Lecture 2: Metastable Helium BEC

Baruntse 7129m Nepal, 1988

Course Outline

LECTURE 1:
Monday June 25th, 2.00 p.m.
ATOM OPTICS WITH METASTABLE HELIUM

LECTURE 2:
Monday June 25th, 3.30 p.m.
METASTABLE HELIUM BEC

LECTURE 3:
Tuesday June 26th, 2.00 p.m.
QUANTUM STATISTICS, COHERENCE AND CORRELATIONS

LECTURE 4:
Tuesday June 26th, 3.30 p.m.
COHERENCE AND CORRELATION EXPERIMENTS AT ANU

Lecture 2 Outline

LECTURE 2: METASTABLE HELIUM BOSE-EINSTEIN CONDENSATES

Why He* BEC formation is hard

- Penning ionisation
- He*-He* Scattering Length

He* BEC experiments at other labs (now including Vienna)

- Orsay
- ENS
- Amsterdam

He* BEC experiments at the Australian National University

- Creating a BEC
- Creating an atom laser
- Stable and reproducible sources

Why is He* BEC hard?

PENNING IONISATION: **20eV + 20eV = 40eV > 25.6eV IP**

- $He^* + He^* \rightarrow He + He^+ + e^-$ (Penning ionisation - PI)
- $He^* + He^* \rightarrow He_2^+ + e^-$ (associative ionisation - AI)

- PI loss rate ~ 10^{-10} cm^3/s for unpolarised He* (5×10^{-9} with MOT light)

- Limits MOT densities to $\leq 5 \times 10^{-9}$ cm^3 => large MOT diameters ~ 1cm

- But angular momentum conservation helps for spin polarised He* in a *magnetic trap*, since it's the spin-dipole interaction that allows PI to occur

$$He^* (J=1) + He^* (J=1) \rightarrow He (J=0) + He^+ (J=1/2) + e^- (J=1/2)$$

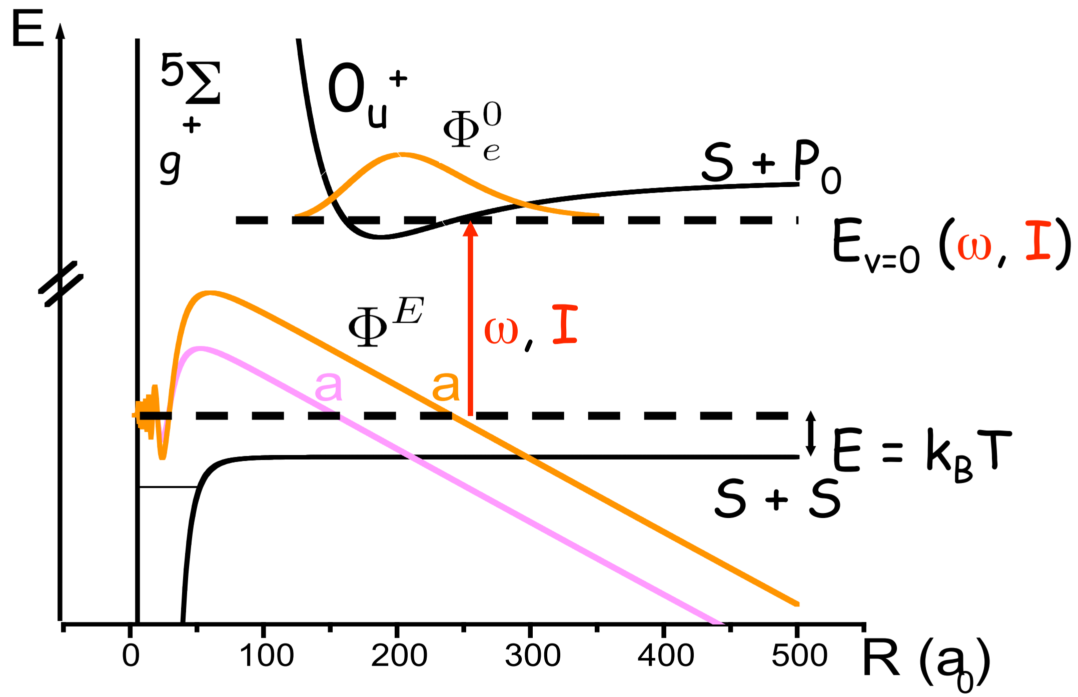
- PI loss rate ~ 10^{-14} cm^3/s for spin polarised He*, *but creates enough ions so that it can be used as a free non-invasive density diagnostic*

SCATTERING LENGTH

- Until someone tried to make a BEC, no one knew whether the scattering length was large enough to enable efficient evaporative cooling!

a - the Scattering Length

- “a” is determined by subtle quantum mechanical effects which depend sensitively on the interatomic potentials
- Knowledge of the behaviour of bound states - principally the binding energy of the least bound state or the relative light shift of different levels - can thus be used to determine “a”
- However, because of the extreme sensitivity of “a” to small changes in potentials, theory calculations require very accurate interatomic potentials



Why is a knowledge of “a” important ?

- Determines the scattering cross section ~ $8\pi a^2$ => 1400 nm^2 for He* !
- Hence determines
  - the evaporative cooling rate (critically)
  - the critical temperature (less dramatically)
  - the condensed fraction (less dramatically)
- Also determines if ultracold atoms above T_c are in the collisional regime
  - Most alkalis are in the collisionless regime
  - He* can be prepared the collisional or hydrodynamic regime where λ_{mfp} < trap size (Leduc et al. 2002) and can be described as a two component fluid (condensed and uncondensed)
- If “a” is a significant fraction of the He* separation (few % c.f. 0.1% for alkalis), deviations from mean field theory may occur
- Determines the scattering length for ^{3}He* - ^{4}He* by scaling

Determining "a" for He*

- From the total number of atoms N_0 in the BEC (ENS, Orsay, VU)

$$a = \sigma / 15N_0 \times (2\mu / h\omega)^{5/2}$$

  $\sigma = (h/m\omega)^{1/2}$ is the size of the ground state of the trap
  ω = the mean trap frequency
  μ= the chemical potential derived from time-of-flight data
  Requires careful measurement of N_0 (usually known to 50%)

- From the dependence of Penning ionisation rates as a function of the onset of condensation T_c (Orsay) derived from TOF

- From photoassociation spectroscopy (ENS) where (a) single-photon excitation determines "a" by the effect of light shifts (b) two-photon excitation measures the energy of the least bound state

- From inelastic collision rates (Orsay) where quantum effects play a role via the scattering length

Orsay He* Scattering Length "a"

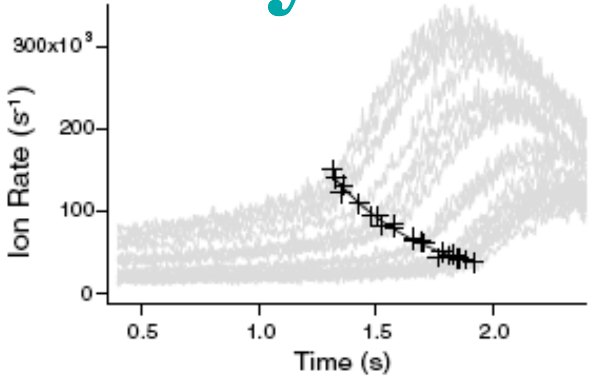


FIG. 1. Variation of the ion rate as the atomic cloud is cooled through the phase transition for various initial densities (gray curves). The rf-knife frequency at $t = 0$ is 2 MHz. The sudden increase of the ion rate (crosses) occurs at the BEC transition. The solid line passing through the transition points constitutes our empirical relation, named threshold curve.

T_c onset (Seidelin et al. 2004)

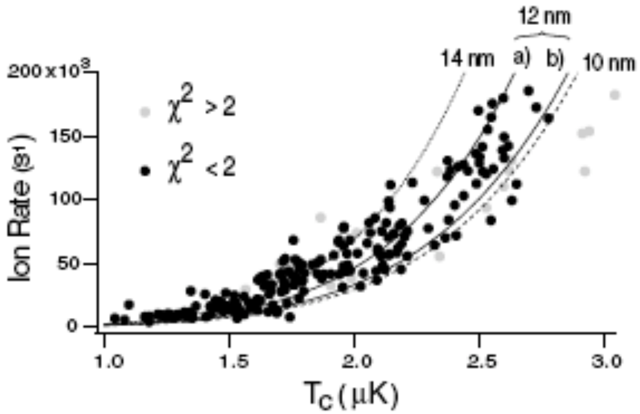


FIG. 3. Ion rate versus critical temperature. The points correspond to the results of 280 runs for which the ion rate was deemed sufficiently close to the condensation threshold. Gray indicates runs for which χ^2 in the TOF fits was above 2. The dashed line is the theoretical estimate for $a = 10$ nm, the dotted line for $a = 14$ nm [both including interaction corrections of Eq. (4)]. The two solid lines correspond to $a = 12$ nm, (a) with interactions and (b) without interactions, and illustrate the size of their effect.

Ion vs T_c depends on a

Loss rate (2 and 3 body) depends on "a" (Sirjean et al. 2002)

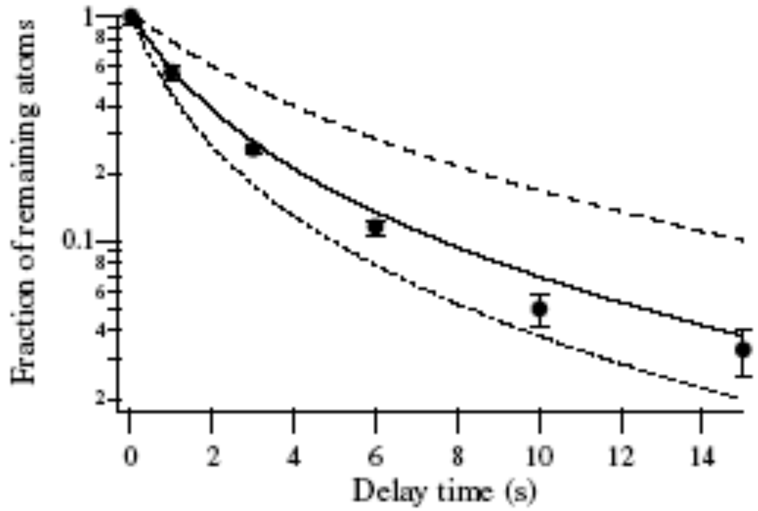
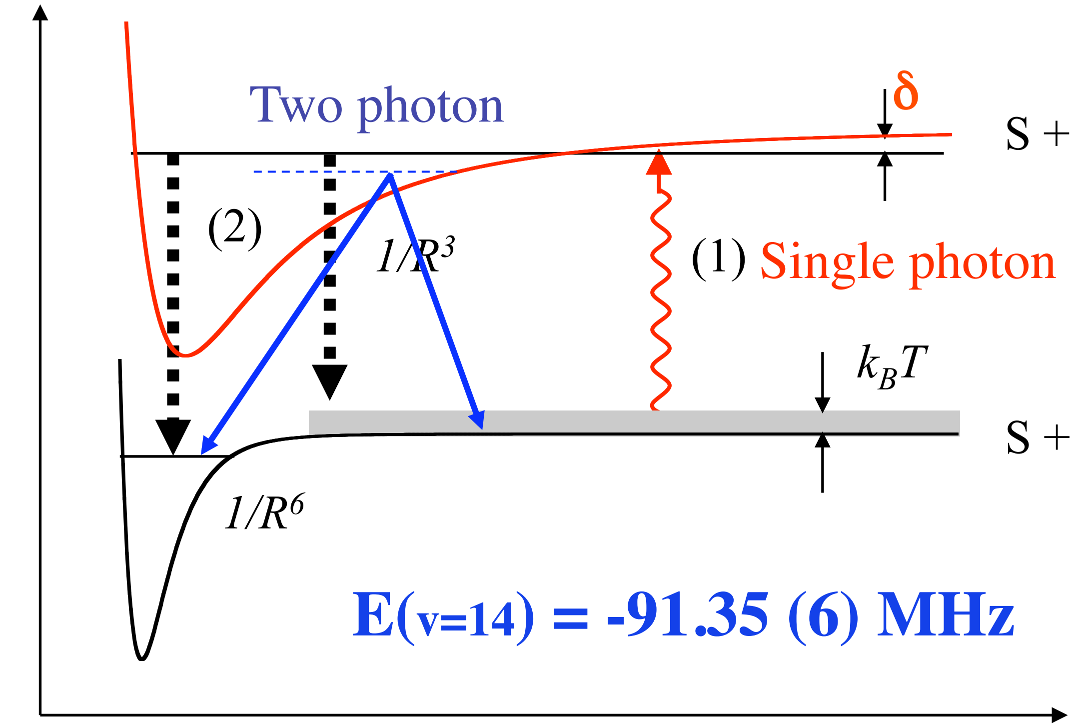


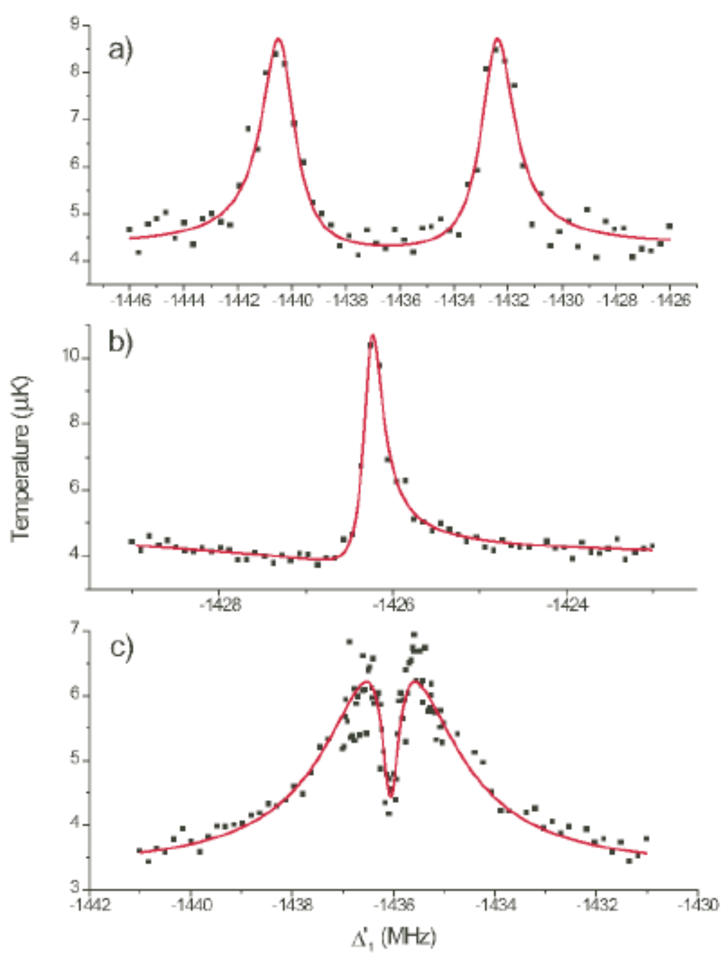
FIG. 3. Fraction of remaining atoms measured by TOF as a function of time. The rf shield is on and the cloud remains a quasipure condensate during the decay. The lines correspond to the predicted atom decay according to Eq. (3) with the fitted value of the two- and three-body rate constants for $a = 10$ nm (dashed line), $a = 20$ nm (solid line), and $a = 30$ nm (dotted line). The case of $a = 10$ nm is not necessarily excluded because other, nonionizing losses could be present.

Photoassociation Spectroscopy

Energy



Two photon signals



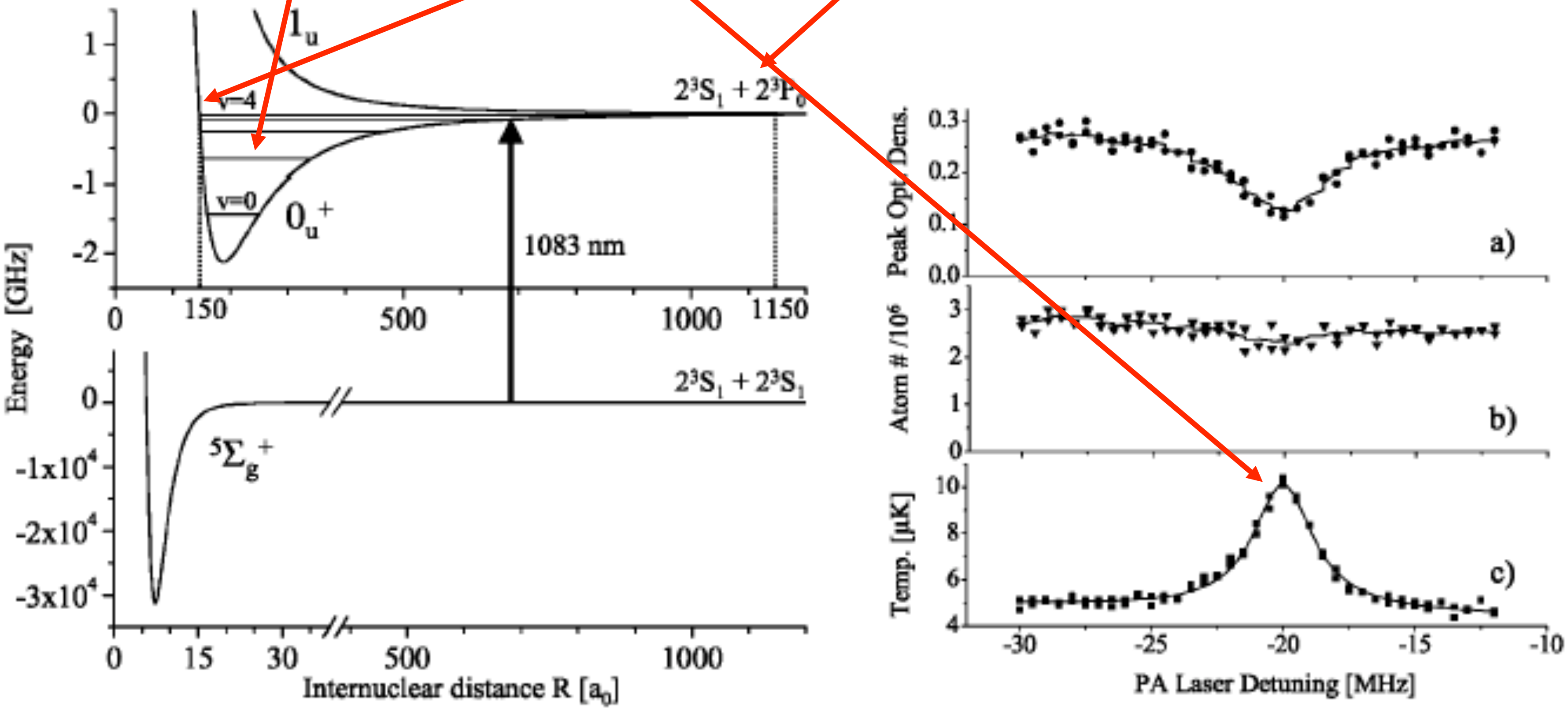
(1) Laser excitation of an unbound pair of atoms
to a bound state in a molecular potential we

(2) Spontaneous and/or stimulated decay
back to a bound or free S+S state => *heating*

(3) Raman measurement of least bound state energy

Giant helium dimers

- Five bound states observed with *single photon* 1083nm excitation
- All have inner turning points ~ 150 a_o, with outer turning points up to ~ 1150a_0 (> 60nm!)



J. Leonard et al., Phys. Rev. Lett. **91**, 073203 (2003)

$^4He^*$ - $^4He^*$ Scattering Length

Reference	Year
Robert (IO)	2001
Santos (ENS)	2001
Gadea	2002
Tol (VU)	2004
Seidelin (IO)	2004
Leduc (ENS)	2005
Dickinson	2004
Leduc (ENS)	2006
Whitt. (JCU)	2006

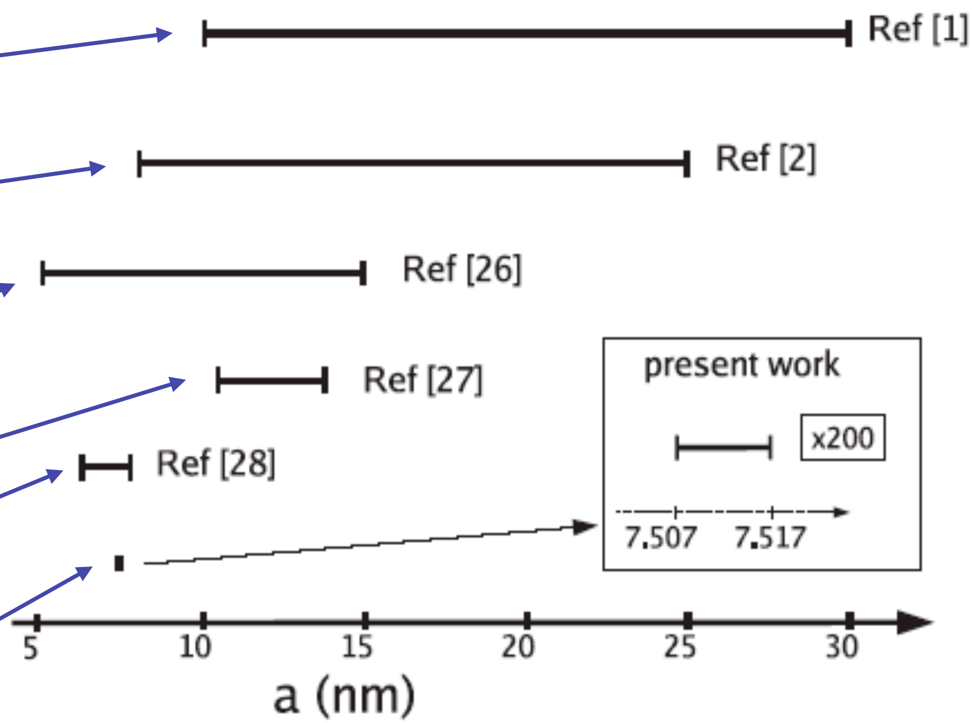


FIG. 1. Comparison of the present result with previous experimental determinations of the *s*-wave scattering length *a* of spin-polarized metastable helium: from the expansion of the condensate [1,2], from the evaporative cooling rate [26], from the observation of inelastic collisions [27], and from light-induced frequency shifts in one-photon photoassociation [28].

