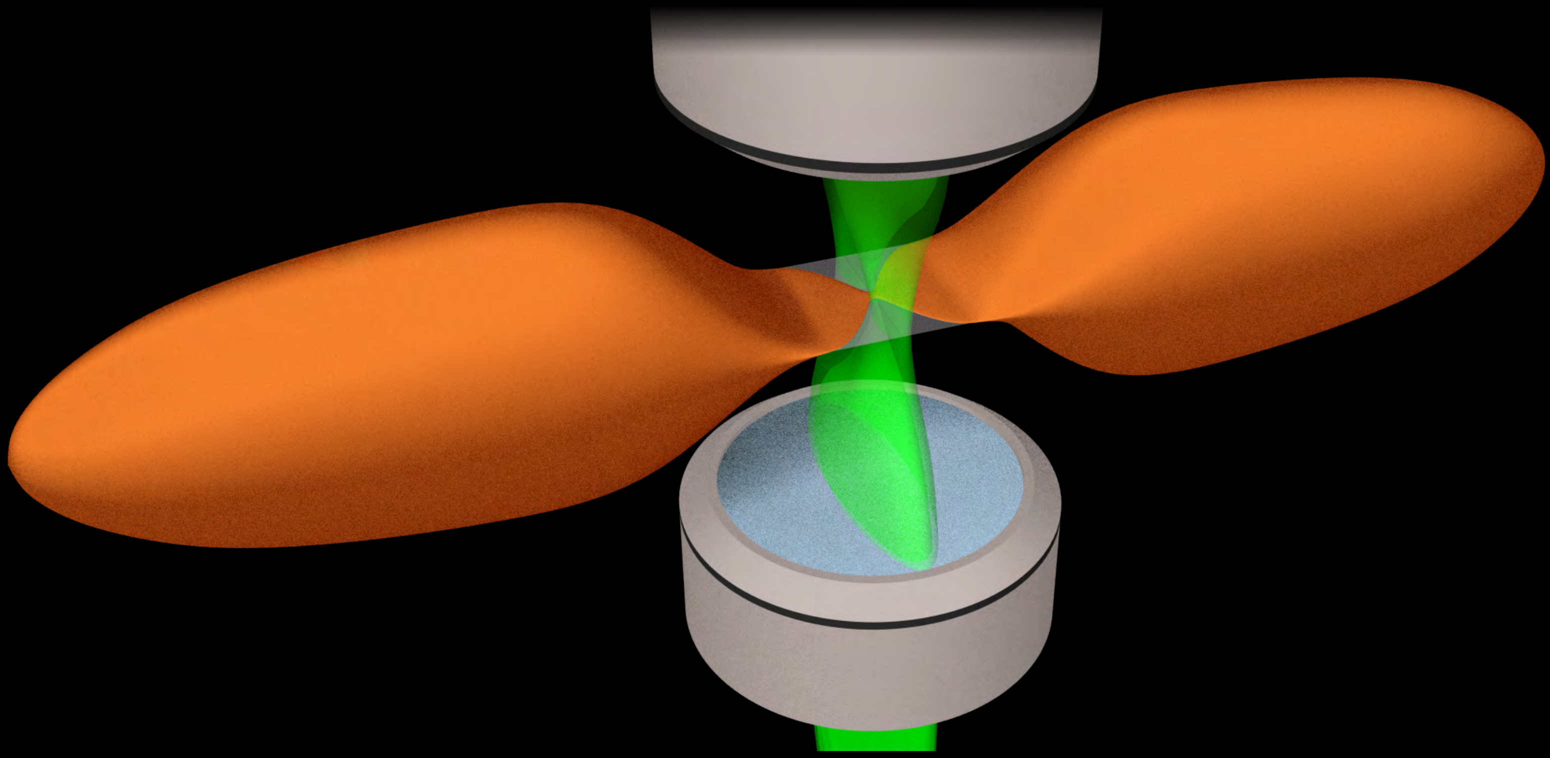
Mesoscopic transport experiments with cold atoms



Jean-Philippe Brantut

Institute of Physics, EPFL

Ultra-cold atoms

- Density scales: 10^{12} cm^{-3}
  - Interparticle spacing comparable with the wavelength of visible light

    Optical lattices, disorder, mesoscopic structures

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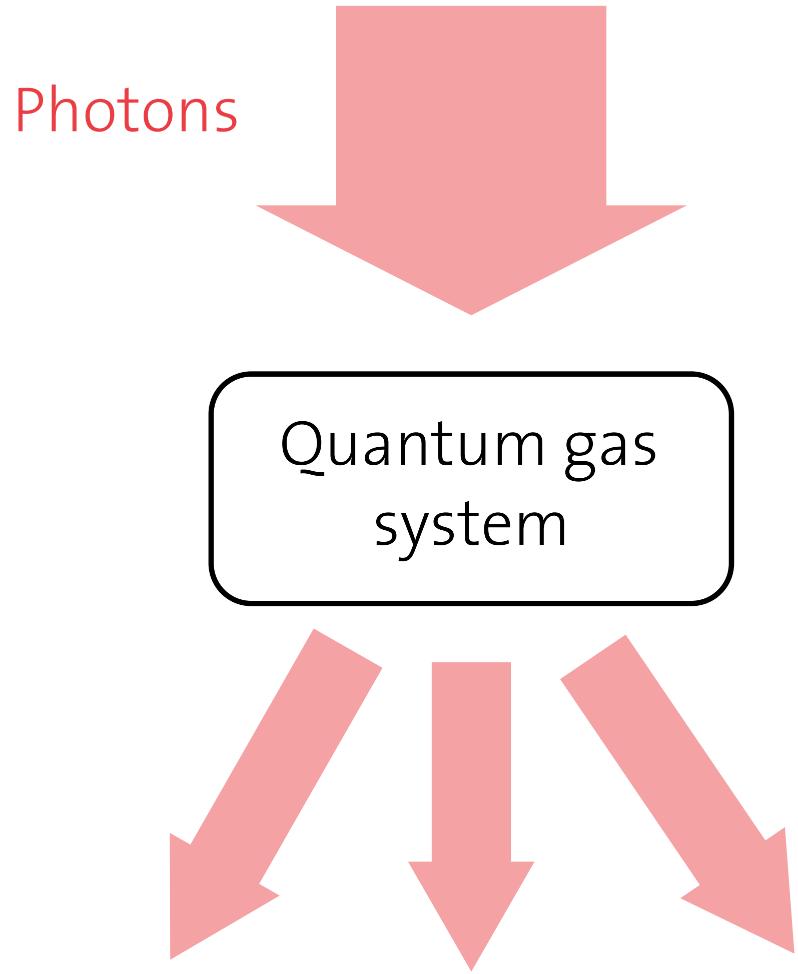
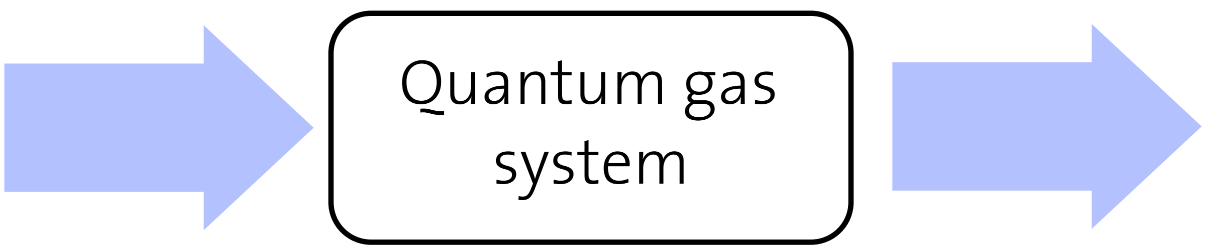
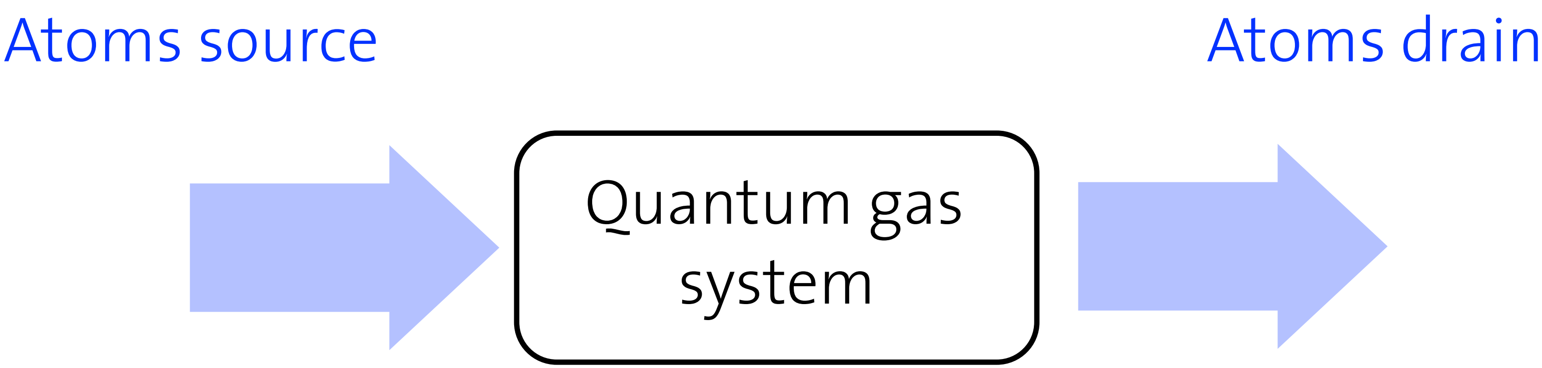
- Neutral particles with a complex internal structure
  - Controls the mechanical action of light onto atoms
  - Spectroscopic addressing of internal degrees of freedom
  - Short range (contact) interactions tunable by control fields

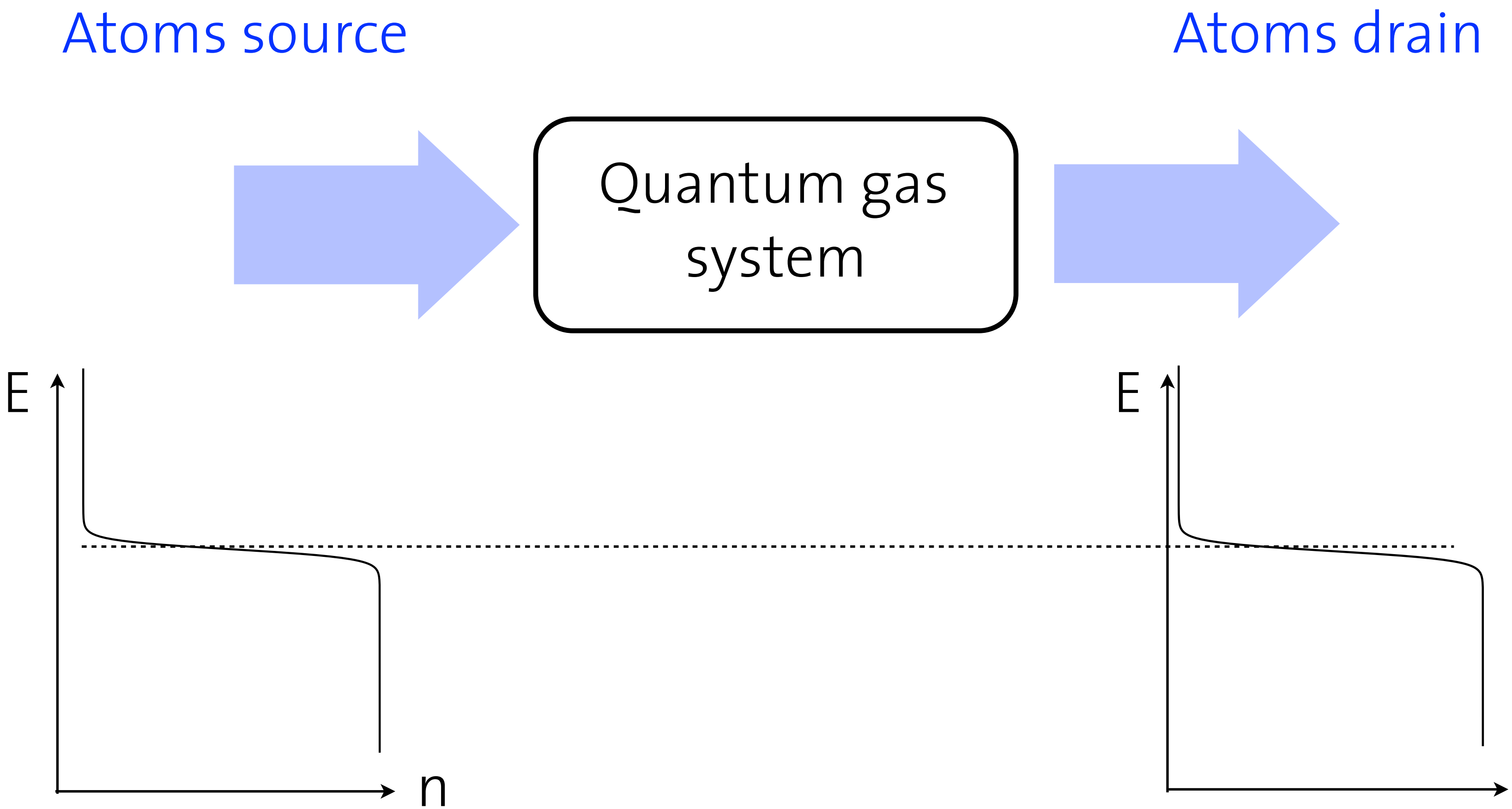
Quantum gas system


Photons
Quantum gas system

Atoms

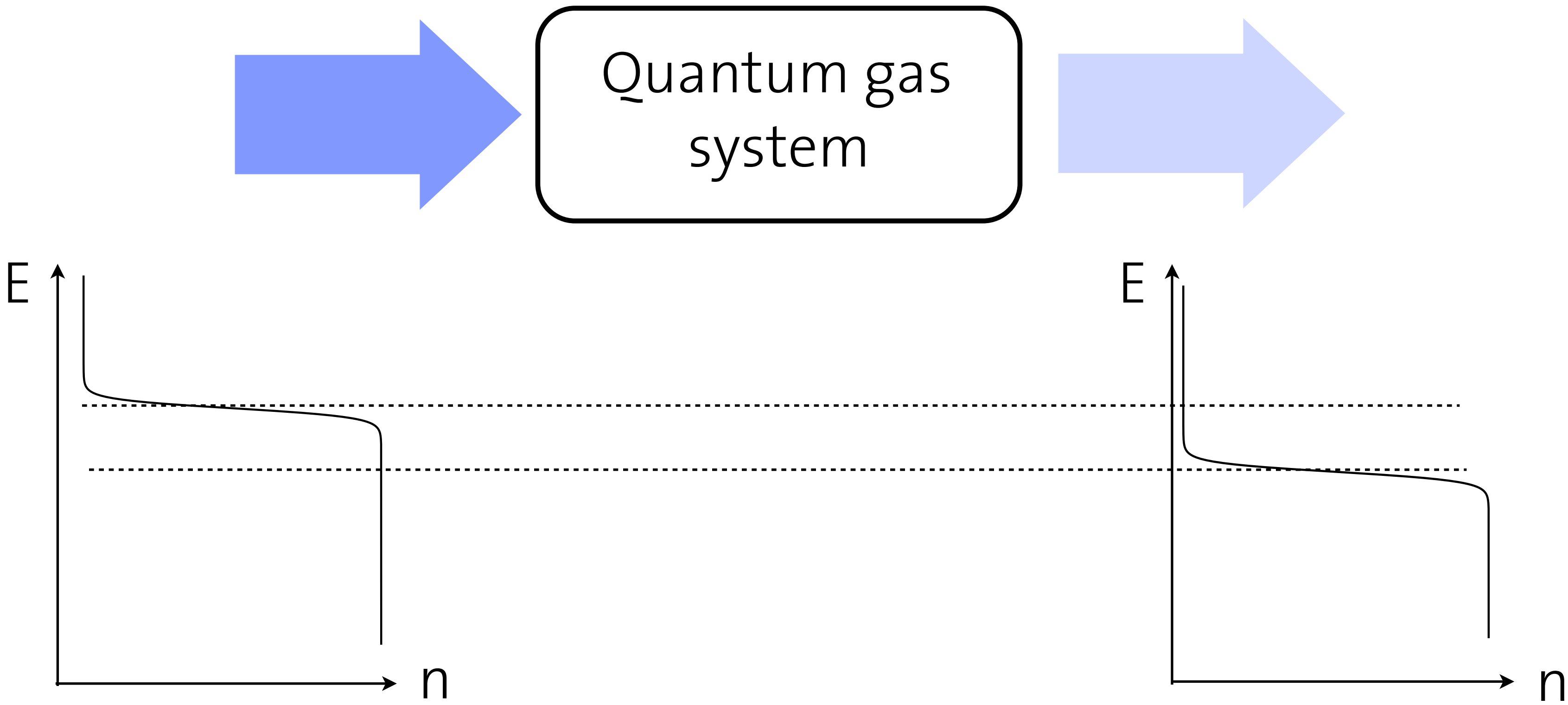


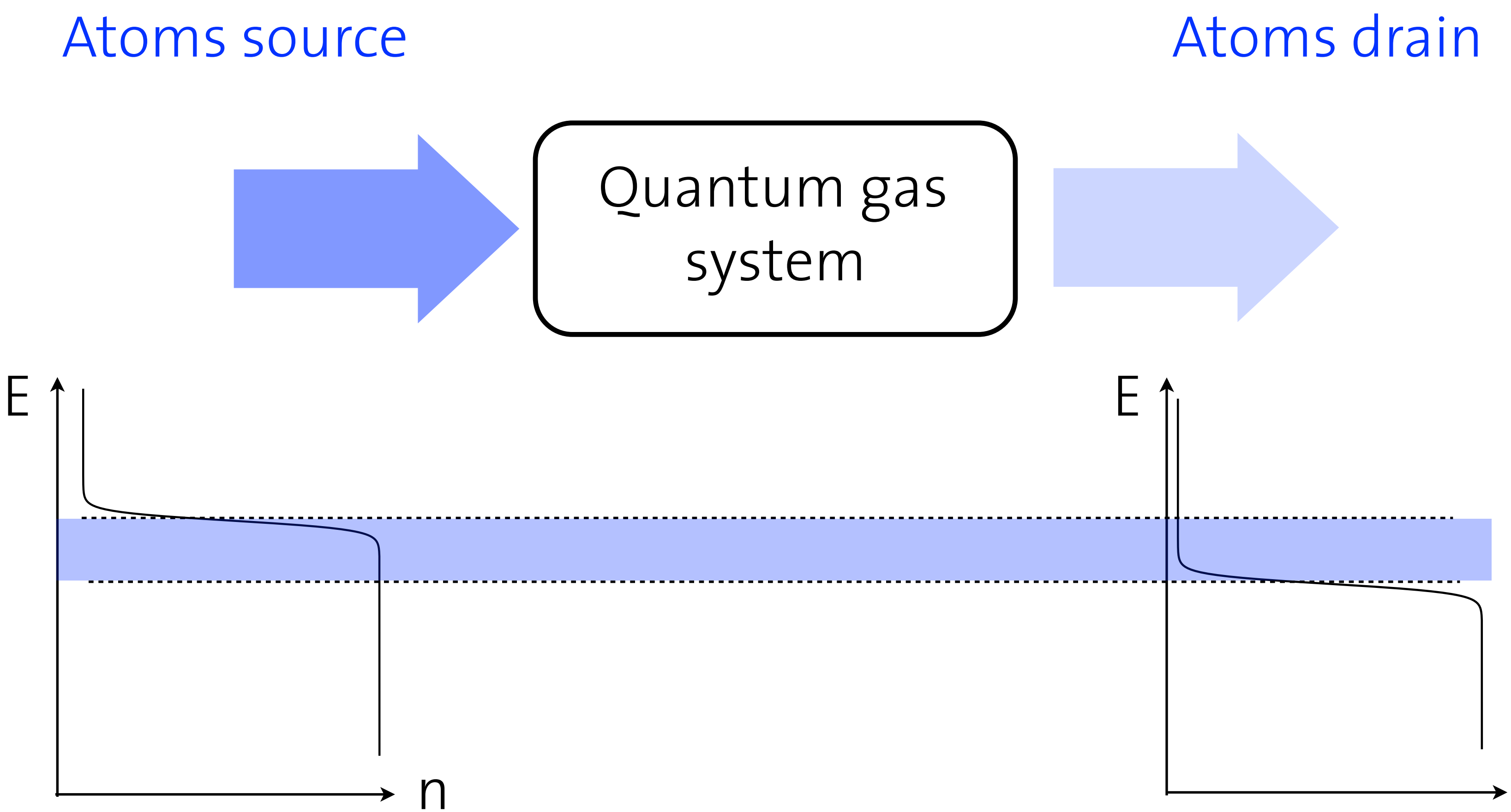

Atoms source
Atoms drain
Quantum gas
system


Atoms source
Atoms drain
Quantum gas system
E
n
E
n

Atoms source

Atoms drain




Atoms source
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E
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- Quantum Point Contact for cold Fermions
  - Transport measurement technique
  - Quantized conductance

