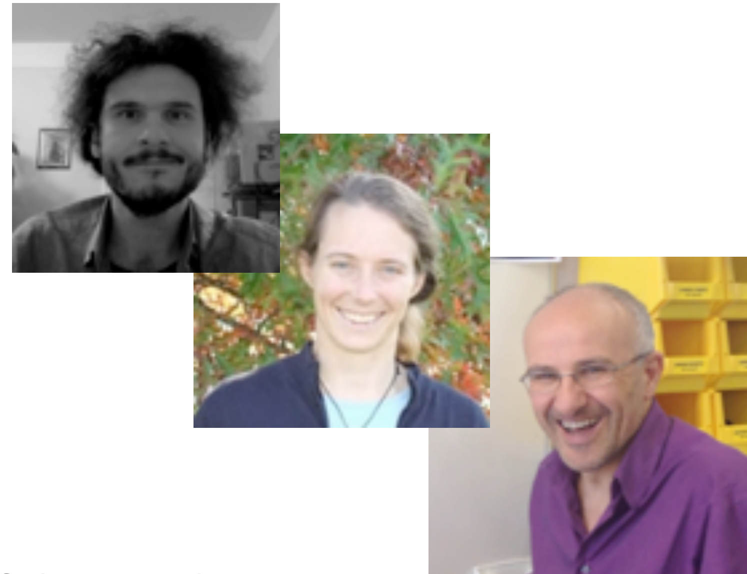
S. Krinner *et al*, arXiv:1311:5174 (2013)



J.P. Brantut *et al*, Science **342**, 713 (2013)

Transport properties of cold Fermions with tunable interactions / disorder / dimensionality

Towards quantum simulation of mesoscopic devices



Experiment: (ETH Zürich)

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D. Stadler
T. Esslinger
D. Husmann
S. Haüsler
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Discussions :

T. Giamarchi, J. Blatter, W. Zwerger, L. Pollet, T. Bourdel, D. Shahar, V. Shenoy, V. Josse, P. Lugan, C. Mueller, S. Pilati, M. Mueller, T. Ihn, Y. Imry, D. Shepelyanski

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FNSNF
Swiss National Science Foundation

QSIT Quantum Science and Technology
National Centre of Competence in Research

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