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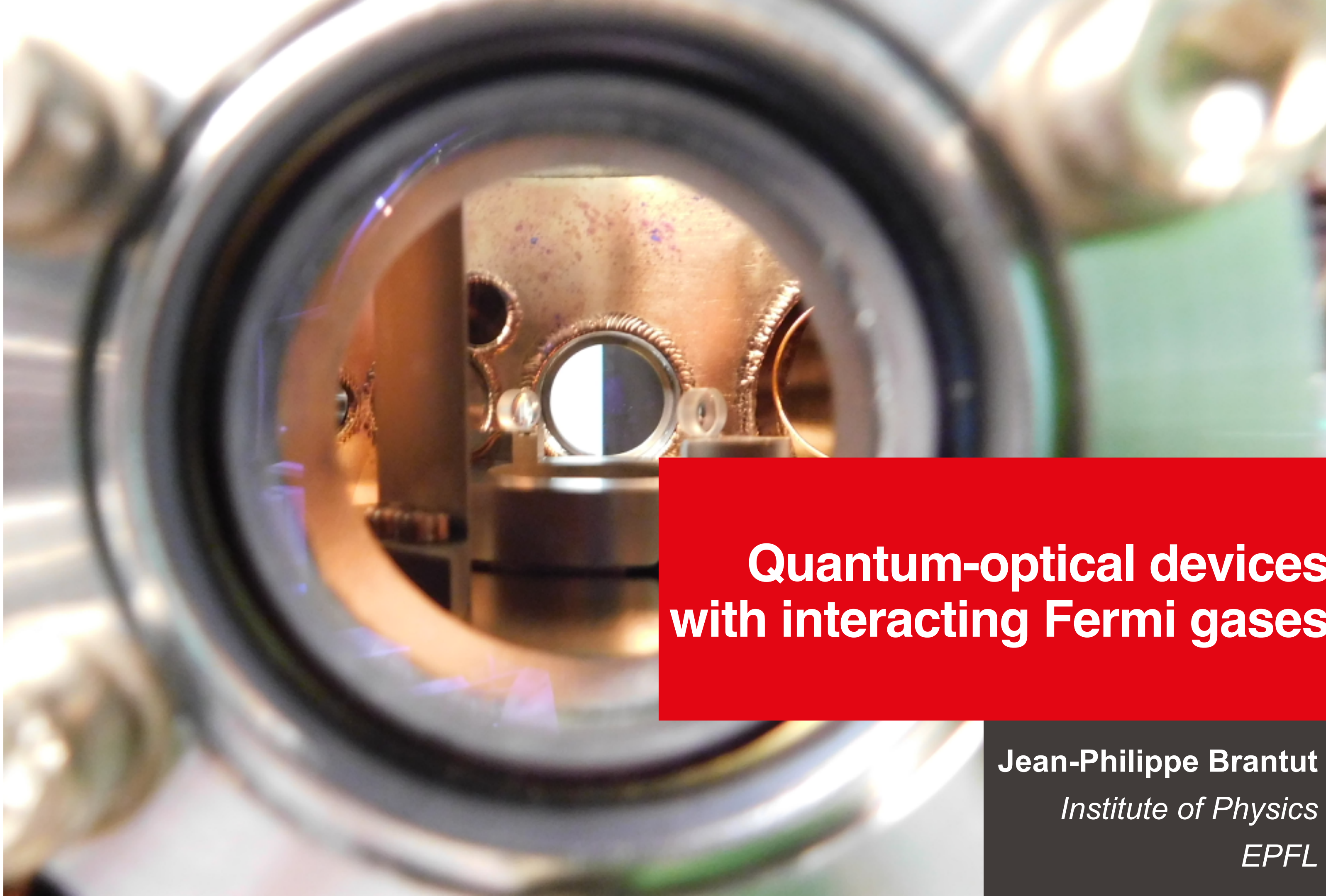

Quantum-optical devices with interacting Fermi gases

Jean-Philippe Brantut
Institute of Physics
EPFL

Quantum matter: computation meets experiments

Tunable Fermi gas

- Directly interaction with light, with $\lambda_F \sim \lambda_L$

$$\vec{d}(\omega) = \alpha(\omega)\vec{E}(\omega) \longrightarrow V_{\mathrm{dip}} = \frac{1}{2}\alpha(\omega)E^2(\omega)$$

Tunable Fermi gas

- Directly interaction with light, with $\lambda_F \sim \lambda_L$
- Charge-neutral constituents, short-range ***tunable*** interactions

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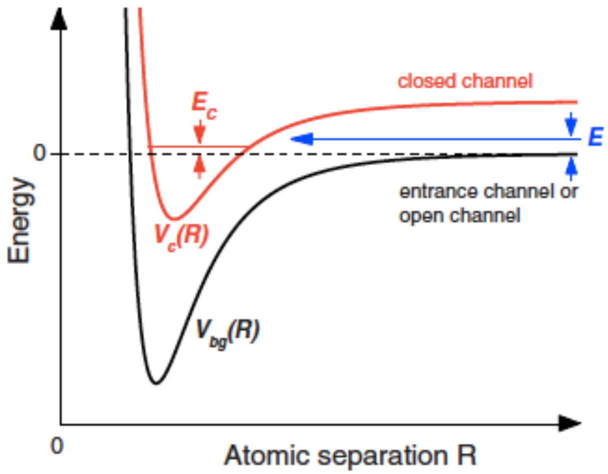
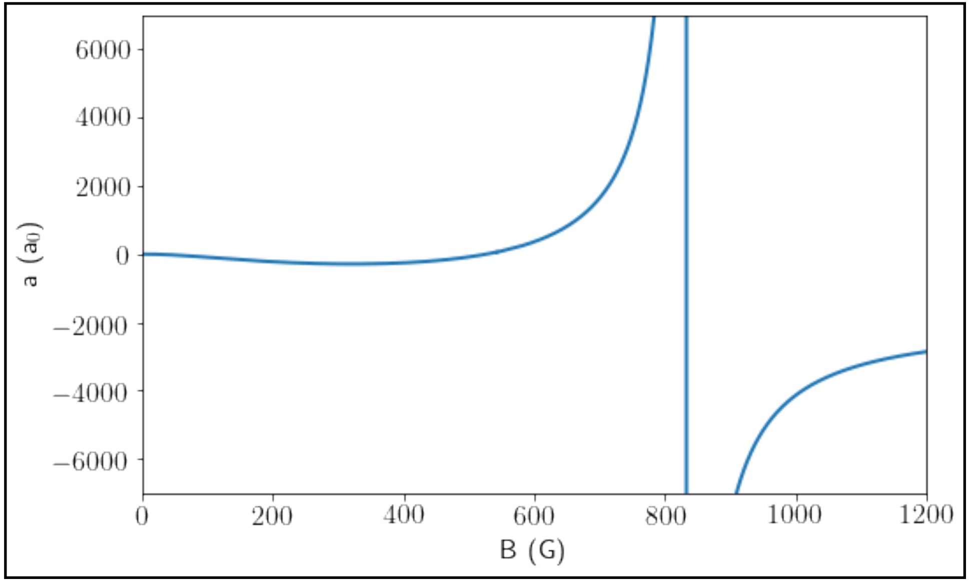




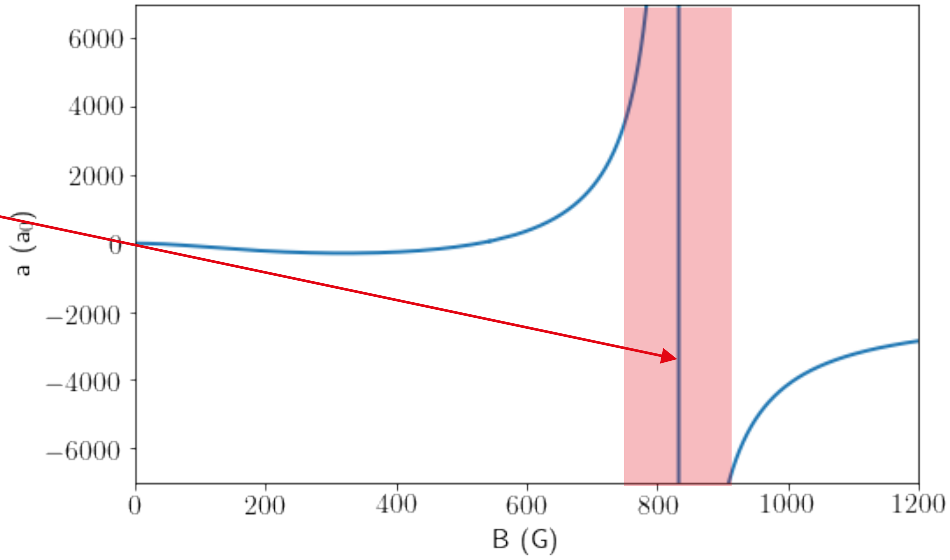
C. Chin, *et al*, Rev. Mod. Phys **82** 1225 (2010)

Tunable Fermi gas

Jean-Philippe Brantut

- Directly interaction with light, with $\lambda_F \sim \lambda_L$
- Charge-neutral constituents, short-range ***tunable*** interactions

Strongly interacting regime
BEC-BCS crossover



Tunable Fermi gas

- Directly interaction with light, with $\lambda_F \sim \lambda_L$
- Charge-neutral constituents, short-range ***tunable*** interactions

Controlled quantum material !

