# Ultracold atoms in strong disorder: towards the Anderson transition

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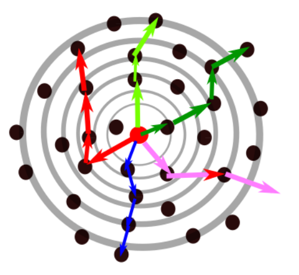
## Transport in disordered media


Light propagation in atmosphere

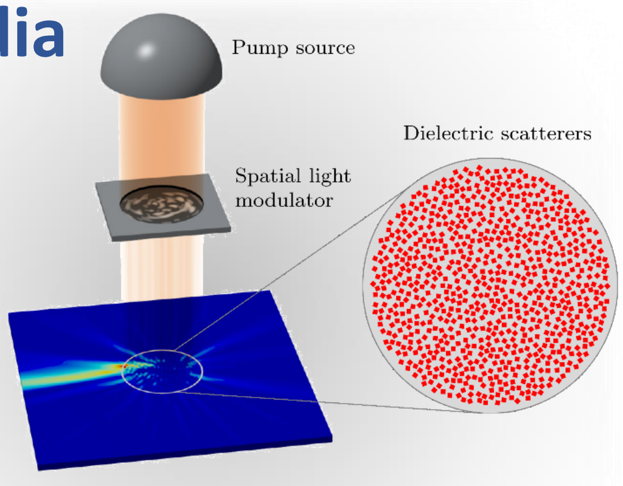

Sismic wave propagating in earth


Electronic conduction in metals



**Coherent** wave propagation is affected by **interference effects** due to disorder

Control of the emission pattern of a random laser

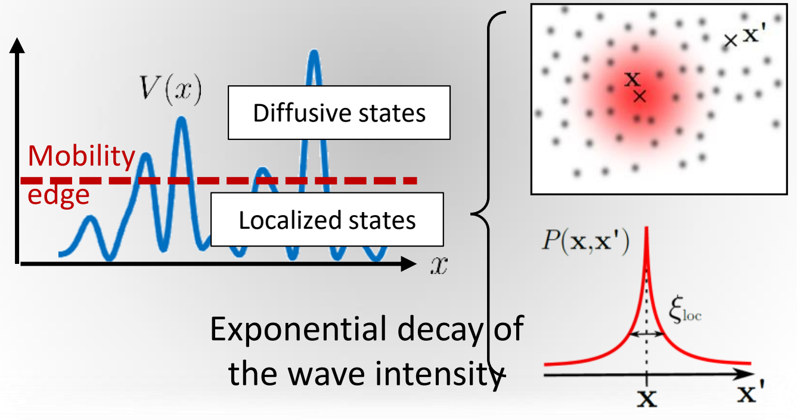


Hisch et al., *Phys. Rev. Lett.* **111**, 023902 (2013)

**Anderson localization**

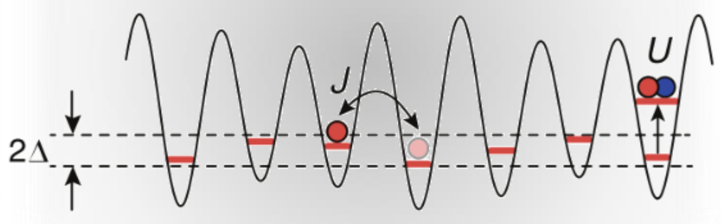
**Disorder-based applications**

3D Anderson phase transition



Exponential decay of the wave intensity

**Many-body localization**
(disorder and interactions)

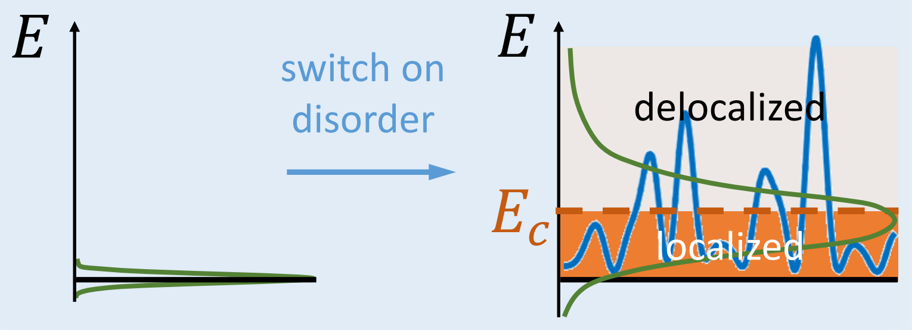


Schreiber et al., *Science* **349**, 842 (2015)

