THE UNIVERSITY OF QUEENSLAND
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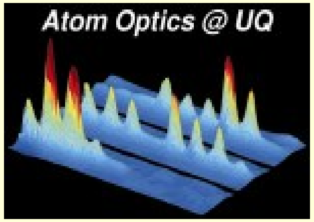
UQ experimental QAO program

Norman Heckenberg



ARC Program Grant 2003-7

- Quantum Atom Optics and Single Atom Detection with Micro-Bose-Einstein Condensates

- Micro-BEC
- Quantum atom optics
- Atom detection and counting

C1

UQ BEC Team

- **Staff**
  - Prof H. Rubinsztein-Dunlop
  - A/Prof N. Heckenberg
  - Prof G. Milburn
  - Dr. C. Holmes
  - Dr. M. Davis
  - Dr Chris Vale
- **Students**
  - Adrian Ratnapala
  - Stuart Holt
  - Tom Campey
  - Otto Vainio
- **Former Members/Visitors**
  - Ben Upcroft
  - Martin Lenz
  - Greg Kocuiba
  - Mirek Walkiewicz
  - Jozsef Fortagh
  - Sean Drake
  - Doug Turk

Slide 3

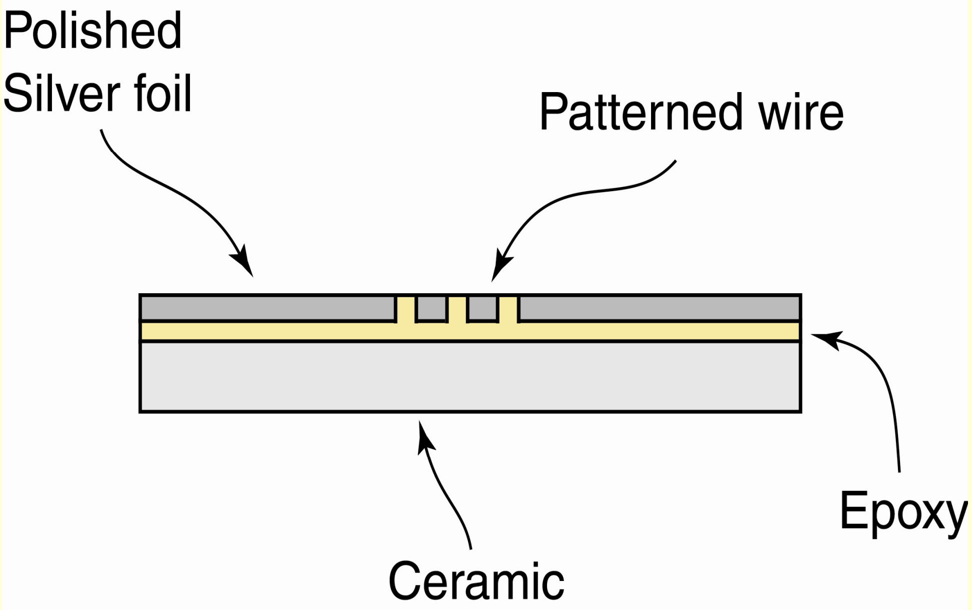
C1 Vale, 9/03/2003

Micro-BEC = Atom Chips

- Atom optics - Control and manipulation of atomic deBroglie waves
- **Atom Chips**: Allow us to place atom optical elements very close to a BEC.
- main advantages:
    - o "Easy" to produce BECs (lower currents)
    - o Tight and complex trapping potentials
    - o Integration with optics, electronics etc?

UQ Atom Chip

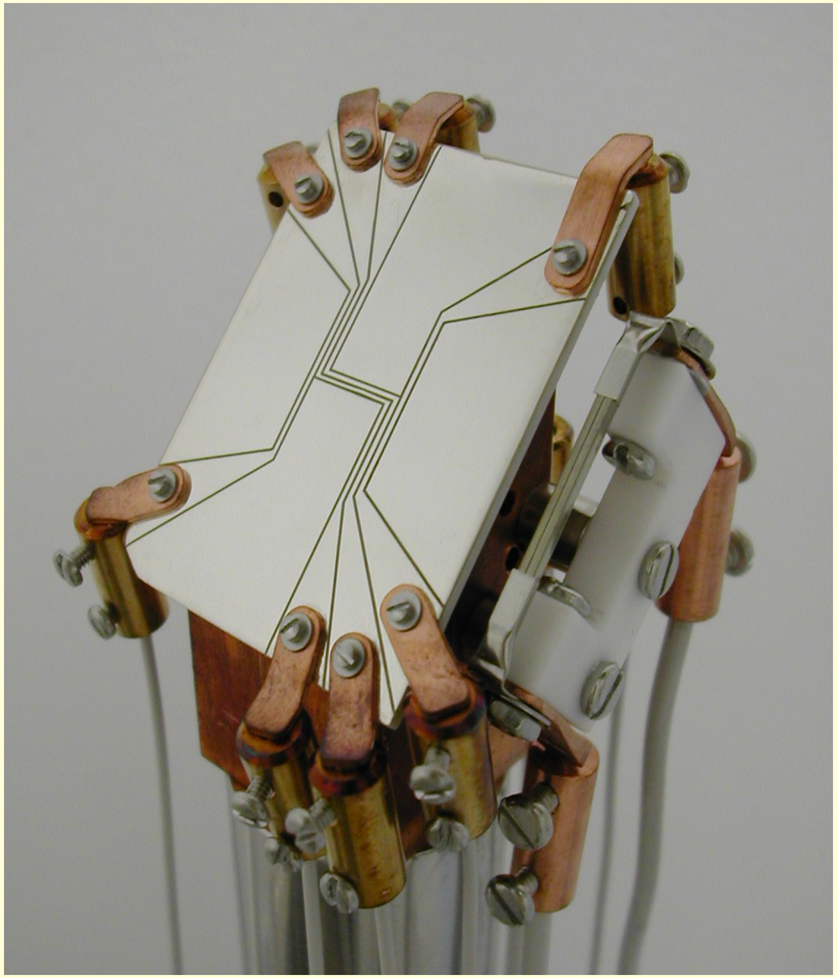
- A silver foil (125 μm) glued to a ceramic substrate.



- Silver polished to mirror finish (thickness ≈ 90 μm).
- All materials UHV compatible.

UQ Atom Chip

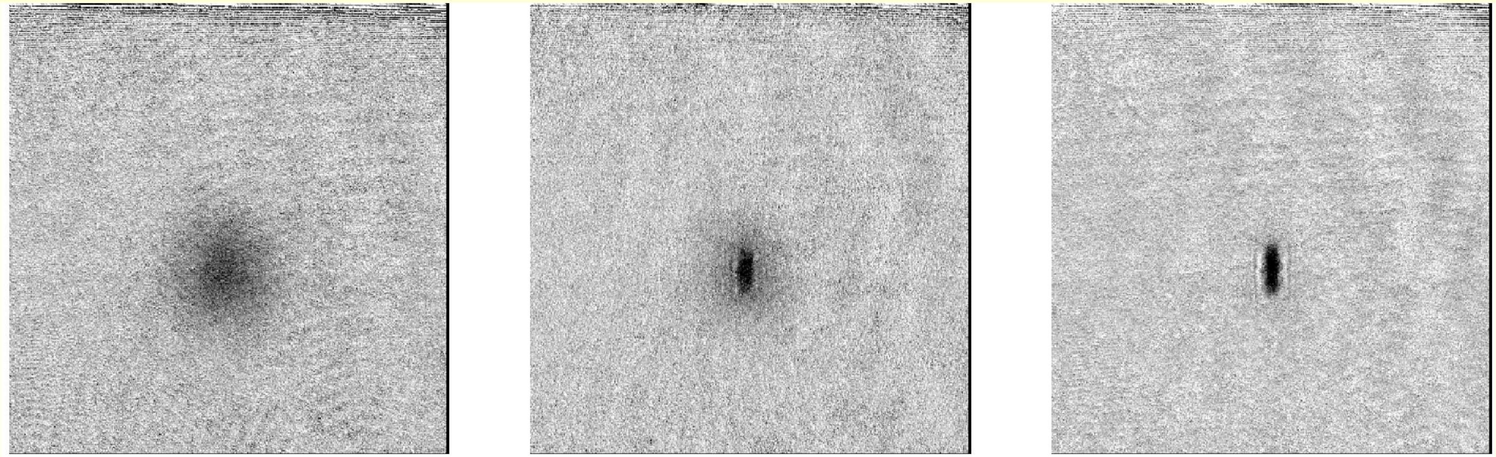
- Wires patterned with a micro-cutter (150 μm diameter).
- Electrical connections made with copper tabs screwed onto chip.
- Mirror surface for MOT.
- Z- Wires for magnetic trap.



CJV *et al.*, J. Phys B **37**, 2959 (2004)

^{87}Rb BEC

- ~ 4 X 10^4 atoms
- T = 200 nanoK
- View after expansion



N = 2 X 10^5
T = 700nK
Thermal Cloud

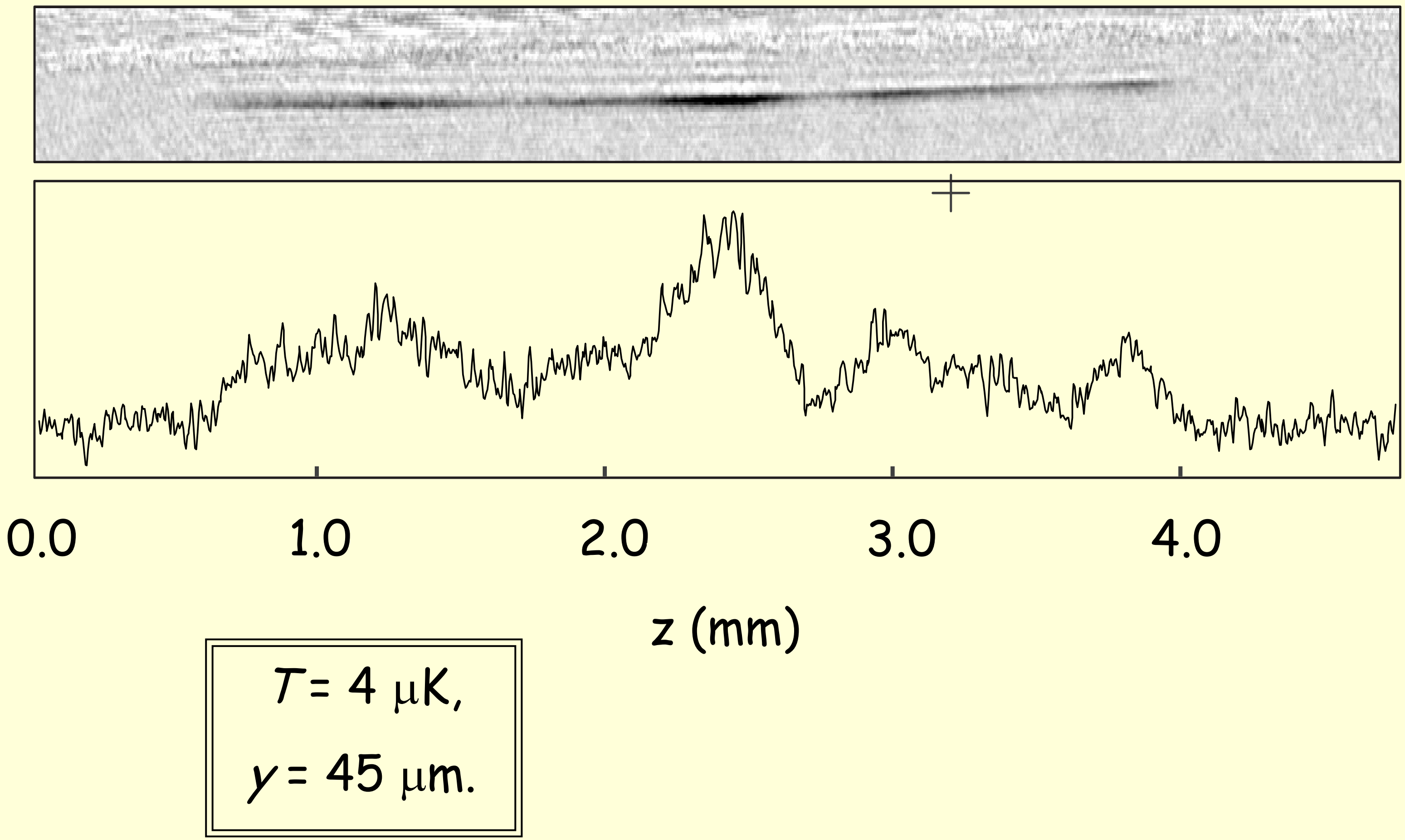
N = 8 X 10^4
T = 450 nK
Partial BEC

N_0 = 4 X 10^4
T = 200 nK
Almost Pure BEC

CJV *et al.*, J. Phys B **37**, 2959 (2004)