- Interacting systems
  - Feshbach resonances
  - Fate of quantized conductance across the BCS-BEC crossover
  - Mesoscopic lattices

- Future prospects

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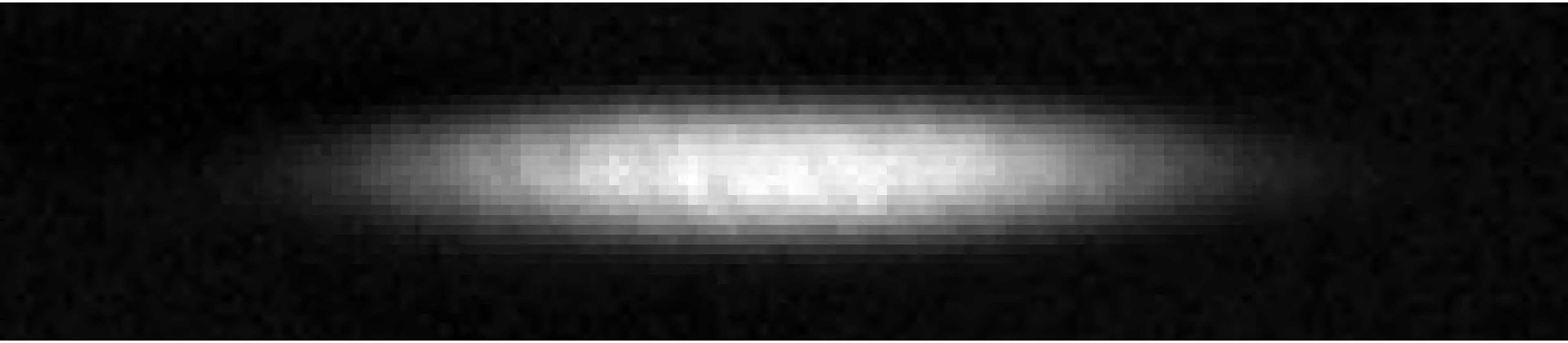
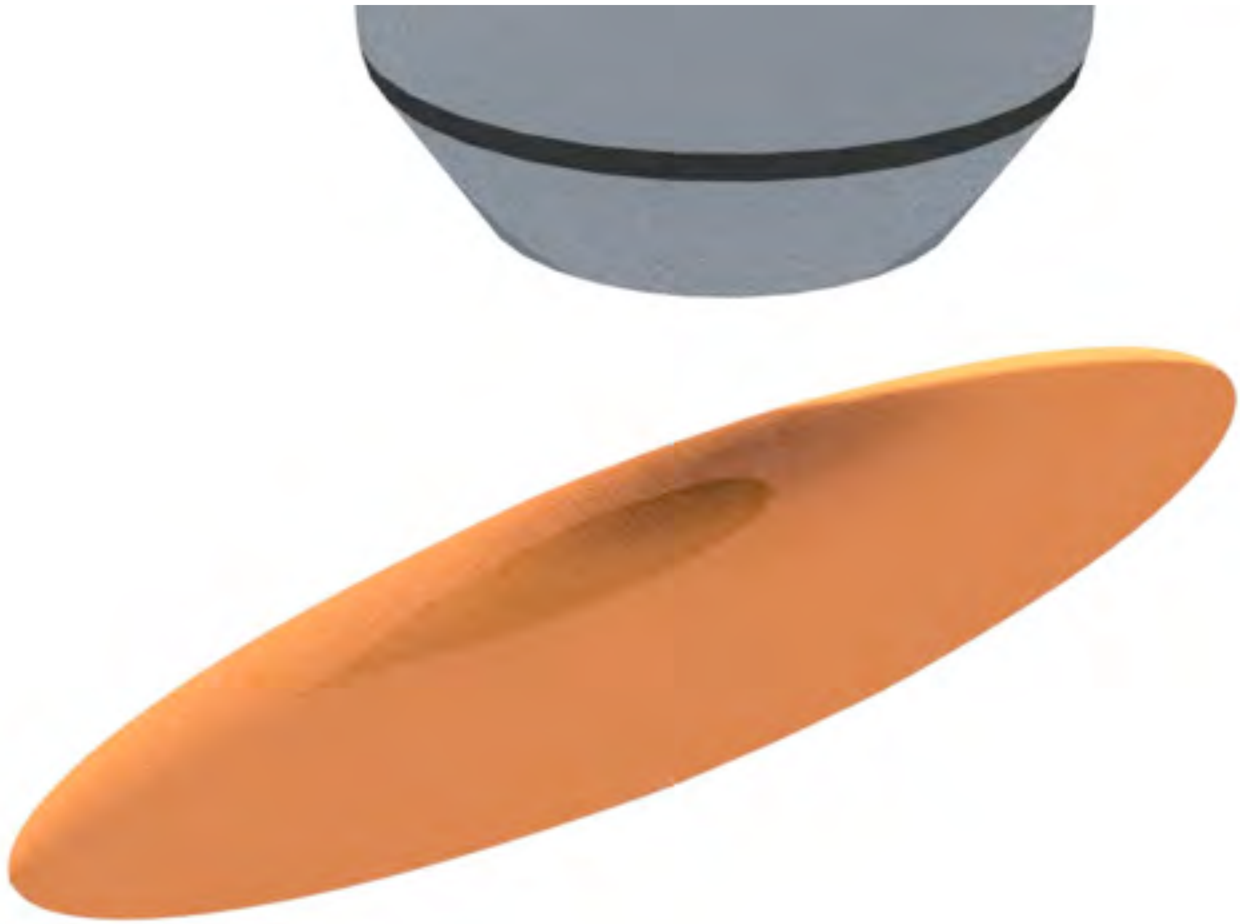
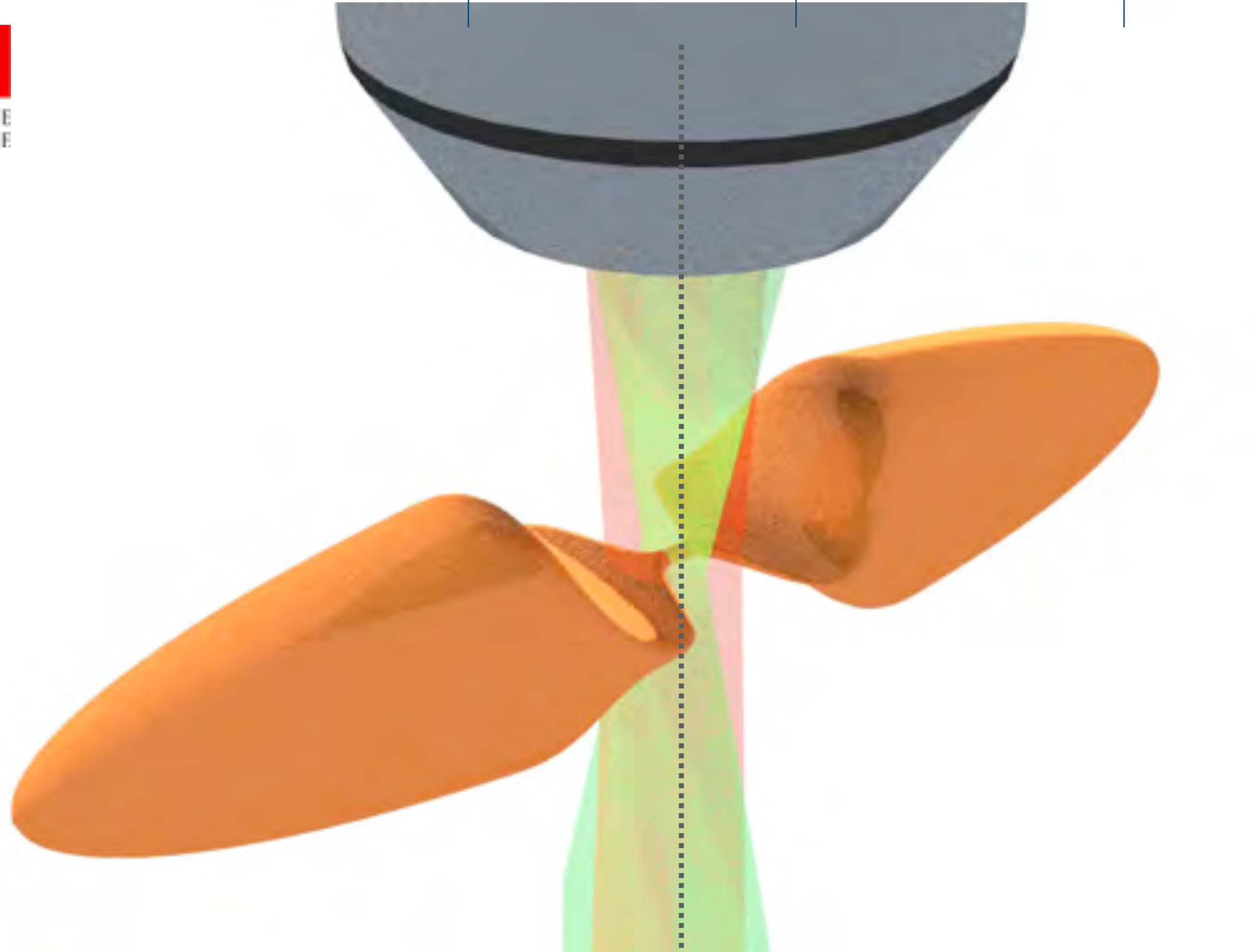


~ 10^5 ^{6}Li atoms

$T = 0.1\, T_F$

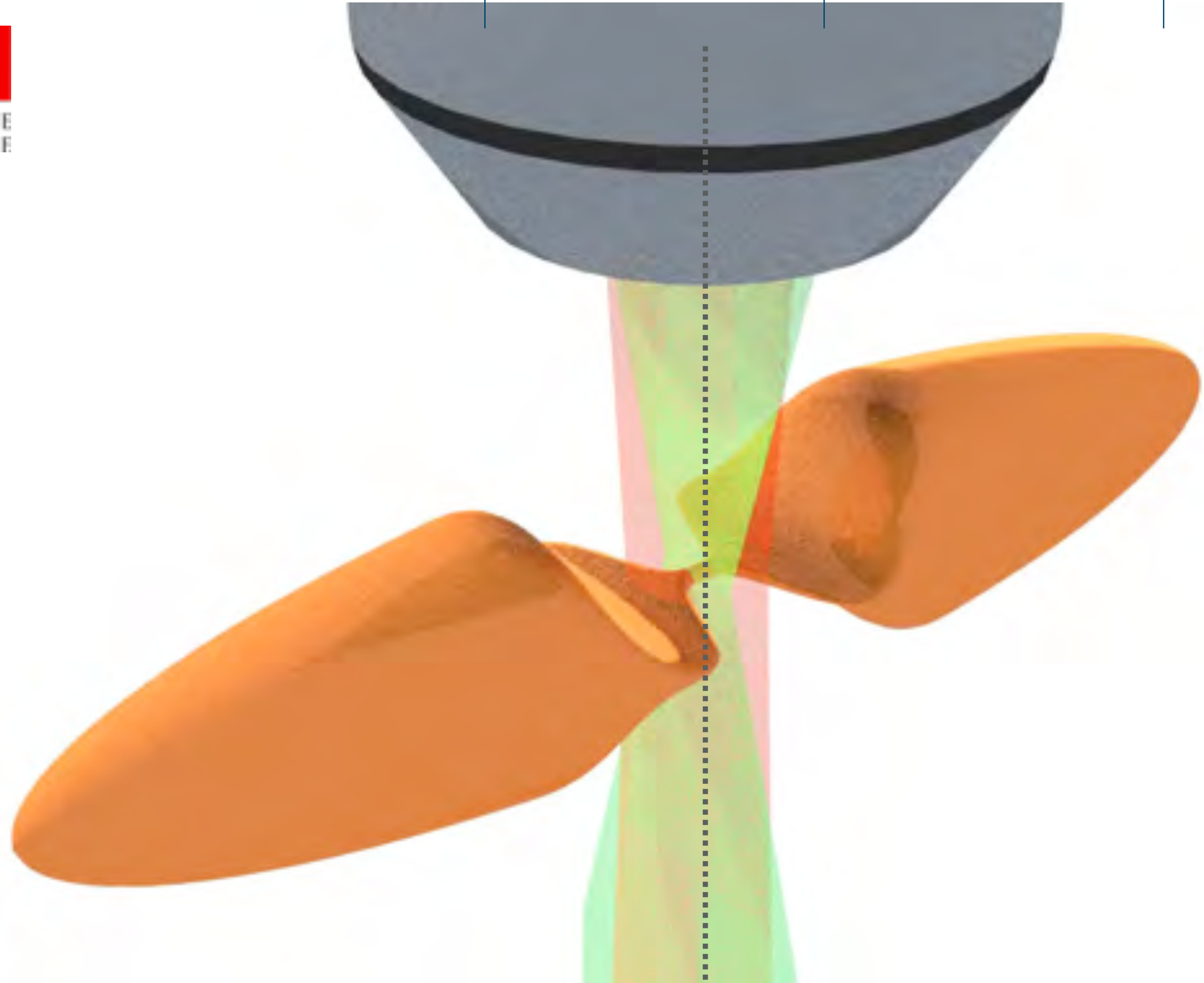




N_{Left}
μ_{Left}

N_{Right}
μ_{Right}

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE



N_{Left}
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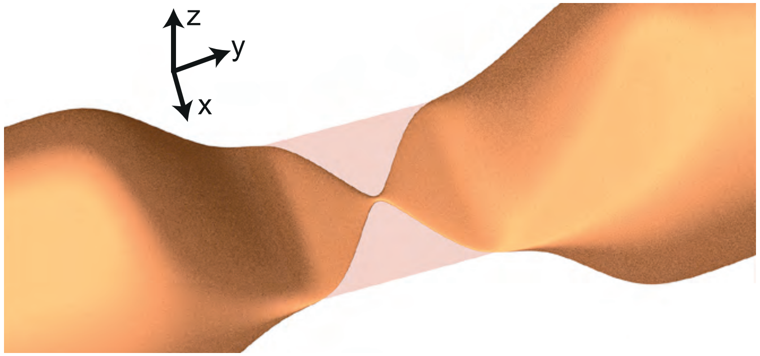
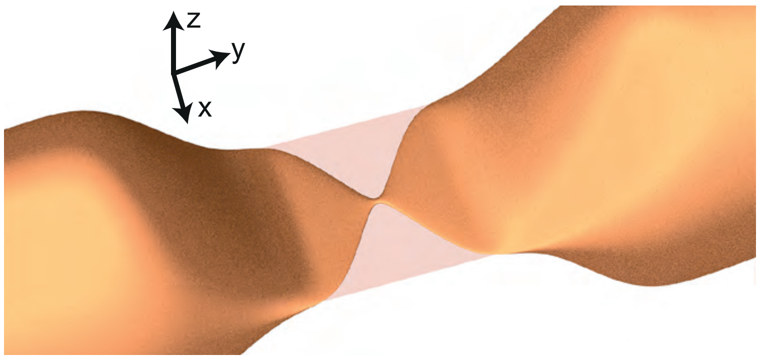


x-frequency	1 - 50 kHz
z-frequency	10 kHz
Chemical potential	0.352 µK + Vg
Temperature	42 nK



