Quantum Problem Generators

Tilman Esslinger   ETH Zürich

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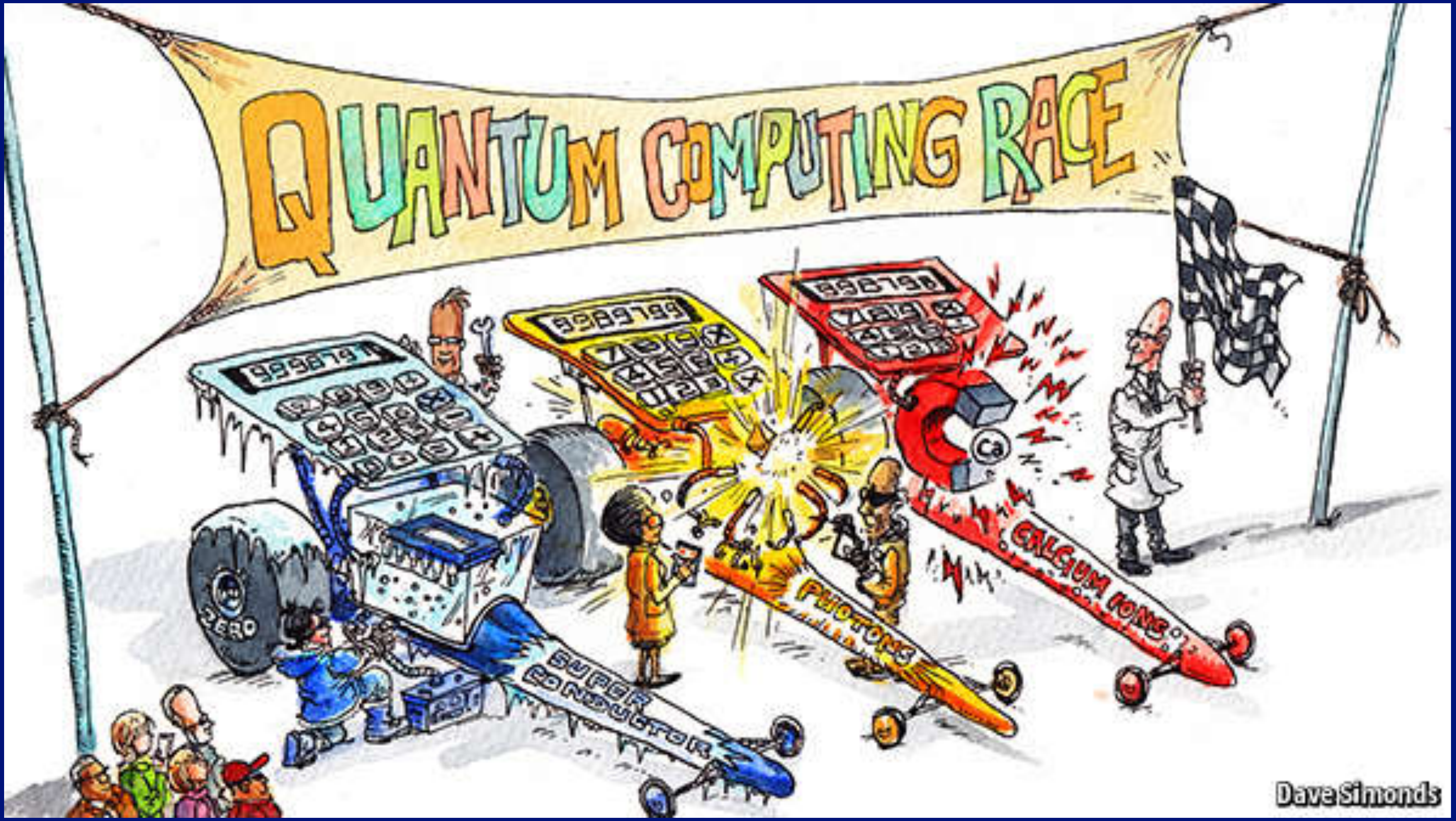
Cold Bosonic Atoms in Optical Lattices

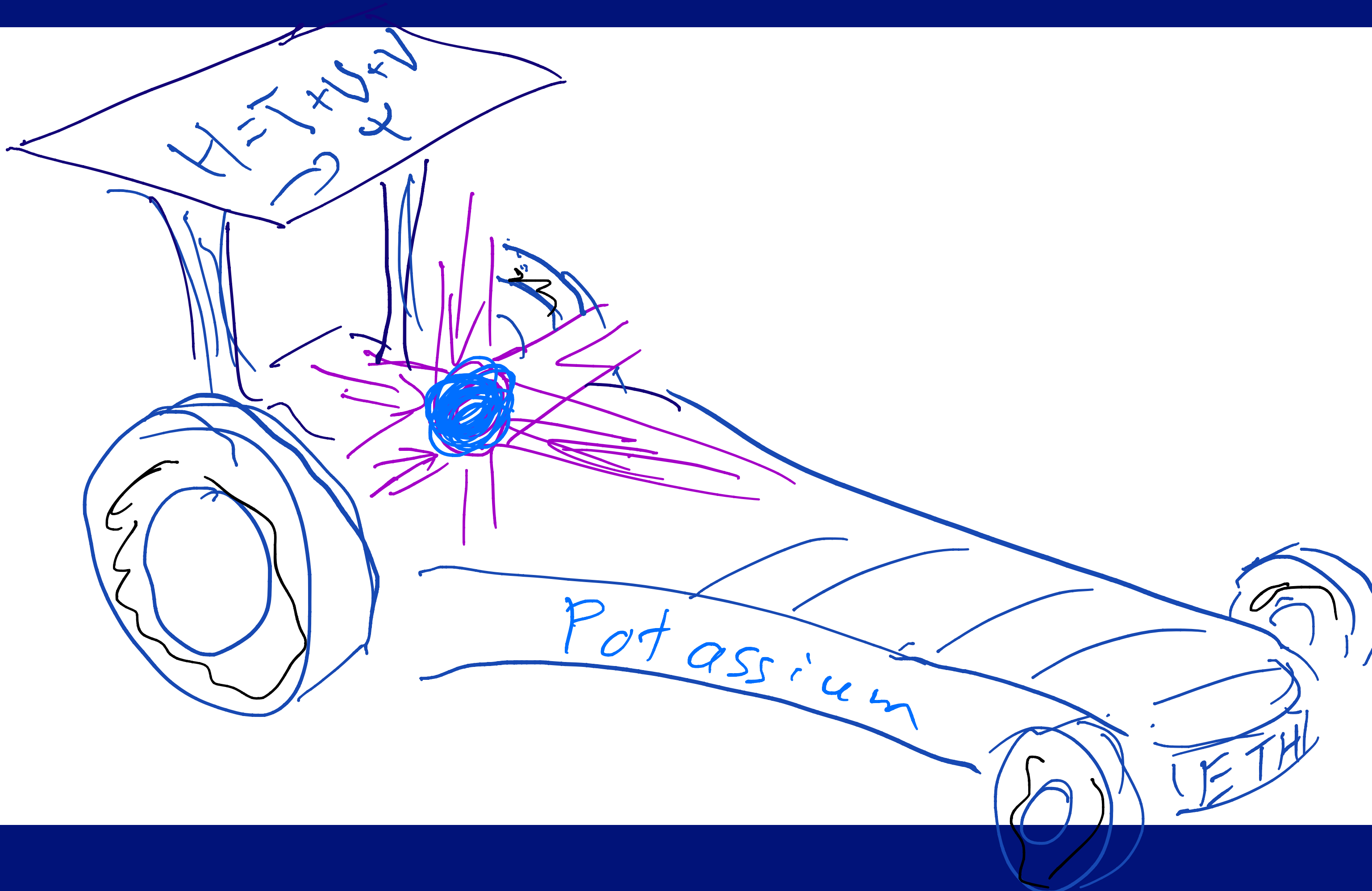
D. Jaksch,[1,2] C. Bruder,[1,3] J. I. Cirac,[1,2] C. W. Gardiner,[1,4] and P. Zoller[1,2]
[1]*Institute for Theoretical Physics, University of Santa Barbara, Santa Barbara, California 93106-4030*
[2]*Institut für Theoretische Physik, Universität Innsbruck, A-6020 Innsbruck, Austria*
[3]*Institut für Theoretische Festkörperphysik, Universität Karlsruhe, D-76128 Karlsruhe, Germany*
[4]*School of Chemical and Physical Sciences, Victoria University, Wellington, New Zealand*
(Received 26 May 1998)

The dynamics of an ultracold dilute gas of bosonic atoms in an optical lattice can be described by a Bose-Hubbard model where the system parameters are controlled by laser light. We study the continuous (zero temperature) quantum phase transition from the superfluid to the Mott insulator phase induced by varying the depth of the optical potential, where the Mott insulator phase corresponds to a commensurate filling of the lattice ("optical crystal"). Examples for formation of Mott structures in optical lattices with a superimposed harmonic trap and in optical superlattices are presented. [S0031-9007(98)07267-6]

PACS numbers: 32.80.Pj, 03.75.Fi, 71.35.Lk



The Economist June 20th 2015


H=T+U+V
Potassium
ETH

Calculations
Communication
Creation of knowledge
…

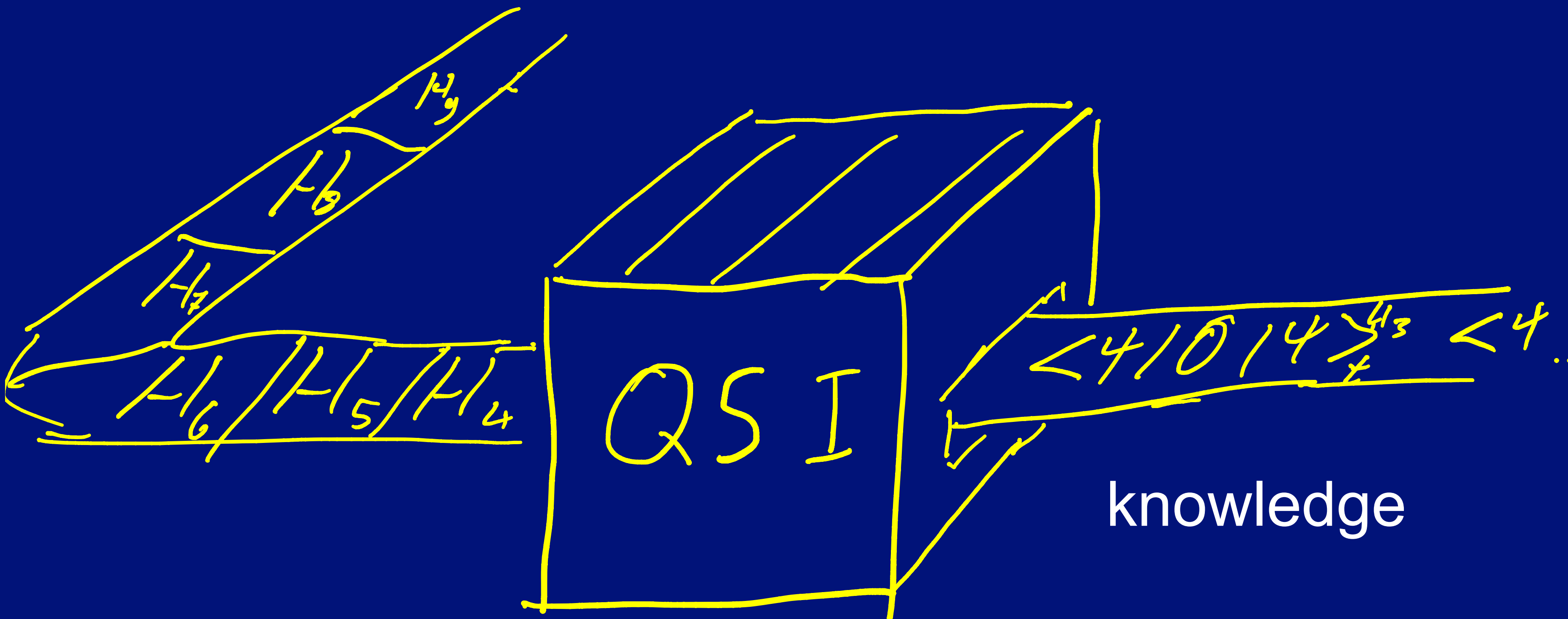
Quantum Simulator

What should it look like?

What should it do?


D:wave

What should a Quantum Simulator do?

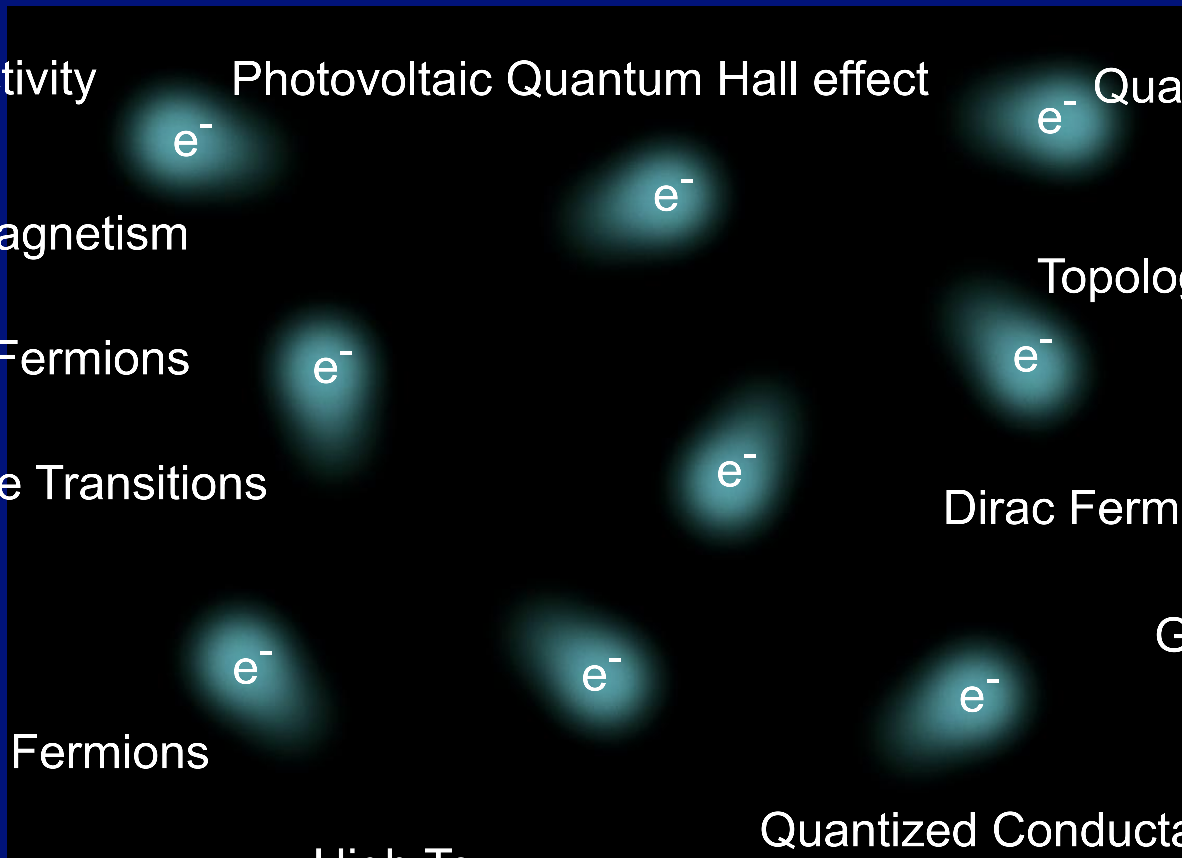


knowledge

Which Hamiltonian?

Metals
Insulators

Superconductivity
Photovoltaic Quantum Hall effect
Quantum Hall Effect



Quantum Magnetism
Topological Insulators
Weyl Fermions
Quantum Phase Transitions
Dirac Fermions
Graphene
Majorana Fermions
Quantized Conductance
High Tc

Why quantum simulation?

Different approach

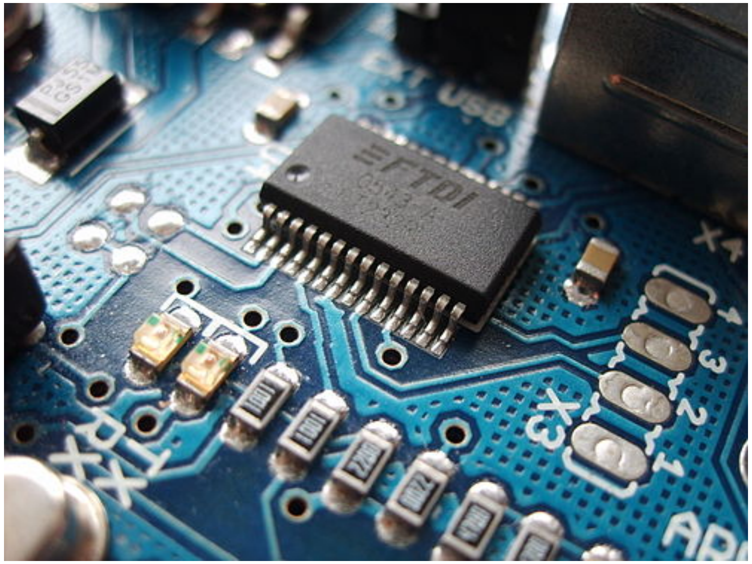
New problems

Surprises

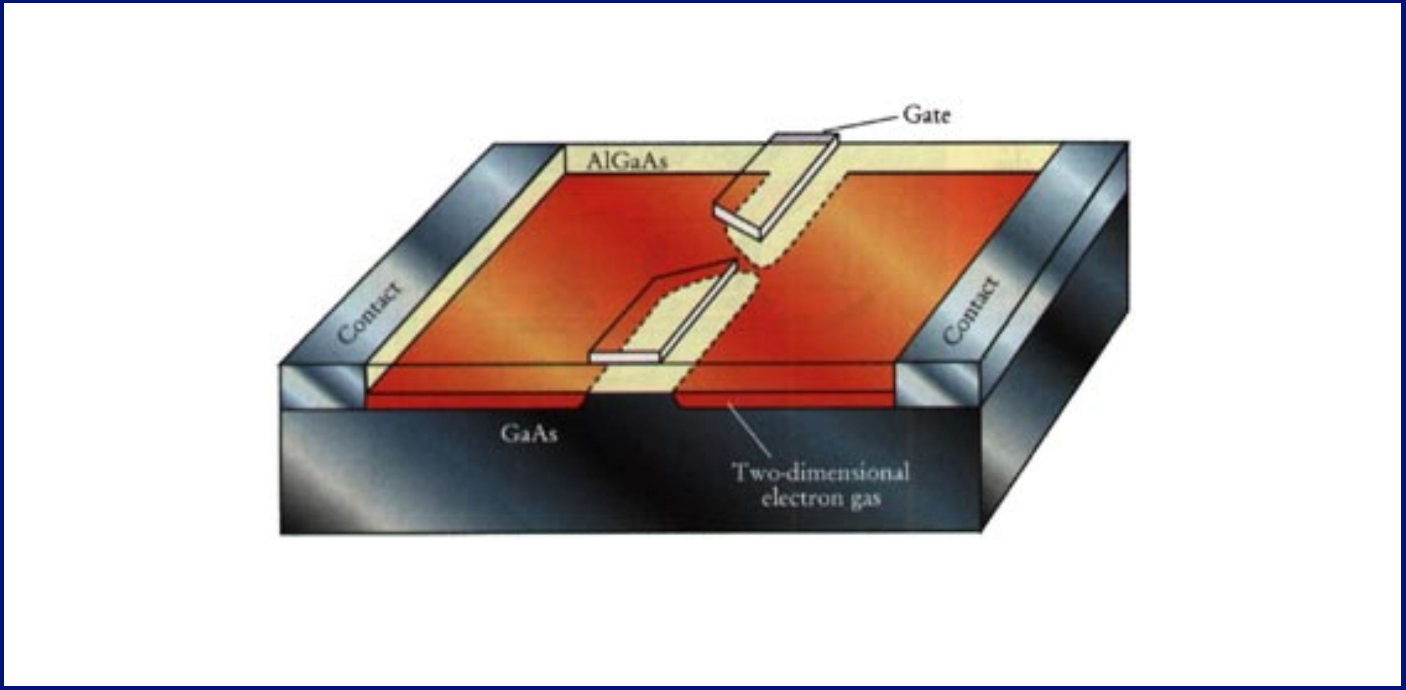
Quantum Simulation of Devices

Short and long-range interactions

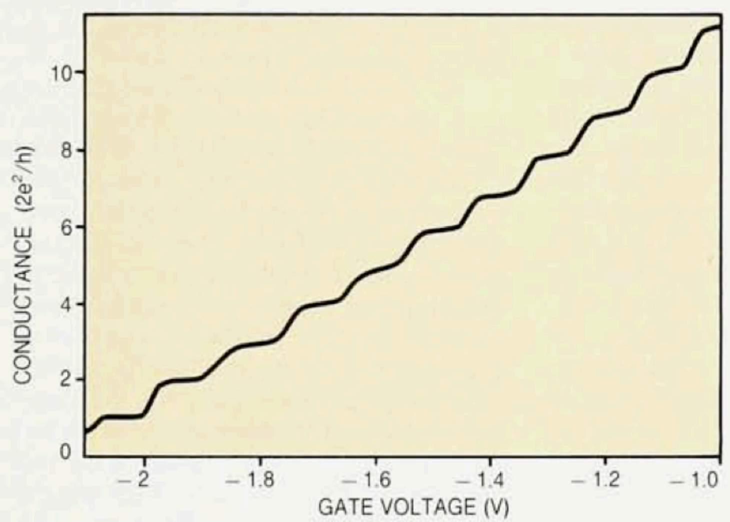
Quantum Simulation of Devices



Simulation of Quantum Devices?



Quantized Conductance



Conductance of a narrow channel connecting two two-dimensional reservoirs of electrons increases in steps of $2e^2/h$ when the width of the channel increases. The more negative the gate voltage is, the narrower the channel is. (Adapted from reference 1.)

