Suppression and revival of weak localization by manipulation of time reversal symmetry

Varenna school on
Quantum matter at ultralow temperature

JULY 11, 2014

Alain Aspect – Institut d'Optique – Palaiseau

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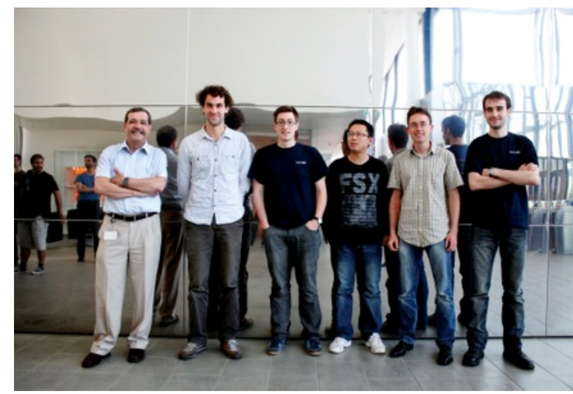
Groupe d'Optique Atomique du

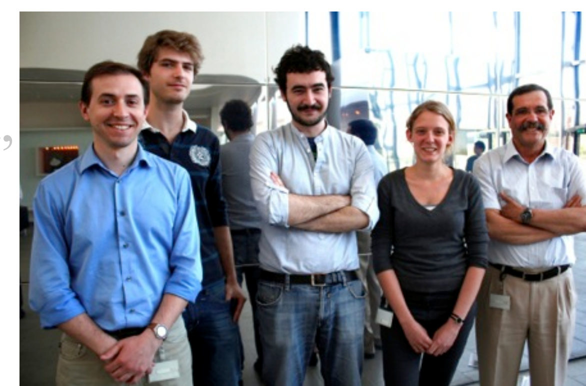
Laboratoire Charles Fabry de l'Institut d'Optique

Post doc and PhD applications welcome

Photo Jean-François Dars

Anderson localisation in the Atom Optics group at Institut d'Optique





Experiments (Philippe Bouyer →Bordeaux)

1. **Vincent Josse,** J. Billy, A. Bernard, P. Cheinet, F. Jendrzejewski, K. Müller, J. Richard, V. Volchkov
2. **Thomas Bourdel,** J. P. Brantut, M. Robert dSV, B. Allard, T. Plisson , G. Salomon, L. Fouché

and our electronic wizards: A.Villing, F. Moron

Theory (Laurent Sanchez Palencia): M. Piraud, L.Pezze, G. Carleo, S Lellouch, G. Boeris

Collaborations: M Lewenstein, G Shlyapnikov, M Holzmann, C Müller, A Altland

The team for CBS and CBSR

Philippe Bouyer | Alain Aspect | Vincent Josse | <u>Kilian Müller</u> | Fred Jendrzejewski | Jérémie Richard | Valentin Volchkov | Vincent Denechaud

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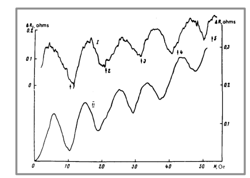
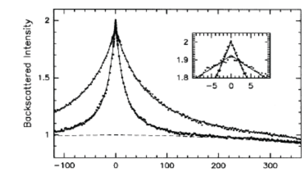
Suppression and revival of weak localization by manipulation of time reversal symmetry: CBSR

1. Weak localization: from Cond. Matt. to AMO Physics





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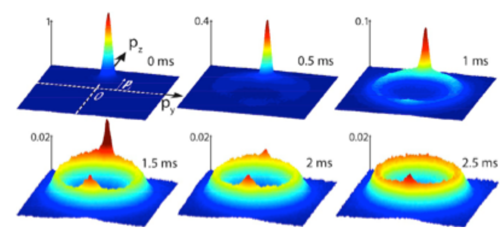

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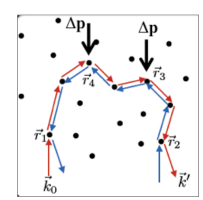

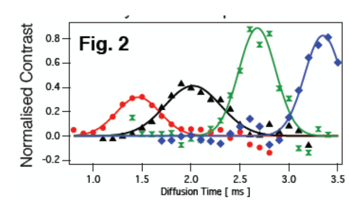

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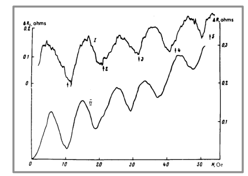

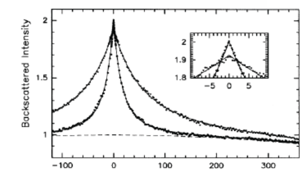

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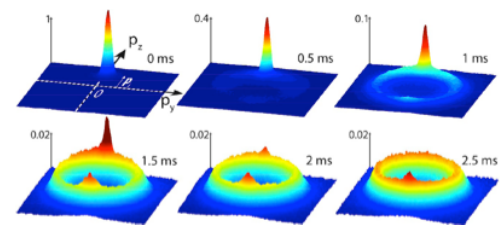

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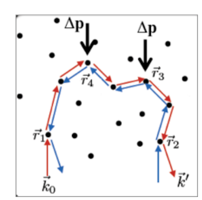
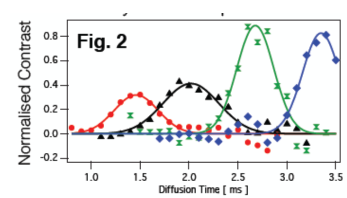


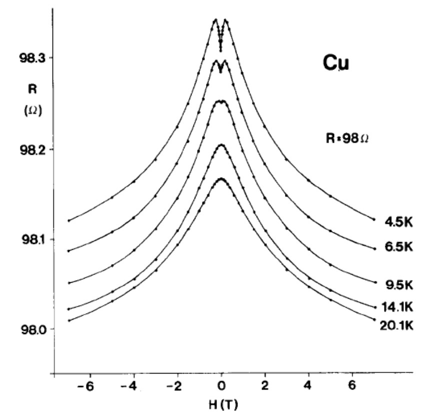


Weak localization in disordered metallic thin films

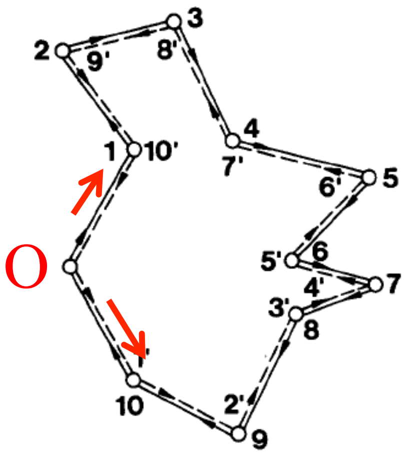
G. Bergmann, Physics reports107, 1 (1984)

Magneto-resistance anomaly

Resistivity of a thin film decreases when a magnetic field is applied (perp to film)



Interpretation of the maximum at $B = 0$ as a quantum transport effect



Interference between amplitudes associated with counter-propagating elastic scattering paths returning close to origin: probability NOT to propagate increases : resistivity augmented.