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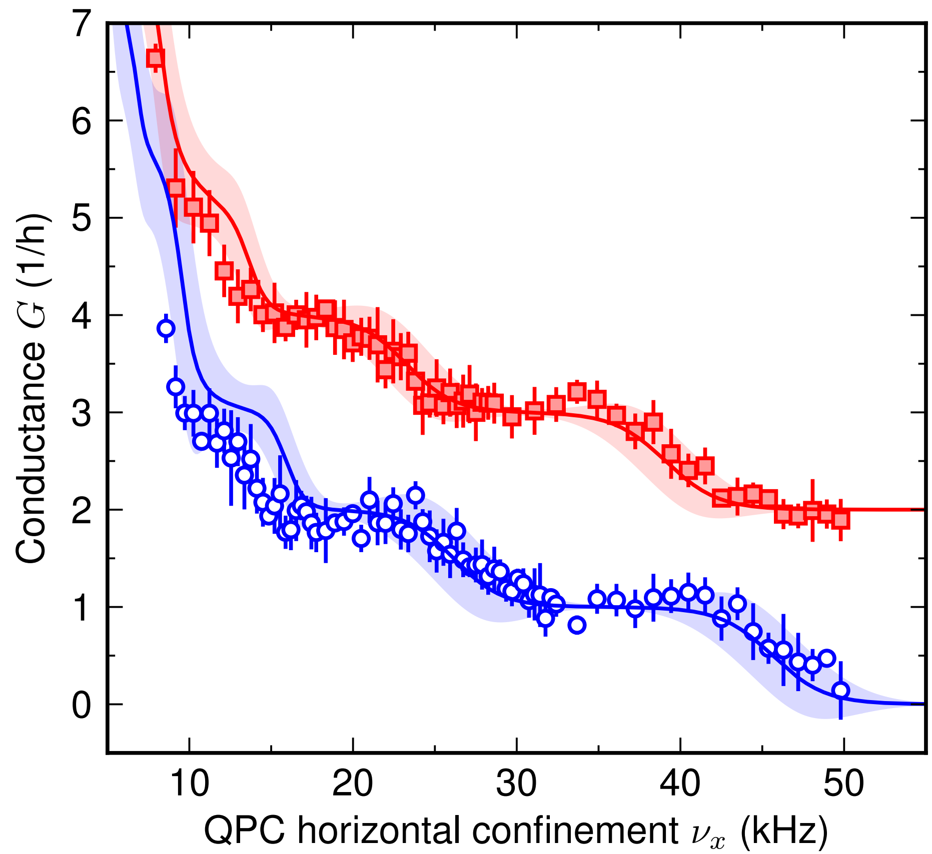
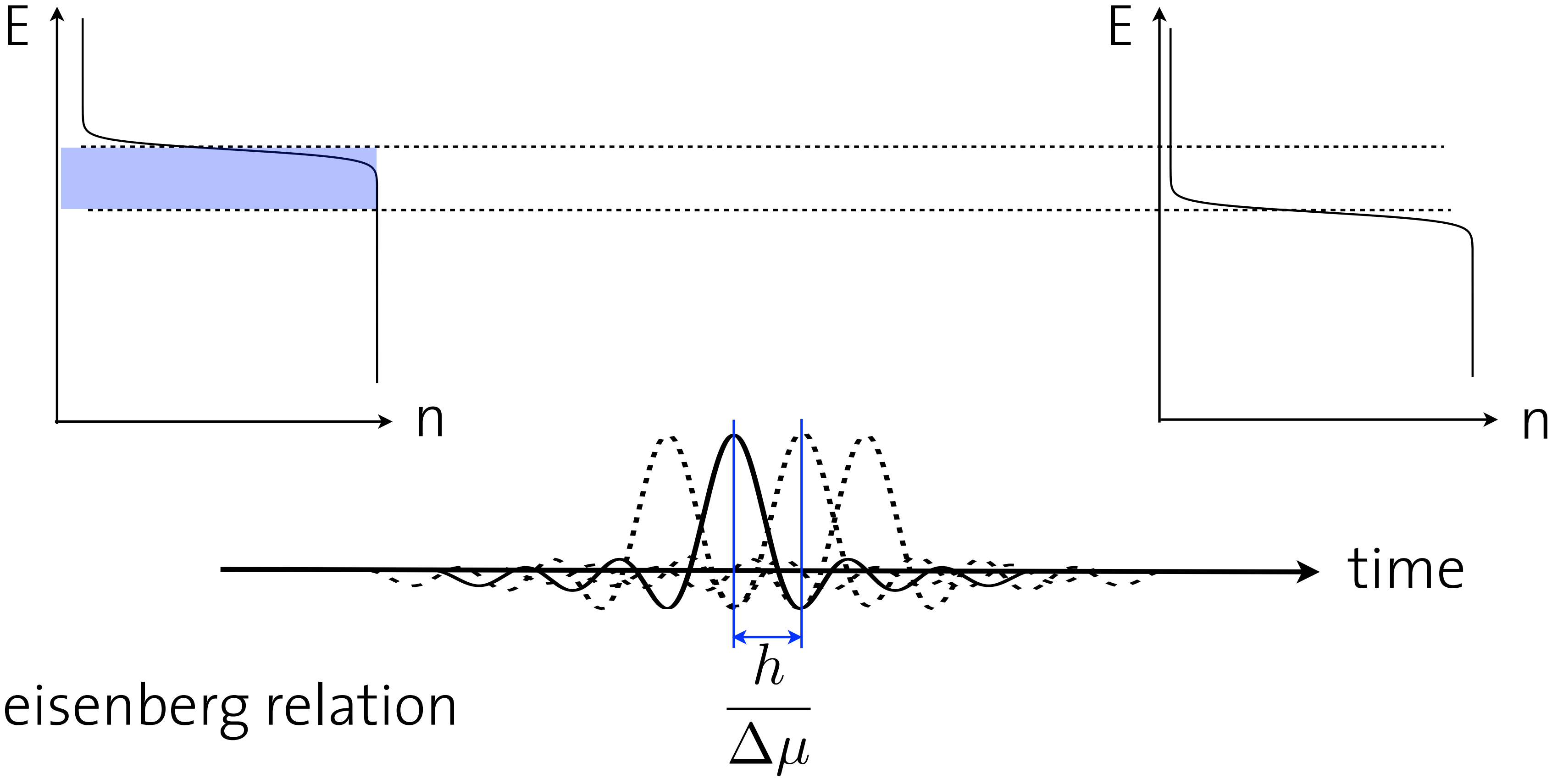
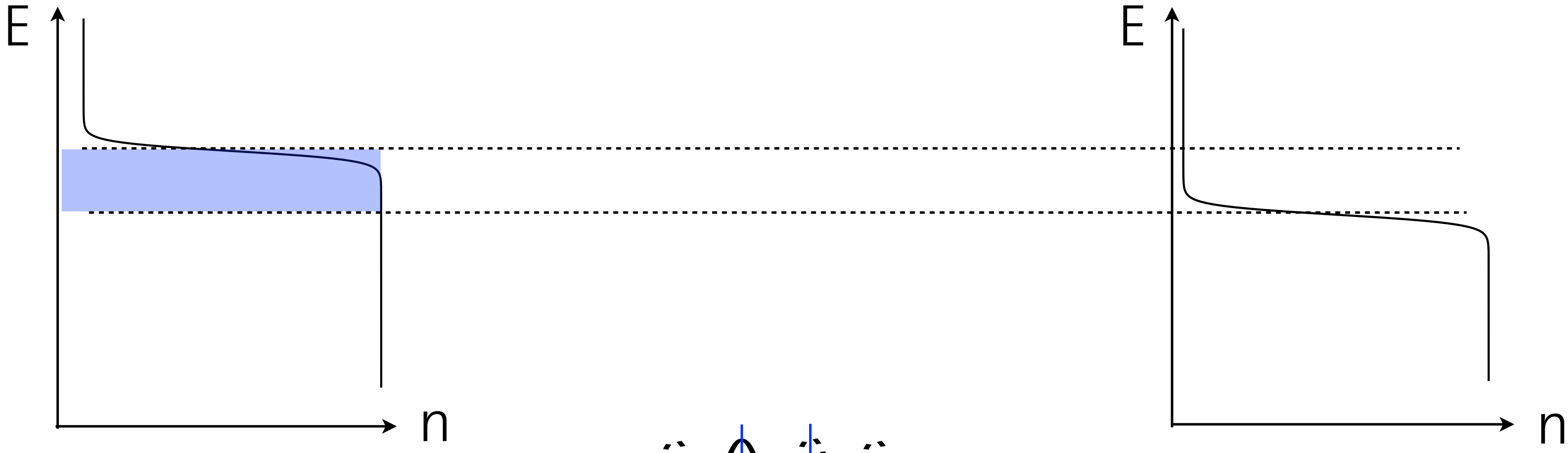


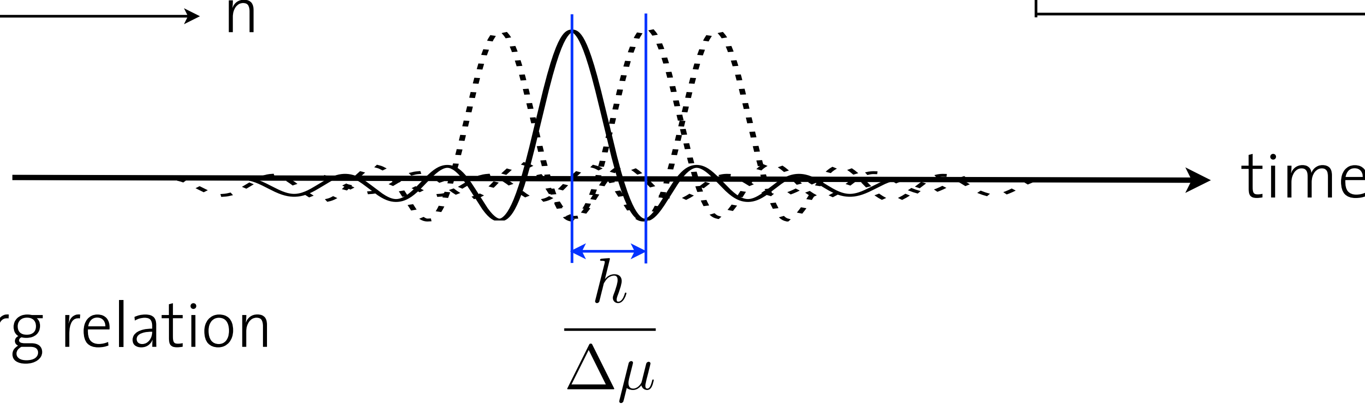
S.Krinner *et al*, Nature ***517***, *64-67 (2015)*


E
n
E
n



Heisenberg relation





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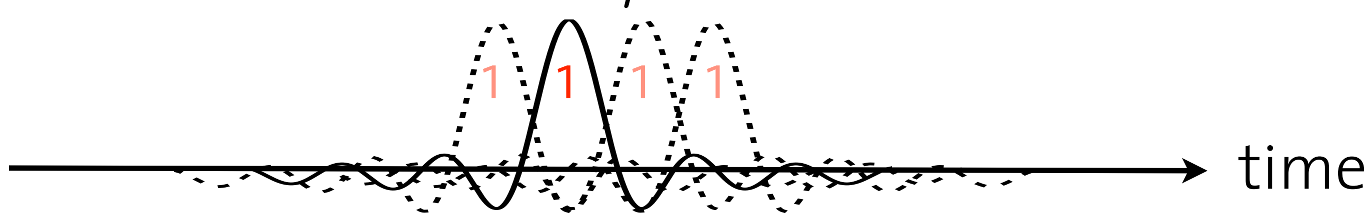
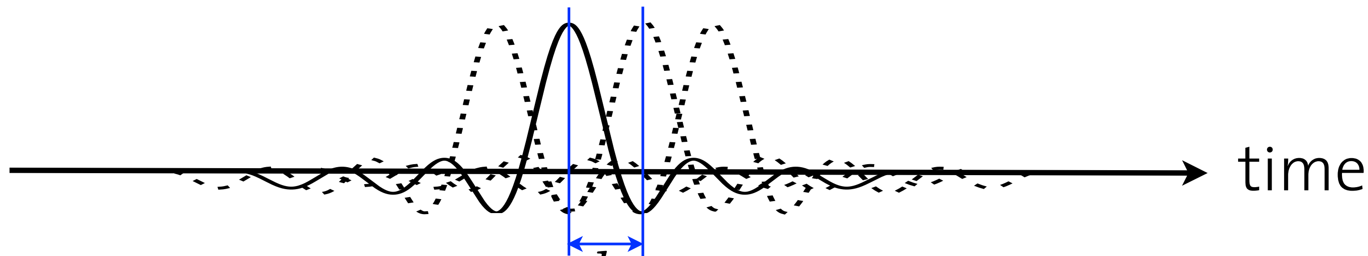
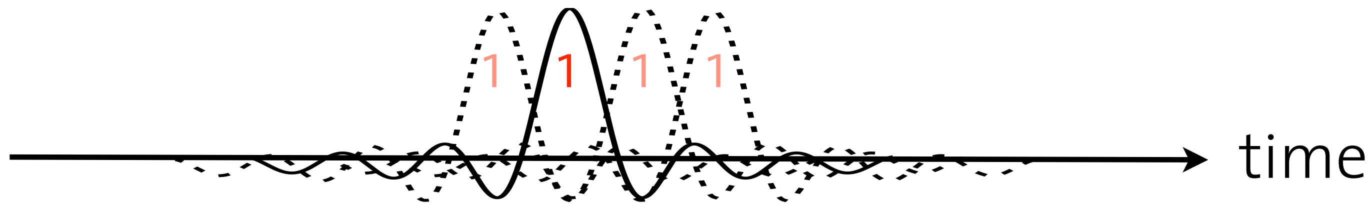


Pauli principle



$$\frac{h}{\Delta\mu}$$

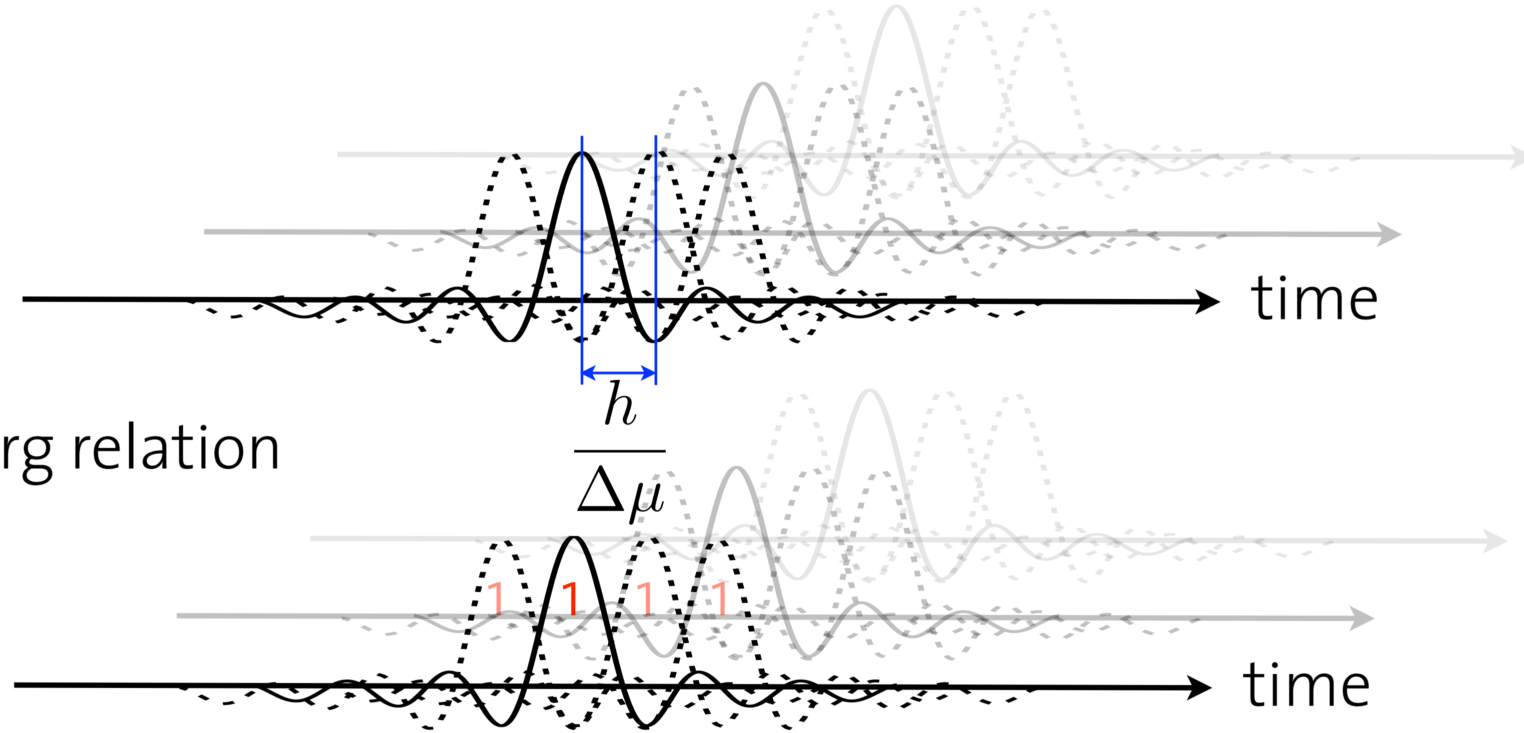
Heisenberg relation



Pauli principle

$$I = \frac{\Delta\mu}{h}$$

Heisenberg relation



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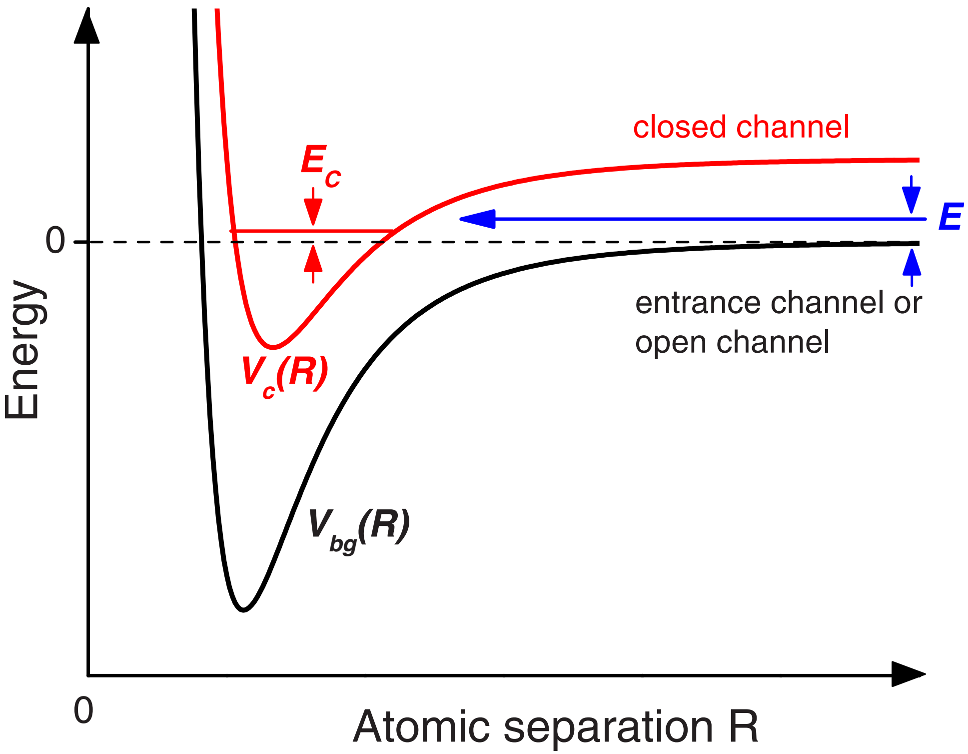
How do atoms interact ?



- van der Waals potential
  - Depends on electrons spin orientation

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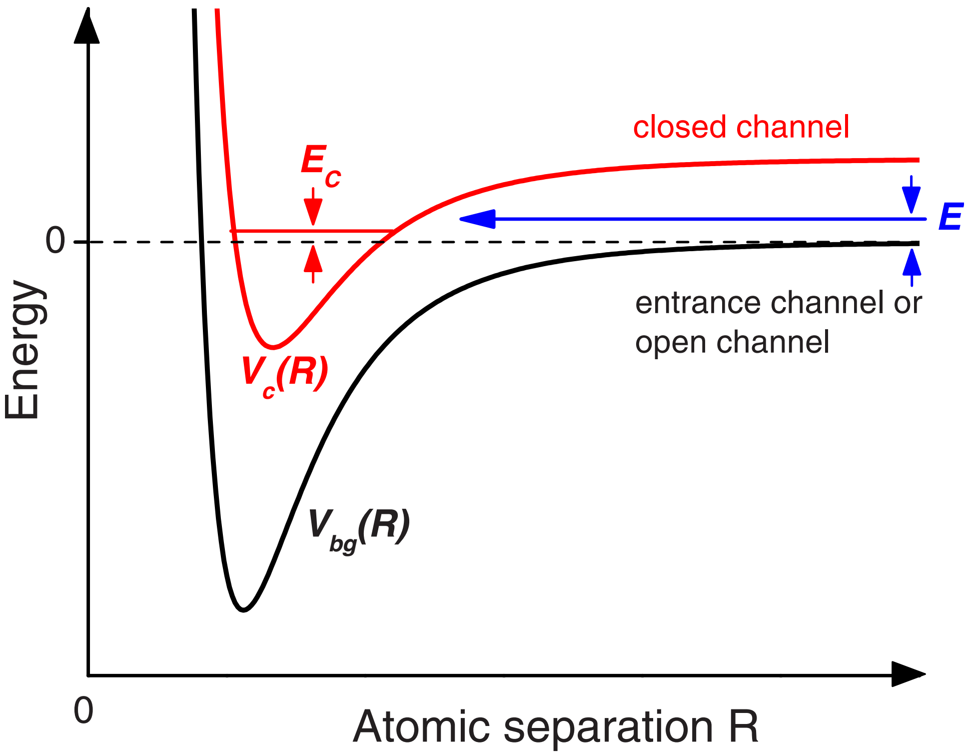

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  - B field: brings the bound state at the dissociation threshold of the triplet potential