## Spectroscopic approach to study the Anderson transition

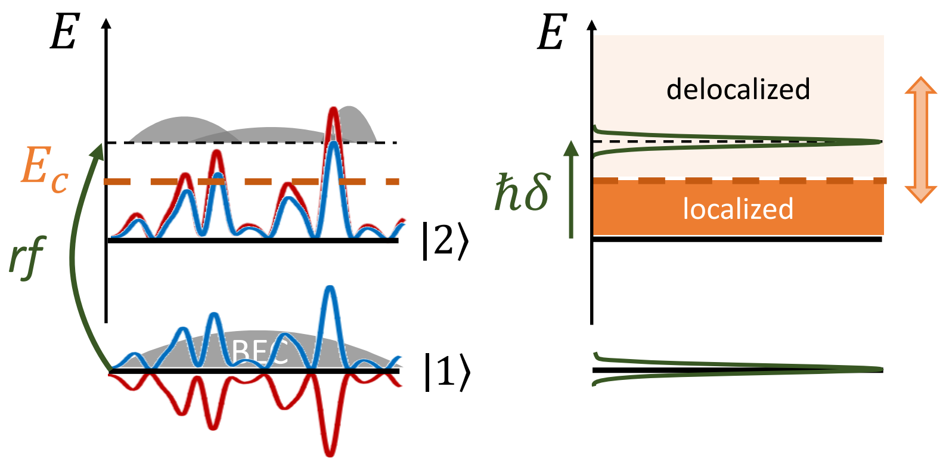
**State-dependent disorder with long-lifetime:** can be realized by combining attractive (red) and repulsive (blue) laser speckles

**Current limitation:** broad energy distribution that spans across the mobility edge



→ Need for a narrow energy distribution !

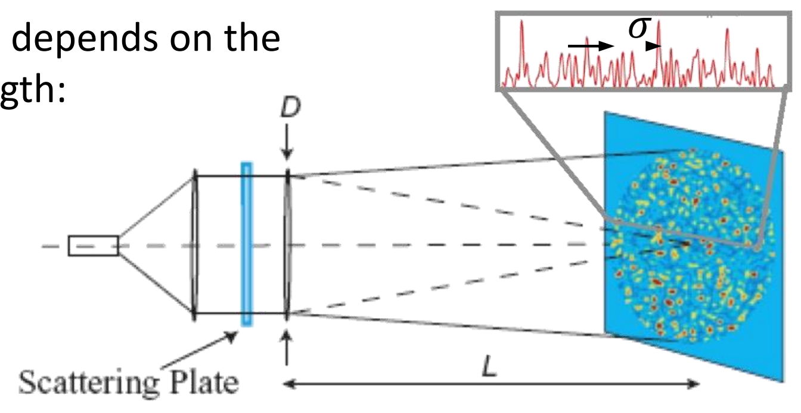
- BEC prepared in a disorder-insensitive state
- The atoms are transferred by radiofrequency into state $|2\rangle$ where they experience disorder
- Possibility to scan the energy across the mobility edge $E_c$ by scanning the detuning of the radio-frequency.



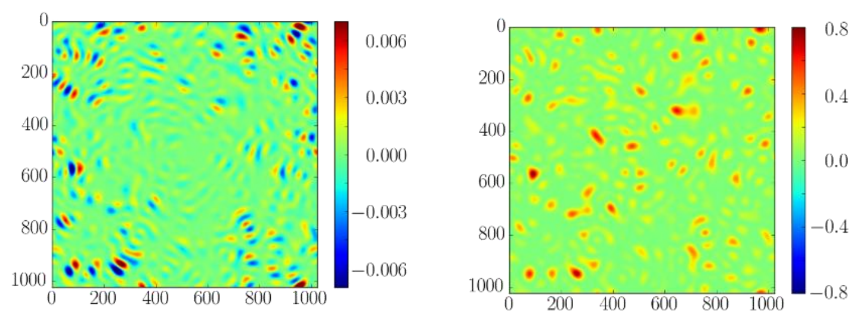
**Towards the realization of bi-chromatic speckle disorder**