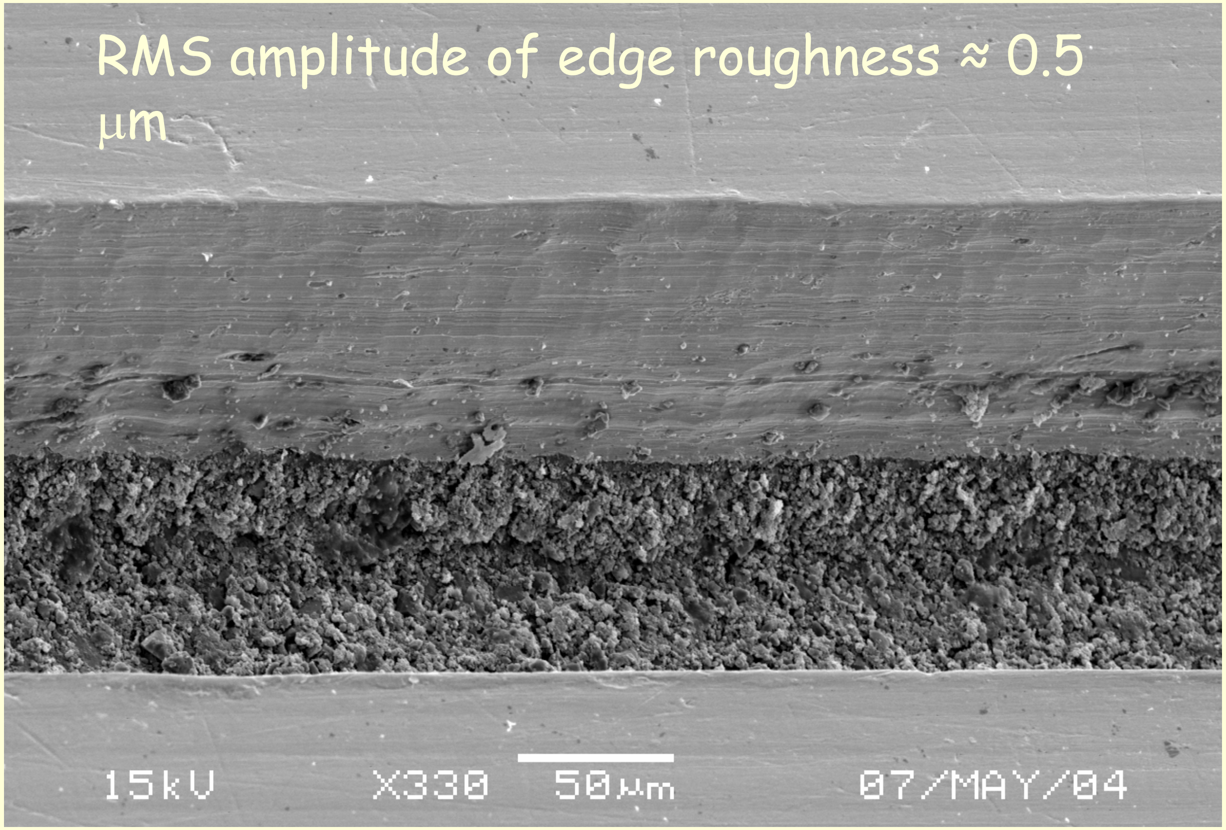
Fragmentation

- When very cold atom clouds are brought very close to a conducting wire the cloud fragments into lumps.



Fragmentation

- If the conductor is not perfectly straight…



- Our fragmentation appears to be due to edge roughness.

Fire in an air duct…

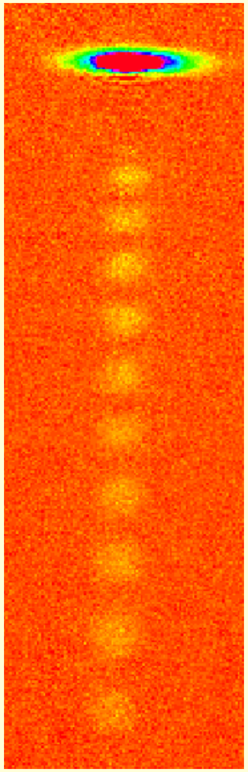
- Experiment not burnt, but covered in soot

Shifted to a new building…

Interfering/ Beating Atom Lasers

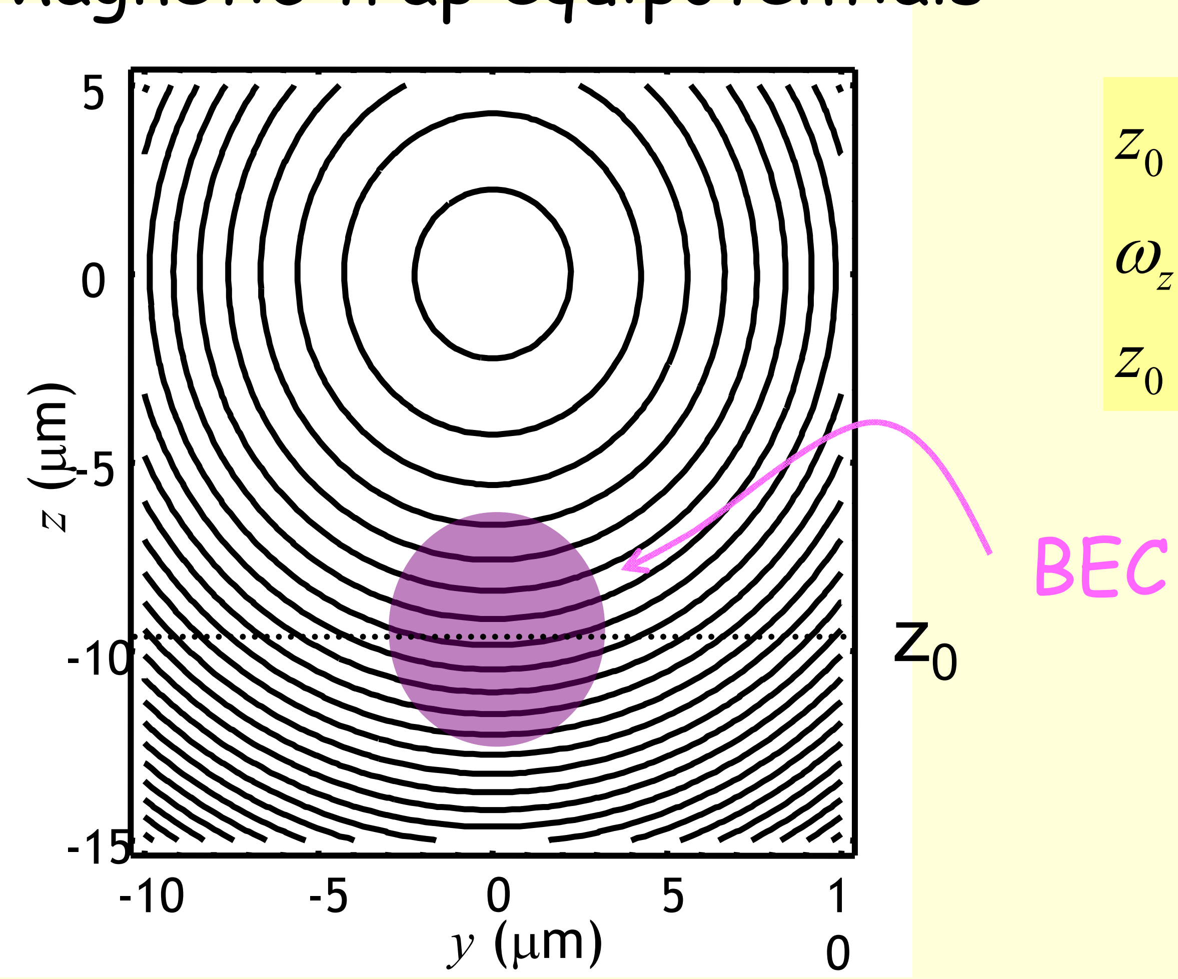
Otto Vainio &Chris Vale

- Dual output atom laser
- Bloch, Hänsch and Esslinger (2000)
- RF outcoupling with 2 frequencies



