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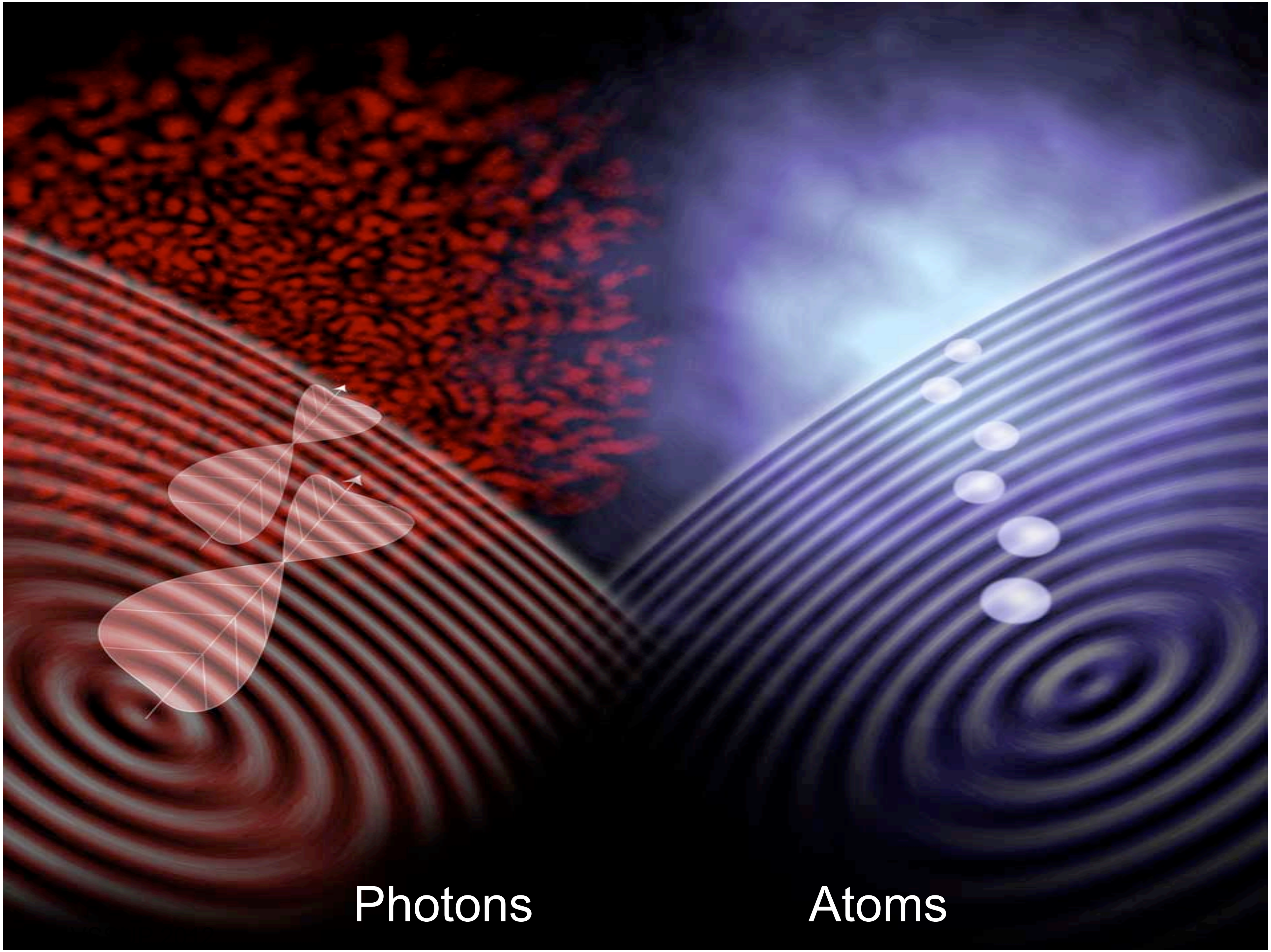
Quantum Correlations : a test of matter-wave coherence

Professor Ken Baldwin

Director,

ARC Centre of Excellence for Quantum-Atom Optics,

The Australian National University


Photons
Atoms

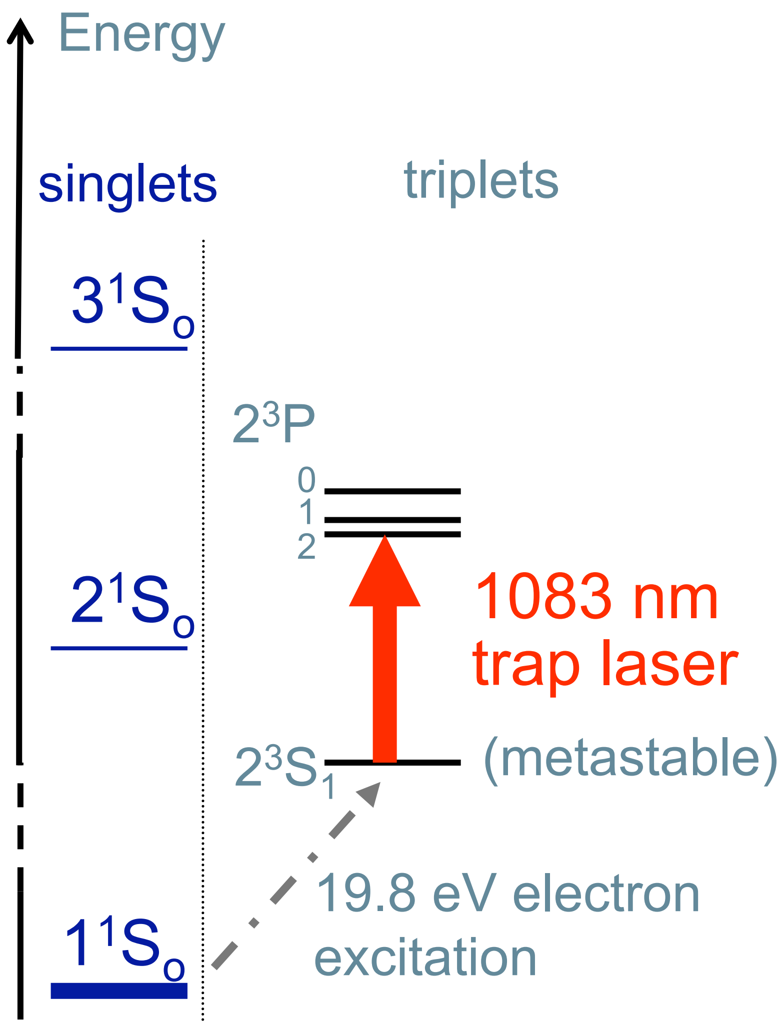
Metastable Helium

- Metastable 2^3S_1 helium (He*) :
  - A long lived (~8000s) state that acts as an effective "ground state" for atom optics
    Hodgman et al. PRL **103**, 053002 (2009)
  - Has ~20 eV of internal energy
  - This enables efficient *single particle detection* e.g. microchannel plate (MCP)