When $^4He^*$ $a = 9.4nm$ => infinite for $^3He^*$ - $^4He^*$: => $28.8 \pm 3.6nm$

He* : Pros

- ✓ Large stored energy - 20eV
  - ✓ exposures for atom lithography
  - ✓ EASY DETECTION - single He*
  - ✓ de-excite: low background
- ✓ No nuclear spin for ^{4}He*
  - ✓ Simple energy structure
  - ✓ No repumping needed
- ✓ Big recoil velocity 9 (26) cm/s
  - ✓ Make good beamsplitters
- ✓ Low sat. int. 0.17 (3.3) mW/cm^2
  - ✓ Low power (diode) lasers
- ✓ Large magnetic moment $2\mu_B$
  - ✓ Easier magnetic control
- ✓ Large scattering length a = +7.512 nm
  - ✓ Efficient evaporation
  - ✓ ^{3}He* - ^{4}He* a is larger ~ + 30 nm

He* : Cons

- ✓ Large stored energy 20eV
  - ✗ Penning ionization losses
  - ✗ Low number densities
  - ✓ BUT drops by >10^4 in B field
- ✓ Nuclear spin for ^{3}He*
  - ✗ ^{3}He* repumper needed
- ✓ Big recoil velocity 9 (26) cm/s
  - ✗ High recoil temperature
- ✓ Large magnetic moment $2\mu_B$
  - ✗ Susceptible to stray fields
- ✓ Hard to make
  - ✗ Low numbers
  - ✗ Complex apparatus

Lecture 2 Outline

LECTURE 2: METASTABLE HELIUM BOSE-EINSTEIN CONDENSATES

Why He* BEC formation is hard

- Penning ionisation
- He*-He* Scattering Length

He* BEC experiments at other labs (now including Vienna)

- Orsay
- ENS
- Amsterdam

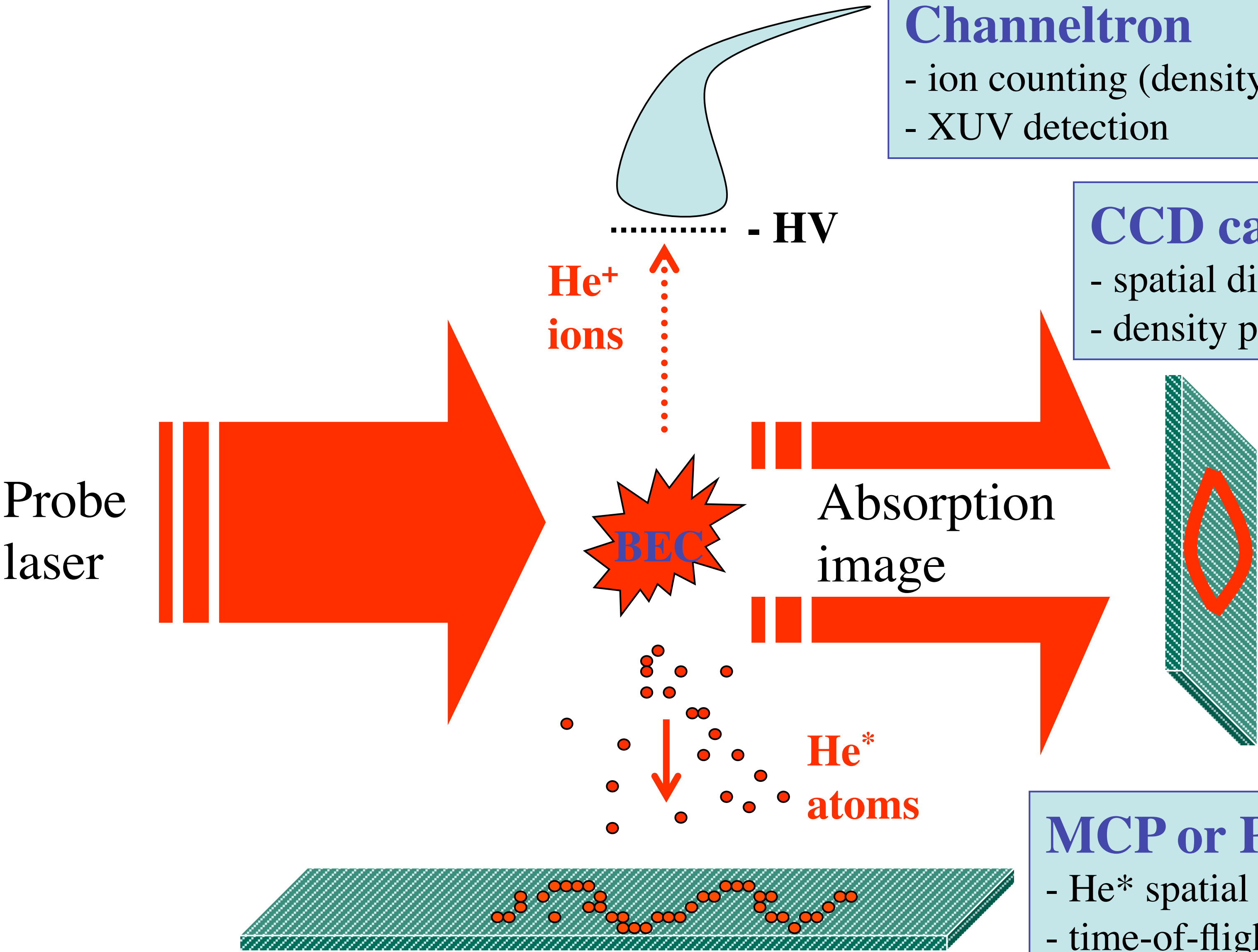
He* BEC experiments at the Australian National University

- Creating a BEC
- Creating an atom laser
- Stable and reproducible sources

World He* BEC experiments

Lab	*Experiment / Detectors*	*BEC*	*Already investigated /* *Future Aims*
Orsay	Chamber / MCP + PSD	2001	*a* value, T_c, Penning ionisation, HBT / Particle correlations, spectroscopy
ENS	Glass cell / Absorption	2001	*a* value, hydro regime, big mols 1- and 2-D lattices with MCP
VU	Chamber / MCP + Abs.	2005	*a* value, HBT Fermions / $^4He^*$-$^3He^*$ Bose-Fermi Mixtures
ANU	2 Chambers / MCP+abs.+CEM	2005	Application of atom correlations, studies of EPR and quantum non-locality
Vienna	??	2011	Young's two slit - quantum non-locality

He* BEC Detection



Channeltron
- ion counting (density probe)
- XUV detection

CCD camera
- spatial distribution
- density profiling/ T

MCP or PSD
- He* spatial profiling
- time-of-flight T(K)

Orsay He* BEC

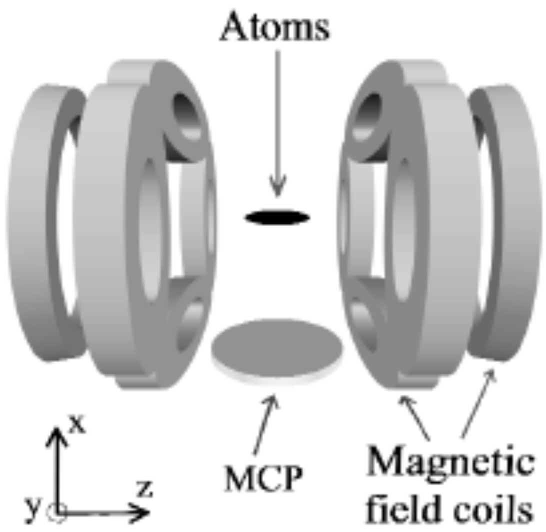
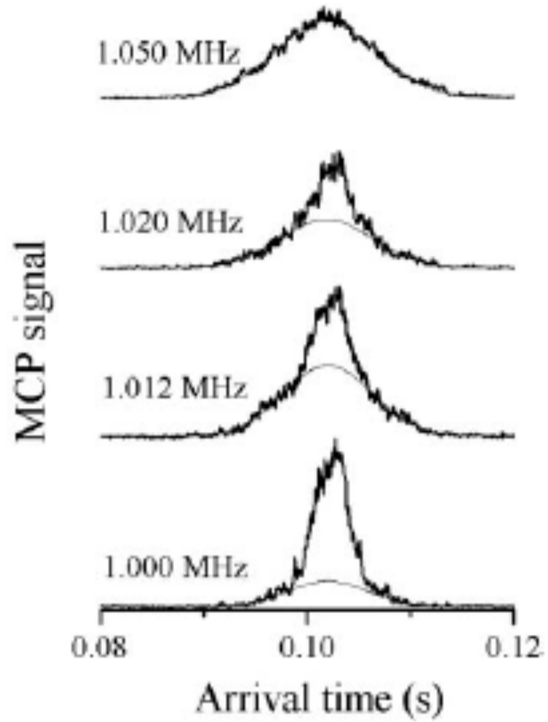


Fig. 1. Schematic diagram of the apparatus (not to scale). The coils that form the magnetic trap are outside the vacuum in reentrant flanges. The microchannel plate is 5 cm below the center of the trap. The incoming He* beam propagates along the *y* axis (horizontally). The three pairs of magneto-optical trap laser beams (not shown) propagate along the *z* axis and at 45° to the *x* and *y* axes.



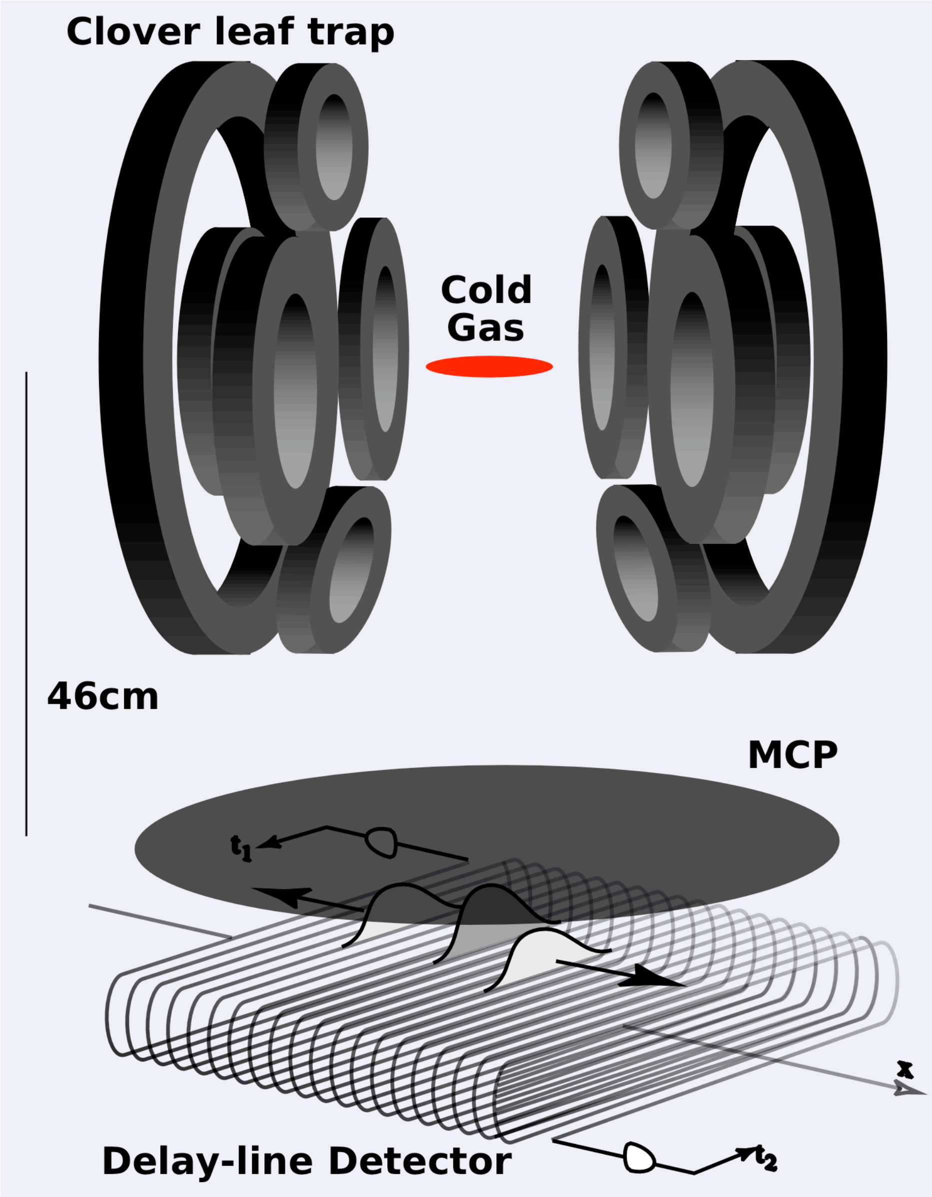
- BEC He* atoms ~ 10^6 at ~ 1μK
- Magnetic trap lifetime ~ 35s

  With beamline shut ~ 200s

TOF data for He* BEC/thermal atoms arriving on the MCP

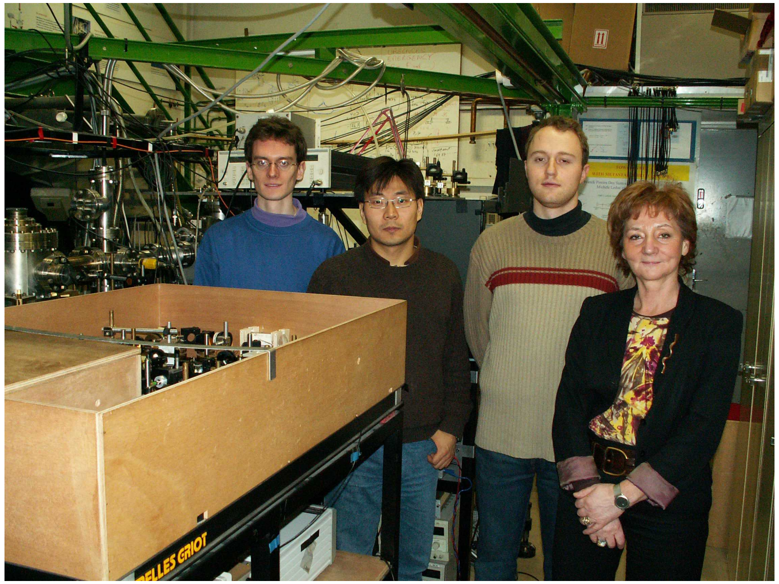
Robert et al., Science **292**, 461 (2001)

Orsay 3D atom detector

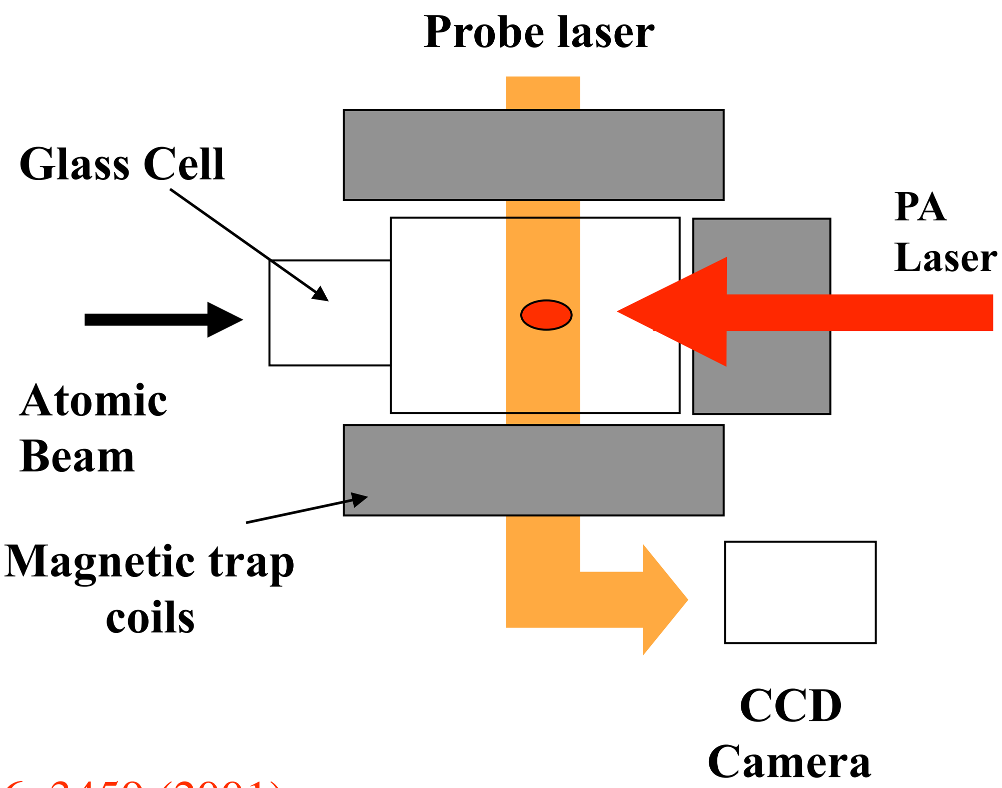


- He* atoms (m=0) fall with same velocity ~3 m/s onto 80mm MCP, 12 μm c-c
- Electrons incident on 3 or 4 100μm c-c wires
- Excellent time (vertical) resolution ~ 1 ns (~1 nm)
- Delay-line anode gives in plane resolution (~ 500 μm) Roentdek/ISITech
- ~ 10^4 parallel detectors
- Cloverleaf trap in Amsterdam and Orsay

ENS He* BEC

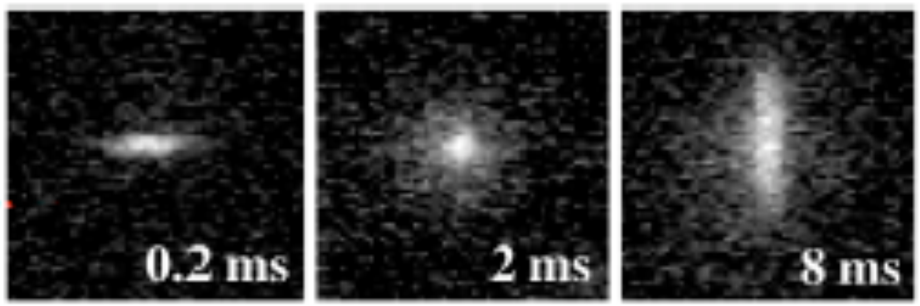


Steven Moal, Jaewan Kim, Max Portier, Michele Leduc

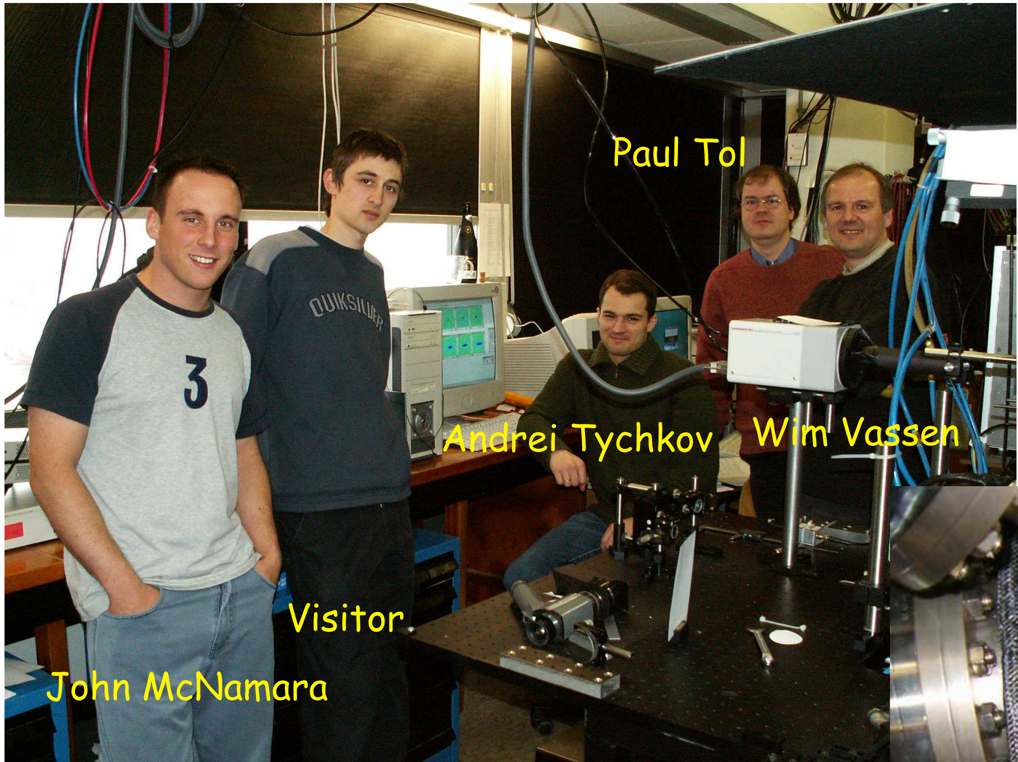


Pereira dos Santos et al., Phys. Rev. Lett. 86, 3459 (2001)

