TECHNISCHE UNIVERSITÄT KAISERSLAUTERN

individual quantum systems

Nonequilibrium dynamics of quantum gases in time-dependent disorder

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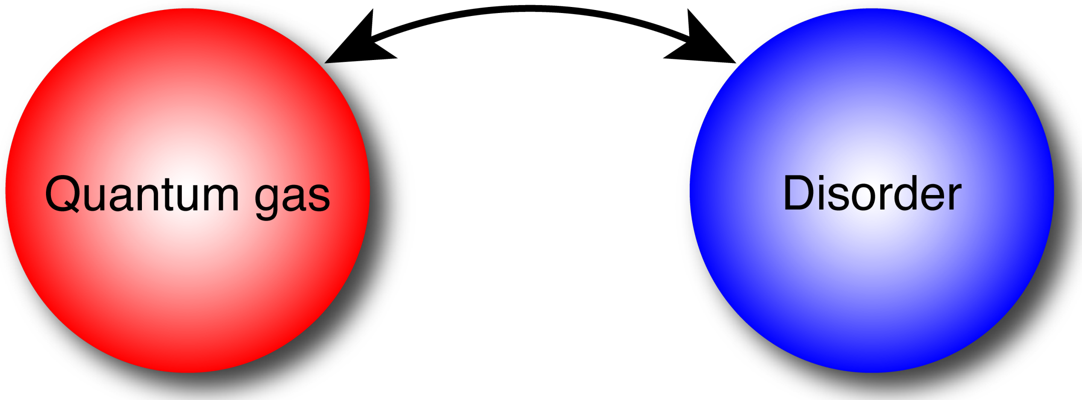
Technische Universität Kaiserslautern

SPICE workshop *Dissipative Phases of Entangled Quantum Matter*
SFB QuCoLiMa Talk – May 3rd 2021

Outline



Noninteracting gases in disorder
Anderson localization

J. Billy et al., Nature 453, 891 (2008)
G. Roati et al., Nature 453, 895 (2008)
S. Kondov et al., Science 334, 66 (2011)

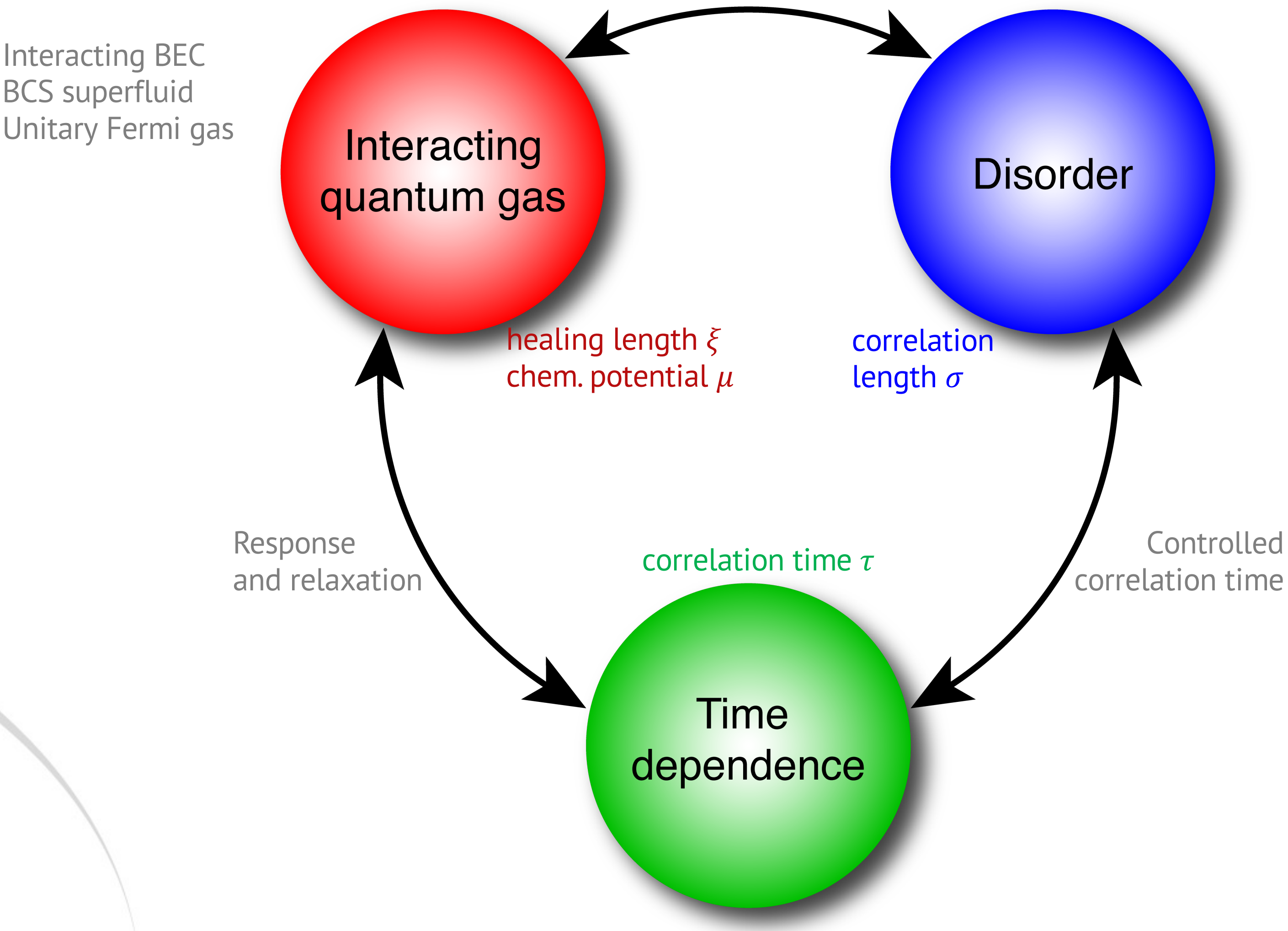
Lokalization in interacting lattice systems:

M. Schreiber et al., Science 349, 842 (2015)
A. Lukin et al., Science 364, 256 (2019)

Weakly interacting gases:

J. Lye et al., PRL 95, 070401 (2005)
Y. Chen et al., PRA 77, 033632 (2008)
D. Dries et al., PRA 82, 033603 (2010)

Outline



What dominates the response of a quantum system to and relaxation after time-dependent disorder?

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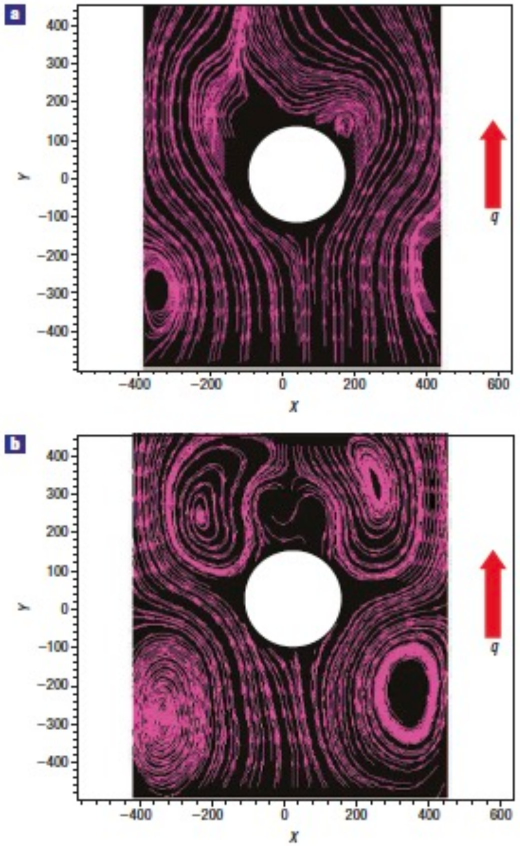
Nonequilibrium Quantum Systems

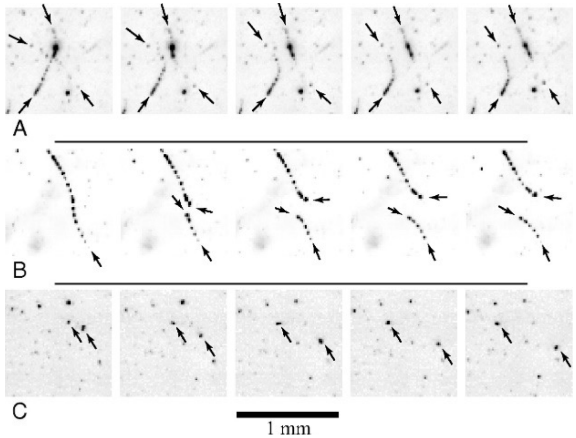
individual quantum systems

Large-scale turbulence in He-II



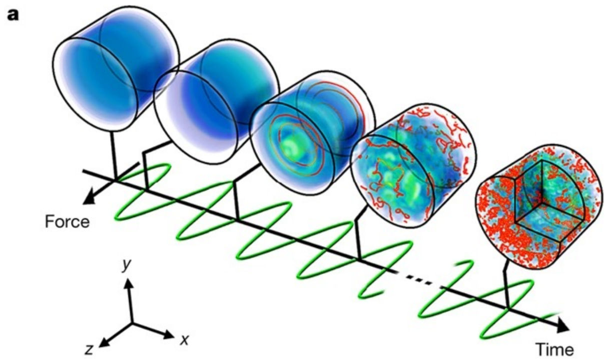
Zhang and Sciver,
Nature Phys. **1**, 36 (2005)

Reconnecting vortices in He-II



Bewley et al., *PNAS* **105**, 13707 (2008)

Turbulence in trapped atomic gases



White et al., PNAS 111, 4719 (2014)
Navon et al., Nature 539, 72 (2016)

Nonequilibrium Quantum Systems

$$\psi(\vec{r},t) = \sqrt{n(\vec{r})} \times e^{i\varphi}$$

(Superfluid) amplitude

Quantum phase

What are the contributions of density and phase coherence for quantum dynamics?

What limits the relaxation of a nonequilibrium quantum system?

