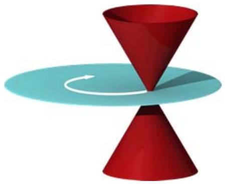
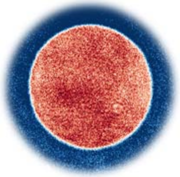
Probing superfluid and 2D Fermi gases

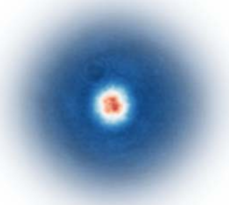
K. Hueck, L. Sobirey, N. Luick, J. Siegl, K. Morgener, W. Weimer,
T. Lompe, H. Moritz

Outline

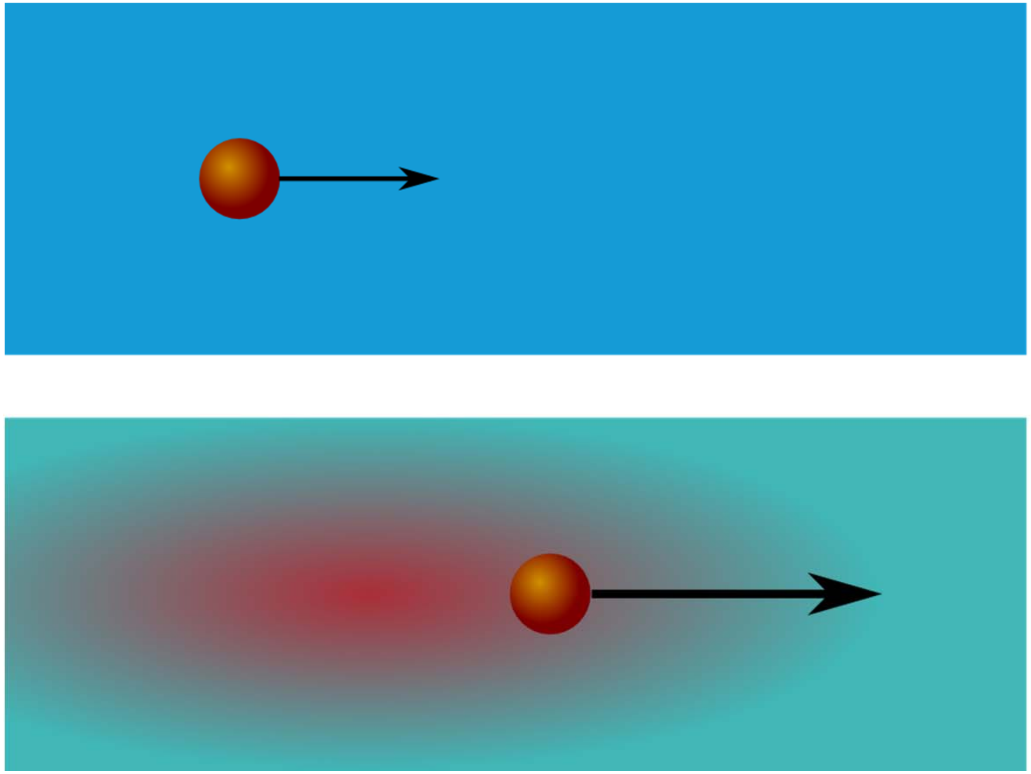
 **3D Critical velocity**

 Homogeneous 2D Fermi gases

 Equation of state

 Momentum Distribution

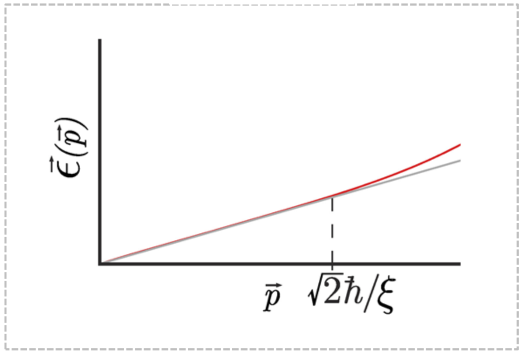
Landau's critical velocity



$v < v_c$

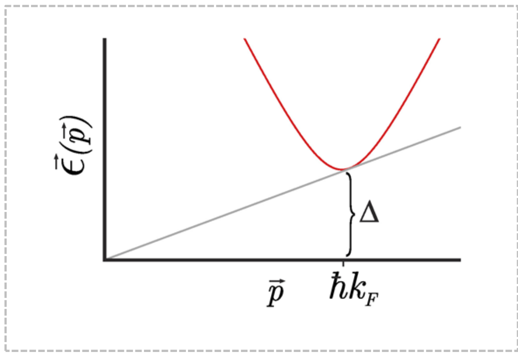
$v > v_c$

BEC

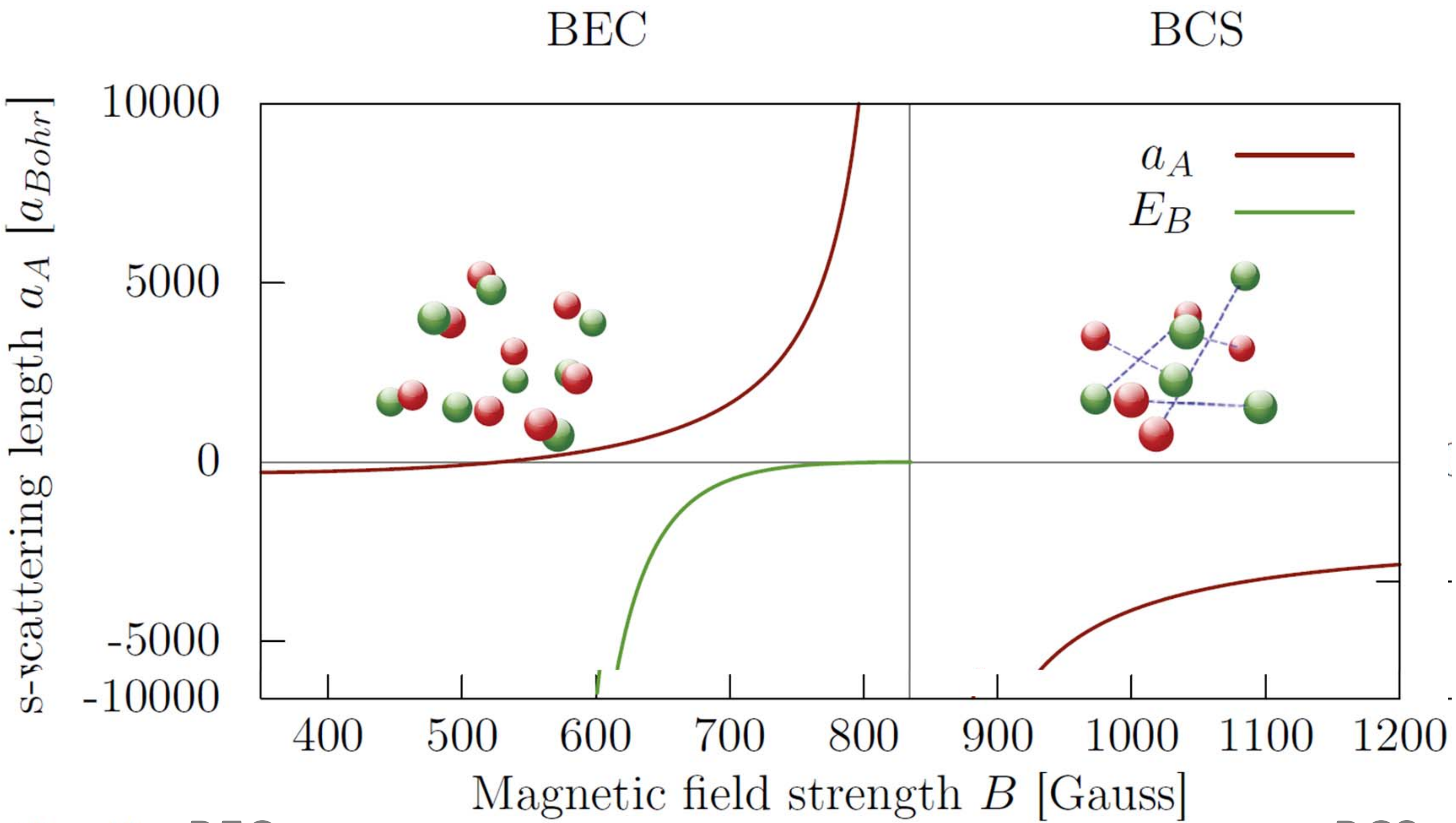


$$v_c = \min_k \left(\frac{\epsilon(k)}{\hbar k} \right)$$

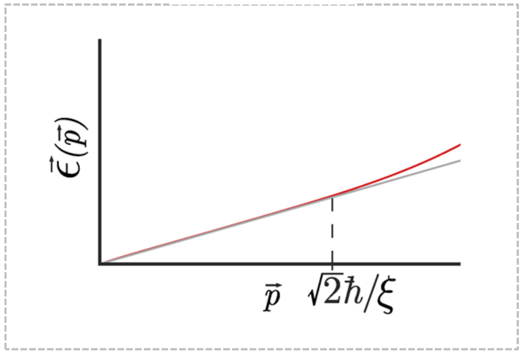
BCS



BEC-BCS crossover

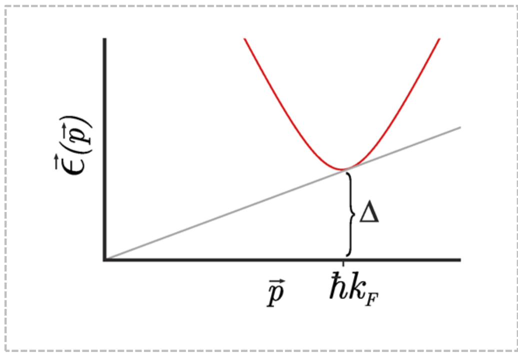


BEC

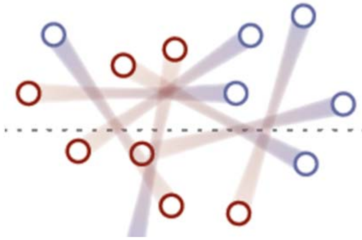


?

