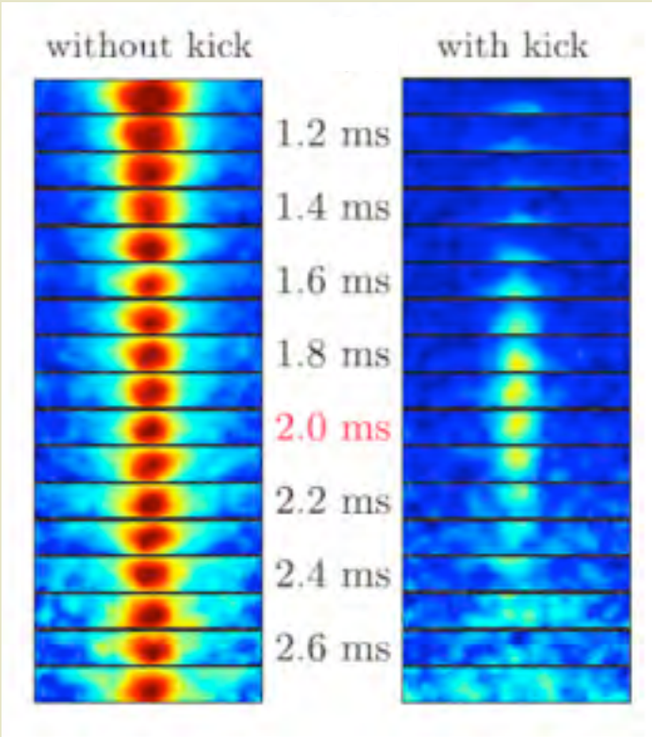
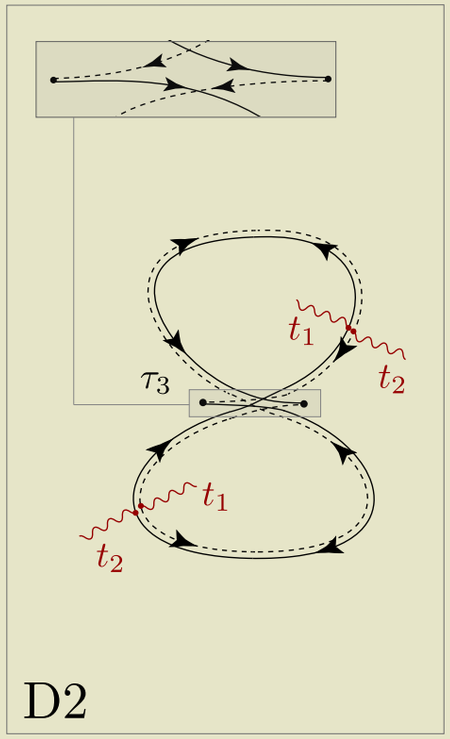
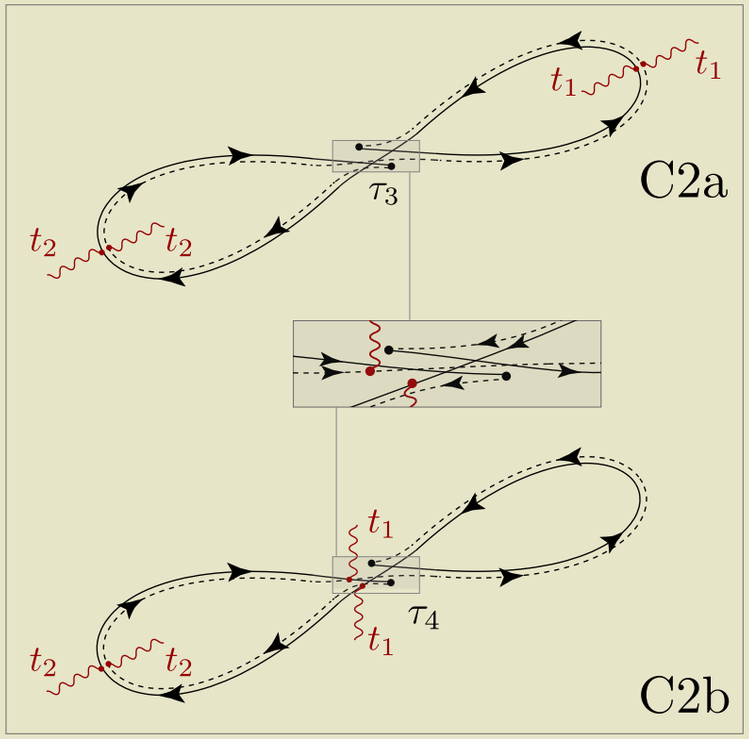
aspects of Anderson Localization with Cold Atoms







Tobias Micklitz

CBPF Centro Brasileiro de Pesquisas Físicas

collaborations: A. Altland, C. Müller (theory)
A. Aspect, V. Josse (experiment)

Motivation

Ultra cold atoms in a laser speckle: a quantum simulator for Anderson localization

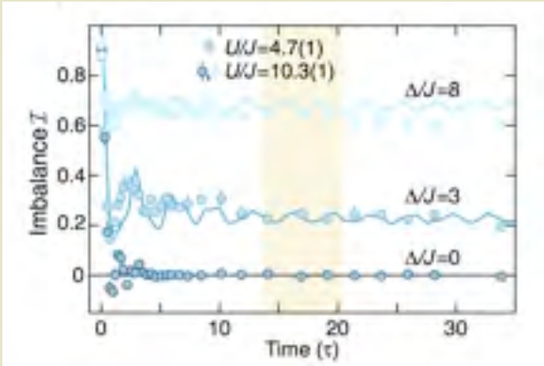
Alain Aspect – Institut d'Optique – Palaiseau

tunable system parameters:

- full control of the trapping potentials (lattice geometry, effective dimensionality), random potentials (disorder), interactions (by Feshbach resonances or density), type of quantum statistics (ultracold bosons or fermions)
- closed system (no coupling to bath, decoherence)

recent examples:

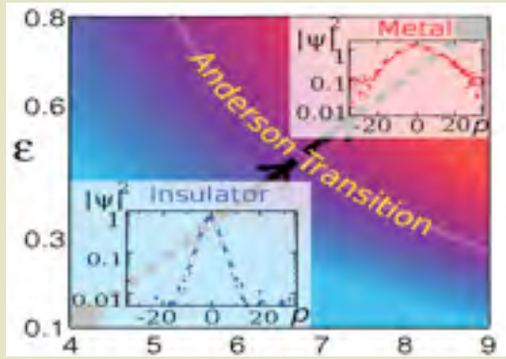
observation of many-body localization?



Observation of many-body localization of interacting fermions in a quasi-random optical lattice

Michael Schreiber, Sean S. Hodgman, Pranjal Bordia, Henrik P. Lüschen, Mark H. Fischer, Ronen Vosk, Ehud Altman, Ulrich Schneider and Immanuel Bloch

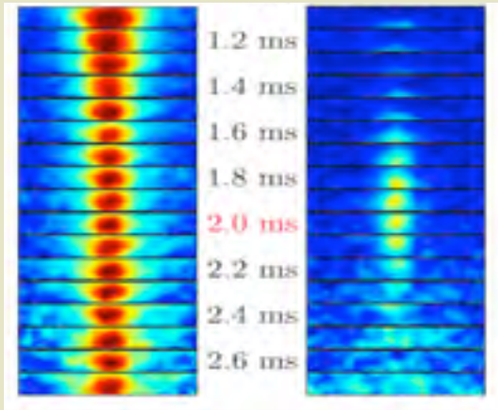
(dynamical) localization transition



PHYSICAL REVIEW LETTERS

Experimental Observation of the Anderson Metal-Insulator Transition with Atomic Matter Waves

weak-localization echo



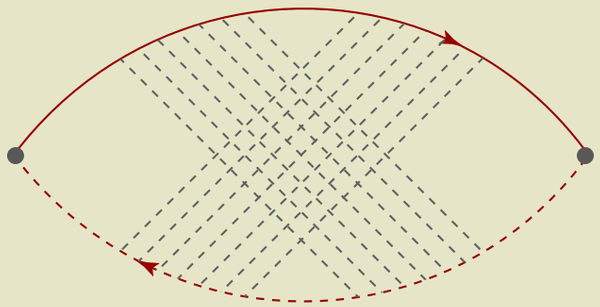
PHYSICAL REVIEW LETTERS

Suppression and Revival of Weak Localization through Control of Time-Reversal Symmetry

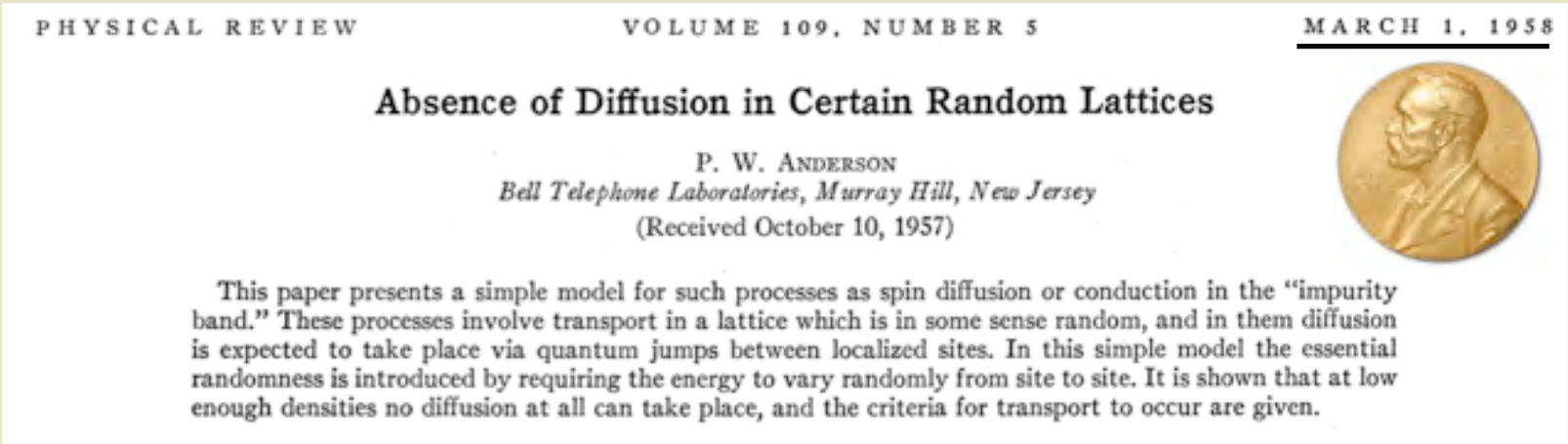
focus here: single-particle physics...

Outline

- introduction Anderson localization (AL)
- quantum quench experiment
- forward scattering peak as a signature of strong AL
- echo-spectroscopy at the onset of AL



Anderson Localization (AL)



PHYSICAL REVIEW VOLUME 109, NUMBER 5 MARCH 1, 1958

Absence of Diffusion in Certain Random Lattices

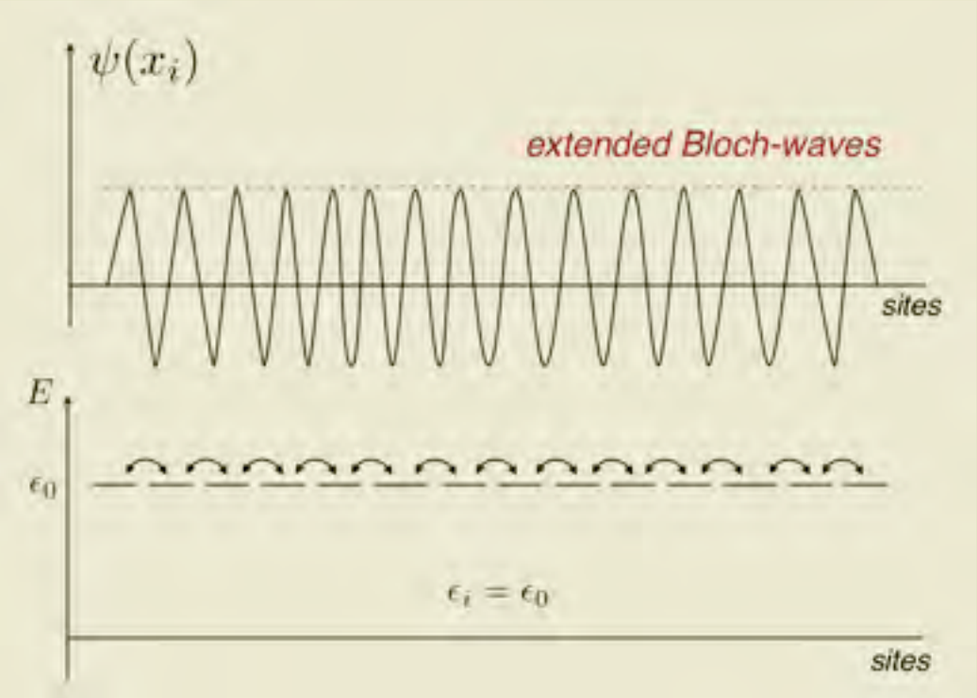
P. W. ANDERSON
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received October 10, 1957)

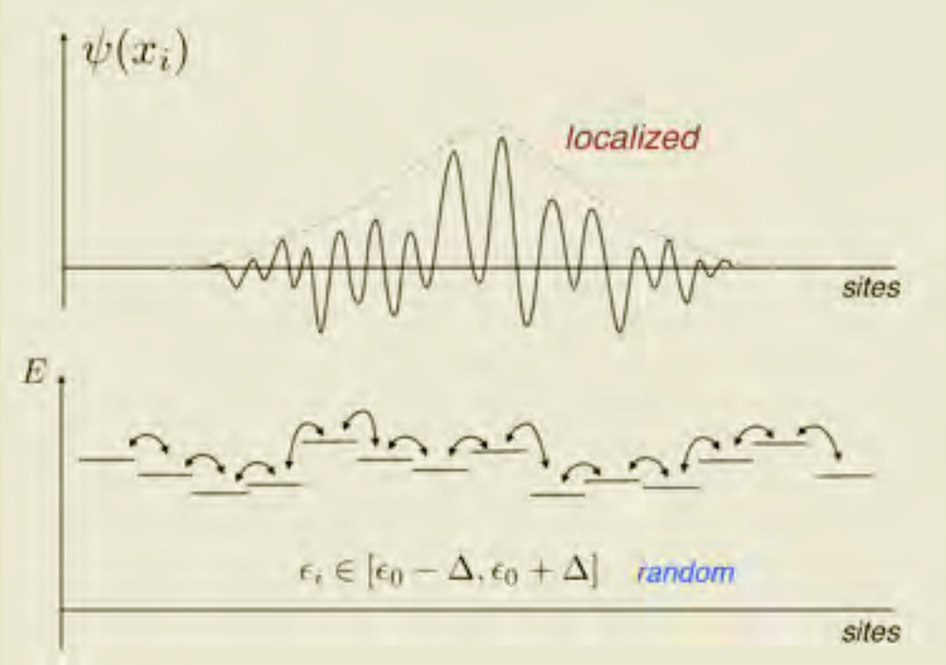
This paper presents a simple model for such processes as spin diffusion or conduction in the "impurity band." These processes involve transport in a lattice which is in some sense random, and in them diffusion is expected to take place via quantum jumps between localized sites. In this simple model the essential randomness is introduced by requiring the energy to vary randomly from site to site. It is shown that at low enough densities no diffusion at all can take place, and the criteria for transport to occur are given.

single-particle wave-function in a (macroscopic) disordered quantum system can be exponentially localized

"Absence of diffusion in certain lattices" (Anderson,1958)

1d example: $H = t\sum_{\langle ij\rangle} c_j^\dagger c_i + \sum_i \epsilon_i c_i^\dagger c_i \quad \epsilon_i \in [\epsilon_0 - \Delta, \epsilon_0 + \Delta]$ (random)





role of dimensionality:

"gang of four" (1979)

Abrahams, Anderson, Licciardello, Ramakrishnan

$$\beta(g) = \frac{d\ln g}{d\ln L}$$

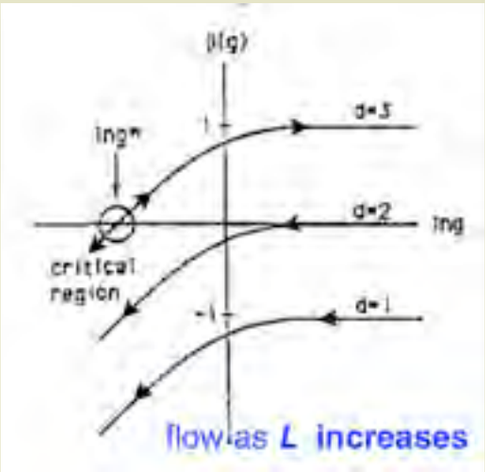
depends only on conductance itself! $g(bL) = f_b(g(L))$

qualitative behavior of β

$g \gg 1$ ohmic: $g \sim L^{d-2} \to \beta(g) = d-2$

$g \ll 1$ insulating: $g \sim e^{-L/\xi} \to \beta(g) = \ln g$

smooth interpolation by monotonic function



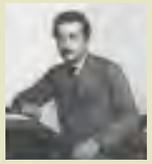
in an infinite system at T=0:

"all states are (Anderson) localized by disorder in *d<3*"

"localization of high-energy/short wave-length waves by random potentials":

different from classical trapping in a random potential...

quantum vs. classical diffusion



classically: random walk

$$\langle r^2\rangle = Dt \quad \text{(Markovian process)}$$

quantum mechanically: interference

$$\langle r^2\rangle \underset{t\to\infty}{\longrightarrow} \text{const.} \quad \text{(system has memory)}$$

*...a **quantum interference phenomenon!***

microscopic origin: the onset of localization

"What is the probability to propagate from *A* to *B* ?"

Semiclassical limit $S_\gamma/\hbar \gg 1$

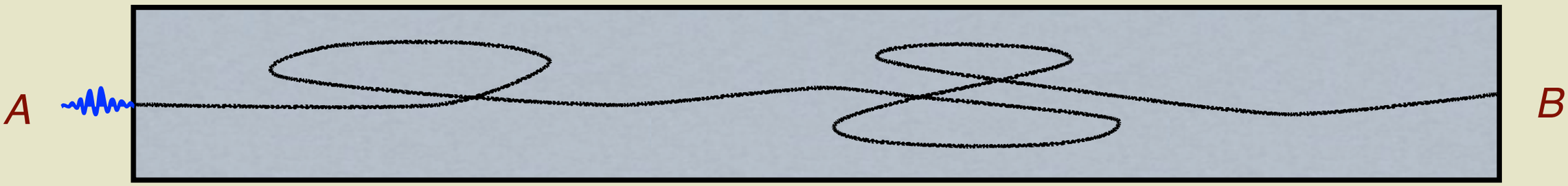
$$P_{A\to B} \simeq \sum_\gamma \Big| \underbrace{A_\gamma}_{\text{(classical diffusion)}} \overset{\text{classical paths}}{} \Big|^2 + \sum_{\gamma\gamma'} \Big(\underbrace{A_\gamma A^*_{\gamma'}}_{\text{(quantum interference)}} \overset{\text{different classical paths with same action}}{} \Big)$$

Q: What are the relevant classical paths giving rise to quantum-interference corrections?