- Knowns*: phase-diagram, thermodynamics, response functions, collective modes…

* in free space (no lattice)

JILA, ENS, Rice, Innsbrück, MIT…

Tunable Fermi gas

- Directly interaction with light, with $\lambda_F \sim \lambda_L$
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Tunable Fermi gas

- Directly interaction with light, with $\lambda_F \sim \lambda_L$
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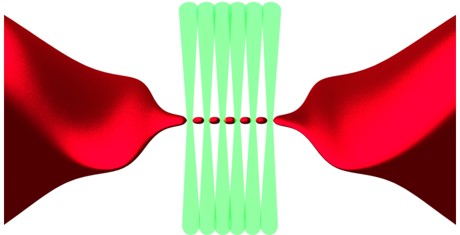
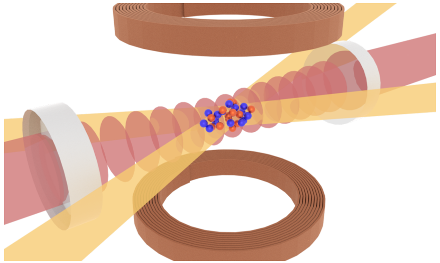
- Device-like systems: mesoscopic lattice



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

- Quantum interfacing with photons



K. Roux *et al*, arXiv:1911.11151

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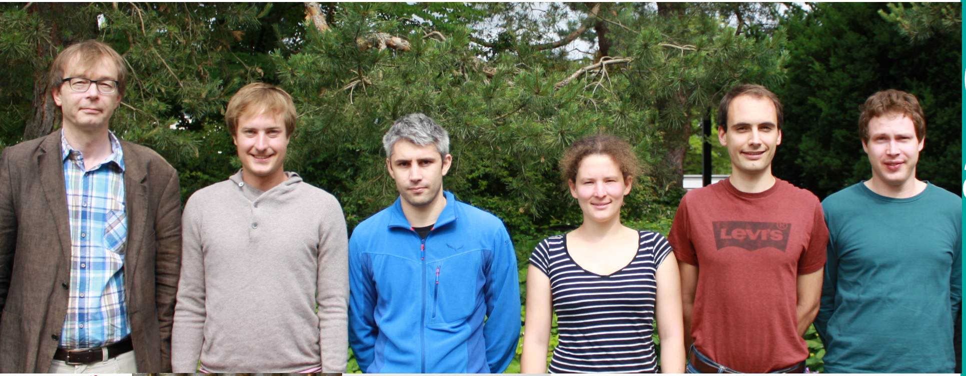
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich



UNIVERSITÉ DE GENÈVE

Quantum transport in a mesoscopic lattice

ETHZ/EPFL:

T. Esslinger, D. Husmann, JPB, L. Corman, M. Lebrat, S. Häusler

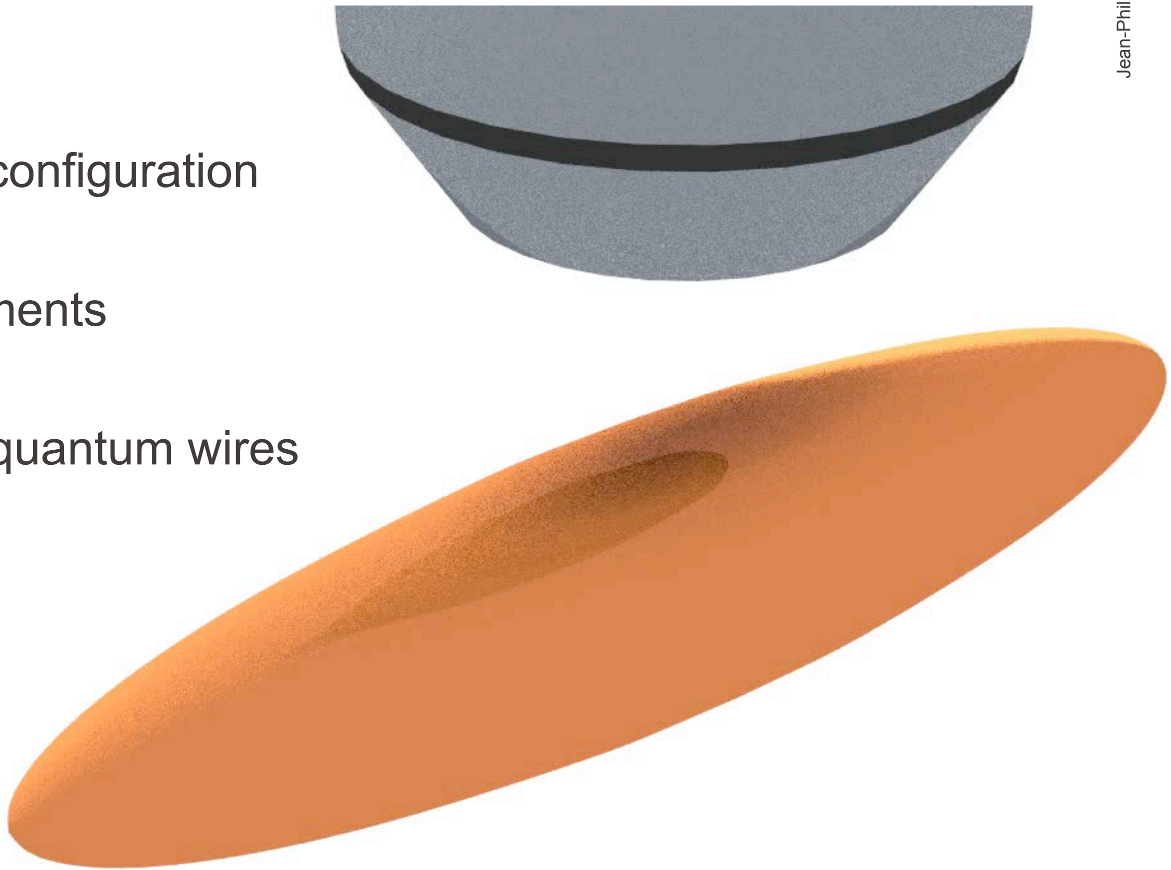
Geneva:

P. Grisins, T. Giamarchi

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

Quantum transport

- Landauer two-terminal configuration
- Conductance measurements
- Single-mode QPC and quantum wires



