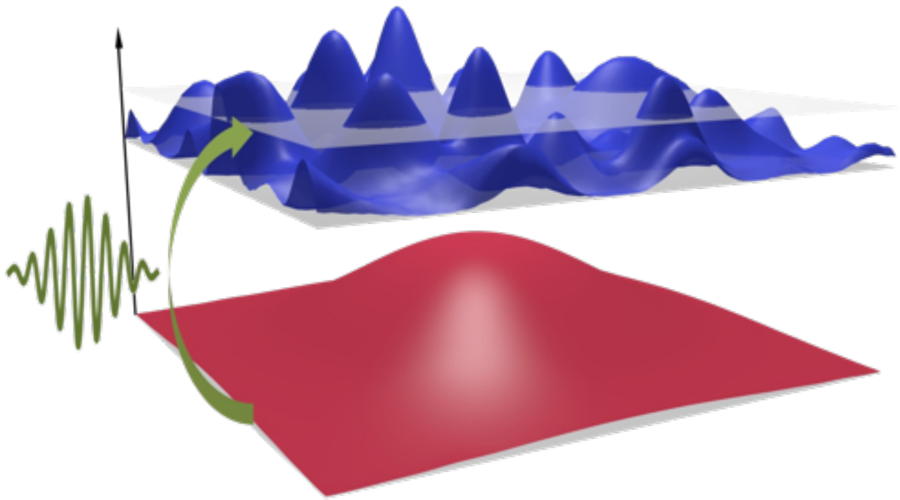
3D Anderson Transition with ultracold atoms



Vincent Josse

Quantum Gases Group – Institut d'Optique, Palaiseau, France

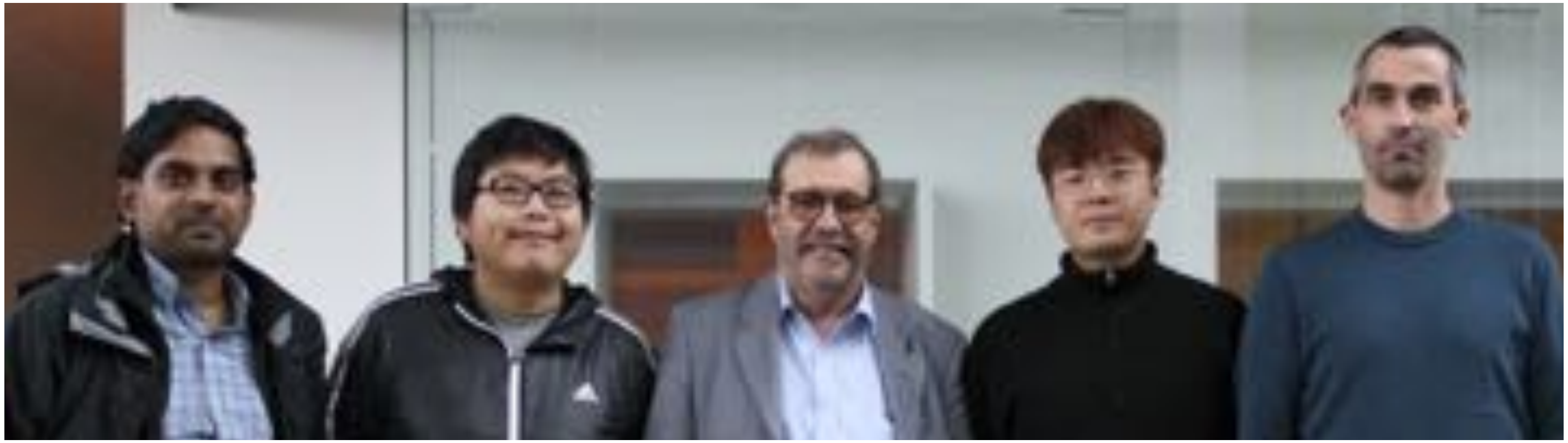
GDR Complexe, Institut Langevin, December 7th, 2022

INSTITUT d'OPTIQUE GRADUATE SCHOOL

université PARIS-SACLAY

SIMONS FOUNDATION

Quantum Transport Team, Institut d’Optique, France



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Yukun Guo
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Niranjan Myneni
Baptiste Lecoutre (ex)

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Alain Aspect

Theory collaborators

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M. Filoche   *S. Mayboroda*

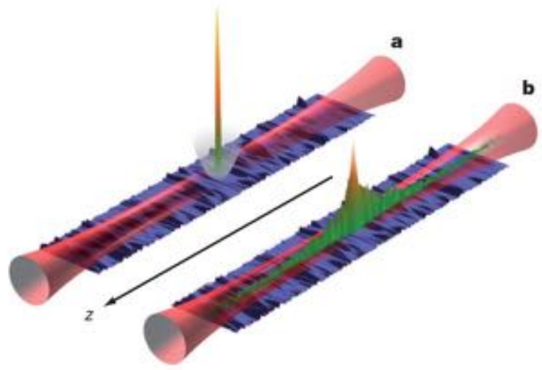
Connexion with the « landscape theory »

SIMONS FOUNDATION

Ultracold atoms and disorder

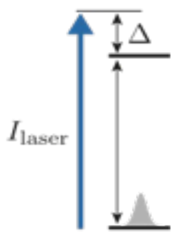
2008 : Anderson Localization (1D)

Direct observation of matter waves stopped by (weak) disorder !

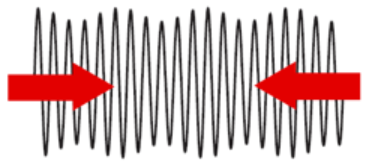


Palaiseau : J. Billy et al, Nature (2008)
LENS: G. Roati et al, Nature (2008)

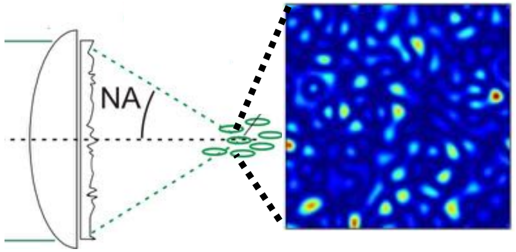
Well controlled disordered potential created with light



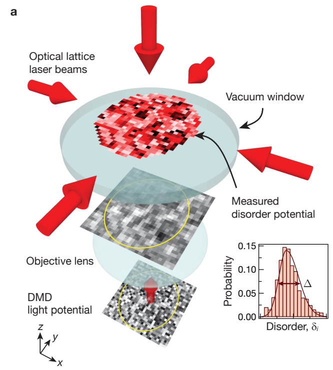
$$V(\mathbf{r}) \propto \frac{I(\mathbf{r})}{\Delta}$$



Bichromatic lattice



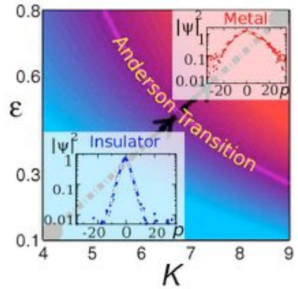
Laser speckle disorder



Arbitrary potentials using spatial light modulators

An other approach :
Dynamical localization in Kicked Rotors sytems
(mapping to AL)

C. Miniatura



Chabé et al., PRL (2008);
Hainaut et al. , Nat. Comm. (2018)

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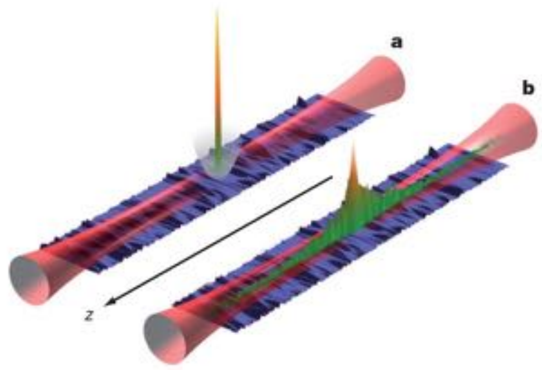

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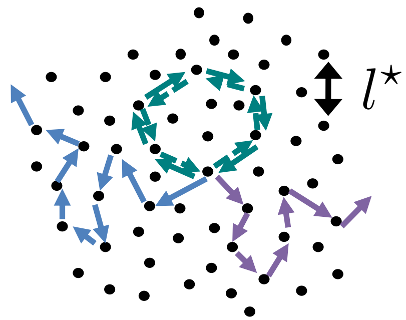
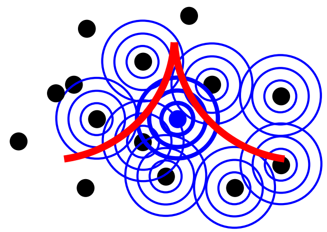
A "challenge" = 3D Anderson transition



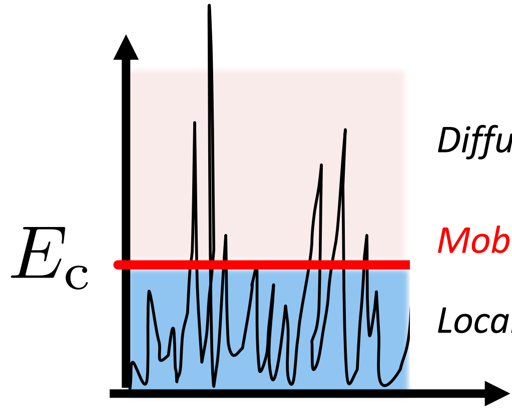
Diffusion in weak disorder

$$k\, l^\star \sim 1$$

Ioffe-Regel criterion

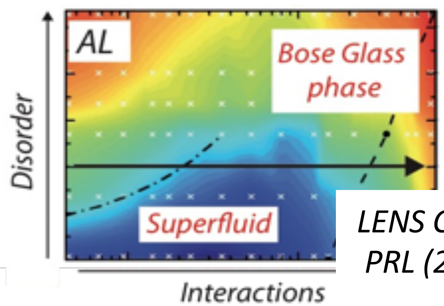


Localization in "extreme" disorder



Beyond: disorder and interactions

Bose glass phase



LENS C. D'Errico et al. PRL (2014)

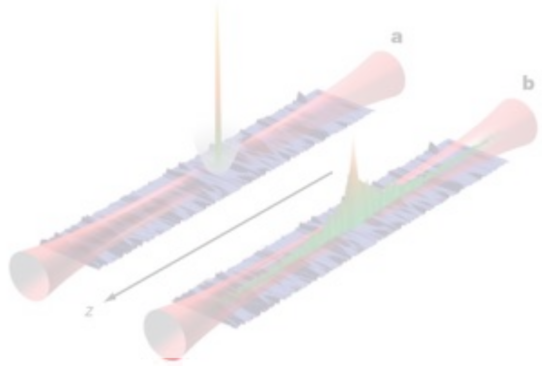
Many-body localization

M. Schreiber et al. Science (2015)
J.Y. Choi (Science 2016)

Ultracold atoms and disorder

2008 : Anderson Localization (1D)

Direct observation of matter waves stopped by (weak) disorder !



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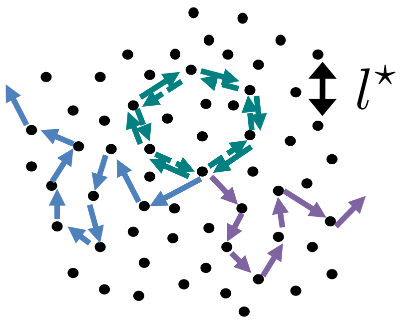
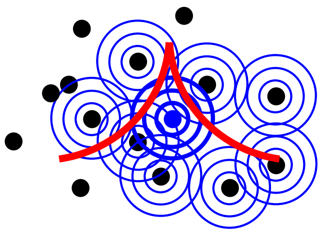


Diffusion in weak disorder

$$k\,l^\star \sim 1$$

$\Longrightarrow$

Ioffe-Regel criterion



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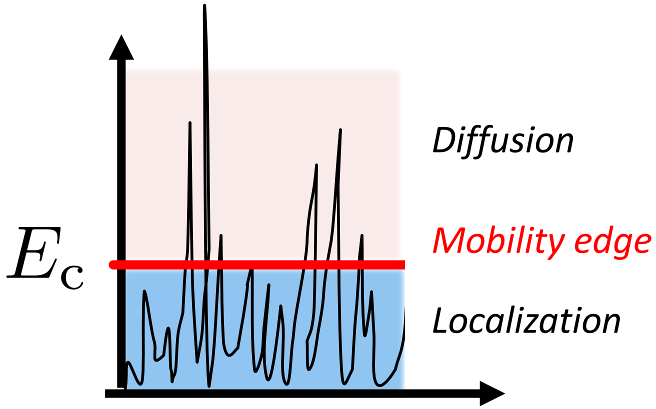


⇨ Evidences of 3D localization ...