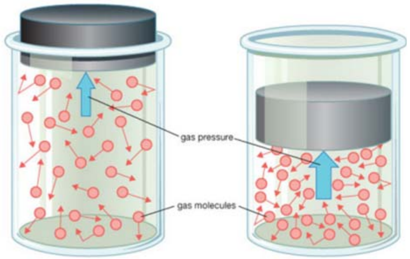
BCS



The critical velocity



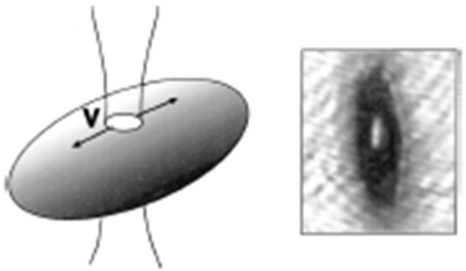
strong correlations



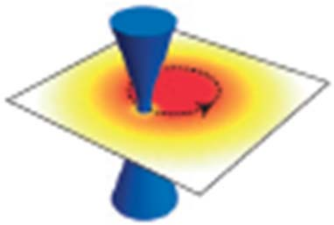
knowing ground state not enough

→ phonons, pair breaking, vortices

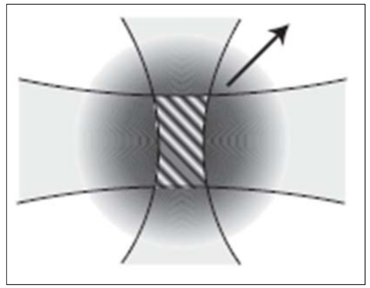
performative aspect: v_c and T_c matter



3D BEC



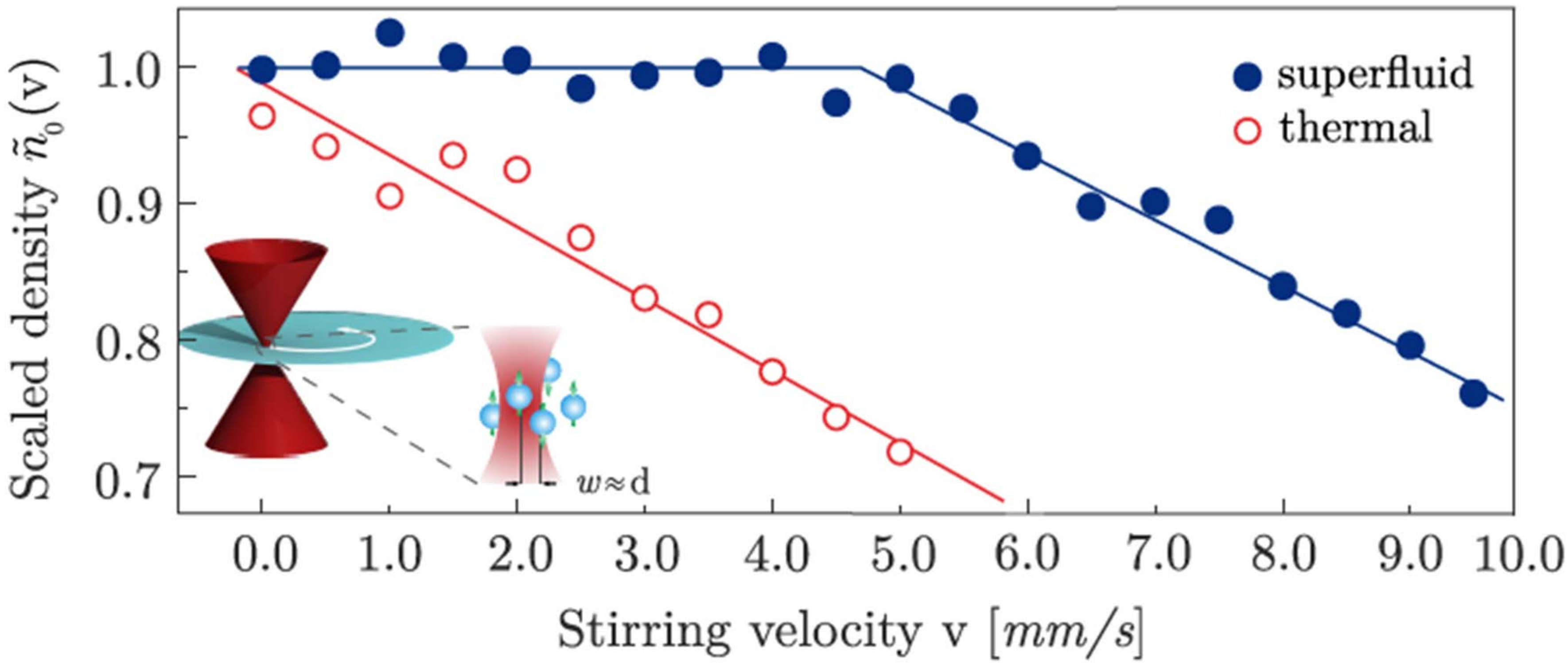
2D Bose/BKT



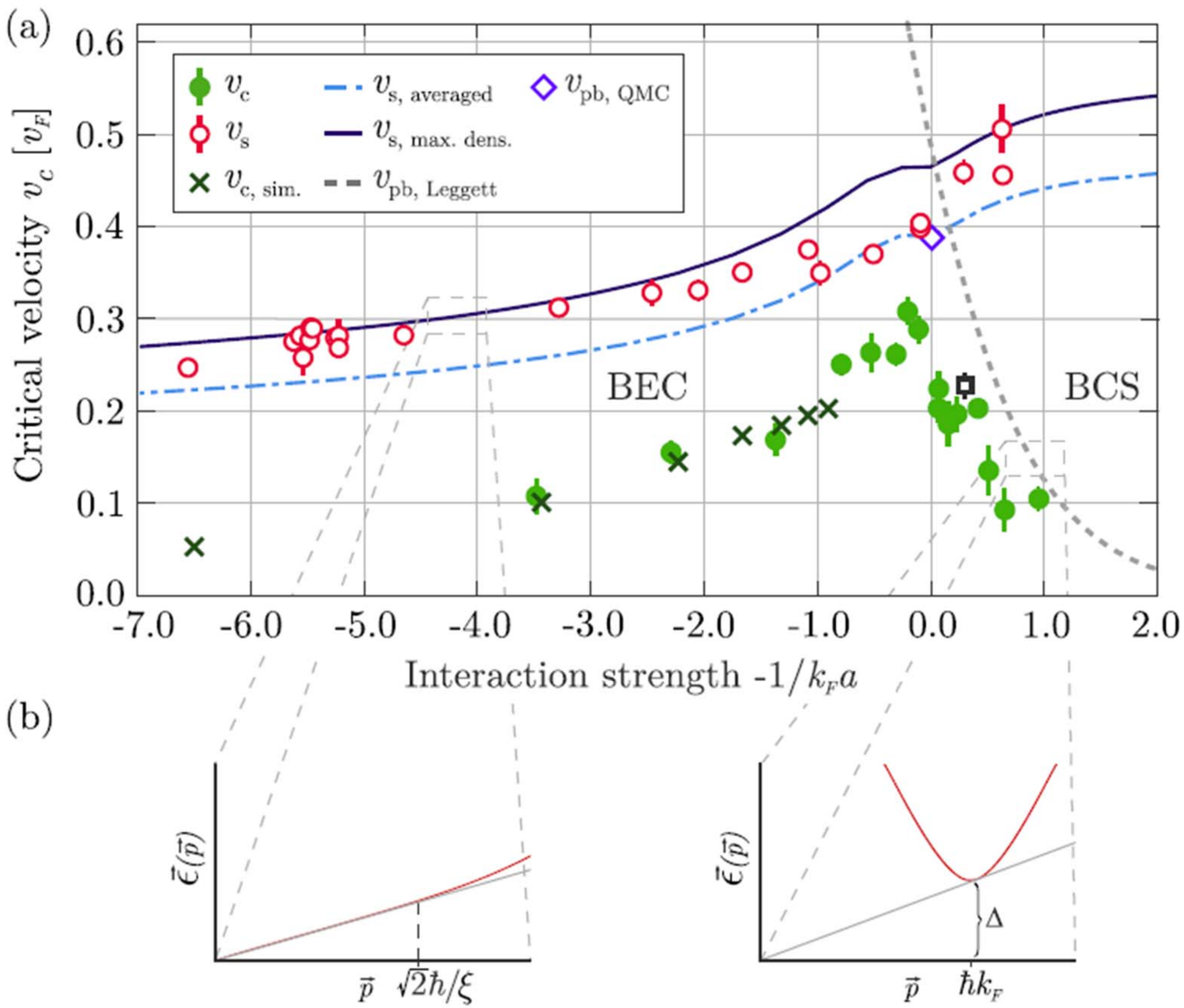
3D Fermi

3D BEC: C. Raman et al., Phys. Rev. Lett. 83, 2502 (1999)
2D BKT: R. Desbuquois et al., Nature Phys. 8, 645 (2012)
3D Fermi: D. E. Miller et al., Phys. Rev. Lett. 99, 070402 (2007)
BEC rings A. Ramanathan et al., Phys. Rev. Lett. 106, 130401 (2011)

Critical velocity



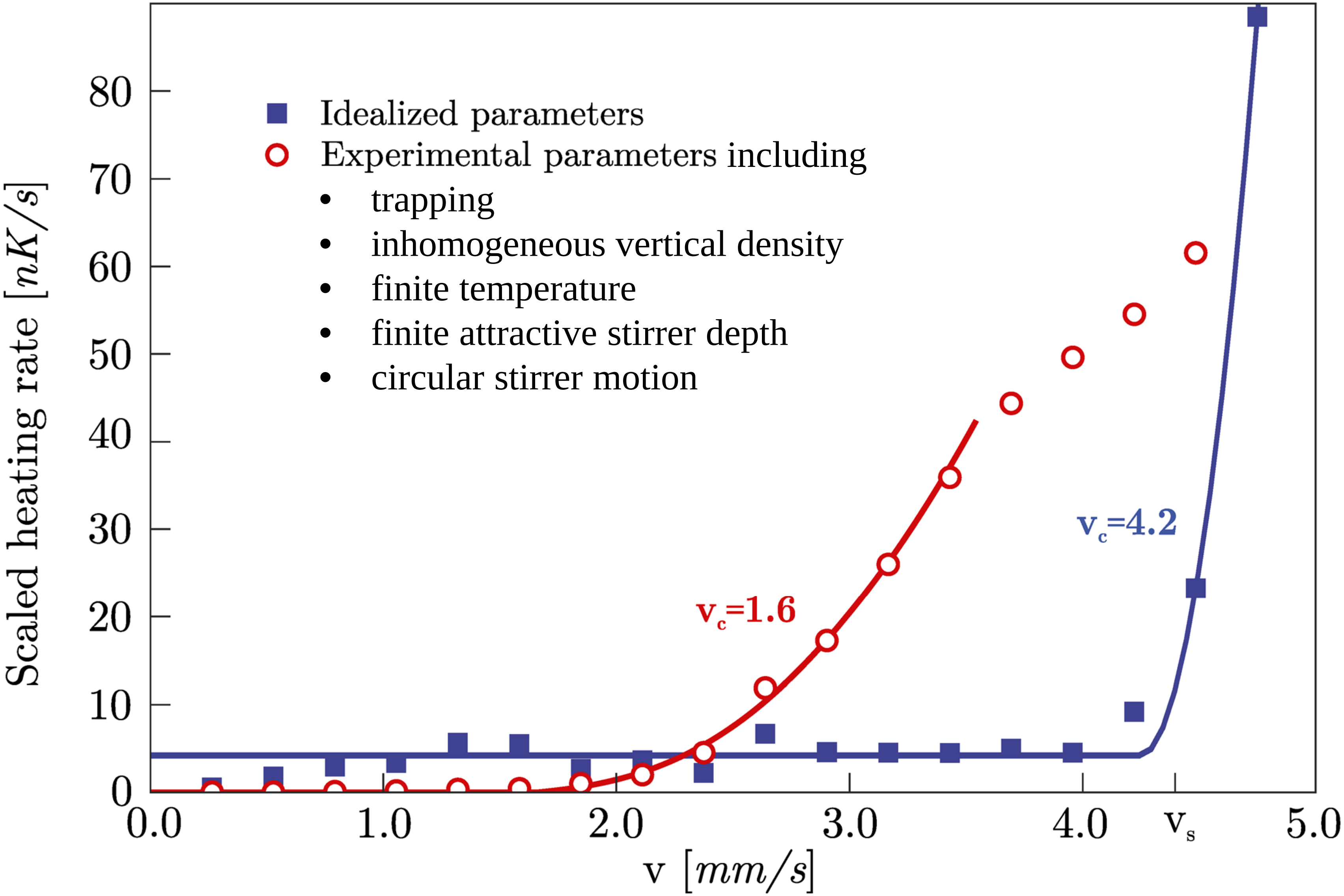
Critical velocity and speed of sound



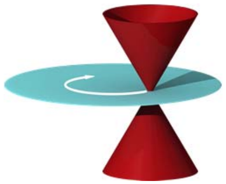
W. Weimer et al., PRL 114, 095301 (2015); V. Singh et al. PRA 93, 023634 (2016)