The disorder correlation length $\sigma$ depends on the wavelength:

$$\sigma = \frac{\lambda L}{\pi D}$$



Numerical calculations:



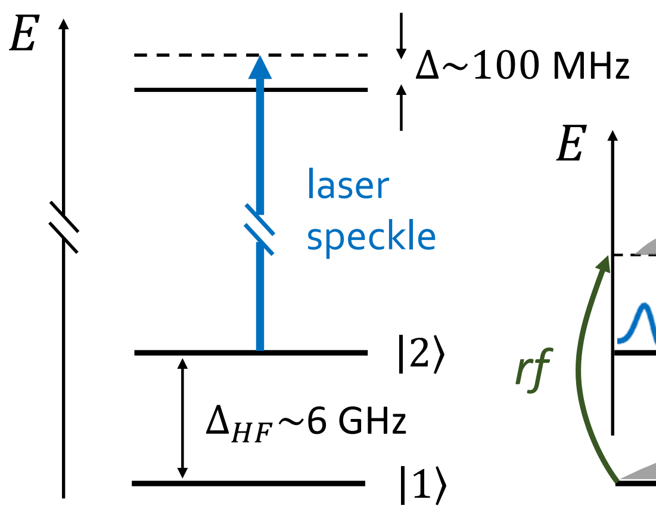
residual disorder on state $|1\rangle$ (increased scale)

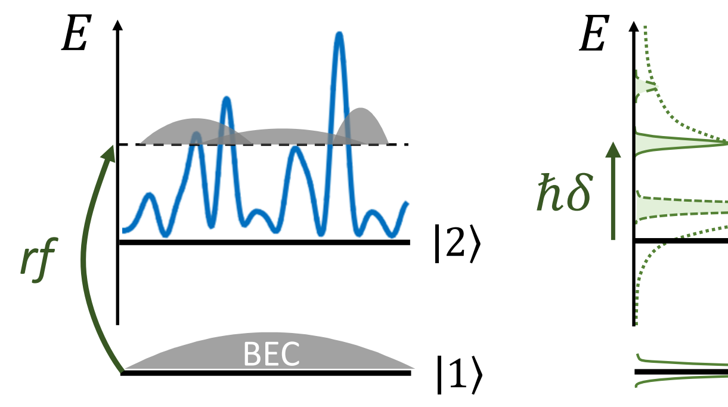
disorder on state $|2\rangle$

## Proof-of-principle: measurement of spectral functions

**State-dependent disorder**

- BEC prepared in a disorder-insensitive state
- The atoms are transferred by radiofrequency into state $|2\rangle$ where they experience disorder