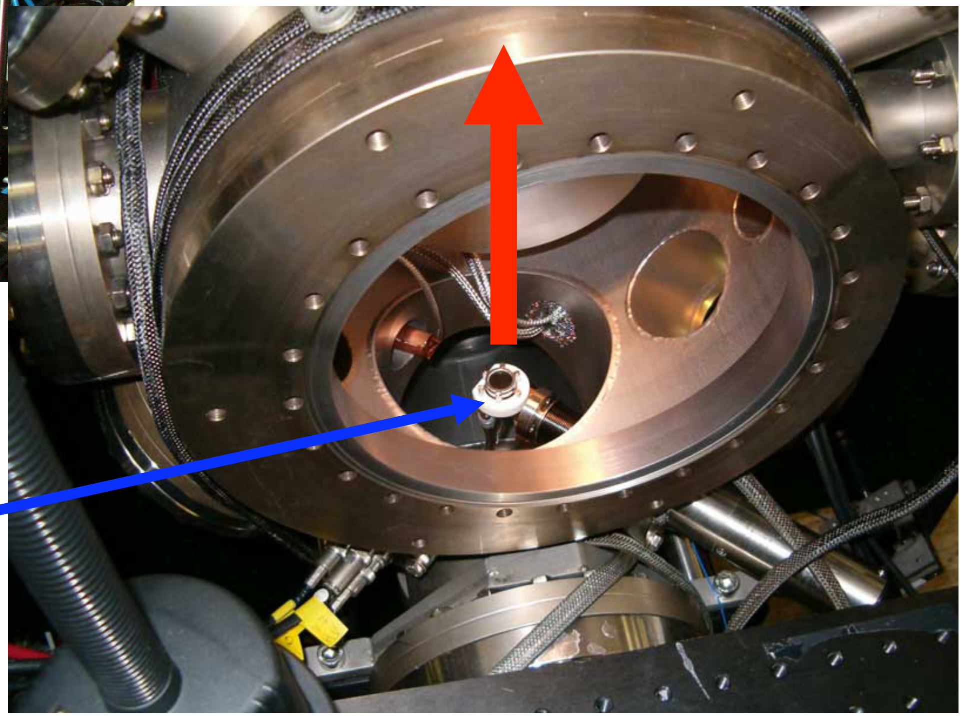
BEC ~ 7 x 10^6 atoms at ~ 1-5μK
Magnetic trap lifetime ~ 30s
Beam bender - shutter, no valve



VU Amsterdam He* BEC

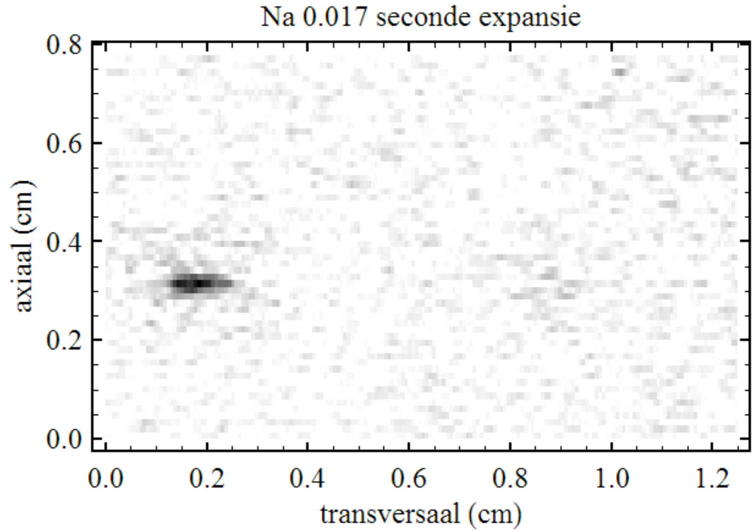


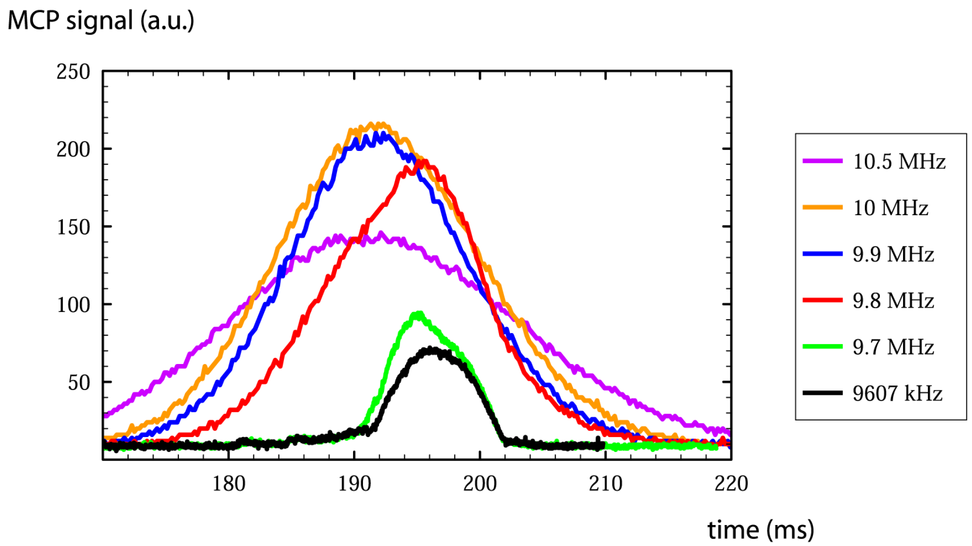
Absorption
Imaging
laser



Movable (20mm)
MCP ~ 17cm
below BEC

VU BEC results





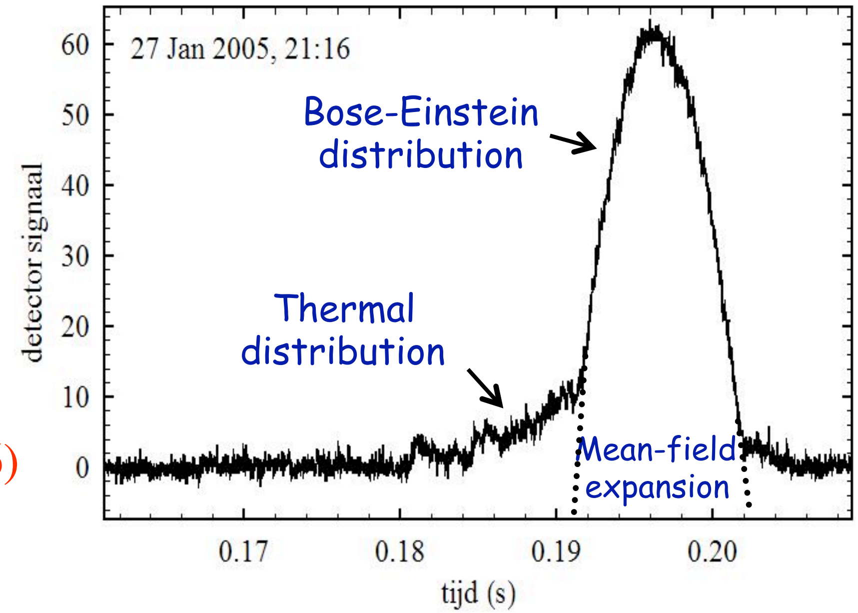
BEC ~ 8(2) x 10^5 atoms

(now > 10^7 atoms)

Magnetic trap lifetime ~ 180s

Beam bender - shutter, no valve

Tychkov et al., Phys. Rev. A **73,** 031603R (2006)



Lecture 2 Outline

LECTURE 2: METASTABLE HELIUM BOSE-EINSTEIN CONDENSATES

Why He* BEC formation is hard

- Penning ionisation
- He*-He* Scattering Length

He* BEC experiments at other labs (now including Vienna)

- Orsay
- ENS
- Amsterdam

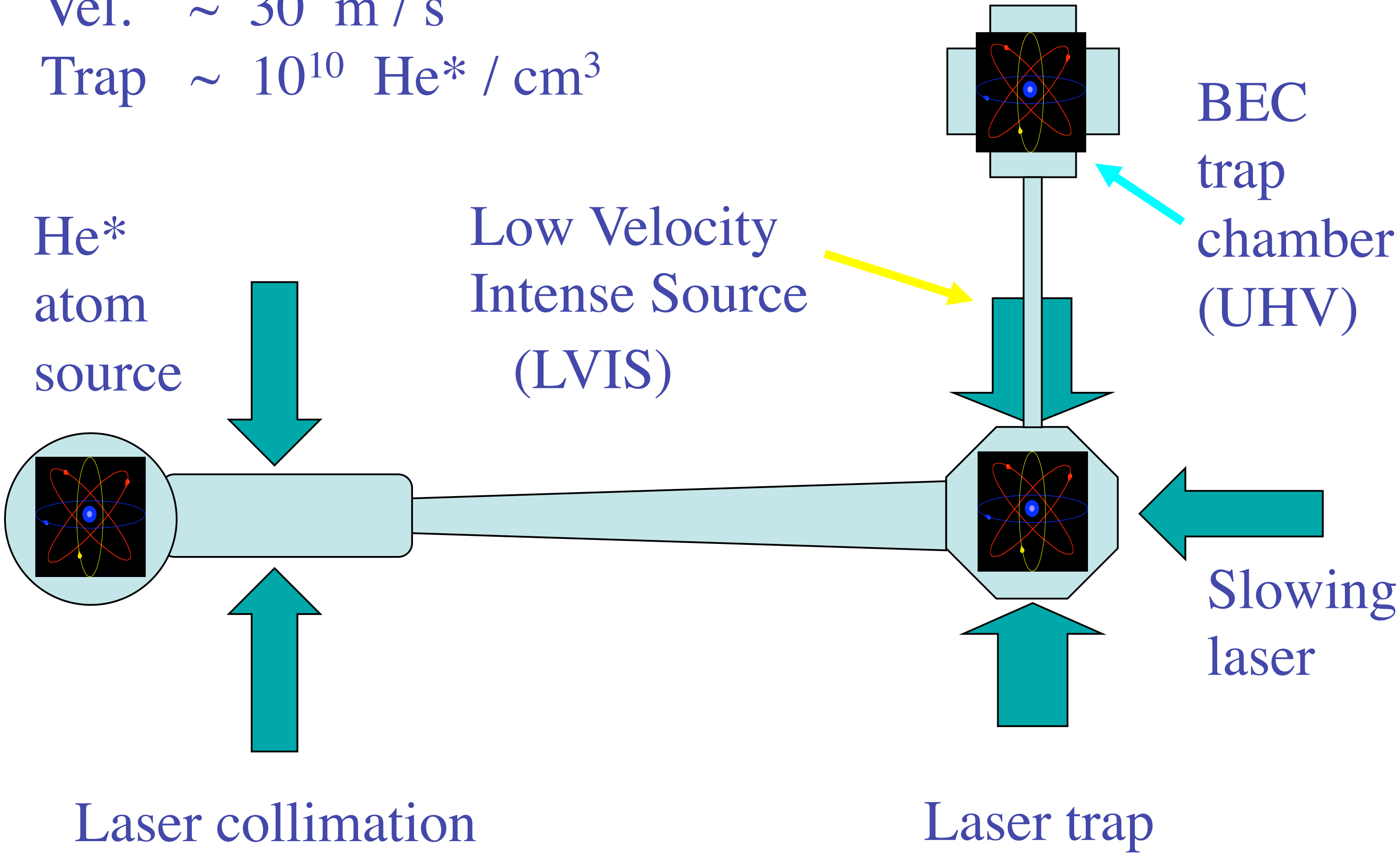
He* BEC experiments at the Australian National University

- Creating a BEC
- Creating an atom laser
- Stable and reproducible sources

BEC Bright Beam System

Swansson et al.; Applied Physics B; Rev. Sci. Inst. 77, 046103 (2006)

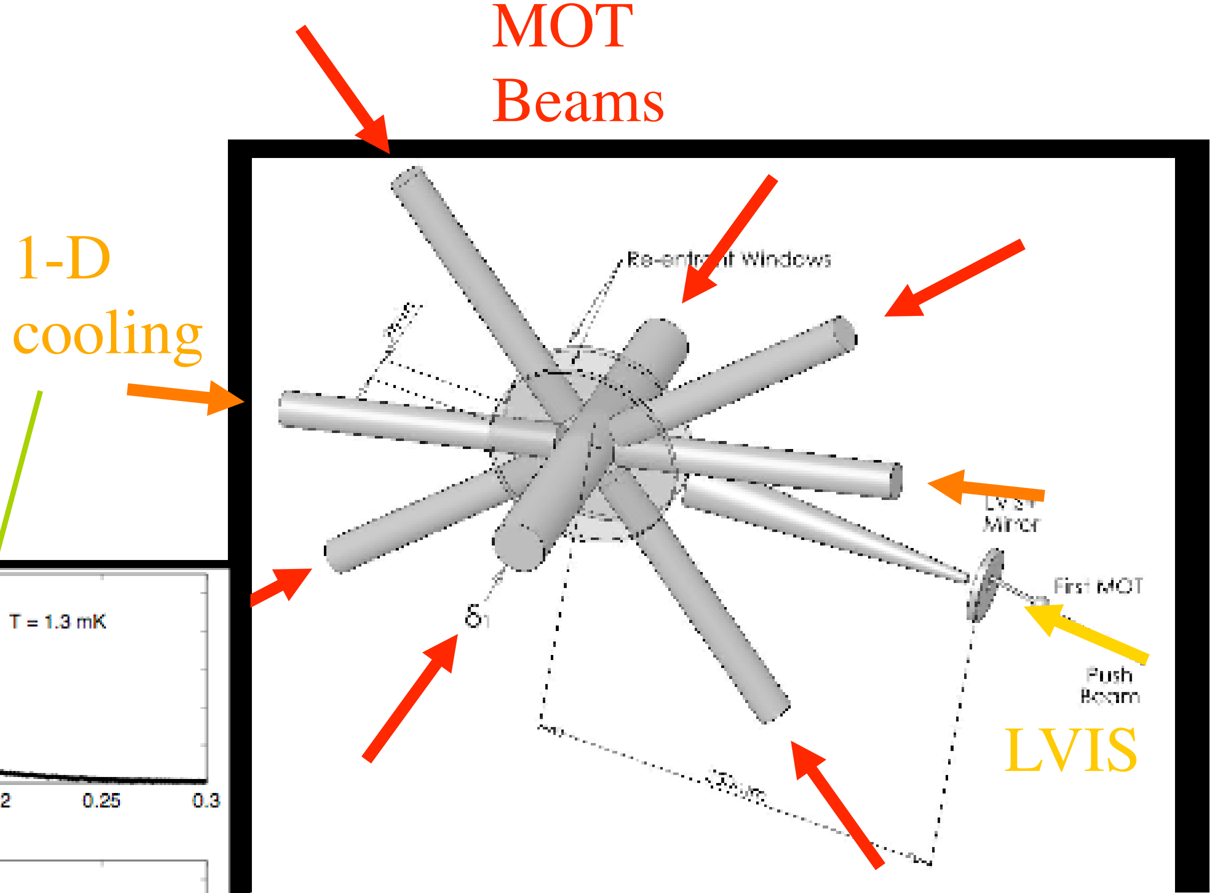
LVIS ~ 2 x 10^{10} He* / s
Vel. ~ 30 m / s
Trap ~ 10^{10} He* / cm^3

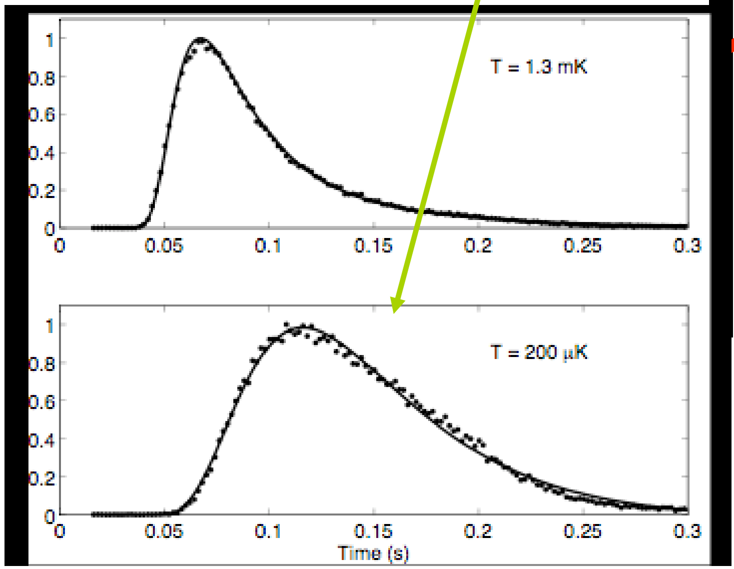


2nd MOT and 1-D cooling

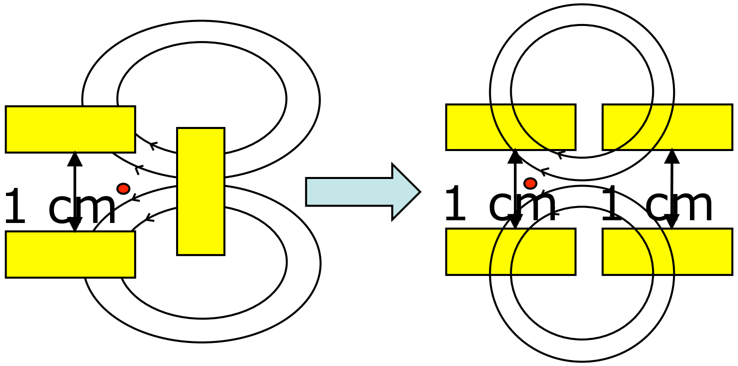
Load 5 x 10^8 He* from LVIS into second MOT

1D cooling:
Schmidt (Stuttgart, 2003)
Vassen (Amsterdam, 2005)