Trapped BEC - Gravitational Sag

Magnetic trap equipotentials

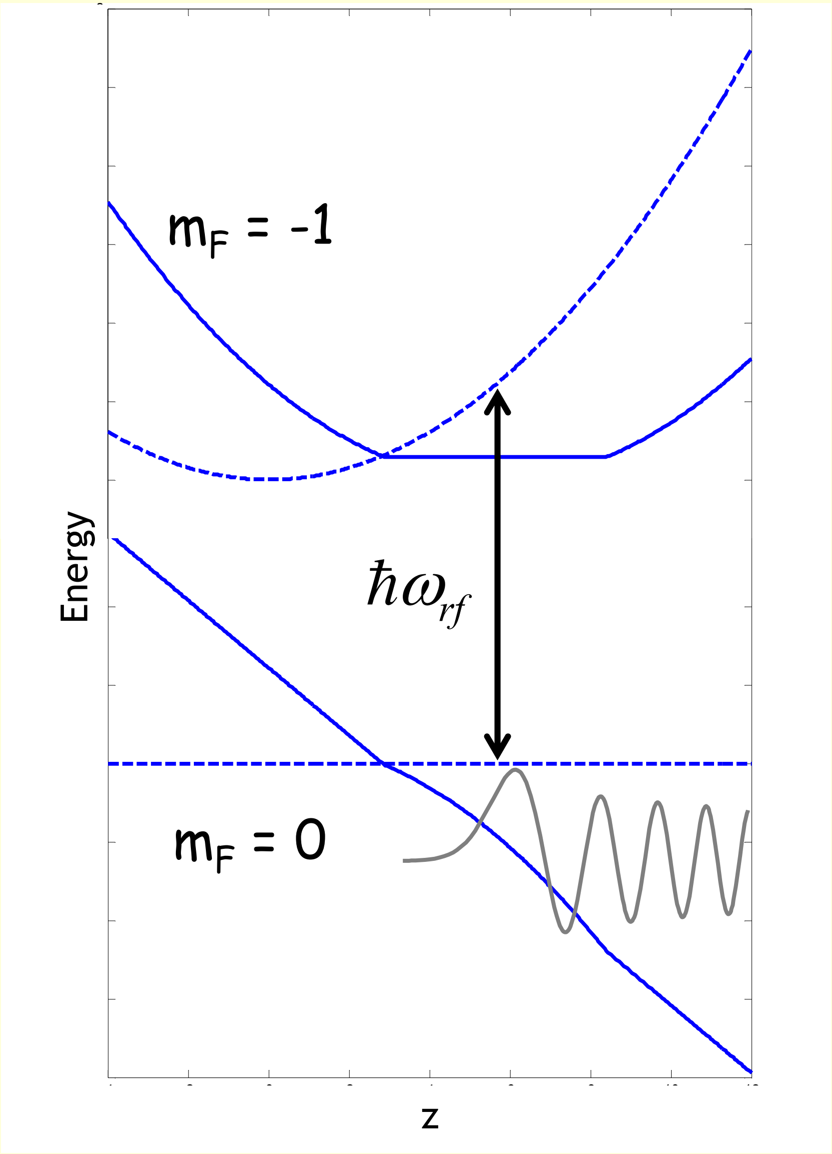


$$z_0 = -g / \omega_z^{\ 2}$$

$$\omega_z = 2\pi \times 160\,\mathrm{s}^{-1}$$

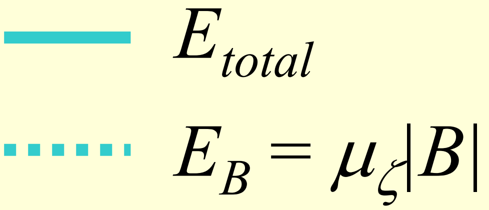
$$z_0 = 9.7\ \mu\mathrm{m}$$

RF Outcoupling

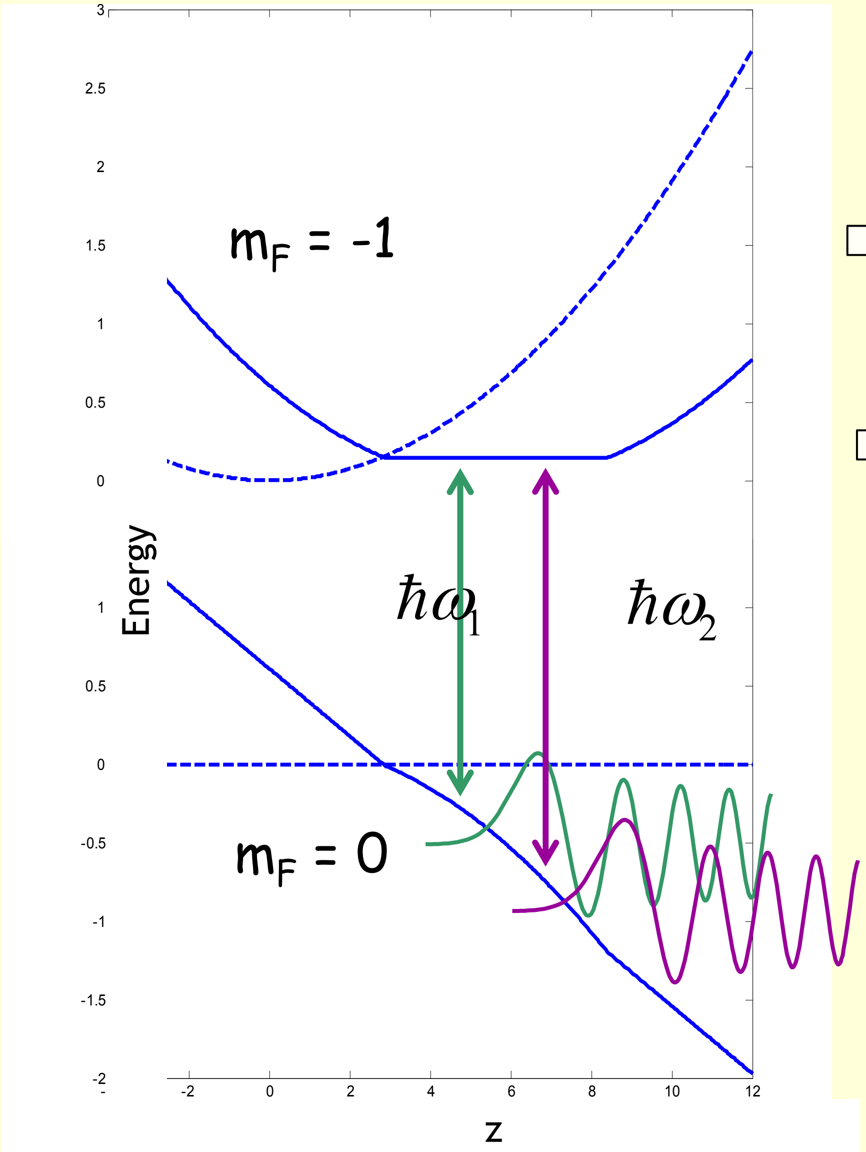


- Outcouple atoms from points which satisfy resonant condition:

$$\hbar\omega_{rf} = \mu_B g_F |B(z)|$$



Outcoupling with Two RF Fields



Two rf fields

⇨ Two resonant points/surfaces/regions

⇨ Two outcoupled beams

Interfere or beat

E_{total}

$E_B = \mu_\zeta |B|$

Previous work

- Bloch, Esslinger and Hänsch (2000) measured spatial coherence of BEC under the condition:

$$\Delta E_{rf} = \hbar(\omega_1 - \omega_2) = mg\Delta z$$

- Gravitational energy difference is exactly equal to the energy difference between the two RF fields
- 1-D Analysis in terms of spatial interference
- Condition not general - true only when the outcoupling points are centred around z_0

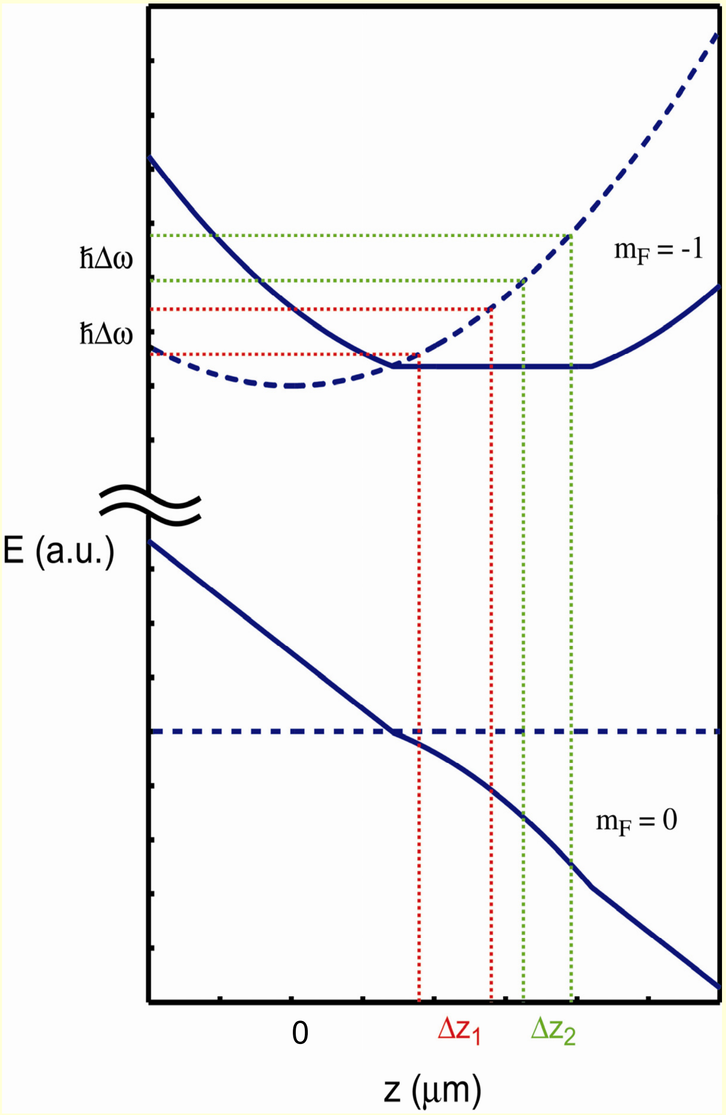
More generally…

- However, in a harmonic trap:

$$|B(z)| \propto z^2$$

- Therefore, the spacing between outcoupling heights is not fixed

$$\Delta z \propto \frac{\Delta\omega_{rf}}{z_{oc}}$$



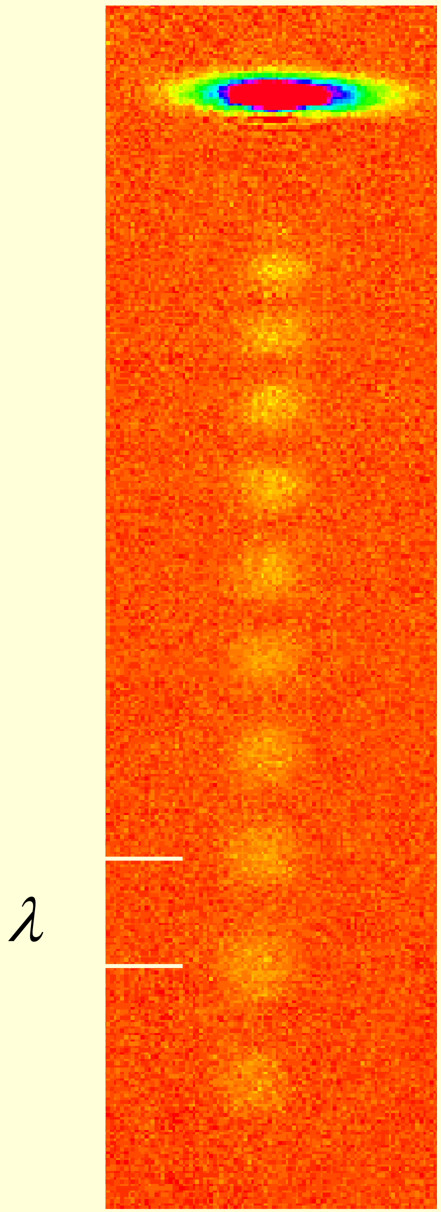
But this does not change the fringe spacing

- The energy difference between the two allowed paths is always:

$$\Delta E_{total} = \hbar \Delta \omega_{rf}$$

- So the fringe spacing is:

$$\lambda(z) = \frac{\sqrt{2g(z - z_0)}}{\Delta f_{rf}}$$



Alternative Interpretation

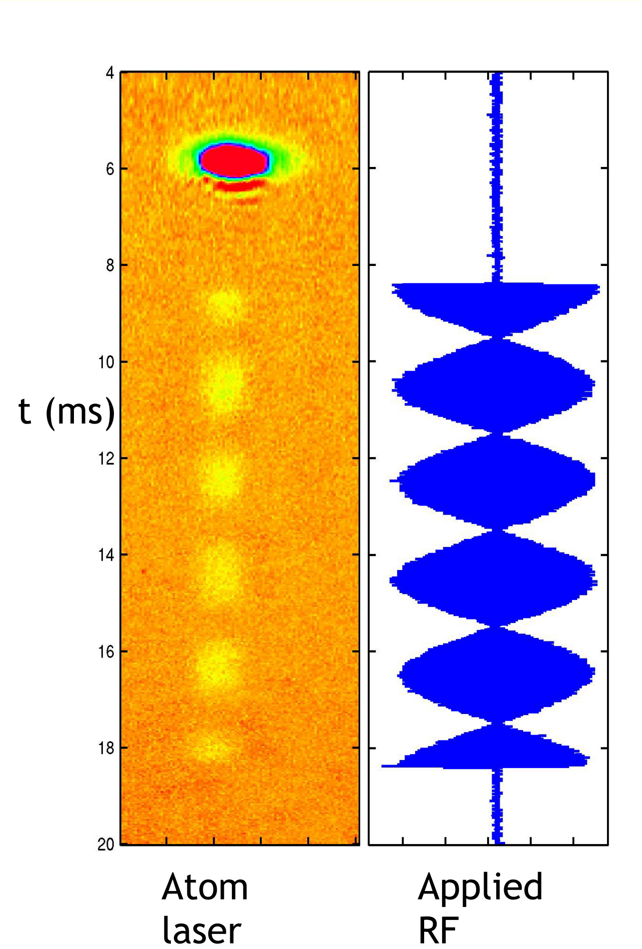
- Summing two fields gives you a modulation

