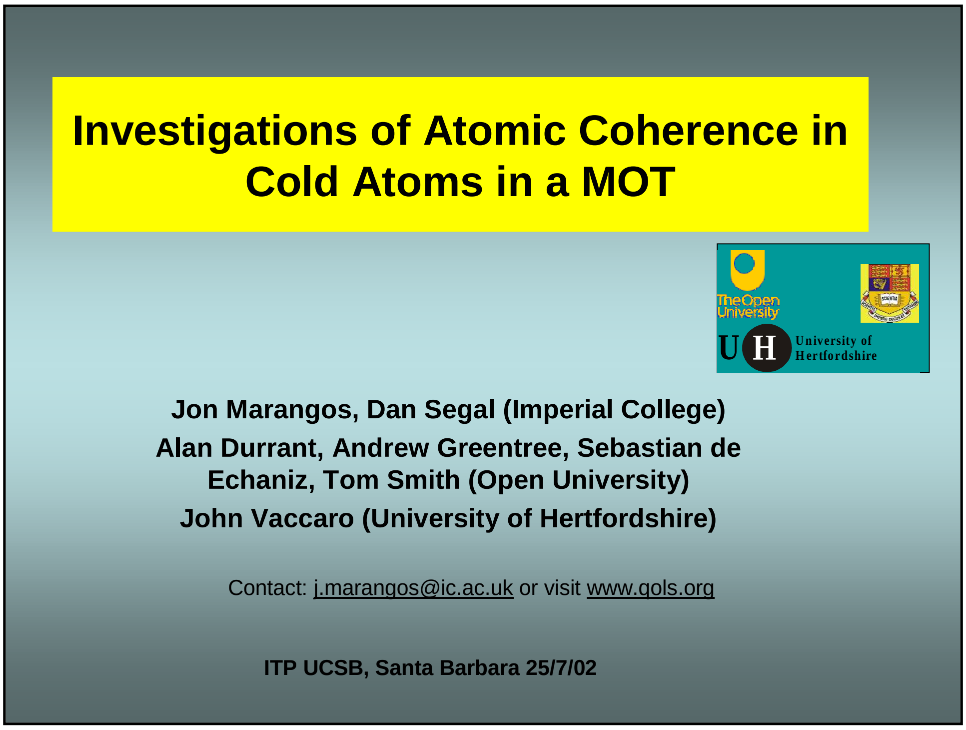

Investigations of Atomic Coherence in Cold Atoms in a MOT

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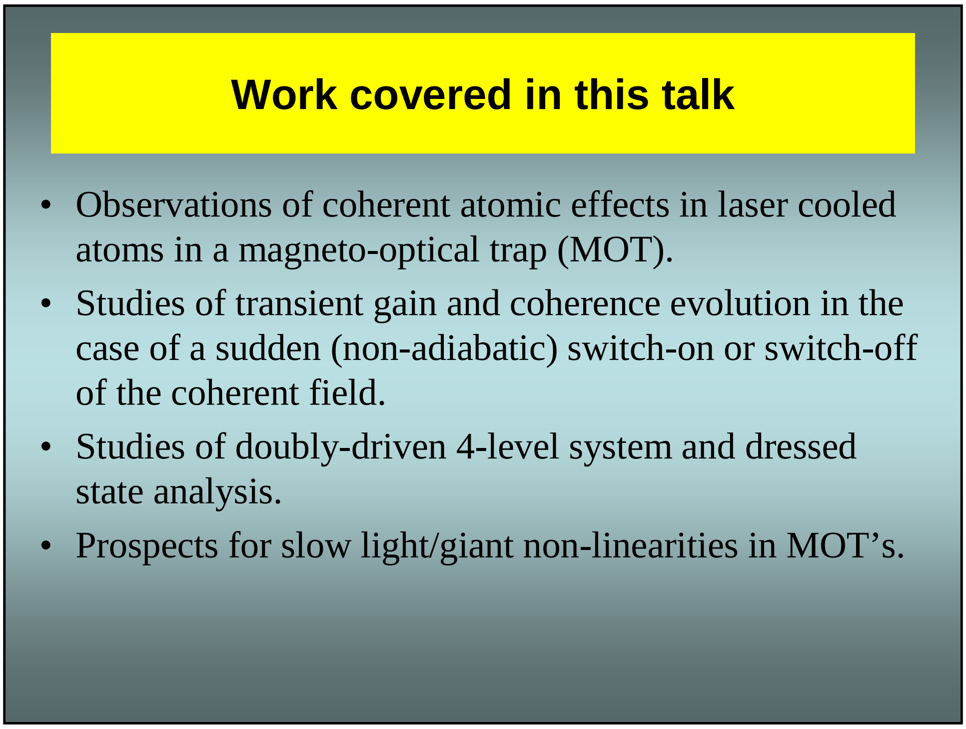
ITP UCSB, Santa Barbara 25/7/02



Work covered in this talk

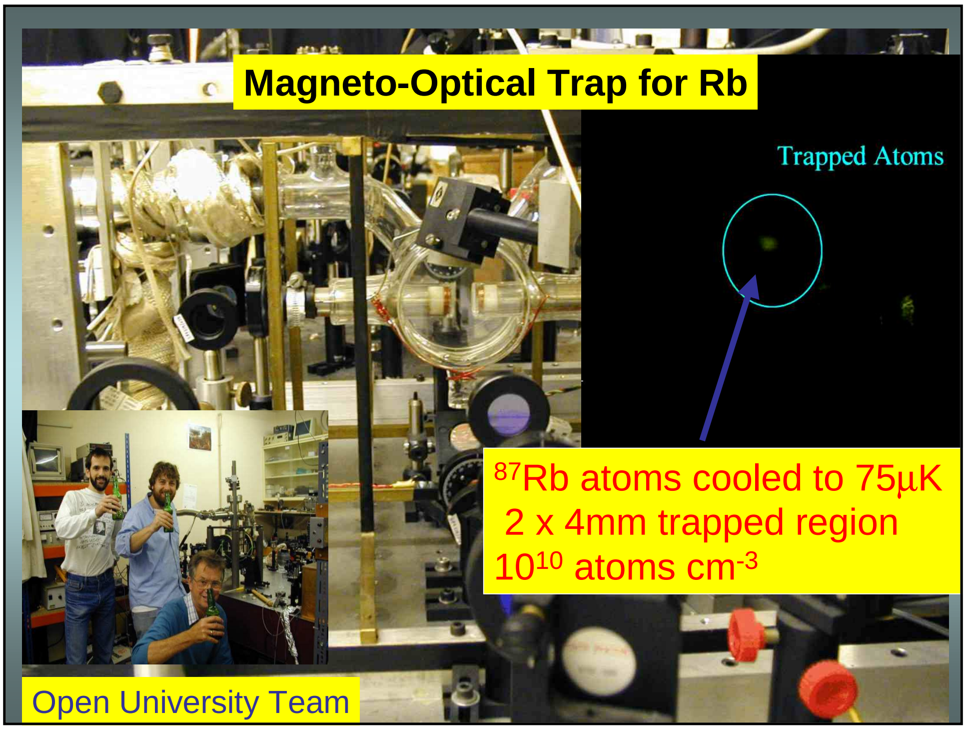
- Observations of coherent atomic effects in laser cooled atoms in a magneto-optical trap (MOT).
- Studies of transient gain and coherence evolution in the case of a sudden (non-adiabatic) switch-on or switch-off of the coherent field.
- Studies of doubly-driven 4-level system and dressed state analysis.
- Prospects for slow light/giant non-linearities in MOT’s.