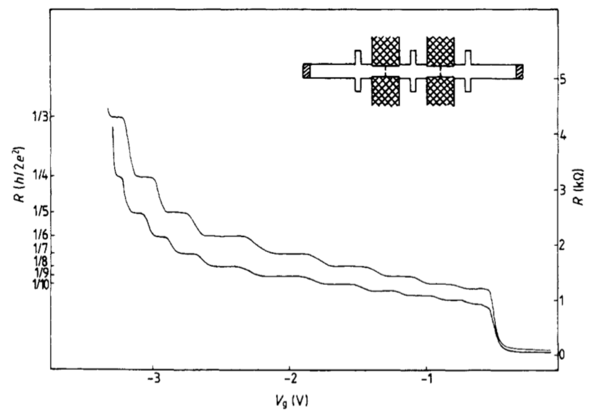
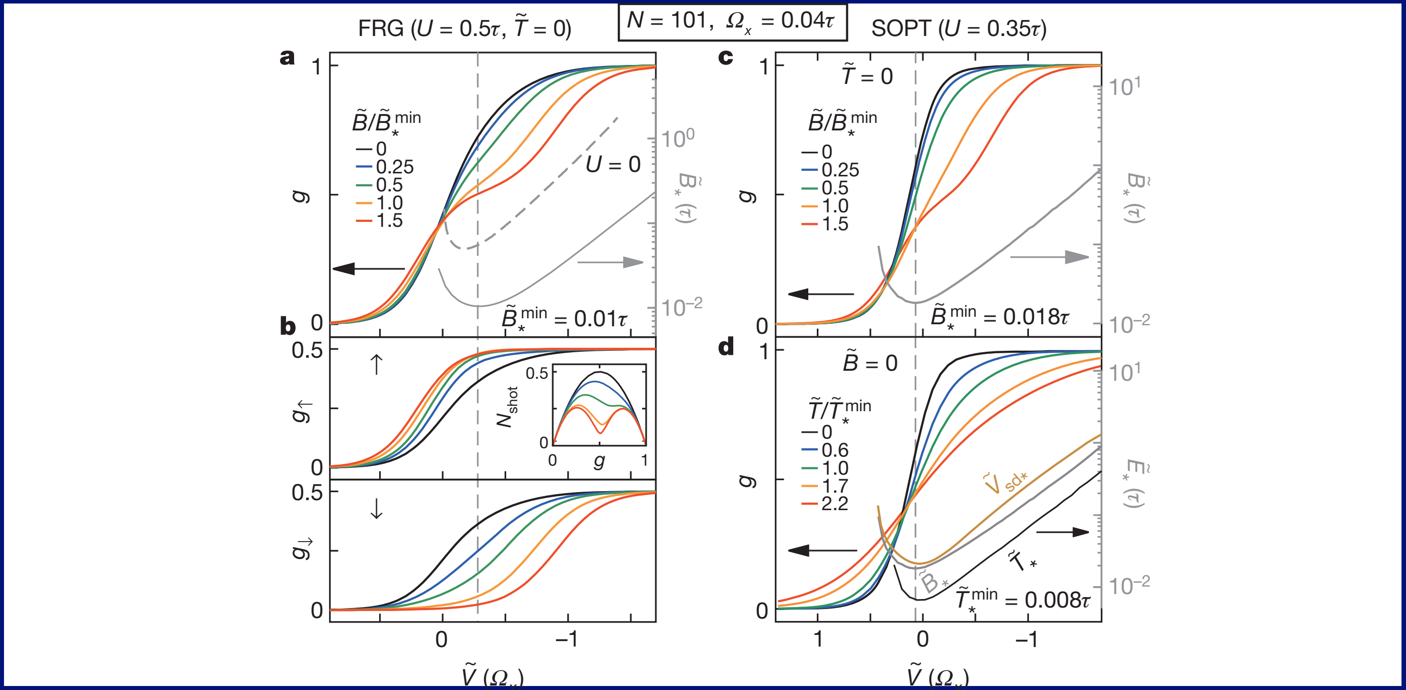


Figure 1. The channel resistance at $T \sim 0.1$ K is plotted as a function of gate voltage for two different carrier concentrations induced by illumination. The existence of a resistance quantised in units of $h/2ie^2$, where i is the number of occupied sub-bands, is illustrated. The inset shows a schematic diagram of the device used in this work. The split gate itself is 0.5 μm wide and 0.4 μm long. Two split gates are illustrated, one of which is selected for the experiment.

B. J. van Wees, H. van Houten, C. W. J. Beenakker, J. G. Williamson, L. P. Kouwenhoven, D. van der Marel, C. T. Foxon, Phys. Rev. Lett. 60, 848 (1988);

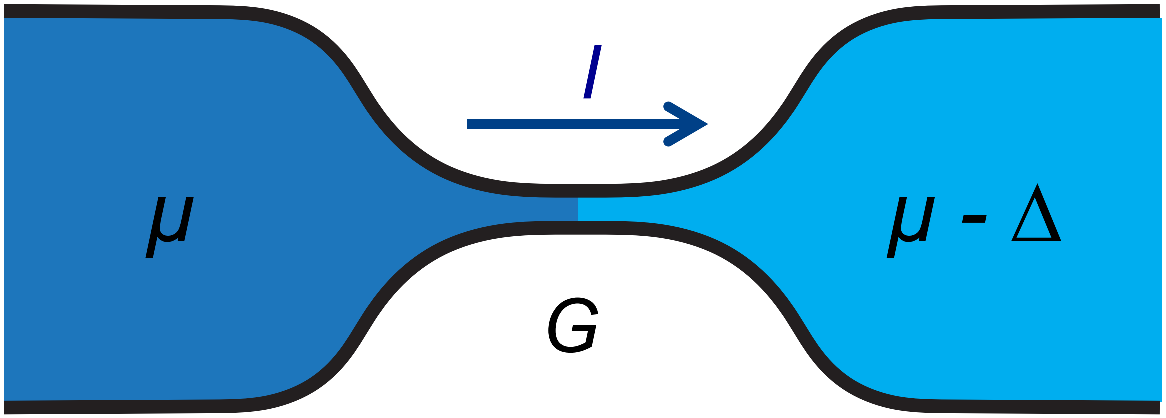
D A Wharam, T J Thornton, R Newbury, M Pepper, H Ahmed, J E F Frost, D G Hasko, D C Peacock, D A Ritchie and G A C Jones, J. Phys. C: Solid State Phys. 21 L209

0.7 Anomaly

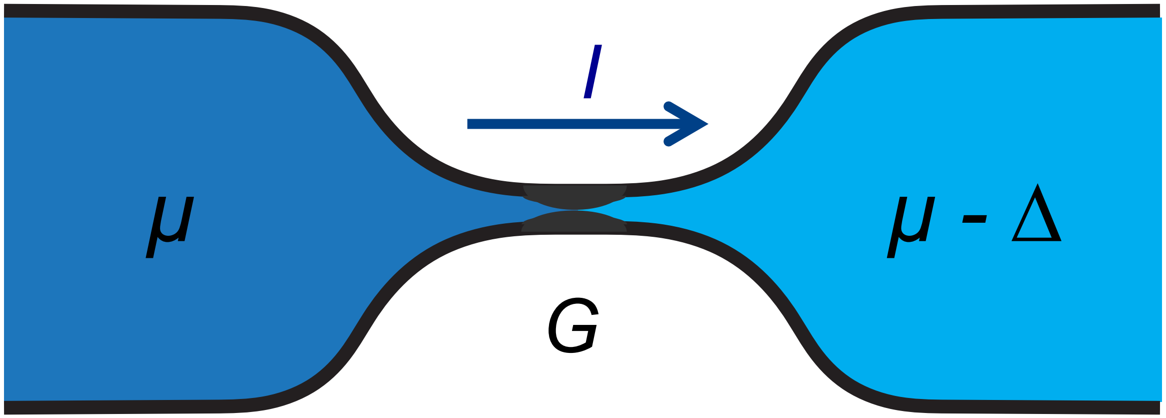


Florian Bauer, Jan Heyder, Enrico Schubert, David Borowsky,
Daniela Taubert, Benedikt Bruognolo, Dieter Schuh, Werner Wegscheider,
Jan von Delft & Stefan Ludwig, Nature 501, 73–78 (05 September 2013)

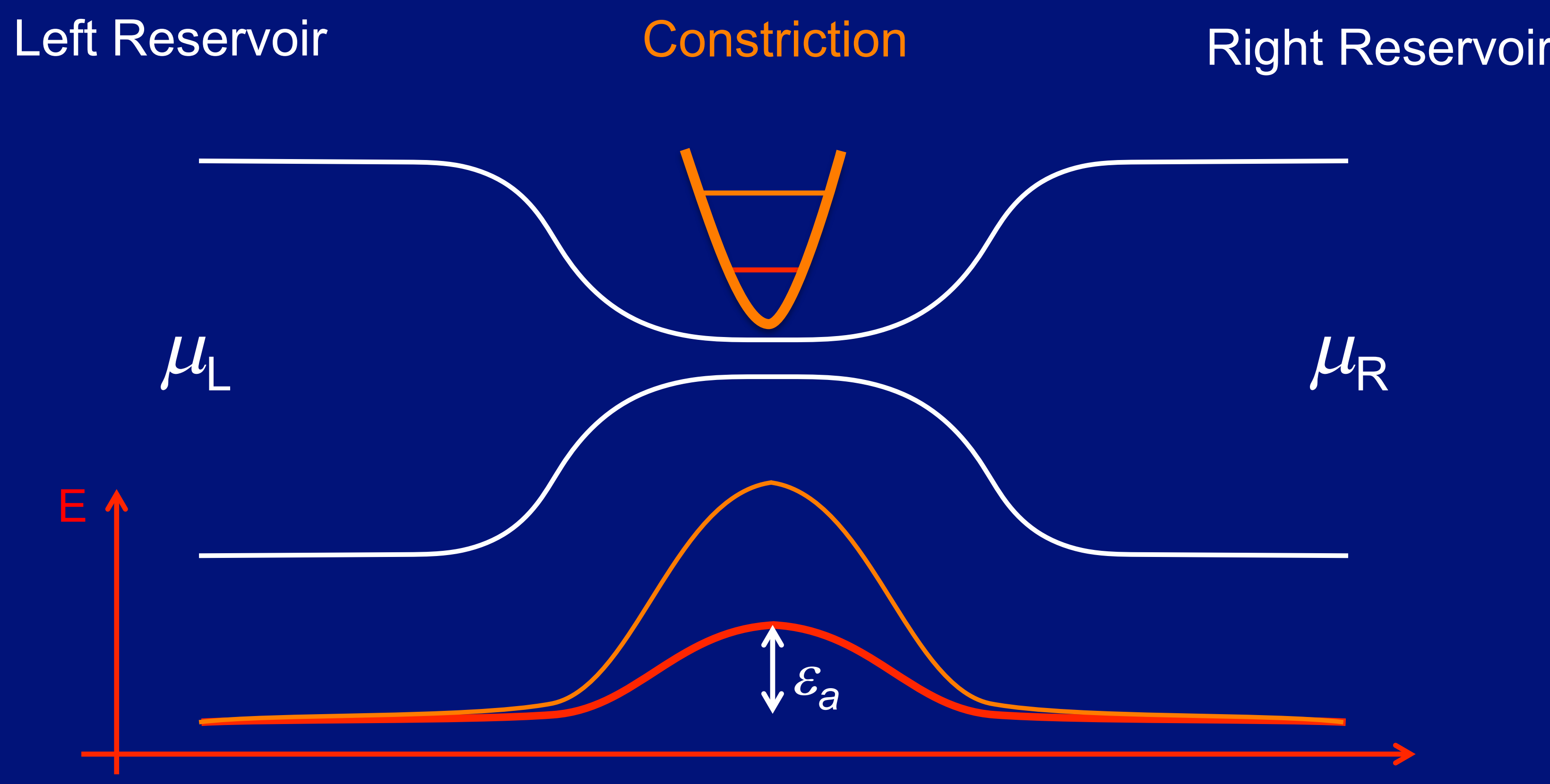
Transport between two Terminals



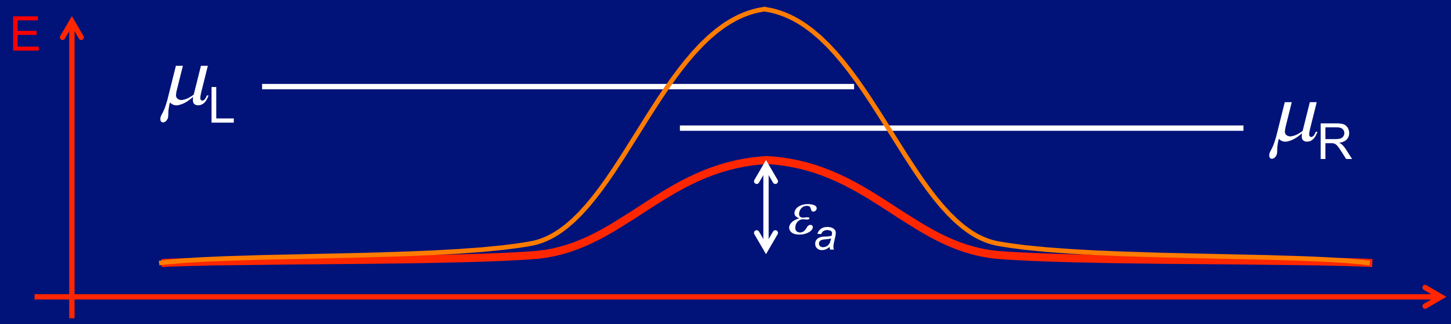
Transport between two Terminals

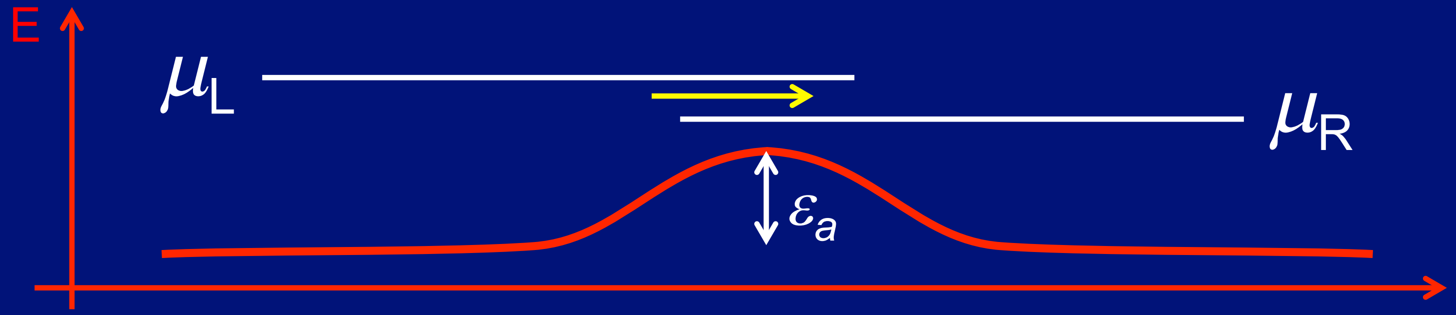


Why?



Left Reservoir
Constriction
Right Reservoir
μ_L
μ_R
E
ε_a

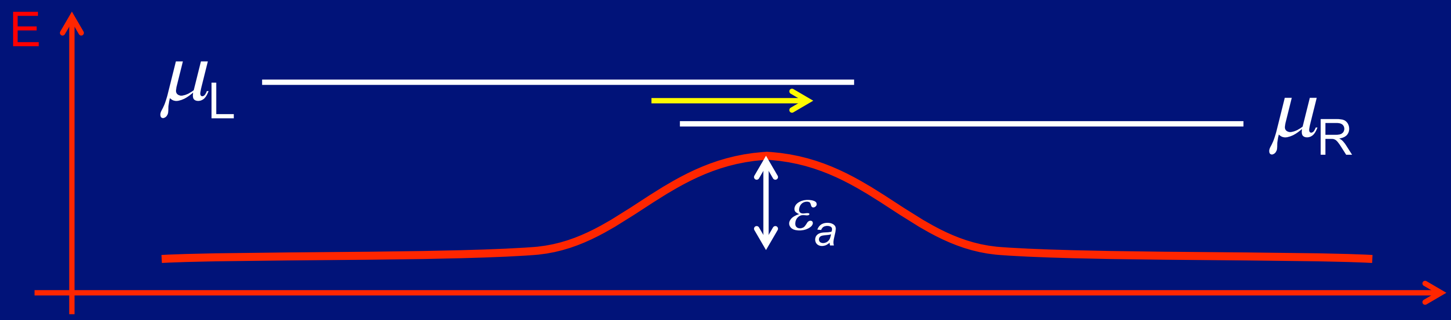

E
μ_L
μ_R
ε_a



E
μ_L
μ_R
ε_a

Current for T=0, T_a=1:

$$I_a = \int_{\varepsilon_F}^{\varepsilon_F+\Delta} d\varepsilon \; g_a(\varepsilon)\; v_a(\varepsilon)\; T_a(\varepsilon)$$



Current for T=0, T_a=1:

$$I_a = \int_{\varepsilon_F}^{\varepsilon_F+\Delta} d\varepsilon \; g_a\left(\varepsilon\right) v_a\left(\varepsilon\right) T_a\left(\varepsilon\right)$$

Current for T=0, T_a=1:

$$I_a = \int_{\varepsilon_F}^{\varepsilon_F+\Delta} d\varepsilon \; g_a(\varepsilon)\, v_a(\varepsilon)\; T_a(\varepsilon) = \frac{\Delta}{h}$$

velocity: $$v_a(\varepsilon) = \frac{\hbar k_a}{m} = \sqrt{2(\varepsilon - \varepsilon_a)/m}$$

density of states:
(right movers) $$g_a(\varepsilon) = \frac{1}{2\pi}\frac{dk_a}{d\varepsilon} = \frac{1}{2\pi\hbar v_a(\varepsilon)}$$

Landauer, Büttiker, Imry

Current for T=0, T_a=1:

$$I_a = \int_{\varepsilon_F}^{\varepsilon_F+\Delta} d\varepsilon \; g_a\left(\varepsilon\right) v_a\left(\varepsilon\right) \; T_a\left(\varepsilon\right) = \frac{\Delta}{h}$$

Conductance $$G = \frac{1}{h}$$

Consequence of Heisenberg + Pauli's principle

Landauer, Büttiker, Imry

Multimode Conductance

$$G = \frac{1}{h}\sum_n \frac{1}{\Delta\mu}\int_{E_n}^{\infty} dE\left[f_L\left(E\right) - f_R\left(E\right)\right]$$

Landauer, Büttiker, Imry

Quantized Conductance in Neutral Matter?

Cold atoms proposal: Thywissen, J. H., Westervelt, R. M. & Prentiss, M. Quantum point contacts for neutral atoms. Phys. Rev. Lett. 83, 3762–3765 (1999).

Quantized Conductance in Neutral Matter?

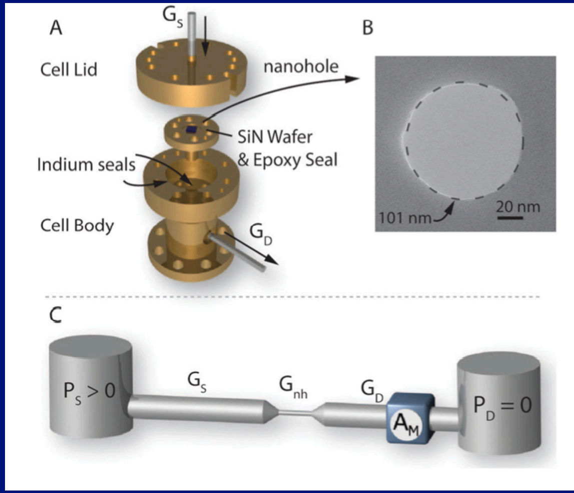
On the Feasibility of Detecting Quantized Conductance in Neutral Matter

Yuki Sato, Byeong-Ho Eom, and Richard Packard

Department of Physics, University of California, Berkeley, CA 94720-7300, USA
E-mail: ysato@socrates.berkeley.edu

(Received May 18, 2005; revised July 18, 2005)

When an electrochemical potential difference (i.e., a voltage) is applied across a metal wire whose transverse dimensions are on the order of the electron's Fermi wavelength, the conductance $G \equiv I/\Delta V$ becomes quantized in units of $2e^2/h$. We present calculations that show that when a chemical potential difference $\Delta\mu_3$ is applied across an array of small apertures whose sizes are comparable to the Fermi wavelength of ^{3}He in a ^{3}He:^{4}He mixture, the mass conductance $G \equiv \left(\frac{I_3}{\Delta\mu_3/m_3^*}\right)$ will be quantized in units of $2m_3^{*2}/h$ where m_3^* is the ^{3}He effective mass. We show that the mass conductance will be quantized for a 0.1% mixture passing through 10 nm diameter pores at temperatures below 25 mK. The phenomenon should be observable in a filter material made by nuclear track etching.

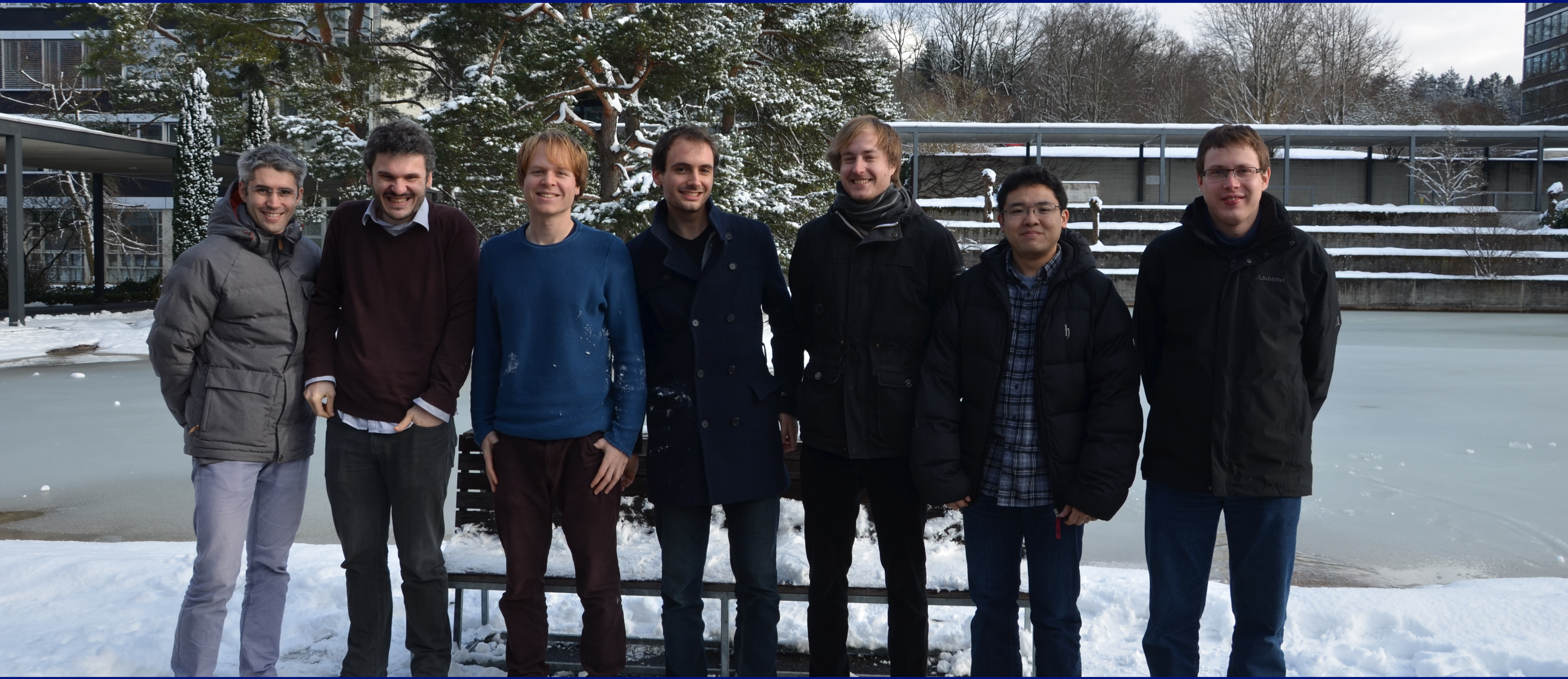


M. Savard, C. Tremblay-Darveau, and G. Gervais, PRL 103, 104502 (2009)

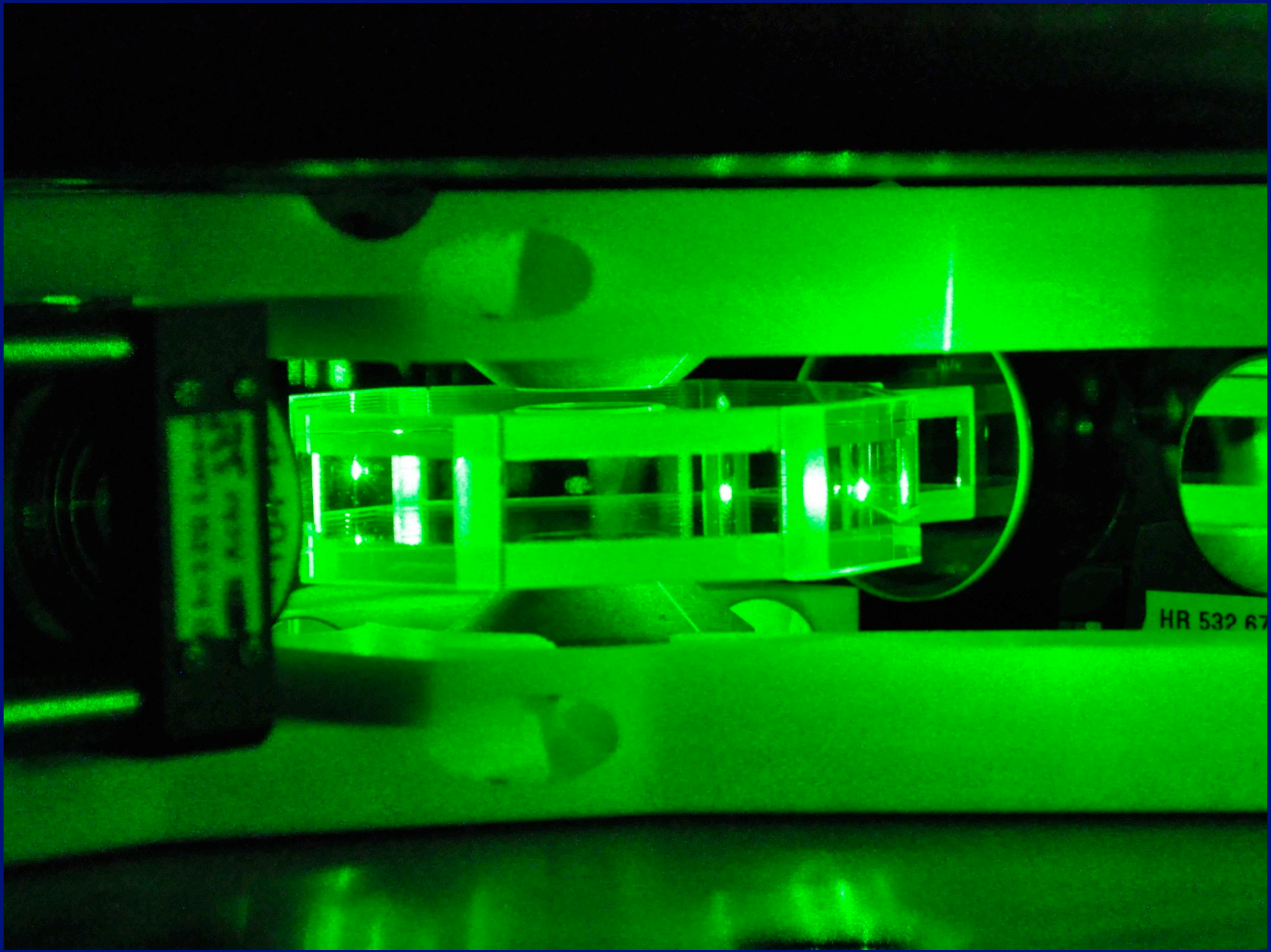
See also: G. Lambert, G. Gervais, and W.J. Mullin, Low Temp. Phys. 34, 249 (2008).