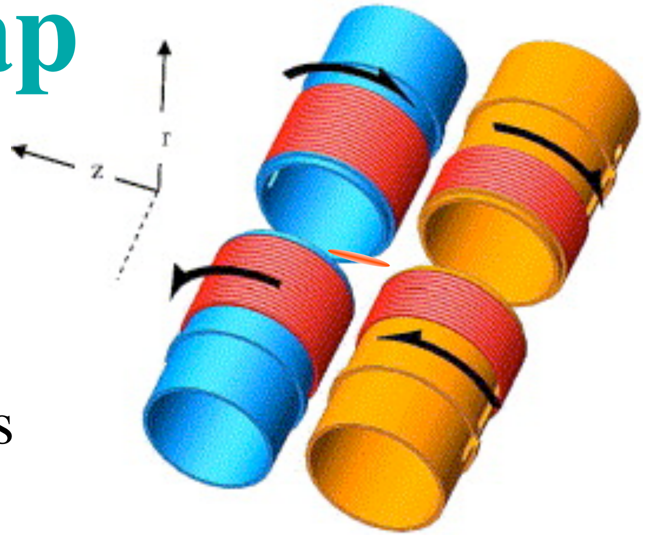


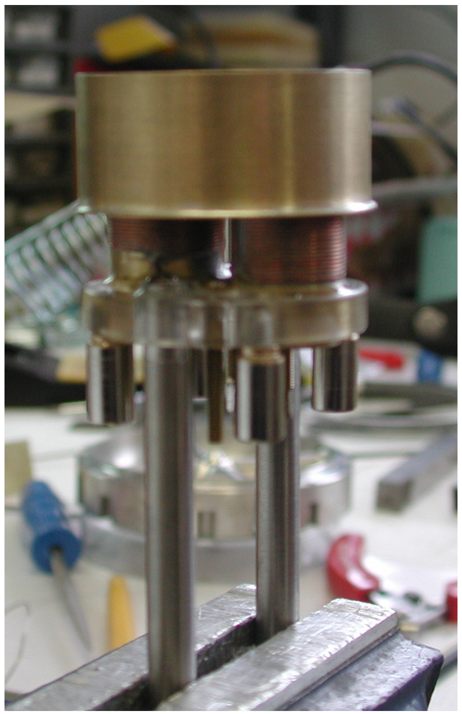


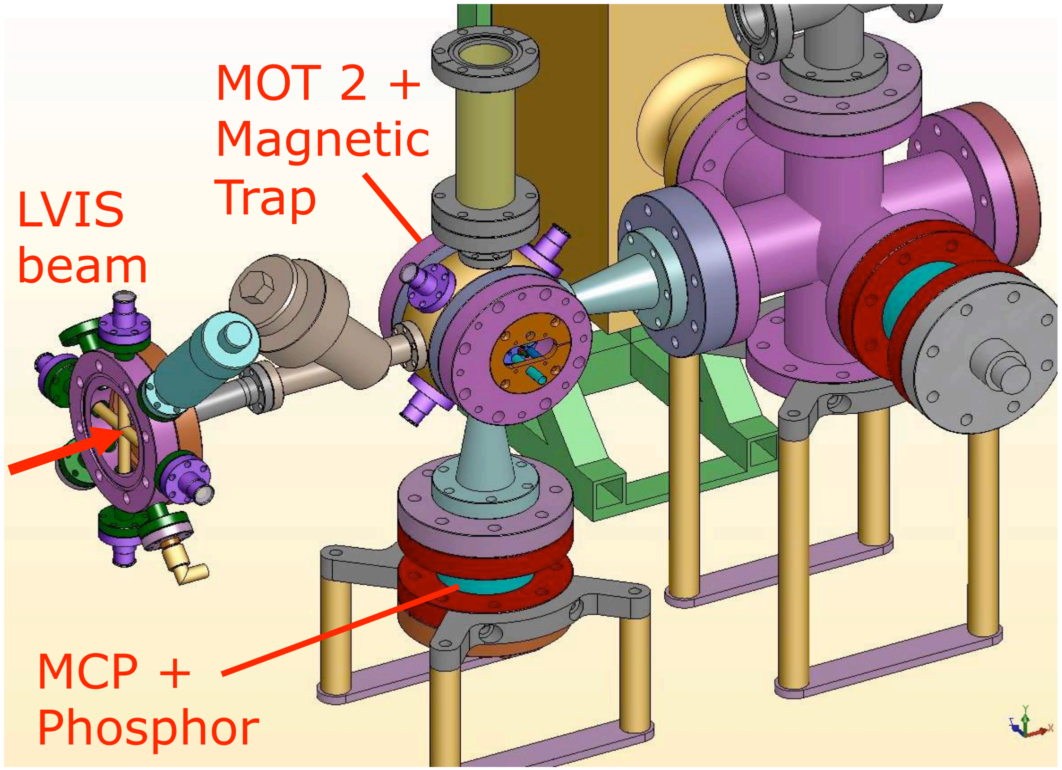
BiQIC Magnetic trap



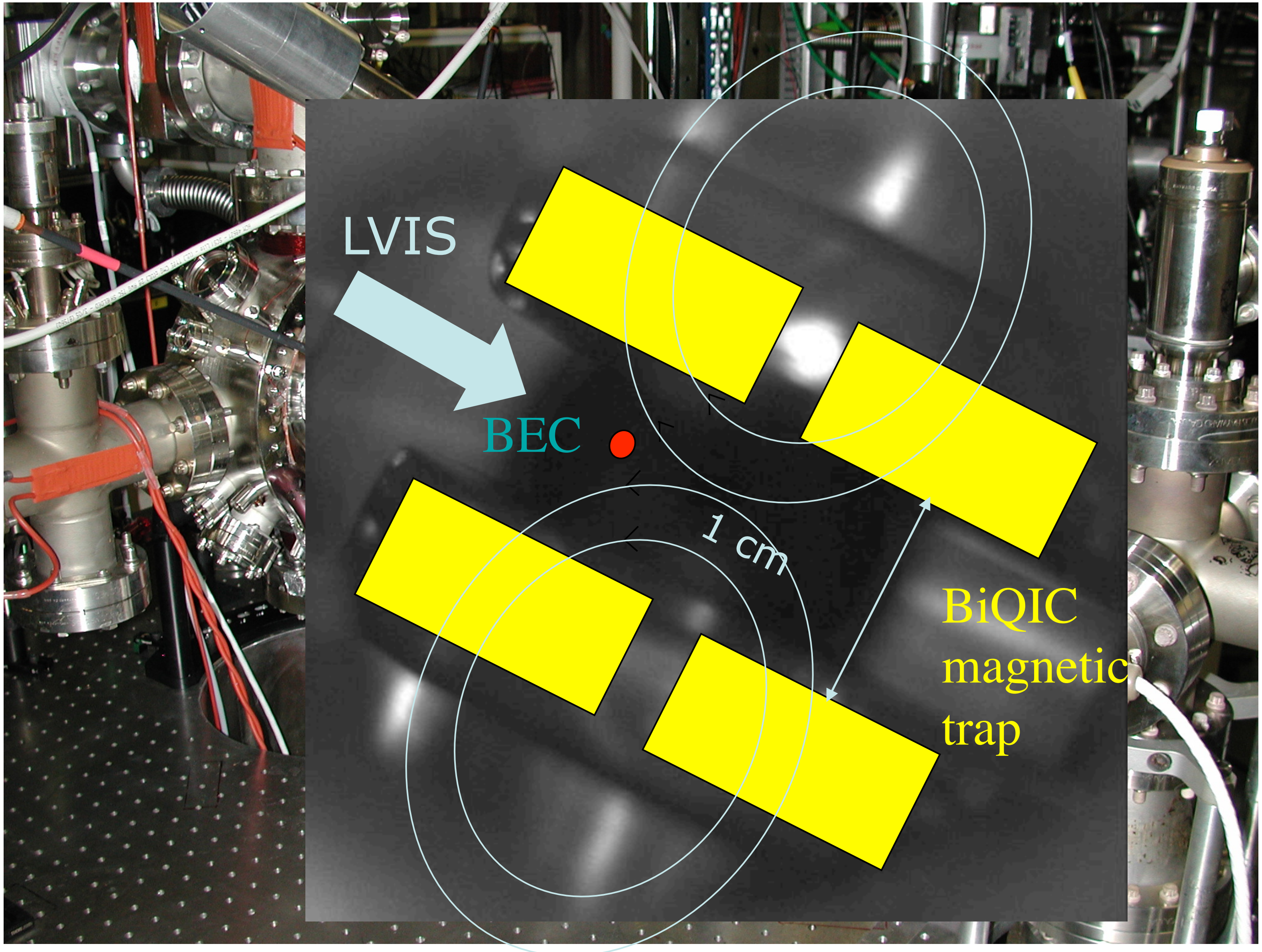
Equivalent coil configurations



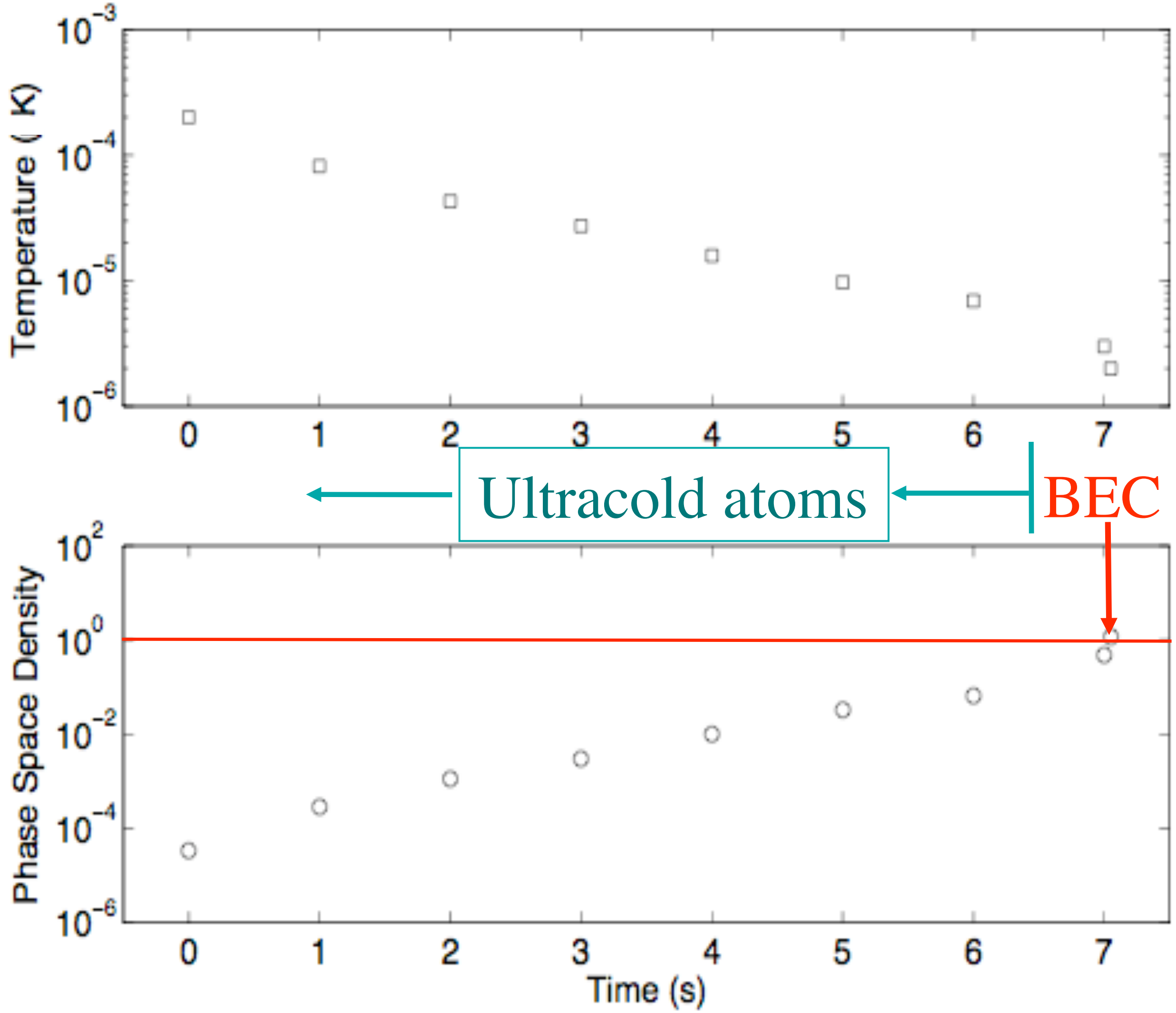




MOT, LVIS + BEC chamber



Temperature and Phase Space Density

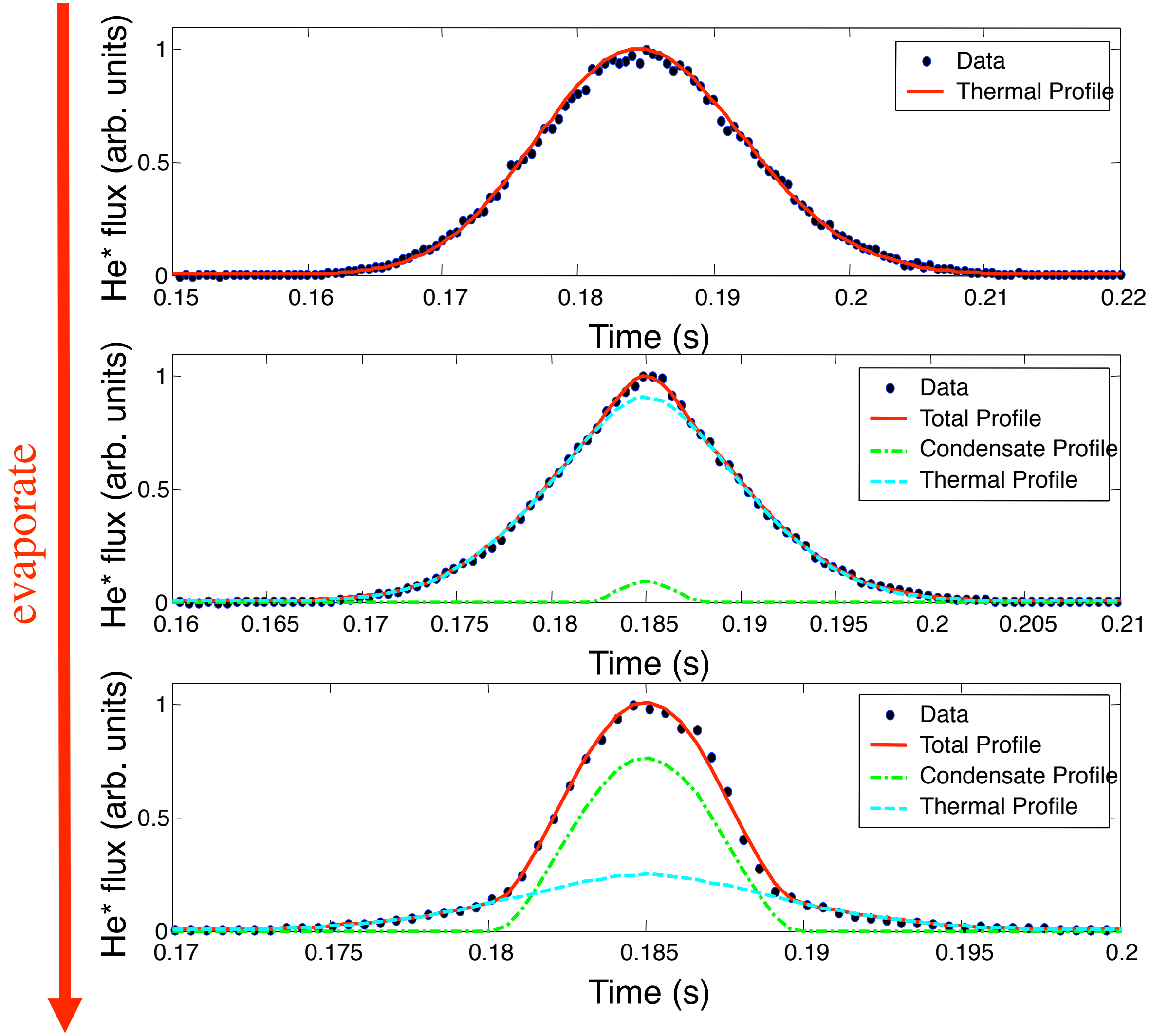


BEC time-of-flight signals

- Start with ~ 1 x 10^8 He* in magnetic trap, and with T ~ 200 μK

- Finish evaporation with ~ 2 x 10^6 He* atoms at transition temp. T_c ~ 2 μK

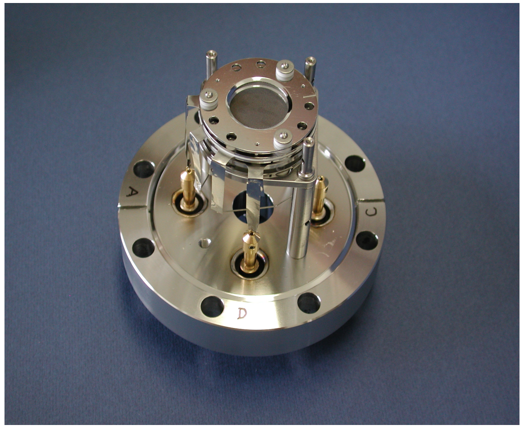
- At just < T_c we have ~ 10^6 He* in BEC

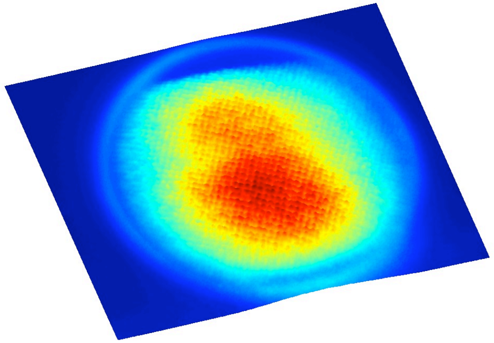


R.G. Dall and A.G. Truscott, Optics Comm. **270**, 255 (2007)

