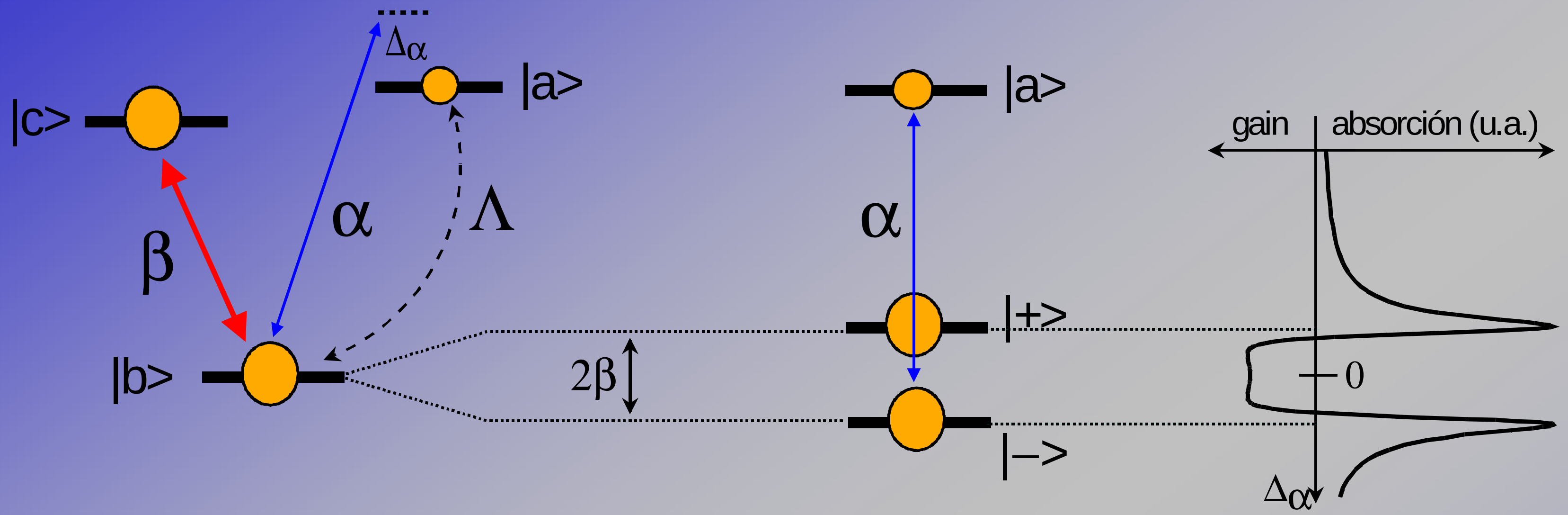
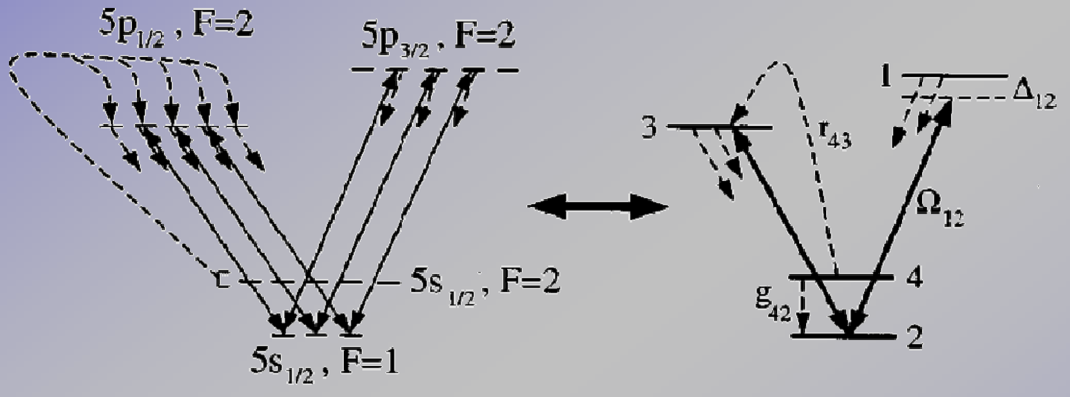
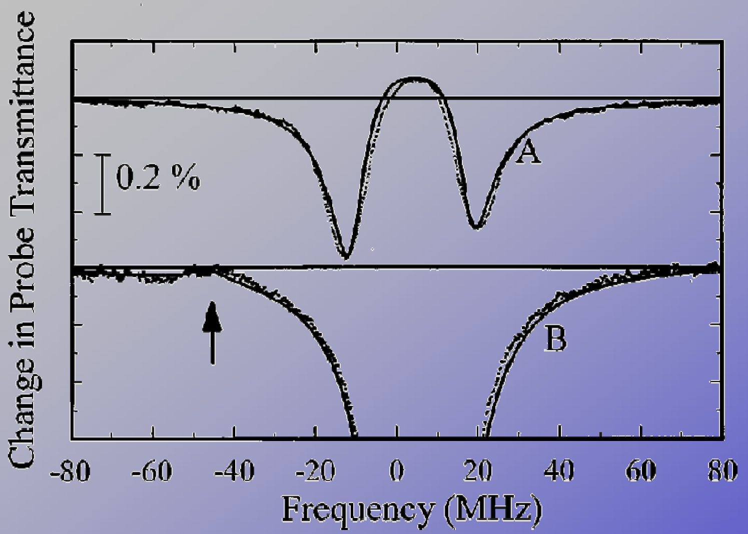






# 4 (SOME) APPLICATIONS OF THREE-LEVEL TECHNIQUES

# OUTLINE

## 4.1 THE QUANTUM ATOM OPTICS GROUP (UAB)

## 4.2 LWI: LASING WITHOUT INVERSION

- LWI IN TWO-LEVEL SYSTEMS
- LWI IN THREE LEVEL SYSTEMS

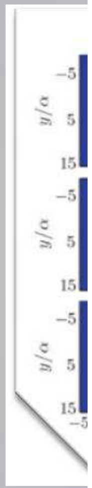
## 4.3 SLAP: SUBWAVELENGTH LOCALIZATION VIA ADIABATIC PASSAGE

- NANOLITHOGRAPHY WITH A NE* MATTER WAVE
- COHERENT PATTERNING OF A 87RB BEC

# QUANTUM ATOM OPTICS GROUP (UAB)

A. Turpin

J. L. Rubio



- **Ultracold atoms**
- **Three-level optics**
- **Conical refraction**

- **Light propagation in co**
- **de Broglie-Bohm quant**
- **Laser-matter interaction**

**6 years ago**

# LASING WITHOUT INVERSION

# LASING WITHOUT POPULATION INVERSION

- ⇨ *Introduction*
- ⇨ *Early history*
  - *Recoil-induced lasing*
  - *LWI in coherently driven two-level systems*
- ⇨ *LWI in coherently driven three-level systems*
- ⇨ *LWI experiments*
- ⇨ *Prospects for frequency up-conversion LWI*

*Atomic coherences and quantum interference effects are being actively investigated to manipulate the optical properties of coherently driven atomic systems.*

- *Amplification and lasing without inversion (AWI and LWI)*

  *Review: Mompart and Corbalán, J. Opt. B: Quantum Semiclass. Opt.* ***2*** *(2000) R7*

- *Inversion without lasing (IWL)*

- *Coherent population trapping (CPT)*

  *Review: Arimondo, in Progress in Optics XXXV (1996)*

- *Electromagnetically induced transparency (EIT)*

  *Review: Harris, Physics Today* ***50*** *(1997) 36*

- *Enhancement of the index of refraction with vanishing absorption*

  *Scully, Phys. Rev. Lett.* ***67*** *(1991) 1855*
  *Zibrov et al., Phys. Rev. Lett.* ***76*** *(1996) 3935*

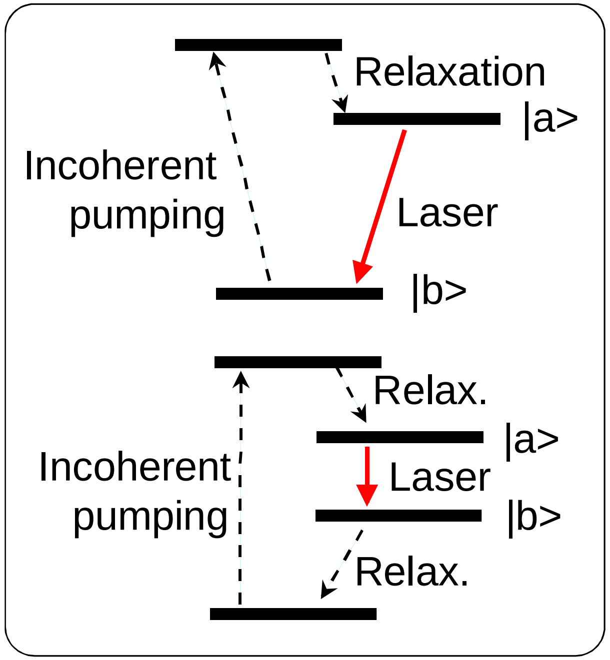
- *Ultraslow group velocity and nonlinear optics at very low light levels*

  *Hau et al., Nature* ***397*** *(1999) 594*
  *Harris, Phys. Rev. Lett.* ***82*** *(1999) 4611*
  *Kash et al., Phys. Rev. Lett.* ***82*** *(1999) 5229*

- *Two-level systems*

$$\frac{\text{stimulated emission rate}}{\text{absorption rate}} = \frac{\rho_{aa} B_{ab}}{\rho_{bb} B_{ba}}$$

$$B_{ab} = B_{ba} \begin{cases} \text{amplification for } \rho_{aa} > \rho_{bb} \\ \text{it is not possible to invert a closed two-level system} \end{cases}$$



- *Threshold pumping power for population inversion*

$P_{th} \propto \omega^4$ *for Doppler broadening*

$P_{th} \propto \omega^6$ *for natural broadening*

⇒ *The main obstacle in the achievement of short-wavelength laser emission is the required pumping power*

- *Interest in LWI derives from its potential for facilitating lasing in the blue or UV by reducing the minimum excited state population required for lasing.*

- *In LWI the reciprocity between stimulated emission and absorption is broken:*

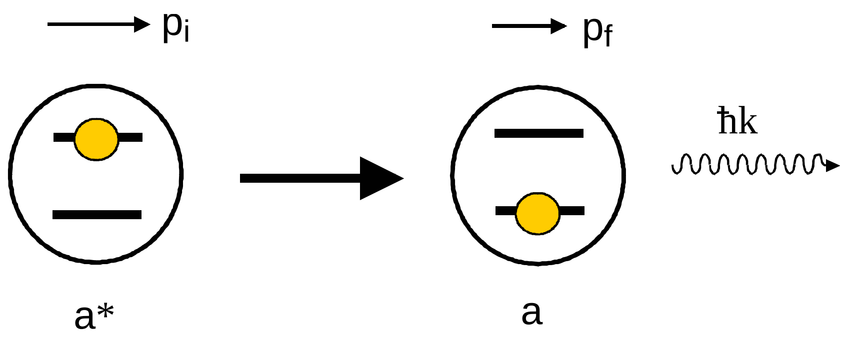
$$B_{ab} \neq B_{ba}$$

- *The idea behind LWI is to prepare the system not only by increasing the upper level population but mainly by exciting atomic coherences*

- *Atomic coherence usually produced by an external coherent (driving) field*

# Recoil-induced lasing without inversion

## Emission

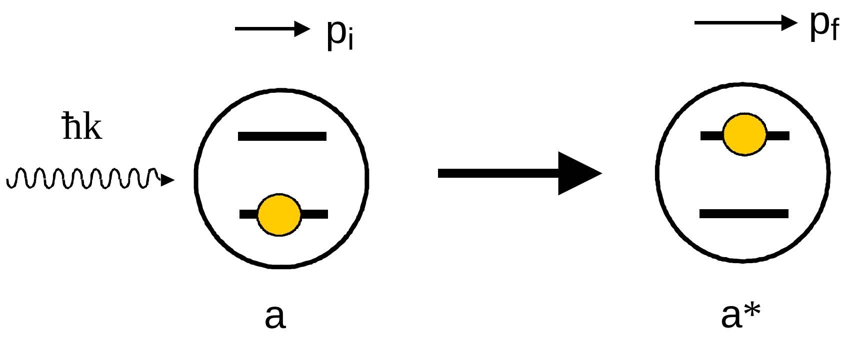


$$p_i = p_f + \hbar k$$

$$\hbar\omega_0 + \frac{p_i^2}{2M} = \hbar c|k| + \frac{p_f^2}{2M}$$

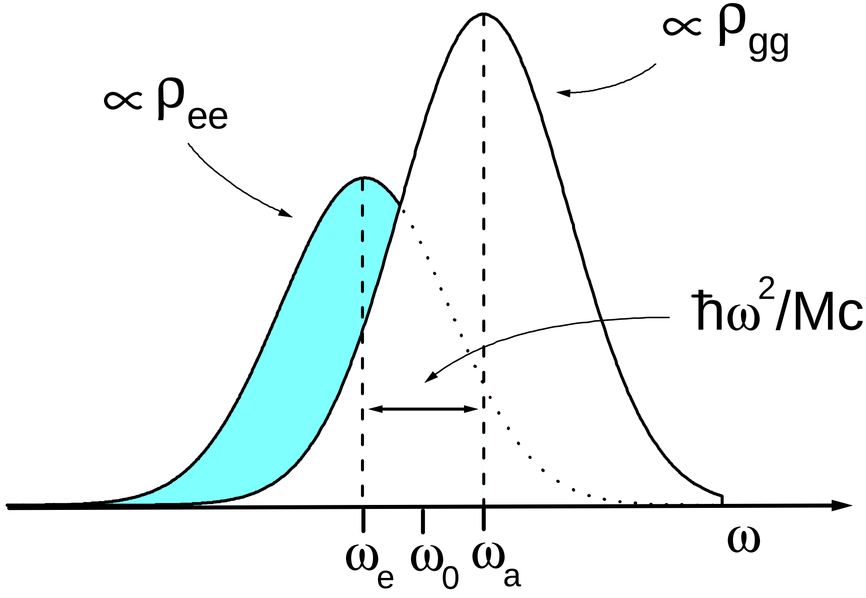
$$\Rightarrow \quad \omega_e = c|k| = \omega_0 - \underbrace{\frac{\hbar k^2}{2M}}_{\text{Recoil shift}} + \underbrace{\frac{kp_i}{M}}_{\text{Doppler shift}}$$

## Absorption



$$\Rightarrow \quad \omega_a = c|k| = \omega_0 + \frac{\hbar k^2}{2M} + \frac{kp_i}{M}$$

⇒ *Recoil-induced frequency shift:* $\frac{\hbar k^2}{M} = \frac{\hbar\omega^2}{Mc^2}$



⇒ *For helium atoms:*
*a few MHz in the visible*
*a few GHz in the ultraviolet*
*a hundred GHz in the x-ray domain*

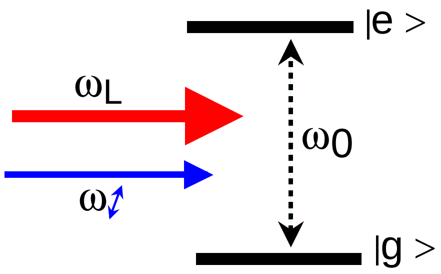
*Inversionless maser action*

*D. Marcuse. Proc. IEEE* ***51*** *(1963) 849*

*Laser cooled metastable atoms*

*H. Ritsch et al.* *Phys. Rev. Lett.* ***74*** *(1995) 678*
*Phys. Rev. A* ***52*** *(1995) 554*

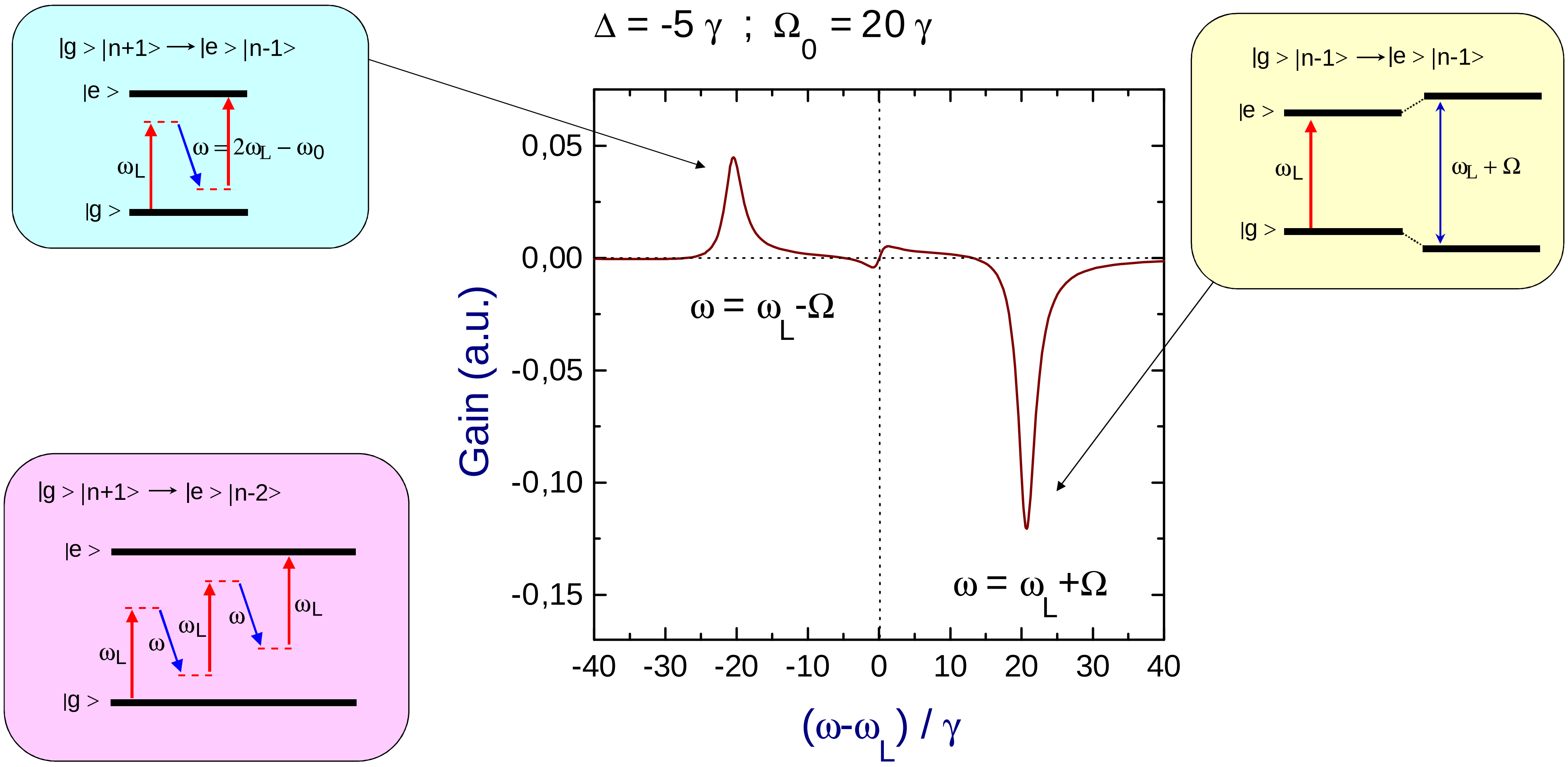
# LWI in coherently driven TWO-level systems

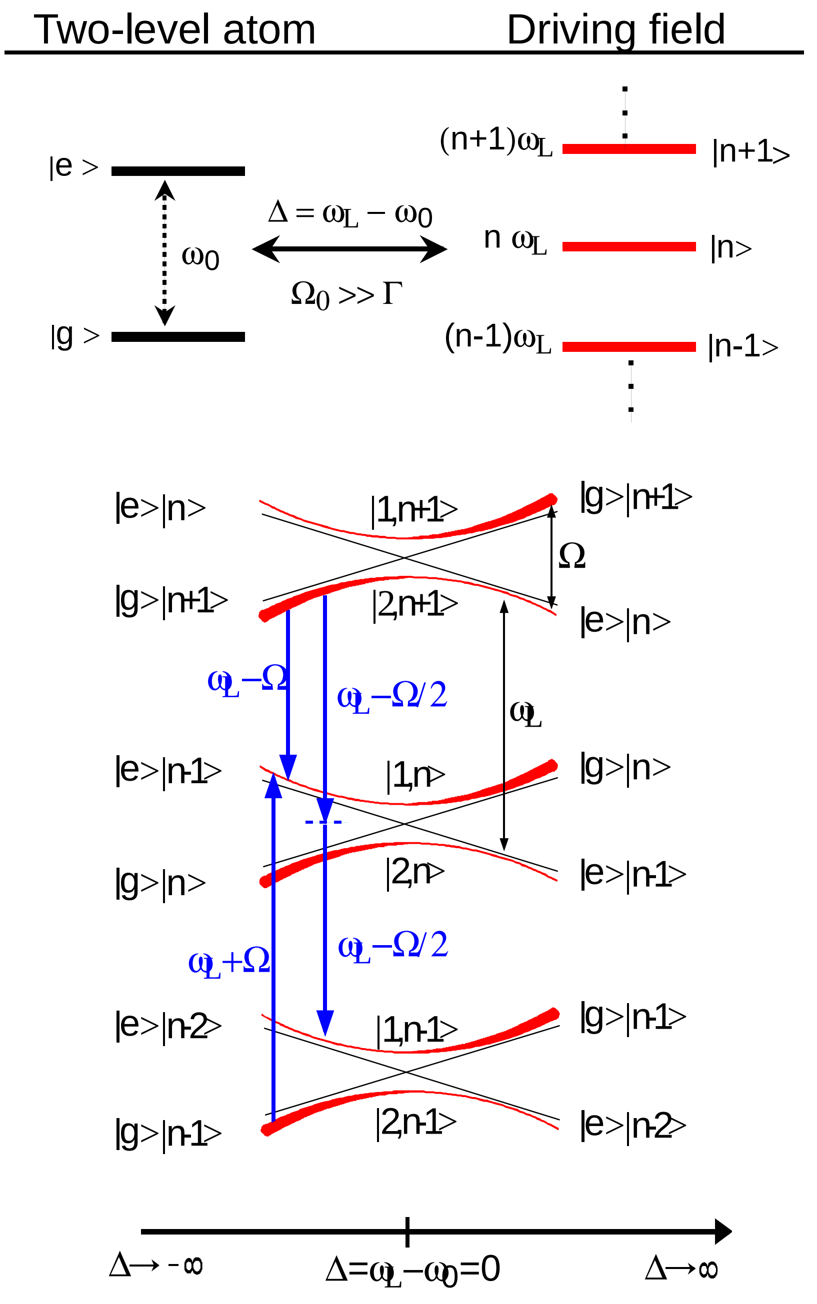


*Rautian and Sobelman (1962)*

*B. R. Mollow. Phys. Rev. A* ***5*** *(1972) 2217*

*S. Haroche, F. Hartmann. Phys. Rev. A* ***6*** *(1972) 1280*





$$\Omega = \sqrt{\Delta^2 + \Omega_0^2}$$

- *Absorption (gain) at* $\omega_L + \Omega$ $(\omega_L - \Omega)$ *first observed by*

  *F. Y. Wu et al., Phys. Rev. Lett.* ***38*** *(1977) 1077*

- *Lasing with hidden inversion at* $\omega_L - \Omega$ *first observed by*

  *G. Khitrova et al., Phys. Rev. Lett.* ***60*** *(1988) 1126*

- *Two-photon lasing with hidden inversion at* $\omega_L - \Omega/2$ *first observed by*

  *D.J. Gauthier et al., Phys. Rev. Lett.* ***68*** *(1992) 464*

- *Lasing without inversion at* $\omega_L$ *first observed by*

  *D. Grandclement et al., Phys. Rev. Lett.* ***59*** *(1987) 40*

  *G. Grynberg and C. Cohen-Tannoudji,*
  *Opt. Comm.* ***96*** *(1993) 150*

$\Rightarrow$ *As probe and drive lasers operate on the same transition. Therefore, they are not useful to frequency up-conversion LWI*

# LWI in coherently driven THREE-level systems

- *Three-level systems:* *Drive and probe fields couple to adjacent transitions sharing a common level*

- *Doppler-free laser spectroscopy*

  *Javan (1957)*
  *Hänsch, Toscheck (1970)*
  *Popov, Popov, Rautian (1970)*

- *Atomic coherence effects*

  *Kocharovskaya and Khanin, Sov. Phys. JETP Lett.* ***48*** *(1988) 630*
  *Scully, Zhu and Gravielides, Phys. Rev. Lett.* ***62*** *(1989) 2813*

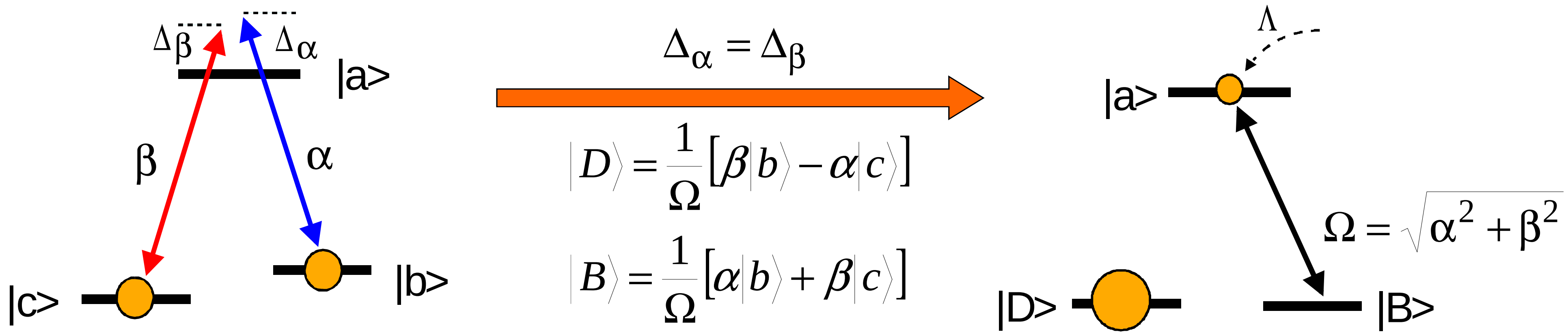
- *Inversion?*

  *(i) Inversion in the CPT basis*

  *(ii) Inversion in the dressed-state basis*

  *(iii) LWI without hidden inversion*

## *(i) Inversion in the CPT basis*



$$\Delta_\alpha = \Delta_\beta$$

$$|D\rangle = \frac{1}{\Omega}[\beta|b\rangle - \alpha|c\rangle]$$

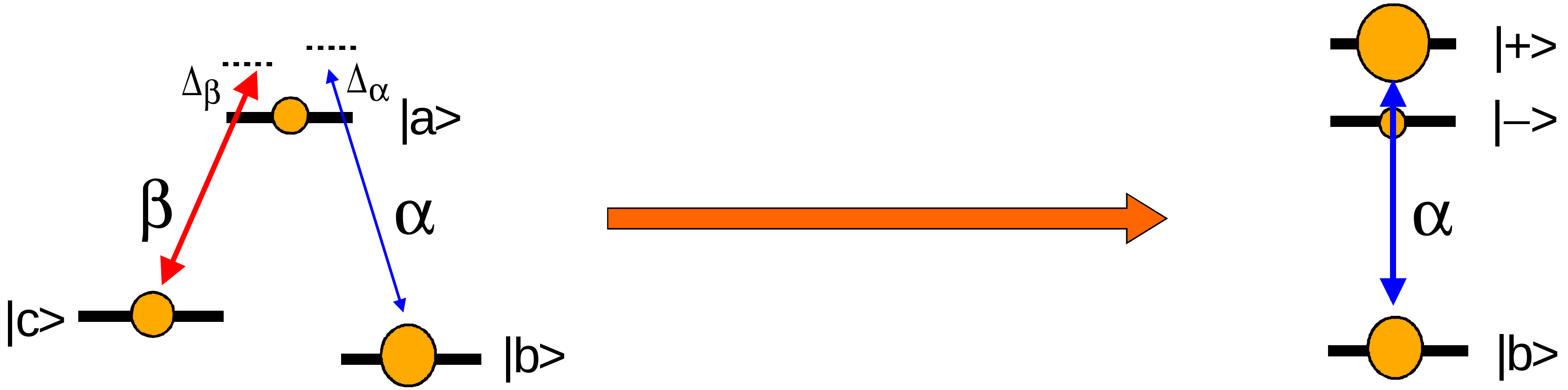
$$|B\rangle = \frac{1}{\Omega}[\alpha|b\rangle + \beta|c\rangle]$$

$$\Omega = \sqrt{\alpha^2 + \beta^2}$$

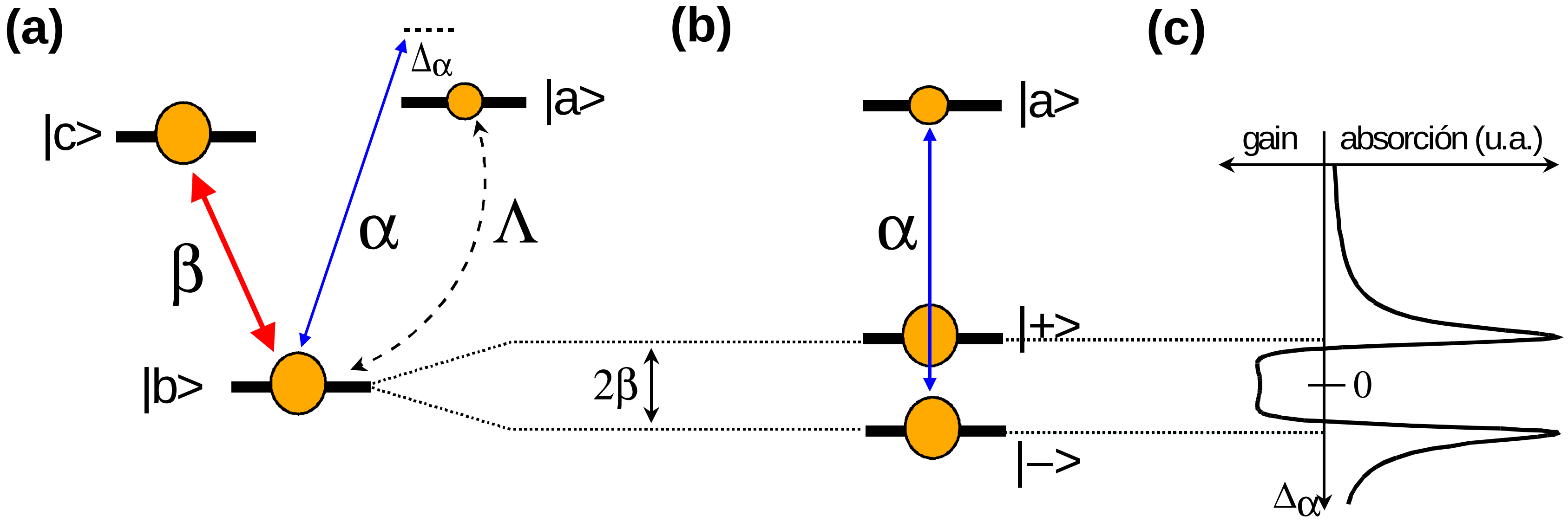
*Alzetta et al., Nuovo Cimento **36 B**, 5 (1976)*