Some related work on atomic coherence and related effects in MOTS

- Roos et al PRL **85** 5547 (2000) (enhanced Raman side-band cooling by elimination of off-resonance coupling using EIT).
- Aspect et al PRL **61** 826 (1988) (Velocity selective coherent population trapping).
- Cataliotti et al Phys Rev A (1997).
- Van der Veldt et al Opt.Commun. **137** 420 (1997).
- Hau et al, Nature **397** 594 (1999) (group velocities in the cold atoms above T_{crit} were reported at ~100ms^{-1})
- Other groups now working on this topic e.g. Harris et al.

Motivations for this research

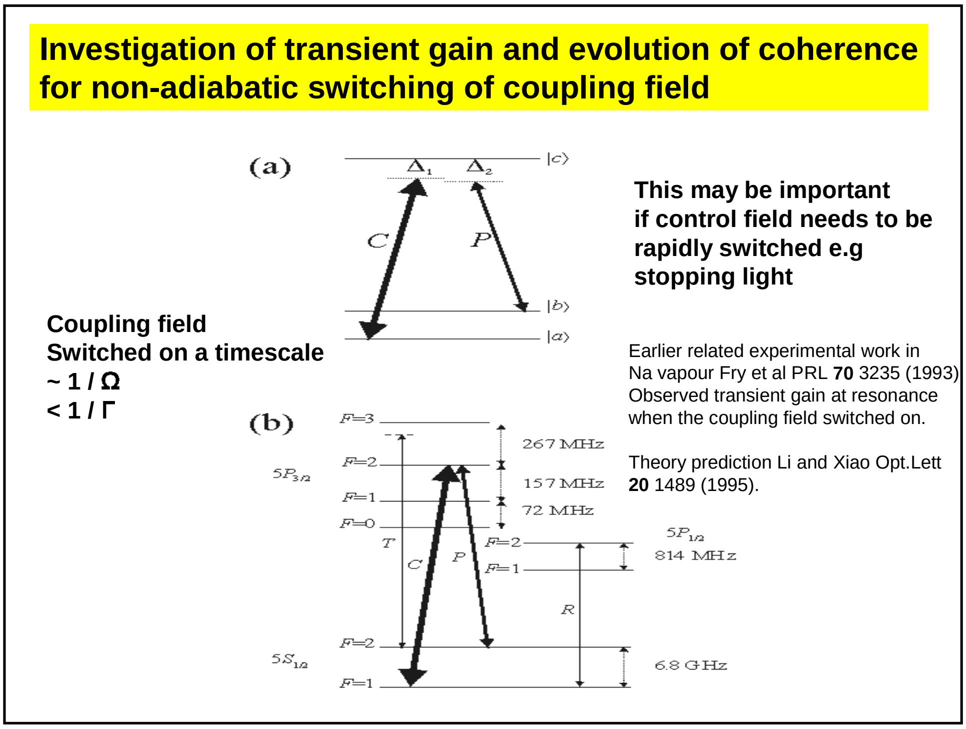
- Investigation of basic atomic coherence (EIT like, dressed states, temporal evolution) in a system free from collisions/atomic motion.
- To understand the effects of non-adiabatic switching of control fields (in the optically thin limit).
- Exploration of prospects for very enhanced non-linearities (Giant Kerr non-linearities, enhanced wave-mixing) in a simple dark-spot MOT.
- Extension of work on slow light from BEC and vapour cell samples.
- Cost of building a MOT <$10k (certainly << cost of BEC), but can be used for non-collinear configurations etc.



Magneto-Optical Trap for Rb

^{87}Rb atoms cooled to 75µK
2 x 4mm trapped region
10^{10} atoms cm^{-3}

Open University Team



Investigation of transient gain and evolution of coherence for non-adiabatic switching of coupling field

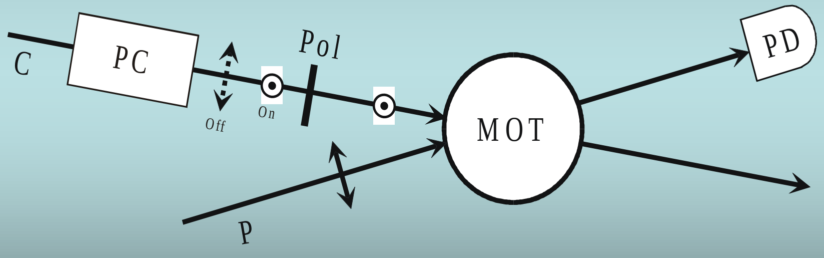
This may be important if control field needs to be rapidly switched e.g stopping light

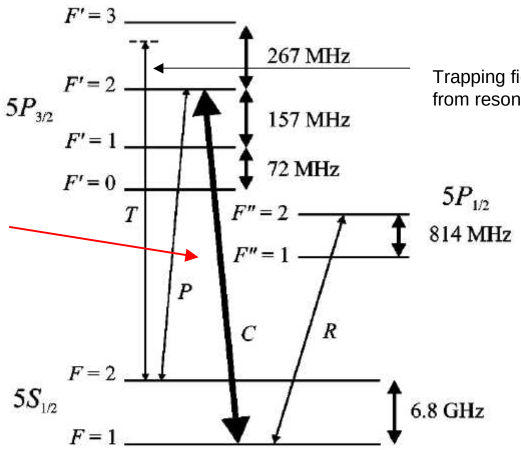
Coupling field
Switched on a timescale
~ 1 / Ω
< 1 / Γ

Earlier related experimental work in Na vapour Fry et al PRL **70** 3235 (1993)
Observed transient gain at resonance when the coupling field switched on.

Theory prediction Li and Xiao Opt.Lett **20** 1489 (1995).

Experimental Set-Up for Non-Adiabatically Switched Control Fields





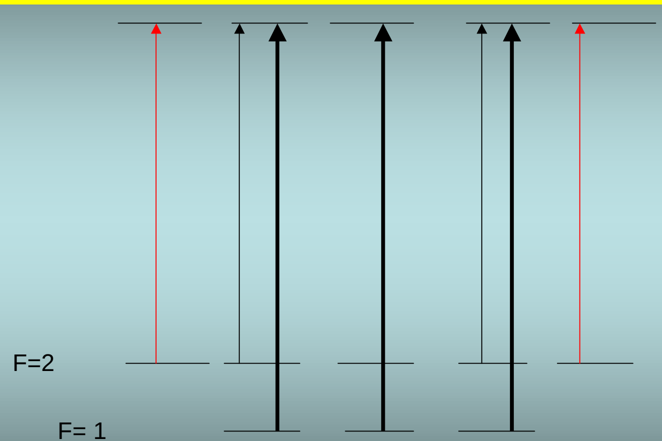
Trapping field detuned -13MHz from resonance.