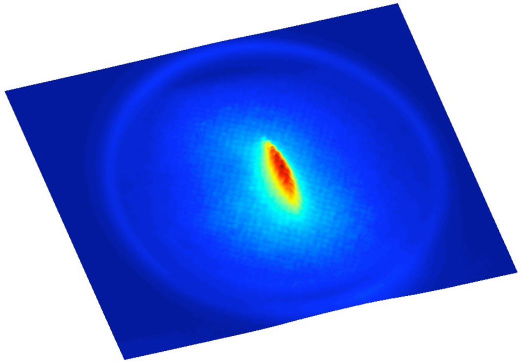
BEC spatial images

MCP 2-D detector

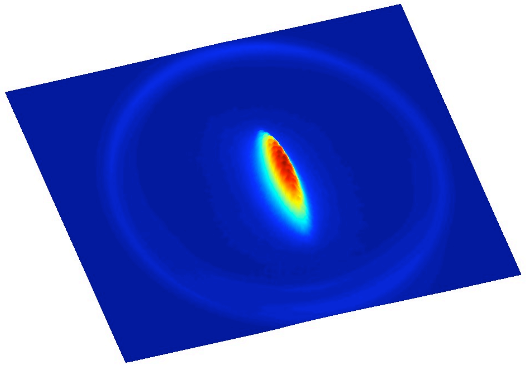




T > T_c

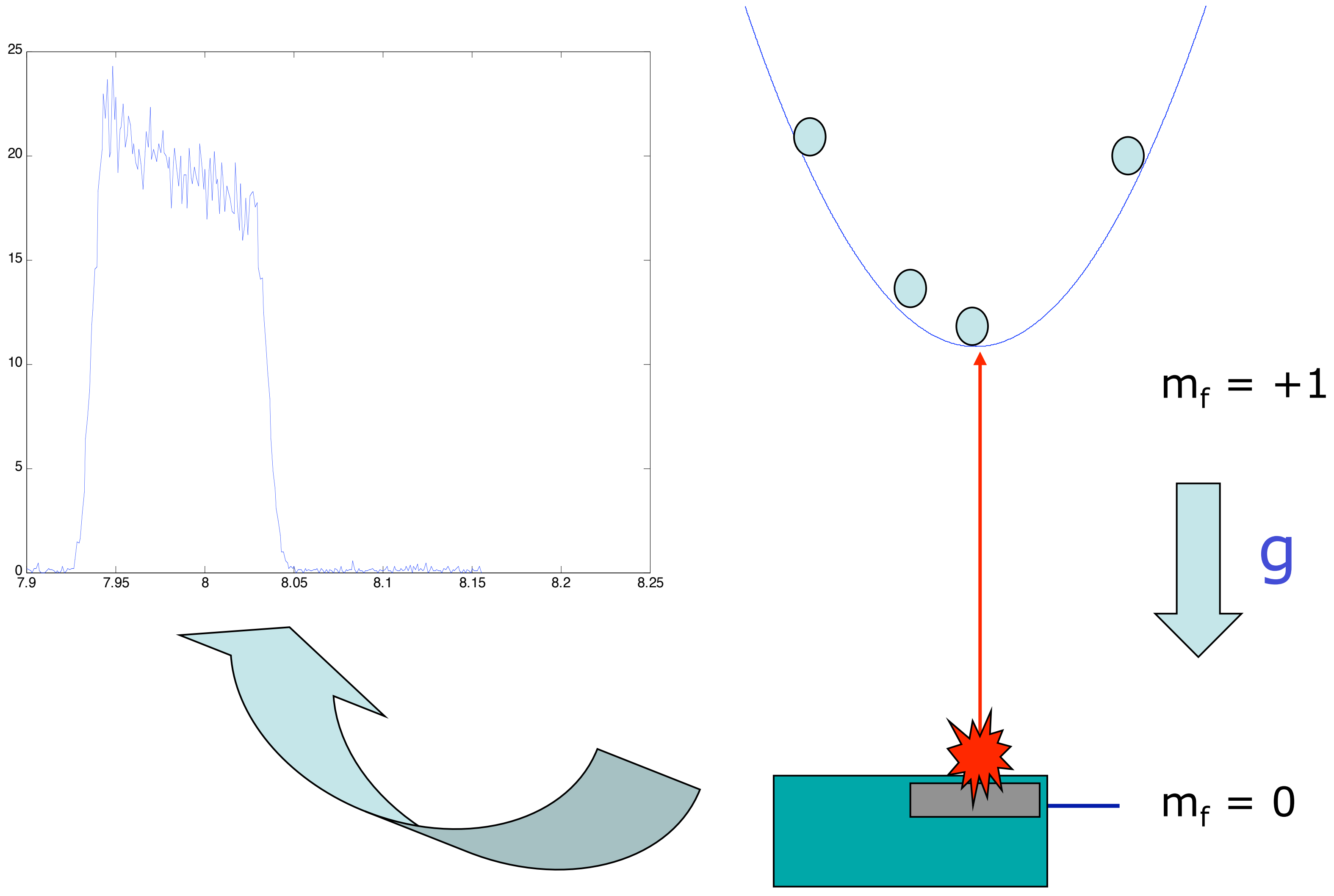


T < T_c

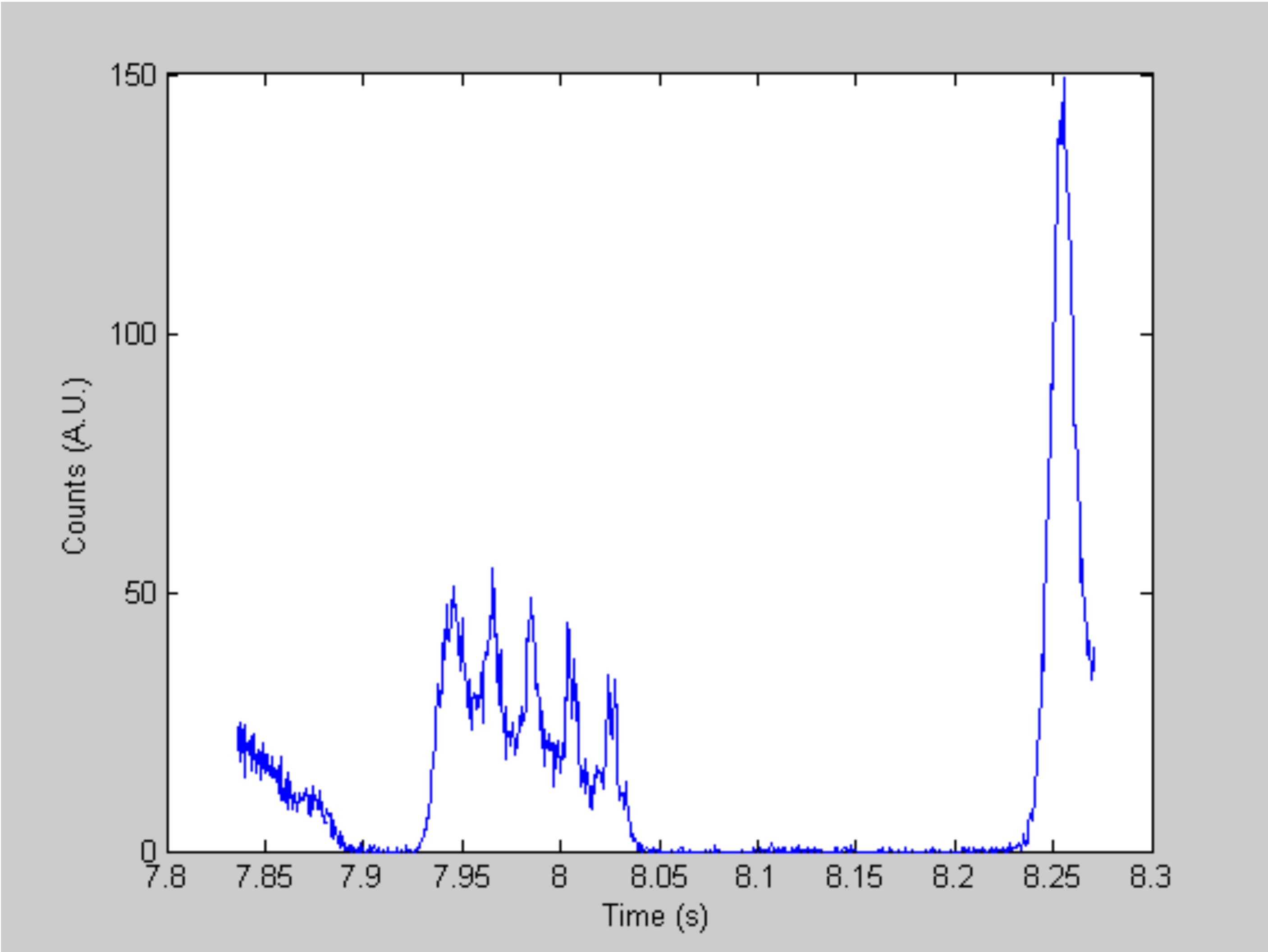


T ~ $0.3T_c$

RF output coupling Atom Laser



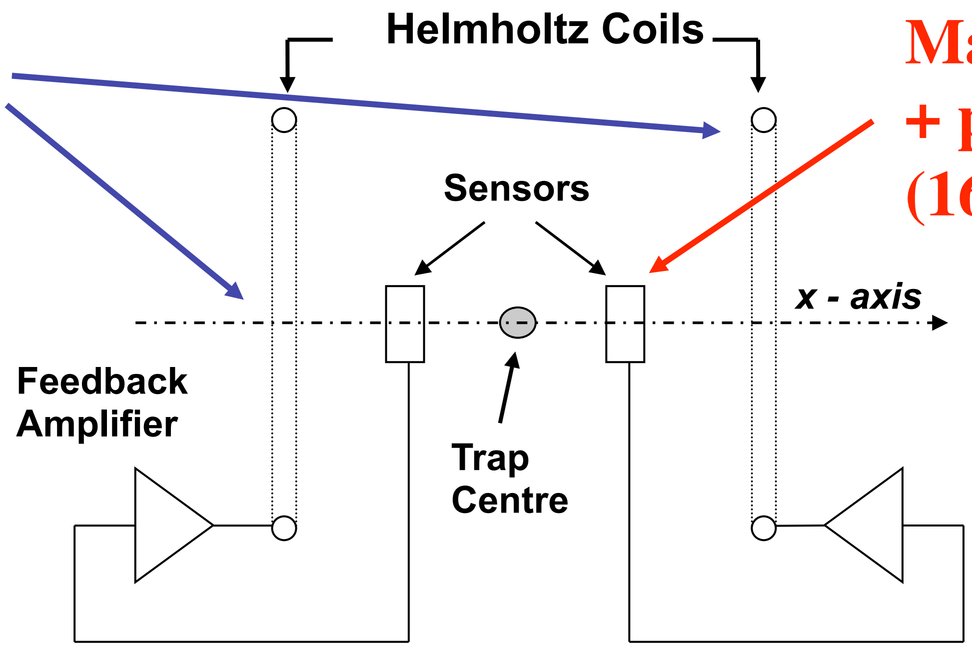
50 Hz magnetic field noise



Magnetic Field “Nuller” Schematic

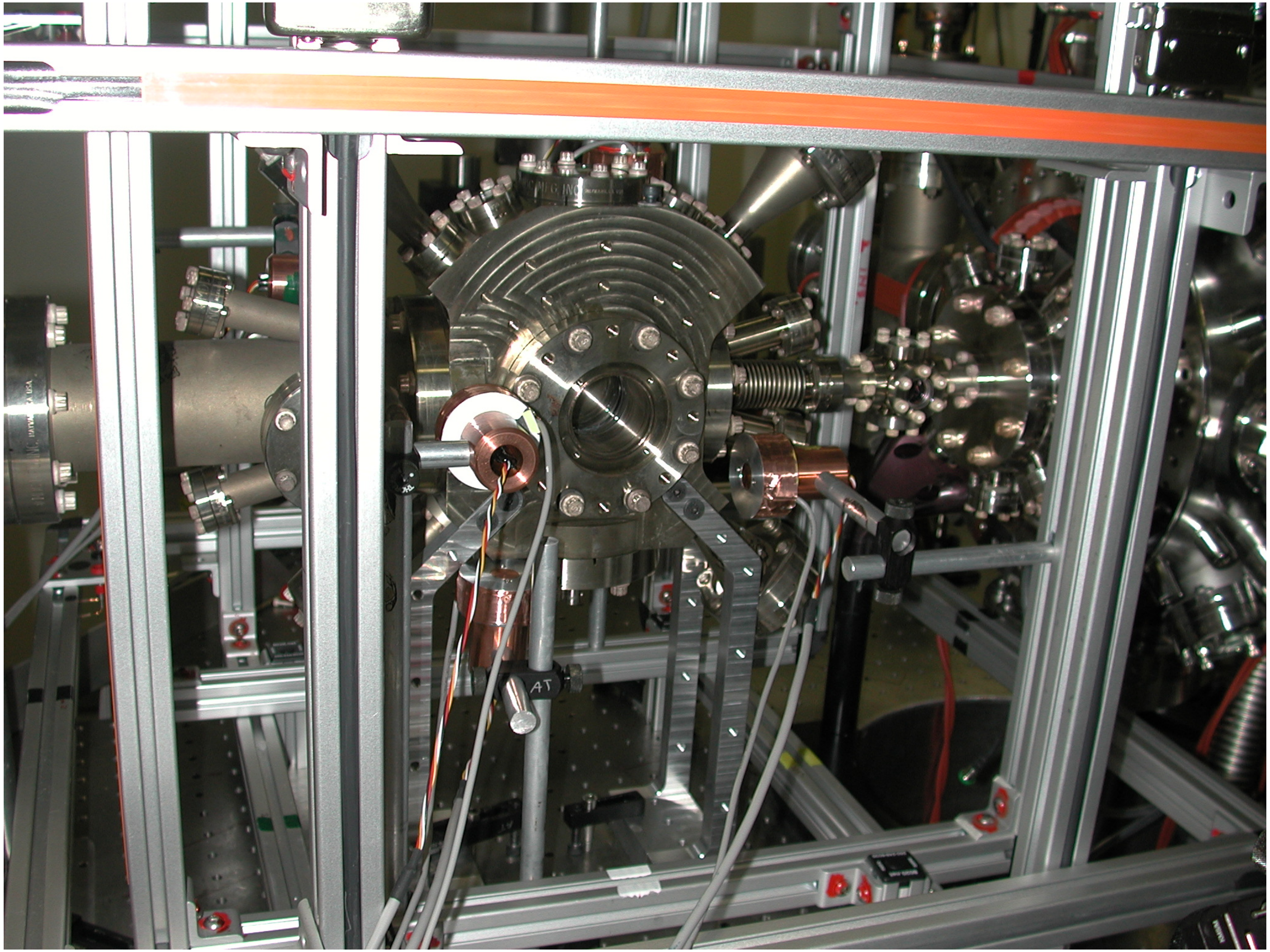
Separate feedback circuits

Magnetic flux gate + pickup coils (16Hz crossover)



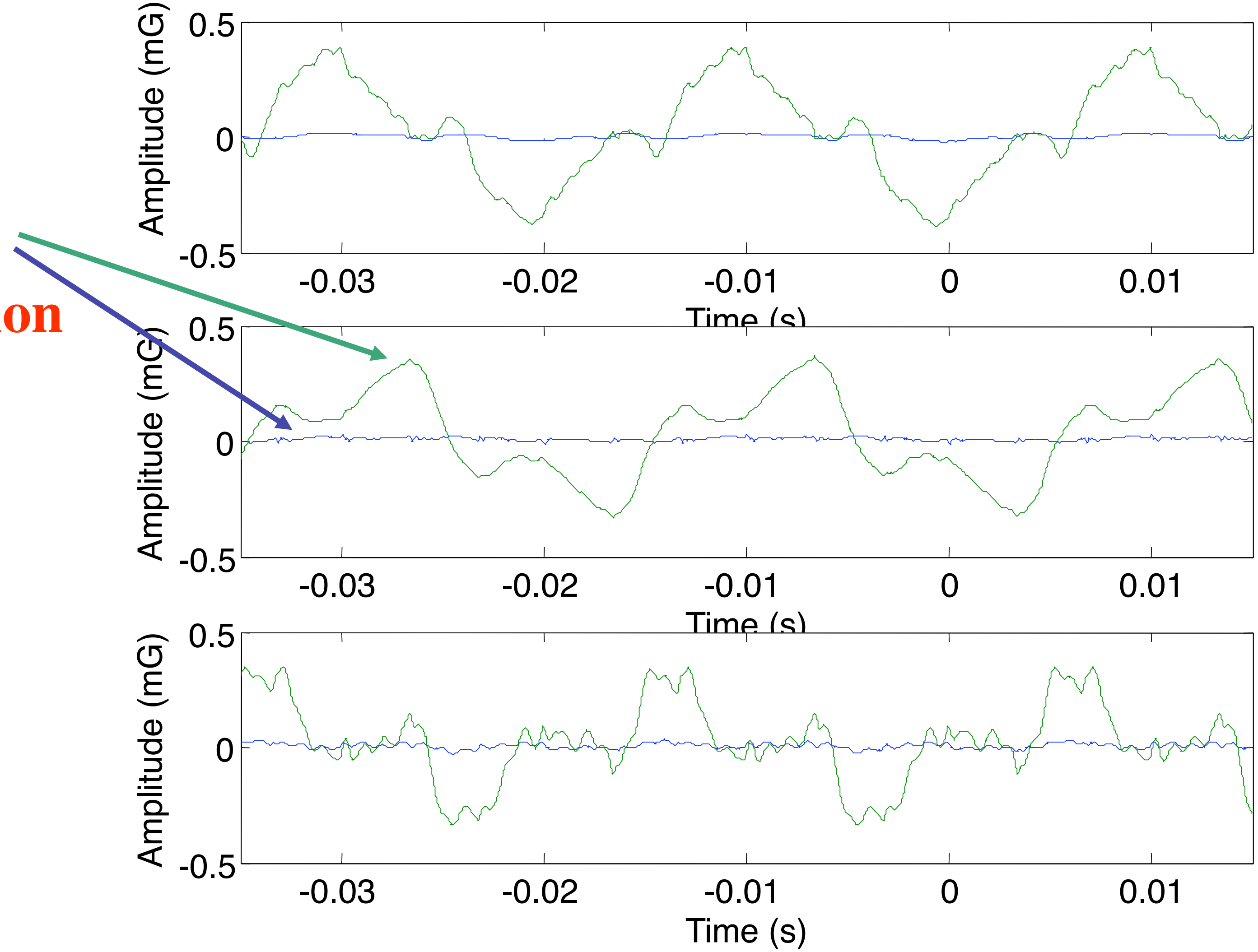
C.J. Dedman, R.G. Dall, L.J. Byron, and A.G. Truscott, Reviews of Scientific Instruments in press (2007)

Nuller installation

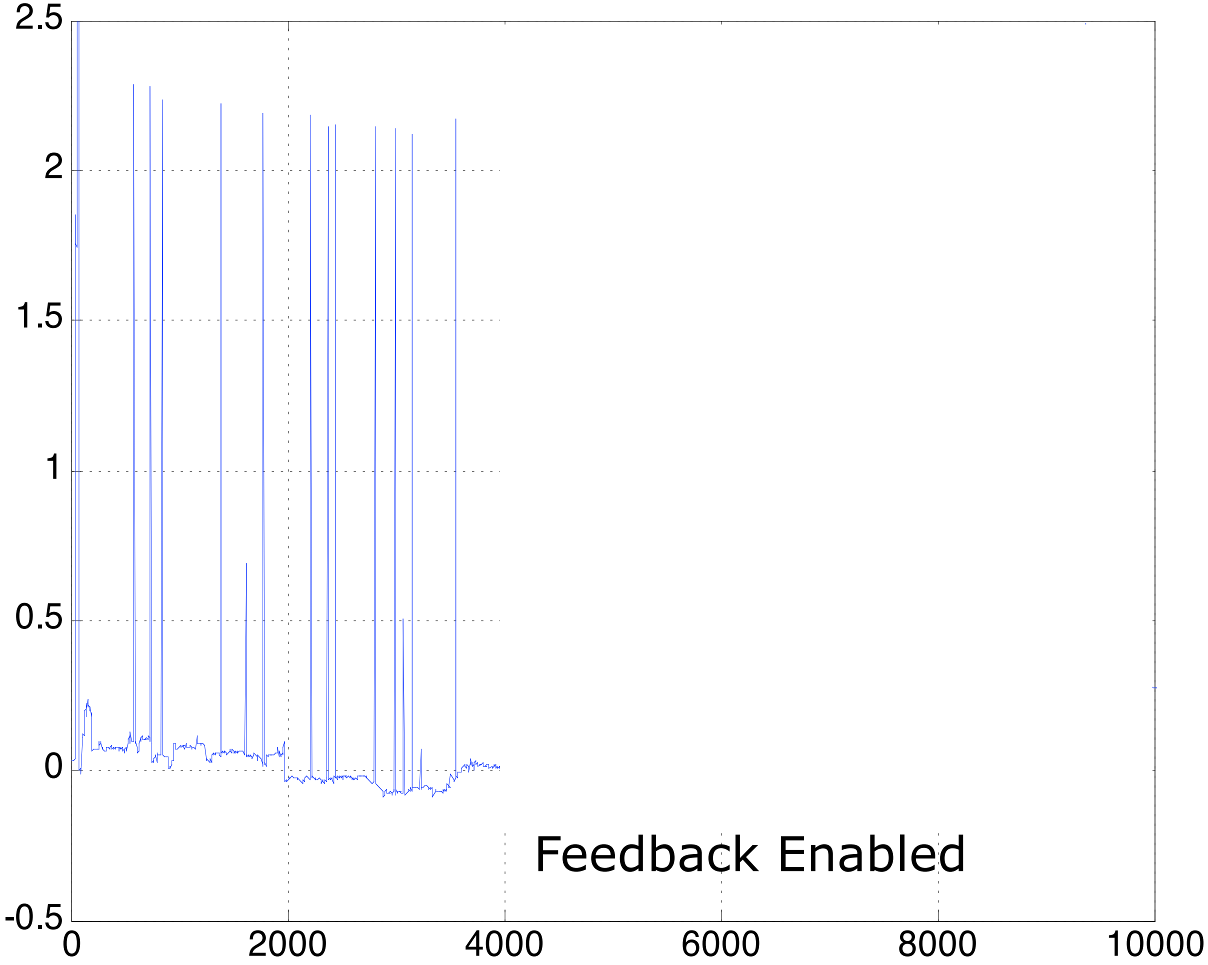


AC Magnetic Noise at trap

25 times suppression



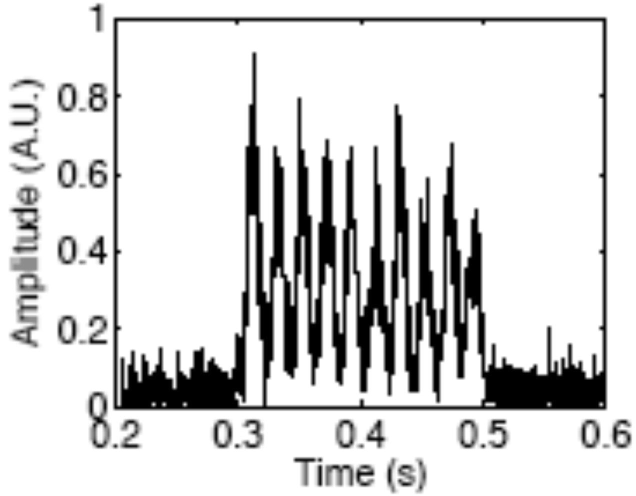
DC magnetic noise



Atom Laser Noise

Without stabilisation

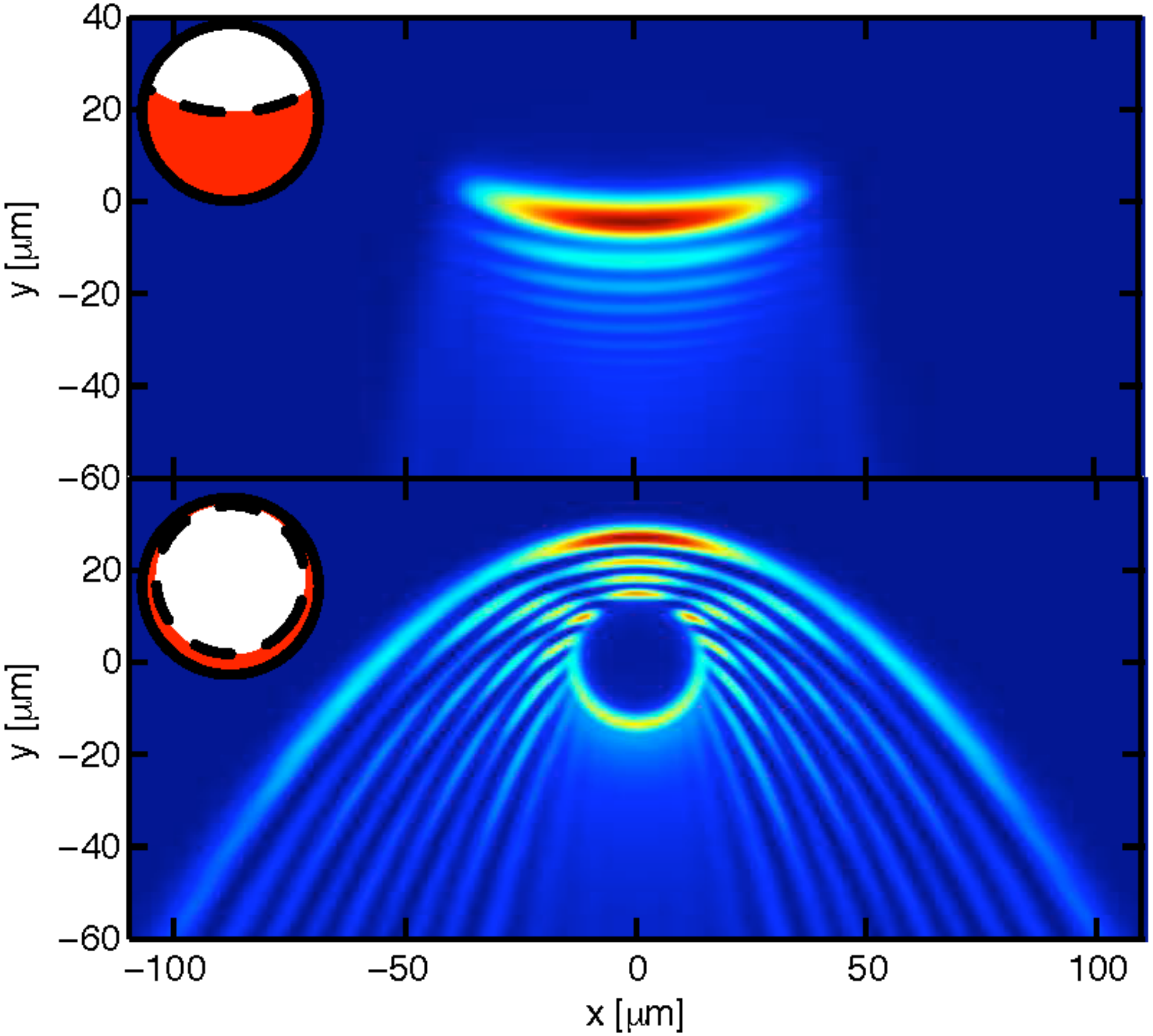
Atom laser output



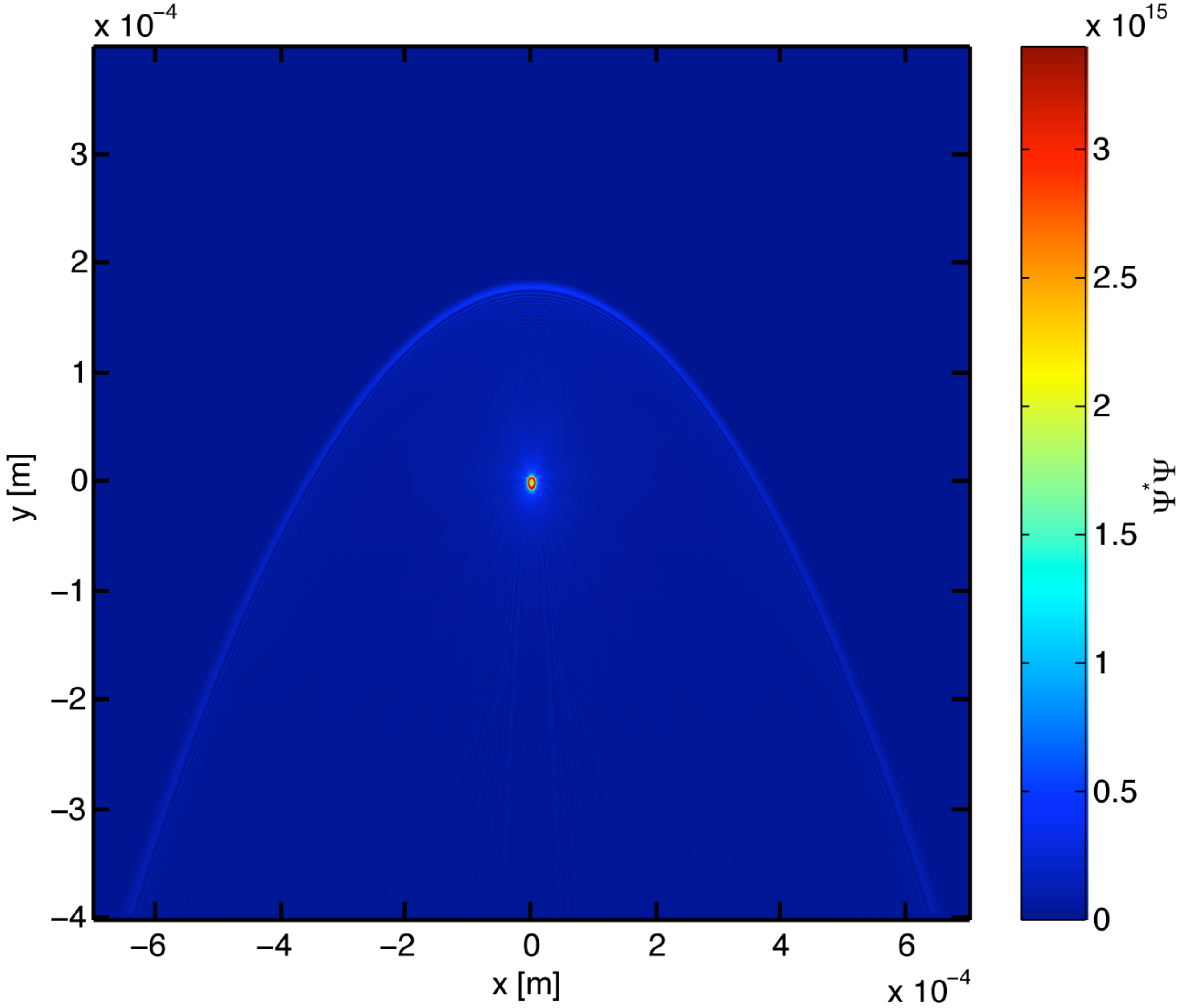
Rb vs. He*: out-coupling surfaces

Rb atoms experience a large sag - almost flat out-coupling surface

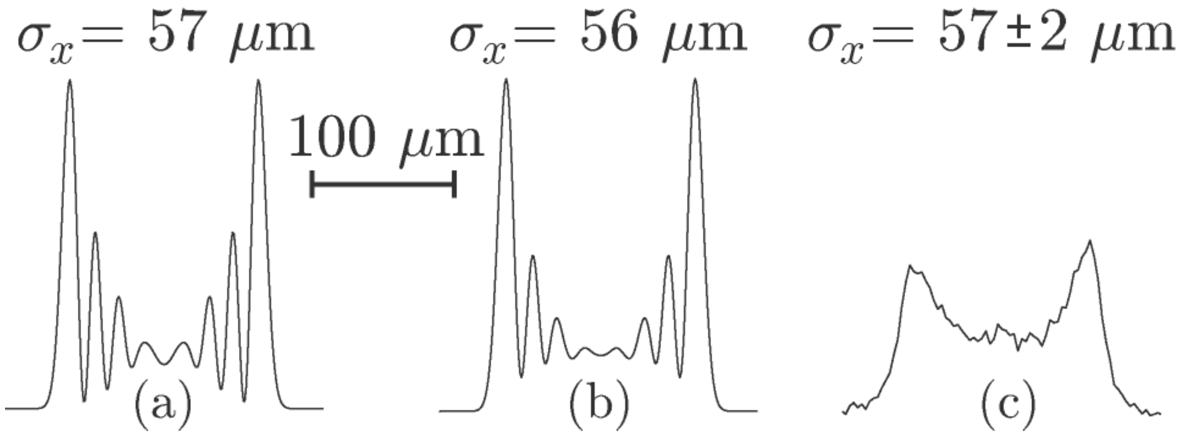
He* atoms experience little sag - spherical shells