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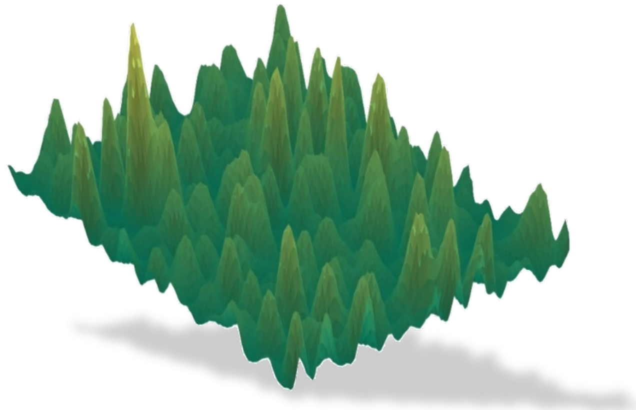
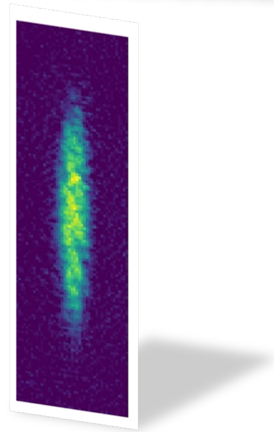
Outline

individual quantum systems

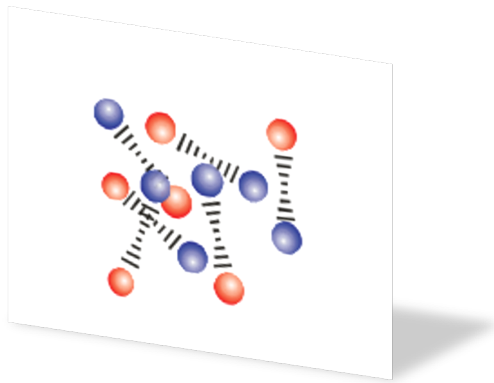
Quantum gases along the BEC-BCS crossover in controlled disorder



Probing the role of long-range coherence for quantum dynamics



Response of a BEC and a unitary gas to disorder with dissipation

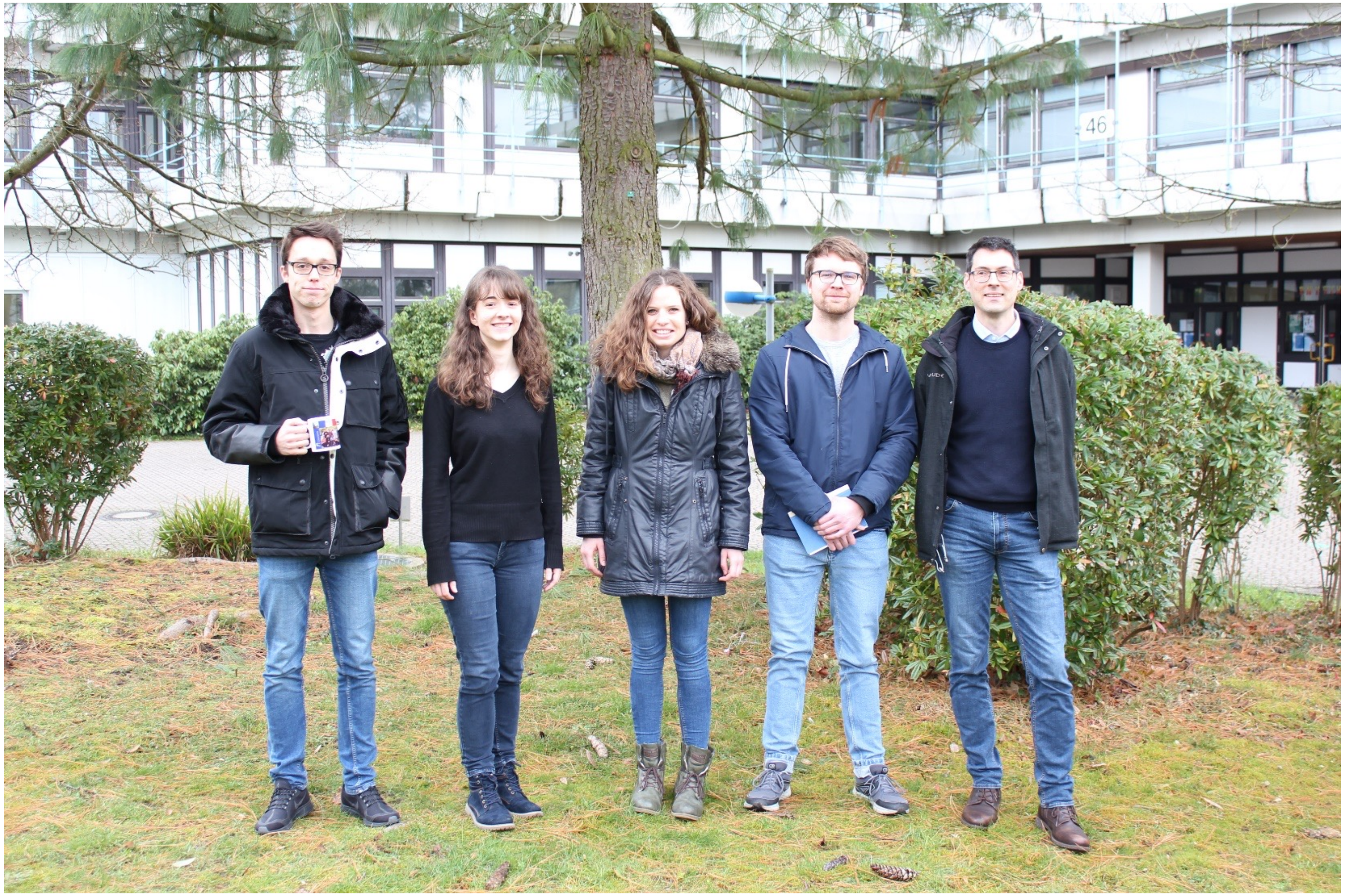


Quantum gases in dynamical disorder

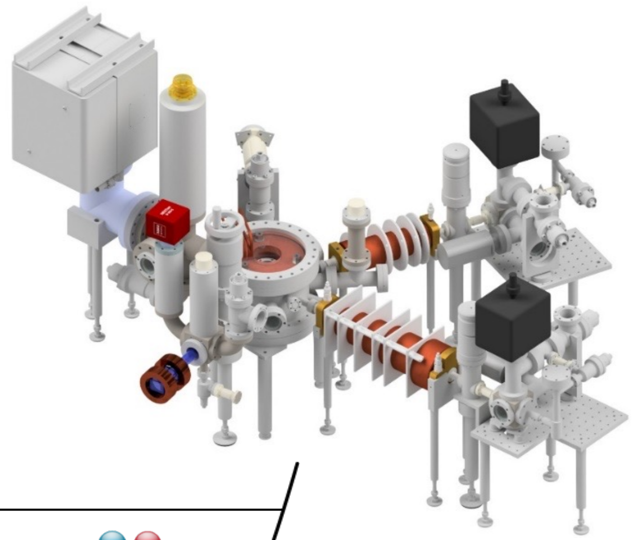
The Tools –

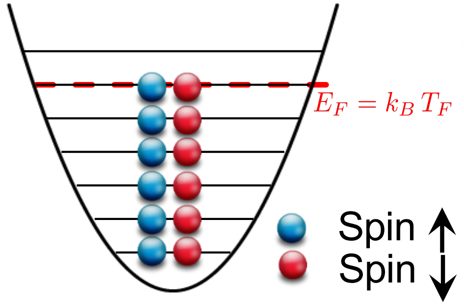
Quantum gases along the BEC-BCS crossover in engineered disorder