A: self-intersecting paths, which exactly depends on the symmetries of the system...

microscopic origin: the onset of localization

self-intersecting paths



role of symmetries:

symmetries/class: $\sum_{\gamma\gamma'} \left(A_\gamma A^*_{\gamma'} \right)$ *different classical paths with same action*

orthogonal (O)

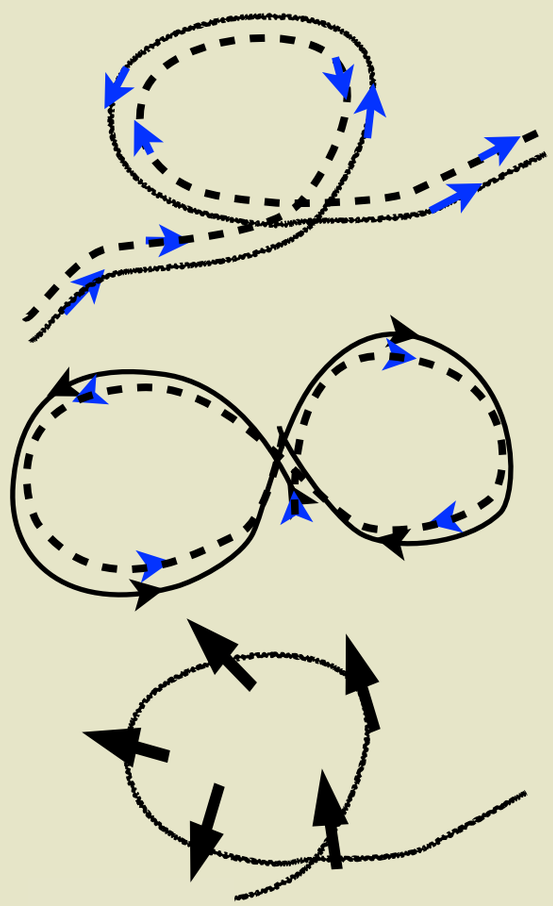
time-reversal	spin-rotational
yes	yes

unitary (U)

time-reversal	spin-rotational
no	yes

symplectic (Sp)

time-reversal	spin-rotational
yes	no

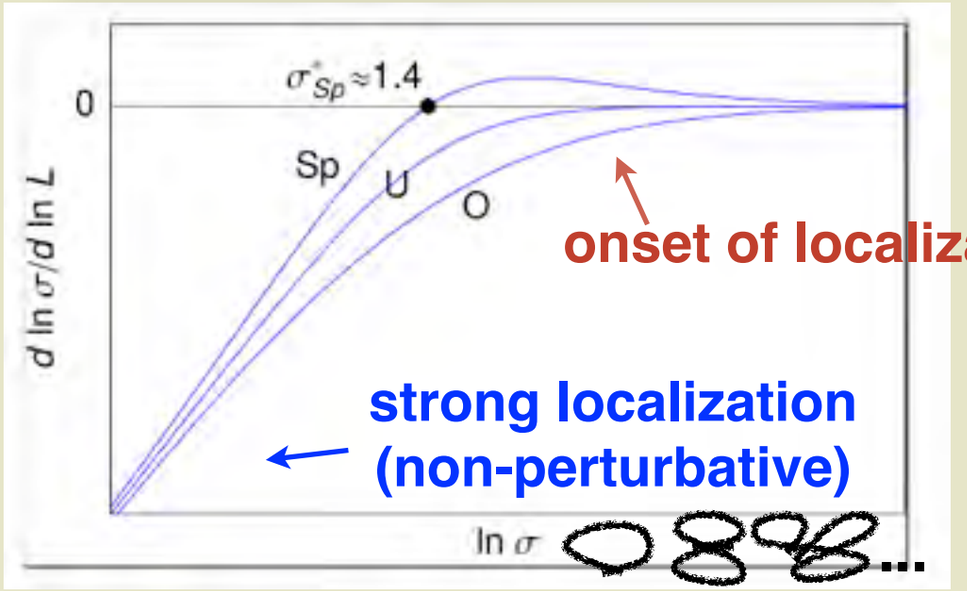


perturbative RG *d=2+*ϵ:

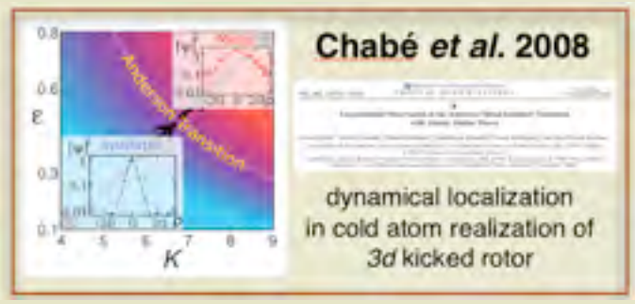
$$\beta(t) = \epsilon - t - \frac{3}{4}\zeta(3)t^4 + \mathcal{O}(t^5) \quad \text{(O)}$$

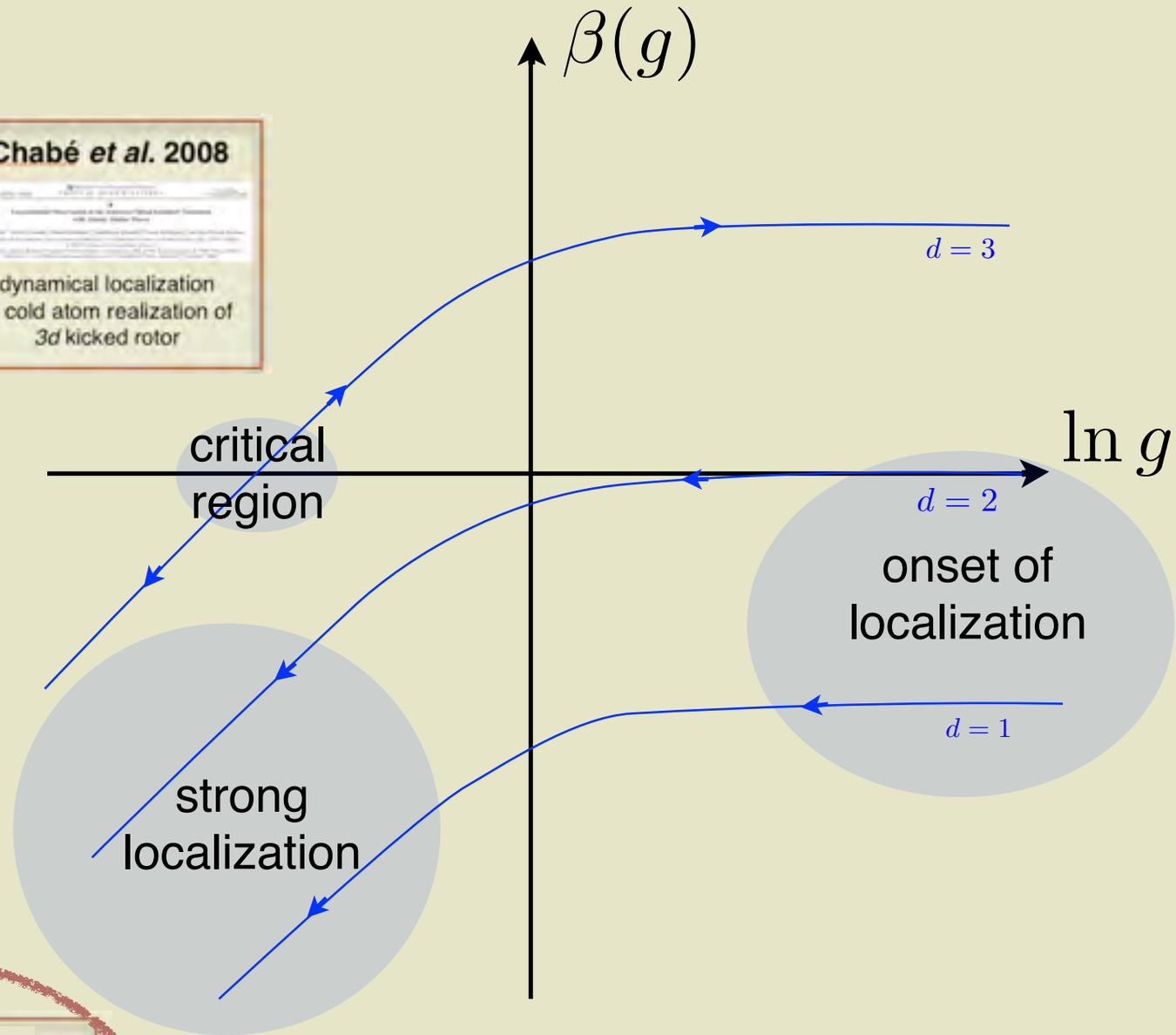
$$\beta(t) = \epsilon - \frac{1}{2}t^2 - \frac{3}{8}t^4 + \mathcal{O}(t^6) \quad \text{(U)}$$

$$\beta(t) = \epsilon + t - \frac{3}{4}\zeta(3)t^4 + \mathcal{O}(t^5) \quad \text{(Sp)}$$

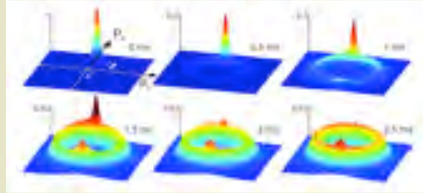


some recent cold atom experiments

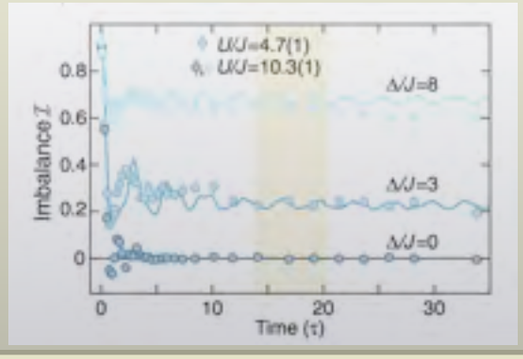




Josse/Aspect (2012)
coherent backscattering

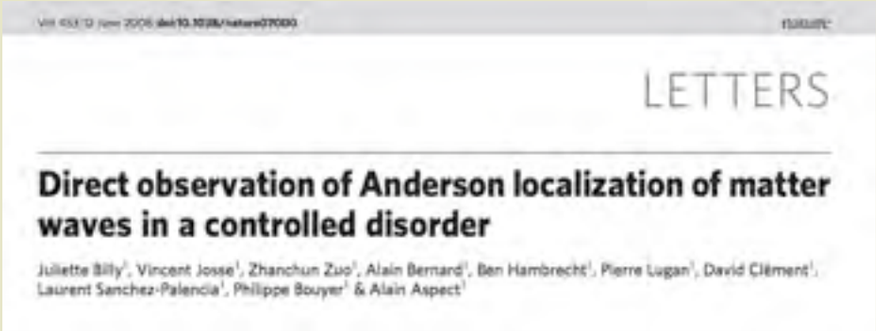


tunable interactions
Bloch (2015)



1d exponential localization of atomic matter wave

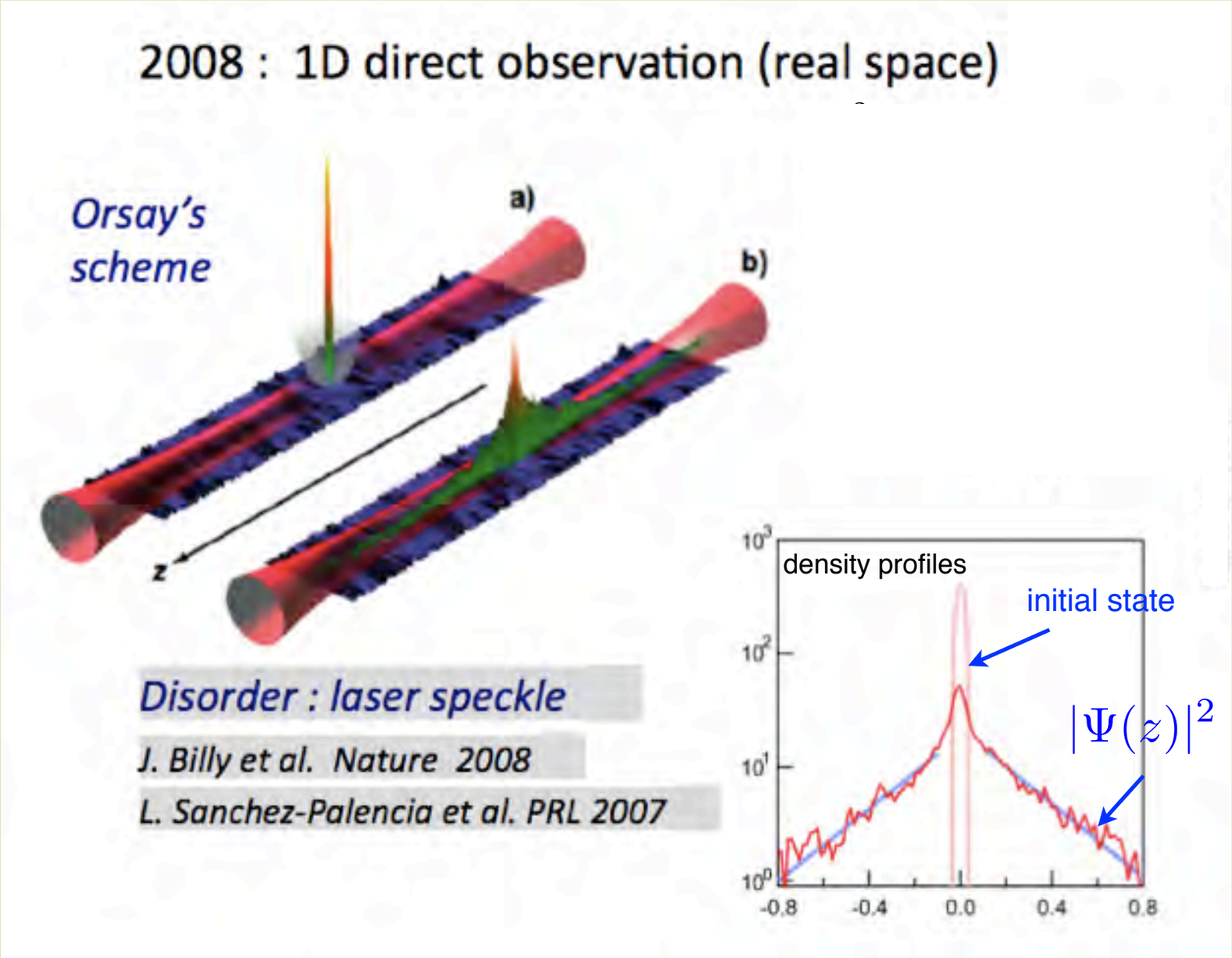
(direct observation of wave-function)


LETTERS

Direct observation of Anderson localization of matter waves in a controlled disorder

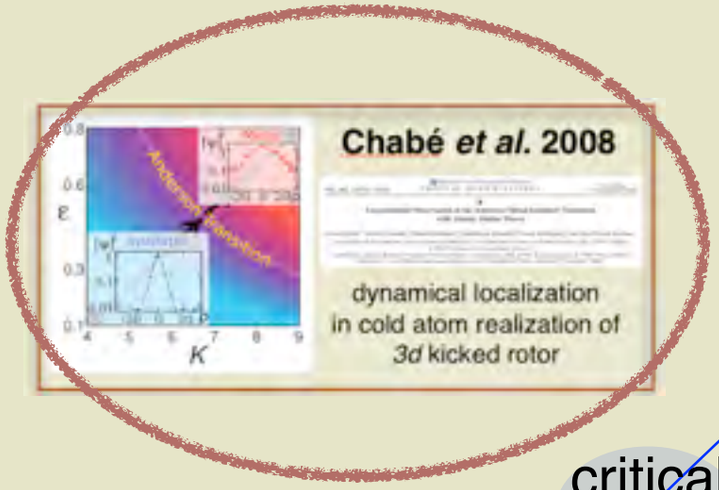
Juliette Billy[1], Vincent Josse[1], Zhanchun Zuo[1], Alain Bernard[1], Ben Hambrecht[1], Pierre Lugan[1], David Clément[1], Laurent Sanchez-Palencia[1], Philippe Bouyer[1] & Alain Aspect[1]

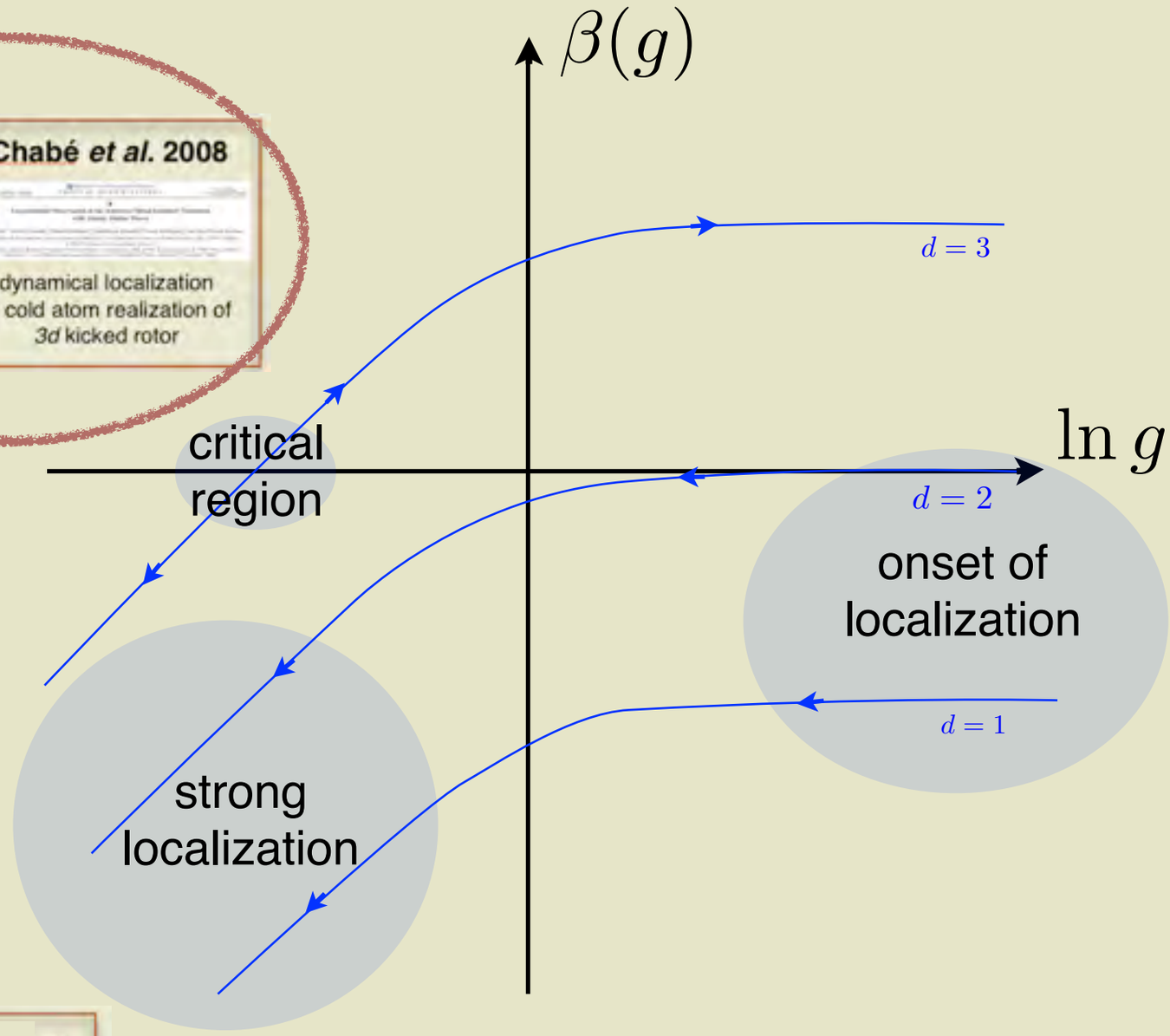
cold atoms released into *1d* wave-guide in presence of disorder



