Chaotic scattering of matter waves

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Luchon, 18th january

Outline

1D scattering on periodic potential

Bragg mirror

Scattering on time-modulated potential

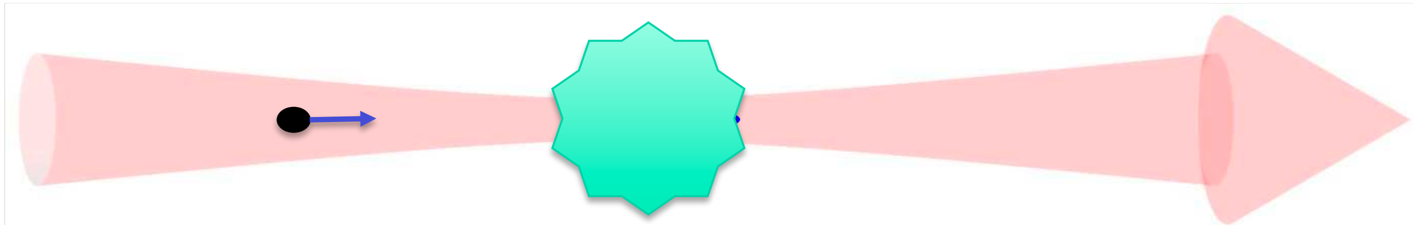
Chaotic scattering

Transition to chaotic scattering

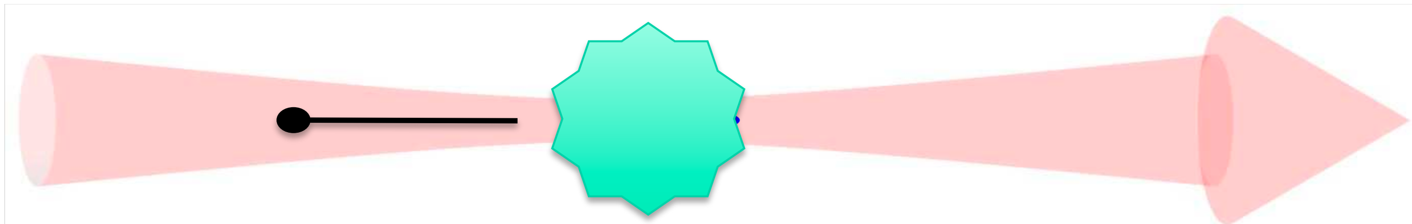
Guided matter wave beam splitter

Matter wave scattering on a localized defect

Launching a Bose-Einstein condensate in an optical guide



Guided atom laser (outcoupled from a trapped Bose-Einstein condensate)



This method gives access to the « trajectory »

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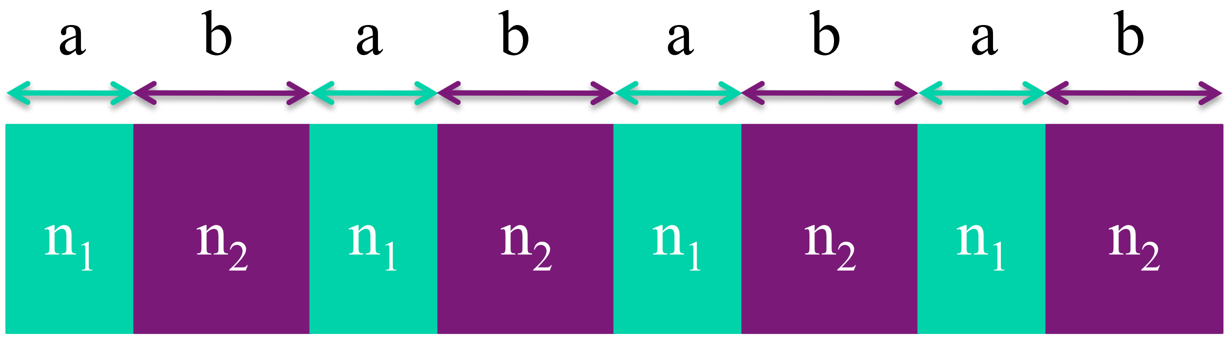
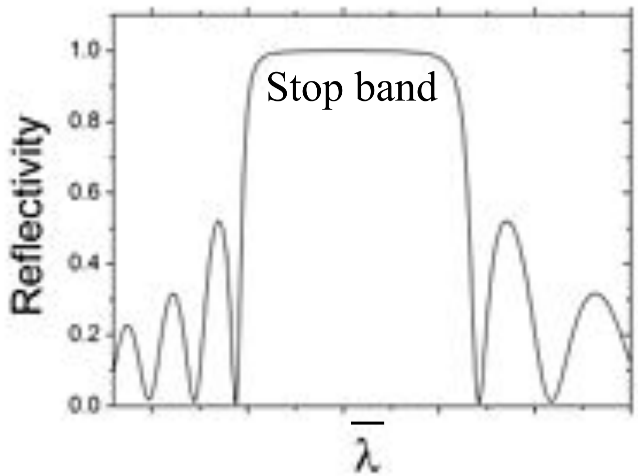
Bragg mirror in optics



Bragg interference condition

$$\bar{k} n_1 a = \bar{k} n_2 b = \frac{\pi}{2} \quad [\pi]$$

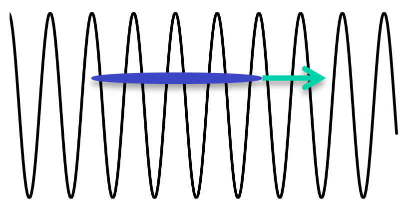
Reflection > 99,99 %



Is it possible to develop « dieletric » atom optics elements?

Iacopo Carusotto – Luis Santos (1998- 2002)

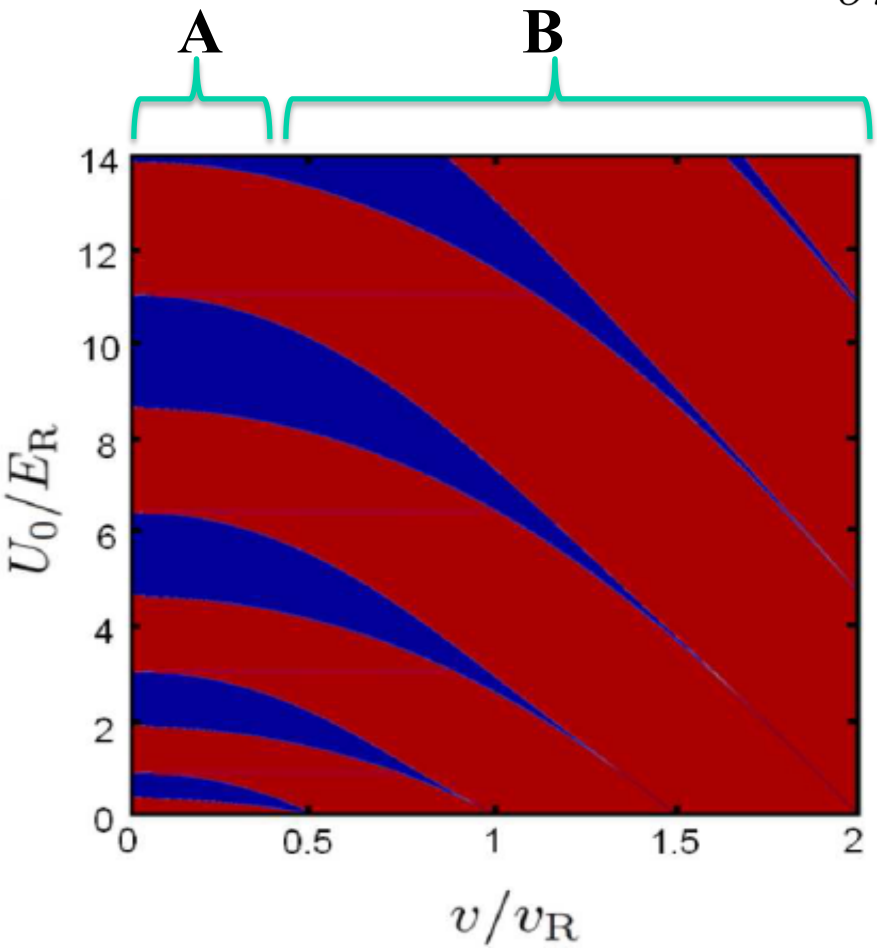
Particle in an infinite periodic potential



$$\frac{-\hbar^2}{2m}\frac{\partial^2\Psi}{\partial x^2} + U_0(1+\sin(2kx))\Psi = E_c\Psi$$

$$\frac{\partial^2\Psi}{\partial \tau^2} + (a - 2q\sin(2\tau))\Psi = 0$$

Mathieu equation

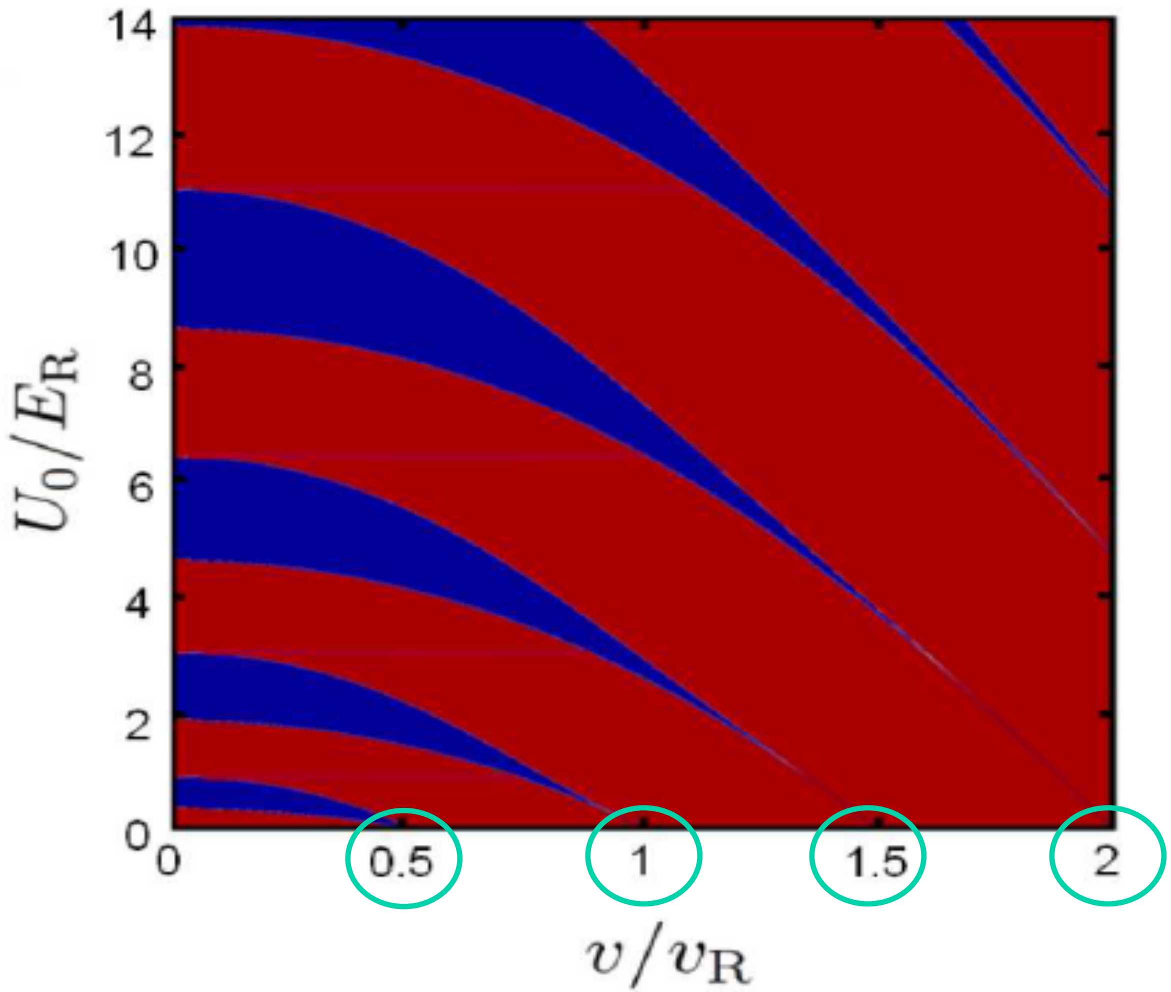


A : dominated by quantum reflection, small penetrability

B : large penetrability

Bragg reflection
(the small potential depth limit)