When $B \neq 0$, different phases for counter propating loops (B breaks time-reversal symmetry): interference washed out

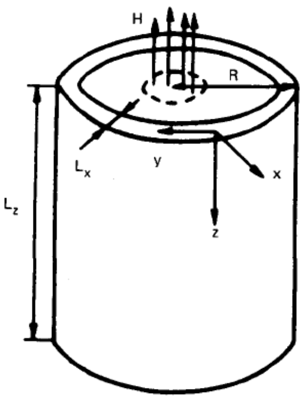
Weak localization in disordered metallic thin films: the AAZ effect a smoking gun of quantum interference

G. Bergmann, Physics reports107, 1 (1984)

The AAZ prediction

BL Altshuler, AG Aronov, BZ Zpivak JETP Lett 33, 94 (1981)

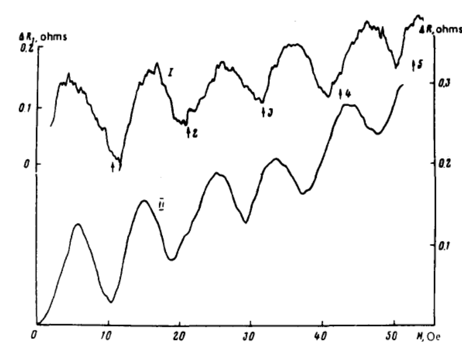
For a thin film on a cylinder, and a magnetic field along the cylinder axis, the phase difference between counter-propagating loops varies linearly with B : interference pattern predicted; maximum of resistance for integer multiples of 2π



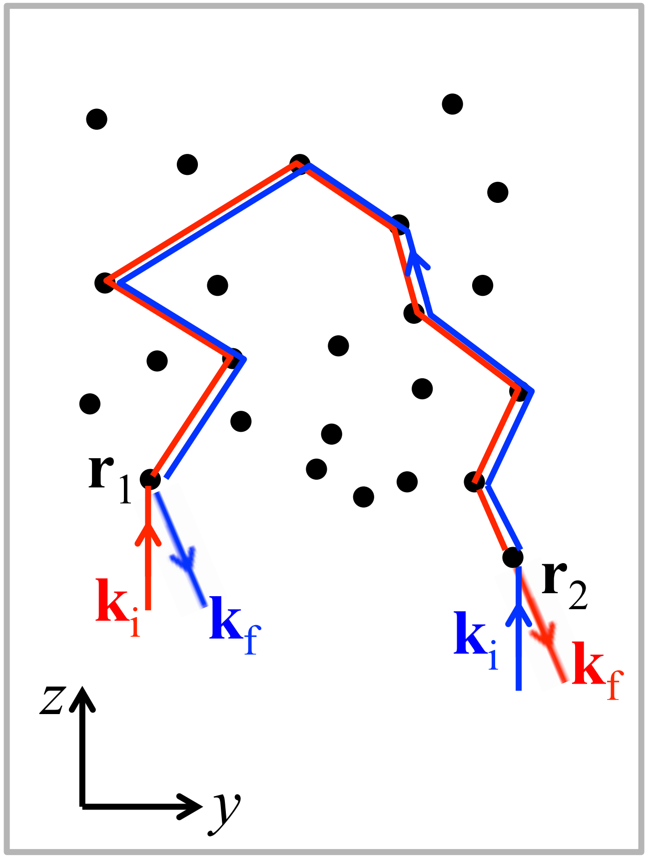
The experimental observation

DY Sharvin and YV Sharvin, JETP Lett 34, 272 (1981)

Resistivity oscillates with B increase: clear two amplitudes interference effect



Coherent Back Scattering (CBS): elementary weak localization



- Input plane wave $\mathbf{k}_\mathrm{i}$
- Output plane wave $\mathbf{k}_\mathrm{f}$

Phase difference between counter-propagating scattering paths

$$\Delta\phi = \varphi_{12} - \varphi_{21} + (\mathbf{k}_\mathrm{i} + \mathbf{k}_\mathrm{f}) \cdot (\mathbf{r}_1 - \mathbf{r}_2)$$

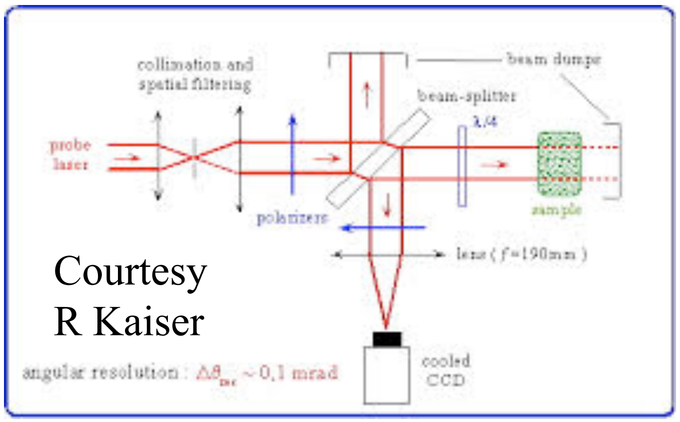
If time reversal symmetry ($\varphi_{12} = \varphi_{21}$)
$\Delta\phi = 0$ for $\mathbf{k}_\mathrm{f} = -\mathbf{k}_\mathrm{i}$

➔ Backward scattering enhanced by factor of 2 by interference effect

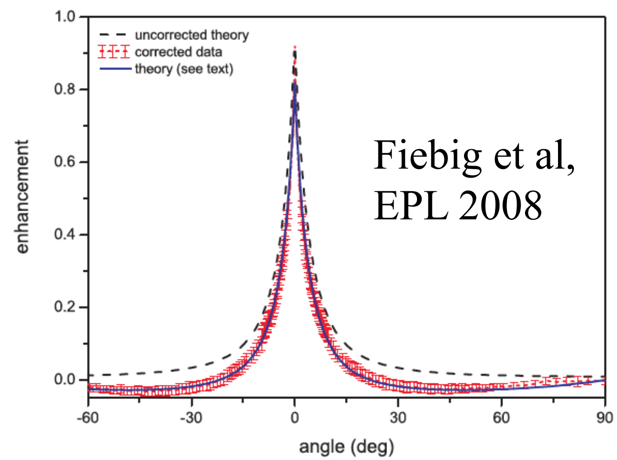
Demands direction resolved detection

Observation of CBS in Optics

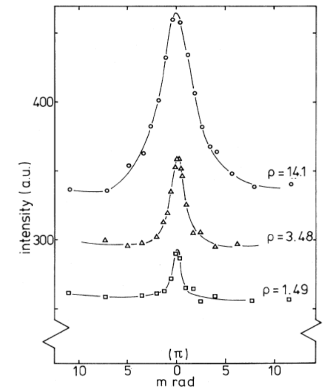
First observed by Kuga and Ishimaru (1984), Van Albada and Lagendijk (1985), PE Wolf and Maret (1985).