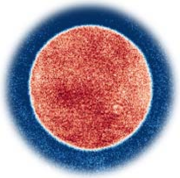
Simulations by Vijay Singh & Ludwig Mathey

Ground state from Monte Carlo, dynamics with truncated Wigner method,

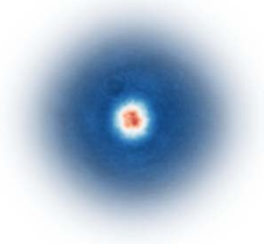


Outline

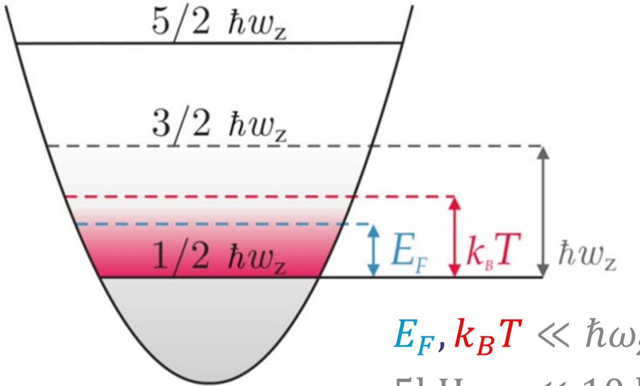

3D Critical velocity


Homogeneous 2D Fermi gases


Equation of state


Momentum Distribution

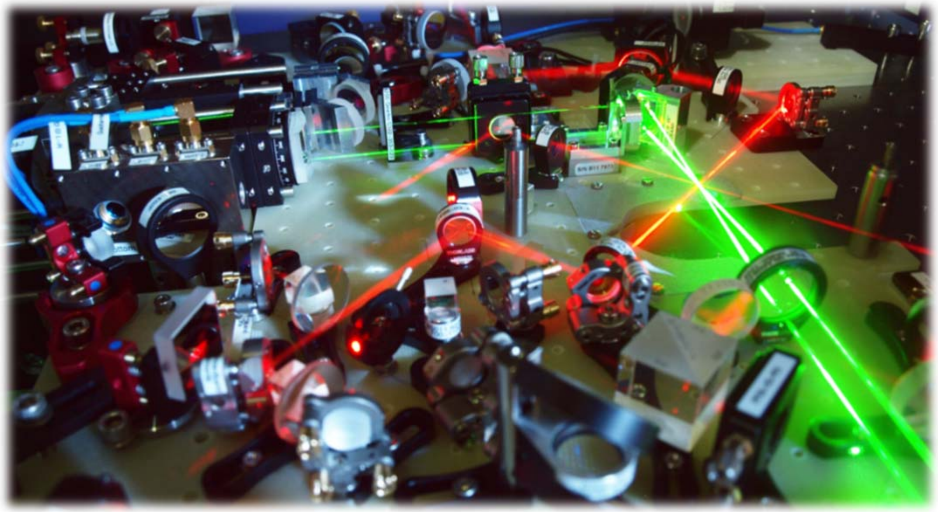
Reducing dimensions

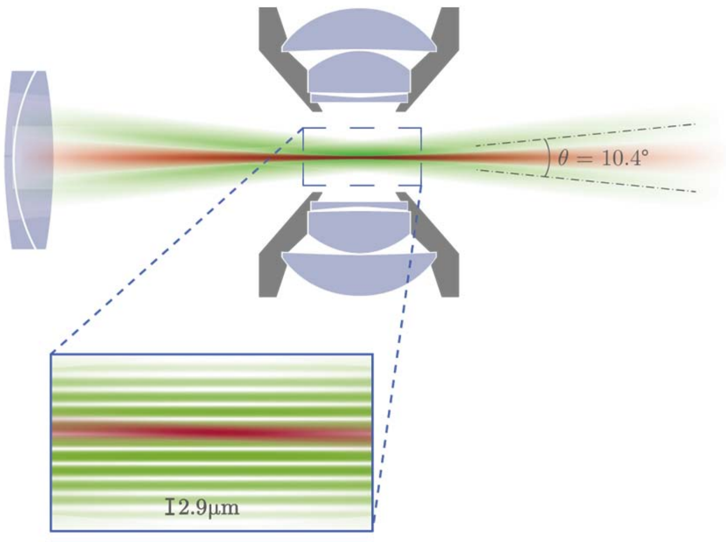


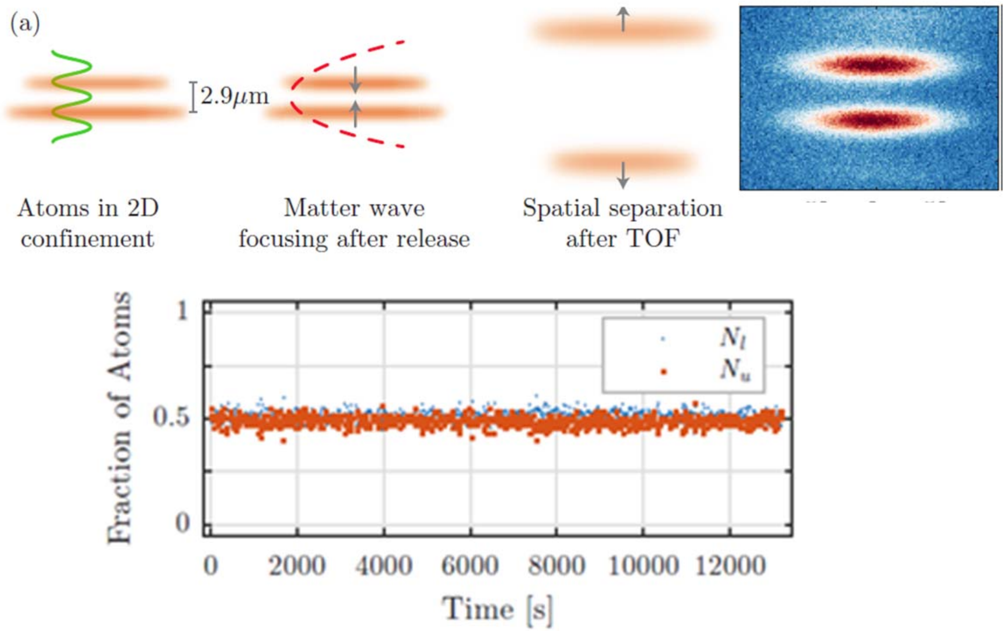
$E_F, k_BT \ll \hbar\omega_z$

5kHz $\ll$ 10 kHz

2D Fermi: Turlapov, Vale, Köhl,
Zwierlein, Thomas Jochim, Bakr, …

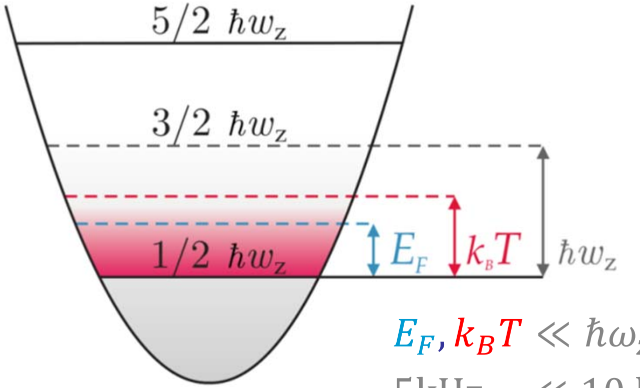






Single or double layer
stable over hours, central layer >90%

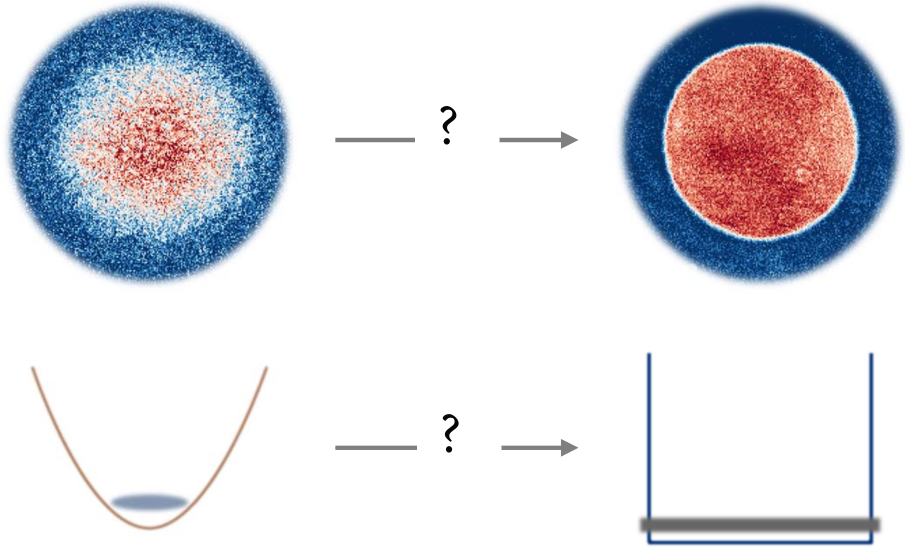
Reducing dimensions



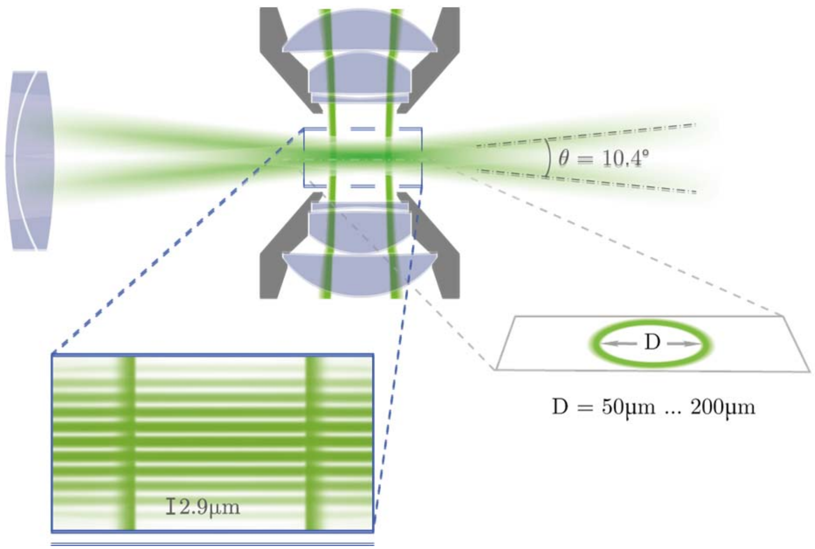
$E_F, k_B T \ll \hbar\omega_z$

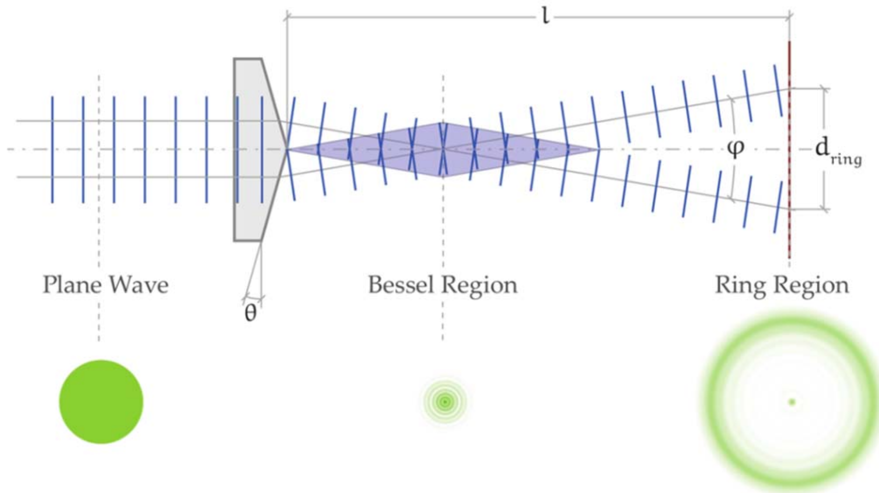
5kHz $\ll$ 10 kHz

2D Fermi: Turlapov, Vale, Köhl, Zwierlein, Thomas Jochim, Bakr, …