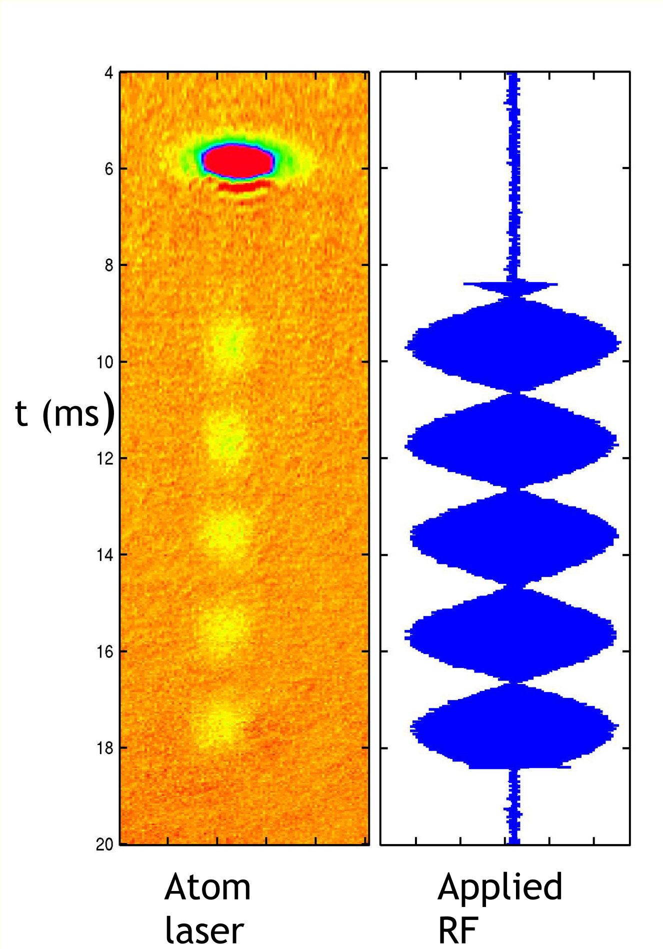
$$\sin(\omega_1 t) + \sin(\omega_2 t) = 2\sin\left(\frac{(\omega_1 + \omega_2)}{2}t\right)\cos\left(\frac{(\omega_1 - \omega_2)}{2}t\right)$$

signal ↗ Envelope ↗

- The outcoupled atom flux is proportional to the modulus squared of the sum of the two probability amplitudes for outcoupling
- These have RF phase imprinted on them
- Flux modulated like $\cos^2(\omega_1 - \omega_2)t/2$

Results of experiment

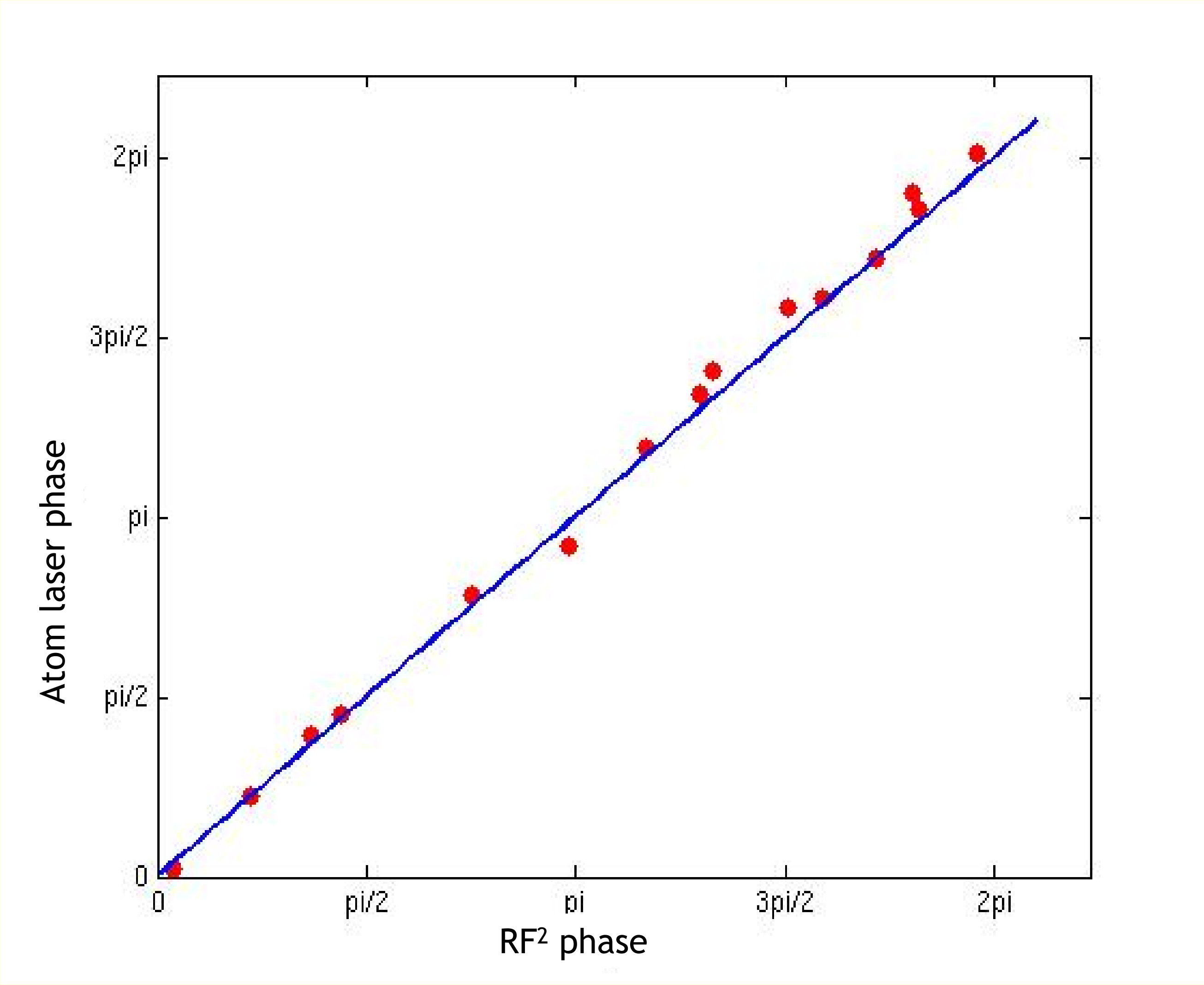




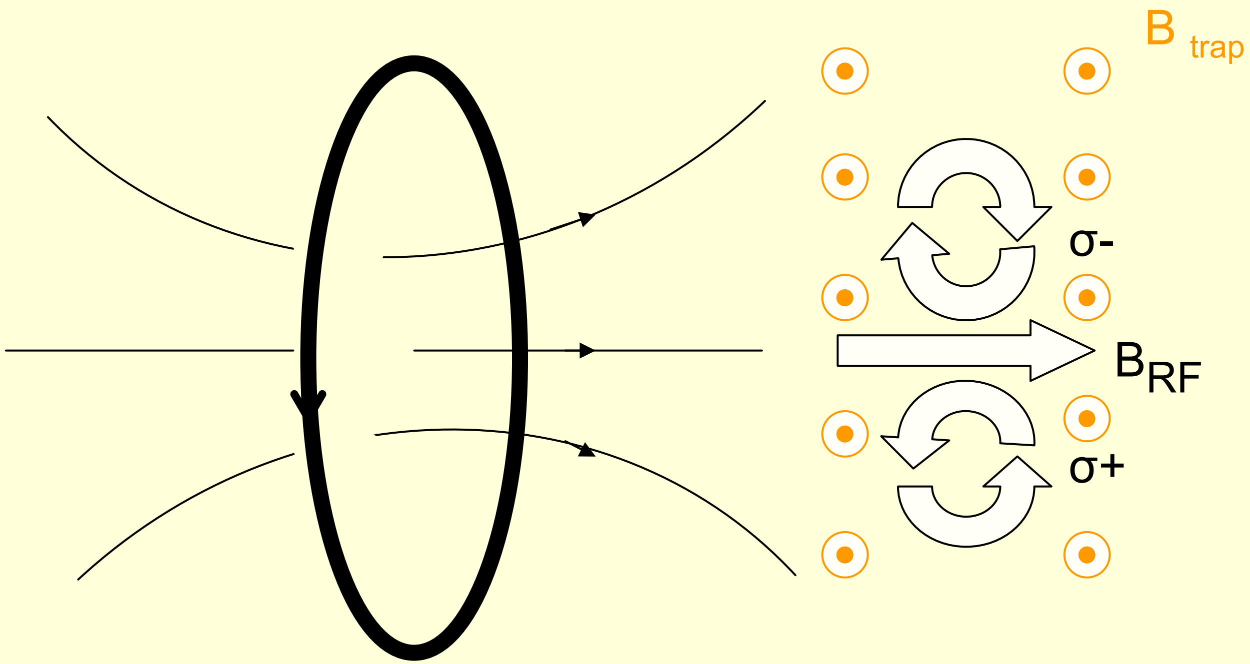
$$N_{oc}(t) \propto \Omega(t)^2$$

Comparison of phases

t (ms)

