The Guided Atom Laser :

a new tool for studying quantum transport phenomena

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Quantum transport phenomena

Transport = Fondamental concepts in physics
Mainly studied in Condensed Matter (conduction of electrons)

Single particule effect (no interactions) : linear propagation

- *Tunneling effect / quantum reflection :*
- *Fabry-Perot cavity effect : resonance on multiple barriers*
- *Bloch oscillations in periodic potential*
- *Anderson localization trough disorder : destructive effects of interferences*

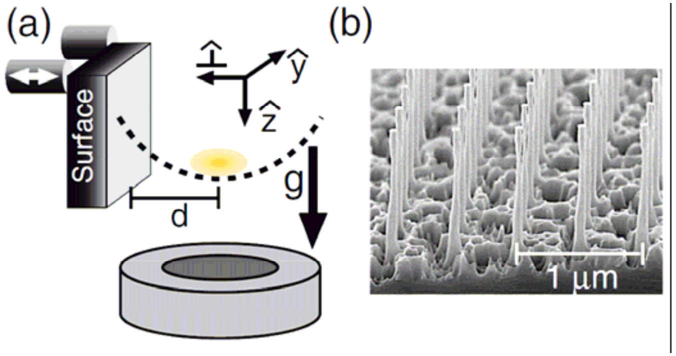
Many body effect (interactions) : non linear propagation

- *Superfluidity*
- *Atomic blockade (analog to Coulomb blockade), Mott insulator behavior*
- *Solitonic propagation (Bright/ Dark)*
- *Hawking radiation …*

Quantum propagation with BECs

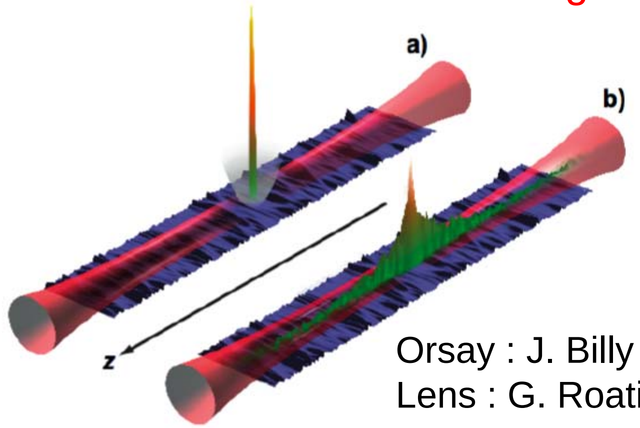
Linear propagation:

ex: quantum reflection on surfaces



T. A. Pasquini et al. PRL 97, 093201 (2006)

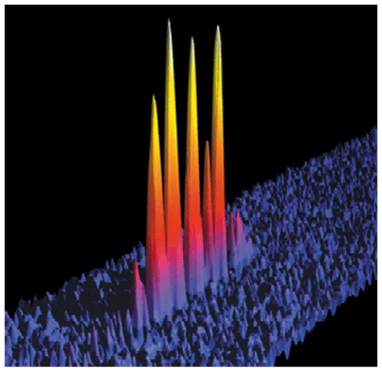
ex: Anderson Localization through disorder



Orsay : J. Billy *et al.* Nature (2008)
Lens : G. Roati *et al.* Nature (2008)

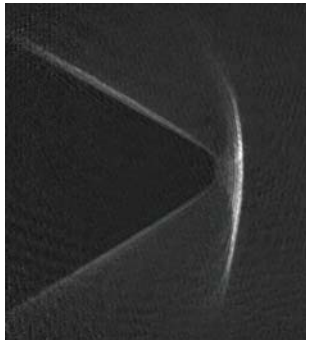
Cf talk of G. Modugno

Non linear : bright or dark solitons / shock waves

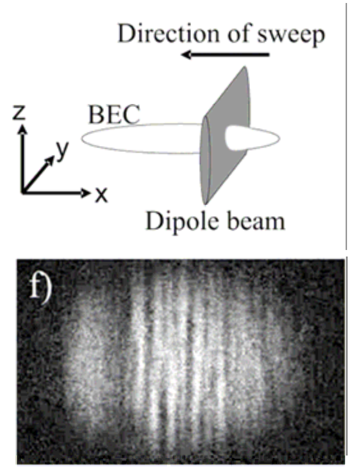


K Strecker *et al.* Nature **417** 150 (2002)

L. Khaykovich *et al.* Science **296**, 1290-1293 (2002)



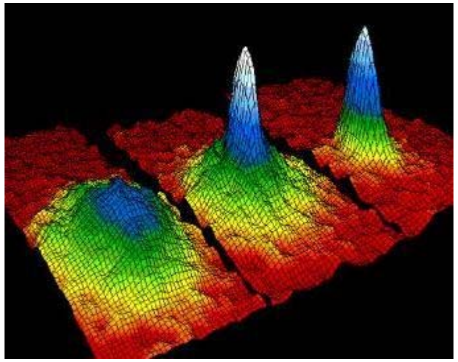
Eric's Cornell group
Jila, Boulder (2005)



+ many theoretical proposals …

An other coherent source : the Atom laser

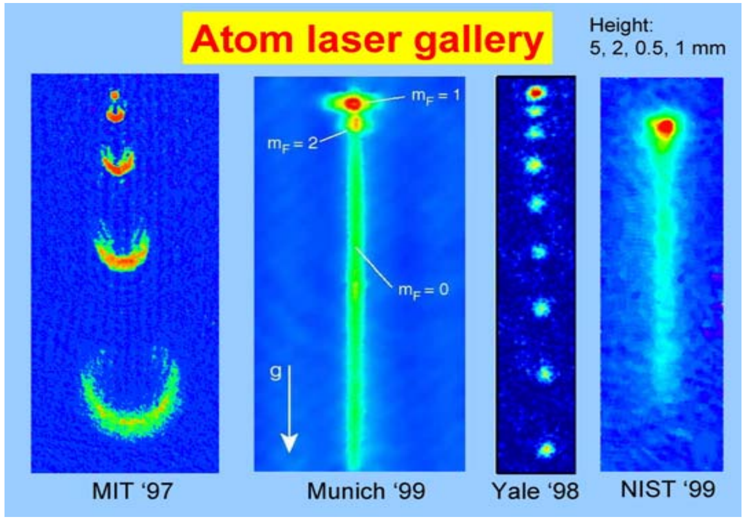
Analogy with (photonic) laser



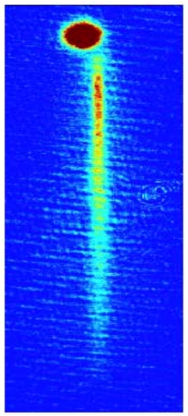
BEC = Optical cavity

All atoms in a the same mode

+ *outcoupling (RF / Raman) = coupling mirror*



Canberra

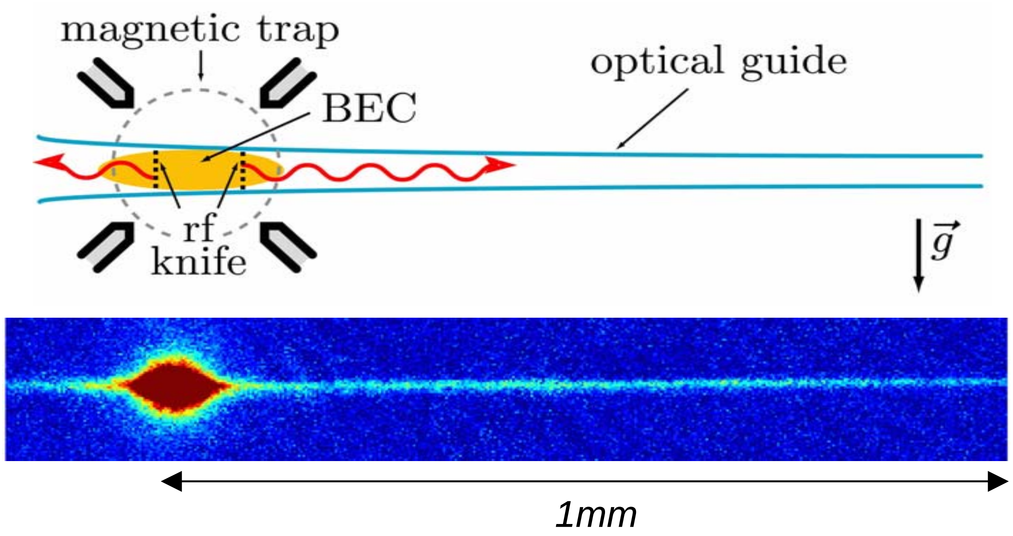


Orsay

- *« Mono-energetic » source*
- *Dilute beam (weak interactions)*
- *Free falling atom Laser : λ_{dB} decreases rapidly*

Guided atom laser principle

Coupling into a horizontal (optical) waveguide



Cf talk of I. Carusotto !

W. Guerin *et al.*, PRL 97, 200402 (2006)

⇨ *Propagation at constant velocity over long distance (~ mm)*

⇨ *Low energy = large de Broglie wavelength* $\lambda_{\mathrm{dB}} \simeq \mu\mathrm{m}$

⇨ *« Dilute » atomic beam : mainly supersonic*

See also :

But accelerated atom laser

ENS, Paris : A. Couvert *et al.* Europhys. Lett. 83, 50001 (2008)

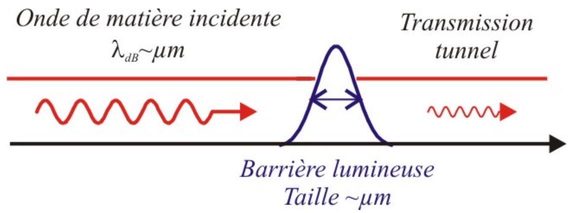
A tool for quantum transport studies

Monoenergetic : adress strongly energy depend phenomenon

λ_{dB} around 1 µm : obstacles made by light patterns

Examples :

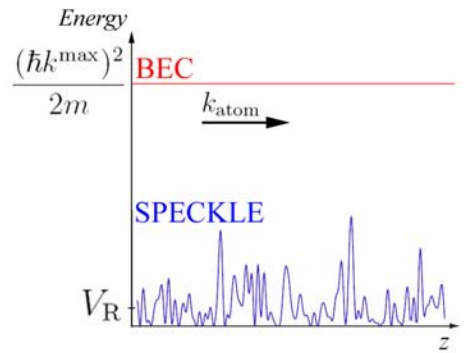
•Tunneling effect through barriers (Thin sheet of light)



$$\frac{\Delta E_{tunnel}}{E_{laser}} \sim \frac{\sqrt{2}}{\pi}\frac{\lambda_{dB}}{w}$$

Linear propagation

•Transmission through disorder (speckle)

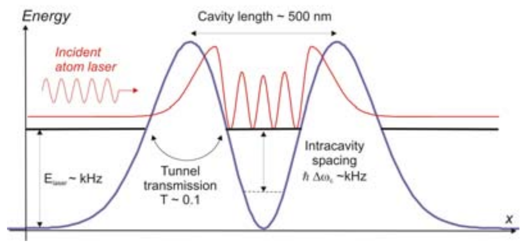


Linear propagation

Localization condition:

$$\lambda_{dB} \leq \text{"speckle grain"}$$

•Fabry-Perot Cavity (TEM_{01} mode)
Atom interactions : Blockade effect

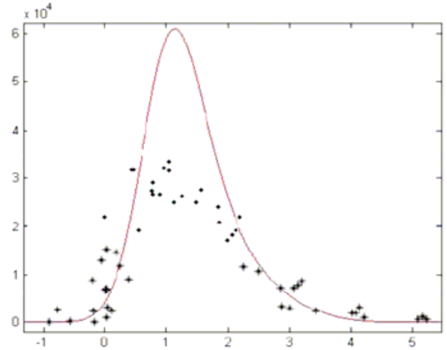


Non–linear propagation !

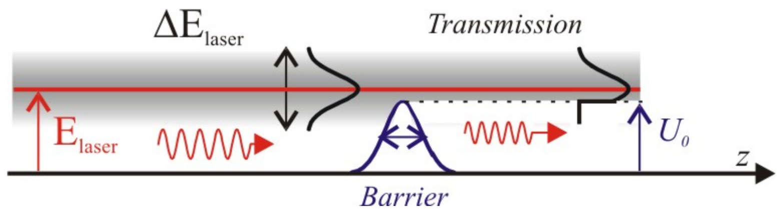
Towards (strong) antibunching

Outline

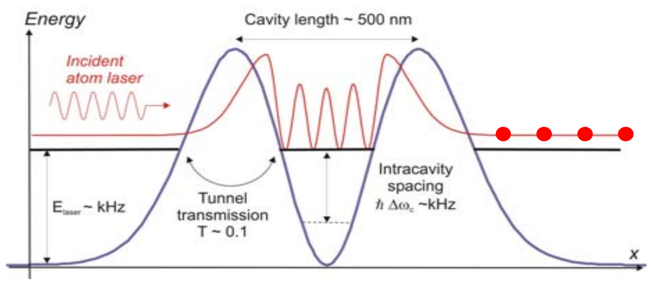
Properties of the guided atom laser



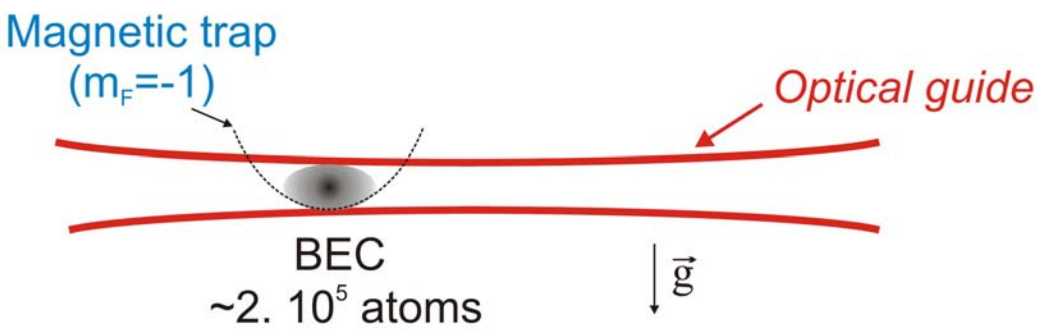
A direct linewidth measurement

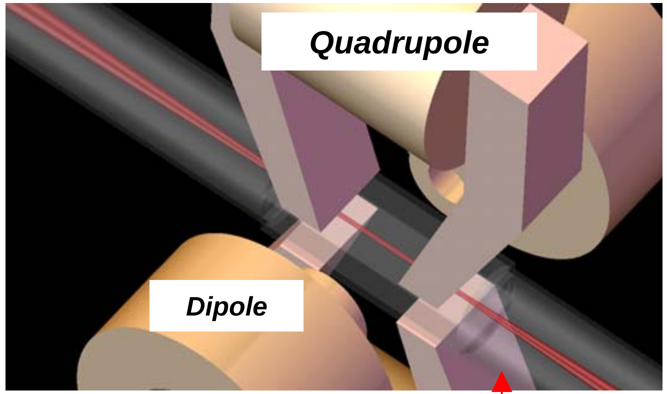


Perspectives



Hybrid BEC apparatus (^{87}Rb)





Optical waveguide (YAG@1064nm)

- Optical guide : transverse confinement $\omega_{\perp}/2\pi \simeq 70$ to $400\ Hz$
- Magnetic field : longitudinal trapping $\omega_z/2\pi \simeq 5$ to $60\ Hz$