Courtesy
R Kaiser



Fiebig et al,
EPL 2008

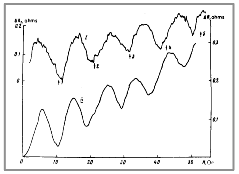


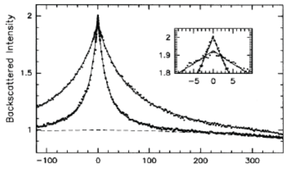
Suppression of CBS by breaking Time Reversal Symmetry

- Magneto-optical effect (Maret et al, 1993)
- Fast variation (ps) of index of refraction (Muskens et al, 2012): demands time resolved detection

Suppression and revival of weak localization by manipulation of time reversal symmetry: CBSR

1. Weak localization: from Cond. Matt. to AMO Physics





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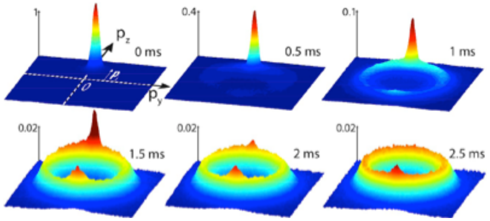

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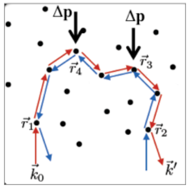
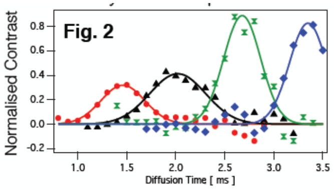


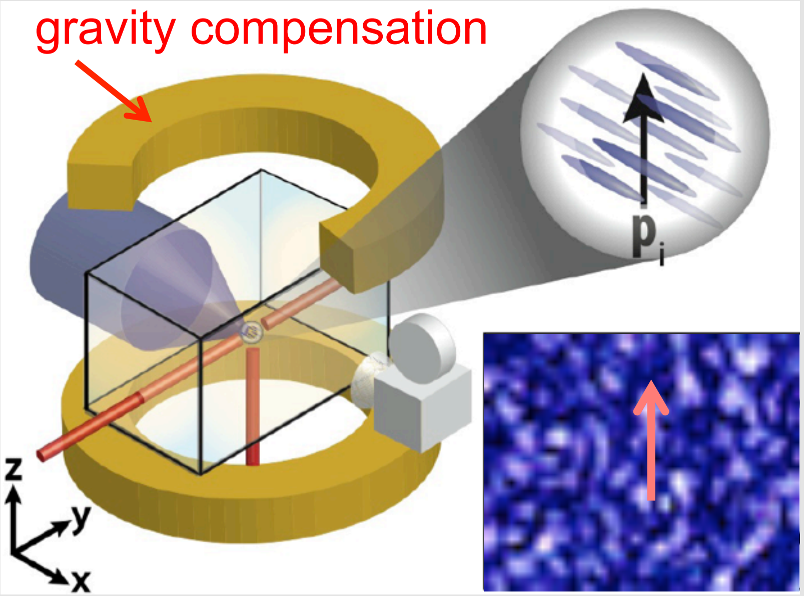


Ultra cold atoms with well defined momentum launched in 2D disorder

Atoms launched with a momentum $\mathbf{p}_i$ in a quasi 2D speckle* (elongated)

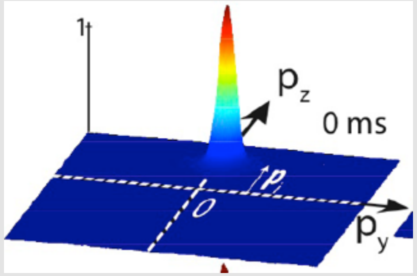
Narrow momentum distribution :

- Harmonic kick on expanding BEC→ stopped atoms
- Magnetic kick



Time of flight ⇒ initial velocities distribution:

$V_i = 3.3 \pm 0.2$ mm / s

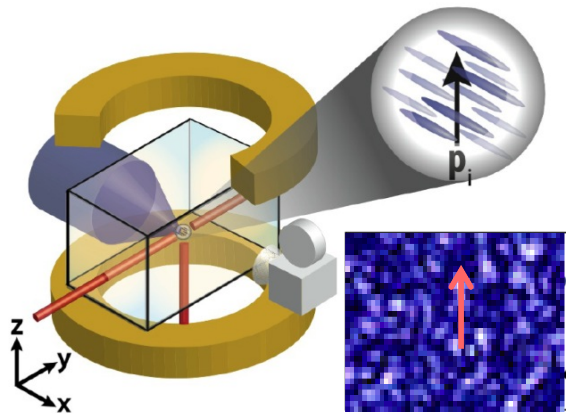


F. Jendrzejewski et al., PRL 109, 195302 (2012)

* Theoretical proposal: Cherroret et al., PRA85, 01604 (2012)

Evolution of momentum distribution in the disordered potential

Atoms launched in 2D disorder with well defined momentum $\mathbf{p_i}$.
Disorder switched off after delay *t*



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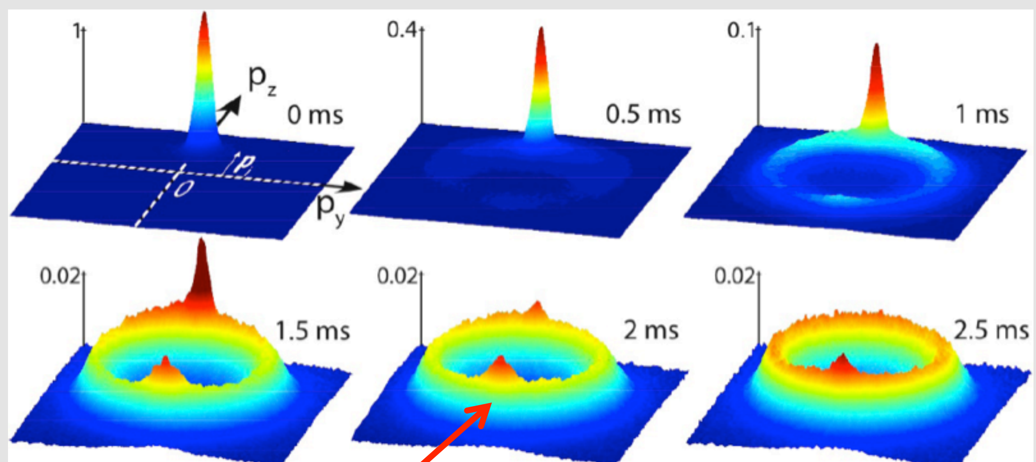
➔Momentum distribution after diffusion time *t*



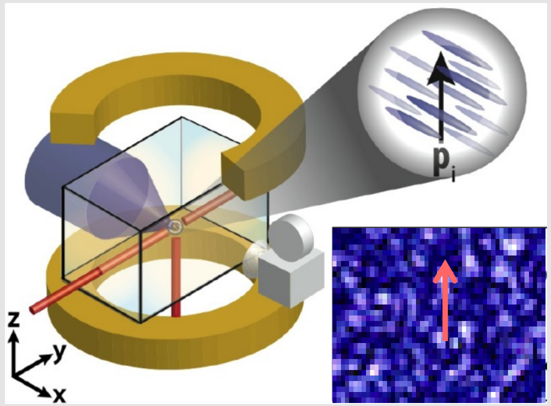
- Elastic scattering ring: determination of scattering and transport times
- Coherent Back Scattering peak

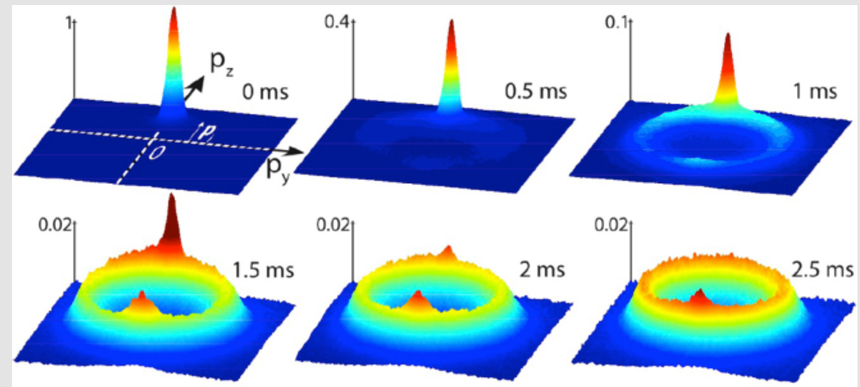
Related results G. Labeyrie et al., EPL 100, 66001 (2012)