S. Kondov et al, Science (2011)

F. Jendrzejewski et al, Nat. Phys. (2012)

G. Semeghini et al, *Nat. Phys.* (2015)

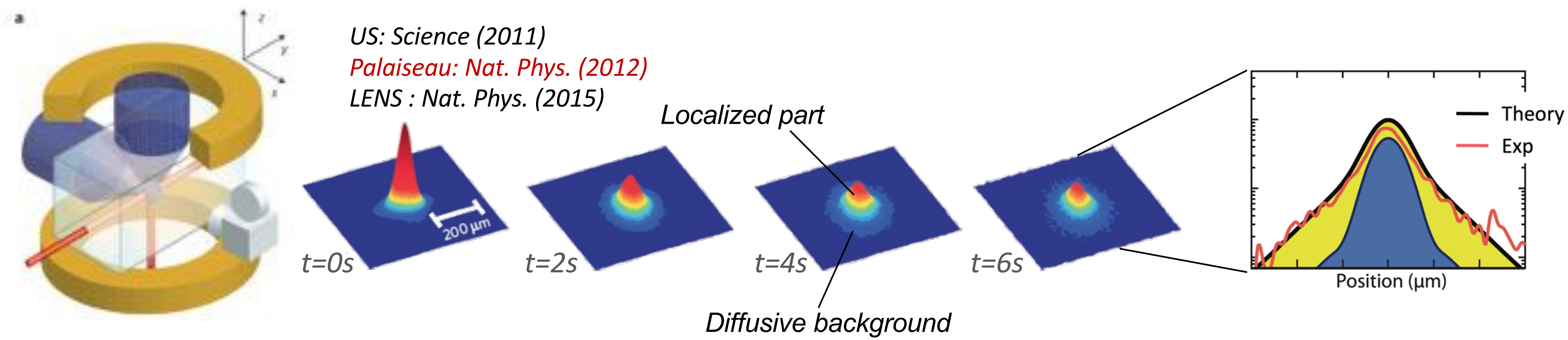
... but difficult experiments

⇨ Deviations between numerics and experiments call for further investigation

M.Pasek, G. Orso, and D. Delande PRL (2017)

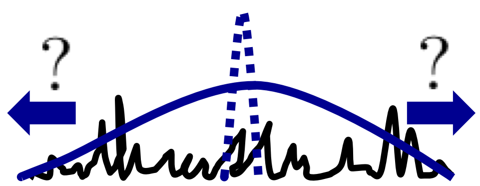
« Bottleneck » for the Anderson transition

E.g. Palaiseau's experiment



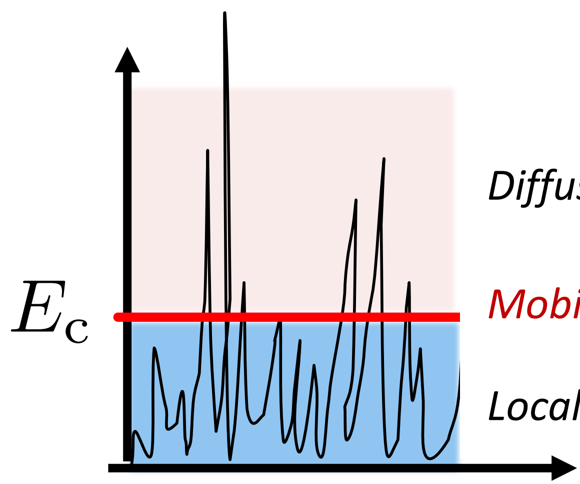
A common feature : co-existence of both phases (localized and diffusive)

Principle of the experiment:
monitor the expansion of a point source



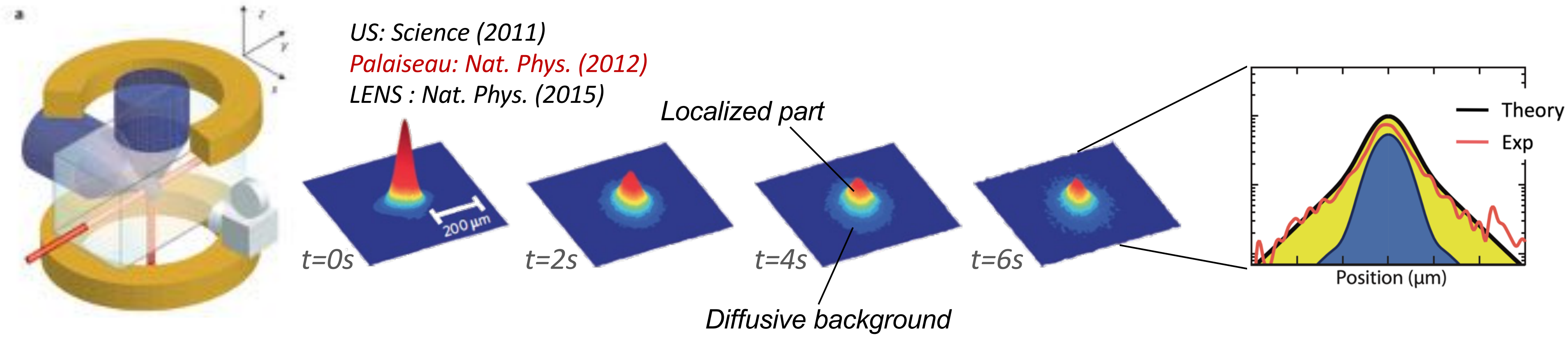
Need very long expansion time (seconds)

$$D \to 0$$



« Bottleneck » for the Anderson transition

E.g. Palaiseau's experiment



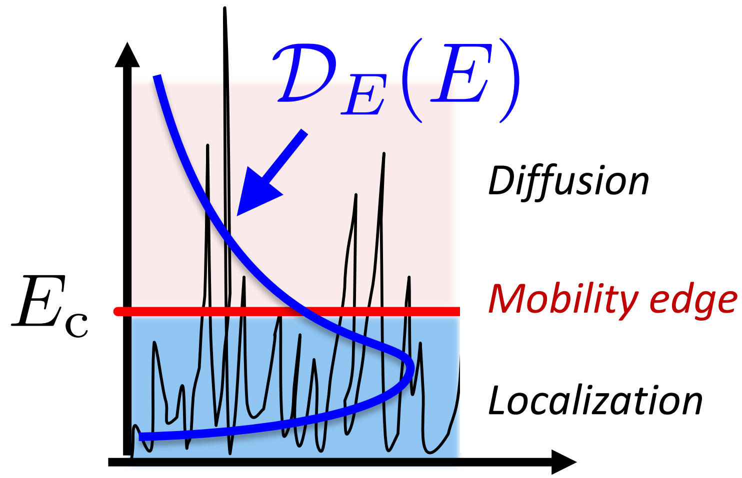
A common feature : co-existence of both phases (localized and diffusive)

The origin : energy broadening
induced by the strong disorder

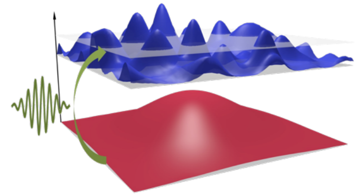
$$kl^\star \sim 1$$ *= "extreme" disorder*

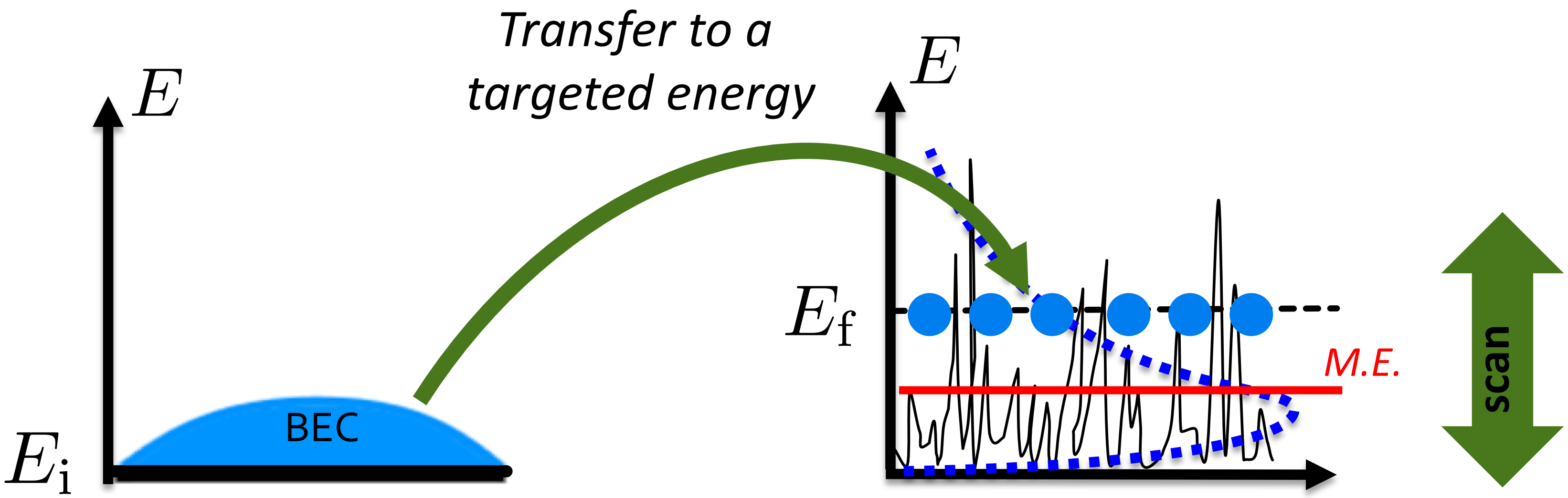
→ Energy distribution spans across the mobility edge

→ To go beyond : Control of the energy of the atoms in strong disorder



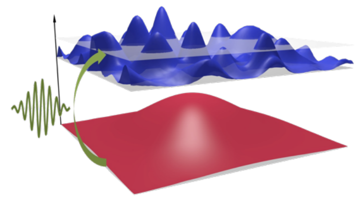
Energy resolved transfer

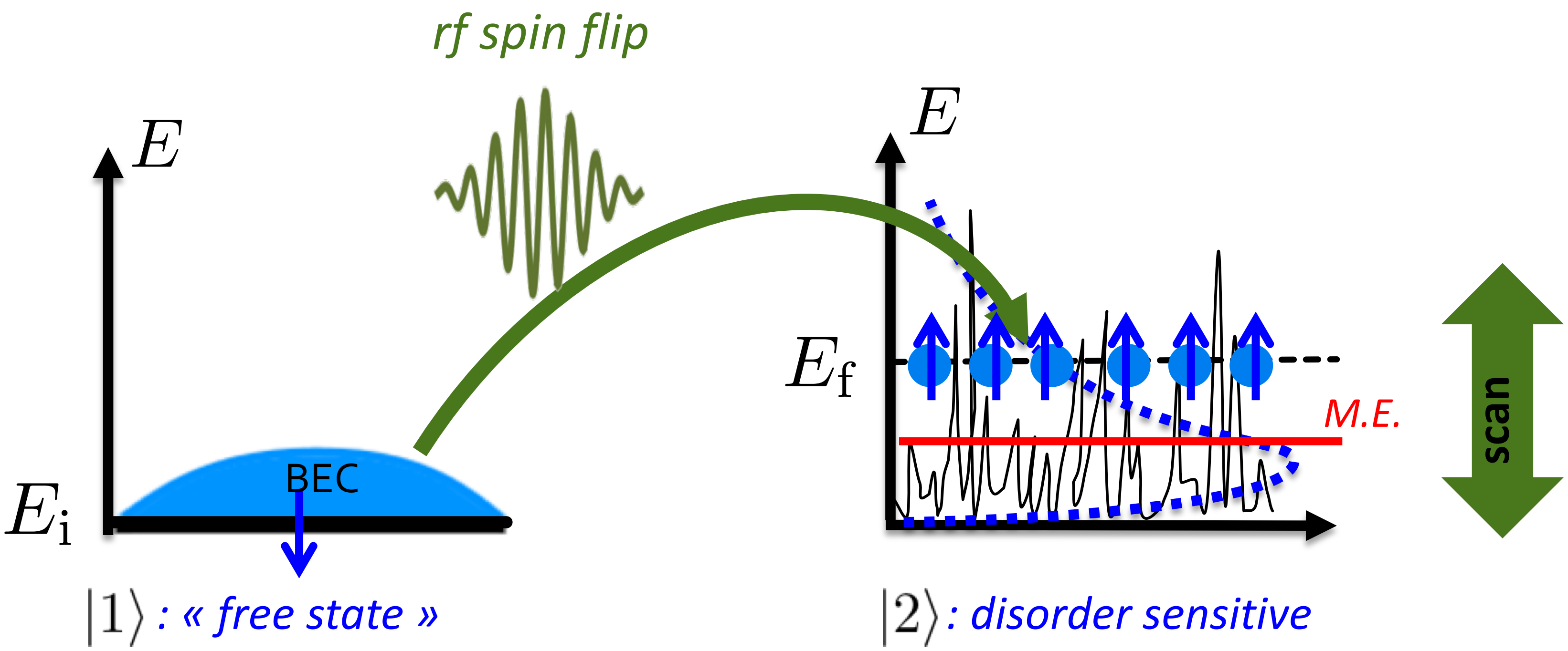




Ideal experiment : populate well defined energy states
and scan accros the mobility edge

Energy resolved transfer





Principle: use state-dependent disordered potential

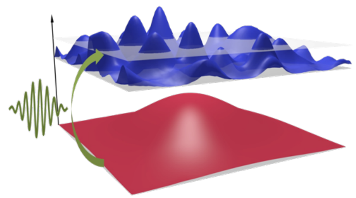
rf

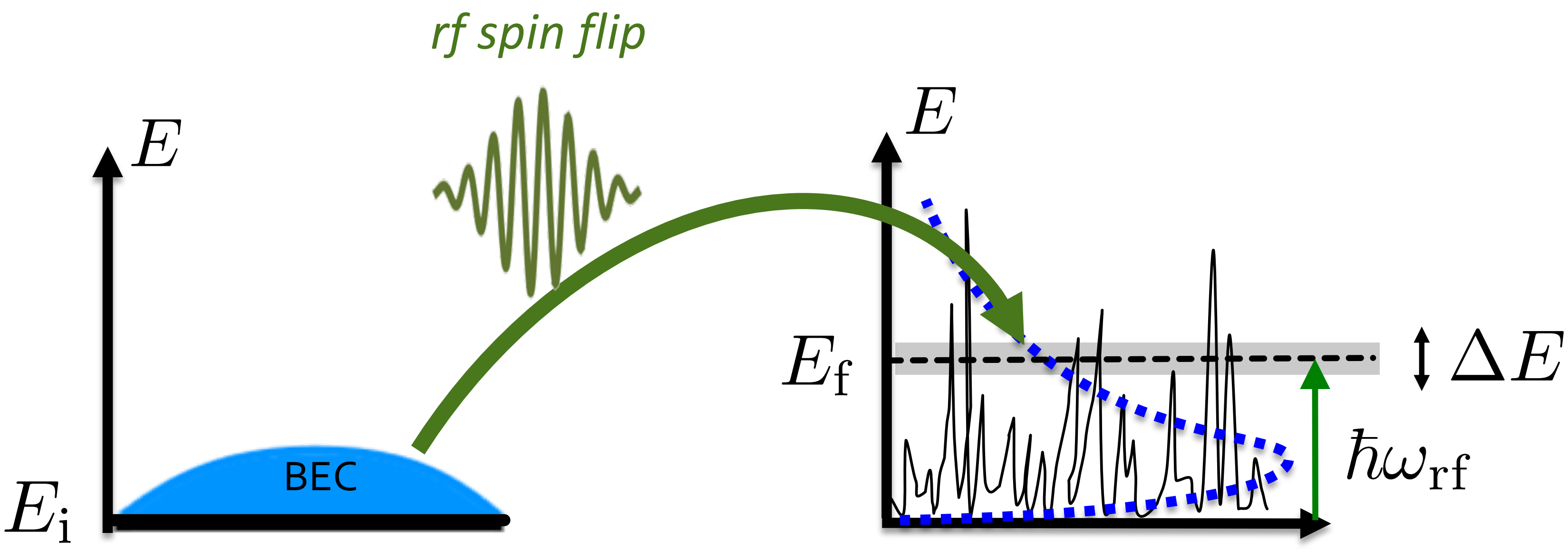
↓ : Initial state $|1\rangle$ does not feel disorder = "free" state