Red : allowed; blue : forbidden



d lattice spacing

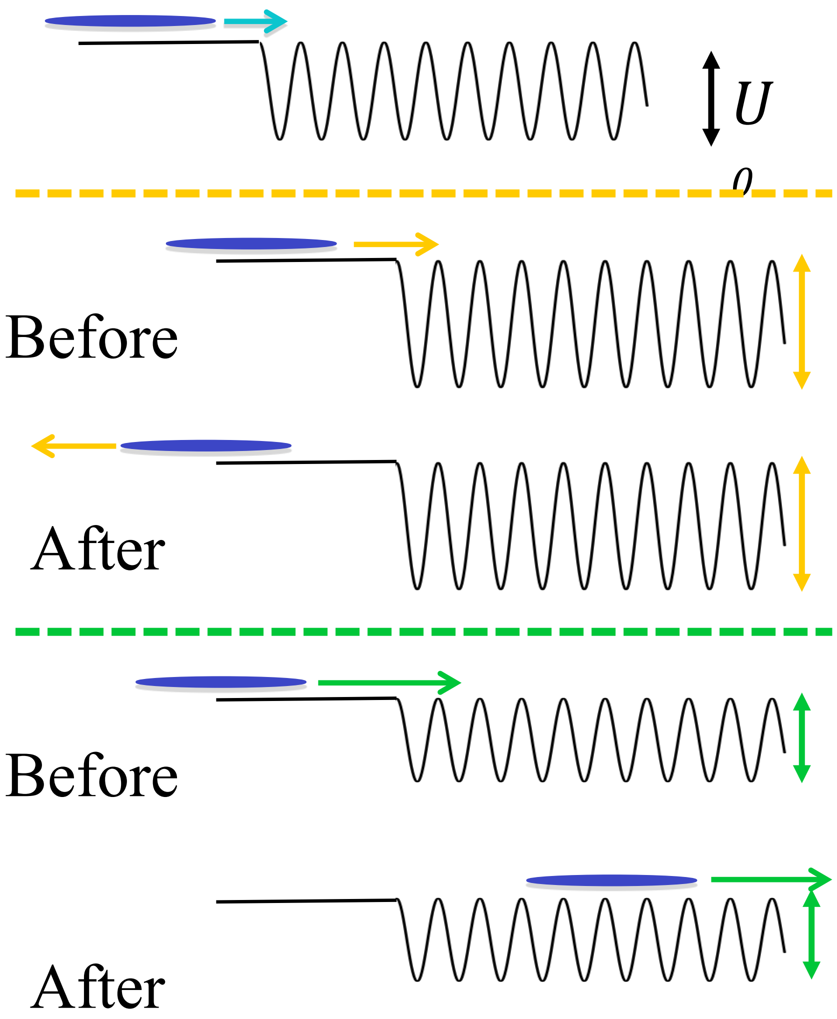
$$2d = n\lambda \sin\Theta$$

$$\lambda = h/(mv)$$

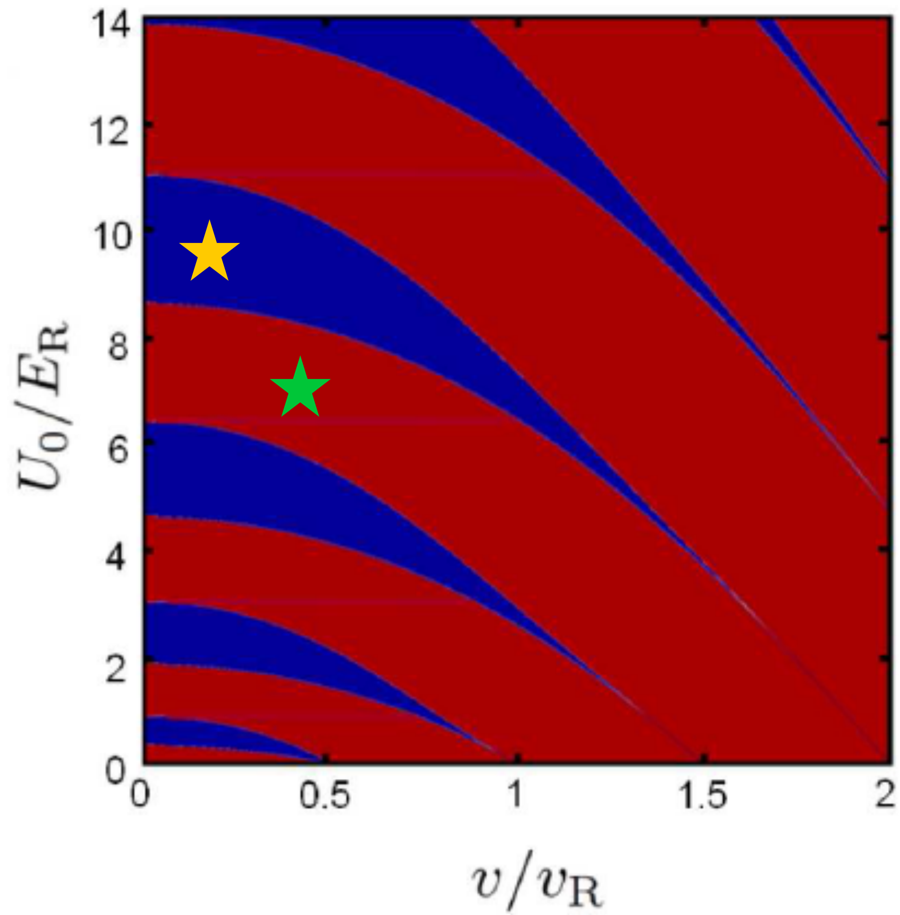
$$\Theta = \pi/2$$

$$v = nv_R/2$$

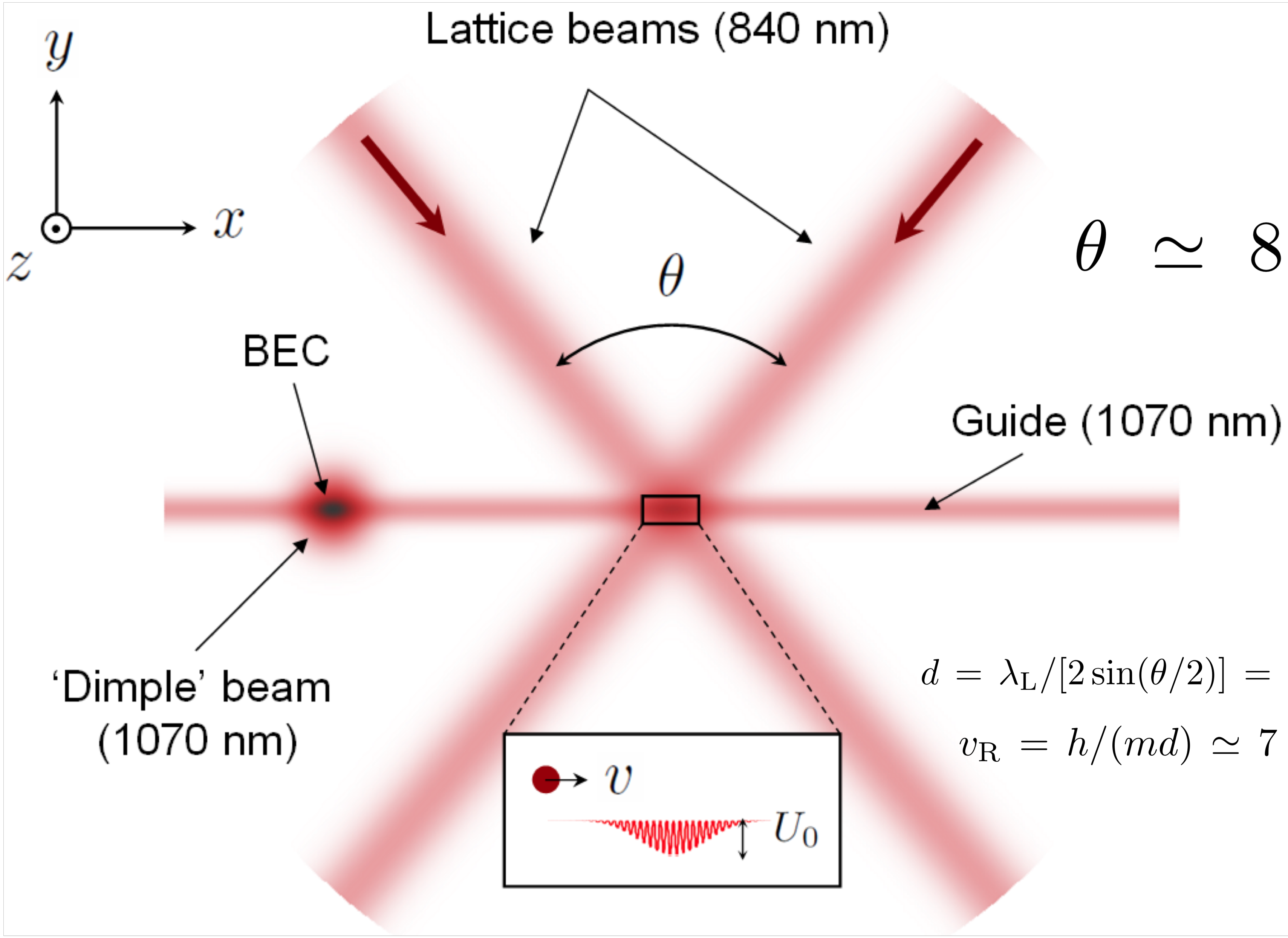
Simple picture of the scattering



Red : transmitted ; blue : reflected



Experimental setup

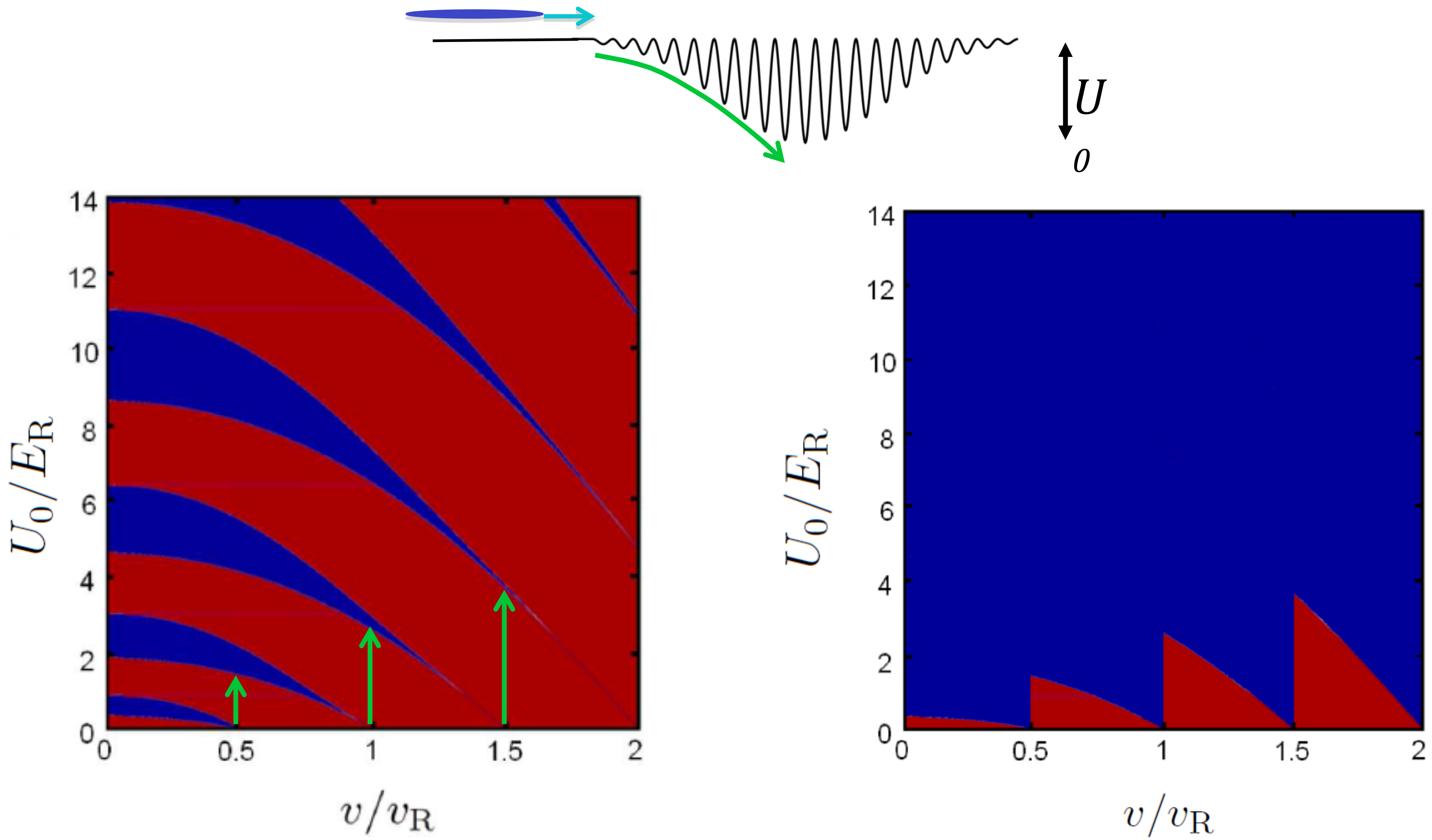


$$\theta \simeq 81^\circ$$