Atomic Coherent Back Scattering as an evidence of coherence

Atoms launched with $\mathbf{p}_i$

Momentum distribution after diffusion time t

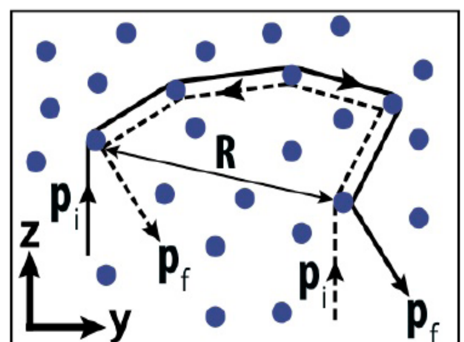




- Elastic scattering ring: determination of scattering and transport times
- Coherent Back Scattering peak

CBS peak: interference between counter propating multiple scattering paths for $\mathbf{p}_f = -\mathbf{p}_i$

Width decreases as $R^{-1} = (2Dt)^{-1/2}$



F. Jendrzejewski et al., PRL 109, 195302 (2012)

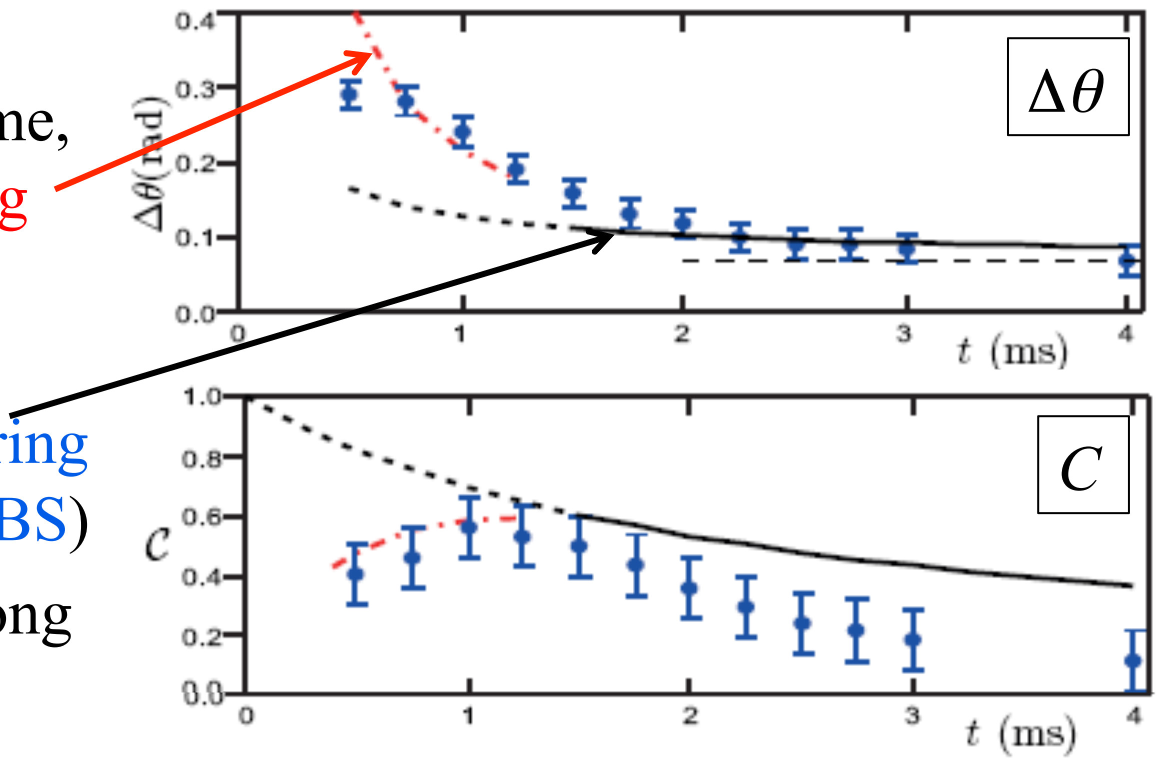
Peak width evolution agrees with model (no adjust. parameter)

Time resolved observation of atomic CBS

Evolution of CBS peak contrast C and width $\Delta\theta$, from short times to long times regime

Cross over

- from short times regime, where single scattering dominates (no CBS)
- to long times regime where multiple scattering dominates ($\Rightarrow$ pure CBS)
- Reduced contrast at long time: not strictly 2D



Good agreement, without adjustable parameter: direct evidence of the role of coherence in quantum transport

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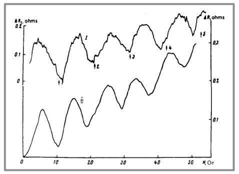

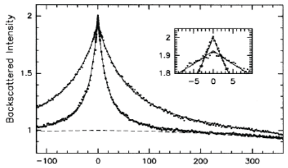

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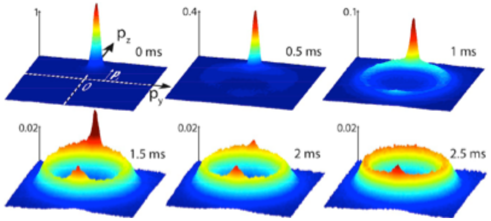

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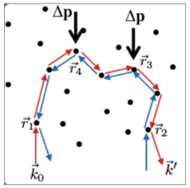
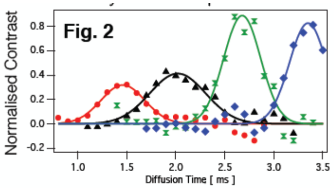
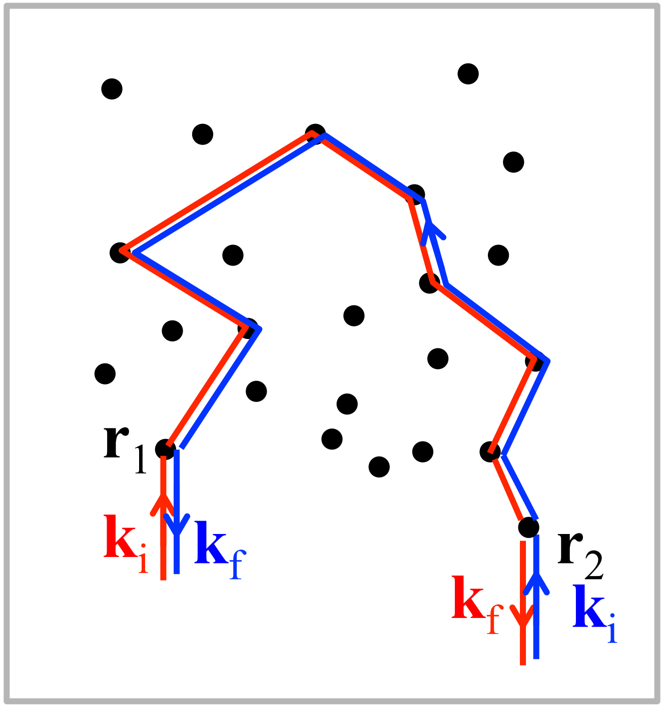