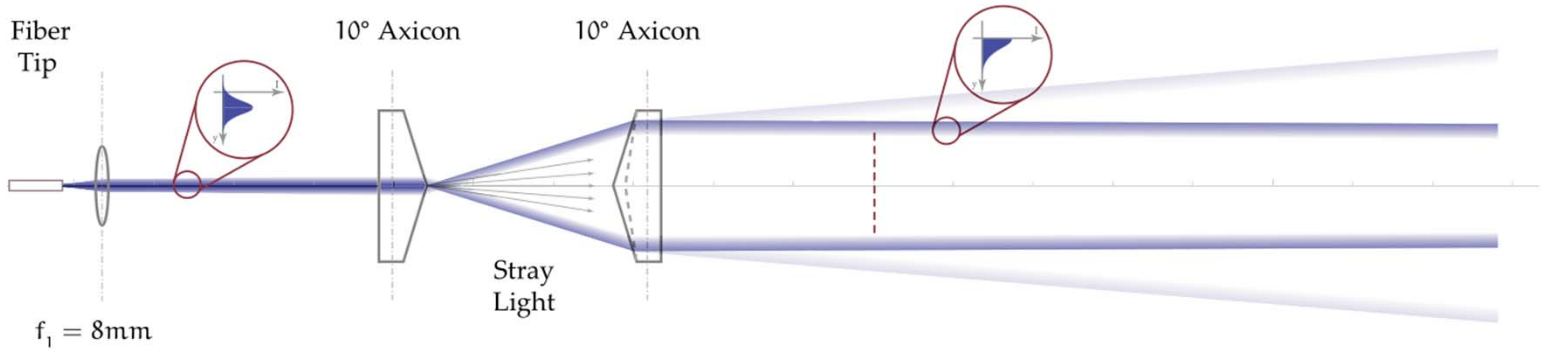
3D Fermi in box: Zwierlein Group



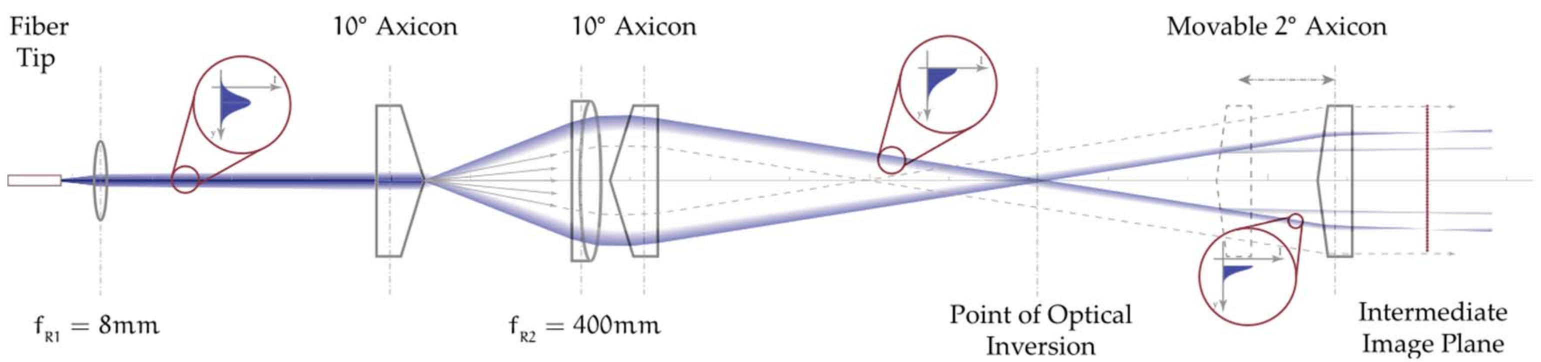


Creating a steep ring without disorder inside

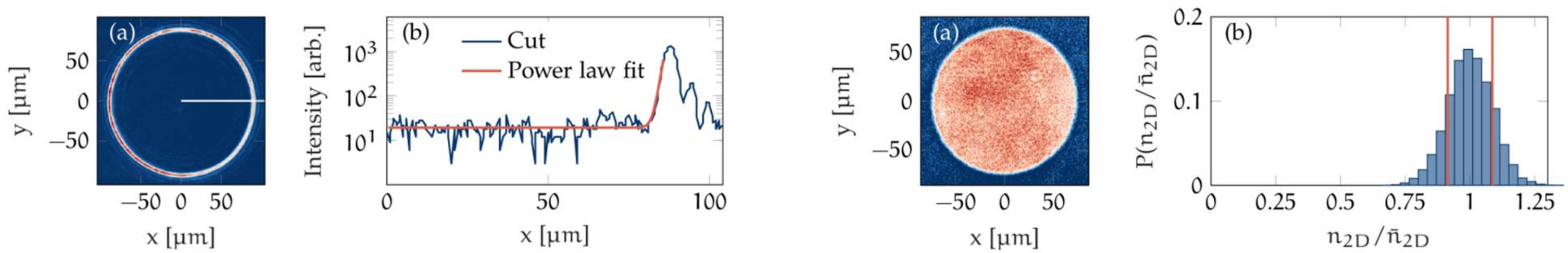
Simplest setup



Steeper, less stray light inside



Flatness and steepness



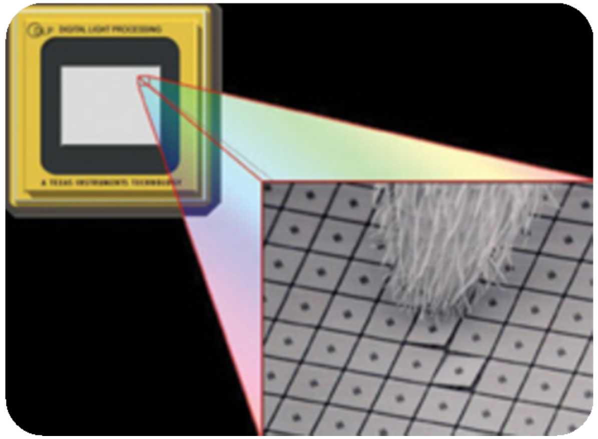
$V(x) = Ax^{\xi} = Ax^{87\pm5}$

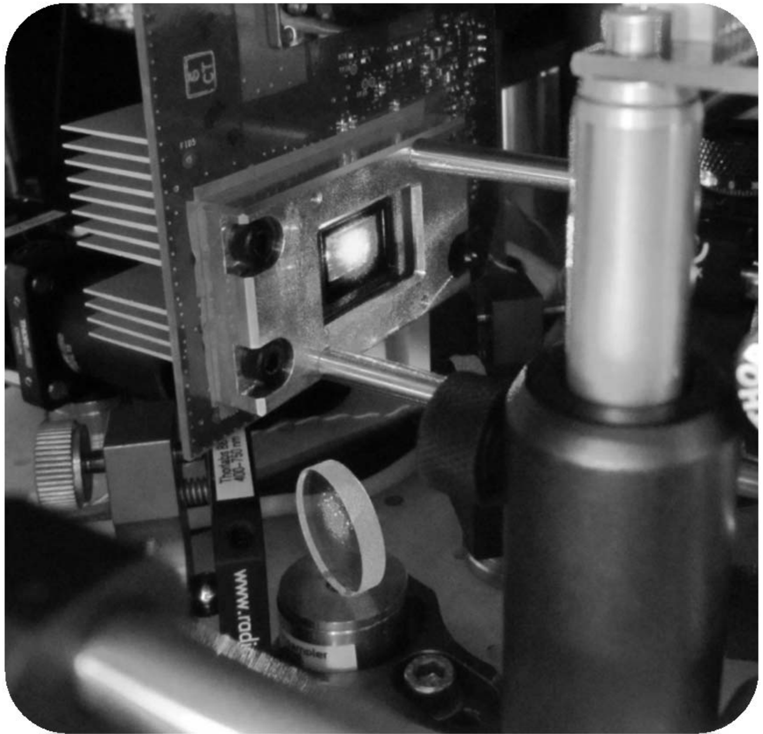
75 img's averaged

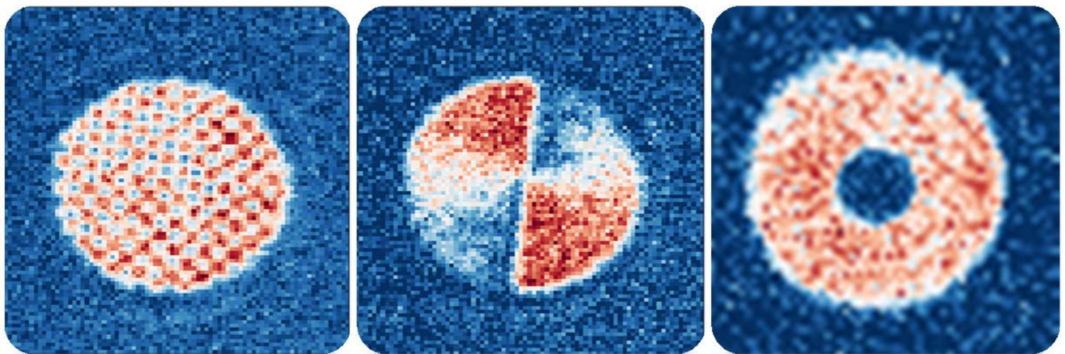
$\sigma_n = 8.6\,\%$

Tunable potential landscapes

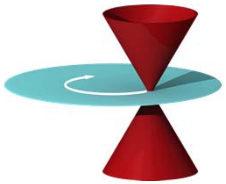
- Digital micromirror array (DMD) imaged onto atoms
  - 25 pixels per resolved spot → 25 gray scales
  - A hardware extension was developed to generate truly static patterns[K. Hueck et al., RSI 88, 016103 (2017)]
  - Development of Matlab class to control the DMD[GitHub]
- For transport measurements through 2D
  - Disordered media
  - Josephson barrier/oscillations
  - Driven systems
- Embedded systems, Interfaces