↑ : Final state $|2\rangle$ "embedded" in disorder = "disorder sensitive " state

In practice: $|1\rangle$ and $|2\rangle$ are Zeeman magnetic sublevel of ^{87}Rb

Energy resolved transfer





$|1\rangle$ *: « free state »* $|2\rangle$ *: disorder sensitive*

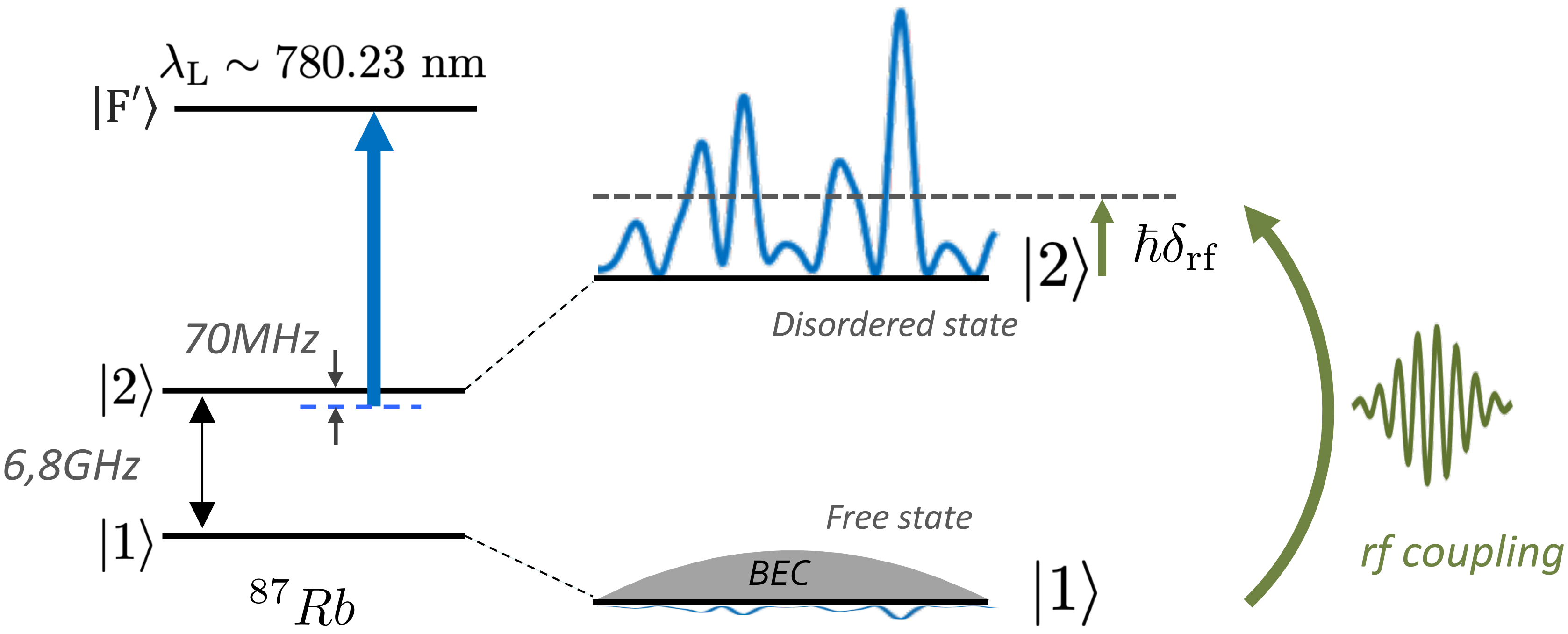
Spectroscopic transfer = well defined energy state in the disorder

$$\begin{cases} E_\mathrm{f} = E_\mathrm{i} + \hbar\omega_\mathrm{rf} & \text{: tuned via rf frequency} \\ \Delta E = \hbar / t_\mathrm{coupling} & \text{: tuned via coupling time (as low as } 10\ \mathrm{Hz}\text{)} \end{cases}$$

In practice: $|1\rangle$ *and* $|2\rangle$ *are Zeeman magnetic sublevel of* ^{87}*Rb*

First implementation of the scheme

Internal state dependent potential using near resonant light and the hyperfine splitting of ^{87}Rb atoms



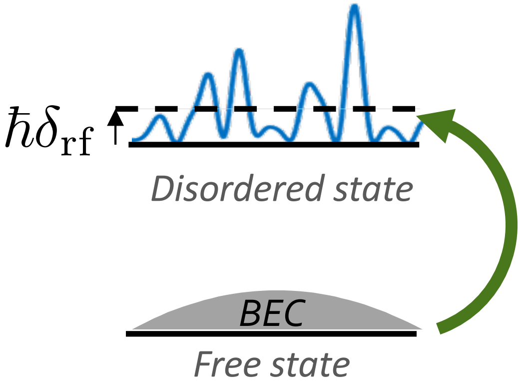
$$V_1 \ll V_2$$

(around 1/100)

$$V_{1,2}(\mathbf{r}) = \frac{I(\mathbf{r})}{\Delta_{1,2}}$$

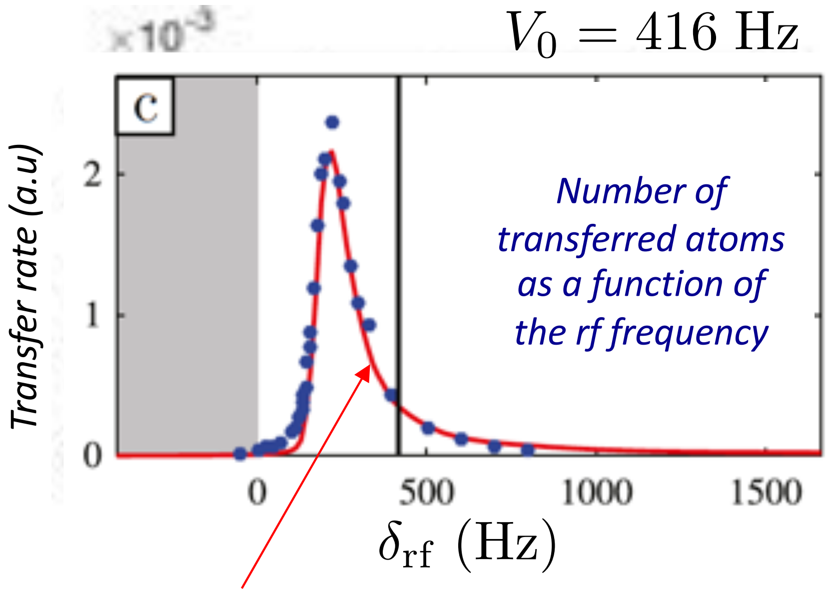
Transfer rate and spectral functions

1st validation of the scheme



Look at the transfer rate

$$\Gamma \propto |\langle \Psi_{\mathrm{BEC}} | E \rangle|^2 \, \rho(E)$$



Numerics by M. Pasek and D. Delande

- *Proof of principle: we can populate well defined energy states and control it!*

M. Pasek

D. Delande

Transfer rate and spectral functions

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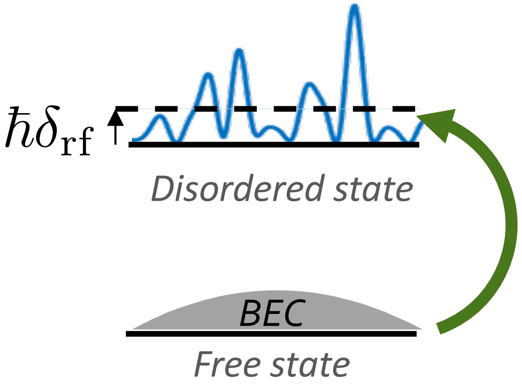
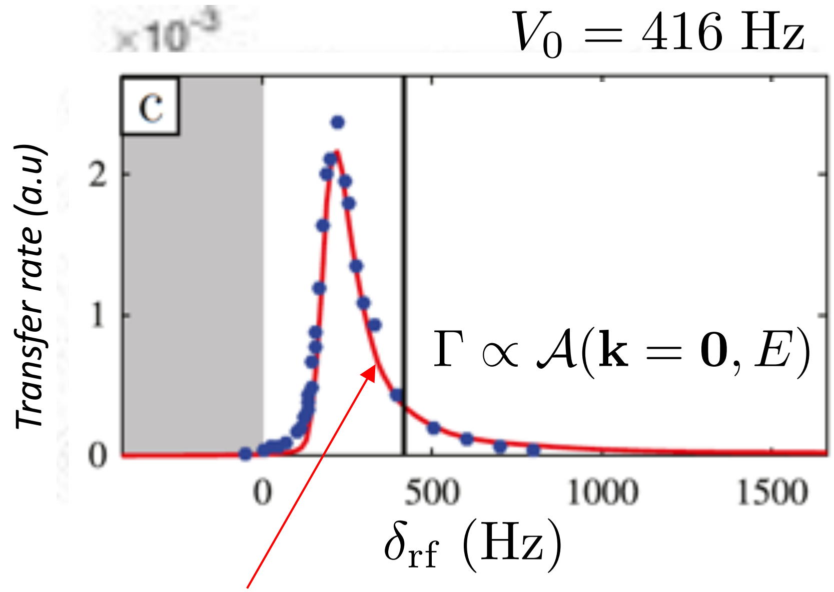


Look at the transfer rate

$$\Gamma \propto |\langle \Psi_{\rm BEC}|E\rangle|^2 \, \rho(E)$$
$$\sim |\langle \mathbf{k}=\mathbf{0}|E\rangle|^2 \, \rho(E)$$



Numerics by M. Pasek and D. Delande

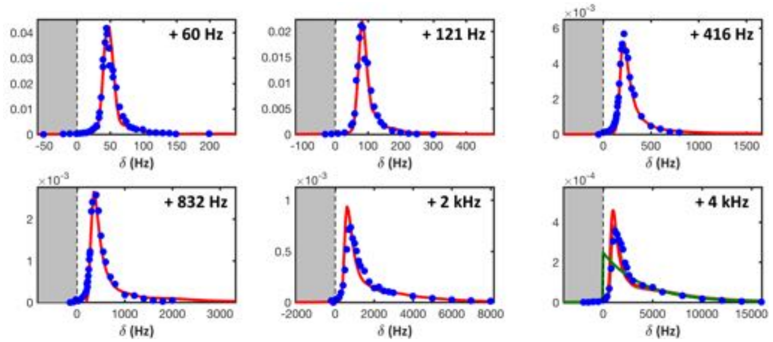
- *Proof of principle: we can populate well defined energy states and control it!*

- *Direct measurement of the <u>spectral functions</u>: Thourough investigation of the scattering properties from **<u>quantum</u>** to **<u>classical</u>** disorder regimes*

M. Pasek

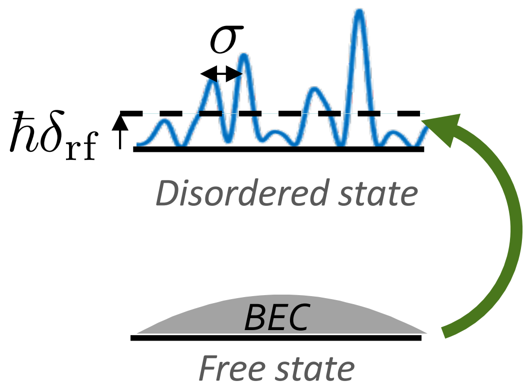
D. Delande

*V. Volchkov et al., PRL **120**, 060404 (2018)*
*J. Richard et al., PRL **122**, 100403 (2019)*
*A. Signoles et al., New J. Phys. **21**, 105002 (2019)*



Transfer rate and spectral functions

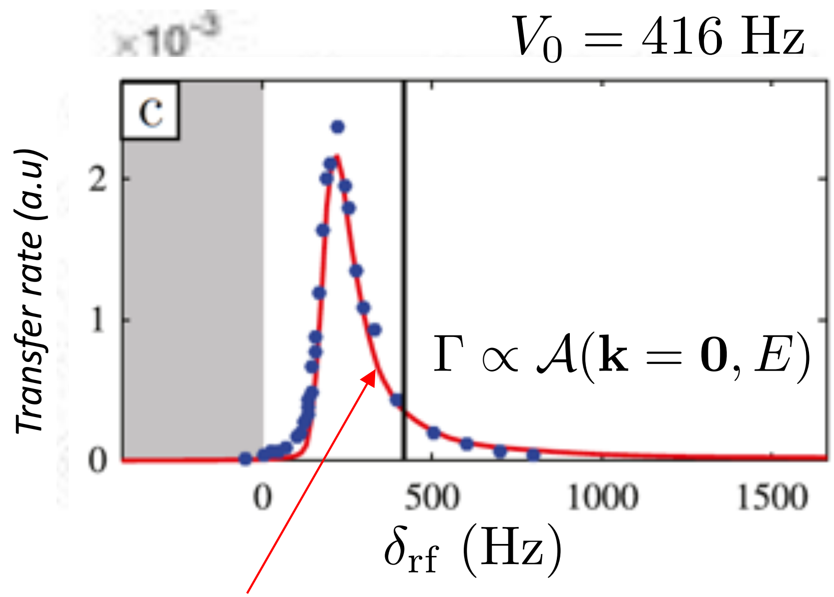
1st validation of the scheme



$$E_\sigma = \hbar^2/m\sigma^2$$

Look at the transfer rate

$$\Gamma \propto |\langle \Psi_{\rm BEC}|E\rangle|^2 \, \rho(E)$$
$$\sim |\langle \mathbf{k}=\mathbf{0}|E\rangle|^2 \, \rho(E)$$



Numerics by M. Pasek and D. Delande

M. Pasek

D. Delande

- *Proof of principle: we can populate well defined energy states and control it!*

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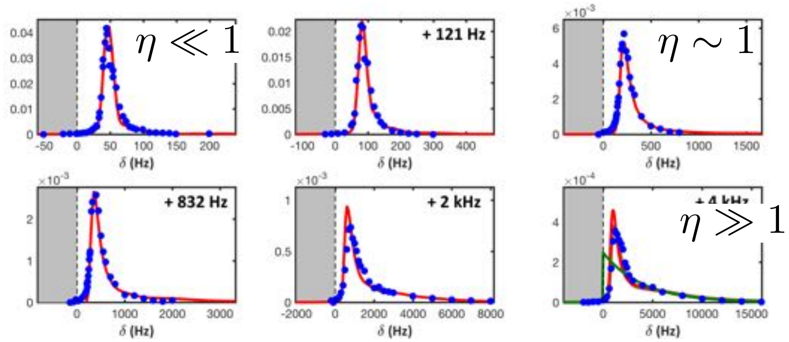
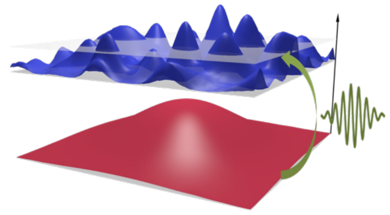


Relevant disorder normalized amplitude

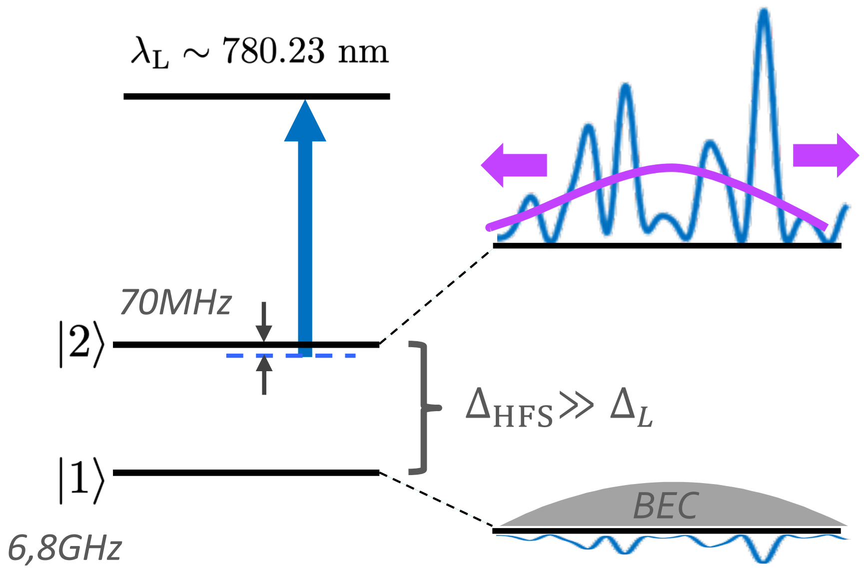
$$\eta = V_0/E_\sigma$$

Correlation energy

Transport properties ?