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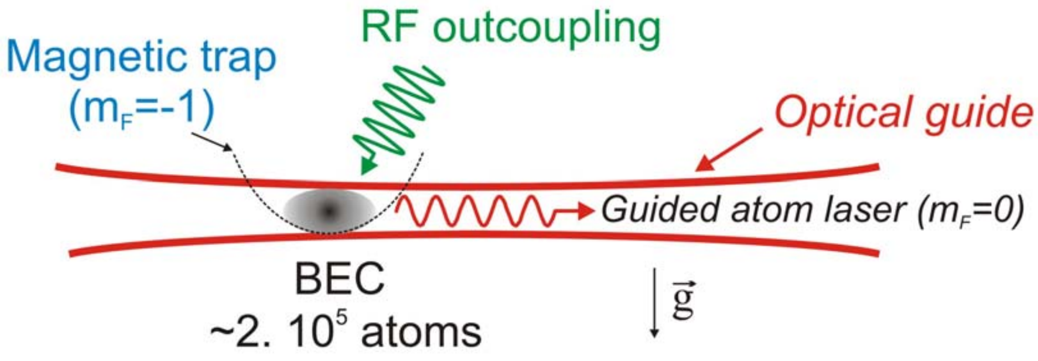

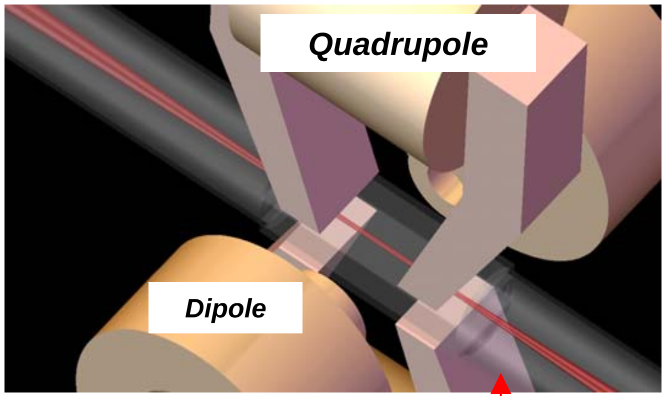

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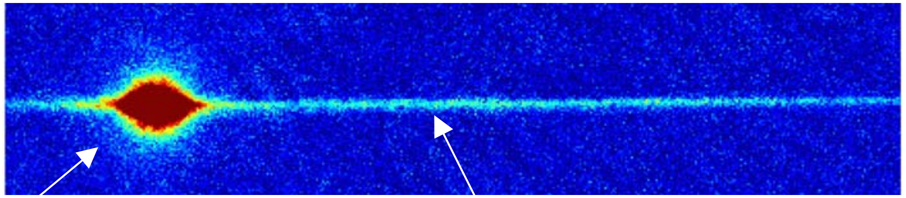


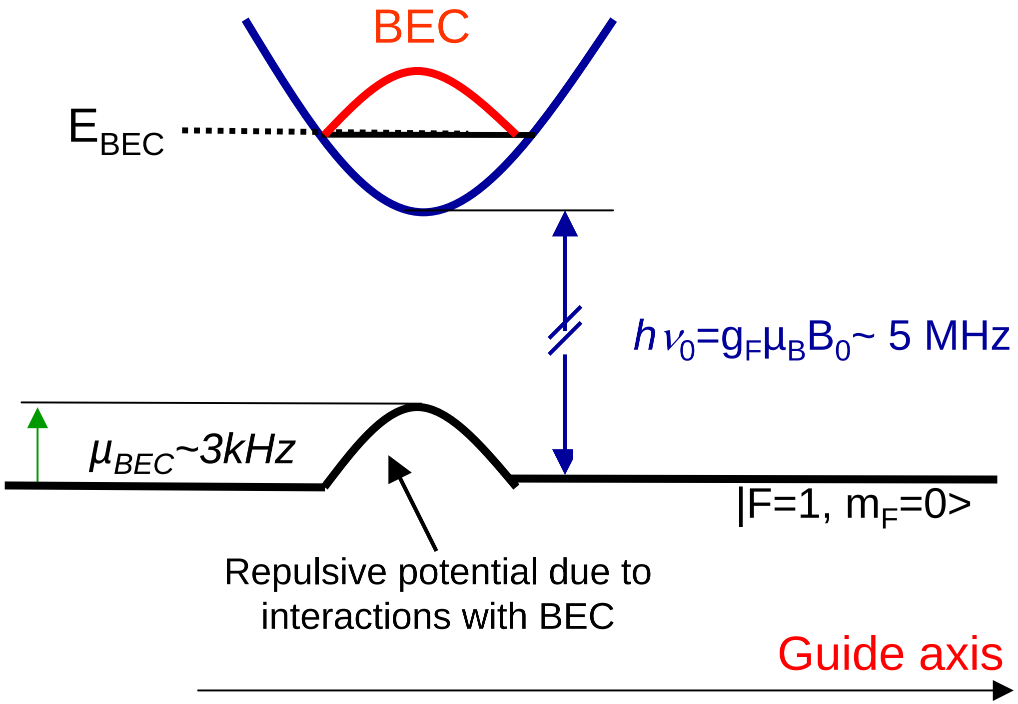
Trapped BEC
(m_F=-1)

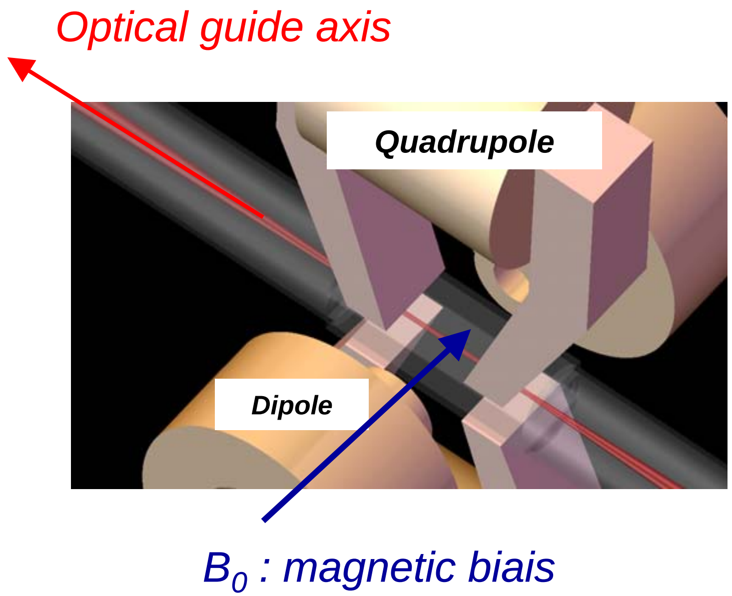
Atom laser (m_F=0):
magnetic insensitive

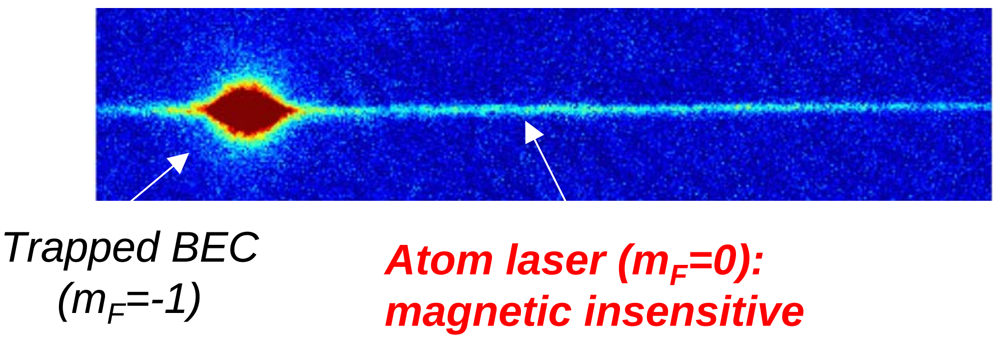
RF outcoupling
$\rightarrow$ Guided Atom Laser (GAL)

W. Guerin *et al.*, PRL 97, 200402 (2006)

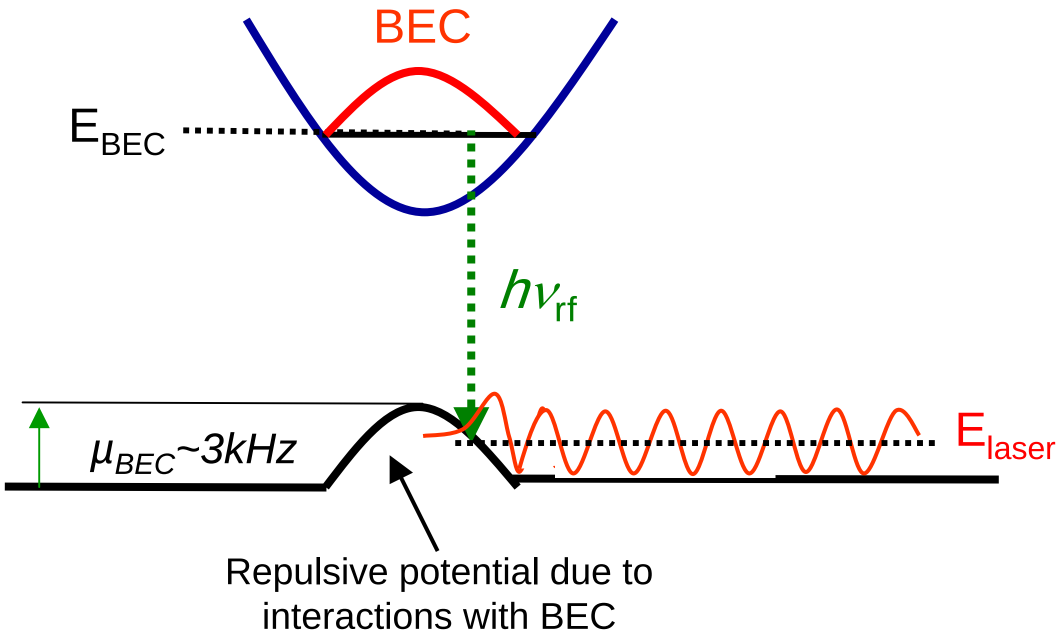
GAL principle : Energy diagram

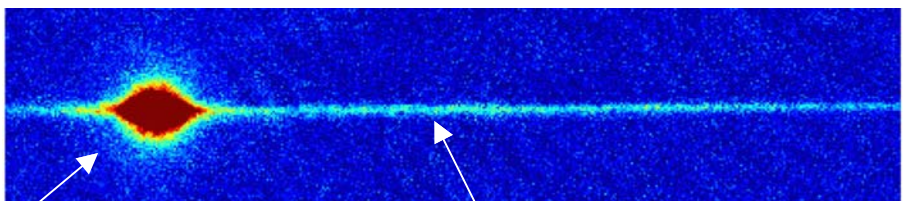






GAL principle : RF outcoupling





Trapped BEC (m_F=-1)

Atom laser (m_F=0): magnetic insensitive

- Outcoupling condition

$$h\nu_{RF} = E_{BEC} - E_{Laser}$$

- E_{laser} (velocity) = initial repulsive interactions with trapped BEC

- *Typical parameters*

N_{BEC} ~ 2.10^5 atoms

$\nu_{//}$ ~ 25 Hz

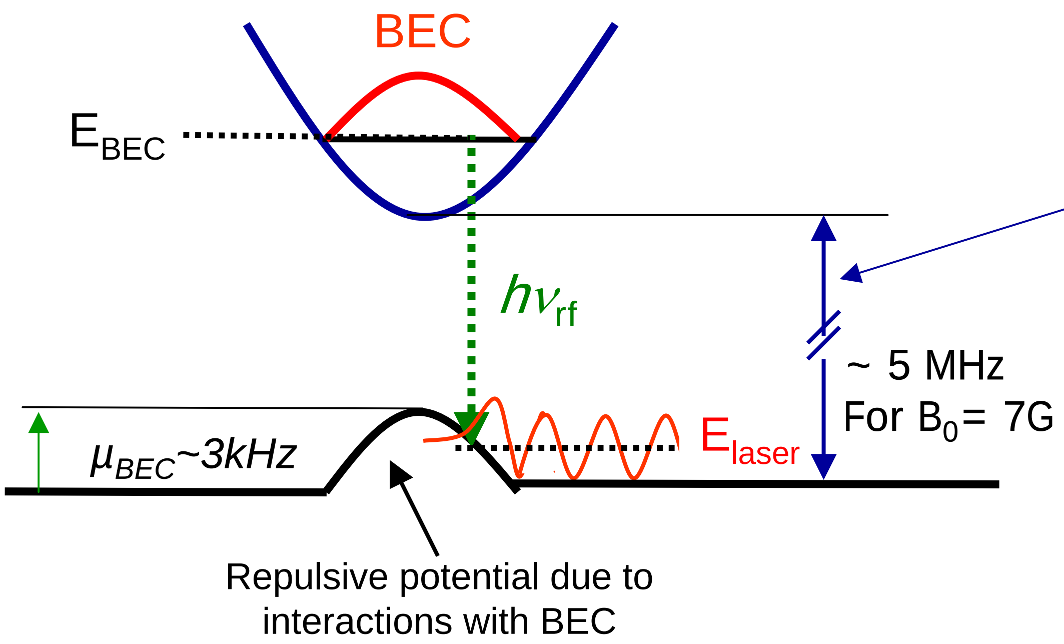
$\nu_{\perp}$ ~ 350 Hz

$\Rightarrow \mu_{BEC}$ ~ 3.5 kHz

$\Rightarrow v_{laser}$ ~ qq mm/s

$\Rightarrow \lambda_{dB}$ ~ µm

Sensibility to magnetic field



- Laser energy depends on B_0

$$E_{Laser} = g_F \mu_B B_0 + \mu_{BEC} - h\nu_{RF}$$

- Width of the coupling ~ kHz

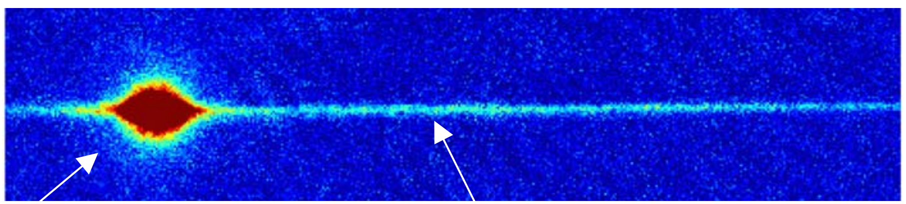
Requirement on magnetic fluctuations

$$\Delta E_{Laser} \leq 1kHz \Leftrightarrow \Delta B_0 \leq 1mG$$

Needs :

- magnetic shielding
- Ultra stable power supply

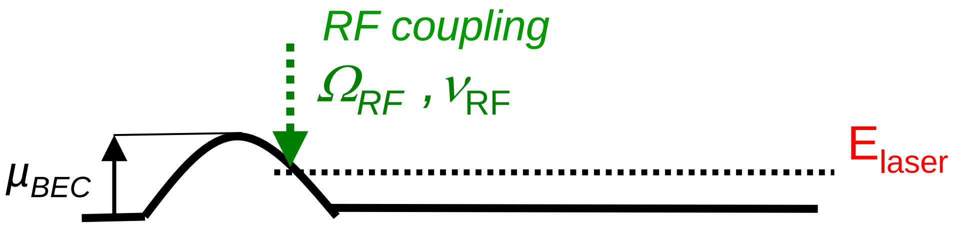
$$\frac{\Delta B_0}{B_0} = \frac{\Delta I}{I} \leq 10^{-4}$$



Trapped BEC (m_F=-1)

Atom laser (m_F=0): magnetic insensitive

Theoretical description of propagation



Quasi 1D regime : adiabatic transverse dynamic

$$\omega_\perp >> \omega_z$$

$$\Psi(\vec{r},t) = \phi_l(z,t) \, . \; \psi_\perp(\vec{r}_\perp, z)$$

Longitudinal dynamics

Atom laser = *1D non-linear schrödinger equation* + *source (BEC)*

$$i\hbar\frac{\partial\phi_l}{\partial t} = [-\frac{\hbar^2}{2m}\frac{\partial^2\phi_l}{\partial z^2} + V(z) + \mu(z)]\phi_l(z,t) + \frac{\Omega_R}{2}F(z,t)\psi_{BEC}$$