$$d = \lambda_L/[2\sin(\theta/2)] = 650 \text{ nm}$$

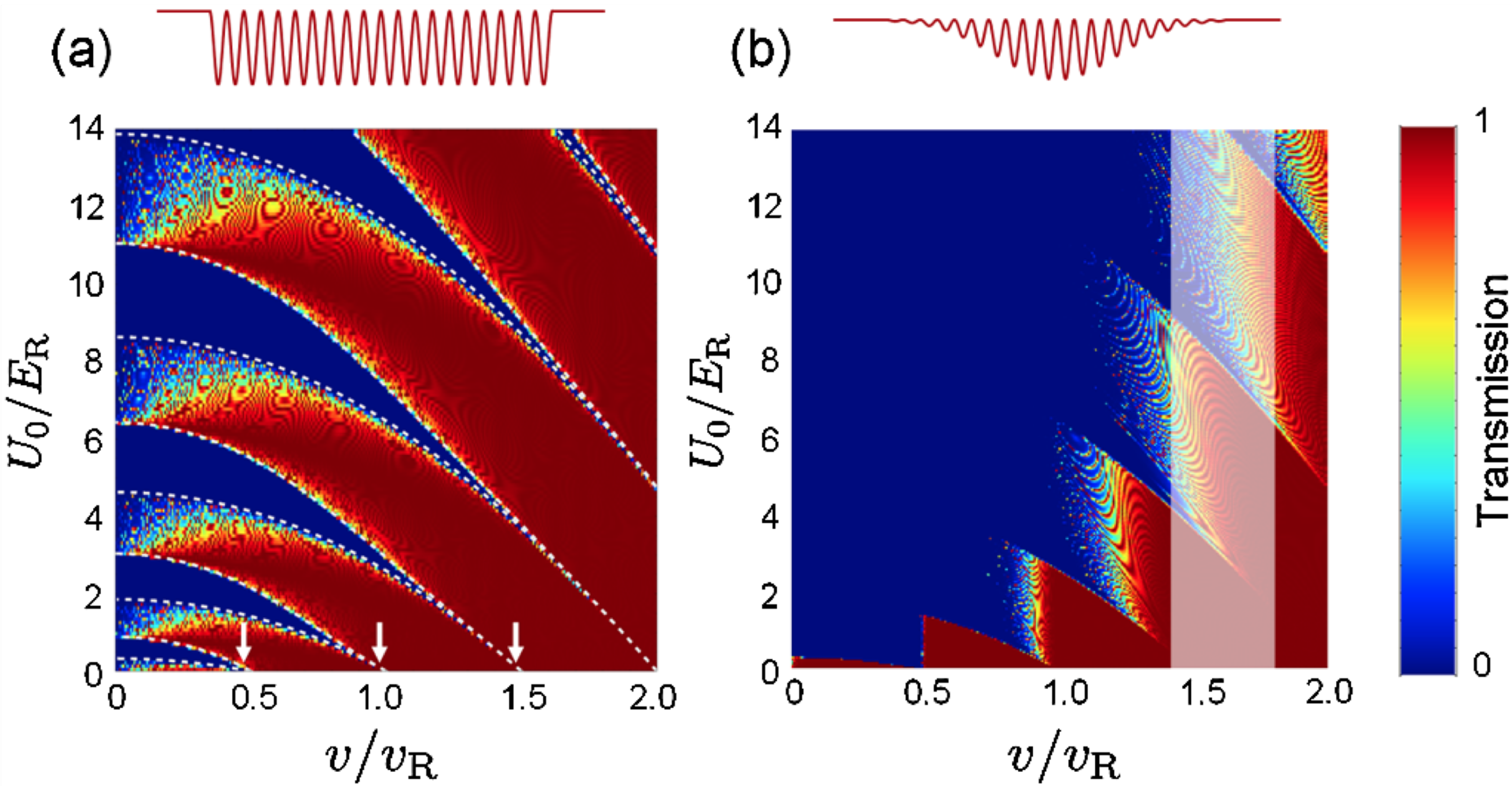
$$v_R = h/(md) \simeq 7 \text{ mm/s}$$

Probing an optical lattice with an envelope



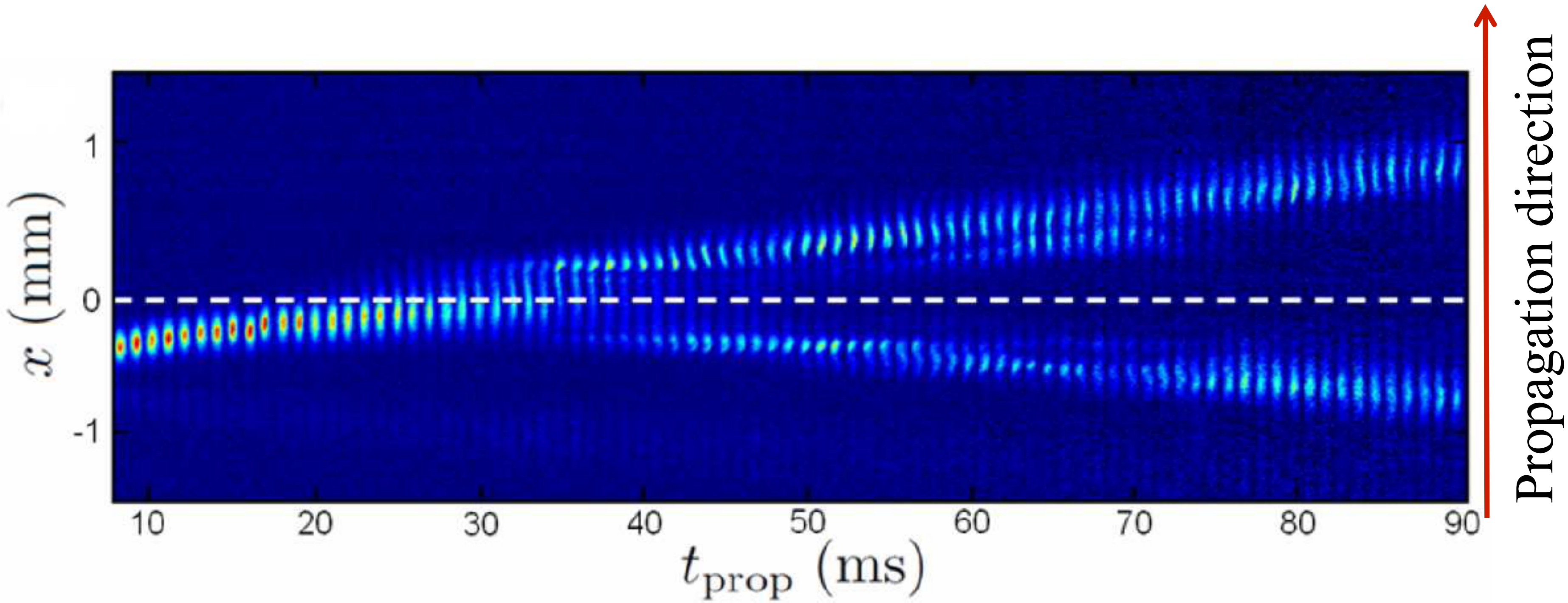
The response of the system contains a fingerprint of the band structure of the lattice

Probing an optical lattice (the real system)



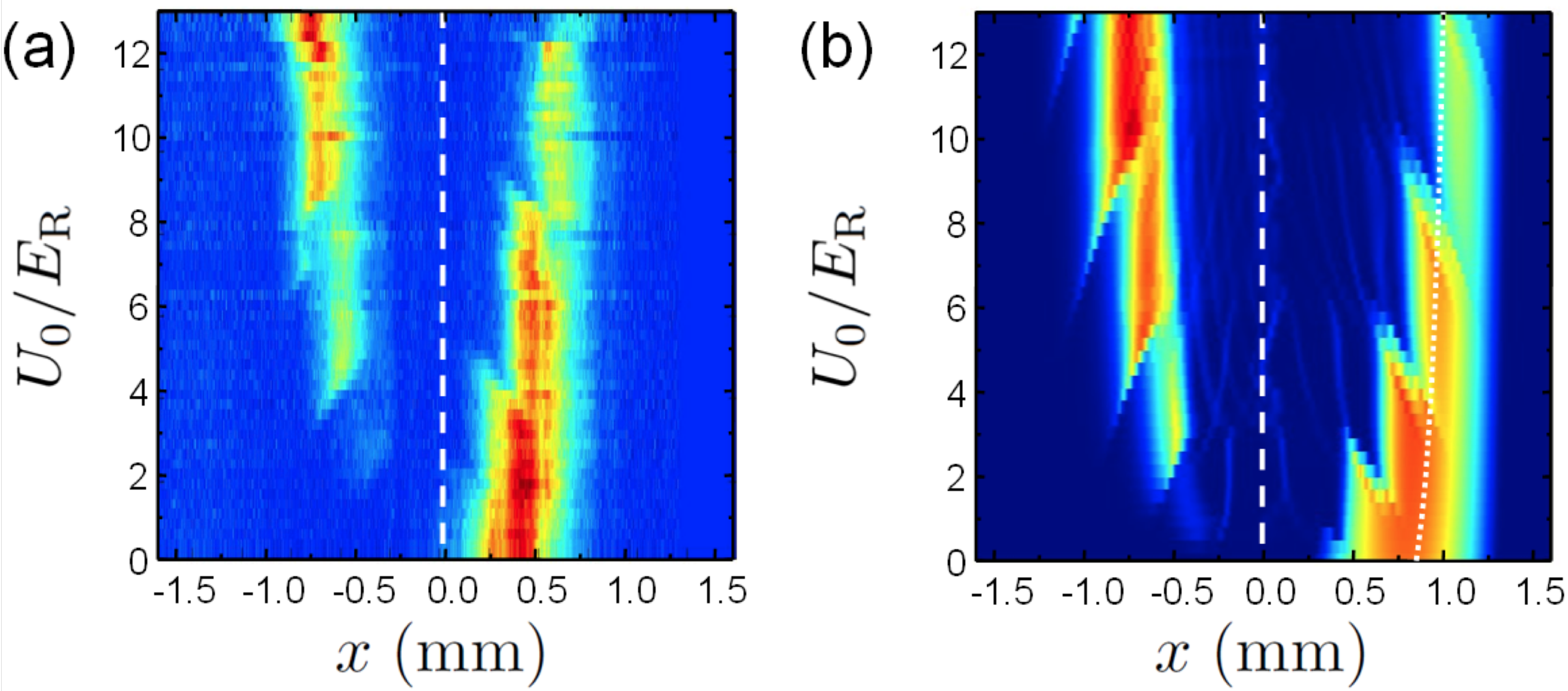
Probing an optical lattice (the real system)