CBS and time reversal symmetry



CBS relies on equality of the action integrals along the trajectories $\mathbf{r}_1 \rightarrow \mathbf{r}_2$ and $\mathbf{r}_2 \rightarrow \mathbf{r}_1$: $\varphi_{12} = \varphi_{21}$

Based on time reversal symmetry of equations of motion

- No magnetic field
- No time depending potential

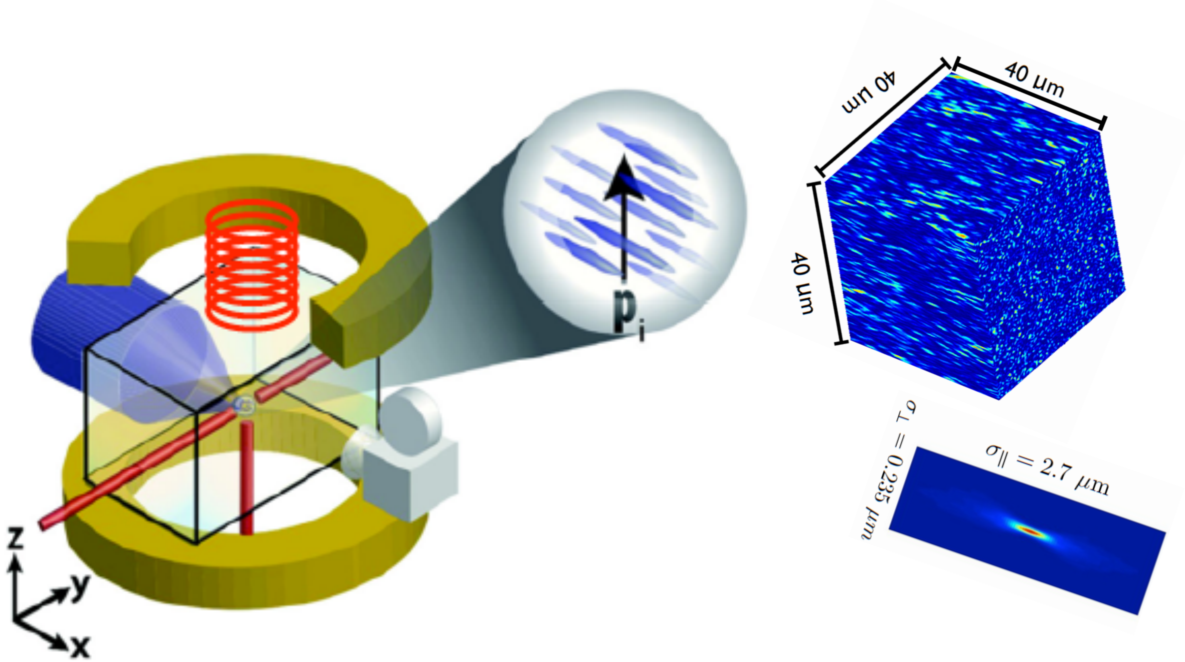
Breaking time reversal symmetry expected to destroy CBS (equivalently, weak localization).

Experimental evidence

- Magneto-resistance in thin films
- Suppression of optical CBS in magneto-optical media
- Suppression of optical CBS by fast change in index of refraction

Manipulating TRS in CBS of ultra-cold atoms?

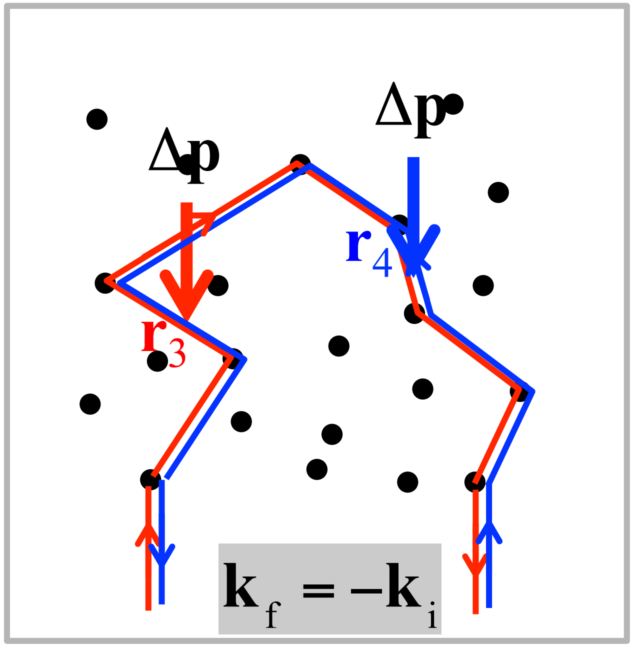
Breaking time reversal symetry in CBS of ultra-cold atoms



Manipulating time reversal Symmetry for CBS of ultra cold atoms :

- Artificial gauge fields equivalent to a magnetic field?
- Time dependent potential: time dependent magnetic field gradient

Breaking Time Reversal Symmetry with a pulsed potential



- Atoms launched at $t = 0$
- Momentum kick $\Delta\mathbf{p}$ at T
- Observation at later time
- Time Reversal Symmetry broken:

$$\Delta\phi_{\text{kick}} = \Delta\mathbf{p}\cdot(\mathbf{r}_3 - \mathbf{r}_4)/\hbar$$

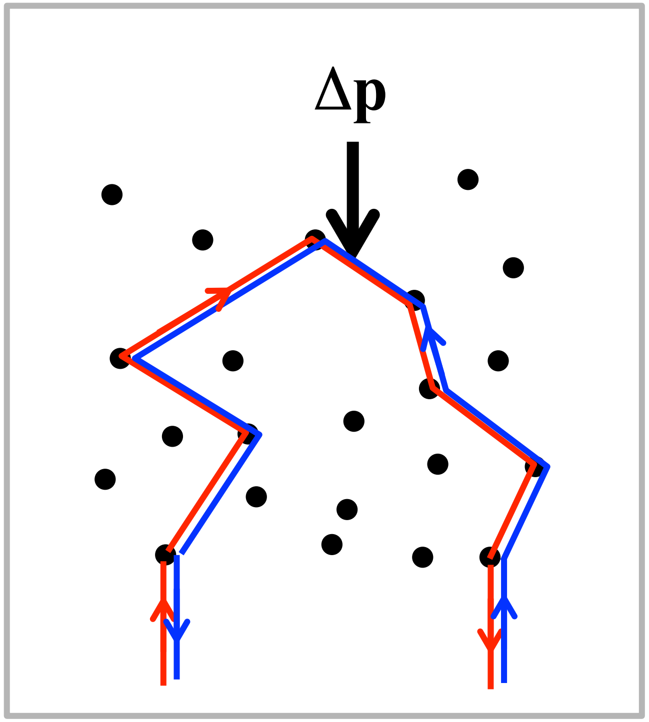
(perturbative calculation)

CBS destroyed for all $t > T$?