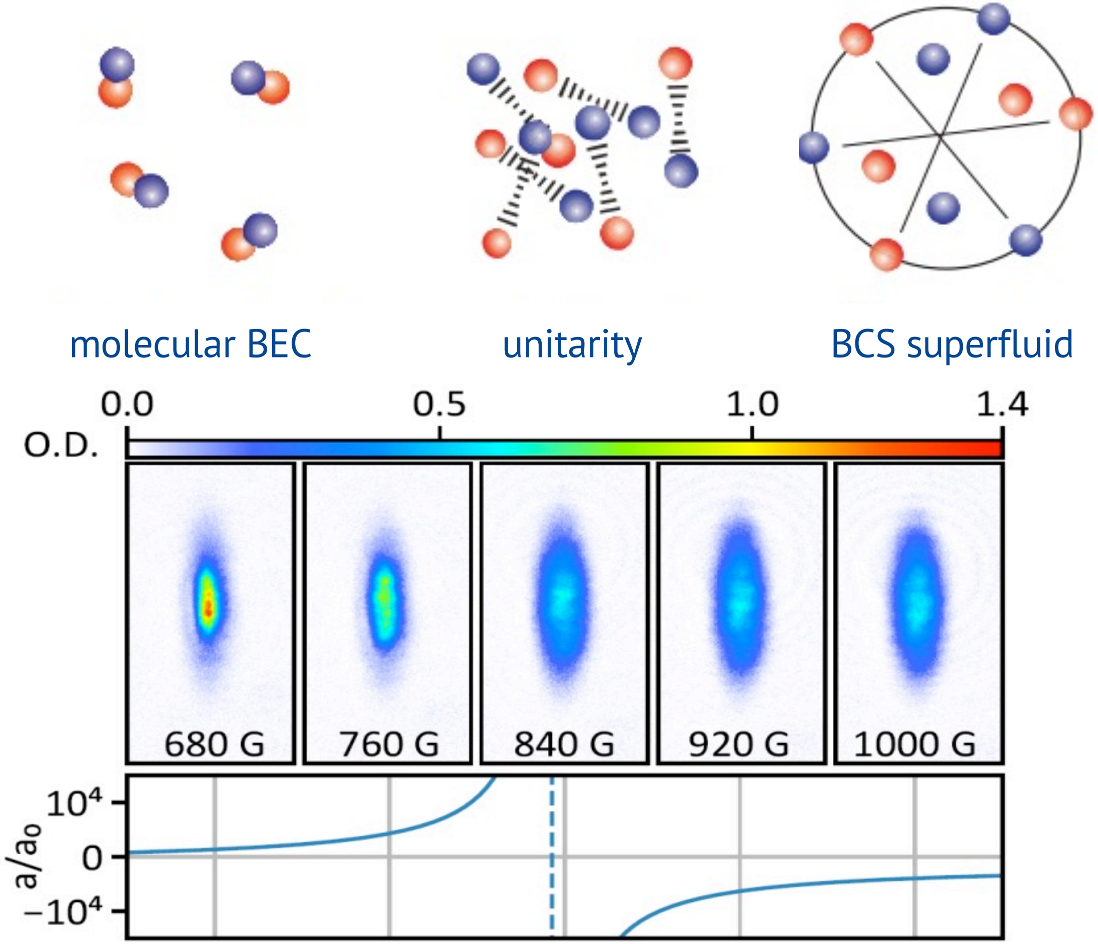
Fermi Team



Degenerate fermionic Li gases



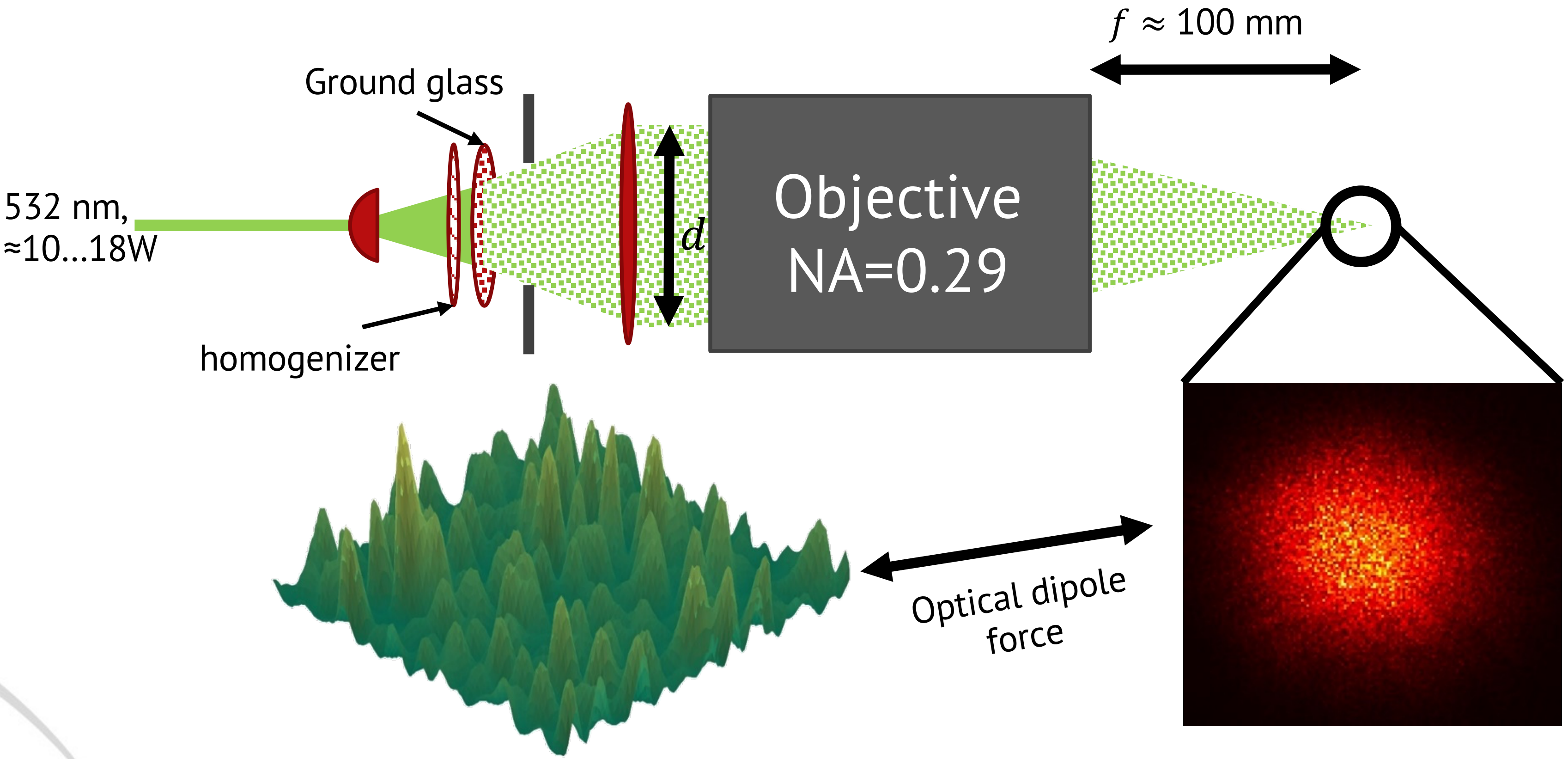




$N = 10^5 \dots 10^6$ ^{6}Li atoms
$T \approx 100$ nK
$\frac{N_0}{N} \geq 0.6$ condensate fraction in BEC

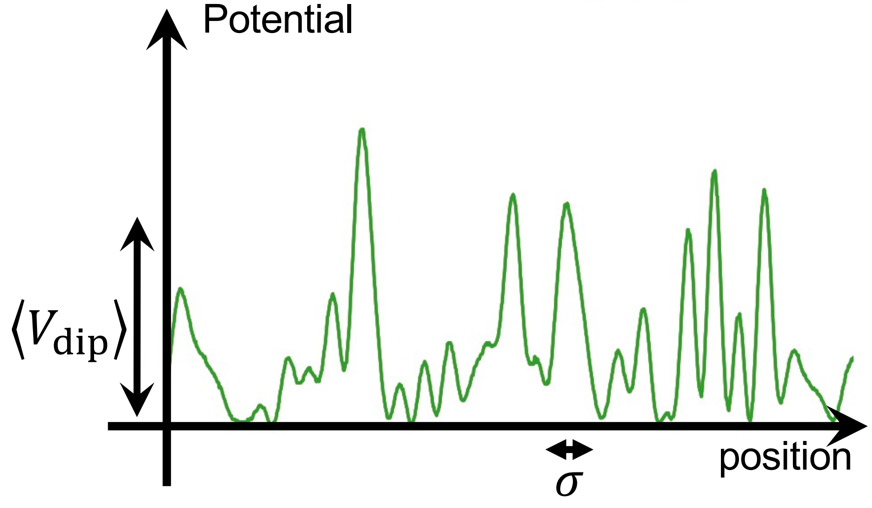
B. Gänger, J. Phieler et al., *Rev. Sci. Instr.* **89**, 093105 (2018)

Disordered optical potentials



B. Nagler, M. Radonjić, S. Barbosa, J. Koch, A. Pelster, and A. Widera
New J. Phys. **22**, 033021 (2020)

Characterization of 3D speckels



- Mean potential depth

$$\langle V_{\text{DIP}} \rangle \sim P/w^2$$

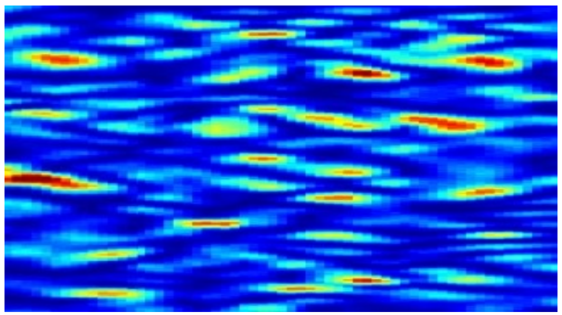
- Correlation length $\sigma_{\text{trans}} \sim \lambda f/d$

$$C(\overrightarrow{\delta r}) = \langle V(\vec{r})V(\vec{r} + \overrightarrow{\delta r}) \rangle$$

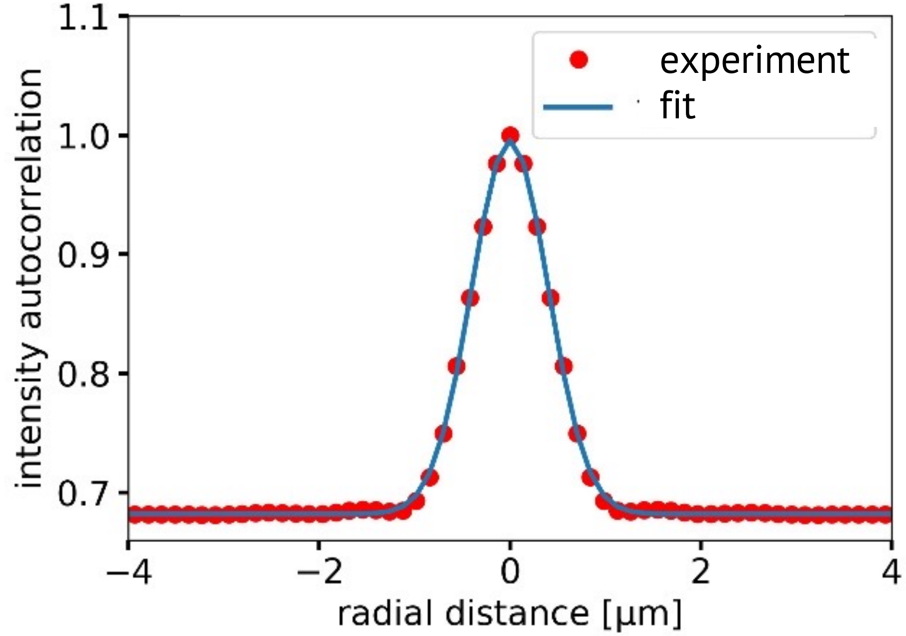
- anisotropic

$$\frac{\sigma_{\text{long}}}{\sigma_{\text{trans}}} \approx 6$$

Propagation direction

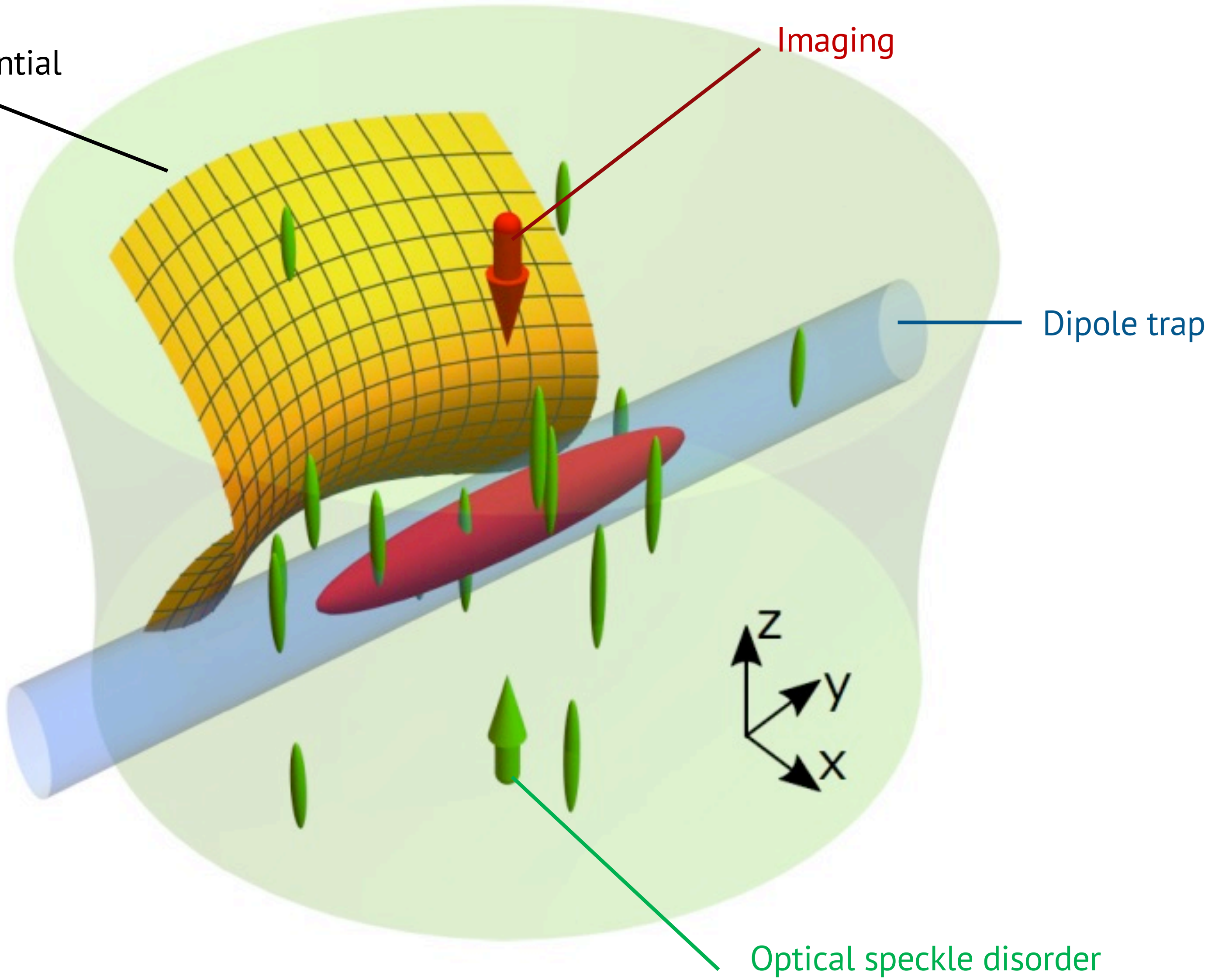


[6]