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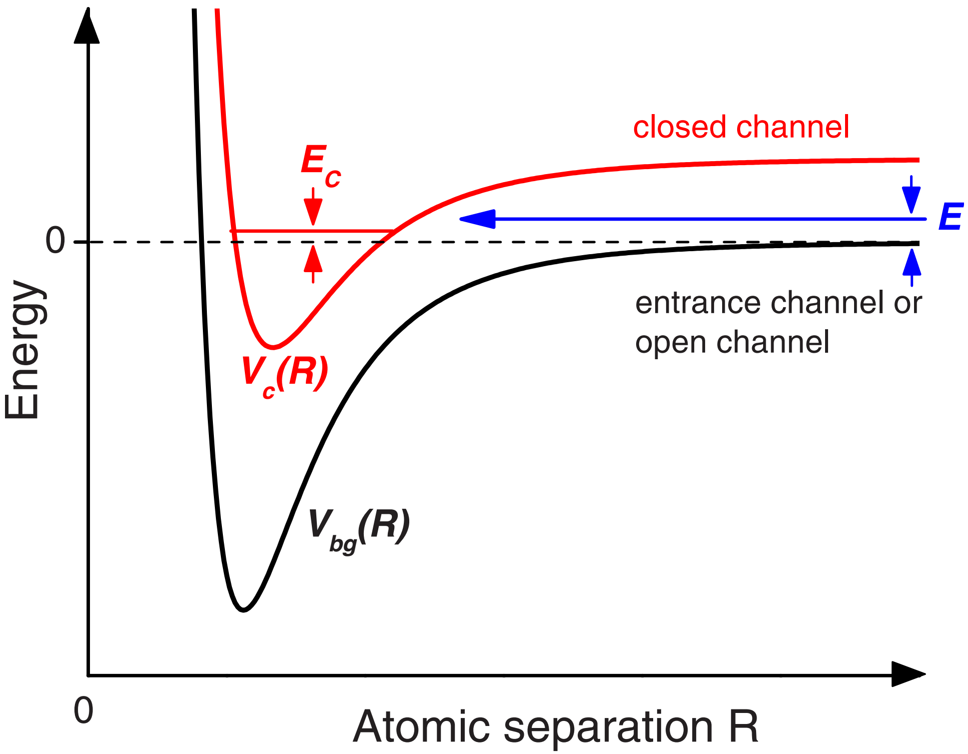
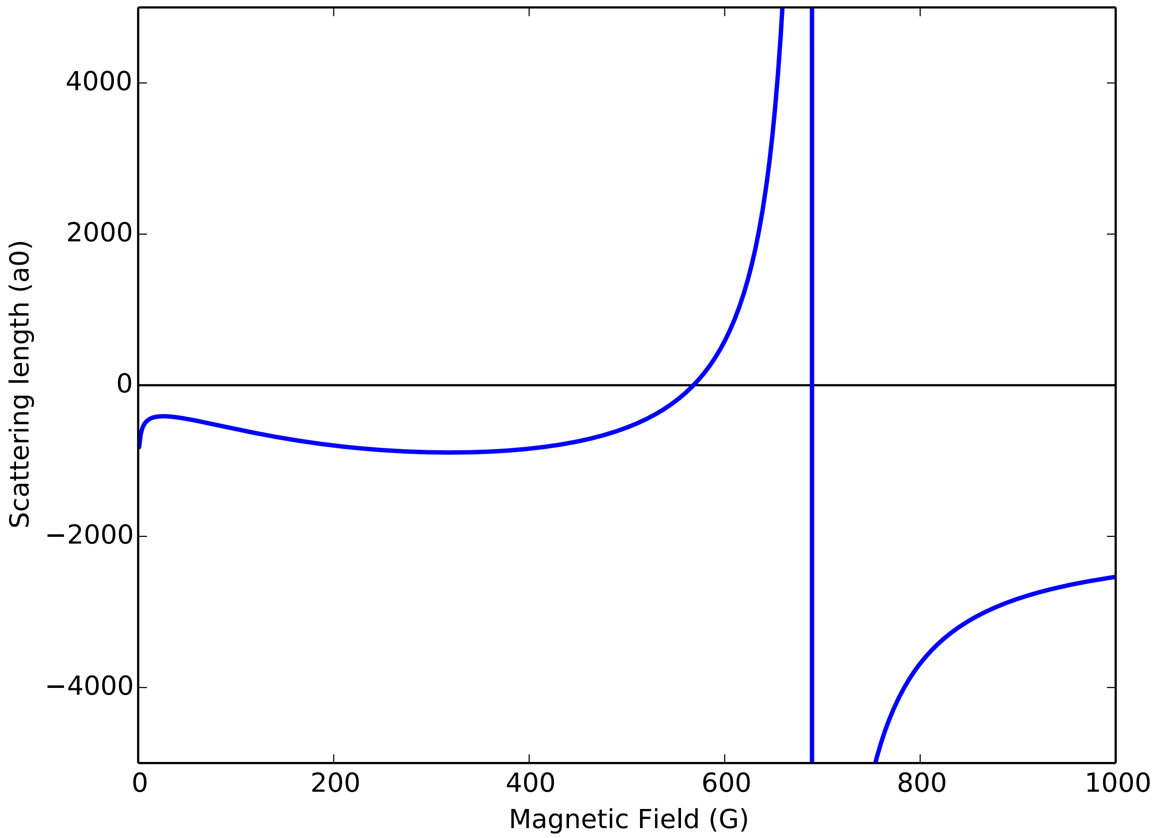


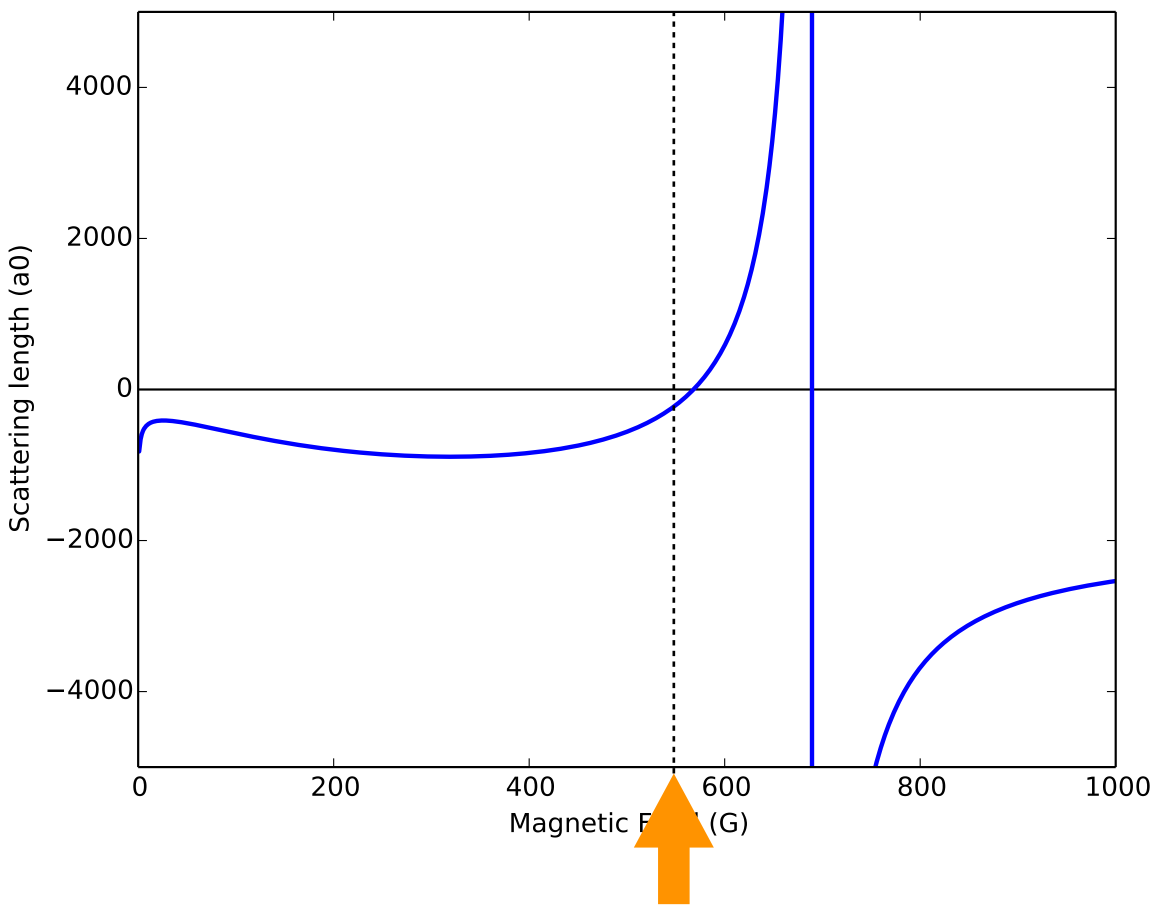
- van der Waals potential
  - Depends on electrons spin orientation
  - Bound states in the singlet potential
  - B field: brings the bound state at the dissociation threshold of the triplet potential
- Scattering resonance for any small channel coupling

Feshbach resonance

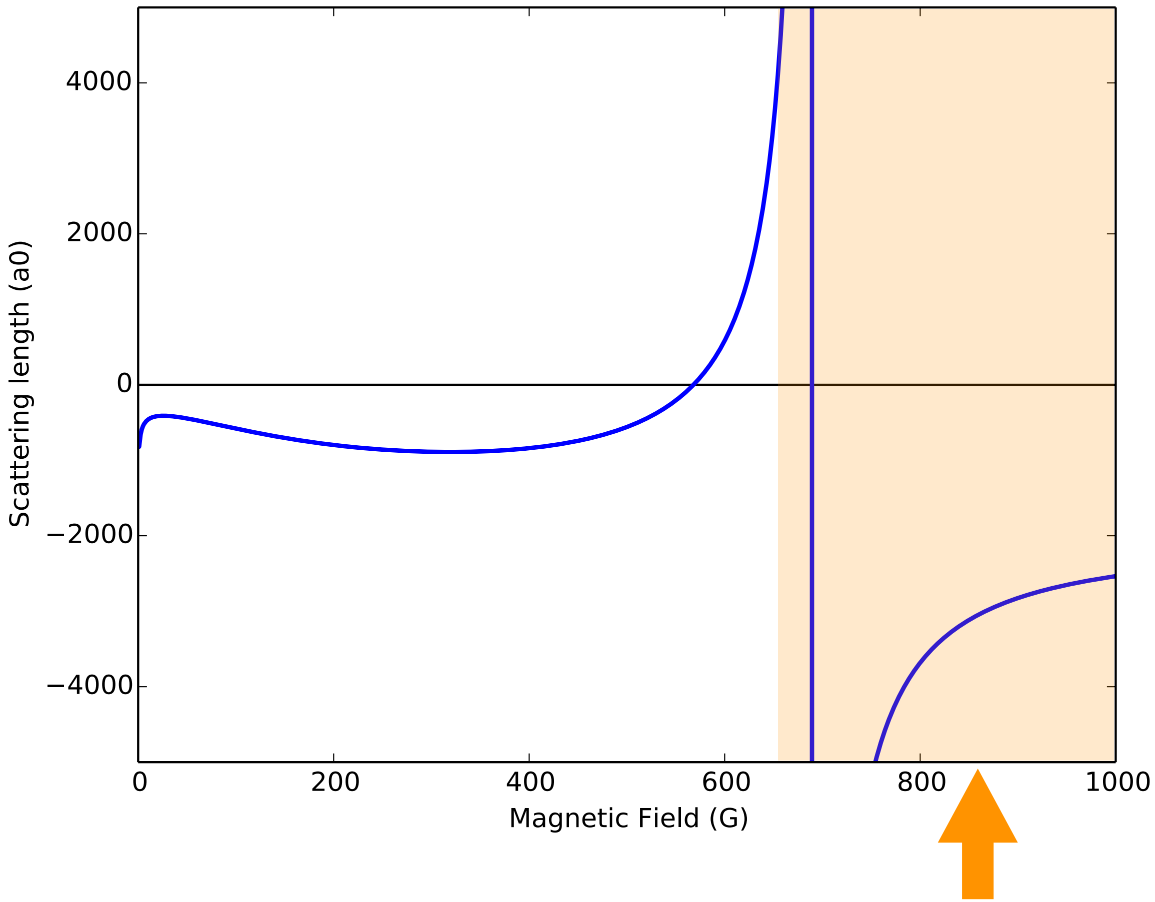


ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Feshbach resonance

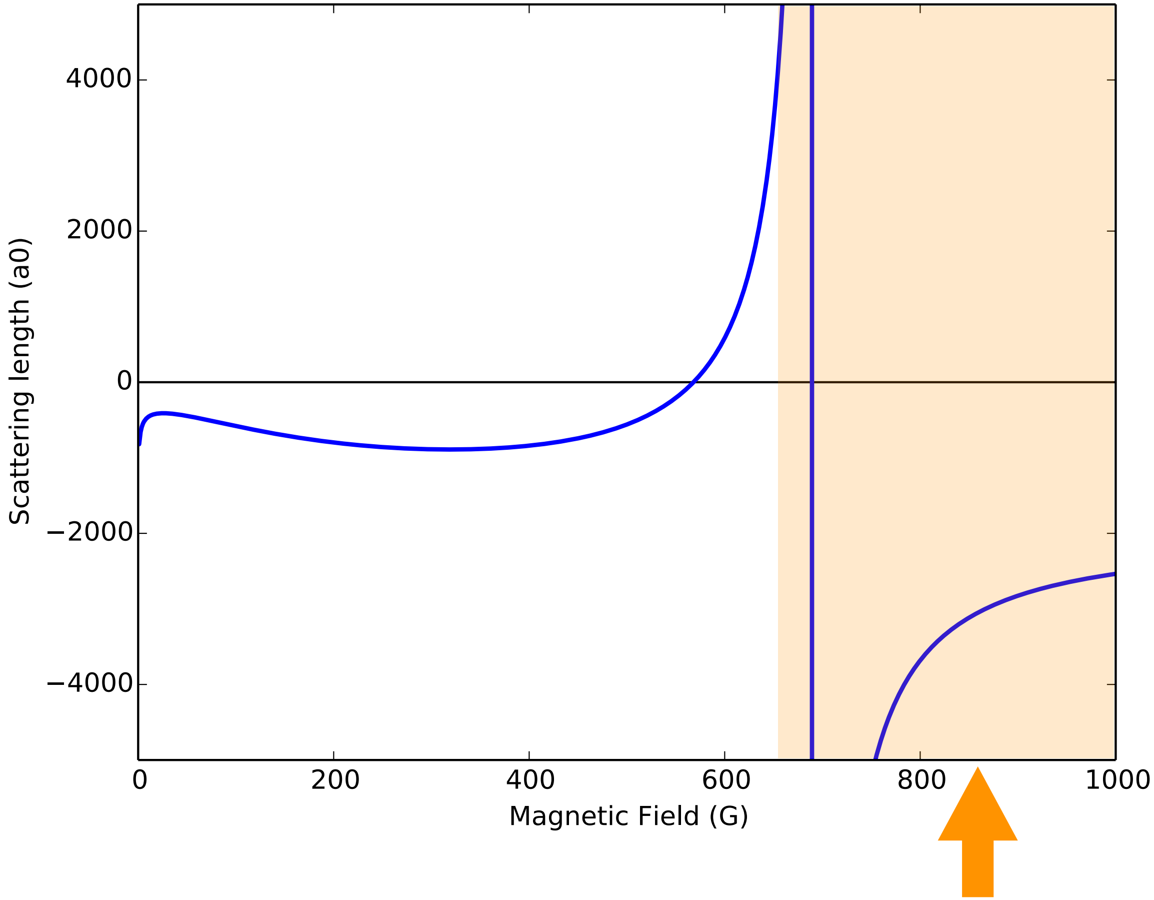


Feshbach resonance



Equation of state : N. Navon *et al*, Science **328** 729 (2010)

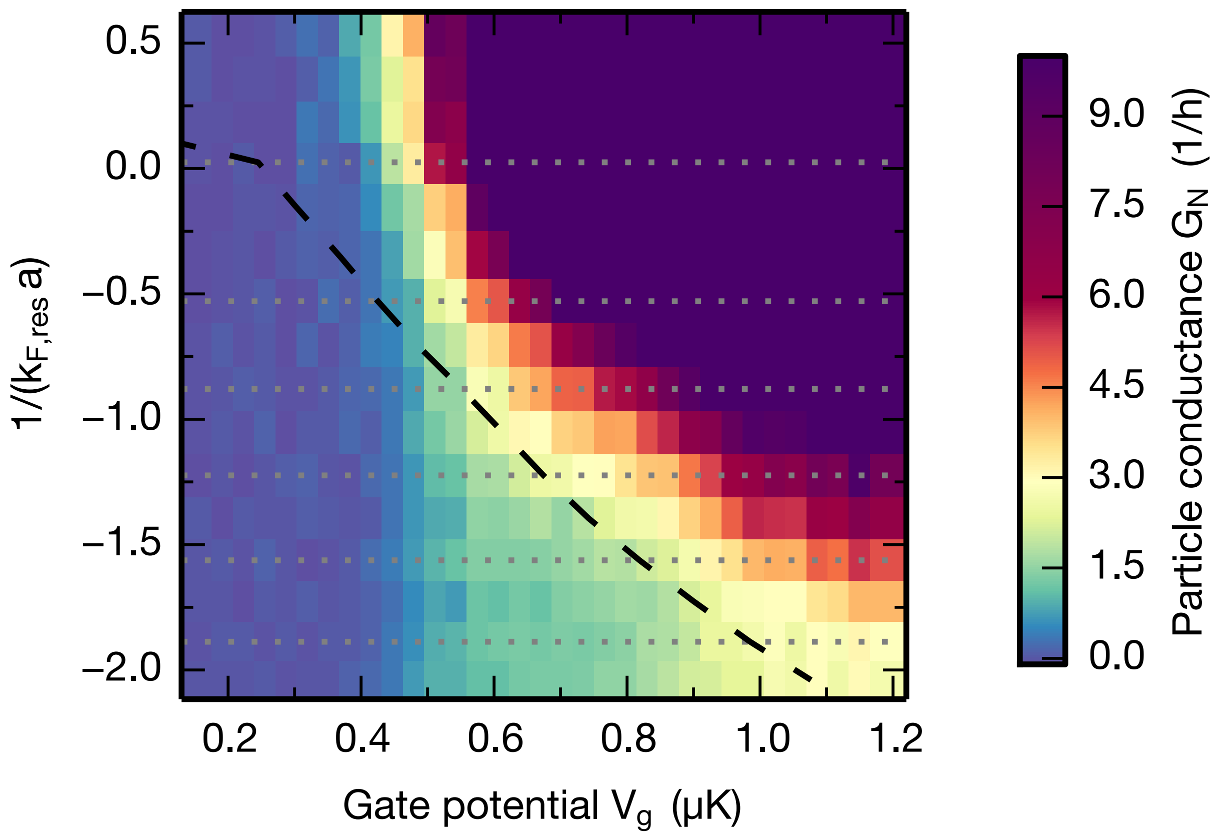
Feshbac



Equation of state : N. Navon *et al*, Science **328** 729 (2010)

- Many-body physics (BCS-BEC crossover):
  - Attractive interactions lead to Cooper pairing at low Temperature
  - Negative a: BCS type pairing / Positive a: chemically bound molecules form a BEC

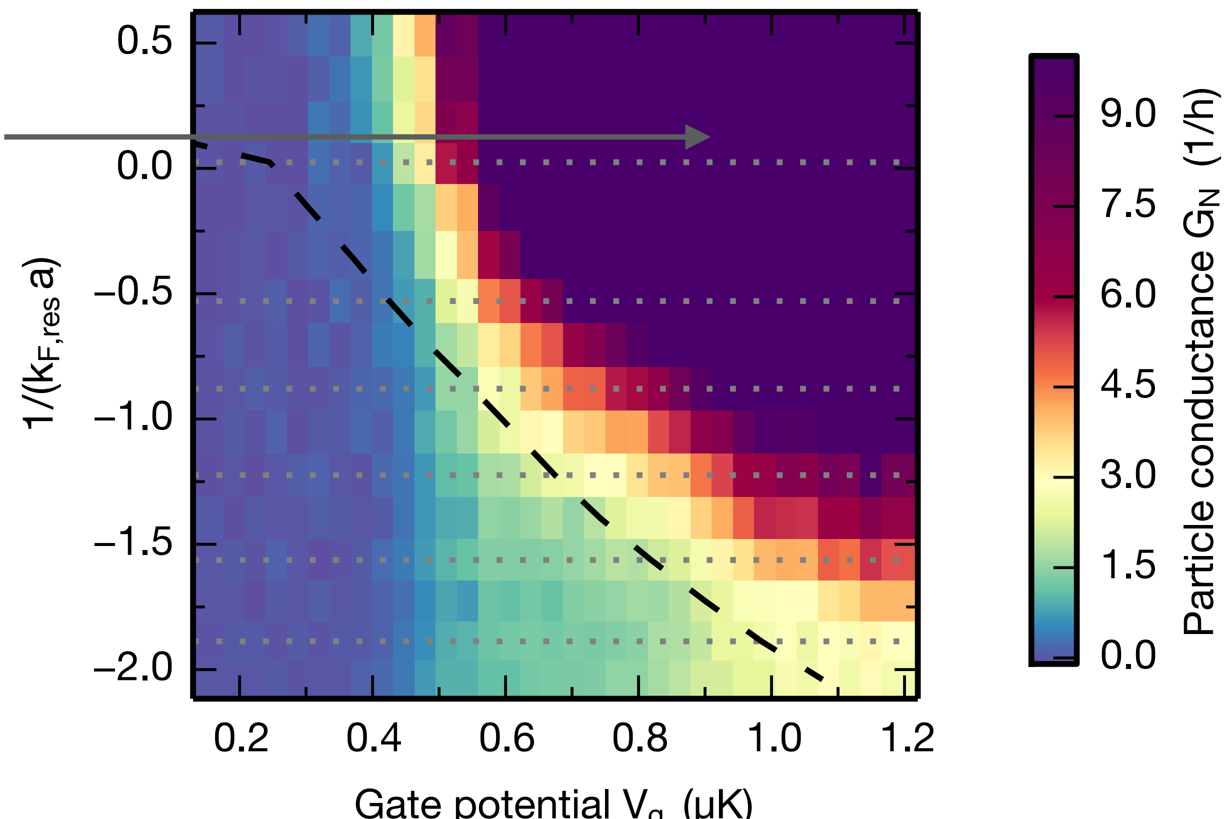
Interactions: from weak to strong



S.Krinner *et al*, PNAS **29** 8144 (2016)