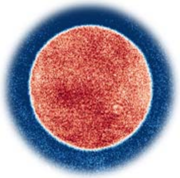




Outline

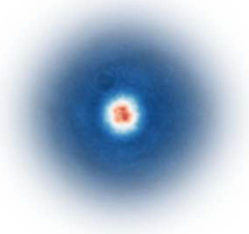


3D Critical velocity



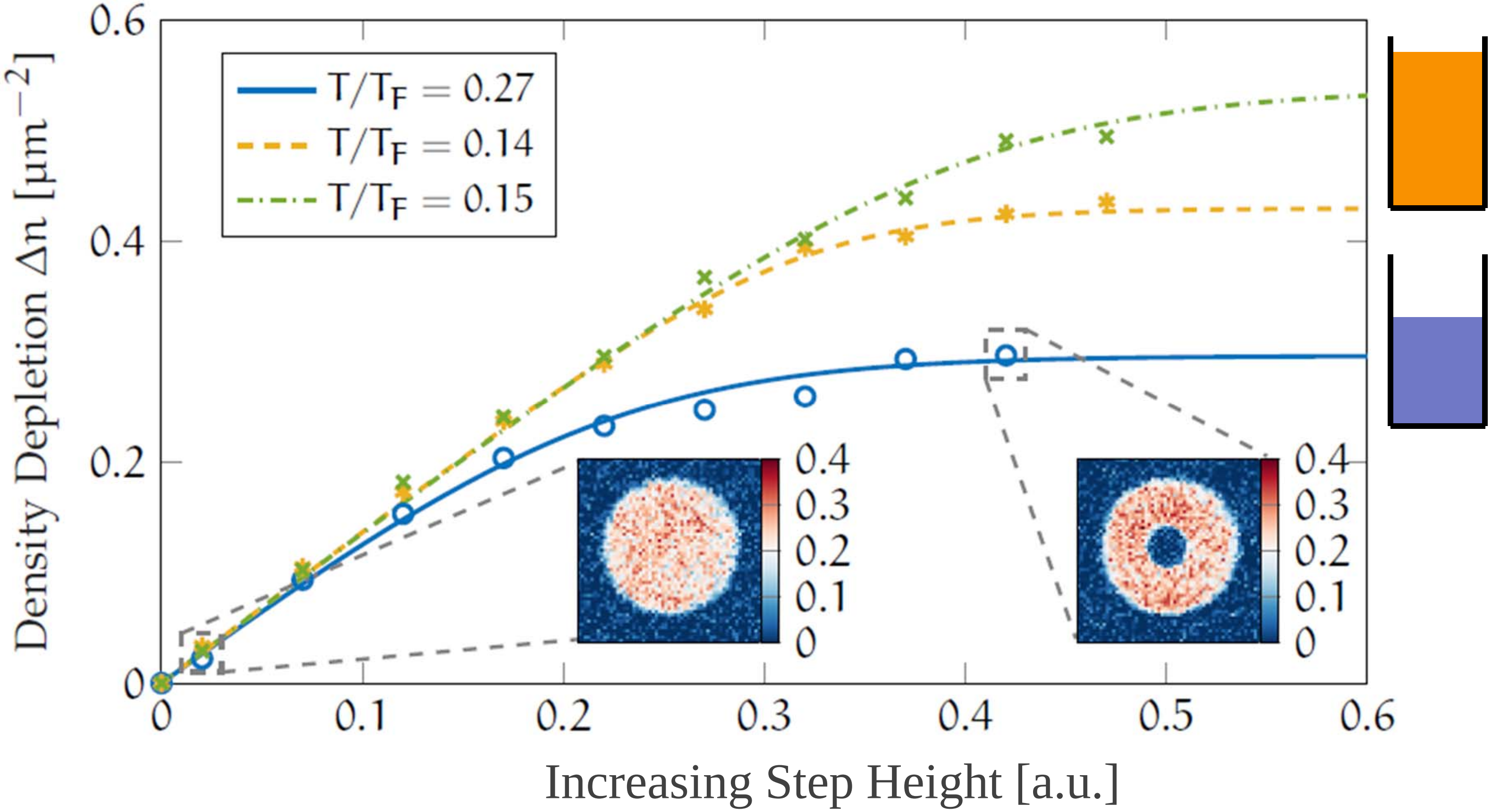
Homogeneous 2D Fermi gases

Equation of state



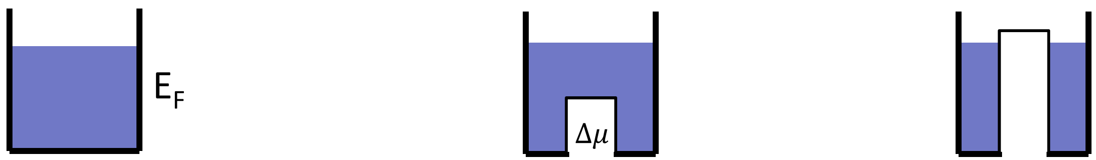
Momentum Distribution

Equation of state $n(\mu, T)$ of ideal Fermi gas



⇒ decreasing density and increasing Δn

$$n\lambda_{dB}^2 = \log[1 + \exp(\beta\mu)]$$

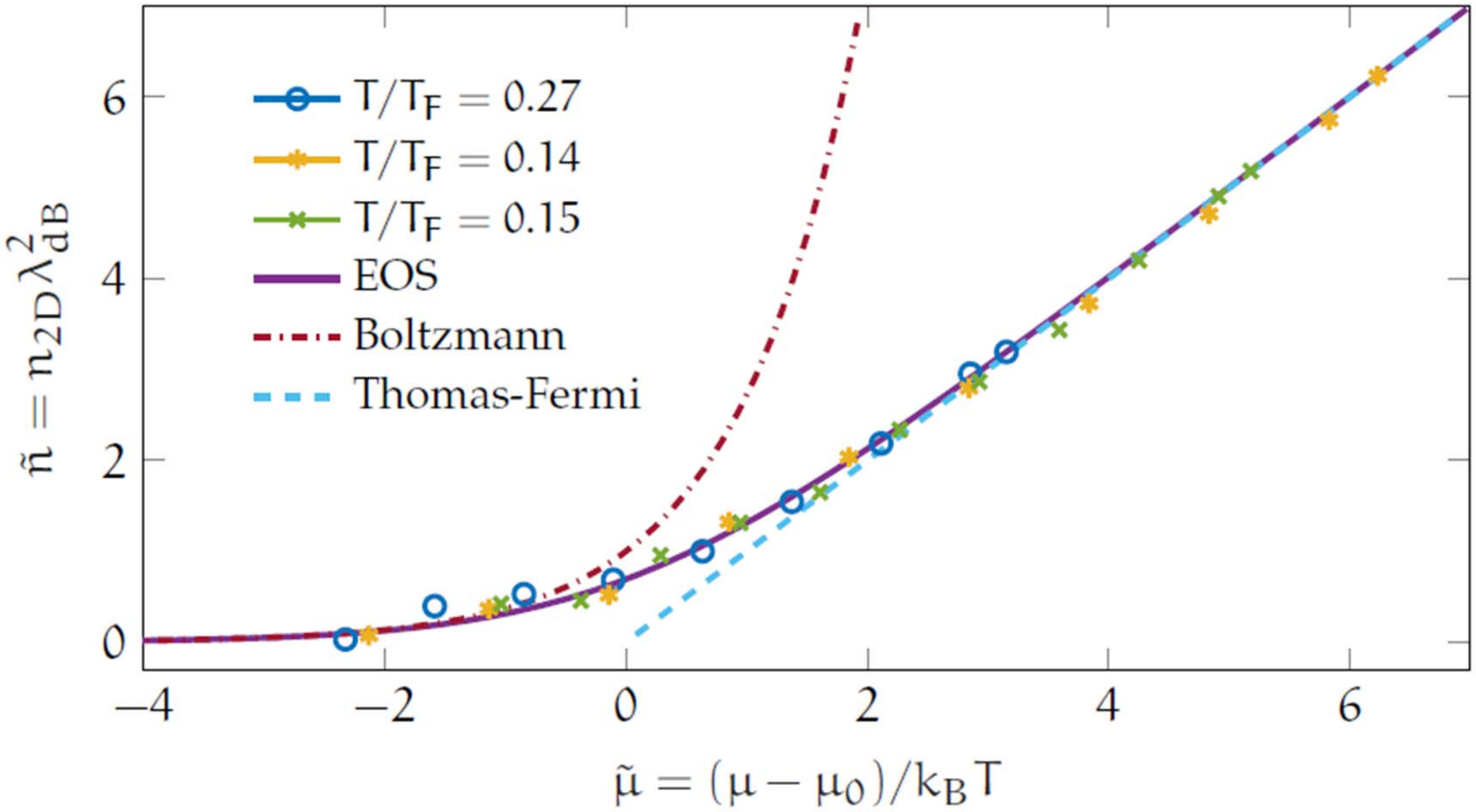


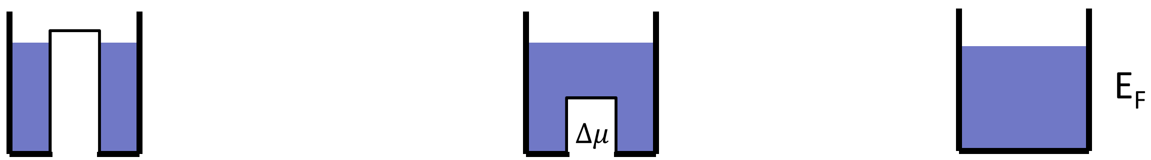
2D EOS: Bose gases Chin & Dalibard groups, Fermi gases: Turlapov, Vale, Jochim groups

K. Hueck et al. arXiv:1704.06315 (2017)

Scale invariant equation of state $n(\mu, T)$

Theory: $n\lambda_{dB}^2 = \log[1 + \exp(\beta\mu)]$





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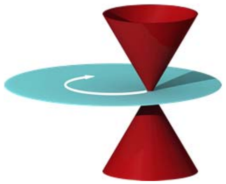