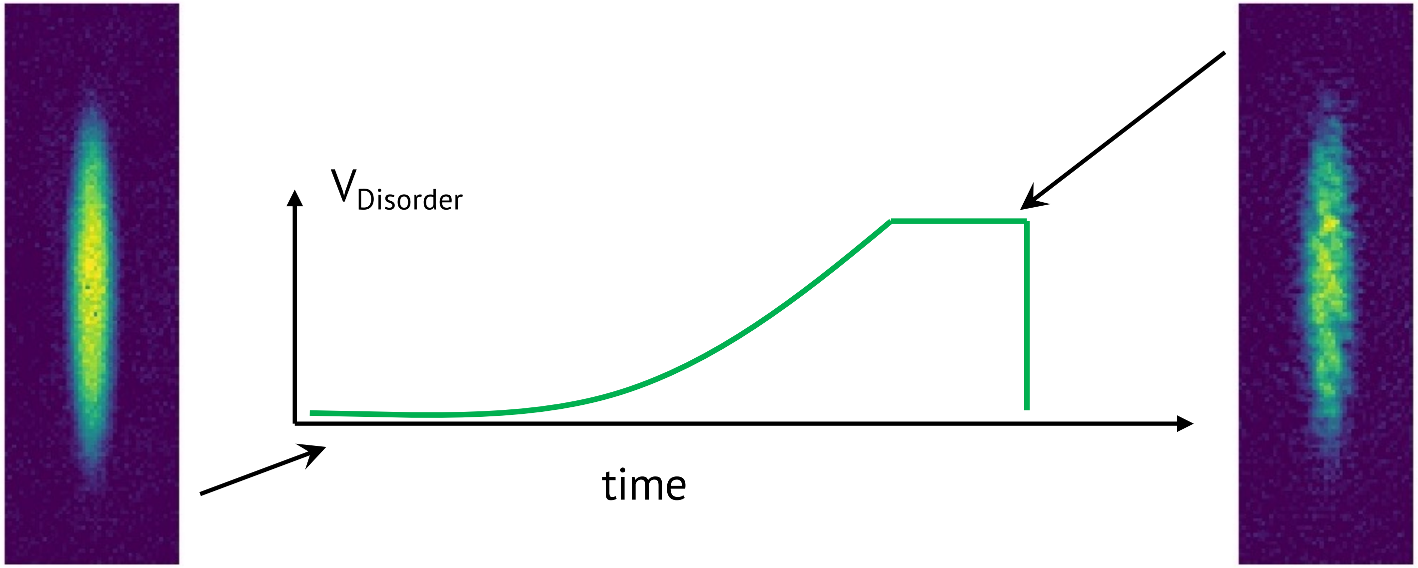
[6] McGehee et al., Three-Dimensional Anderson Localization in Variable Scale Disorder

Experimental Setup

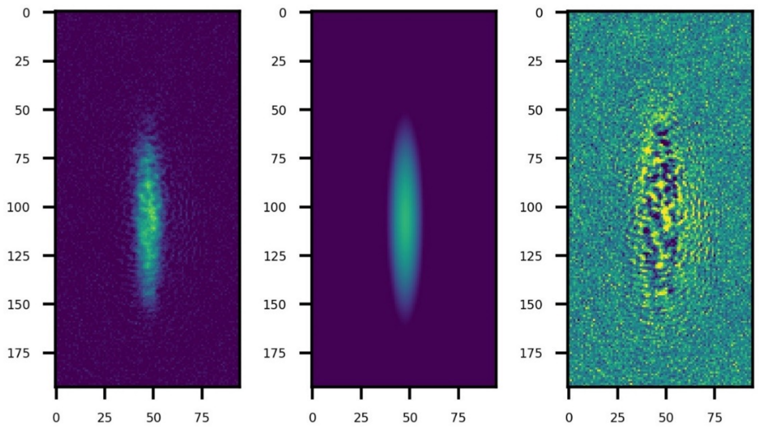


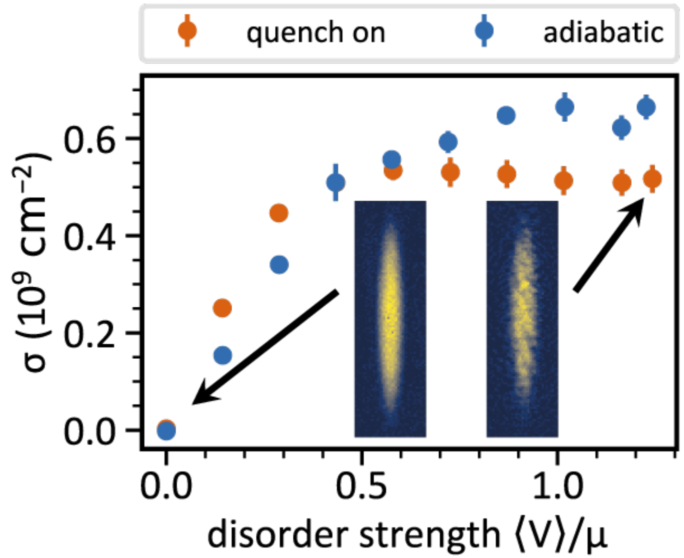
Molekular BEC response to disorder quenches

Density response to disorder

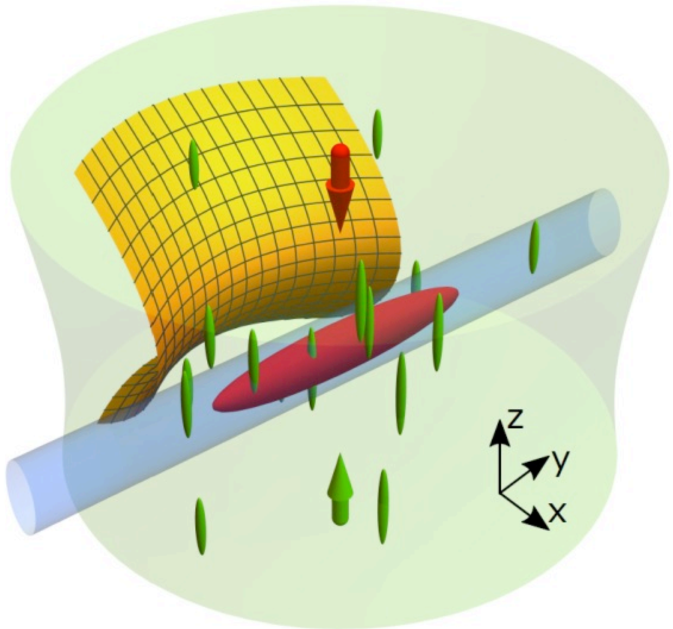


Fluctuations can be quantified:

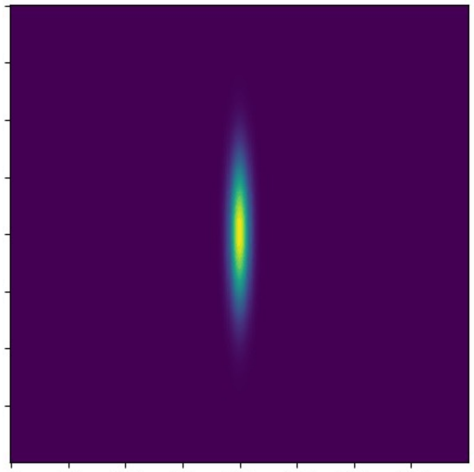




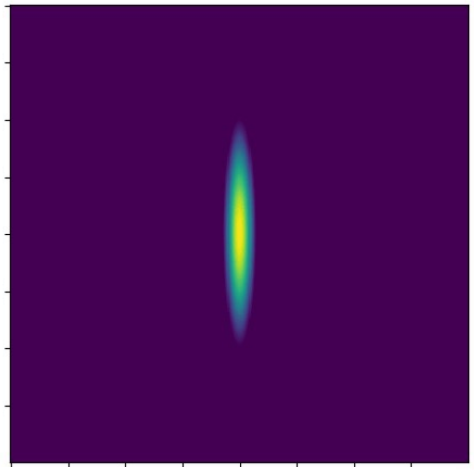
Hydrodynamic Expansion



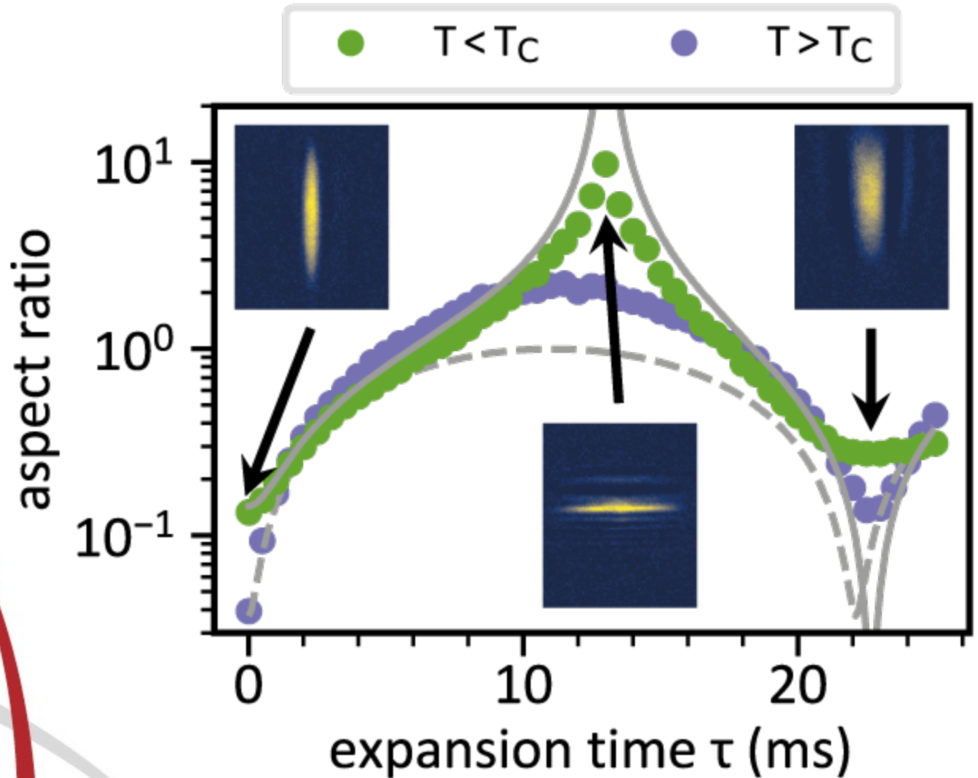
Thermal expansion

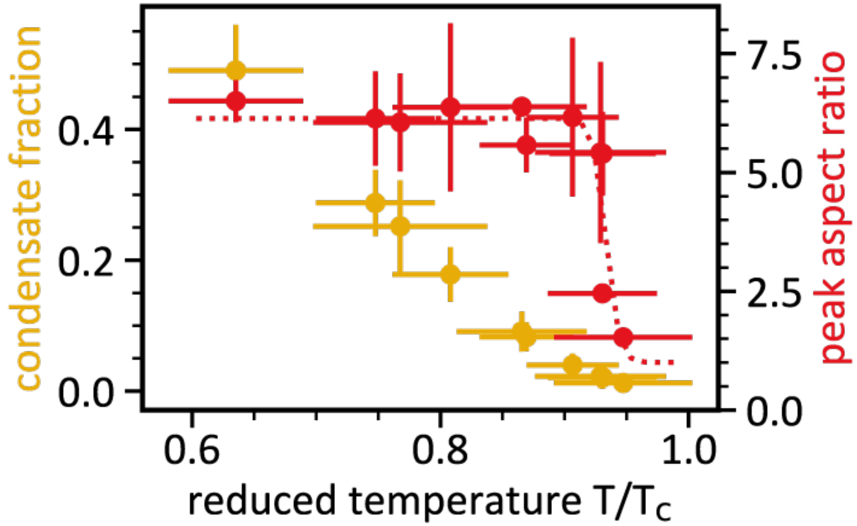


Hydrodynamic expansion



Hydrodynamic expansion

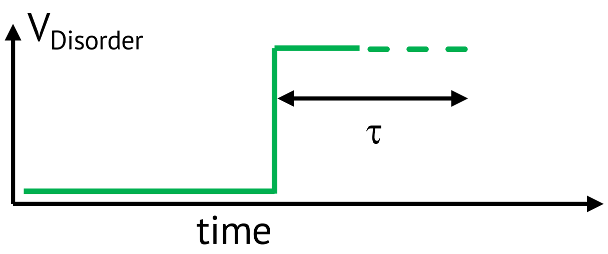


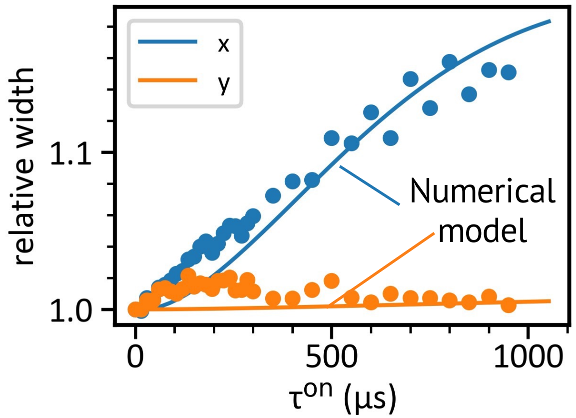


The peak aspect ratio is a measure of long-range coherence.

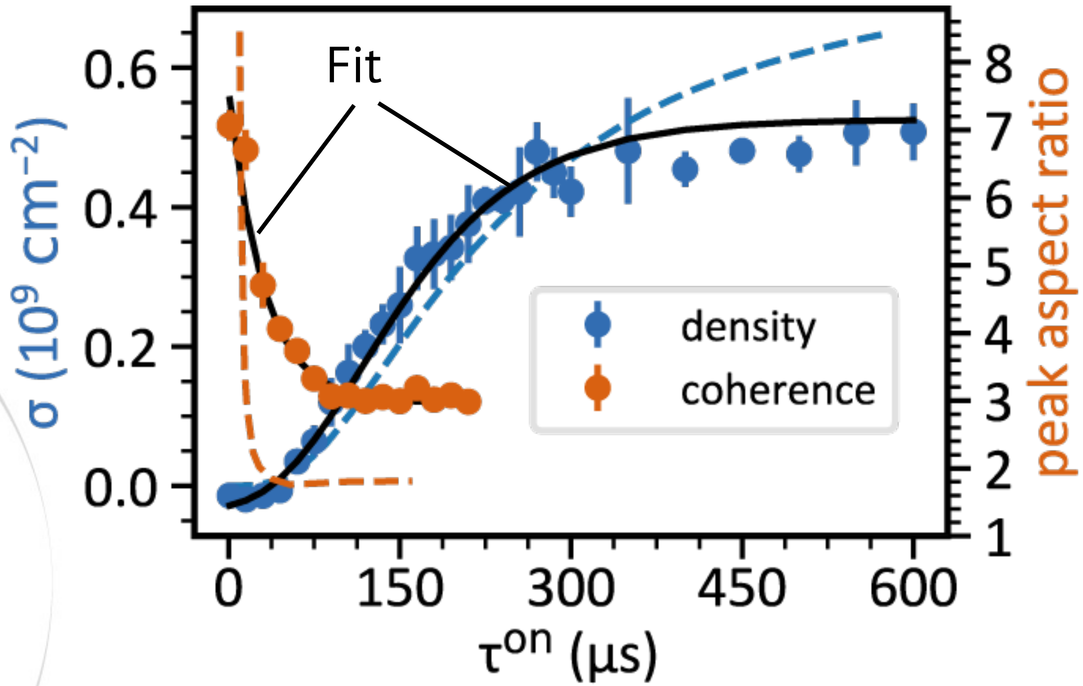
Nagler et al., arXiv:1911.04748

Quenching into disorder





What is the **time scale** on which the density and phase coherence respond?



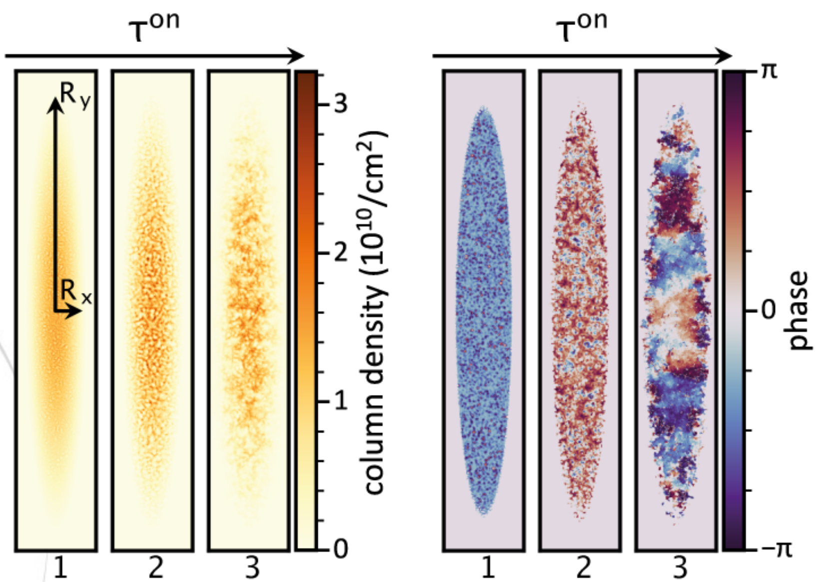
Dashed lines:

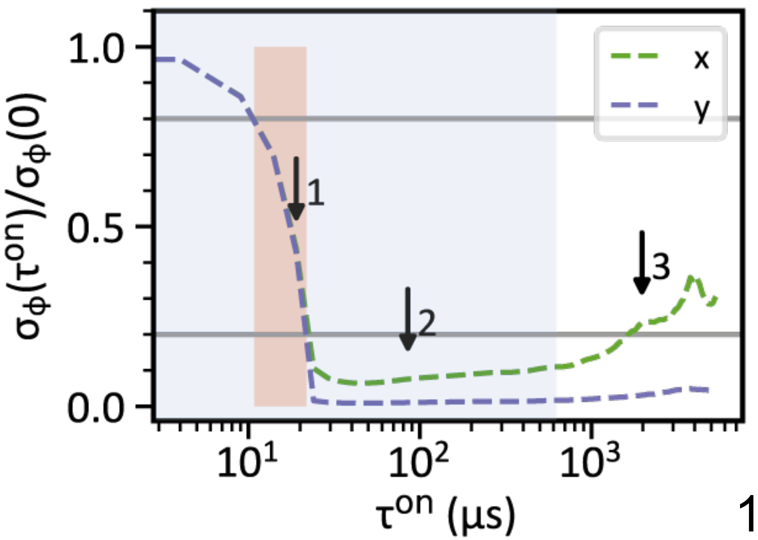
3D GPE Simulation

3D numerical simulations

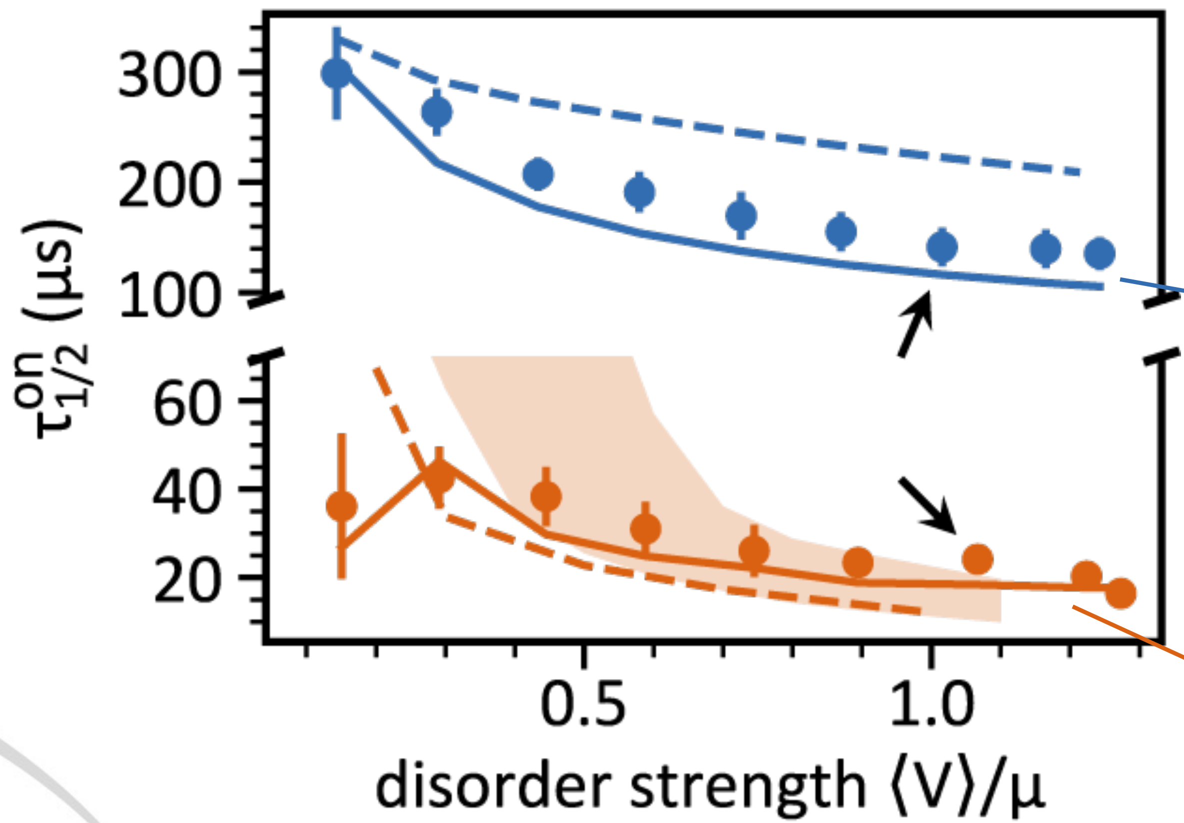
- Split-step Crank-Nicolson approach
- 3D simulation on grid (300,2200,450) with cell size 160 nm
- Speckle shows same statistical properties as in experiment
- Takes optical resolution of speckle and imaging into account
- Assumes $T = 0$
- 1ms time evolution simulation requires 2 hours of computation time.