*Arimondo y Orriols, Lett. Nuovo Cimento **17**, 333 (1977)*

## *(ii) Inversion in the dressed-state basis*



## *(iii) AWI in any meaningful basis: Λ and V schemes*



*Intense and resonant drive field, i.e.,* $\Delta_\beta = 0$

*On resonance probe gain, i.e., for* $\Delta_\alpha \approx 0$

*Some particular conditions between decay and pumping rates are needed*

PHYSICAL REVIEW A VOLUME 59, NUMBER 6 JUNE 1999

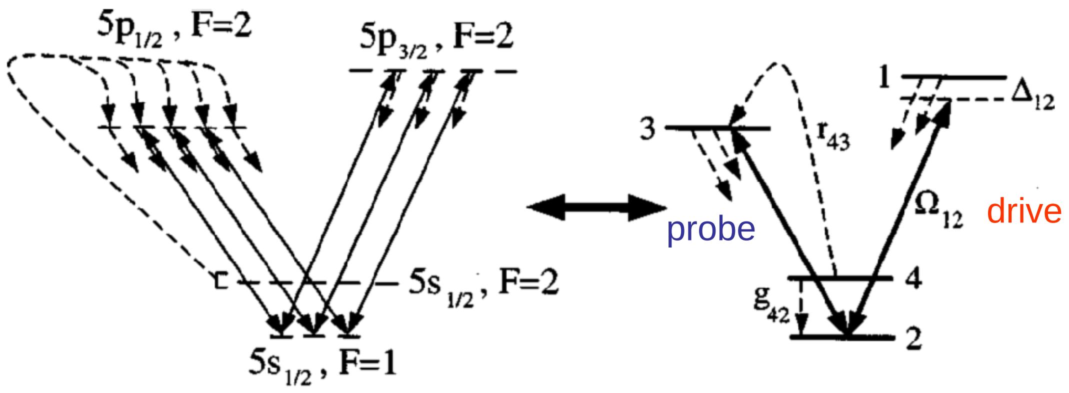
# Interference-induced optical gain without population inversion in cold, trapped atoms

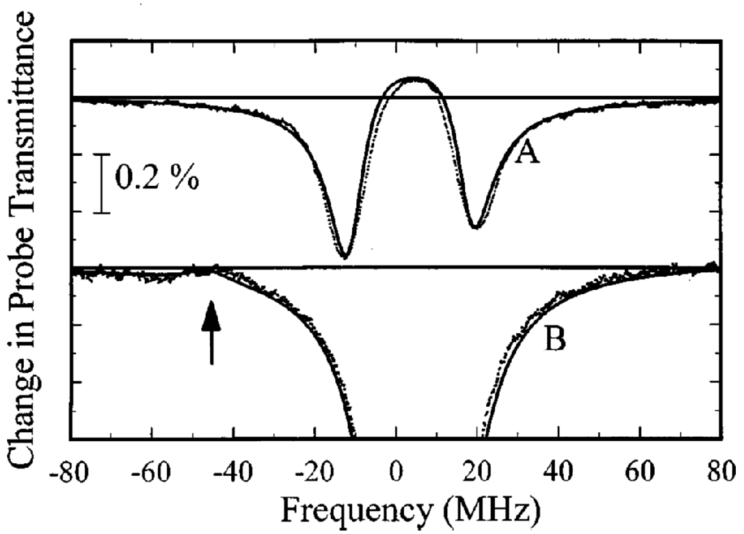
J. Kitching* and L. Hollberg
*Time and Frequency Division, National Institute of Standards and Technology, M.S. 847.10, 325 Broadway, Boulder, Colorado 80303*

(Received 28 December 1998)

Continuous-wave (cw) optical gain of $1.3\times10^{-2}$ cm$^{-1}$ is obtained on a probe transition in a driven, three-level, V-type atomic system. The atoms exhibit no population inversion between the probe excited state and the dressed ground states of the combined atom-drive Hamiltonian. This gain without population inversion is interpreted as direct evidence of quantum interference, arising from coherences established in the atom by the applied optical fields. Agreement with a simple four-level theoretical model is excellent.

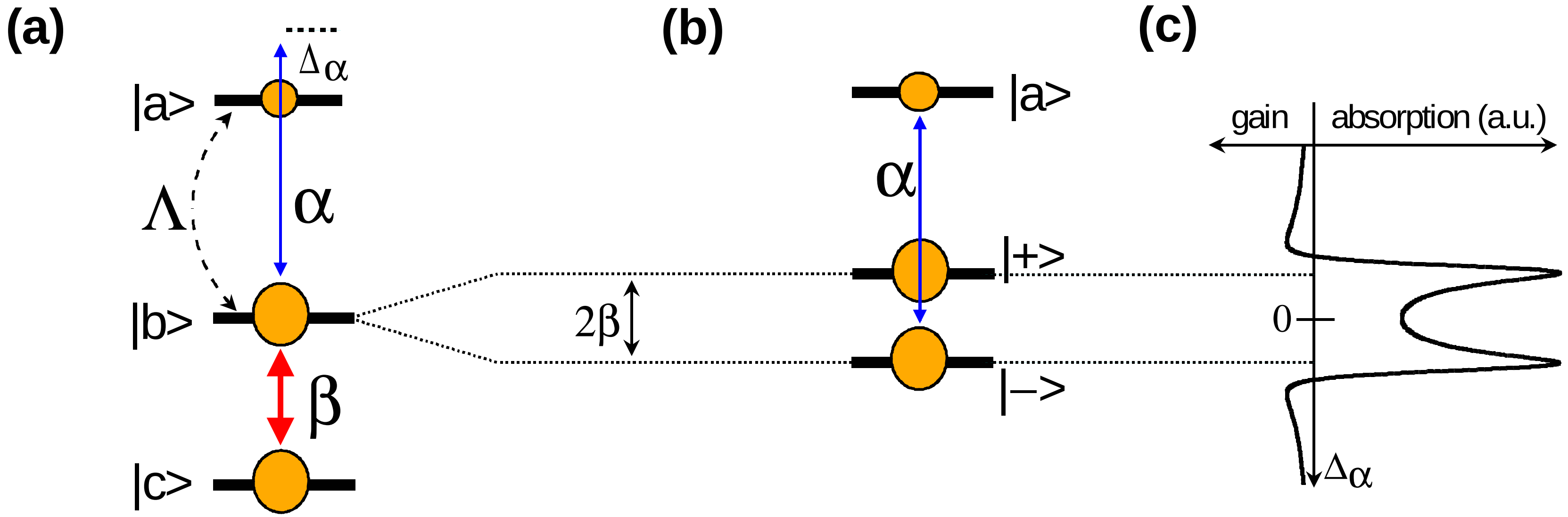
[S1050-2947(99)01306-2]





(A) $\Delta_{drive} = 0$
(B) $\Delta_{drive} = 45$ MHz

# *AWI in the bare and dressed-state basis: cascade schemes*



*Intense and resonant drive field, i.e.,* $\Delta_\beta = 0$

*Out of resonance probe gain, i.e., for* $|\Delta_\alpha| > \beta$

# Nature of LWI: density-matrix analysis

*Gain spectrum of the probe field for a resonant drive field ($\Delta_\beta = 0$)*

| | |
|---|---|
| $s = +1$ | $\Lambda$ and V schemes |
| $s = 0$ | cascade schemes |

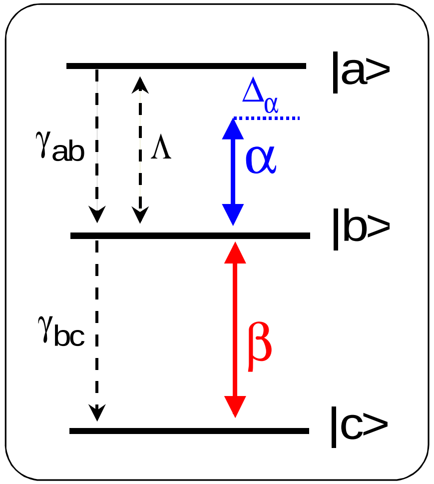
$$\frac{y_a}{\alpha} = A_1 + A_2 \quad \left\{ \begin{aligned} A_1 &= n_a \frac{\beta^2\Gamma_{ab} + \left(\Delta_\alpha^2 + \Gamma_{ab}^2\right)\Gamma_a}{\left(\beta^2 - \Delta_\alpha^2 + \Gamma_a\Gamma_{ab}\right)^2 + \Delta_\alpha^2\left(\Gamma_a + \Gamma_{ab}\right)^2} \\ A_2 &= \frac{(-1)^s \beta y_b \left(\beta^2 - \Delta_\alpha^2 + \Gamma_a\Gamma_{ab}\right)}{\left(\beta^2 - \Delta_\alpha^2 + \Gamma_a\Gamma_{ab}\right)^2 + \Delta_\alpha^2\left(\Gamma_a + \Gamma_{ab}\right)^2} \end{aligned} \right.$$

**Lorentzians at** $\Delta_\alpha \approx \pm\beta$

**Dispersives at** $\Delta_\alpha \approx \pm\beta$

(interference term)

| | |
|---|---|
| $y_a$ | Imaginary part of the coherence at the probed transition ($\alpha y_a$>0 amplification) |
| $y_b$ | Imaginary part of the coherence at the driven transition ($\beta y_b$>0 amplification) |
| $n_a$ | Population difference at the probed transition ($n_a$ > 0 inversion) |
| $\Gamma_a$ | Coherence relaxation rate at the probed transition |
| $\Gamma_{ab}$ | Coherence relaxation rate at the two-photon transition |



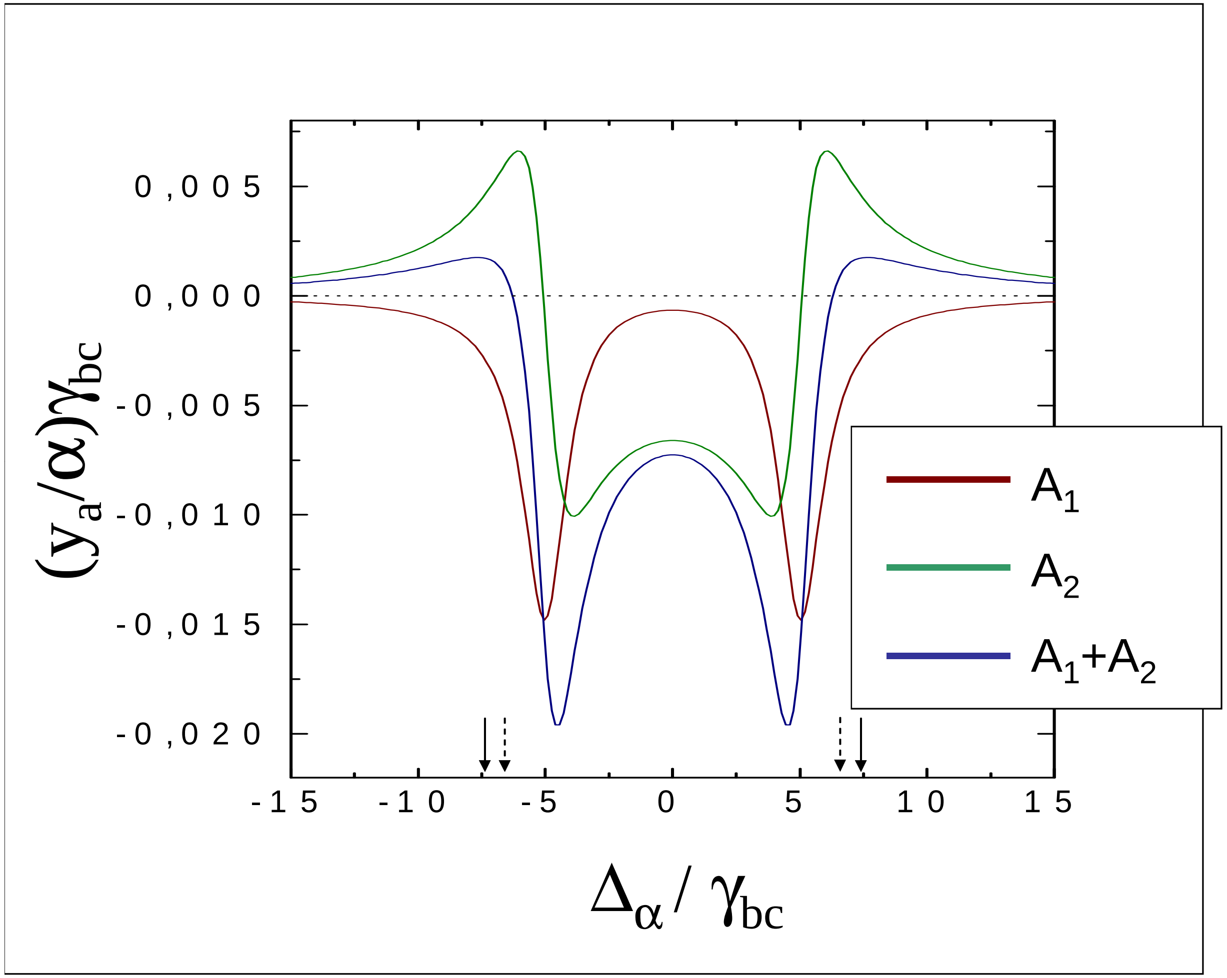
$\beta = 5\gamma_{bc}$

$\Delta_\beta = 0$

$\alpha = 0.01\gamma_{bc}$

$\gamma_{ab} = 0.1\gamma_{bc}$

$\Lambda = \gamma_{bc}$



$$\int_{-\infty}^{+\infty} A_2 d\Delta_\alpha = 0$$

*Cataliotti et al.*
*Phys. Rev. A* ***56****, 2221 (1997)*

Gain appears at $\Delta_\alpha \approx 0$ if

$$(-1)^{s+1}\beta y_b < \Gamma_{ab} n_a$$

It cannot be fulfilled if $n_a < 0$ (no-inversion) and $\Gamma_{ab} \to \infty$ (no two-photon processes)

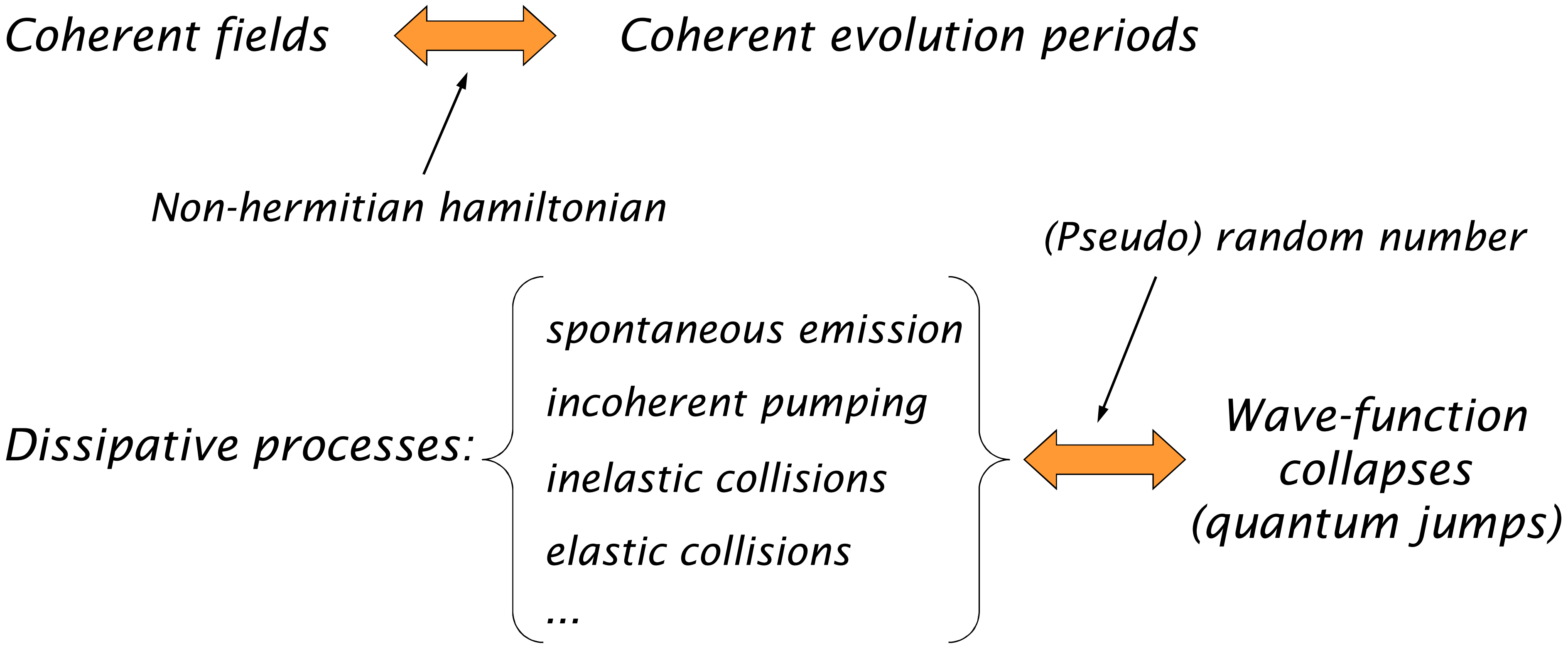
AWI at $\Delta_\alpha \approx 0$ due to two-photon processes

Gain appears at $|\Delta_\alpha| > \beta$ if

$$(-1)^{s}\beta y_b < \Gamma_a n_a$$

AWI at $|\Delta_\alpha| > \beta$ due to one-photon processes

# Quantum-jump approach to LWI



*Coherent fields* ⟷ *Coherent evolution periods*

*Non-hermitian hamiltonian*

*(Pseudo) random number*

*Dissipative processes:*
- *spontaneous emission*
- *incoherent pumping*
- *inelastic collisions*
- *elastic collisions*
- *...*

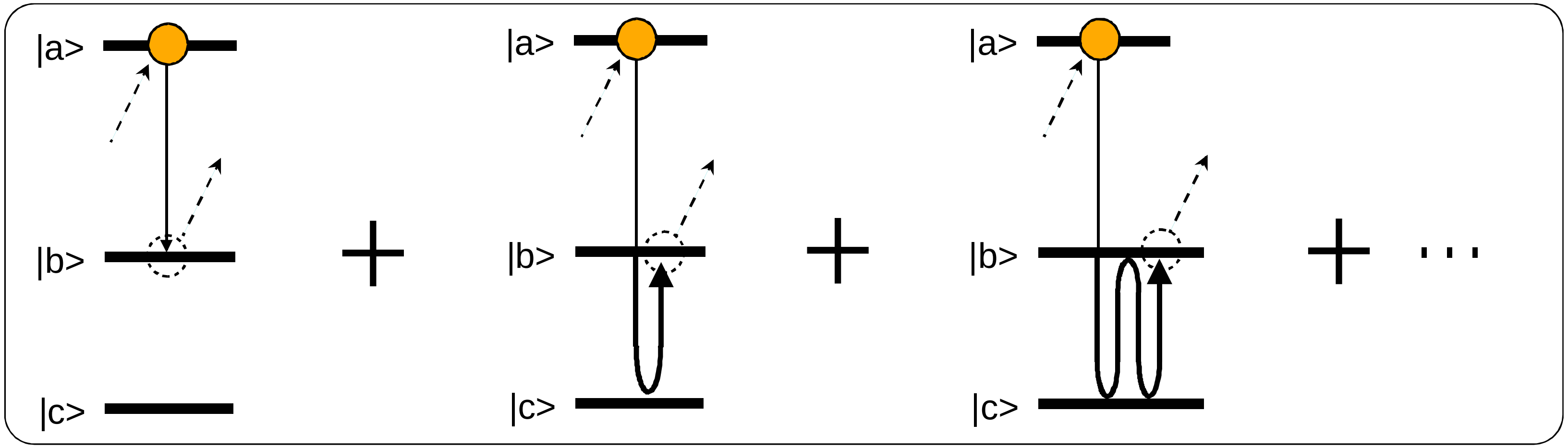
⟷ *Wave-function collapses (quantum jumps)*

*Dalibard, Castin, Molmer, Phys. Rev. Lett.* ***68****, 580 (1992)*
*Cohen-Tannoudji, Zambon, Arimondo, J. Opt. Soc. Am. B* ***10****, 2107 (1993)*

*The time evolution of the atomic system is pictured as consisting of a series of coherent evolution periods separated by quantum-jumps occurring at random times*

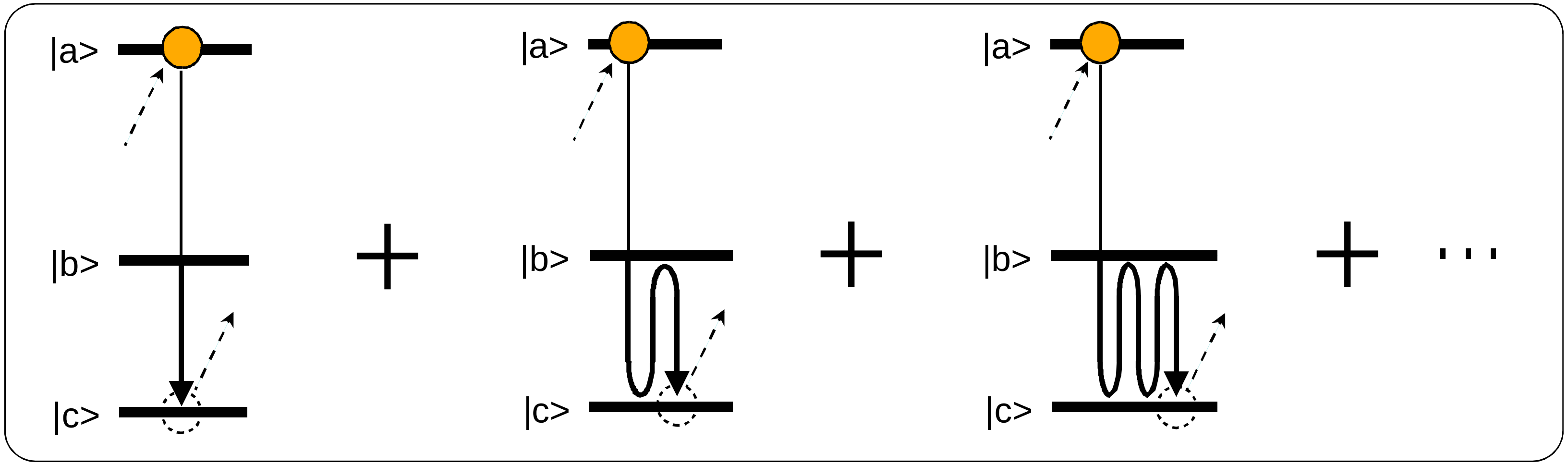
*Period (i,j) starts in atomic state |i> and ends in state |j>*

*Period (a,b)   (one-photon probe gain)*   $\Delta N_{\alpha} = +1,\ \Delta N_{\beta} = 0$



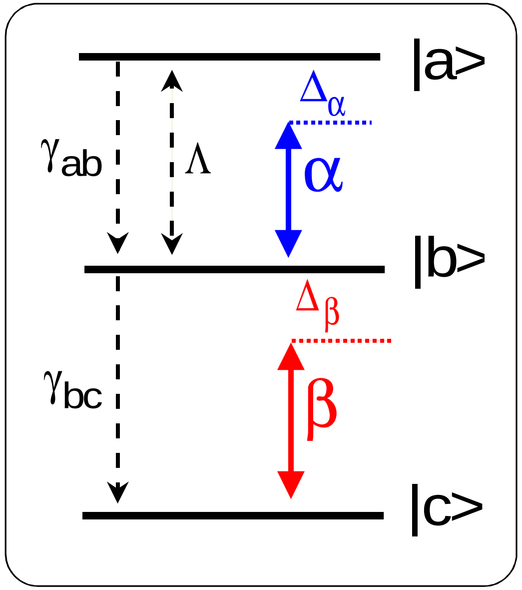
*Period (b,a),   reverse processes (one-photon loss)*