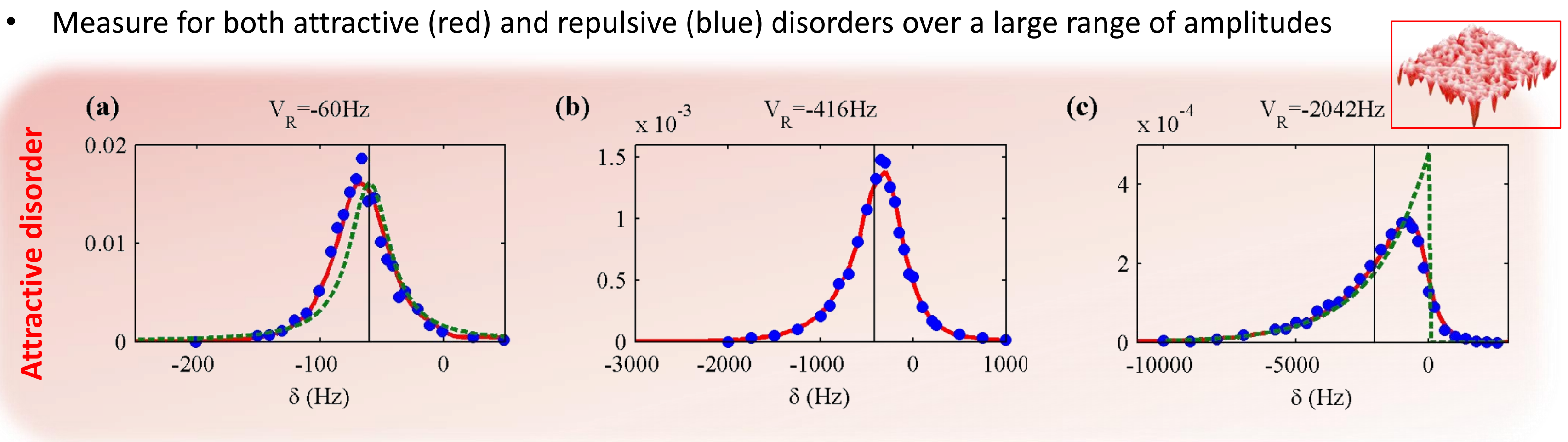


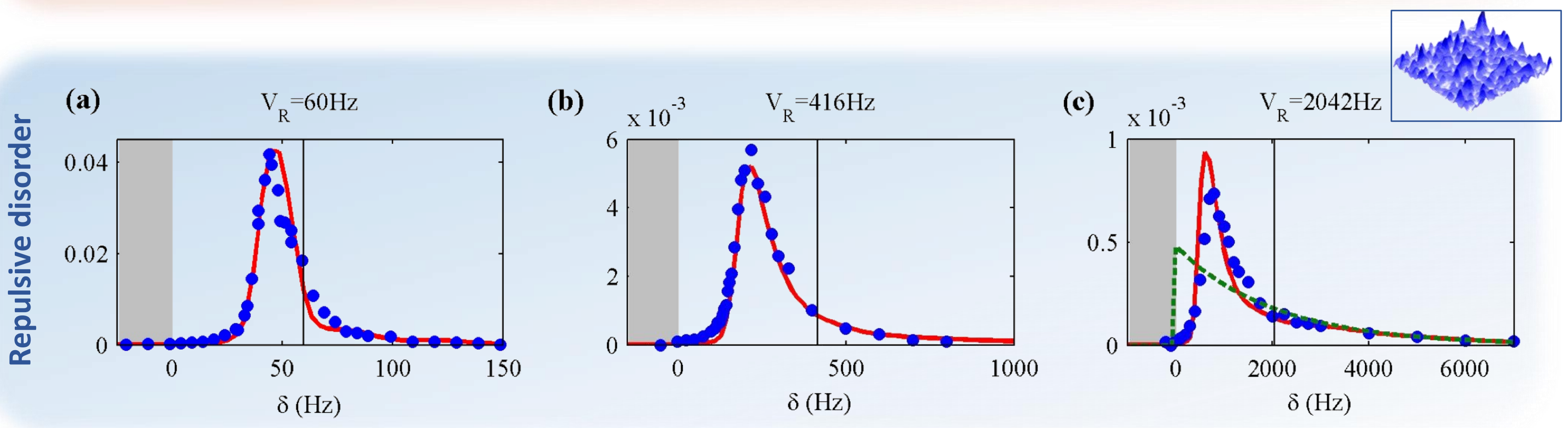


by scanning the detuning, we can measure the energy distribution in disorder

**Measurement of the spectral functions** (in collaboration with the group of *D. Delande* at LKB)

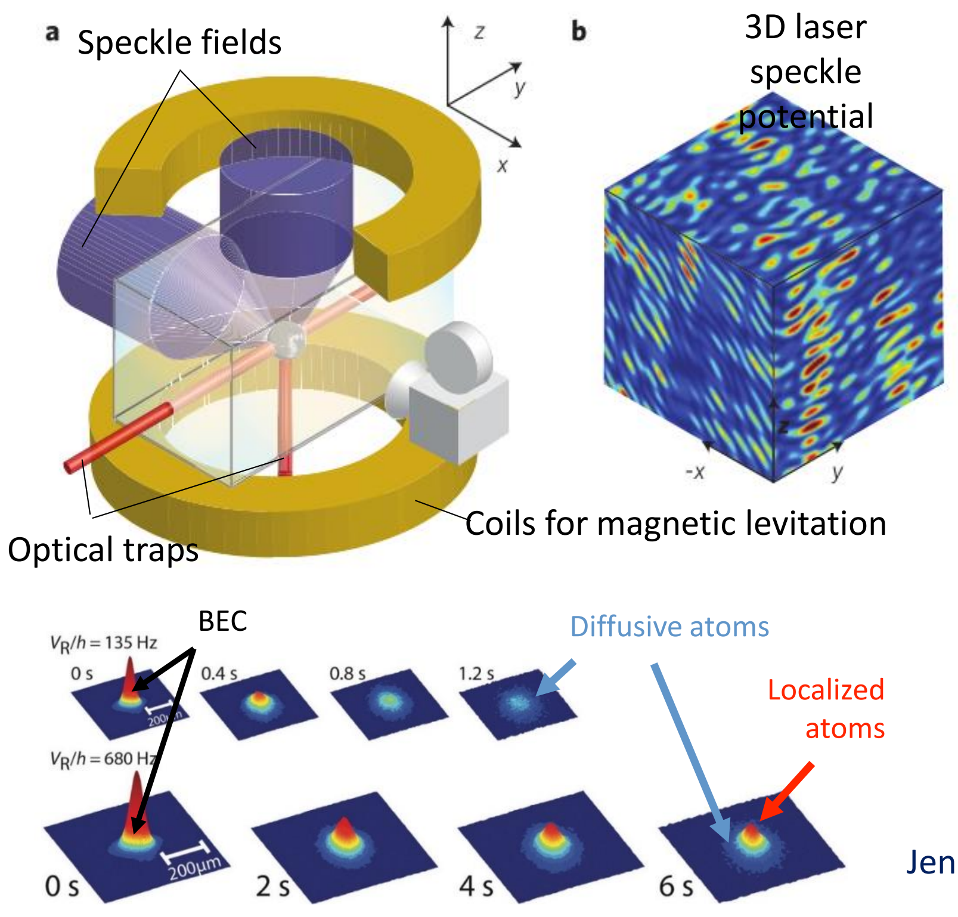
- The rf transfer rate is proportional to the spectral function $A\left(E=\hbar\delta,\vec{k}=\vec{0}\right) \propto \left|\langle\vec{k}|E\rangle\right|^2 \rho(E)$
- Measure for both attractive (red) and repulsive (blue) disorders over a large range of amplitudes