Not if $\mathbf{r}_3 = \mathbf{r}_4$ *i.e.* $t = 2T$

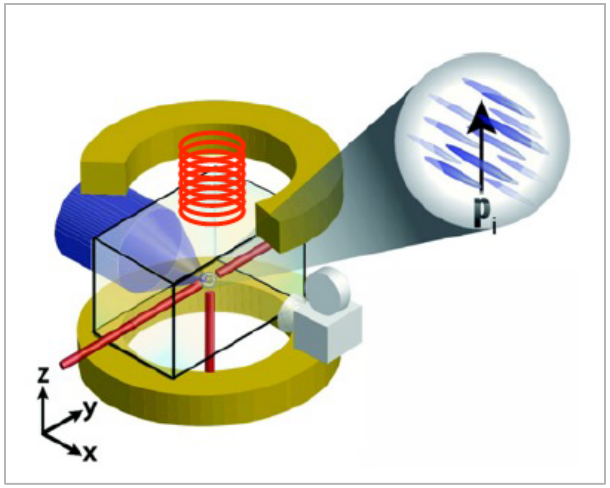
Theoretical proposal by T. Micklitz, A. Altland and C. Müller

Revival for observation at $t = 2T$: Coherent Back Scattering Revival

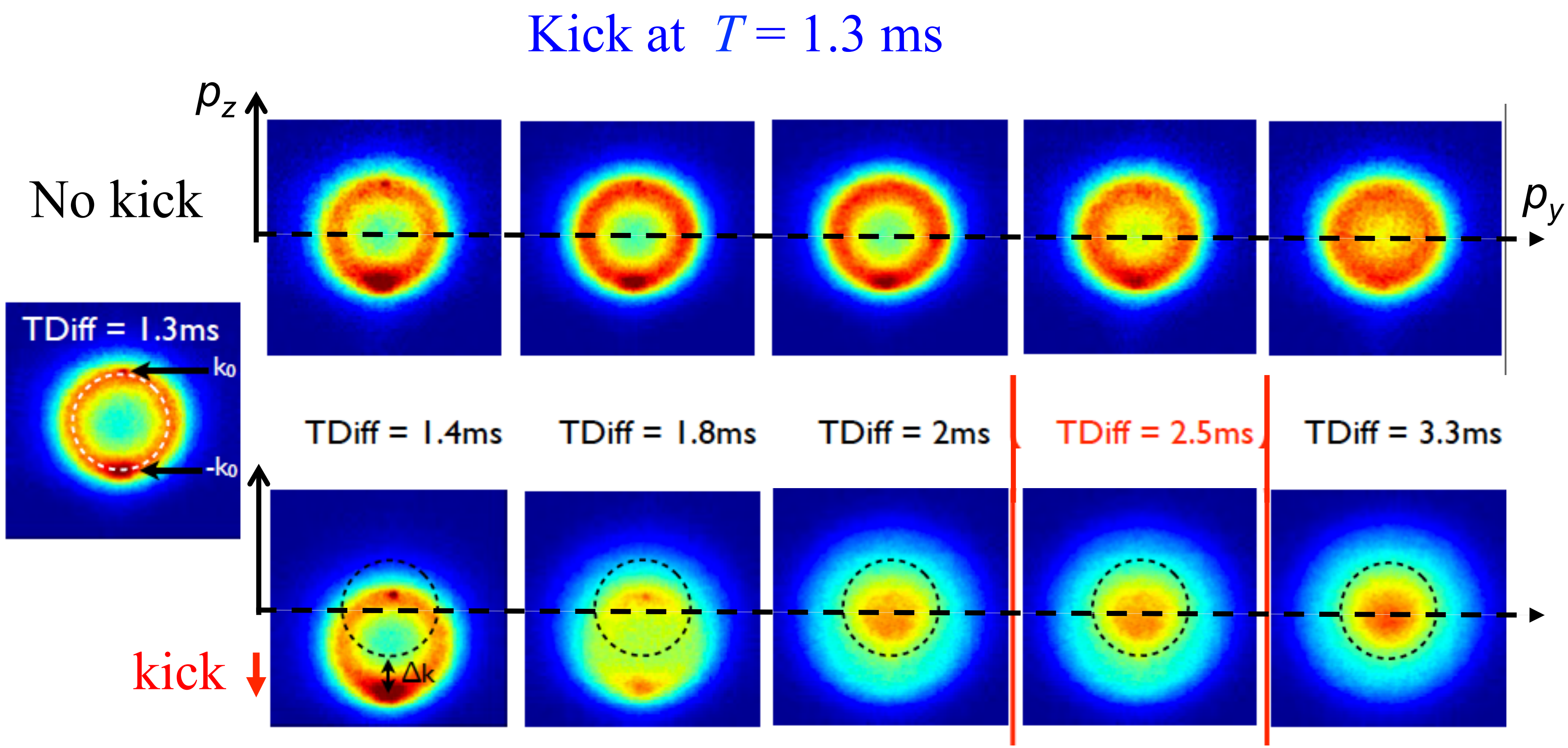


- Atoms lauched at $t = 0$
- Kick $\Delta\mathbf{p}$ at T
- Observation at $t = 2T$
- time reversal symmetry restored
- CBS revival at $t = 2T$?

Worth trying the experiment
(kick with supplementary magnetic field gradient applied for 160 μs)



Experimental observation



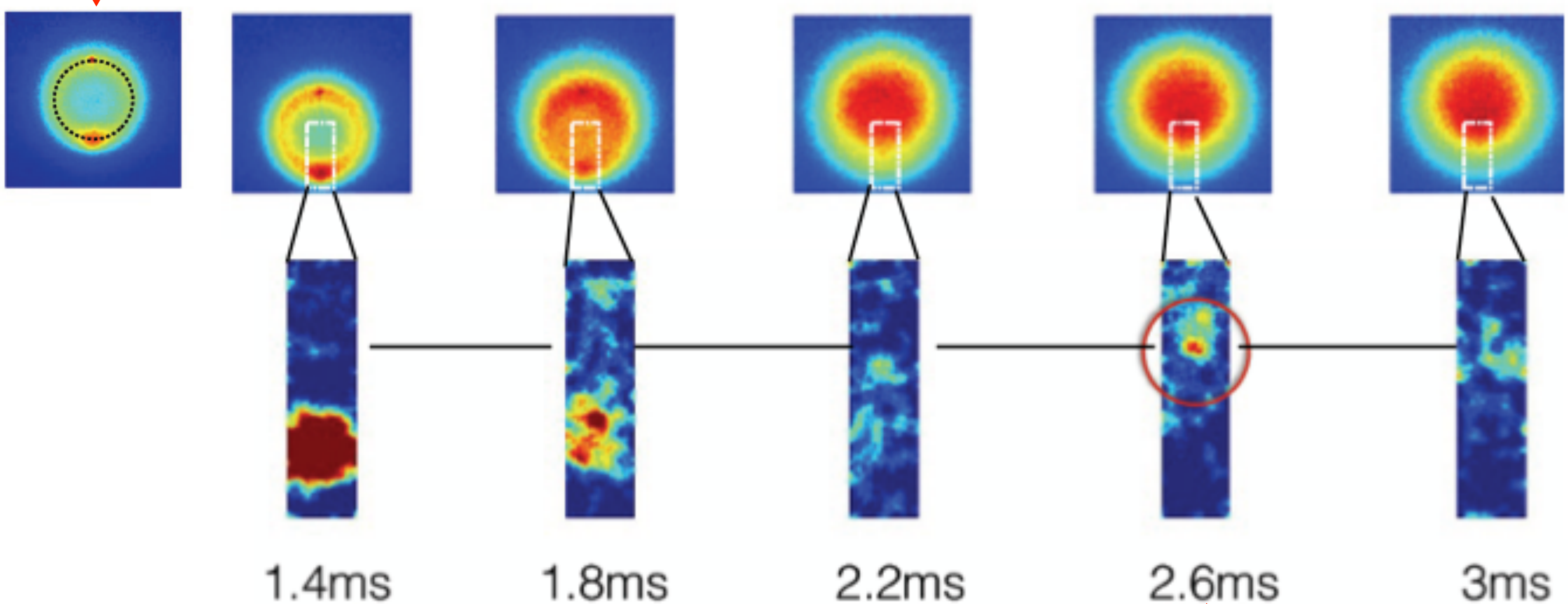
- The kick displaces all atoms by Δ**p** in momentum space
- Isotropy of **p** distribution restored after Boltzmann time

Do we observe a revival ?