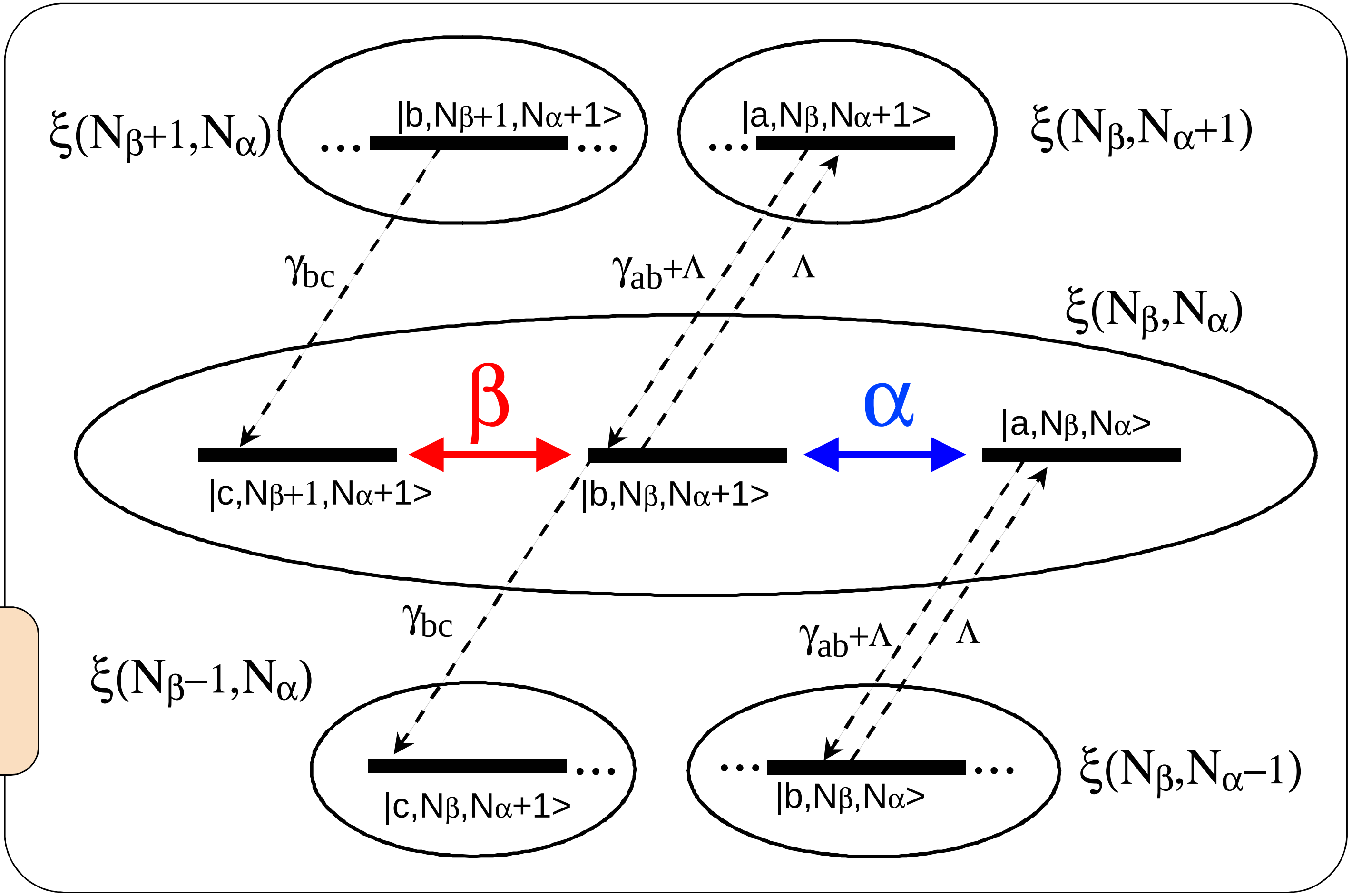
*Period (a,c)   (two-photon gain)*   $\Delta N_{\alpha} = +1,\ \Delta N_{\beta} = +1$



*Period (c,a),   reverse processes (two-photon loss)*

# Example: cascade scheme





$N_\alpha$ probe photon number
$N_\beta$ driving photon number

period (a,b) → $\Delta N_\alpha = +1,\ \Delta N_\beta = 0$ → one-photon gain
period (b,a) → $\Delta N_\alpha = -1,\ \Delta N_\beta = 0$ → one-photon absorption
period (a,c) → $\Delta N_\alpha = +1,\ \Delta N_\beta = +1$ → two-photon gain
period (c,a) → $\Delta N_\alpha = -1,\ \Delta N_\beta = -1$ → two-photon absorption

*P(i,j)* *probability that a coherent evolution randomly selected from a quantum trajectory starts in |i> and ends in |j>*

*1-photon gain:*

$$P(a,b) = \Lambda \frac{\gamma_{bc} + \Lambda}{\gamma_{bc} + 2\Lambda} \int_0^{+\infty} \left| c_{ab}(\tau) \right|^2 d\tau$$

*1-photon absorption:*

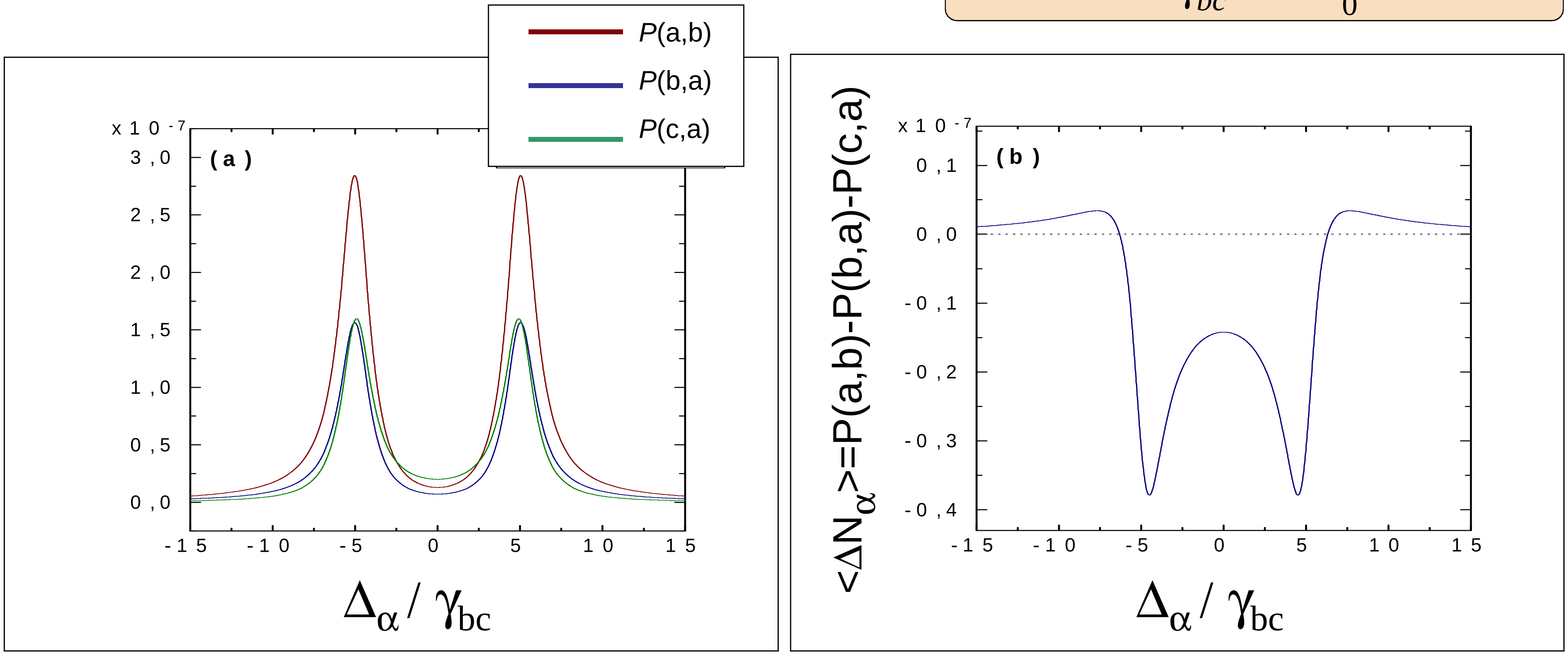
$$P(b,a) = \Lambda \frac{\gamma_{ab} + \Lambda}{\gamma_{bc} + 2\Lambda} \int_0^{+\infty} \left| c_{ab}(\tau) \right|^2 d\tau$$

*2-photon gain:*

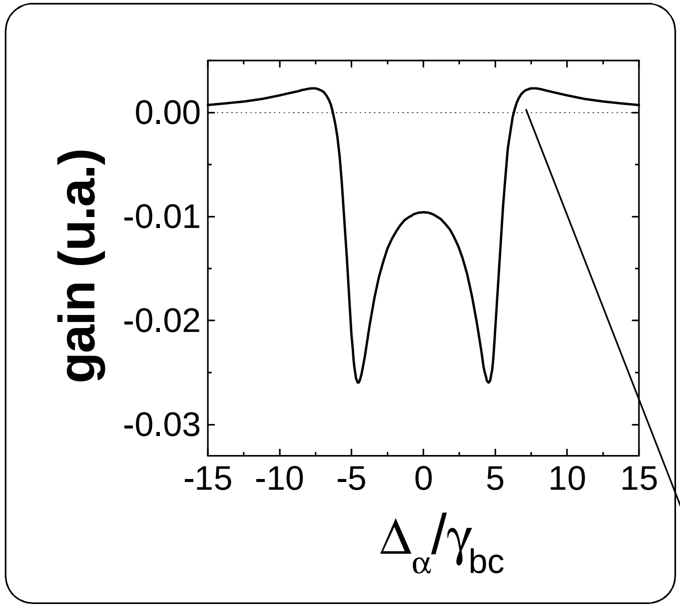
$$P(a,c) = 0$$

*2-photon absorption:*

$$P(c,a) = \gamma_{bc} \frac{\gamma_{ab} + \Lambda}{\gamma_{bc} + 2\Lambda} \int_0^{+\infty} \left| c_{ac}(\tau) \right|^2 d\tau$$



# *Monte Carlo simulation*



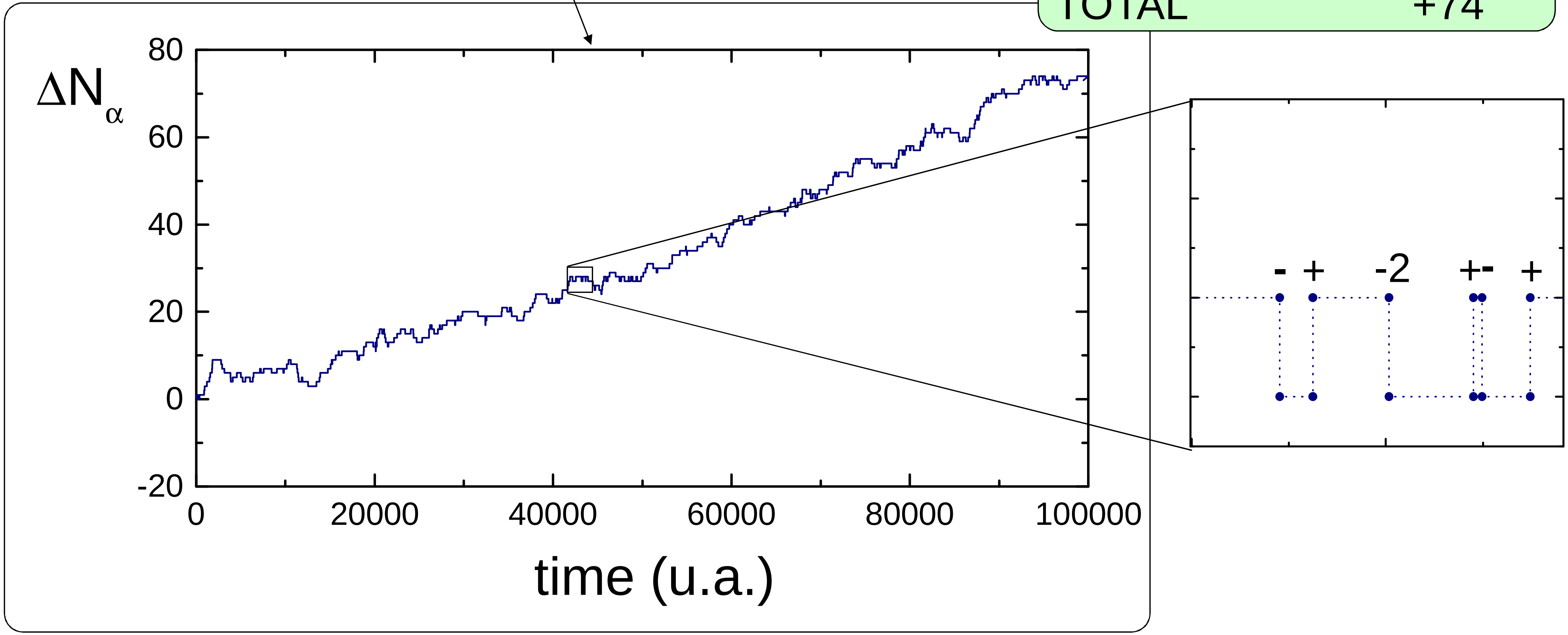
$\beta = 5\gamma_{bc}$ $\gamma_{ab} = 0.1\gamma_{bc}$

$\Delta_\beta = 0$ $\Lambda = \gamma_{bc}$

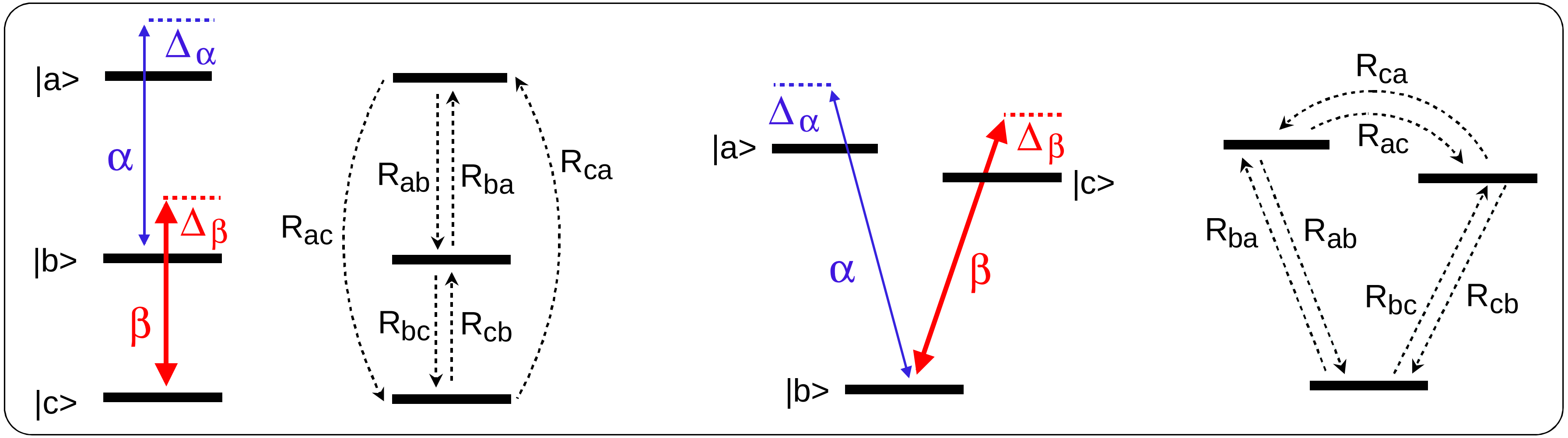
$\alpha = 0.01\gamma_{bc}$

$\Delta_\alpha = 7.5\ \gamma_{bc}$

| | |
|---|---|
| **one-photon gain:** | **194** |
| **one-photon abs.:** | **86** |
| **two-photon gain:** | **0** |
| **two-photon abs:** | **34** |
| TOTAL | +74 |



# Coherent evolution periods and Einstein B coefficients



## Quantum-jump theory

$$\langle \Delta N_\alpha \rangle = P(a,b) - P(b,a) + P(a,c) - P(c,a)$$

## Einstein theory

$$\frac{d}{dt} n_\alpha = \hbar \omega_\alpha n_\alpha \left( \rho_{aa} B_{ab} - \rho_{bb} B_{ba} + \rho_{aa} B_{ac} - \rho_{cc} B_{ca} \right)$$

$$\left.\right\} \; P(i,j) = c \rho_{ii} B_{ij}$$

$$\frac{B_{ab}}{B_{ba}} \equiv 1 + \left( \Delta B_{1p} \right)$$

$$\frac{B_{ac}}{B_{ca}} \equiv 1 + \left( \Delta B_{2p} \right)$$

$$\Longrightarrow$$

$$\Delta B_{1p} = \frac{R_{bc} - R_{cb}}{R_{ba} + R_{cb}}$$

$$\Delta B_{2p} = \frac{R_{cb} - R_{bc}}{R_{bc}}$$

*J. Mompart and R. Corbalán, Phys. Rev. A* ***63****, 063810 (2001)*

# CW and self-pulsing LWI

*To find LWI conditions perform a LSA of the trivial solution, $\alpha$ = 0, of the Maxwell-Schrödinger equations for the system*

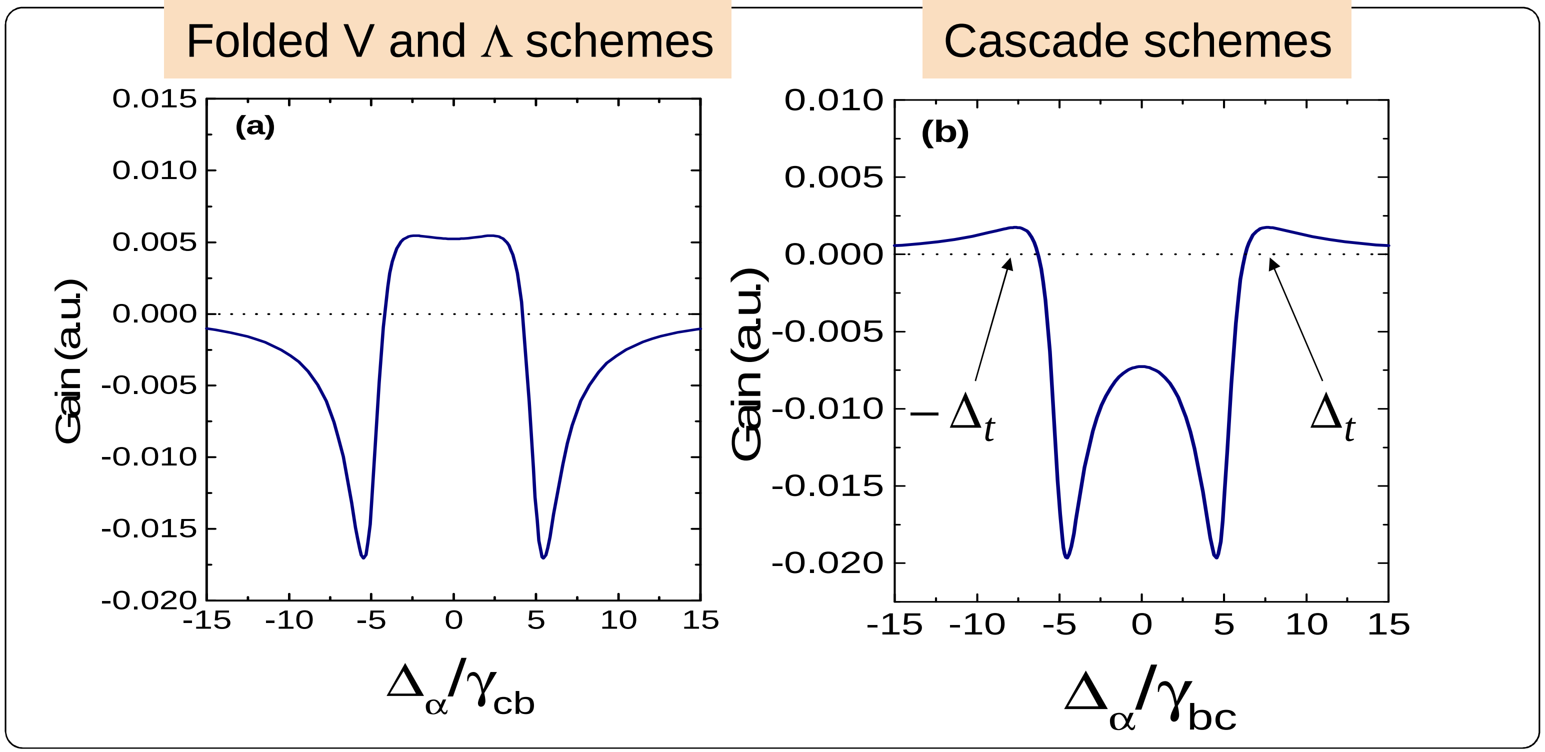
Sánchez-Morcillo, Roldán, de Valcárcel, Quantum Semiclass. Opt. **7**, 889 (1995)
Vladimirov, Mandel, Yelin, Lukin, Scully, Phys. Rev. E **57**, 1499 (1998)

*For resonant ($\Delta_\alpha = \Delta_\beta = 0$) homogeneously broadened closed three-level systems:*

*Folded V and $\Lambda$ schemes* → *pitchfork bifurcation* → *cw LWI*

*Cascade schemes* → *Hopf bifurcation* → *self-pulsing LWI*

$$\left\{e^{-i(\omega_\alpha+\Delta_t)t} + e^{-i(\omega_\alpha-\Delta_t)t}\right\} + c.c. = 2\cos\Delta_t t e^{-i\omega_\alpha t} + c.c$$


Folded V and $\Lambda$ schemes

Cascade schemes

# Experiments

| | AUTHORS | MEDIUM | DRIVE (nm) | PROBE (LASER) (nm) | $\omega_\alpha / \omega_\beta$ | REFERENCE |
|---|---|---|---|---|---|---|
| PULSED AWI | Nottelman *et al.* | Sm vapor cell ($\Lambda$) | 570.68 | 570.68 | 1 | PRL **70,** 1783 (1993) |
| | Fry *et al.* | Na vapor cell ($\Lambda$) | 589.86<br>558.43 | 589.86<br>558.43 | 1 | PRL **70,** 3235 (1993) |
| | van der Veer *et al* | Cd vapor cell ($\Lambda$) | 326 | 479 | 0.68 | PRL **70**, 3243 (1993) |
| CW AWI | Kleinfeld and Streater | K vapor cell (4-level) | 766.5 | 769.9 | 1 | PRA **49**, R4301 (1994)<br>PRA **53**, 1839 (1996) |
| | Zhu and Lin<br>Zhu *et al.* | Rb vapor cell ($\Lambda$) | 780 | 780 | 1 | PRA **53**, 1767 (1996)<br>OC **128**, 254 (1996) |
| | Sellin *et al.* | Ba atomic beam (cascade) | 554 and 821 | 821 | 0.67 | PRA **54**, 2402 (1996) |
| | Fort *et al.* | Cs vapor cell ($V$) | 852 | 894 | 0.95 | OC **139**, 31 (1997) |
| | Shiokawa *et al* | Laser cooled Rb atoms ($\Lambda$) | 780 | 780 | 1 | QELS QPD2 paper (1997) |
| | Hollberg *et al.* | Laser cooled Rb atoms ($V$) | 780 | 795 | 0.98 | PRA **59**, 4685 (1999) |
| LWI (CW) | Zibrov *et al.* | Rb vapor cell ($V$) | 780 | 795 | 0.98 | PRL **75**, 1499 (1995) |
| | Padmabandu *et al* | Na atomic beam ($\Lambda$) | 589.76 | 589.43 | 1 | PRL **76**, 2053 (1996) |
| LWI (PULSED) | de Jong *et al.* | Cd vapor cell ($\Lambda$) | 326 | 479 | 0.68 | PRA **57**, 4869 (1998) |
| LBT | Peters and Lange | Ne vapor cell (double-$\Lambda$) | 824.9 | 611.8 | 1.35 | APB **62**, 221 (1996) |

⇒ *These experiments demonstrate the validity of the idea of LWI*

⇒ *Any LWI has operated yet in the frequency up-conversion regime*

# *Frequency up-conversion difficulties:*

## *(i) Doppler broadening*

*Most experiments use <u>Doppler free configurations</u> in vapour cells*

*V. Ahufinger, J. Mompart, and R. Corbalán Phys. Rev. A **60** (1999) 614.*

## *(ii) Propagation effects*

*Rapid depletion of the driving field*

*M. Lukin et al., Laser Phys. **6** (1996) 436.*

*J. Mompart, V. Ahufinger, R. Corbalán,F. Prati, J. Opt. B: Quantum Semiclass. Opt.**2** (2000), 359*

## *(iii) Decay rates*

*Particular conditions between decay rates that significantly restrict the number of suitable atomic candidates*

*J. Mompart, R. Corbalán and R. Vilaseca, Opt. Commun. **147** (1998) 299*

## *(iv) Incoherent pumping*

*Particular conditions for the lower threshold values depending on the scheme*

*Upper threshold value to prevent destroying atomic coherences*

# SUBWAVELENGTH LOCALIZATION VIA ADIABATIC PASSAGE

J. Mompart, V. Ahufinger, G. Birkl, Phys. Rev. A **79**, 053638 (2009)

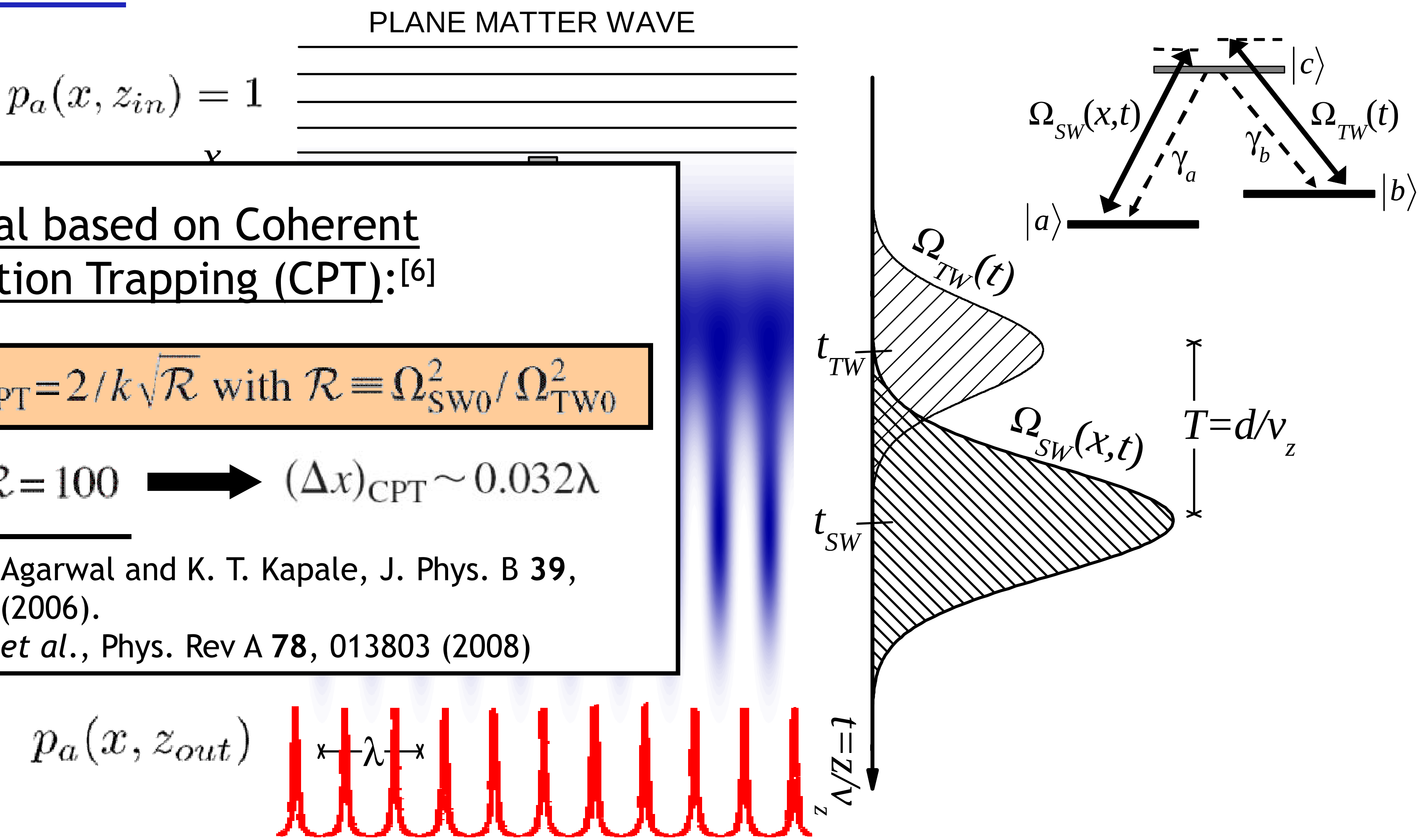
Single-site addressing of ultracold atoms beyond the diffraction limit
via position-dependent adiabatic passage.
D. Viscor, J. L. Rubio, G. Birkl , J. Mompart, V. Ahufinger
Phys. Rev. A. **86**, 063409 (2012)

Nanoscale resolution for fluorescence microscopy via adiabatic passage.
J. L. Rubio, D. Viscor, V. Ahufinger, J. Mompart
Optics Express. **21** 22139 (2013)

# Outline of the talk

- Subwavelength localization via adiabatic passage (SLAP)
- Nanolithography with a Ne* matter wave
- Coherent patterning of a two component $^{87}$Rb BEC
- Conclusions