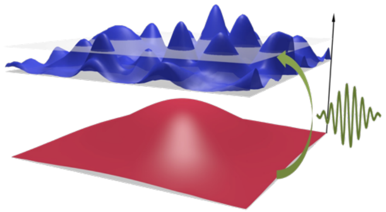


State dependent optical disorder



Probe the transport properties for well-defined energy states (diffusive or localized?)

Transport properties ?



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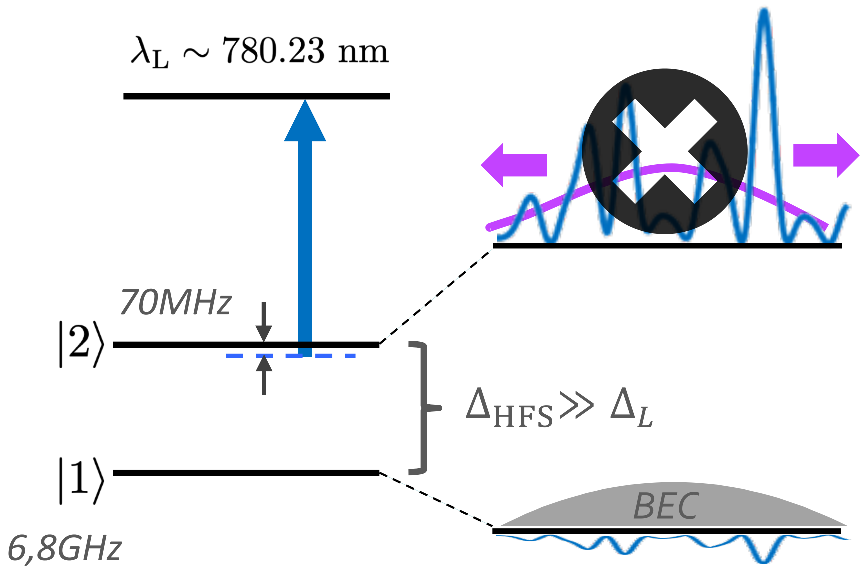
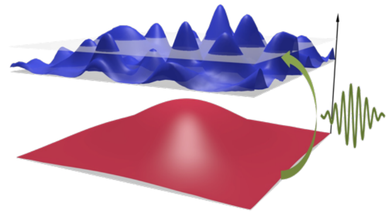


Quasi-resonant laser
= high photon scattering rate

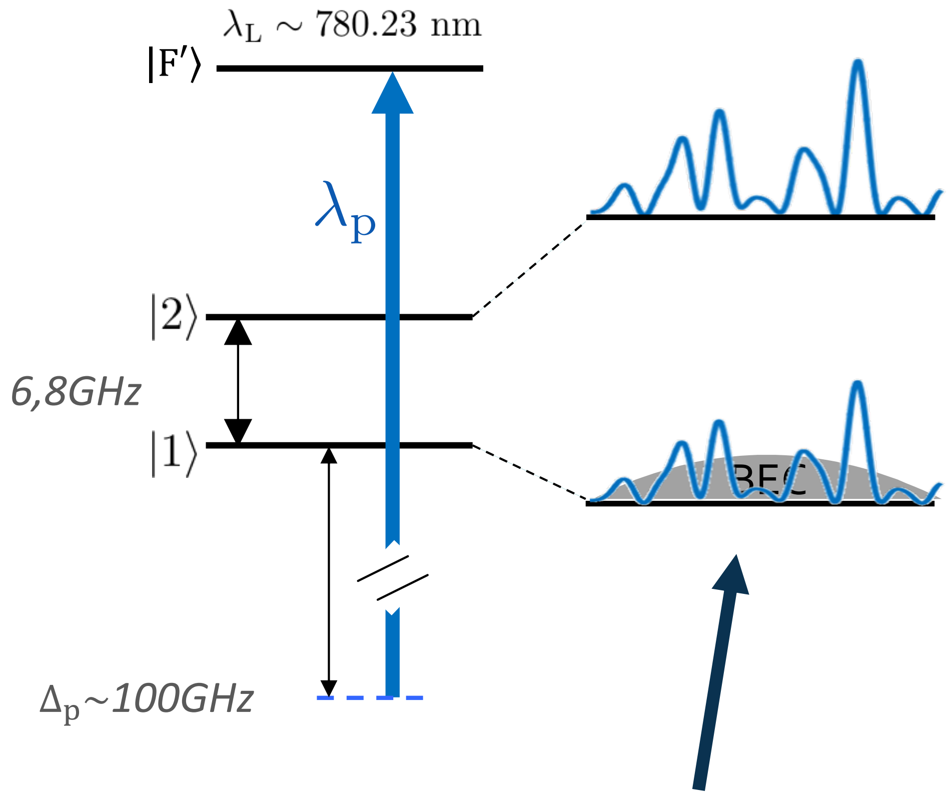
Lifetime ~10ms only
but we need seconds …

Probe the transport properties for well-defined energy states (diffusive or localized?)

Bichromatic speckle disorder



Long lifetime state dependent optical disorder ?

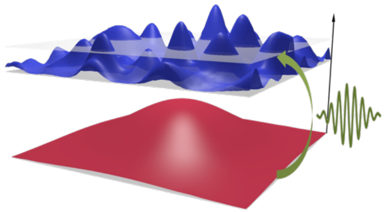


$$V_{1,2}(\mathbf{r}) = \frac{I(\mathbf{r})}{\Delta_{1,2}}$$

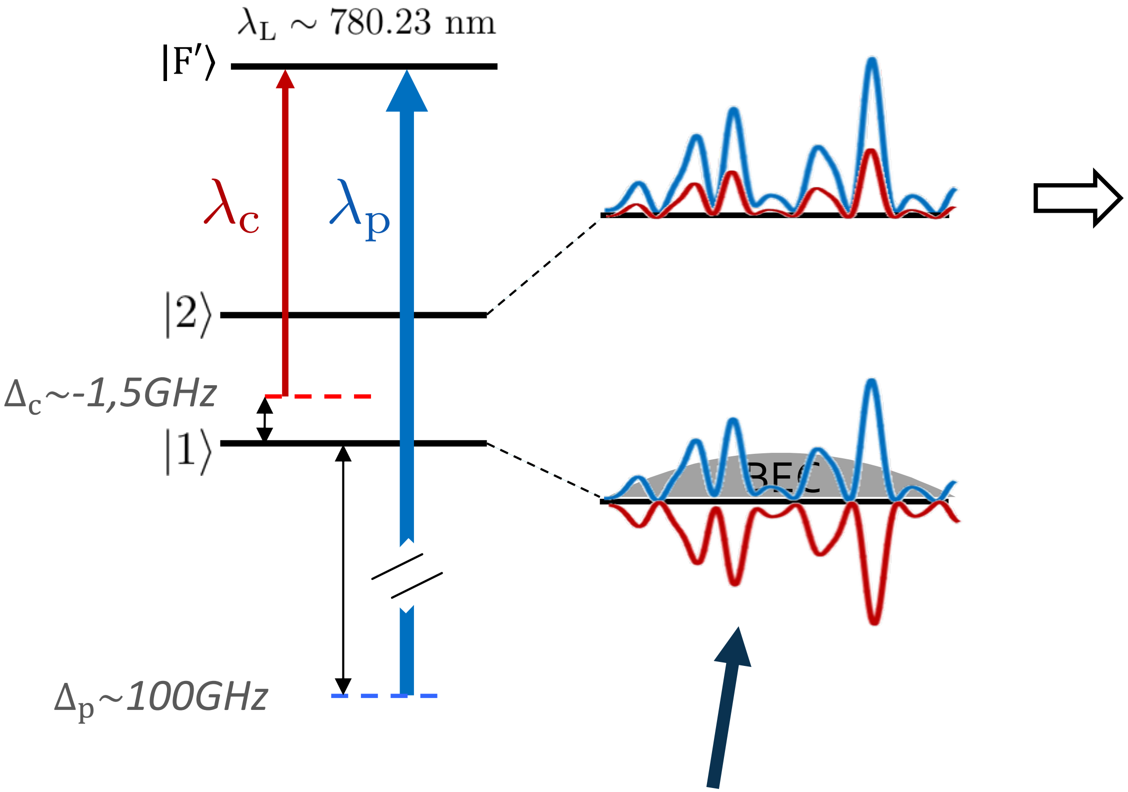
Increase the detuning of the laser
improve the lifetime
BUT loose the state selectivity

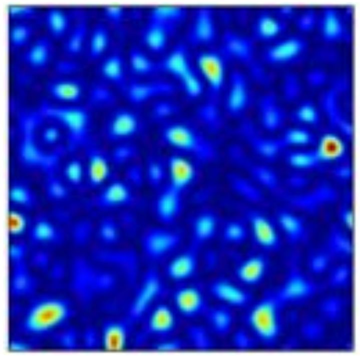
$$\Gamma_{sp} \propto \frac{1}{\Delta_{1,2}}$$

Bichromatic speckle disorder



Long lifetime state dependent optical disorder ?



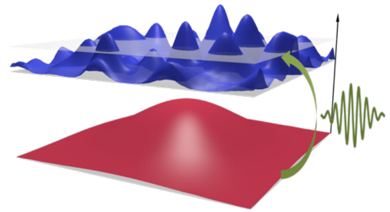


$$V_{1,2}(\mathbf{r}) = \frac{I(\mathbf{r})}{\Delta_{1,2}}$$

Add a second laser to
compensate « exactly » in state 1
while it sums up in state 2

$$\Gamma_{sp} \propto \frac{1}{\Delta_{1,2}}$$

Bichromatic speckle disorder



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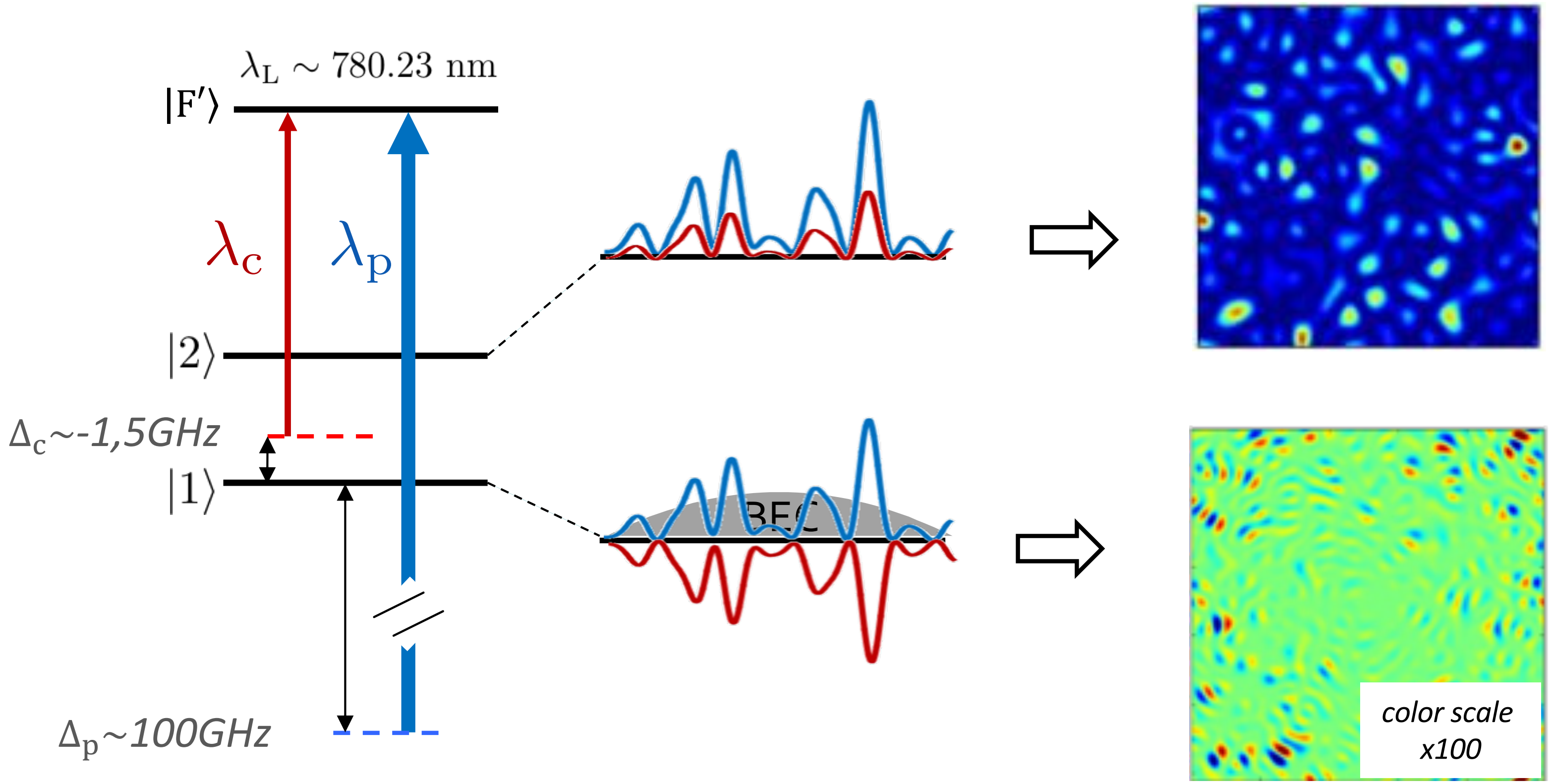