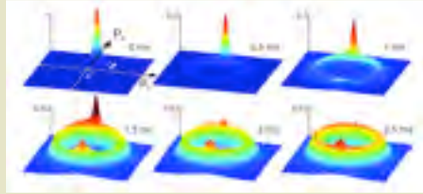
$$|\Psi(z)|^2 \sim e^{-2|z|/\xi_{\rm loc}}$$

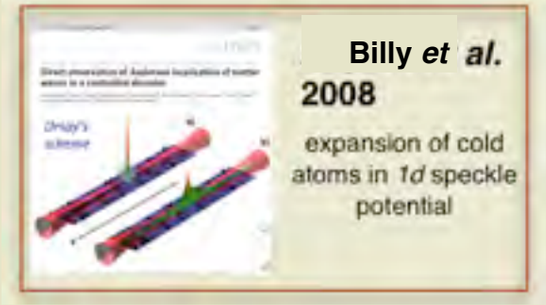
some recent cold atom experiments



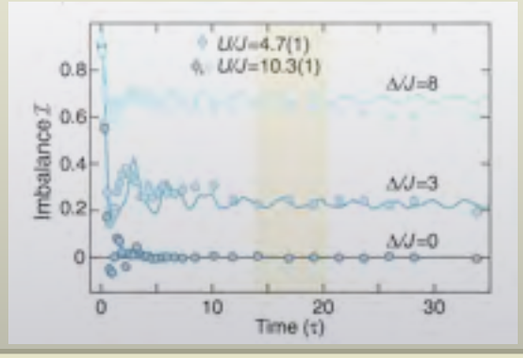


Josse/Aspect (2012)
coherent backscattering





tunable interactions
Bloch (2015)



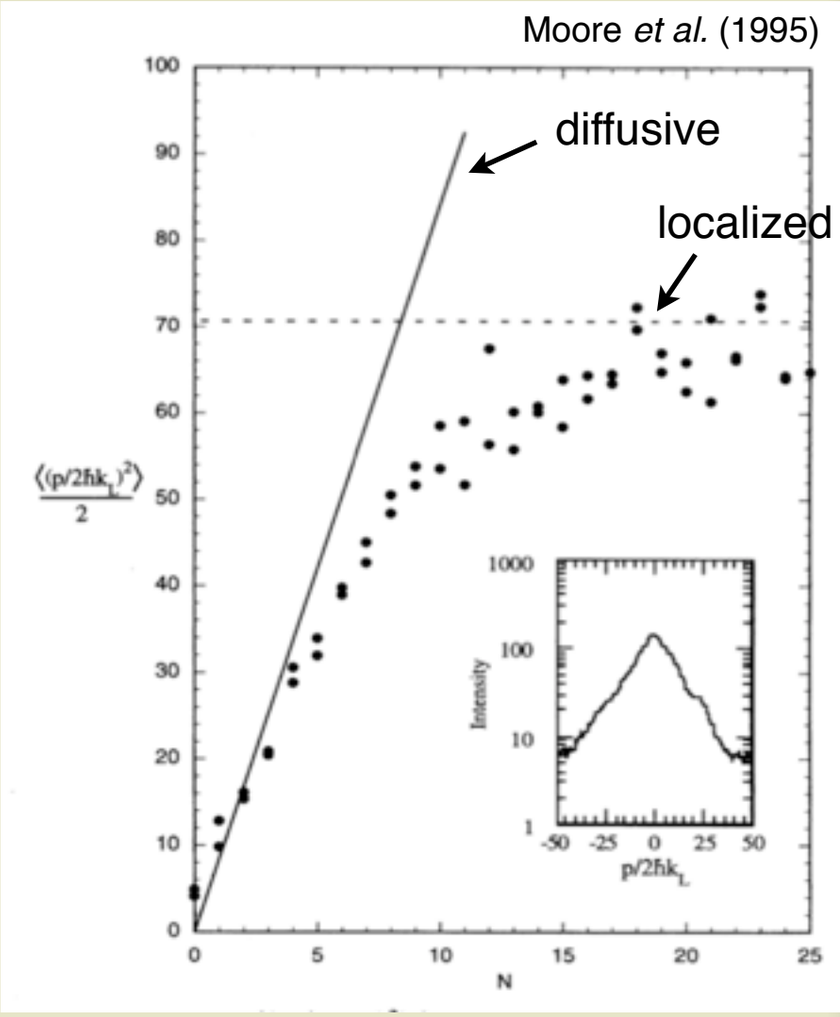
3d AL-transition in cold atom realization of kicked rotor

$$\hat{H} = \frac{\hat{p}^2}{2} + K\cos\hat{x}\,[1 + \epsilon\cos(\omega_2 t)\cos(\omega_3 t)]\sum_n \delta(t-n)$$

quasi-periodic kicked rotor

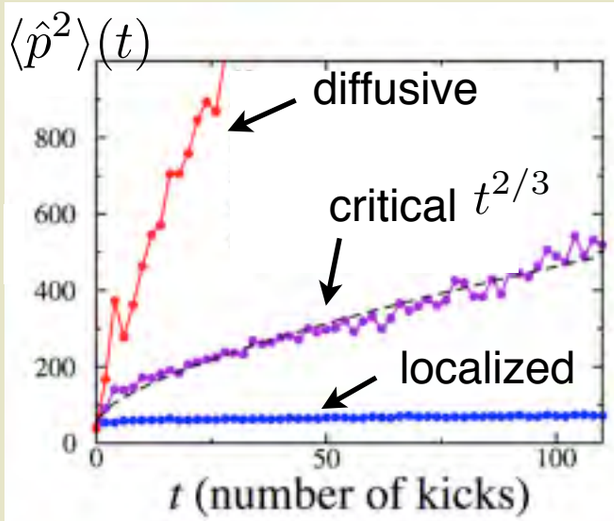
$\epsilon = 0$ equivalent to ***1d* disordered** system

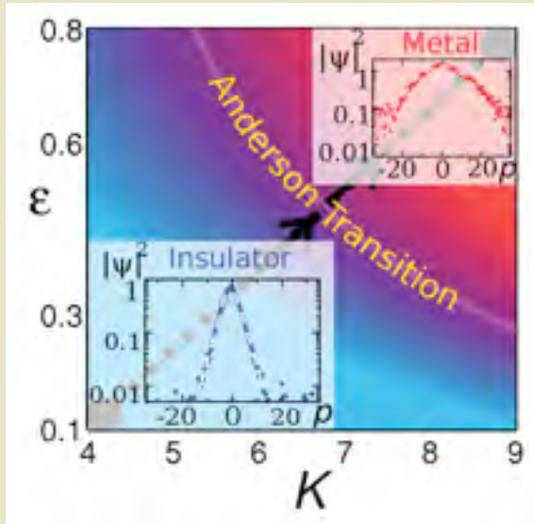
Moore *et al.* (1995)



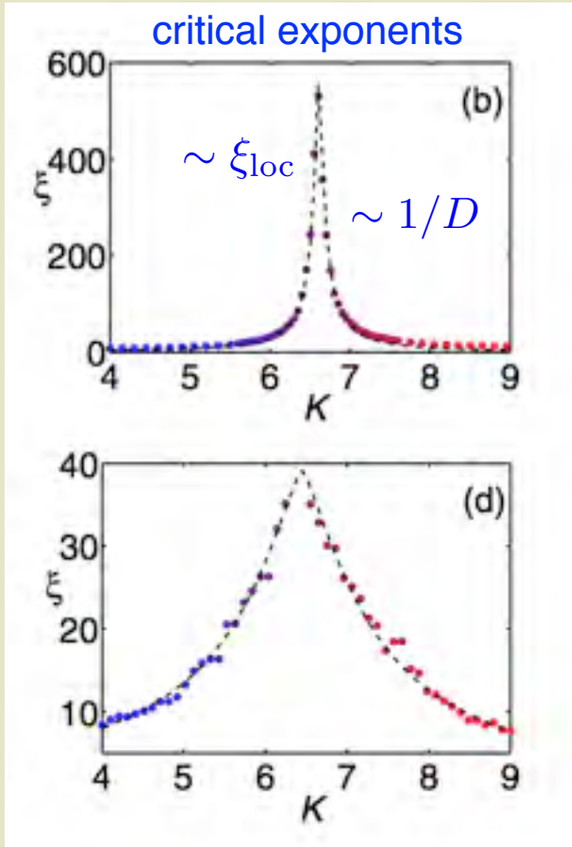
(dynamical) localization in momentum-space

$\epsilon \neq 0$ equivalent to ***3d* disordered** system





Chabé *et al.* (2008)



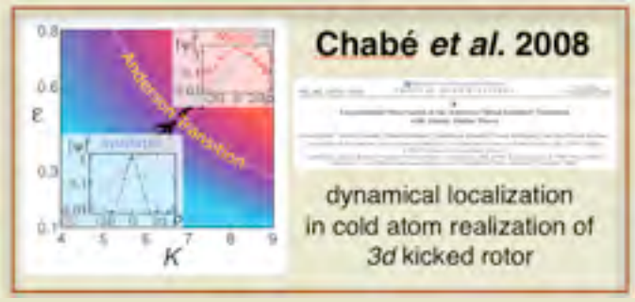
$$\xi \sim |K - K_c|^{-\nu}$$

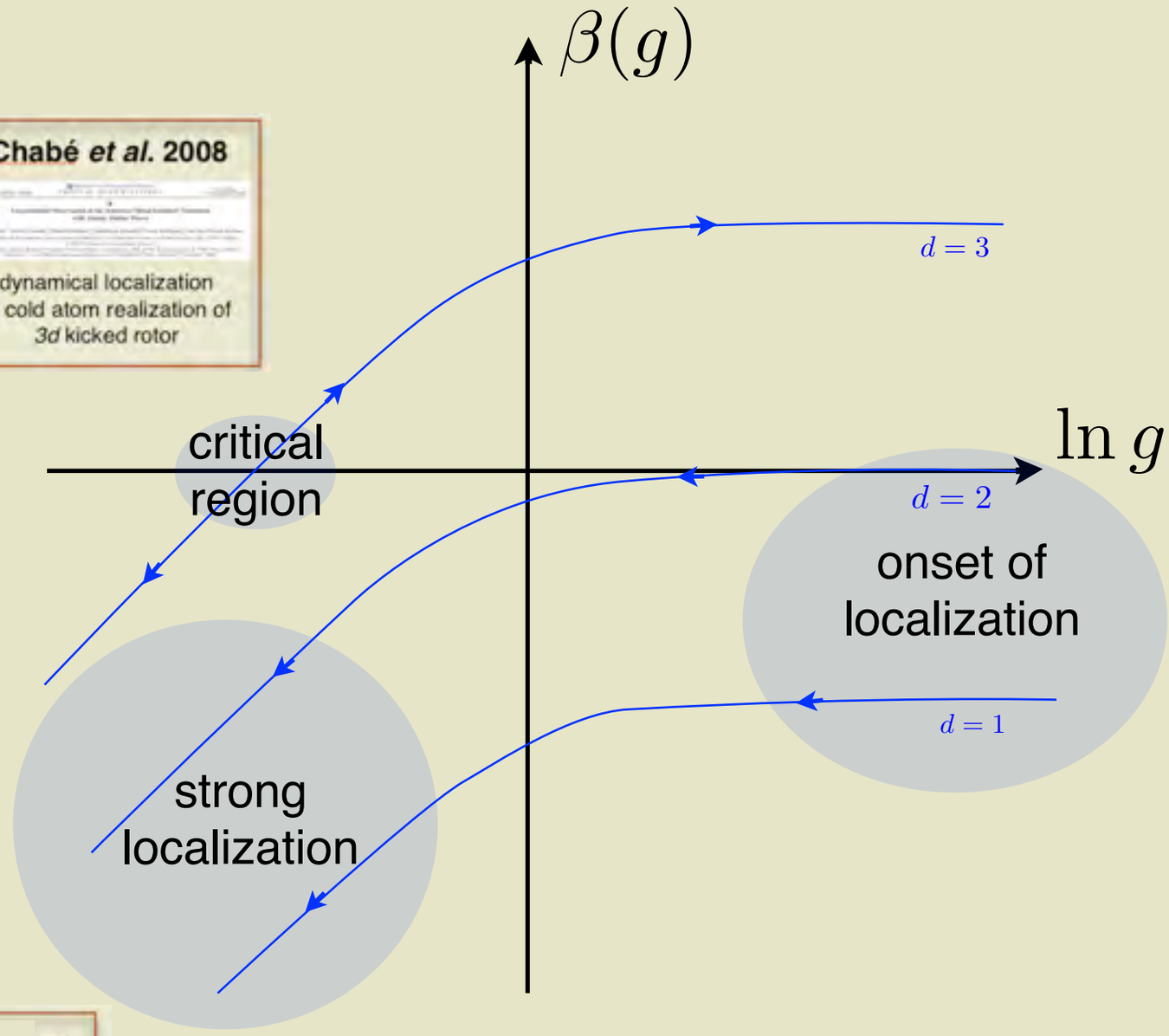
$\nu = 1.60$ (theory)

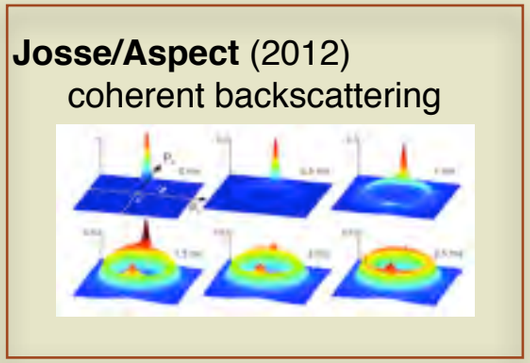
$\nu = 1.4 \pm 0.3$ (experiment)

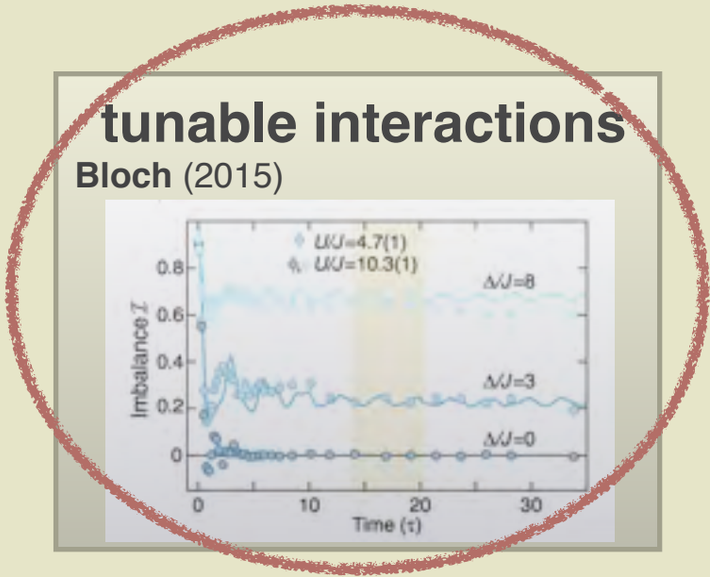
see also Lemaríe *et al.* (2010)

some recent cold atom experiments









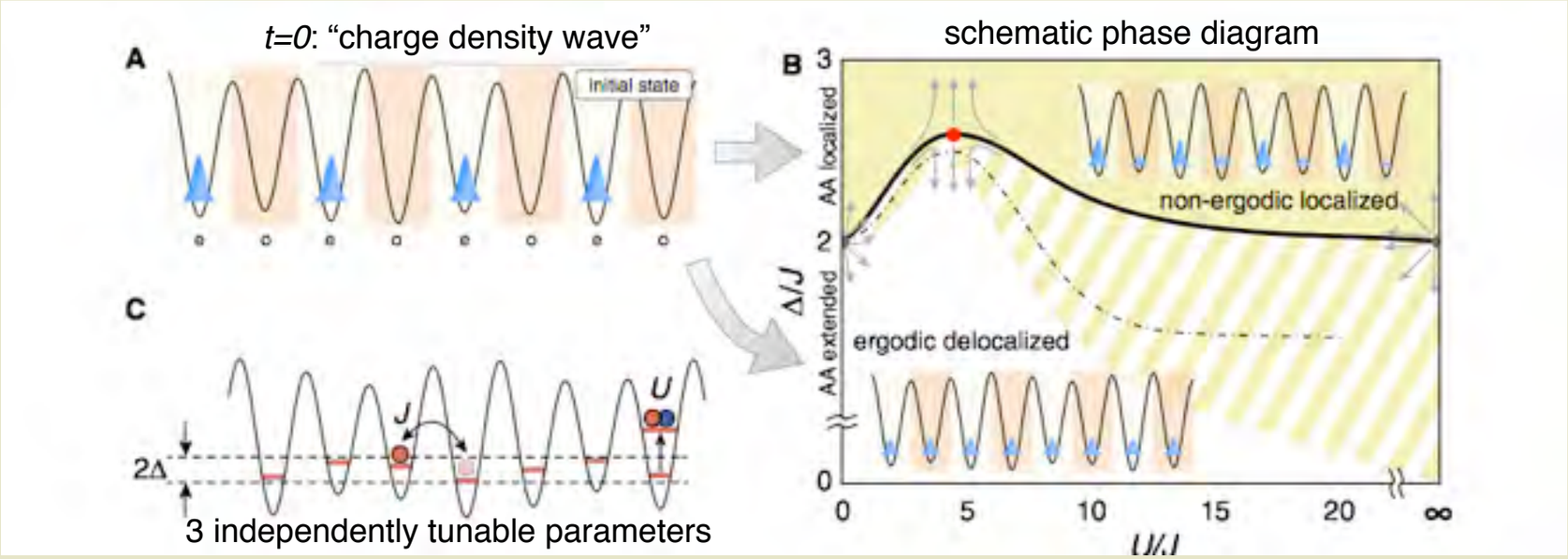
many-body localization of interacting atoms in quasi-random potential?