# SUBWAVELENGTH LOCALIZATION VIA ADIABATIC PASSAGE. BASIC IDEA:

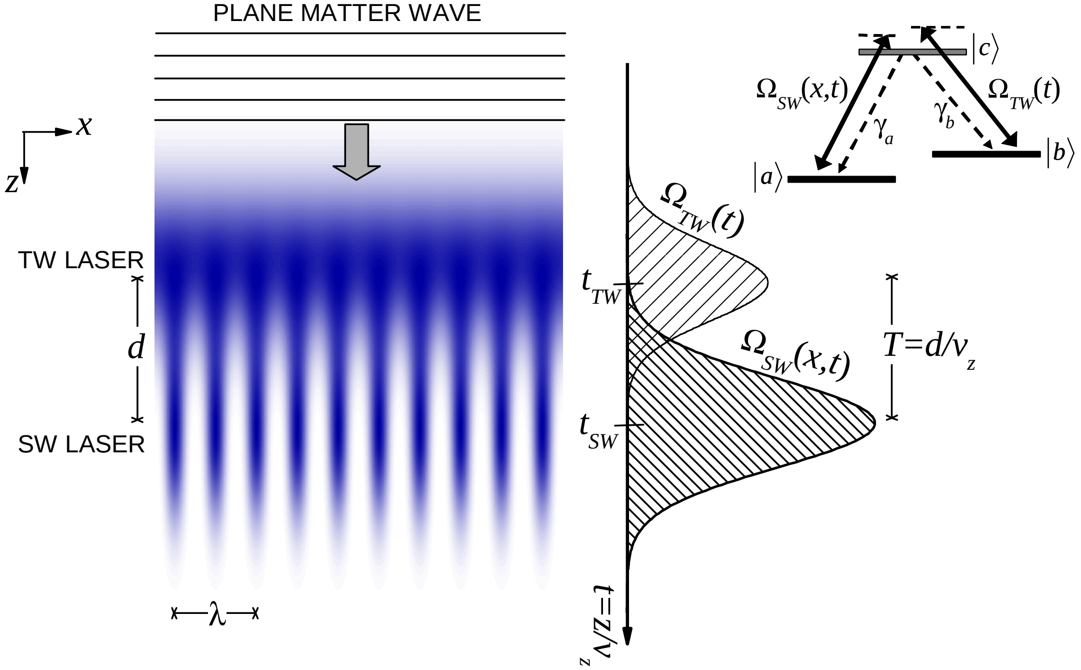


Proposal based on Coherent Population Trapping (CPT):[6]

$$(\Delta x)_{\text{CPT}}=2/k\sqrt{\mathcal{R}} \text{ with } \mathcal{R}\equiv\Omega^2_{\text{SW0}}/\Omega^2_{\text{TW0}}$$

For $\mathcal{R}=100$ → $(\Delta x)_{\text{CPT}}\sim 0.032\lambda$

G. S. Agarwal and K. T. Kapale, J. Phys. B **39**, 3437 (2006).
H. Li *et al*., Phys. Rev A **78**, 013803 (2008)



## Definitions:

$$\Omega_{TW}(t)=\Omega_{TW0}\exp[-(t-t_{TW})^2/\sigma_{TW}^2]$$

$$\Omega_{SW}(x,t)=\Omega_{SW0}\sin kx\exp[-(t-t_{SW})^2/\sigma_{SW}^2]$$

$$T=t_{SW}-t_{TW}=d/v_z$$

$$\mathcal{R}\equiv\Omega_{SW0}^2/\Omega_{TW0}^2$$

## Adiabaticity condition:

$$\Omega_{SW0}^2\sin^2 kx+\Omega_{TW0}^2>\left(\frac{A}{T}\right)^2 \Longrightarrow \boxed{(\Delta x)_{SLAP}=(\Delta x)_{CPT}\frac{1}{2}\sqrt{\left(\frac{A}{T\Omega_{TW0}}\right)^2-1}\,.}$$

$$(\Delta x)_{CPT}=2/k\sqrt{\mathcal{R}}\text{ with }\mathcal{R}\equiv\Omega_{SW0}^2/\Omega_{TW0}^2$$

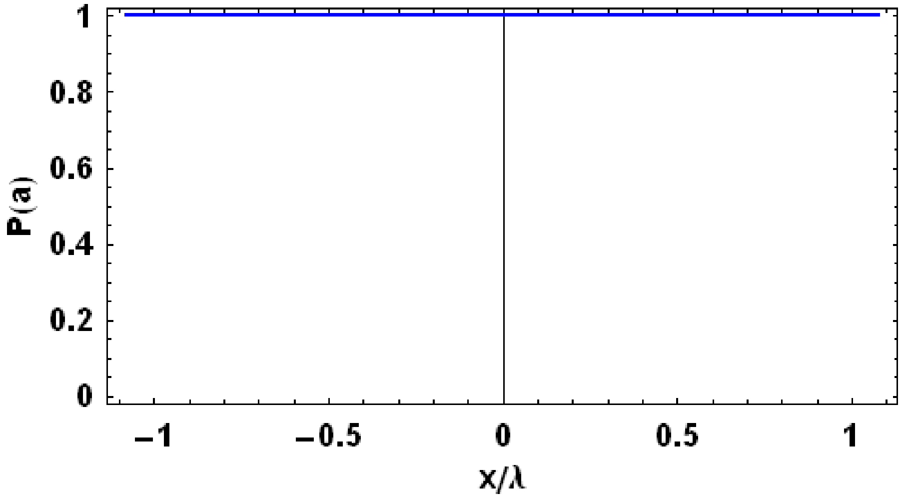
## Super-localization regime::

$$(\Delta x)_{\mathrm{SLAP}} < (\Delta x)_{\mathrm{CPT}} \quad \Longrightarrow \quad T\Omega_{\mathrm{TW0}} = \frac{d}{v_z}\Omega_{\mathrm{TW0}} > \frac{A}{\sqrt{5}} \quad \Longrightarrow \quad T\Omega_{\mathrm{TW0}} > 4.5$$

**Simulation:** $T\Omega_{\mathrm{TW0}} = 10$

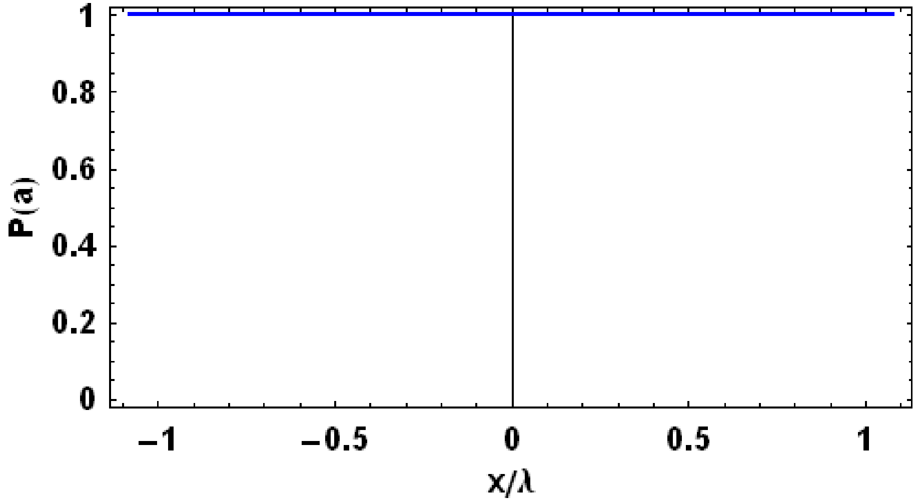
- $\mathcal{R}=100,\ \gamma\sigma_{\mathrm{TW}}=\gamma\sigma_{\mathrm{SW}}=5,\ \Delta_{\mathrm{TW}}=\Delta_{\mathrm{SW}}=0,\ \gamma T=10$
- $\gamma T=10$ for the SLAP case
- $\gamma T=0$ for the CPT case

**CPT**



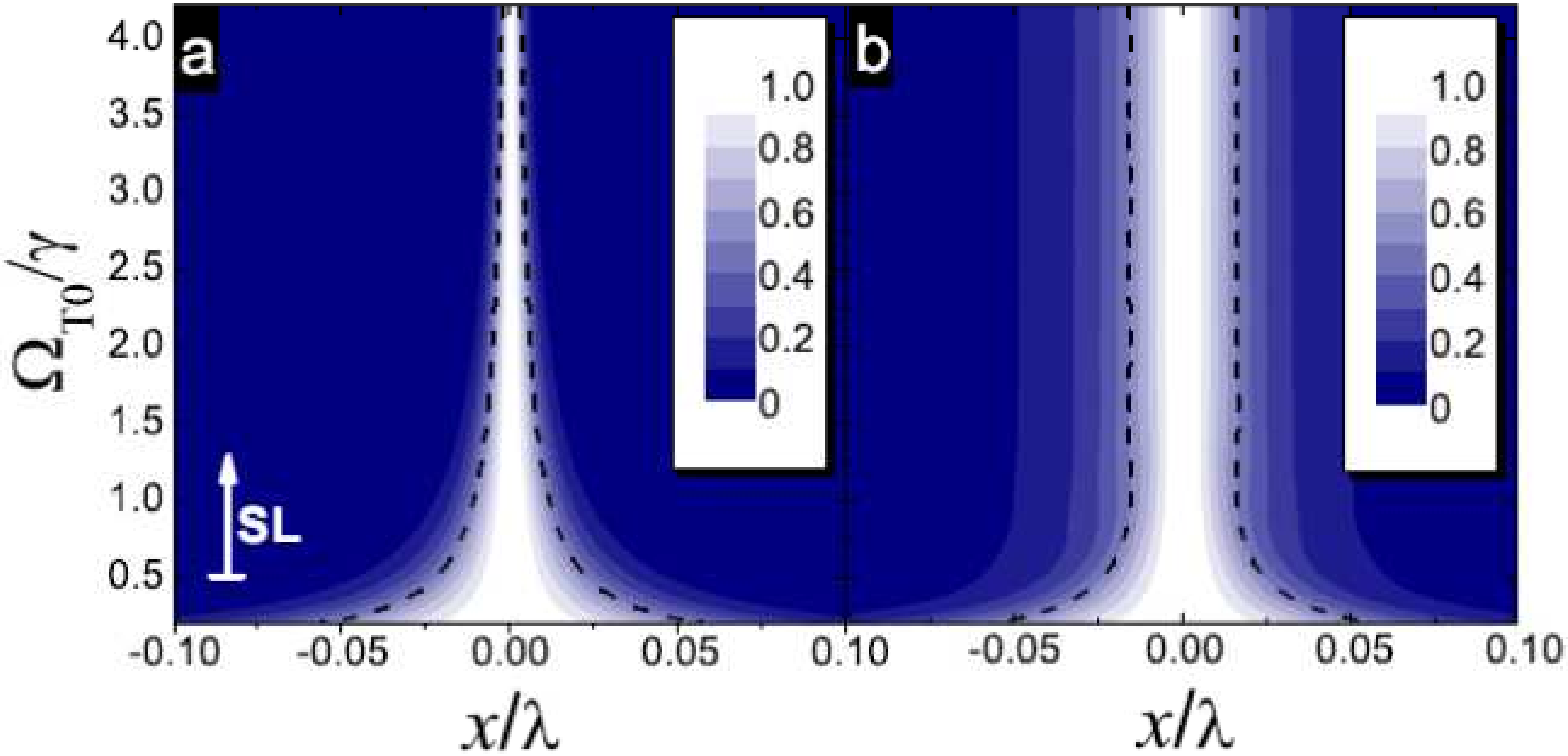
$(\Delta x)_{\mathrm{CPT}} \sim 0.032\lambda$

**SLAP**



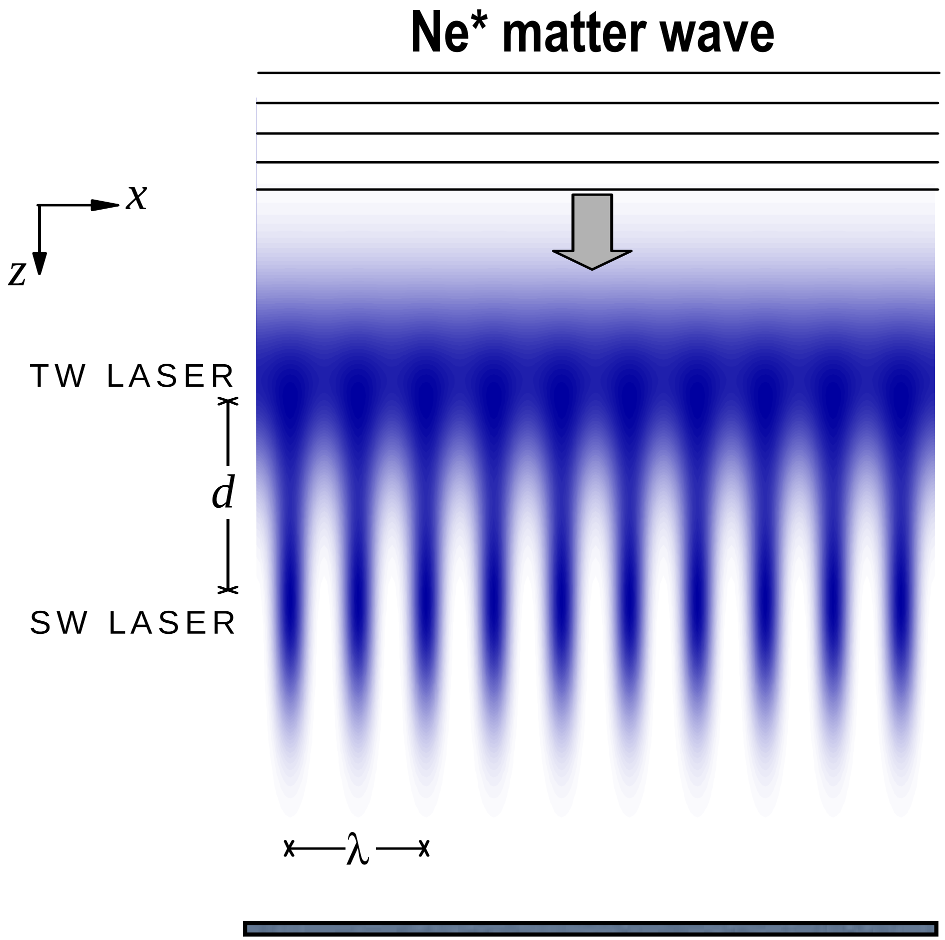
$(\Delta x)_{\mathrm{SLAP}} = 0.005\lambda$

SLAP CPT $(\Delta x)_{\mathrm{CPT}} \sim 0.032\lambda$

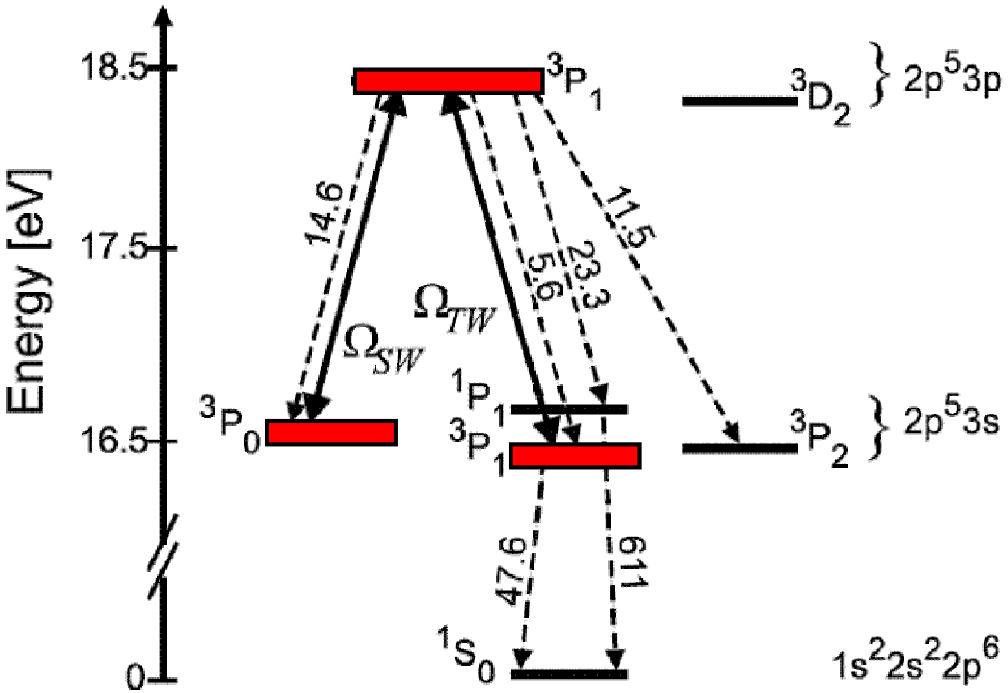


- $\mathcal{R}=100,\ \gamma\sigma_{\mathrm{TW}}=\gamma\sigma_{\mathrm{SW}}=5,\ \Delta_{\mathrm{TW}}=\Delta_{\mathrm{SW}}=0,\ \gamma T=10$
- $\gamma T=10$ for the SLAP case
- $\gamma T=0$ for the CPT case

# NANOLITHOGRAPHY WITH A Ne* MATTER WAVE:



Substrate sensitive to the high internal energy of metaestable Ne* (16.6 eV)

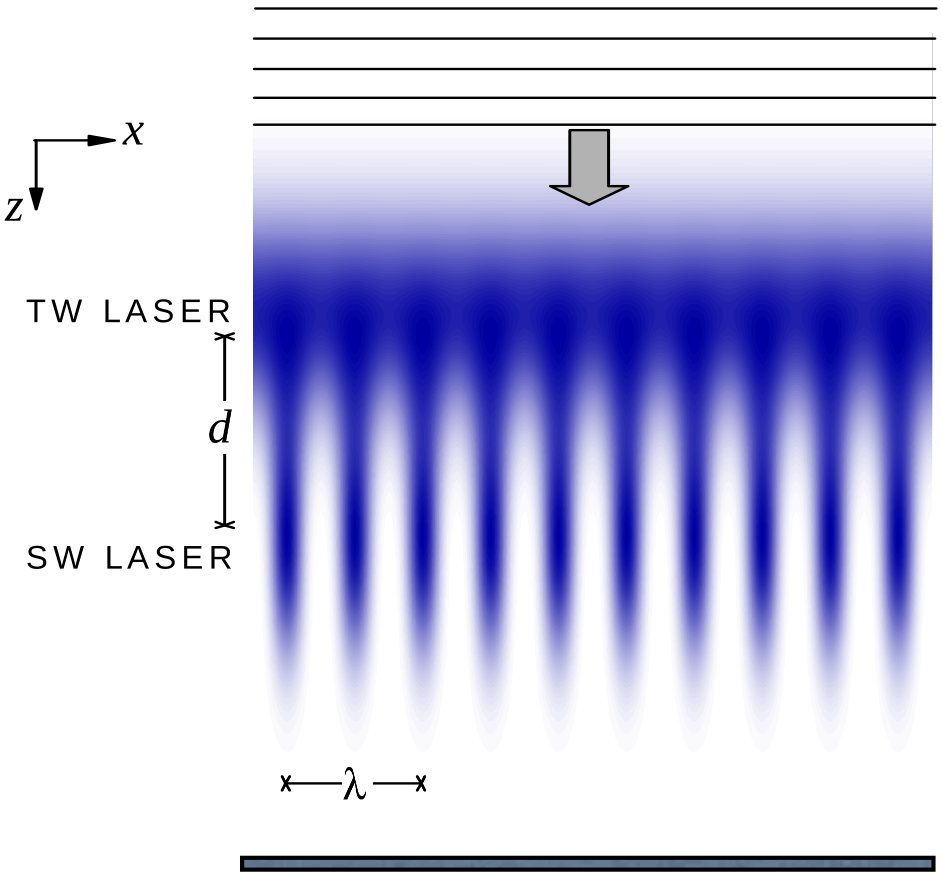


energy levels and Einstein A coefficients (in units of $10^6$ $s^{-1}$)

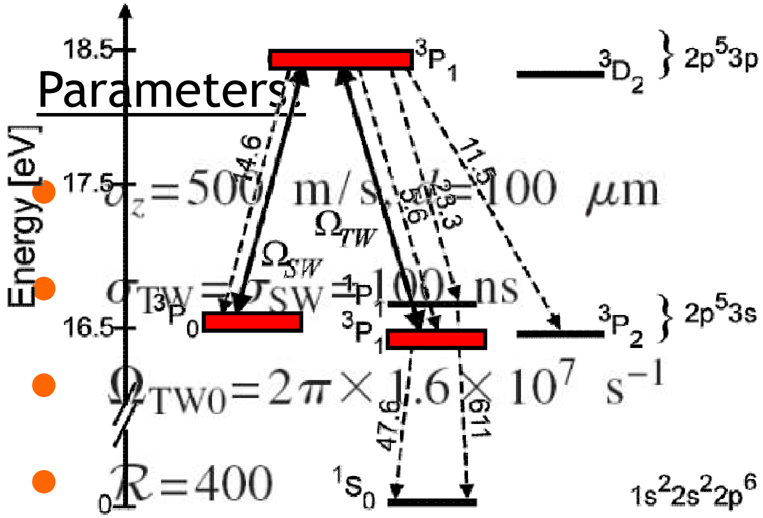
$\lambda_{TW} = 603.0$ nm

$\lambda_{SW} = 616.4$ nm

## Ne* matter wave

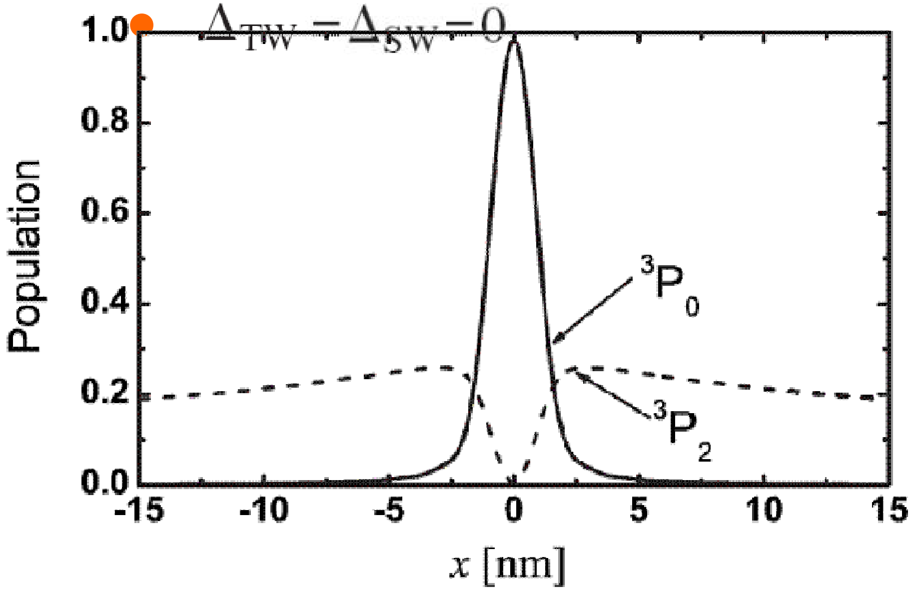


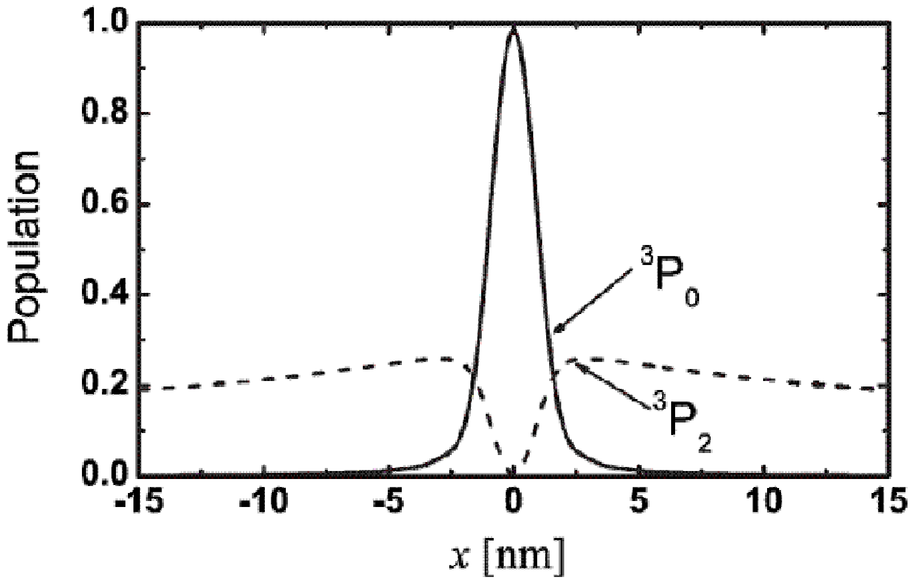
Substrate sensitive to the high internal energy of metaestable Ne* (16.6 eV)

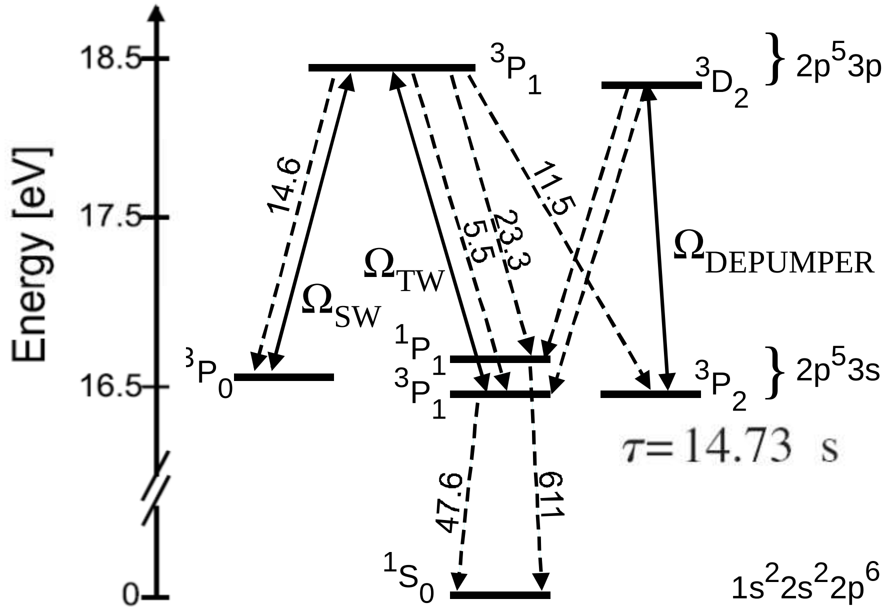


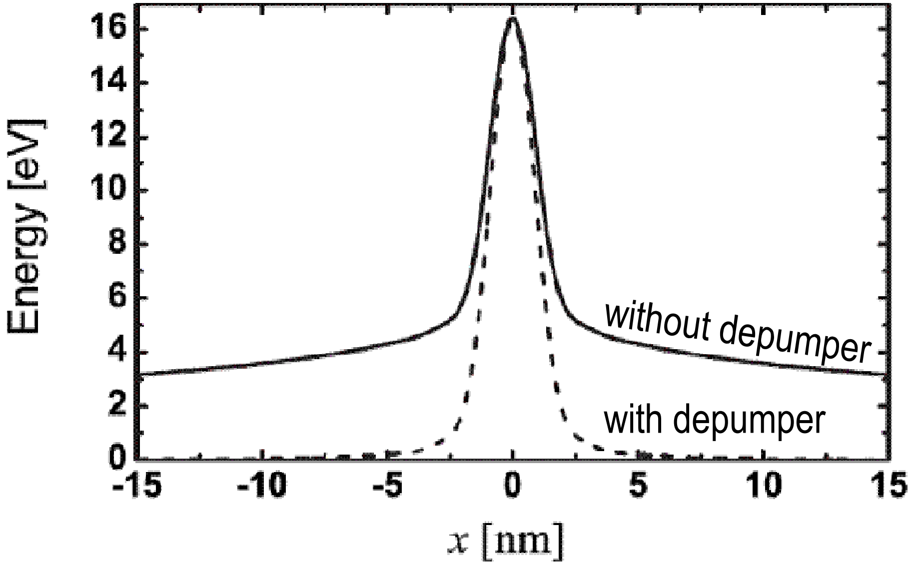
Parameters:

- $v_z = 500$ m/s, $d = 100$ $\mu$m
- $\sigma_{TW} = \sigma_{SW} = 100$ ns
- $\Omega_{TW0} = 2\pi \times 1.6 \times 10^7$ $s^{-1}$
- $\mathcal{R} = 400$
- $\Delta_{TW} = \Delta_{SW} = 0$