Disorder sensitive state with « long » lifetime (1.7 s)

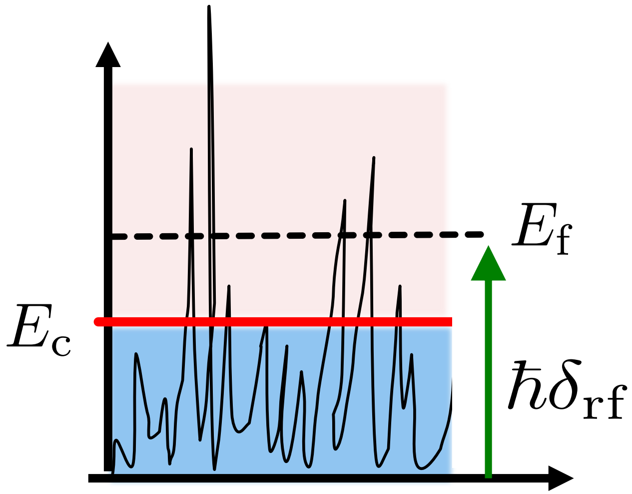
Efficient subtraction of the two speckles (negligible spatial decorrelation)

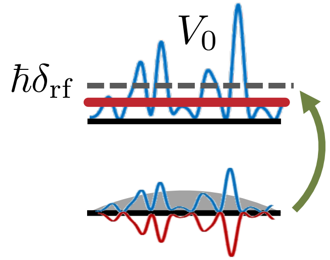
B. Lecoutre et al. EPJD (2022)

Features for : $|\lambda_p - \lambda_c| \lesssim 100\ \mathrm{GHz}$

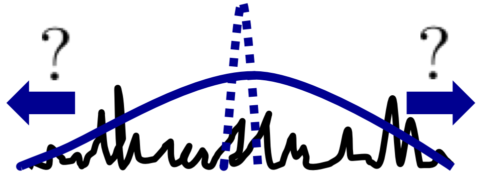
- *“Long” lifetime : 1.7 second is a achieved with the “bichromatic” scheme*
- *Low impact of the fundamental decorrelation between the two speckle fields*

Probe transport properties





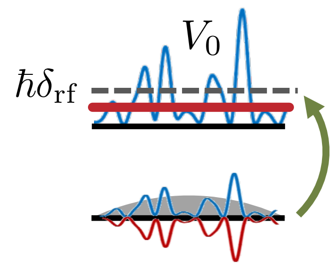
Preliminary data …
… work in progress

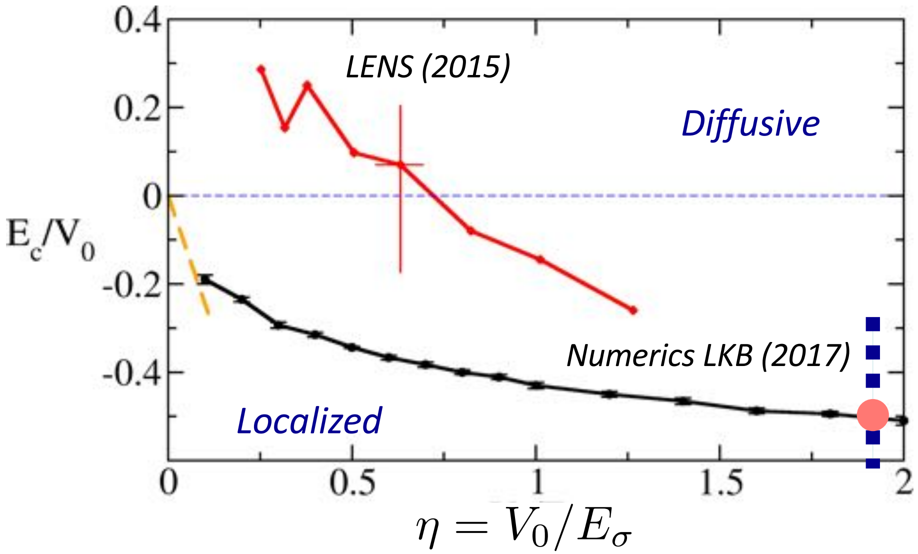


Experimental procedure :

- *Set the bichromatic speckle properties for a chosen disorder amplitude* V_0
- *Transfer the atoms at a given energy :* $E_f = \hbar\delta_\mathrm{rf}$
- *Probe the transport properties (expansion in disorder) : diffusive or localized ?*
- *Signature of a "mobility edge" by scanning the rf frequency ?*

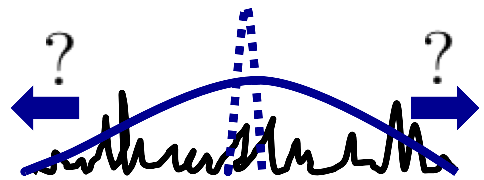
Probe transport properties





$$V_0 = 832\ \mathrm{Hz}$$

$$\eta = V_0/E_\sigma \sim 2$$

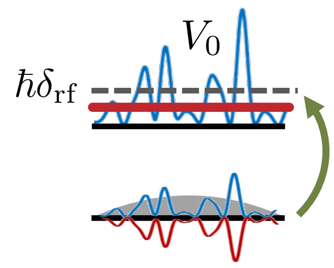


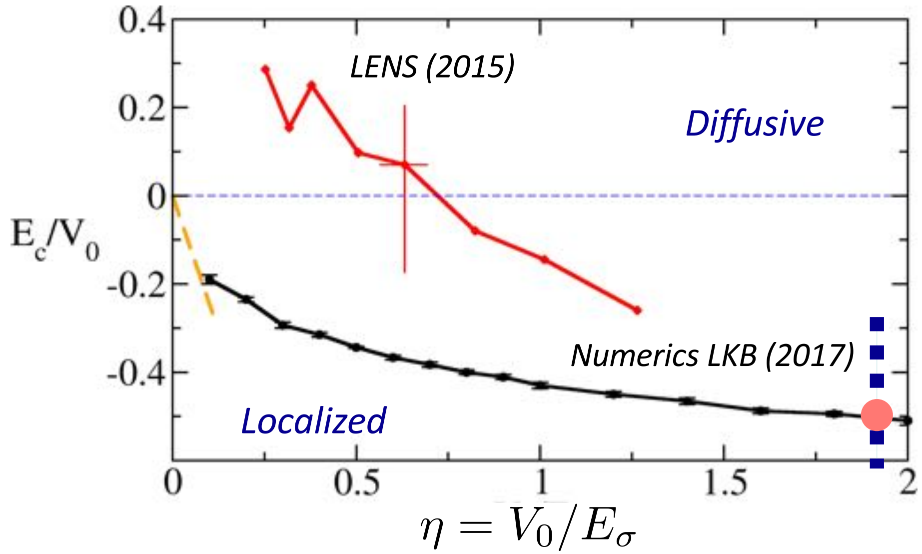
Experimental procedure :

- *Set the bichromatic speckle properties for a chosen disorder amplitude* V_0
- *Transfer the atoms at a given energy :* $E_f = \hbar\delta_{\rm rf}$
- *Probe the transport properties (expansion in disorder) : diffusive or localized ?*
- *Signature of a "mobility edge" by scanning the rf frequency ?*
- *Compare to numerics !*

M.Pasek, G. Orso, and D. Delande PRL (2017)

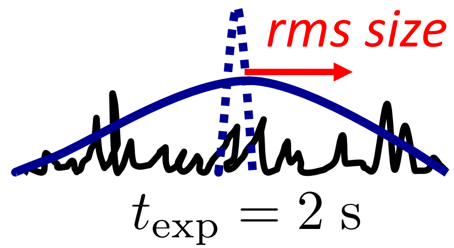
Observation of the mobility edge ?





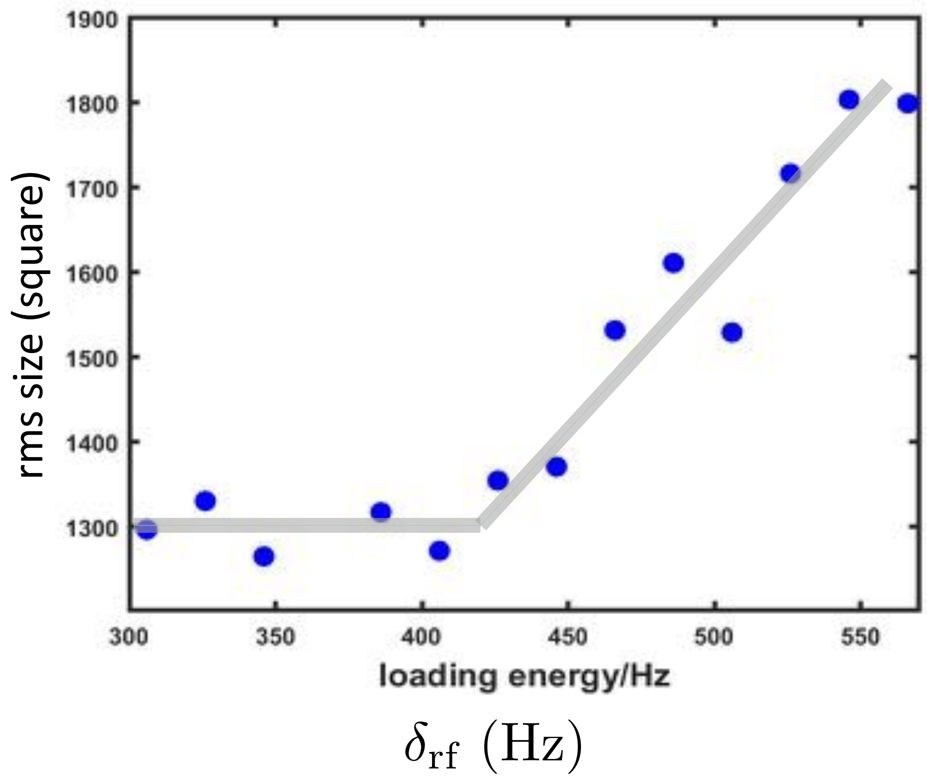
$$V_0 = 832 \text{ Hz}$$

$$\eta = V_0/E_\sigma \sim 2$$

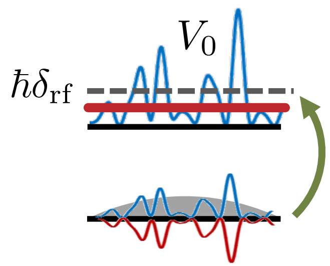


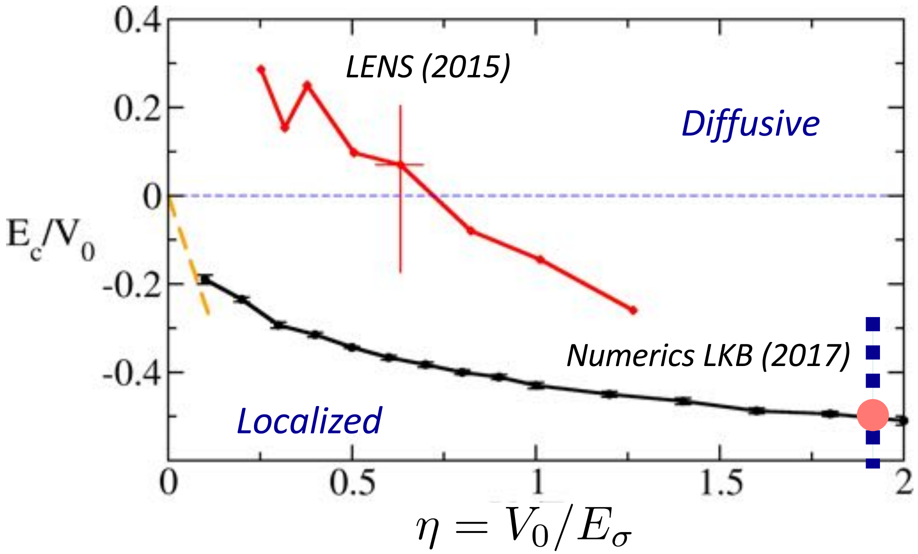
Size of the atomic cloud for a **fixed expansion time (2s)** in disorder

Seems there is a “critical” energy …



Observation of the mobility edge ?





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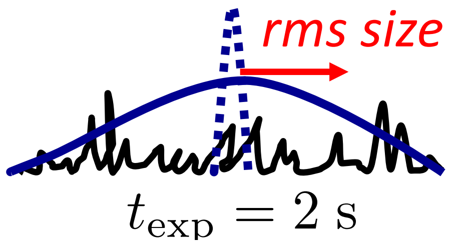
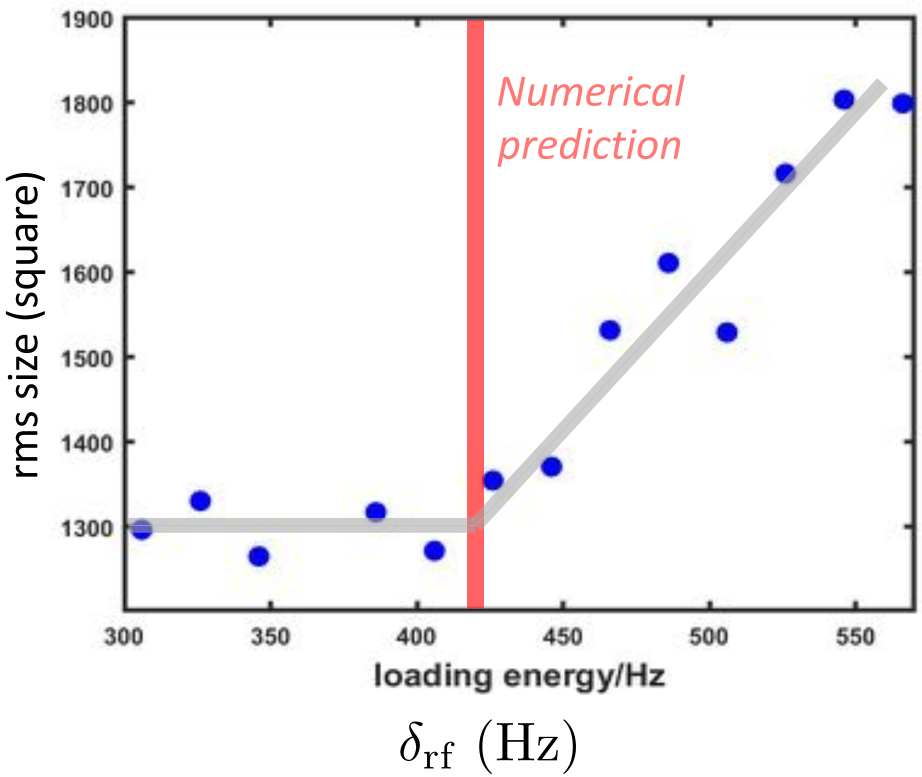