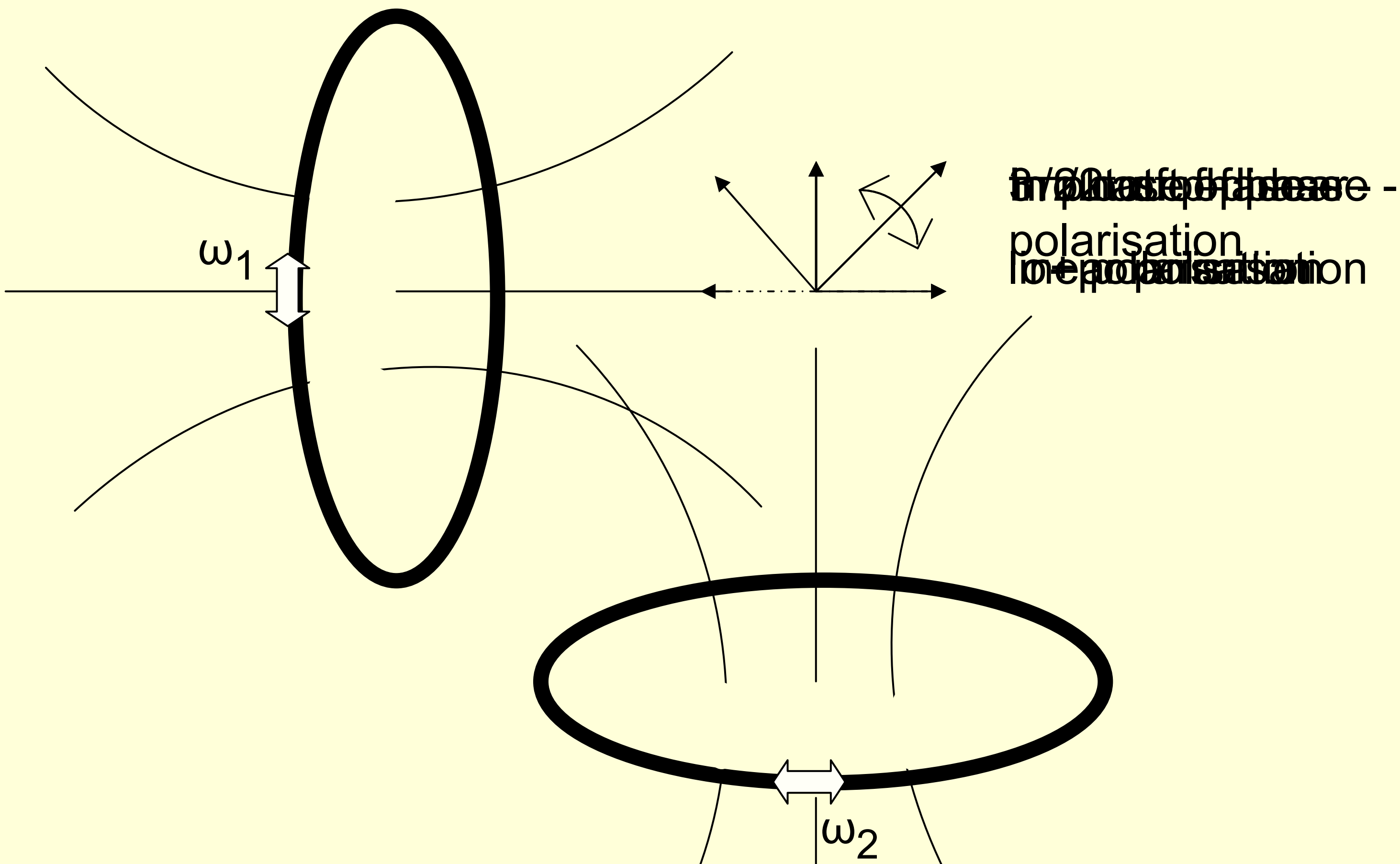


Single RF coil driven by two outcoupling frequencies

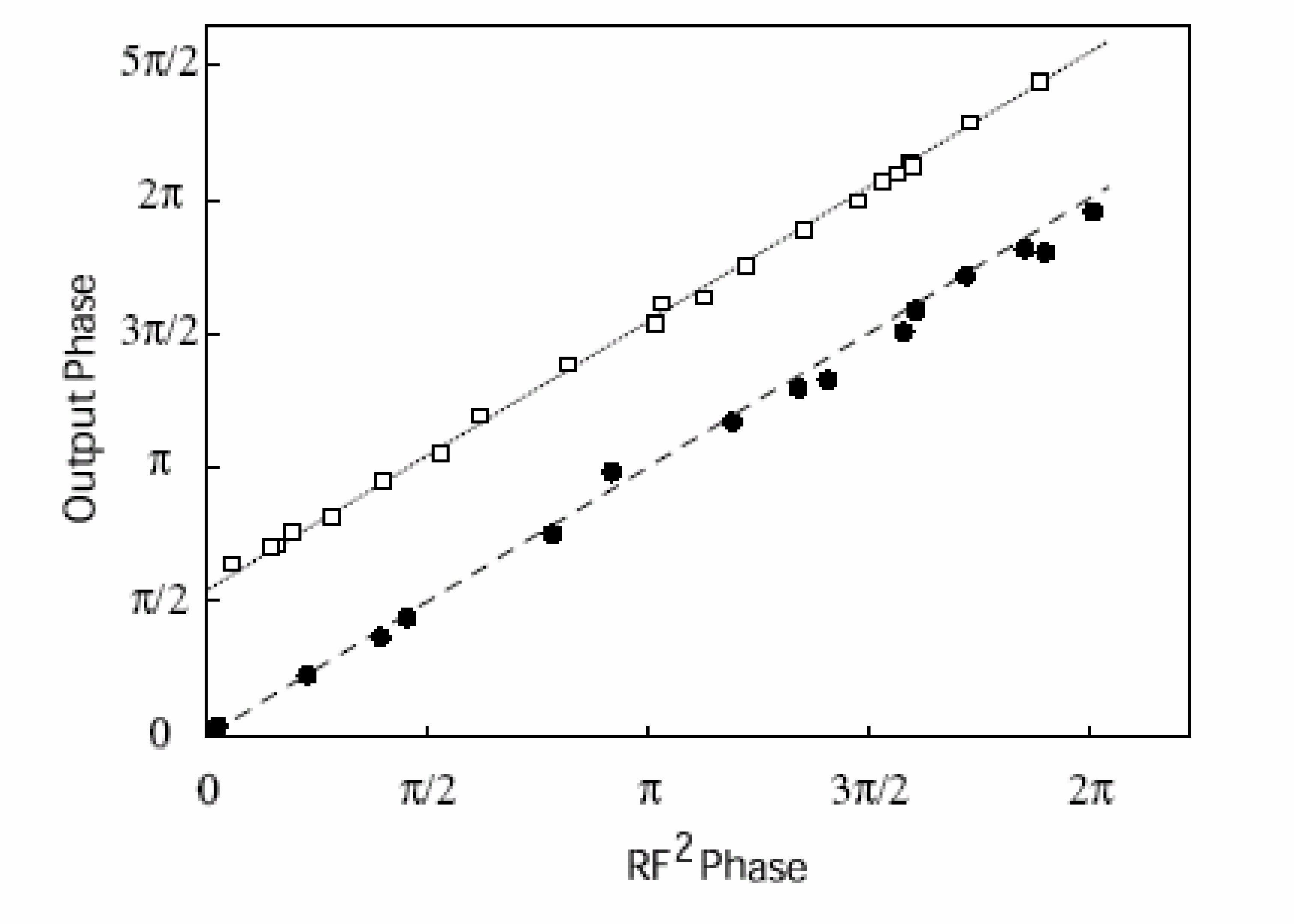


Maximum outcoupling at maximum field amplitude

Two orthogonal RF outcoupling coils

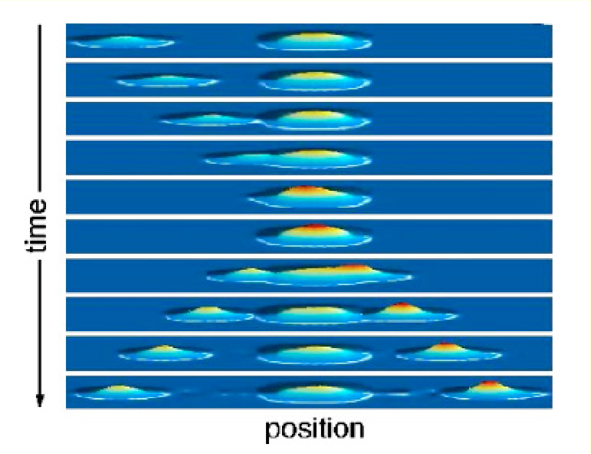


Maximum outcoupling for σ+ ie when signals π/2 out of phase


5π/2
2π
3π/2
π
π/2
0
Output Phase
0
π/2
π
3π/2
2π
RF 2 Phase

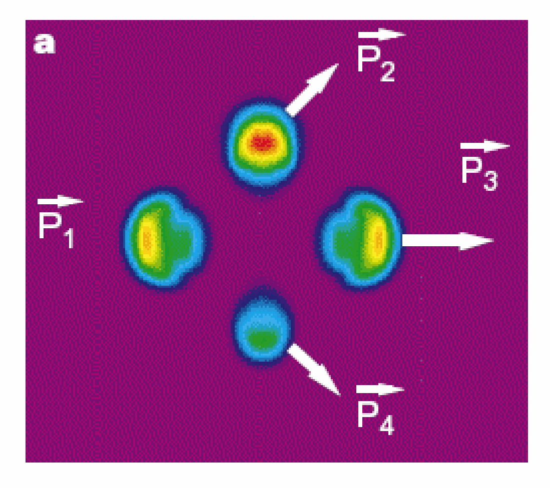
Accurate Atom Number Detection

Example future applications



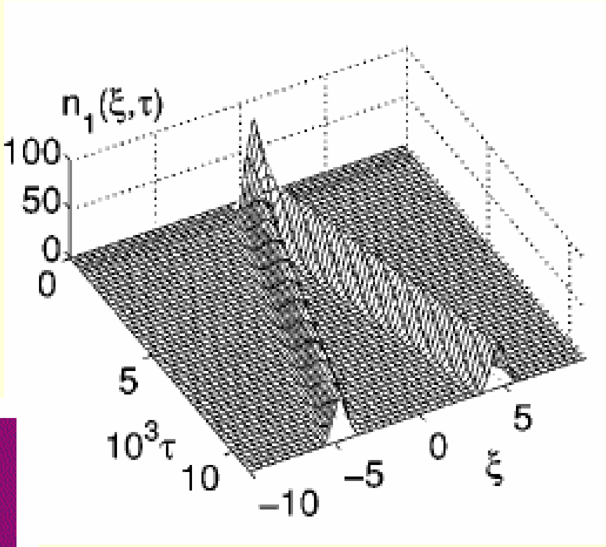
K. Kherunstsyan, Phys. Rev. A **71**, 053609 (2005)

Matter wave amplification



L. Deng *et al.*, Nature **398**, 218 (1999)

Four-wave mixing



K. Kheruntsyan & P.D. Drummond, Phys. Rev. A **66**, 031602(R) (2002)

Molecular down conversion

What sort of detector??

- To study quantum statistics of atom numbers in condensates we would like a detector with accuracy better than $1/\sqrt{N}$, typically:

$$\frac{\Delta N}{N} < \frac{1}{\sqrt{N}} \approx 10^{-3}$$

- Absorption imaging doesn't really offer this kind of accuracy (usually a few %).
- **Possible solution 1: Photoionisation**
- **Possible solution 2: optical cavity**

Optical Cavity

- Tapered fibre lenses on chip
- Low-Q cavity
- Active cavity
- Poster –Adrian Ratnapala
- Experiments with beads in water

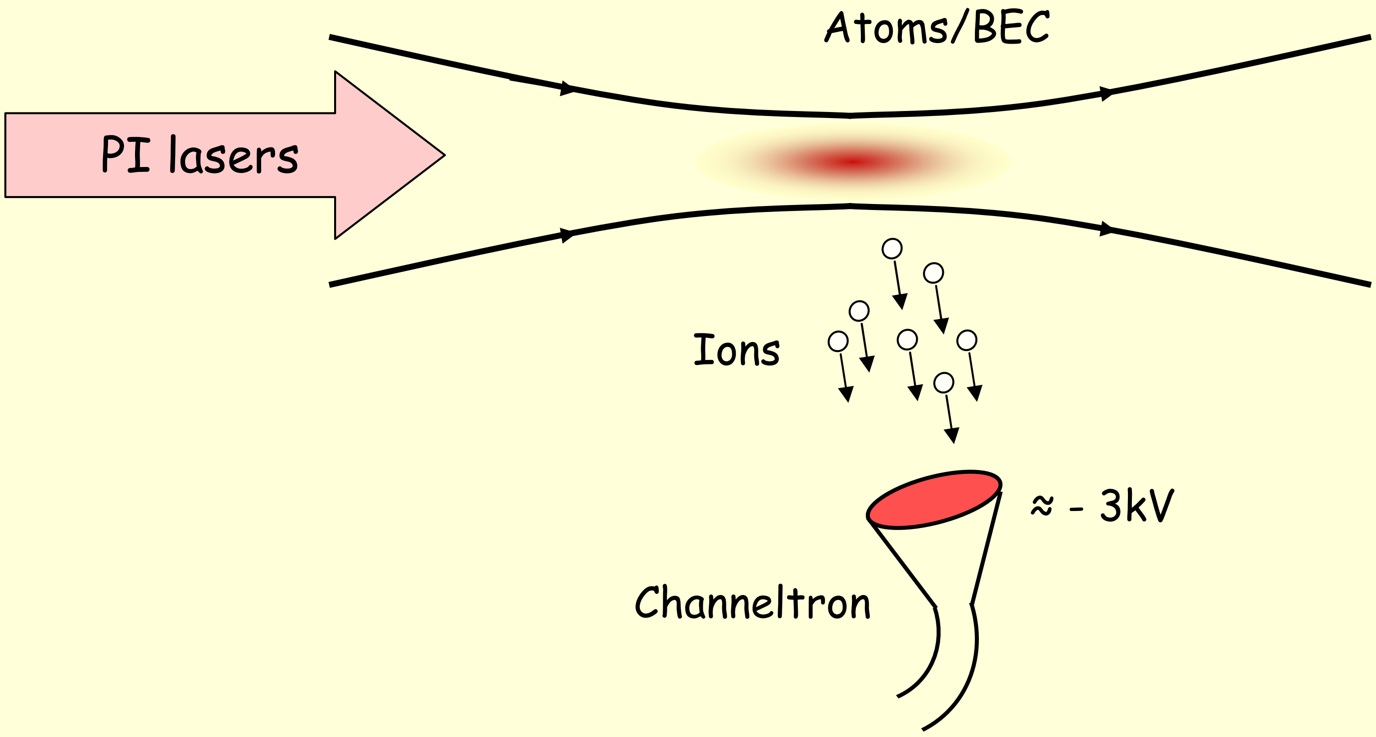
Photoionisation

Tom Campey

1. Single atom detection with efficiencies of ~80%
2. Atom counting with uncertainties significantly less than $1/\sqrt{N}$

Both schemes involve photoionisation followed by ion detection.