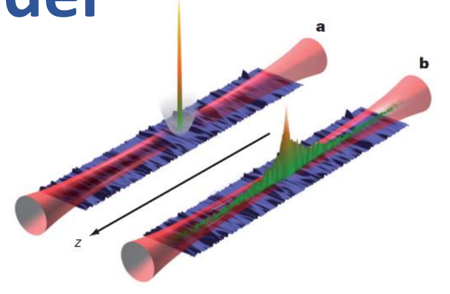


Volchkov et al., *Phys. Rev. Lett.* **118**, 060404 (2017)

## Transport of matterwaves in optical disorder



**Observation of Anderson localization with cold atoms**



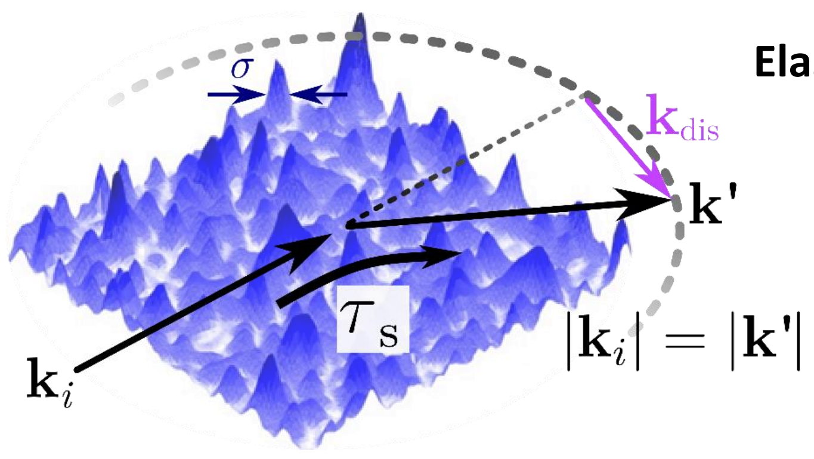
- Localization in 1D system (LCF, LENS)
- Localization in 3D (Urbana Champaign, LCF, LENS)

**Main objectives**

- measurement of the mobility edge
- observation of the critical regime in 3D
- role of the microscopic disorder parameters

Jendrzejewski et al., *Nature Physics* **8**, 398 (2012)