$U_0 \simeq 11 E_R$ Experiment: example of result



Bragg mirror results

Experiment **Numerical simulation**

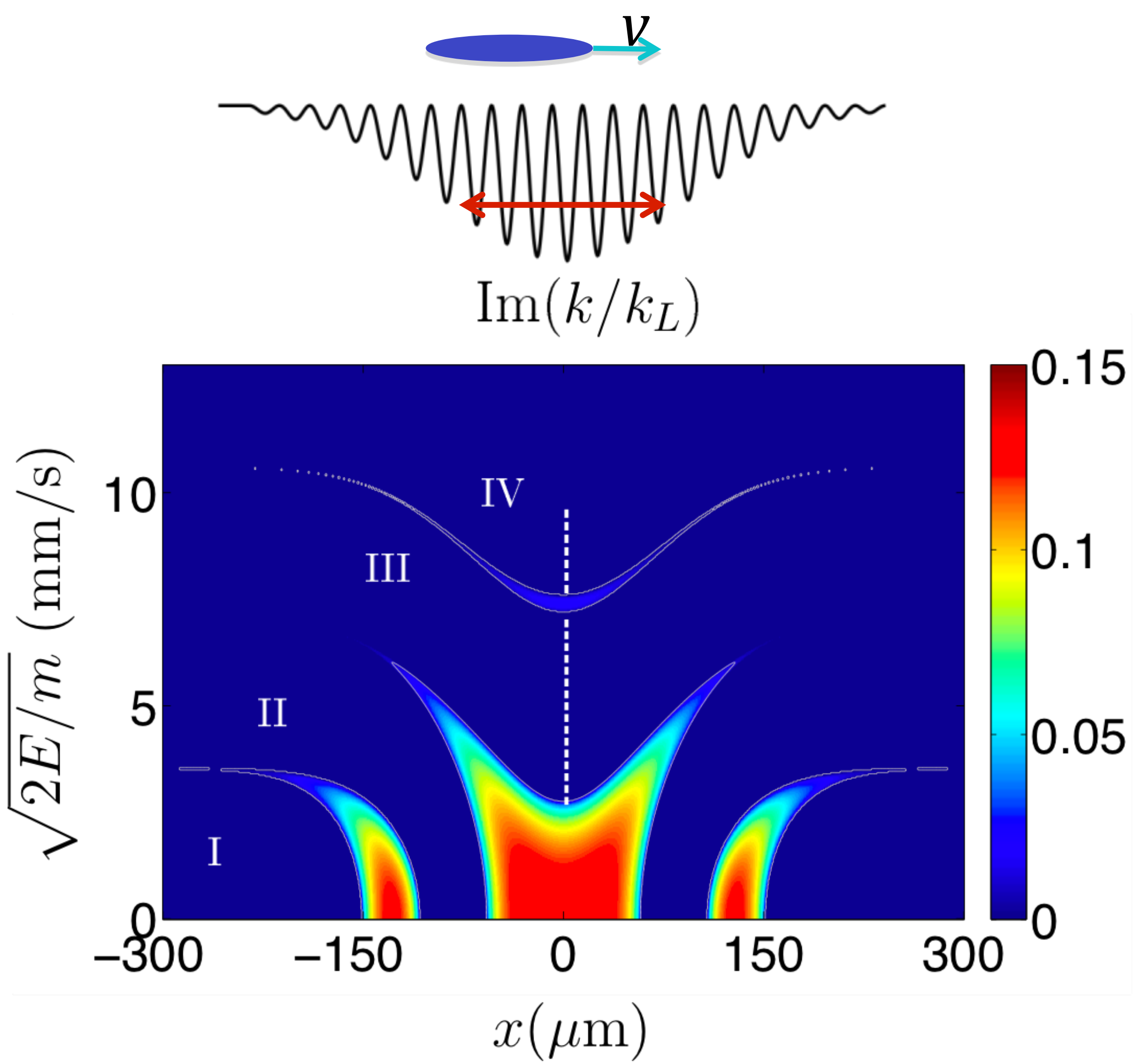


Scattering experiment enables to probe directly the band structure

Tunable velocity filter: low pass / high pass / notch / band pass filter

Ch. Fabre et al. PRL **107**, 230401 (2011)

Cavity with imaginary walls

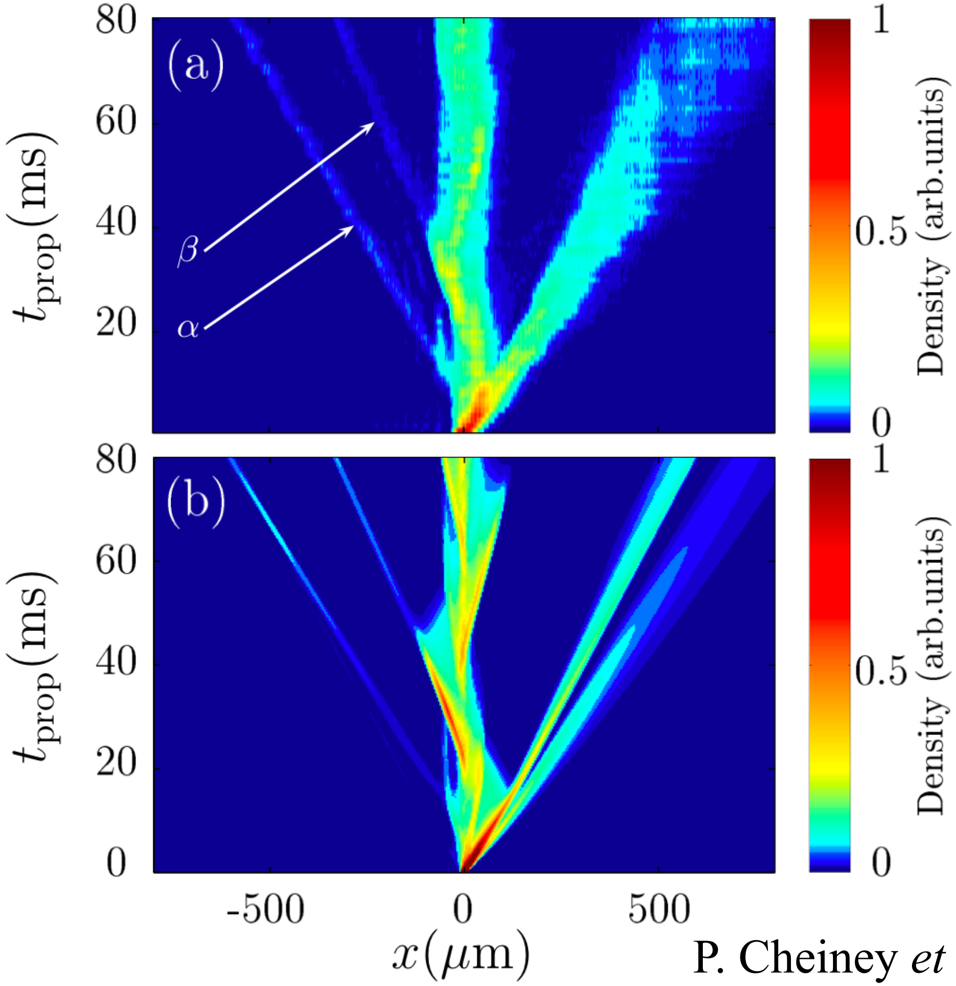


The envelope « projects » the band gap in position space

Spatial gaps

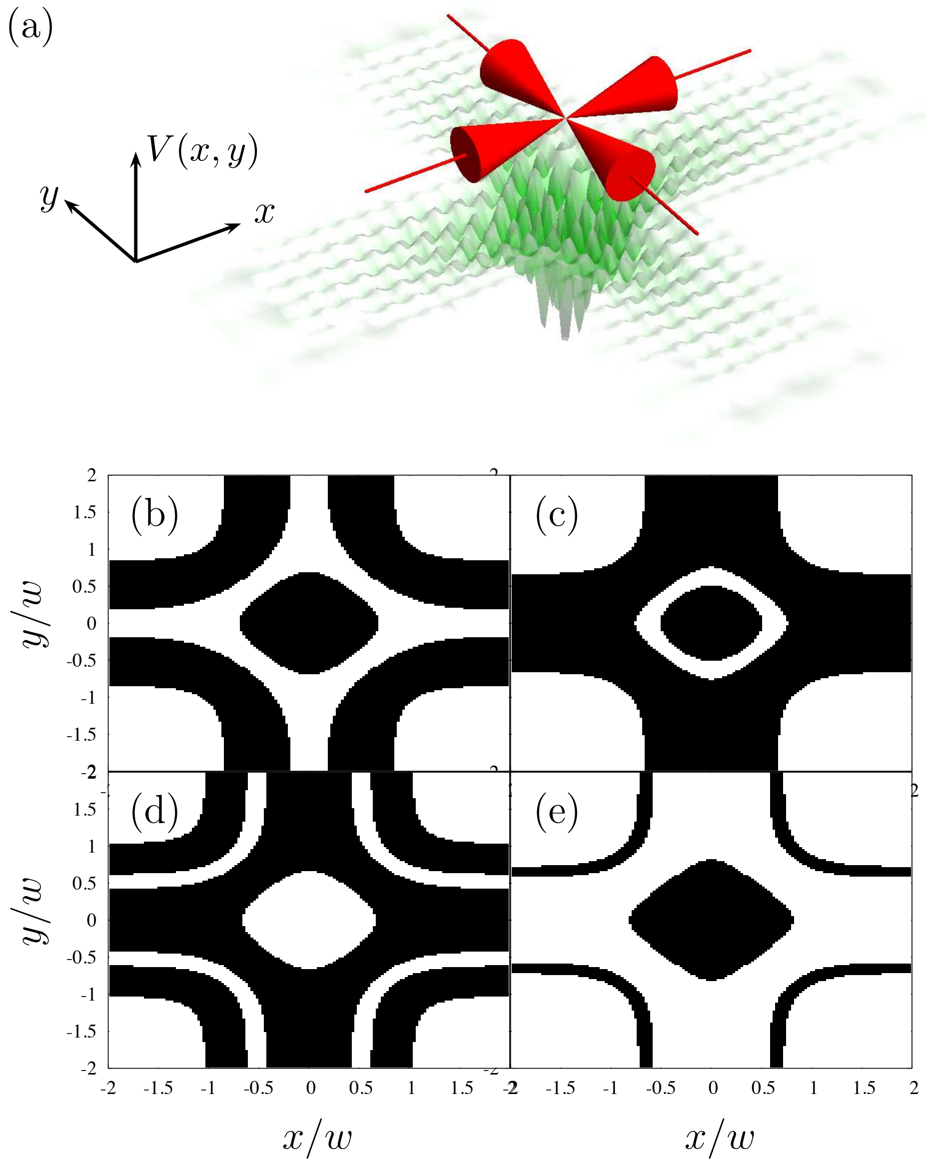
Tunable tunnel barriers

A Landau Zener transition projected in position space corresponds to a tunnel event through the barrier provided by the local band gap.