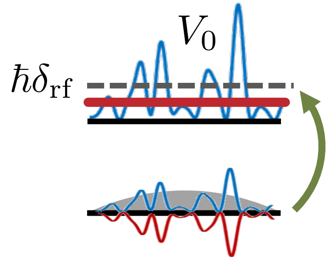
Size of the atomic cloud for a **fixed expansion time (2s)** in disorder

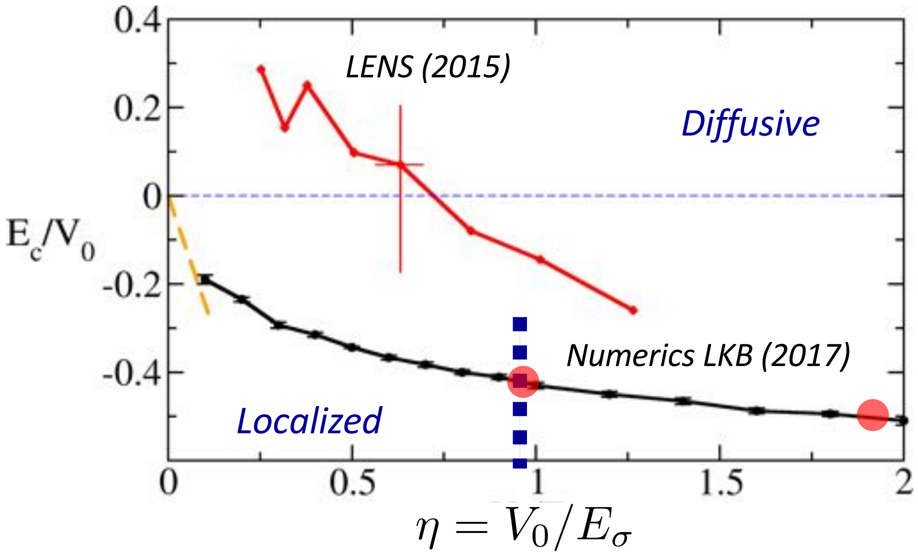
Seems there is a “critical” energy …

… very close to the numerical prediction of the mobility edge !



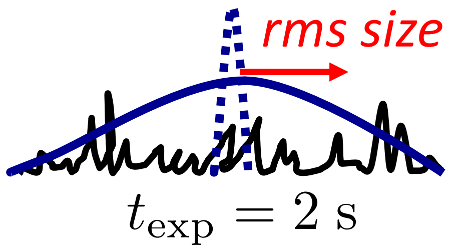
Observation of the mobility edge ?





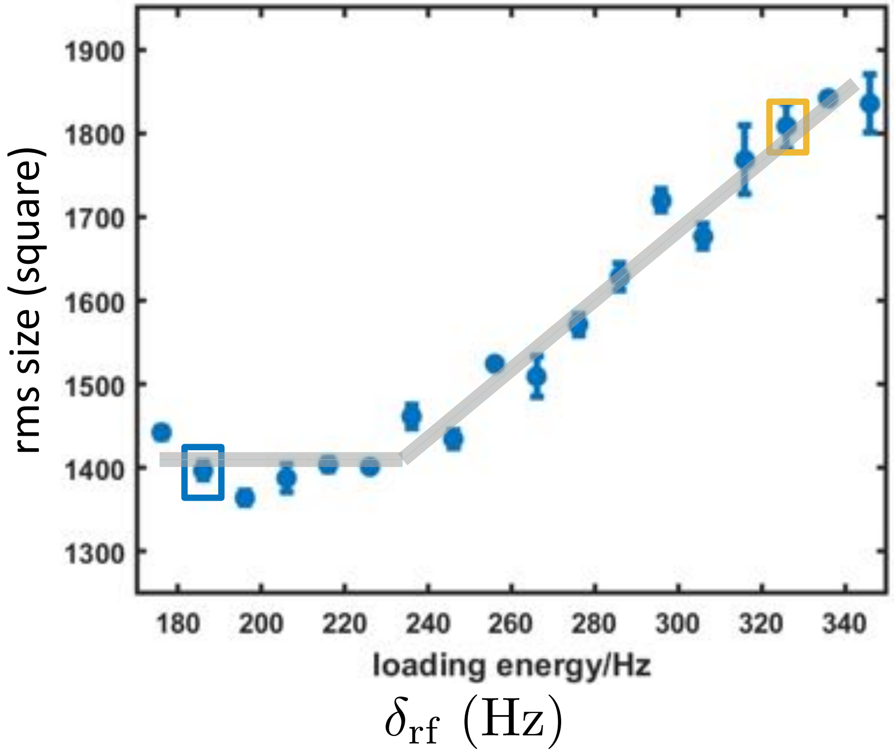
$$V_0 = 416 \text{ Hz}$$

$$\eta = V_0/E_\sigma \sim 1$$

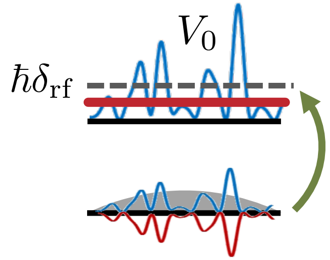


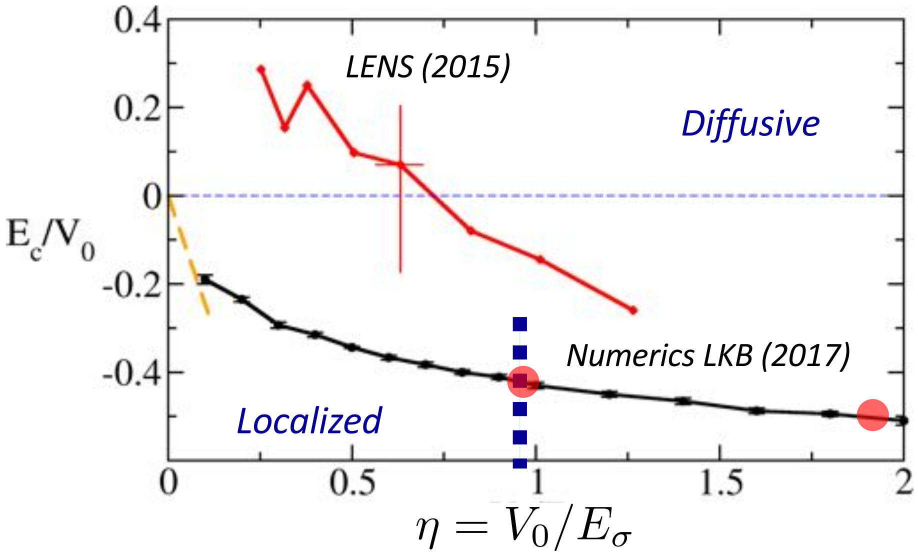
Same happens at lower disorder strength

$$V_0/E_\sigma \sim 1$$



Observation of the mobility edge ?





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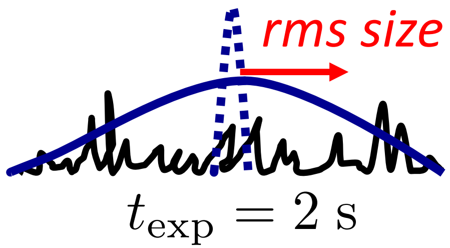
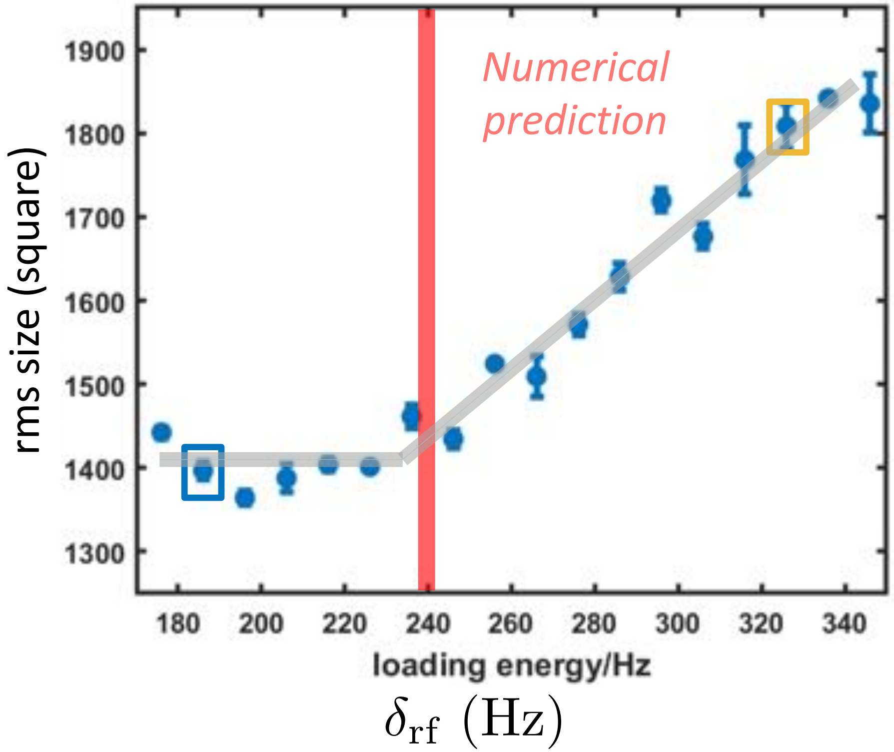
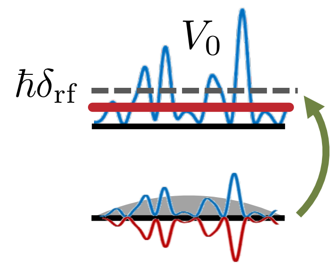


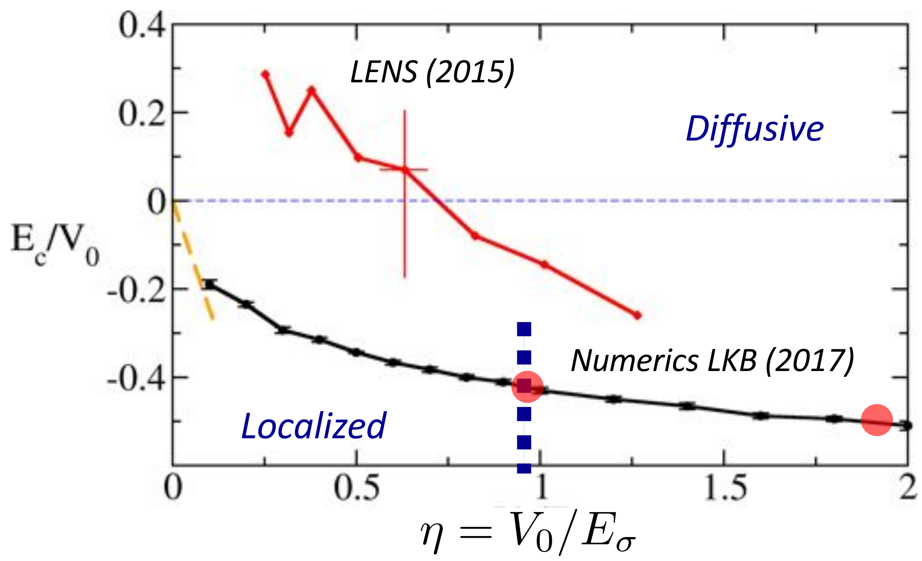
Same happens at lower disorder strength

... Still compatible with numerical predictions of mobility edge !



Observation of the mobility edge ?





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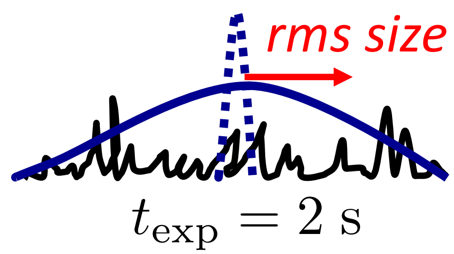
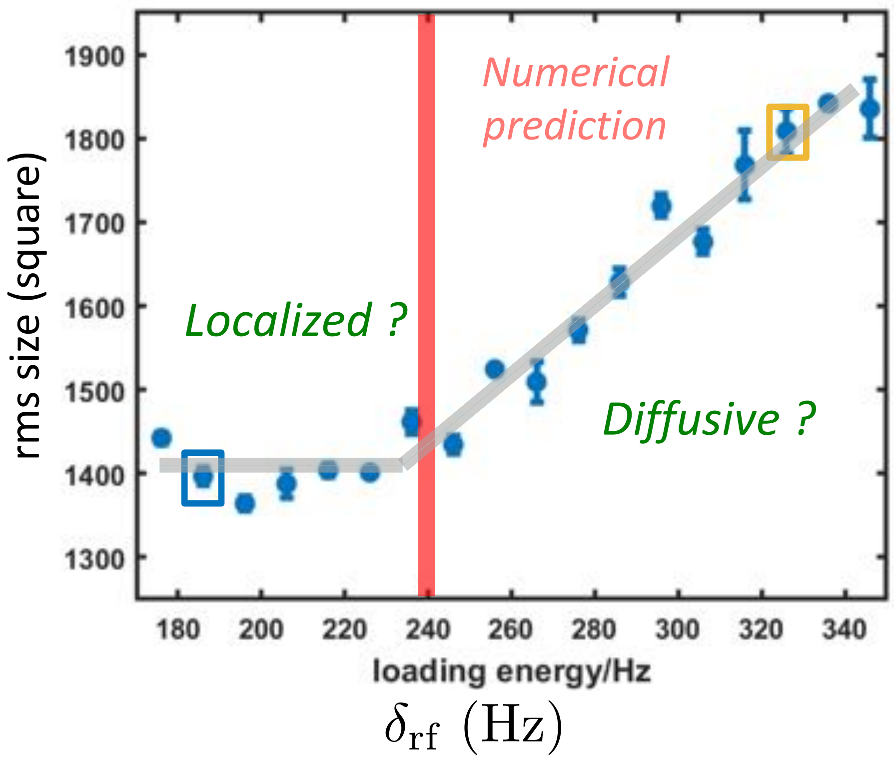




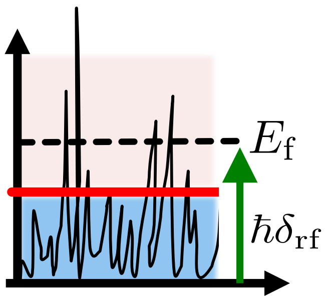
Is it really a mobility edge ?