## Elastic scattering time from weak to strong scattering



**Elastic scattering time:** mean time between two scattering events.

First-order Born approximation: lifetime picture

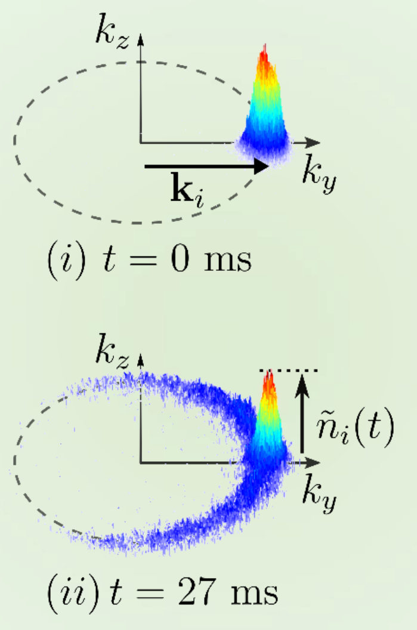
$$\frac{\hbar}{\tau_s} = \sum_{k'} \underbrace{\tilde{C}(\boldsymbol{k_i}-\boldsymbol{k'})}_{\text{coupling = correlation function}} \underbrace{\delta(\epsilon_{k_i}-\epsilon_{k'})}_{\text{energy conservation}}$$

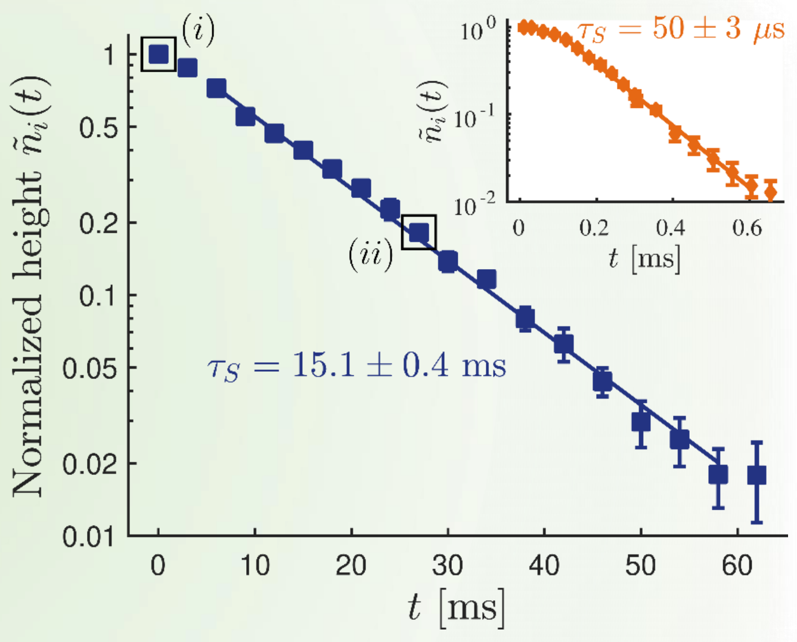
A matter-wave of **initial momentum $\boldsymbol{k_i}$** propagating in a disordered potential $V(\boldsymbol{r})$ experiences a scattering event after **a typical time $\boldsymbol{\tau_s}$.**

**Experimental measurement of $\boldsymbol{\tau_s}$:**

- Preparation of a well-defined momentum state $|\boldsymbol{k}_i\rangle$
- Evolution in a quasi-2D disordered potential during a time $t$
- Imaging of the momentum distribution (long time-of-flight)