Quantum transport

- Landauer two-terminal configuration
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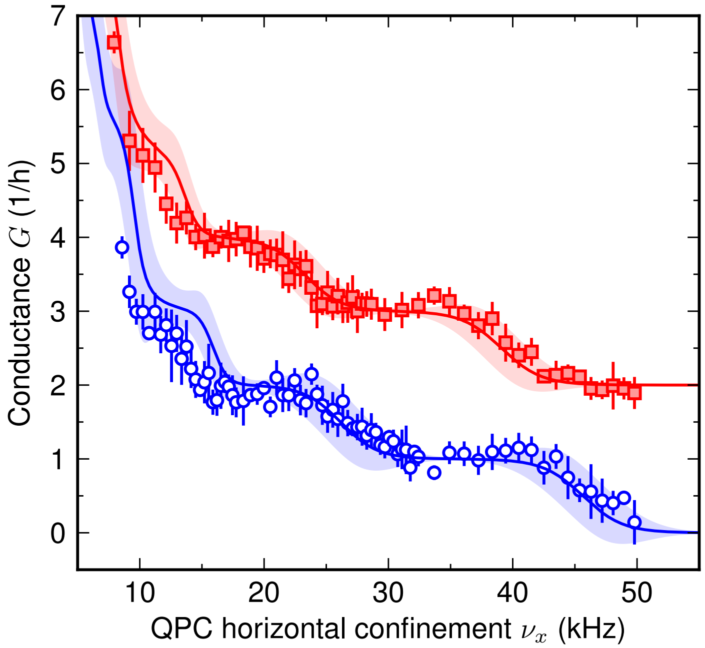
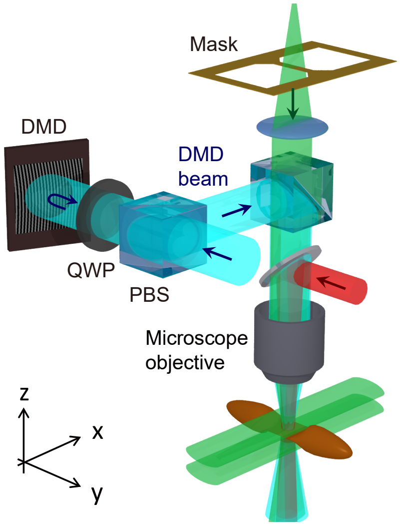
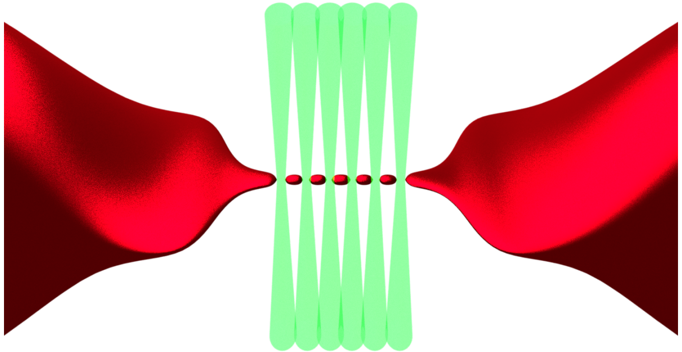


S. Krinner *et al,* Nature **517**, 64-67 (2015)

S. Krinner, T. Esslinger and **JPB**,
J. Phys.: Condens. Matter **29** 343003 (2017)

Quantum transport

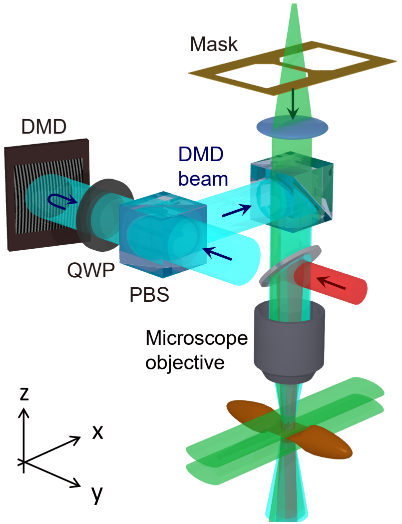


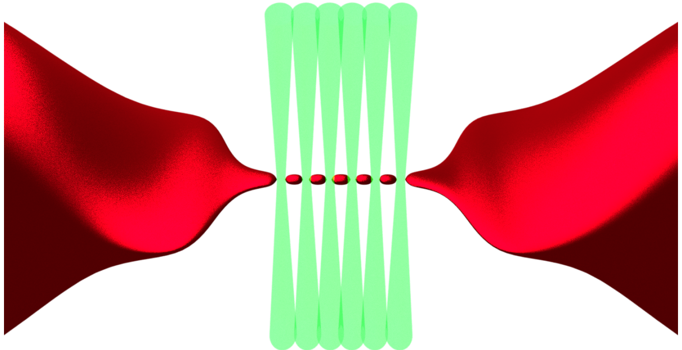


- Projection of a mesoscopic lattice
  - Site-by-site control
  - Low depth < E_R

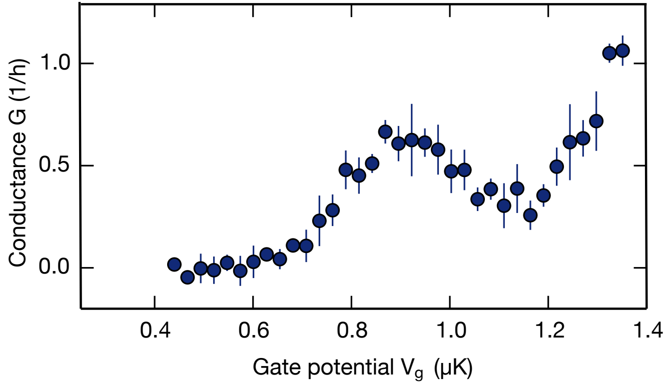
M. Lebrat *et al*, Phys. Rev. X **8** 011053 (2018)

Quantum transport



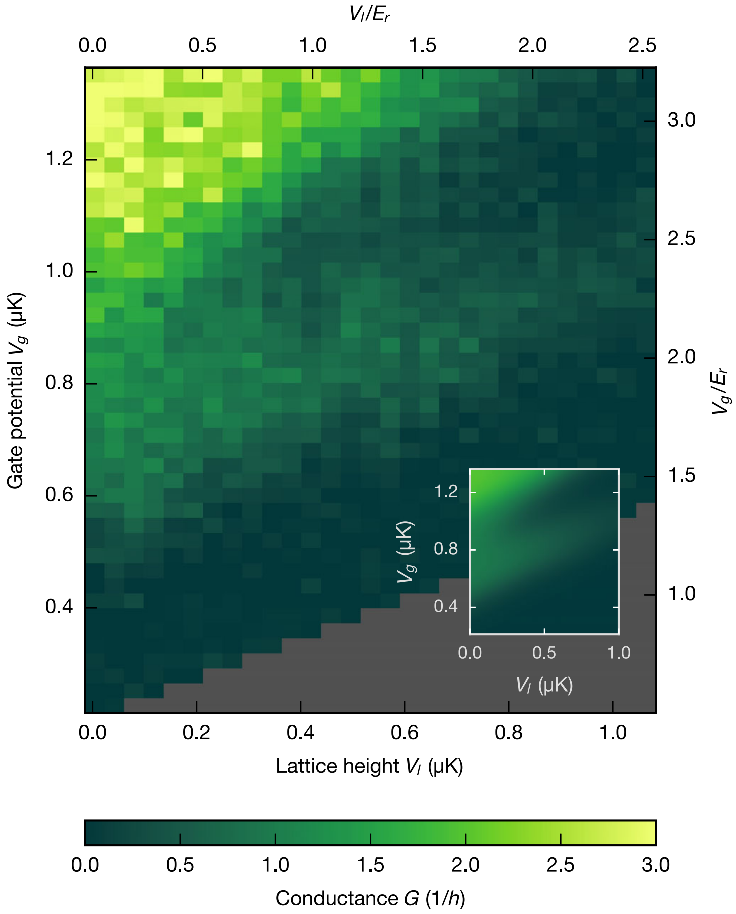


- Projection of a mesoscopic lattice
  - Site-by-site control
  - Low depth
- Onset of band structure