Young et al., *Comput. Phys. Commun.* **220**, 503 (2017)
Muruganam and Adhikari, *Comput. Phys. Commun.* **180**, 1888 (2009)





Response to quenches into disorder



Dashed lines:

3D GPE Simulation

Solid lines:

On which time scale does a particle traverse the resolution length?

$$t_d^{on} \propto \sqrt{\alpha \eta_{x,y} / \langle V \rangle}$$

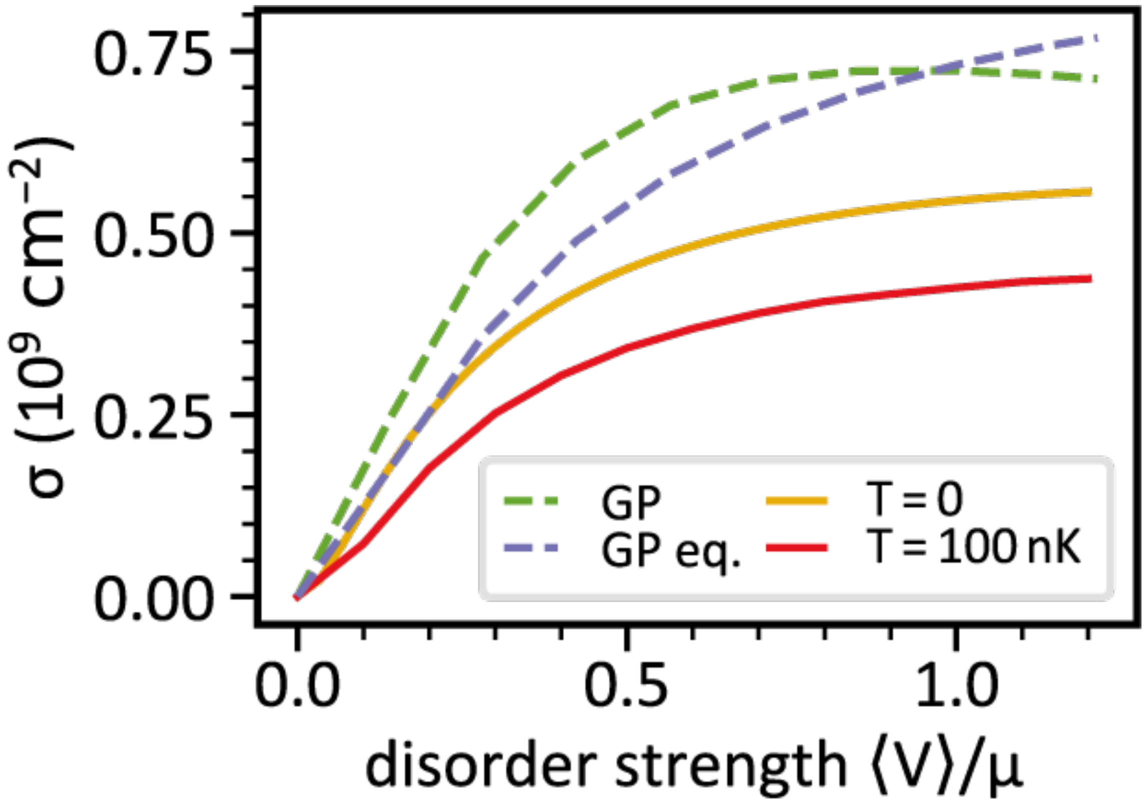
2.2 μm resolution   Correlation length

On which time scale do two points separated by speckle correlation length acquire phase difference of π?

$$t_\phi^{on} \propto \hbar / \langle V \rangle$$

- Density responds one order of magnitude slower than quantum hydrodynamics
- Time scale of quantum hydrodynamics can be related to long-range phase coherence
- Numerics systematically deviate from experiment.

Effect of finite temperature



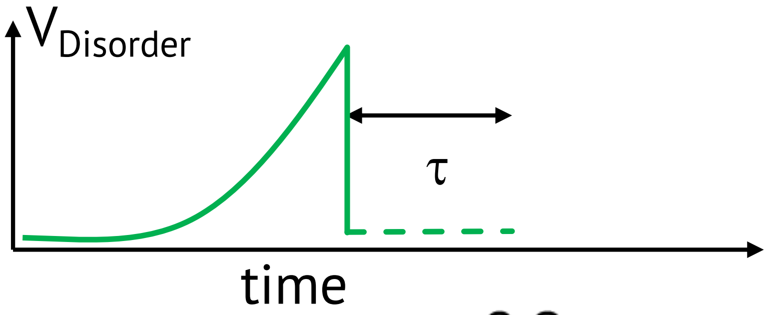
Gross-Pitaevskii simulations

Local-density approximation

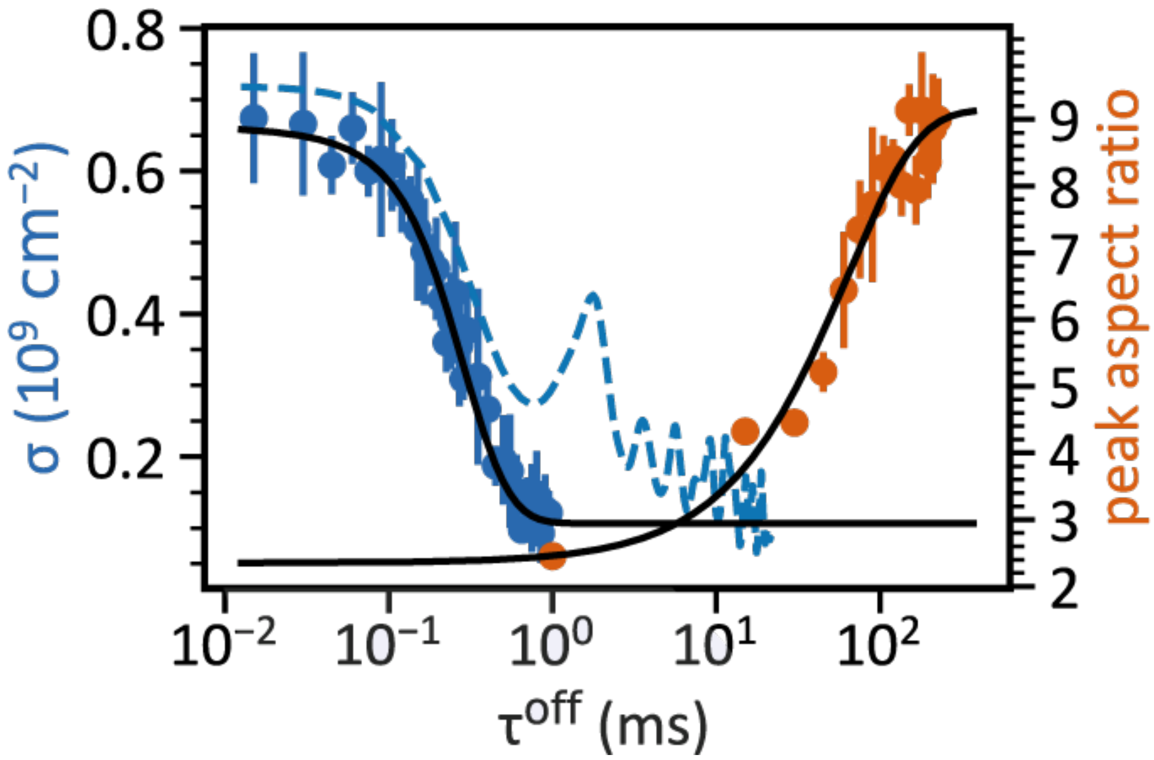
Local-density approximation breaks down

Temperature effects might have a significant impact and lead to the systematic discrepancy with experimental data

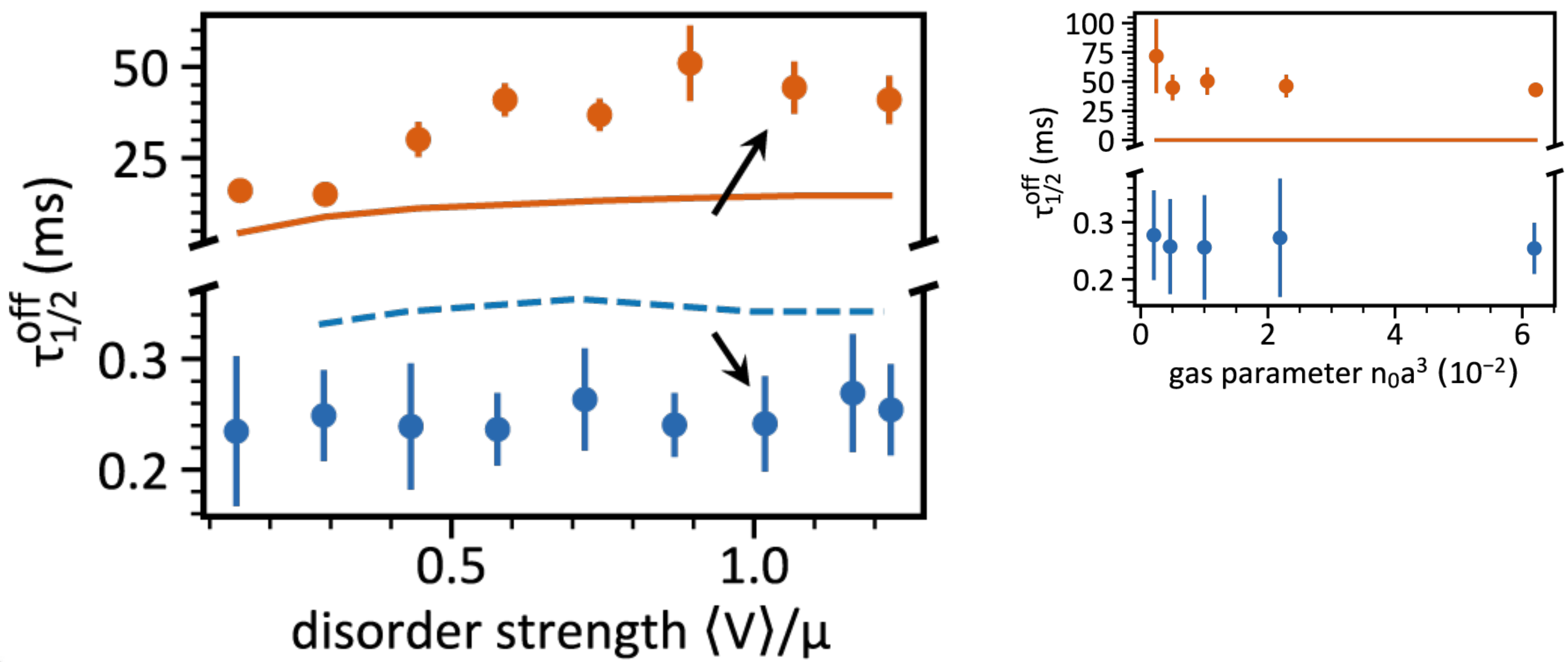
Quenching out of disorder



What is the **time scale** on which the density and phase coherence respond/relax?