Field switched using a Pockels cell

T < 5ns

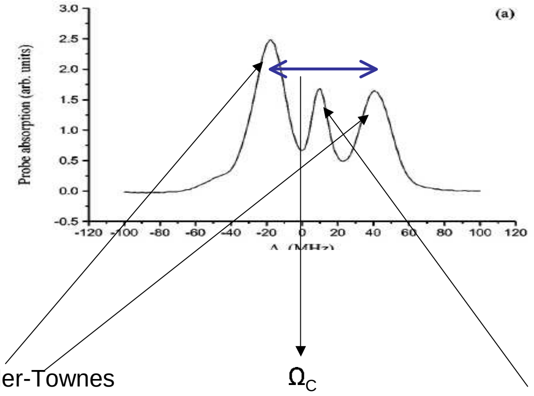
FIG. 1. The ^{87}Rb system in which the experiments are carried out. The atoms are trapped and cooled in a magneto-optical trap by trapping fields T and R. The trapping beams are detuned by -13 MHz from the $F=2$ to $F'=3$ transition of the D_2 line. The probe beam P and the coupling beam C form a Λ EIT system.

In an experimental scheme with π-polarised light there will be some transitions leading to uncoupled absorption that gives a background to the EIT. This is similar to our case.



Full analysis of experimental scheme (Echaniz et al Phys Rev A, 64 013812), show that there are 3 separate Λ schemes and two uncoupled absorptions. The system is analyzed as a simple 3-level system with good qualitative agreement.

Steady-state electromagnetically induced transparency observed in this system



Autler-Townes satellites

Ω_C

Uncoupled absorption masks vanishing absorption

The opacity of the sample is low, gives absorption <50%. Therefore effects observed show coherence and EIT-like effects, but NOT in optically deep medium.

Theoretical modelling of transient effects

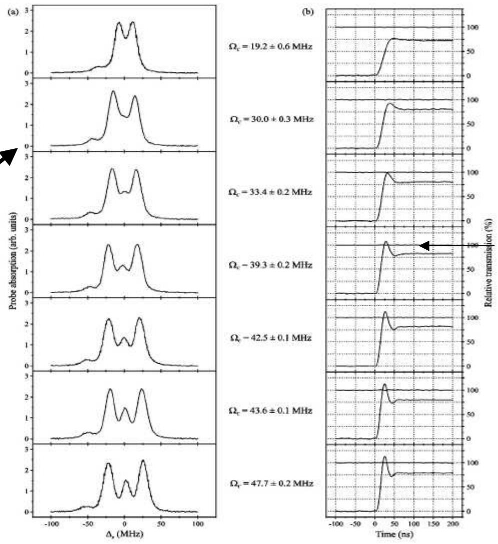
Numerical integration of density matrix equations of motion c.f. Li and Xiao Opt.Lett (1995).

Treated as a 3-level system with known atomic transition moments and field strengths from measured laser parameters.

For modelled results to match the experiments it was important to include an effective spread in probe field detuning to take into account the spatial variation of light shifts due to the Trapping field (still on in these experiments)*

Presence of additional fields in a MOT has important consequences for coherence experiments. In some cases these can be "tuned" out by judicious choice of probe/coupling field. In general experiments should be carried out with trap fields "off".

Resonant turn-on dynamics with coupling field strength



Steady-state data

Transient data

Steady state
EIT like structure
showing uncoupled
Absorption.

Note: Fields tuned
so as to be resonant
with the transitions
in the MOT.

Transient gain observed for Ωc > 40MHz.

Calculations show There is no inversion on the single- photon F'=2 → F=2 or or on Raman transition F=1 → F'=2 → F=2

Numerical and novel analytical treatment

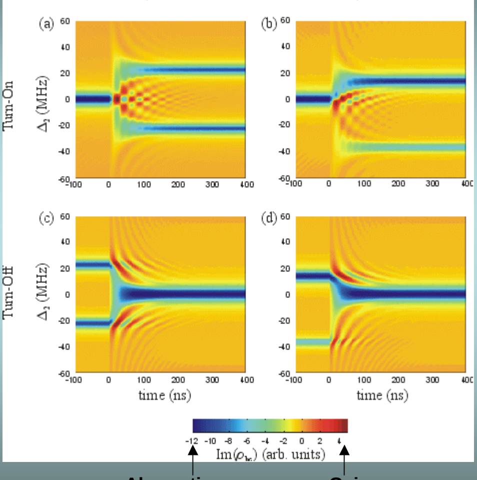
Standard numerical integration of the density matrix equations was used to model the transient results. Also a powerful analytical technique employing the Laplace transform of the complex matrix elements was used and gave Excellent agreement with the numerical results as well as deeper insight.

Both resonant and non-resonant cases needed to be treated. Full analysis for various detuning were needed to compare with experiments. The probe absorption/gain is obtained from $Im\rho_{bc}(t)$.

Turn-on dynamics were modelled numerically, this was required since the system evolves from a simple 2-level to a 3-level system.

Turn-off dynamics could be treated analytically as in this case the evolution is from a 3- to a simple 2-level system.

Theoretical results for turn on and off dynamics

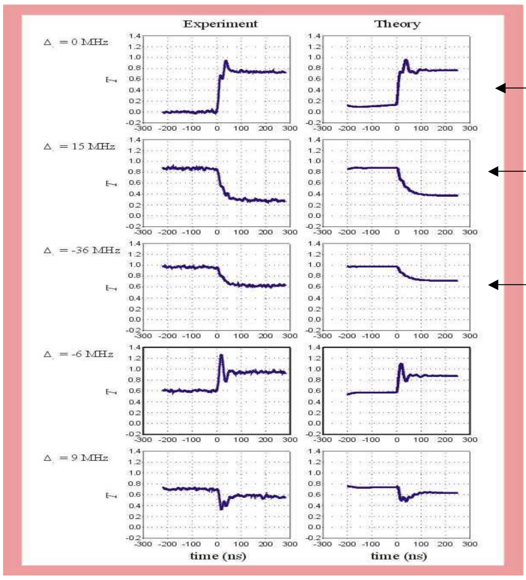


Absorption **Gain**

Detuned coupling field (-23MHz) turn on dynamics

Experiment:

Varying detuning of probe



resonance

major dressed state

minor dressed state

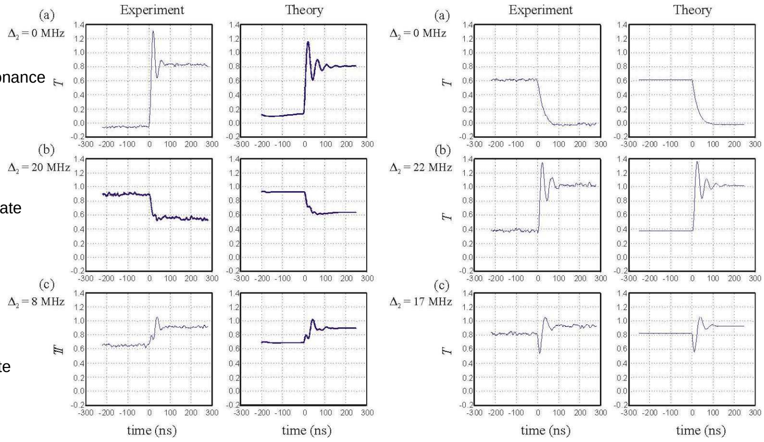
Intermediate detuning

Experiment and theory turn-on and turn-off dynamics

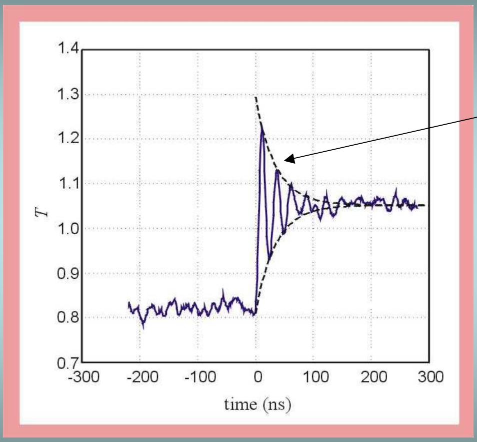
Bare resonance

Dressed state

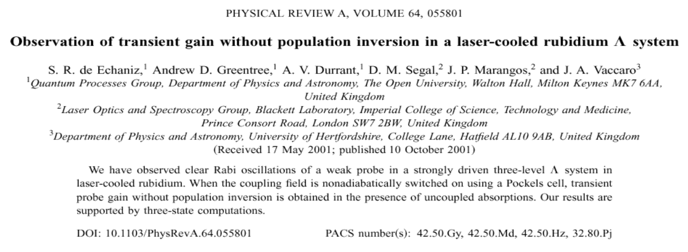
intermediate



Turn-off dynamics at dressed state (experiment)



Spontaneous decay matches observed damping


PHYSICAL REVIEW A, VOLUME 64, 055801

Observation of transient gain without population inversion in a laser-cooled rubidium Λ system

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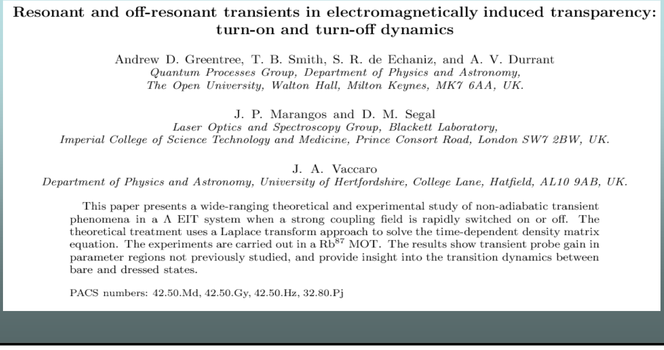
(Received 17 May 2001; published 10 October 2001)

We have observed clear Rabi oscillations of a weak probe in a strongly driven three-level Λ system in laser-cooled rubidium. When the coupling field is nonadiabatically switched on using a Pockels cell, transient probe gain without population inversion is obtained in the presence of uncoupled absorptions. Our results are supported by three-state computations.

DOI: 10.1103/PhysRevA.64.055801 PACS number(s): 42.50.Gy, 42.50.Md, 42.50.Hz, 32.80.Pj

PRA **65** 053802 (2002)



Resonant and off-resonant transients in electromagnetically induced transparency: turn-on and turn-off dynamics

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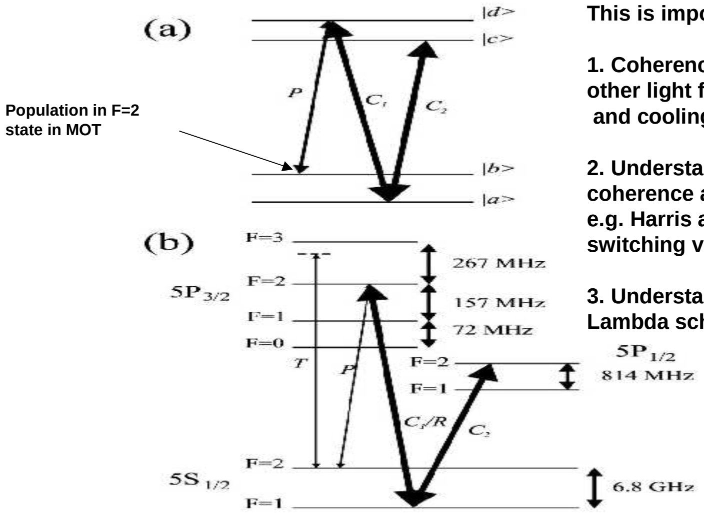
This paper presents a wide-ranging theoretical and experimental study of non-adiabatic transient phenomena in a Λ EIT system when a strong coupling field is rapidly switched on or off. The theoretical treatment uses a Laplace transform approach to solve the time-dependent density matrix equation. The experiments are carried out in a Rb^{87} MOT. The results show transient probe gain in parameter regions not previously studied, and provide insight into the transition dynamics between bare and dressed states.

PACS numbers: 42.50.Md, 42.50.Gy, 42.50.Hz, 32.80.Pj

Understanding the dressed states in doubly-driven 4-level systems



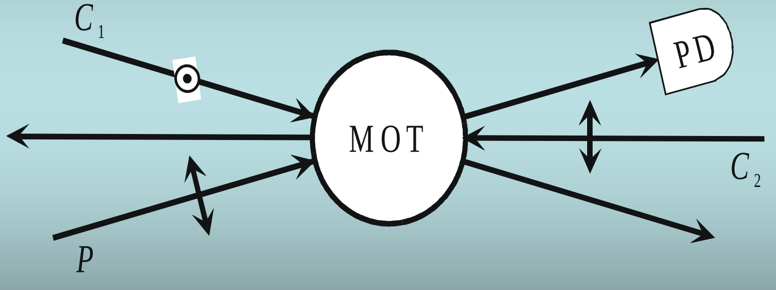
This is important for:

1. Coherence in a MOT when other light fields for trapping and cooling may be present.

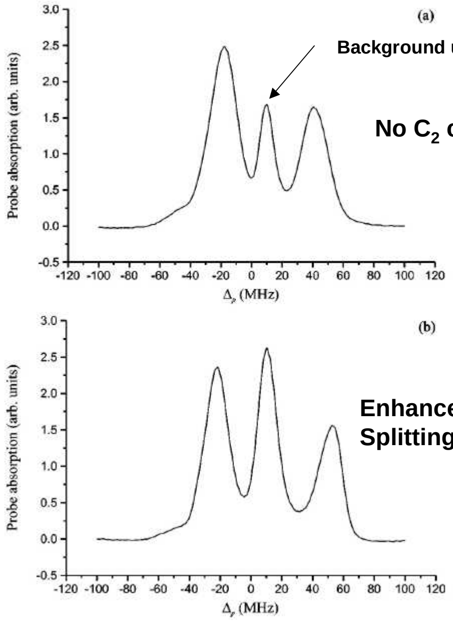
2. Understanding N-system coherence and cross-correlations e.g. Harris and Yamamoto photon switching via non-linear abs.