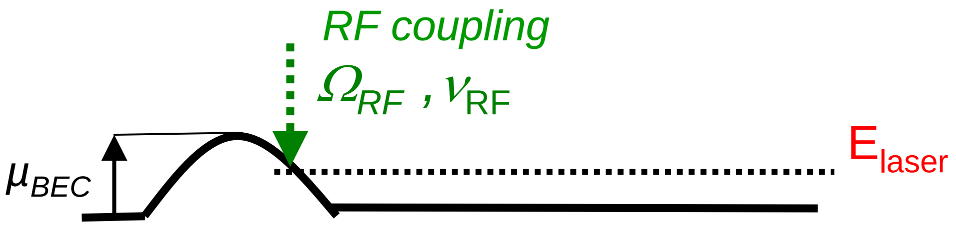
Interatomic interactions (non linear term) :

$$\mu(z) = \hbar\omega_\perp(1 + 2a_s n_{1D}(z))$$

« 1D mean field » (an_{1D} <1)

= Dilute beam

Theoretical description of propagation



$$\omega_\perp >> \omega_z$$

Hydrodynamical equations (stationnary flow)

with
$$\begin{cases} \phi_l = \sqrt{n_{1D}}\; e^{i\mathcal{S}(z,t)} \\ v = \dfrac{\hbar}{m}\dfrac{\partial \mathcal{S}}{\partial x} \end{cases}$$

$$n_{1D}(z)\, v(z) = \mathcal{F}\,,$$

$$\frac{1}{2}mv(z)^2 + V(z) + \mu(z) - \frac{\hbar^2}{2mn^{1/2}}\frac{\partial^2 n^{1/2}}{\partial z^2} = E_{\mathrm{AL}}$$

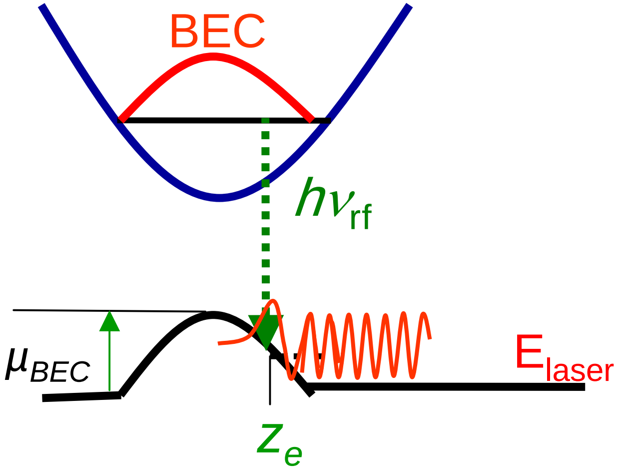
« Quantum pressure »

2 parameters controlled independantly by RF :

- *Flux ↔ RF power (Ω_R) ↔* { *Interactions ?* / *Detection ?* }
- *Energy ↔ RF frequency ν_{RF} ↔ λ_{dB}*

Atomic Flux controlled by RF power

Coupling to a continuum : Fermi Golden Rule



$$\begin{cases} \mathcal{F} = \Gamma(E) N_{BEC} \\ \Gamma(E) = \frac{2\pi}{\hbar}\eta(E)\left(\frac{\hbar\Omega_{\text{rf}}}{2}\right)^2 \frac{1}{N}\left|\int \Psi^*_{\text{BEC}}\Psi_E \, d\boldsymbol{\rho} dz\right|^2 \end{cases}$$

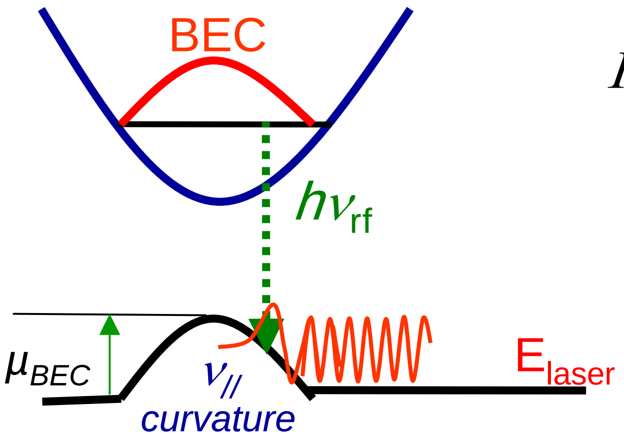
RF power *Overlap Integral*

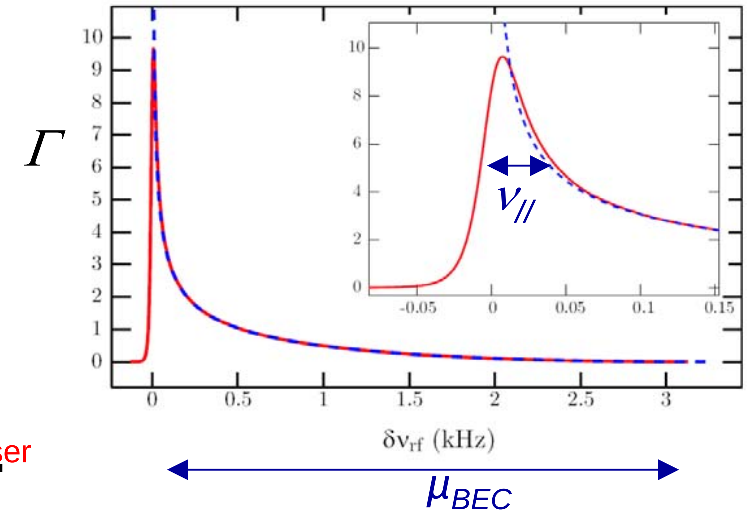
Franck Condon Principle :

$$\left|\int \Psi^*_{\text{BEC}}\Psi_E \, d\boldsymbol{\rho} dz\right|^2 \propto \left|\psi_{BEC}(z = z_e)\right|^2$$

Non zero overlap around the Airy lobe (located at z_e) ➡ ***Coupling at the classical turning point z_e***

Atomic Flux controlled by RF power





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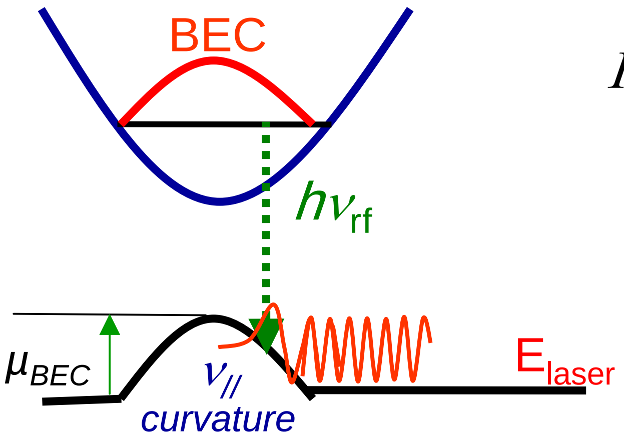
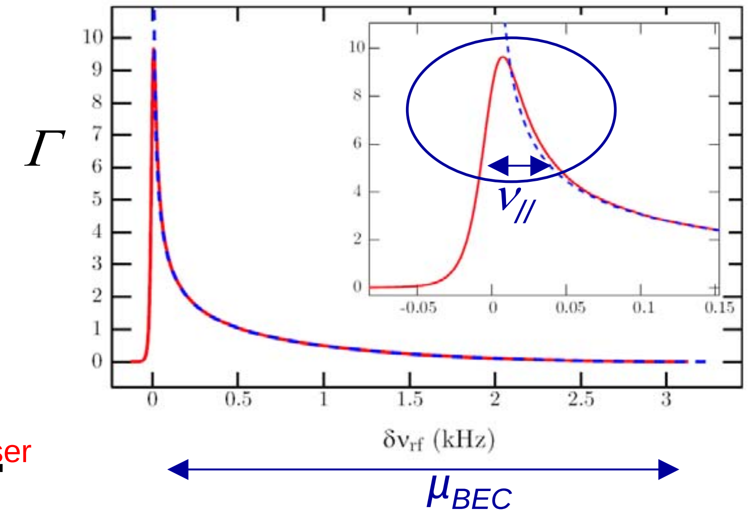




Markov approximation may failed around maximum

Validity of the approach ?

- *Born-Markov approximation $\leftrightarrow$ Weak coupling*

$\Gamma \ll \Omega_{Rabi} \ll \Delta_{continuum}$

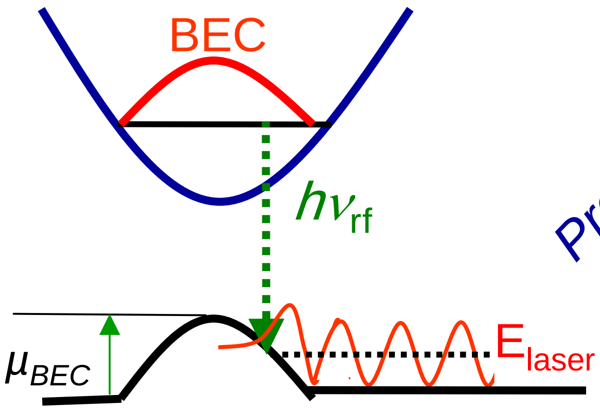
$\Gamma/2\pi \ll \Omega_{Rabi}/2\pi \ll \mu_{BEC}/h$ *(3 kHz)* *On the edge*

$\Gamma/2\pi \ll \Omega_{Rabi}/2\pi \ll \nu_{//}$ *(25 Hz)* *At the top*

- *Adiabatic dynamics (no excitations of the BEC)*

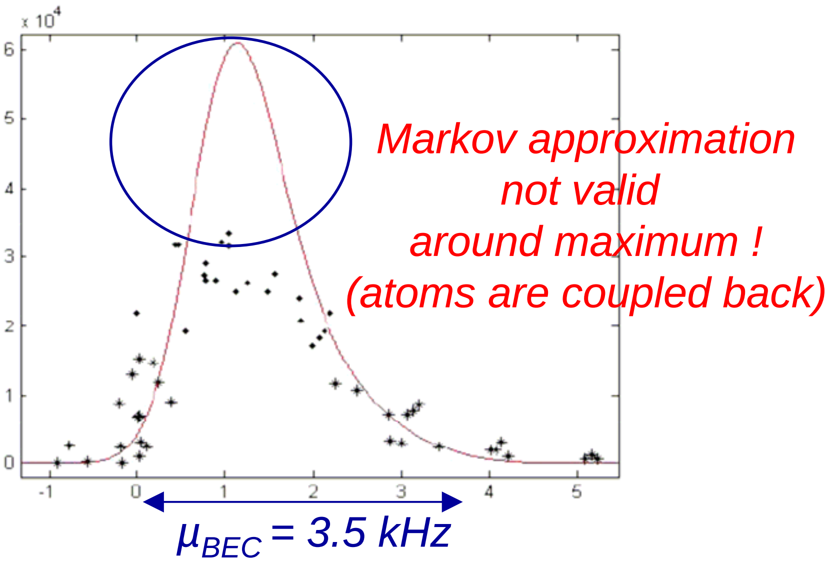
$\Gamma \ll \omega_{\perp}(\omega_{\perp}/\mu_{BEC})$ *(~100 Hz)*

Atomic Flux controlled by RF power



Preliminary results !

Outcoupled atoms vs ν_{RF}



Parameters

N_{bec} : 1.7 10^5 atoms

Ω_{Rabi} ~ 50 Hz ↔ Markov approximation violated at the top

Γ_{top} (predicted) ~ 10 Hz

F_{top} (predicted) ~ 2 10^6 atoms /s

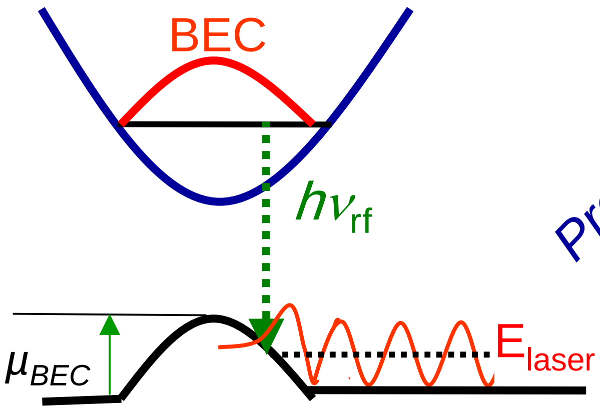
} *x2 compared to observations*

Outcoupling time : 20 ms

+ Technical noise estimated (gaussian convolution) : σ_E~400 Hz

Magnetic field fluctuations δB~ 0.6 mG

Atomic Flux controlled by RF power



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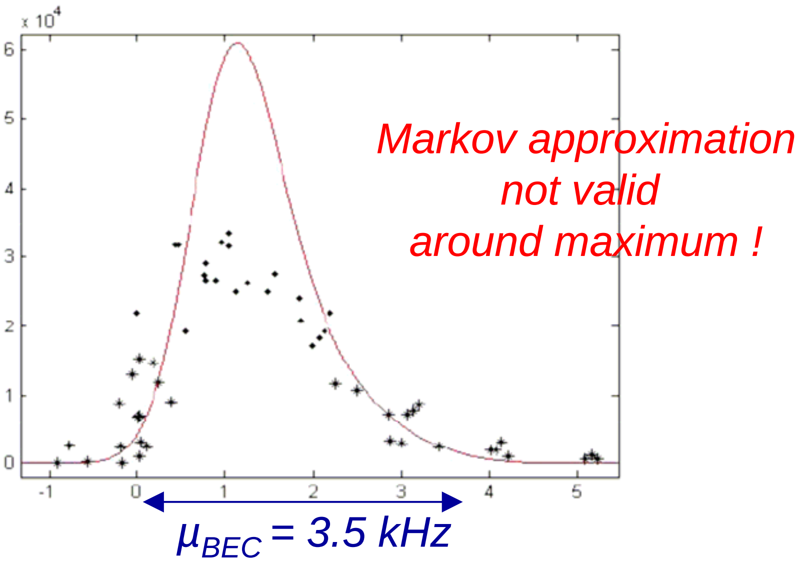


Limitations on the flux

- *Outcoupling conditions*
  - *At the top :* Γ_{top} *(max) ~ 1 Hz* ➡ F_{top} *(max) ~ 2 10^5 atoms /s*
    Limit = Markov approximation
  - *On the edge :* Γ_{edge} *(max) ~ 10 Hz* ➡ F_{edge} *(max) ~ 2 10^6 atoms /s*
    Limit = adiabatic evolution

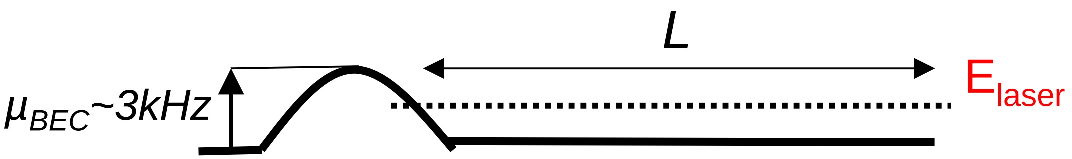
- *Depletion of the BEC*

$$\frac{\Delta N_{BEC}}{N_{BEC}} \approx \Gamma\, t_{laser} \leq 0.2$$

Typical parameters for propagation

In practice : Flux limited by the outcoupling time $\Gamma\, t_{laser} \leq 0.2$

Example : needs of propagation over a distance L ~ 200 µm
(experimental requirement)



V~ 2 mm/s $\Rightarrow$ t_{laser}~ 100 ms

Limitation of flux (BEC depletion): $\Gamma\, t_{laser} \leq 0.2 \Rightarrow \begin{cases} \Gamma_{\max} = 2\ Hz \\ F_{\max} = 4.\,10^5\ atoms/s \end{cases}$

Linear atomic density $(n_{1D})_{\max} = \dfrac{F_{\max}}{v} \approx 200\ atoms/\mu m \quad \Rightarrow \quad (an_{1D})_{\max} \approx 1$

$\Rightarrow$ *Quasi 1D mean field regime*

Linear / nonlinear propagation ?