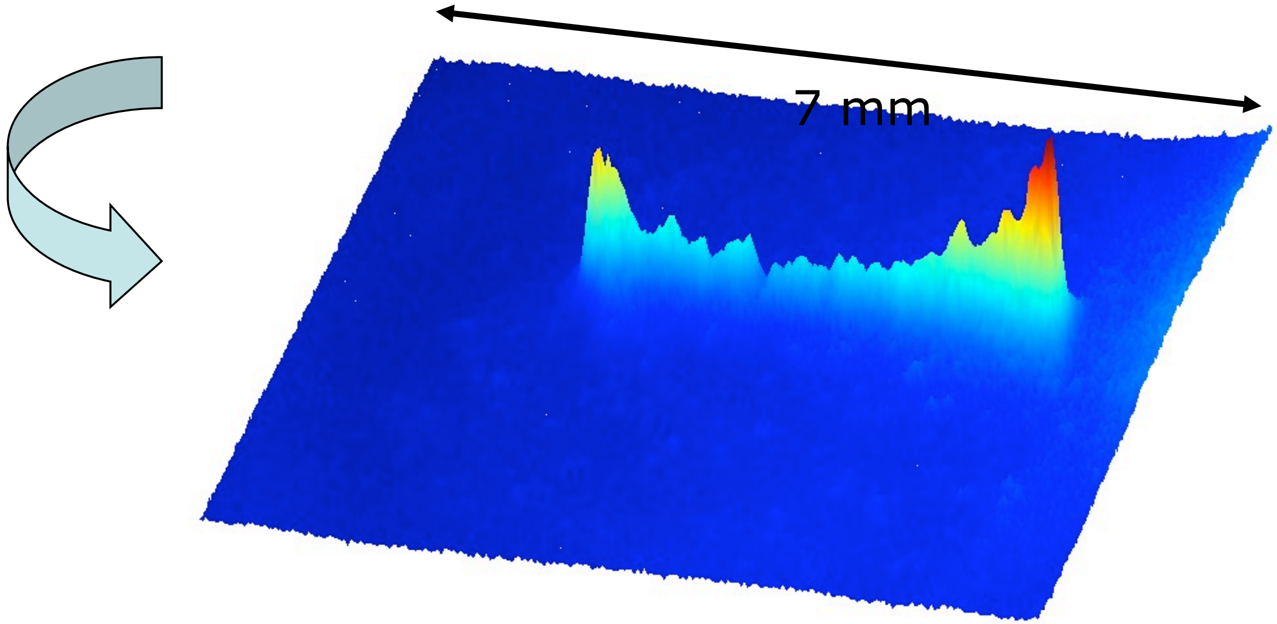
Fountain Effect



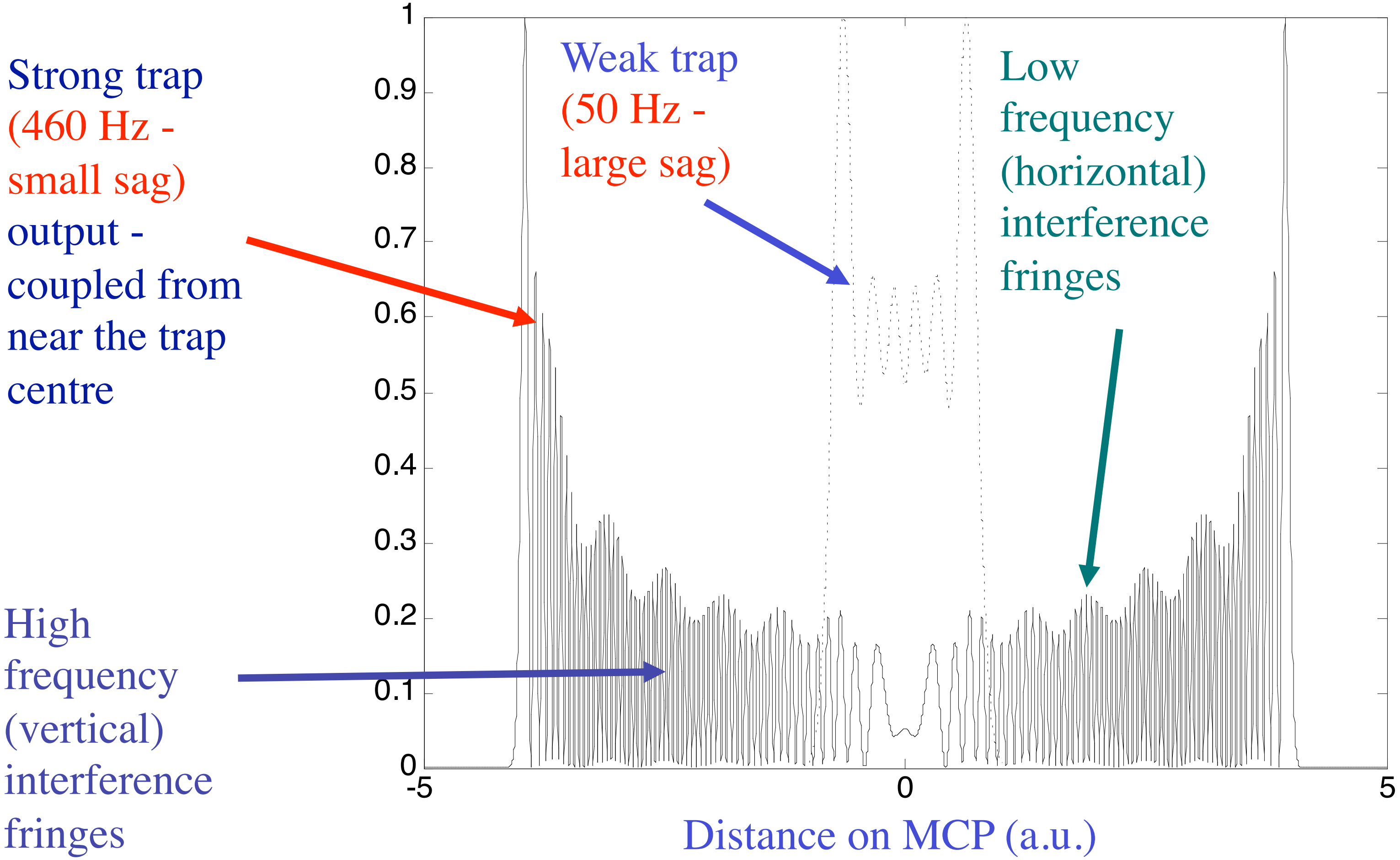
Atom Laser transverse profile



Riou et al.
PRL (2006)

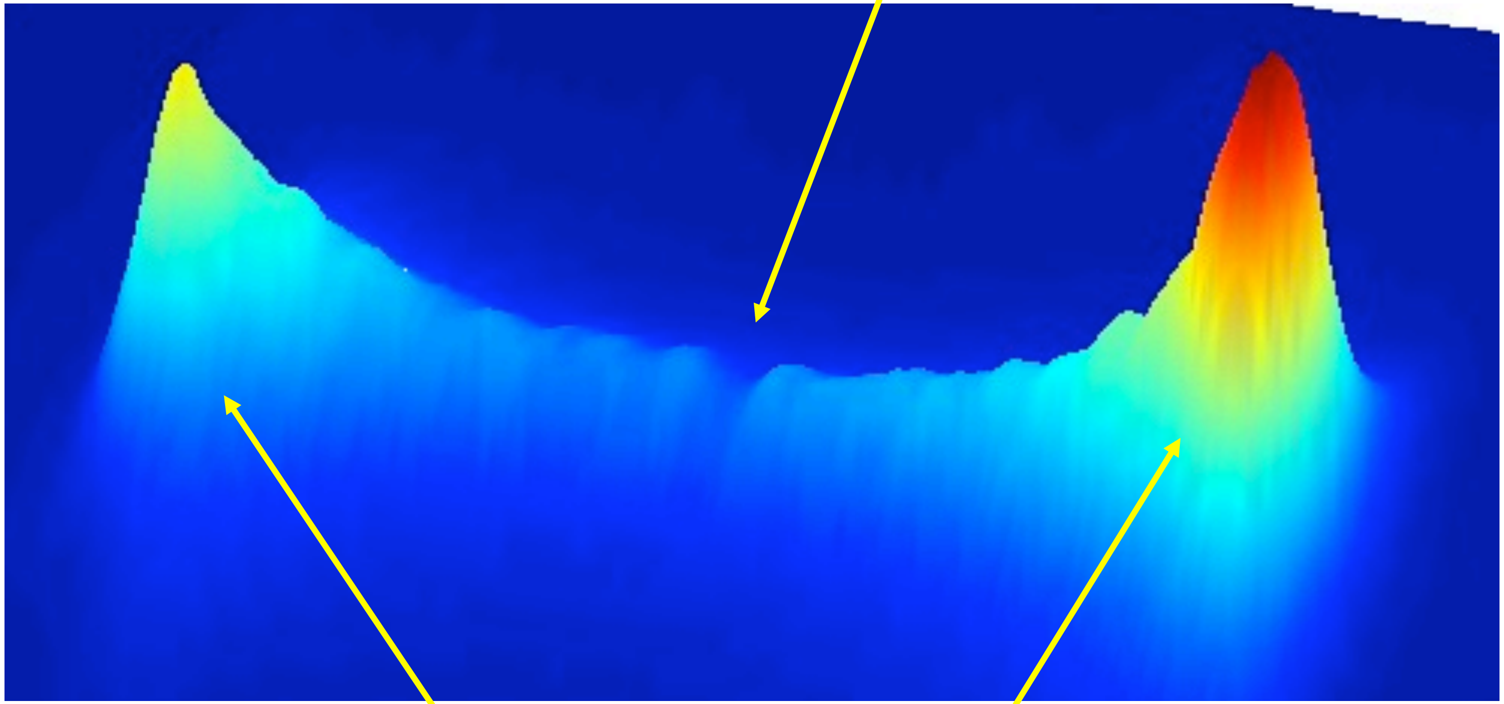


Simulated atom laser transverse spatial profiles



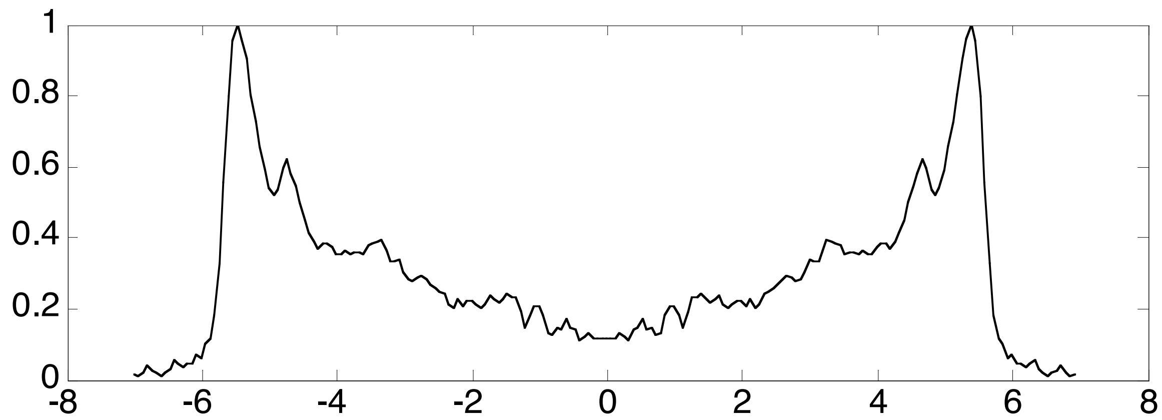
Atom Laser Profile

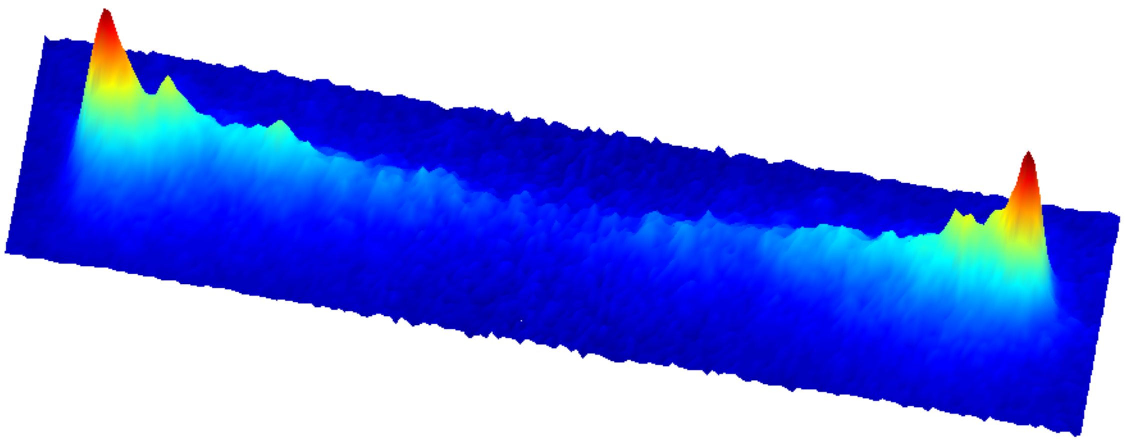
Dip in shadow of BEC



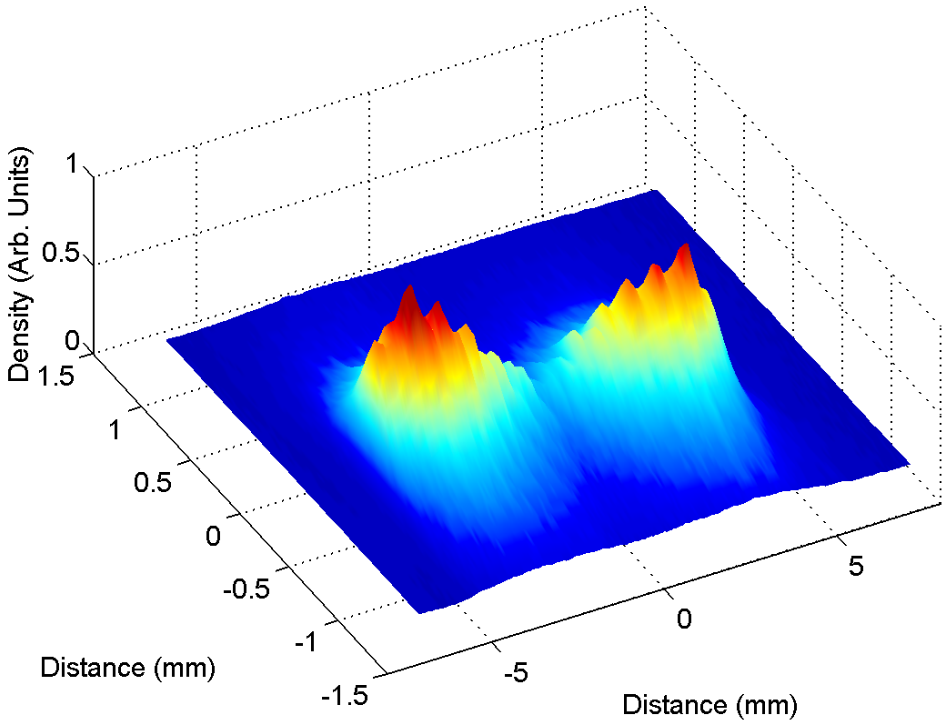
Twin peaked structure

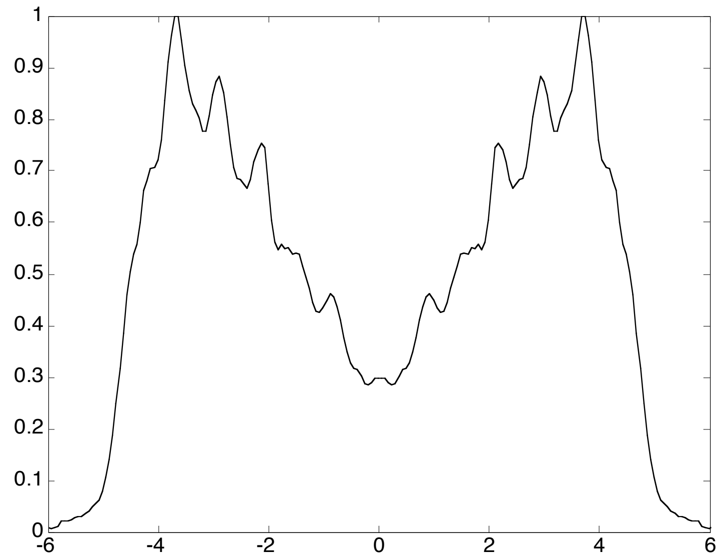
First observation of fringes





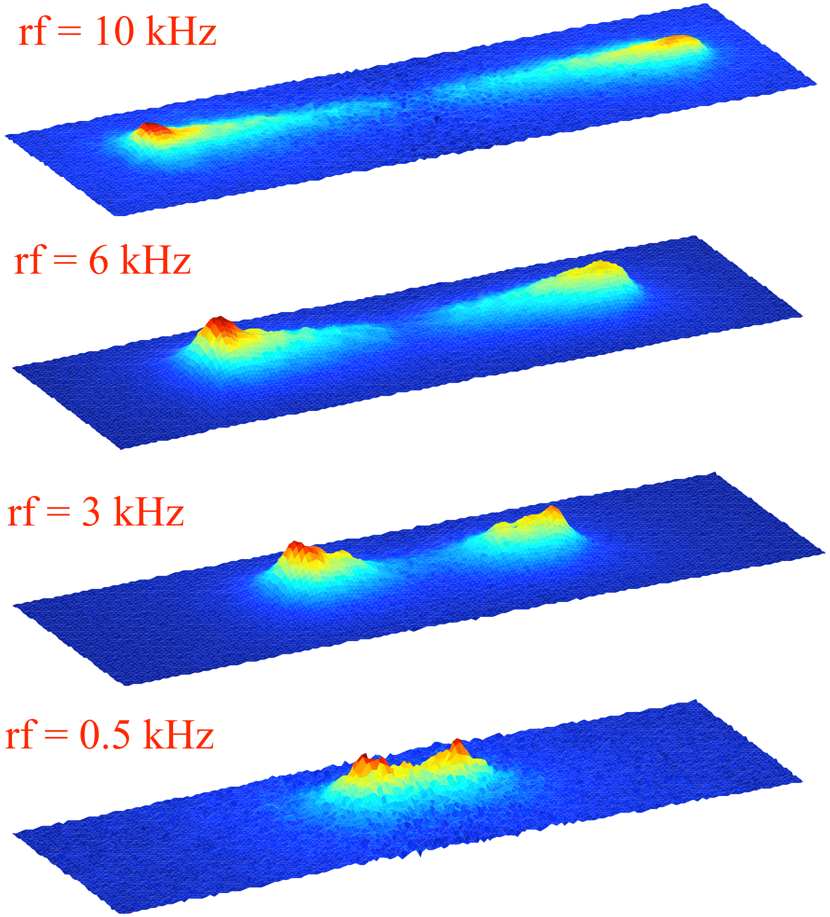
High output-coupling fringes



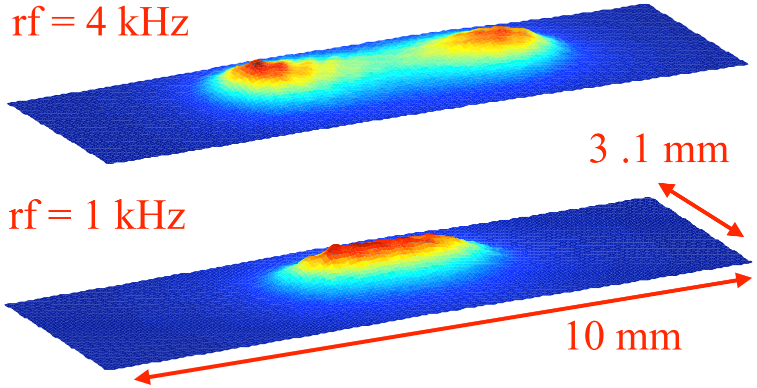


Profiles for two radial frequencies

$f_r = 460$ Hz



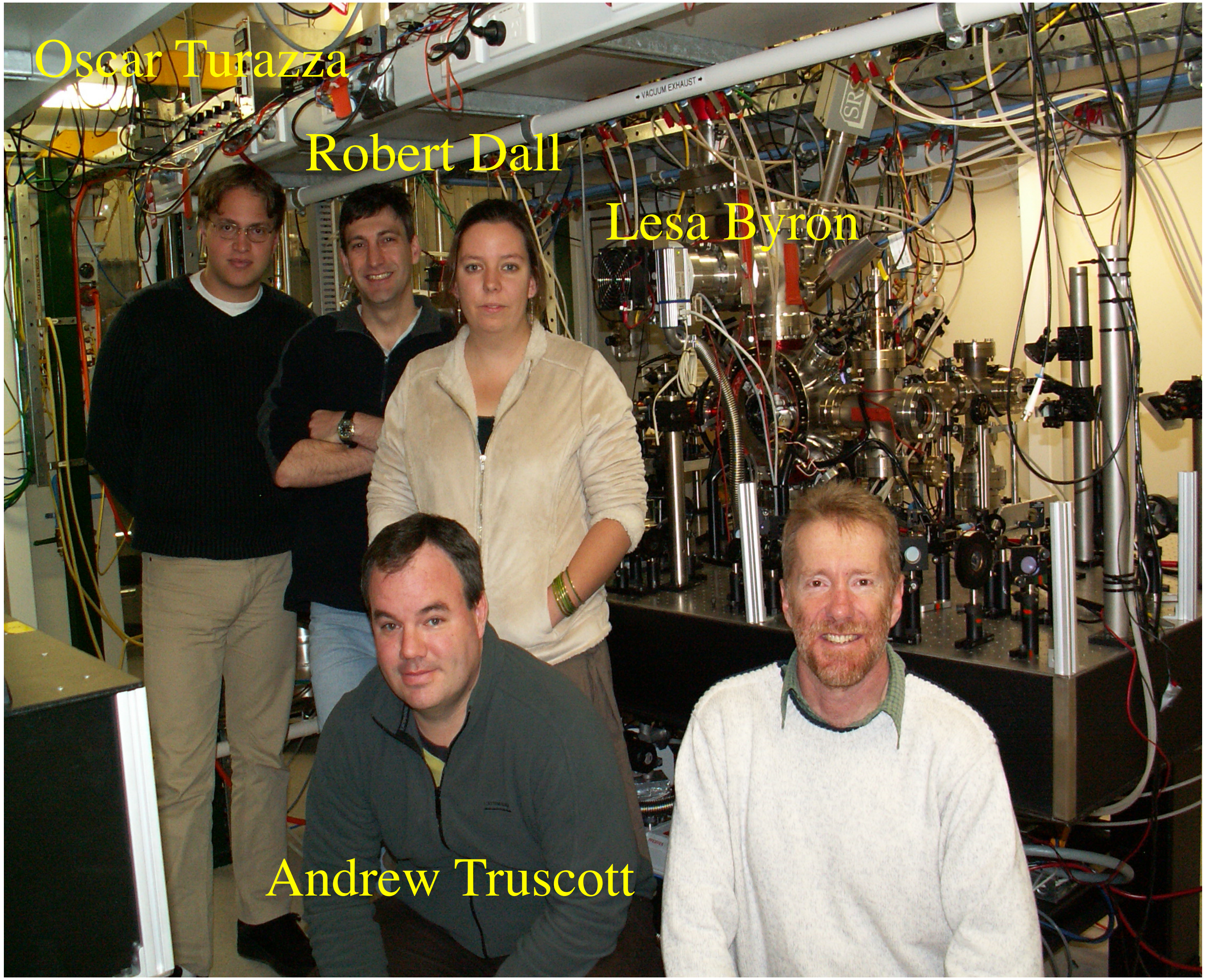
$f_r = 113$ Hz



He* Atom Laser: Conclusions

- Measured spatial profile of a He* atom laser
- Observed predicted interference fringes for the first time
- Atom laser beam not ideal - highly multimode transverse spatial profile