See:

"Metastable helium: Atom optics with nano-grenades", K.G.H. Baldwin, *Contemporary Physics* **46**, 105 (2005)

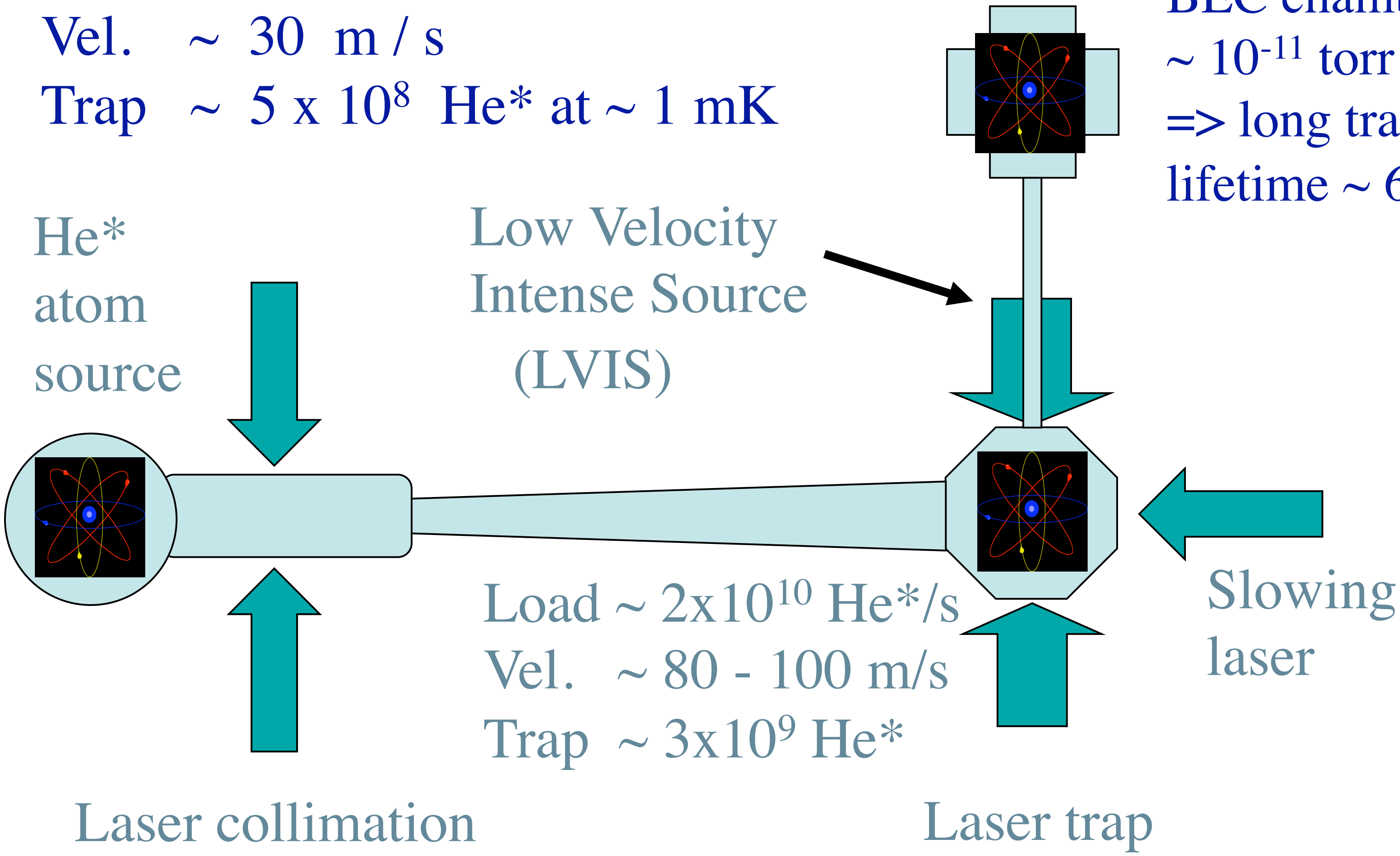
- Our He* BEC apparatus is used for *ultracold atom studies* :
  - Atomic physics: He* lifetimes
  - Atom lasers and atom guiding
  - Quantum statistical effects
    - Exploits efficient single particle detection