Quasi 1D mean field regime (NLSE) : $\leftrightarrow$ *Kerr effect in optics*

$$a n_{1D} < 1$$

$$i\hbar \frac{\partial \phi_l}{\partial t} = \left[-\frac{\hbar^2}{2m}\frac{\partial^2 \phi_l}{\partial z^2} + V(z) + g_{1D}|\phi_l|^2 \right] \phi_l(z,t) + \mathrm{source}$$

Important parameters for nonlinear behavior:

- Velocity of sound :

$$c = \sqrt{\frac{2\hbar\omega_\perp}{m}}\sqrt{a n_{1D}} \quad \Rightarrow \quad c \approx 0.5 - 2\ mm.s^{-1}$$

Subsonic flows reachable?

- Healing length :

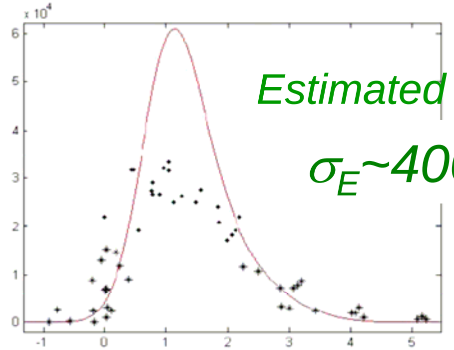
$$\zeta = \frac{\hbar}{mc} \quad \Rightarrow \quad \zeta \approx 0.4 - 1.6\ \mu m$$

Question : How is modified the outcoupling process for « strong » interactions ?

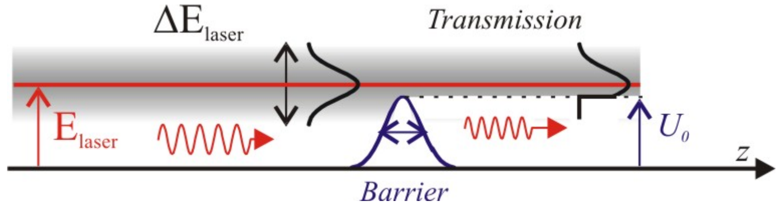
But : non linearities can be amplified (obstacles, compression…)

Outline

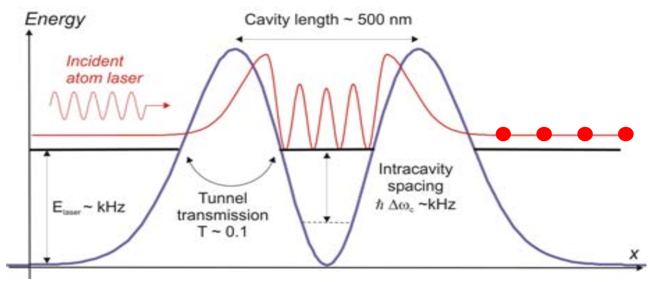
Properties of the guided atom laser



A direct linewidth measurement

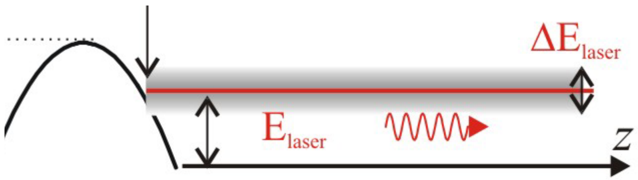


Perspectives



Linewidth of an atom laser

Linewidth in the Markov approximation (weak coupling)



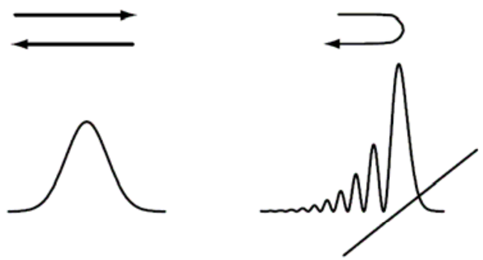
$$\Delta E = \hbar \max\left(\Gamma\,;\frac{1}{t_c}\right)$$

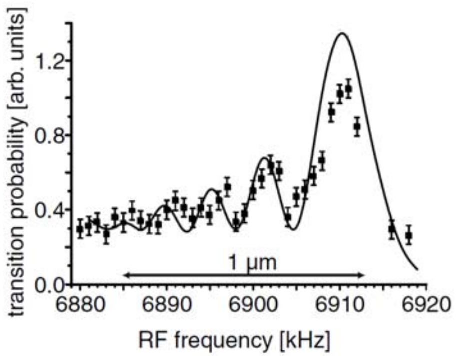
with $\Gamma\, t_{laser} \leq 1$ *Bec depletion*

$$\Delta E_{laser} = \frac{h}{t_{laser}}$$

In practice:
Linewidth limited by the outcoupling time

First order coherence ($g^{(1)}$)





$$t_{laser} = 1.5\ ms$$

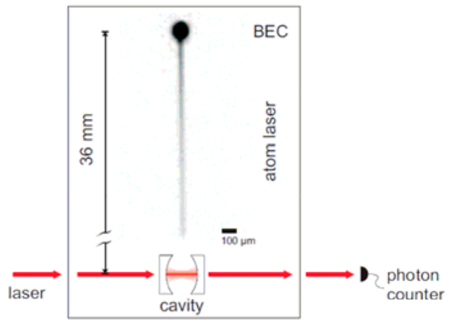
$$\Delta E_{laser} = 700 \pm 200\ Hz$$

Fourier limited …
But short outcoupling time

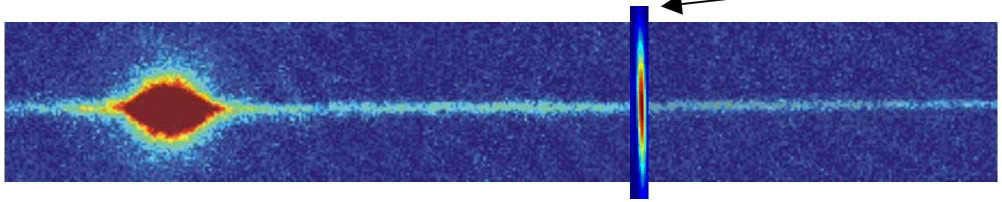
M. Köhl et al. PRL **87**,160404 (2001)

Also measurement of second order coherence ($g^{(2)}$)

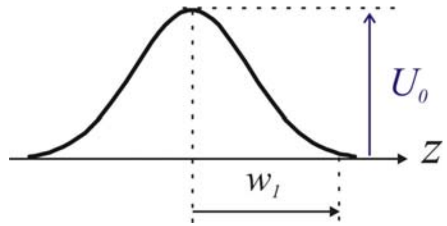
A. Öttl *et al.* PRL **95**,090404 (2005)



Transmission through a (thick) barrier



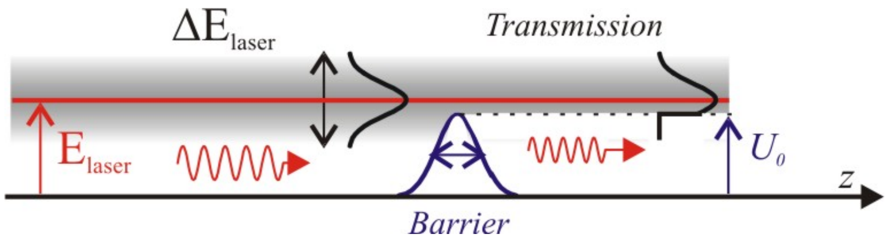
« Thick » barrier made by blue light (405 nm)



$w_1 = 4\ \mu m$

Simplified picture :

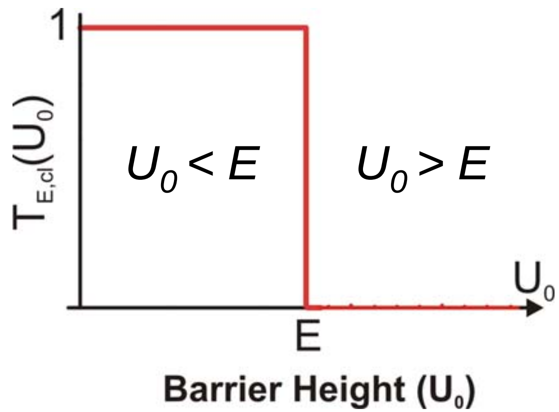
- *Thick barrier* = *negligible tunneling effect* $\lambda_{dB} << w$
- *Low density* = *one particule problem* $c << v$



$$T_{laser}(U_0) = \frac{\int_0^\infty T_E(U_0)\mathcal{D}(E)dE}{\int_0^\infty \mathcal{D}(E)dE} \propto \int_{U_0}^\infty \mathcal{D}(E)dE$$

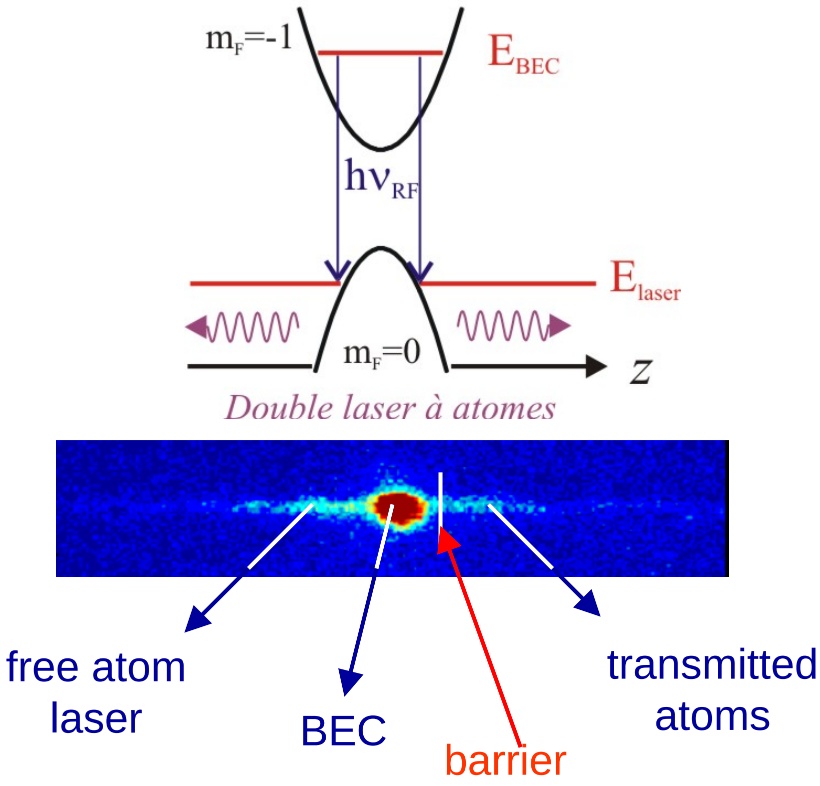
= «Foucault » method in optics

Classical transmission (Heavyside)



Transmission through a (thick) barrier

Experimental scheme : normalisation by a 2nd atom laser



Transmission through a (thick) barrier

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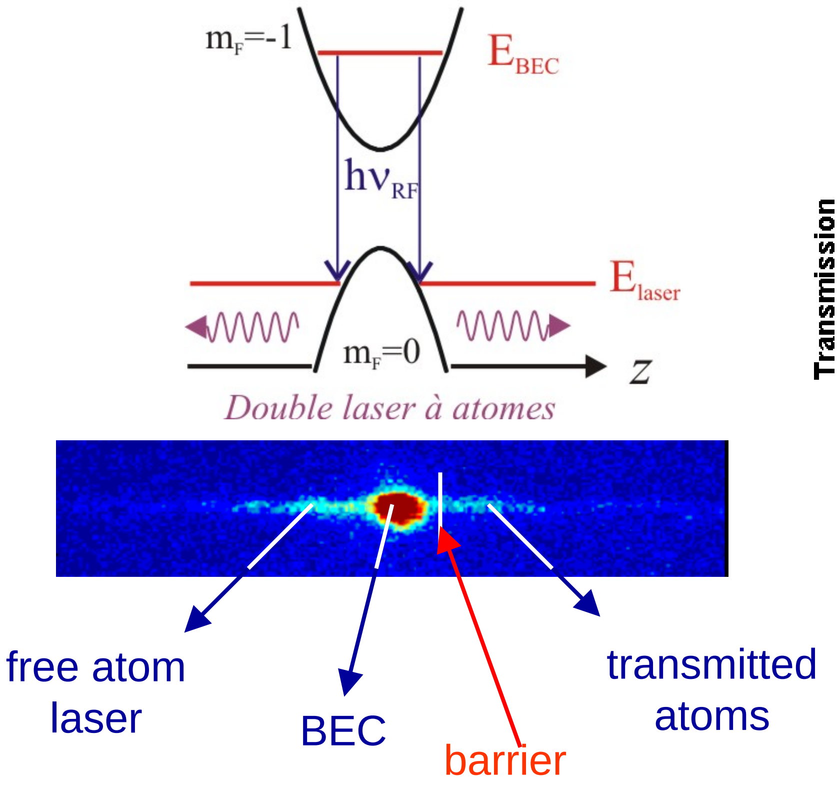
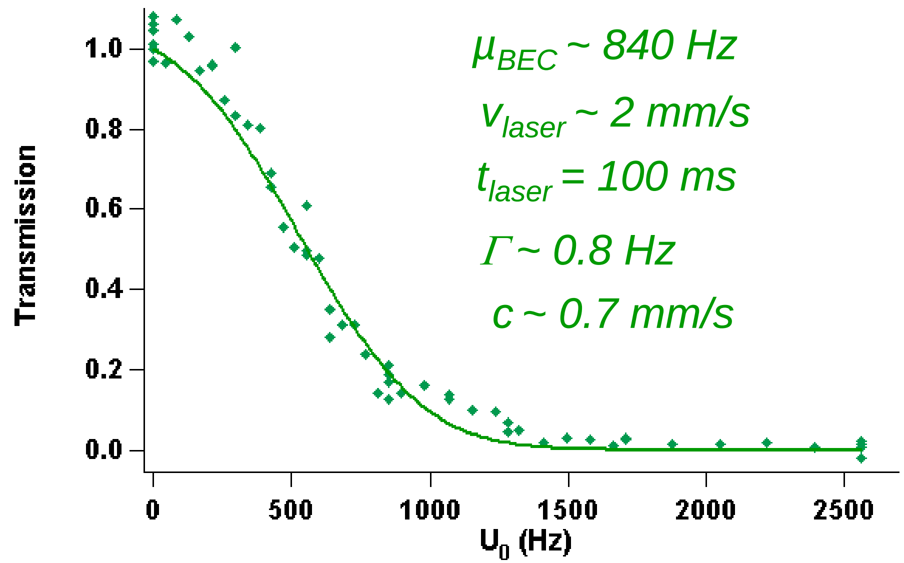