Quantized Conductance in Neutral Matter?

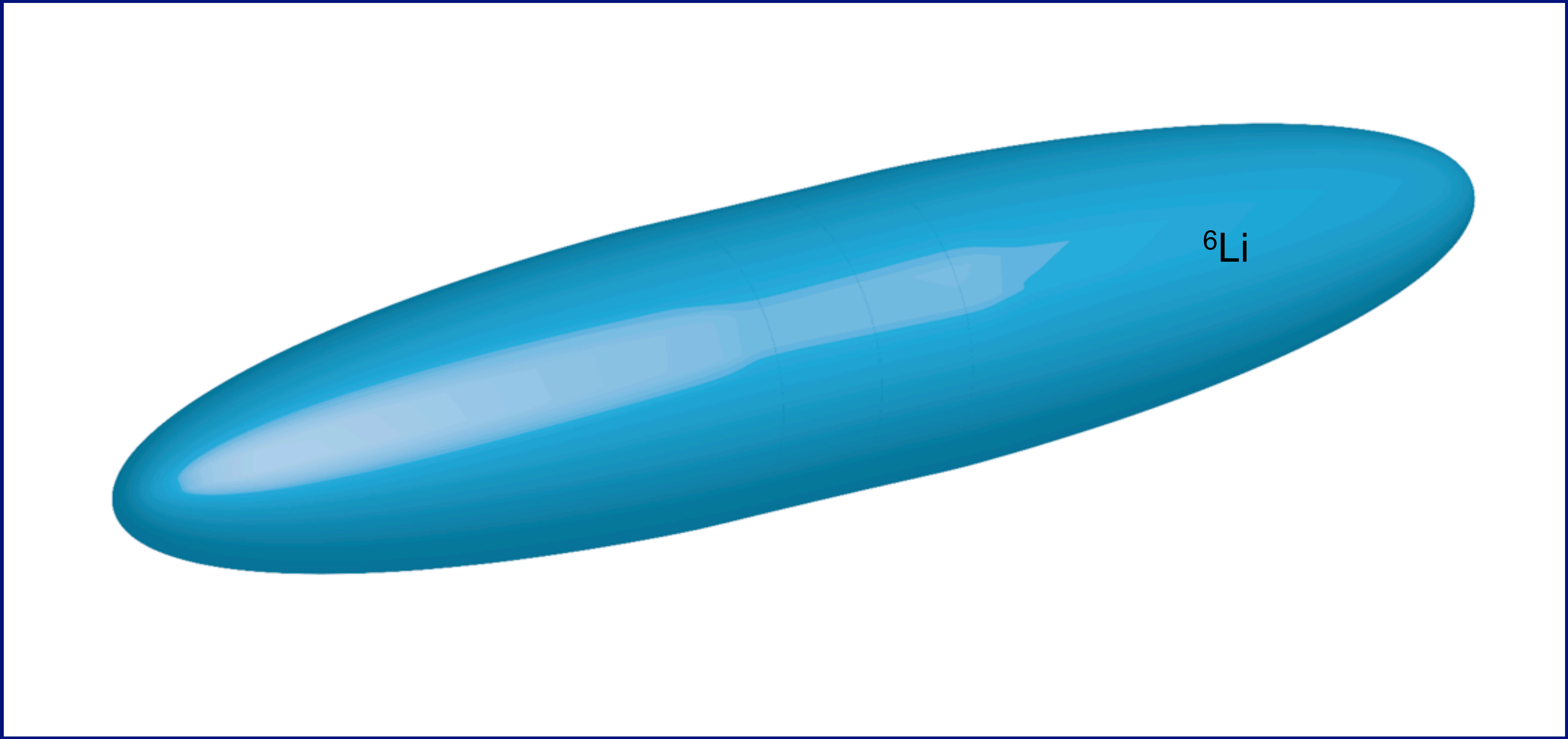
- Method to measure conductance
- Ballistic channel
- Quantum degenerate Fermi gas
- Resolve individual conduction channels
- Adiabatic regime
- Applicability of Landauer theory
  (mean free path > trap)



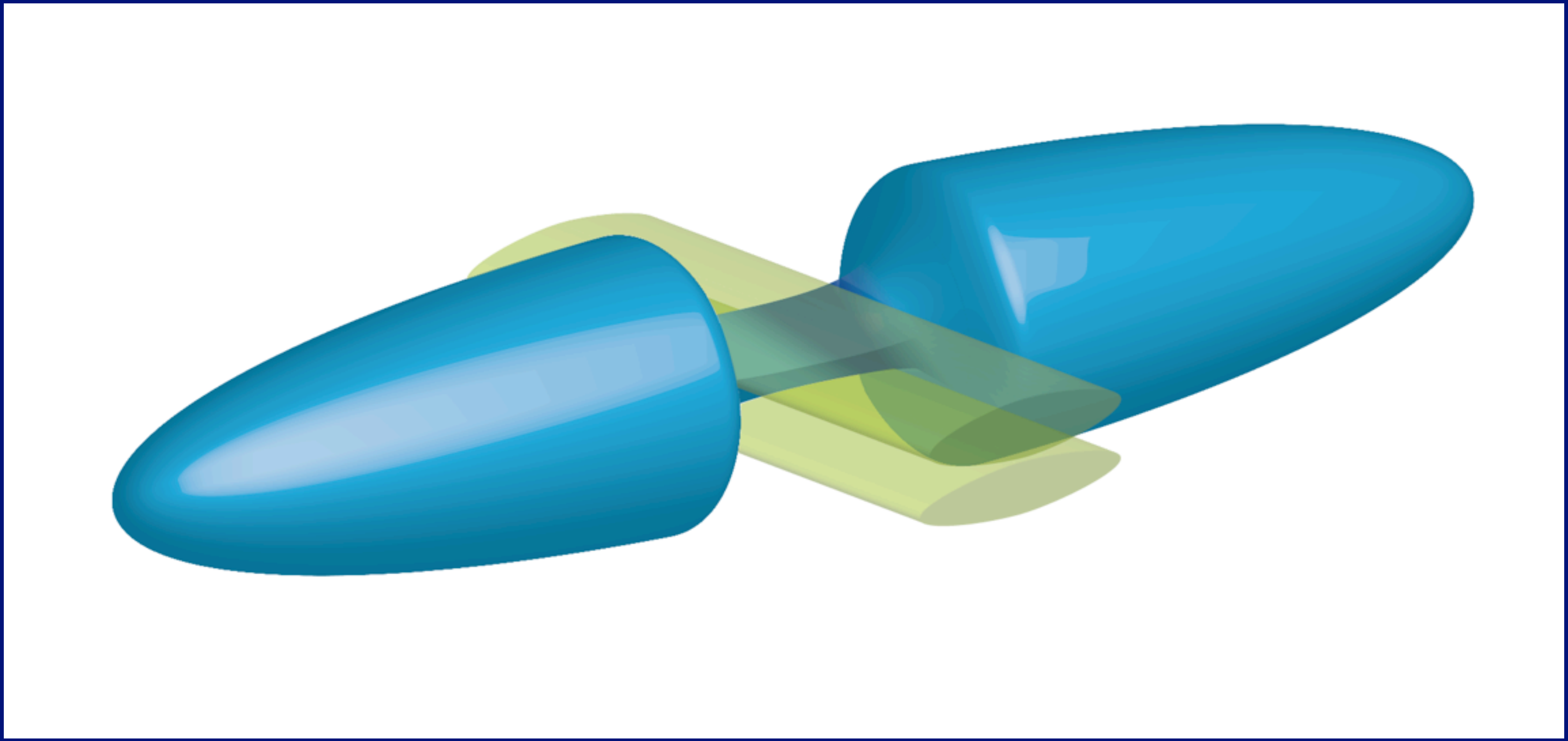
Jean-Philippe Brantut, Charles Grenier, Sebastian Krinner, Martin Lebrat, Dominik Husmann, Shuta Nakajima, Samuel Häusler



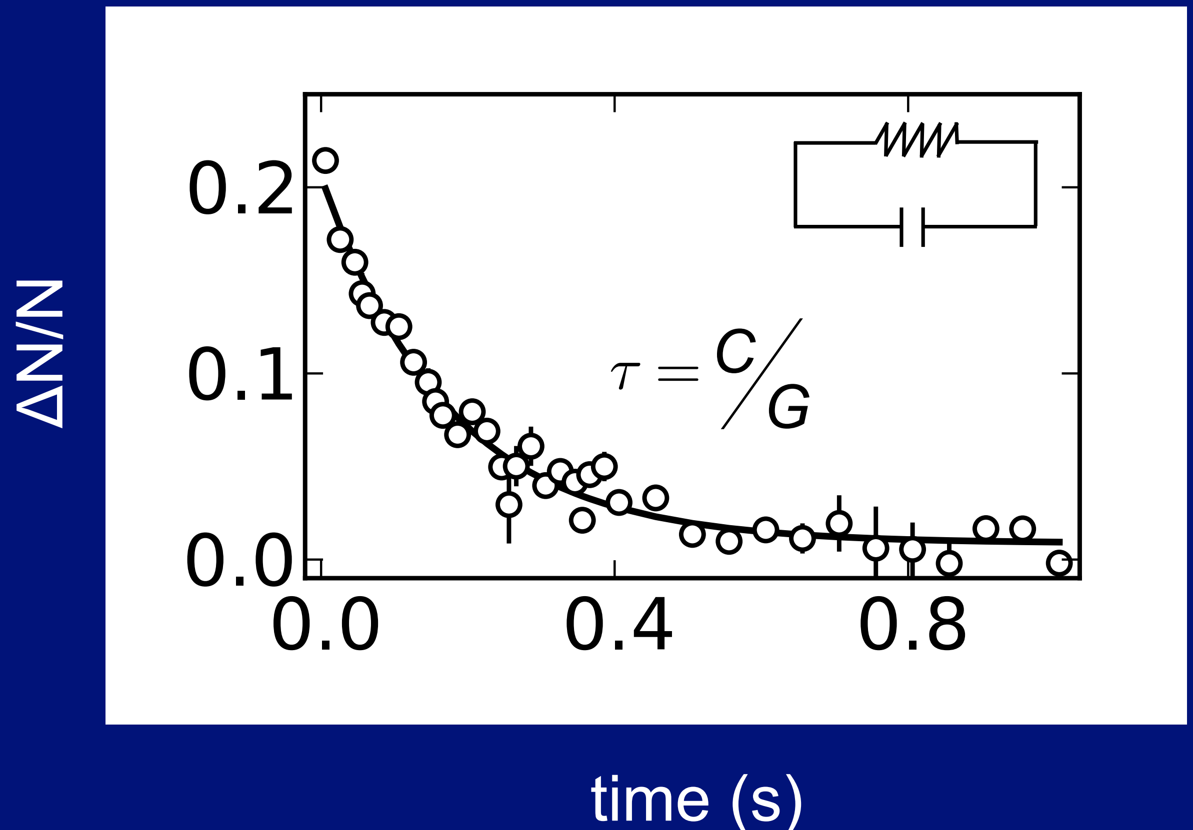
Thanks to Henning Moritz now @ Hamburg



^{6}Li



Battery discharge

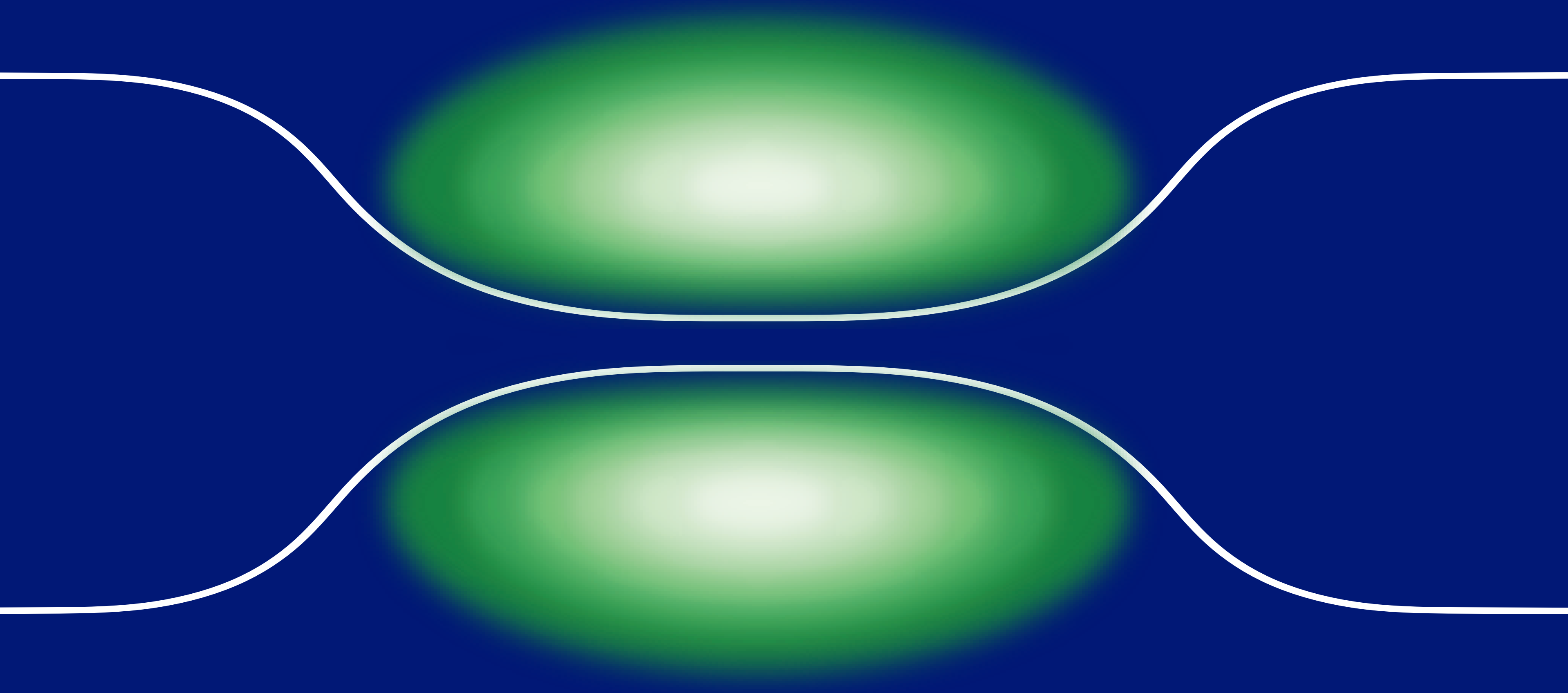


$$\frac{d}{dt}\Delta N = -\frac{G}{C}\Delta N$$

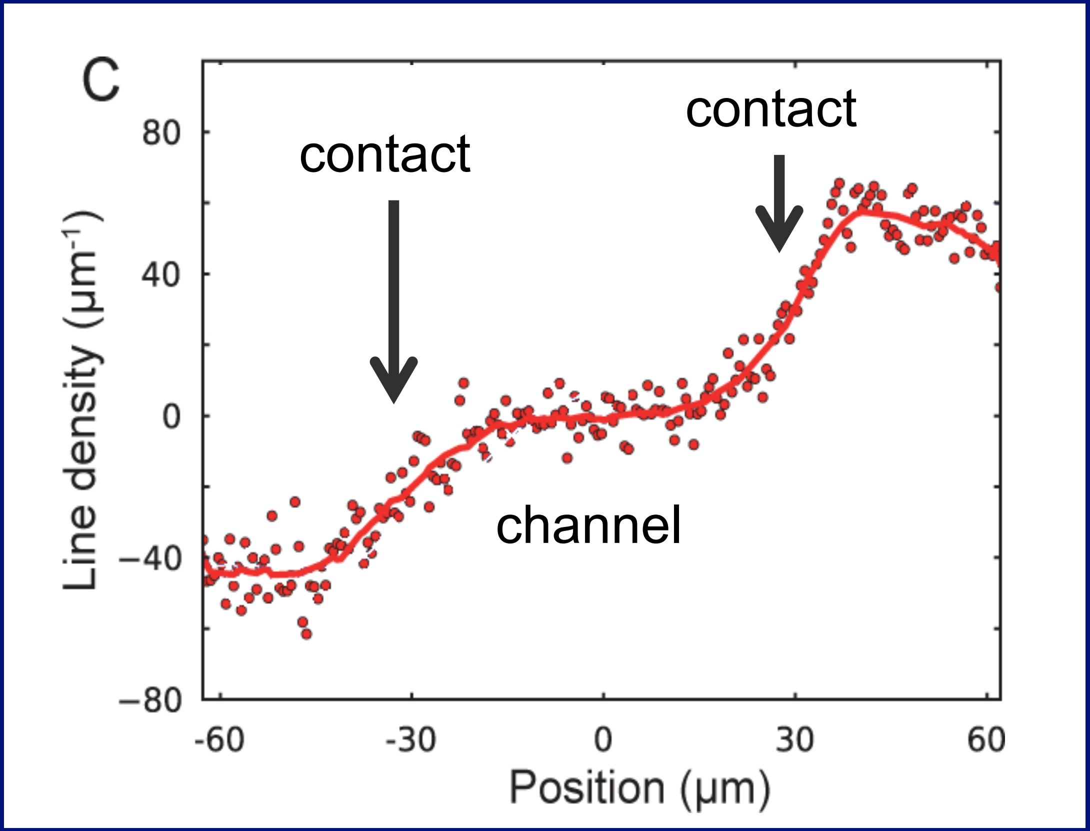
G: conductance

C: compressibility $\partial N/\partial \mu$

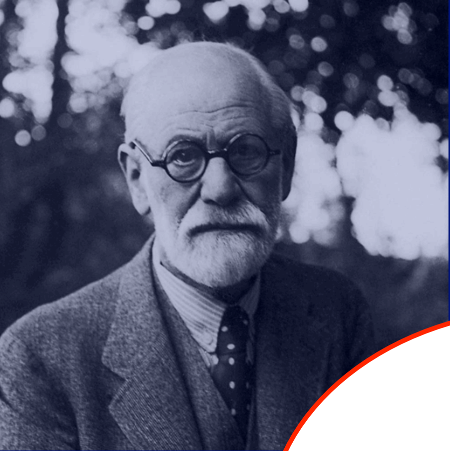
Resistance?



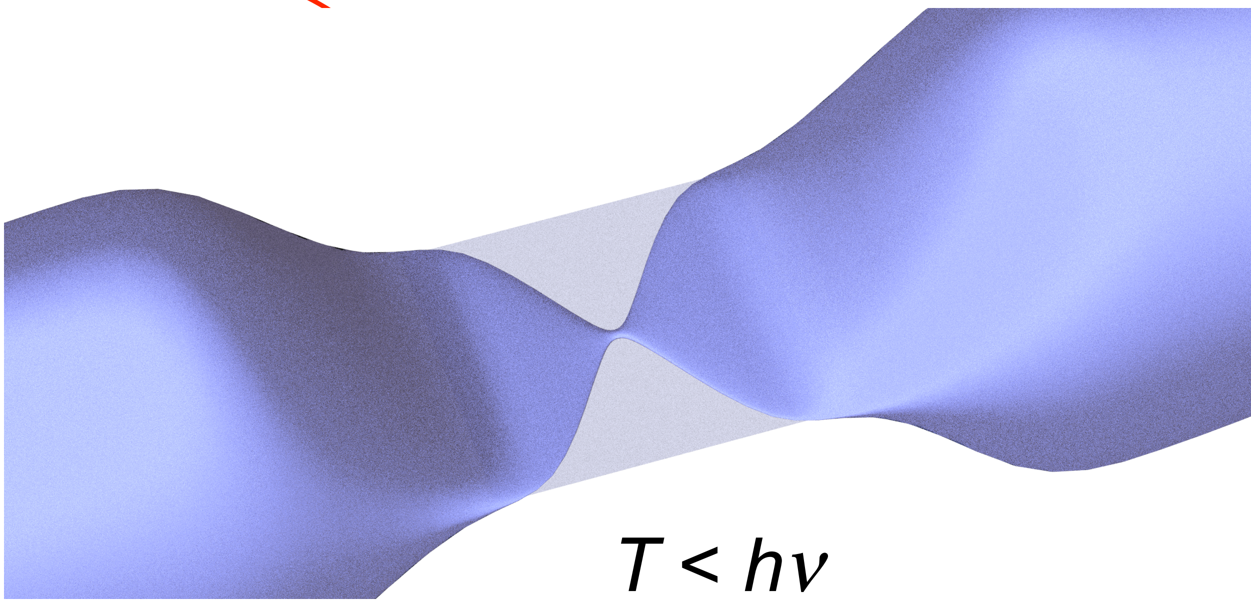
Ballistic Multimode Channel



J.-P. Brantut, J. Meineke, D. Stadler, S. Krinner, T. Esslinger, Science 337, 1069 (2012)