3. Understanding fwm in double Lambda scheme

Set-up for doubly driven experiments



Polarisation choice to minimize uncoupled absorption. Coupling beams ~300mW/cm^2 , probe ~ 2mW/cm^2.



Background uncoupled absorption

No C_2 coupling

Enhanced absorption and Splitting with C_2 on

Theoretical treatment of doubly-driven 4-level system

This was treated as a V system coupled to two strong fields C_1 and C_2 and probed From a 4th level by a weak field.

Hamiltonian of the form:

$$H = \begin{bmatrix} \Delta_1 & \Omega_2/2 & \Omega_1/2 \\ \Omega_2/2 & \Delta_1 - \Delta_2 & 0 \\ \Omega_1/2 & 0 & 0 \end{bmatrix}$$

Doubly dressed energies and dressed state vectors can be derived from this. In the case of resonance $\Delta_1 = \Delta_2 = 0$ the dressed state energies are:

$$E_1 = \frac{1}{2}\sqrt{\Omega_1^2 + \Omega_2^2}$$

$$E_2 = 0$$

$$E_3 = -\frac{1}{2}\sqrt{\Omega_1^2 + \Omega_2^2}$$

Theoretical treatment of doubly-driven 4-level system

There are 3-dressed states

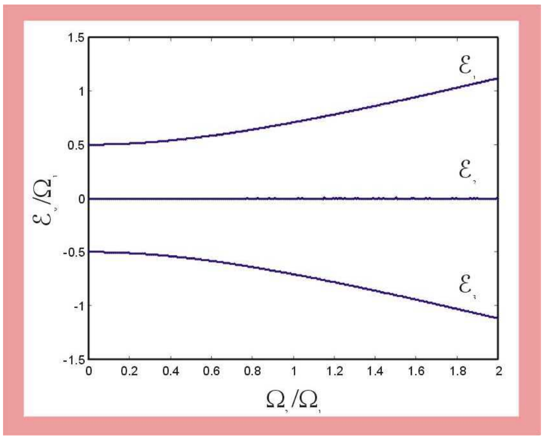
$|D_1>$, $|D_2>$ and $|D_3>$.

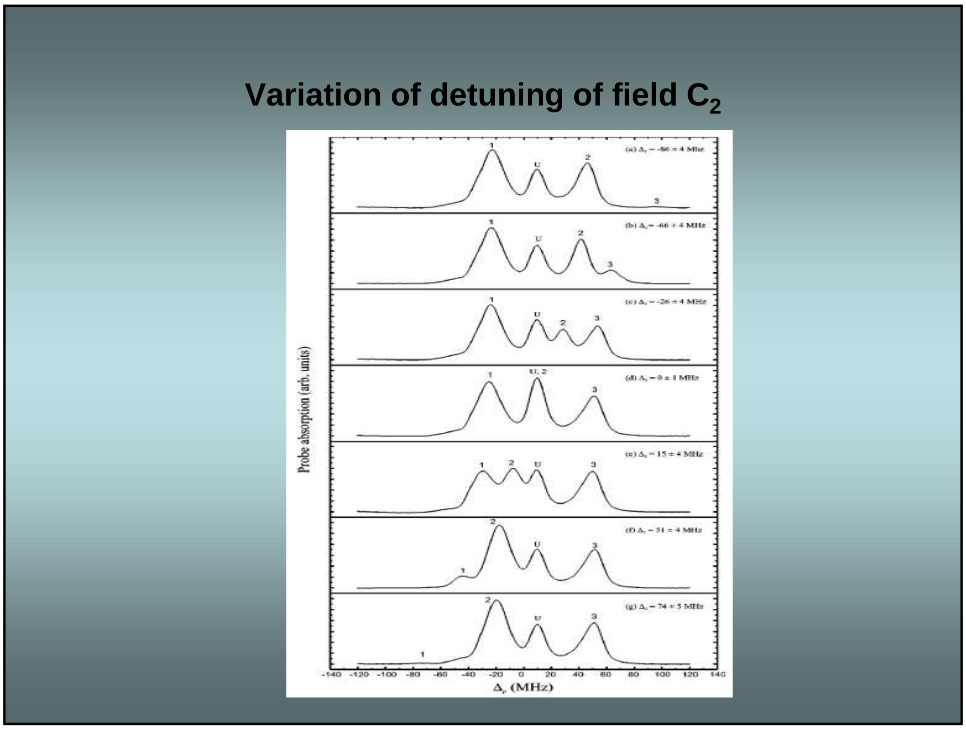
The outer dressed states $|D_1>$ and $|D_3>$ dominate when if $\Omega_1/\ \Omega_2>>1$.

The inner dressed state $|D_2>$ dominates when $\Omega_1/\ \Omega_2<<1$.

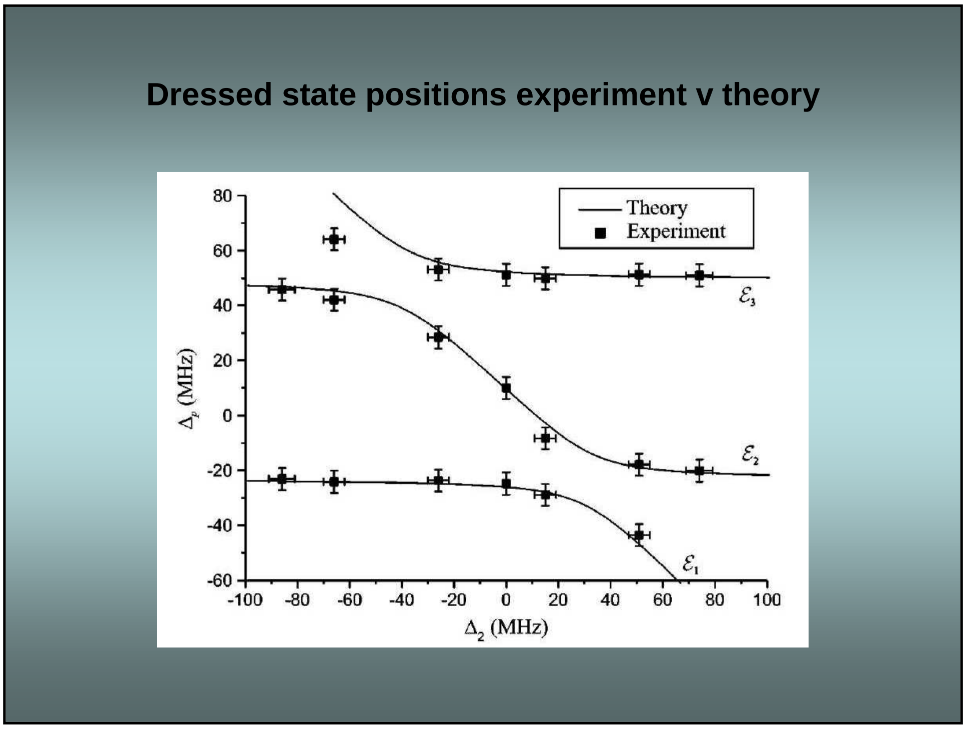
In general treated for detunings that are non-zero, positions of the 3 dressed states shift as the coupling field is tuned.