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

Quantum transport



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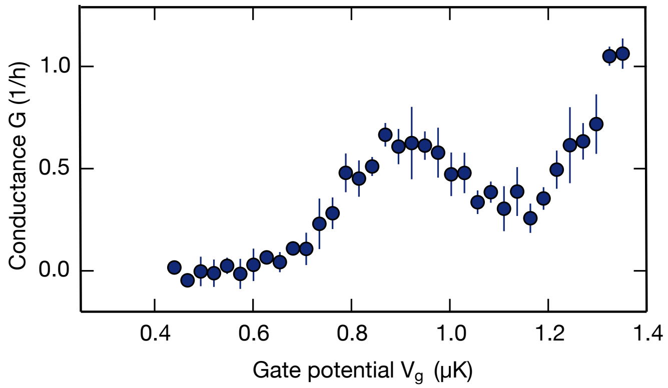
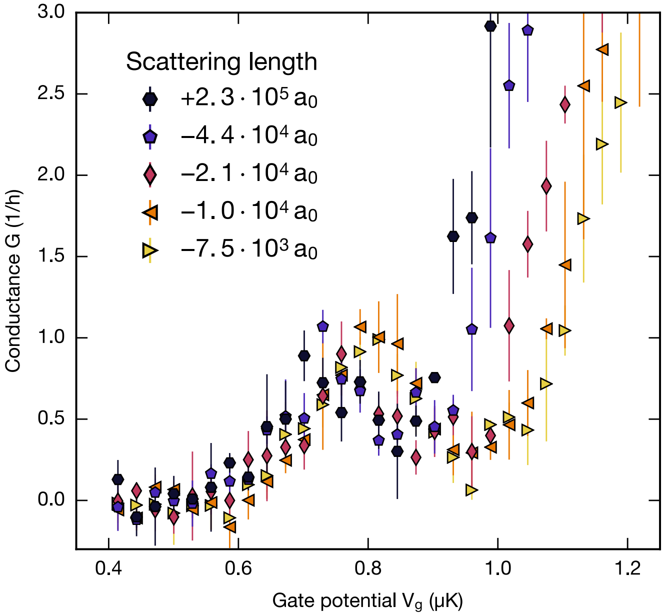


M. Lebrat *et al*, Phys. Rev. X **8** 011053 (2018)

Interactions

- Evolution of transport as interactions are increased

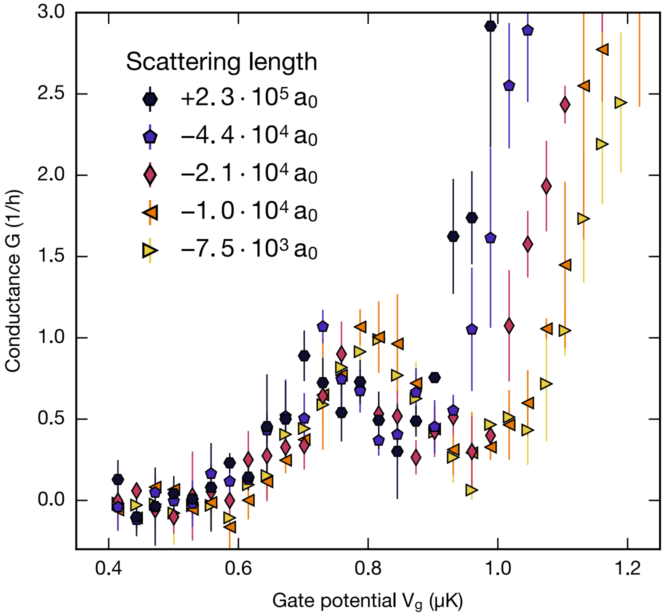


- No effect of strong interactions
- No effect of the superfluid character of the leads

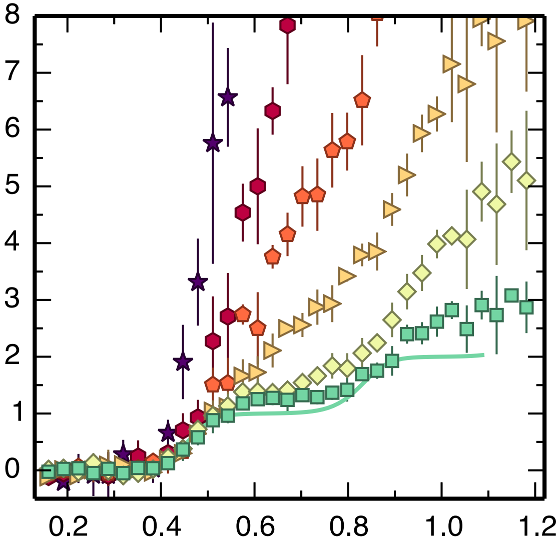
M. Lebrat *et al*, Phys. Rev. X **8** 011053 (2018)

Interactions

- Evolution of transport as interactions are increased



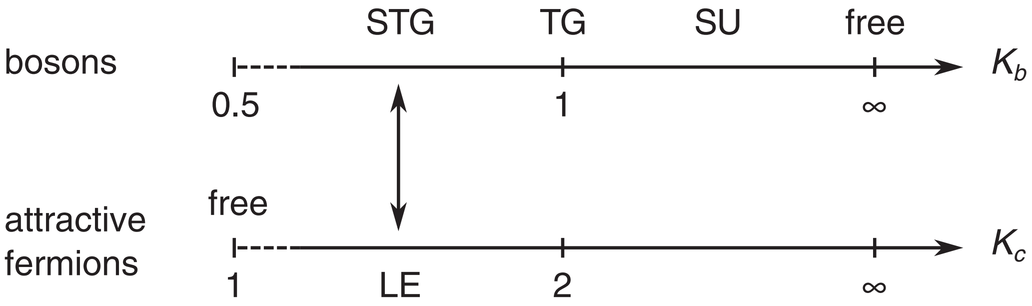
Without lattice:



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

Interactions: model

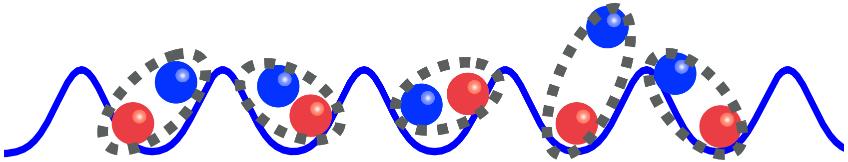
- Luther-Emery liquid:
  - Spin-gap formation due to interactions + confinement



A. Luther and V. J. Emery, Phys. Rev. Lett. **33**, 589 (1974).

Interactions: model

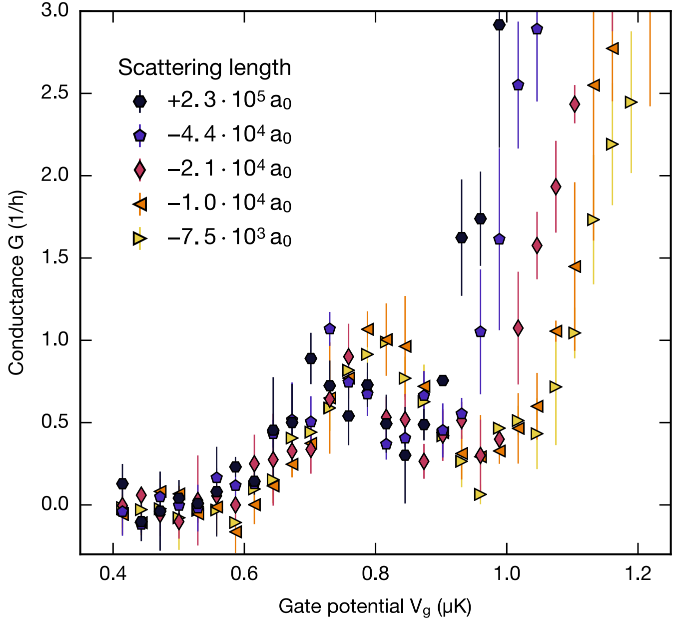
- Luther-Emery liquid:
  - Spin-gap formation due to interactions + confinement
  - Pinning of pairs in the weak lattice at commensurability



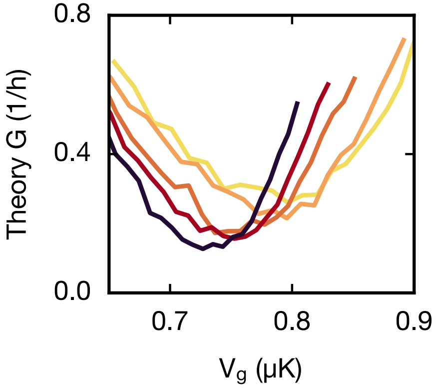
- Smooth crossover from Mott gap to band gap !