Observation of many-body localization of interacting fermions in a quasi-random optical lattice

Michael Schreiber[1,2], Sean S. Hodgman[1,2], Pranjal Bordia[1,2], Henrik P. Lüschen[1,2], Mark H. Fischer[3], Ronen Vosk[3], Ehud Altman[3], Ulrich Schneider[1,2] and Immanuel Bloch[1,2]
[1]Fakultät für Physik, Ludwig-Maximilians-Universität München, Schellingstr. 4, 80799 Munich, Germany
[2]Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching, Germany
[3]Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot 76100, Israel

does localized phase withstand interactions in a **closed system**?

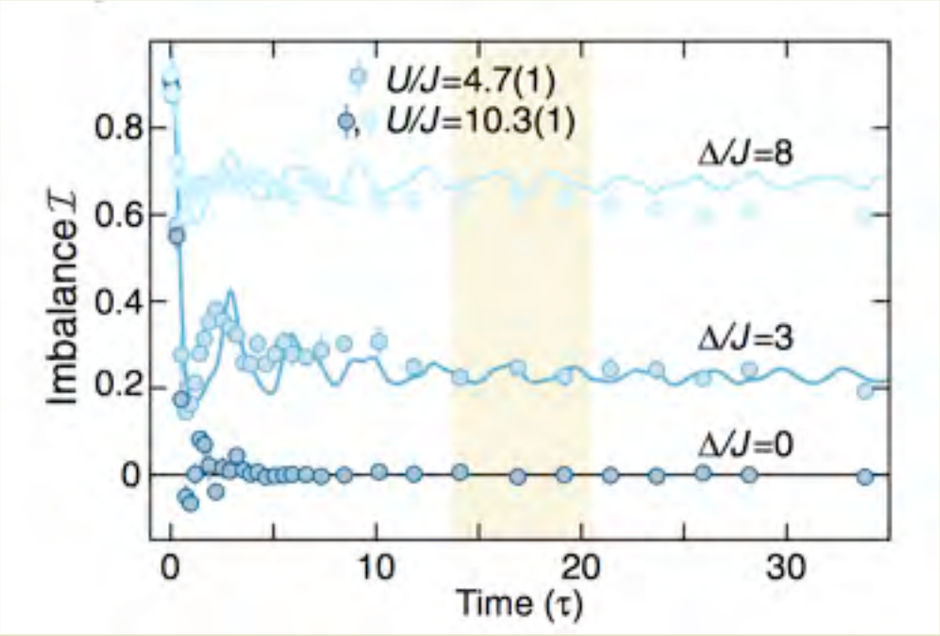
does an initial local perturbation (here density) decay to zero?



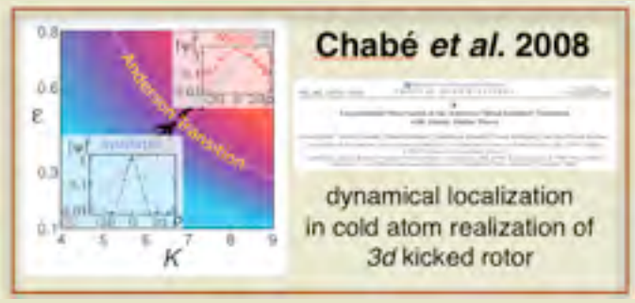
imbalance:

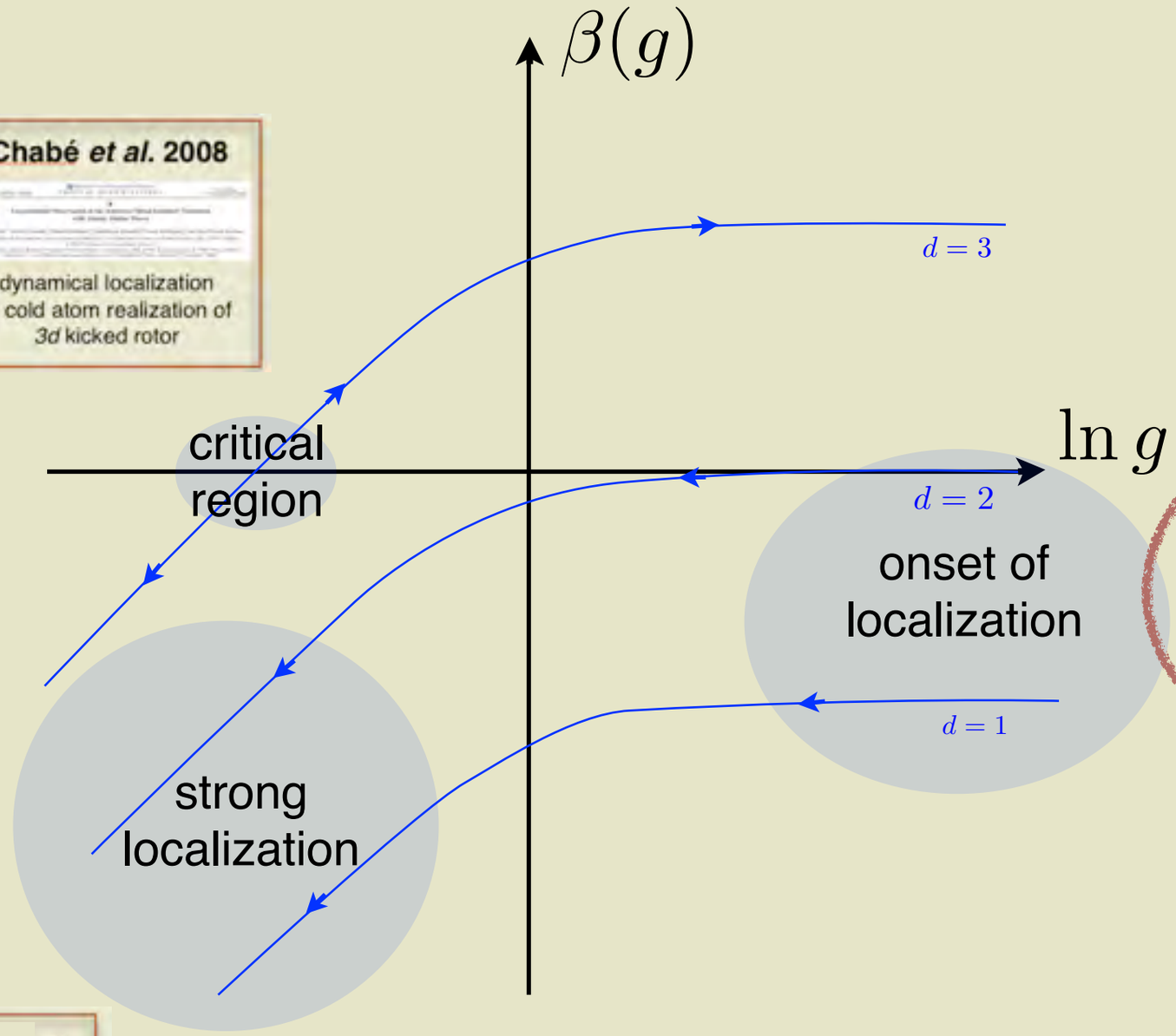
$$I(t) = \frac{N_e(t) - N_o(t)}{N_e(t) + N_o(t)} \neq 0\,?$$

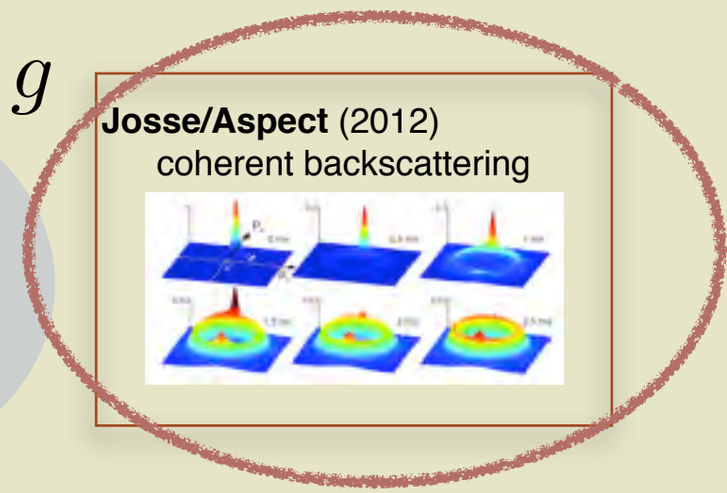
as $t \to \infty$

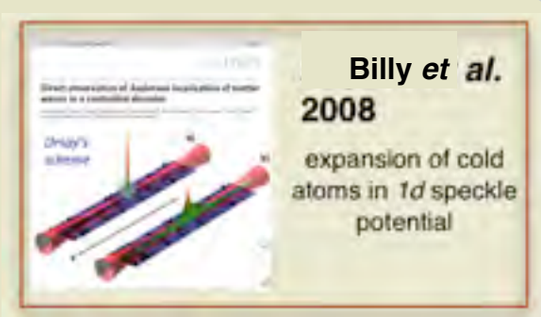


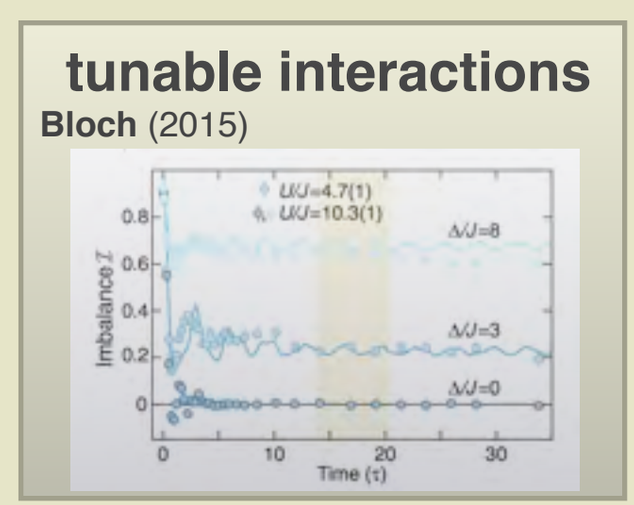
some recent cold atom experiments



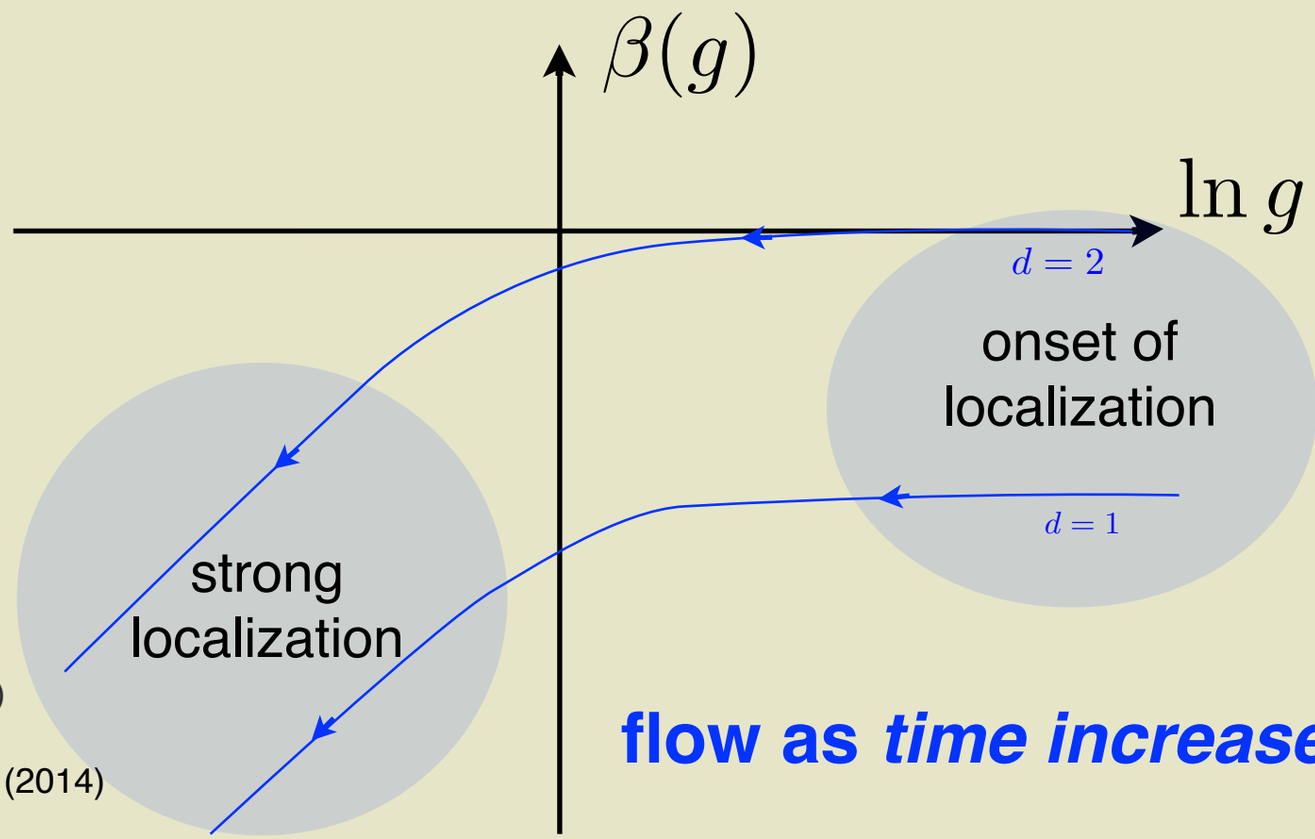




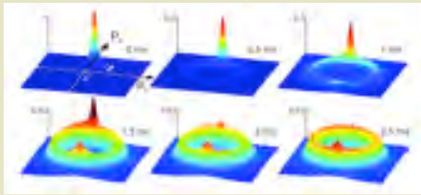




in this talk: cold atom “quench experiment”



Josse/Aspect 2012
coherent backscattering



echo-spectroscopy
TM, Müller, Altland, (2015)

forward scattering peak
Karpiuk, *et al.* (2012)
TM, Müller, Altland, (2014)
Ghosh *et al.* (2014)
Lee, Grémaud, Miniatura, (2014)

flow as *time increases*

quantum quench experiment:

- controlled observation of strong Anderson localization
- control parameter: time

Quantum Quench Experiment

Selected for a Viewpoint in *Physics*

PRL **109,** 195302 (2012) PHYSICAL REVIEW LETTERS week ending 9 NOVEMBER 2012

Coherent Backscattering of Ultracold Atoms

F. Jendrzejewski,[1] K. Müller,[1] J. Richard,[1] A. Date,[1] T. Plisson,[1] P. Bouyer,[2] A. Aspect,[1] and V. Josse[1,*]

[1]*Laboratoire Charles Fabry UMR 8501, Institut d'Optique, CNRS, Univ Paris Sud 11, 2 Avenue Augustin Fresnel, 91127 Palaiseau cedex, France*

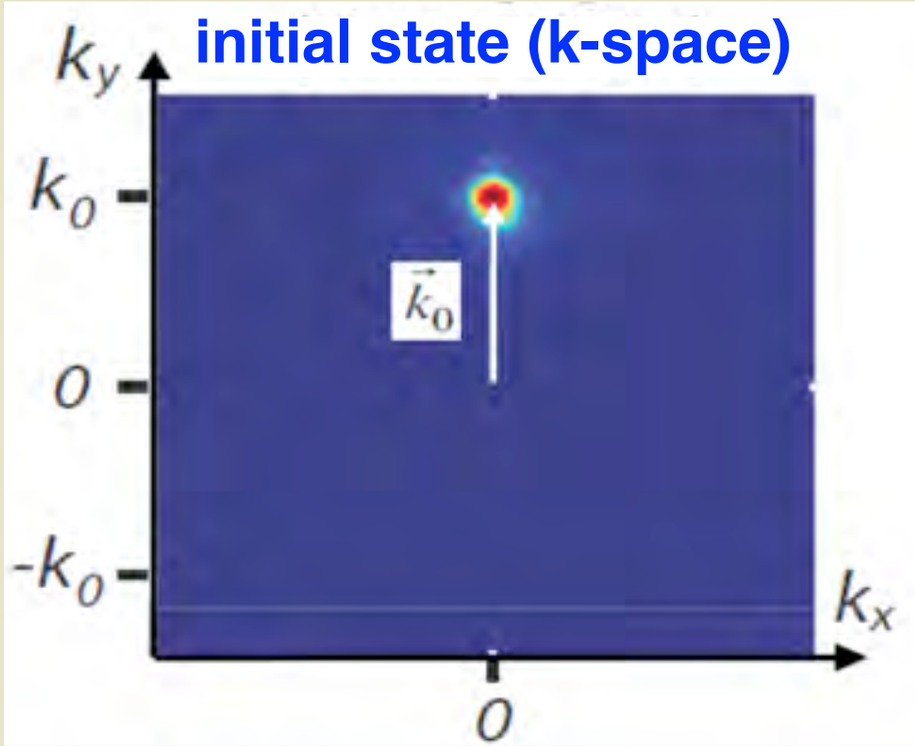
[2]*LP2N UMR 5298, Univ Bordeaux 1, Institut d'Optique and CNRS, 351 cours de la Libération, 33405 Talence, France*

(Received 19 July 2012; published 5 November 2012)

Quantum Quench Experiment

preparation of initial state:

1. cooling of atomic cloud in optical dipole trap, BEC of atoms in F =2, m_F =-2 ground sublevel
2. suppress interatomic interactions by releasing atomic cloud and letting it expand
3. freeze motion of atoms by switching on harmonic potential for well chosen amount of time almost
4. give atoms finite momentum without changing spread by applying additional magnetic gradient during 12 ms



Selected for a Viewpoint in *Physics*

PRL **109,** 195302 (2012) PHYSICAL REVIEW LETTERS week ending 9 NOVEMBER 2012

Coherent Backscattering of Ultracold Atoms

F. Jendrzejewski,[1] K. Müller,[1] J. Richard,[1] A. Date,[1] T. Plisson,[1] P. Bouyer,[2] A. Aspect,[1] and V. Josse[1,*]

[1]*Laboratoire Charles Fabry UMR 8501, Institut d'Optique, CNRS, Univ Paris Sud 11, 2 Avenue Augustin Fresnel, 91127 Palaiseau cedex, France*

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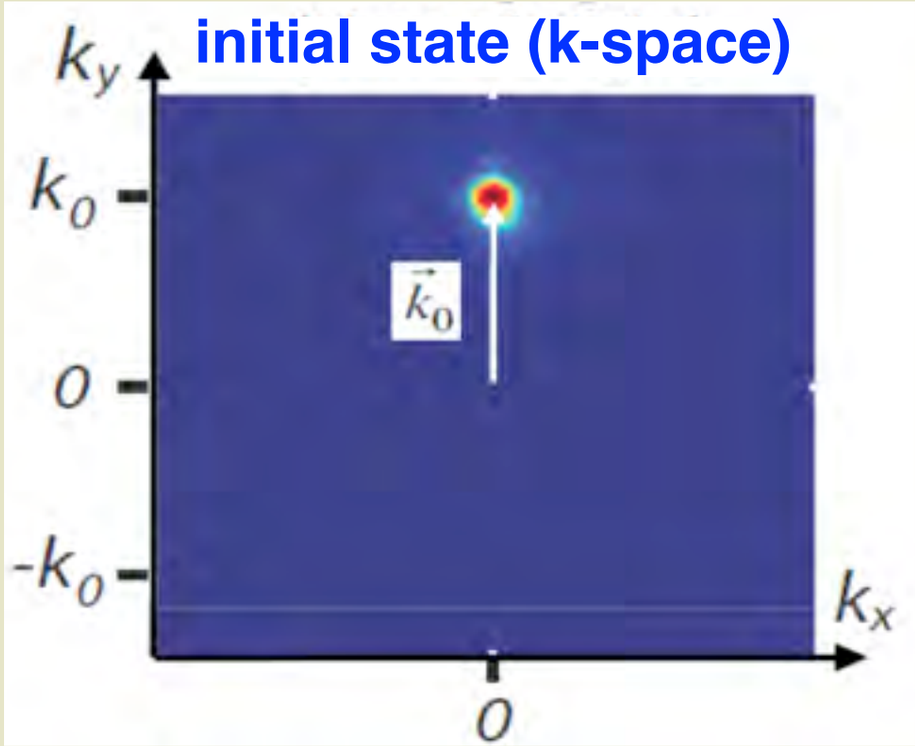
(Received 19 July 2012; published 5 November 2012)