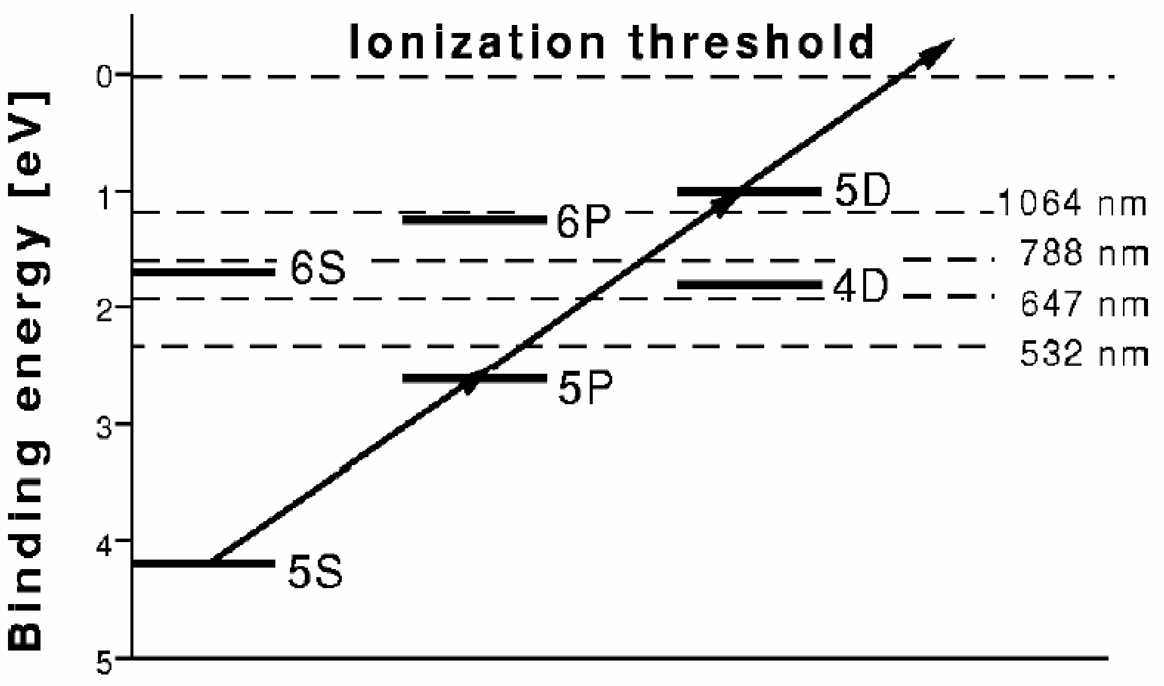
Proposed photoionisation scheme



• Ions are accelerated towards channeltron and detected there

Efficient Photoionisation

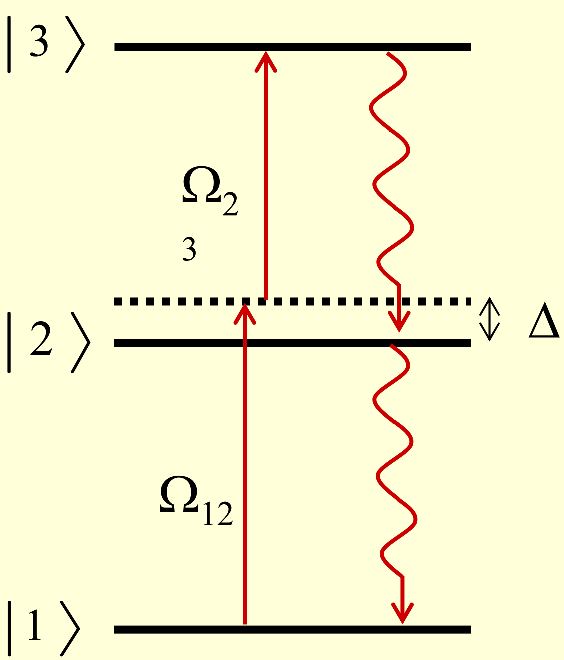
- Use STImulated Raman Adiabatic Passage (STIRAP) to transfer from 5S to 5D state.
- Ionise with pulsed Nd:YAG laser.



Duncan *et al.*, PRA **63** 043411, (2001).

STIRAP (Theory)

- Coherently transfer population from |1> to |3>
- Use counter-intuitive pulse order



$$\hat{H} = \frac{\hbar}{2}\begin{bmatrix} 0 & \Omega_{12}(t) & 0 \\ \Omega_{12}(t) & 2\Delta & \Omega_{23}(t) \\ 0 & \Omega_{23}(t) & 0 \end{bmatrix}$$

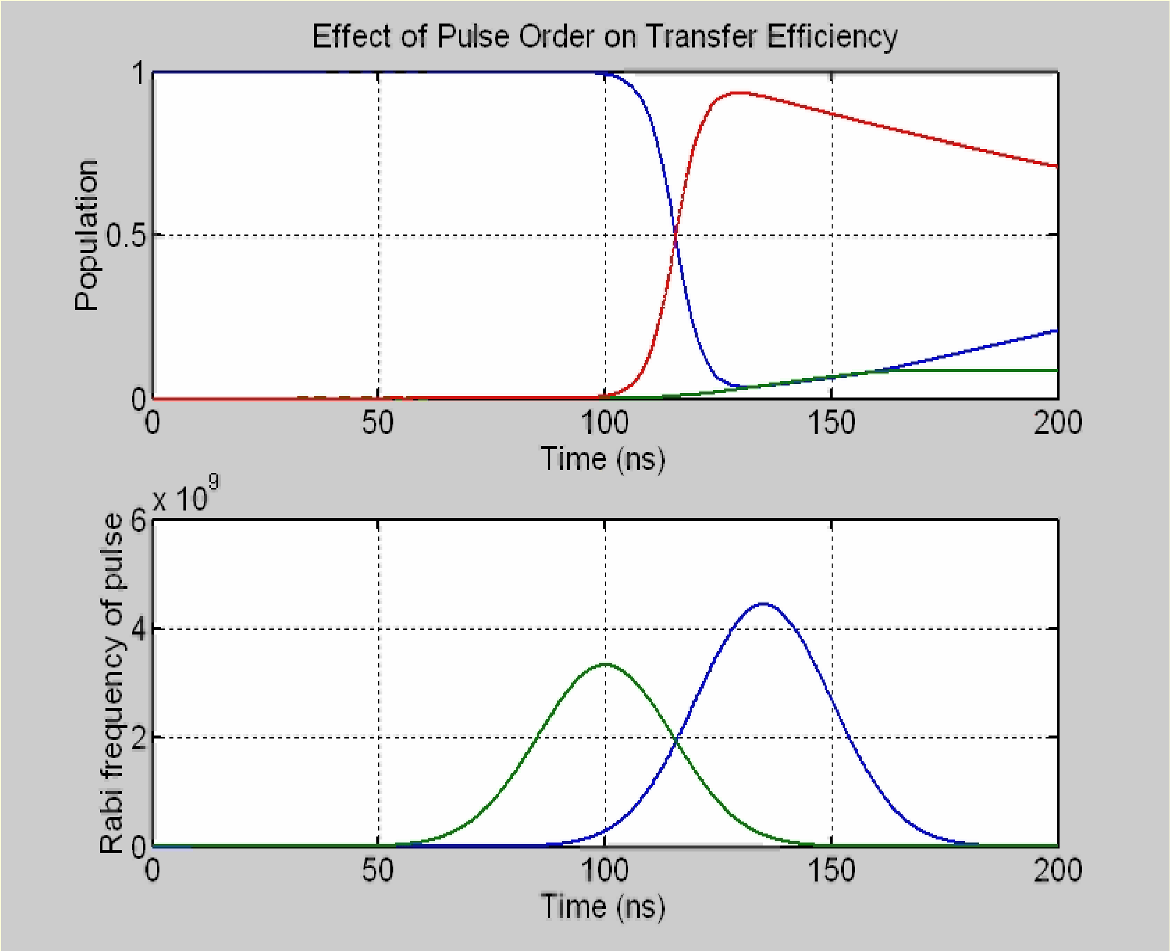
One eigenstate of $\hat{H}$ is:

$$\left|\psi_0(t)\right\rangle = \cos(\theta(t))\left|1\right\rangle - \sin(\theta(t))\left|3\right\rangle$$

where, $\tan(\theta(t)) = \Omega_{12}(t)/\Omega_{23}(t)$

STIRAP (Theory)