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

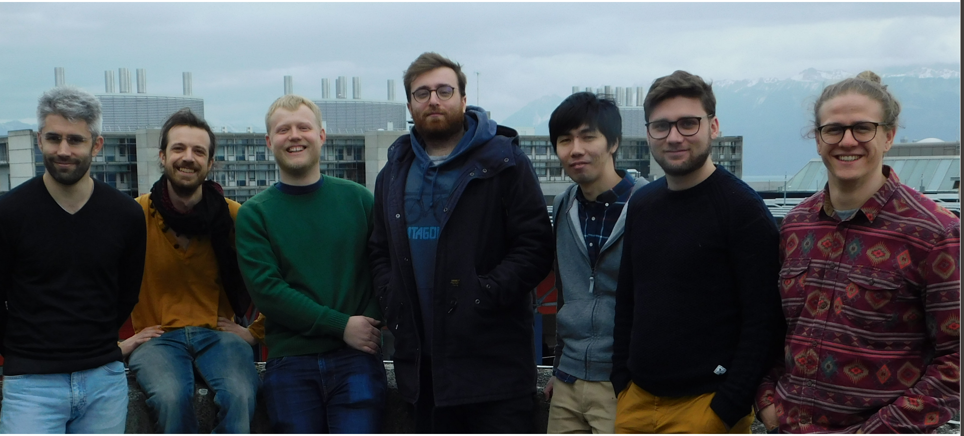
Interactions: model



- Agreement with theory close to commensurability
- Includes:
  - Finite size
  - Inhomogeneity
  - Finite temperature



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



Strongly interacting Fermions strongly coupled with light

EPFL

K. Roux, H. Konishi, V. Helson, T. Zwettler, JPB

K. Roux, H. Konishi, V. Helson and **JPB**
arXiv:1911.11151

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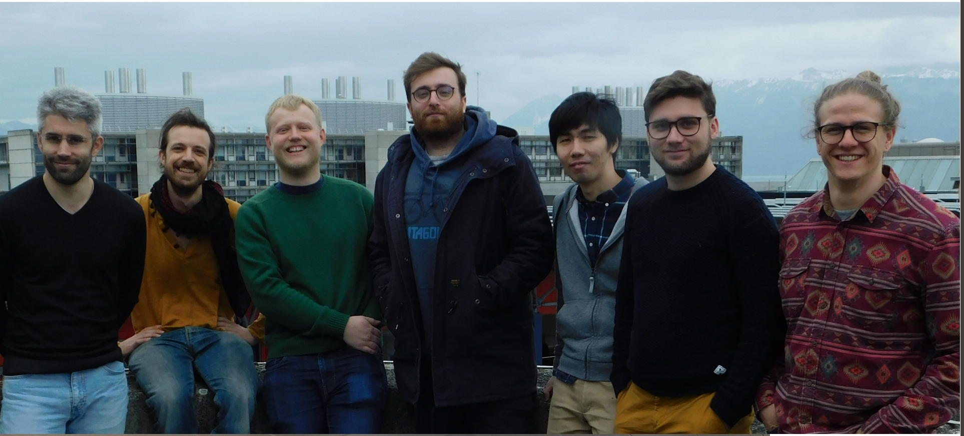

09.2016

Strongly interacting Fermions strongly coupled with light

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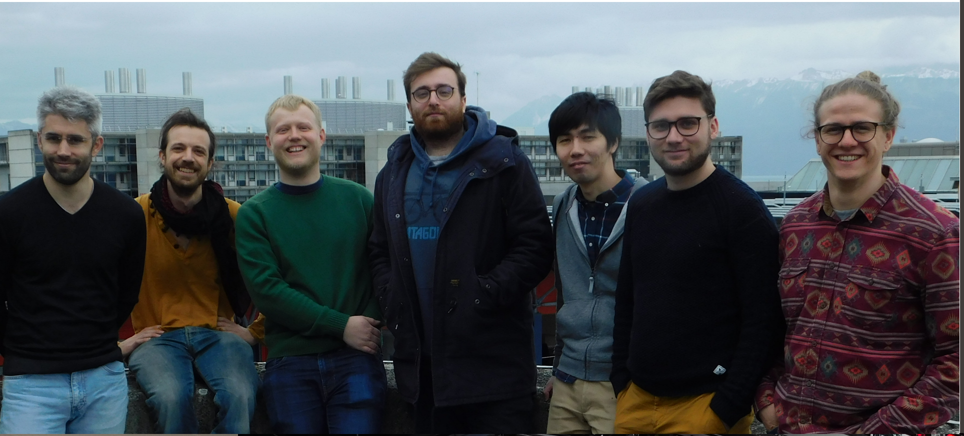

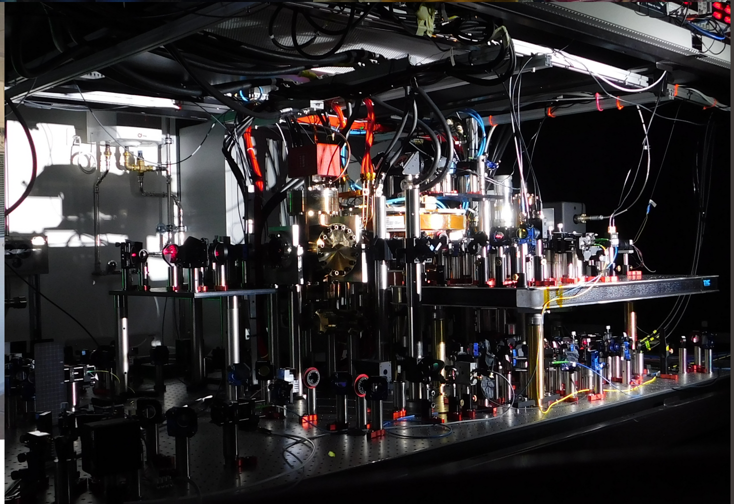

2019

Strongly interacting Fermions strongly coupled with light

EPFL

K. Roux, H. Konishi, V. Helson, T. Zwettler, JPB

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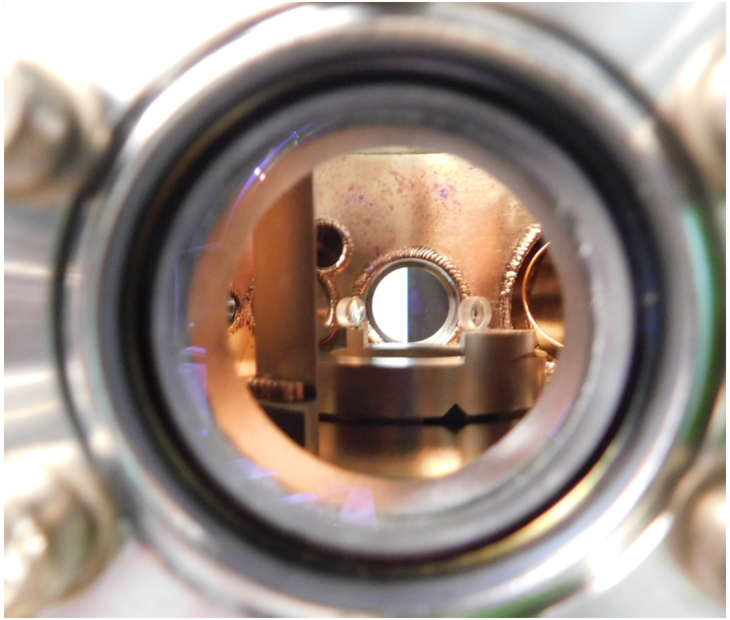
arXiv:1911.11151

Cavity QED with Fermi gases



- High finesse cavity for strong light-matter coupling

	671 nm	1064 nm / 532 nm
Linewidth	77 kHz	1.4 MHz
Finesse	47’000	2’800
Cooperativity	2	
Waist	45 µm	50 µm / 38 µm

- *Weakly interacting BECs:*
  ENS, ETHZ, Hamburg, Stanford, Singapore, Tübingen

K. Roux, H. Konishi, V. Helson and **JPB**
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Cavity QED with Fermi gases

- High finesse cavity for strong light-matter coupling

	671 nm	1064 nm / 532 nm
Linewidth	77 kHz	1.4 MHz
Finesse	47’000	2’800
Cooperativity	2	
Waist	45 µm	50 µm / 38 µm