$\mu_{BEC} \sim 840$ Hz

$v_{laser} \sim 2$ mm/s

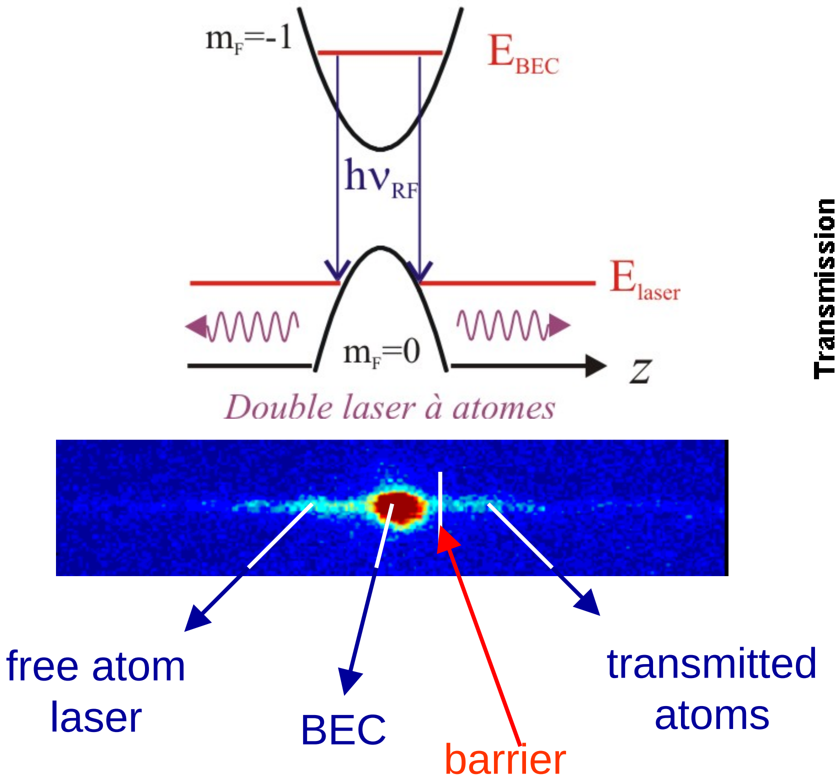
$t_{laser} = 100$ ms

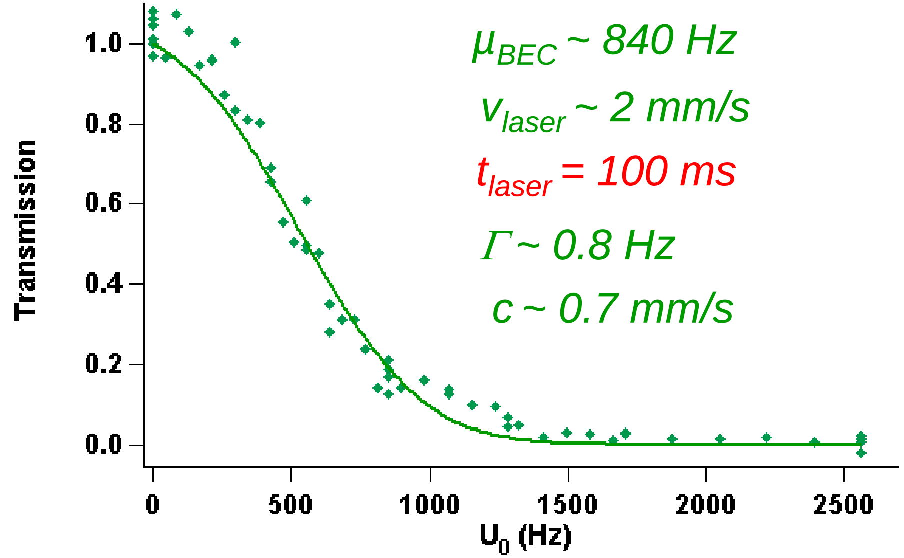
$\Gamma \sim 0.8$ Hz

$c \sim 0.7$ mm/s

Transmission through a (thick) barrier

Experimental scheme : normalisation by a 2nd atom laser





Fit with a gaussian distribution

$$\mathcal{D}(E) \propto e^{-\frac{(E-E_0)^2}{2\sigma_E}}$$

E_0 = 530Hz mean energy

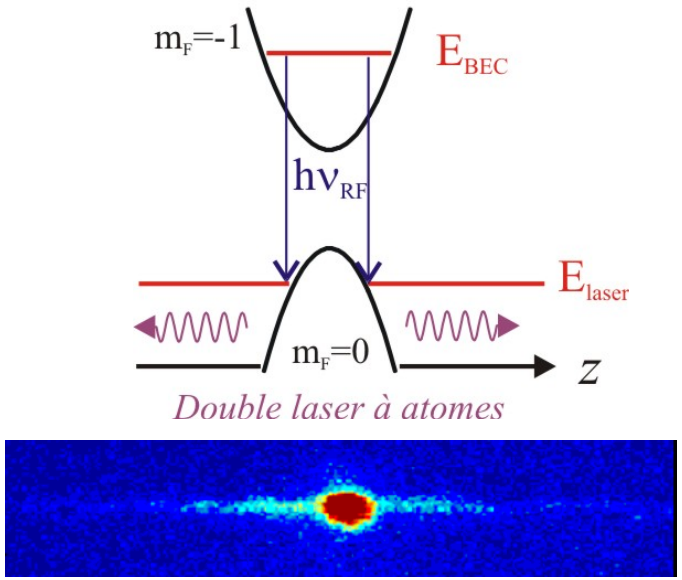
σ_E = 290 +/- 40 Hz rms

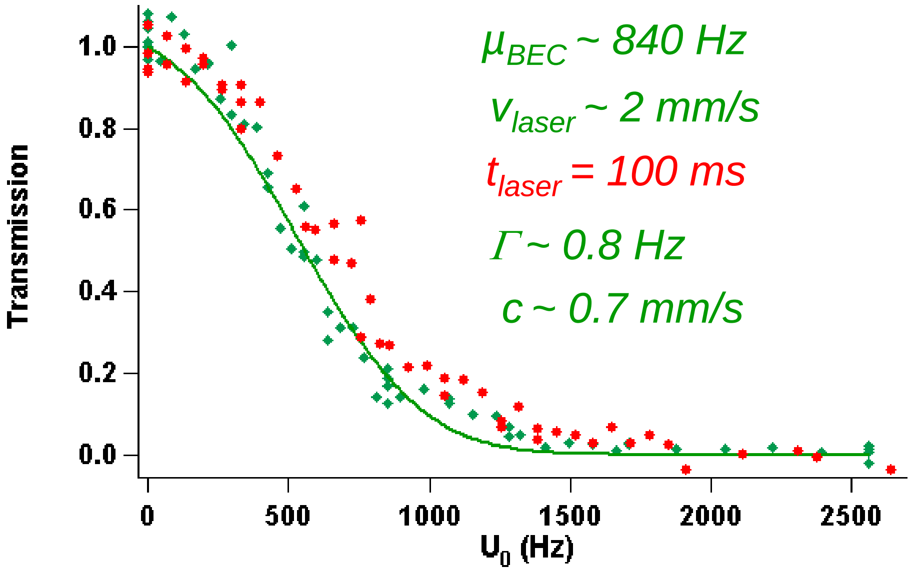
Not Fourier limited

Will be improved by active stabilization of magnetic field

Transmission through a (thick) barrier

Experimental scheme : normalisation by a 2nd atom laser

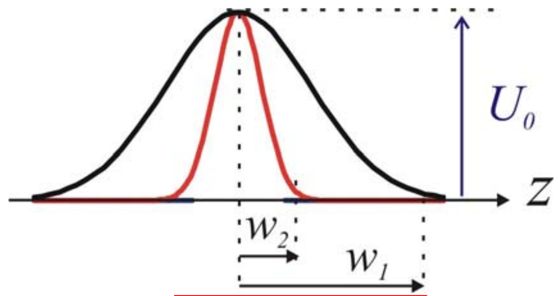




Quantum tunneling ? … try with thinner barrier

Discrepancy is due to positionning uncertainties
(only dilatation) (around 20 % uncertainties)

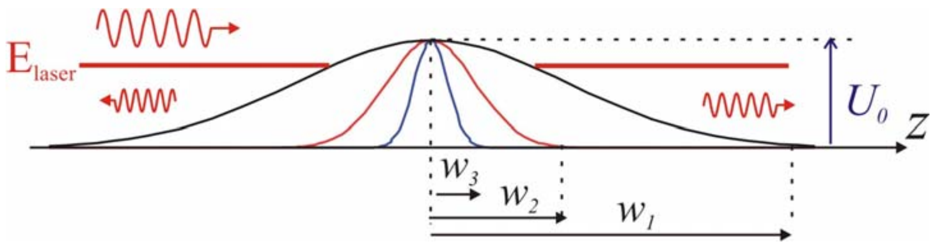
Further studies for the evaluating the effect of interactions …

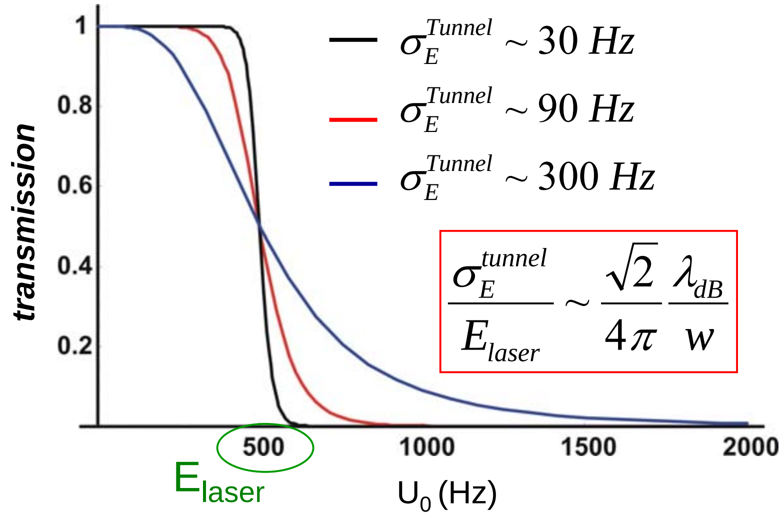


$w_2 = 1.3\ \mu m$

Quantum tunneling observable?

Monoenergetic transmission (E_{laser}= 500 Hz)





Different thickness

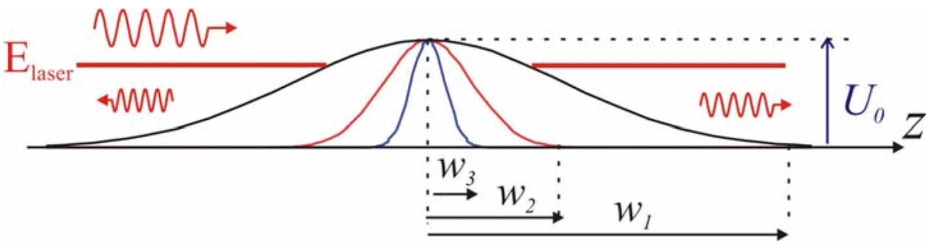
W_1= 4 µm (N.A.=0.05)

W_2= 1.3 µm (N.A.=0.15)

W_3= 0.5 µm (N.A.=0.5)

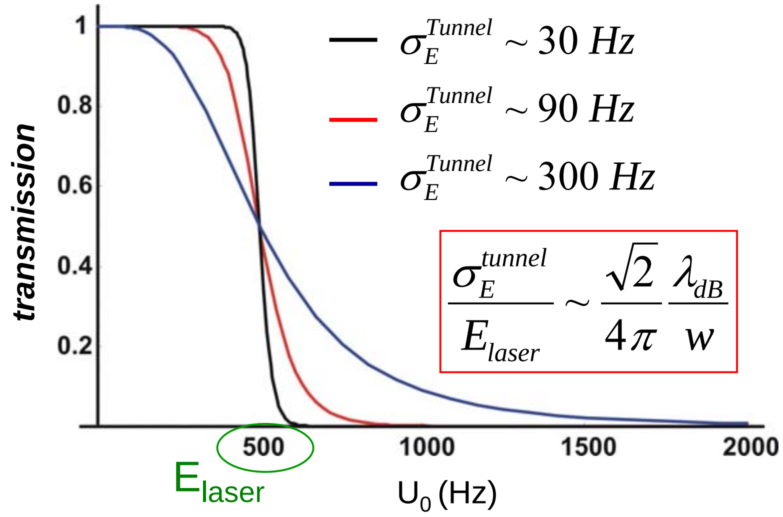
Quantum tunneling observable?

Monoenergetic transmission *(E_{laser}= 500 Hz)*



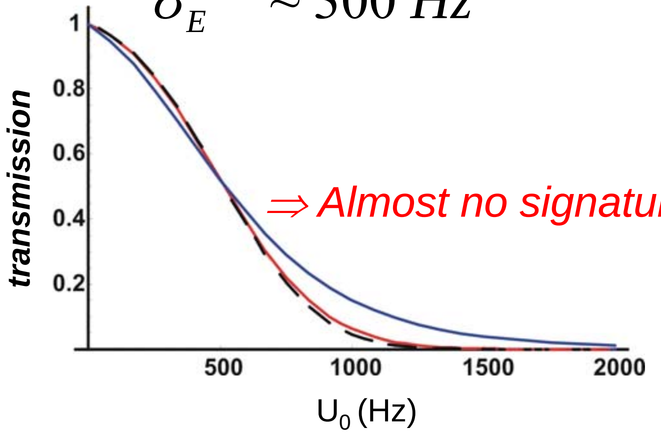
Different thickness

W_1= 4 μm (N.A.=0.05)
W_2= 1.3 μm (N.A.=0.15)
W_3= 0.5 μm (N.A.=0.5)



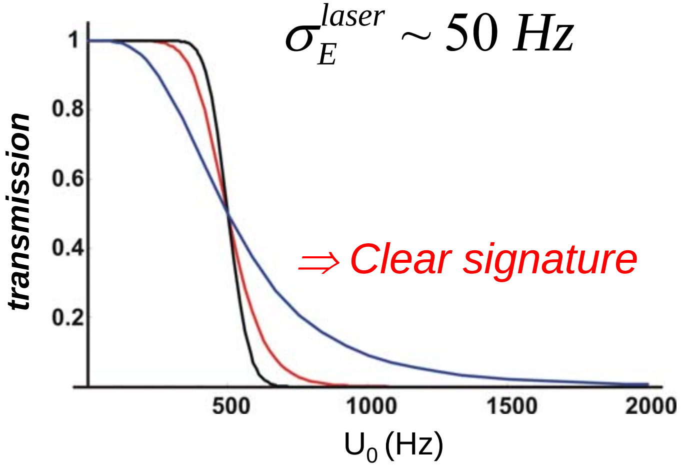
Broad atom laser (currently)

$$\sigma_E^{laser} \sim 300\ Hz$$



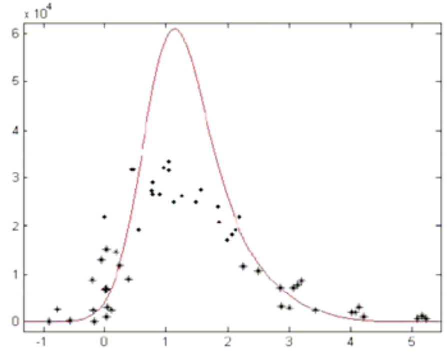
Smaller linewidth (future…)

$$\sigma_E^{laser} \sim 50\ Hz$$

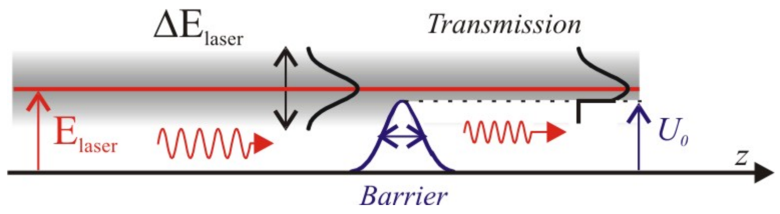


Outline

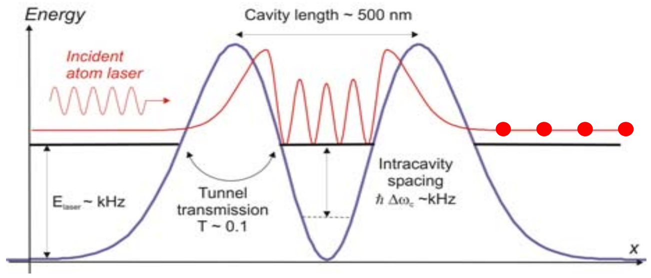
Properties of the guided atom laser



A direct linewidth measurement

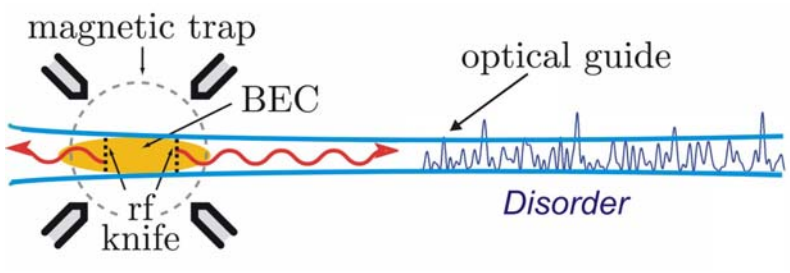


Perspectives



Some proposals

Transmission through disorder:



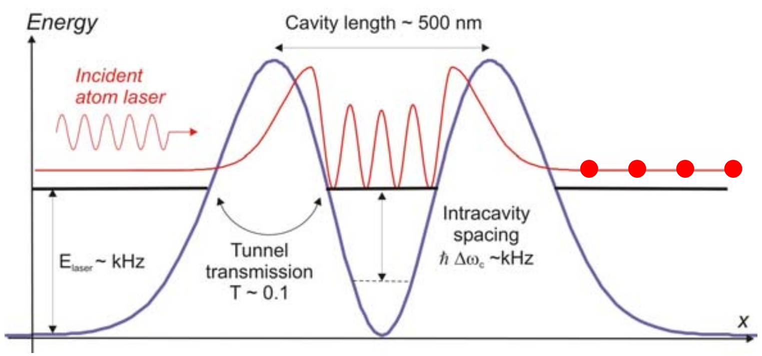
- *« exotic » behavior on localization length*

  L. Sanchez-Palencia *et al.* PRL **98**, 210401 (2007)

- *Anderson localisation vs superfluidity*

  T. Paul *et al.* PRL, 98, 210602 (2007)

Atom blockade at the output of a cavity



- *Frequency filtering*
- *Non classical atomic state preparation*

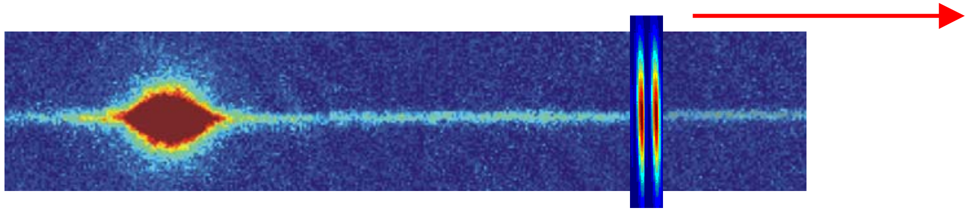
  I. Carussotto PRA **63**, 023610 (2001)

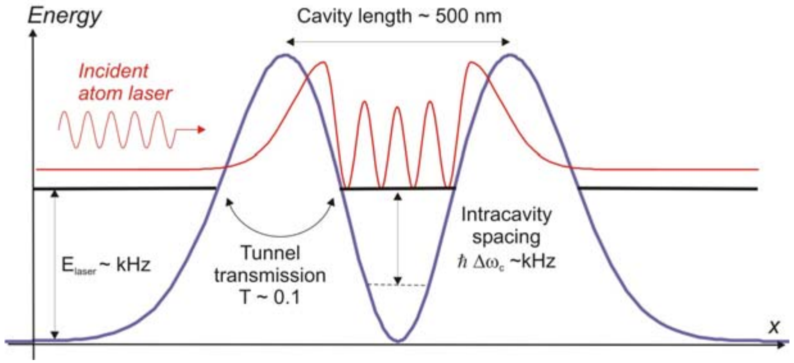
Hawking radiation ?

R. Balbinot *et al.* PRA **78**, 021603 (2008)
I. Carusotto et al. New. J. Phys. (2008)

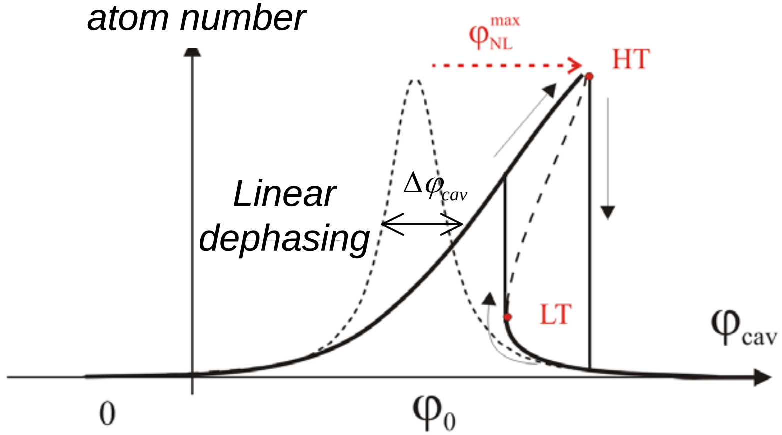
Atom blockade effect

Transmission through a double barrier (TEM01)





Inter-atomic interaction = Optical Kerr effect in cavity ($n=n_0+n_1 I$)



« Classical » picture : bistability

•Bistability threshold : $\varphi_{NL} = \Delta\varphi_{cav}/2$

$\Rightarrow$ Maximum atomic number

$$N_{\max} = \frac{\kappa}{2\omega_{NL}}$$

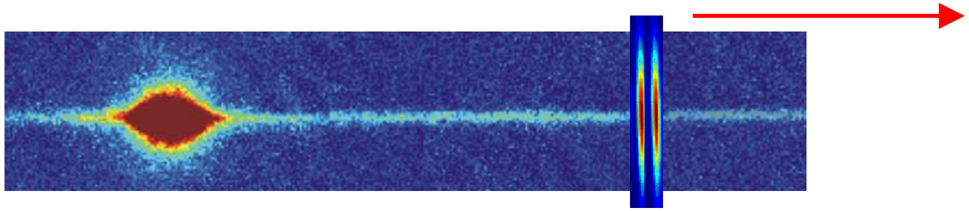
Cavity linewidth (κ)

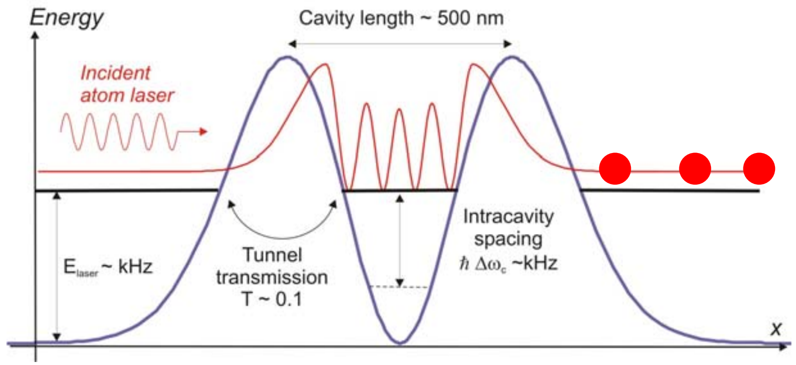
Atomic interaction (ω_{NL})

• Weak interactions : N_{max}>>1 $\Rightarrow$ Squeezing

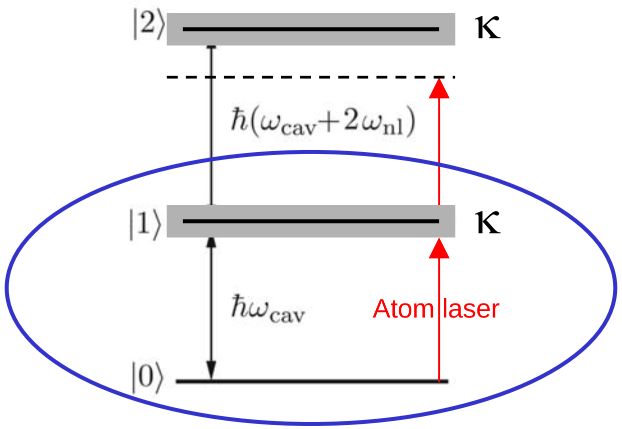
Atom blockade effect

Transmission through a double barrier (TEM01)





Inter-atomic interaction = Optical Kerr effect in cavity ($n=n_0+n_1I$)

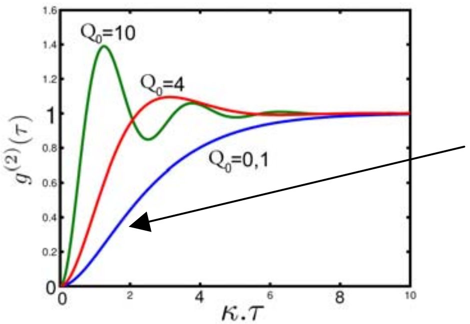


Quantum picture : atom blockade

• Strong interaction : N_{max}<<1

$$N_{\max} = \frac{\kappa}{2\omega_{NL}}$$

⇒ Two level system (fluorescence resonance) :

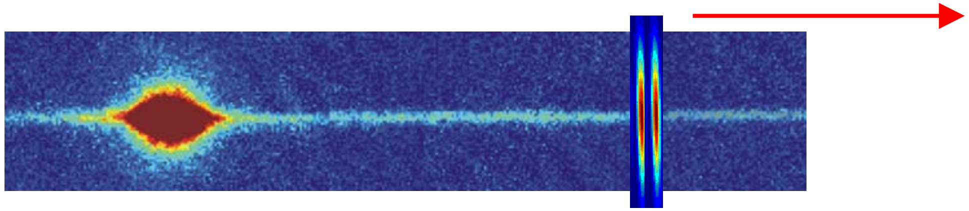


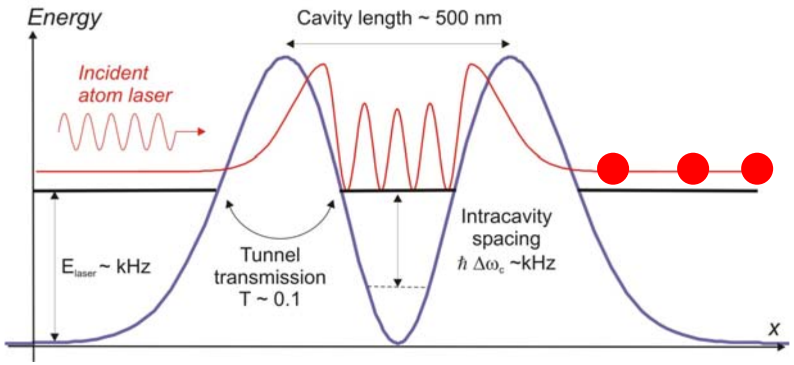
Anti-bunching

I. Carussotto PRA **63**, 023610 (2001)

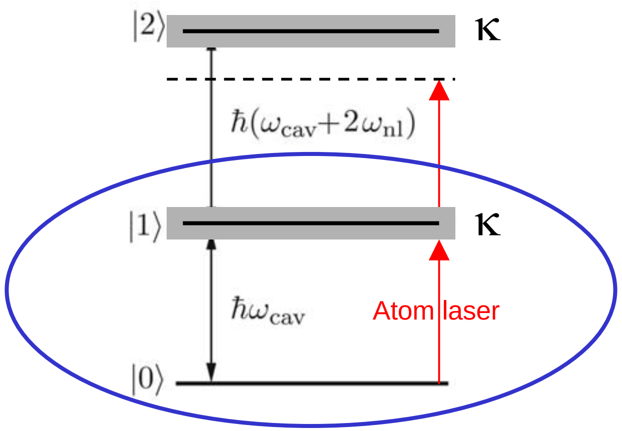
Atom blockade effect

Transmission through a double barrier (TEM01)





Inter-atomic interaction = Optical Kerr effect in cavity ($n=n_0+n_1I$)



Quantum picture : atom blockade

Some realistic numbers

- Barrier thickness ~ 0.5 µm
- ω_{cav} ~ 1kHz $\Rightarrow$ round trip τ~ 1ms
- Tunneling T~ 0.1 $\Rightarrow$ width κ~30 Hz
- Non linear interactions ω_{NL}~3 Hz

$$N_{max} = \frac{\kappa}{2\omega_{NL}} \approx 5$$

Summary

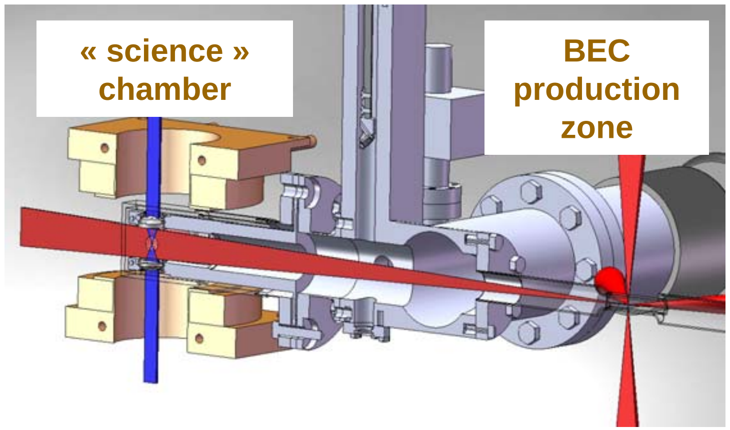
Guided atom laser :
Suitable tool for studying quantum transport phenomena