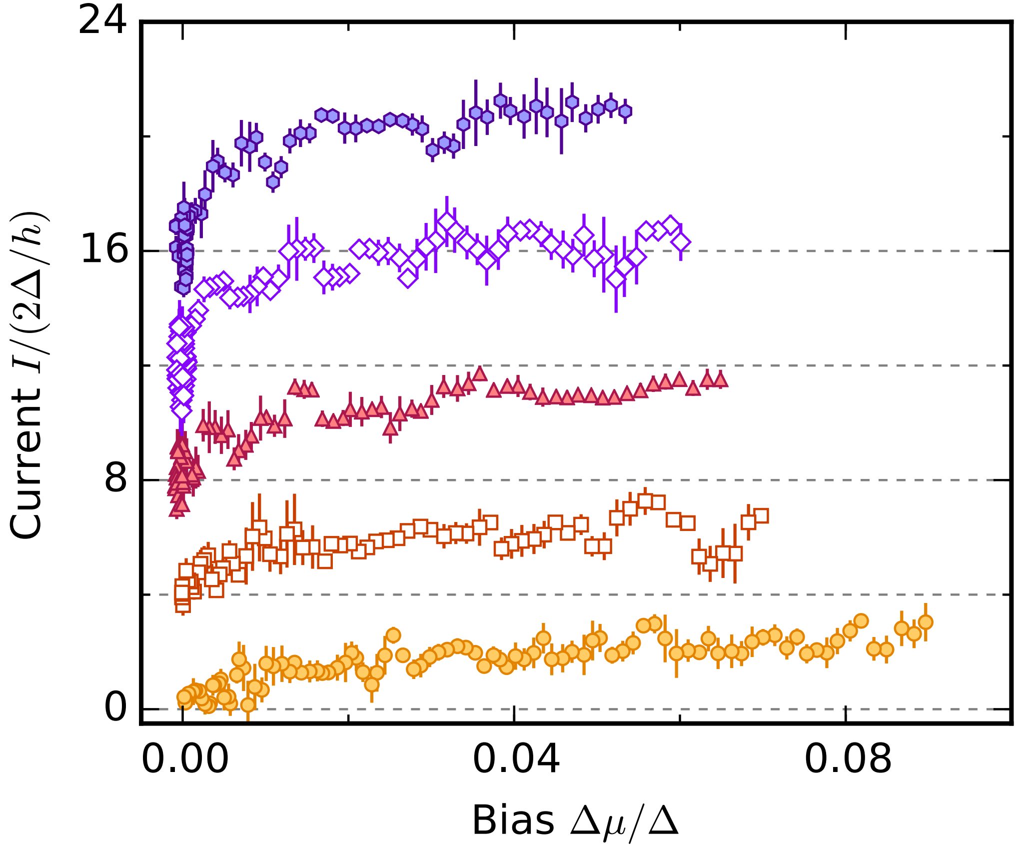
Interactions: from weak to strong

Superfluid regime



S.Krinner *et al*, PNAS **29** 8144 (2016)

Superfluid regime: non linear response

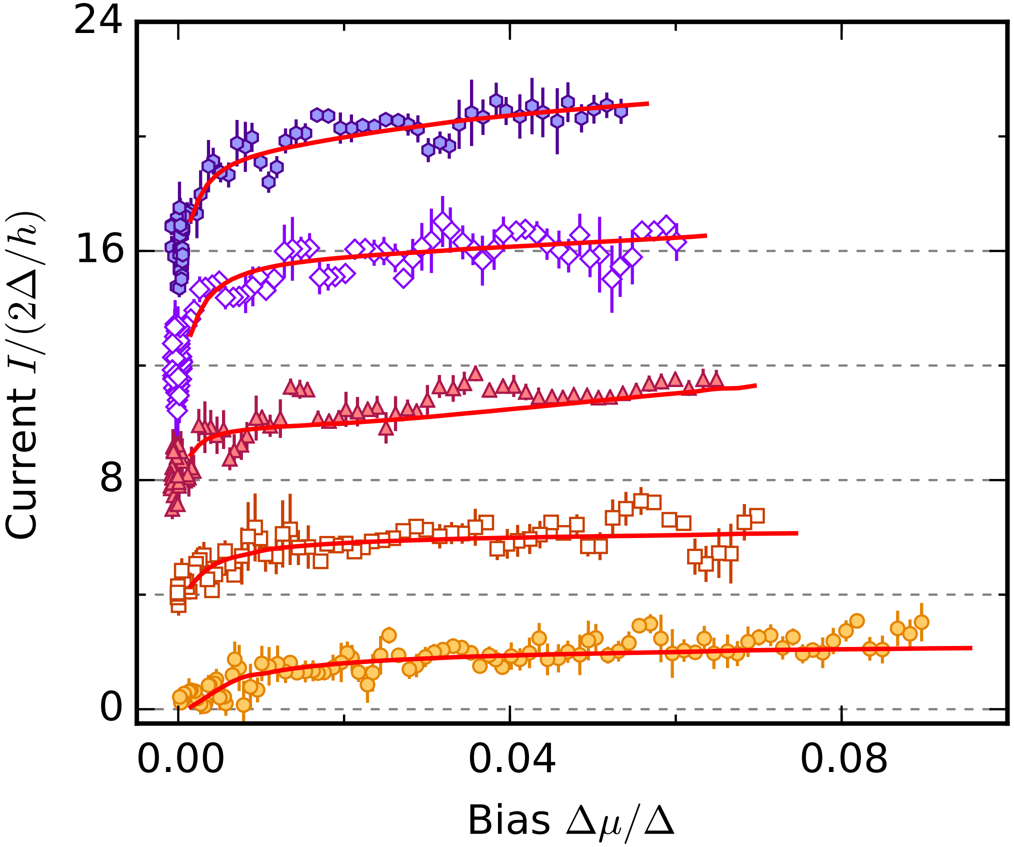


At unitarity, the physics is universal:

equation of state and pairing gap are known

D. Husmann *et al*, Science **350** 1498 *(2015)*

Superfluid regime: non linear response

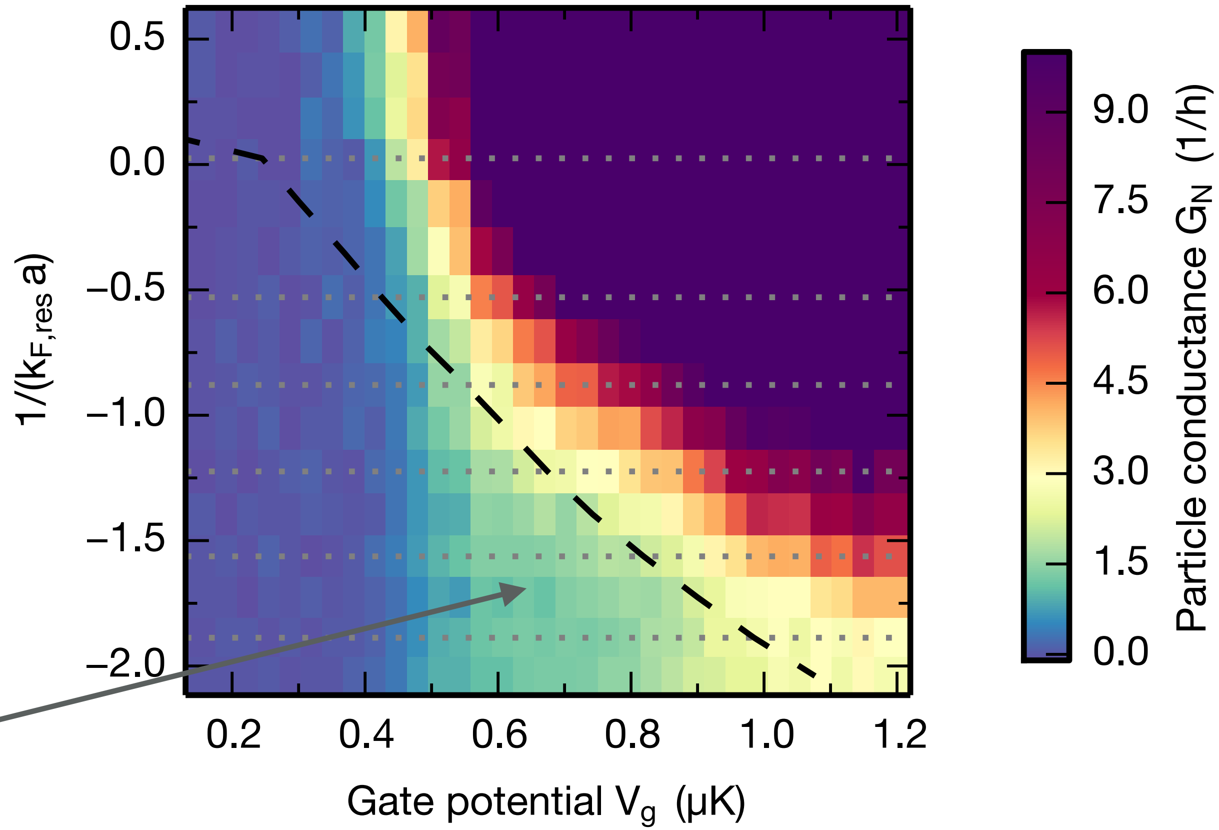


Multiple Andreev Reflection theory

S. Uchino and T. Giamarchi

D. Husmann *et al*, Science **350** 1498 *(2015)*

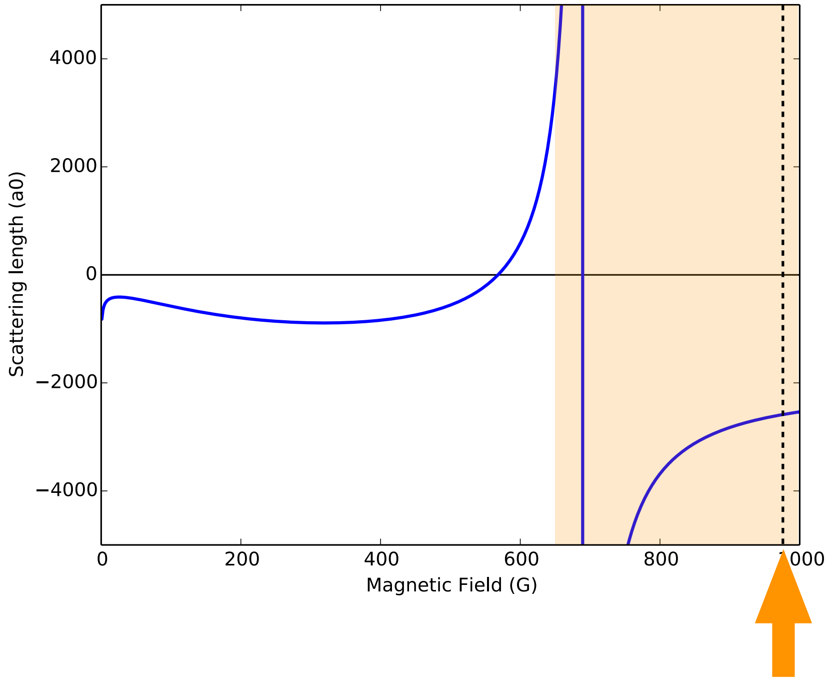
Interactions: from weak to strong

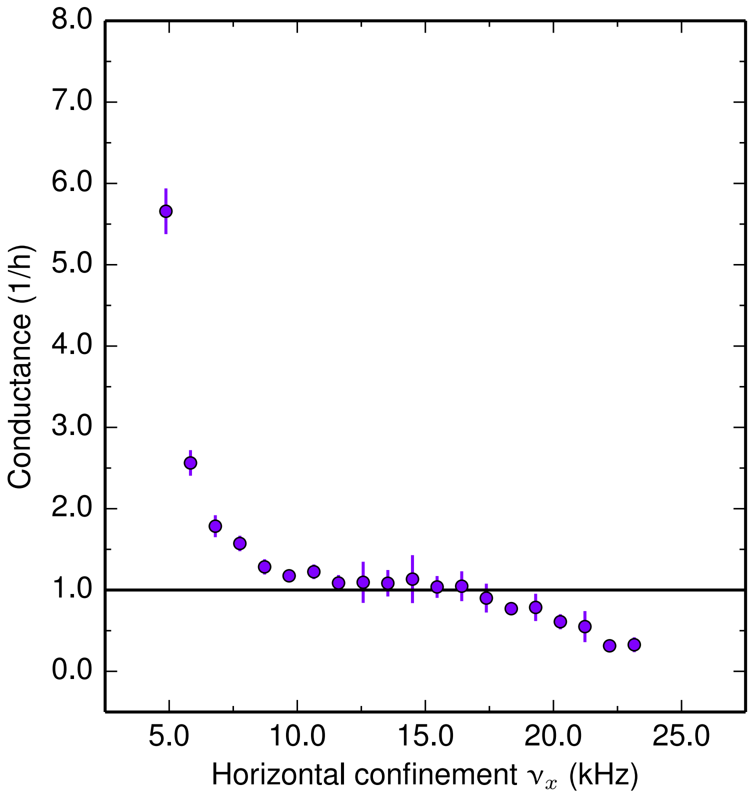


Normal regime

S.Krinner *et al*, PNAS **29** 8144 (2016)

How normal is the ‘normal’ regime ?





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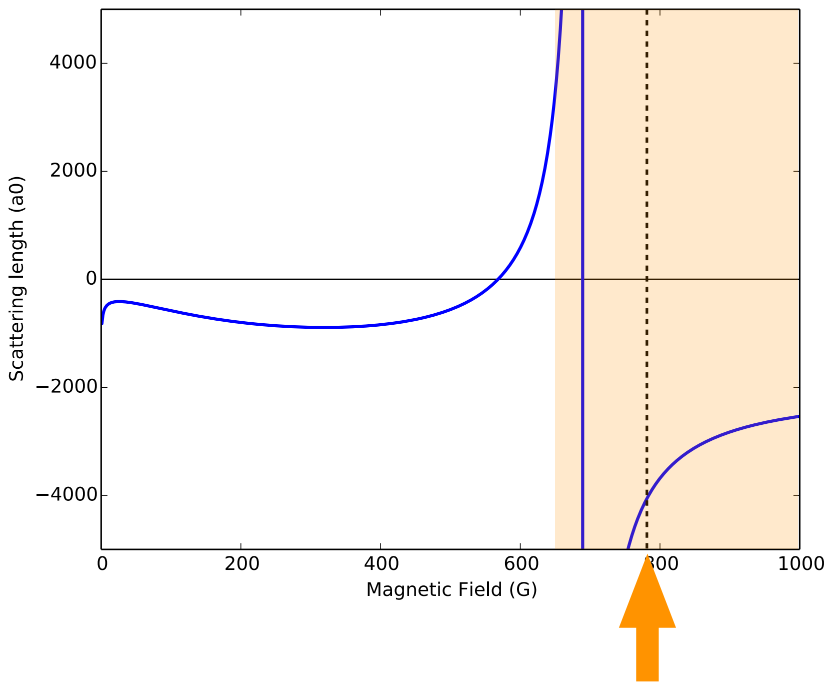

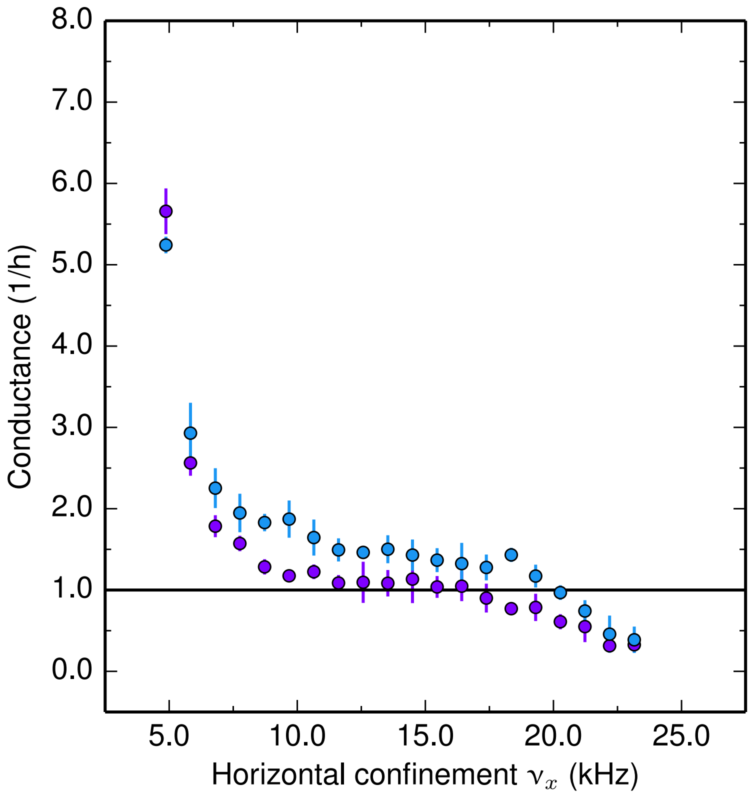

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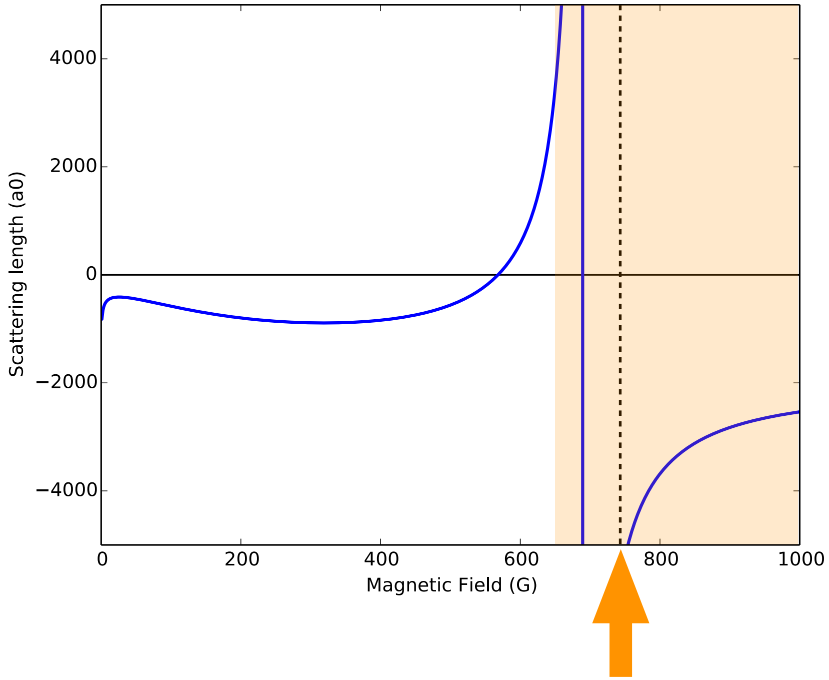