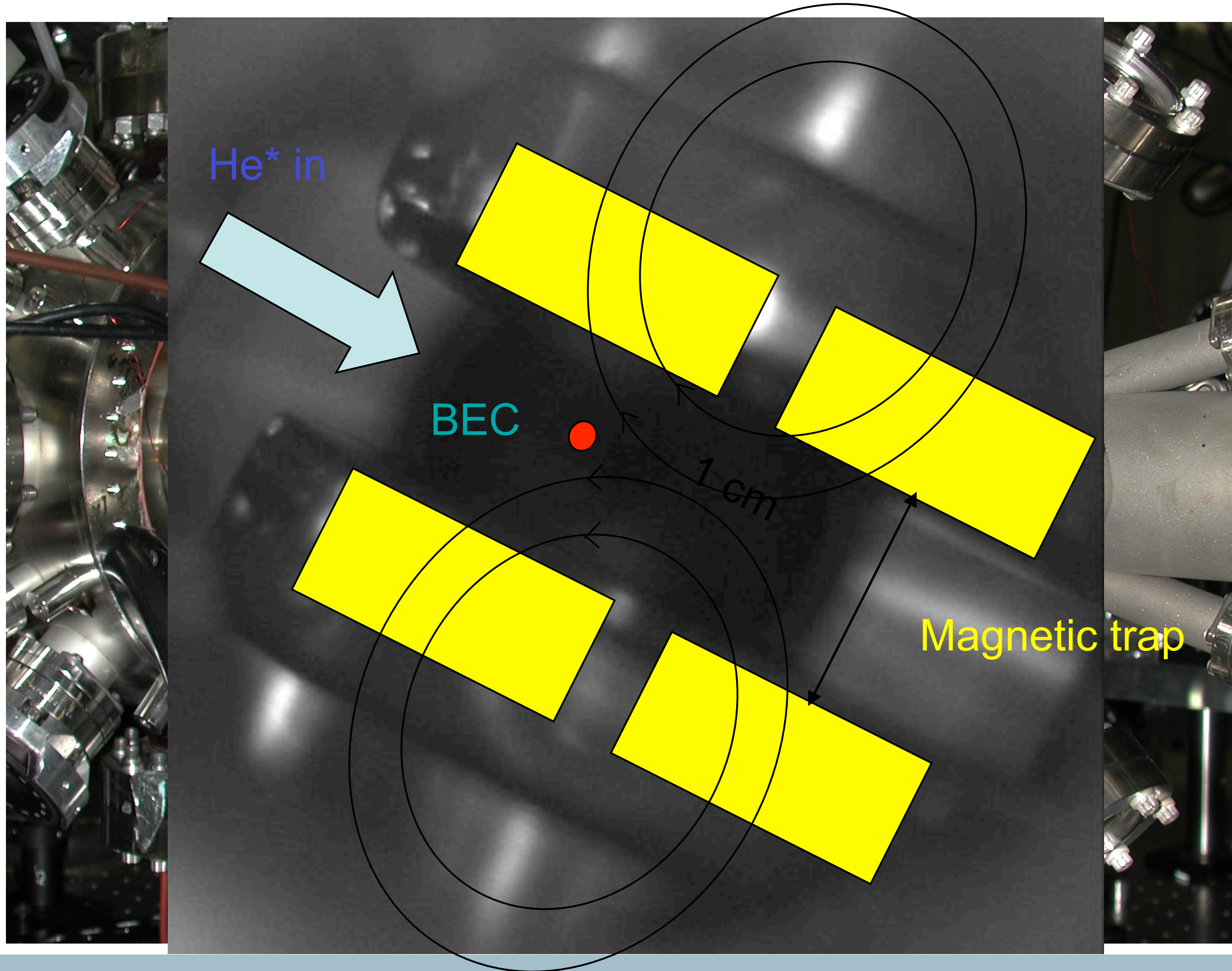
He* BEC Facility

LVIS ~ 2 x 10^{10} He* / s
Vel. ~ 30 m / s
Trap ~ 5 x 10^{8} He* at ~ 1 mK

BEC chamber
~ 10^{-11} torr
=> long trap
lifetime ~ 60s



BEC chamber



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Detection Stack

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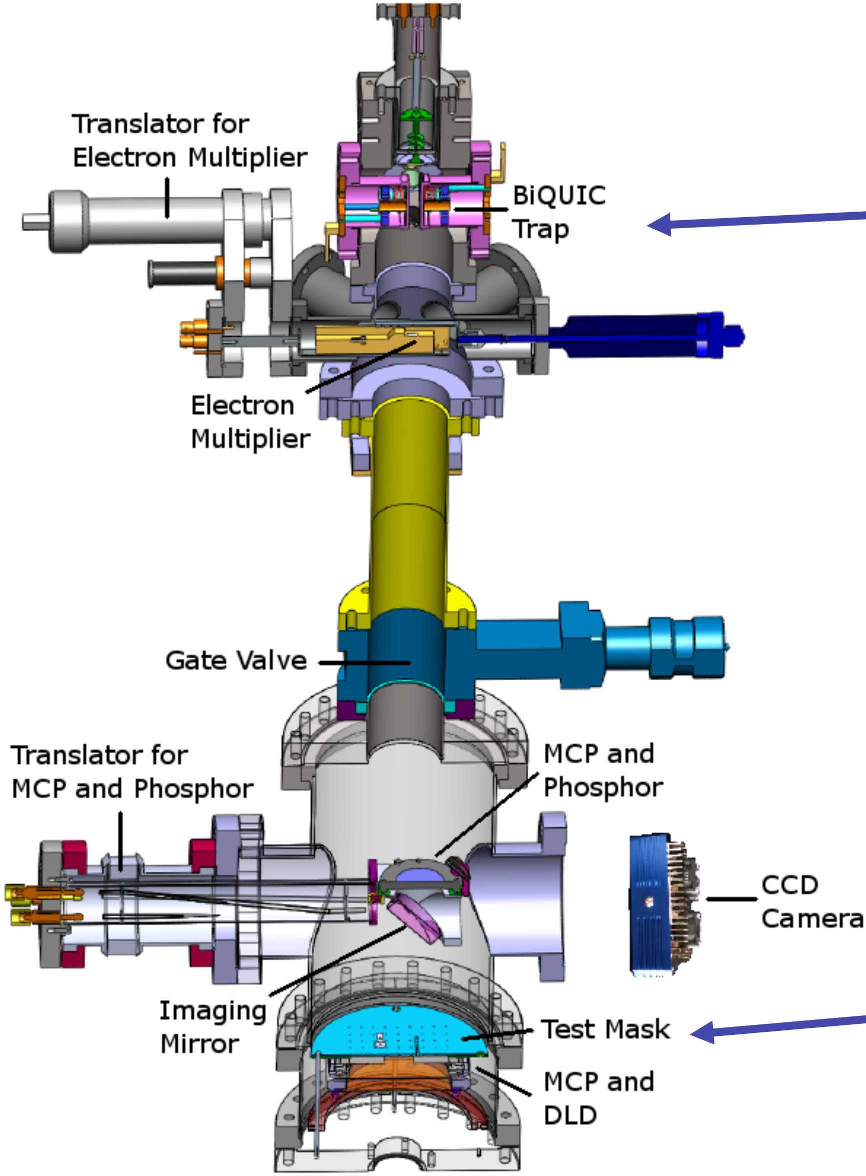
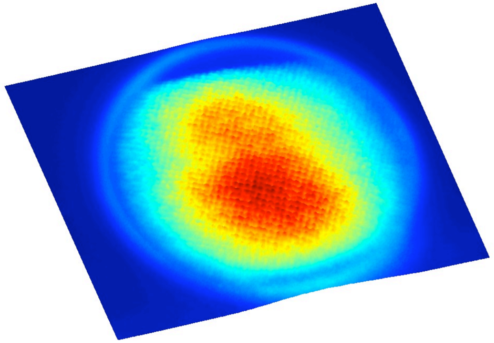
~ 800 mm