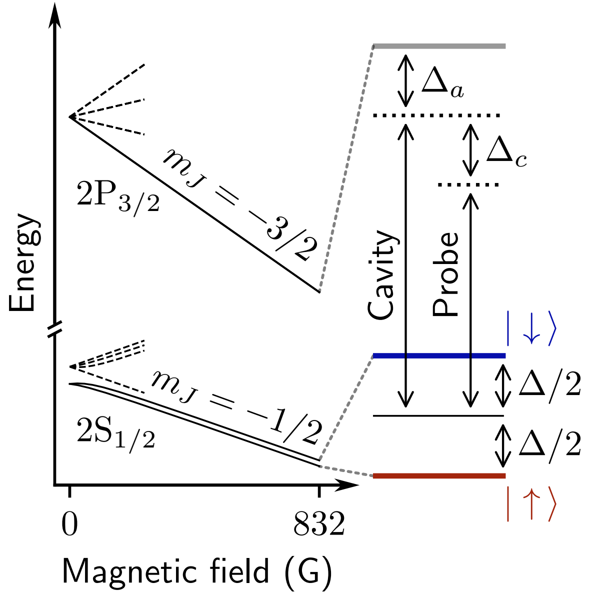
- Combined with unitary Fermi gases
  - Compact bulk-machined electromagnets

K. Roux, B. Cilenti, V. Helson , H. Konishi and **JPB**
SciPost Phys. **6** 048 (2019)

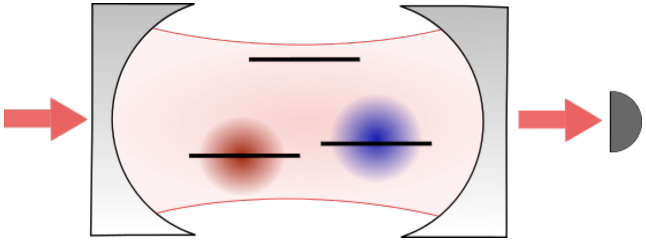
K. Roux, H. Konishi, V. Helson and **JPB**
arXiv:1911.11151

Cavity QED with Fermi gases

- **Strong light-matter coupling for the unitary Fermi gas**



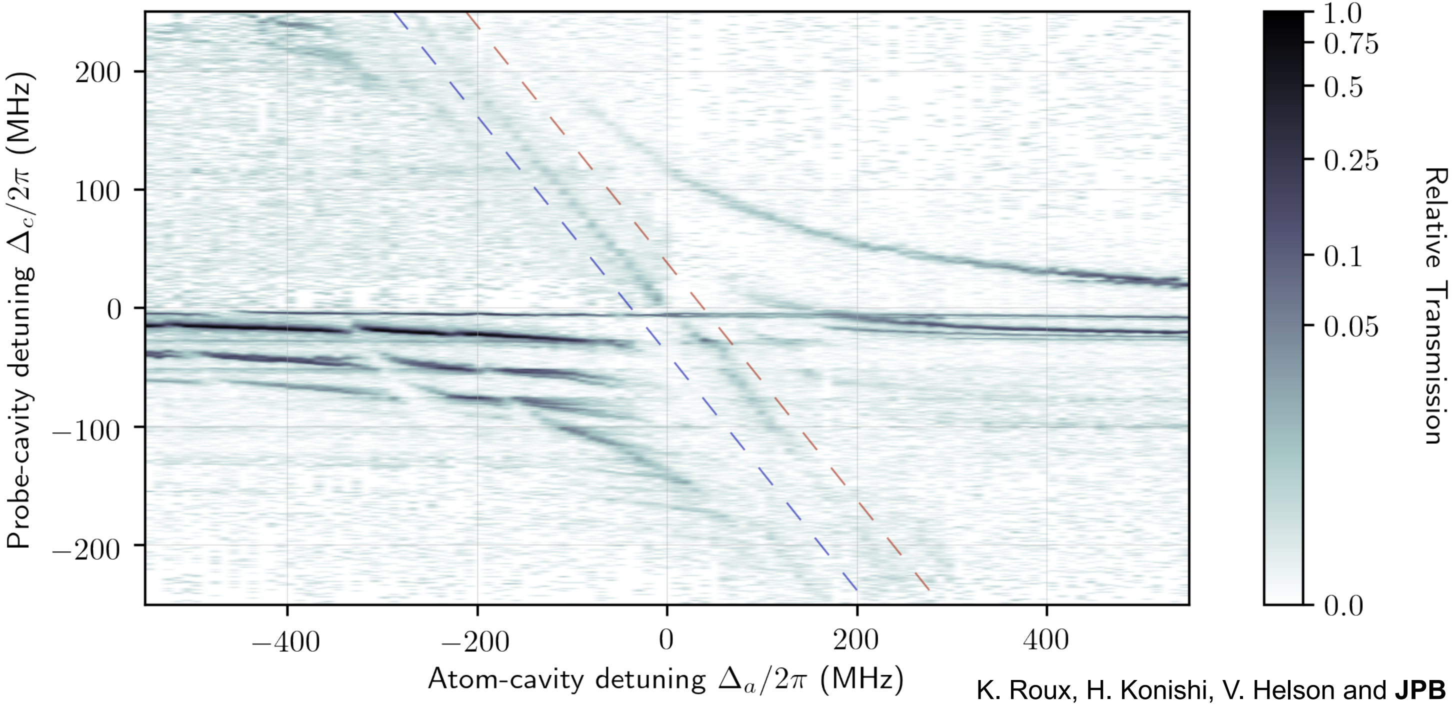
- Transmission spectroscopy in the linear regime
- Mixture of two hyperfine states



K. Roux, H. Konishi, V. Helson and **JPB**
arXiv:1911.11151

Cavity QED with Fermi gases

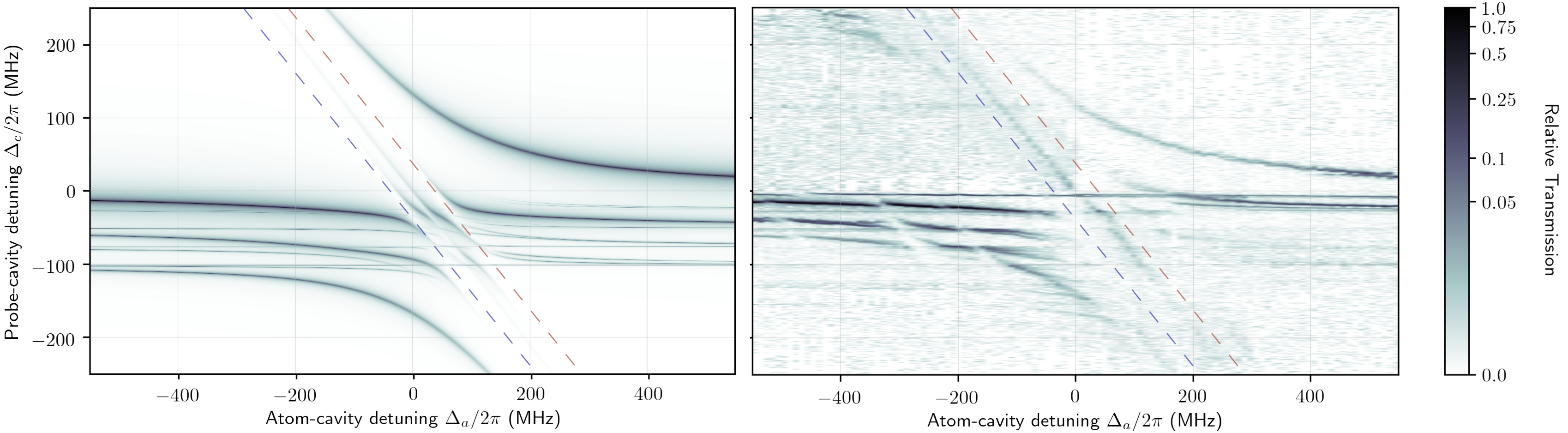
- **Coupled photon-Fermion spectrum**



K. Roux, H. Konishi, V. Helson and **JPB**
arXiv:1911.11151

Cavity QED with Fermi gases

- **Coupled photon-Fermion spectrum**
  - Theory for light-matter interactions
  - No fit parameter