Currently: work in progress

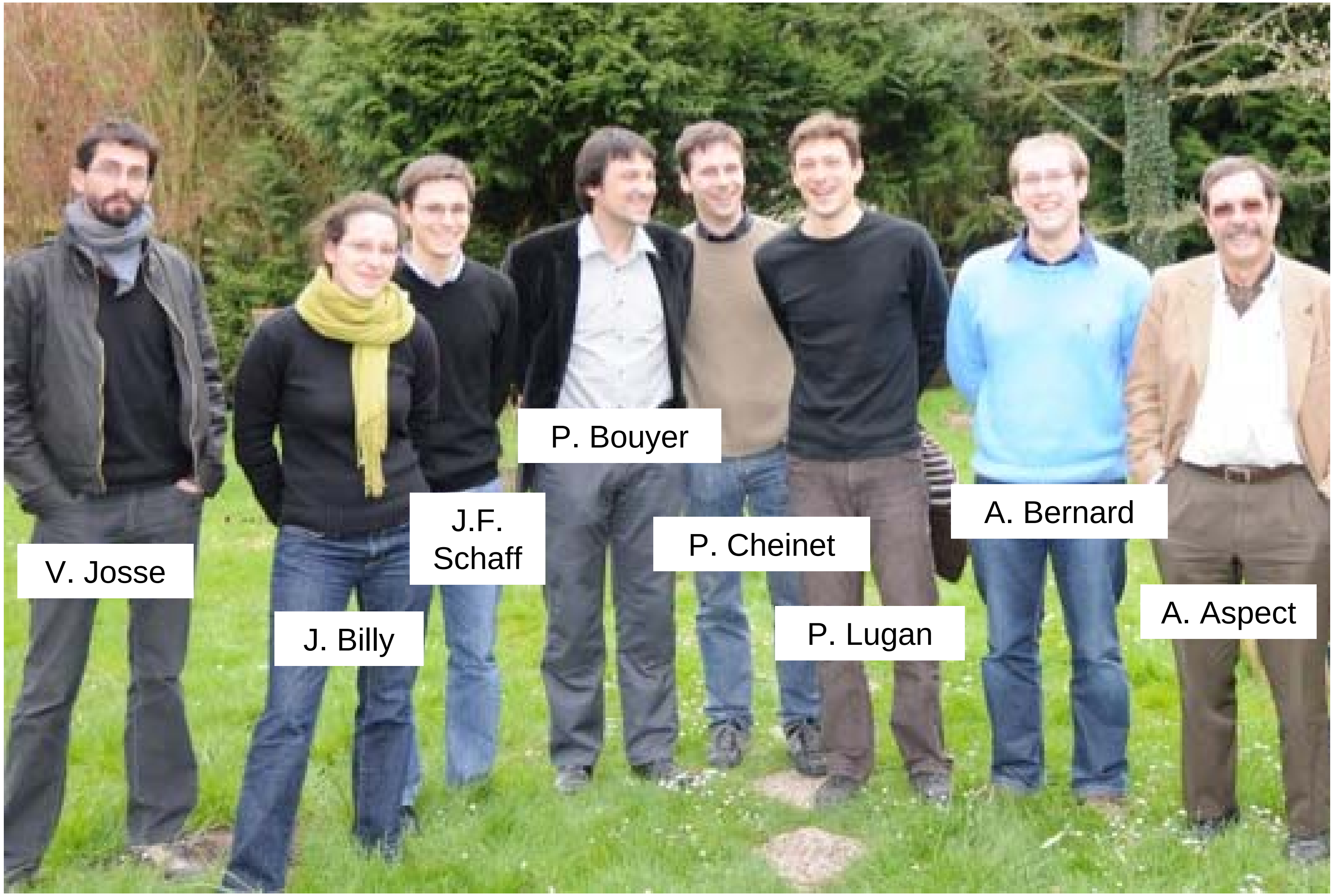
Moving to a new institute (Orsay → Palaiseau)

New setup with higher numerical access, improved stabilty

Future : many ideas …

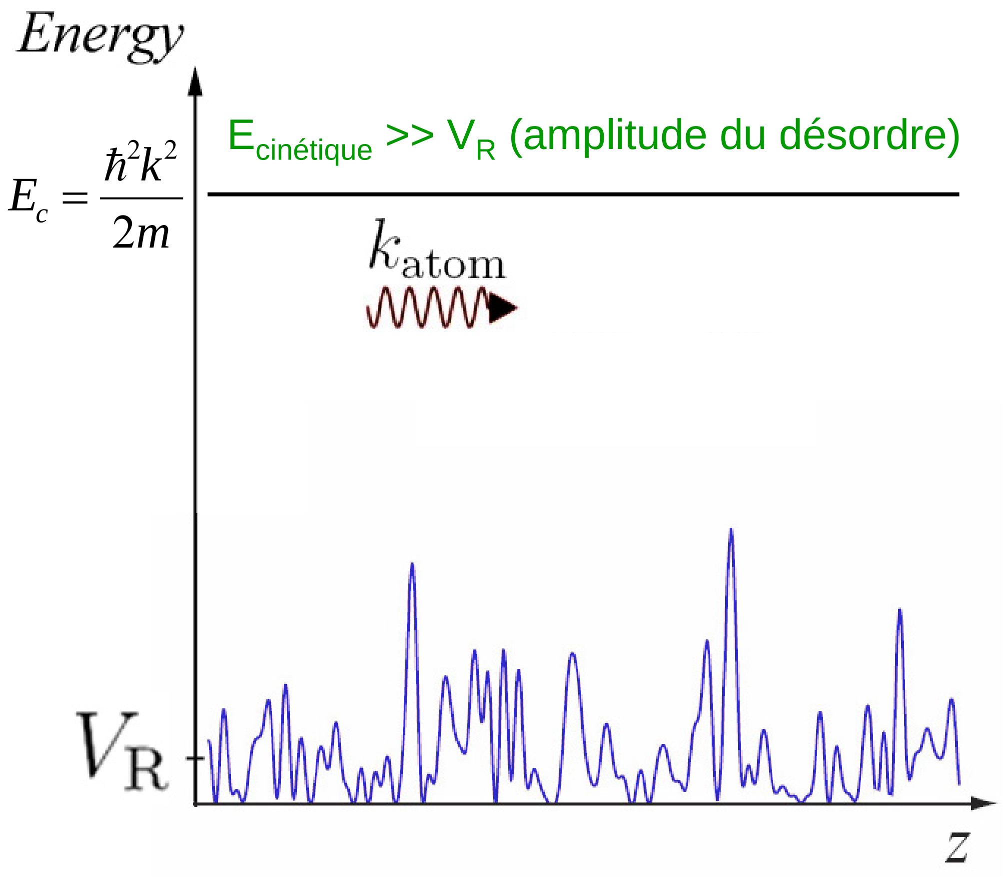


The Team


P. Bouyer
J.F. Schaff
P. Cheinet
A. Bernard
V. Josse
J. Billy
P. Lugan
A. Aspect

Transport quantique à travers un potentiel désordonné

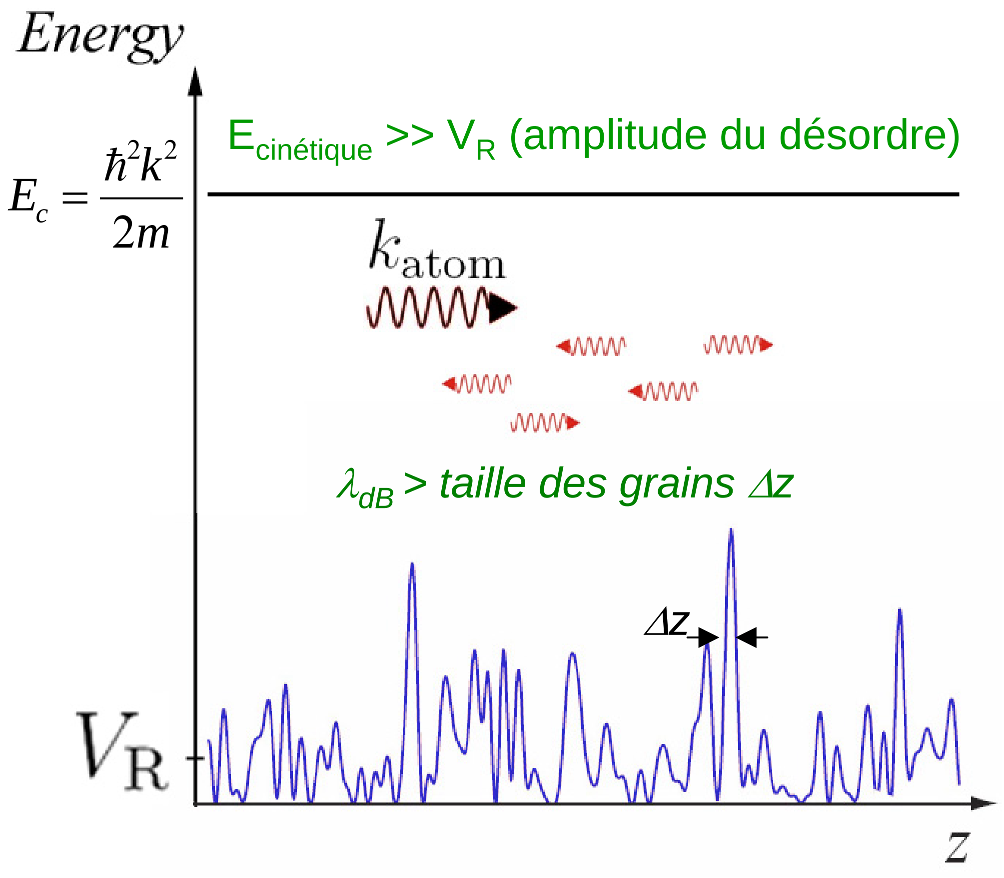
Description intuitive de la localisation d'Anderson (1958) :



Classique: transmission des atomes

Transport quantique à travers un potentiel désordonné

Description intuitive de la localisation d'Anderson (1958) :

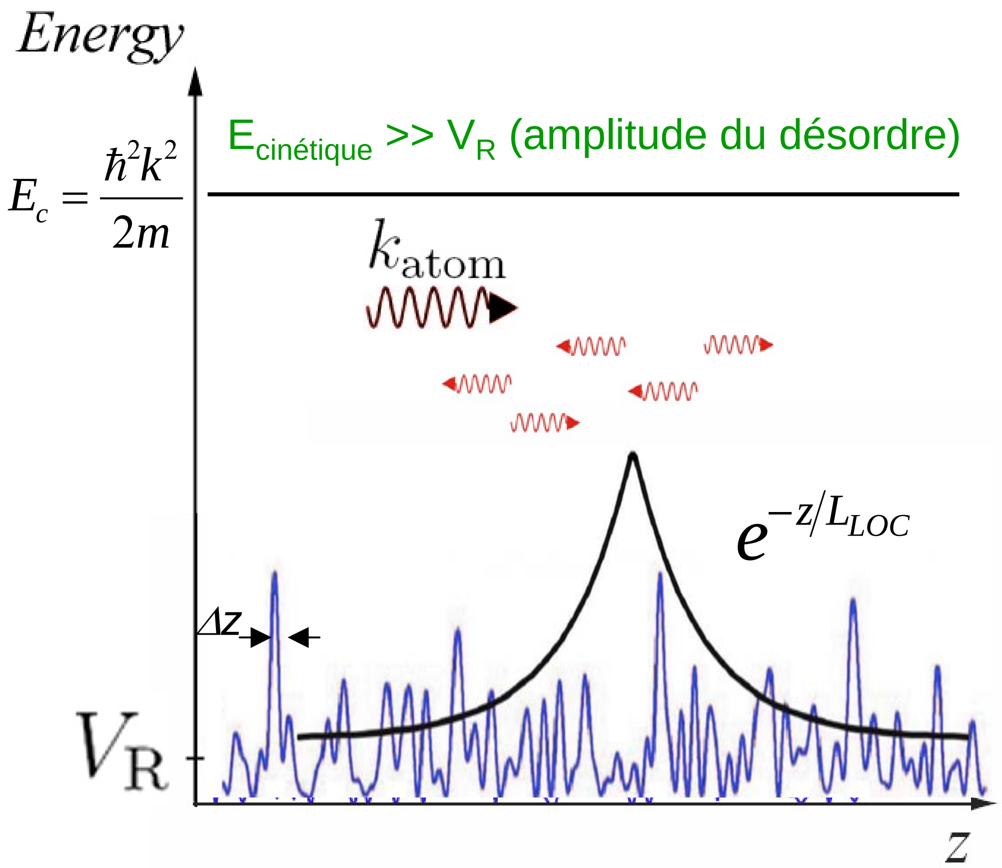


Classique: transmission des atomes

Quantique: interférences destructives entre les réflections multiples sur les barrières

Propagation quantique à travers un potentiel désordonné

Description intuitive de la localisation d'Anderson (1958) :



Classique: transmission des atomes

Quantique: interférences destructives entre les réflections multiples sur les barrières

→ *Décroissance exponentielle de la fonction d'onde*

→ *Arrêt de la propagation (Localisation d'Anderson)*

→ *Transition conducteur-isolant dû au désordre pour certains matériaux*

Observations expérimentales

Depuis 10 ans avec différents types d'ondes (optique, micro-ondes, acoustique)

+ récemment avec des ondes de matières !

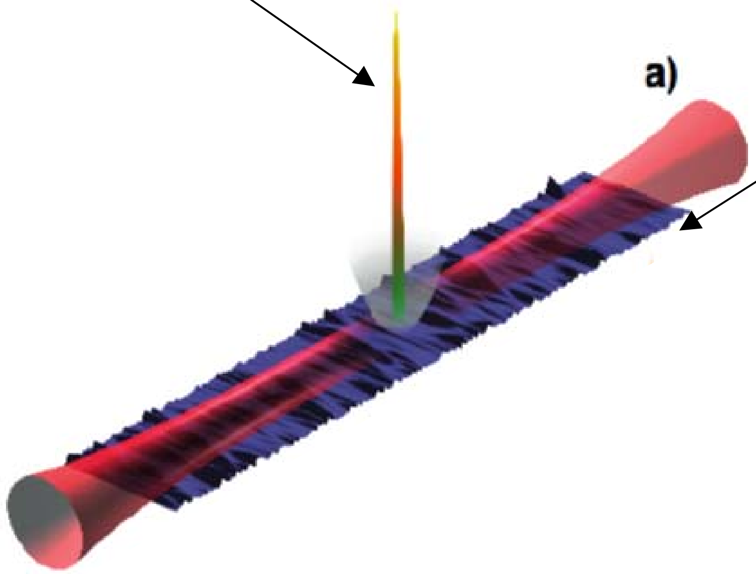
Orsay: J. Billy *et al.*, Nature (in press)

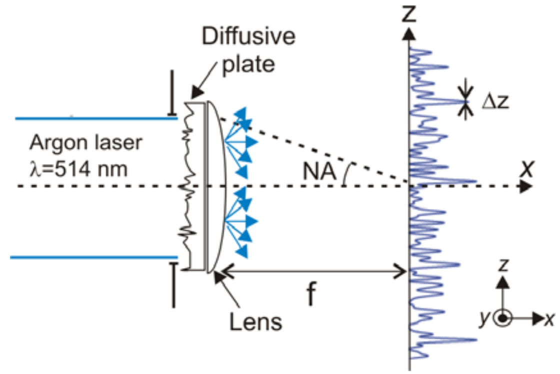
Florence: G. Roati *et al.*, Nature (in press)

Localisation d’un BEC en expansion (Orsay 2008)

1. Préparation du condensat (piège mixte magnétique + guide optique)

2. Désordre = potentiel optique d’un champ de « speckle » créé par un diffuseur





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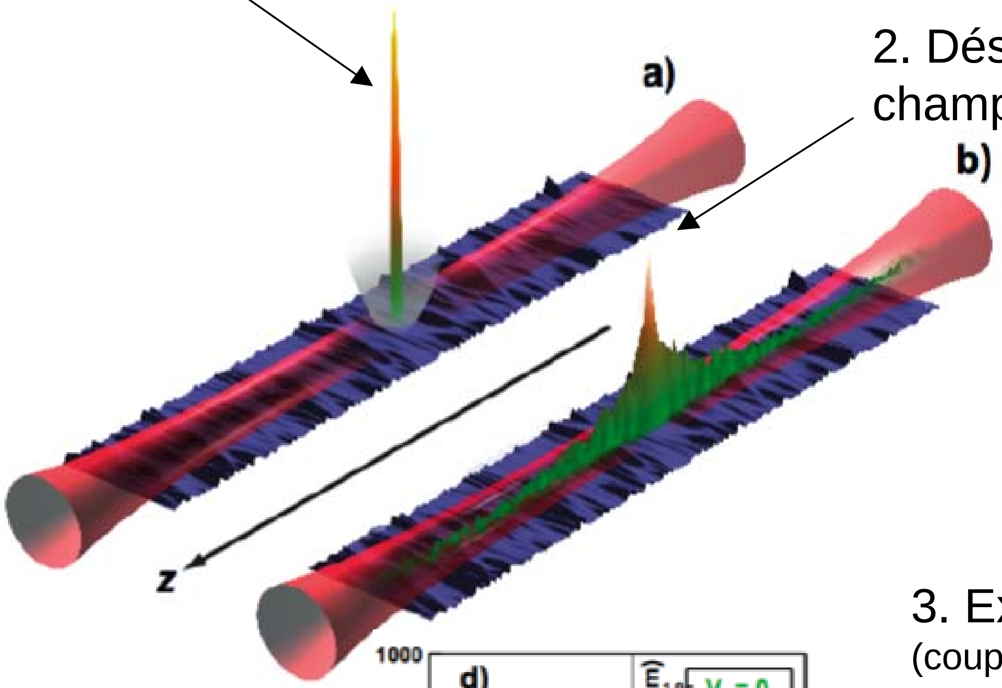
1. Préparation du condensat (piège mixte magnétique + guide optique)



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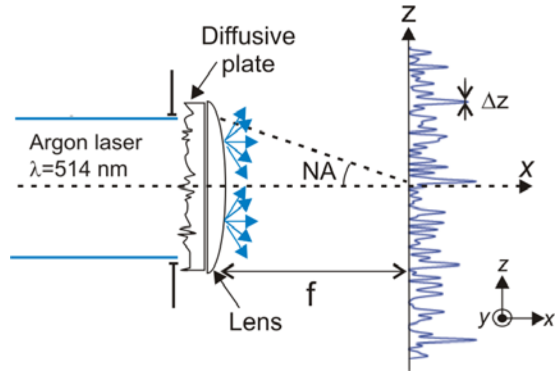
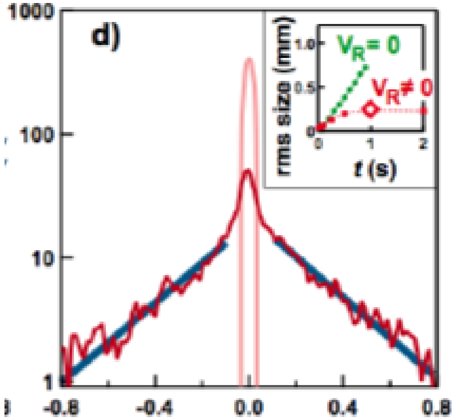


3. Expansion du BEC dans le guide
(coupure du champ magnétique)

= superposition d'ondes planes avec différentes impulsions k.