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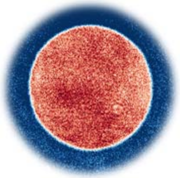
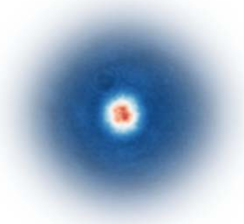


Homogeneous 2D Fermi gases

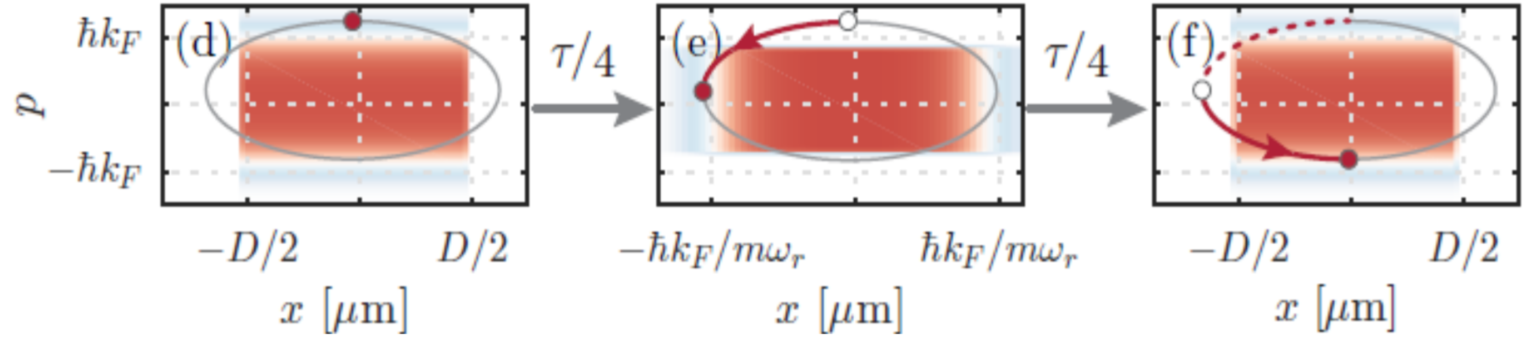
Equation of state

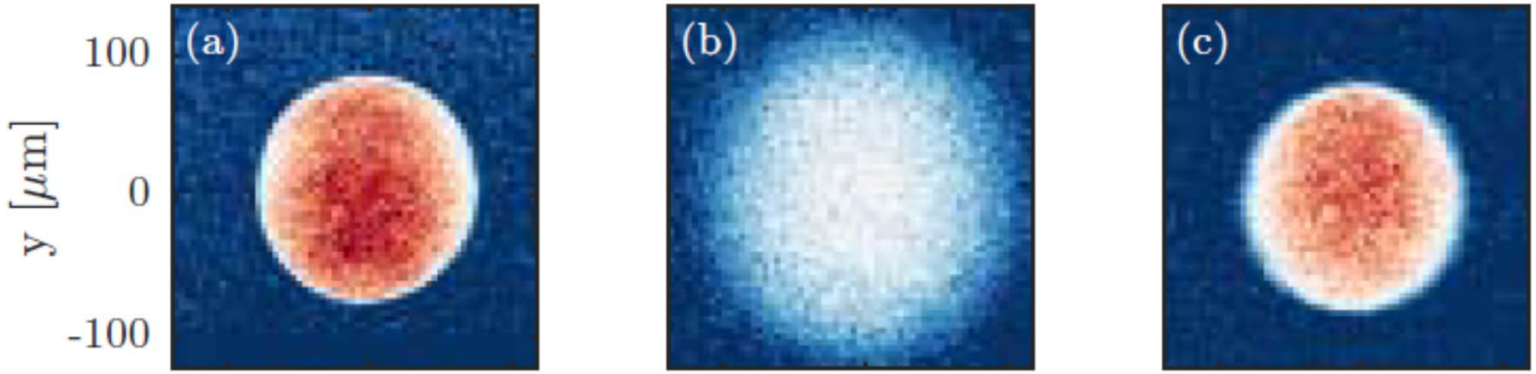


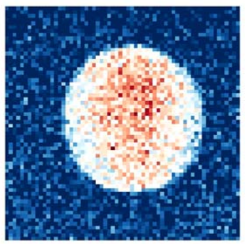
Momentum Distribution – a nonlocal probe

To momentum space and back …

free evolution in HO = rotation in phase space



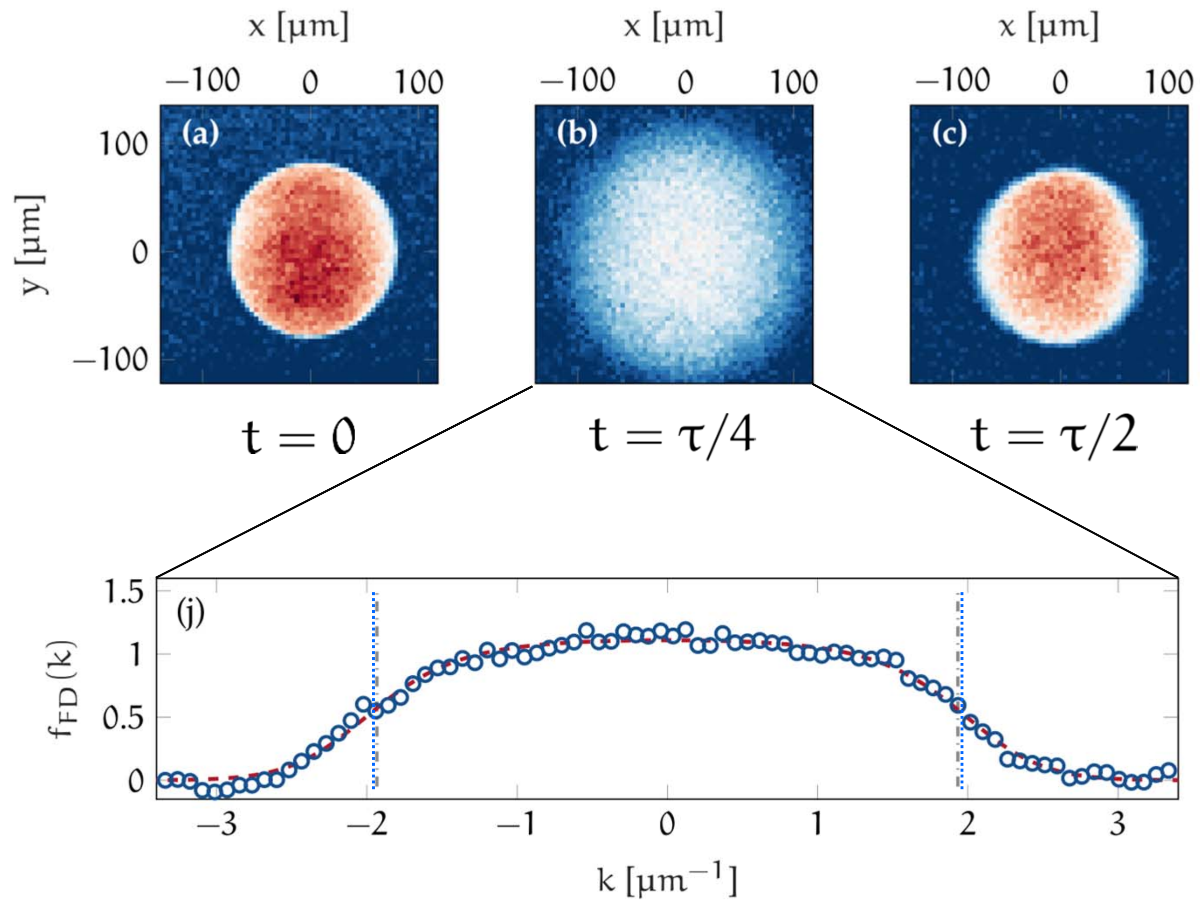




Matter wave focussing: Bose: Walraven, Cornell, Bouchoule, van Druten groups
Fermions: Jochim group

K. Hueck et al. arXiv:1704.06315 (2017)

Thermometry: $n(k) = f(k, T, \mu)$



$$f_{FD}(k) = \frac{1}{1 + \exp\left[\beta\left(\frac{\hbar^2 k^2}{2m} - \mu_0\right)\right]}$$

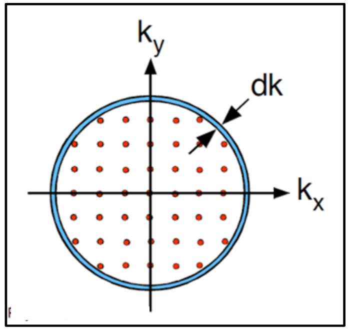
$$T/T_F = 0.31 \pm 0.02$$

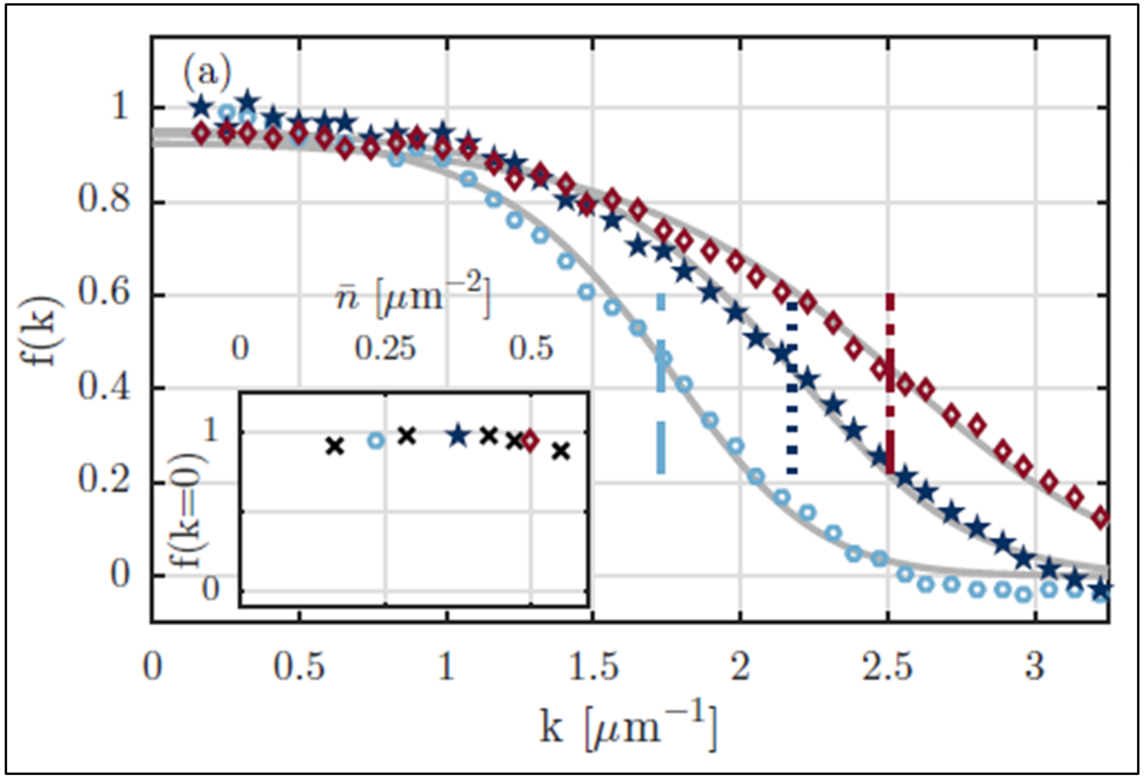
$$k_{F,dens} = \sqrt{4\pi n_{2D}}$$

K. Hueck et al. arXiv:1704.06315 (2017)

Pauli blocking in momentum space

box diameter D ⇒ single k-mode occupies area $A_k = 16\pi/D^2$
Measure n(k): If one atom per A_k ⇒ unit occupation $f(k) = 1$