Dressed state energies as a function of coupling field strength ratio



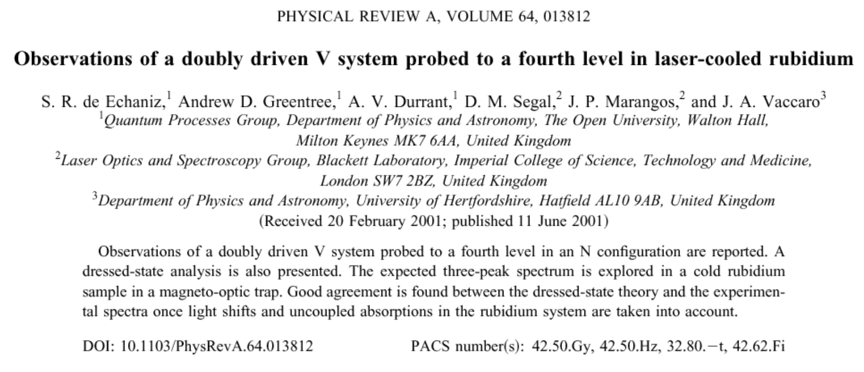


Variation of detuning of field C_2



Dressed state positions experiment v theory

Understanding the dressed states in doubly-driven 4-level systems



PHYSICAL REVIEW A, VOLUME 64, 013812

Observations of a doubly driven V system probed to a fourth level in laser-cooled rubidium

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(Received 20 February 2001; published 11 June 2001)

Observations of a doubly driven V system probed to a fourth level in an N configuration are reported. A dressed-state analysis is also presented. The expected three-peak spectrum is explored in a cold rubidium sample in a magneto-optic trap. Good agreement is found between the dressed-state theory and the experimental spectra once light shifts and uncoupled absorptions in the rubidium system are taken into account.

DOI: 10.1103/PhysRevA.64.013812 PACS number(s): 42.50.Gy, 42.50.Hz, 32.80.−t, 42.62.Fi

Summary of work on atomic coherence in MOT

1. MOT's can be an ideal systems for studying dressed states.
2. Care must be taken to account for the effects of other electromagnetic fields in the trapping phase of the MOT.
3. Transient gain without inversion has been studied.
4. A detailed understanding of population evolution amongst the dressed states has been obtained.
5. 4-level systems with two strong driving fields have been studied as a precursor to studying the 4-level N scheme in the few photon limit.

What Next?
Slow light and giant non-linearities in a MOT!

- Need larger densities so that opacity high. [Dark spot MOT]

- Schemes with no uncoupled absorption. [F=1 populated state in dark-spot].

- Phase-locking between lasers. Derive probe and coupling laser from common source. [must minimize two-photon dephasing to achieve very sharp EIT]

Atomic media for slow-light experiments

● BEC

In Na BEC N=3x10^{12}cm^{-3}, T=450nK (10^{12}cm^{-3} just above critical temperature) L=250μm.

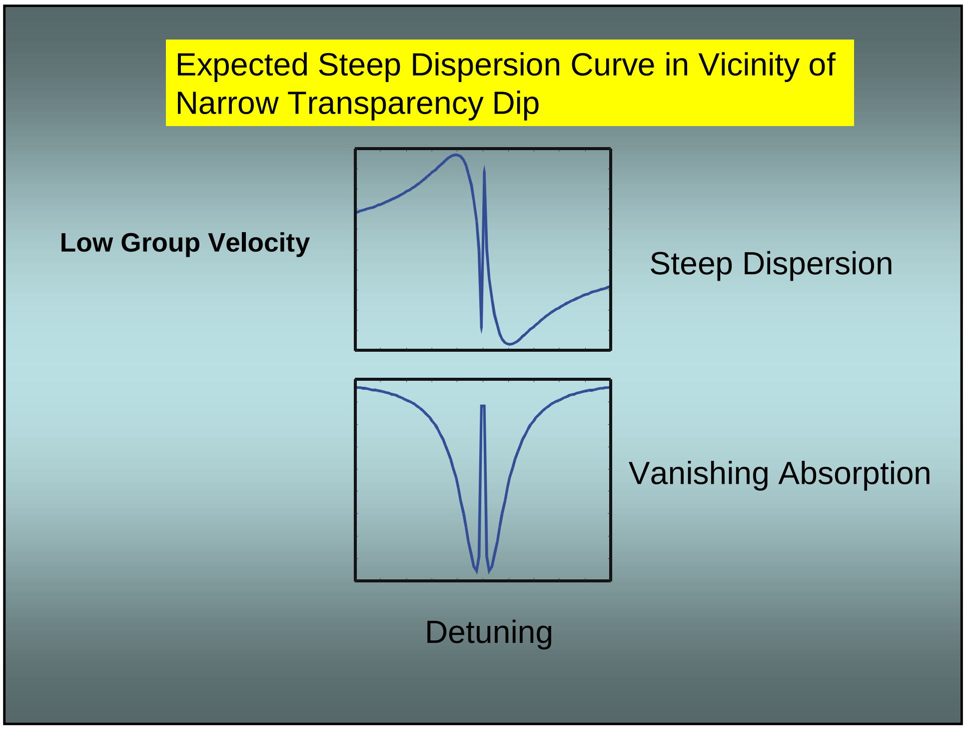
● “Hot” Vapour

N> 10^{12}cm^{-3}, T>300K and L>2cm (could be much longer).

● MOT

Standard MOT – N~2x10^{10}cm^{-3}, T=75μK, L=5mm

Dark SPOT- N>10^{11}cm^{-3}, T=50μK, L>10mm (also easier to realise schemes without uncoupled absorption in ^{87}Rb).



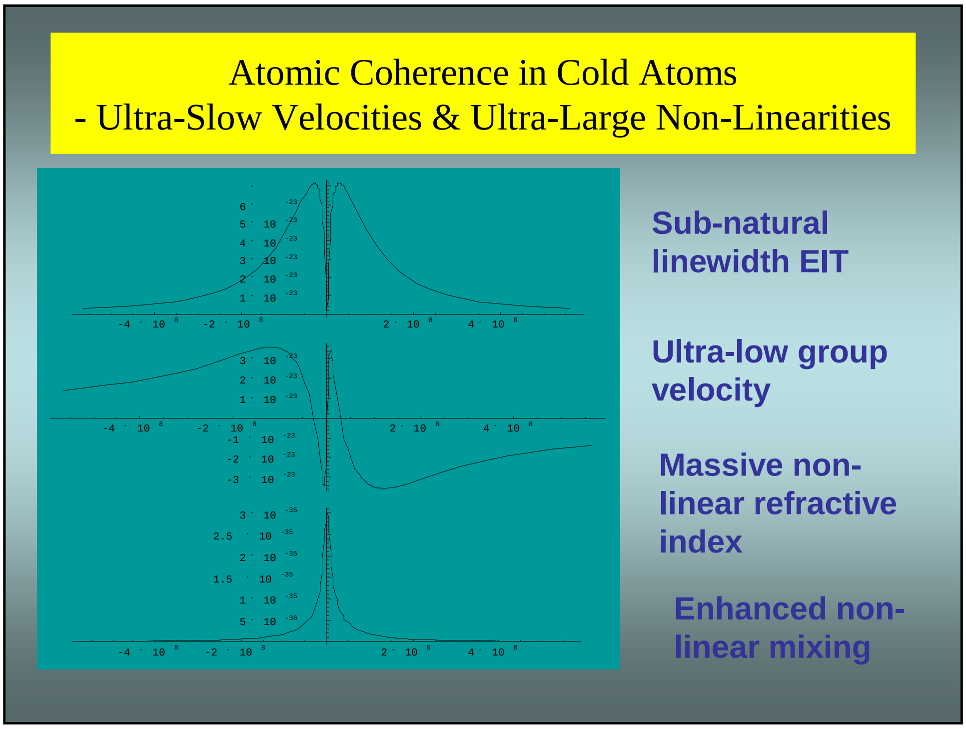
Expected Steep Dispersion Curve in Vicinity of Narrow Transparency Dip