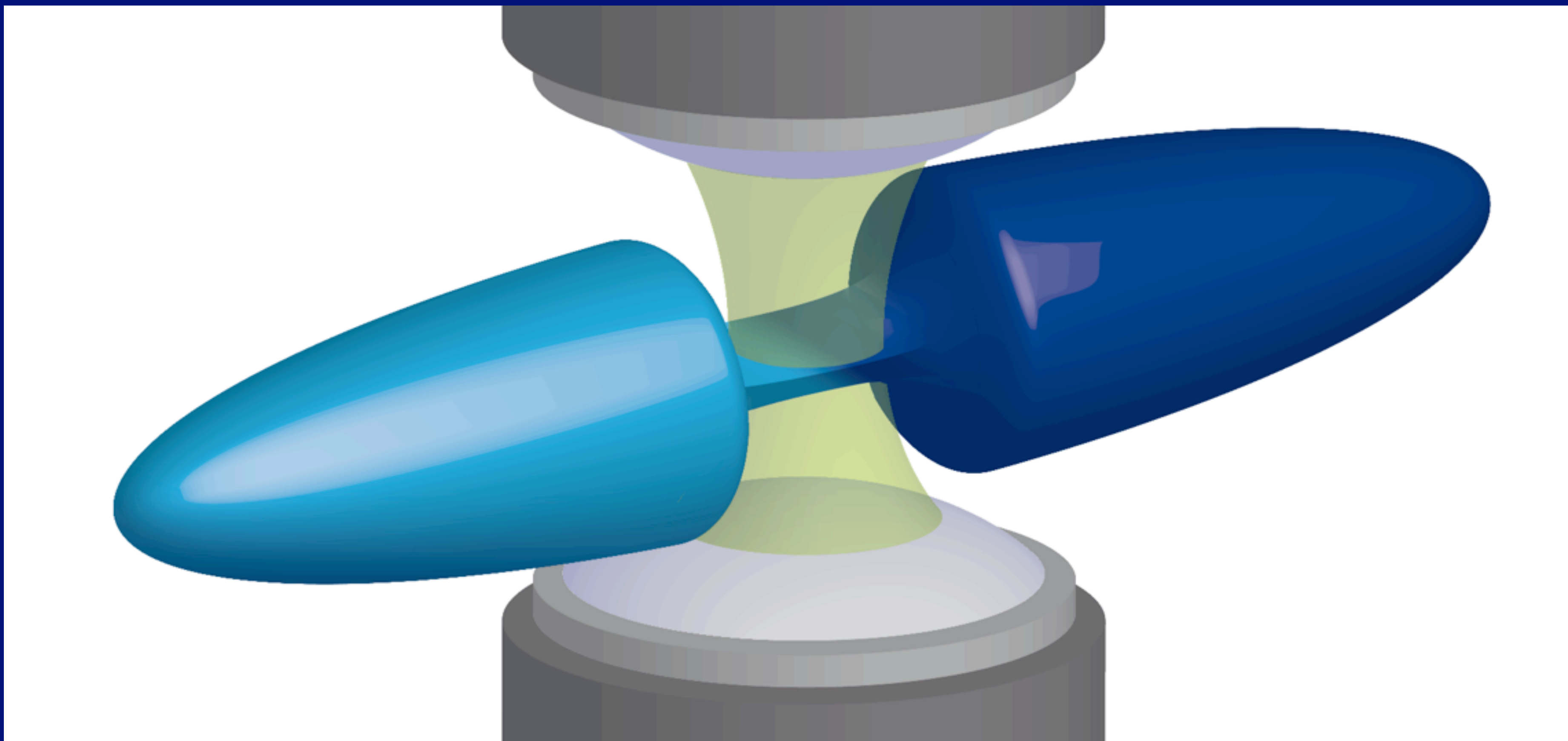
Dreams and worries

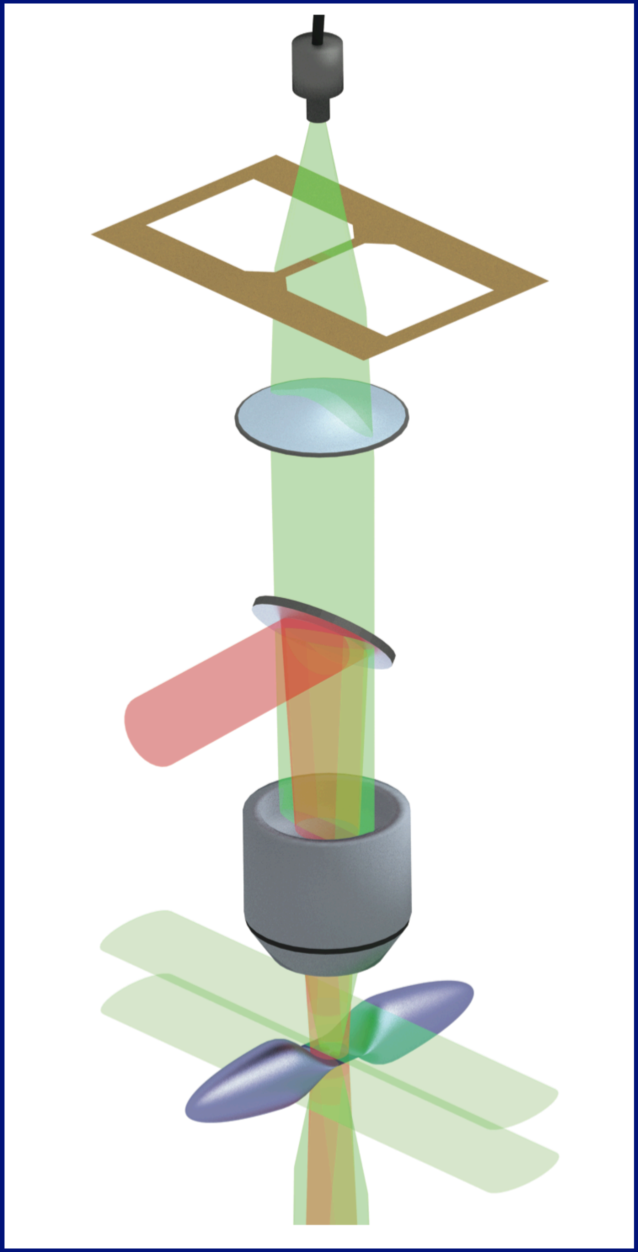


$T < h\nu$

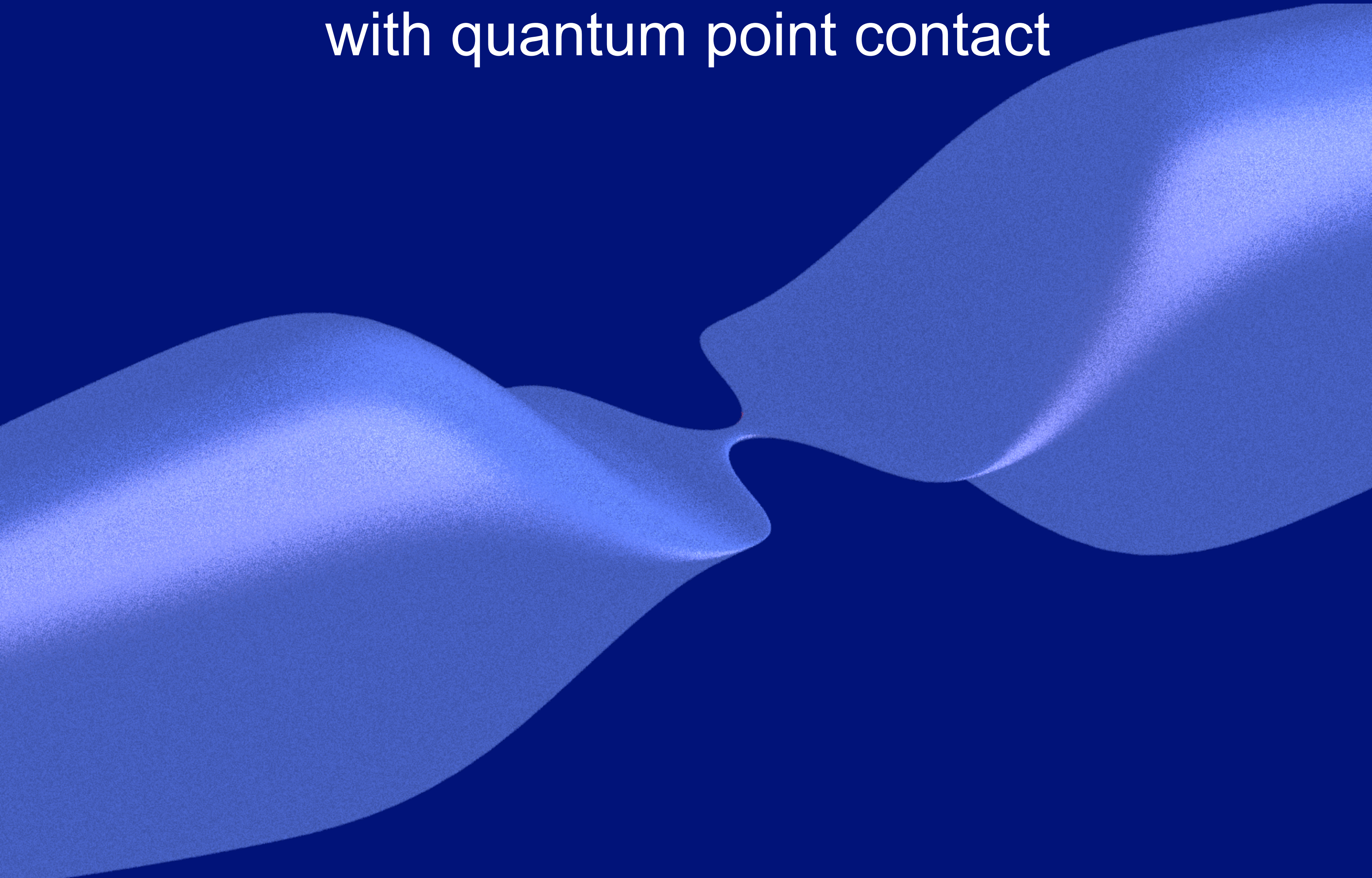
10 atoms in channel

Single Mode Channel?





Connecting two strongly correlated superfluids with quantum point contact



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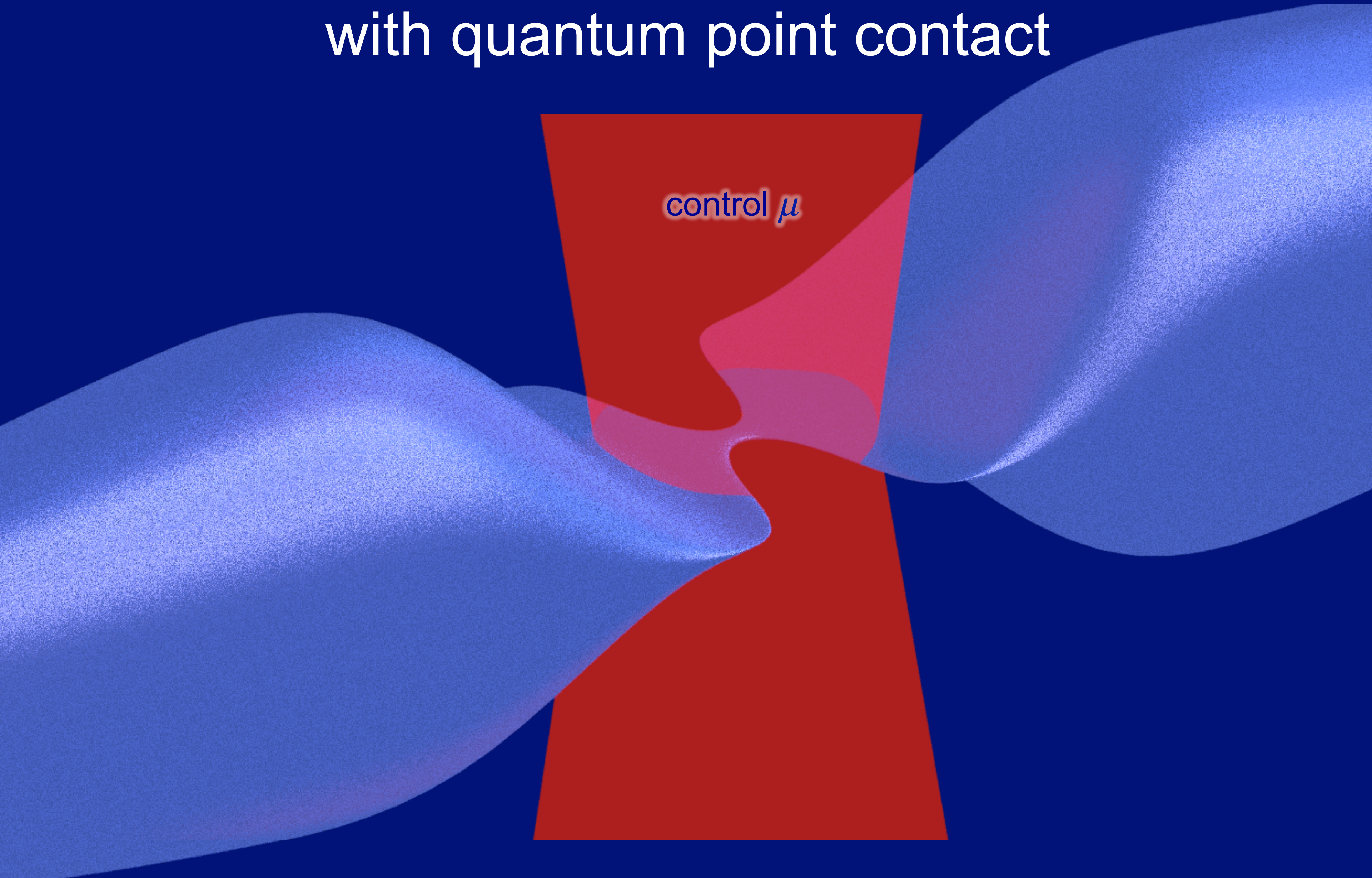
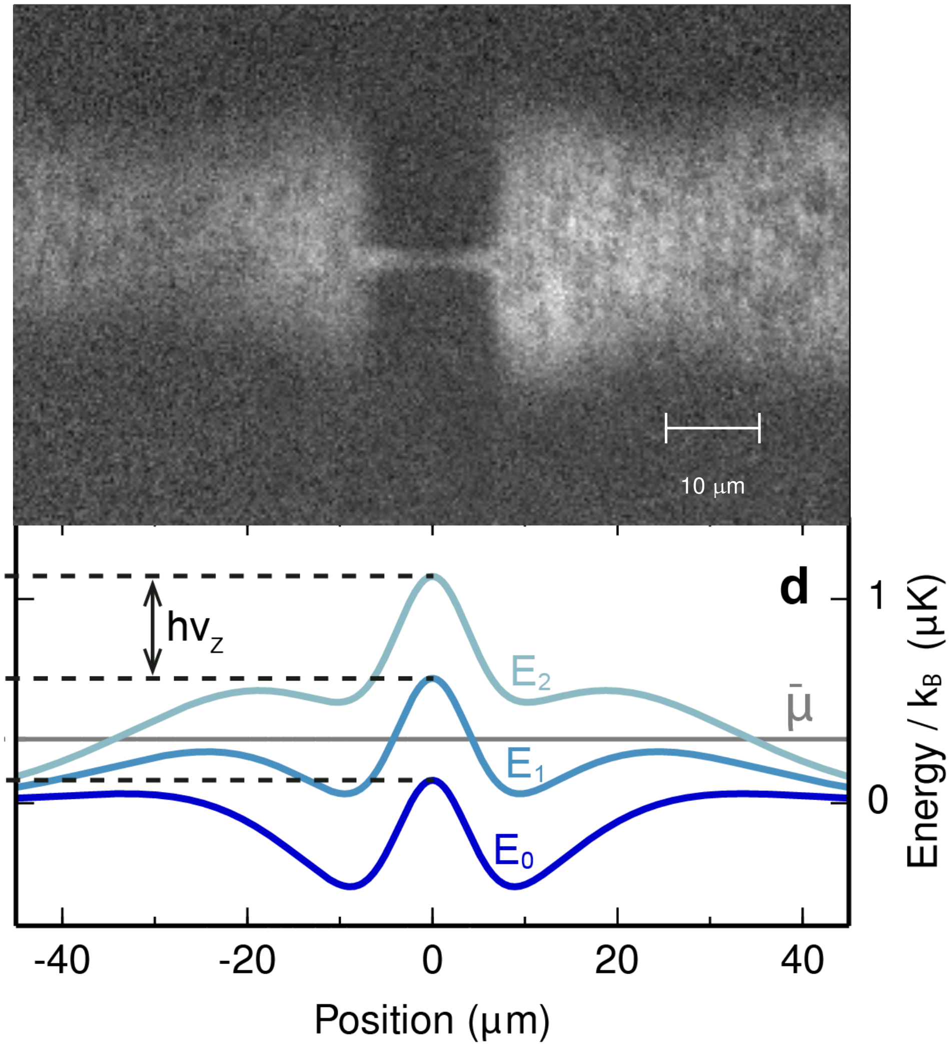
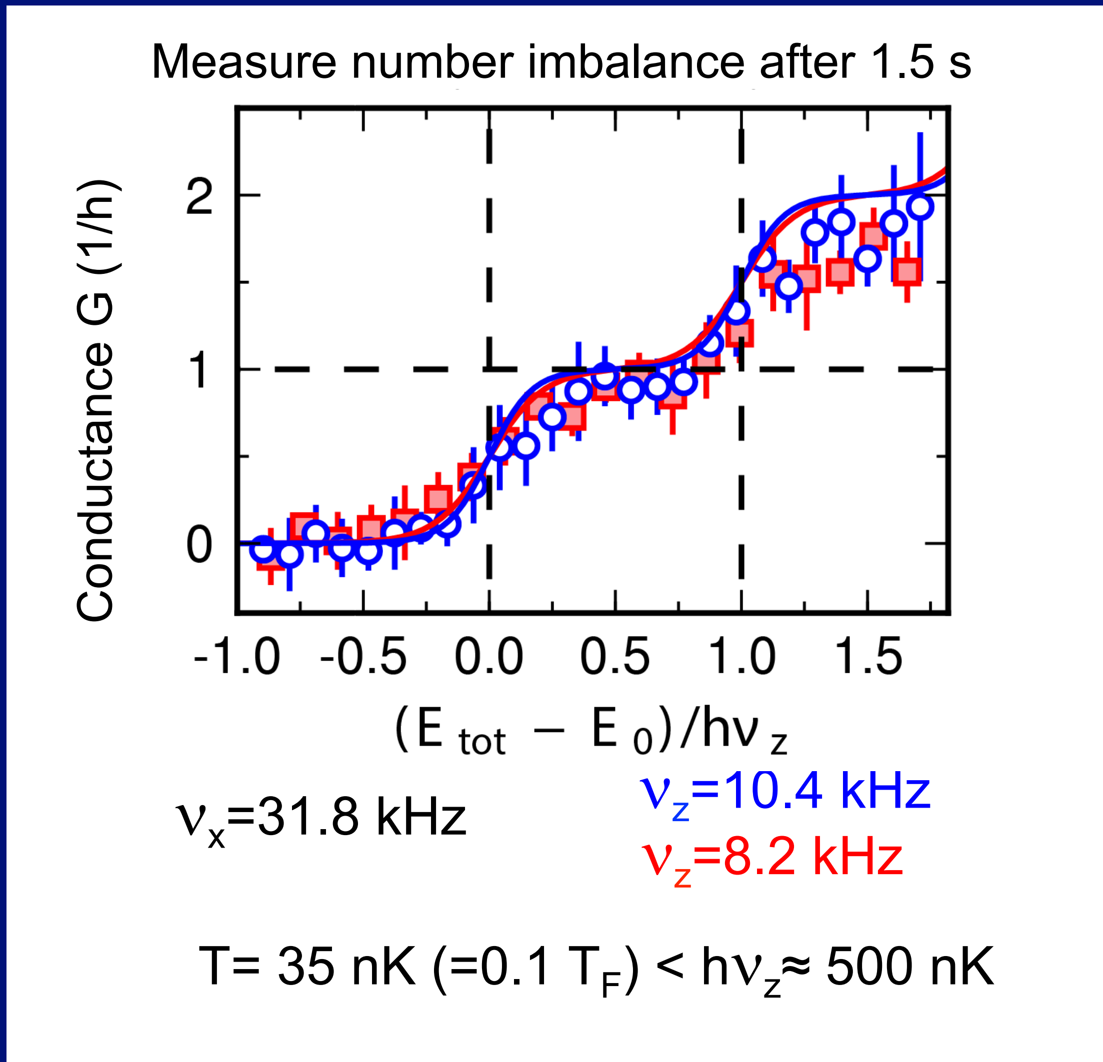


Quantum Point Contact

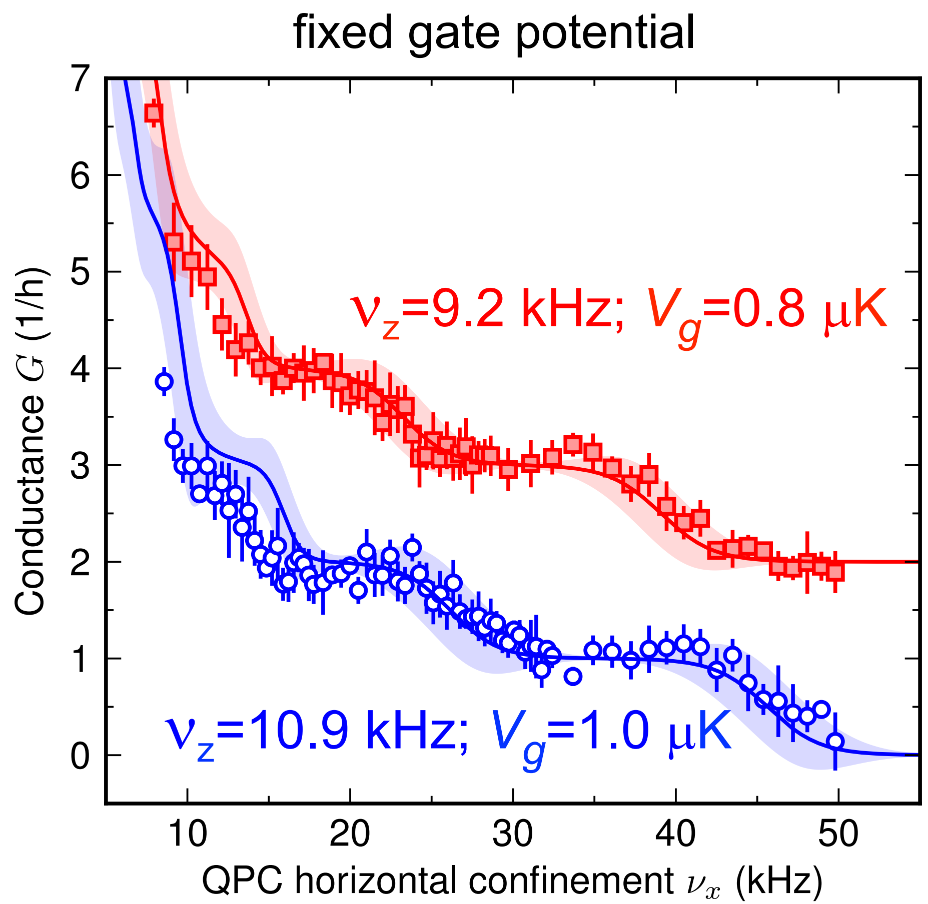


Quantum Point Contact



S. Krinner, D. Stadler, D. Husmann, J.P. Brantut and T. Esslinger, Nature 517, 64 (2015)

Quantum Point Contact



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Connecting two strongly correlated superfluids with quantum point contact

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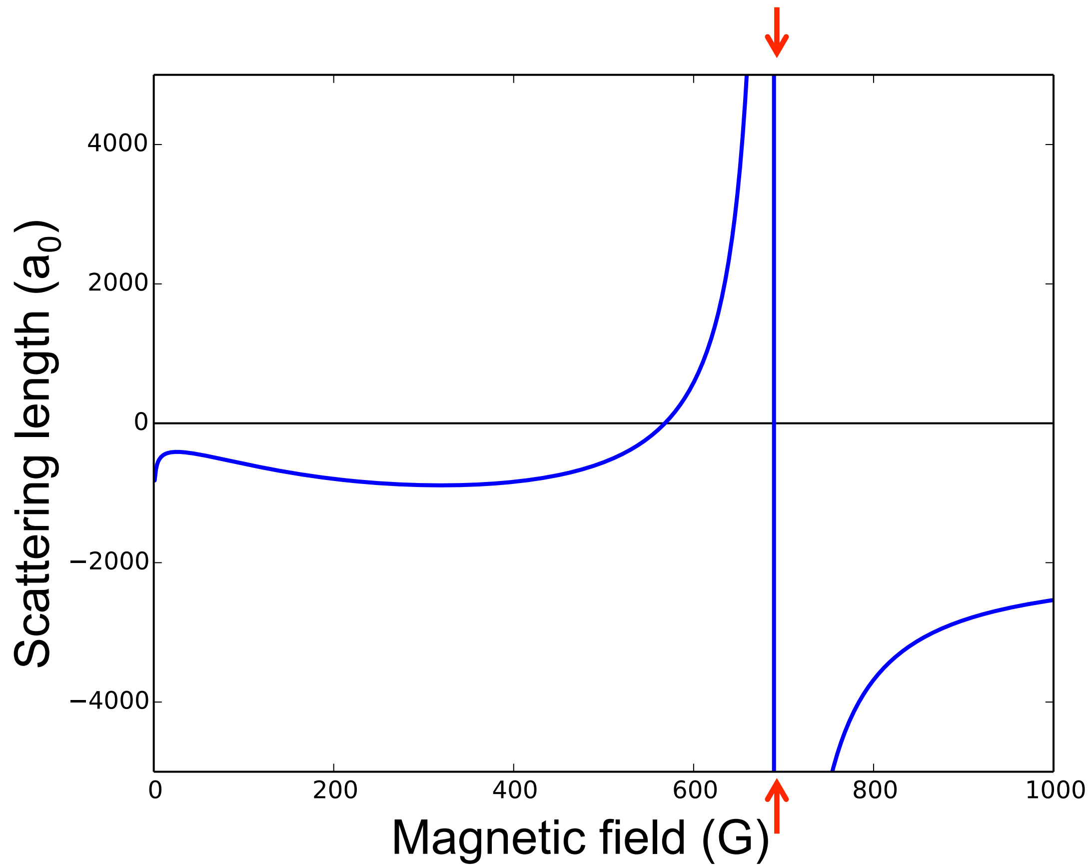