Quantum Quench Experiment

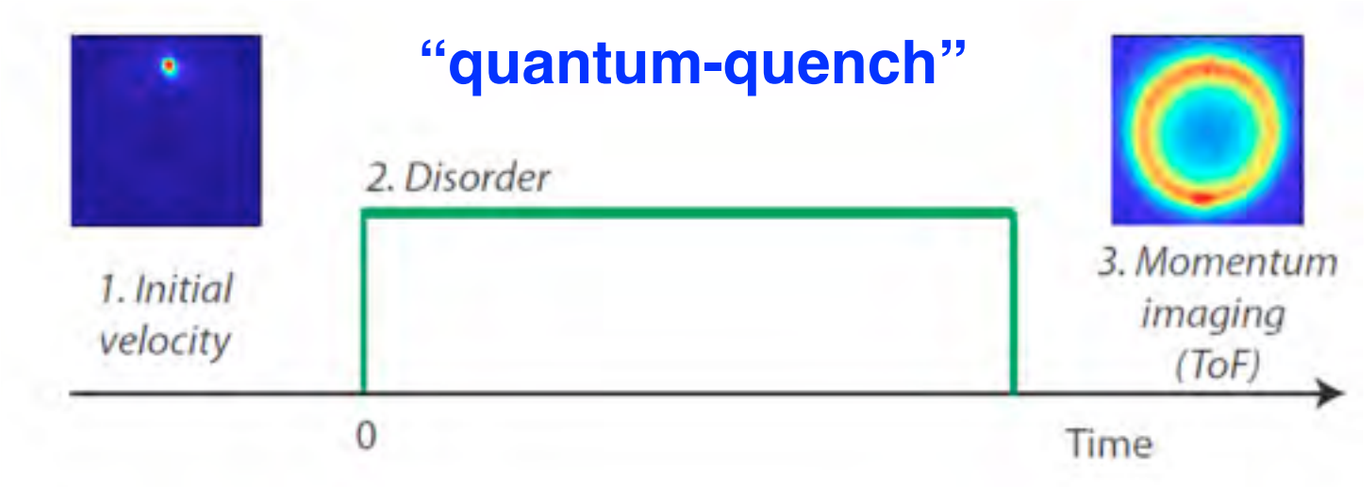
preparation of initial state:

1. cooling of atomic cloud in optical dipole trap, BEC of atoms in F =2, m_F =-2 ground sublevel
2. suppress interatomic interactions by releasing atomic cloud and letting it expand
3. freeze motion of atoms by switching on harmonic potential for well chosen amount of time almost
4. give atoms finite momentum without changing spread by applying additional magnetic gradient during 12 ms



experiment:

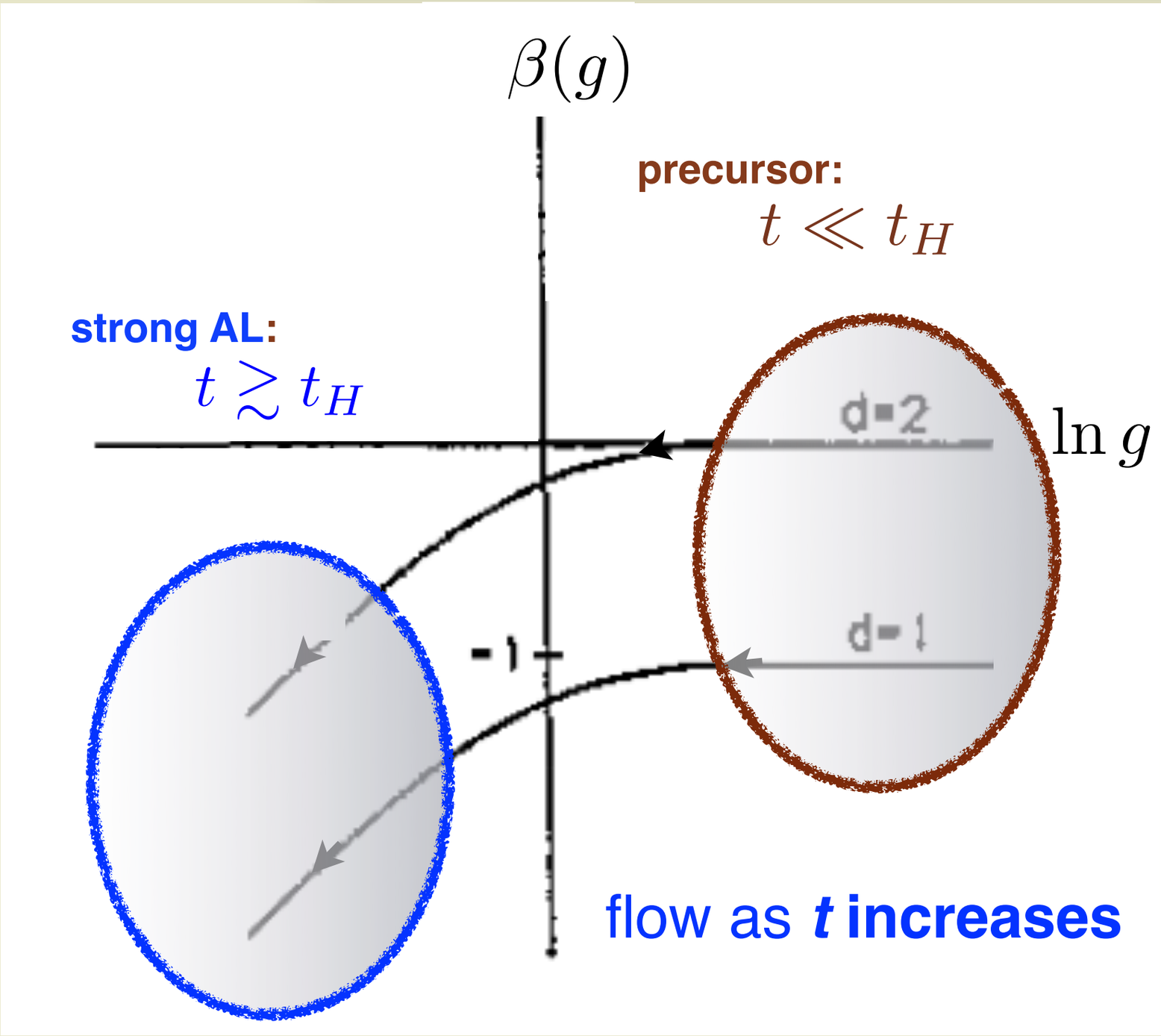
- release atoms from optical trap and suspend against gravity by magnetic levitation
- switch on anisotropic laser speckle disordered potential (2d: elongated along one axis)
- let atoms scatter for a time *t*
- switch off the disorder and monitor momentum distribution at time *t* (time of flight imaging)



low densities... "it's all single-particle physics"

study momentum-correlations in time

observable: $\mathcal{C}_{\mathbf{k}_\mathrm{i}\mathbf{k}_\mathrm{f}}(t) = \overline{|\langle \mathbf{k}_\mathrm{f}|e^{-i\hat{H}t}|\mathbf{k}_\mathrm{i}\rangle|^2}$

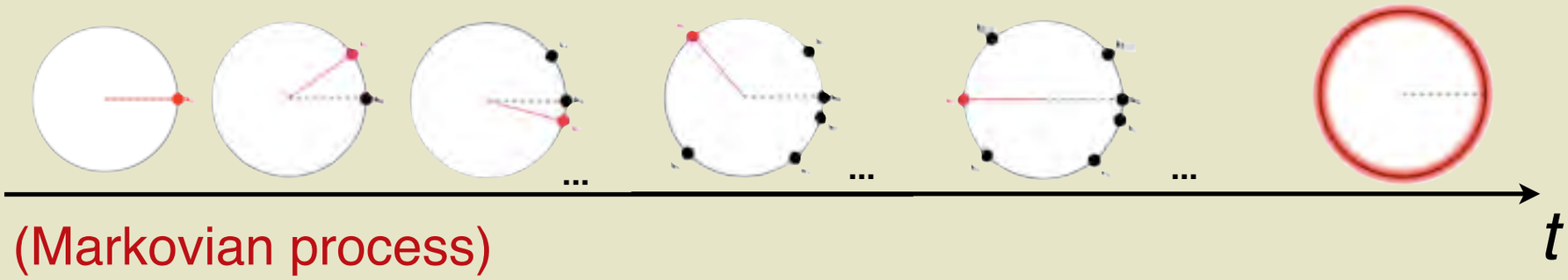


quantum quench experiment:

- controlled observation of Anderson localization
- observable: momentum -distribution
- control parameter: time

Classical vs. quantum diffusion

classical: isotropic redistribution of atoms over energy-shell



(Markovian process)

⇨ no momentum-correlations

quantum interference

(system has memory)

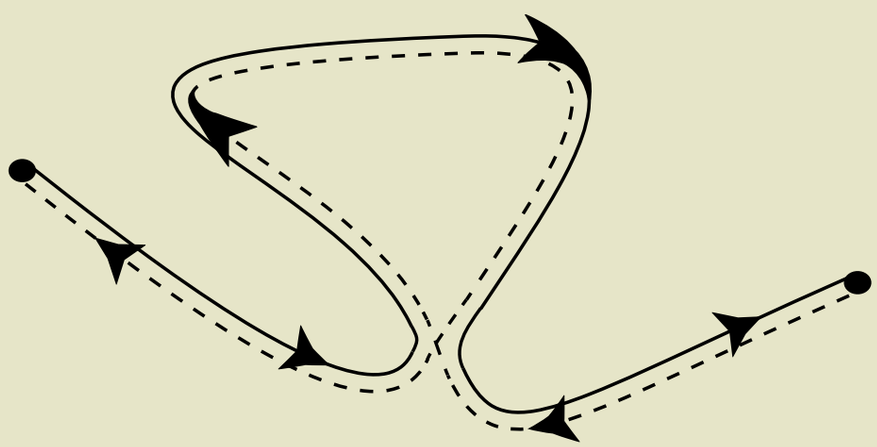
⇨ momentum-correlations

Momentum-Correlations

Precursor Effects 1

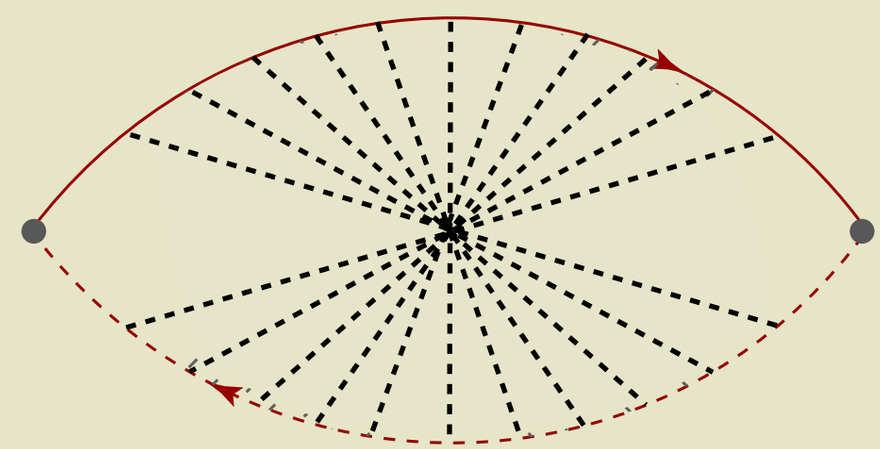
leading contribution **(orthogonal class)**

space-correlations



$P(\mathbf{r} \to \mathbf{r}, t)$

momentum-correlations



$P(\mathbf{k} \to -\mathbf{k}, t)$

⇨ peak in **back-scattering** direction

“coherent back-scattering”

Coherent Backscattering peak

Experiment 2012 **(orthogonal class)**

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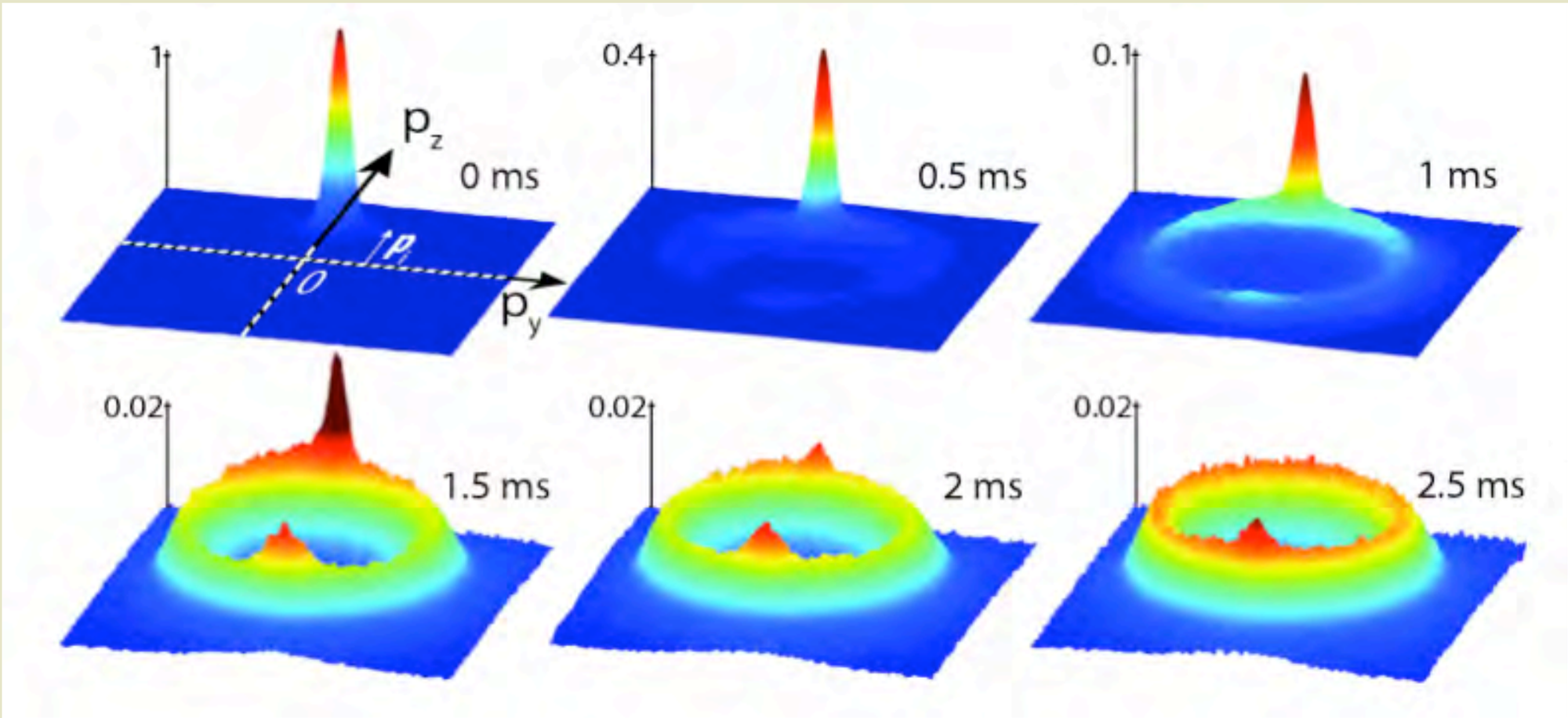
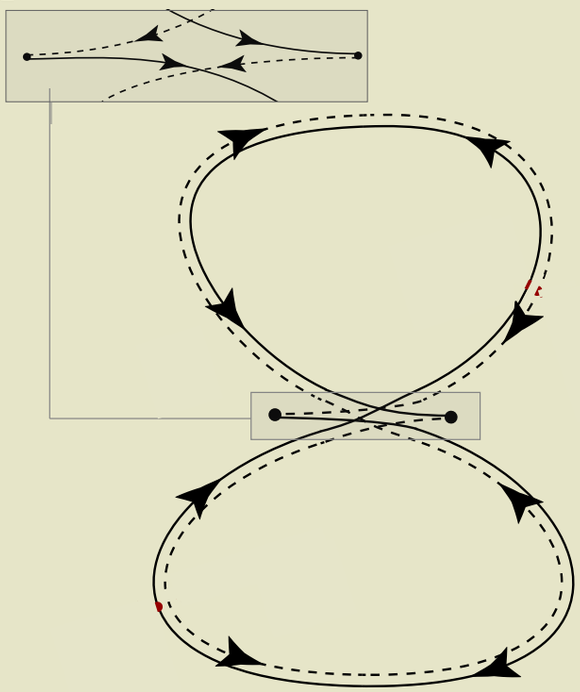