Localized versus Diffusive behavior ?

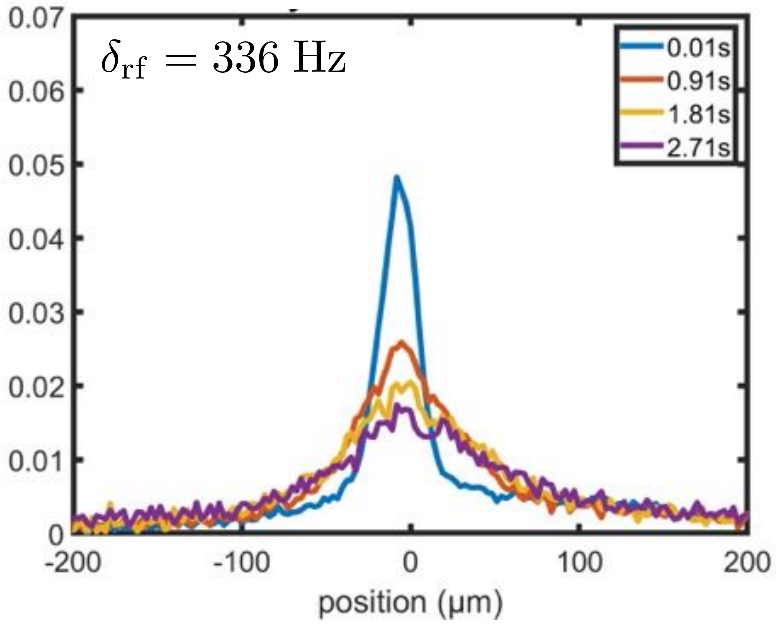
We need to look at the time evolution

Transport properties

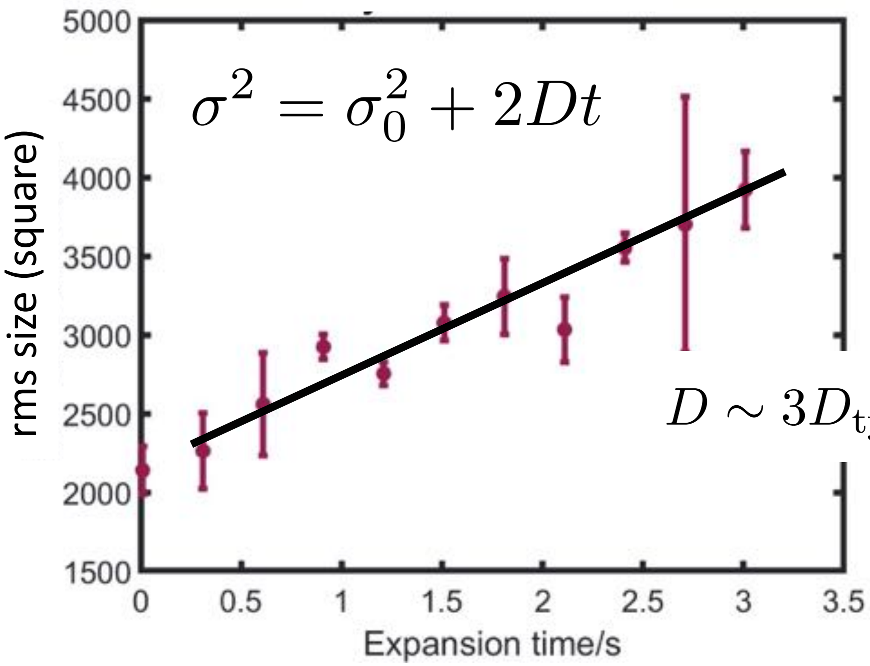
Profiles at different expansion times
"diffusive regime"



$\eta = V_0/E_\sigma \sim 1$



Very slow expansion !



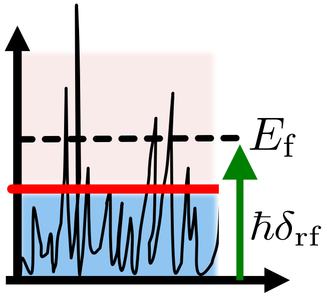
Compatible with very slow diffusion above the mobility edge

$$D \sim 3D_{\mathrm{typ}} = \frac{\hbar}{m} \sim 700\ \mu\mathrm{m}^2/s$$

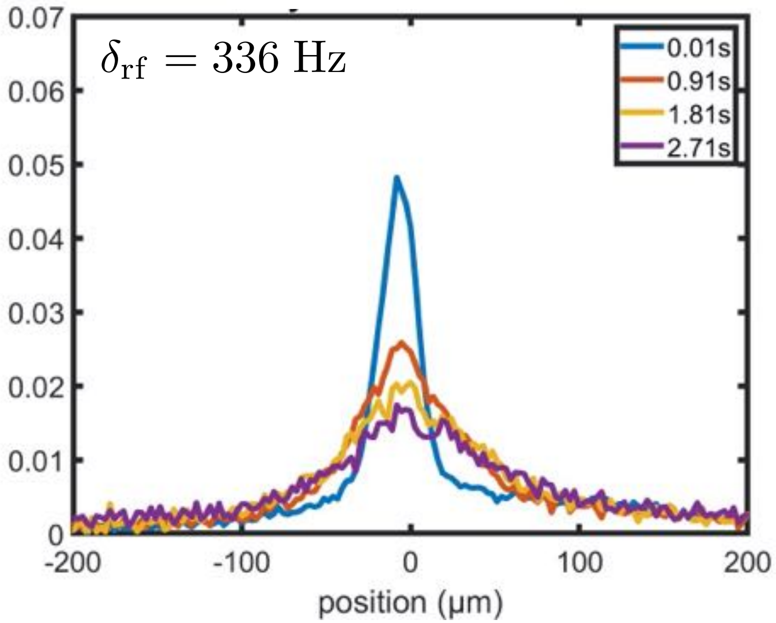
$$kl^\star \sim 3$$

Transport properties

Profiles at different expansion times
"diffusive regime"

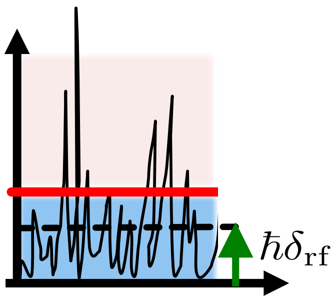


$$\eta = V_0/E_\sigma \sim 1$$

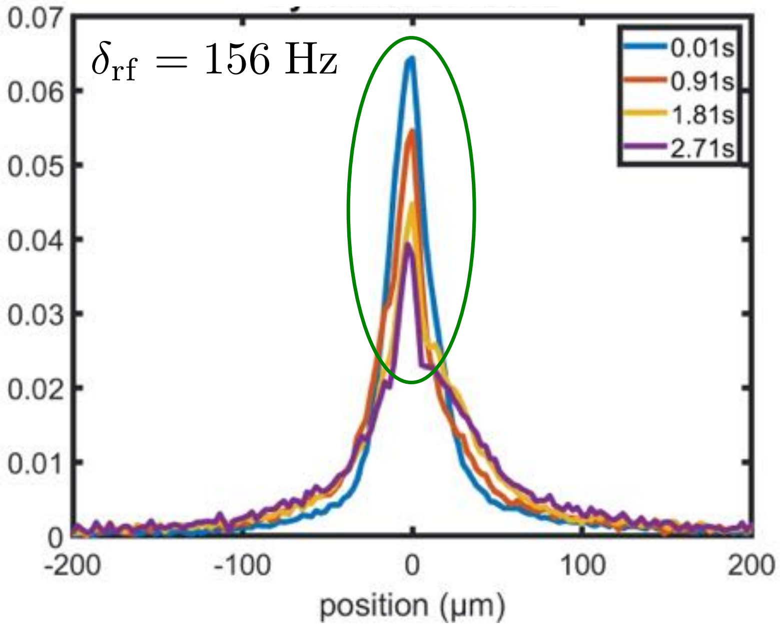


A clear difference between the two regimes ! (especially in the center)

Profiles at different expansion times
"localized regime"

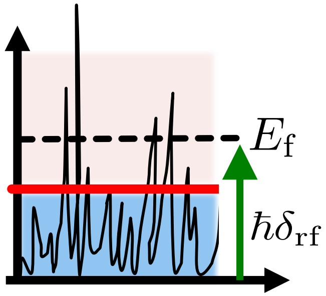


$$\eta = V_0/E_\sigma \sim 1$$



Transport properties

Profiles at different expansion times
"diffusive regime"



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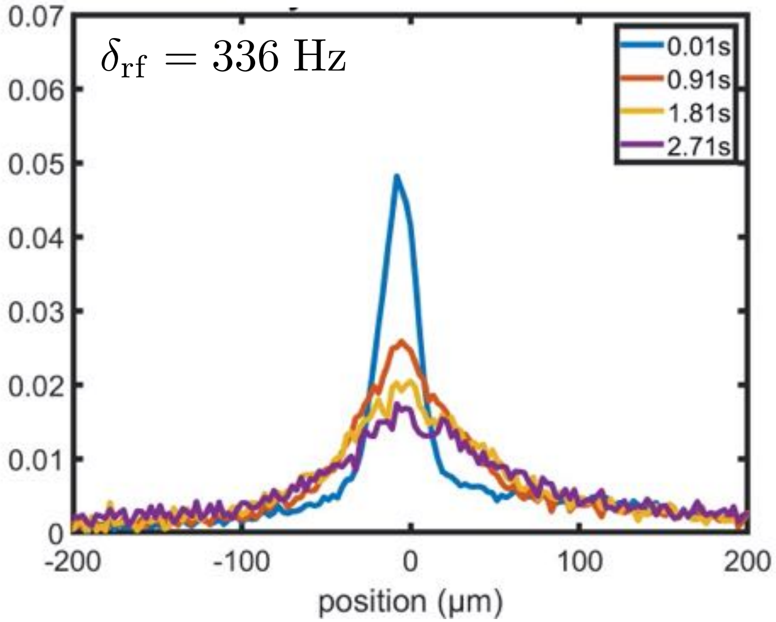
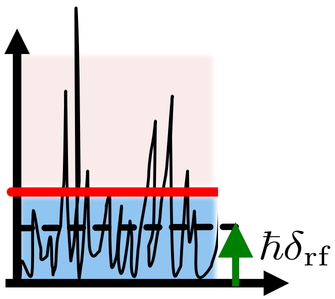
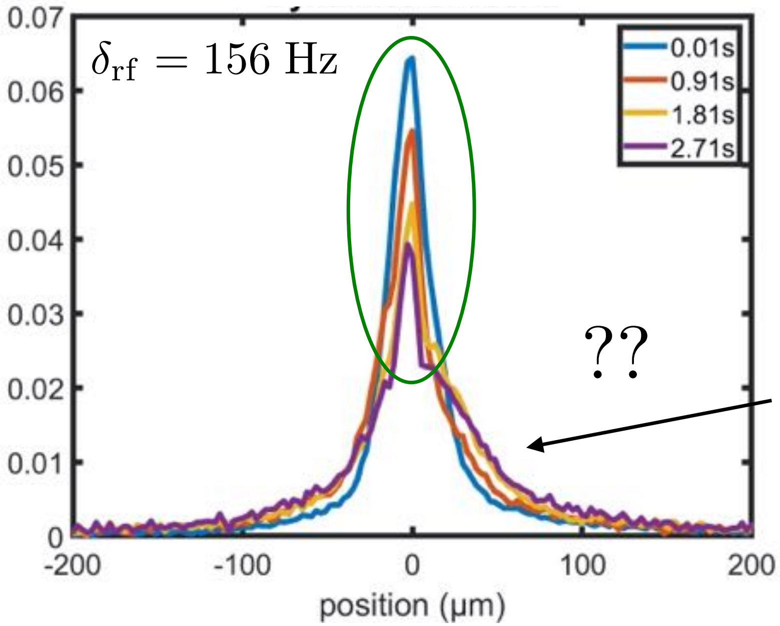


Work in progress !

Profiles at different expansion times
"localized regime"



$\eta = V_0/E_\sigma \sim 1$



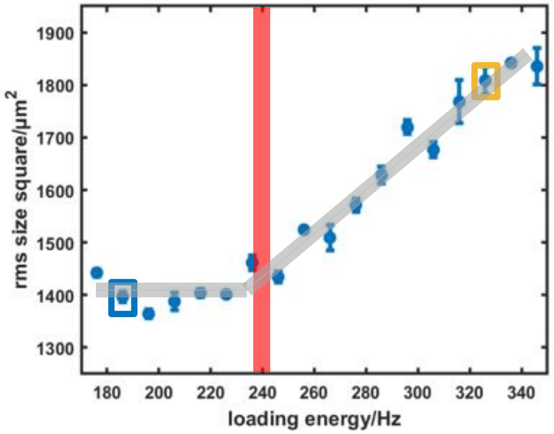
But questions remain : still an expanding part in the "localized" phase.

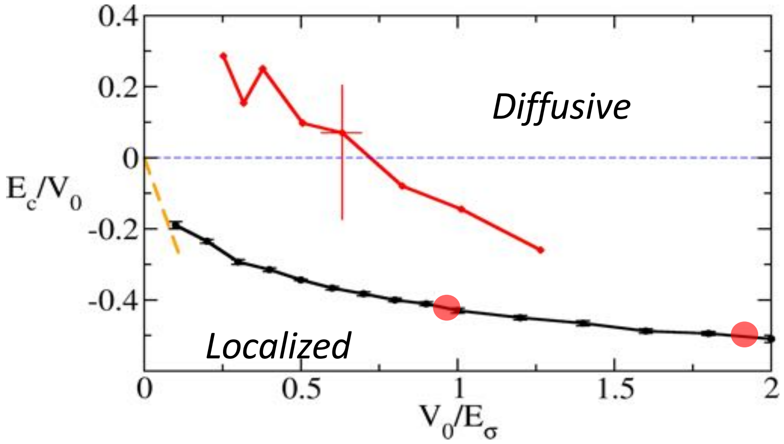
Excitation process due to finite lifetime ?

Conclusion

Evidence of a “critical energy” in 3D disorder for matter waves

In close agreement with numerical estimation of the mobility edge





Only the beginning, work in progress

Solve current issues on transport properties (residual excitations ?)