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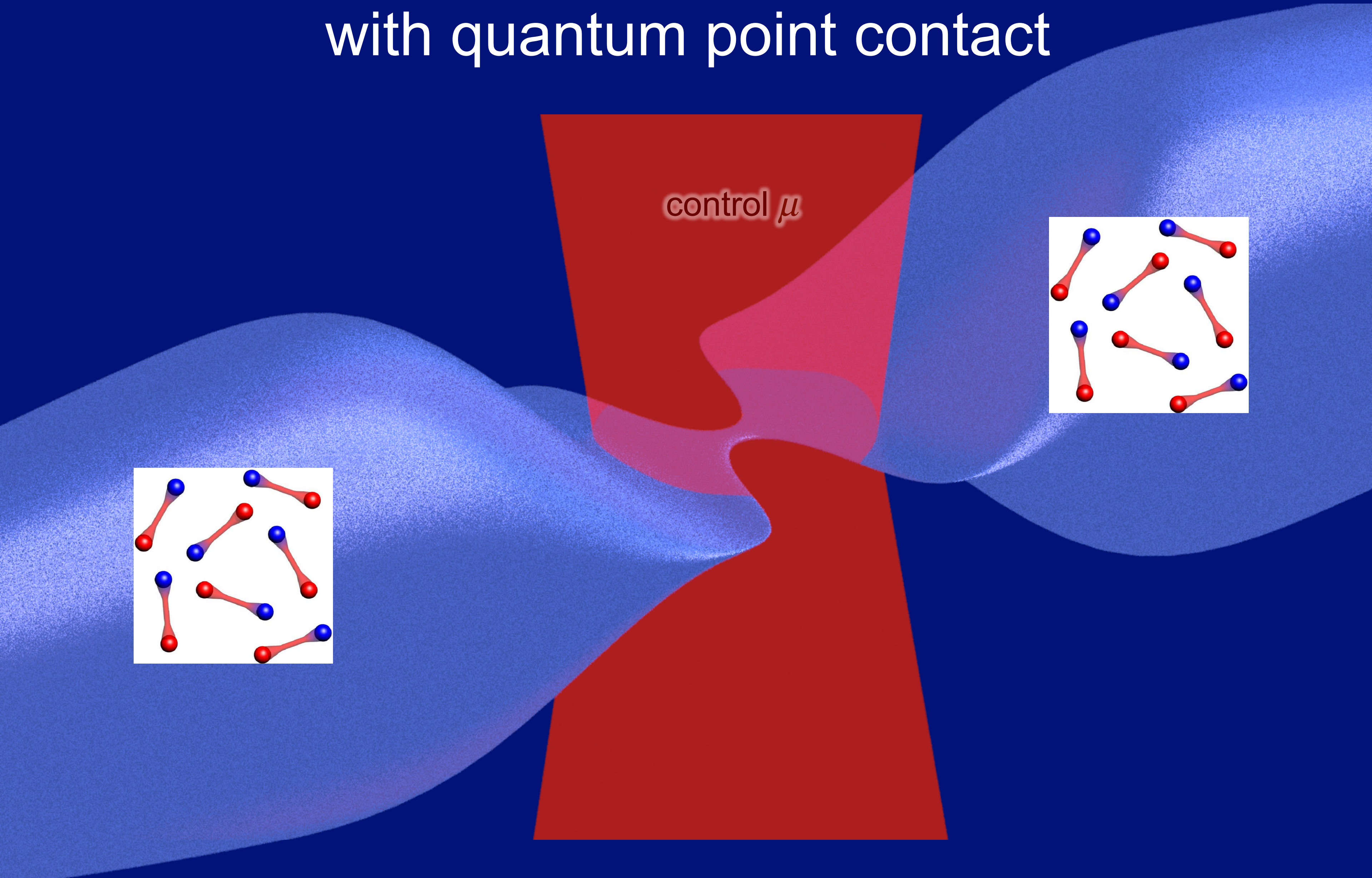

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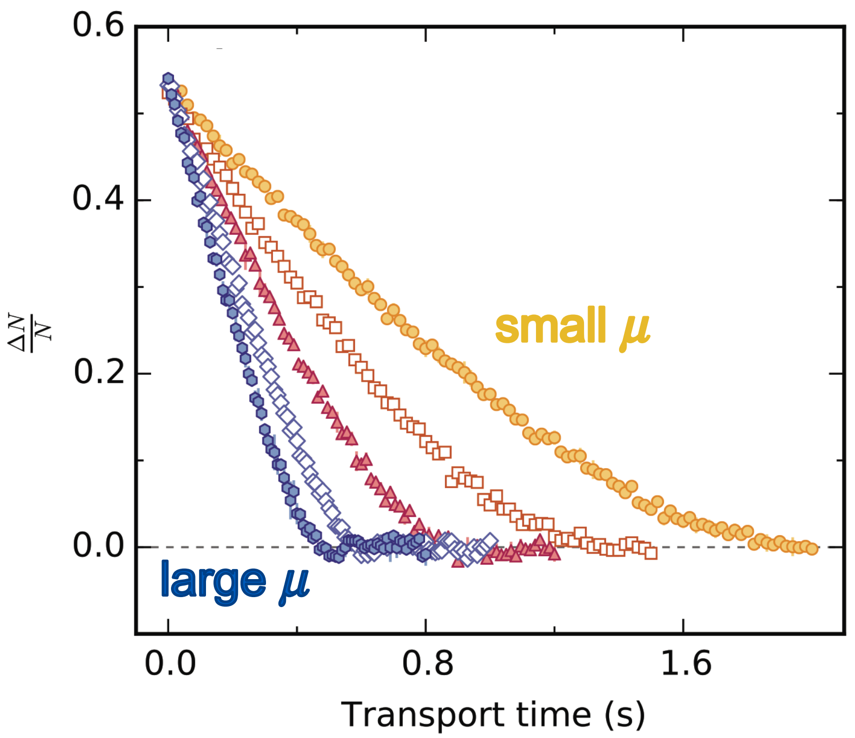

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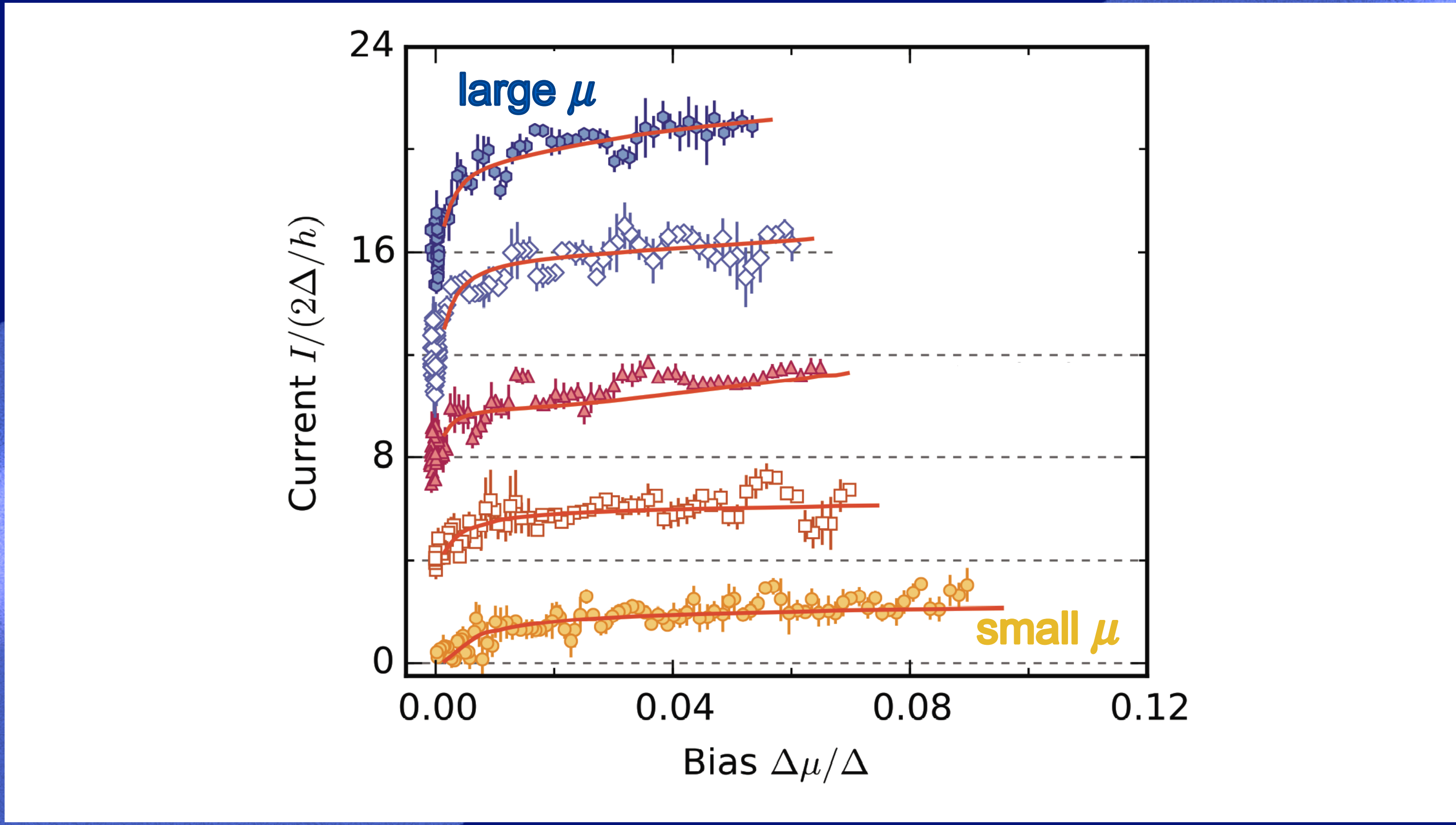
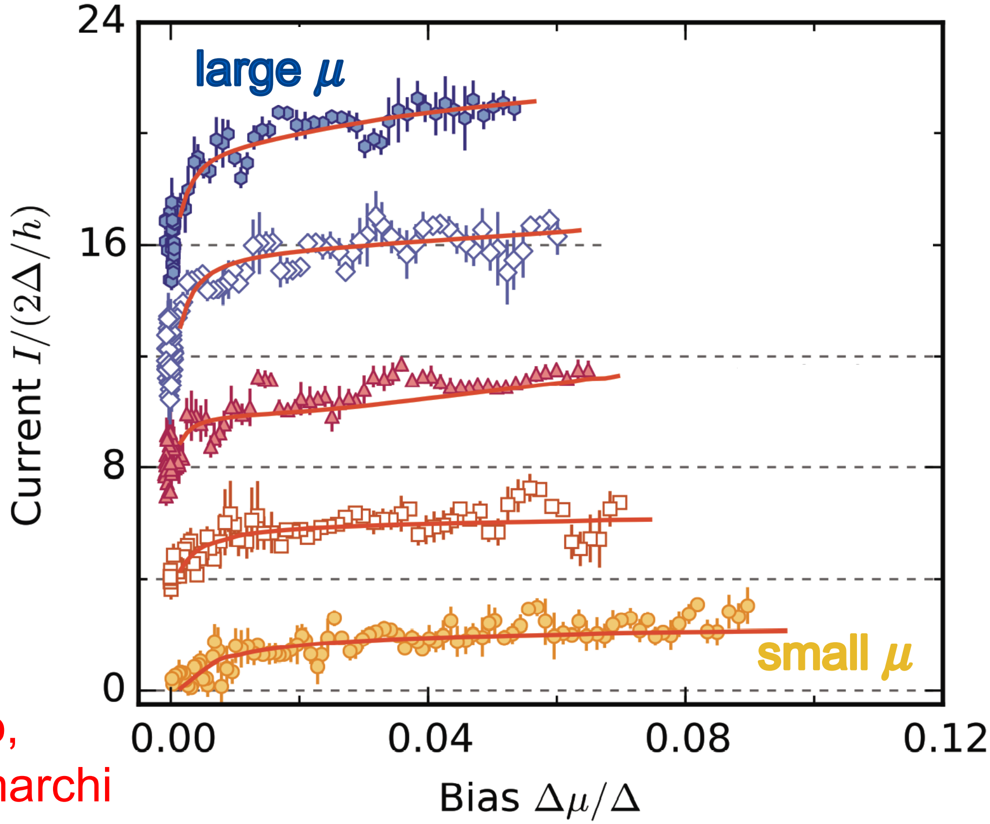


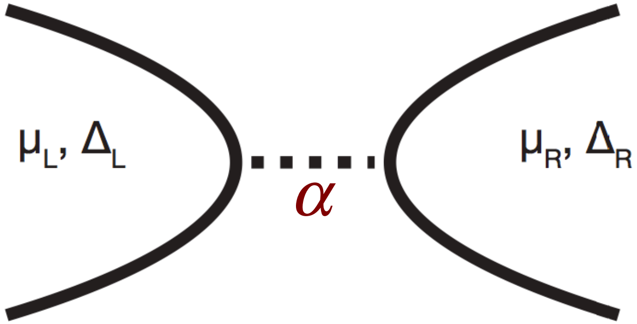
Connecting two strongly correlated superfluids with quantum point contact

Theory:
Shun Uchino,
Thierry Giamarchi



Dominik Husmann, Shun Uchino, Sebastian Krinner, Martin Lebrat, Thierry Giamarchi, Tilman Esslinger, Jean-Philippe Brantut, Science 350, 1498-1501 (2015)

Connecting two strongly correlated superfluids with quantum point contact



large proximity effect
point-like connection (transparency α)
Keldysh formalism in mean-field approximation

Theory:
Shun Uchino,
Thierry Giamarchi

Dominik Husmann, Shun Uchino, Sebastian Krinner, Martin Lebrat, Thierry Giamarchi, Tilman Esslinger, Jean-Philippe Brantut, Science 350, 1498-1501 (2015)

Connecting two strongly correlated superfluids with quantum point contact

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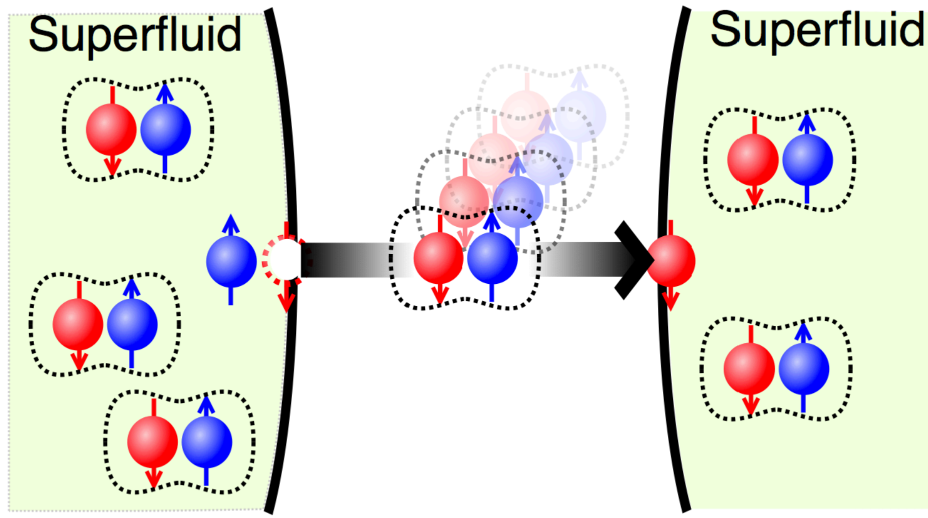
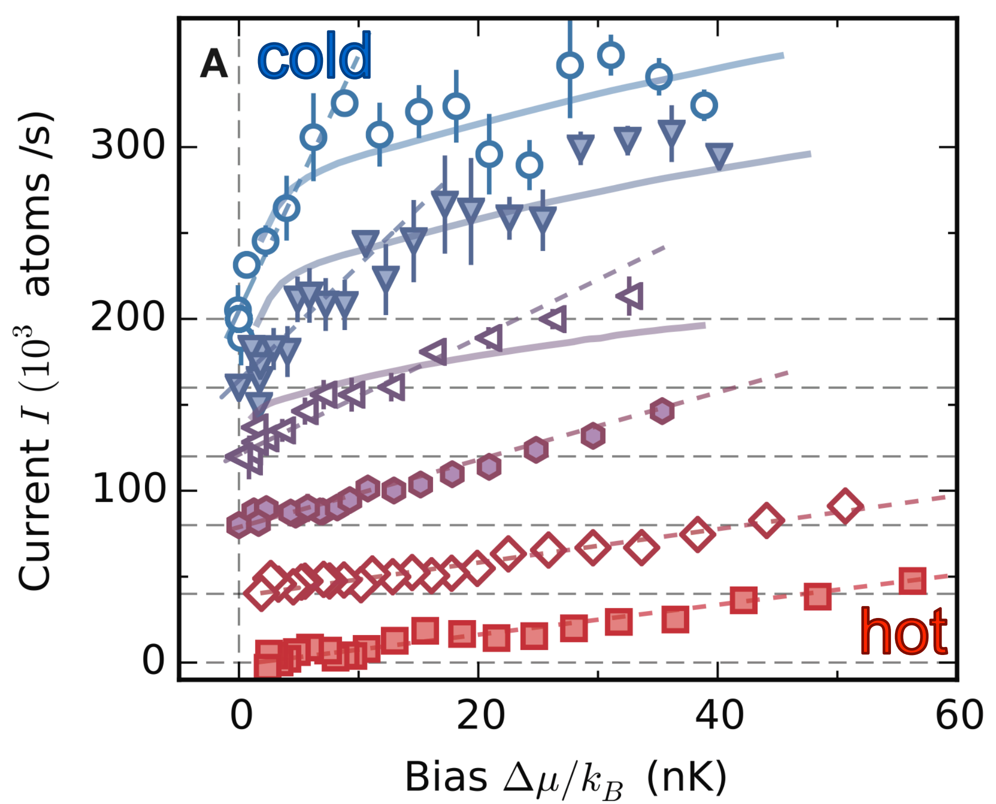


Gap for single particle transfer bridged by coherent transfer of n pairs (multiple Andreev reflection)

Dominik Husmann, Shun Uchino, Sebastian Krinner, Martin Lebrat, Thierry Giamarchi, Tilman Esslinger, Jean-Philippe Brantut, Science 350, 1498-1501 (2015)
Josephson Effect: G. Valtolina, , A. Burchianti, A. Amico, E. Neri, K. Xhani, J. A. Seman, A. Trombettoni, A. Smerzi, M. Zaccanti, M. Inguscio, G. Roati, Science 3501505-1508 (2015).

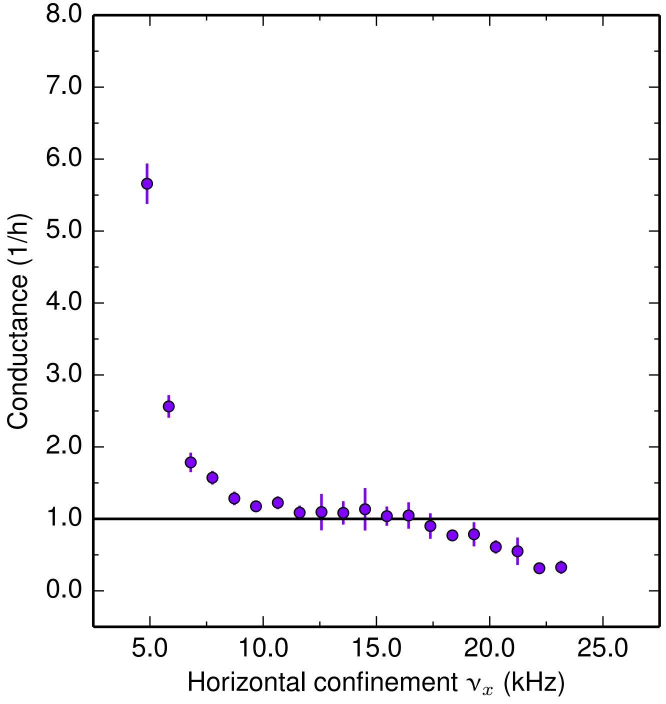
Finite temperature transport properties

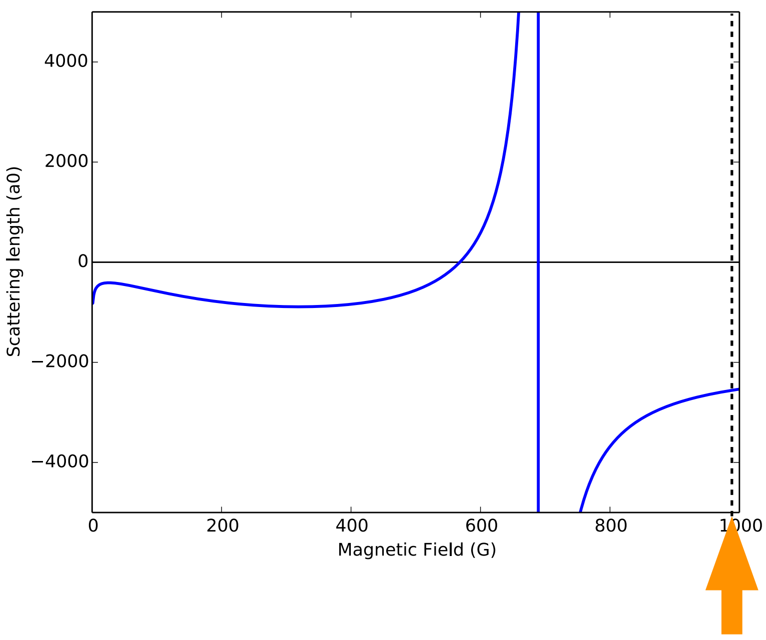


Dominik Husmann, Shun Uchino, Sebastian Krinner, Martin Lebrat, Thierry Giamarchi, Tilman Esslinger, Jean-Philippe Brantut, accepted Science, arXiv:1508.00578