↘ $\boldsymbol{\tau_s}$ **= decay time** of the population in the initial state

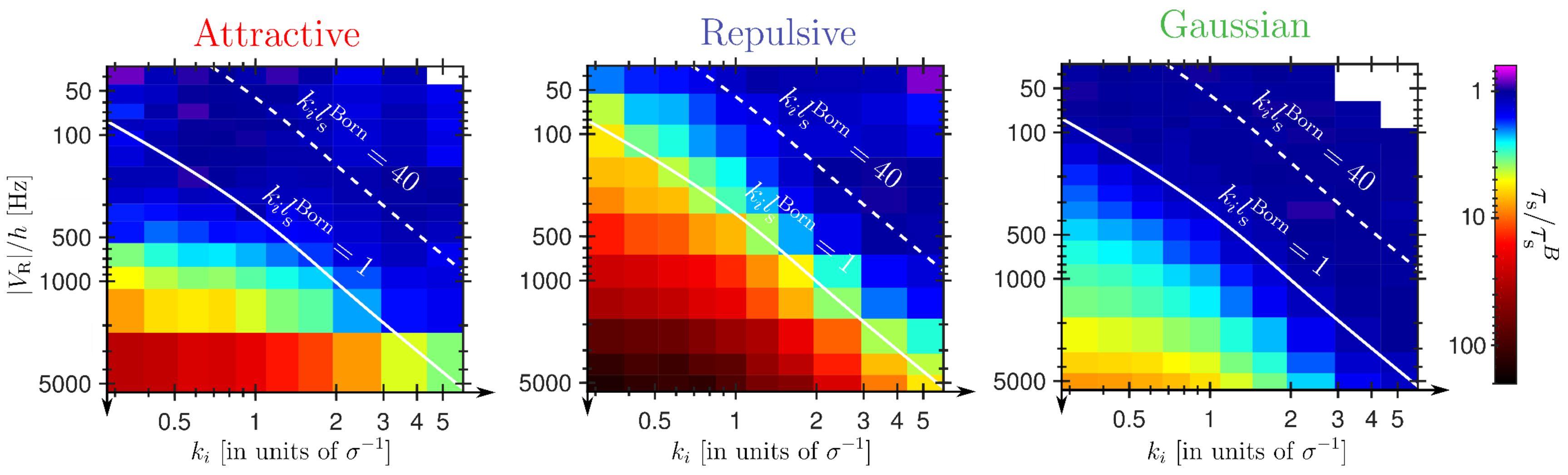




Richard et al., *Phys. Rev. Lett.* **122**, 100403 (2018)

**Crossover from weak to strong scattering regimes**

We extract the scattering time for numerous initial momenta $\boldsymbol{k}_i$ and disorder strengh $V_{\mathrm{R}}$. The values are compared to predictions based on the first-order Born approximation.



- Large **deviations to first-order Born approximation** are observed for strong scattering strength $\boldsymbol{k}_i l_s \ll 1$.
- The location of the **crossover depends on the amplitude probability distribution** of the disorder P(V).

  → for Gaussian disorder, crossover corresponds to $\boldsymbol{k}_i l_s \sim 1$.

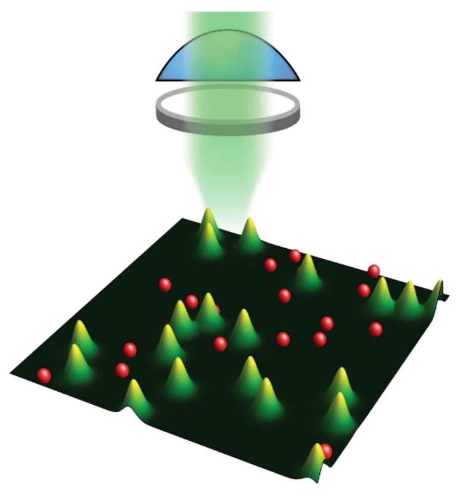
  → for laser speckle disorder, crossover corresponds to $\boldsymbol{k}_i l_s \sim 40$.
- Scattering time in the strong scattering regime cannot be tackled by higher-order Born approximation or Self-Consistent Born Approximation. At $\boldsymbol{k}_i = 0$, it is in good agreement with the measured width of spectral functions.

Signoles et al., New J. *Phys.* **21**, 105002 (2019)

## Future perspectives

**Localization with « tailored » disordered potential**

→ Studying the universality of the transition with respect to the microscopic details of the disorder (spatial correlations, anisotropy, amplitude distribution, etc.).
→ At long-term, engineering specific localization properties by designing the disorder.



Morong & DeMarco, *Phys. Rev. A* **92**, 023625 (2015)

**Anderson localization and symmetry breaking**

→ Exploring the exotic phase transitions that emerge when symmetry properties are changed, e.g. using artificial gauge fields or spin-orbit coupling.

**Interplay between disorder and interactions**

→ Studying how localization is suppressed by weak interactions, resulting in sub-diffusive transport.
→ Observing how interactions affect thermalization in disordered systems and lead to many-body localization.