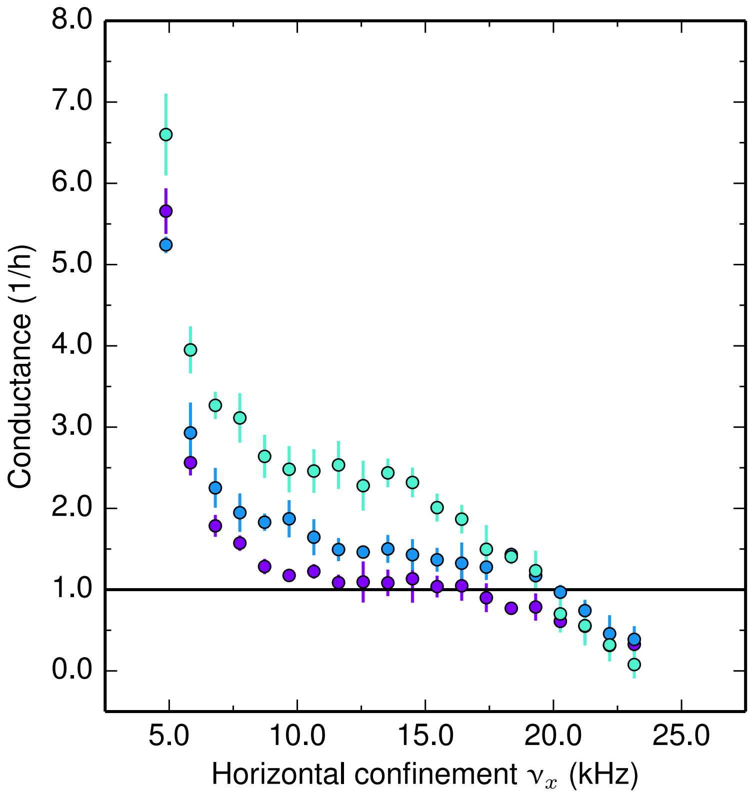

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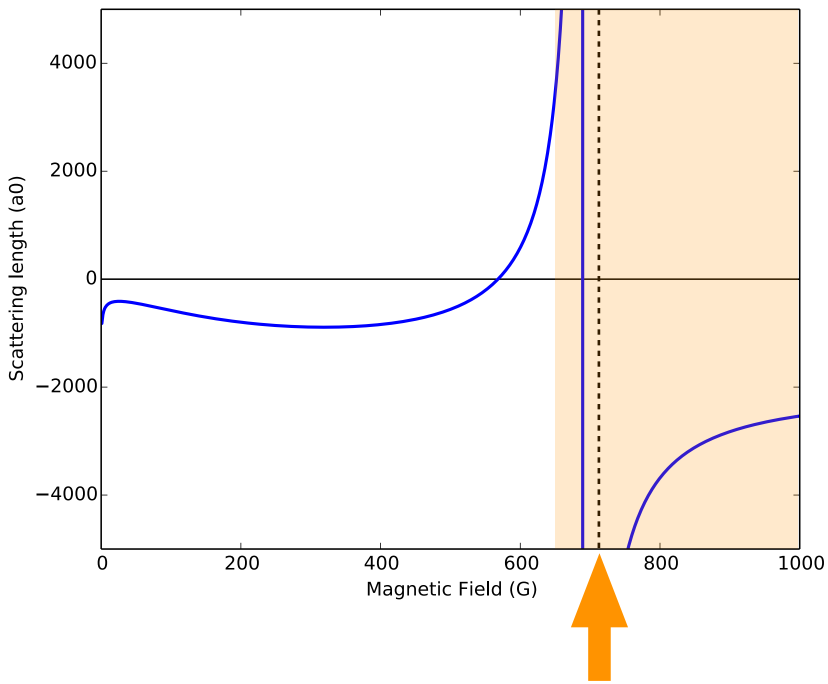

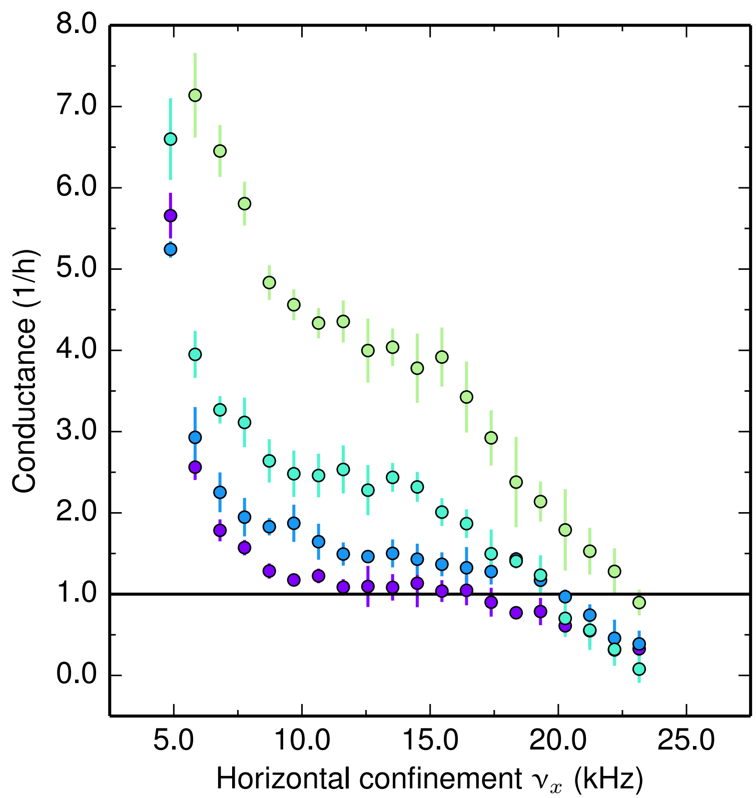

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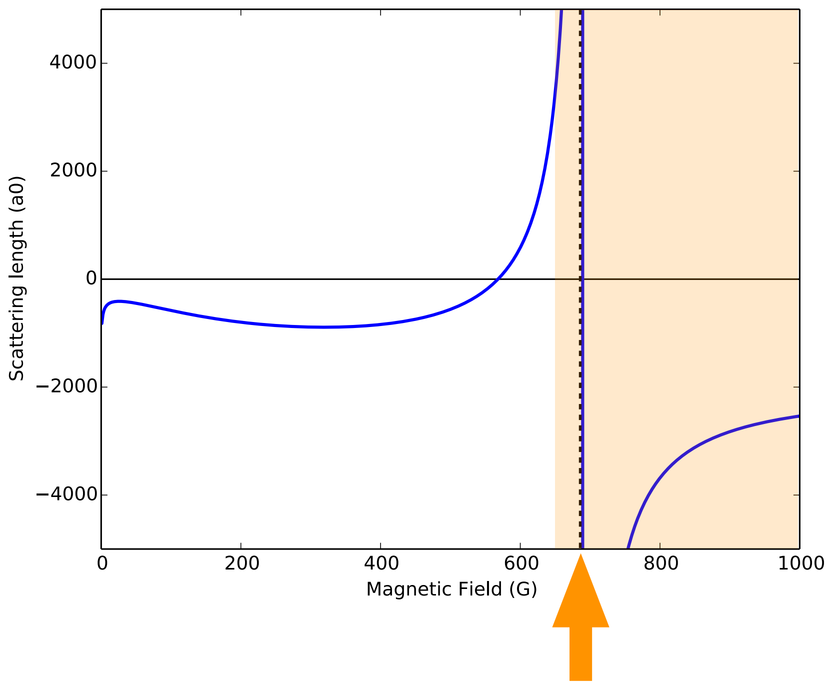
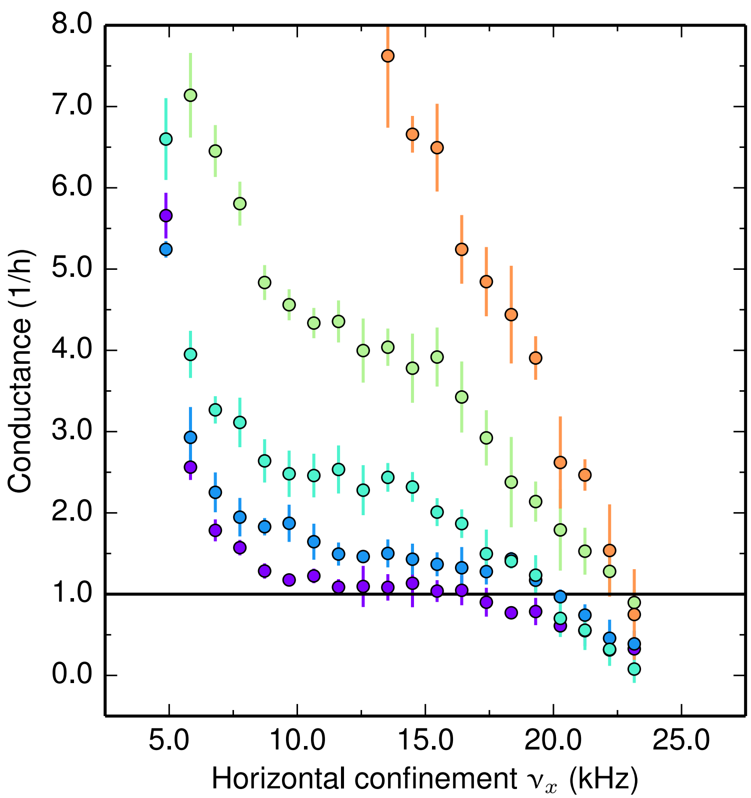




How normal is the 'normal' regime ?

- Conductance plateau above 1/h ?

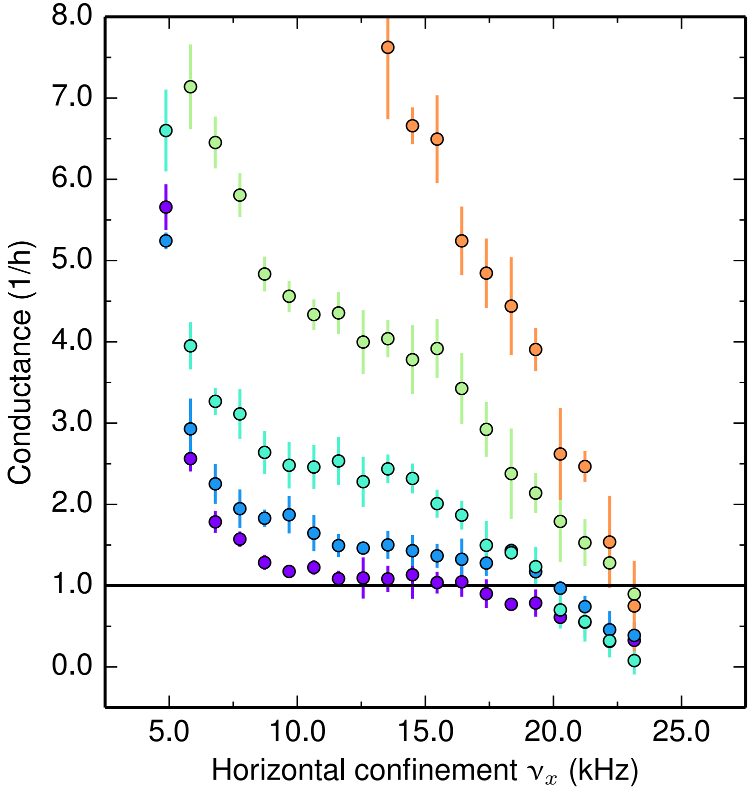
- confinement induced pairing

M.Kanász-Nagy, L. Glazman, T. Esslinger , E. A. Demler
PRL **117**, 255302 (2016)

- superfluid fluctuations in the leads

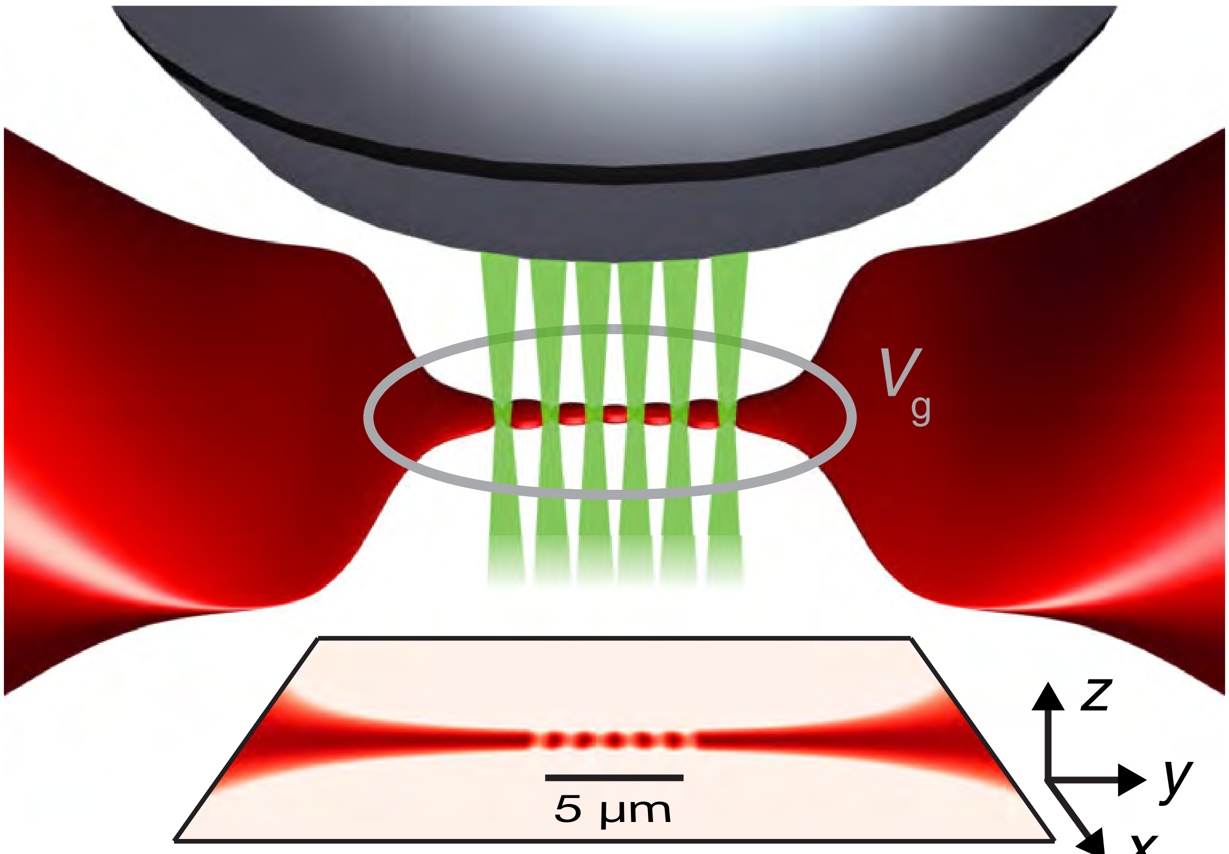
S. Uchino and M. Ueda
PRL **118**, 105303 (2017)

B. Liu, H. Zhai and S. Zhang
PRA **95**, 013623 (2017)



Microscopic control: lattice patterns

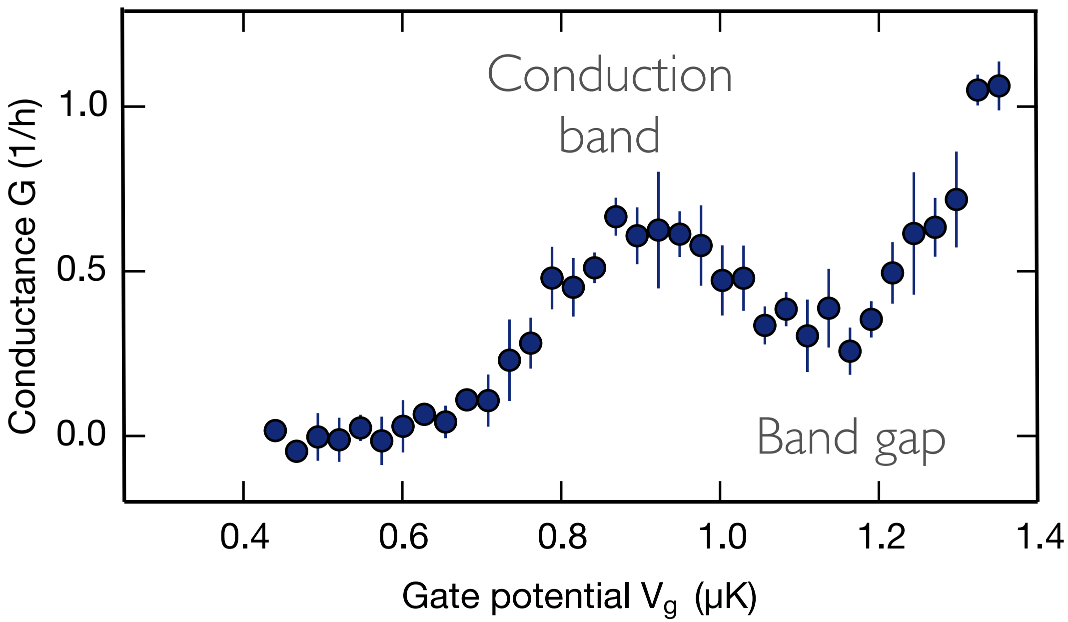
Theory by P. Grisins and T. Giamarchi, University of Geneva