P. Cheiney *et al.* EPL **103**, 50006 (2013)

Spatial gaps: a new method to design Matter wave cavities

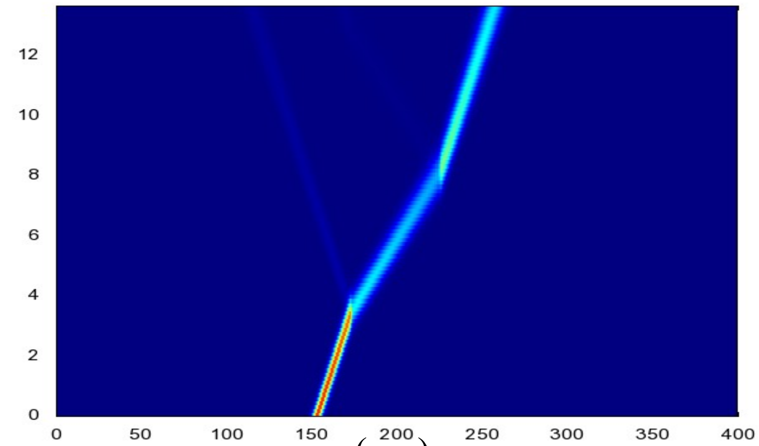


F. Damon *in preparation*

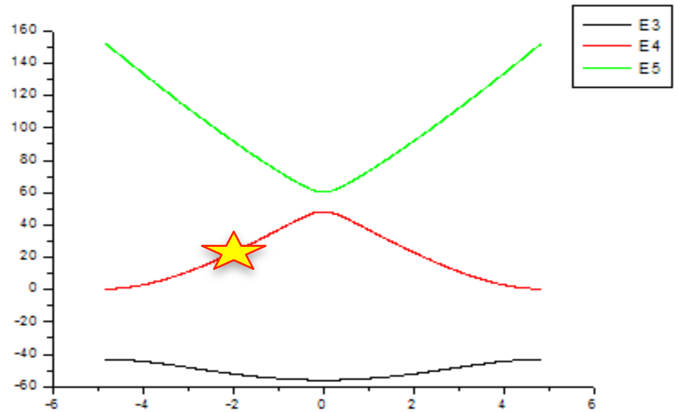
Reflection induced by driving interband transitions

- Evolution of the wavepacket in position space
- Band structure diagram

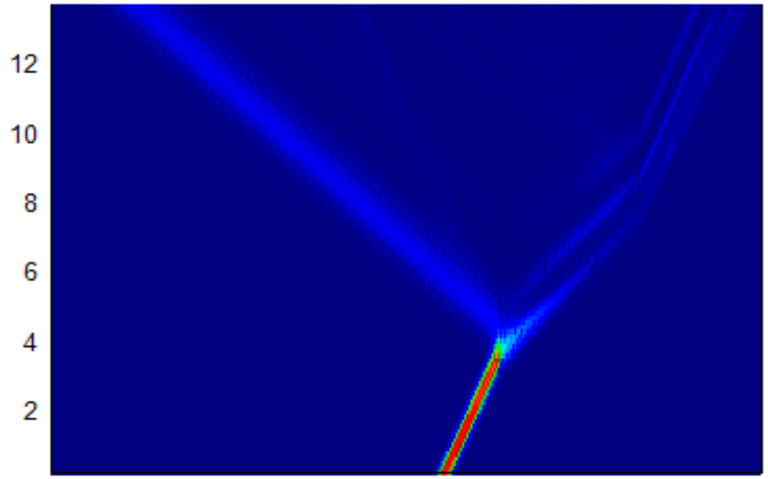
time



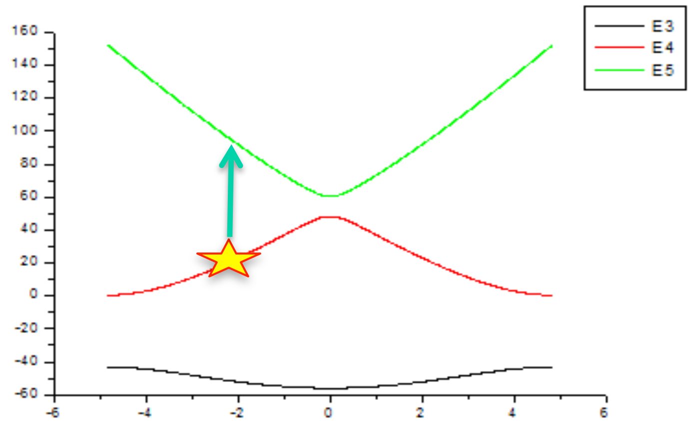
x (μm)



time

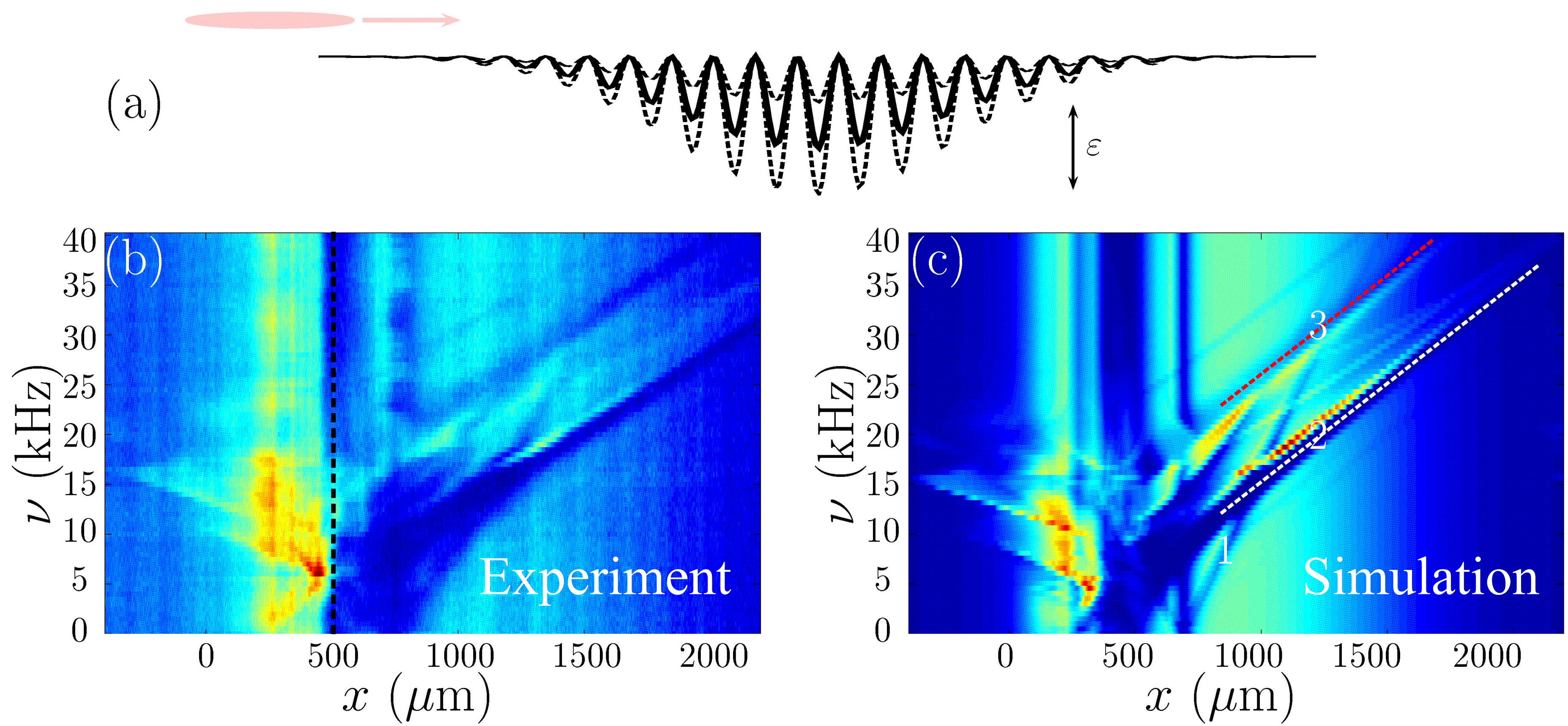


x (μm)



Scattering on time-dependent barriers

$v_0 = 11.25$ mm.s^{-1}
$\Delta v = 6$ mm.s^{-1}
$U_0 = 2E_R$



P. Cheiney *et al.* PRA **87**, 013623 (2013)

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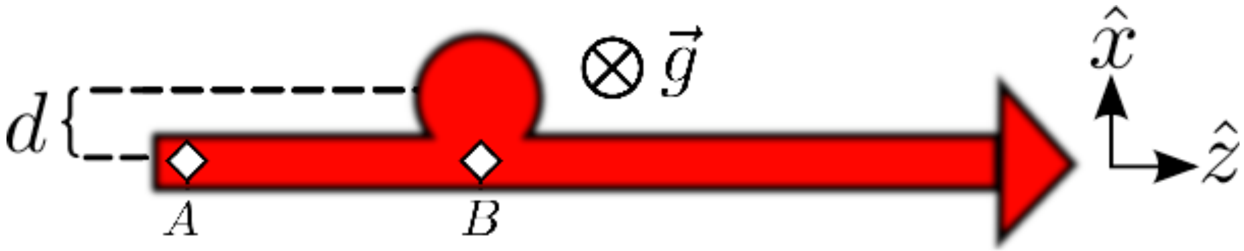
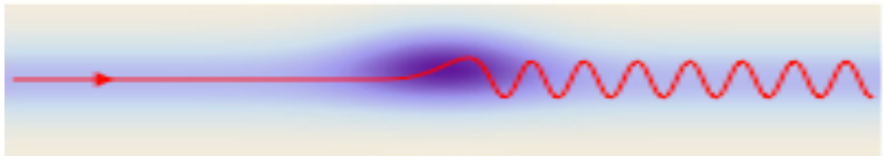
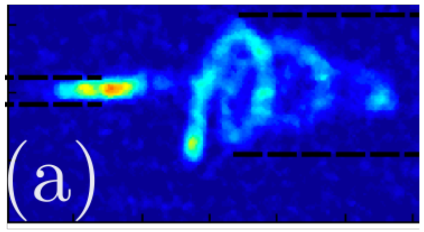
Transition to chaotic scattering

Guided matter wave beam splitter

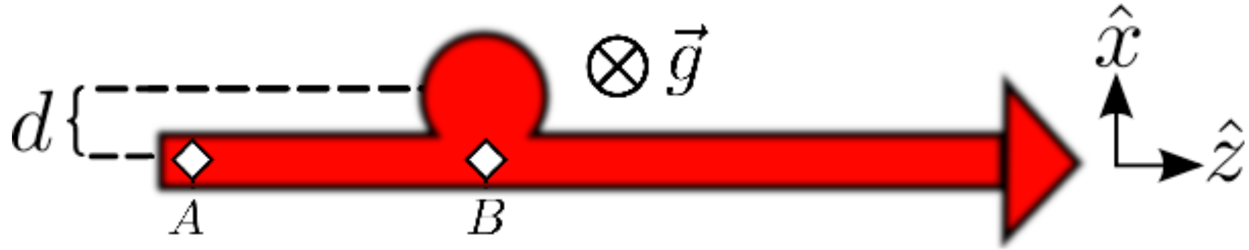
Attractive potential (90°)