Momentum-Correlations

Precursor Effects 2

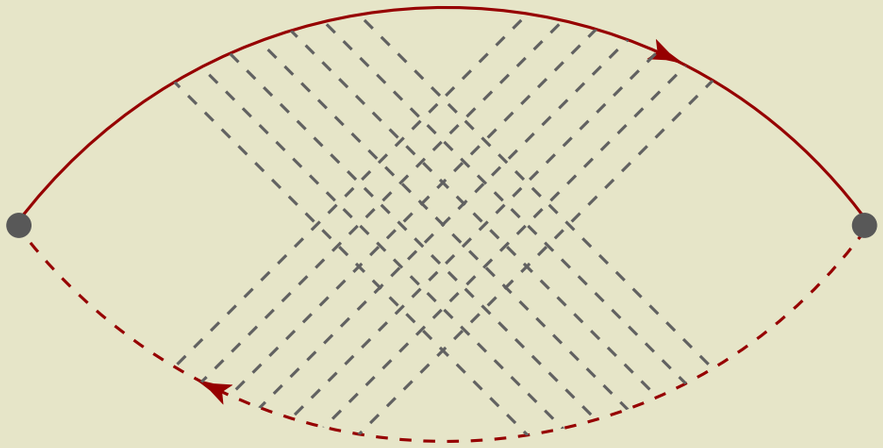
leading contribution **(unitary class)**

space-correlations



$P(\mathbf{r} \to \mathbf{r}, t)$

momentum-correlations



$P(\mathbf{k} \to \mathbf{k}, t)$

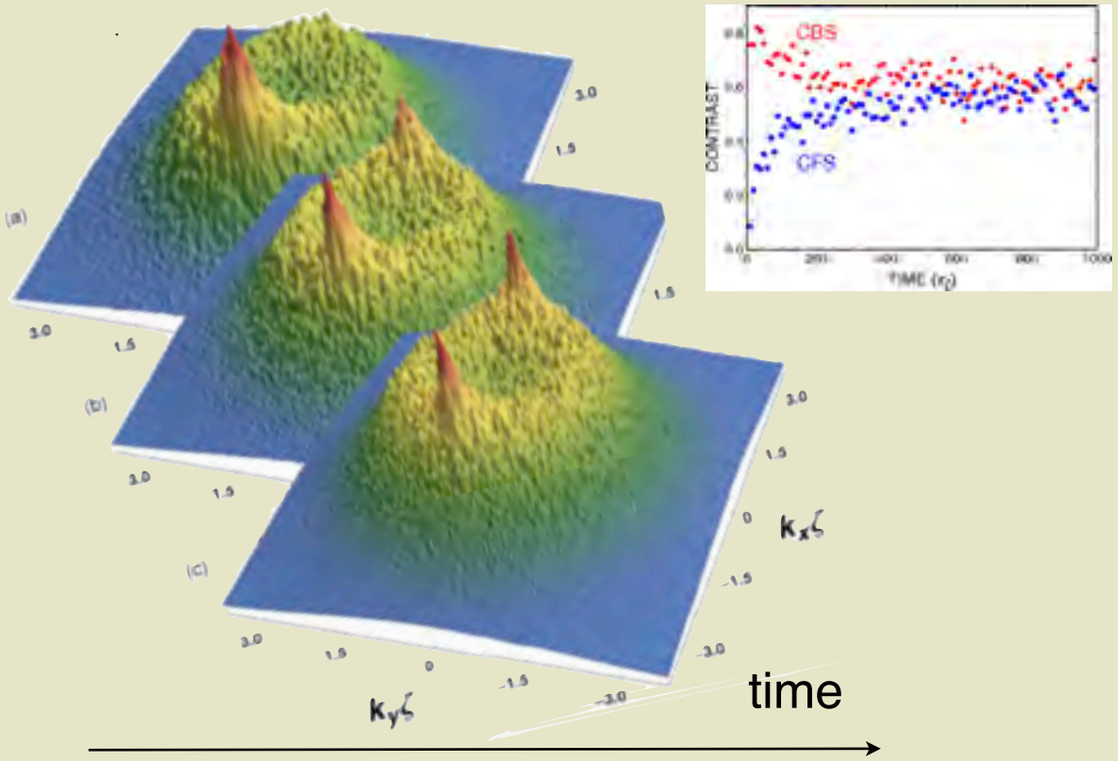
⇨ peak in **forward-scattering** direction

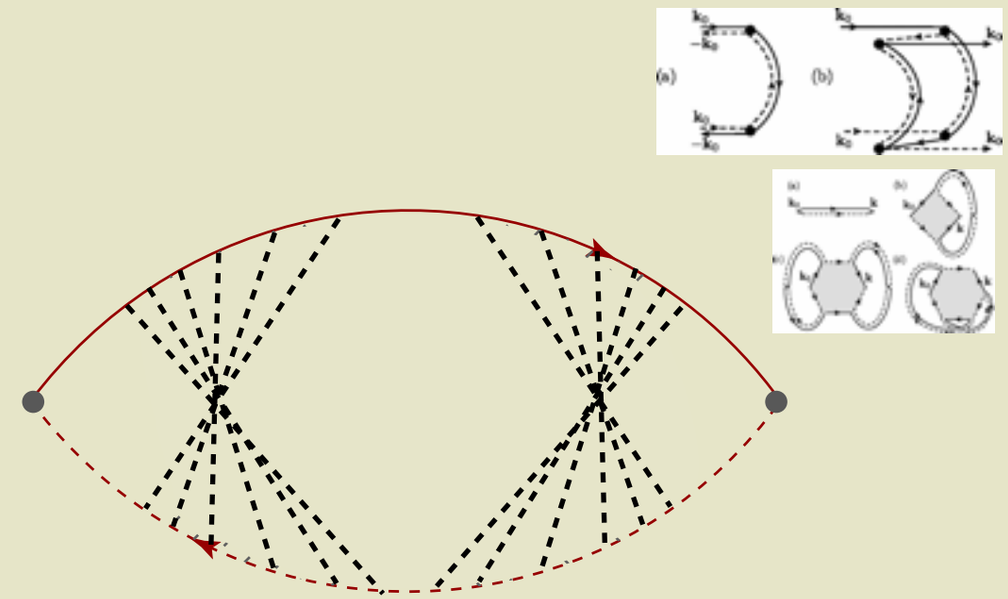
“coherent forward-scattering”

simulation + phenomenology

(*2d*, orthogonal class)

[T. Karpiuk, N. Cherroret, K.L. Lee, B. Grémaud, C.A. Müller, C. Miniatura, PRL **109**, 190601 (2012)]





perturbation theory + *self-consistent theory for localization*

fwd-peak builds up on long time-scales ($t \gtrsim t_H$), i.e. pronounced in strongly localized regime

a signature of strong localization...

fwd-peak: field theory

$$S[Q] = \pi\nu \int d\mathbf{x}\, \mathrm{str}\left(\frac{D}{4}(\partial_{\mathbf{x}} Q)^2 - i\eta Q\Lambda\right)$$

symmetry-breaking

$\eta \sim t_H/t$

$Q(x) \in$

"sphere x hyperboloid dressed with Grasmann variables"

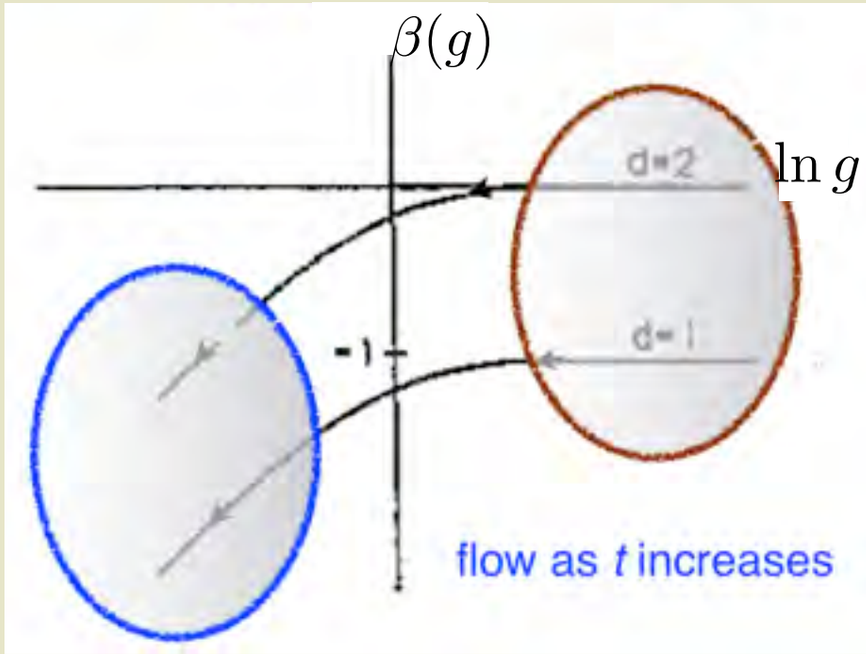
analogy: $H[\vec{S}] = \int d\mathbf{x}\left(J(\partial_{\mathbf{x}}\vec{S})^2 - \vec{S}\cdot\vec{h}\right)$

$\vec{S} \in$ 

strong AL: $t \gtrsim t_H$

(non-perturbative regime)

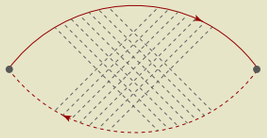
Fwd peak = ???



precursor: $t \ll t_H$

(perturbative regime,

Goldstone-modes = diffusion)

Fwd peak =  + ...

$\propto \sqrt{t/t_H}$

$\mathbf{q} = \mathbf{k}_\mathrm{i} - \mathbf{k}_\mathrm{f}$

$$\mathcal{C}(\mathbf{q},\eta) = \delta_{\mathbf{0},\mathbf{q}^\perp}\langle \mathrm{tr}\left(\mathcal{P}_{-+}\, Q(q)\, \mathcal{P}_{+-}\, Q(-q)\right)\rangle_S$$

$$\langle \ldots \rangle_S = \int \mathcal{D}Q e^{S[Q]}(\ldots)$$

solution strategy

quasi *1d* geometry:

$$S[Q] = \int dx \left(\alpha \, \mathrm{str}(\dot{Q}^2) + V(Q) \right)$$

$$\alpha \, \mathrm{str}(\dot{Q}^2) = \pi\nu \mathrm{str} \left(\frac{D}{4} (\partial_x Q)^2 \right)$$
$$V[Q] = -i\pi\nu\eta \, \mathrm{str} \, (Q\Lambda)$$

- Functional integral $\longmapsto$ "Schrödinger equation"

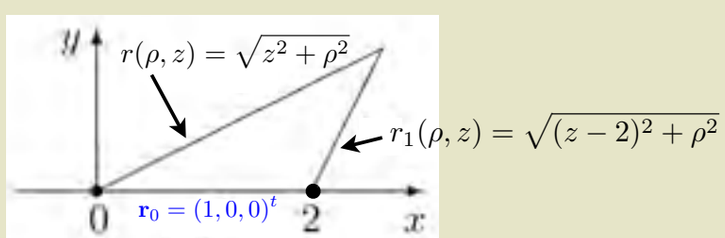
radial-symmetric *V[Q]*: few relevant variables λ_1, λ

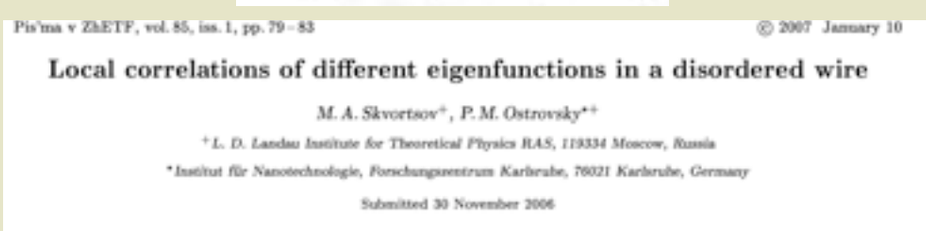
$$\mathcal{C}(q,\eta) \propto \int_1^\infty \int_{-1}^1 \frac{d\lambda_1 d\lambda}{\lambda_1 - \lambda} \left[\Psi_1^q(\lambda_1,\lambda) + \Psi_1^{-q}(\lambda_1,\lambda) \right] \Psi_0(\lambda_1,\lambda)$$

$$\boxed{\begin{aligned} (\Delta_Q + V(\lambda_1,\lambda)) \, \Psi_0 &= 0 \\ (2\Delta_Q + 2V(\lambda_1,\lambda) - iq\xi_{\mathrm{loc}}) \, \Psi_1^q &= (\lambda_1 - \lambda)\Psi_0 \end{aligned}}$$

- elliptic coordinates $\longmapsto$ "*3d* Coulomb-problem"

$$\boxed{\begin{aligned} \lambda &= (r - r_1)/2 \\ \lambda_1 &= (r + r_1)/2 \end{aligned}}$$




Pis'ma v ZhETF, vol. 85, iss. 1, pp. 79 – 83 © 2007 January 10

Local correlations of different eigenfunctions in a disordered wire

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[+]L. D. Landau Institute for Theoretical Physics RAS, 119334 Moscow, Russia

[*]Institut für Nanotechnologie, Forschungszentrum Karlsruhe, 76021 Karlsruhe, Germany

Submitted 30 November 2006

$$\boxed{\hat{H}_0 = -\frac{r_1^2 r}{2} \left[\Delta_0 - \frac{2\kappa}{r} \right] \frac{1}{r_1}}$$

$$\Delta_0 \equiv \partial_z^2 + \rho^{-1} \partial_\rho \rho \partial_\rho$$
$$\kappa \equiv -i\eta t_H/2$$

***3d*-Laplace + *1/r*-potential**

fwd-peak from Coulomb-problem

using *3d*-variables:

$$\mathcal{C}(0,\omega) \propto \int \frac{d\mathbf{r}}{r}\Phi_0(\mathbf{r})\Phi_1(\mathbf{r})$$

$$\left(\partial_{\mathbf{r}}^2 + \frac{\kappa}{r}\right)\Phi_0(\mathbf{r},t) = 0$$

$$\left(\partial_{\mathbf{r}}^2 + \frac{\kappa}{r}\right)\Phi_1(\mathbf{r},t) = \frac{1}{r}\Phi_0(\mathbf{r},t)$$

$$\Rightarrow \quad \boxed{\begin{aligned}\mathcal{C}(0,\eta) &= 32\pi\xi\langle\mathbf{r}_0|\hat{G}_0\frac{1}{\hat{r}}\hat{G}_0\frac{1}{\hat{r}}\hat{G}_0|\mathbf{r}_0\rangle \\ &= 8\pi\xi\partial_\kappa^2 G_0(\mathbf{r}_0,\mathbf{r}_0)\end{aligned}}$$

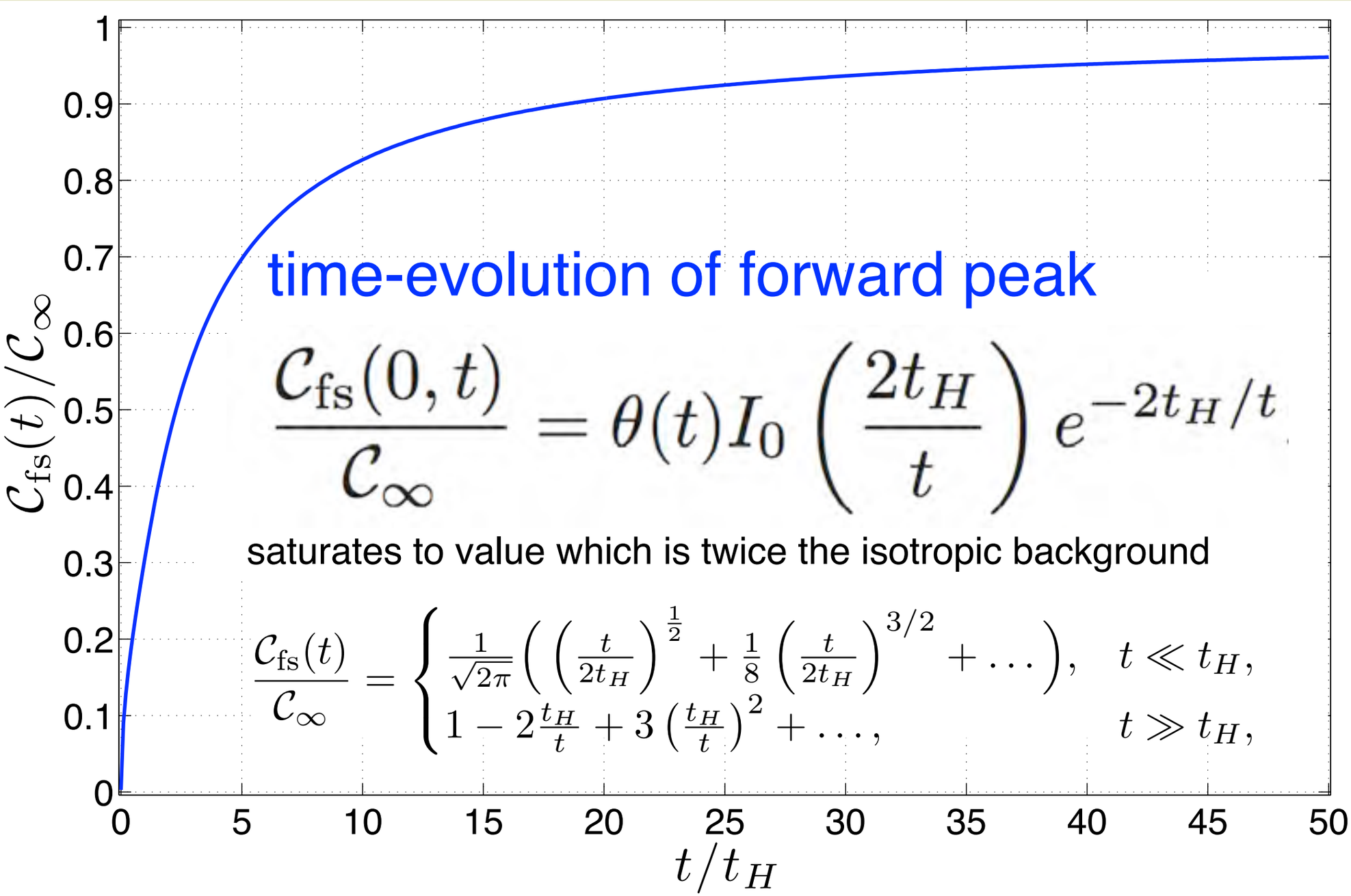
Green's function for *3d* non-relativistic Coulomb-problem:

$$\left[\Delta_0 - \frac{2\kappa}{r}\right]G_0(\mathbf{r},\mathbf{r}') = \delta(\mathbf{r}-\mathbf{r}')$$

analytical results

L. Hostler (1964):

$$G_0(\mathbf{r},\mathbf{r}') = \frac{(\partial_u - \partial_v)\sqrt{u}K_1(2\sqrt{\kappa u})\sqrt{v}I_1(2\sqrt{\kappa v})}{2\pi|\mathbf{r}-\mathbf{r}'|}, \qquad \begin{aligned} u &= r + r' + |\mathbf{r}-\mathbf{r}'| \\ v &= r + r' - |\mathbf{r}-\mathbf{r}'| \end{aligned}$$



for details see:
T. M., C. A. Müller, A. Altland, Phys. Rev. Lett. **112**, 110602 (2014)

analytical results

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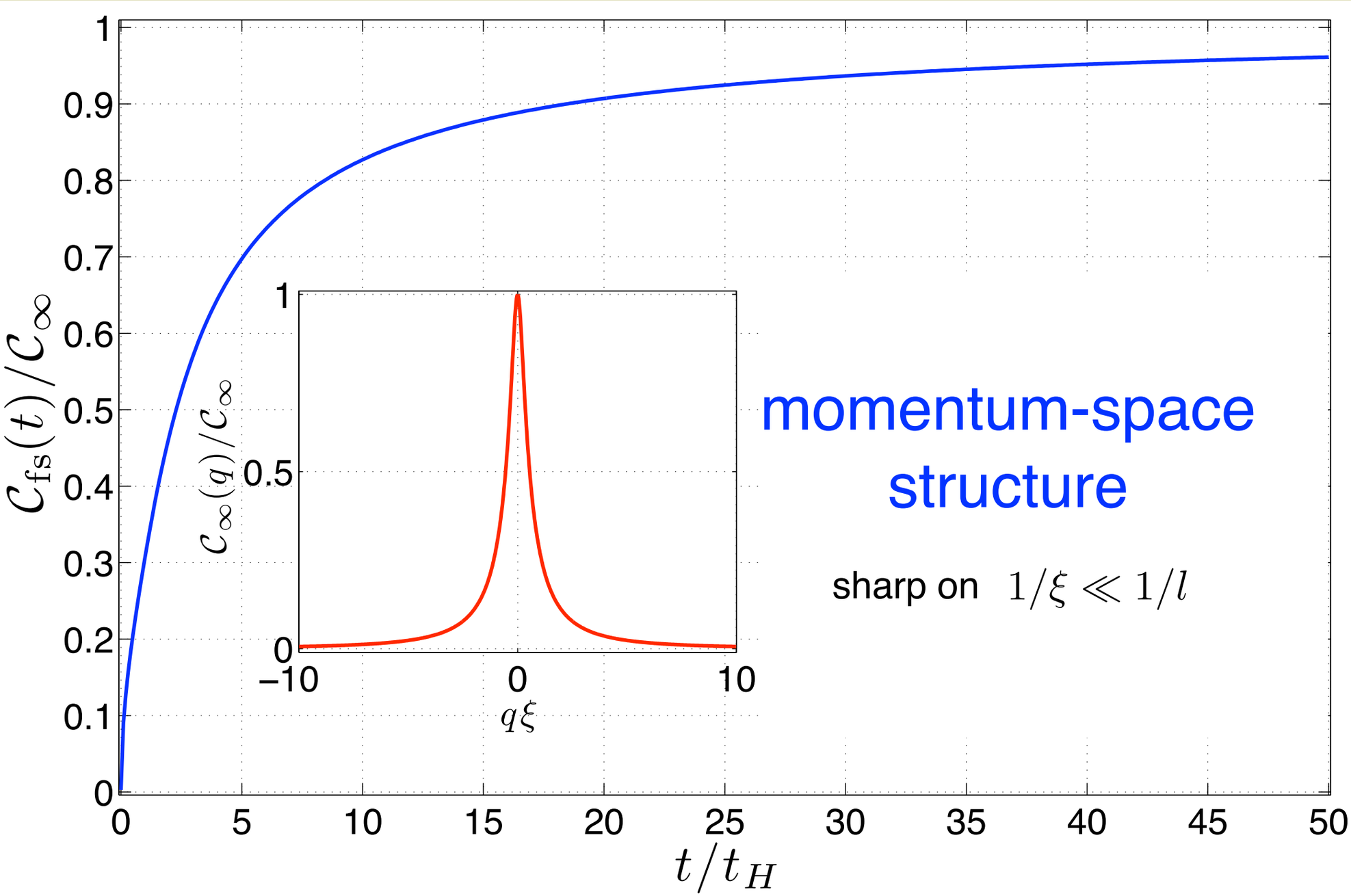