Quenching out of disorder



Long-range phase coherence needs two orders of magnitude longer to relax compared to the density.

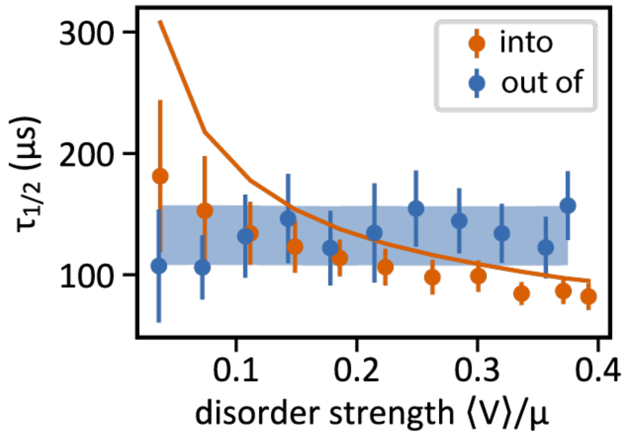
The measured time scale is longer than all time scales in the problem.

Phase excitations are long lived, maybe topologically protected.

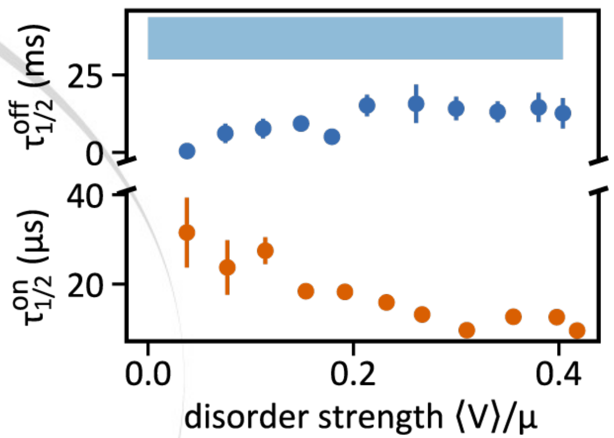
Toward respons of a unitary gas with dissipation

Disorder quenches at unitarity

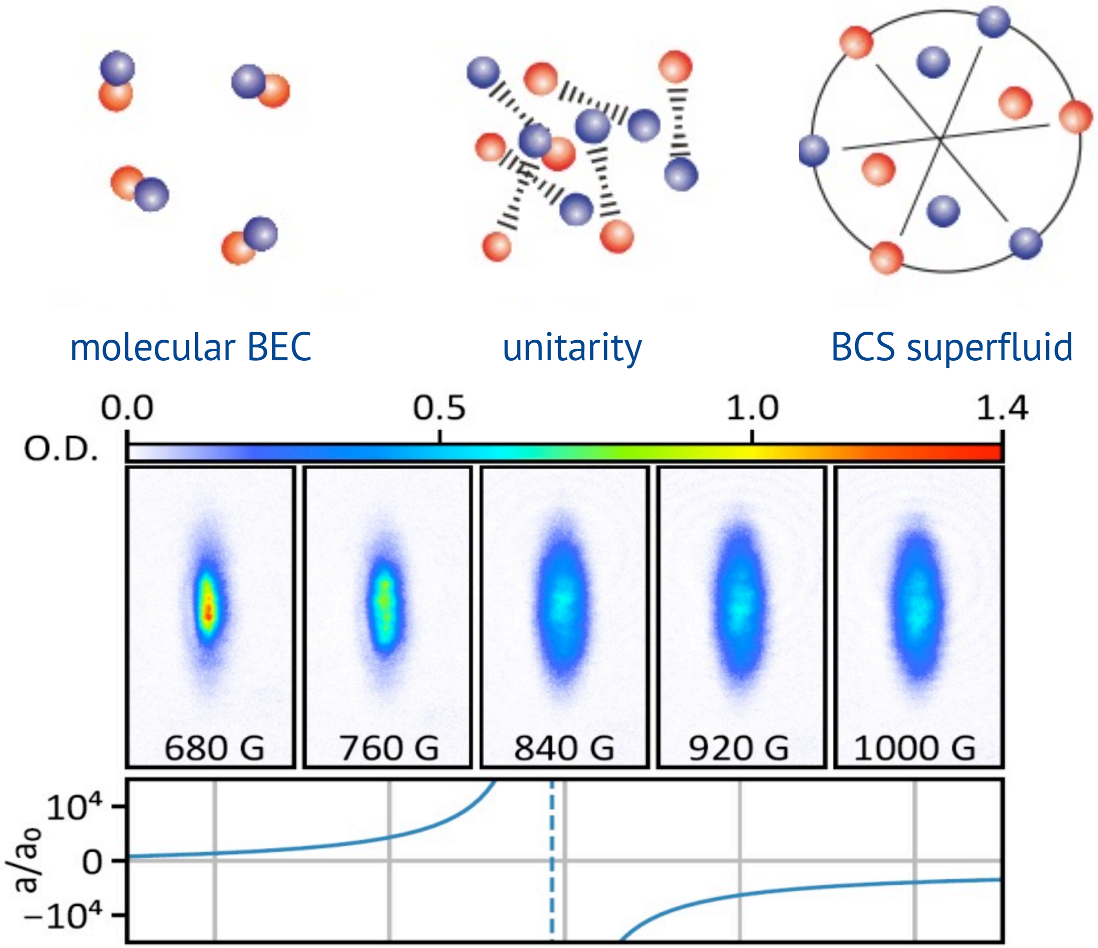
Density response @ unitarity



Phase-coherence response @ unitarity



(Data unpublished)

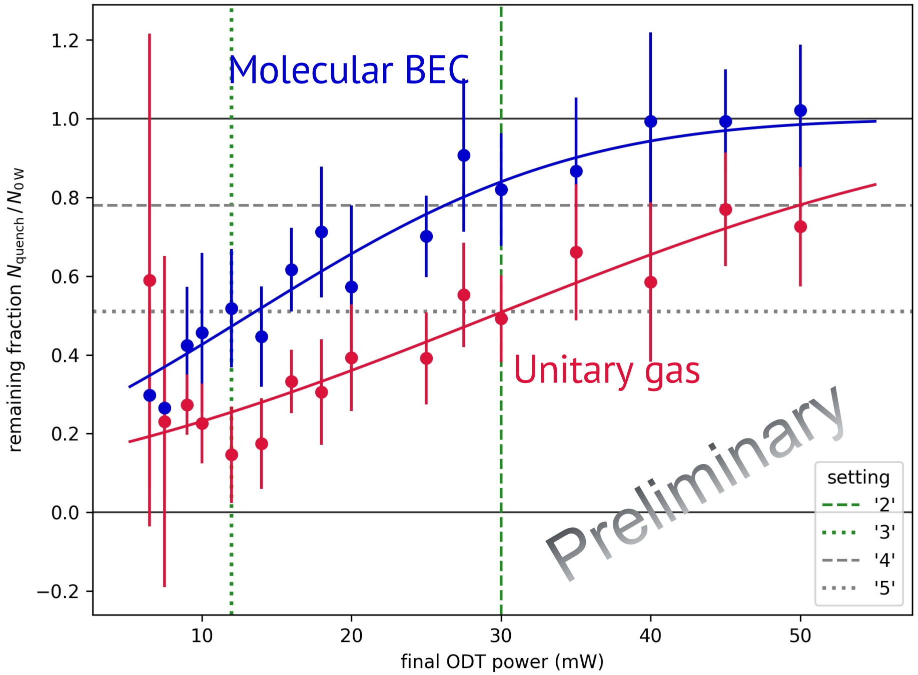


Quenches into disorder show comparable time scales.

For quenches out of disorder, long-range coherence is established faster.

Disorder quenches with dissipation

Adjust the trap such that atoms are removed by repulsive disorder speckle.



Which system will relax faster and re-establish quantum properties?

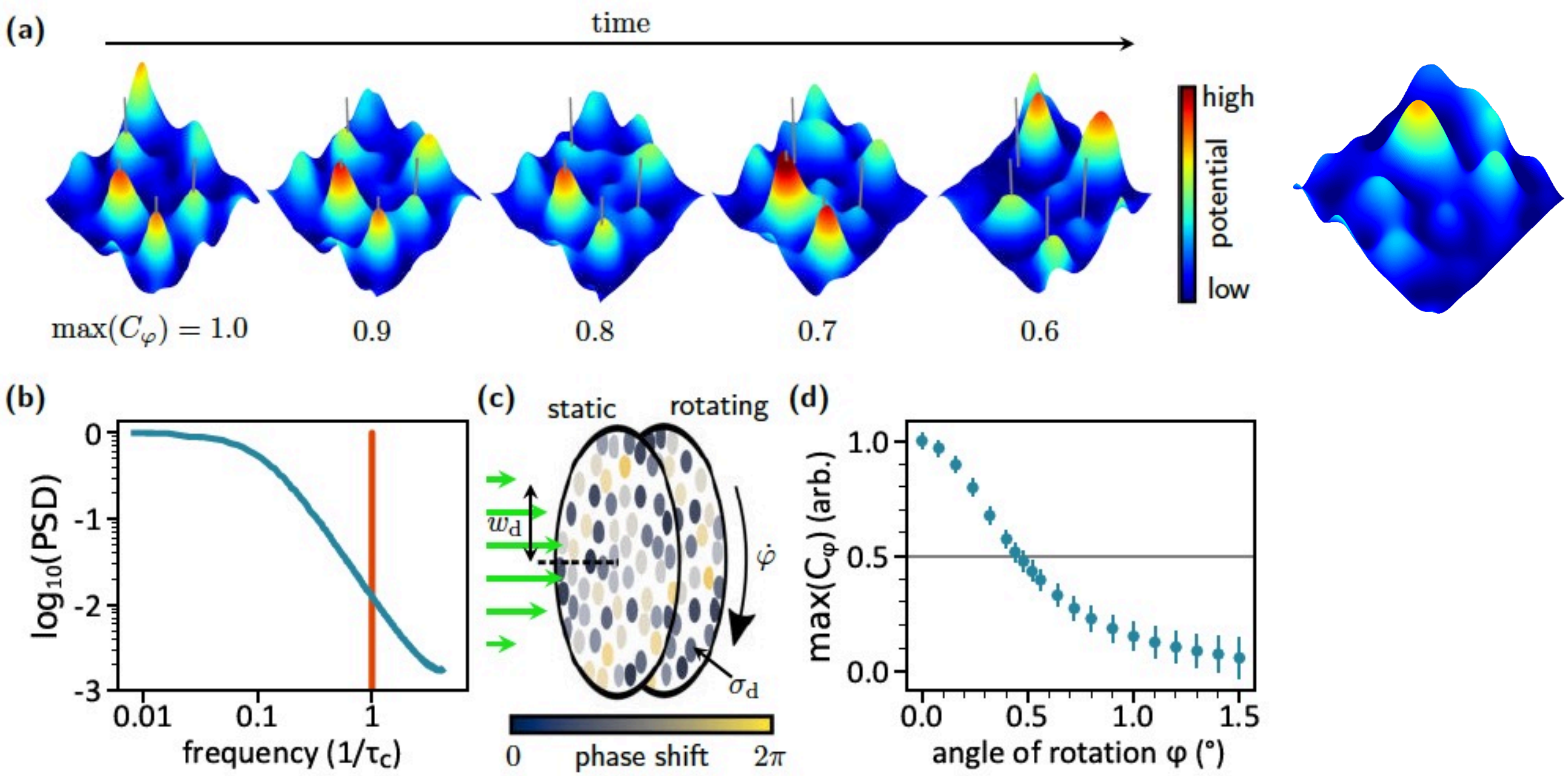
Preliminary observations (work in progress):

- The time scales of density response are not affected by dissipation, neither for quench into nor out of.
- The time scales for quench into disorder are not affected by dissipation, neither in BEC nor unitary regime, for phase-coherence response.
- The relaxation to long-range phase coherence of a unitary gas is unaffected by dissipation, a mBEC needs much longer to establish phase coherence (up to one order of magnitude) -> re-condensation?