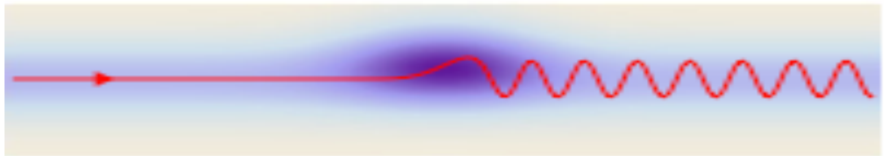




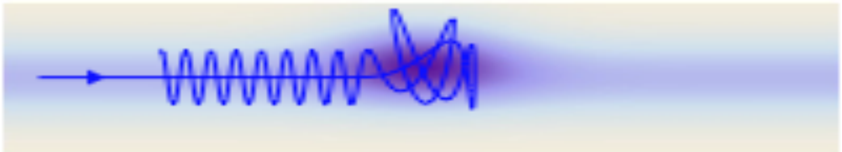


Local attractive potential (LAP) at 90°





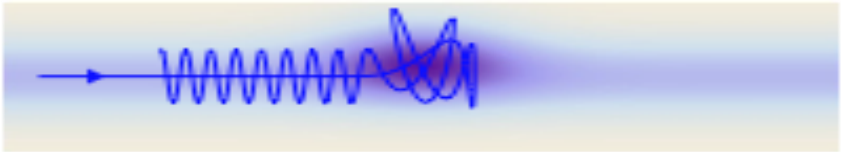
Weak coupling
(between longitudinal and
Transverse degrees of freedom)

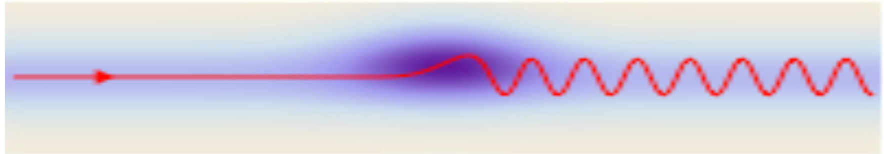


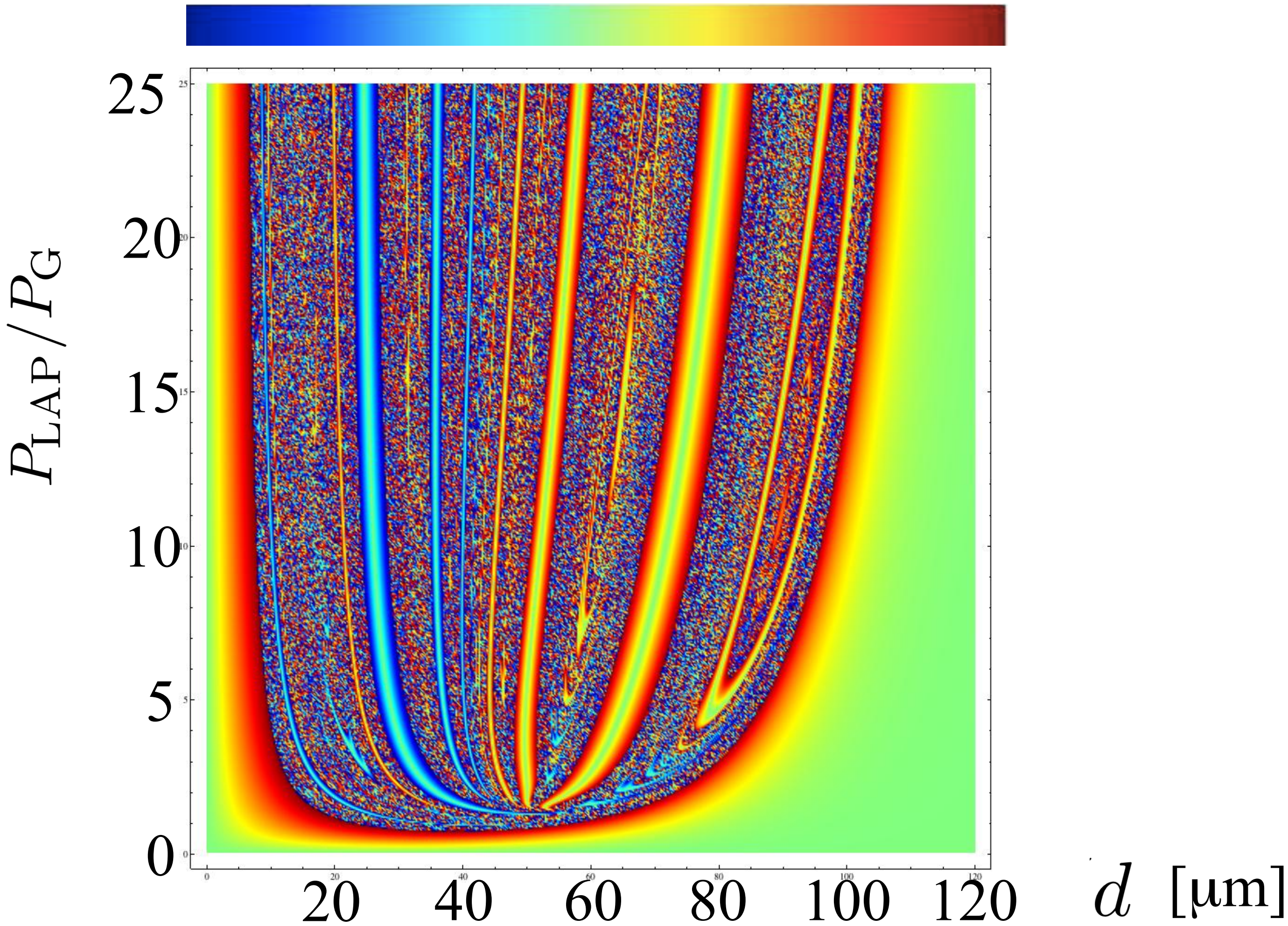
Strong coupling

G. L. Gattobigio *et al.* PRL **107**, 254104 (2011)

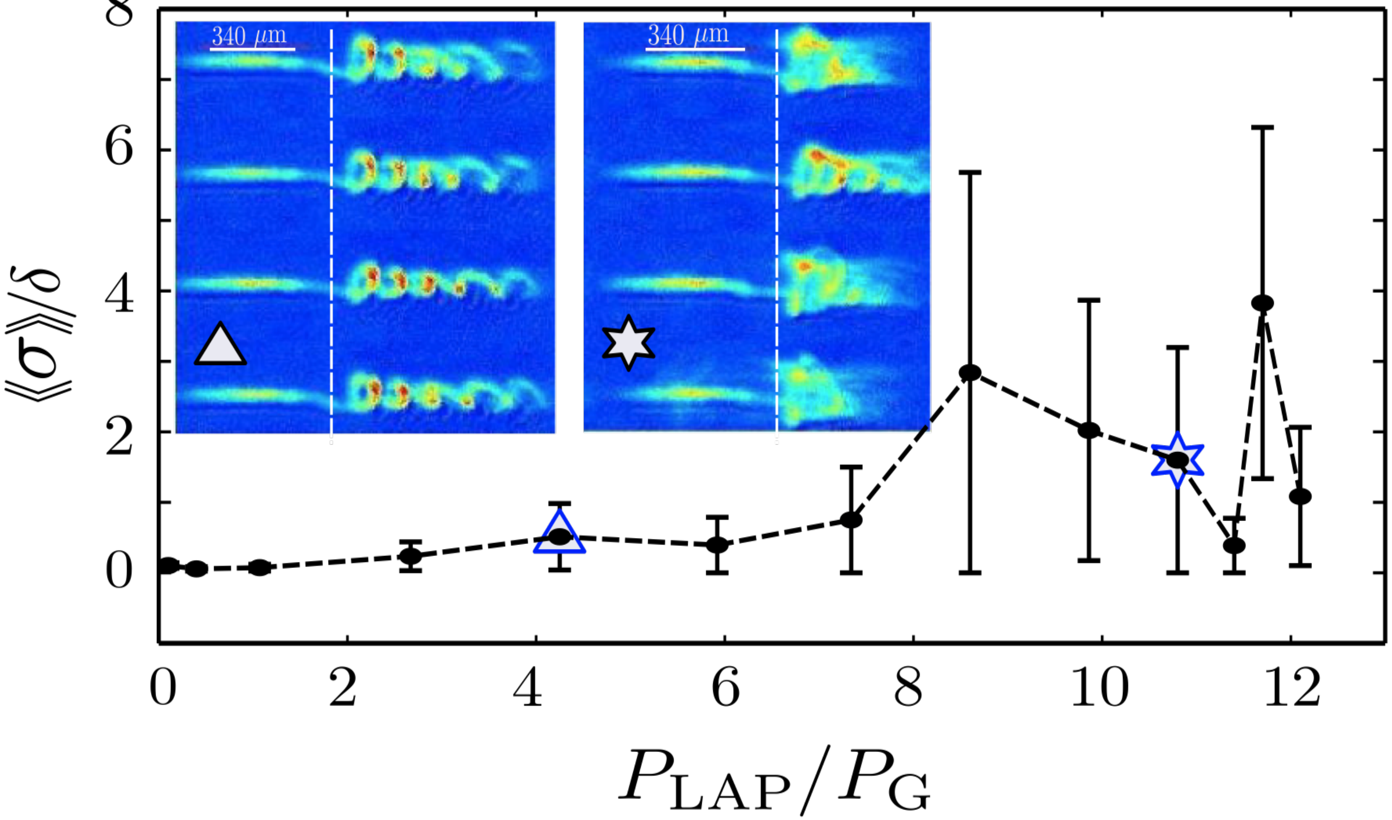
LAP at 90° : classical mechanics analysis

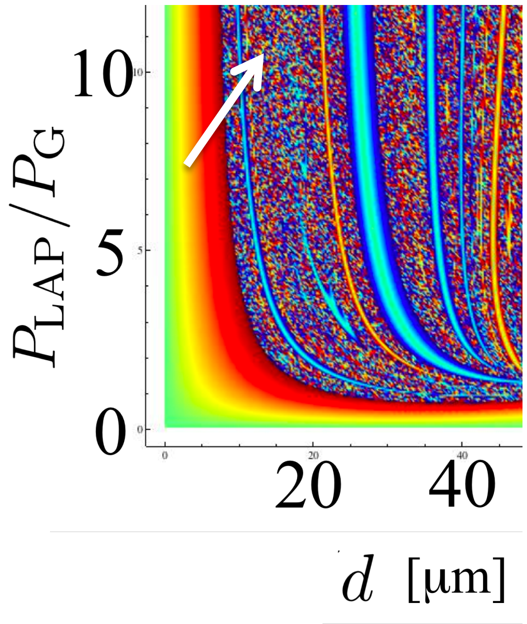






Experimental results





G. L. Gattobigio *et al.* PRL **107**, 254104 (2011)

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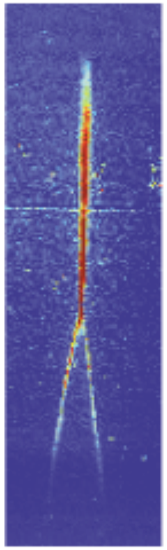
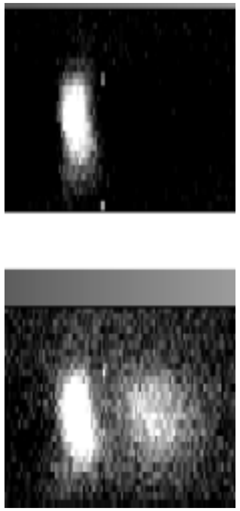
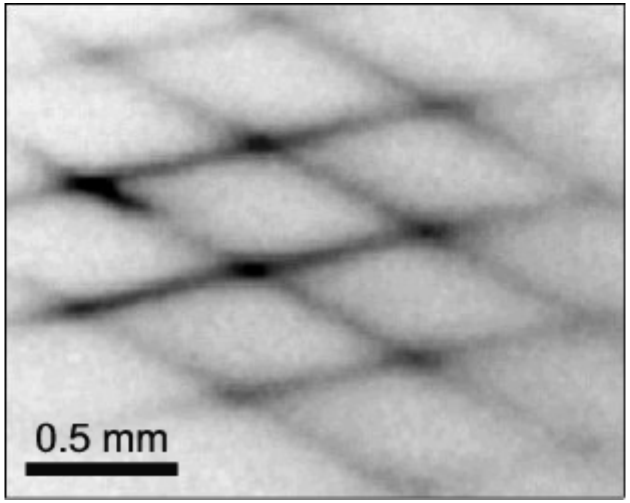
Previous studies on the splitting of a matter beam