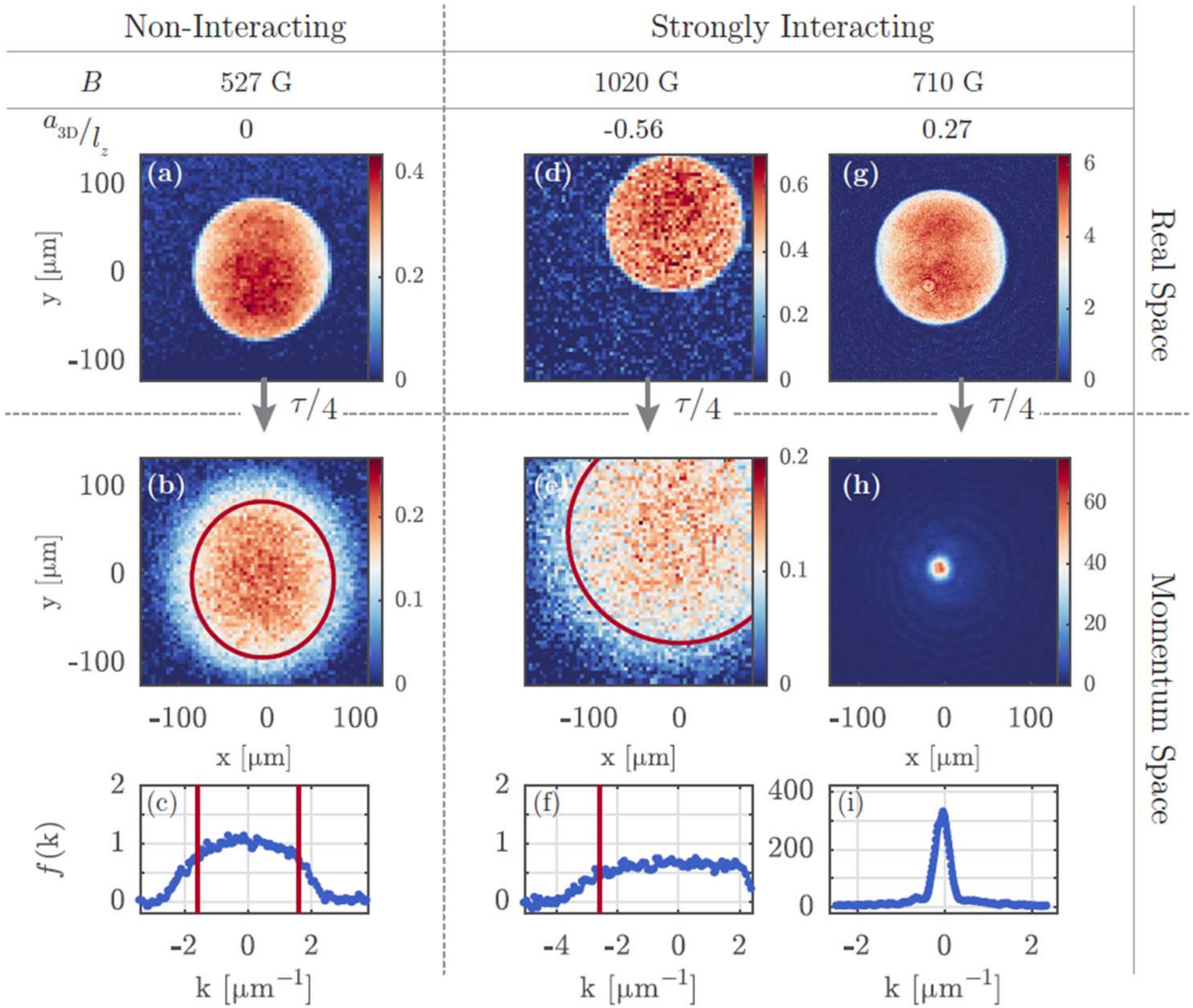




$f(k)$ saturates for increasing n ⇒ evidence for Pauli blocking

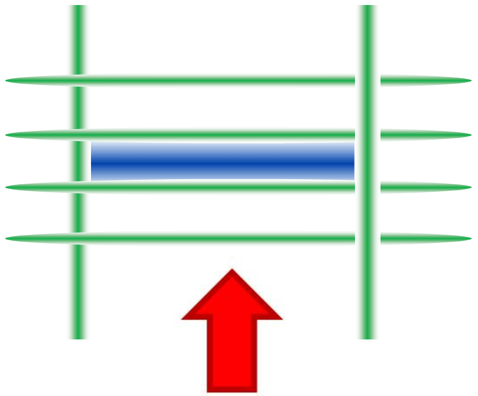
Pauli blocking in momentum space: B. Mukherjee (Zwierlein group), PRL 118, 123401 (2017) K. Hueck et al. arXiv:1704.06315 (2017)

Interacting 2D gases

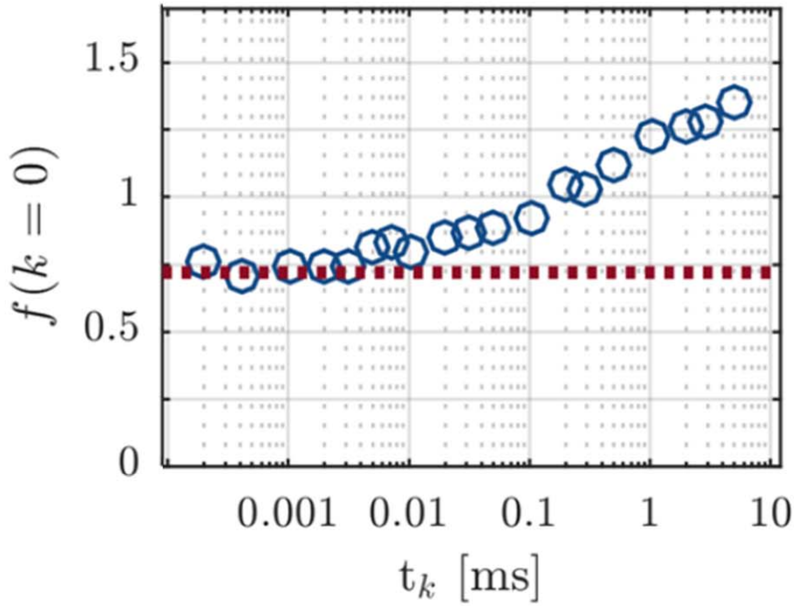


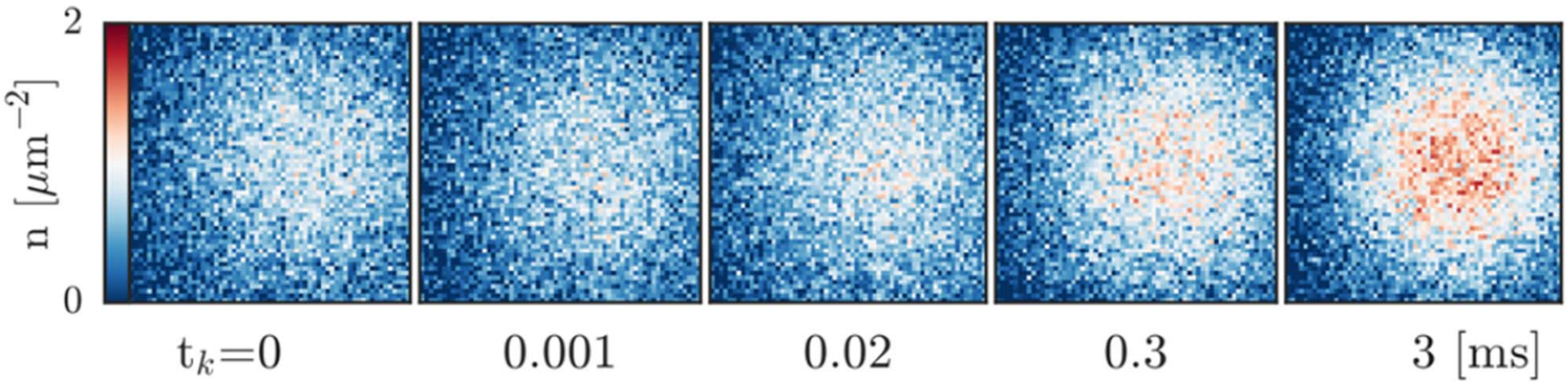
K. Hueck et al. arXiv:1704.06315 (2017)

Non-interacting expansion – remove one spin



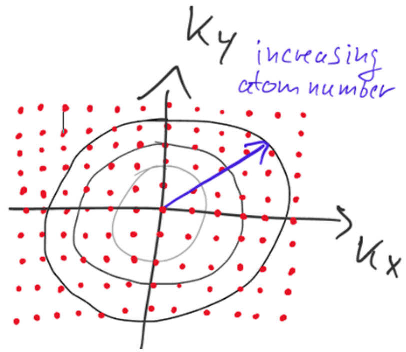
free interacting expansion $t = 0$
spin removal pulse at $t = t_k$
free non-interacting exp $t = T/2$