(Data unpublished)

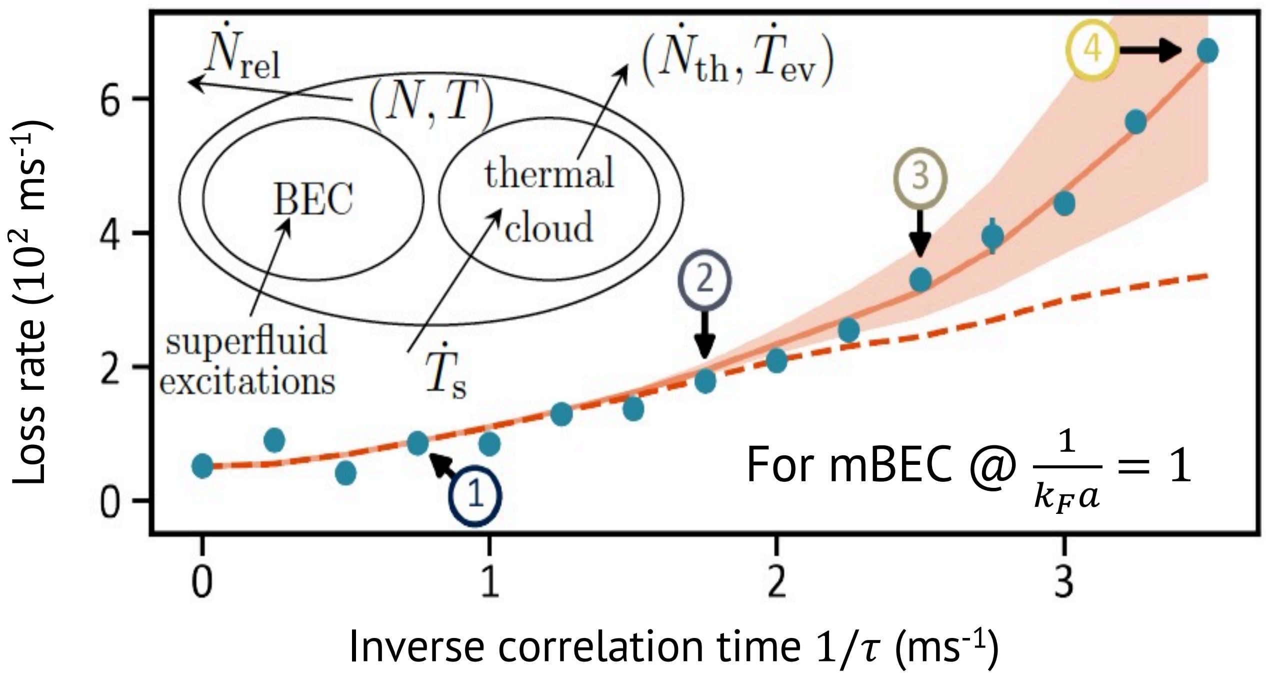
Dynamics in time-dependent disorder potentials

Tuning correlation times



B. Nagler, PhD thesis, 2020

Gas dynamics in dynamical disorder

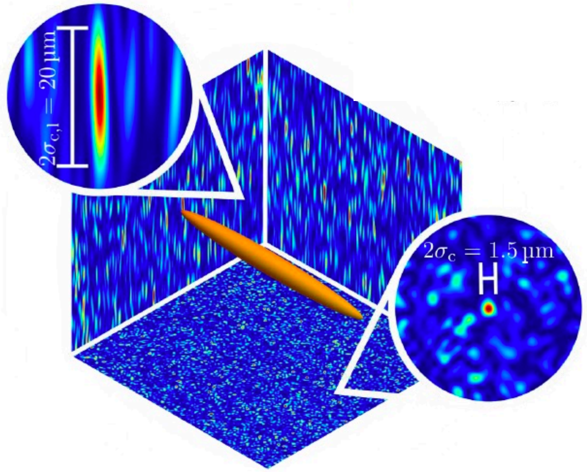


Cf. Effect on localization: J. Marino's group: Phys. Rev. B **98**, 054302

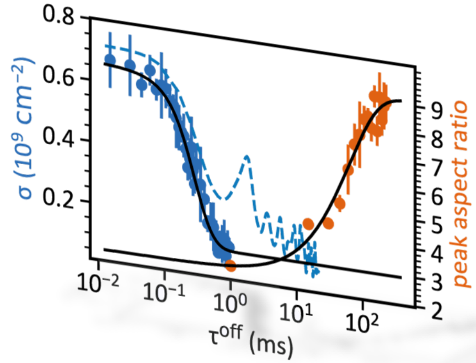
B. Nagler, S. Hiebel, S. Barbosa, J. Koch, and A. Widera
preprint, arXiv:2007.11523

Summary

Density and phase-coherence response can be unravelled after disorder quenches

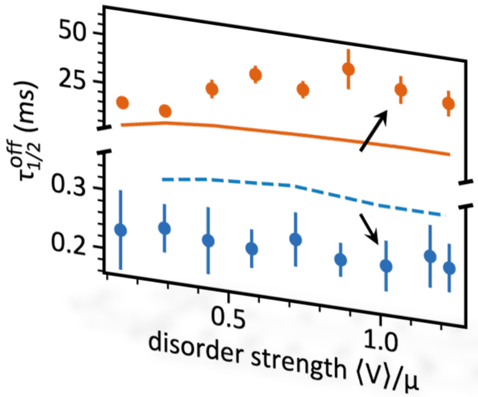


Phase coherence dominates the quantum dynamics: it breaks down faster and revives slower than density



At unitarity, coherent dynamics is re-established much faster…

… even when dissipation is strong.



BEC needs increased times to establish coherent dynamics

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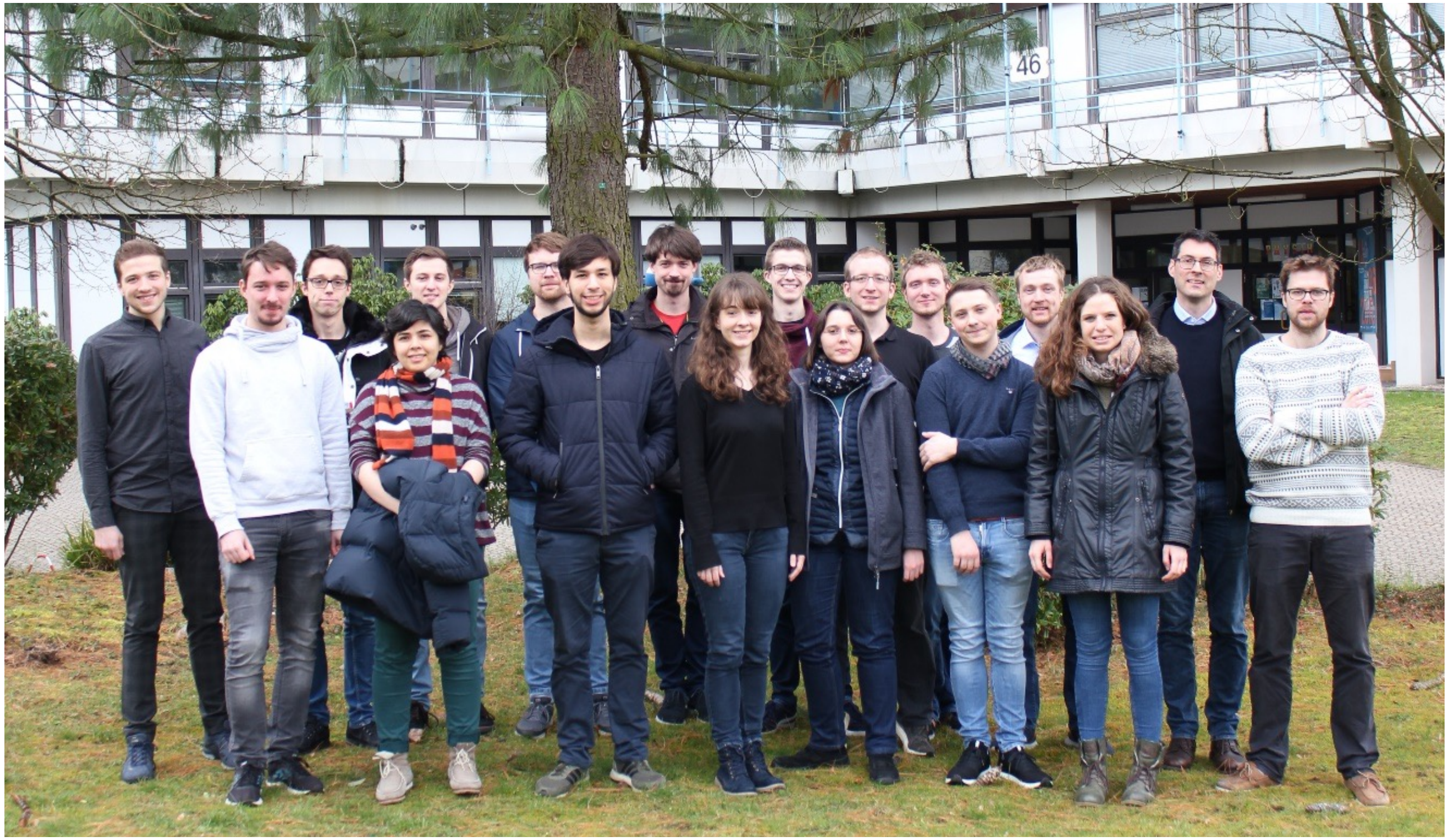
The team

individual quantum systems



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