Low Group Velocity

Steep Dispersion

Vanishing Absorption

Detuning



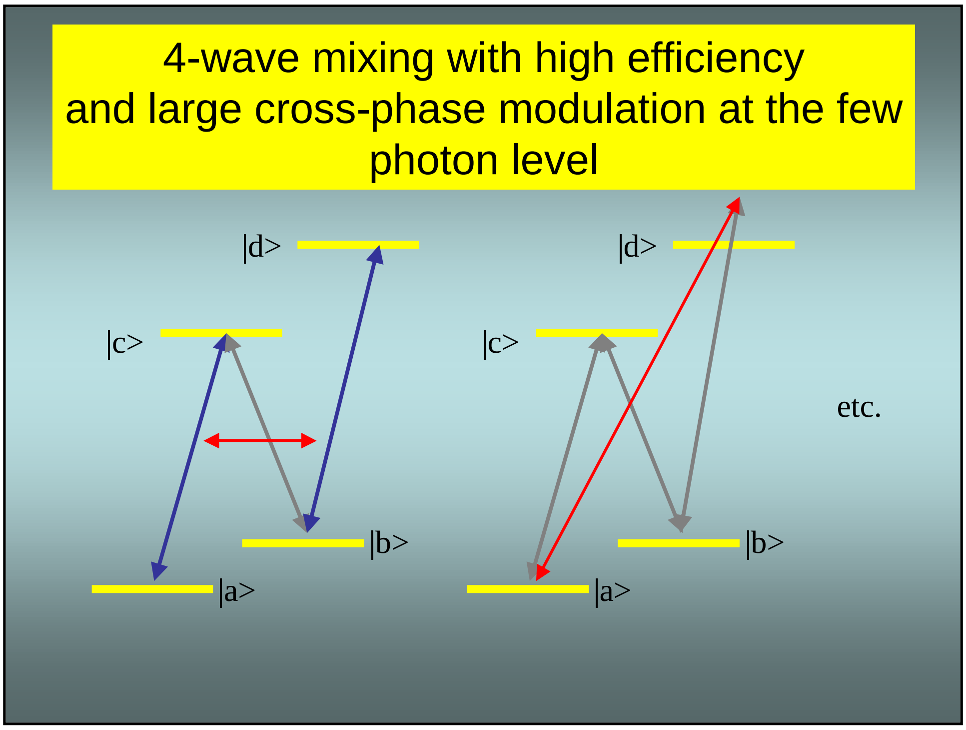
Atomic Coherence in Cold Atoms - Ultra-Slow Velocities & Ultra-Large Non-Linearities