PRL **85**, 5483 (2000)
Schmiedmayer (Innsbruk)

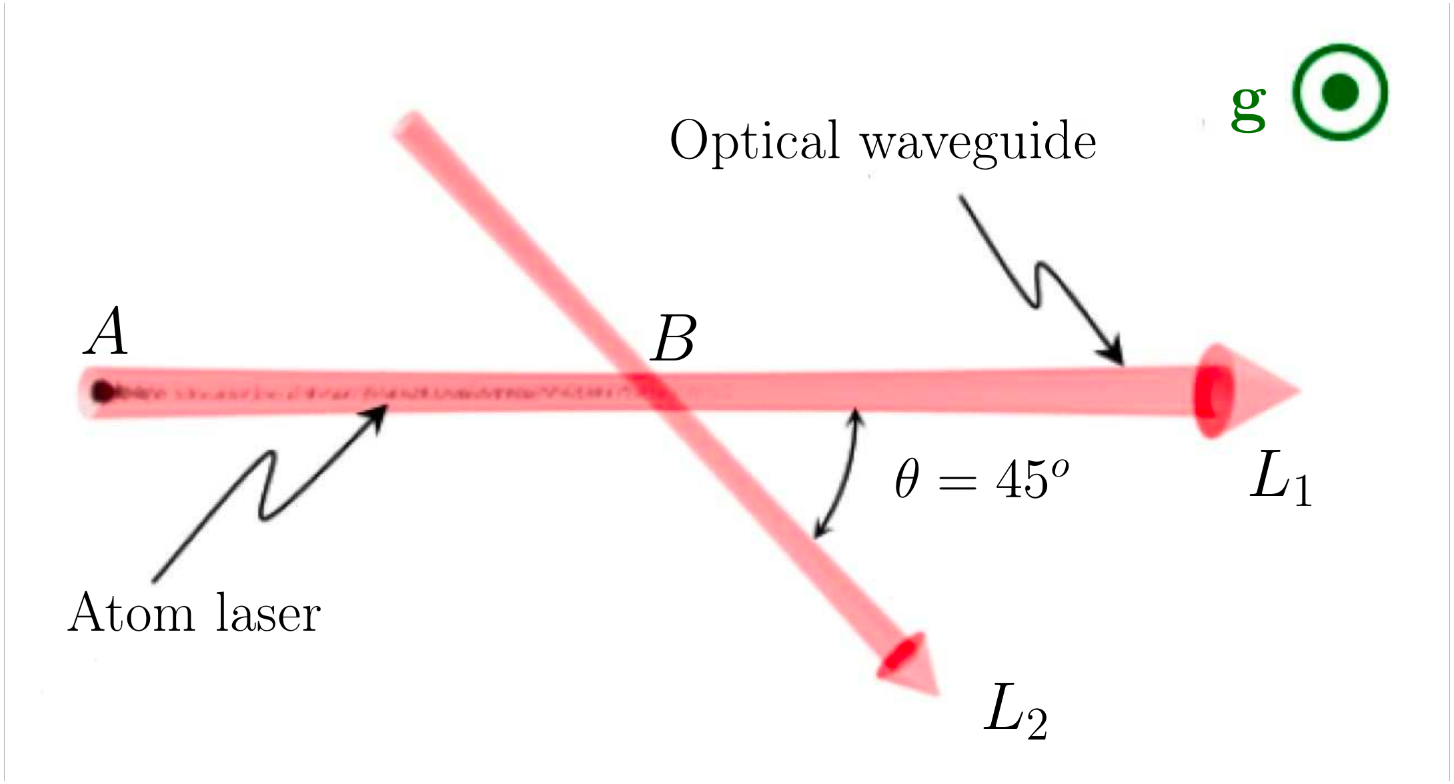


PRL **85**, 5543 (2000)
Pruvost (Orsay)

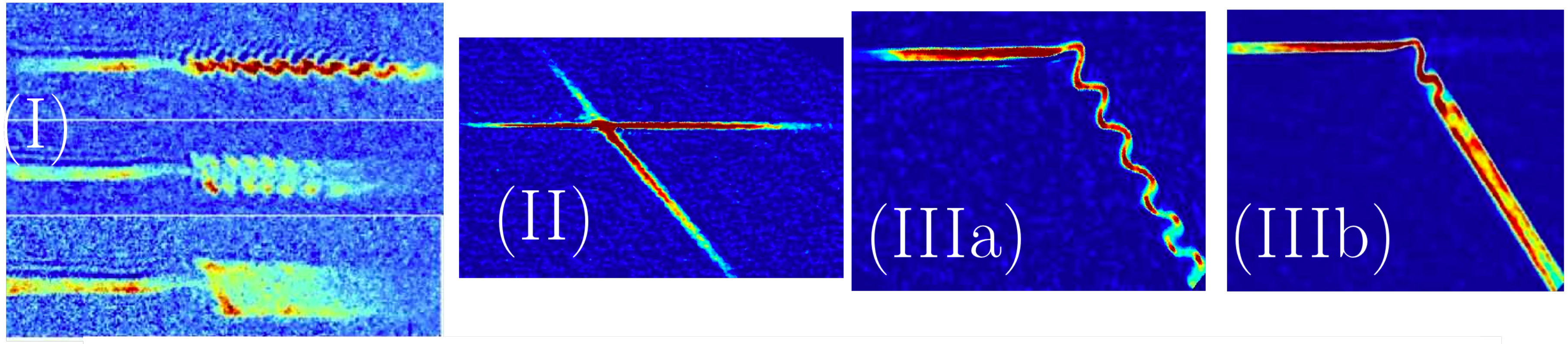


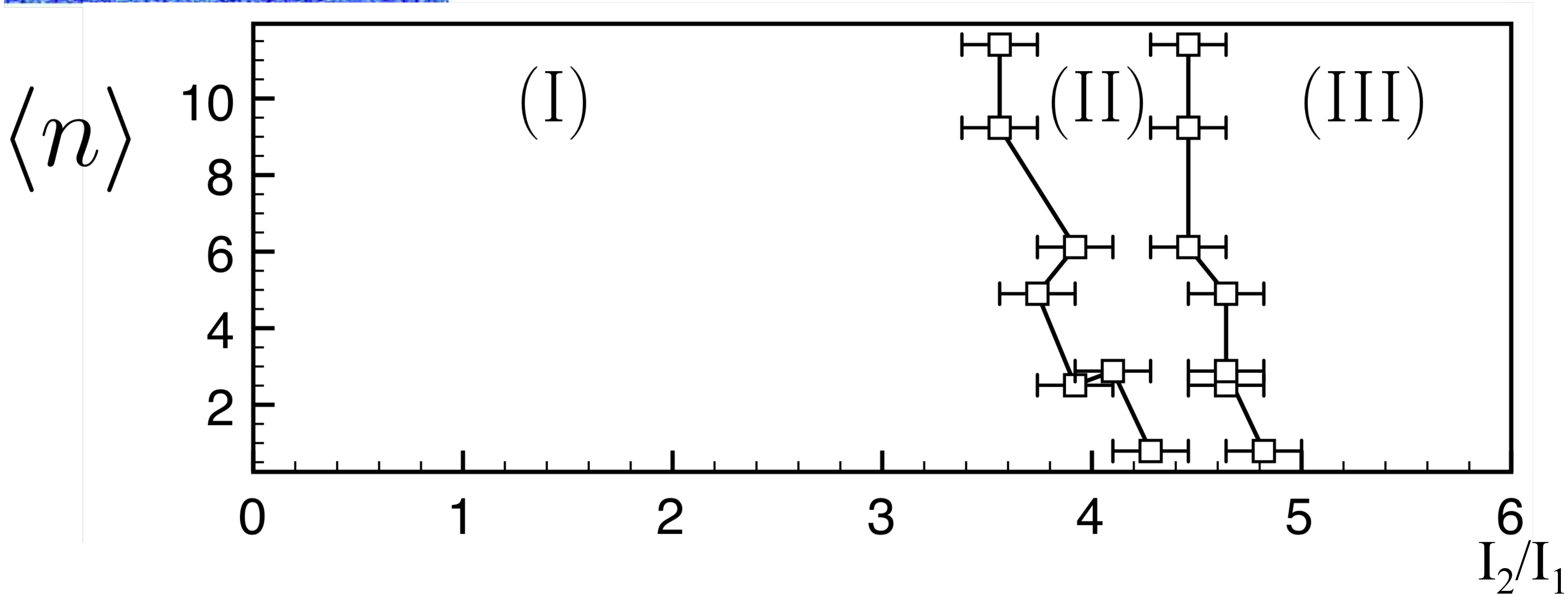
PRL **89**, 220402 (2002)
Birkl (Hannover)

Beam splitter configuration



Experimental observation





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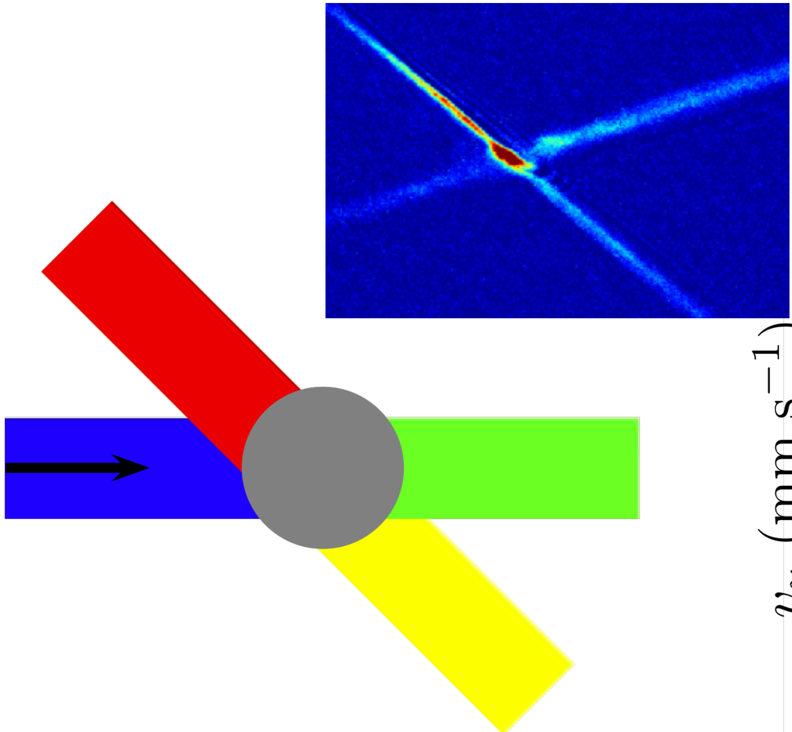
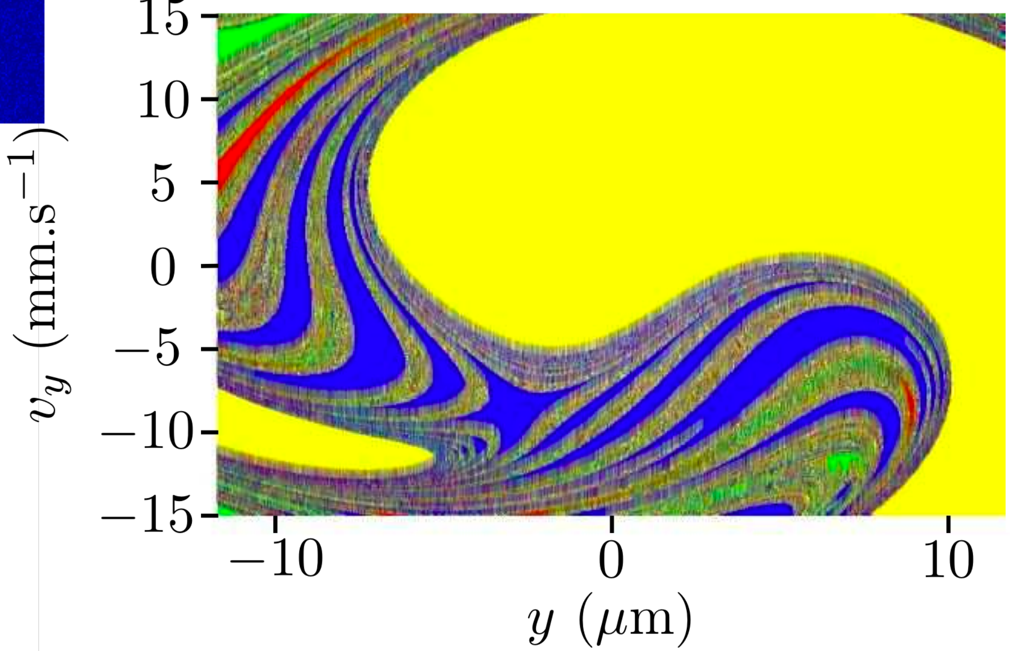
Regime (II) dominated by chaos