Evidence for a revival

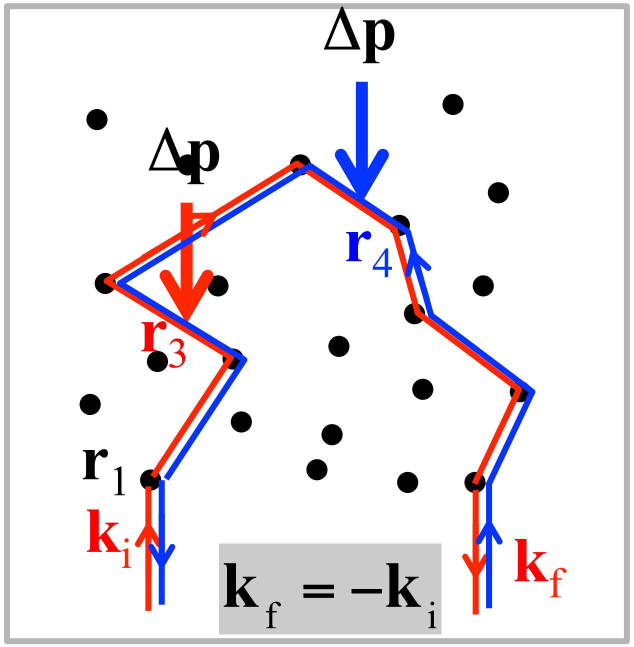
Echo expected "on shell" (at the same energy as the initial energy)
Only a small fraction of the atoms fulfill that condition: "serious" background subtraction needed

Kick at $T = 1.3$ ms



Signal is tiny, but it is there, at the revival time

CBSR expected "on shell"



Phase difference between counter-propating scattering paths :

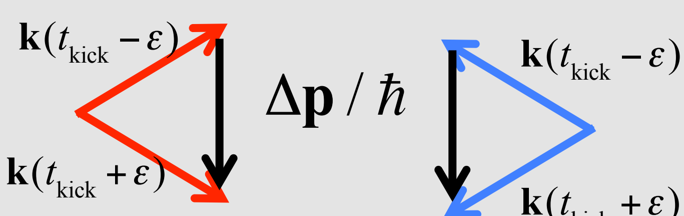
$$\Delta\phi = (\mathbf{k}_{\mathrm{i}} + \mathbf{k}_{\mathrm{f}}) \cdot (\mathbf{r}_1 - \mathbf{r}_2) + \Delta\mathbf{k} \cdot (\mathbf{r}_3 - \mathbf{r}_4)$$

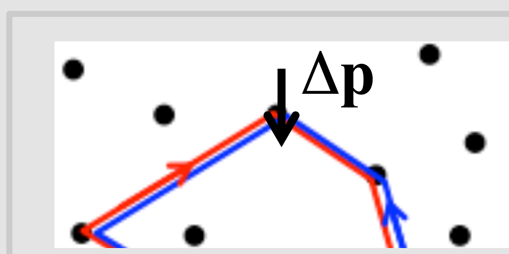
$$\Delta\phi = 0 \quad \text{if} \quad \mathbf{r}_3 = \mathbf{r}_4 \quad \text{and} \quad \mathbf{k}_{\mathrm{f}} = -\mathbf{k}_{\mathrm{i}}$$

$$p_{\mathrm{f}} = p_{\mathrm{i}} \Rightarrow \left(\frac{p^2}{2m}\right)_{\mathrm{f}} = \left(\frac{p^2}{2m}\right)_{\mathrm{i}}$$

- Perturbative case: $p_{\mathrm{f}} \simeq p_{\mathrm{i}}$ if $\Delta\mathbf{p} \bullet \mathbf{k} \approx 0$ with $\mathbf{k}$ = path at kick

- Non perturbative : $\left|\mathbf{k}(t_{\mathrm{kick}} + \varepsilon)\right| = \left|\mathbf{k}(t_{\mathrm{kick}} - \varepsilon) + \Delta\mathbf{p} / \hbar\right|$