- Population transfer vs. pulse timing



— $5D_{5/2}$ population

— $5P_{3/2}$ population

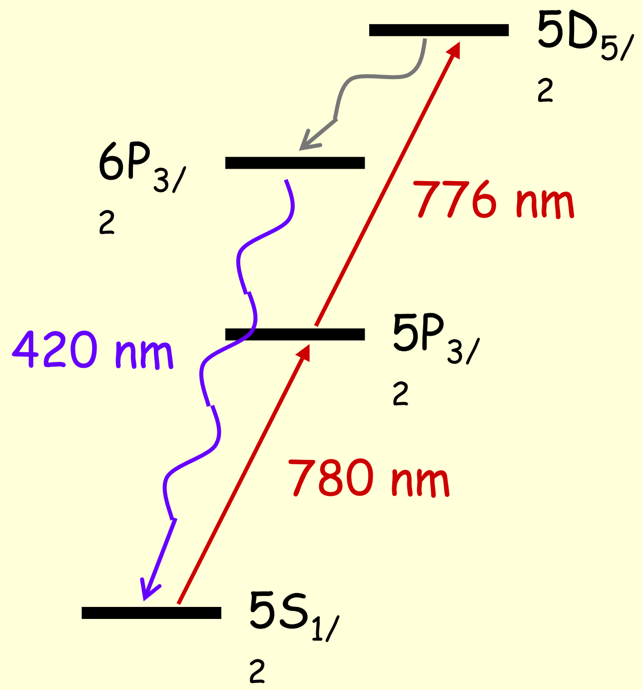
— $5S_{1/2}$ population

— Ω_{23} Rabi freq

— Ω_{12} Rabi freq

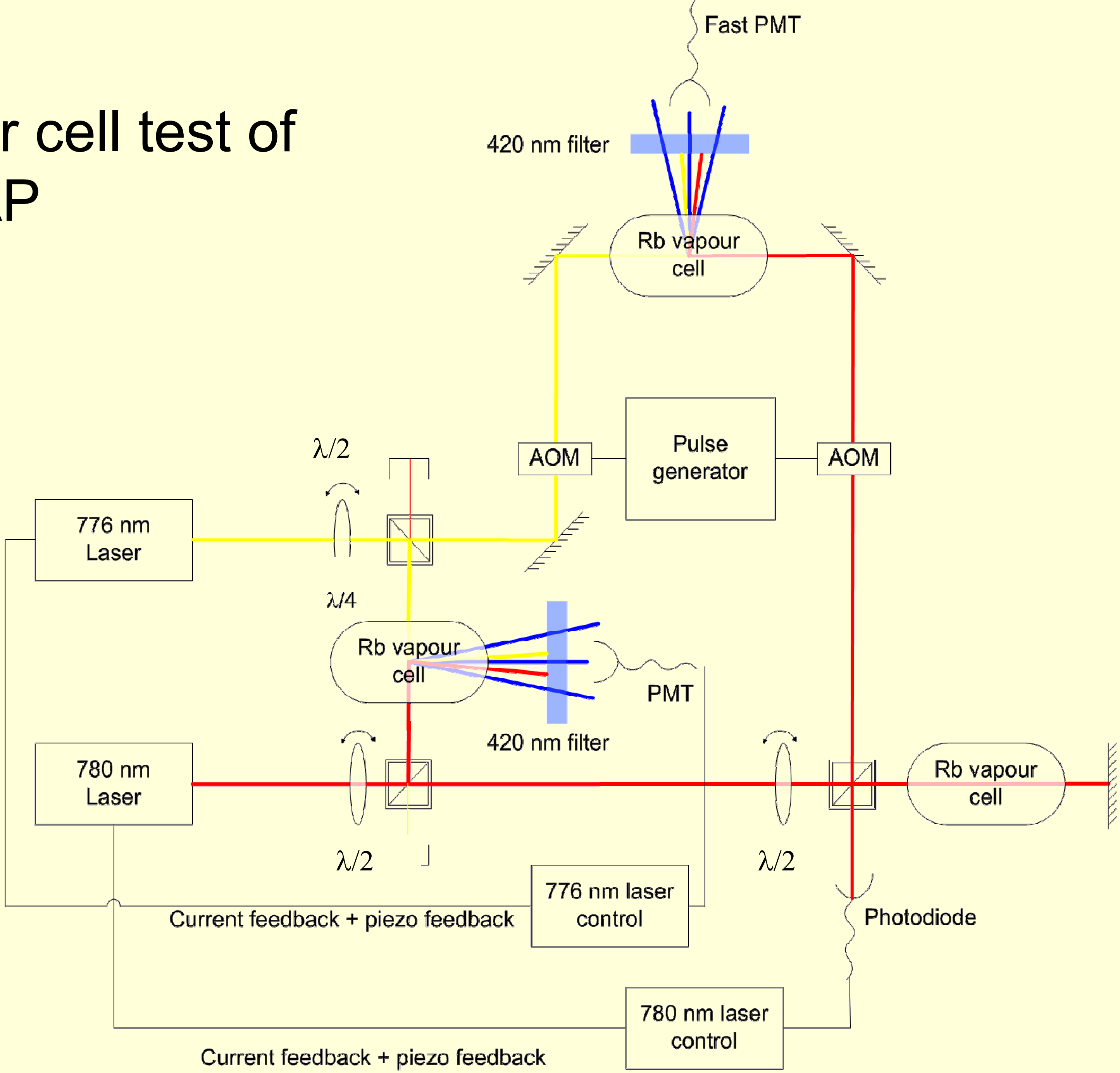
STIRAP (Experiment)

- A signature of the 5D state population is 420nm fluorescence



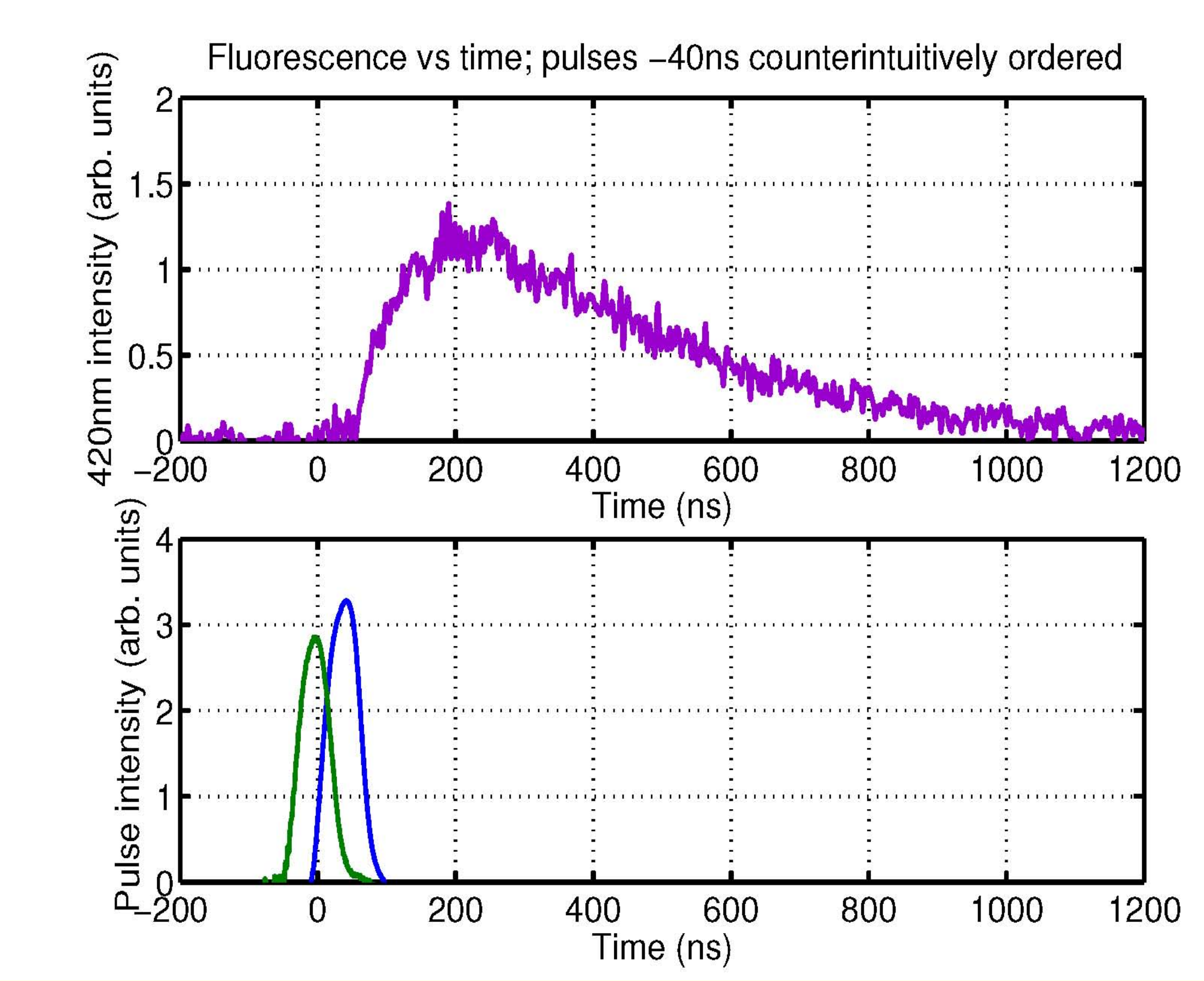
- Measure blue fluorescence to obtain STIRAP efficiencies