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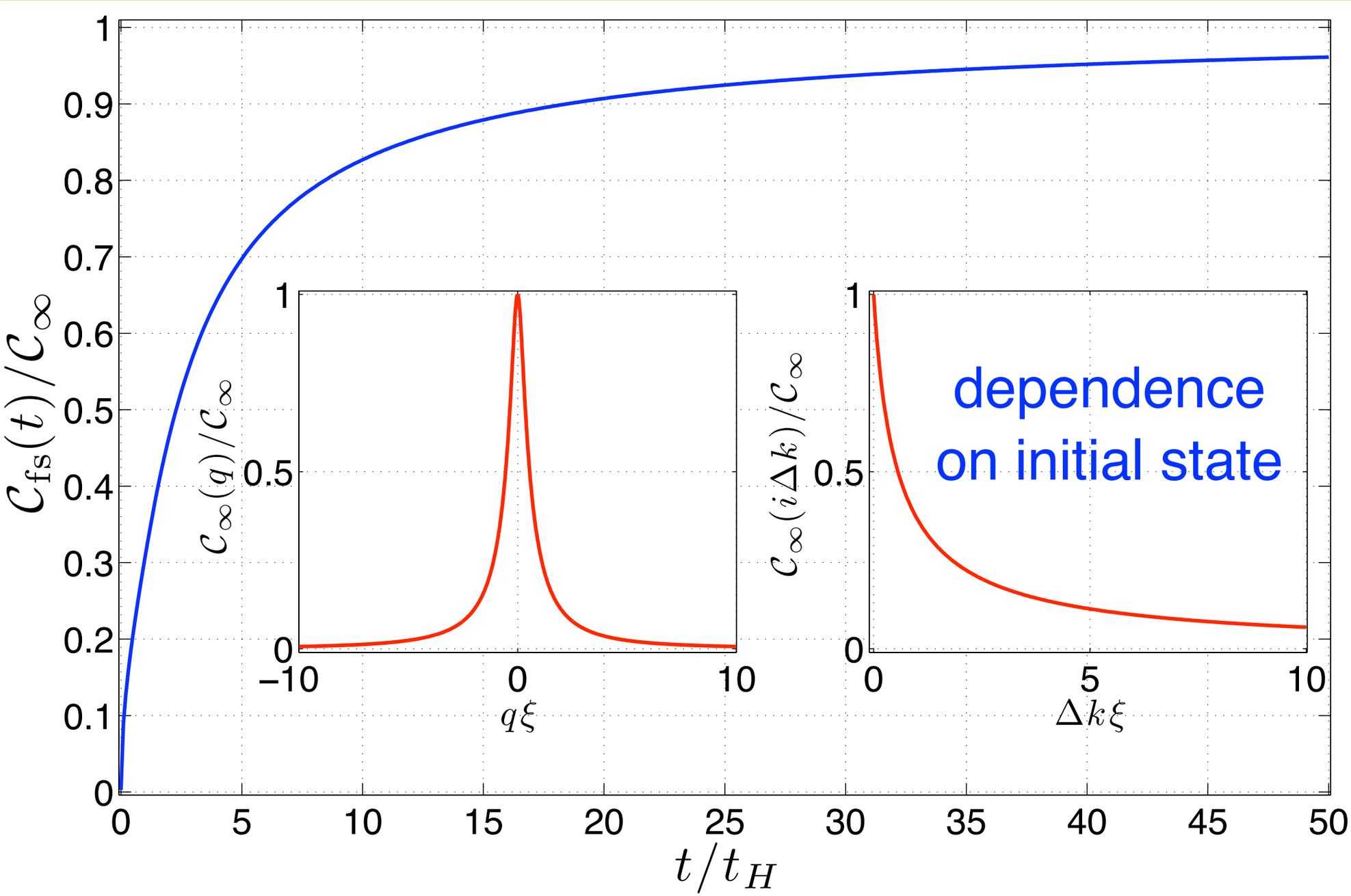


for details see:
T. M., C. A. Müller, A. Altland, Phys. Rev. Lett. **112**, 110602 (2014)

fwd-peak and level statistics

$\mathcal{C}_{\rm fs}(t)$ is the **form factor**, i.e. Fourier-transform of **level-level correlation function** $K_2(\omega) = \frac{1}{\nu_0^2}\langle \nu(\epsilon)\nu(\epsilon+\omega)\rangle - 1$

eigenstate-representation

$$\mathcal{C}_{\rm fs}(t) \propto \int d\epsilon \int d\omega\, e^{i\omega t} \sum_{\alpha\beta} \langle |\alpha(\mathbf{k}_{\rm i})|^2 |\beta(\mathbf{k}_{\rm i})|^2 \delta(\epsilon_+ - E_\alpha)\delta(\epsilon_- - E_\beta)\rangle$$

$$\epsilon_\pm = \epsilon \pm \omega/2$$

$$\alpha(\mathbf{k}) = \langle \alpha | \mathbf{k} \rangle$$

level-level correlations

$$\langle \nu(\epsilon_+)\nu(\epsilon_-)\rangle = \sum_{\alpha\beta} \langle \delta(\epsilon_+ - E_\alpha)\delta(\epsilon_- - E_\beta)\rangle$$

wave-function statistics in momentum-space is GUE independent of $L/\xi_{\rm loc}$

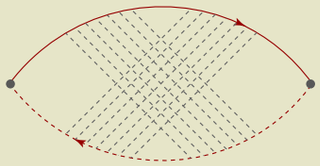
$$\frac{\mathcal{C}_{\rm fs}}{\mathcal{C}_{\rm bgn}} = \frac{\langle \alpha(\mathbf{k}_{\rm i})\alpha^*(\mathbf{k}_{\rm i})\alpha(\mathbf{k}_{\rm i})\alpha^*(\mathbf{k}_{\rm i})\rangle}{\langle \alpha(\mathbf{k}_{\rm i})\alpha^*(\mathbf{k})\alpha(\mathbf{k})\alpha(\mathbf{k}_{\rm i})\rangle} = 2$$

saturation value as $t \gg t_{\rm H}$

fwd-peak and level statistics

$\mathcal{C}_{\rm fs}(t)$ is the **form factor**, i.e. Fourier-transform of **level-level correlation function** $K_2(\omega) = \frac{1}{\nu_0^2}\langle \nu(\epsilon)\nu(\epsilon+\omega)\rangle - 1$

$K_2(\omega) \propto \omega^{-3/2}$



$$\frac{\mathcal{C}_{\rm fs}(t)}{\mathcal{C}_\infty} = \begin{cases} \frac{1}{\sqrt{2\pi}}\left(\left(\frac{t}{2t_H}\right)^{\frac{1}{2}} + \frac{1}{8}\left(\frac{t}{2t_H}\right)^{3/2} + \dots\right), & t \ll t_H, \\ 1 - 2\frac{t_H}{t} + 3\left(\frac{t_H}{t}\right)^2 + \dots, & t \gg t_H, \end{cases}$$

$K_2(\omega) \propto \delta(\omega)$ ... $- 4\ln\omega$

self-correlations

Mott scale (2 resonant levels)

spectral correlations of a *finite*-size Anderson insulator

$$K_L(\omega) = -\frac{\xi_{\rm loc}}{L}\mathcal{K}(4\omega/\Delta_\xi),$$

$$\mathcal{K}(z) = {\rm Re}\,\frac{8}{\sqrt{iz}}\left(K_1(\sqrt{iz})I_0(\sqrt{iz}) - K_0(\sqrt{iz})I_1(\sqrt{iz})\right)$$

fwd-peak: long-time asymptotics

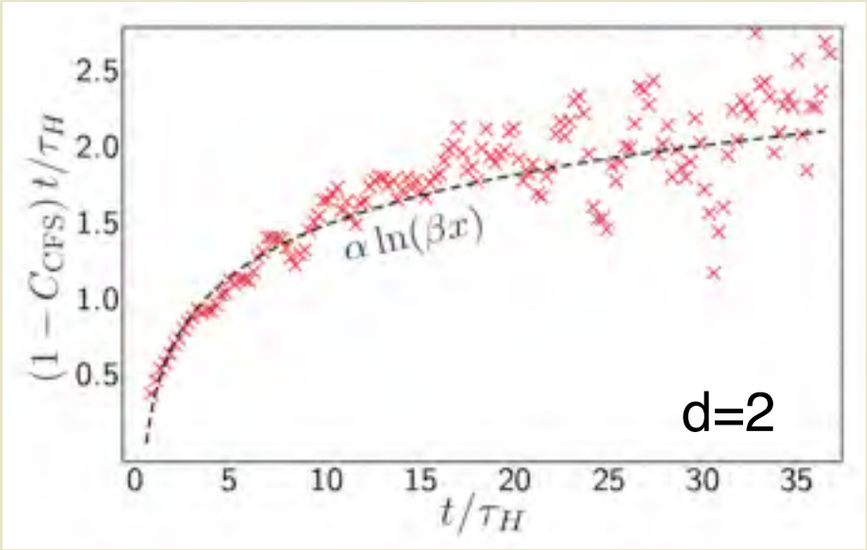
"two resonant levels"

$$H = \begin{pmatrix} \epsilon + \delta\epsilon & \Delta_\xi e^{-\frac{|\mathbf{x}-\mathbf{x}'|}{\xi_{\rm loc}}} \\ \Delta_\xi e^{-\frac{|\mathbf{x}-\mathbf{x}'|}{\xi_{\rm loc}}} & \epsilon - \delta\epsilon \end{pmatrix}$$

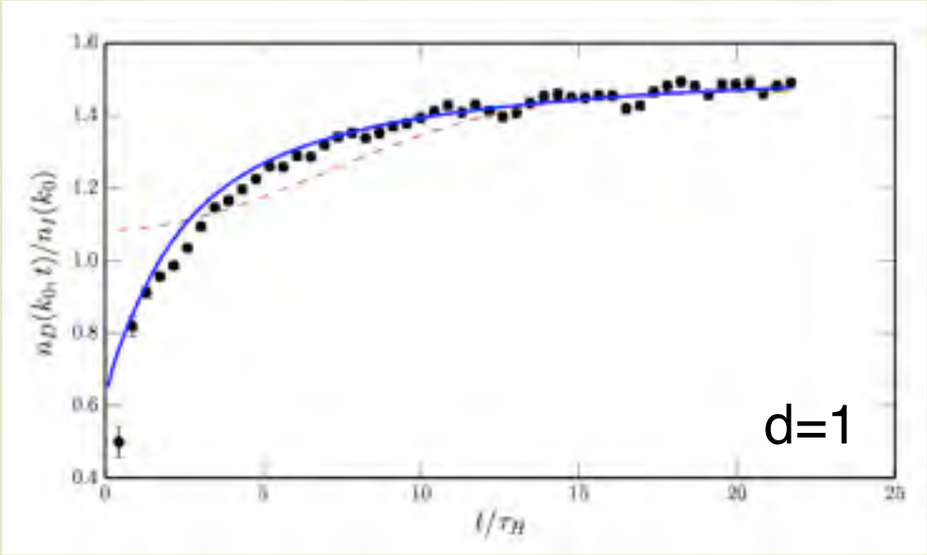
$$\Rightarrow \quad K(\omega) \propto -\left(\frac{\xi_{\rm loc}}{L}\right)^d \ln^d(\omega/\Delta_\xi)$$

$$\boxed{\frac{\mathcal{C}_{\rm fs}(t)}{\mathcal{C}_\infty} = 1 - \frac{\gamma_1 t_H}{t} \ln^{d-1}(\gamma_2 t/t_H)}$$

long-time asymptotic general *d*



[S. Ghosh, N. Cherroret, B. Grémaud, C. Miniatura, D. Delande, Phys. Rev. A **90**, 063602 (2014)]



[K. L. Lee, B. Grémaud, C. Miniatura, Phys. Rev. A **90**, 043605 (2014)]

experiments: still challenging...

tunability of cold atoms

full control of system paramaters opens new ways to study localization phenomena

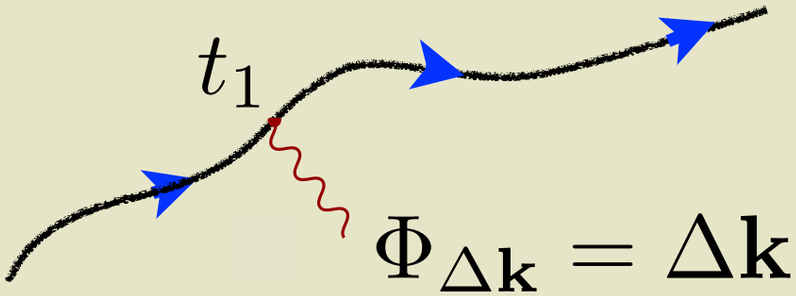
possible to **manipulate system on short time scales!** (compared to elastic scattering time)

a proposal to study onset of localization

[TM, C. A. Müller, A. Altland, PRB. 9**1**, 064203 (2015)]

in the quench experiment:

- release atoms from trap, **suspend against gravity by magnetic levitation**
- possible to change magnetic field on short time scales
- field pulse weak enough to not change the path of atom
- atoms pick up a coordinate-dependent phase

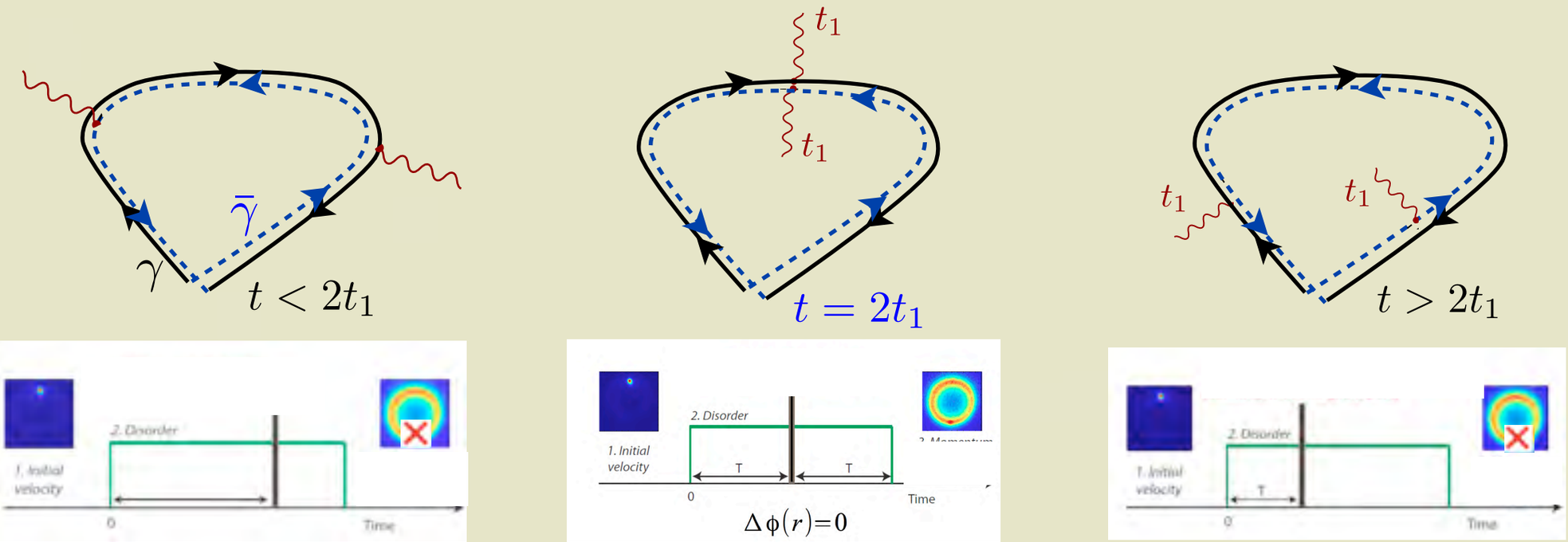


$$\Phi_{\Delta\mathbf{k}} = \Delta\mathbf{k} \cdot \mathbf{r}_\gamma(t_1)$$

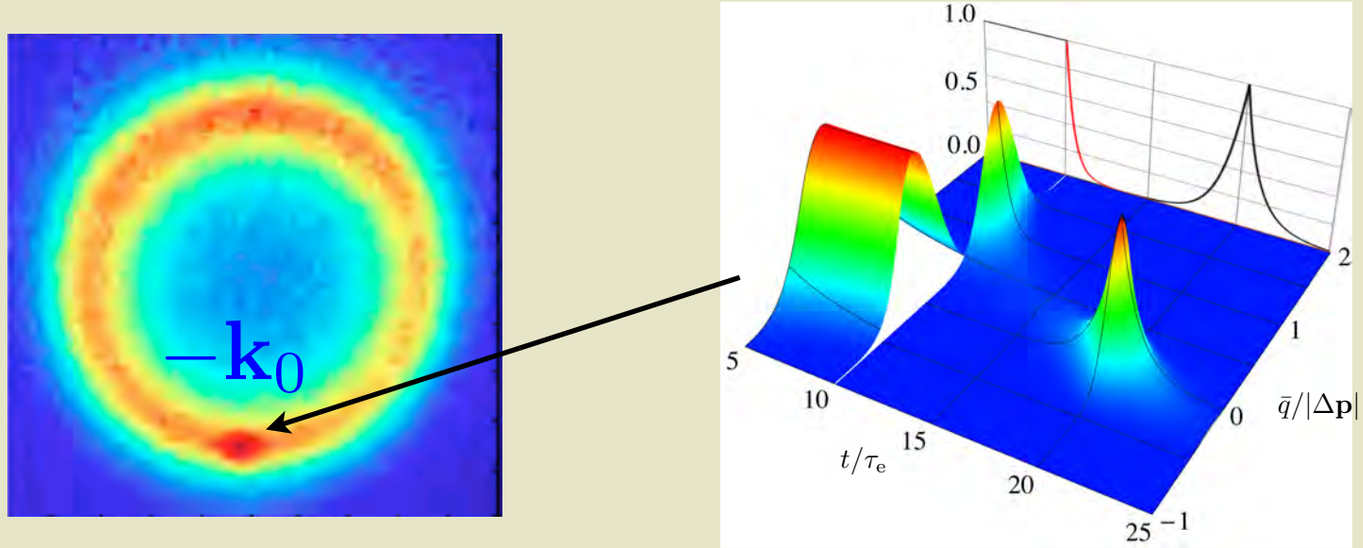
Coherent backscattering echo

(orthogonal class)