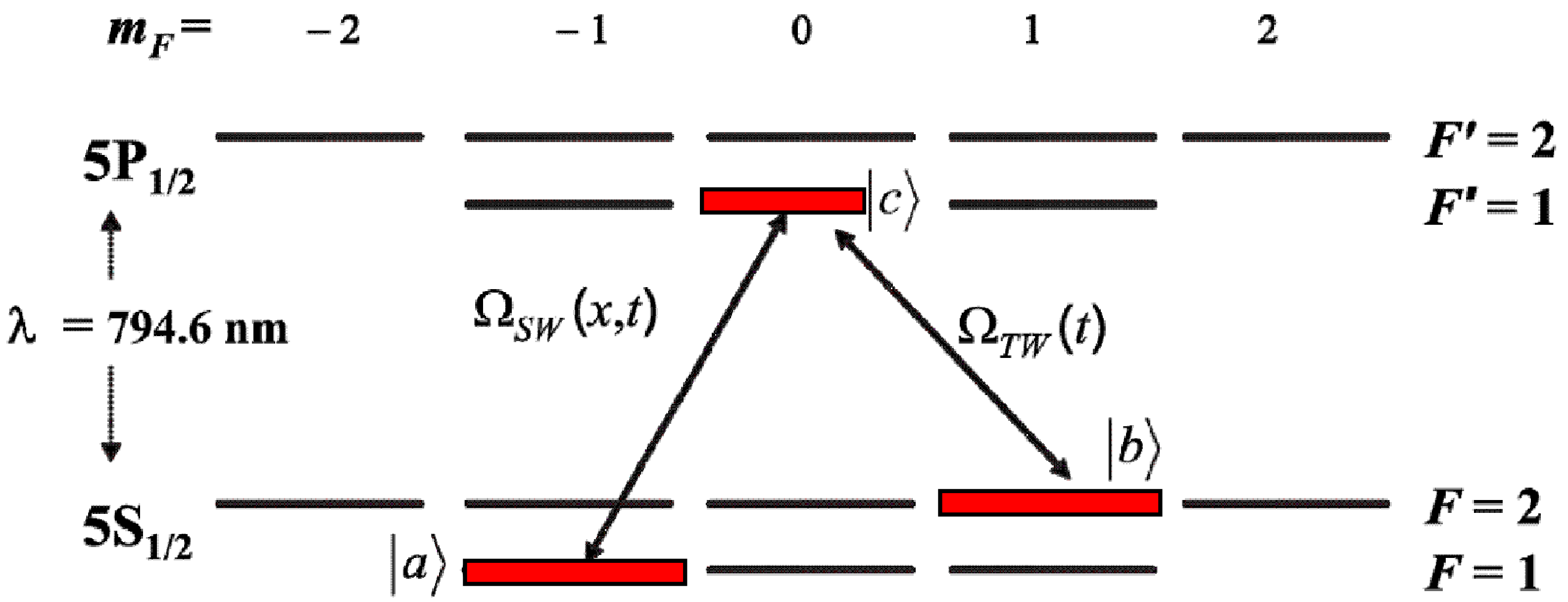
## Transversal velocity spread:

$\overline{\Delta v_x}$ rms transversal velocity spread

$$T\overline{\Delta v_x} \ll (\Delta x)_{\mathrm{SLAP}} \Longrightarrow \Delta v_x / v_z \ll (\Delta x)_{\mathrm{SLAP}} / d$$

$$\left.\begin{array}{l} v_z = 500 \ \mathrm{m/s} \\ \overline{\Delta v_x} = 1\,\mathrm{cm/s} \\ d = 20 \ \mu\mathrm{m} \end{array}\right\} \Longrightarrow \Delta x = 0.4\,\mathrm{nm}$$

# COHERENT PATTERNING OF A TWO COMPONENT $^{87}$Rb BEC



$$\left.\begin{array}{l} |a\rangle=|F=1, m_F=-1\rangle \\ |b\rangle=|F=2, m_F=1\rangle \end{array}\right\} \text{two component BEC}$$

$$|c\rangle=|F'=1, m_F=0\rangle \qquad \Gamma=2\pi\times5.41\times10^6 \ \mathrm{s}^{-1}$$

# 1D Coupled Gross-Pitaevskii equations:

$$i\hbar\frac{d\psi_a}{dt} = \left[ -\frac{\hbar^2}{2m}\triangle + V_a(x) + g_{aa}|\psi_a|^2 + g_{ab}|\psi_b|^2 \right]\psi_a + \frac{1}{2}\hbar\Omega_{\mathrm{SW}}(x,t)\psi_c,$$

$$i\hbar\frac{d\psi_b}{dt} = \left[ -\frac{\hbar^2}{2m}\triangle + V_b(x) + g_{bb}|\psi_b|^2 + g_{ab}|\psi_a|^2 \right]\psi_b + \frac{1}{2}\hbar\Omega_{\mathrm{TW}}(t)\psi_c + \hbar(\Delta_{\mathrm{SW}} - \Delta_{\mathrm{TW}})\psi_b,$$

$$i\hbar\frac{d\psi_c}{dt} = \frac{1}{2}\hbar\Omega_{\mathrm{SW}}(x,t)\psi_a + \frac{1}{2}\hbar\Omega_{\mathrm{TW}}(t)\psi_b - i\frac{\Gamma}{2}\psi_c + \hbar\Delta_{\mathrm{SW}}\psi_c,$$

## Definitions and parameters:

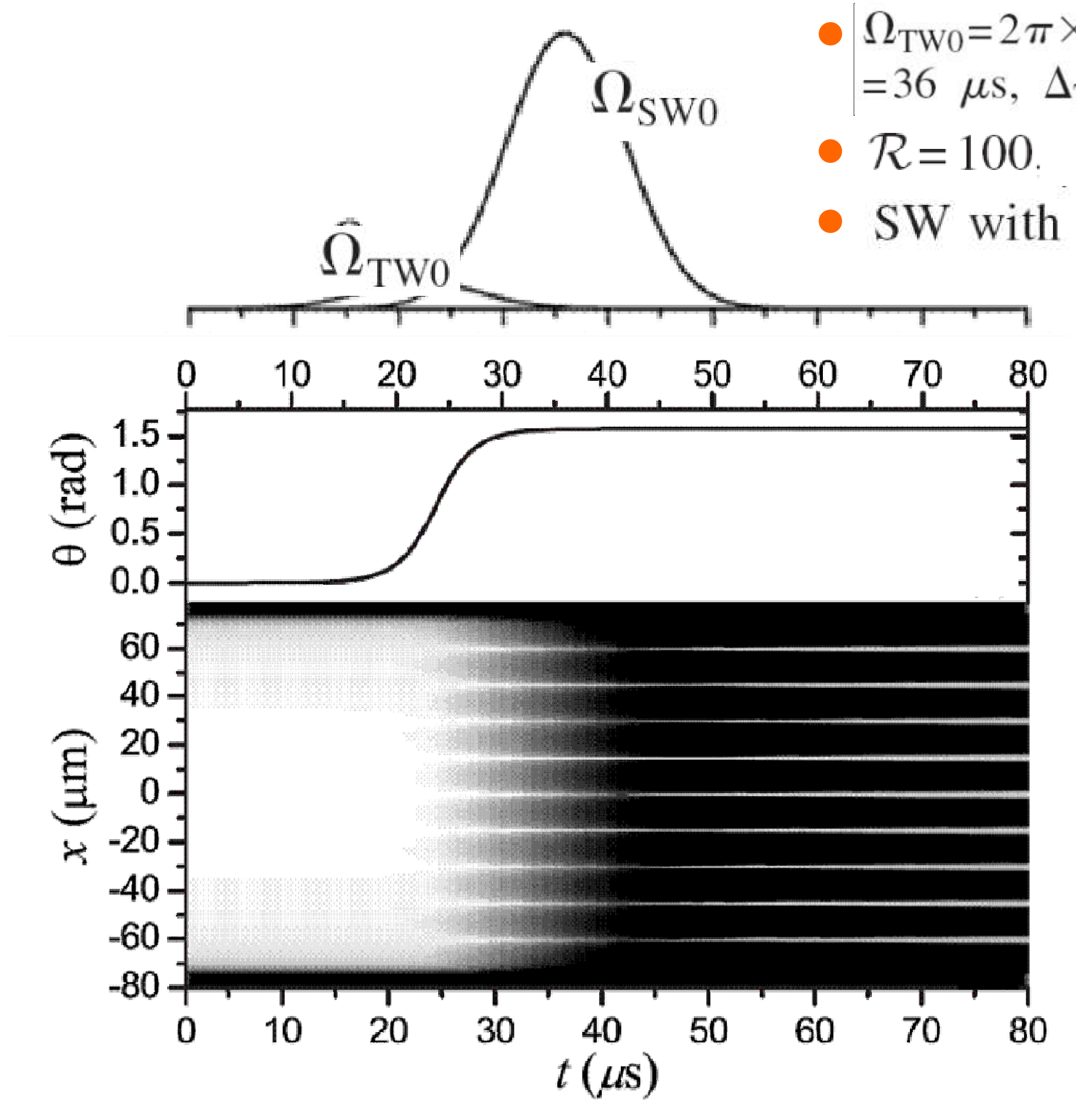
- $g_{ij} = 2\hbar a_{ij}\omega_t$
- $s$-wave scattering lengths
- $a_{aa} : a_{ab} : a_{bb} = 1.03 : 1 : 0.97$

Average: $55(3)$ Å

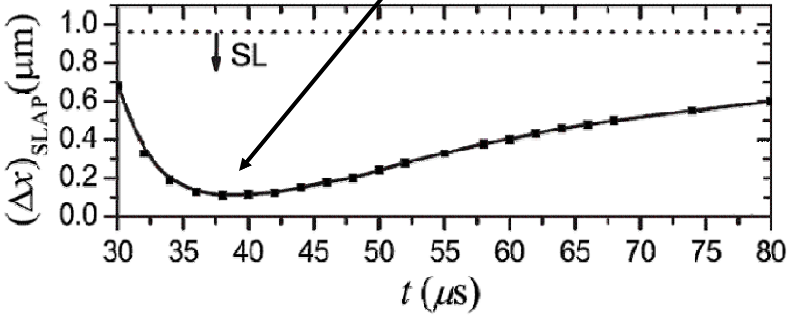
- $V_a(x) = V_b(x) = m\omega_x^2 x^2 / 2$
- BEC of $5\times 10^4$ atoms.

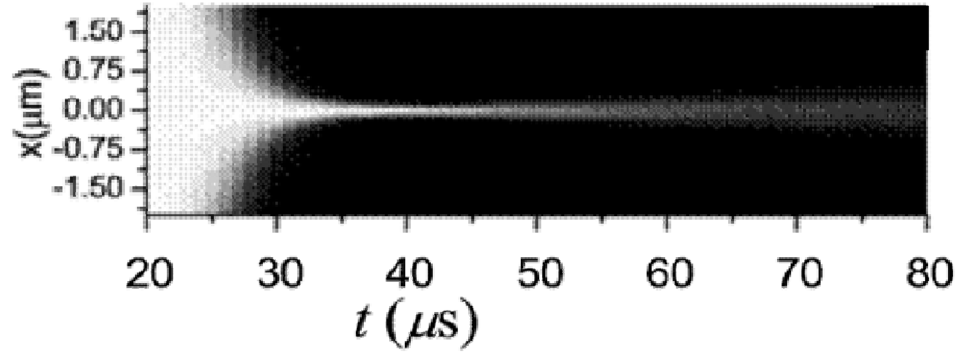
# Narrow structures at the Heisenberg limit

- $\Omega_{\mathrm{TW0}}=2\pi\times 10\times 10^{6}\ \mathrm{s}^{-1}$, $\sigma_{\mathrm{TW}}=\sigma_{\mathrm{SW}}=8\ \mu\mathrm{s}$, $t_{\mathrm{TW}}=22\ \mu\mathrm{s}$, $t_{\mathrm{SW}}=36\ \mu\mathrm{s}$, $\Delta_{\mathrm{TW}}=\Delta_{\mathrm{SW}}=0$, $\omega_x=2\pi\times 14\ \mathrm{s}^{-1}$, and $\omega_t=2\pi\times 715\ \mathrm{s}^{-1}$.
- $\mathcal{R}=100.$
- SW with 15 μm period



**Beam quality factor:**
$M^2=(2/\hbar)\Delta x\Delta p_x\approx 0.6$





# CONCLUSIONS:

- Subwalength Localization via Adiabatic Passage (SLAP):

  ⇒ **Coherent** and **robust** technique for state selective atom localization

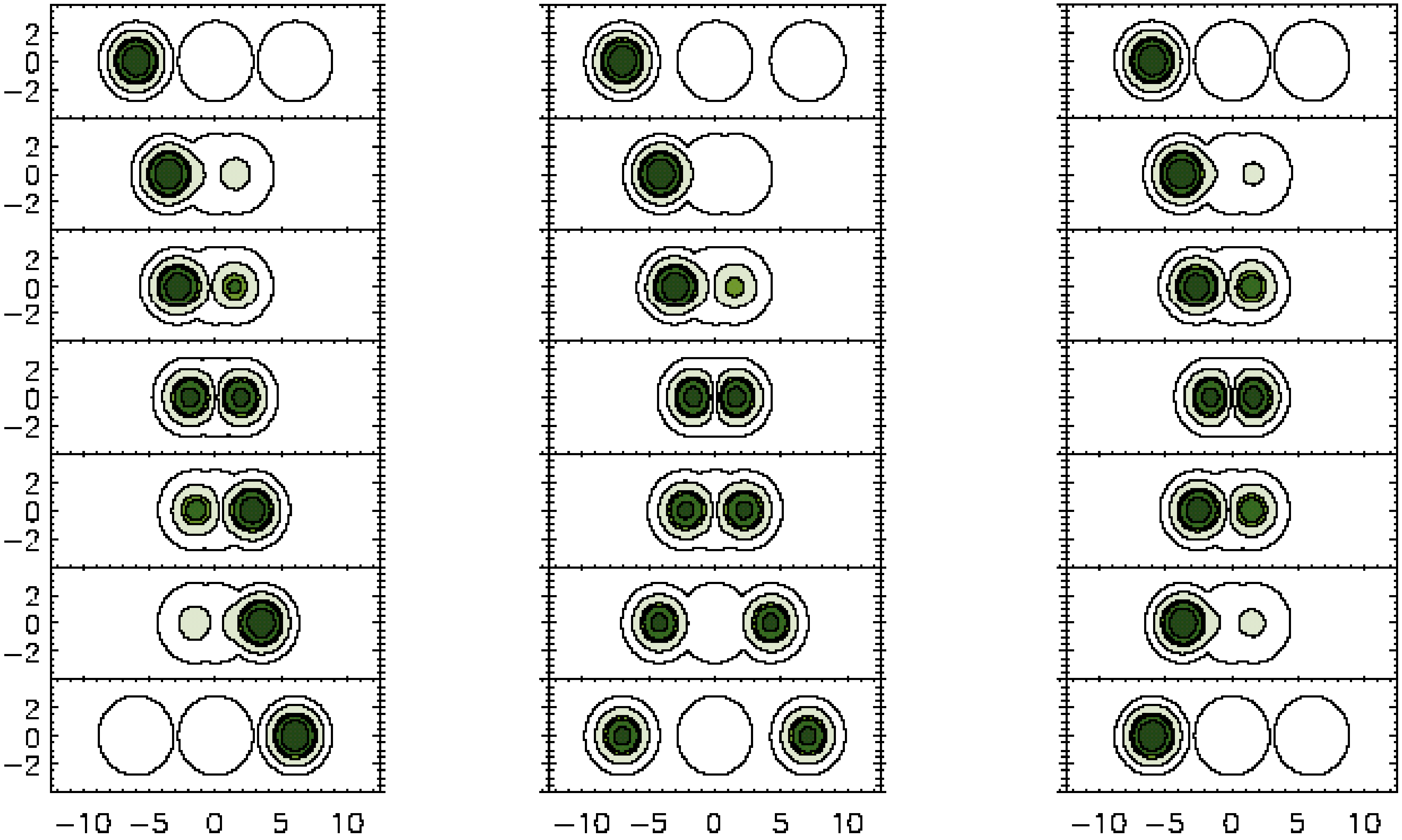
$$(\Delta x)_{\mathrm{SLAP}} = (\Delta x)_{\mathrm{CPT}} \frac{1}{2} \sqrt{\left(\frac{A}{T\Omega_{\mathrm{TW0}}}\right)^2 - 1} \quad \left\{ \begin{array}{l} (\Delta x)_{\mathrm{CPT}} = 2/k\sqrt{\mathcal{R}} \\ \text{with } \mathcal{R} \equiv \Omega_{\mathrm{SW0}}^2 / \Omega_{\mathrm{TW0}}^2 \end{array} \right.$$

- Nanolithography with a Ne* matter wave:

  ⇒ High energy state localization with a FWHM down to the nanometer

- Coherent patterning of a two component $^{87}$Rb BEC:

  ⇒ Narrow structures with $M^2 = 0.6$ (beating the Heisenberg limit)



# 5

# THREE-LEVEL ATOM OPTICS

# Outline

1 DARMSTADT EXPERIMENT: ATOMS IN OPTICAL MICROTRAPS

2 THREE-LEVEL ATOM OPTICS

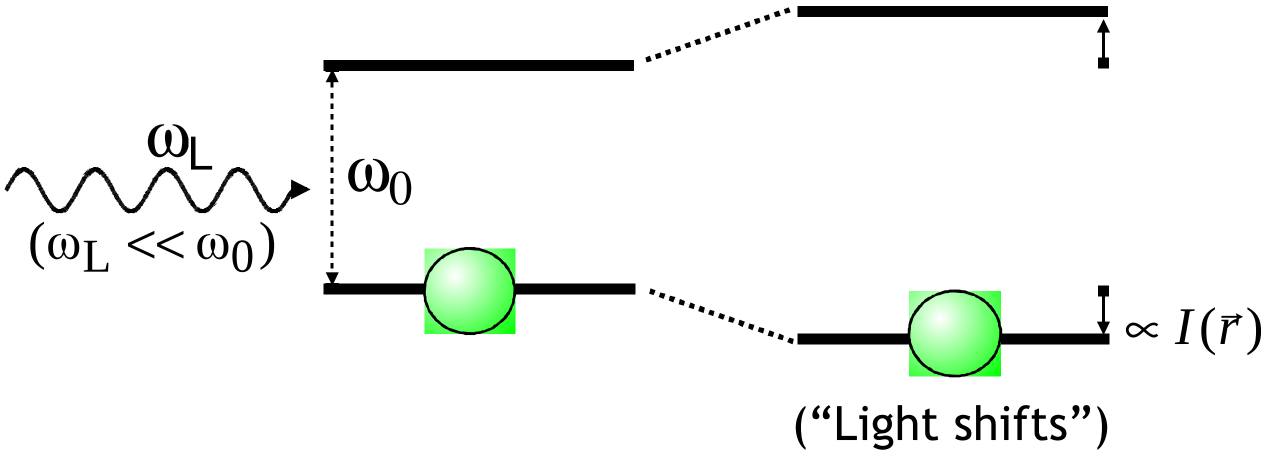
- 2a Matterwave STIRAP in an optical triple well potential
- 2b Matterwave transport without transit?
- 2c Coherent control of defects
- 2d Matterwave STIRAP in optical waveguides
- 2e Future work

3 CONCLUSIONS

# 1 DARMSTADT EXPERIMENT: ATOMS IN OPTICAL MICROTRAPS

# OPTICAL TRAPS FOR NEUTRAL ATOMS

● **LIGHT SHIFTS AND DIPOLE FORCE**



$$U(\vec{r}) = -\frac{3\pi c^2}{2\omega_0^3}\left(\frac{\Gamma}{\omega_0-\omega_L}+\frac{\Gamma}{\omega_0+\omega_L}\right)I(\vec{r}) \Longrightarrow \vec{F}(\vec{r}) = -\nabla U(\vec{r})$$

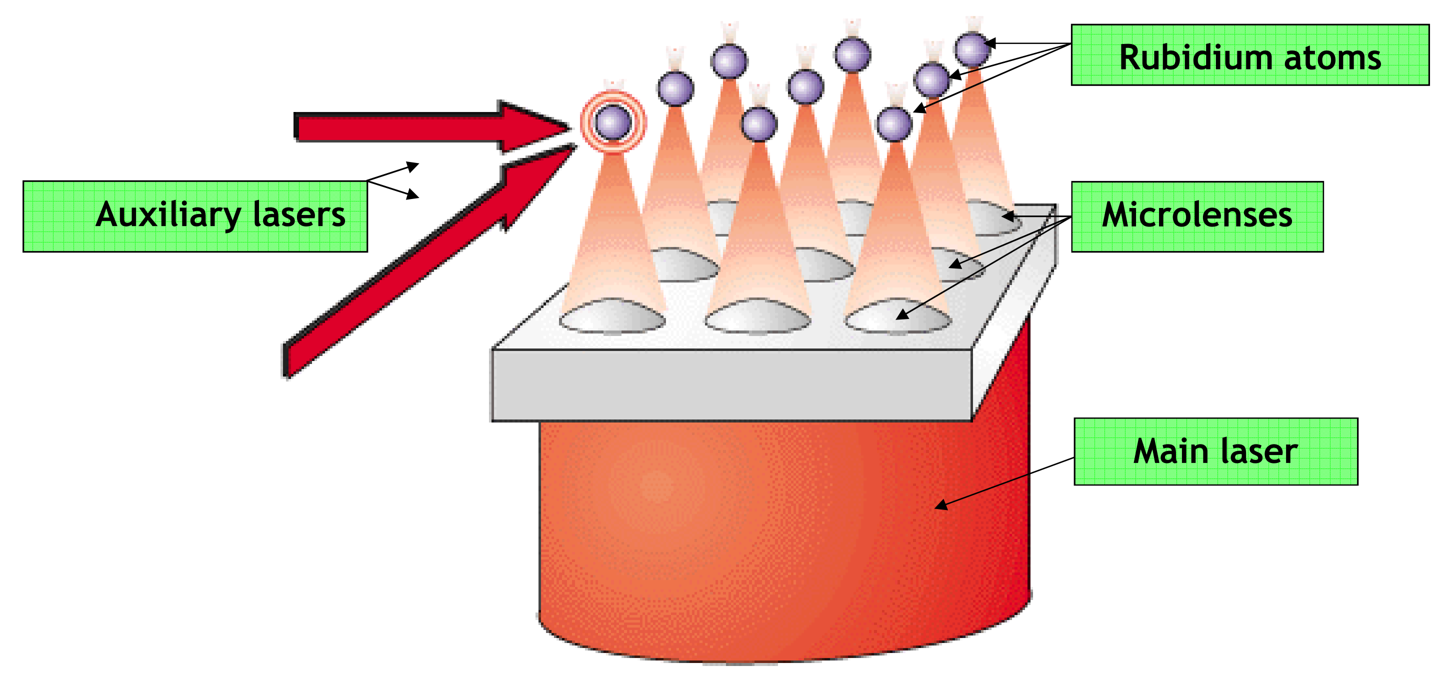
Some experimental results

- Cooling to the ground state of the trap (98.5%):

  *S.E. Hamann et al., Phys. Rev. Lett.* ***80****, 4149 (1998)*

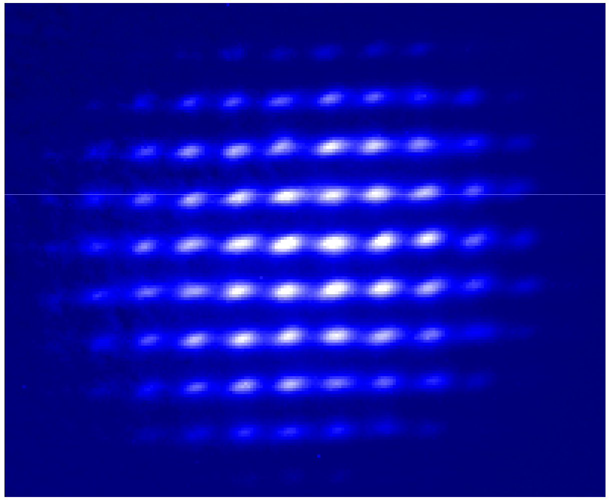
- Trapping single atoms: *V. Gomer et al., Phys. Rev. Lett.* ***85****, 3777 (2000)*
  *N. Schlosser et al., Nature* ***411****, 1024 (2001)*

# SCHEMATICS OF THE HANNOVER-DARMSTADT APPROACH



## PROF. G. BIRKL’s GROUP (HANNOVER-DARMSTADT)

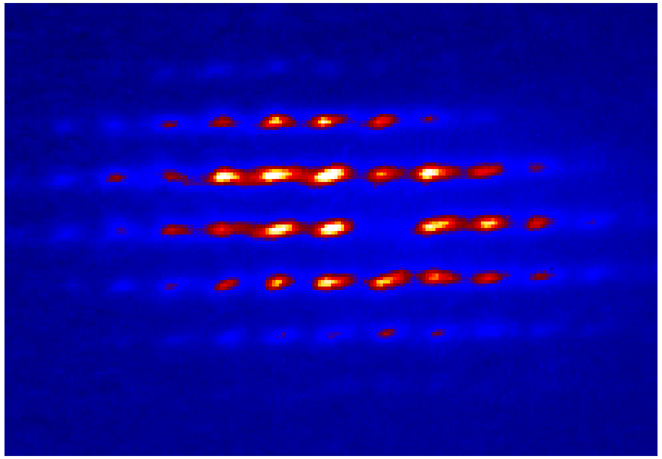
### FLOURESCENCE OF NEUTRAL ATOMS IN 2D MICROTRAP ARRAYS (~80 traps):

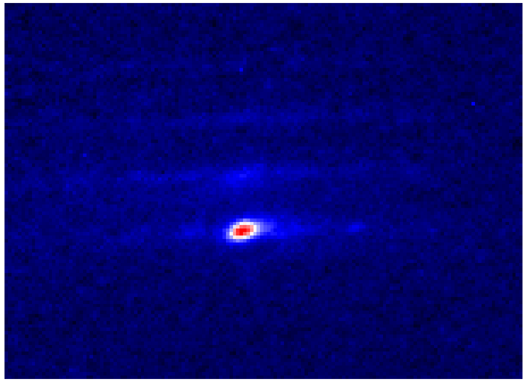


- P = 1 mW per trap
- WIdth of the traps 7 μm
- Trap deepth 1 mK
- Atoms per traps: 10 to 100
- $\omega_{trap} = 10^5$ Hz

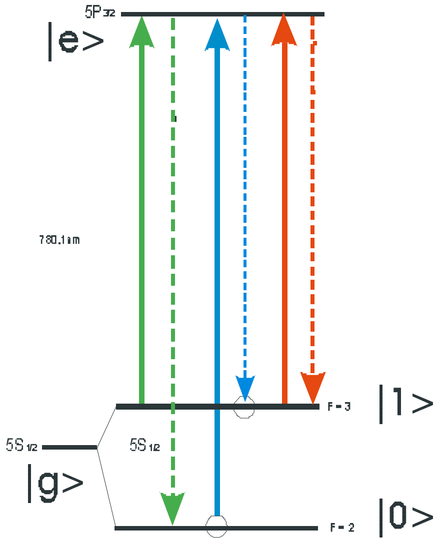
*R. Dumke et al., Phys. Rev. Lett.* ***89****, 097903 (2002)*

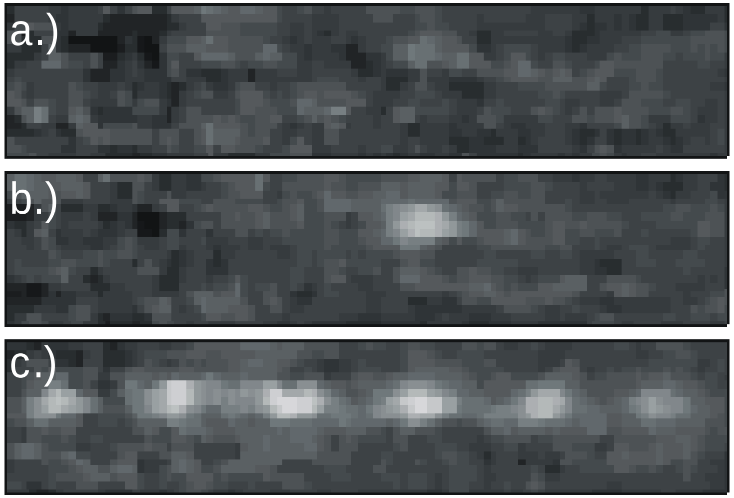
### SINGLE SITE ADRESSING:



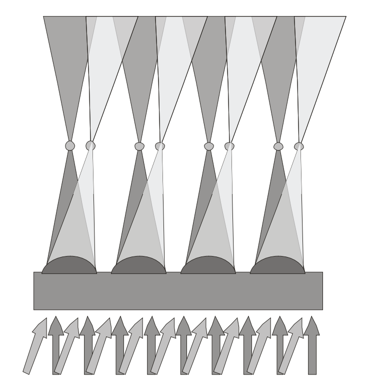


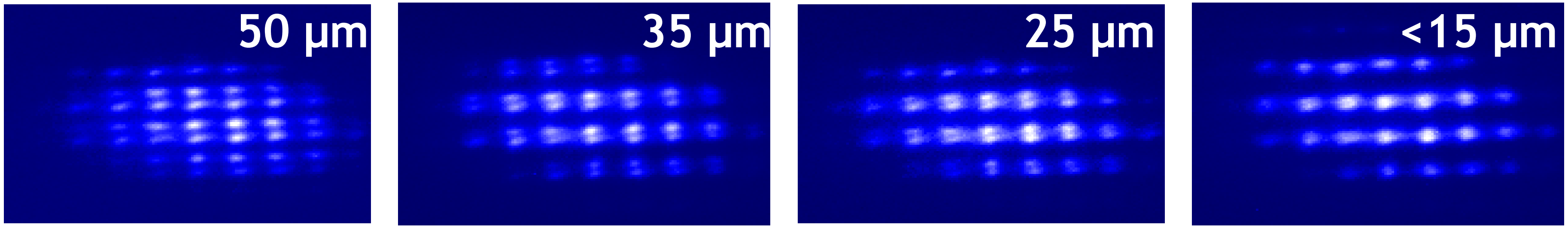
## QUBIT INICIALIZATION AND READOUT

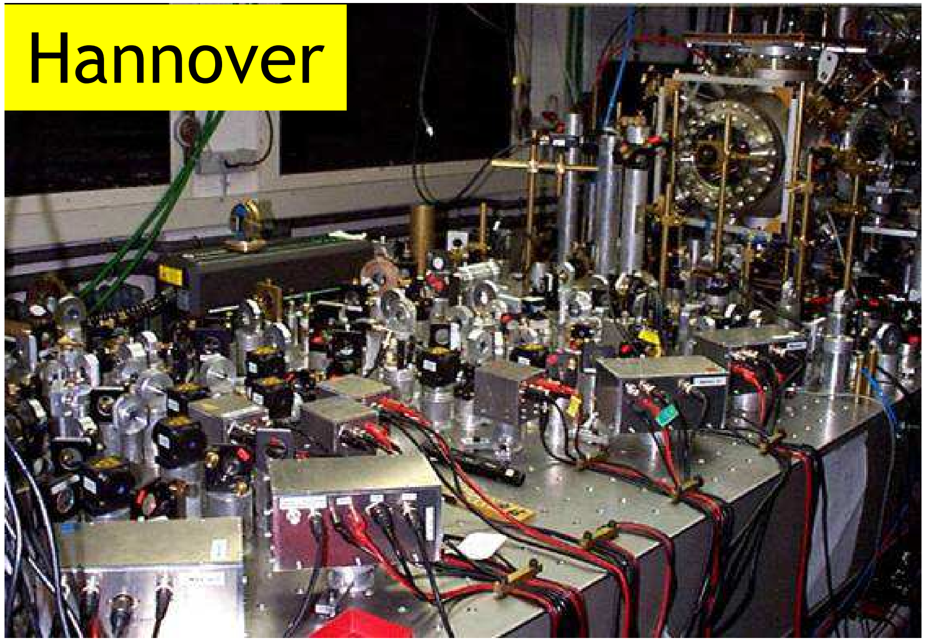


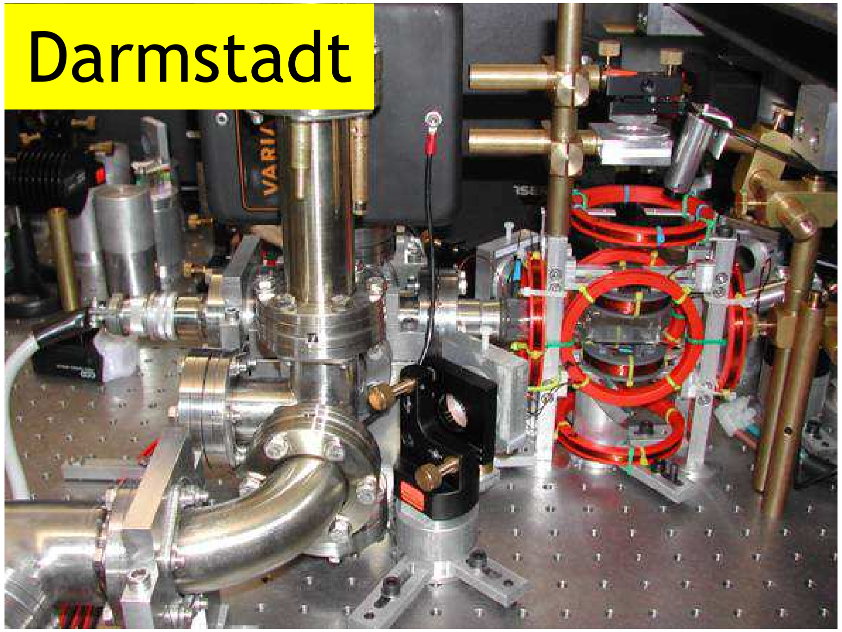


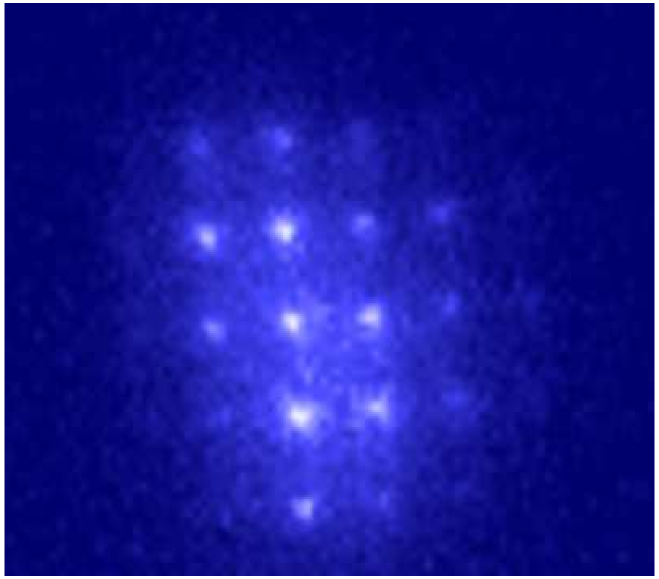
## COHERENT CONTROL OF THE DISTANCE BETWEEN TRAPS

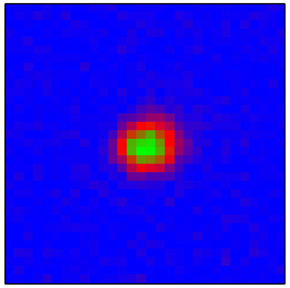


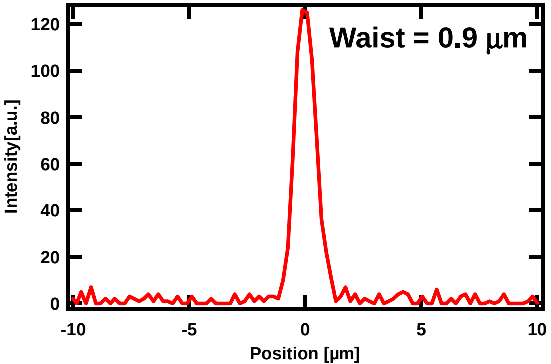






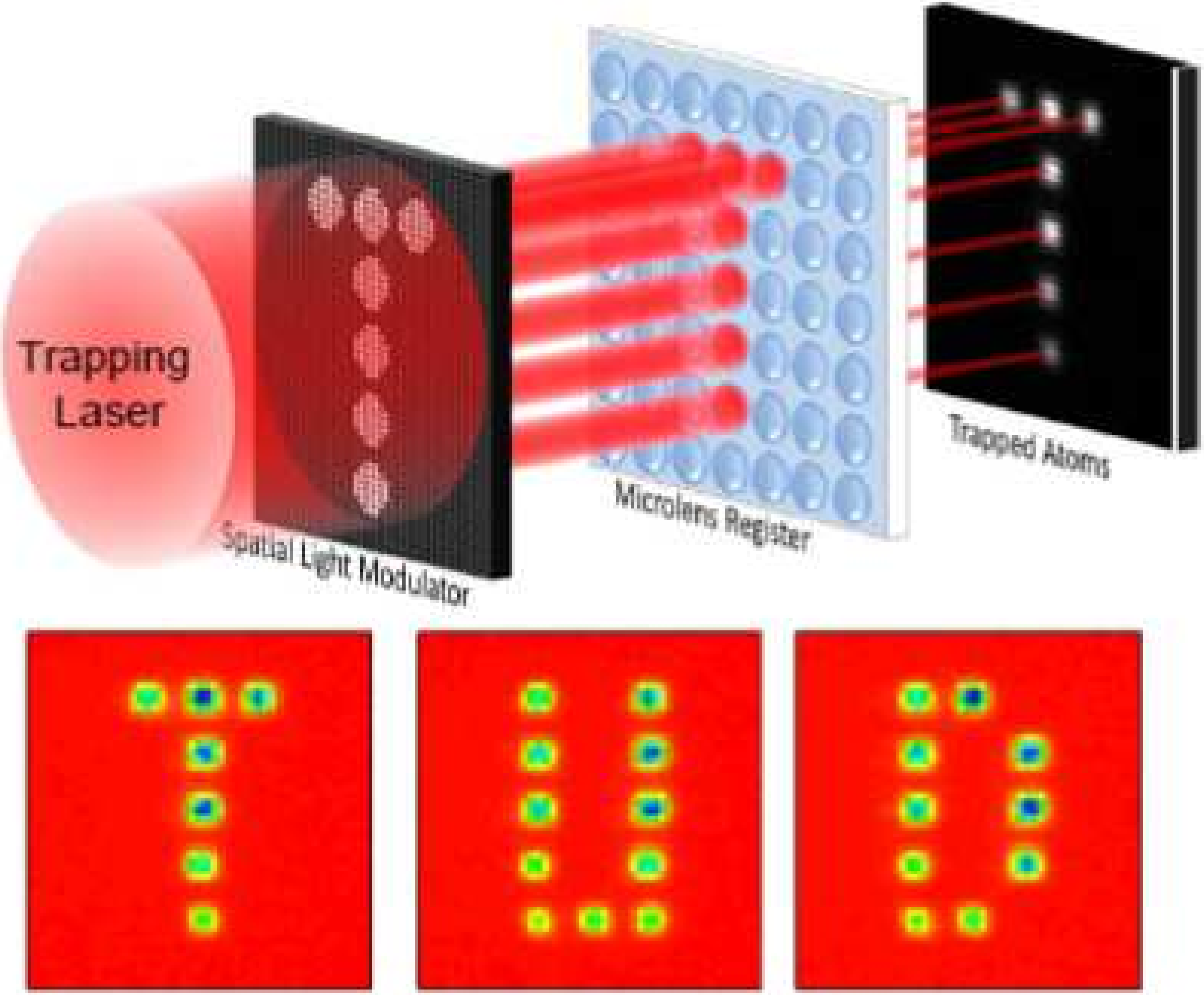






**Parameters**

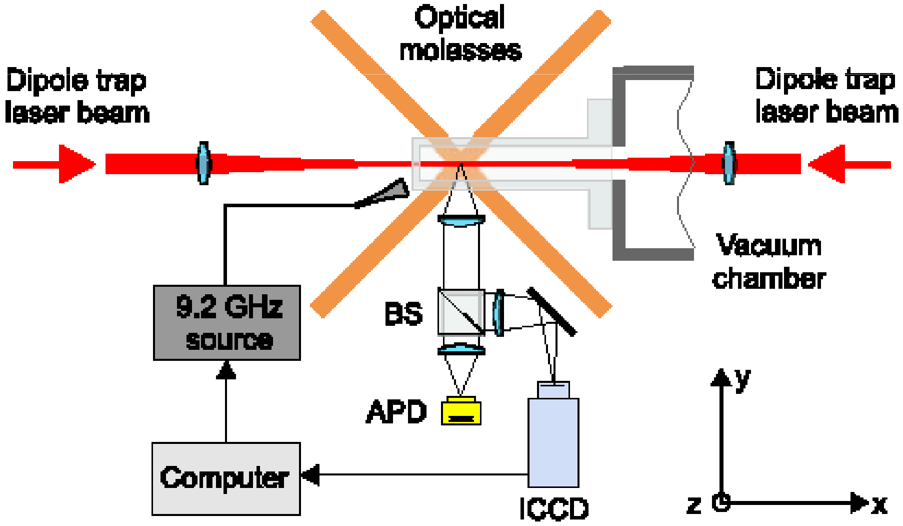
Laser at 796 nm
Solid angle of detection ~1 %
P = 10 mW per trap
$\Delta_L$ = 1.1 nm (for the $D_1$ line)
Trap width: 0.9 µm
Depth: 2.7 mK
Atoms per trap: 1-10
Lifetime: 350 ms

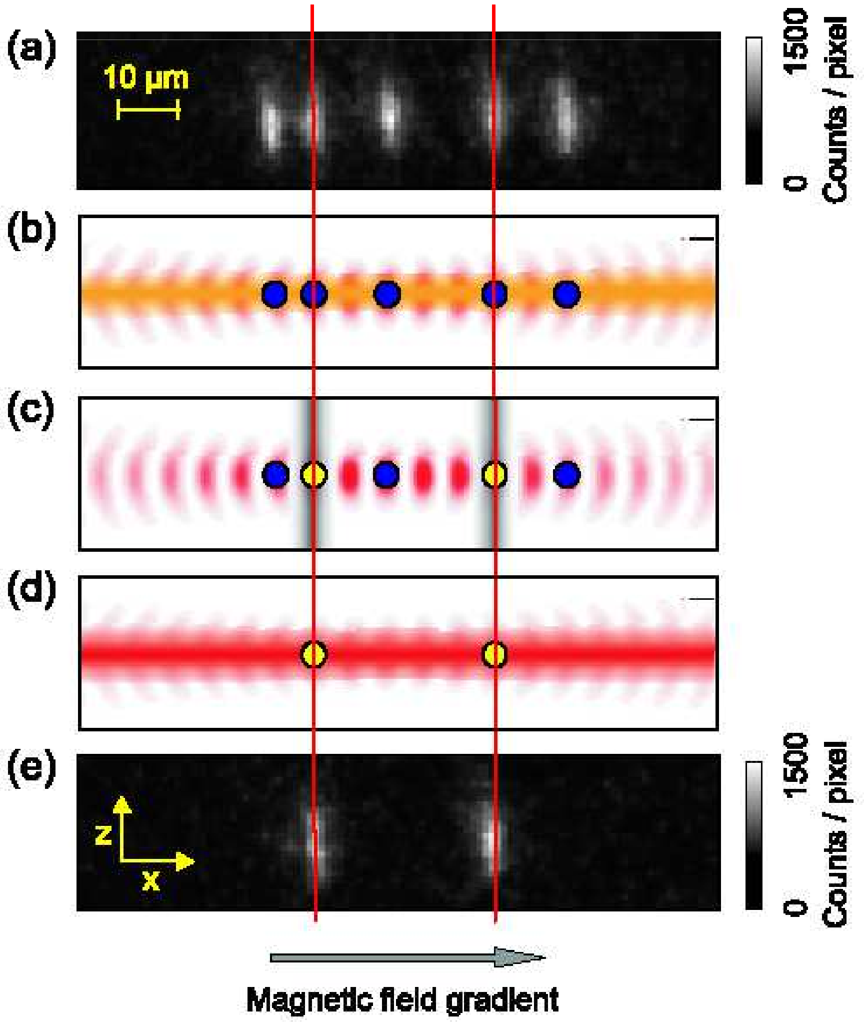

Trapping Laser
Spatial Light Modulator
Microlens Register
Trapped Atoms

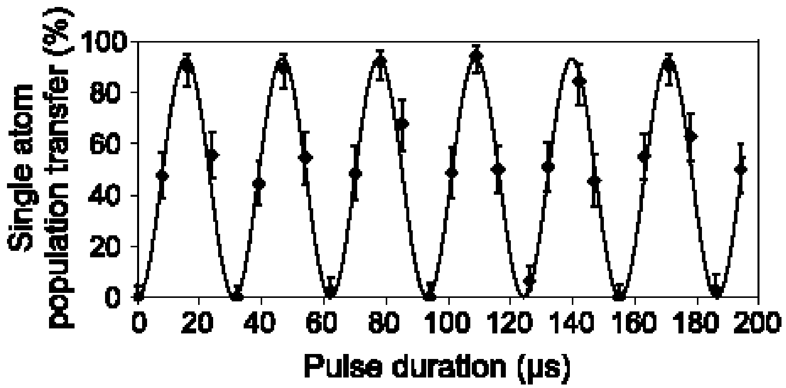
# Neutral Atom Quantum Register

D. Schrader, I. Dotsenko, M. Khudaverdyan, Y. Miroshnychenko, A. Rauschenbeutel, and D. Meschede

Phys. Rev. Lett. **93**, 150501 (2004)



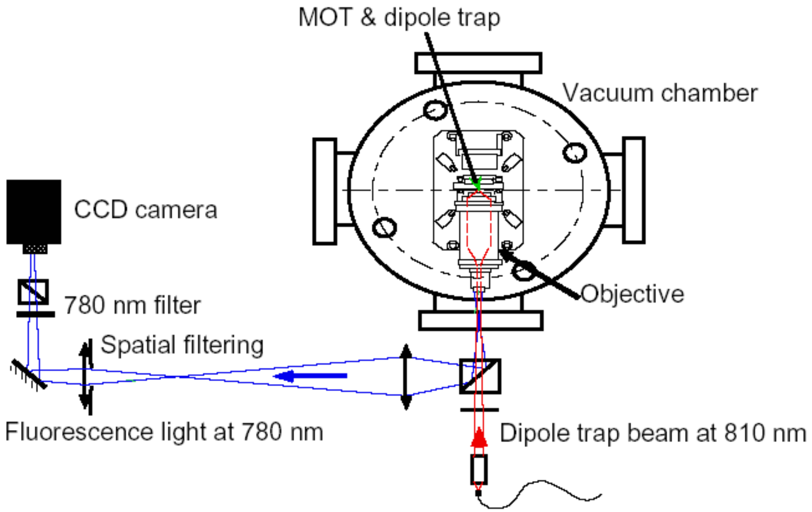


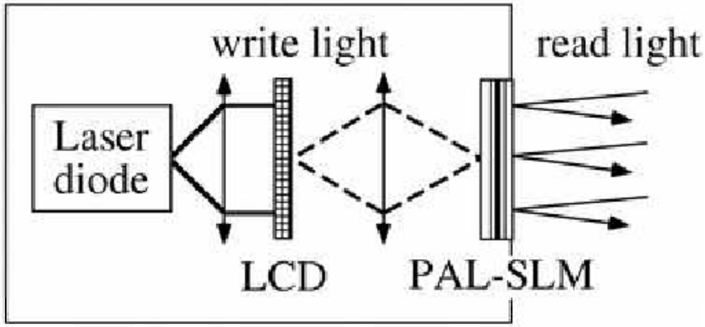


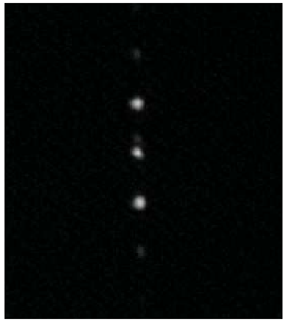
# Holographic generation of microtrap arrays for single atoms by use of a programmable phase modulator

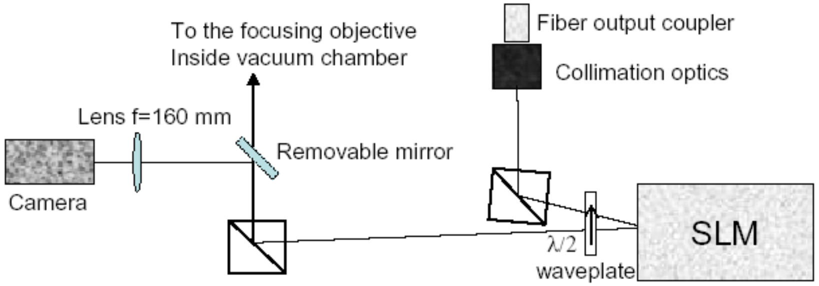
Silvia Bergamini, Benoît Darquié, Matthew Jones, Lionel Jacubowiez, Antoine Browaeys, and Philippe Grangier

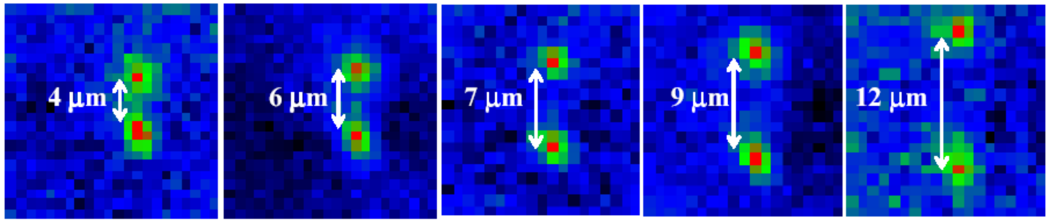
Journal of the Optical Society of America B **21**, 1889-1894 (2004)







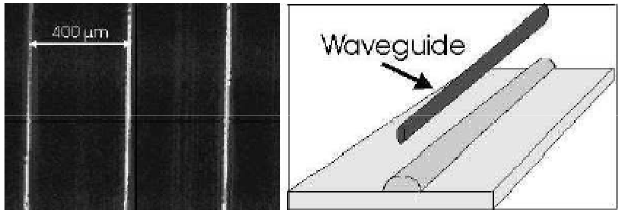


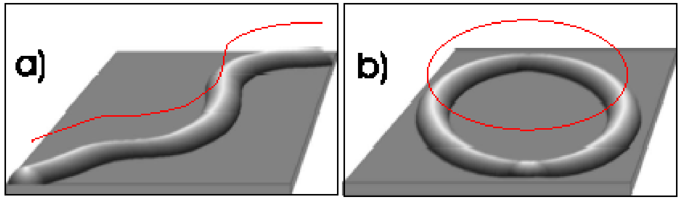


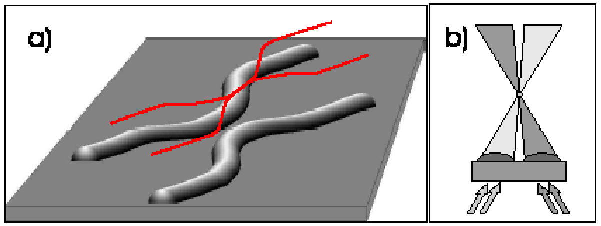
# Optical waveguides for matterwaves: ATOMIC CHIPS

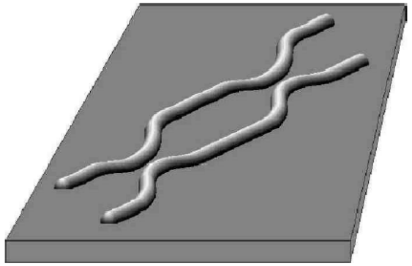
## Atom Optics with Microfabricated Optical Elements

*G. Birkl, F.B.J. Buchkremer, R. Dumke y W. Ertmer, Optics Comm.* ***191****, 67 (2001)*



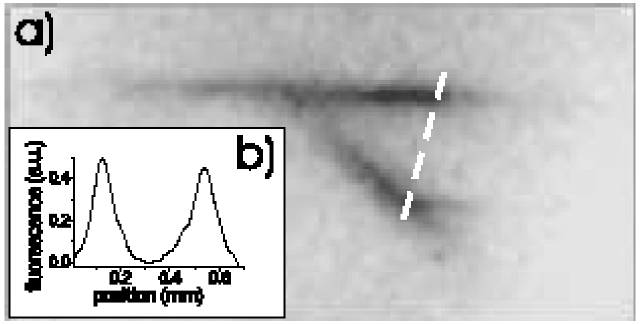


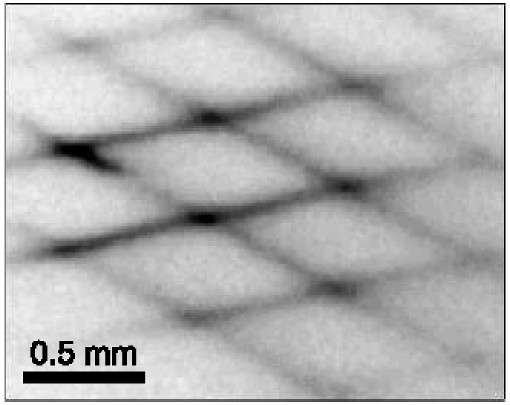




## Interferometer-Type Structures for Guided Atoms

*R. Dumke, T. Müther, M. Volk, W. Ertmer, and G. Birkl, Phys. Rev. Lett.* ***89****, 220402 (2002))*





# 2 THREE-LEVEL ATOM OPTICS

## 2a Matterwave STIRAP in an optical triple well potential

## 2b Matterwave transport without transit?

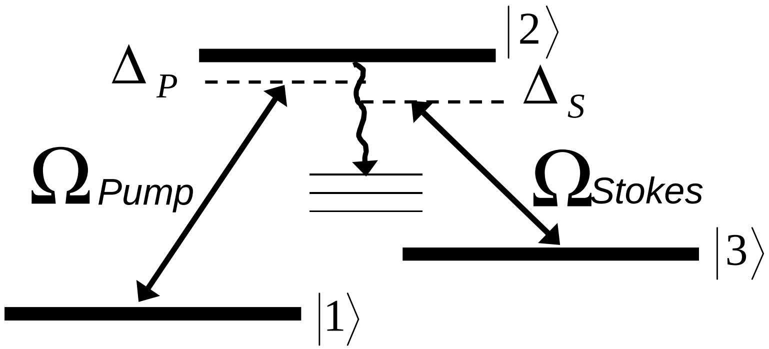
## 2c Coherent control of defects

## 2d Matterwave STIRAP in optical waveguides

# WHAT IS STIRAP?

"Coherent population transfer among quantum states of atoms and molecules"
K. Bergmann, H. Theuer, and B. W. Shore
Rev. Mod. Phys. 70, 1003 (1998)

$$\Omega(t) \equiv \frac{\vec{\mu}\vec{E}_0(t)}{\hbar}$$



$$H(t) = \frac{\hbar}{2}\begin{pmatrix} 0 & \Omega_P(t) & 0 \\ \Omega_P(t) & 2\Delta_P & \Omega_S(t) \\ 0 & \Omega_S(t) & 2(\Delta_P - \Delta_S) \end{pmatrix}$$

Energy eigenstates:

$\Delta_P = \Delta_S (=0)$

$$|+\rangle = \frac{1}{\sqrt{2}}\left[\sin\Theta|1\rangle + |2\rangle + \cos\Theta|3\rangle\right] \qquad \tan\Theta = \Omega_P(t)/\Omega_S(t)$$

$$|D\rangle = \cos\Theta|1\rangle - \sin\Theta|3\rangle \qquad \omega^0 = 0$$

$$|-\rangle = \frac{1}{\sqrt{2}}\left[\sin\Theta|1\rangle - |2\rangle + \cos\Theta|3\rangle\right] \qquad \omega^{\pm} = \pm\sqrt{\Omega_P^2 + \Omega_S^2}$$

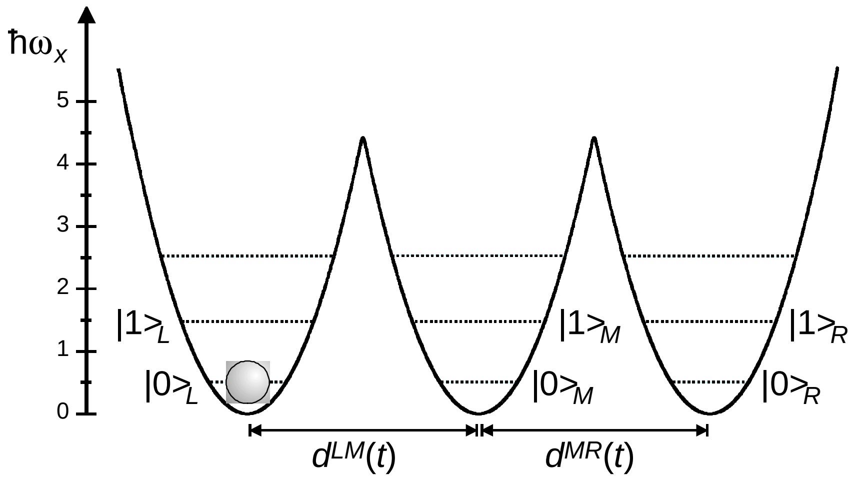
**STIRAP** (Stimulated Raman Adiabatic Passage): $\Theta = 0^o \to \Theta = 90^o$ ➡ $|1\rangle \to |3\rangle$