Sub-natural linewidth EIT

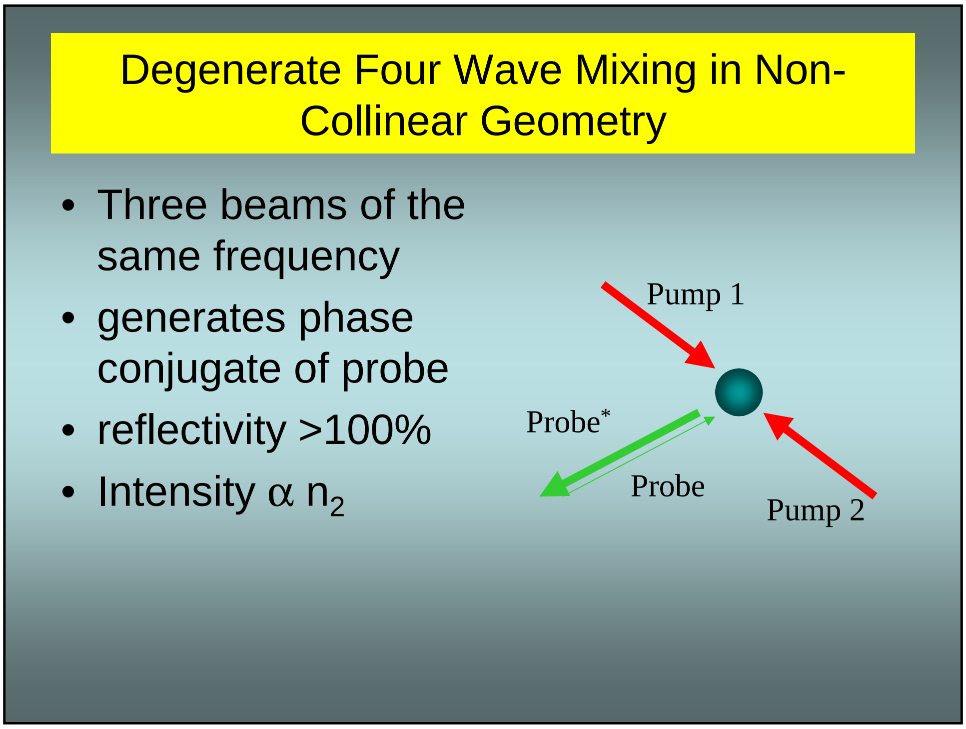
Ultra-low group velocity

Massive non-linear refractive index

Enhanced non-linear mixing

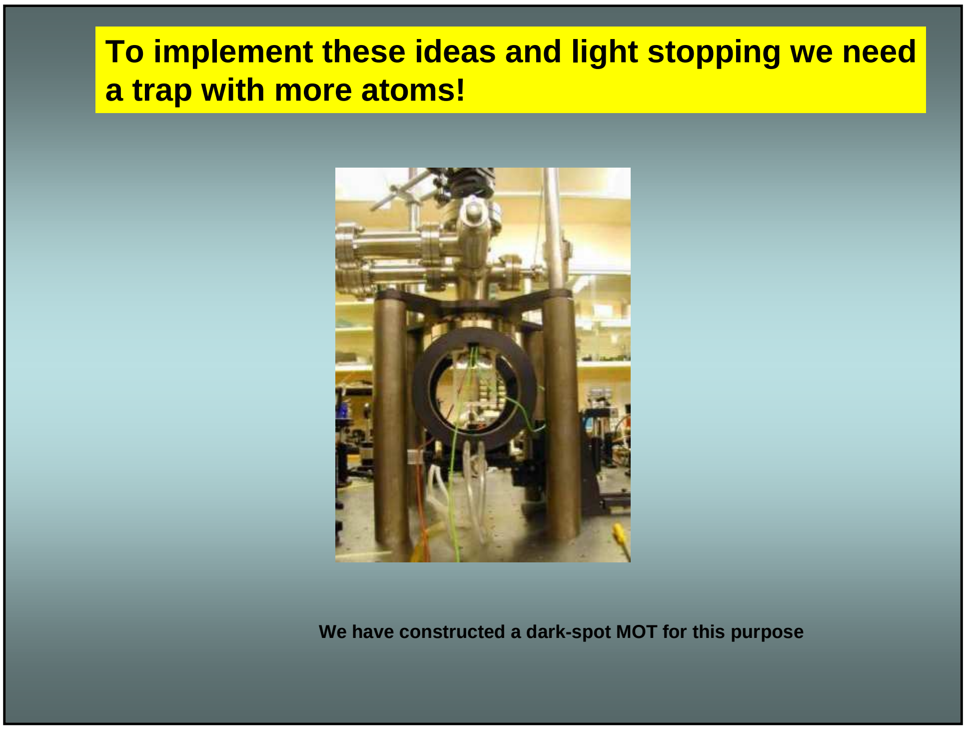


4-wave mixing with high efficiency and large cross-phase modulation at the few photon level



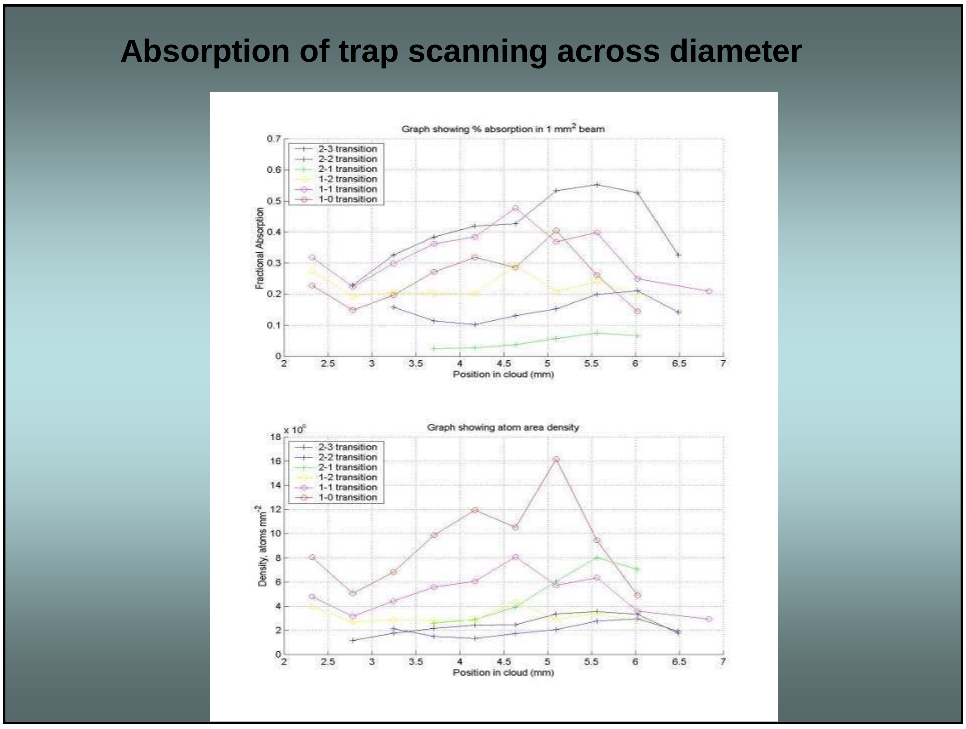
Degenerate Four Wave Mixing in Non-Collinear Geometry

- Three beams of the same frequency
- generates phase conjugate of probe
- reflectivity >100%
- Intensity α n_2

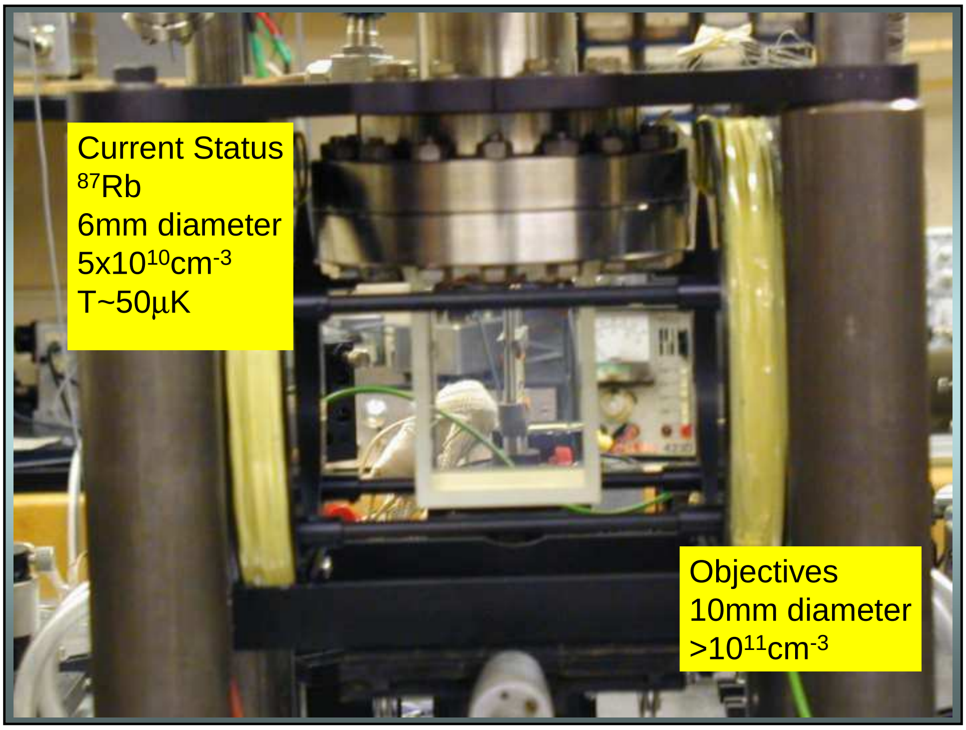


To implement these ideas and light stopping we need a trap with more atoms!

We have constructed a dark-spot MOT for this purpose



Absorption of trap scanning across diameter



Current Status
^{87}Rb
6mm diameter
$5\times10^{10}\,\mathrm{cm}^{-3}$
T~50µK

Objectives
10mm diameter
$>10^{11}\,\mathrm{cm}^{-3}$

Conclusions

- Laser cooled atoms in an MOT are a good medium to study atomic coherence phenomena.
- The optical and magnetic fields for trapping should be switched off for ideal results, but the effects of light shifts can be “tuned-out” to an extent.
- With higher densities in dark SPOT traps slow light, light storage and large non-linearity should be possible to study.