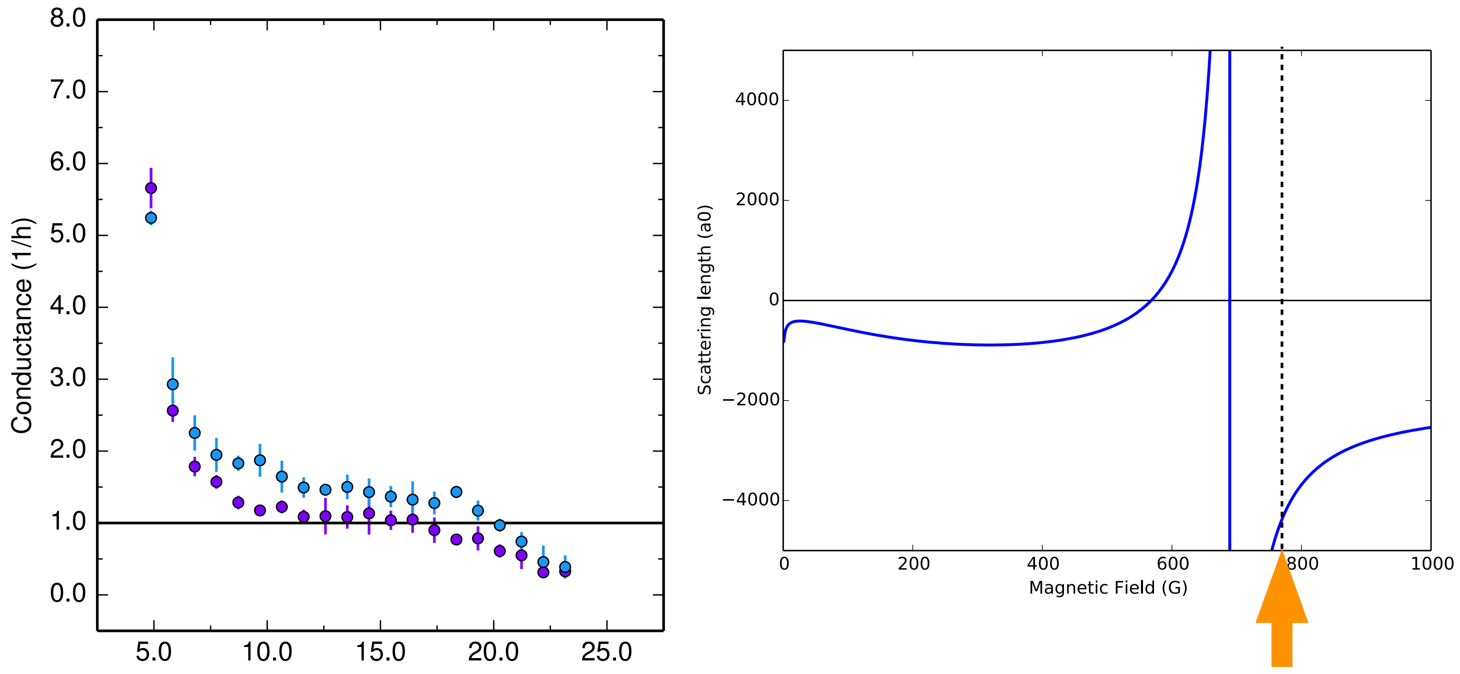
Changing Interactions

Changing Interactions

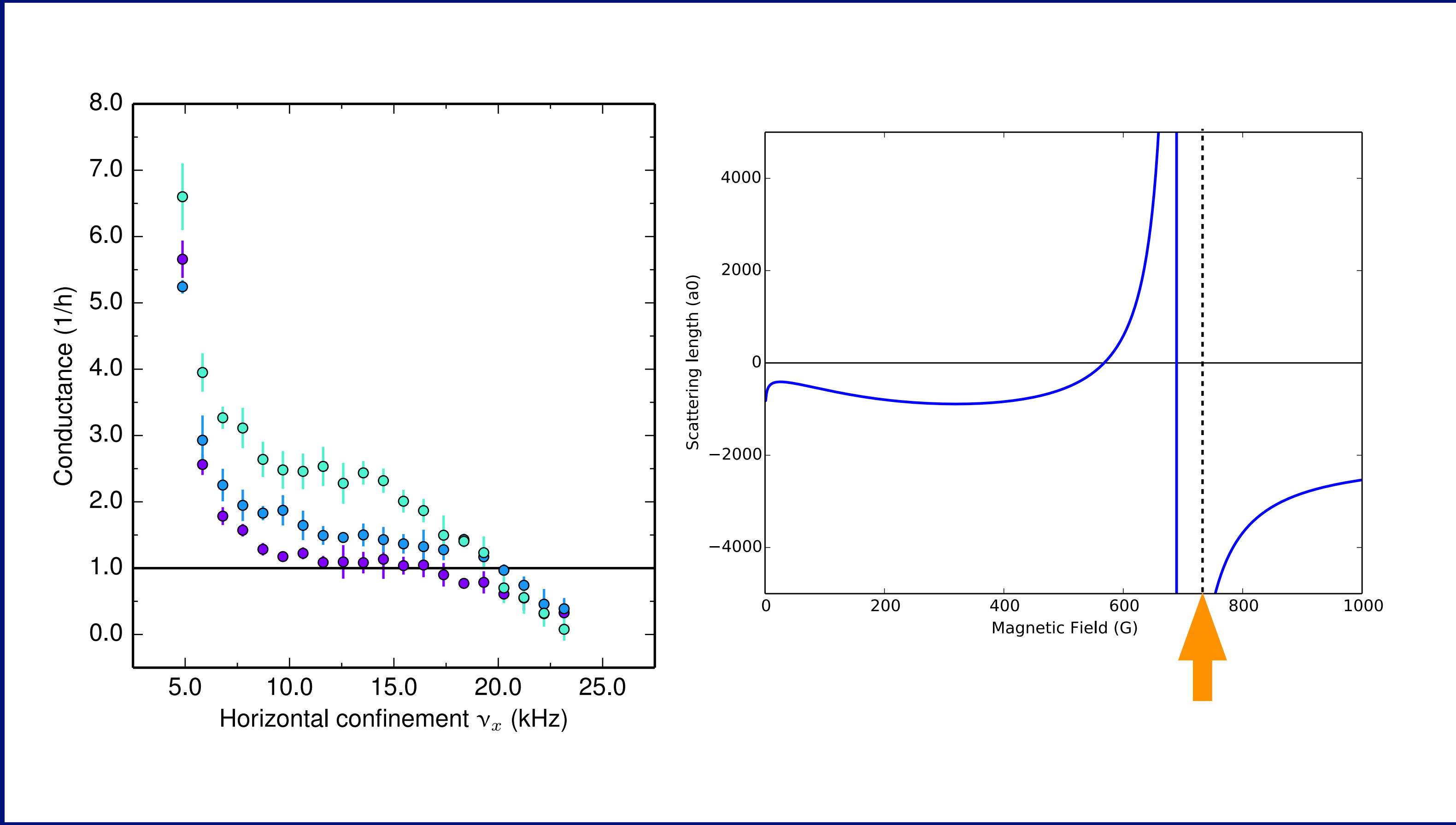




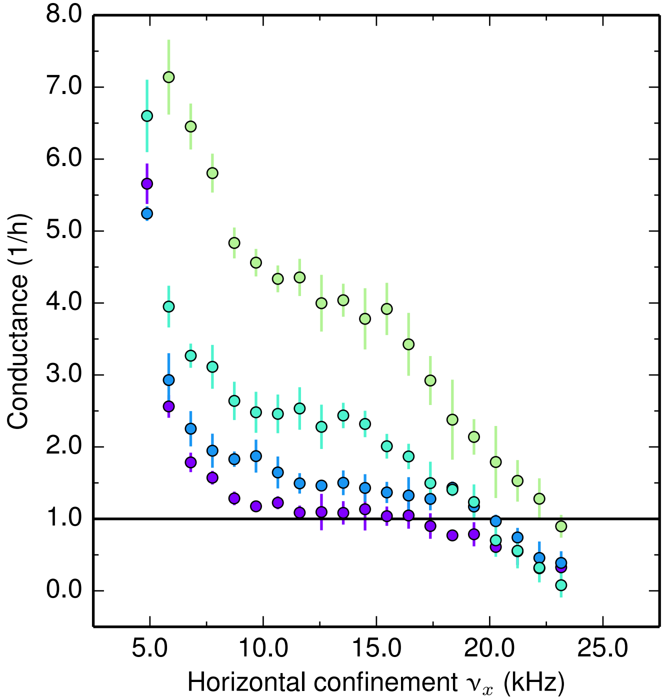
Changing Interactions

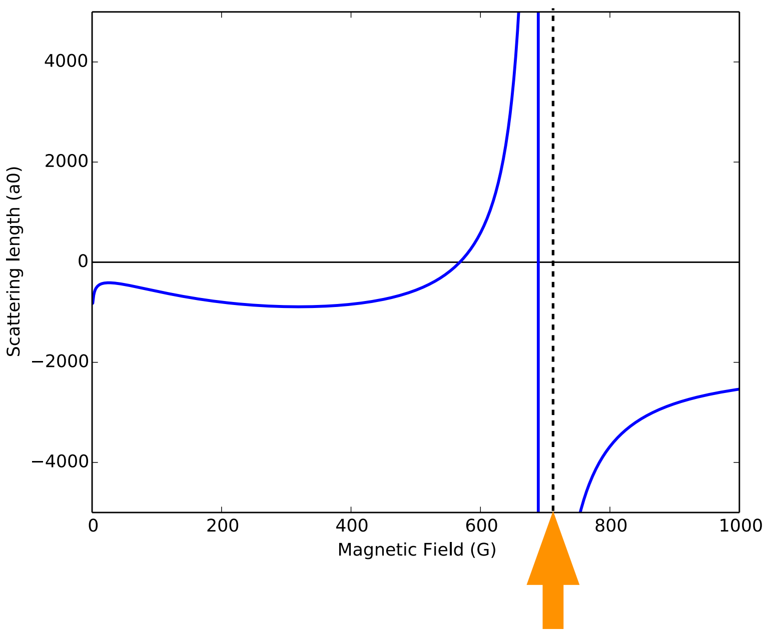


Changing Interactions

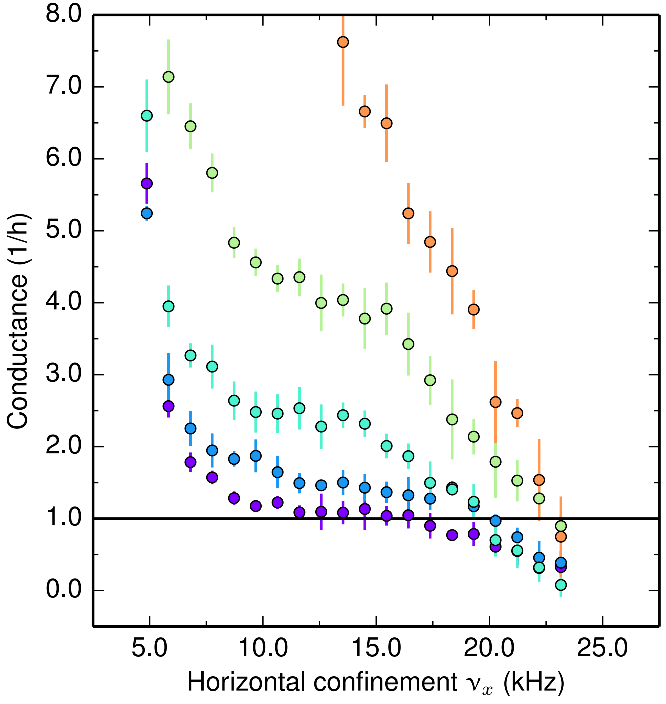


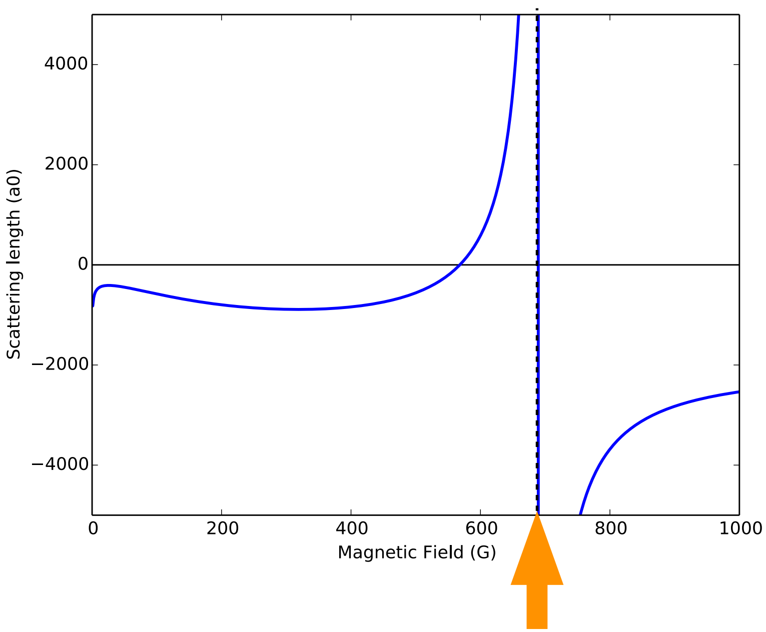
Changing Interactions



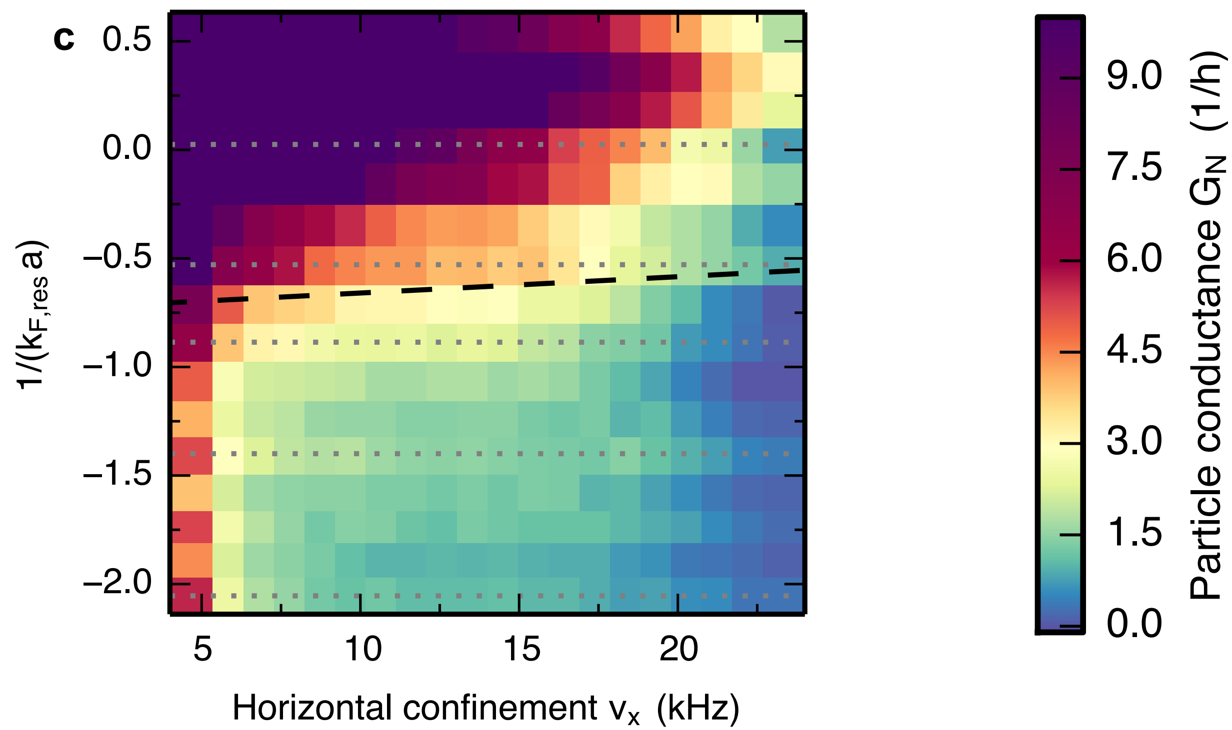


Changing Interactions

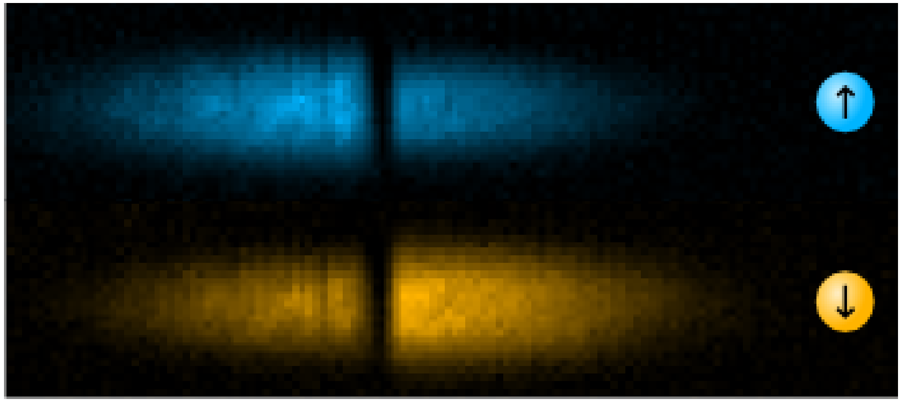




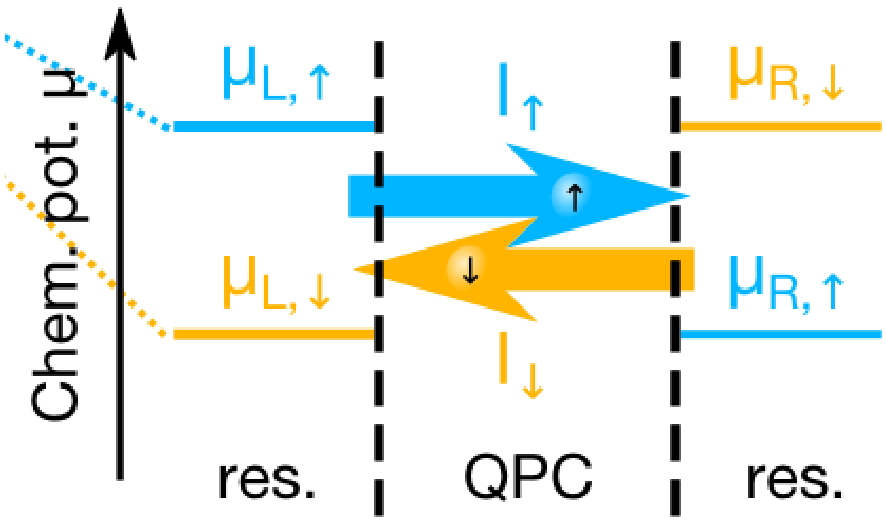
Conductance Map



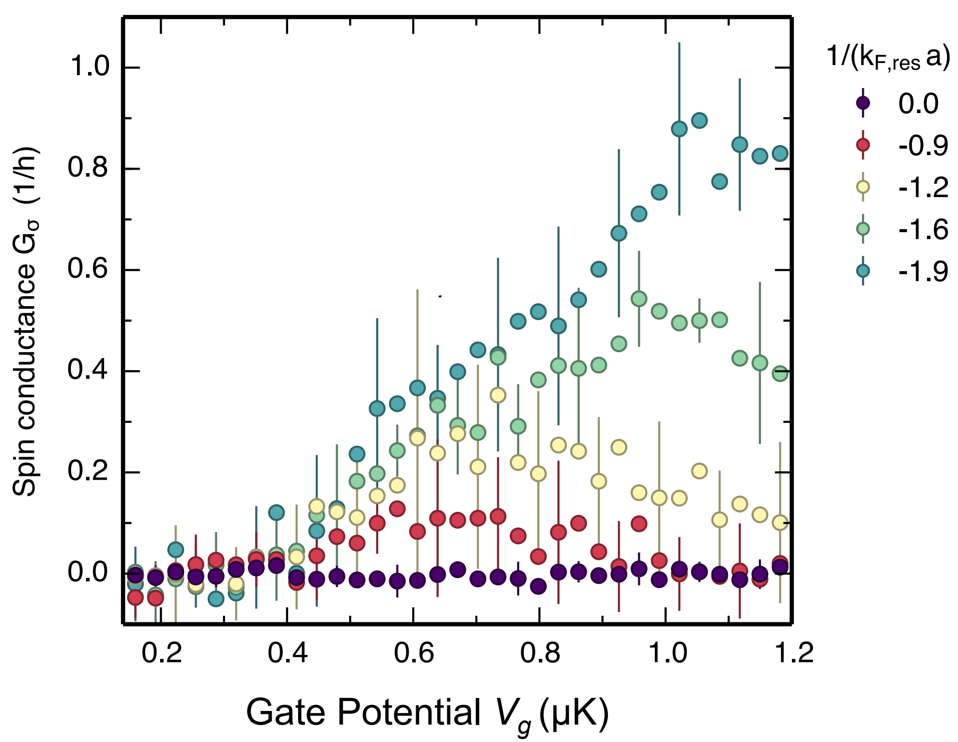
Spin Conductance



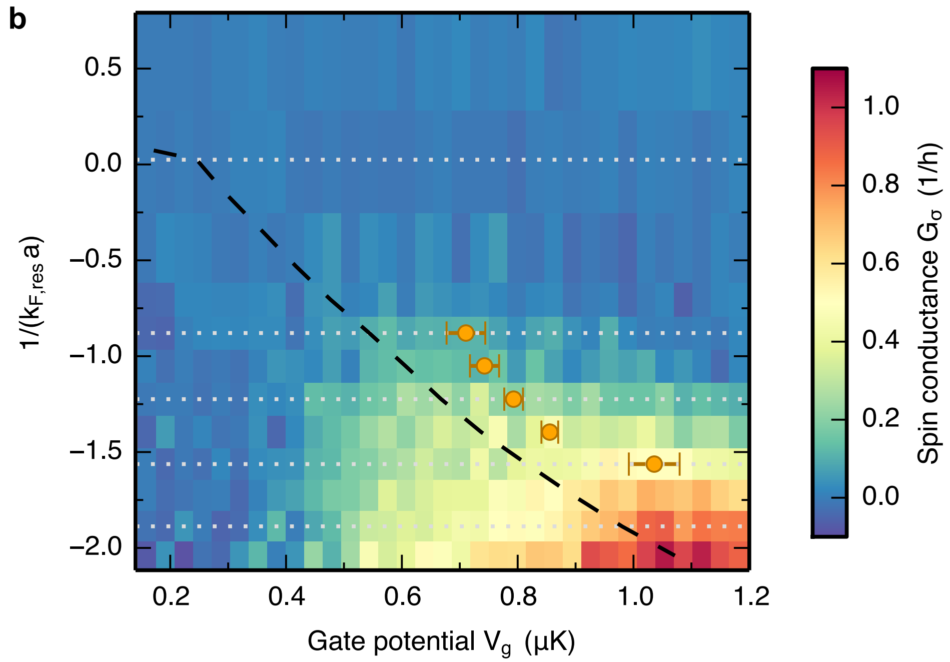
Spin Conductance



Spin Conductance

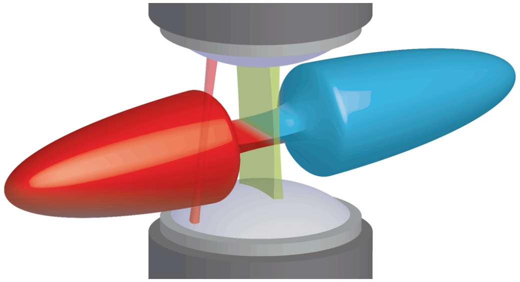


Spin Conductance



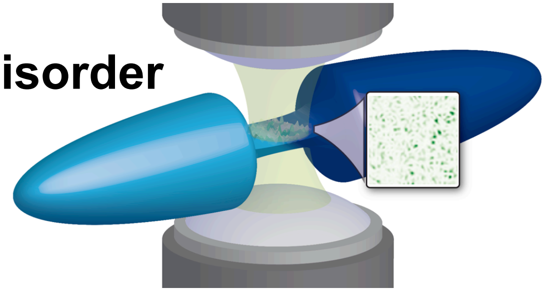
More Possibilities

Thermoelectric Effect



J.-P. Brantut, **C. Grenier**, J. Meineke, D. Stadler, S. Krinner, **C. Kollath**, T. Esslinger**, A. Georges**, Science 342, 713 (2013).