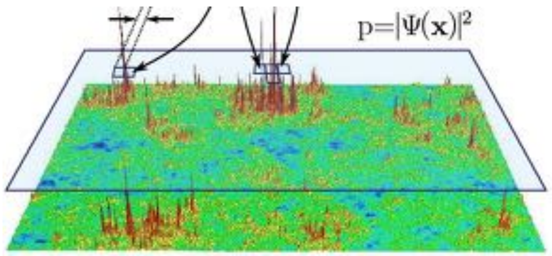
Span from quantum to classical disorder regime

Comparison with the “landscape” theory (M. Filoche & S. Mayroboda)

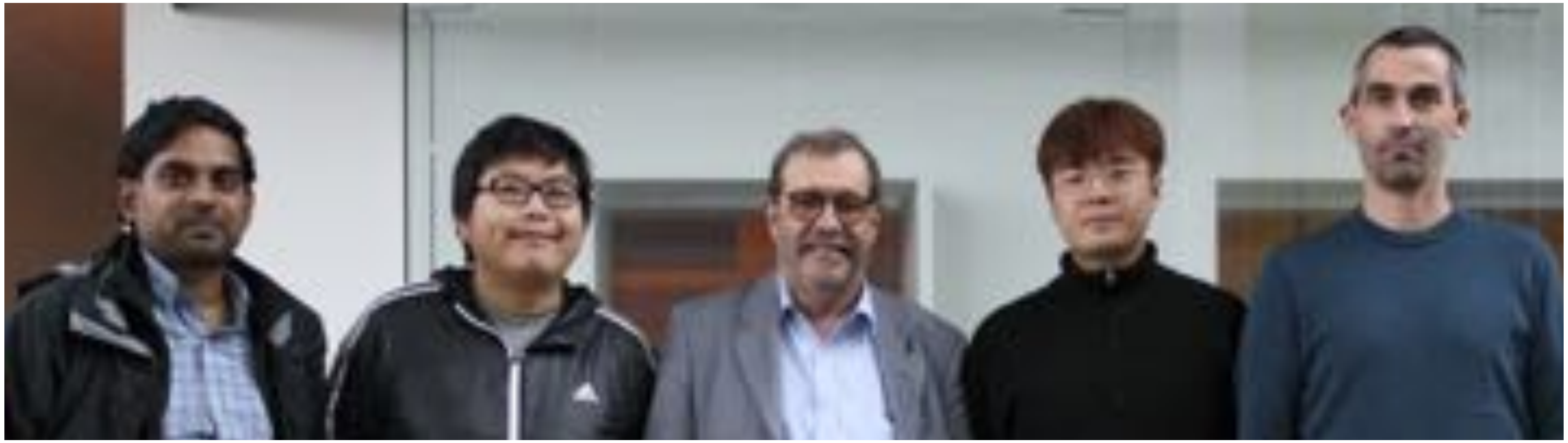
Future : investigation of the critical regime

Critical exponents ?

Observation of multifractality ?



Quantum Transport Team, Institut d'Optique, France



Niranjan Myneni *Xudong Yu* *Alain Aspect* *Yukun Guo* *Vincent Josse*

Baptiste Lecoutre

Poster tomorrow

PhDs
Yukun Guo
Xudong Yu

Post Doc
Niranjan Myneni
Baptiste Lecoutre (ex)

Permanent
Vincent Josse
Alain Aspect

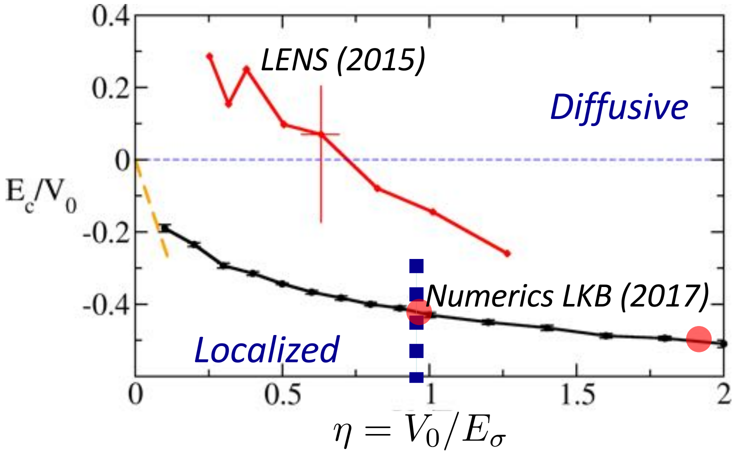
D. Delande, LKB, ENS, Paris

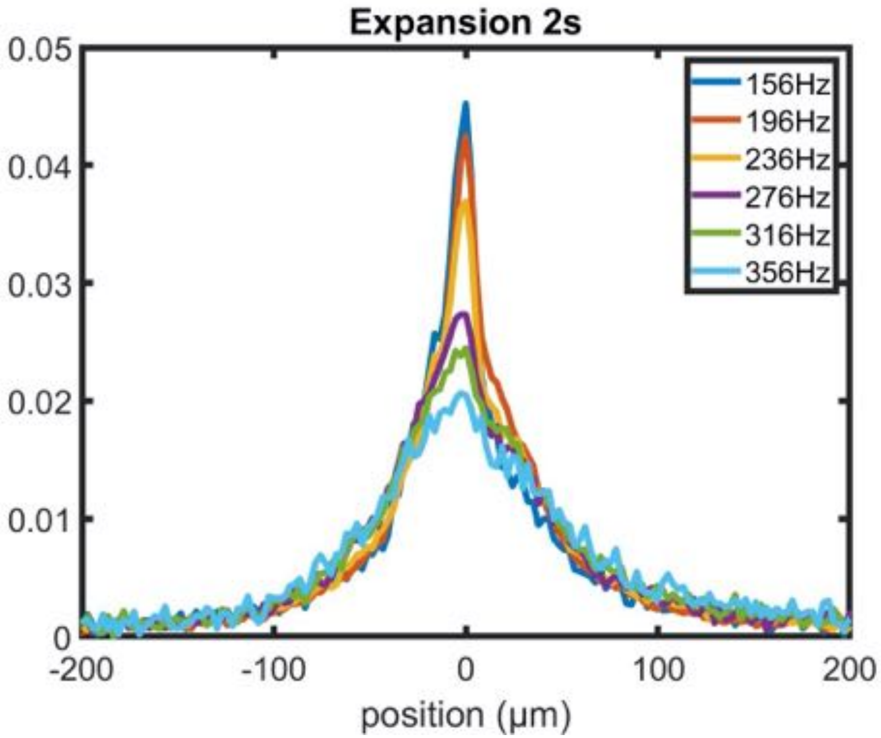
M. Filoche *S. Mayboroda*

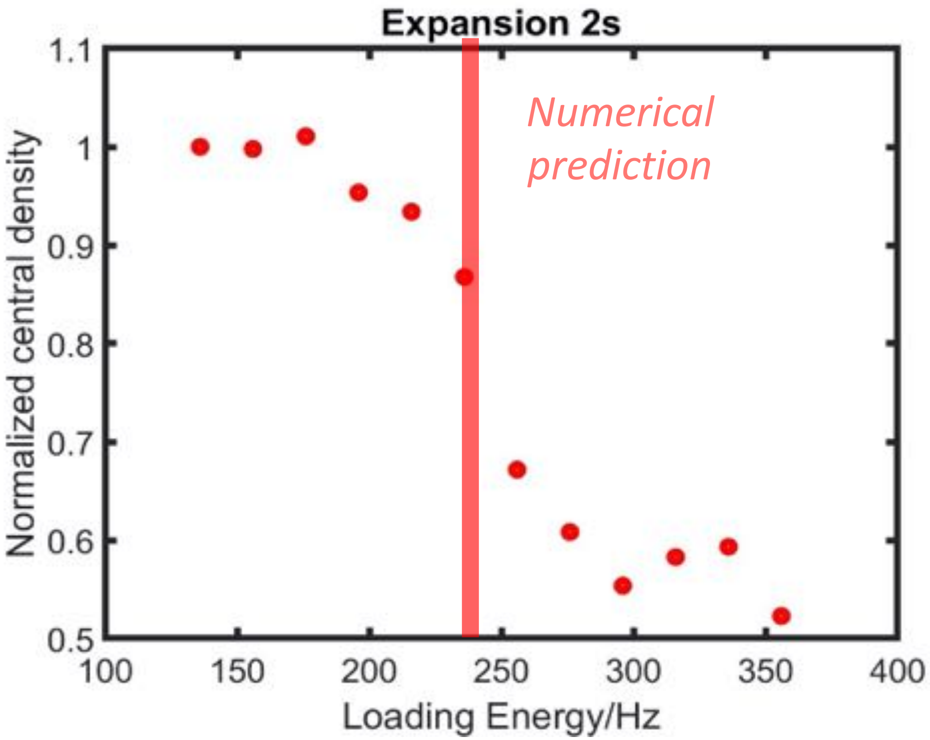
Connexion with the « landscape theory »

SIMONS FOUNDATION

Evidence on the critical energy on the central density

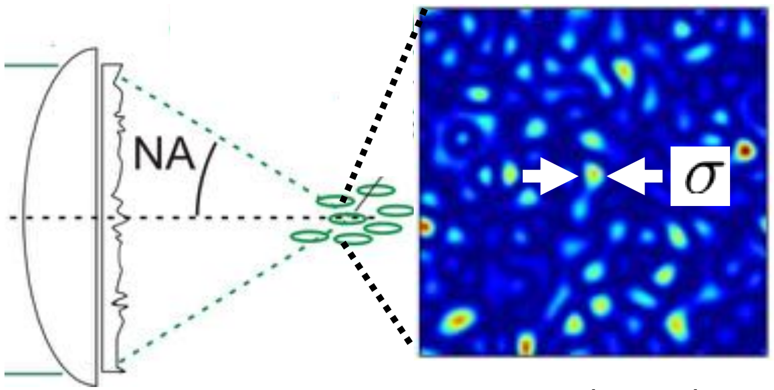




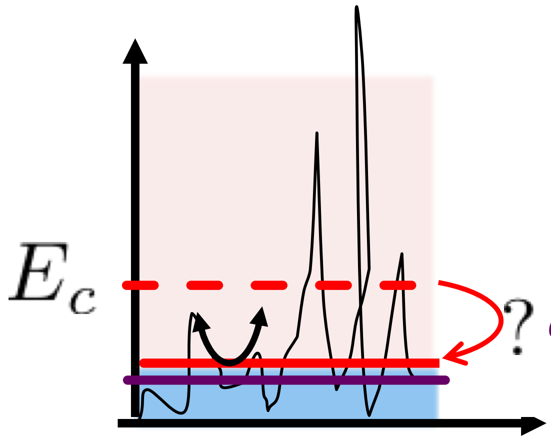


Prospect : « Playing » with the disorder

One example of envisioned study



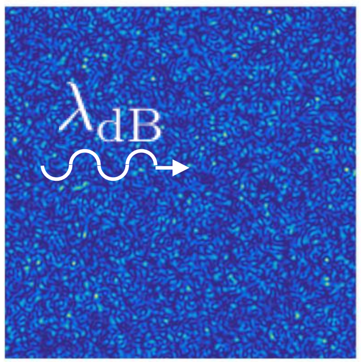
σ *: correlation length tuned by NA*



Mobility Edge
vs
classical percolation

Possibility to control spatial correlation: from "quantum" to "classical" regime

⇨ *Probe the crossover from "genuine" Anderson transition to "classical" percolation*

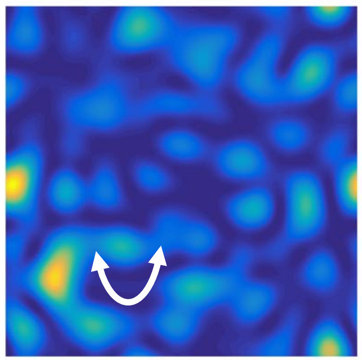


"Quantum" regime
= short correlation

$$\lambda_{\mathrm{dB}} \gg \sigma$$

Important tunneling

Genuine "Anderson" transition



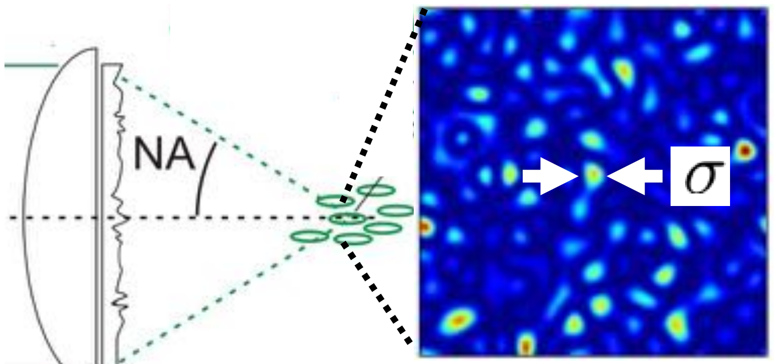
"classical" regime
= long correlation

$$\lambda_{\mathrm{dB}} \ll \sigma$$

Mobility edge moves down towards the classical percolation threshold

Prospect : « Playing » with the disorder

One example of envisioned study



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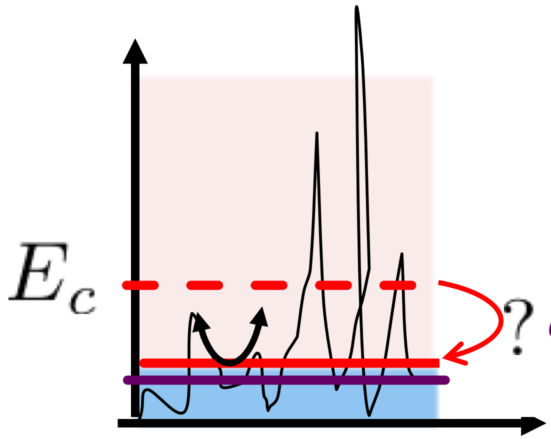

Mobility Edge
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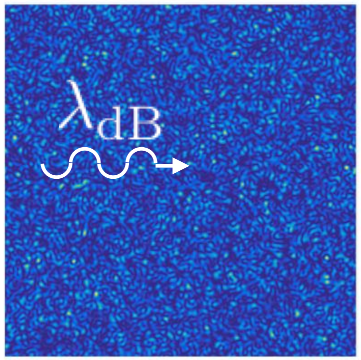

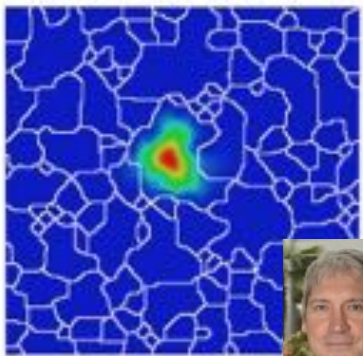

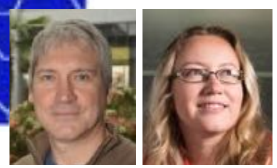

Localization to delocalization transition appears as a percolation process in the "hidden" landscape

PNAS (2012), PRL (2016)

⇨ *Seems a very well adapted theoretical approach*