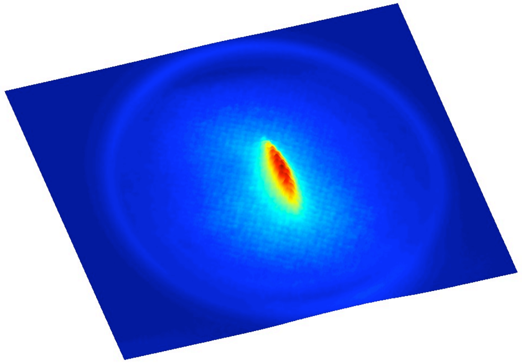
Trapped atoms

Resolution check

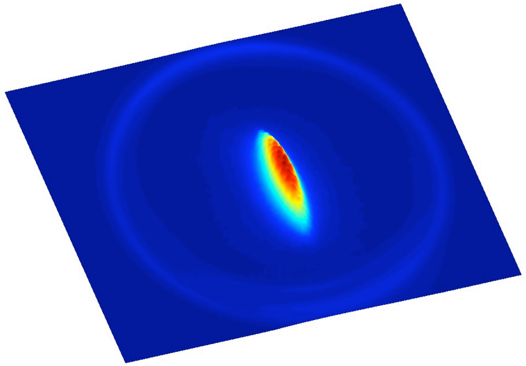
MCP: He* BEC spatial profile



T > T_c

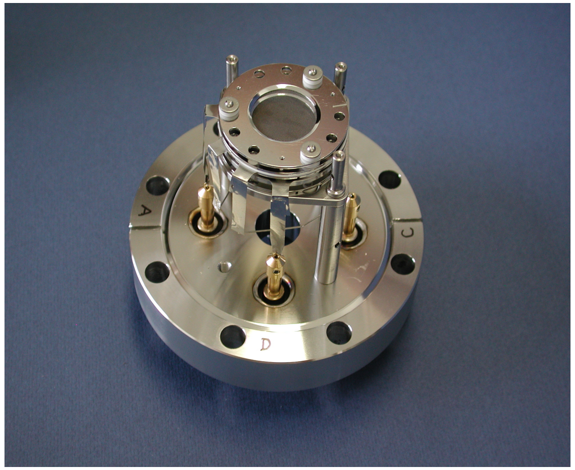


T < T_c



T ~ $0.3T_c$

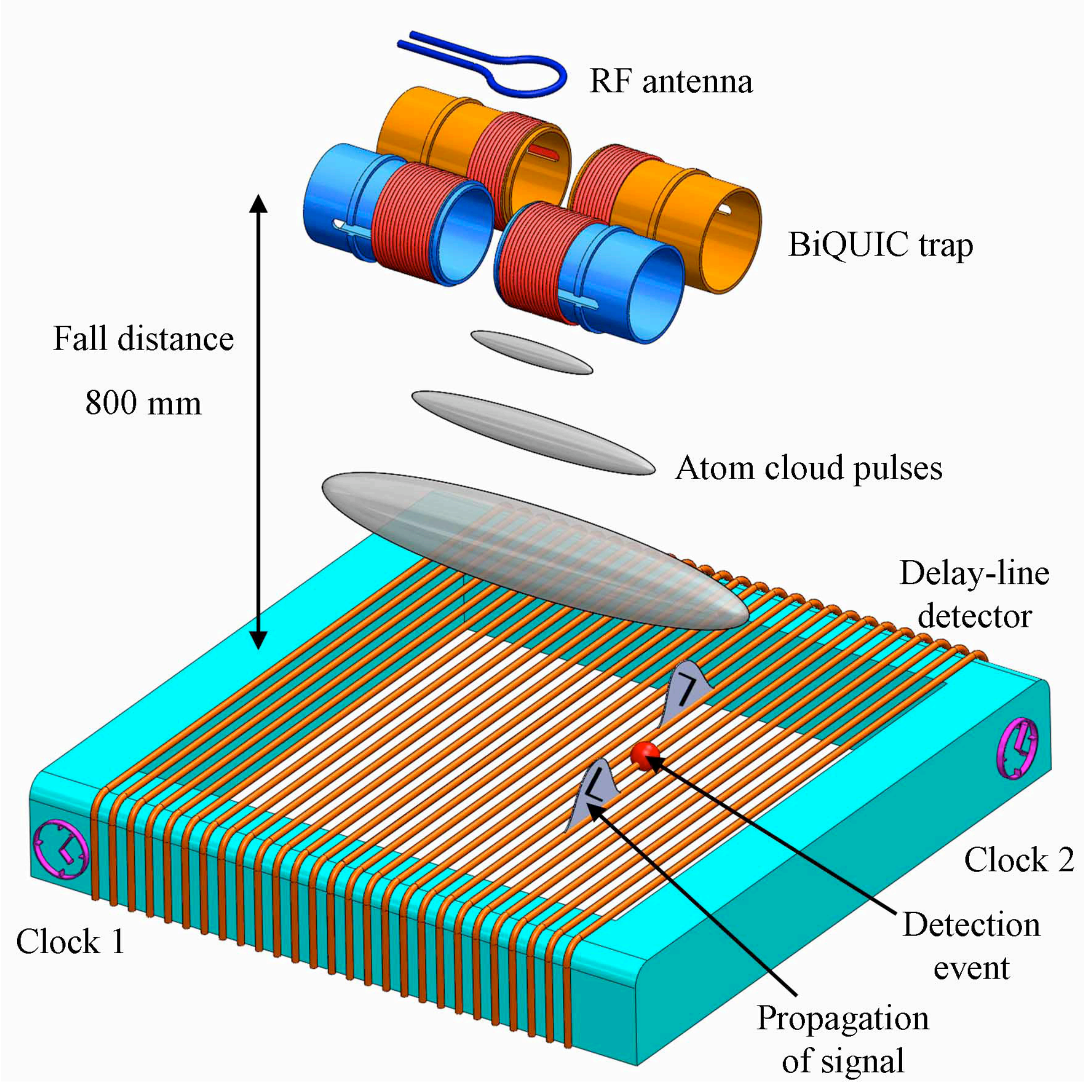
MCP and phosphor 2-D detector



Delay-Line Detector

- High precision temporal and spatial detection

Specifications	
Detector diameter	80 mm
Spatial Resolution	~100 µm
Time resolution	~ few ns
Dead time	20 ns
Maximum count rate	1 MHz