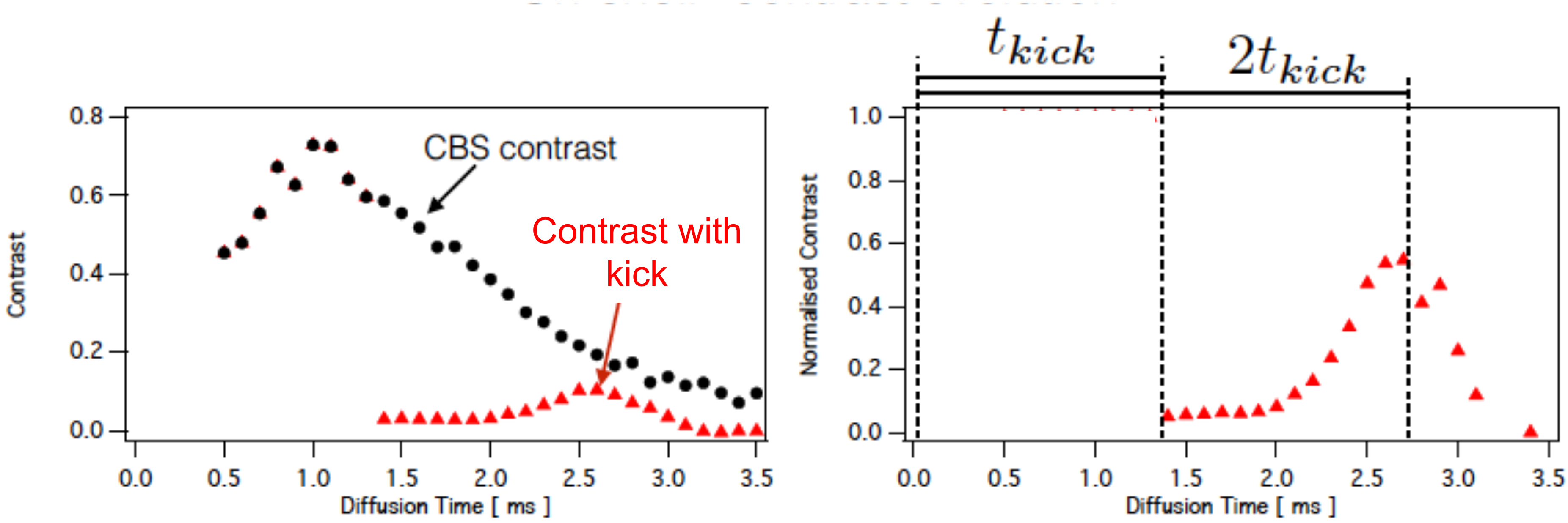




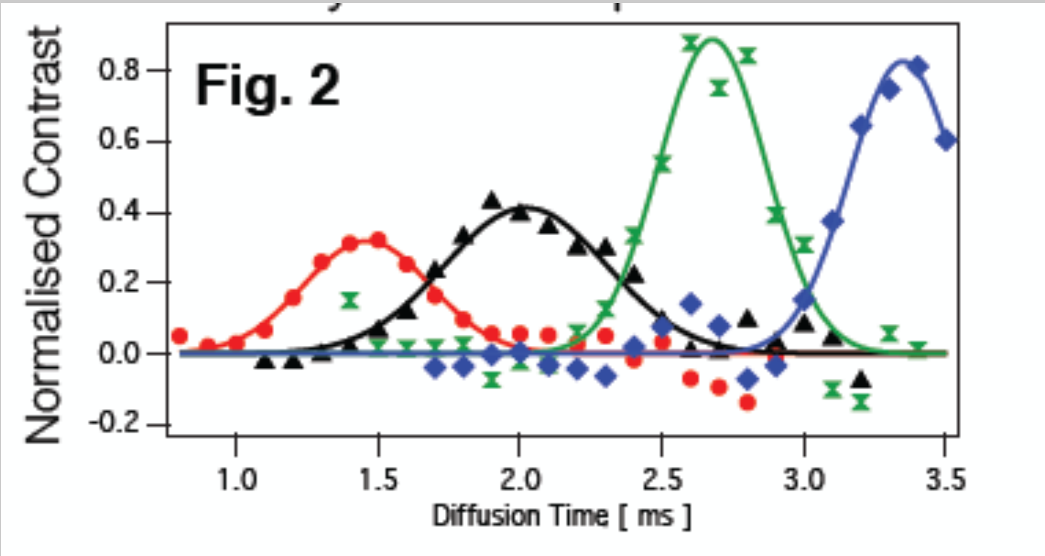
cf. Raman-Nath *vs.* Bragg

Data analysis

Observation at a time when CBS contrast would be much reduced:
we define a normalized echo contrast



Echo for various kick times



Kick times :

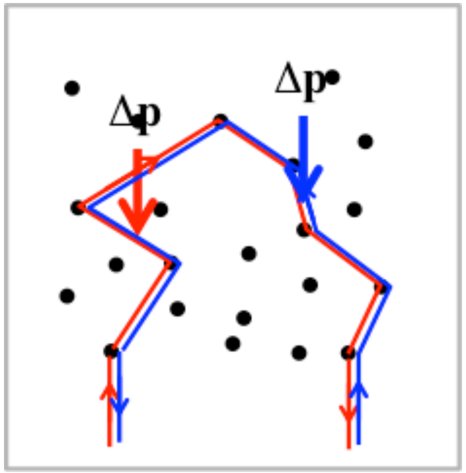
- 0.7 ms
- 1 ms
- 1.3 ms
- 1.6 ms

$$T_{reviv} = 2T_{kick}$$

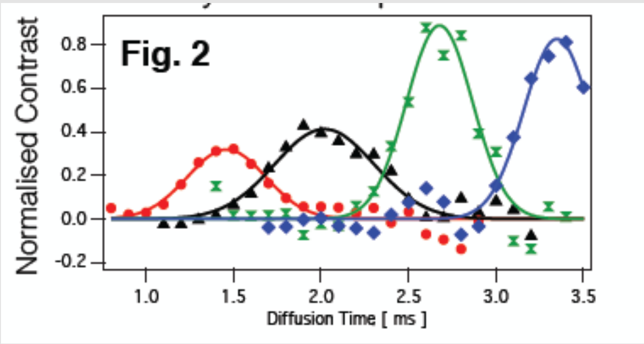
Width and amplitude of the echoes well understood with simple model assuming a mostly ballistic evolution after the kick (cf EE Gorodnichev and D.B. Rogozkin, 1994)

CBSR: a genuine smoking gun of the role of coherence

Breaking time reversal symmetry destroys CBS, an emblematic coherent phenomenon in quantum transport

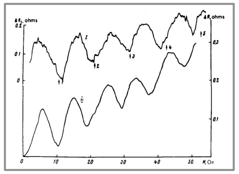
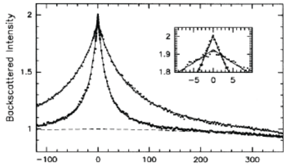


The revival of the CBS peak proves that the destruction of CBS was not due to an ordinary destruction of coherence (by heating for instance).

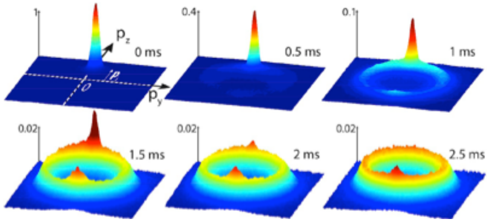


Suppression and revival of weak localization by manipulation of time reversal symmetry: CBSR

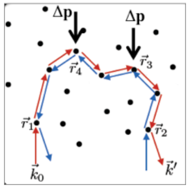
1. Weak localization: from Cond. Matt. to AMO Physics

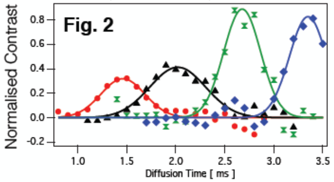



2. 2D Coherent Back Scattering of ultra-cold atoms: time resolved experiments



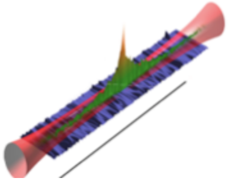
3. Time Reversal Symmetry manipulation : Coherent Back Scattering Revival with ultra-cold atoms, smoking gun of role of coherence. Other possibilities?

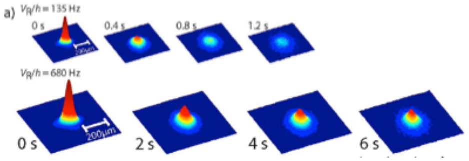


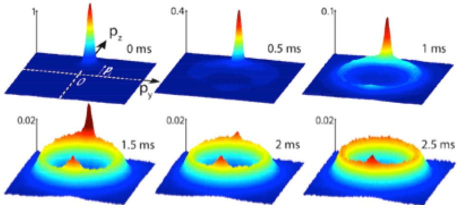


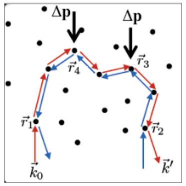
Coherent Back Scattering of ultra-cold atoms in an optical disorder: the role of time reversal symetry

1. Anderson localization of ultra -cold atoms in a laser speckle (1D and 3D): a reminder
2. Coherent Back scattering: a smoking gun of the role of coherence
3. Breaking the time reversal symmetry
4. Outlook and perspectives









Outlook and questions

3D AL
- measure the exact value of the mobility edge
- measure the localization lengths vs energy
- measure critical exponents

Demands a better control of the atom energy in disorder.
Adiabatic ramping of the disorder? Energy selective loading?

2D: AL will not be easy to observe, interesting results already obtained (PRL **104** 220602, NJP **13** 095015; PRA **84** 061606, **85** 033602)

Add controlled interactions: a big challenge for theorists

More evidence of role of coherence in quantum transport:
Kick in 3D? Artificial gauge fields?

A quantum simulator?

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Add controlled interactions: a big challenge for theorists

More evidence of role of coherence in quantum transport:
Scrambling disorder? Artificial gauge fields?

Many challenges for theorists:
genuine **quantum theorists stimulator**