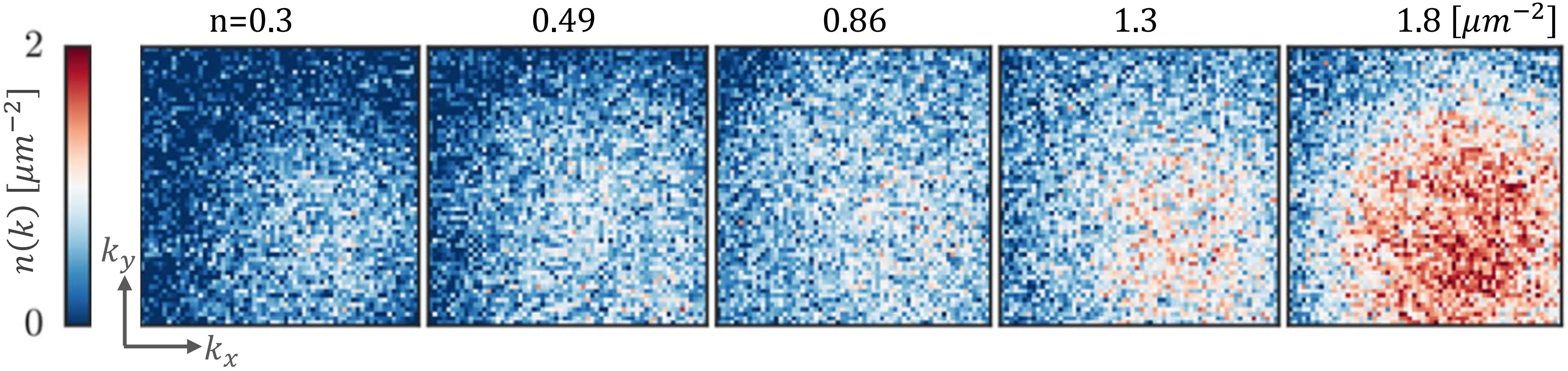


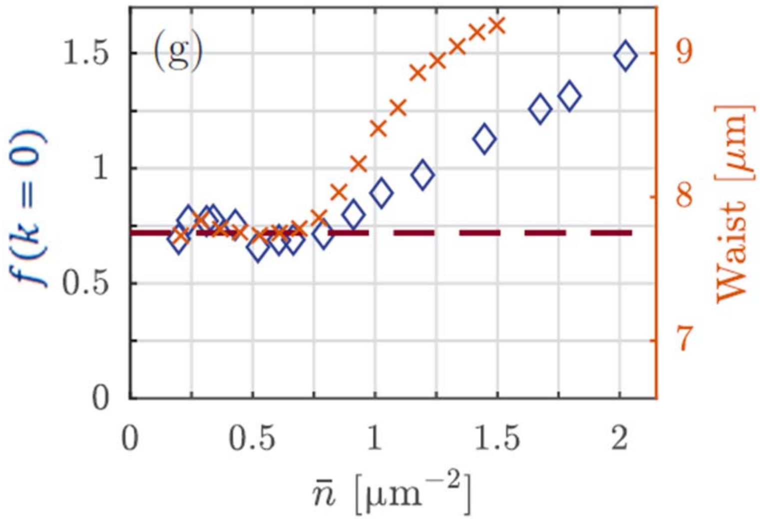
K. Hueck et al. arXiv:1704.06315 (2017)

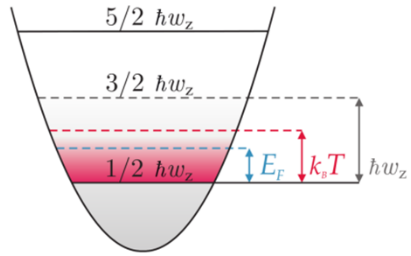
Filling up higher vibrational levels



Increase atom number ⇒ central occupation in momentum $f(k)$ space should not change!



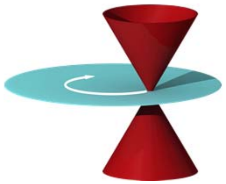




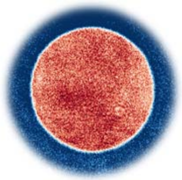
See also: P. Dyke et al., PRA 93, 011604 (2016), Vale Group

K. H. et al. arXiv:1704.06315 (2017)

Summary

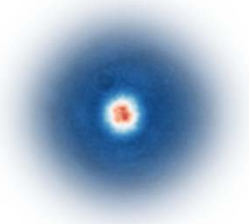


3D Critical velocity



Homogeneous 2D Fermi gases

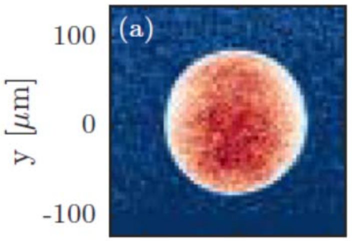
Equation of state



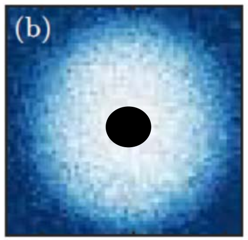
Momentum Distribution – a nonlocal probe

Outlook

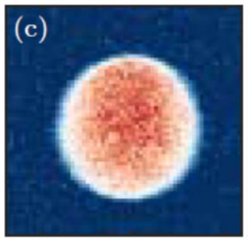
Hole dynamics



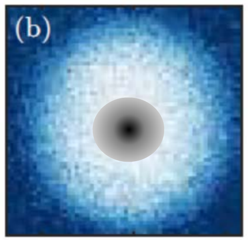
Poke out hole
In k space



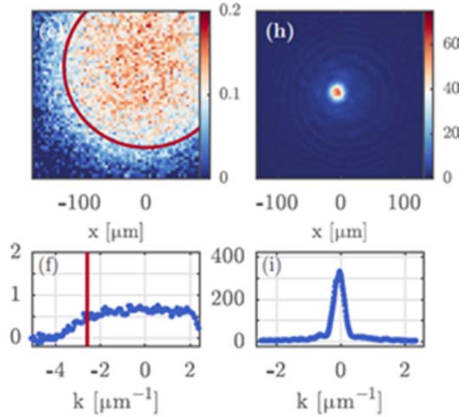
Back to real space
Dynamics, wait

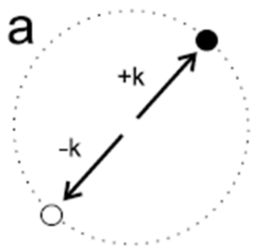


Look in k-space again
Hole diffusion (Auger)?



Interacting and imbalanced gases

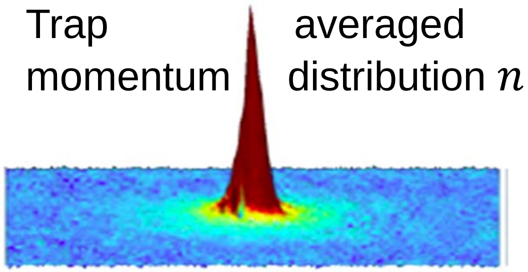


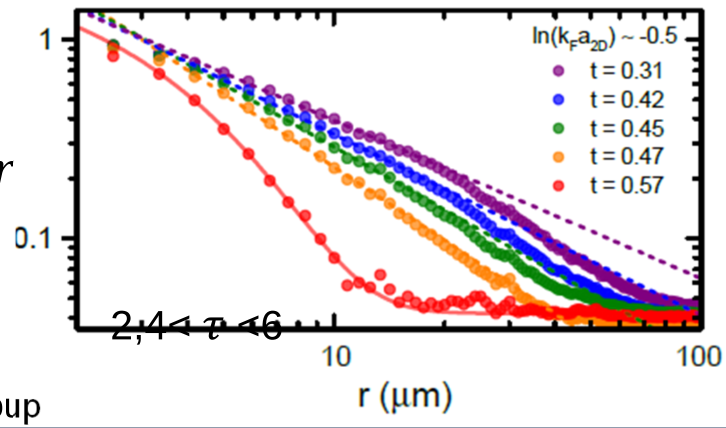


pairs visible in noise
correlations in k-space?

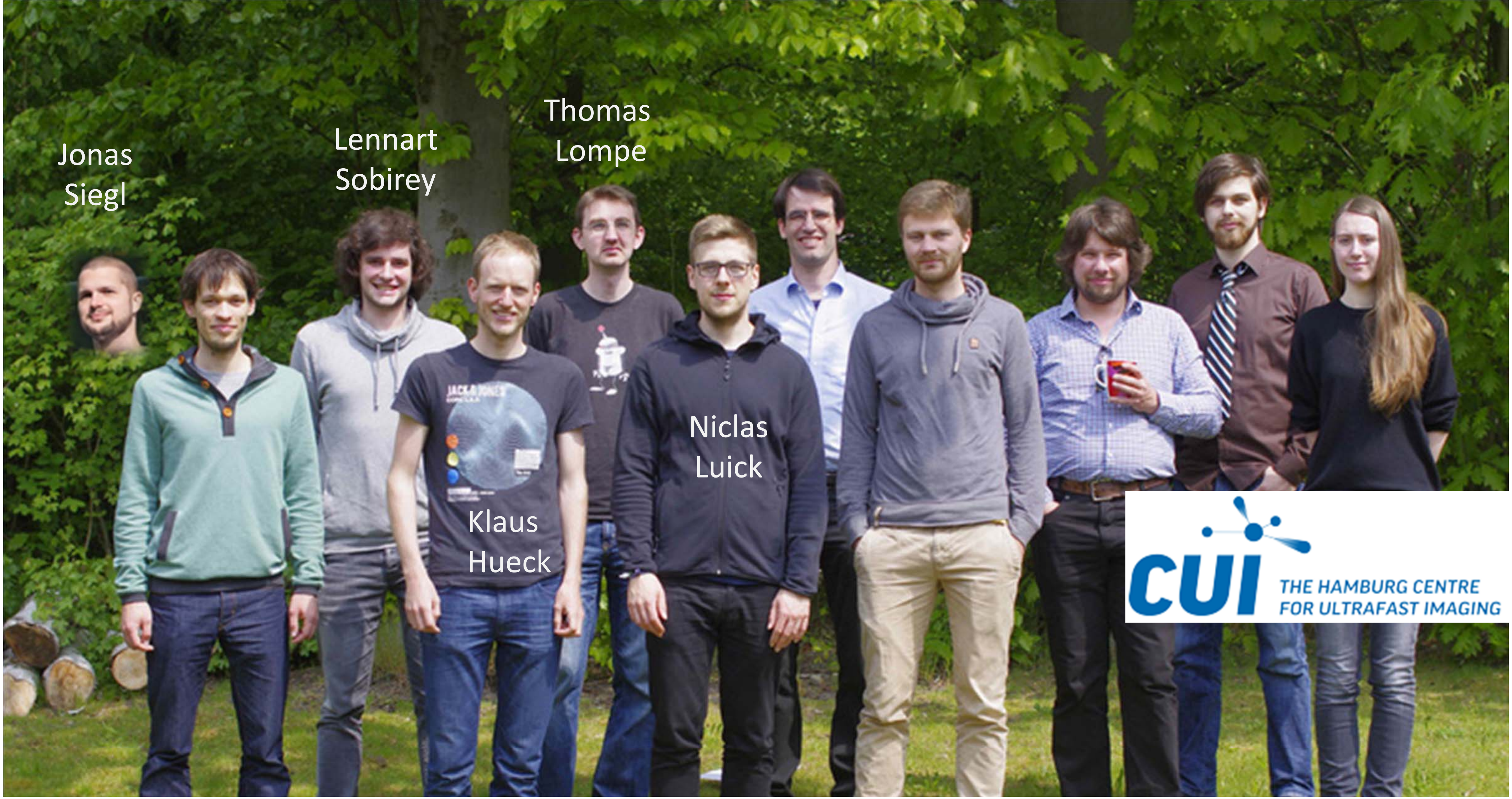
Coherence: g1

Trap averaged momentum distribution $n(k)$ $\xrightarrow{Fourier}$ $g_1(r$





P. A. Murthy et al., PRL 115, 010401 (2015), Jochim group



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SFB

SFB 925: Light induced dynamics and control of strongly correlated quantum systems

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Mesoscopic Fermi Gases

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