A.G. Manning et al., *Optics Express* **18**, 18712 (2010)

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Delay-Line Detector Images

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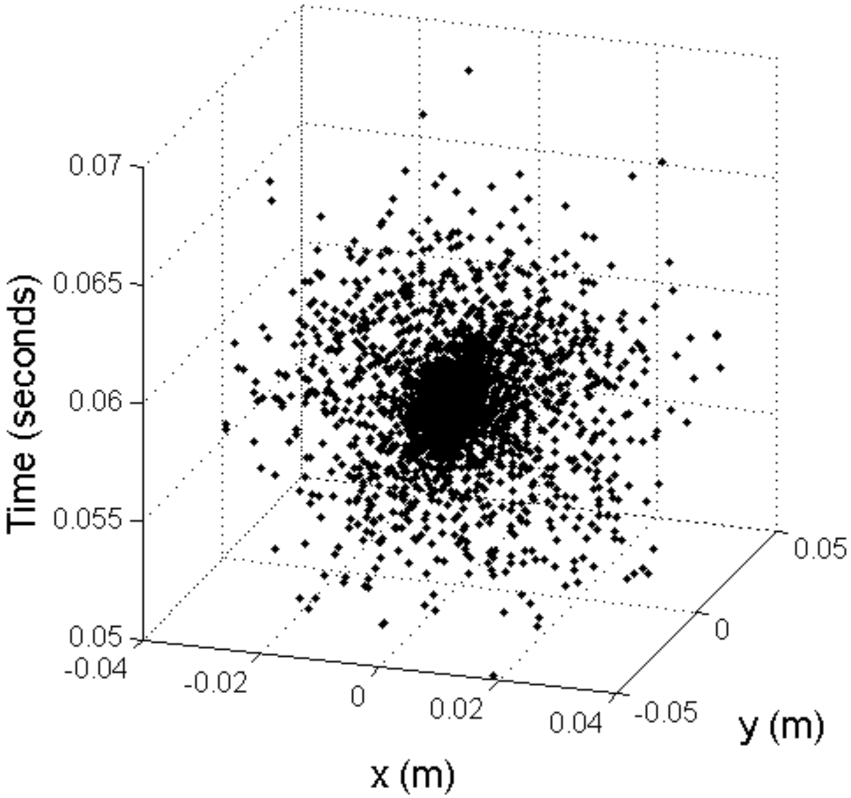
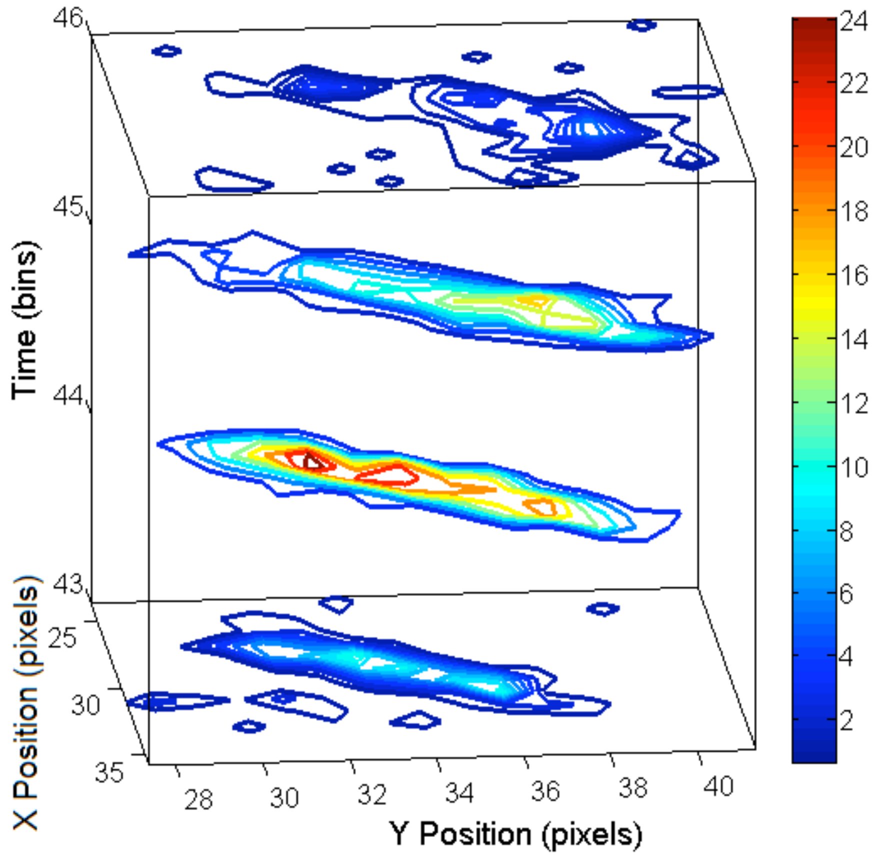
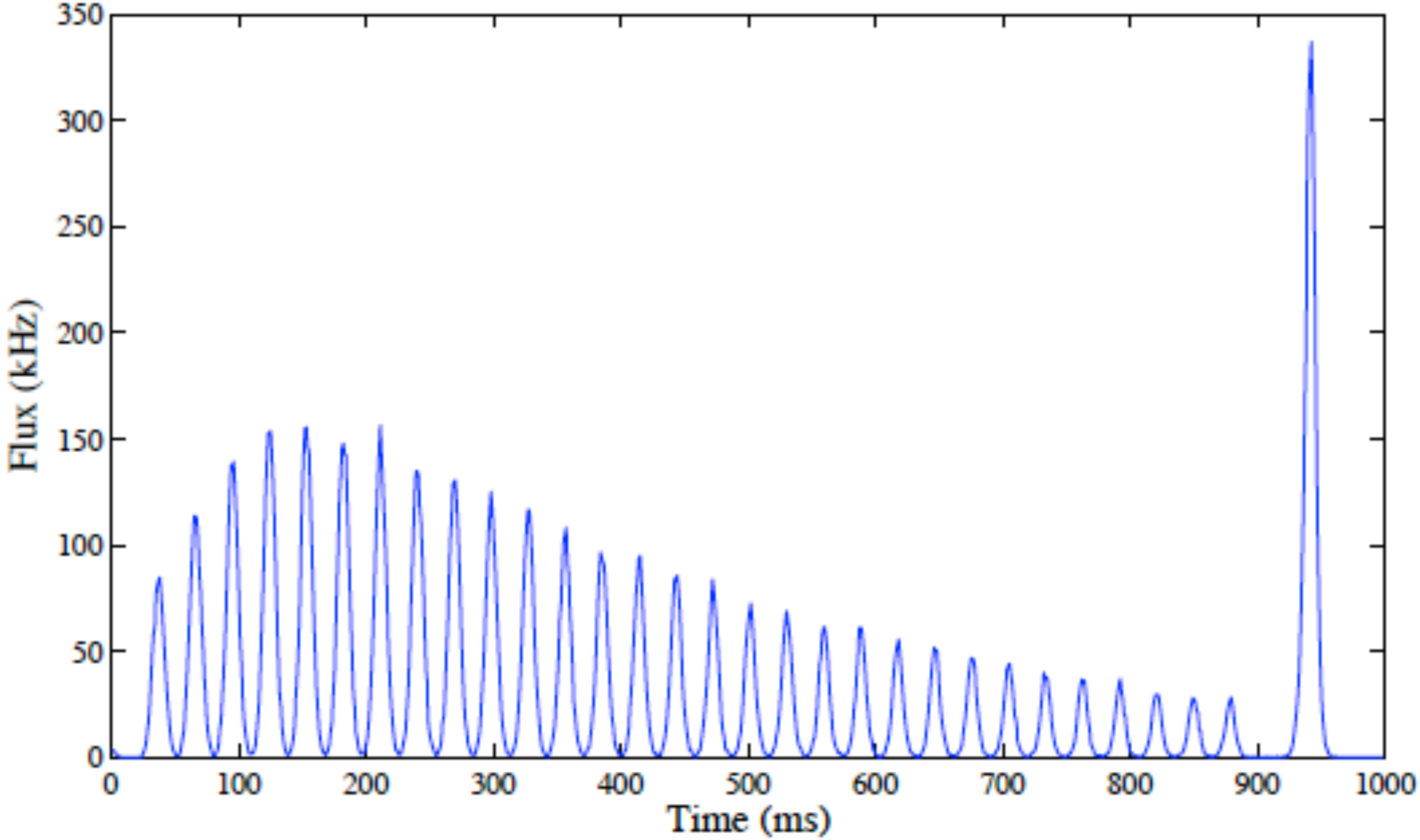
- 3-D spatio-temporal information