M. Lebrat *et al*, Phys. Rev. X **8** 011053 (2018)

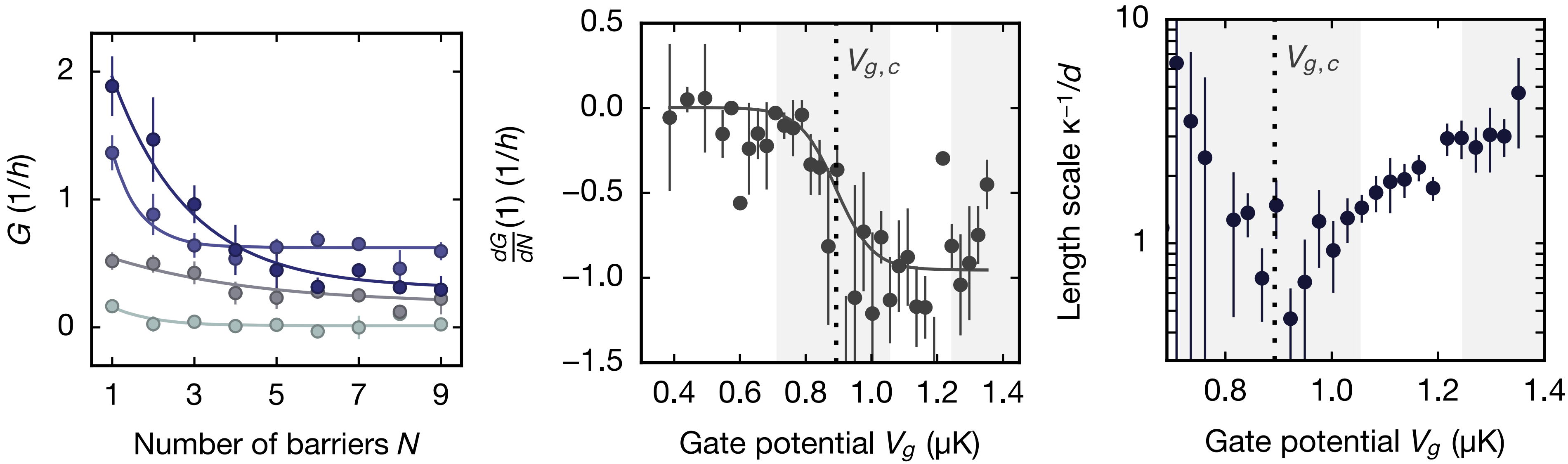
Band structure in transport

- 9 consecutive barriers
- Single mode quantum wire
- Height $0.95\, E_R$



M. Lebrat *et al*, Phys. Rev. X **8** 011053 (2018)

Finite size scaling



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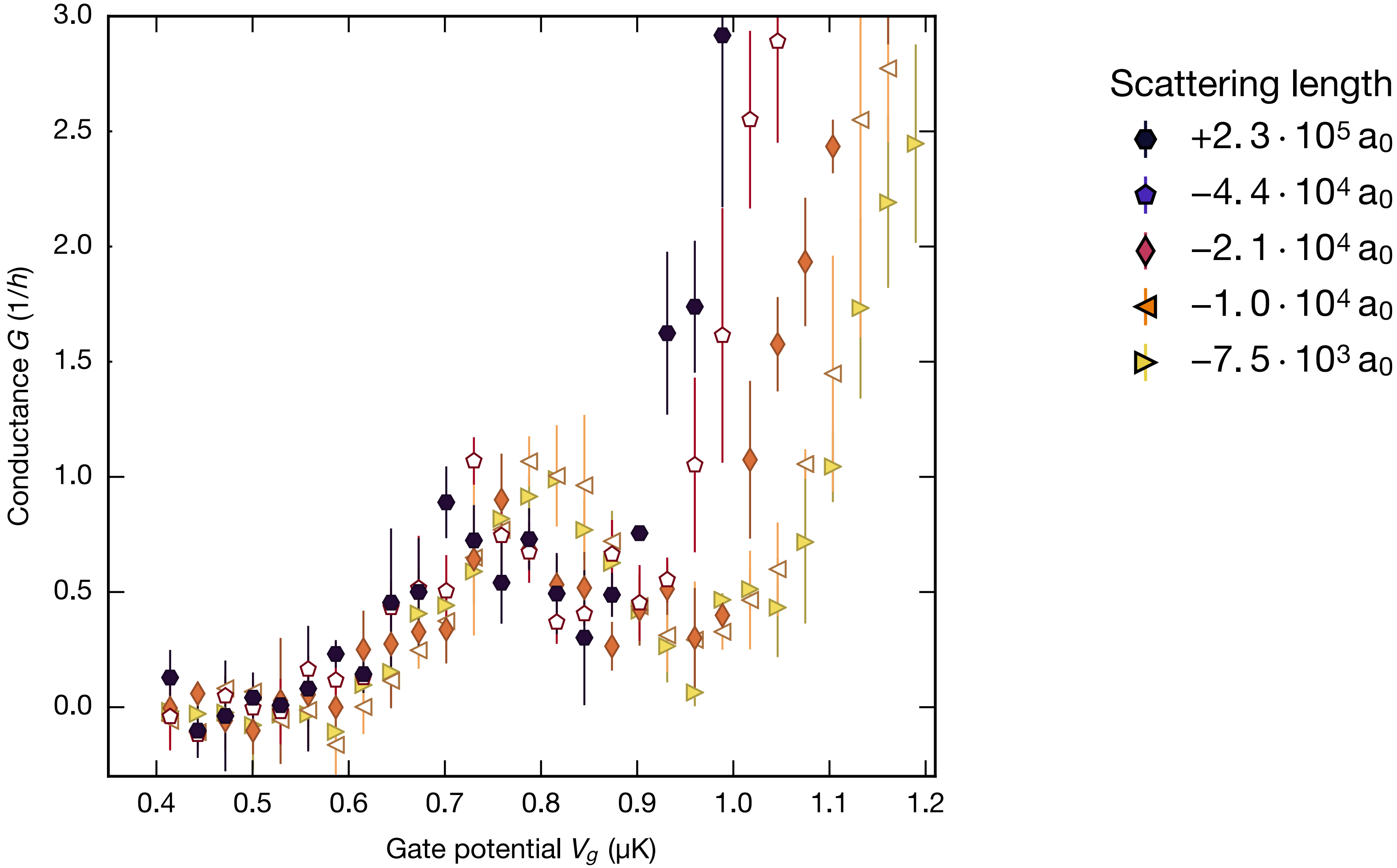
From weak to strong interactions



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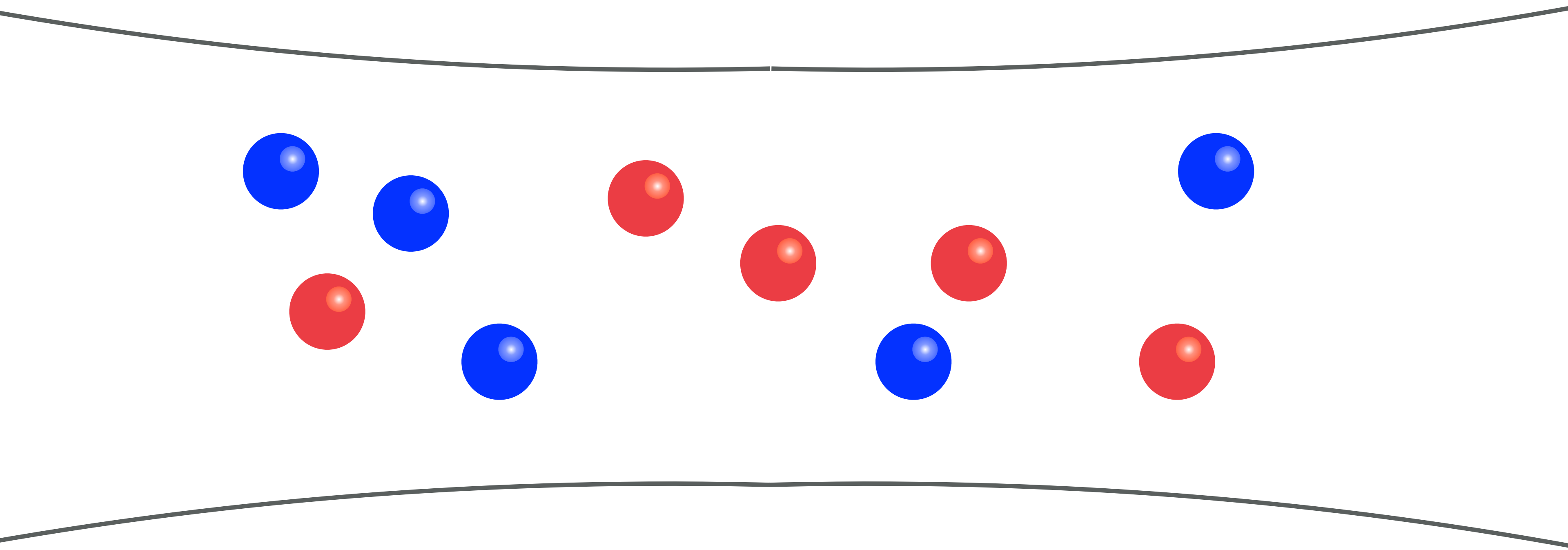

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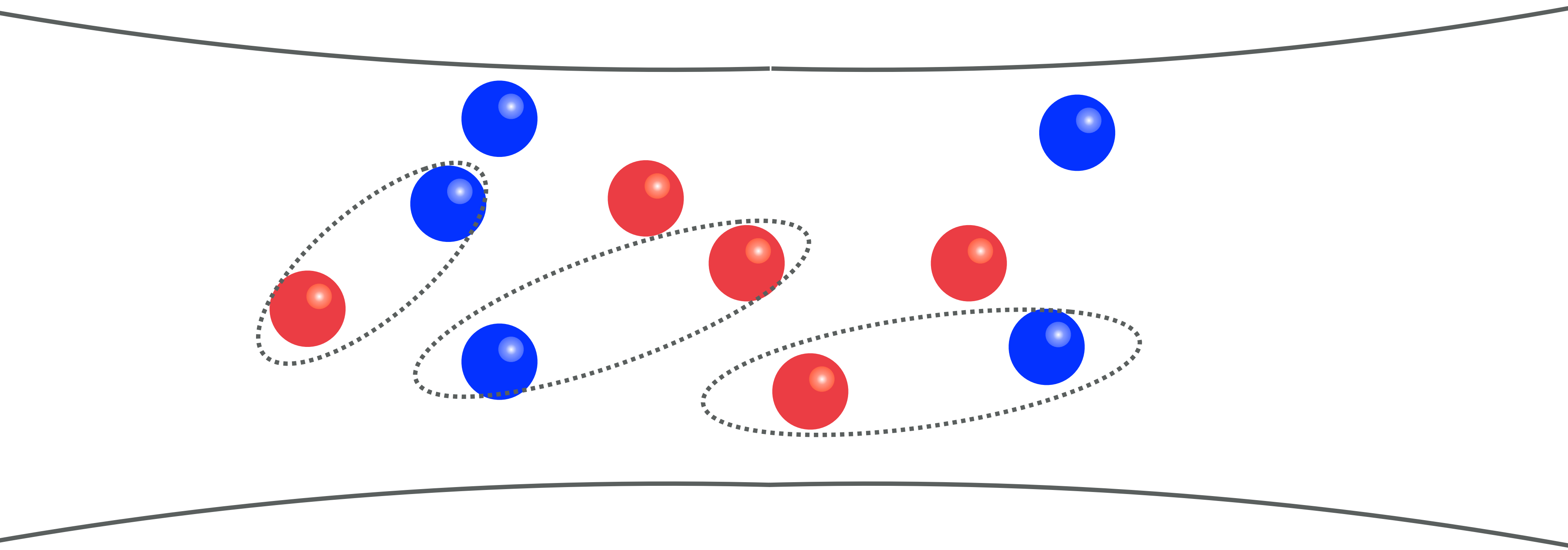

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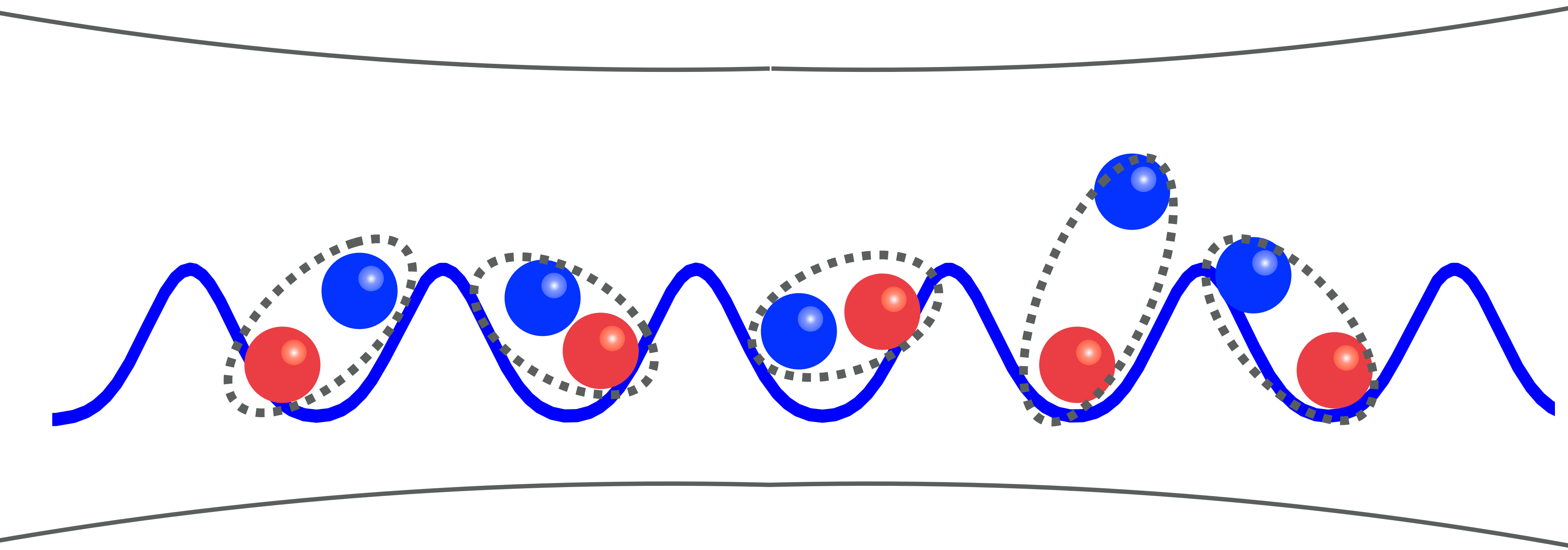
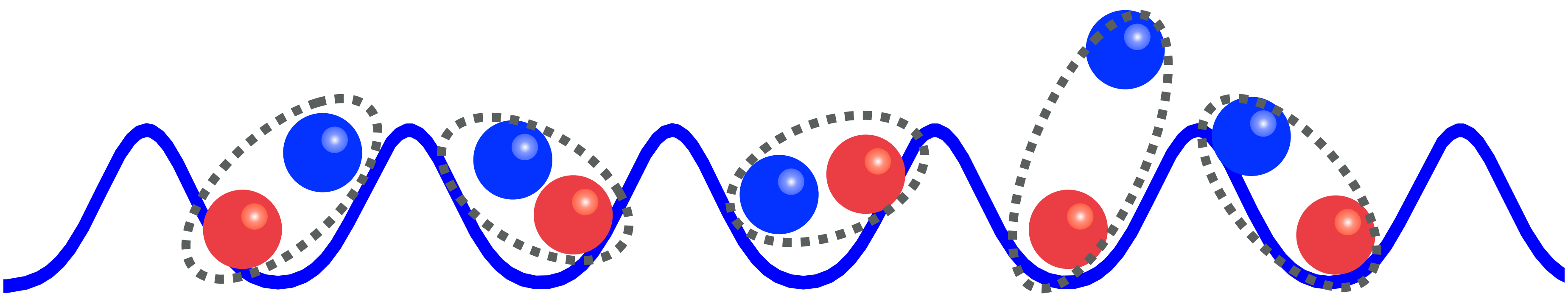


From weak to strong interactions

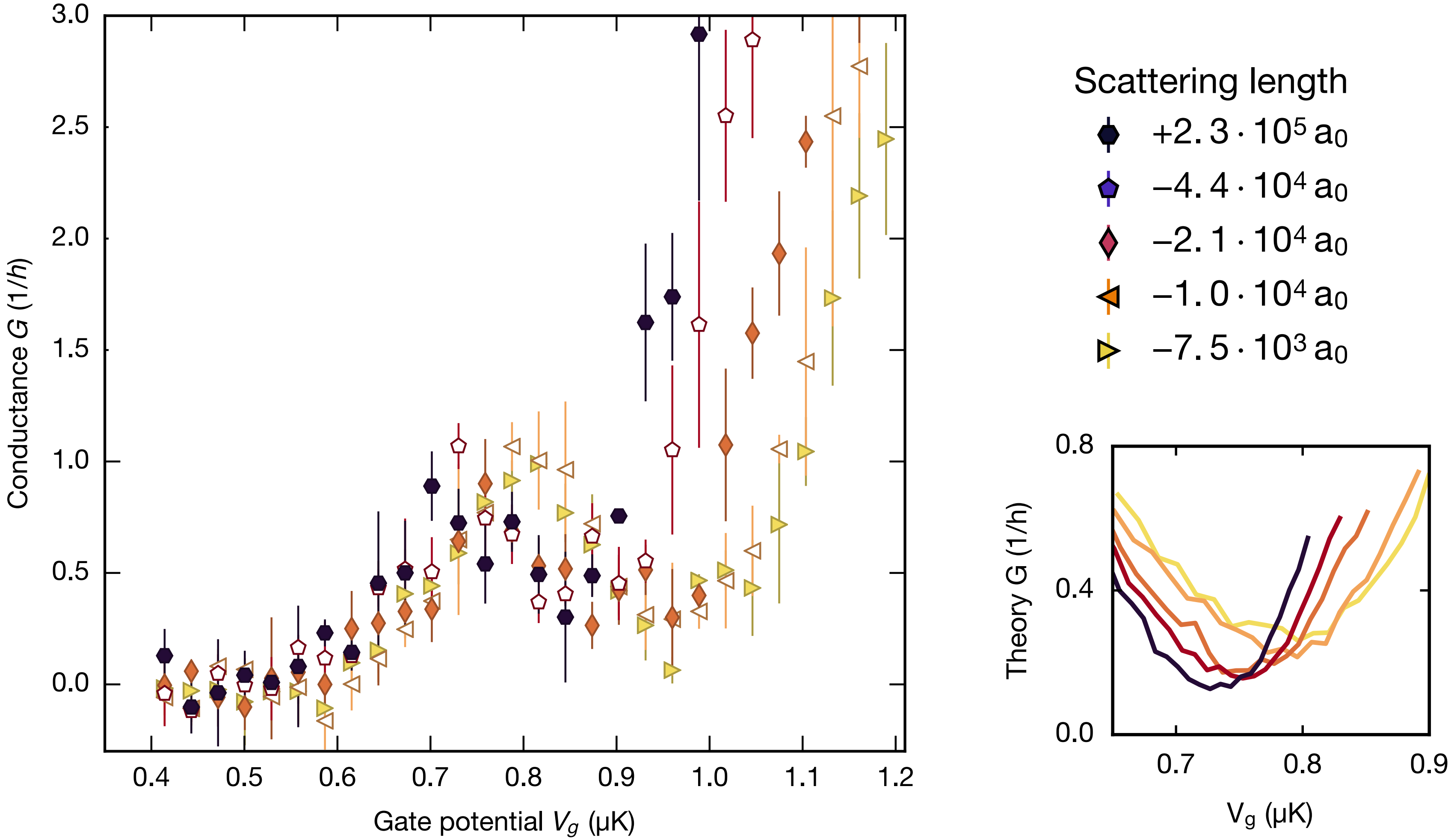
Gapped spin excitations + strong pair repulsion

Luther-Emery liquid
pinned to the weak lattice



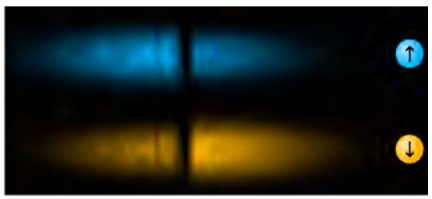
Theory by P. Grisins and T. Giamarchi, University of Geneva

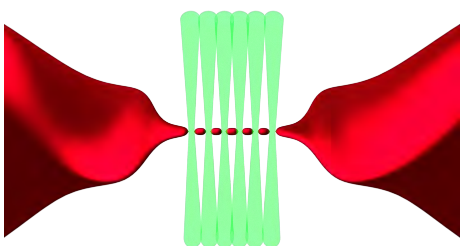
Luttinger liquid model



M. Lebrat *et al*, Phys. Rev. X **8** 011053 (2018)

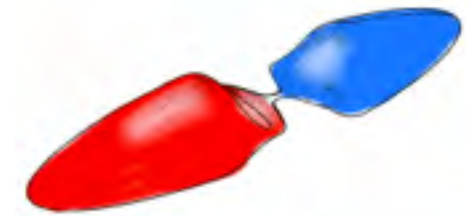
Summary

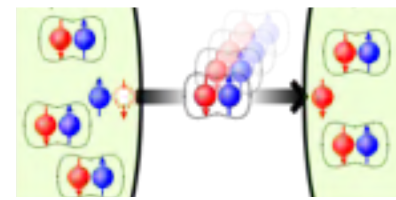




Mesoscopic transport

- Quantum point contact
- Thermoelectric transport
- Spin Transport
- Superfluid flow
- Scanning gate microscope
- …





Review Article:

S. Krinner, T. Esslinger and J.P. Brantut,
Journal of Physics: Condensed Matter **29**, 343003 (2017)

- Quantum Point Contact for cold Fermions
  - Transport measurement technique
  - Quantized conductance

- Interacting systems:
  - Feshbach resonances
  - Fate of quantized conductance across the BCS-BEC crossover
  - Mesoscopic lattices