ANU He* BEC experiment

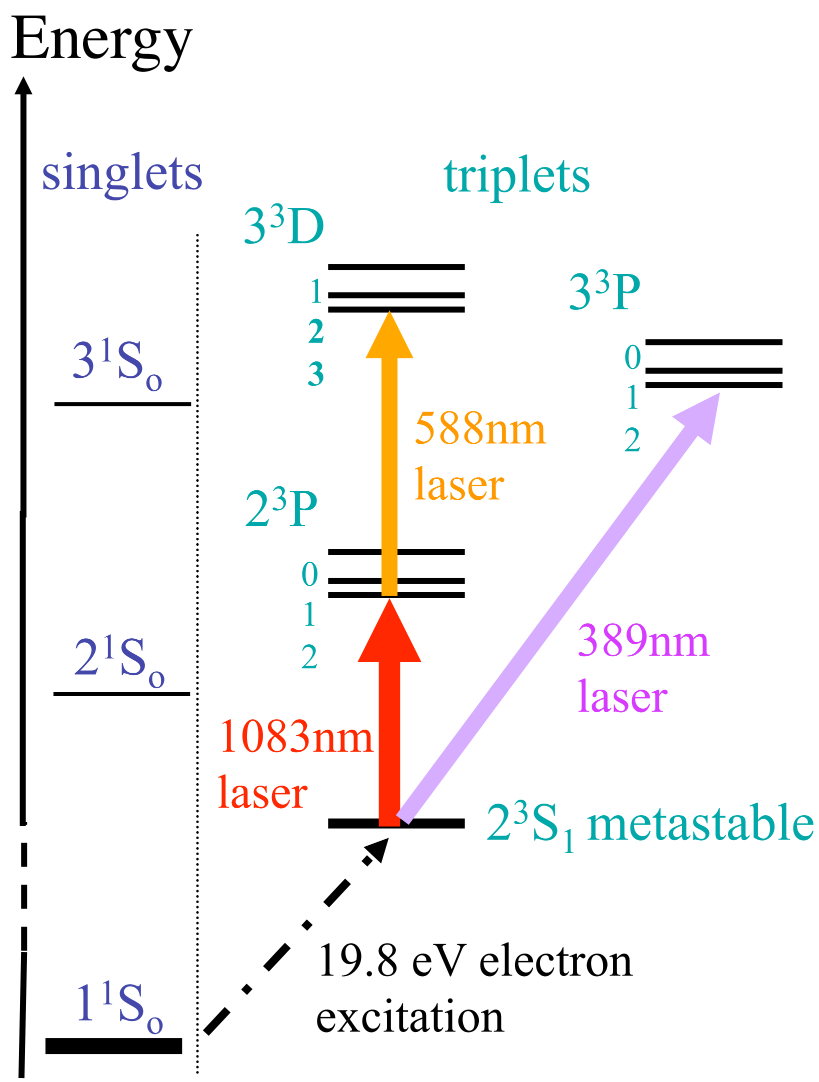


Lecture 3:
Tuesday June 26, 14.00

QUANTUM STATISTICS, COHERENCE AND CORRELATIONS

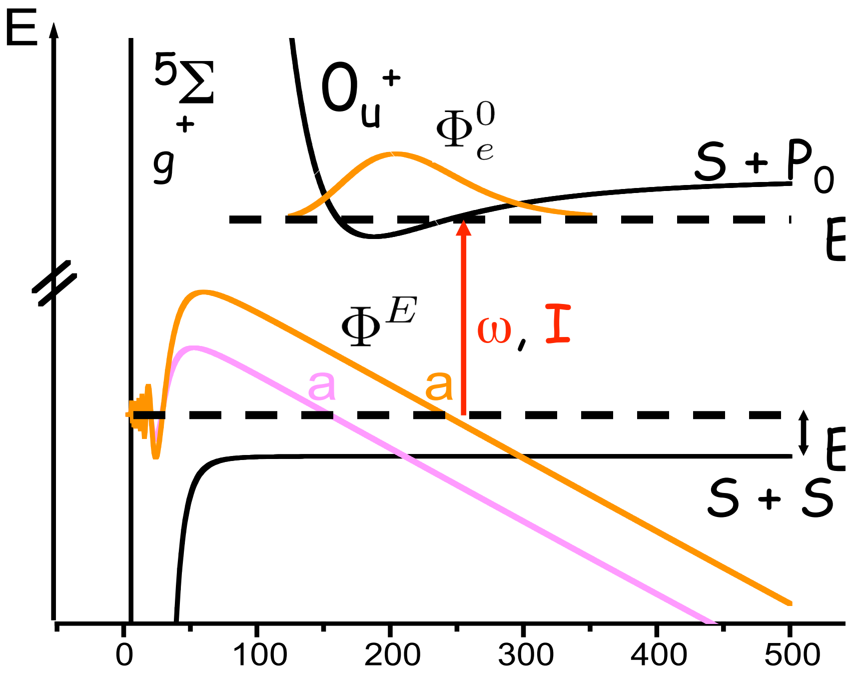
Metastable Helium Properties

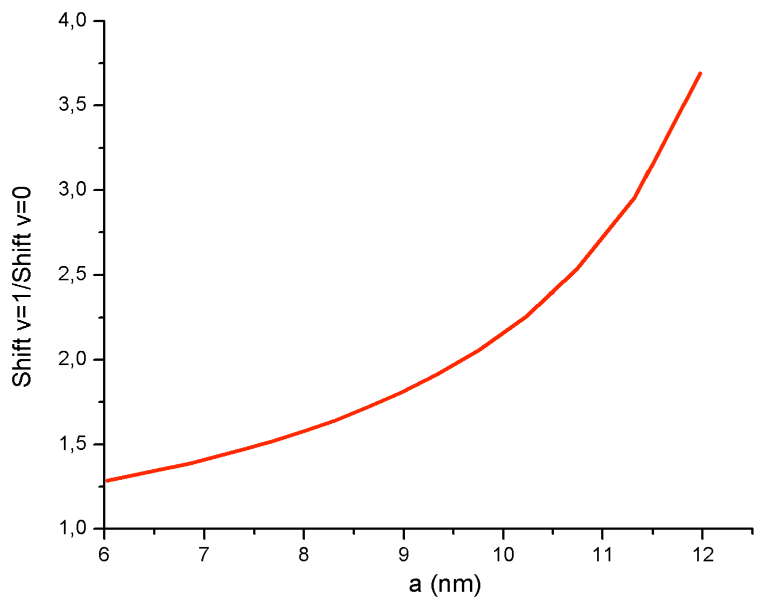
- He* is an important energy pool in astrophysical, atmospheric and plasma physics because of its
  - long 2^3S_1 lifetime ~ 8000s
    - spin flip and ΔL forbidden
    - longest lived metastable
  - ~ 20 eV stored energy
    - easy to detect single atoms
    - MCP, EM, metal plate ~70%
  - large ~ 100's nm^2 x-sections
    - long range potentials
- We excite He* atoms to the 2^3S_1 metastable state in an electric discharge
  - effectively a ground state atom
- Transitions at 1083 (389) nm
  - diode, fibre and frequency doubled lasers to cool and trap



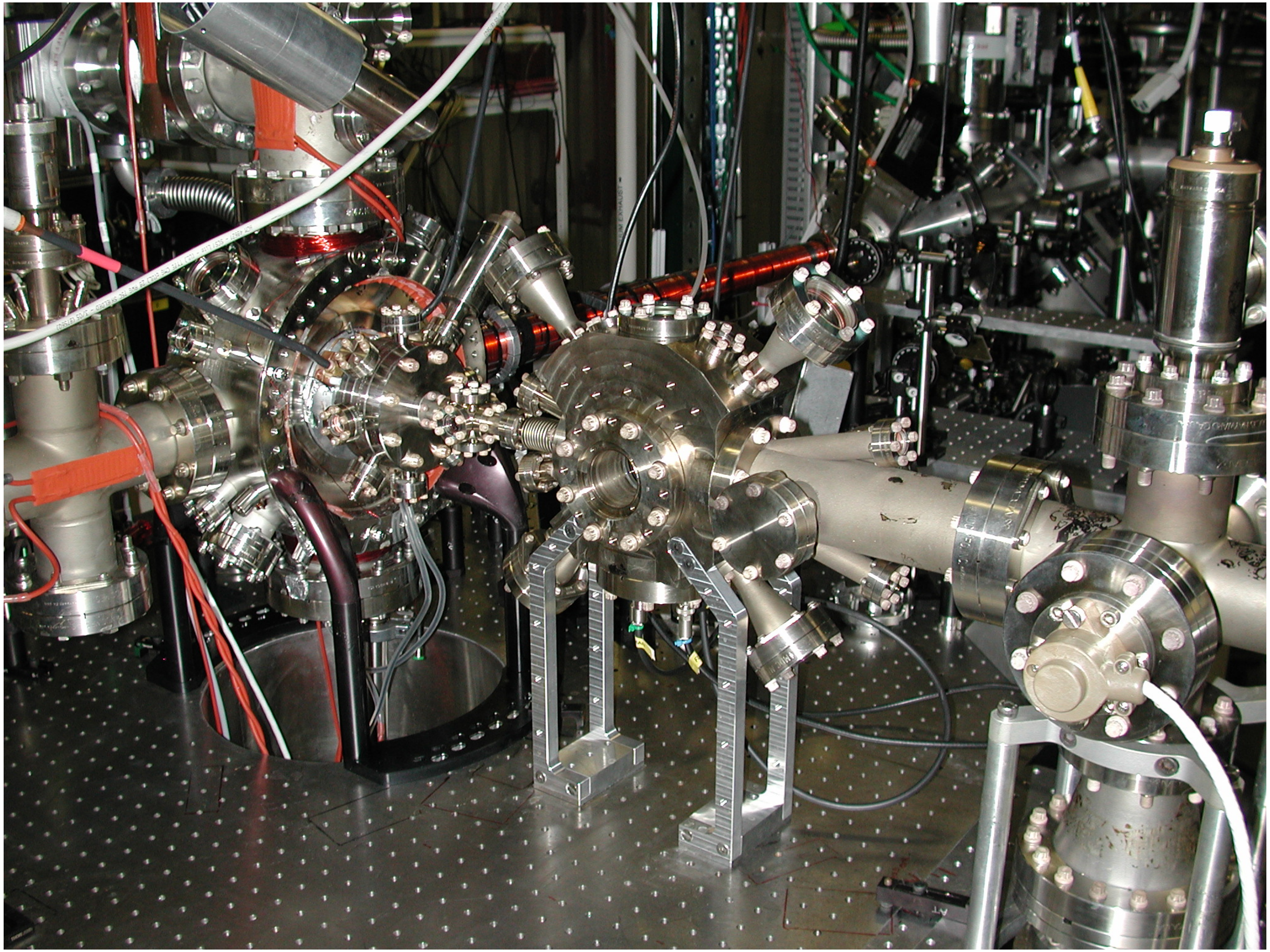
PA Scattering Length

- "a" is determined by subtle quantum mechanical effects which depend sensitively on accurate interatomic potentials
- Knowledge of the behaviour of bound states can thus be used to determine the interatomic potentials, and hence "a"
- However, because of the extreme sensitivity of "a" to small changes in potentials, careful measurements are needed e.g. of light shift of *v* levels



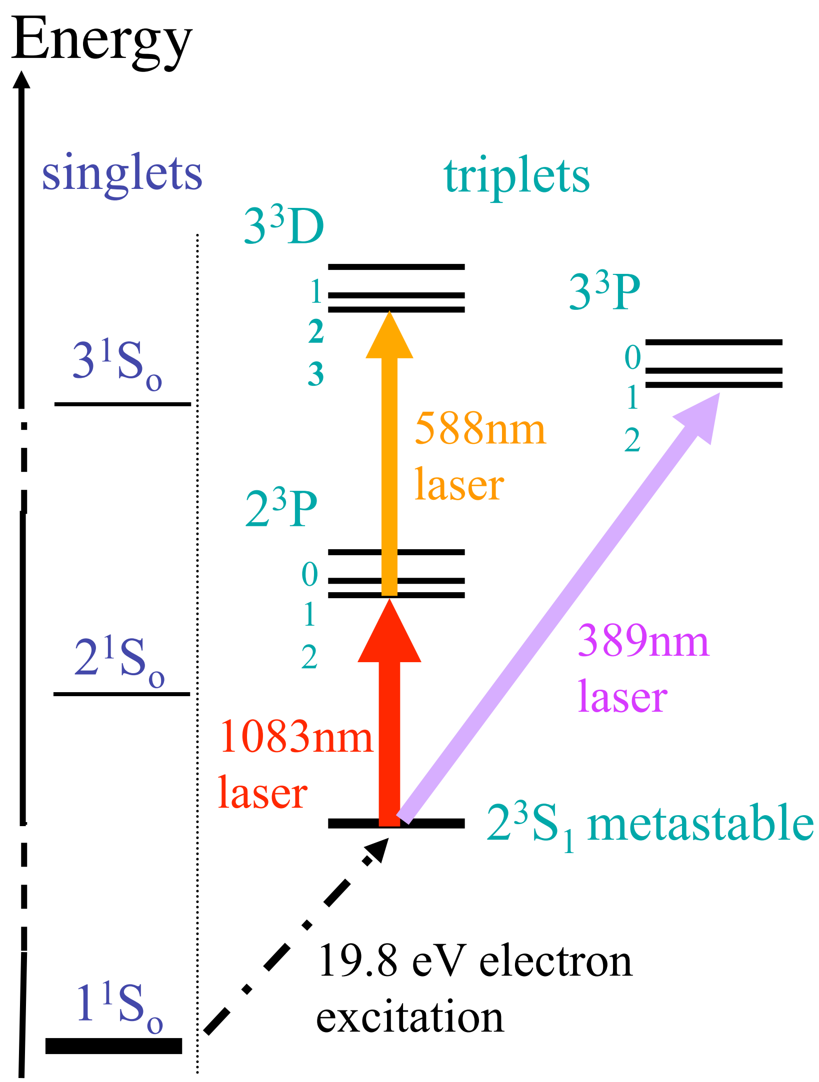


MOT, LVIS + BEC chamber



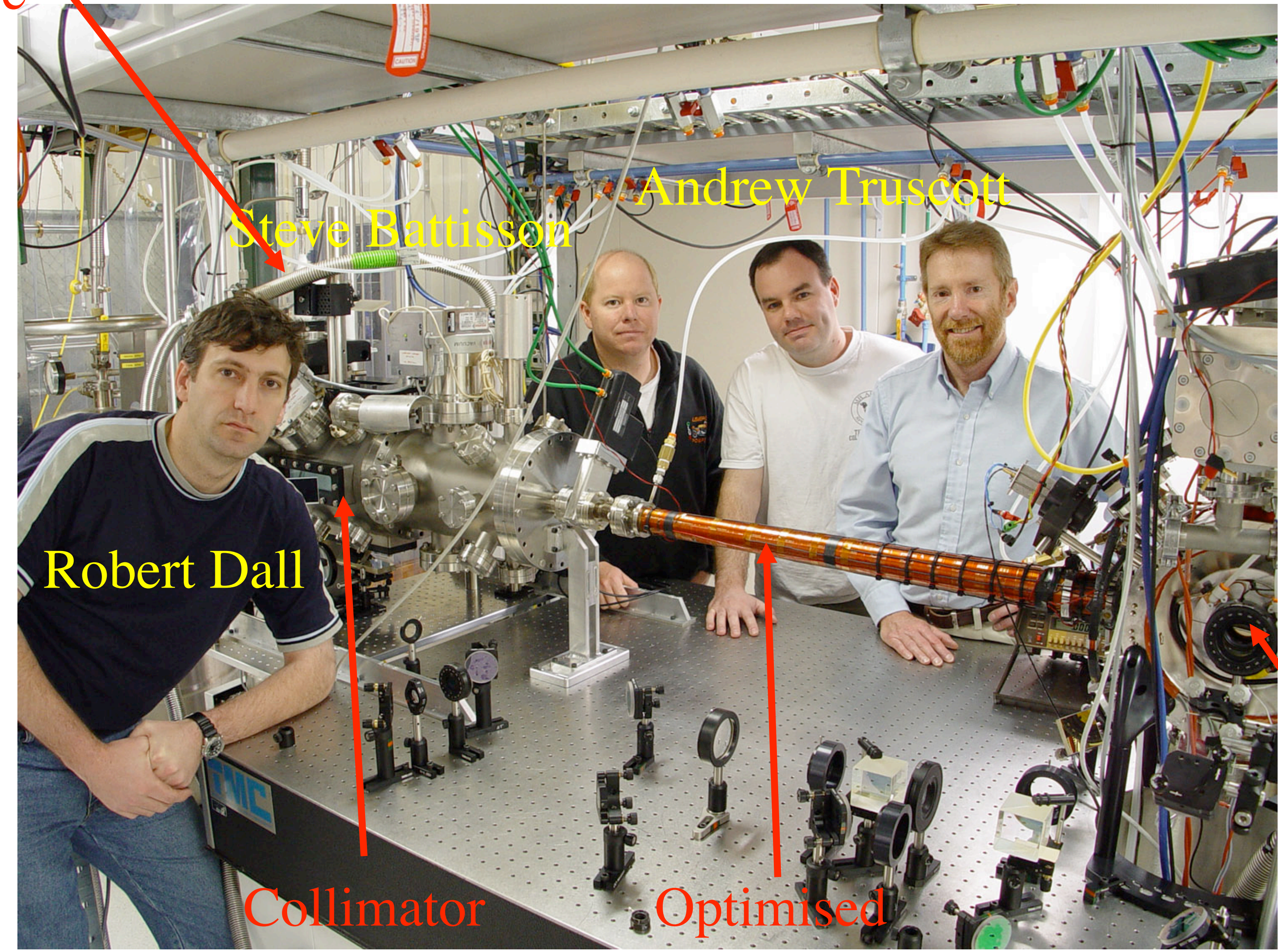
Metastable Helium Properties

- We use He* atoms excited to the 2^3S_1 metastable state
  - created in an electric discharge
- 2^3S_1 lifetime ~ 8000s
  - longest lived metastable species
  - effectively a ground state atom
- Transitions at 1083 (389) nm
  - diode (and other frequency doubled) lasers to cool and trap
- He* has ~20 eV stored energy
  - easy to detect single atoms