A splitter as a result of a chaotic dynamics

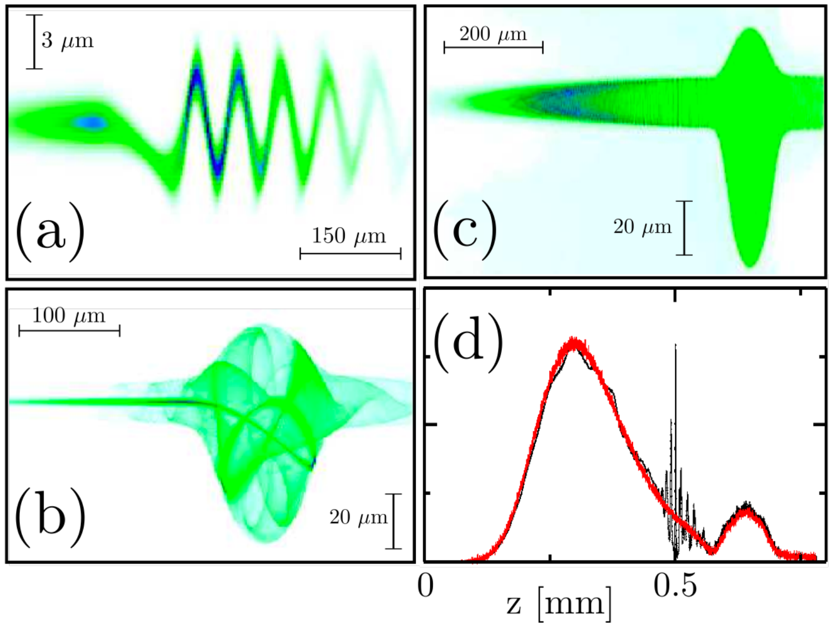
The zone overwhich the chaotic behavior takes place decreases with the angle between the two arms of the beam splitter

Magnifying quantum effects (I)

Confinement : the LAP breaks the mapping between classical and quantum predictions since the harmonicity of the guide is destroyed by the LAP

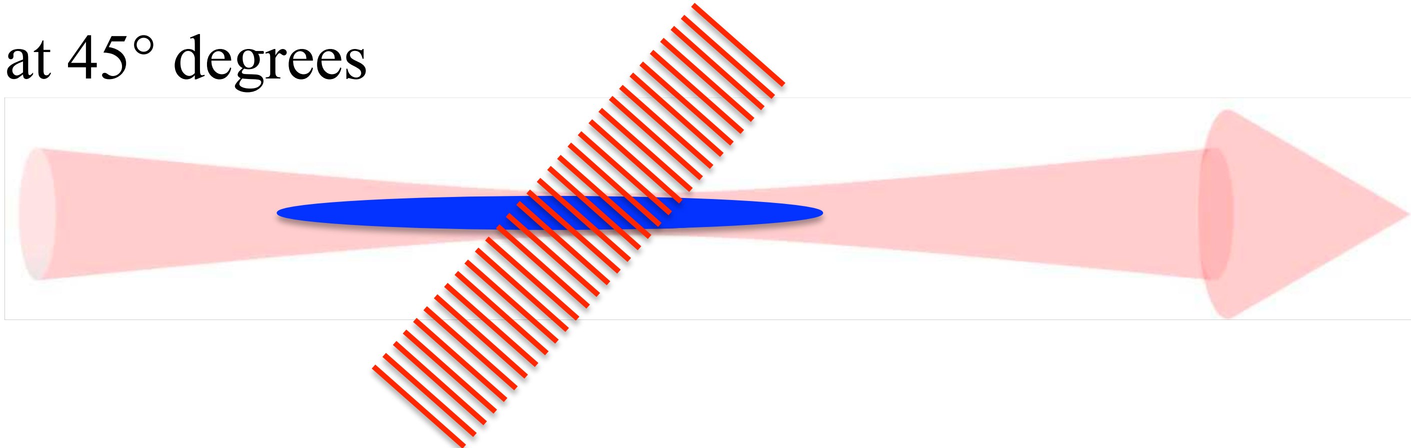
$$\vec{F} = -\langle \vec{\nabla} V \rangle \neq -\vec{\nabla}_{\langle x \rangle} V(\langle x \rangle)$$

1) Tunnel effect (small size defect)
2) Diffraction
3) Interference (long time)

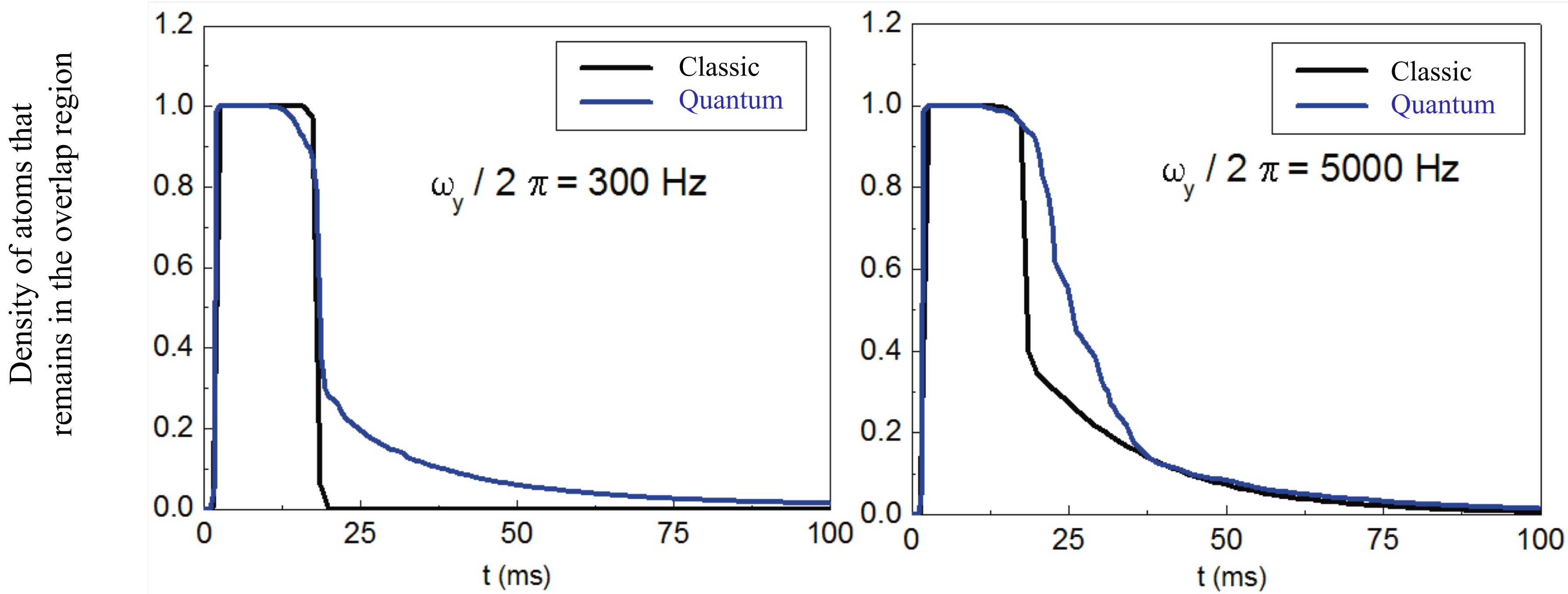


Magnifying quantum effects (II)

Guide + a lattice at 45° degrees



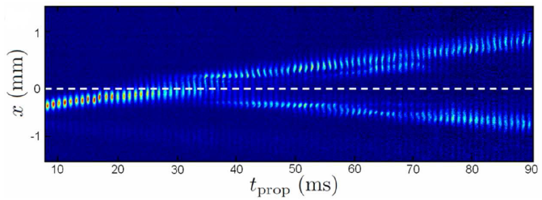
Influence of the confinement (numerical results)

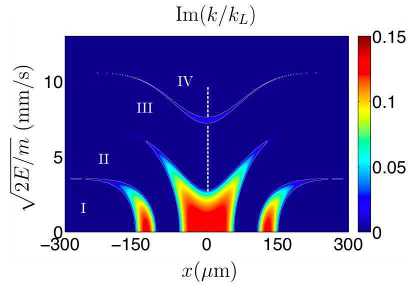


Spatial gaps: a new method to design Matter wave cavities

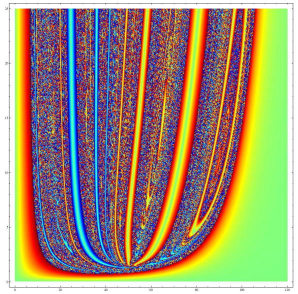
-> development of guided atom optics

1D realization of a Bragg mirror, of a Bragg cavity, selective filter by amplitude modulation

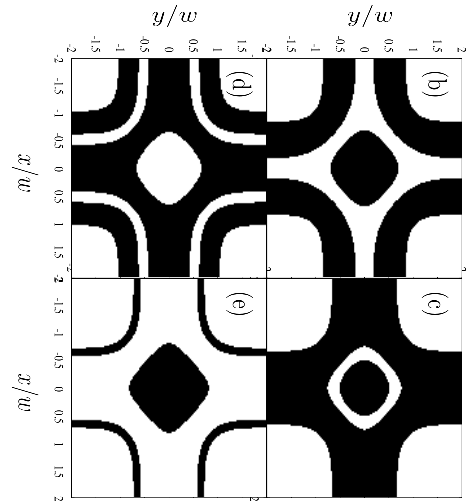


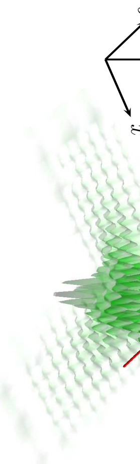


-> design new kind of tunnel barriers by shaping the lattice envelope



2D emergence of chaotic behavior, realization of a beam splitter assisted by chaos, influence of the confinement on the scattering





-> new system in which one can study quantum chaos