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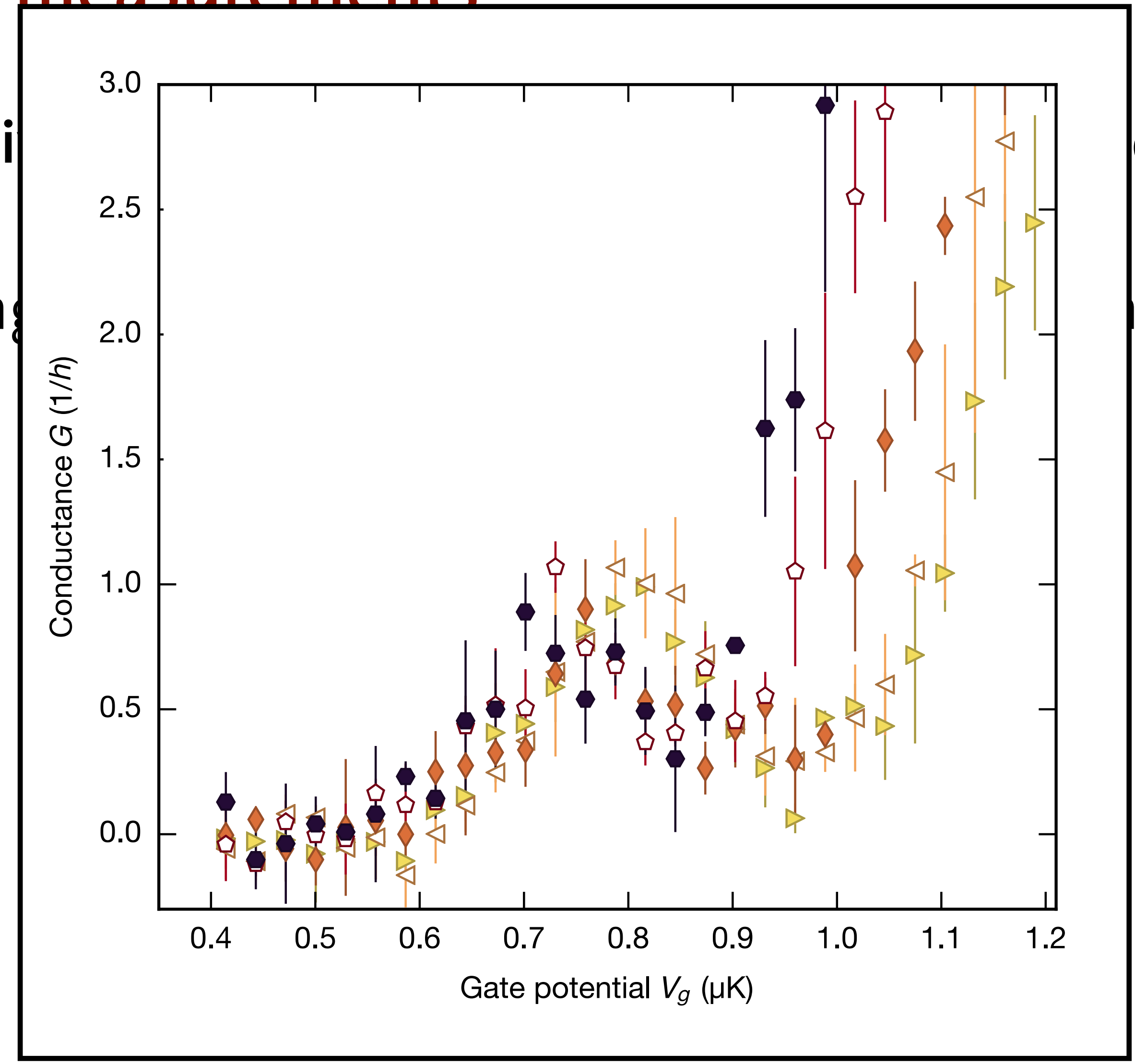
Transport measurements

- **Destructive** measurements of the **total** atom number
- Observing transport implies **sample-to-sample comparison**

Transport measurements

- **Destructi**… er
- Observin… **parison**



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Transport measurements

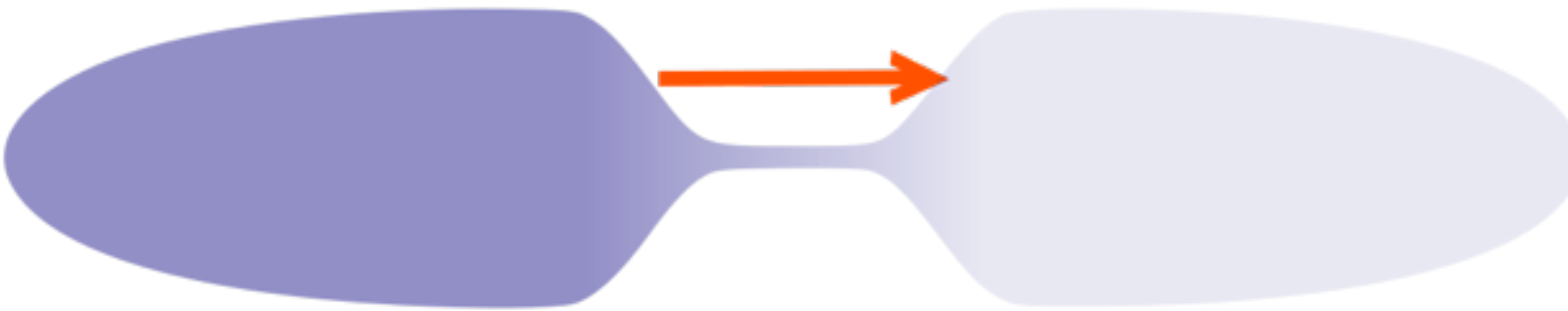
- **Destructive** measurements of the **total** atom number

- Observing transport implies **sample-to-sample comparison**

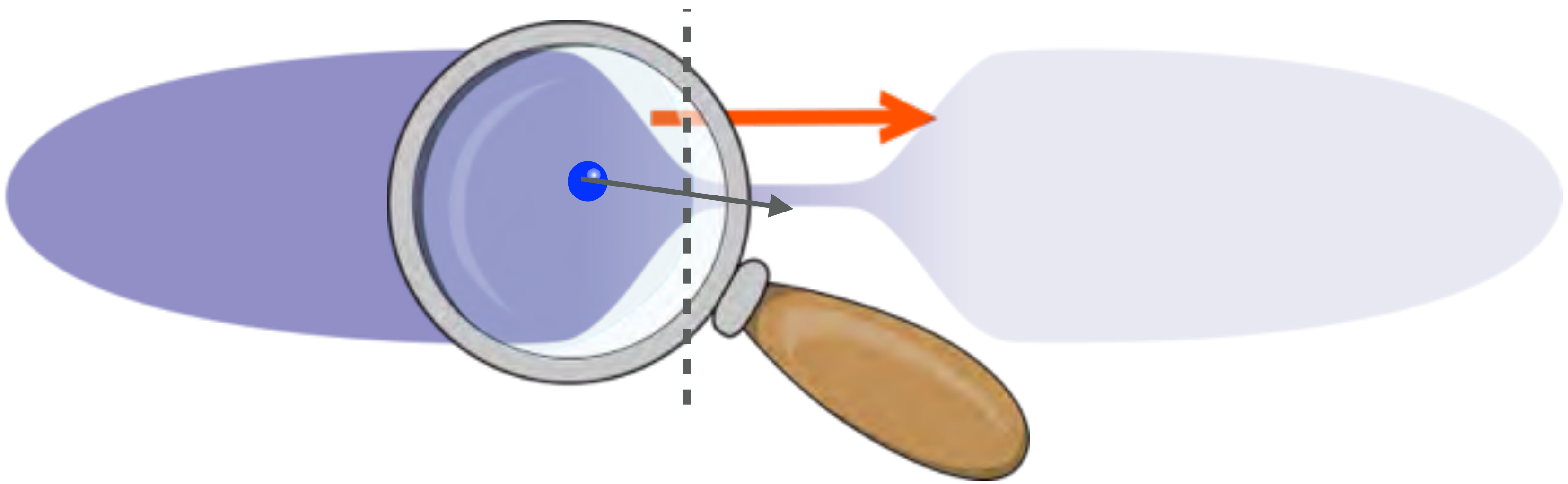
  - Total number of atoms : 10^5
  - Chemical potential : 10 kHz
  - Chemical potential bias : 1 kHz $\Longrightarrow$ I = 1000 at.s^{-1}

Signal is about 1% for a fully open point contact

'Ideal' transport measurement

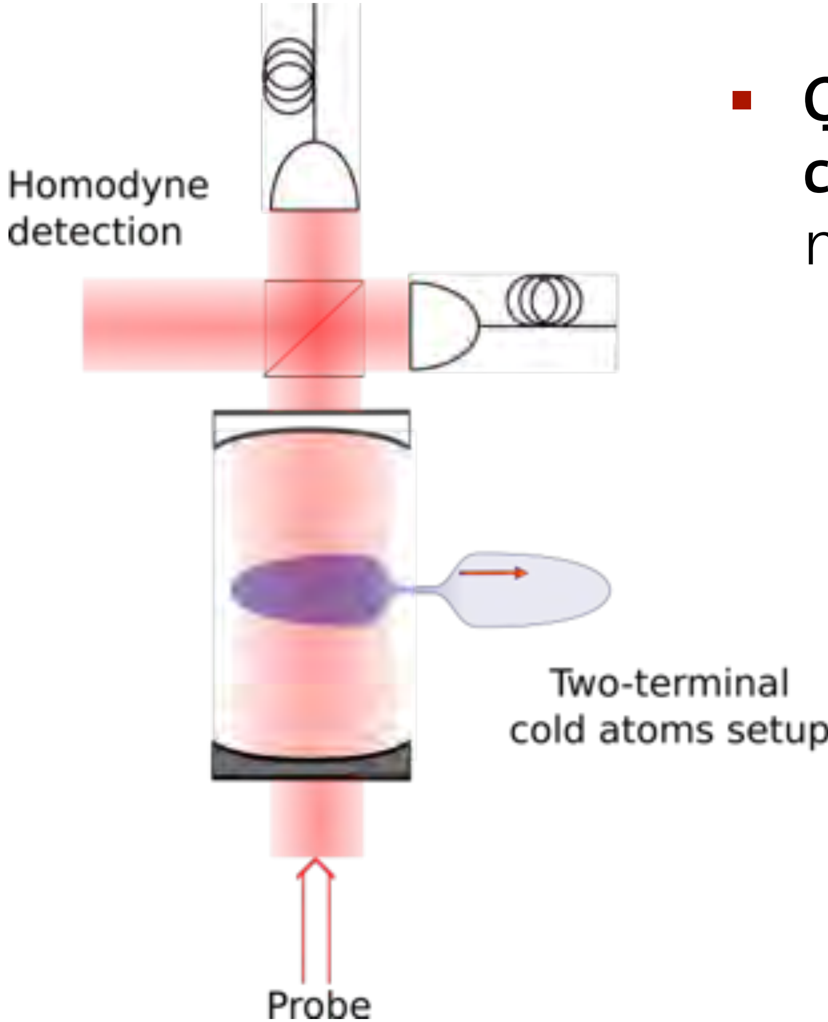


‘Ideal’ transport measurement



Watch the particles entering and leaving the reservoirs in real time

'Ideal' transport measurement



- **Quantum-non demolition** and **continuous** measurement of the number of atoms in a reservoir

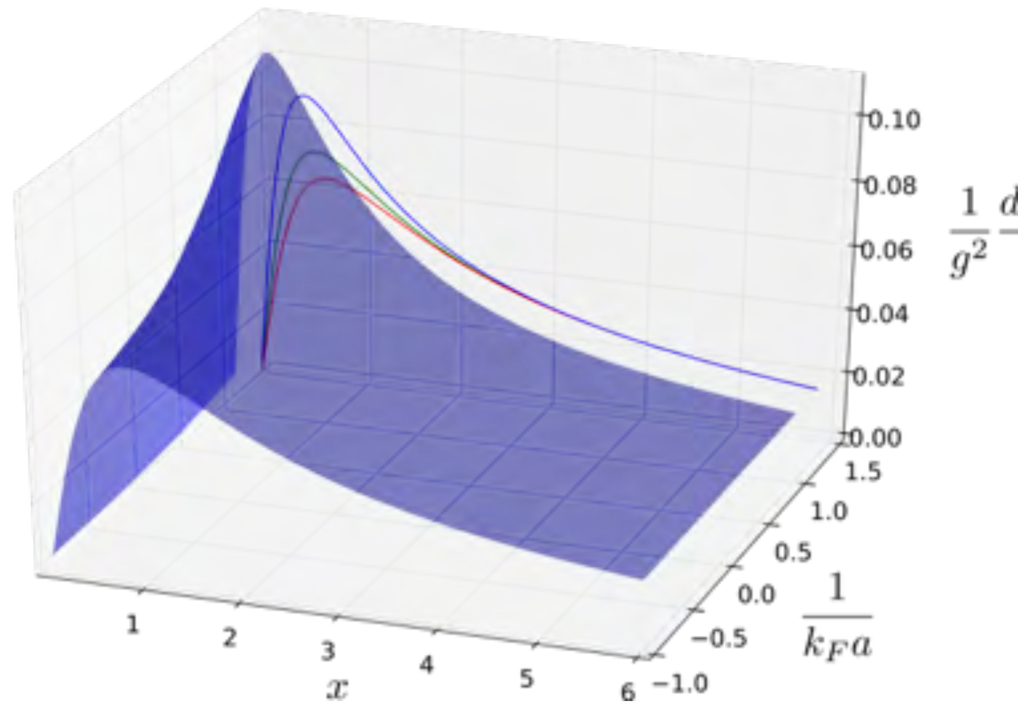
1. Is it possible ?
2. Where is the noise floor ?

S. Uchino, M. Ueda and JPB,
arXiv 1802.04024

Quantum non-demolition measurement

- Energy absorption rate due to measurement

For low enough bandwidth:
QND regime reached regardless of interactions

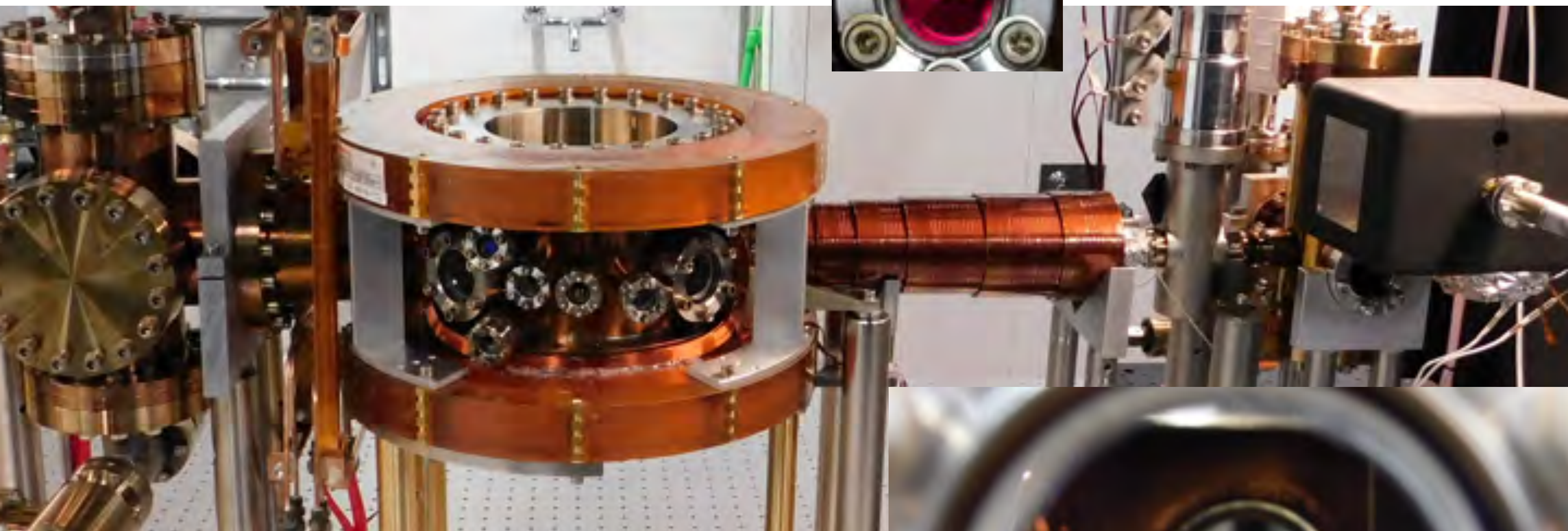


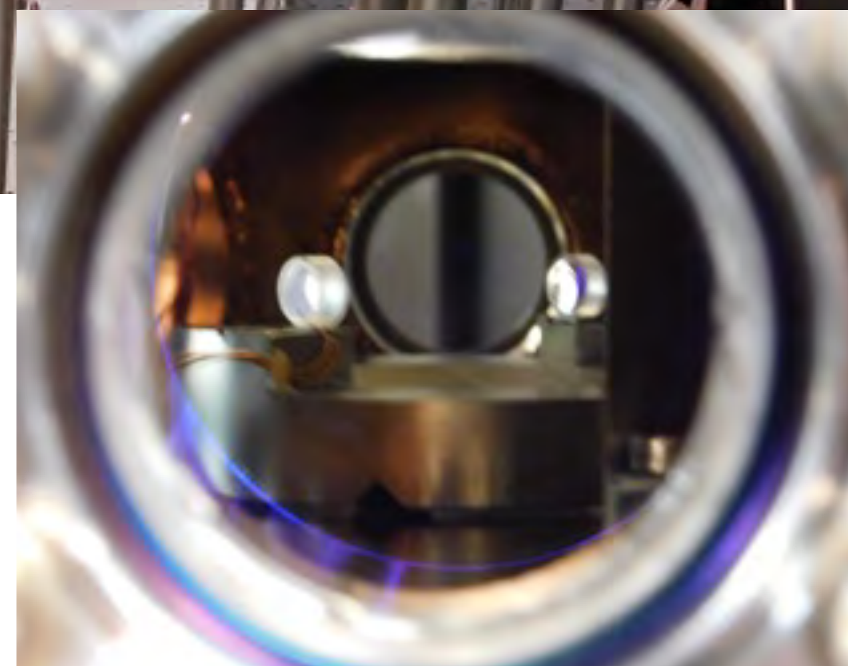
S. Uchino, M. Ueda and JPB,
arXiv 1802.04024

Quantum limit to current measurement

- Measuring N induces back action on the conjugate variable

Experimental setup





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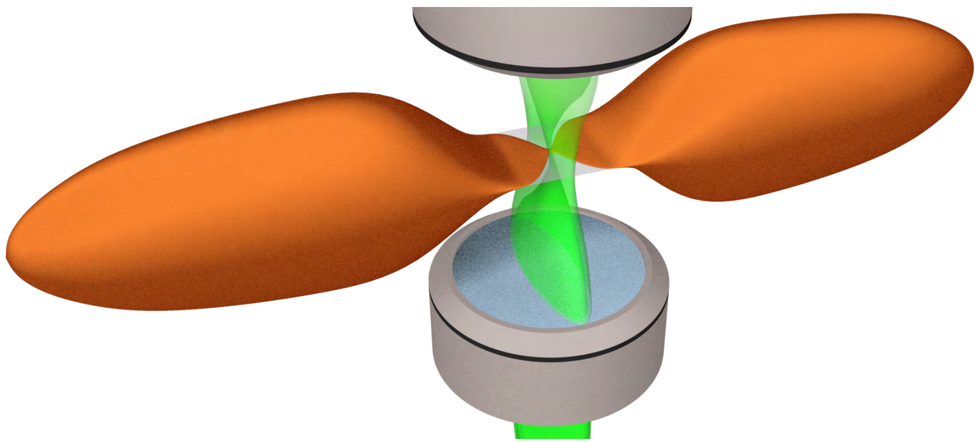

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QSIT Quantum Science and Technology