**Dark State:** $\Theta = 0^o \to \Theta = 45^o \Rightarrow |1\rangle \to \left(|1\rangle - |3\rangle\right)/\sqrt{2}$

**EIT:** $\Theta = 0^o \to \Theta = X^o \to \Theta = 0 \Rightarrow |1\rangle \to |1\rangle$

# EXTENSION TO MATTER WAVES IN OPTICAL MICROTRAPS

Three level atom optics via the tunneling interaction
K. Eckert, M. Lewenstein, G. Birkl, W. Ertmer, R. Corbalán and J. Mompart
Phys. Rev. A **70**, 023606 (2004)

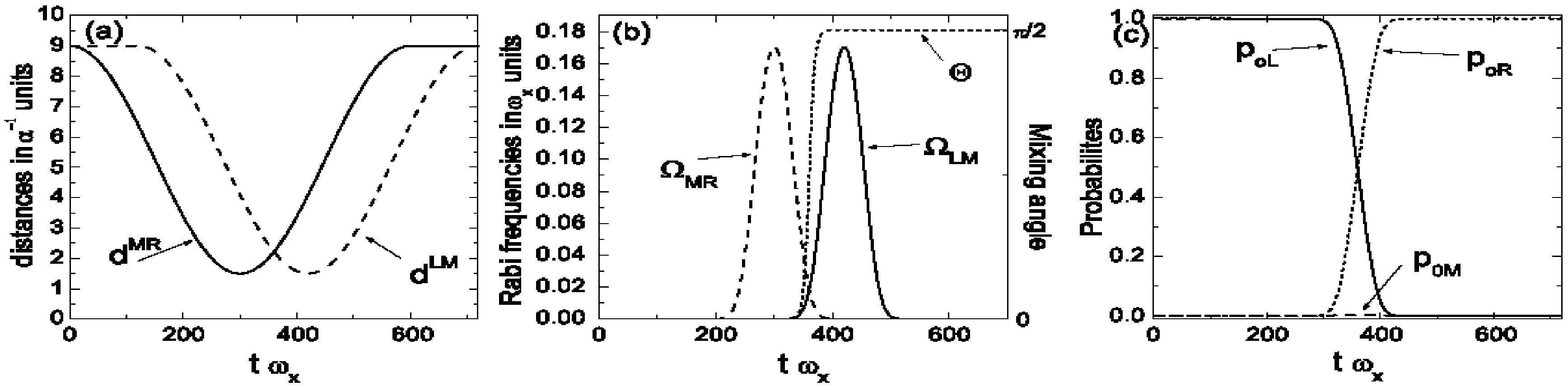


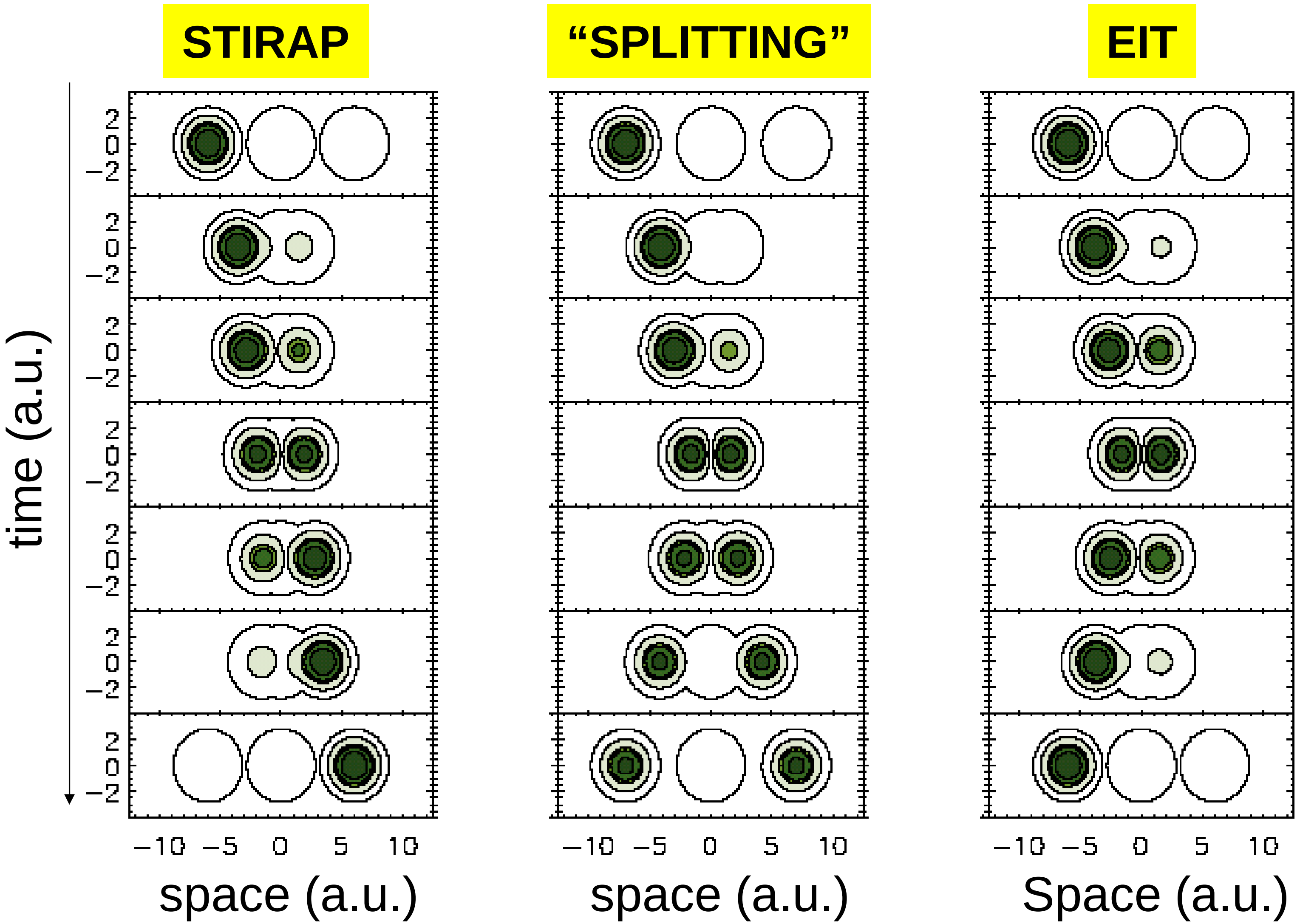
$$H(t)=\frac{\hbar}{2}\begin{pmatrix} 0 & \Omega_{LM}(t) & 0 \\ \Omega_{LM}(t) & 0 & \Omega_{MR}(t) \\ 0 & \Omega_{MR}(t) & 0 \end{pmatrix}$$

$$\frac{\Omega(\alpha d)}{\omega_x}=\frac{-1+e^{(\alpha d)^2}\left(1+\alpha d\left[1-erf\left(\alpha d\right)\right]\right)}{\sqrt{\pi}(e^{(\alpha d)^2}-1)/2\alpha d}$$

$$\left|D(\Theta)\right\rangle=\cos\Theta\left|0\right\rangle_L-\sin\Theta\left|0\right\rangle_R, \qquad \tan\Theta=\Omega_{LM}(t)/\Omega_{MR}(t)$$

whered $\alpha^{-1}\equiv\sqrt{\hbar/m\omega_x}$





**STIRAP**

**"SPLITTING"**

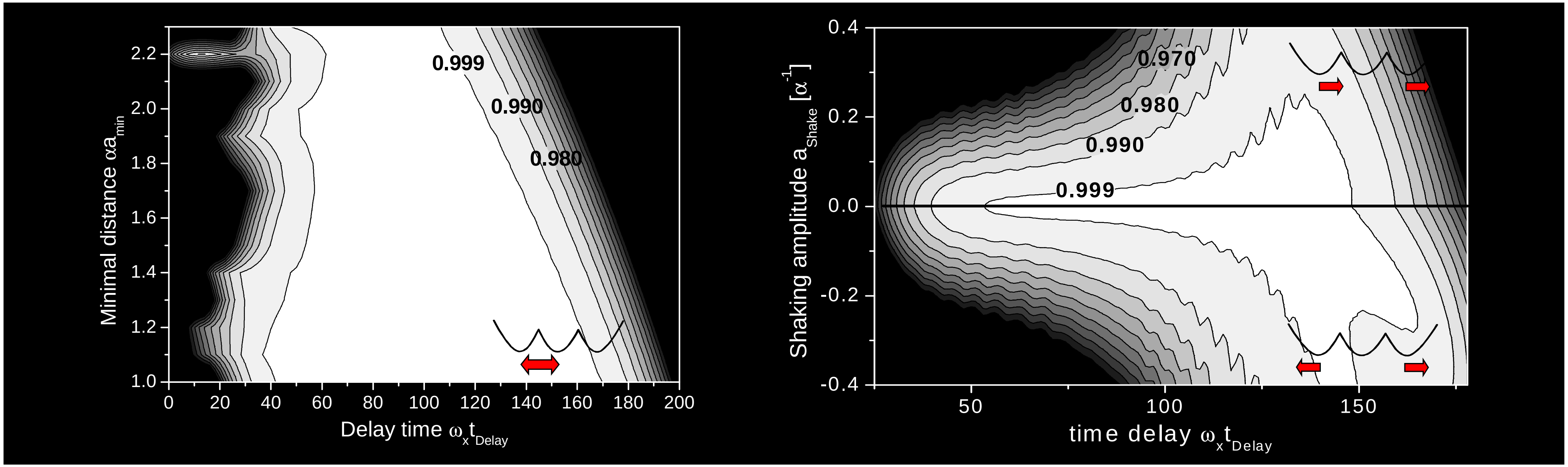
**EIT**

**STIRAP:** Transport
**SPLITTING:** Interferometry
**EIT:** Phase manipulation

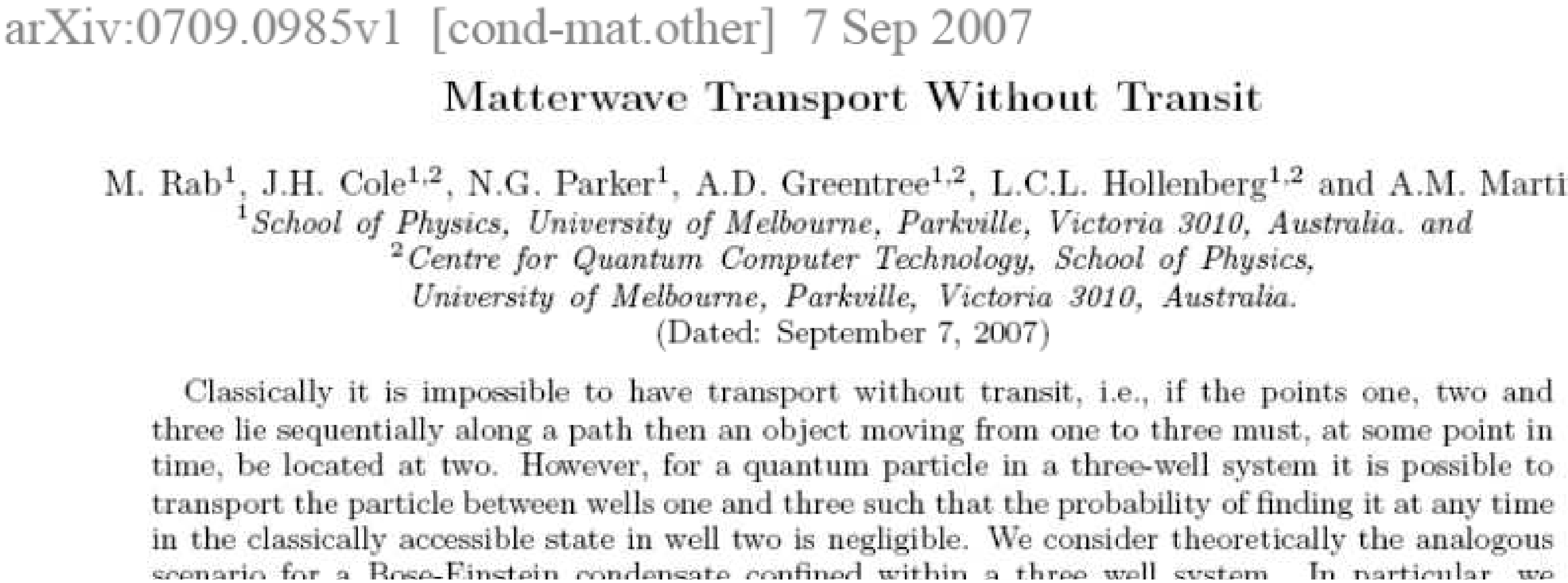
$\omega_{trap} = 10^5$ Hz ⇨

**Time:** ms
**Space:** μm

# MATTERWAVE STIRAP ROBUSTNESS:



# MATTERWAVE TRANSPORT WITHOUT TRANSIT?

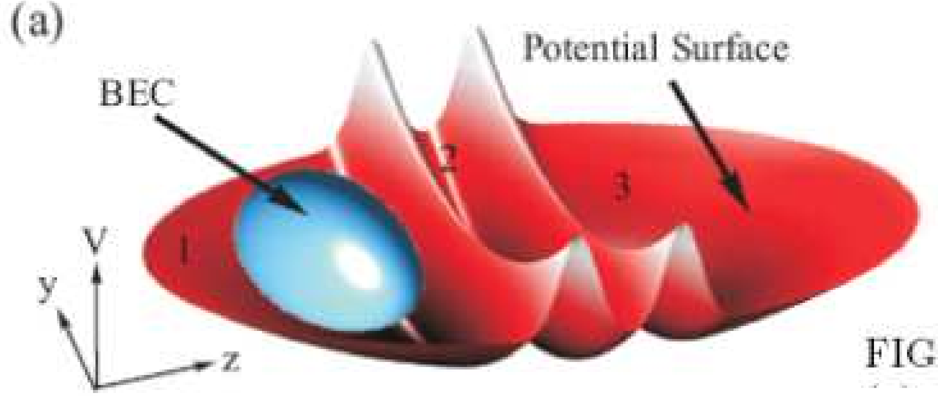


arXiv:0709.0985v1 [cond-mat.other] 7 Sep 2007

## Matterwave Transport Without Transit

M. Rab[1], J.H. Cole[1,2], N.G. Parker[1], A.D. Greentree[1,2], L.C.L. Hollenberg[1,2] and A.M. Martin[1]
[1] *School of Physics, University of Melbourne, Parkville, Victoria 3010, Australia. and*
[2] *Centre for Quantum Computer Technology, School of Physics,*
*University of Melbourne, Parkville, Victoria 3010, Australia.*
(Dated: September 7, 2007)

Classically it is impossible to have transport without transit, i.e., if the points one, two and three lie sequentially along a path then an object moving from one to three must, at some point in time, be located at two. However, for a quantum particle in a three-well system it is possible to transport the particle between wells one and three such that the probability of finding it at any time in the classically accessible state in well two is negligible. We consider theoretically the analogous scenario for a Bose-Einstein condensate confined within a three well system. In particular, we



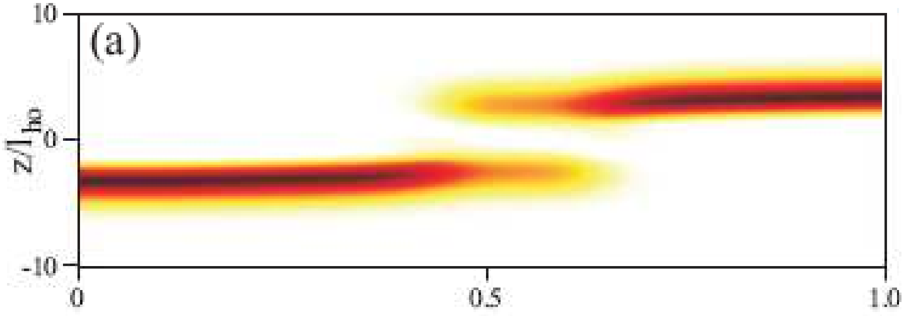


FIG. 3: Dynamics of the system according to the 1D GPE.

# MATTERWAVE TRANSPORT WITHOUT TRANSIT?

Need for relativistic corrections in the analysis of spatial adiabatic passage of matter waves
A. Benseny, J. Bagudà, X. Oriols, and J. Mompart
Phys. Rev. A **85**, 053619 (2012)

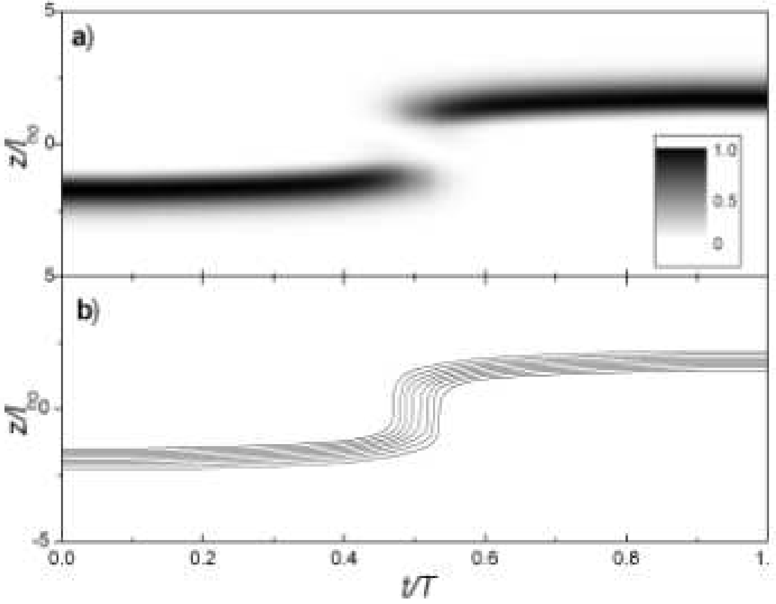


FIG. 1: (a) Time evolution of the condensate density. (b) Current lines calculated with Eq. (4). $z/l_{ho}$ is the position in units of the harmonic oscillator length, $T$ is the total time for the STIRAP-like process.

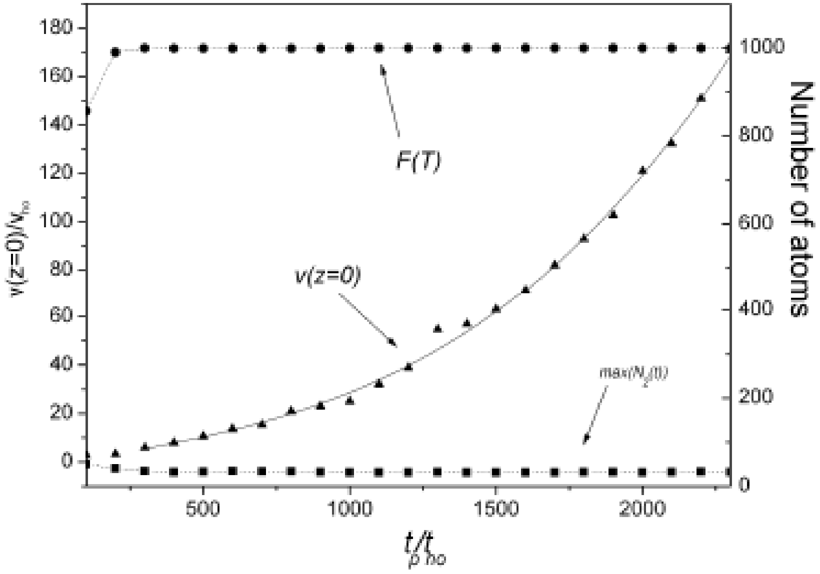
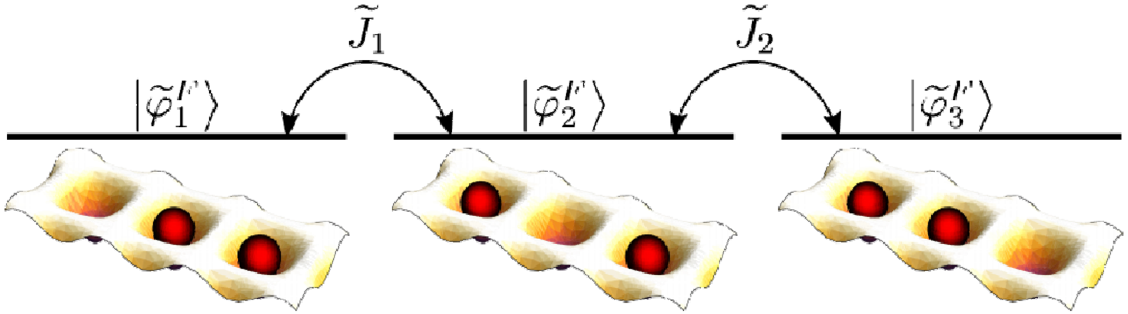


FIG. 2: The maximum velocity of the fluid for different pulse times (in black) in units of $v_{ho} \equiv l_{ho}/t_{ho}$ (triangles) and the quantities $F(t)$ and $\max(N_2(t))$, defined in the text (circles and squares, respectively).

# MATTER WAVE STIRAP for HOLE TRANSPORT

Atomtronics with holes: Coherent transport of an empty site in a triple-well potential
A. Benseny, S. Fernández-Vidal, J. Bagudà, R. Corbalán, A. Picón, L. Roso, G. Birkl, and J. Mompart
Phys. Rev. A **82**, 013604 (2010)



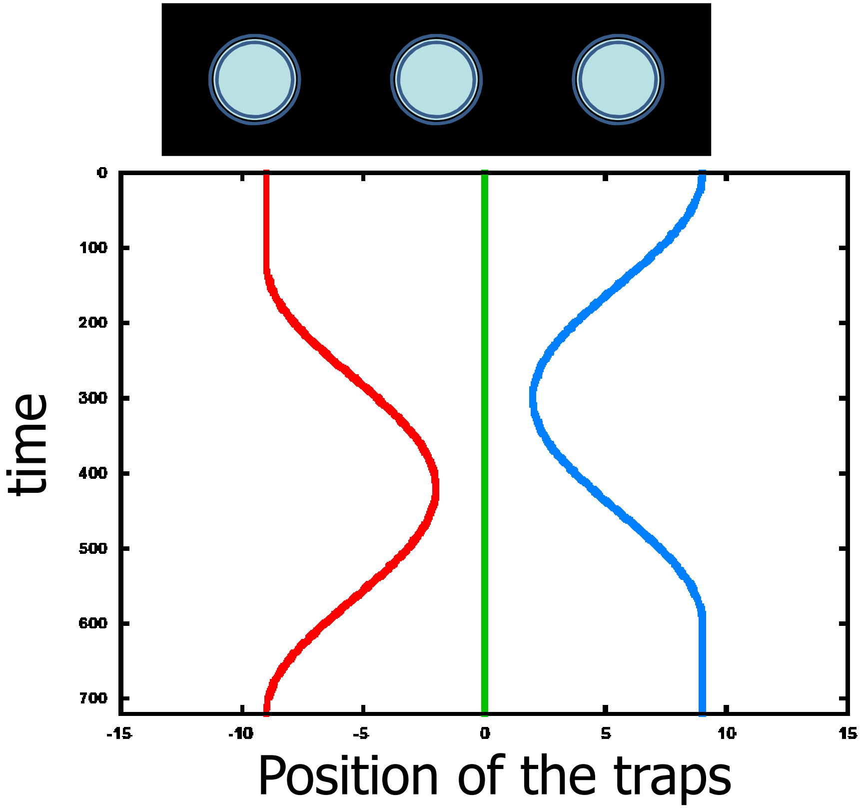
**CONDITIONS**

- 0 or 1 atom per trap
- atoms cooled down to the ground state
- control of tunneling by trap movement

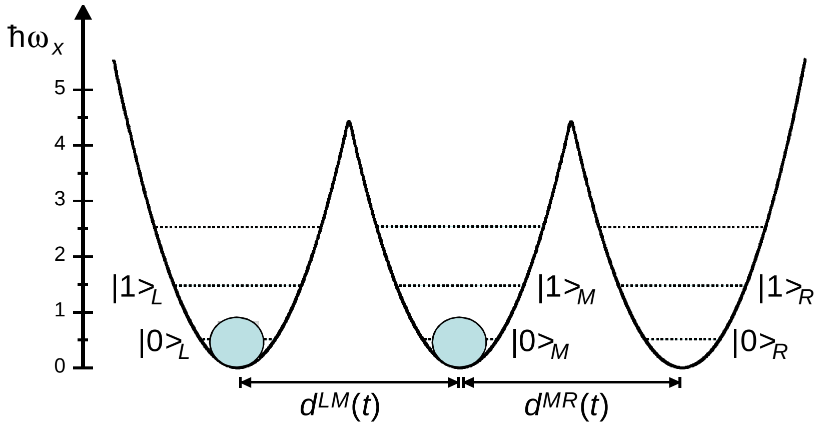
$$H_{3\,\mathrm{TRAPS}} = \hbar \begin{pmatrix} 0 & \tilde{J}_1(t) & 0 \\ \tilde{J}_1(t) & 0 & \tilde{J}_2(t) \\ 0 & \tilde{J}_2(t) & 0 \end{pmatrix}$$

$$|\tilde{D}^F(\Theta(t))\rangle = \cos\Theta(t)\,|\tilde{\varphi}_1^F\rangle - \sin\Theta(t)\,|\tilde{\varphi}_3^F\rangle$$

$$\tan\Theta(t) = \tilde{J}_1(t)/\tilde{J}_2(t)$$



# COHERENT CONTROL OF DEFECTS IN MICROTRAPS ARRAYS



## Hamiltonian for the “hole”:

$$H(t)=\frac{\hbar}{2}\begin{pmatrix} 0 & \Omega_{LM}(t) & 0 \\ \Omega_{LM}(t) & 0 & \Omega_{MR}(t) \\ 0 & \Omega_{MR}(t) & 0 \end{pmatrix}$$