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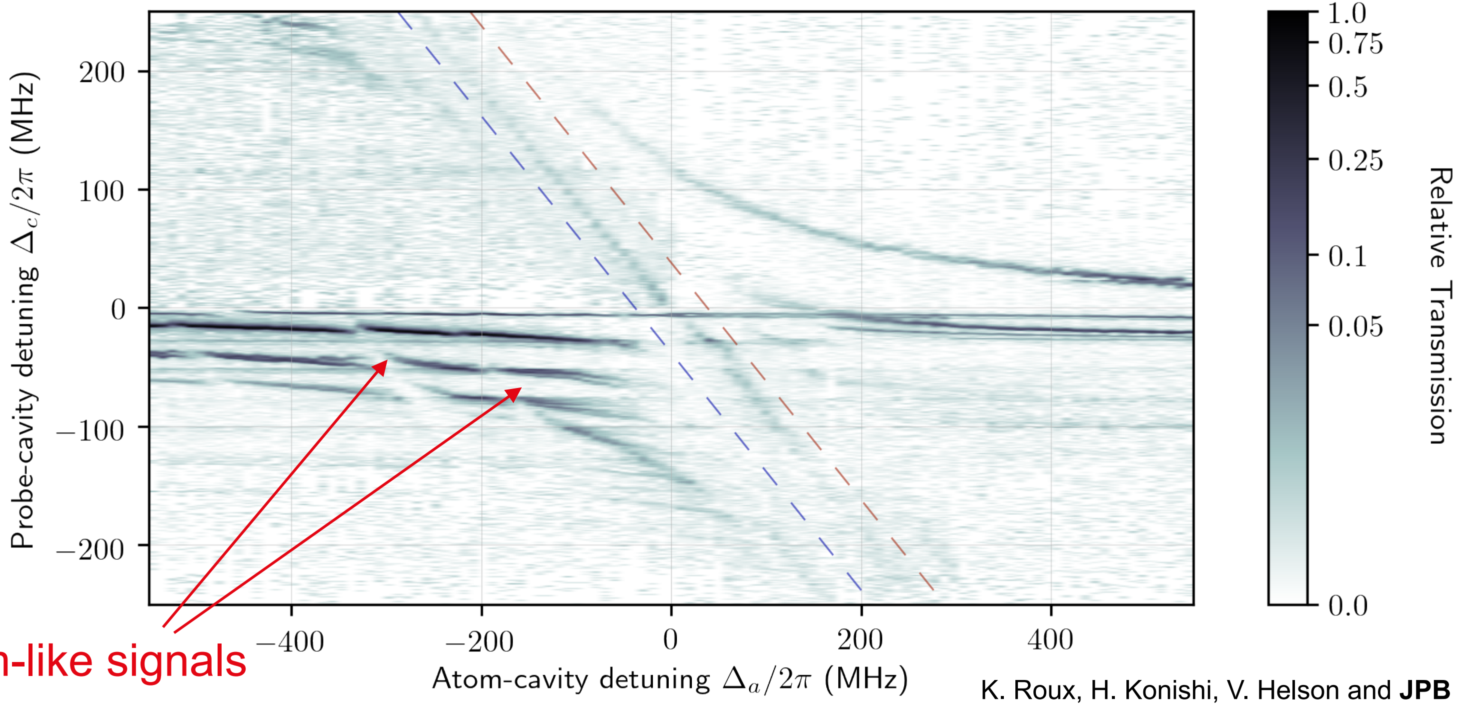
arXiv:1911.11151

Cavity QED with Fermi gases

Jean-Philippe Brantut

- **Coupled photon-Fermion spectrum**

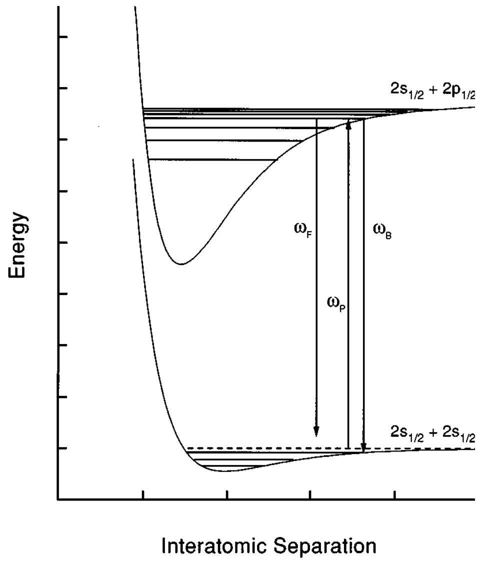


Extra atom-like signals

K. Roux, H. Konishi, V. Helson and **JPB**
arXiv:1911.11151

Cavity QED with Fermi gases

- **Signatures of interactions in the spectrum**
  - Two-atoms optical spectrum: photoassociation



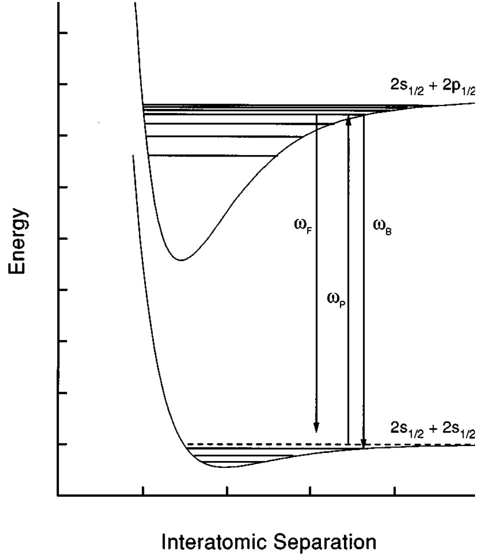
E. Abraham, N. Ritchie, W. McAlexander, and R. Hulet
The Journal of Chemical Physics **103** 7773 (1995)

Cavity QED with Fermi gases

- **Signatures of interactions in the spectrum**
  - Two-atoms optical spectrum: photoassociation
  - Light-matter interaction:

$$\hat{H}_{\text{at-field}} = \frac{\Omega_m}{2}\left(\int dR g(R)\hat{\psi}^\dagger_m(R)\int dr f(r)\hat{\psi}_\uparrow(R+\frac{r}{2})\hat{\psi}_\downarrow(R-\frac{r}{2})\hat{a} + hc\right)$$

$$^6\text{Li}(\uparrow) + {}^6\text{Li}(\downarrow) + \gamma \longrightarrow {}^6\text{Li}_2$$



Cavity QED with Fermi gases

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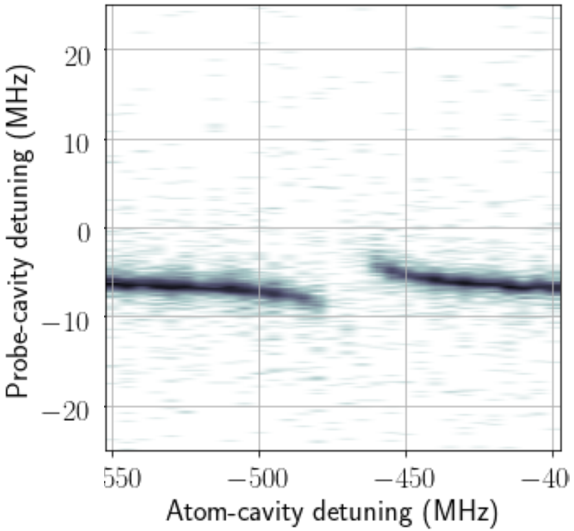


Strong coupling
'pair polaritons'