Disorder



S. Krinner, D. Stadler, J. Meineke, J.-P. Brantut, and T. Esslinger, Phys. Rev. Lett. 110, 100601 (2013).

S. Krinner, D. Stadler, J. Meineke, J.-P. Brantut, and T. Esslinger, Phys. Rev. Lett. 115, 045302 (2015).

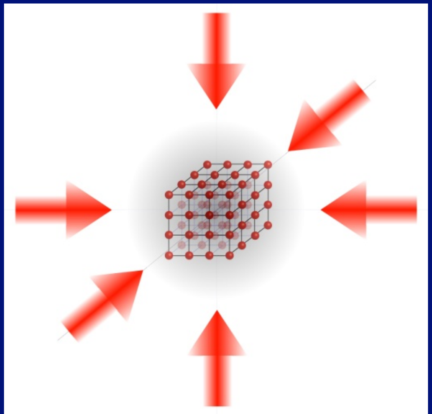
Competing short- and long-range interactions

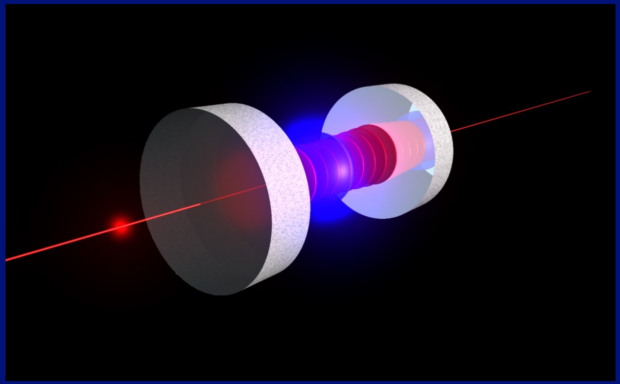
Long-range interactions

Dipolar molecules/atoms

Rydberg atoms

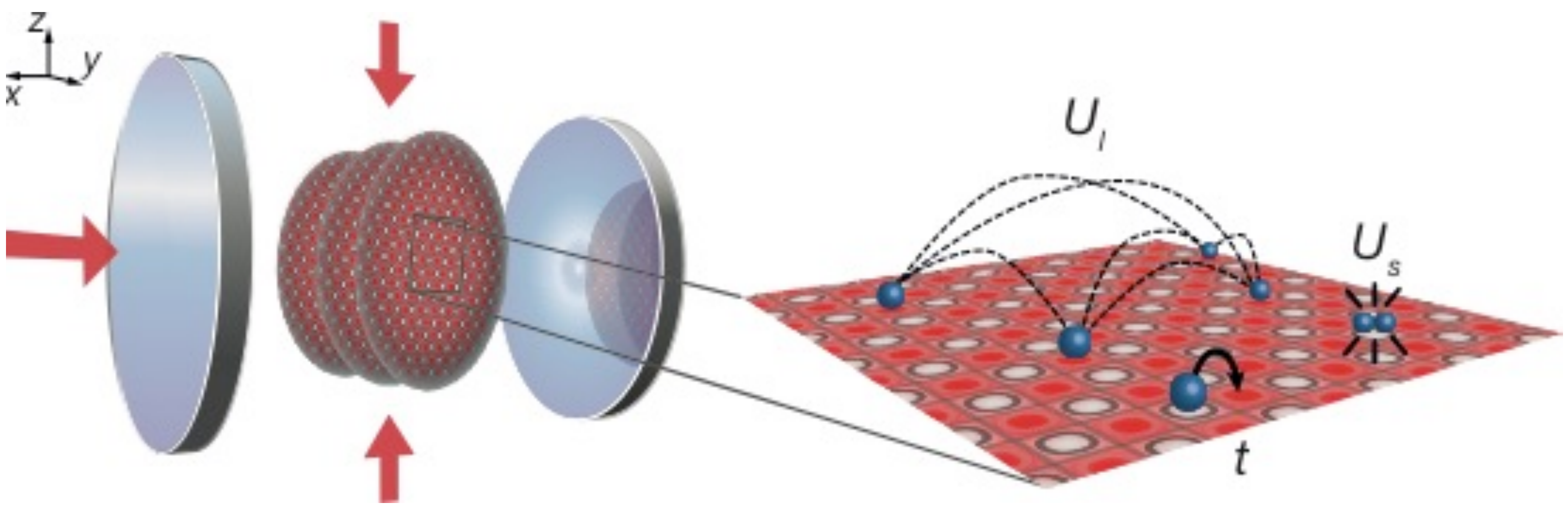
cavity mediated interactions





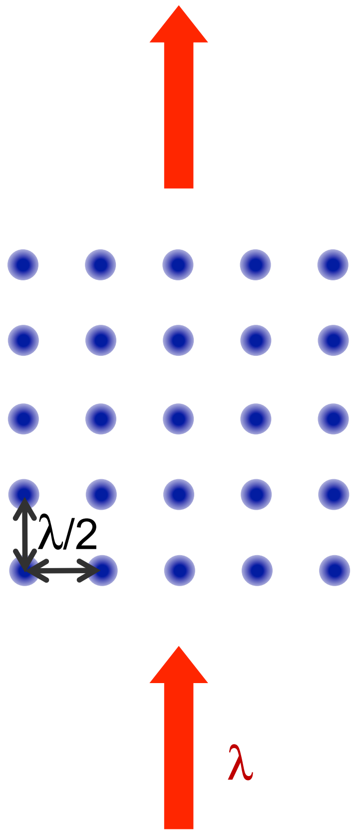
Short-range interactions ⟷ Long-range interactions

Competing short and long-range interactions

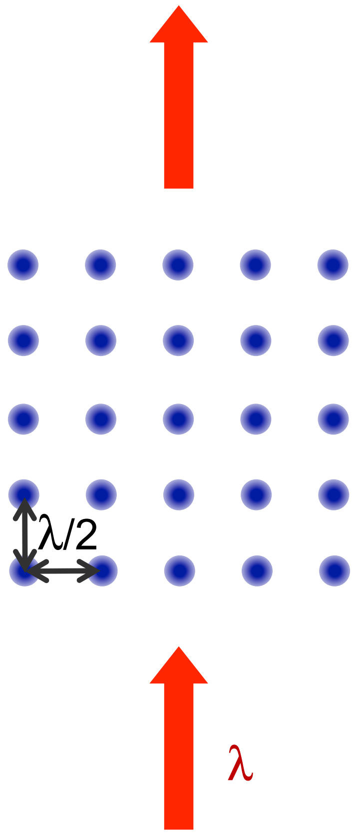
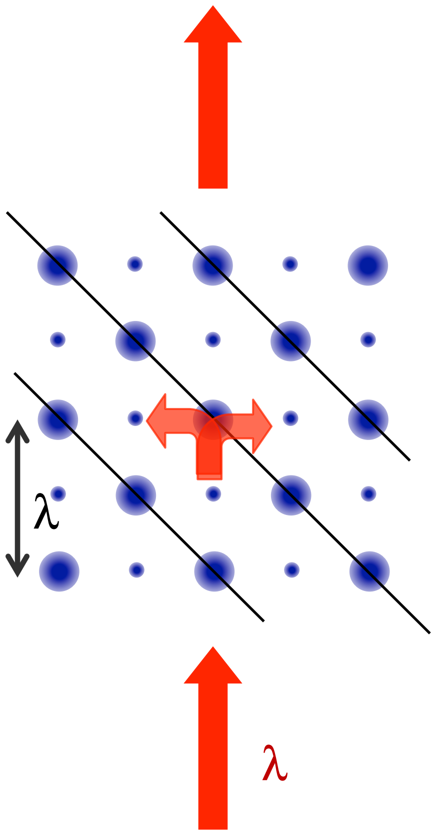


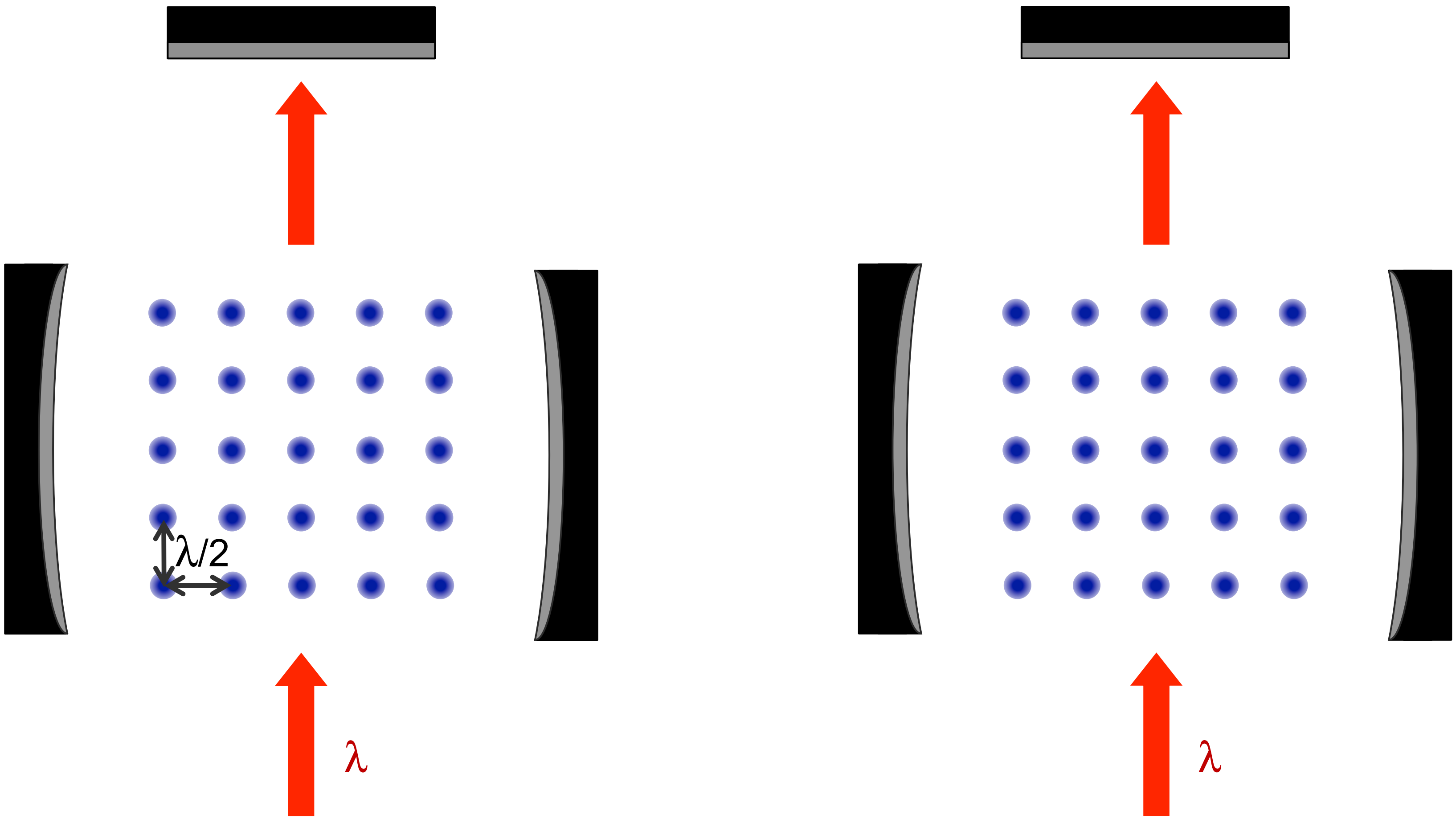
Renate Landig, Lorenz Hruby, Nishant Dogra, Manuele Landini, Rafael Mottl, Tobias Donner, TE, accepted for publication in Nature, arXiv:1511.00007

Related work: J. Klinder, H. Keßler, M. Reza Bakhtiari, M. Thorwart, and A. Hemmerich, Phys. Rev. Lett. 115, 230403 (2015), arXiv: arXiv:1511.00850

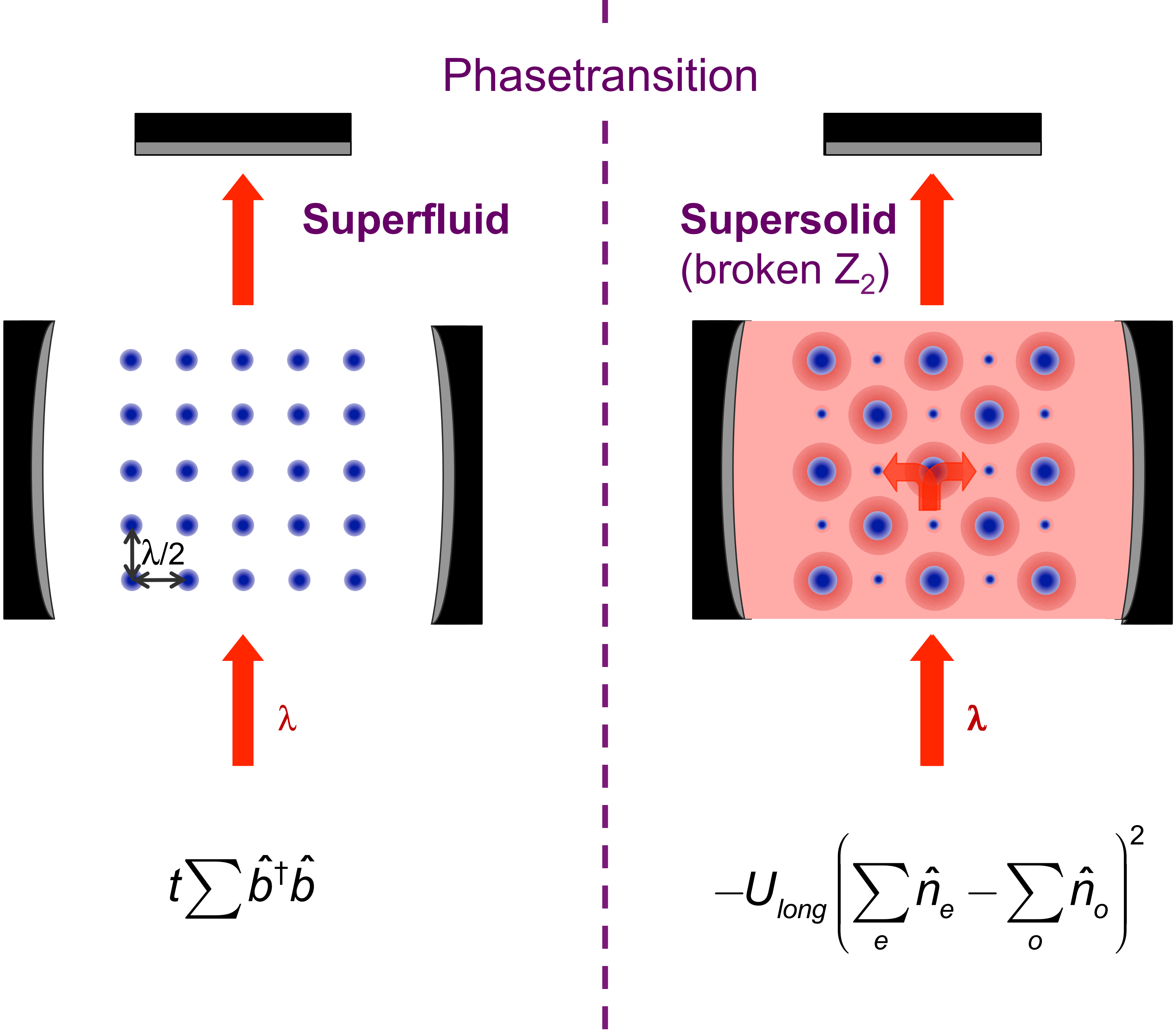


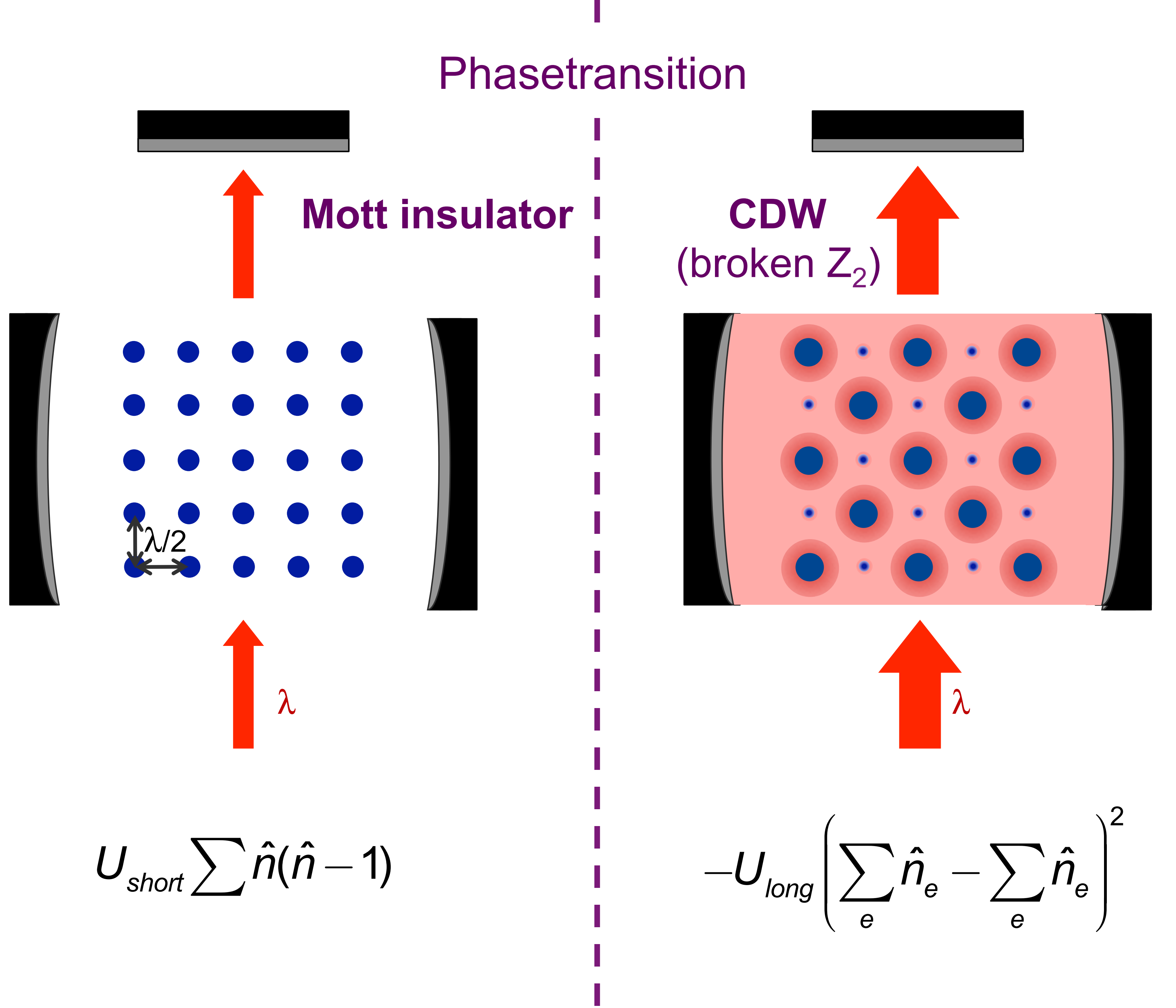
λ/2
λ

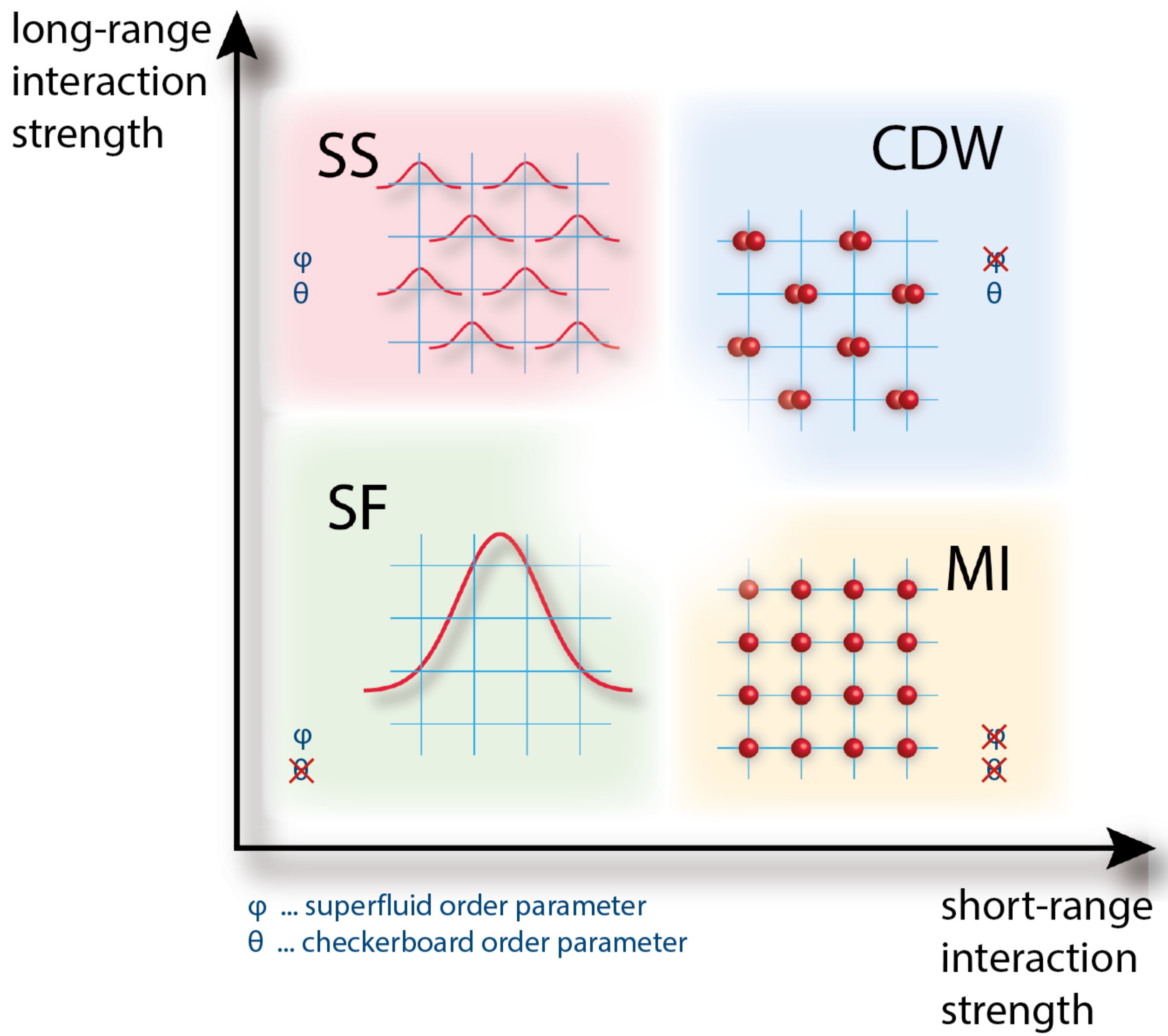

λ/2
λ

λ
λ



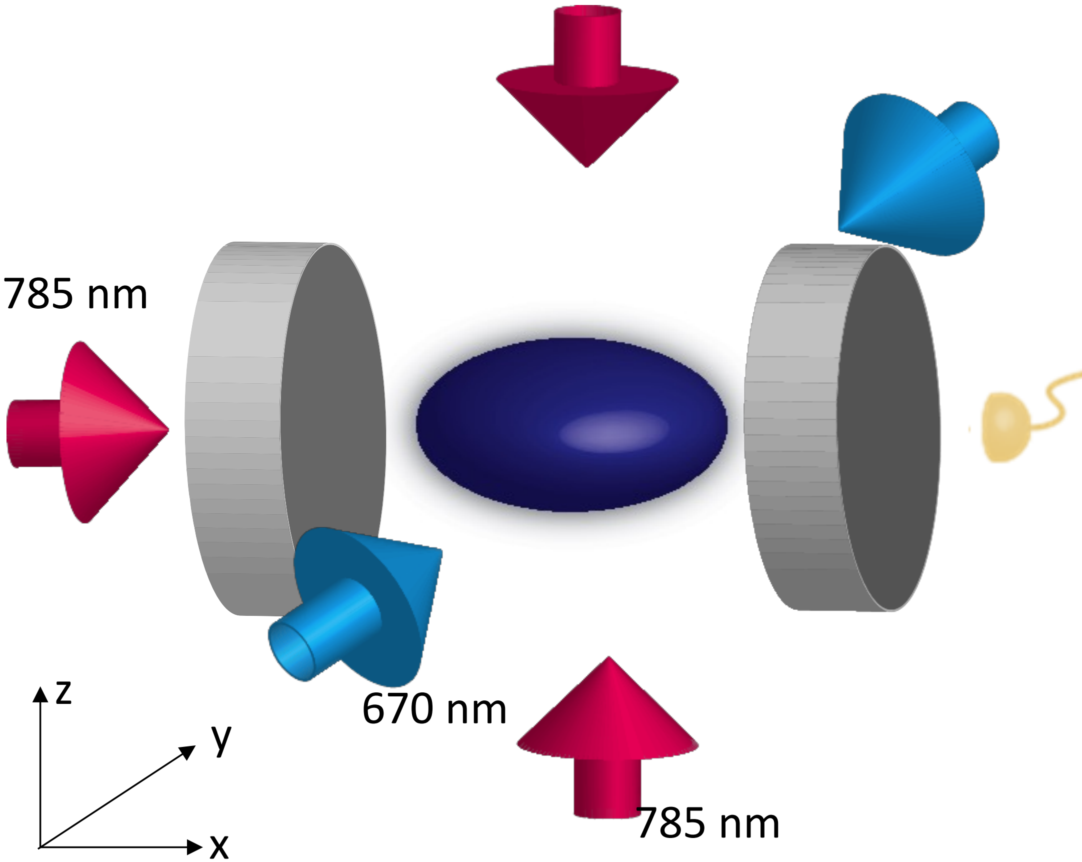
λ/2
λ
λ


Phasetransition
Superfluid
λ
λ/2
$t\sum \hat{b}^{\dagger}\hat{b}$
Supersolid
(broken Z_2)
λ
$-U_{long}\left(\sum_e \hat{n}_e - \sum_o \hat{n}_o\right)^2$


Phasetransition
Mott insulator
CDW
(broken Z_2)
$\lambda/2$
λ
λ
$U_{short}\sum \hat{n}(\hat{n}-1)$
$-U_{long}\left(\sum_e \hat{n}_e - \sum_e \hat{n}_e\right)^2$



Cavity + Atoms Theory: Ritsch, Mekhov, Domokos, Larson, Lewenstein, Morigi, Keeling, Strack, Kollath, Brennecke
Review: H. Ritsch, P. Domokos, F. Brennecke, and T. E., Reviews of Modern Physics 85, 553-601 (2013).