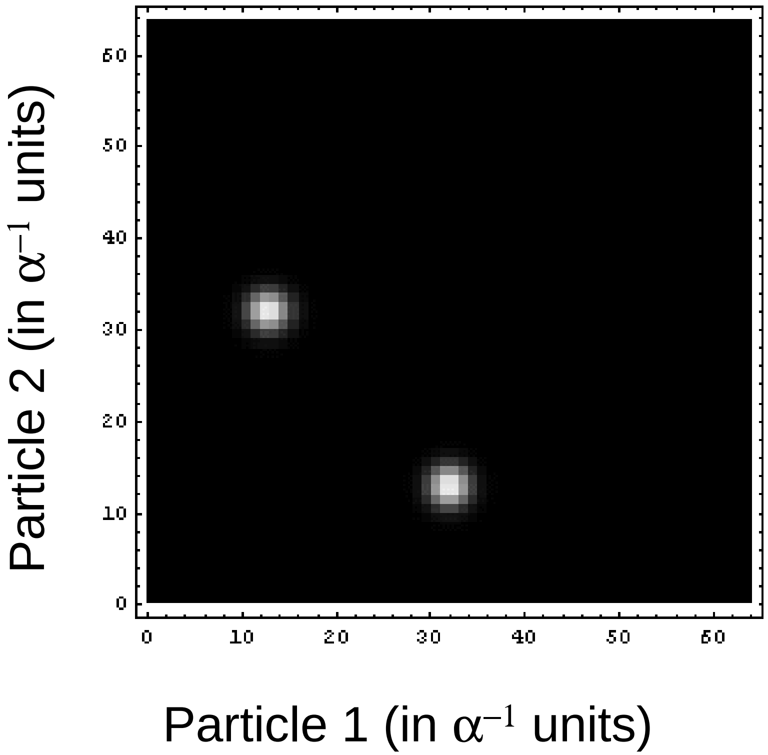
Parameters:

$$d^{MR}_{\max}\alpha=9;\ d^{MR}_{\min}\alpha=1.5;$$

$$d^{LM}_{\max}\alpha=9;\ d^{LM}_{\min}\alpha=1.5;$$

$$t^{MR}_{r}\omega_x=t^{LM}_{r}\omega_x=300;$$

$$t_{delay}\omega_x=120.$$

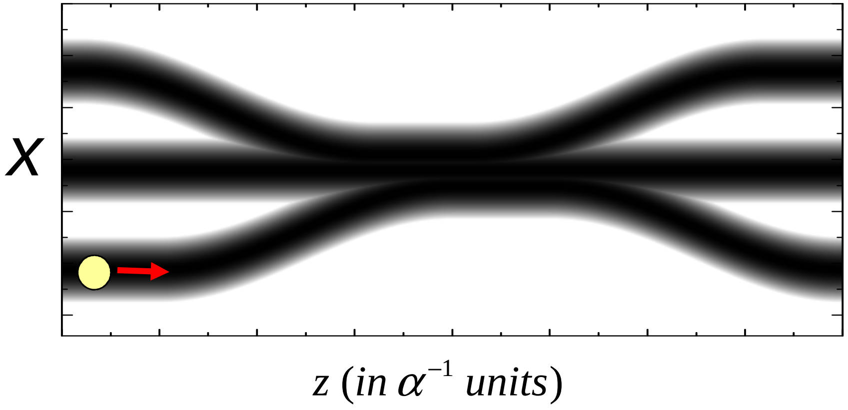


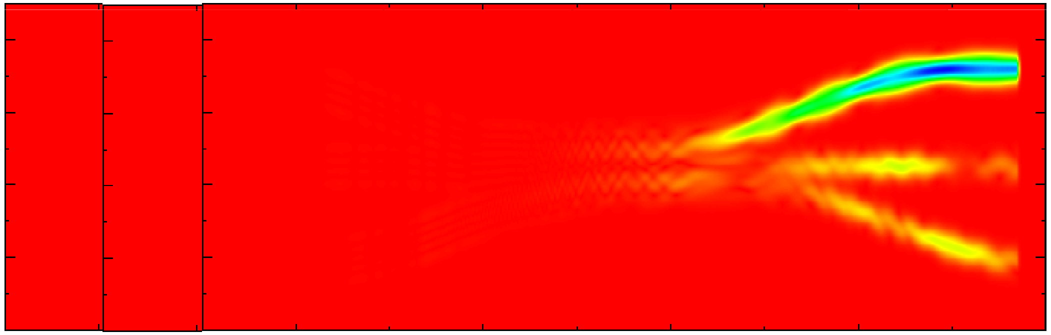
# EXTENSION TO MATTER WAVES IN OPTICAL WAVEGUIDES

**“Three level atom optics in dipole traps and waweguides”**
**K. Eckert, J. Mompart, R. Corbalán, M. Lewenstein and G. Birkl**
**Opt. Comm. 264, 264 - 270 (2006)**

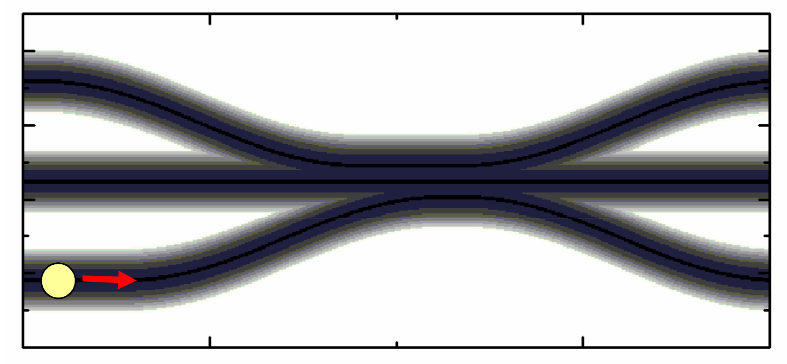
**Parameters**

Transverse harmonic profiles: $d_{\max}\alpha = 8;\ d_{\min}\alpha = 1.5$
In longitudinal direction: $l\alpha = 400$
Initial longitudinal momentum: $p = 5p_{recoil},\ \Delta p = p_{recoil}$





## ATOMIC-“CPT”:

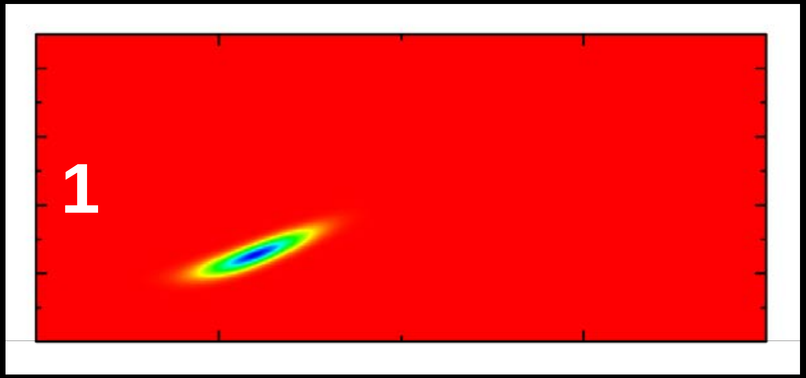


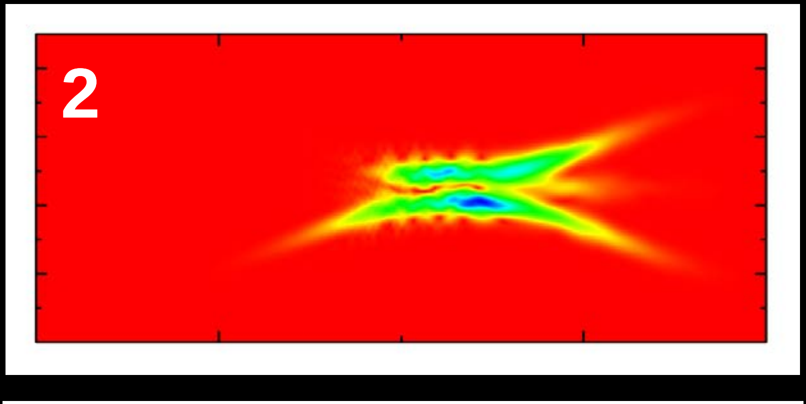
**Parameters:**

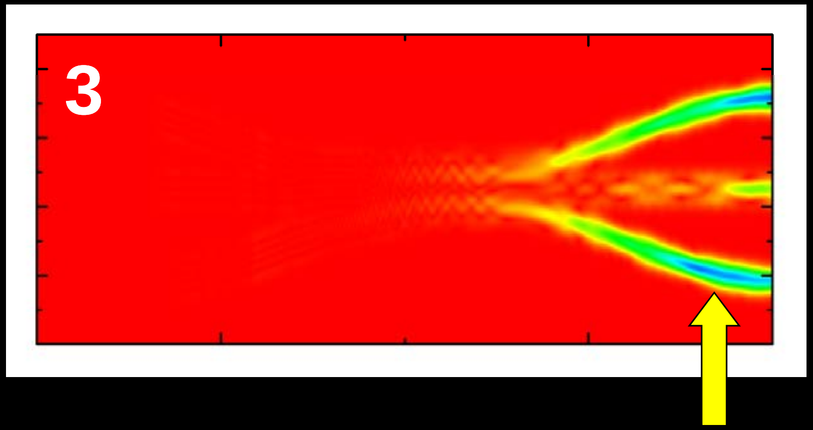
transverse harmonic profiles with $d_{\max}\alpha = 8;\ d_{\min}\alpha = 1.5$

in longitudinal direction : $l\alpha = 400$

inital longitudinal momentum : $p = 5p_{recoil},\ \Delta p = p_{recoil}$

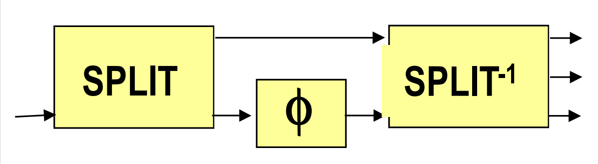


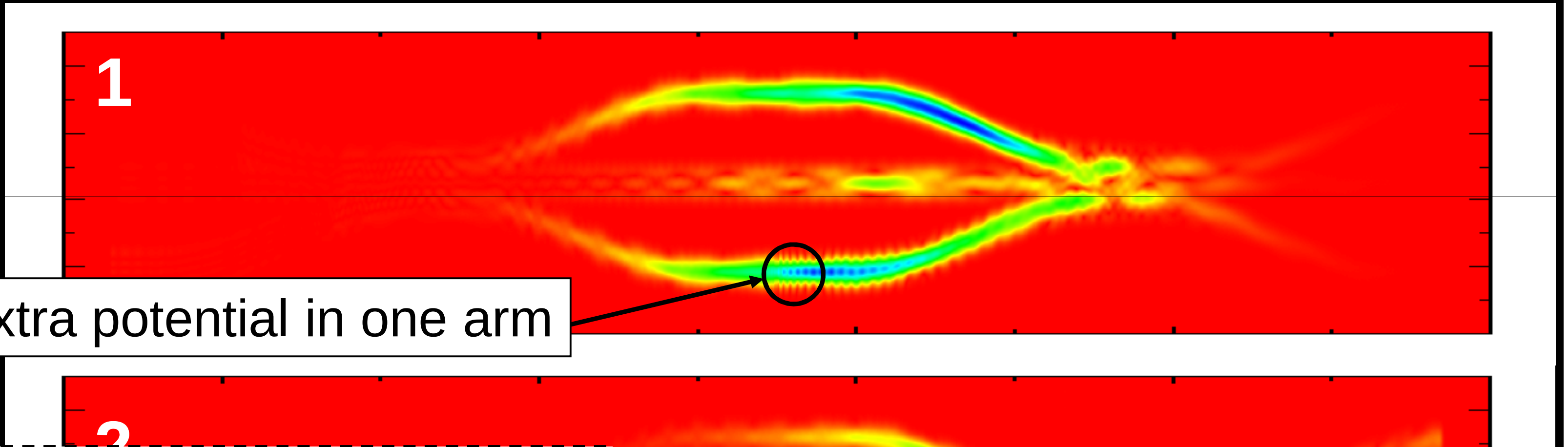




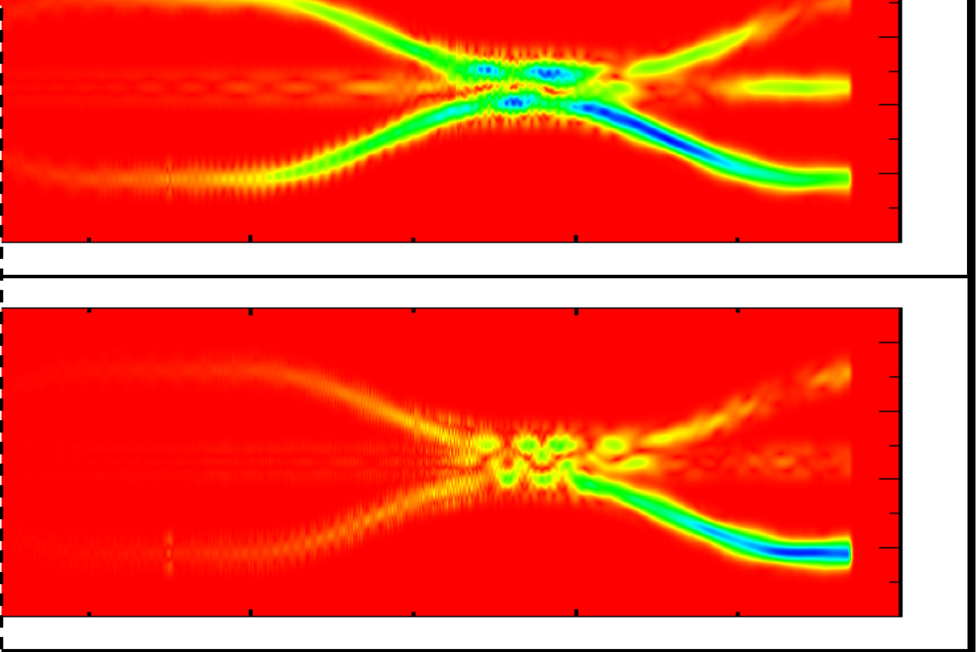
**Matterwave splitter**

## Interferometry

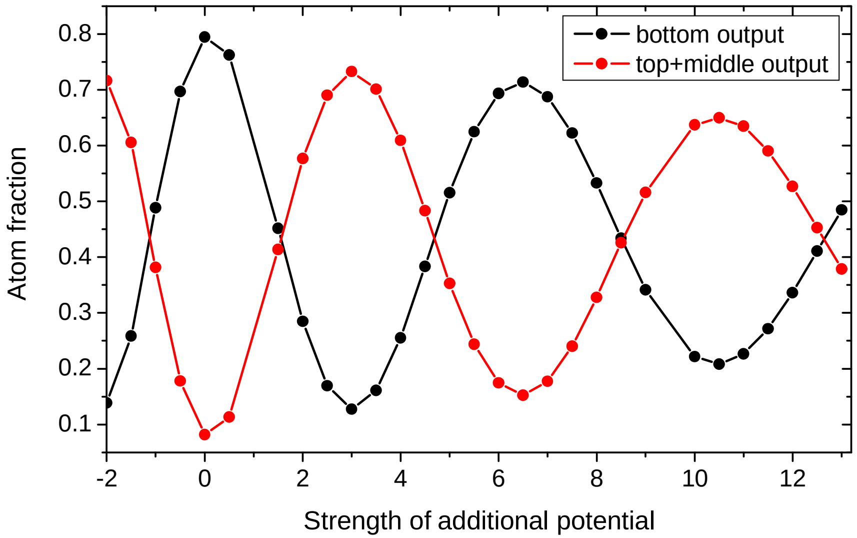




Extra potential in one arm



- Atomic population at each output port as a function of the strength of the additional potential



# ATOMICS

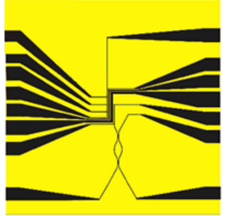
The new field of ATom Optics with MICro-Structures is directed towards **microfabrication** of **atom optical elements** for manipulation, storage, and guiding of neutral atoms

- **Neutral atoms in dipole waveguides:**

- **Neutral atoms in electrostatic and magnetic waveguides:**

*P. Krüger et al., Phys. Rev. Lett.* ***91****, 233201 (2003)*

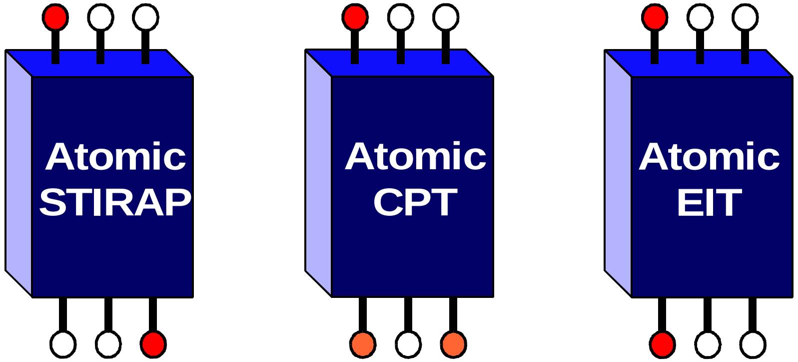
*R. Folman et al., Phys. Rev. Lett.* ***84****, 4749 (2000)*



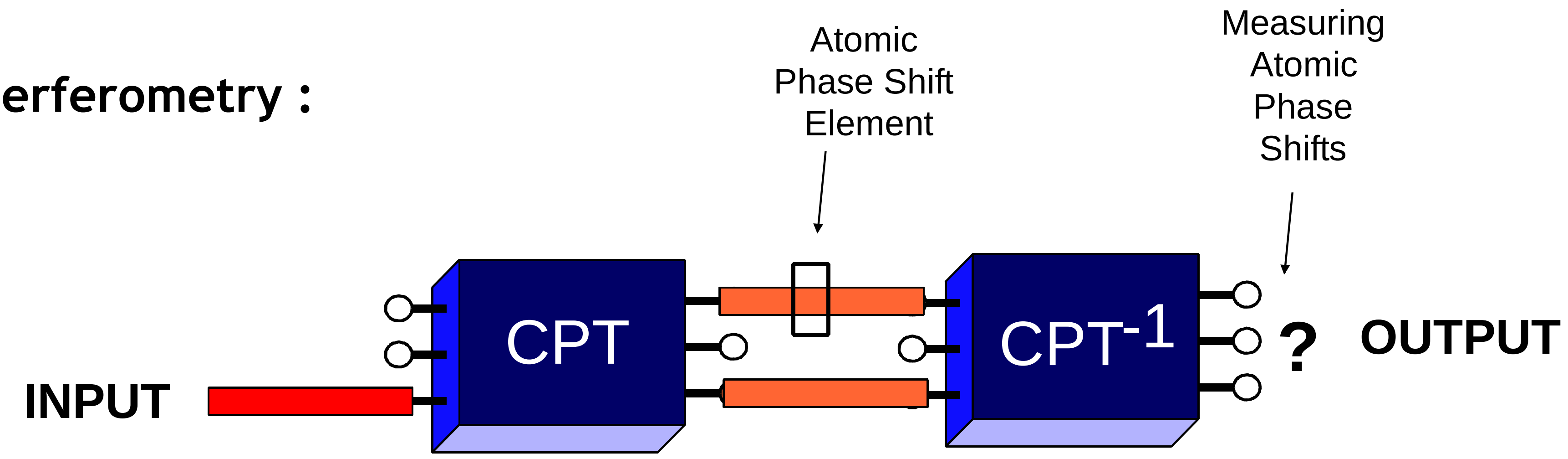
AtomChip Group
University of Heidelberg

J. Schmiedmayer
Group

- **Building blocks of ATOMICS:**

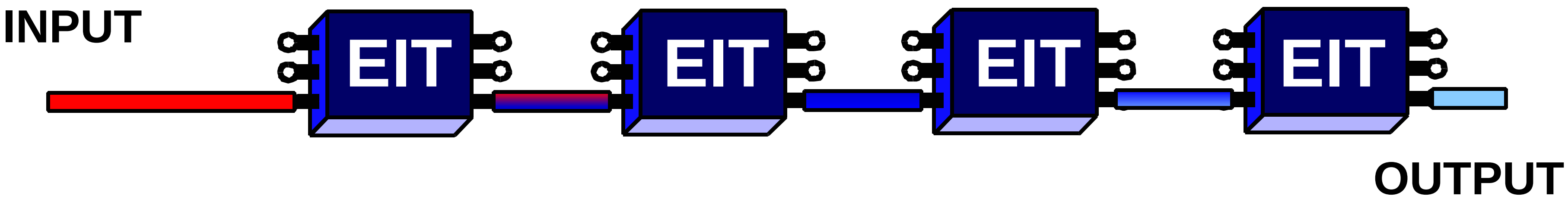


- **Interferometry :**



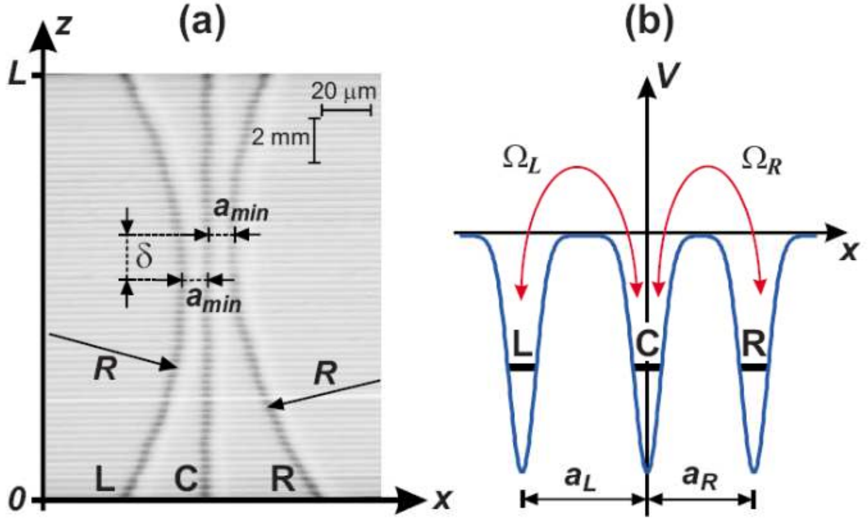
- **Cooling by filtering:**

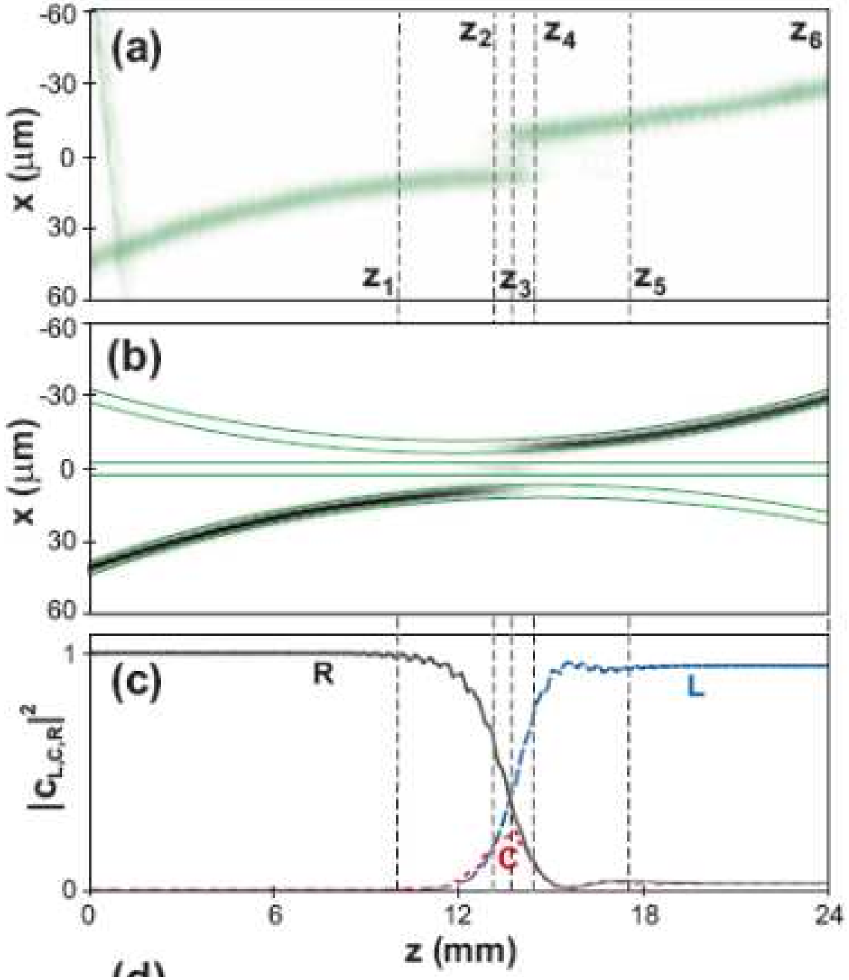
Do matter-wave EIT only for the transverse ground vibrational state



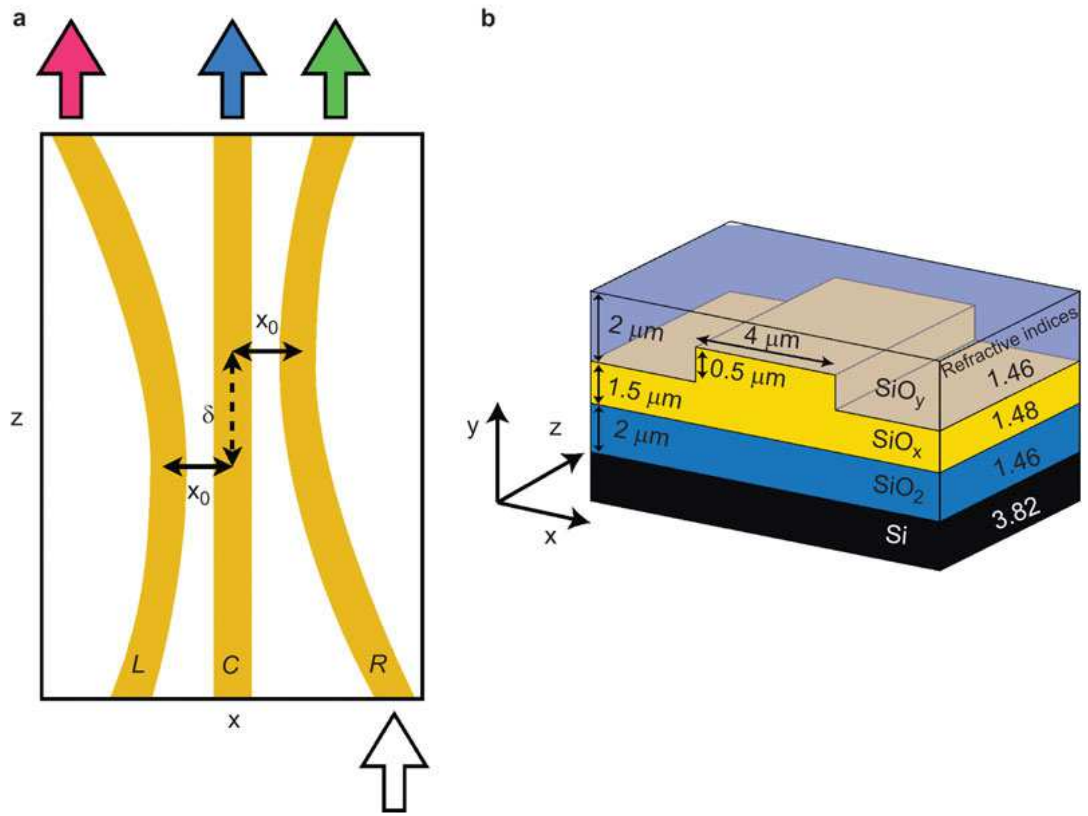
# FROM MATERWAVES TO OPTICAL WAVEGUIDE SYSTEMS

Coherent tunneling by adiabatic passage in an optical waveguide system
S. Longhi, G. Della Valle, M. Ornigotti, and P. Laporta
Phys. Rev. B **76**, 201101(R) (2007)





# Adiabatic Passage of Light in CMOS-Compatible Silicon Oxide Integrated Rib Waveguides.



Adiabatic Passage of Light in CMOS-Compatible Silicon Oxide Integrated Rib Waveguides.
R. Menchon-Enrich  A. Llobera, V. J. Cadarso , J. Mompart, V. Ahufinger
IEEE Photonics Technolopgy Letters. **24**:, 36-538 (2012)

Light spectral filtering based on spatial adiabatic passage
Ricard Menchon-Enrich, Andreu Llobera, Jordi Vila-Planas, Víctor J Cadarso, Jordi Mompart and Veronica Ahufinger
*Light: Science & Applications* (2013) **2**, e90 (2013)

# OUR MOST RECENT RESEARCH IN THIS FIELD

Coherent injecting, extracting, and velocity filtering of neutral atoms in a ring trap via spatial adiabatic passage
Loiko YV, Ahufinger V, Menchon-Enrich R, Birkl G, Mompart J.
European Physical Journal D. 69,147 (2014)

Single-atom interferometer based on two-dimensional spatial adiabatic passage.
Menchon-Enrich R, McEndoo S, Busch T, Ahufinger V, Mompart J. 2014.
Physical Review A. **89** , 053611 (2014)

Tunneling-induced angular momentum for single cold atoms.
Menchon-Enrich R, McEndoo S, Mompart J, Ahufinger V, Busch T.
Physical Review A. **89** 013626 (2014)

2D
three-level
atom optics
for ultracold
atoms

Spatial adiabatic passage processes in sonic crystals with linear defects.
Menchon-Enrich R, Mompart J, Ahufinger V.
Physical Review B. **89** , 094304 (2014)

← RAP for a sonic wave

Blue-detuned optical ring trap for Bose-Einstein condensates based on conical refraction
Turpin A, Polo J, Loiko YV, Küber J, Schmaltz F, Kalkandjiev TK, Ahufinger V, Birkl G, Mompart J.
Optics Express. **23** 1638 (2015)

← Trapping a BEC in a ring

# CONCLUSIONS

Atomic coherence effects in three-level optical systems provides a set of techniques (CPT, EIT, STIRAP) with a huge number of applications.

The extension of these techniques to trapped ultracold atoms coupled via tunneling, i.e., three-level atom optics, is a promising field of research with potential applications in the control of the dynamics of ultracold atoms