Cavity QED with Fermi gases

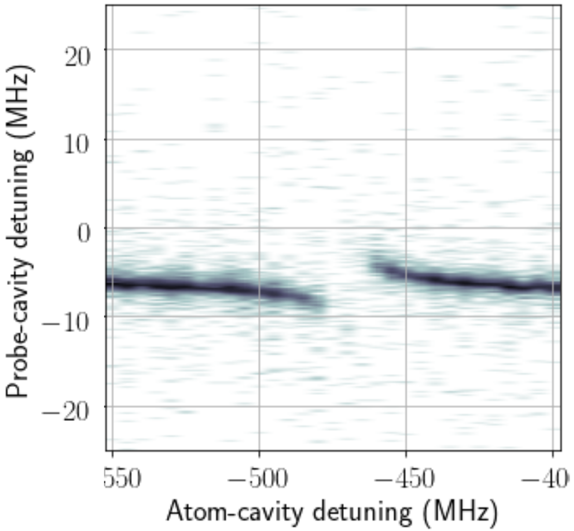
- **Signatures of interactions in the spectrum**
  - Two-atoms optical spectrum: photoassociation

$$\bar{\Omega}^2 = \Omega_m^2 \int dR dr_1 dr_2 |g(R)|^2 \cdot$$

$$f(r_1)f^*(r_2)\left\langle \hat{\psi}_\downarrow^\dagger(R - \frac{r_2}{2})\hat{\psi}_\uparrow^\dagger(R + \frac{r_2}{2})\hat{\psi}_\uparrow(R + \frac{r_1}{2})\hat{\psi}_\downarrow(R - \frac{r_1}{2})\right\rangle$$

Short range two-body correlation function

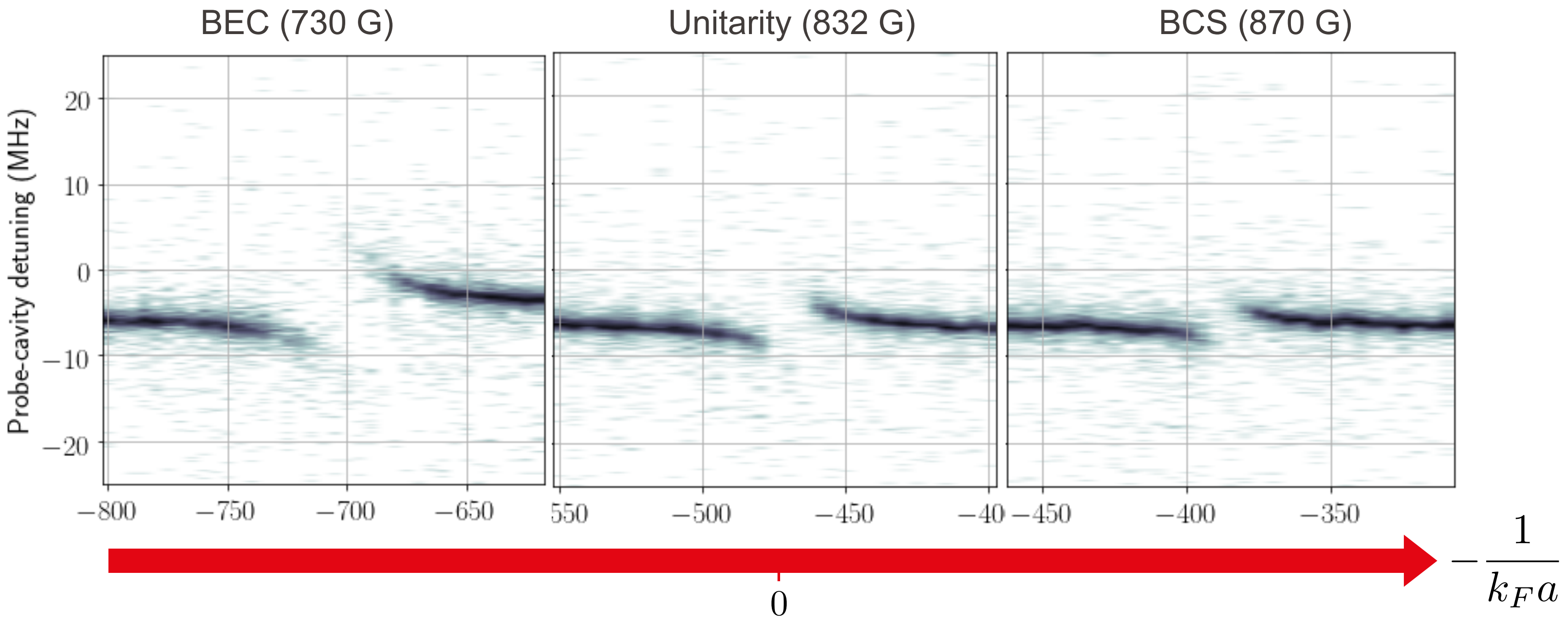
  - *Single photons directly coupled to pairs*



Strong coupling
'pair polaritons'

Cavity QED with Fermi gases

- **Fermion-pair polaritons**

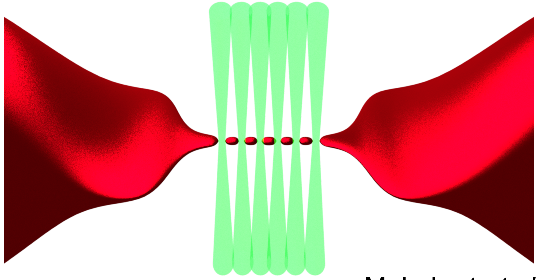


Conclusions

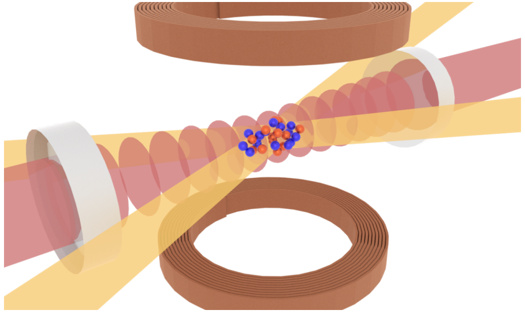
Quantum devices with cold atoms

Extend controls to spin, heat

Search for new states of matter



M. Lebrat *et al*,
Phys. Rev. X **8** 011053 (2018)
S. Krinner, T. Esslinger and **JPB**,
J. Phys.: Condens. Matter **29** 343003 (2017)



K. Roux *et al*, arXiv:1911.11151

Cavity QED with strongly correlated Fermions

Pair polaritons: quantum Feshbach resonances

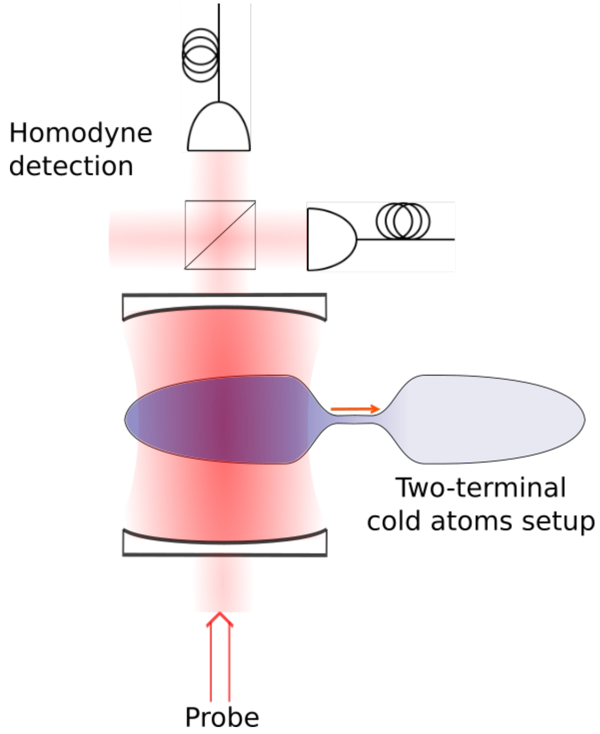
Cavity induced long-range interactions

Quantum-limited particle current measurements

Conclusions

- **Quantum limits to current measurements**
  - Full-counting statistics of particle transfer
  - *Universal* back-action heating
  - In the QND regime: *standard quantum limit* to current measurements

$$\mathcal{S}_{ii}^{\mathrm{imp}}(\omega) = \mathrm{sinc}^2\left(\frac{\omega\tau}{2}\right)\left[\frac{\omega^2\kappa}{4g^2} + |Y(\omega)|^2\,\frac{g^2}{\kappa}\,\frac{1}{1+\frac{4\omega^2}{\kappa^2}}\right]$$



S. Uchino, M. Ueda and **JPB**
Phys. Rev. A **98**, 063619 (2018)

Thanks for your attention

Discussions:

T. Donner, T. Esslinger, R. Hulet, S. Uchino, P.S. Julienne

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Sandoz-Fondation de famille

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