Blue detuned lattice depth: $30E_{rec}$

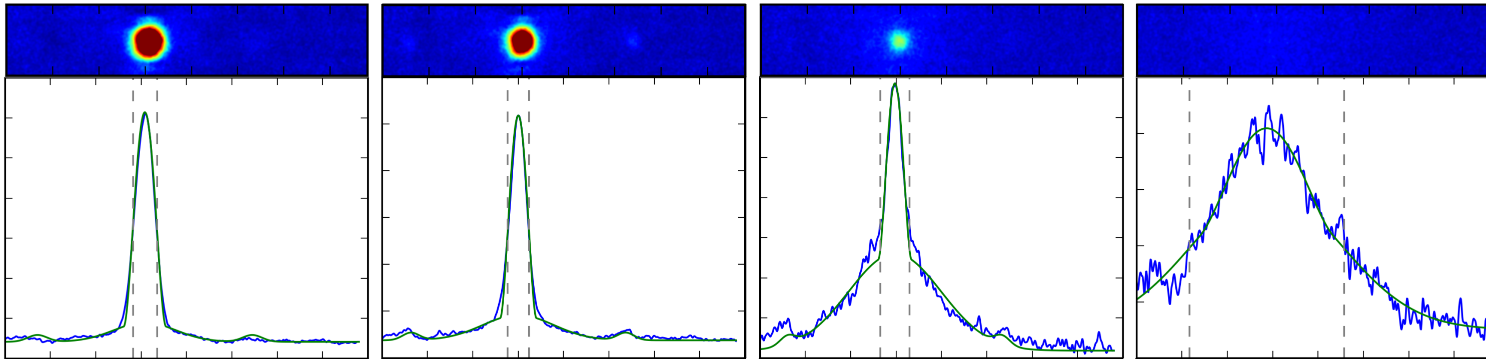
Red detuned lattice depth: $3\text{-}25E_{rec}$

$$U_{long} \propto \frac{P_{785}}{\Delta_c}$$

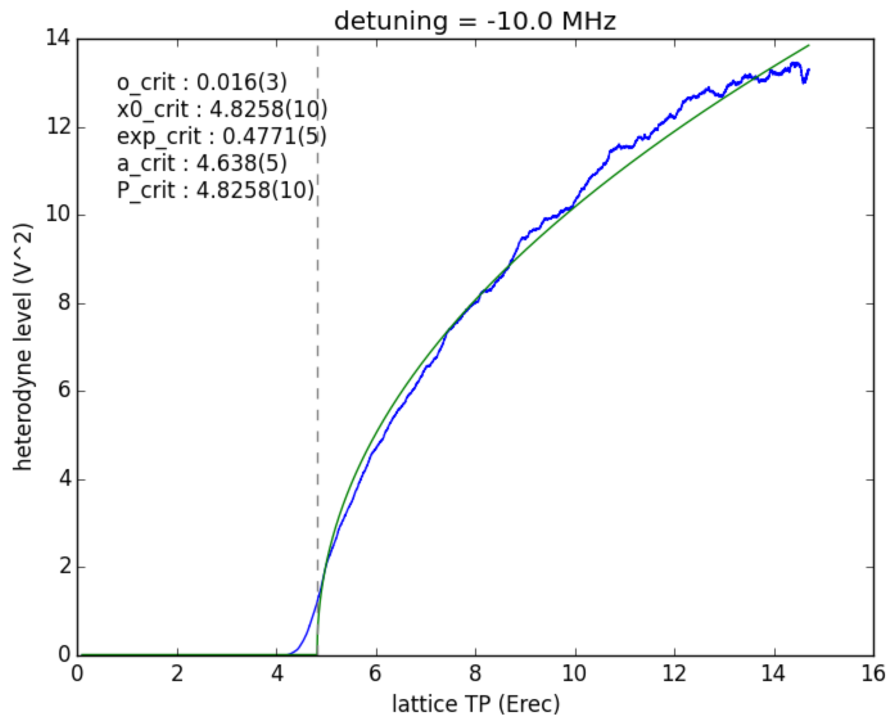
$$U_{short} \propto P_{785}$$

40,000 Rb-87 atoms

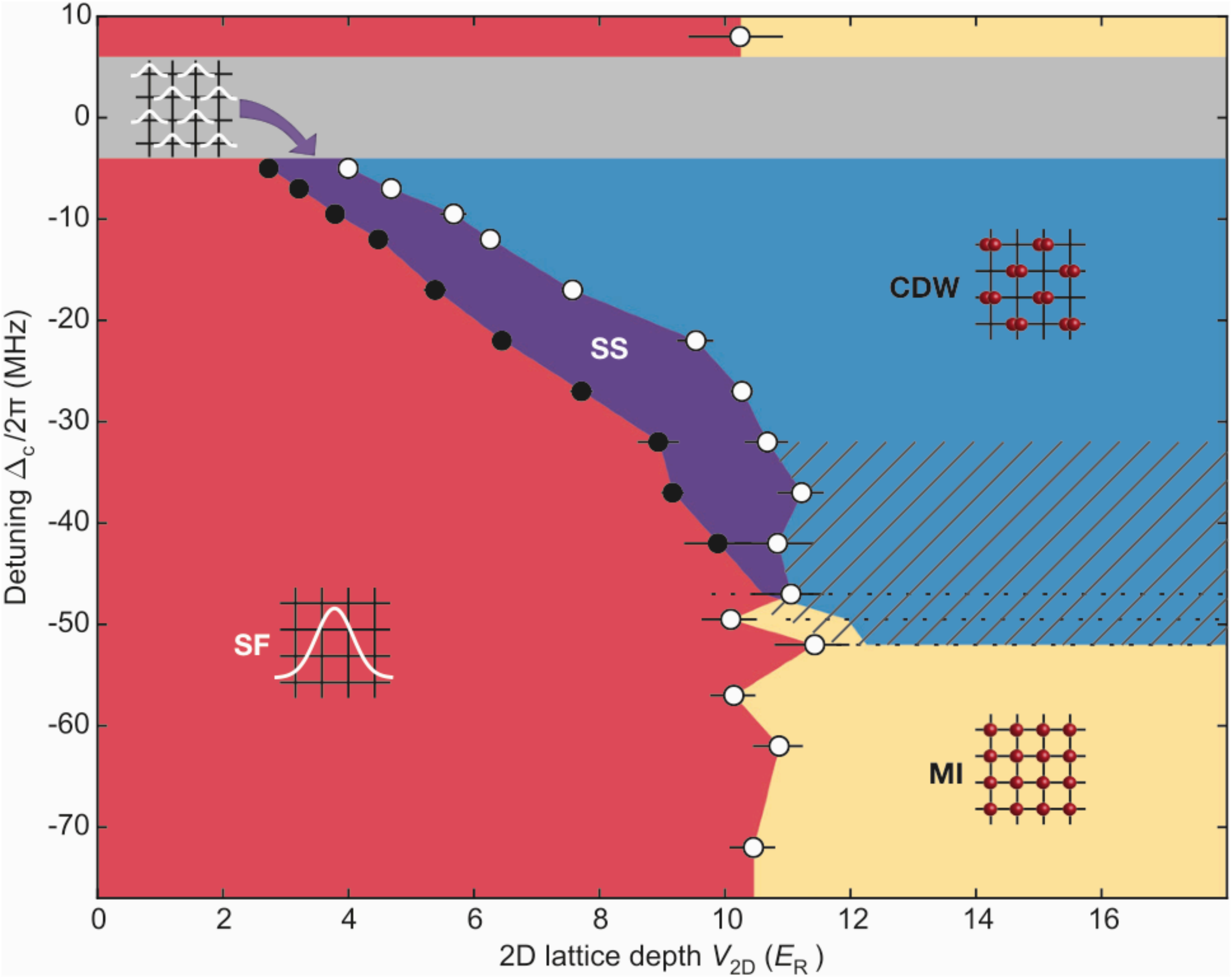
Coherence: Measure of superfluid order parameter



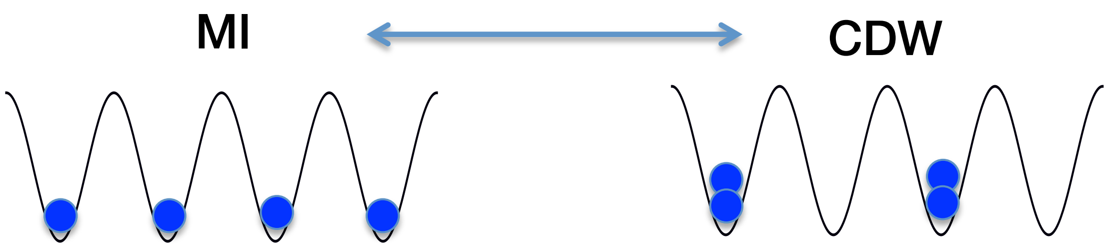
Cavity output: measure of checkerboard order parameter

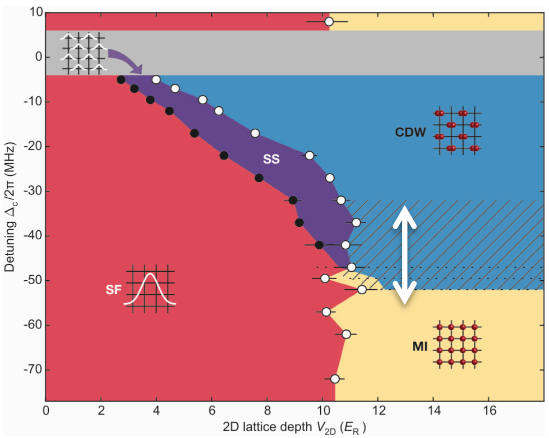


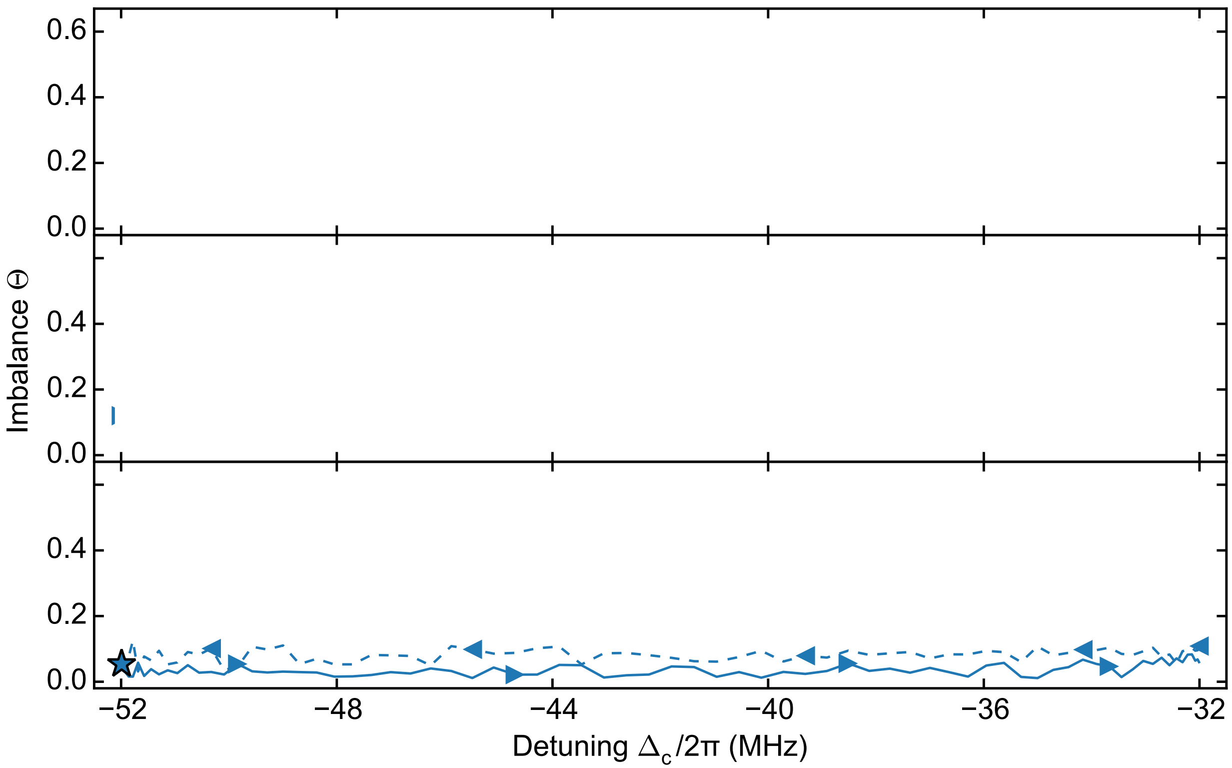
Phase diagram



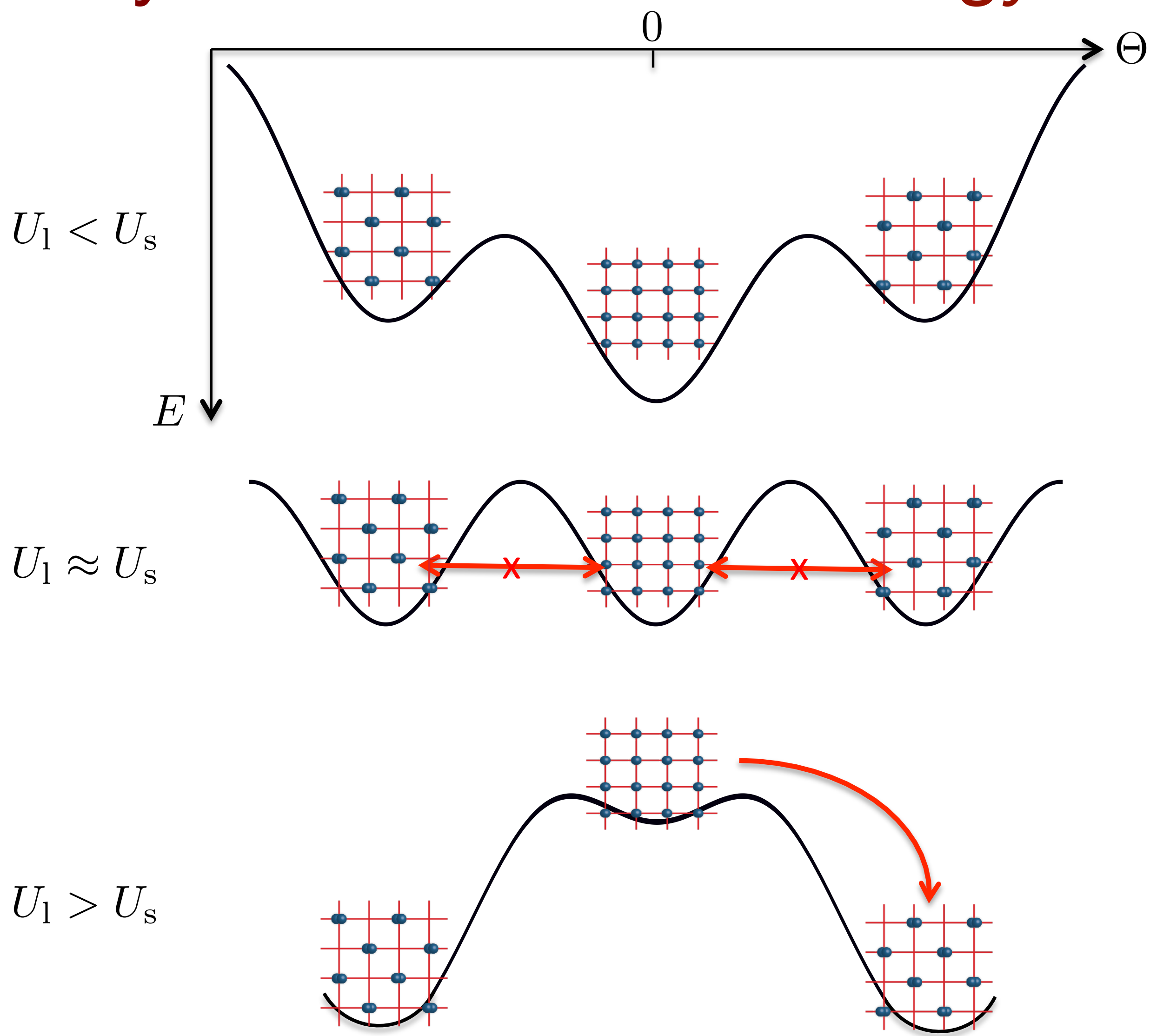
Evolution between CDW & MI







Hysteretic behavior: *Energy landscape*

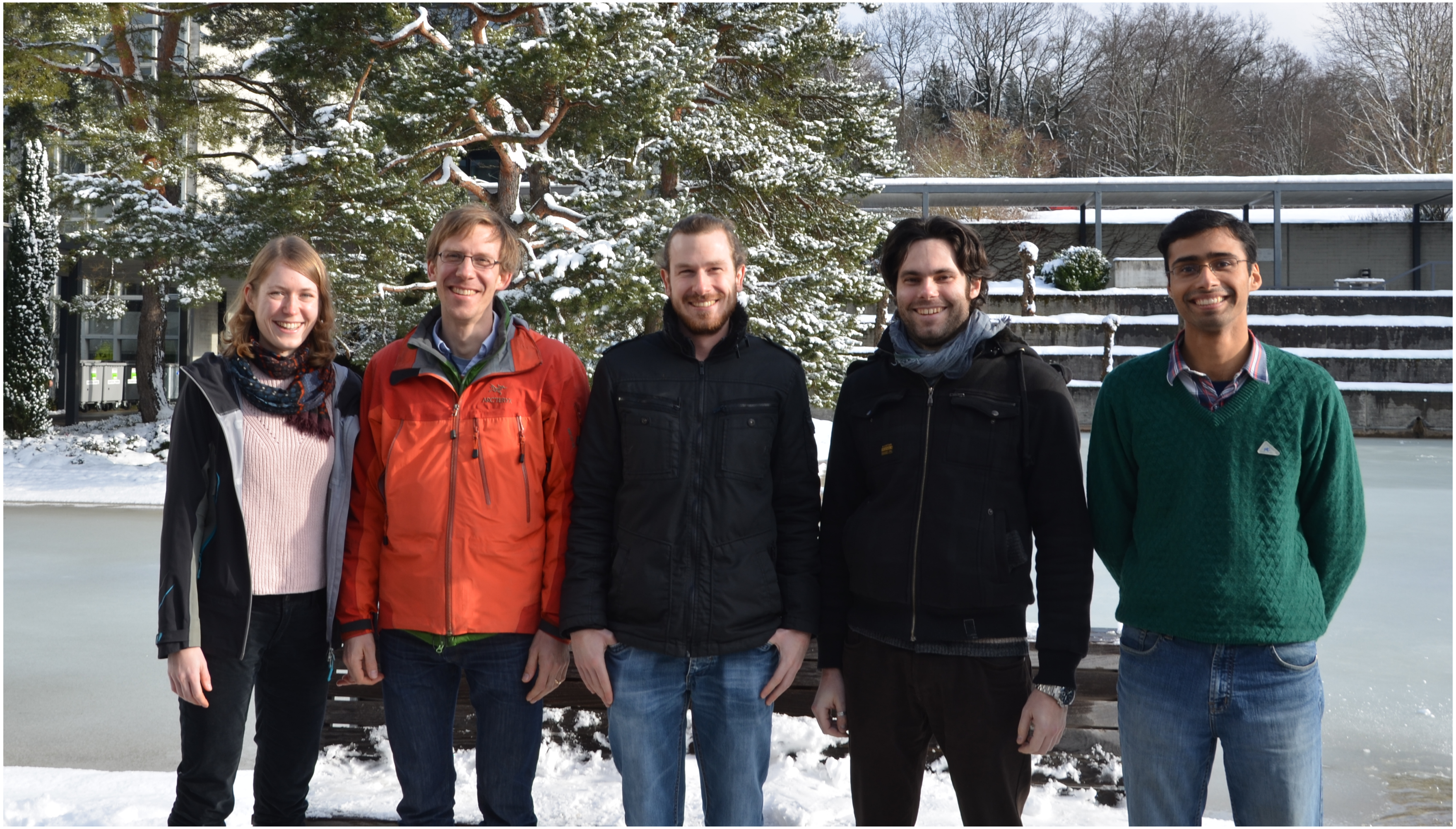


CDW energetically favorable, but blocked by energy barrier

System driven out of metastable state

Ferdinand Brennecke now@University Bonn

Rafael Mottl now@Mettler-Toledo



Renate Landig

Tobias Donner

Lorenz Hruby

Manuele Landini

Nishant Dogra

Deep understanding of many-body quantum physics

Identified the hard problems

$$H = T + U + V$$

Thanks !

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Quantum Gases in Optical Lattices
Gregor Jotzu
Michael Messer
Rémi Desbuquois
Frederic Görg

BEC and Cavity
Tobias Donner
Renate Landig
Lorenz Hruby
Nishant Dogra
Manuele Landini

Lithium Microscope
Jean-Philippe Brantut
Sebastian Krinner
Dominik Husmann
Martin Lebrat
Samuel Häusler
Shuta Nakajima

Impact experiment
Tobias Donner
Julian Leonard
Andrea Morales
Philip Zupancic

Electronics
Alexander Frank

Administration: Stephanie Schorlemer, Eik Szee Goh Aschauer

Former Members: Daniel Greif, Thomas Uehlinger, Rafael Mottl, Moonjoo Lee), David Stadler, Ferdinand Brennecke, Jakob Meineke, Laura Corman (ENS), Leticia Tarruell (ICFO), Torben Müller, Kristian Baumann (Stanford), Silvan Leinss, Robert Jördens (NIST), Bruno Zimmermann, Henning Moritz (Hamburg), Christine Guerlin (Thales), Niels Strohmaier (Hamburg),Thomas Bourdel (Palaiseou), Kenneth Günter, Michael Köhl (Cambrigde), Anton Öttl, Stephan Ritter (MPQ), Thilo Stöferle (IBM), ...

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