a single pulse at $t = t_1$



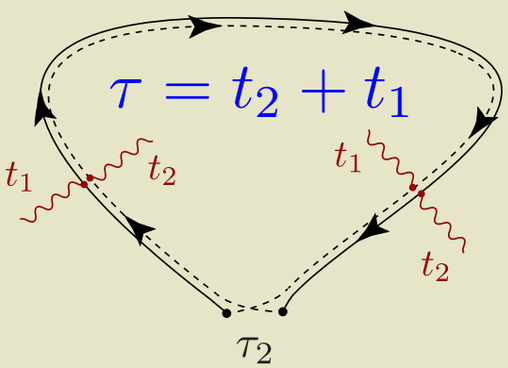
echo-structure in momentum-space



Two-mode echoes

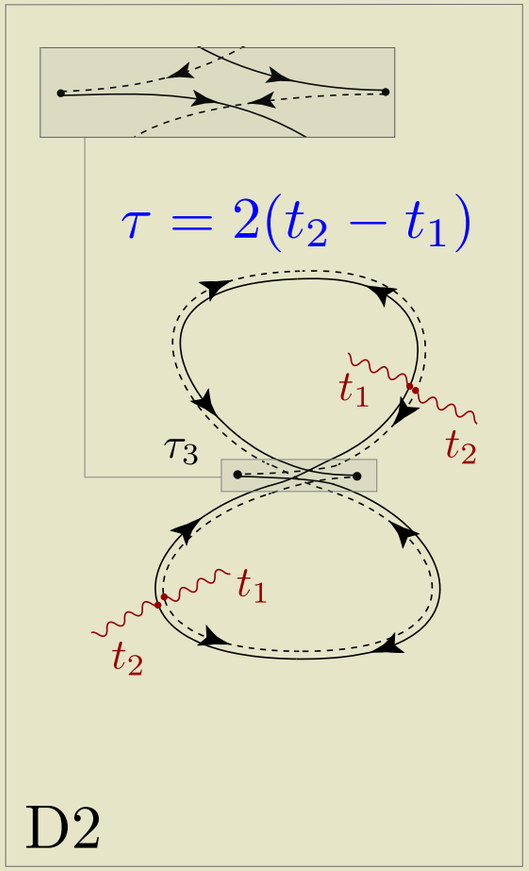
two pulses at
$t = t_1, t_2$

backscattering echo

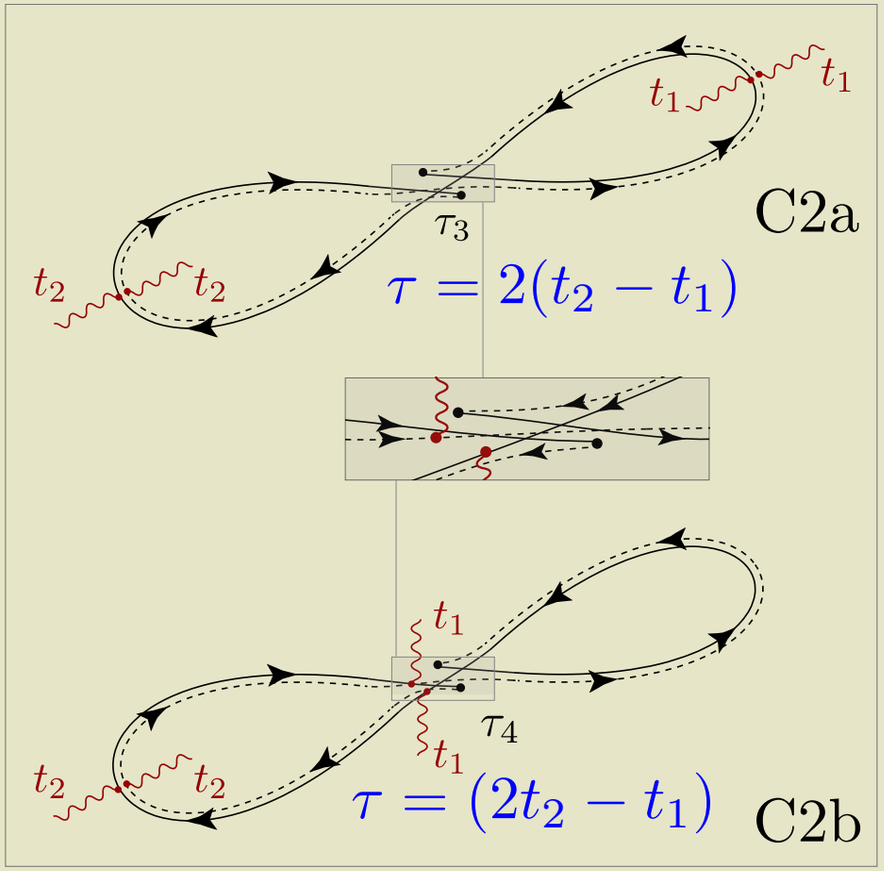


(orthogonal class)

forwardscattering echoes

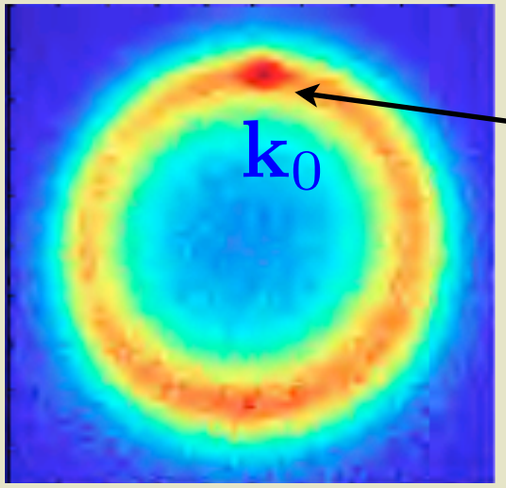


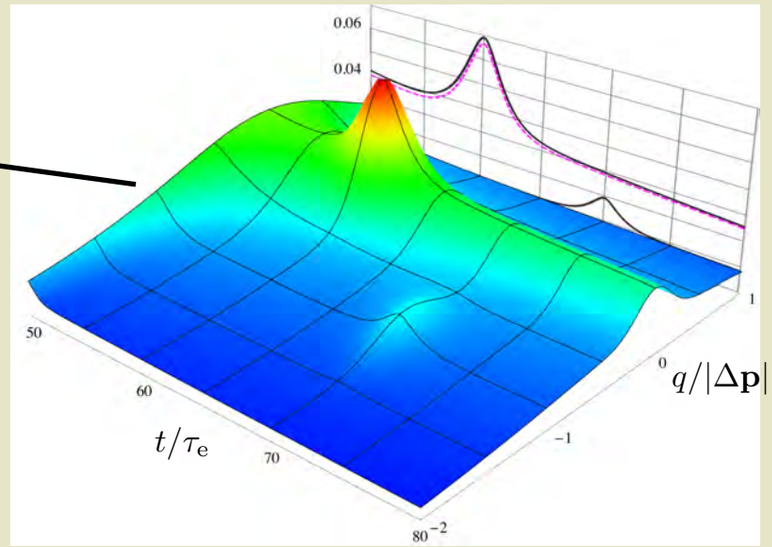
(unitary class)



(orthogonal class)

echo-structure in momentum-space

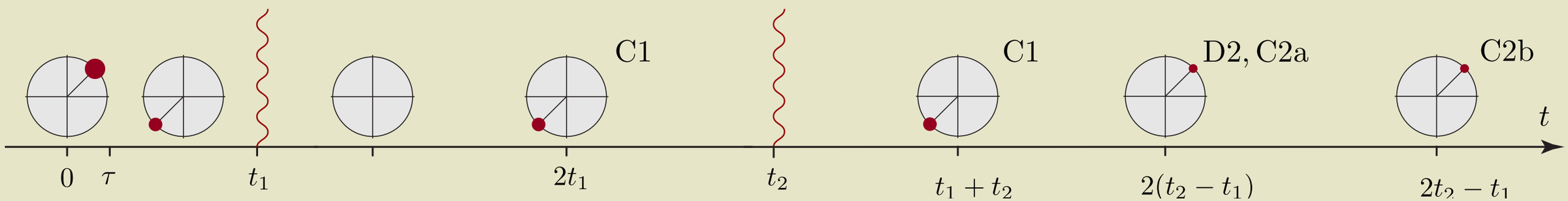




Echo-spectroscopy

at the onset of AL

[TM, C. A. Müller, A. Altland, PRB. 9**1**, 064203 (2015)]

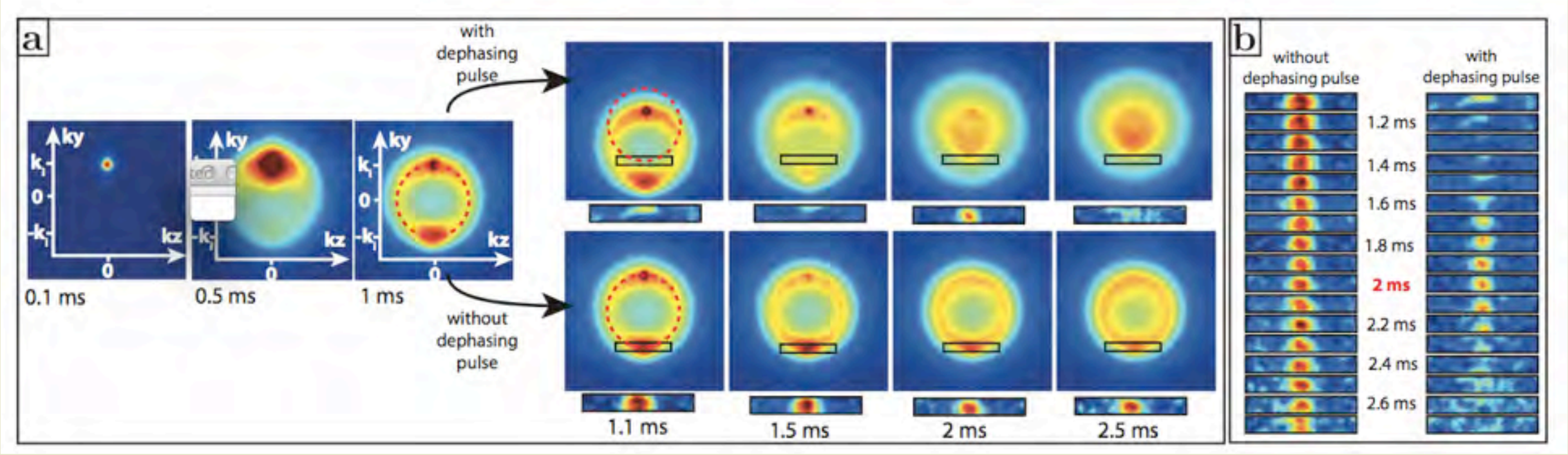


echo-signals in *forward*- and *backward*-scattering directions appear at moments which are in well-defined relations to applied pulses

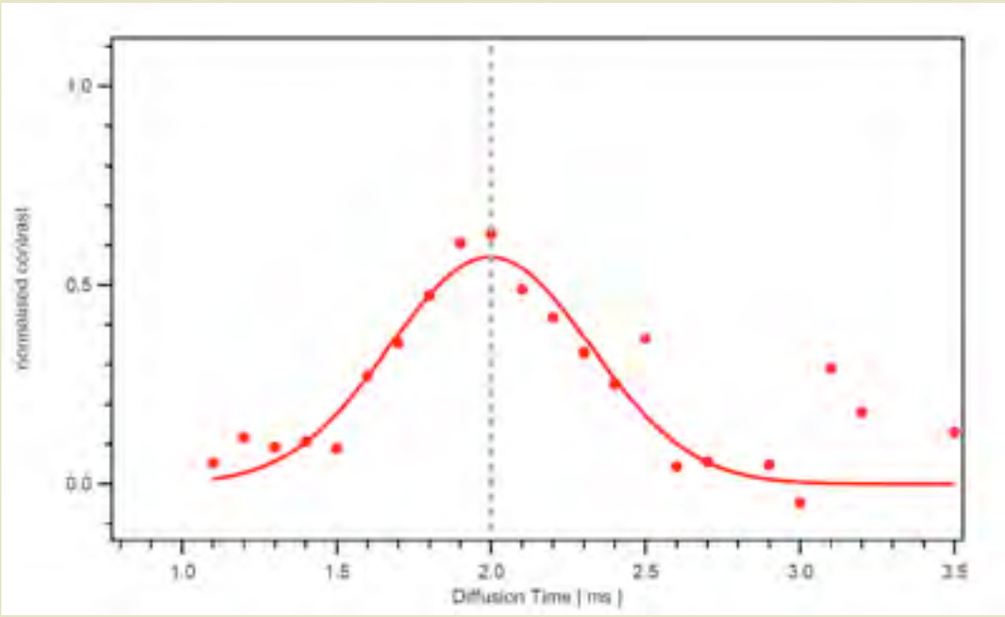
a systematic way to test elementary processes driving AL

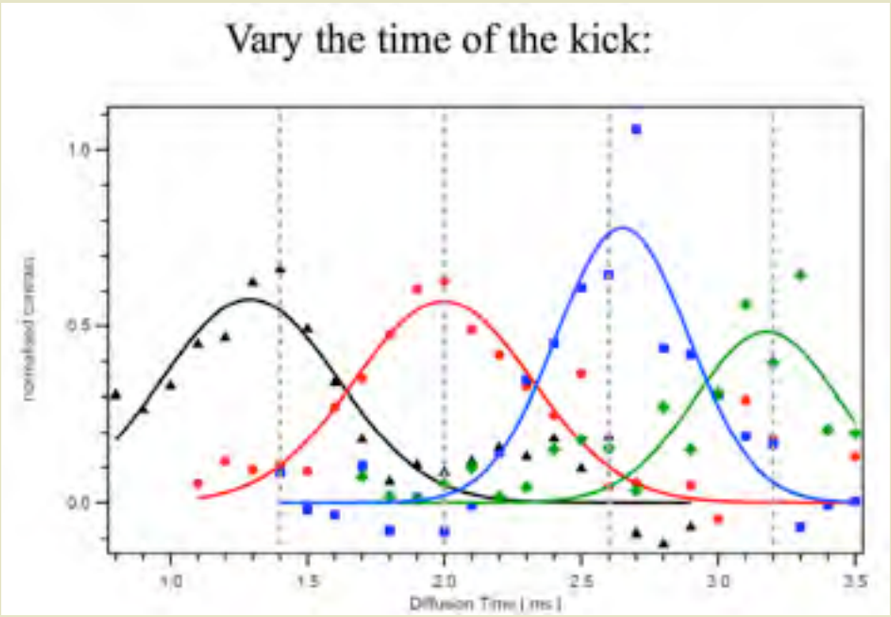
recent experiment: A. Aspect, V. Josse

[K. Müller, J. Richard, V.V. Volchkov, V. Denechaud, P. Bouyer, A. Aspect, V. Josse, PRL (2015)]



coherent backscattering echo



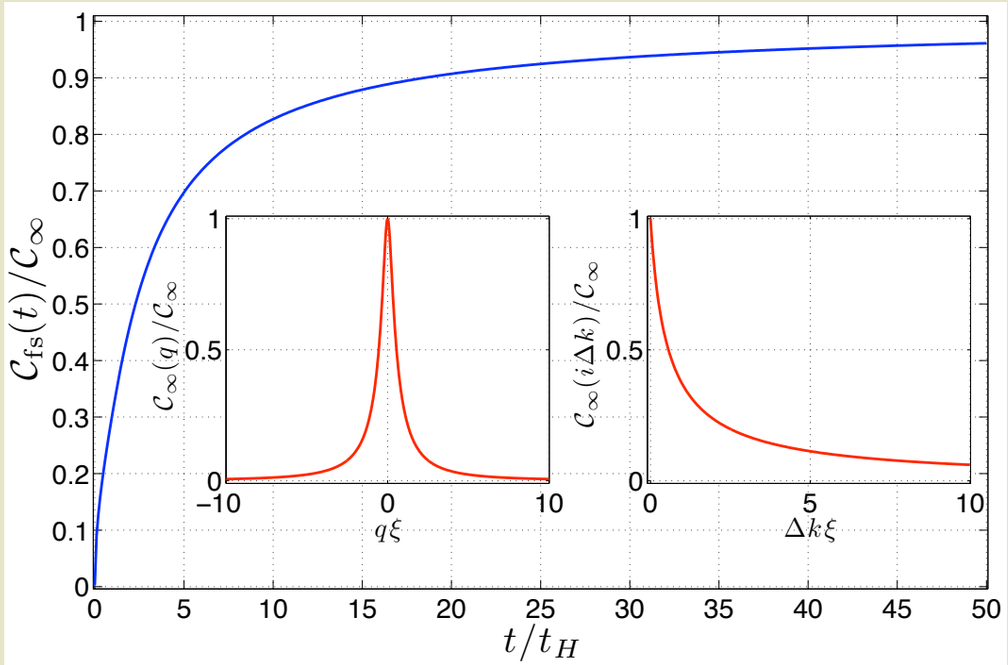


Summary

cold atom quantum quench experiment...

forward peak

- time-resolved portrait of a strong localization phenomenon, with the perspective of observation using current device technology
- direct observation of level-level correlation function of finite size Anderson insulator
- full analytical description by mapping to *3d* Coulomb problem



echo-spectroscopy

- systematic way to study processes driving AL