ANU He* BEC Lab

LHe cooled source

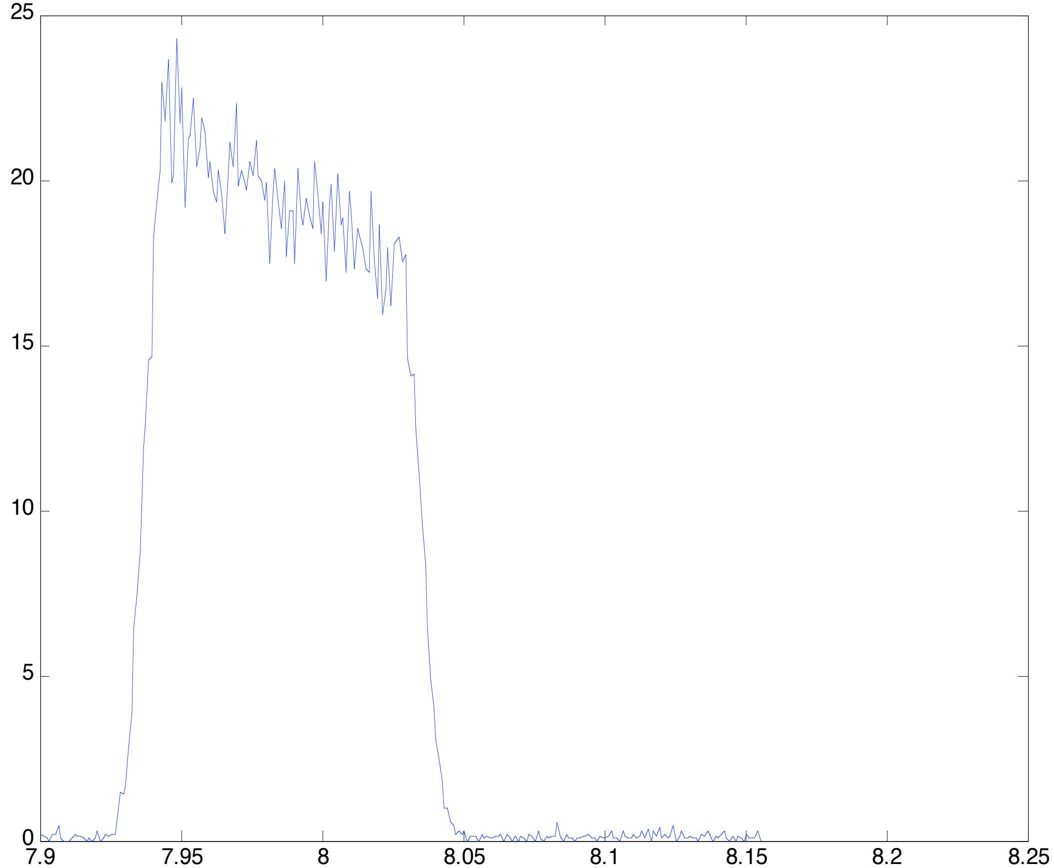


1st MOT stage

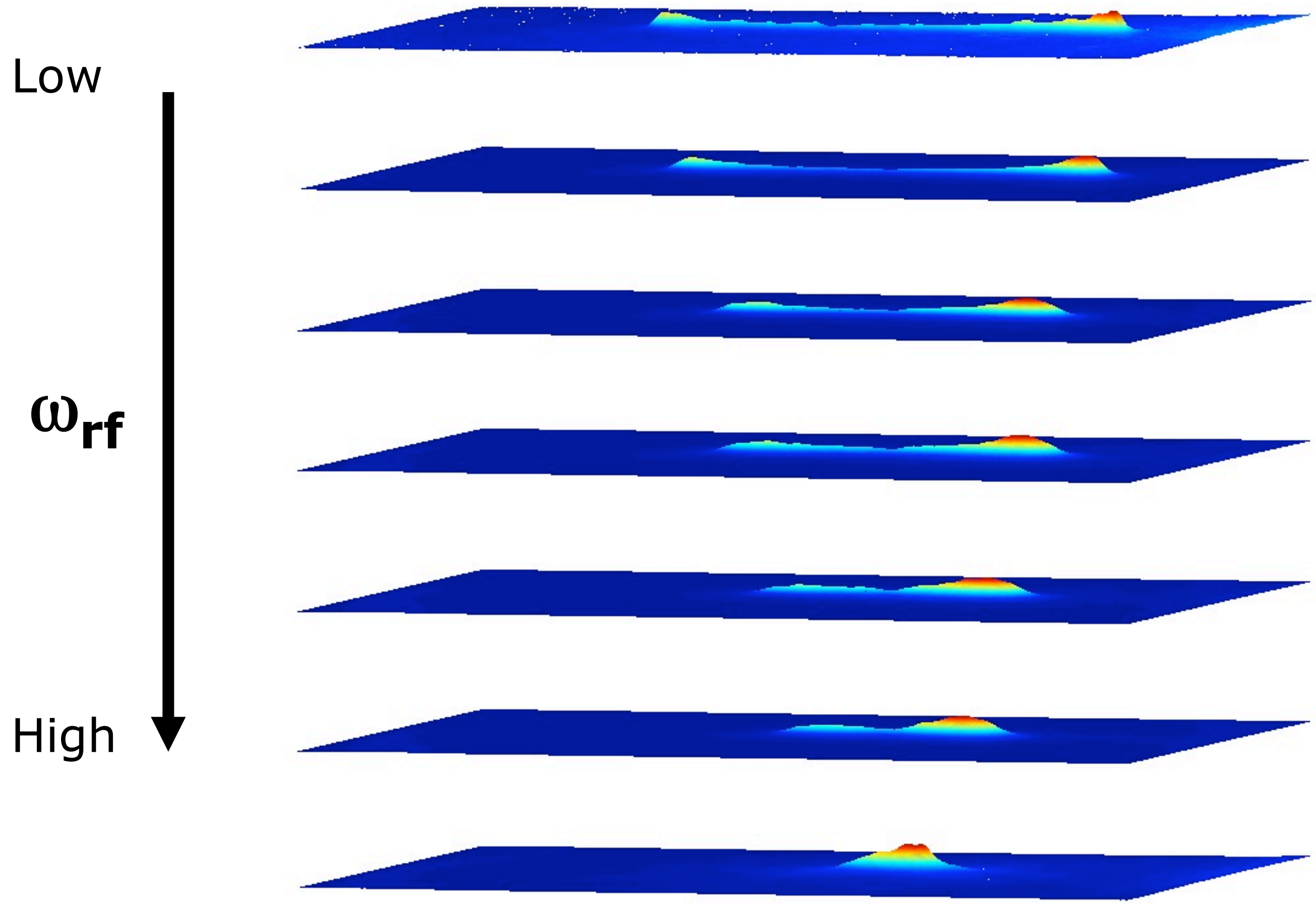
Collimator + deflector

Optimised Zeeman slower

Counting statistics

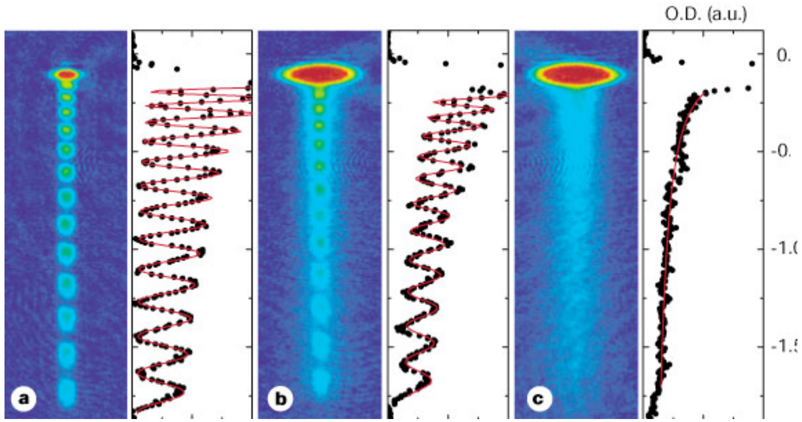


Atom Laser transverse profile



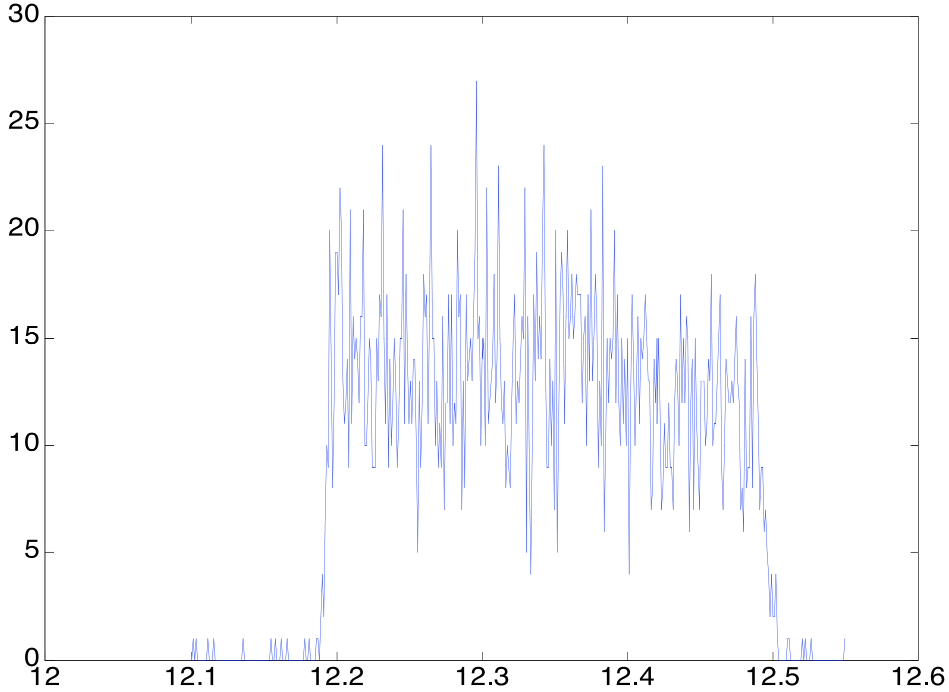
Atom Laser Coherence

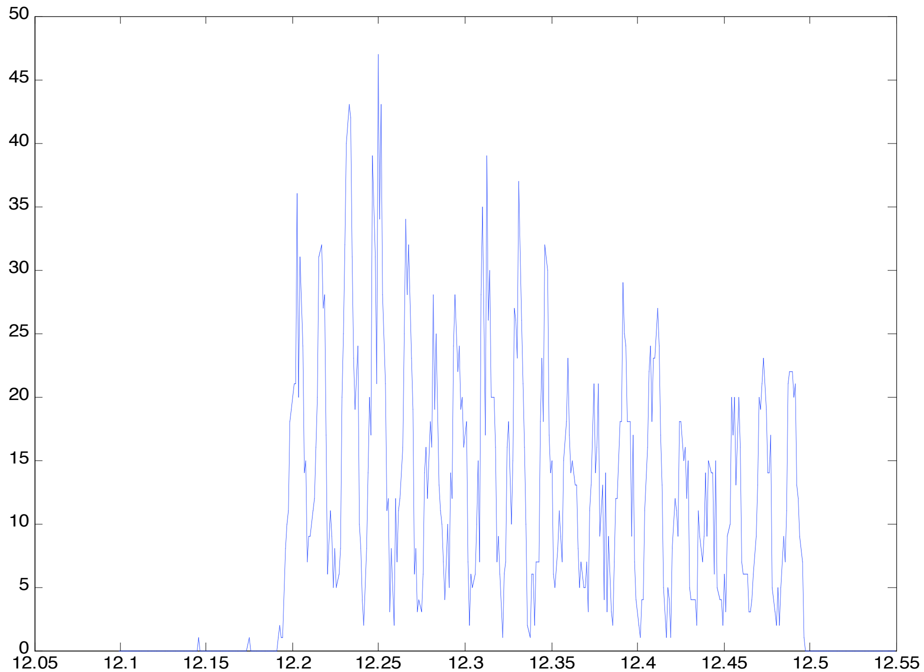
Above T_c



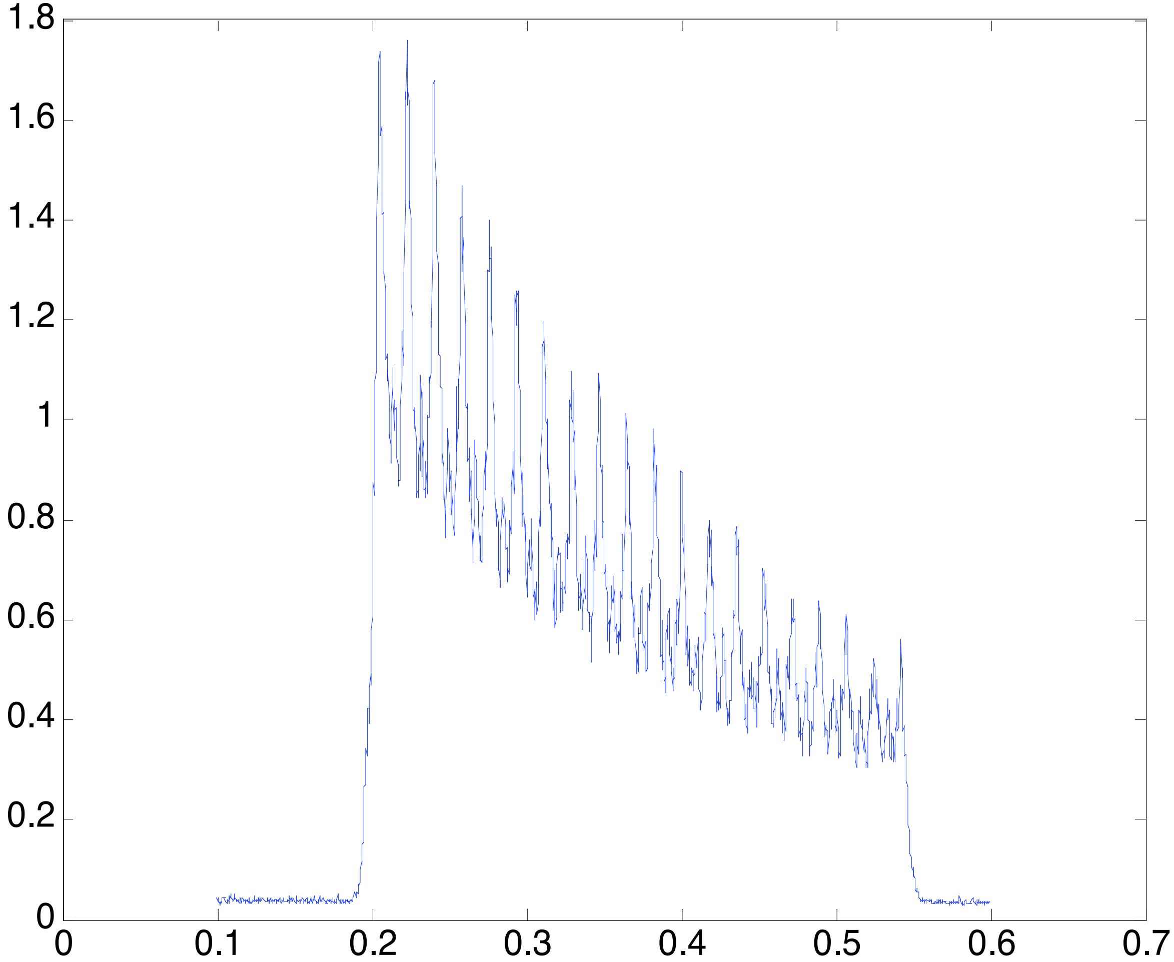
I. Bloch, T. W. Hänsch and T. Esslinger
Nature 403, 166-170 (13 January 2000)

Below T_c

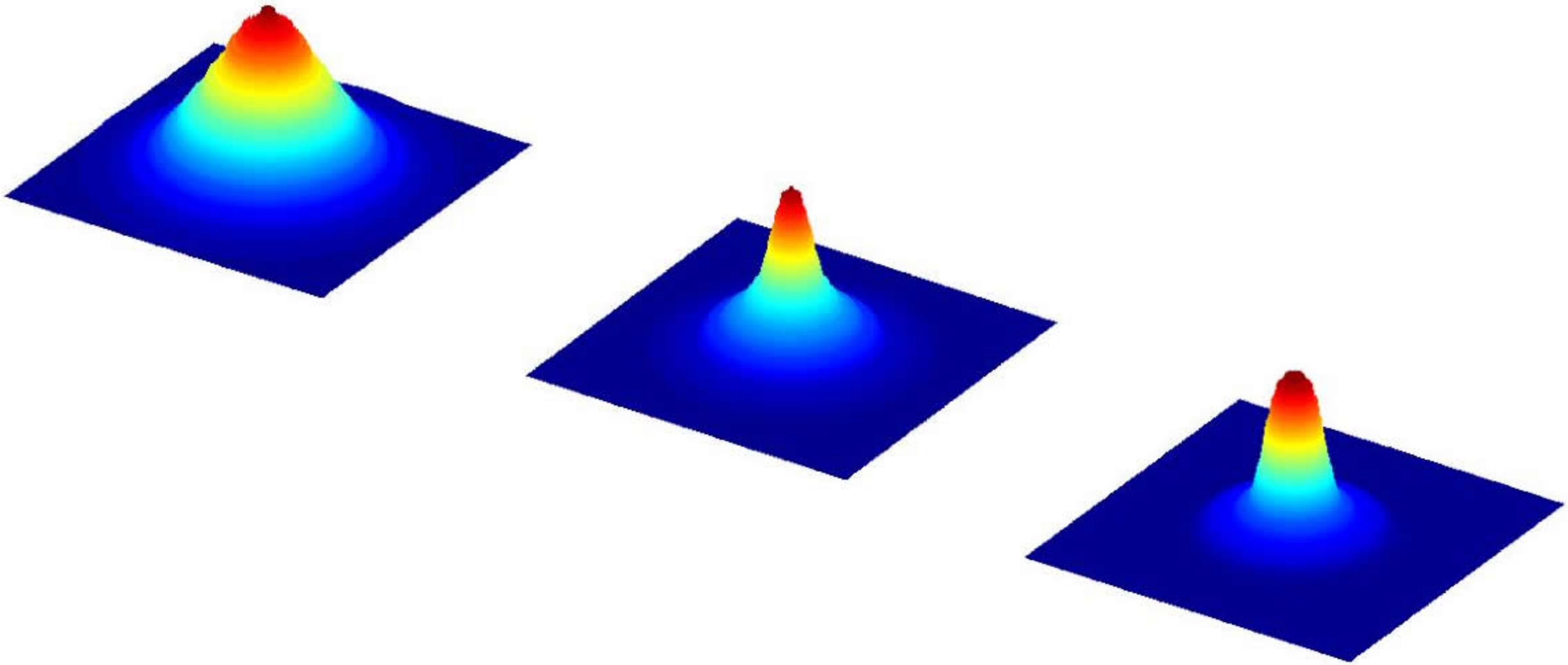




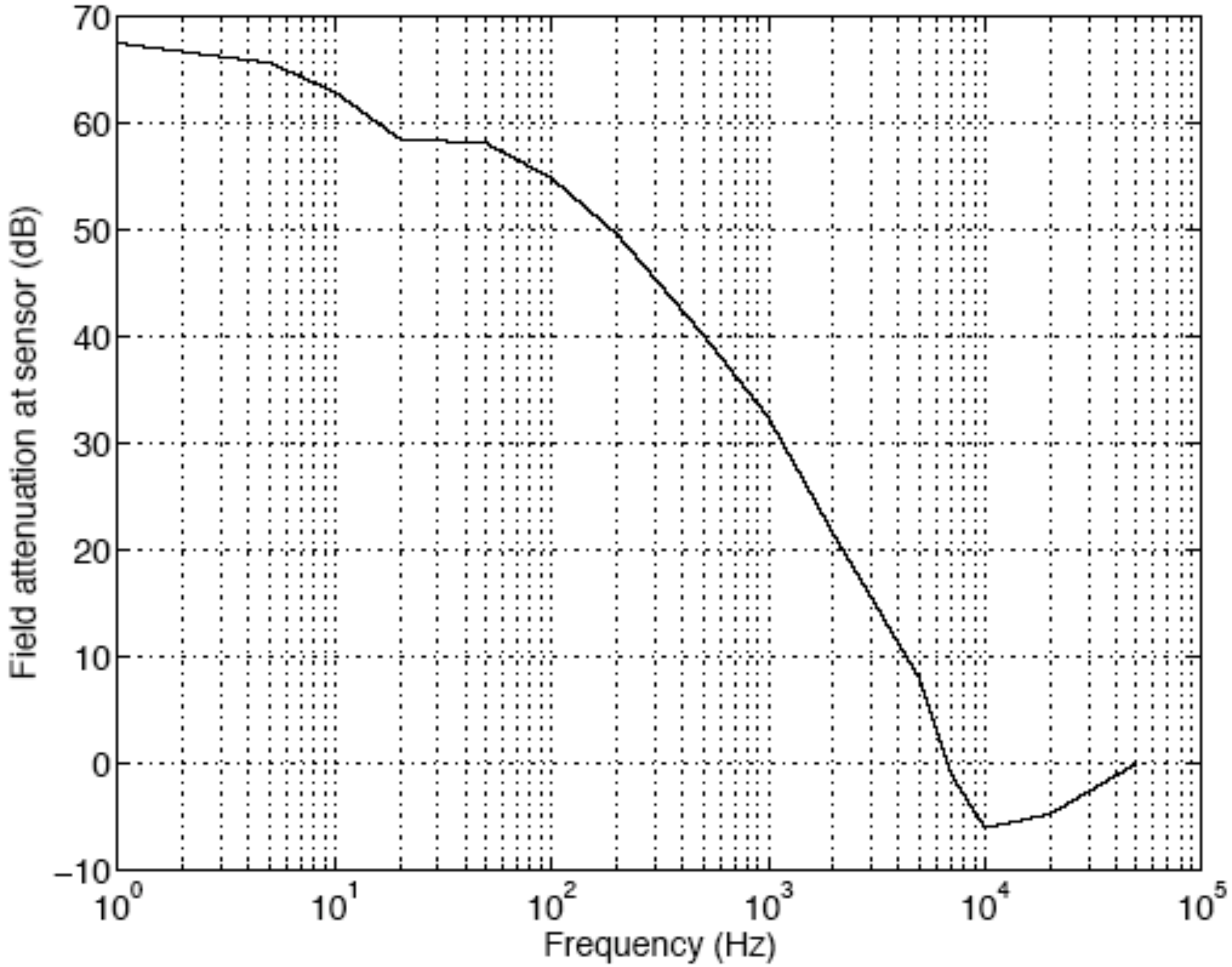
Measuring trap frequency



ANU He* Quantum-Atom Optics



Field attenuation at the sensor



BEC Procedure

- ~ 5 x 10^8 He* atoms in MOT at ~ 1 mK
- Compress MOT by decreasing detuning
- Use 3-D molasses to give 200 μK
- Transfer to weak magnetic trap (84 /75 Hz)
  ~ 1 x 10^8 atoms at 1.3 mK
- 1-D Doppler cooling gives ~ 200 μK
- Compress magnetic trap (560/95 Hz)
- Again, 1-D Doppler cooling gives ~ 200 μK
- Start evaporation with ~ 1 x 10^8 He* atoms