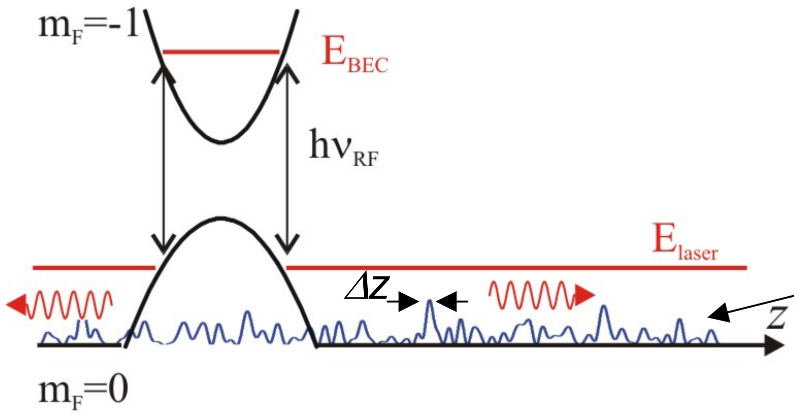


4. Décroissance exponentielle des profils

Condition intuitive validée $\lambda_{dB} > \Delta z$

Taille caractéristique du désordre ~ µm

Localisation du laser à atomes guidé ?



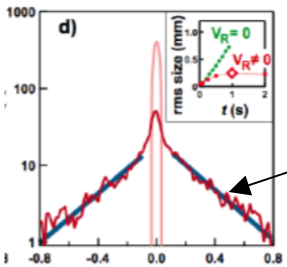
E_{laser} >> V_R (amplitude du désordre)

~ kHz ~ 50 Hz

Désordre crée par le champ de speckle
λ_{dB} > taille des grains Δz

Motivations du laser à atomes / expansion du condensat

- *Caractère monochromatique (une seule onde plane e^{ikx})*
- *Découplage vitesse d'expansion (ν_{RF}) / densité atomique (puissance RF)*

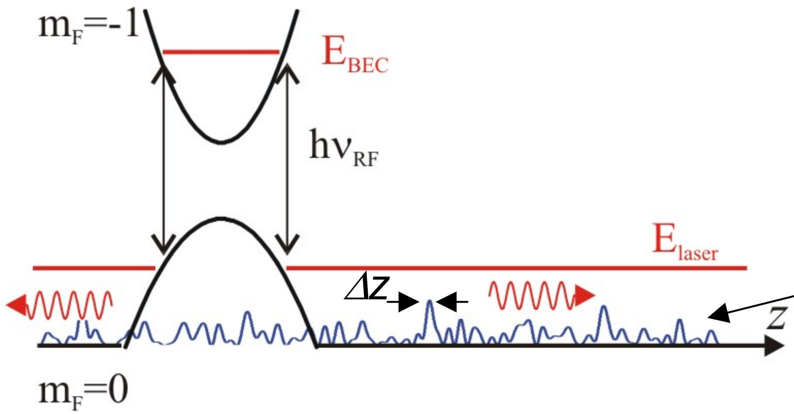


Longueur de localisation $L_{loc}(k)$

Rôle des interactions

La localisation a-t-elle toujours lieu?
(Débats théoriques sur le sujet)

Localisation du laser à atomes guidé



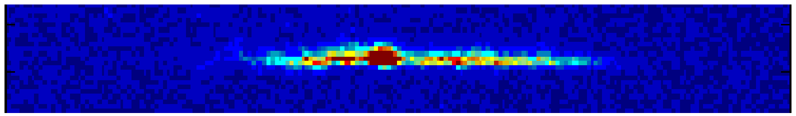
$E_{laser} >> V_R$ (amplitude du désordre)

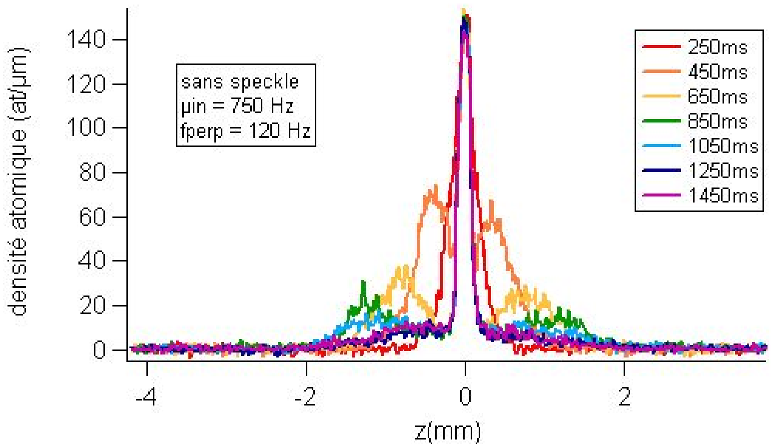
~ *kHz* ~ *50 Hz*

Désordre crée par le champ de speckle
Taille des grains $\Delta z < \lambda_{dB}$

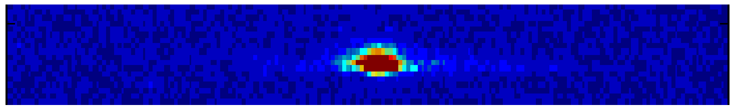
Résultats préliminaires : arrêt de l'expansion du laser à atomes

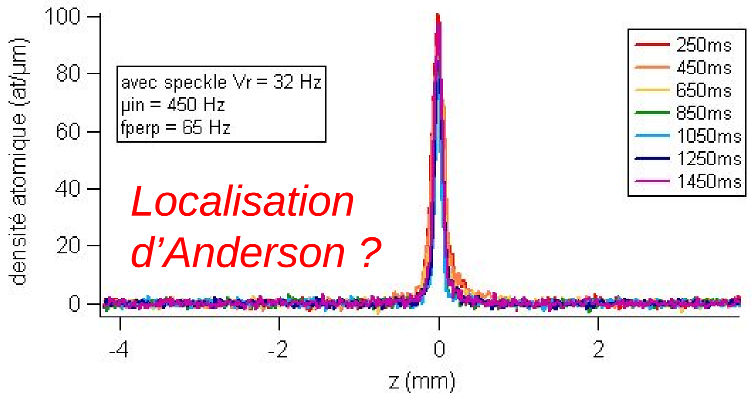
Sans désordre





Avec désordre





Conclusion

Fonctionnement du laser à atomes guidés

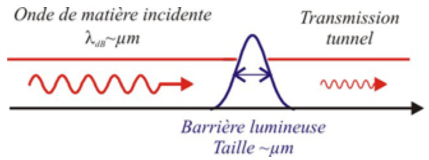
Validation des principes de fonctionnement

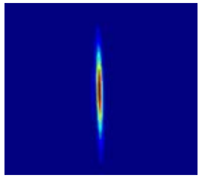
Effort à faire sur la stabilisation magnétique pour améliorer les performances (remise à plat lors du déménagement sur le site de Polytechnique, Palaiseau)

Des premiers pas vers l'étude de la propagation quantique du laser à atomes

Etudes en cours sur le transport à travers un milieu rugueux

Etudes en cours sur l'effet tunnel à travers une barrière optique





Perspectives

Physique fondamentale : *Fabry- Perot non linéaire*
laser à atomes squeezé

Intégration du système sur puces : *brevet avec IXSEA*

Equipe « transport quantique»

Thésards

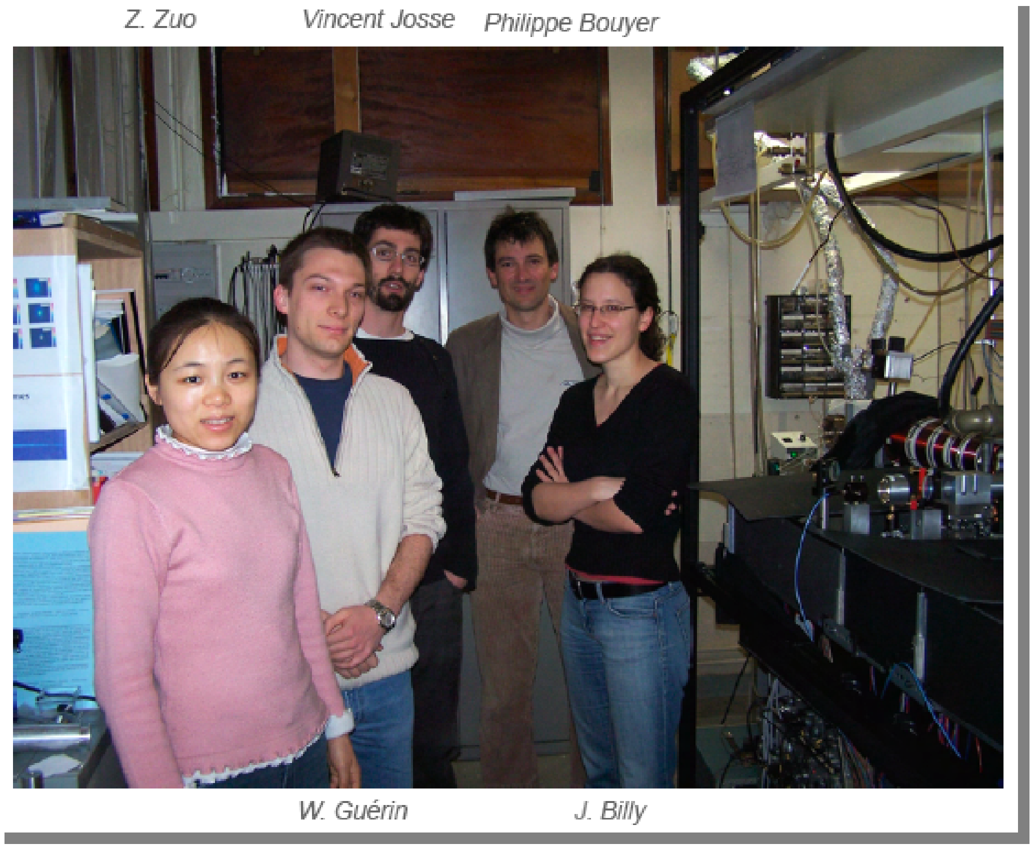
Juliette Billy
Alain Bernard
William Guérin

Post doc

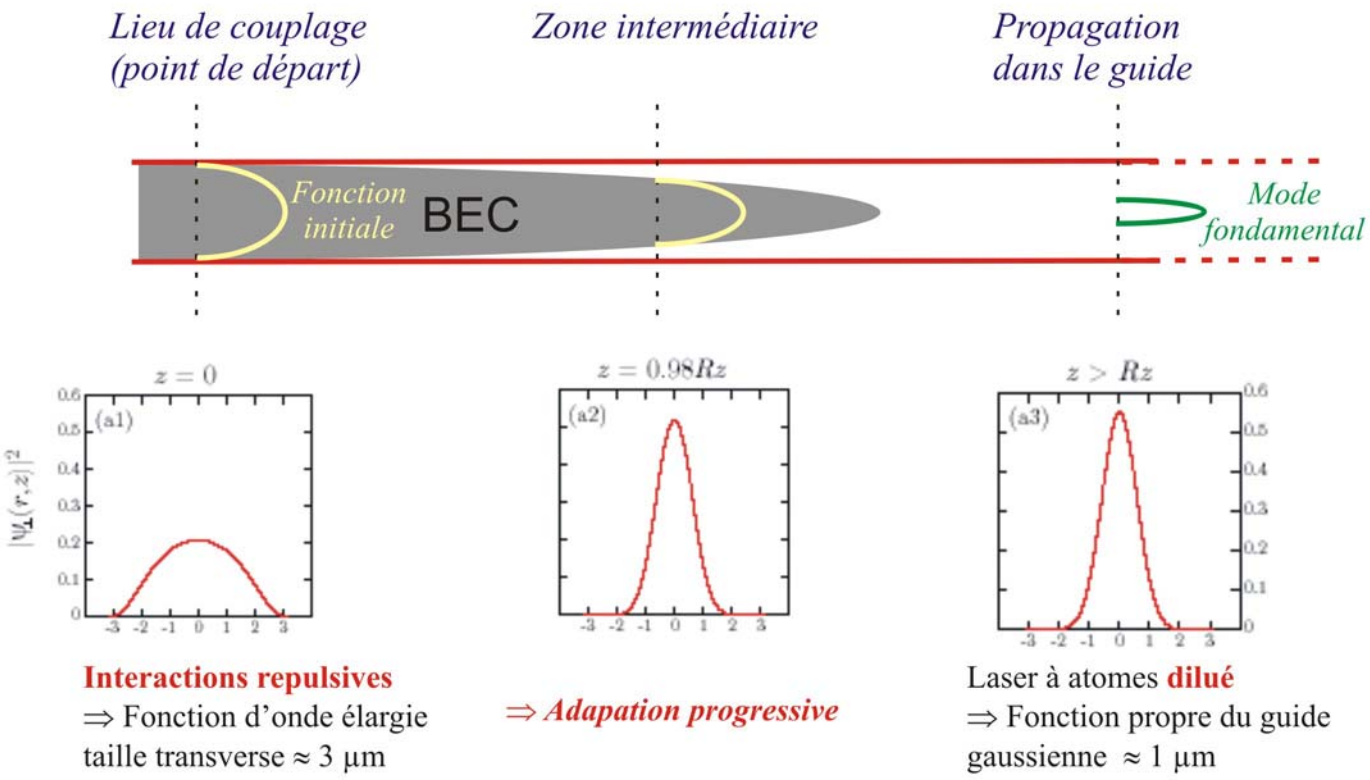
Zanchun Zuo
Patrick Cheinet

Permanents

Vincent Josse
Philippe Bouyer
Alain Aspect



Adaptation de mode



Suivi adiabatique du BEC jusqu'au guide → propagation monomode

Energie transverse mesurée: $E_\perp \sim 5\,\hbar\omega$ →Quelques modes excités (n~2)