Vapour cell test of STIRAP

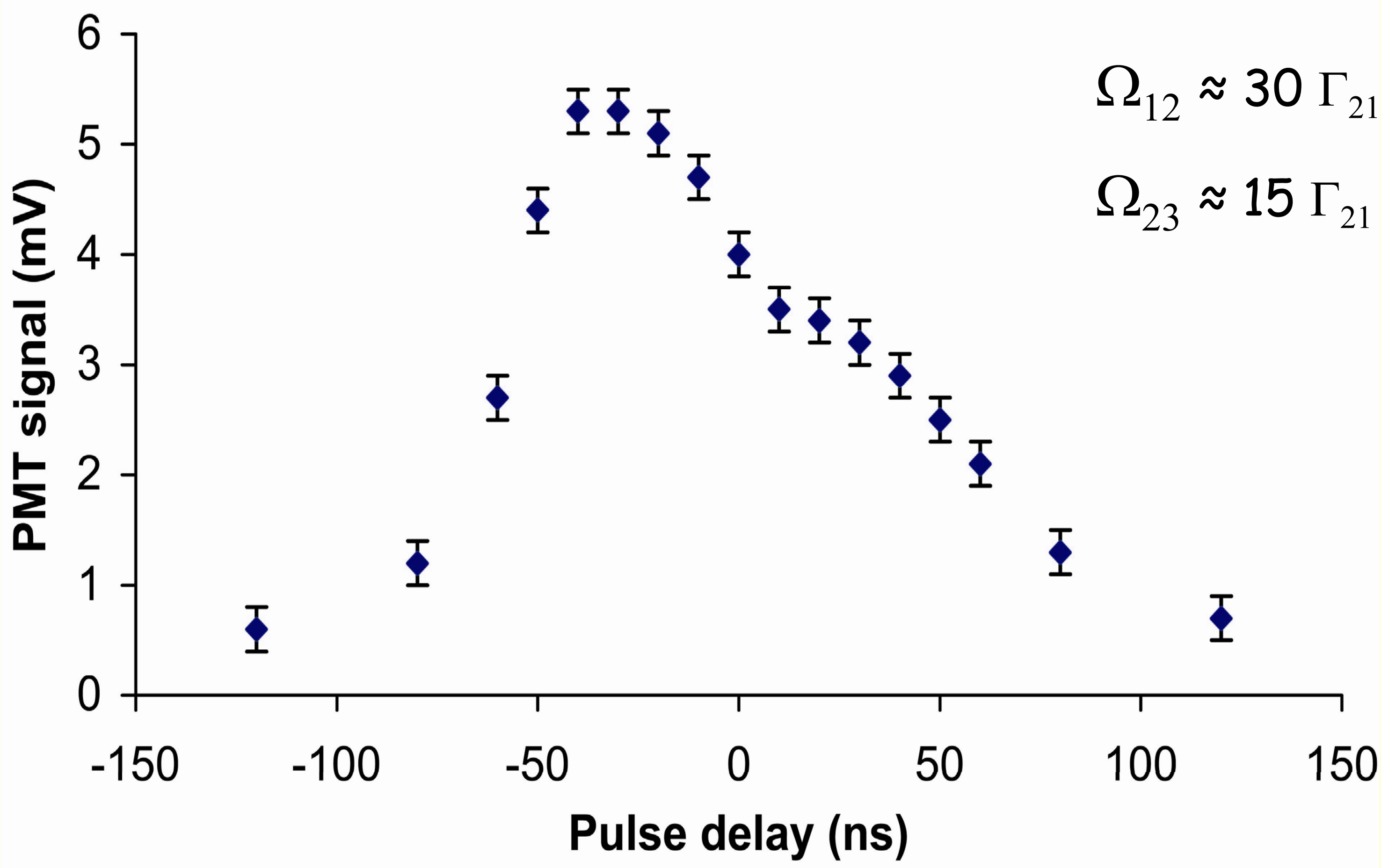


STIRAP Experiment

- The lasers are pulsed on and the blue fluorescence is monitored on a scope

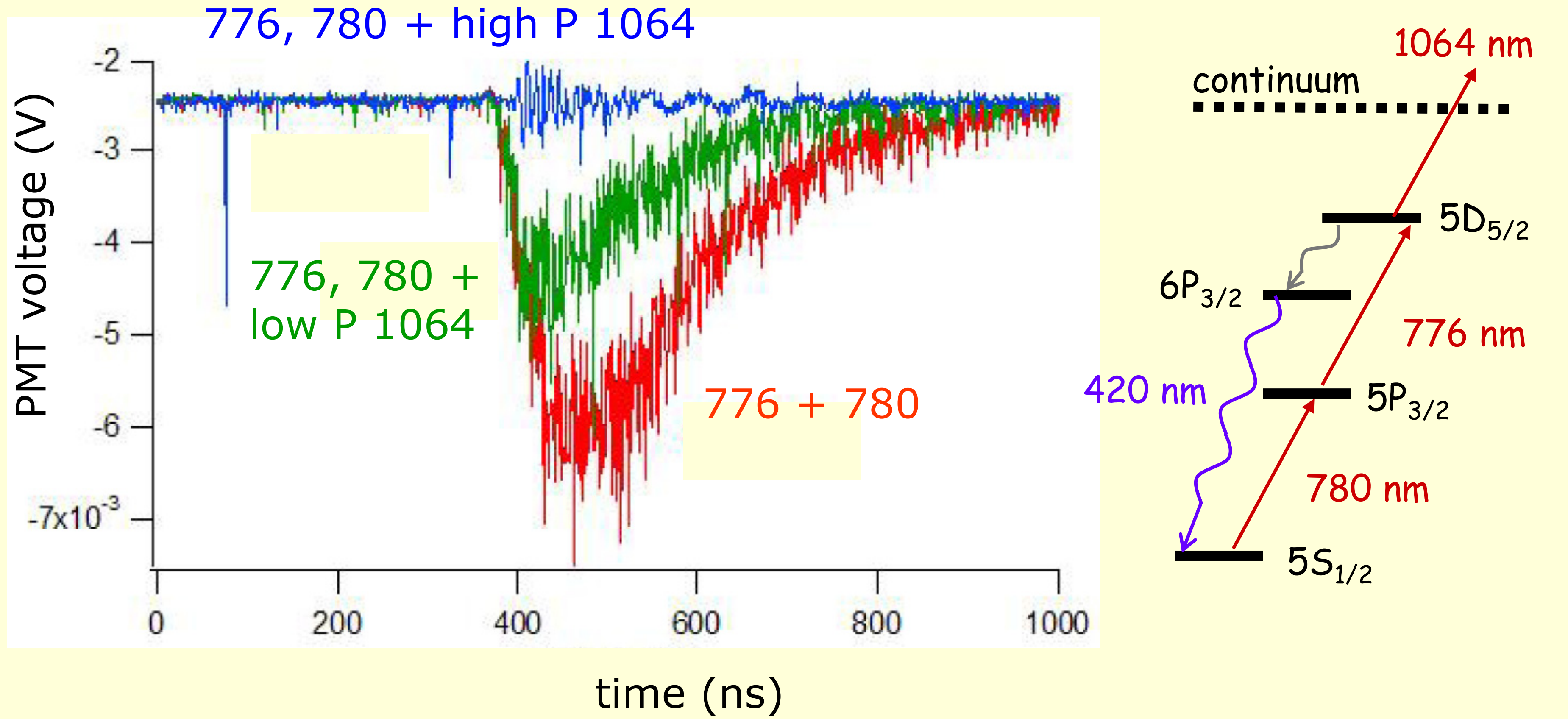


STIRAP Results



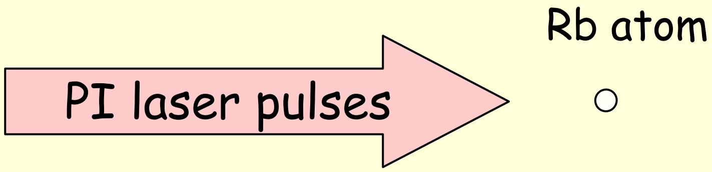
- Counter-intuitive ordering works better!!

PMT signal during STIRAP and photoionisaton (1064nm)



Single atom detection scheme

1. Photoionisation



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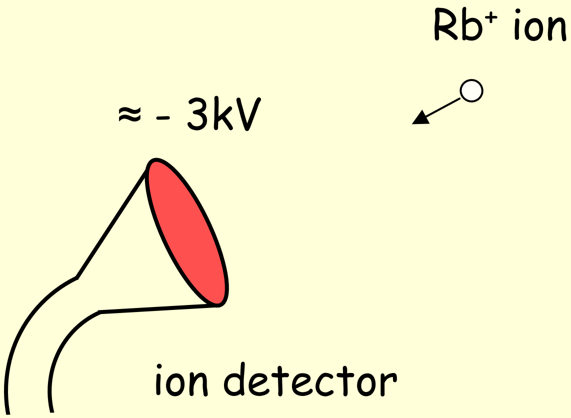
2. Ion detection



Calculation of atom detection efficiency

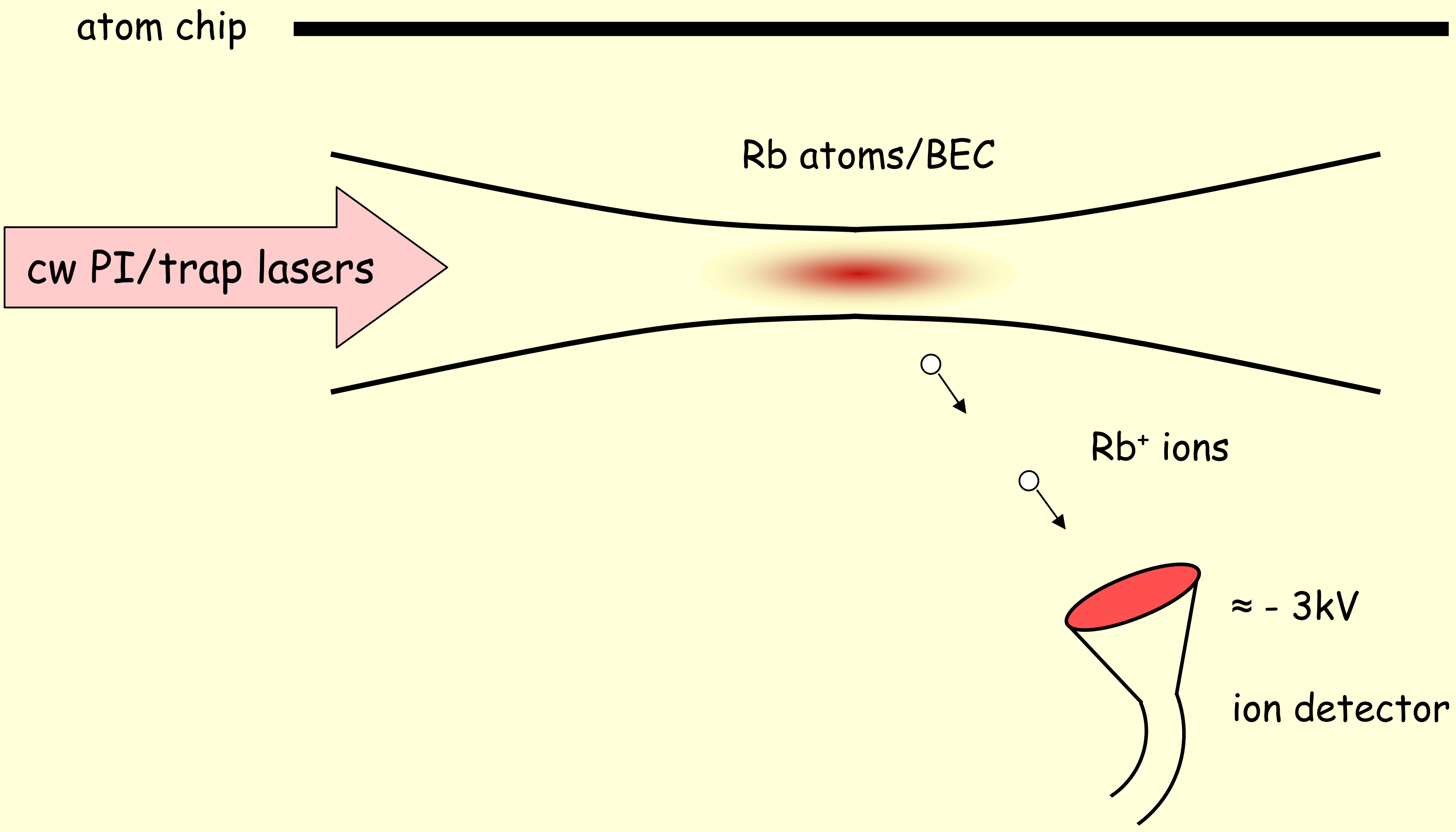
- STIRAP efficiency is ~90%
- Efficiency of ionisation from 5D is ~100%
- Ion detection efficiency is ~90%

⇨

Atom detection efficiency will be ~80%

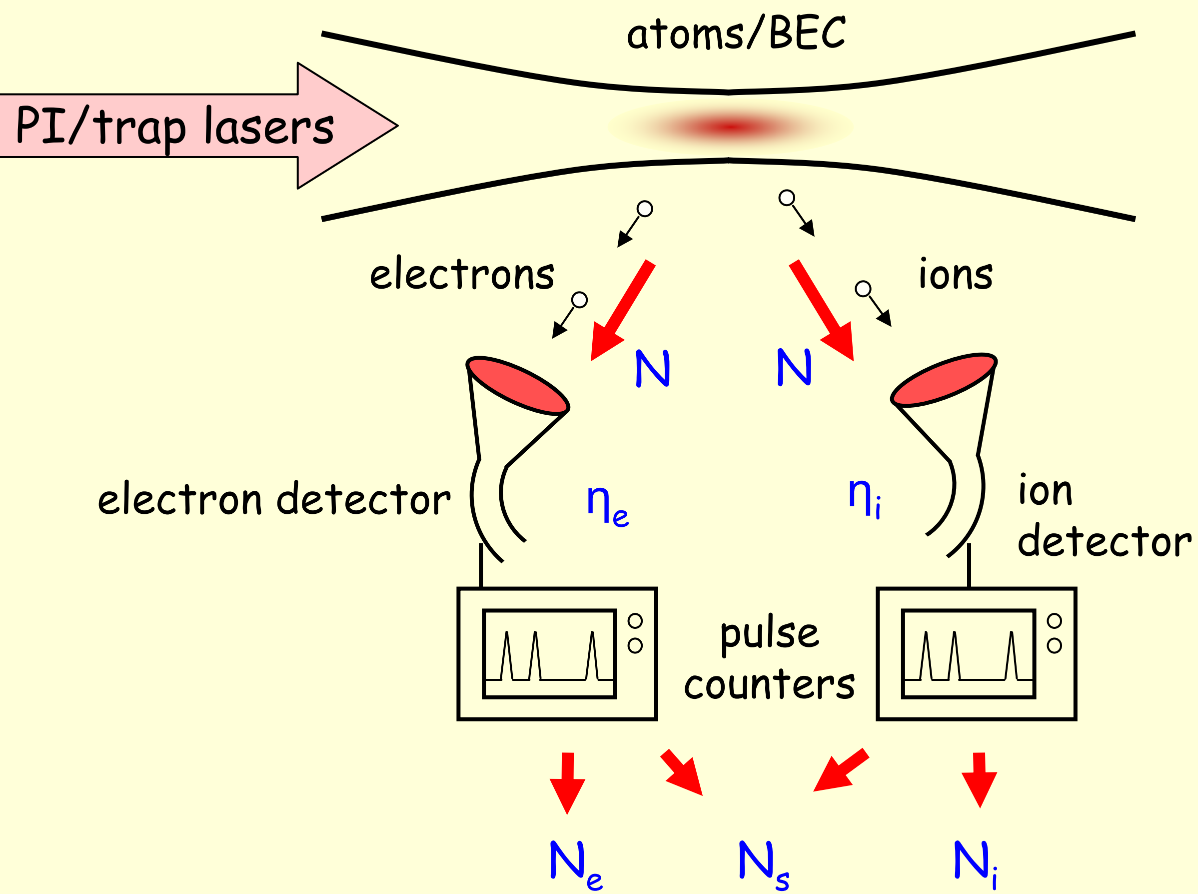
Atom counting
(see poster)

Atom counting scheme



Calibration scheme

NCRP Report 58, A Handbook of Radioactivity Measurements Procedures, second ed., 76 (1985)



$$N_i = \eta_i N$$

$$N_e = \eta_e N$$

$$N_s = \eta_i \eta_e N$$

$$\Rightarrow \eta_i = \frac{N_s}{N_e}$$

Conclusion

- UQ Micro-BEC working well
- Two frequency outcoupling
- Atom counting by photoionisation coming
- Fibre cavity detection