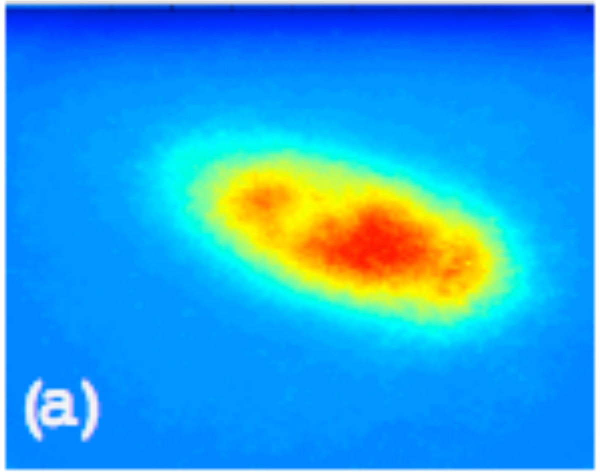


Data acquisition

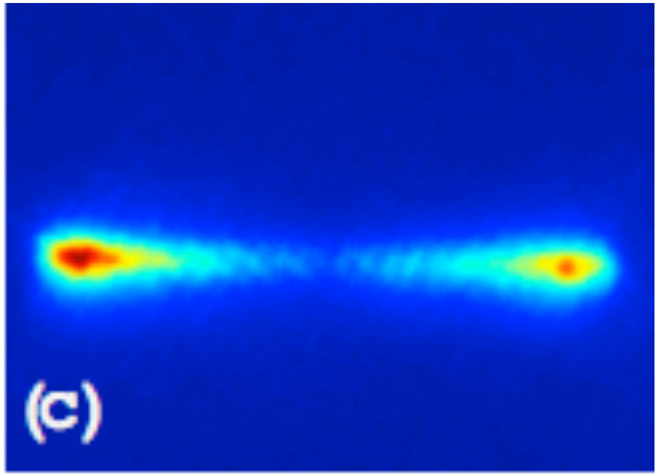


Atom arrival flux showing the pulsed outcoupling from 30 RF pulses

BEC and atom laser images

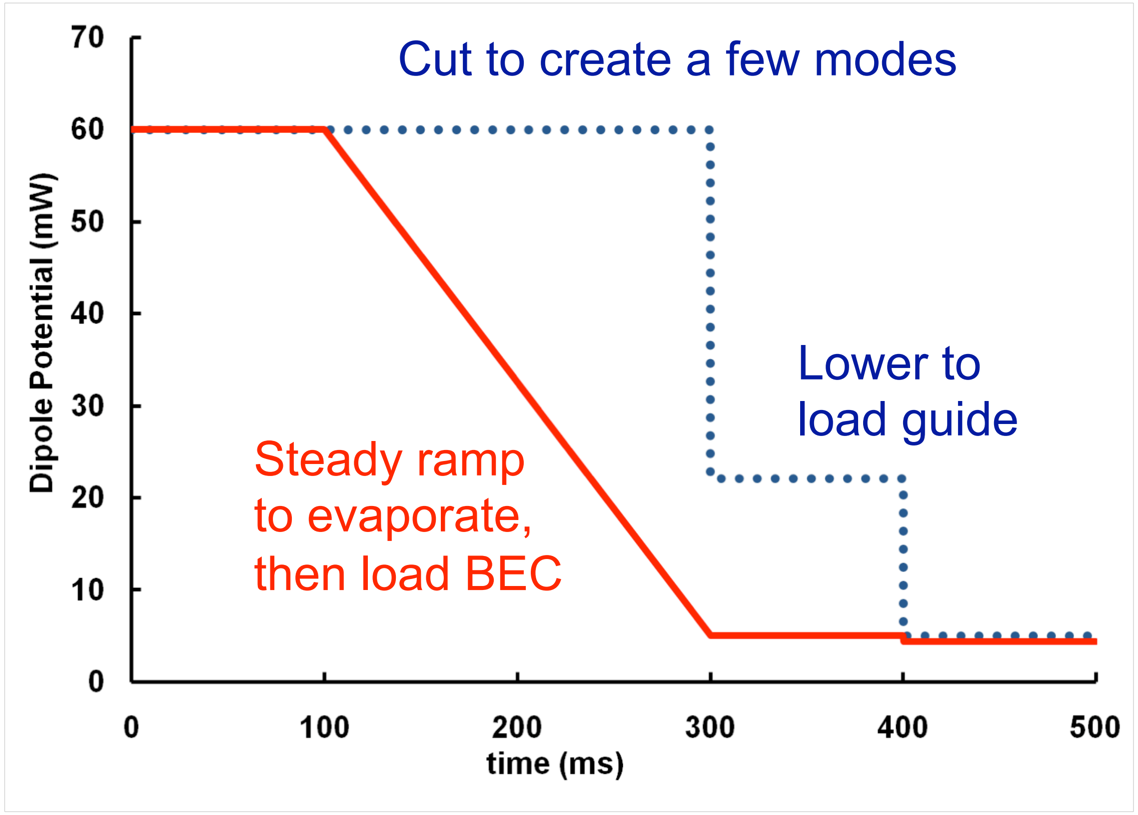


(a) BEC dropped onto MCP

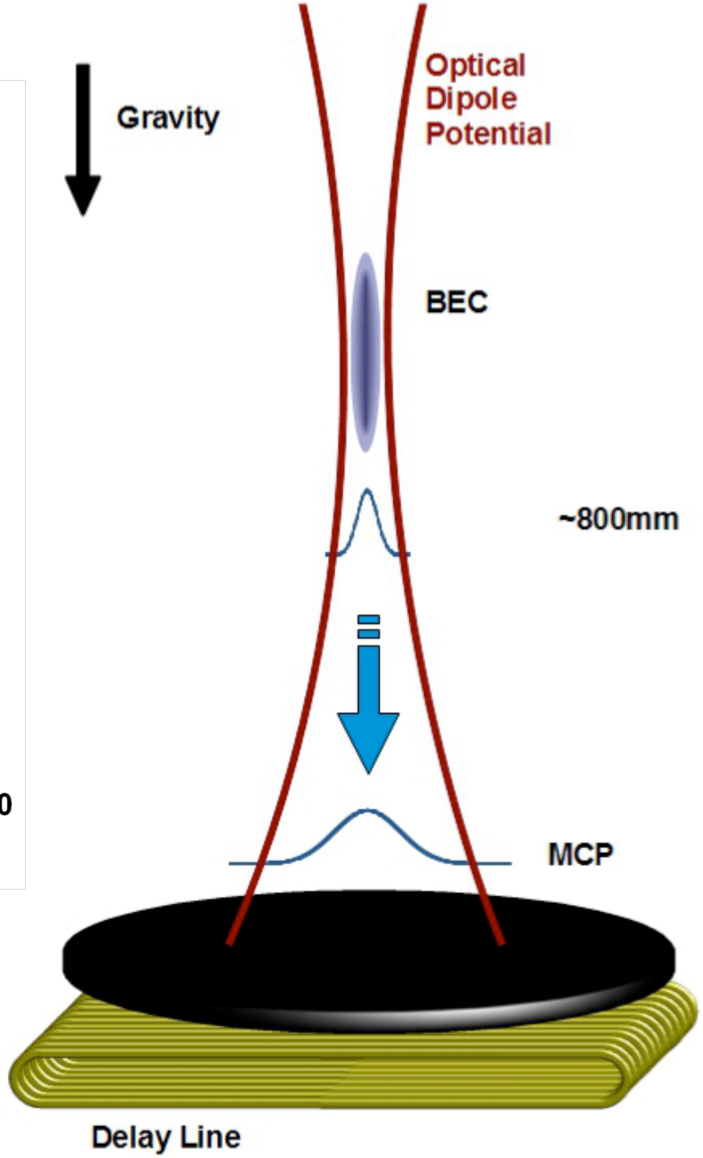


(c) Atom laser profile

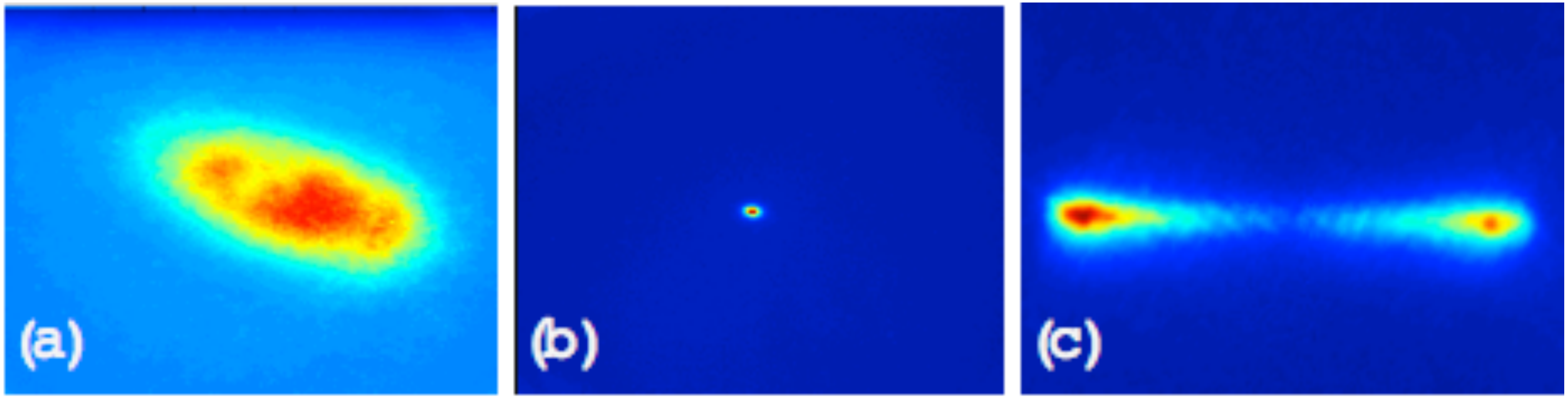
Waveguided matter waves



Laser intensity ramp



Waveguide results



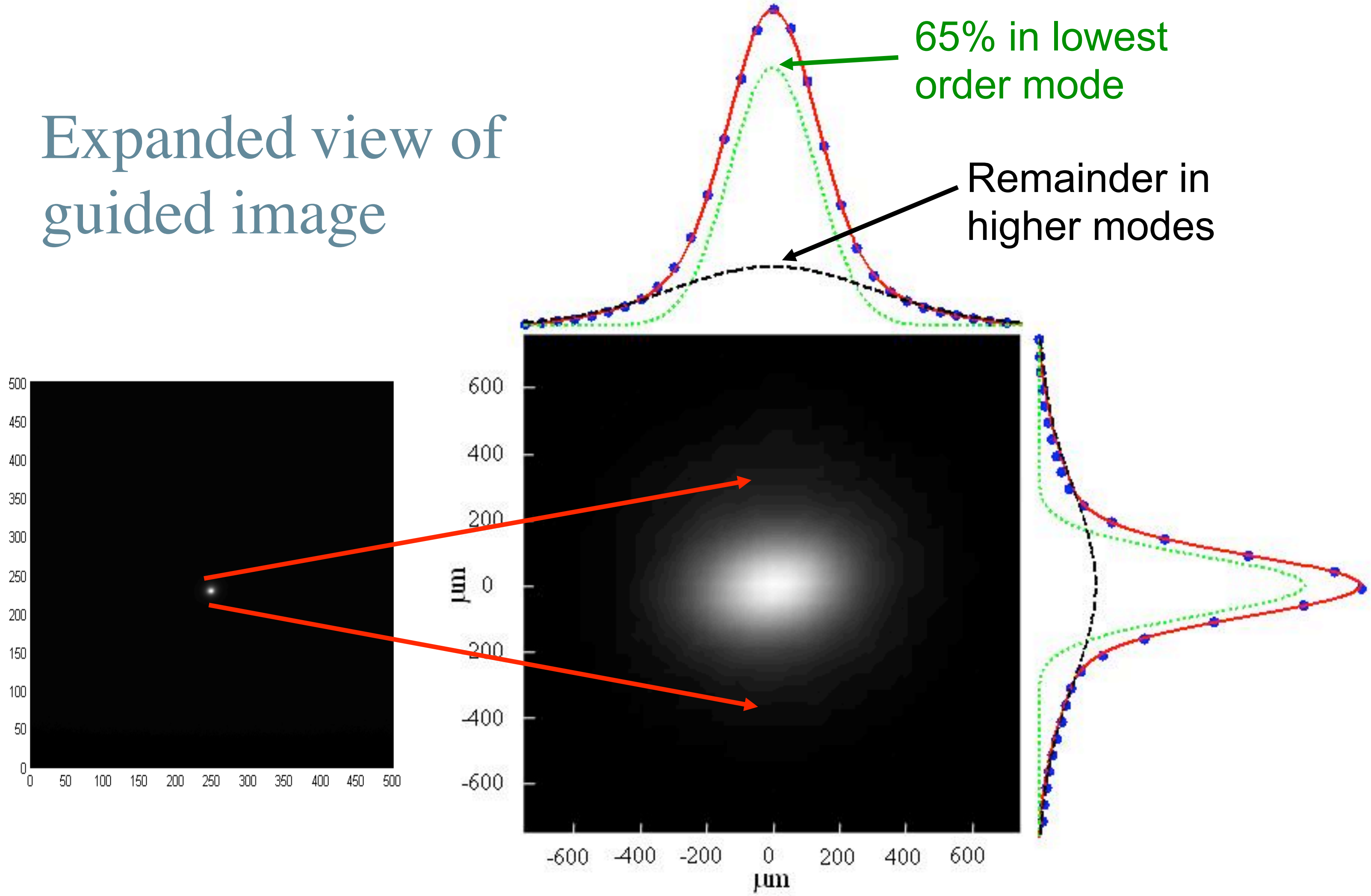
(a) BEC dropped onto MCP

(b) Single mode guided BEC

(c) Atom laser profile

Near-single mode guiding

Expanded view of guided image



"Transverse mode imaging of guided matter waves",
R.G. Dall, S.S. Hodgman, M.T. Johnsson, K. G. H. Baldwin, and A.G. Truscott,
Physical Review A **81**, 011602(R) (2010).

Correlation Functions

First Order Correlation Function $g^{(1)}$

- Measures single particles
- => Amplitude fluctuations

$$g^{(1)}(\tau) = \frac{\langle E^*(t)E(t+\tau)\rangle}{\langle|E(t)|\rangle\langle|E(t+\tau)|\rangle}$$

- Gives fringe visibility in interference

Second Order Correlation Function $g^{(2)}$

- Measures coincidence of particle *pairs*
- => Intensity fluctuations

$$g^{(2)}(\tau) = \frac{\langle I(t)I(t+\tau)\rangle}{\langle I(t)\rangle\langle I(t+\tau)\rangle}$$

- Second order coherence – speckle and HBT effect

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Diffraction: $g^{(1)}$ coherence

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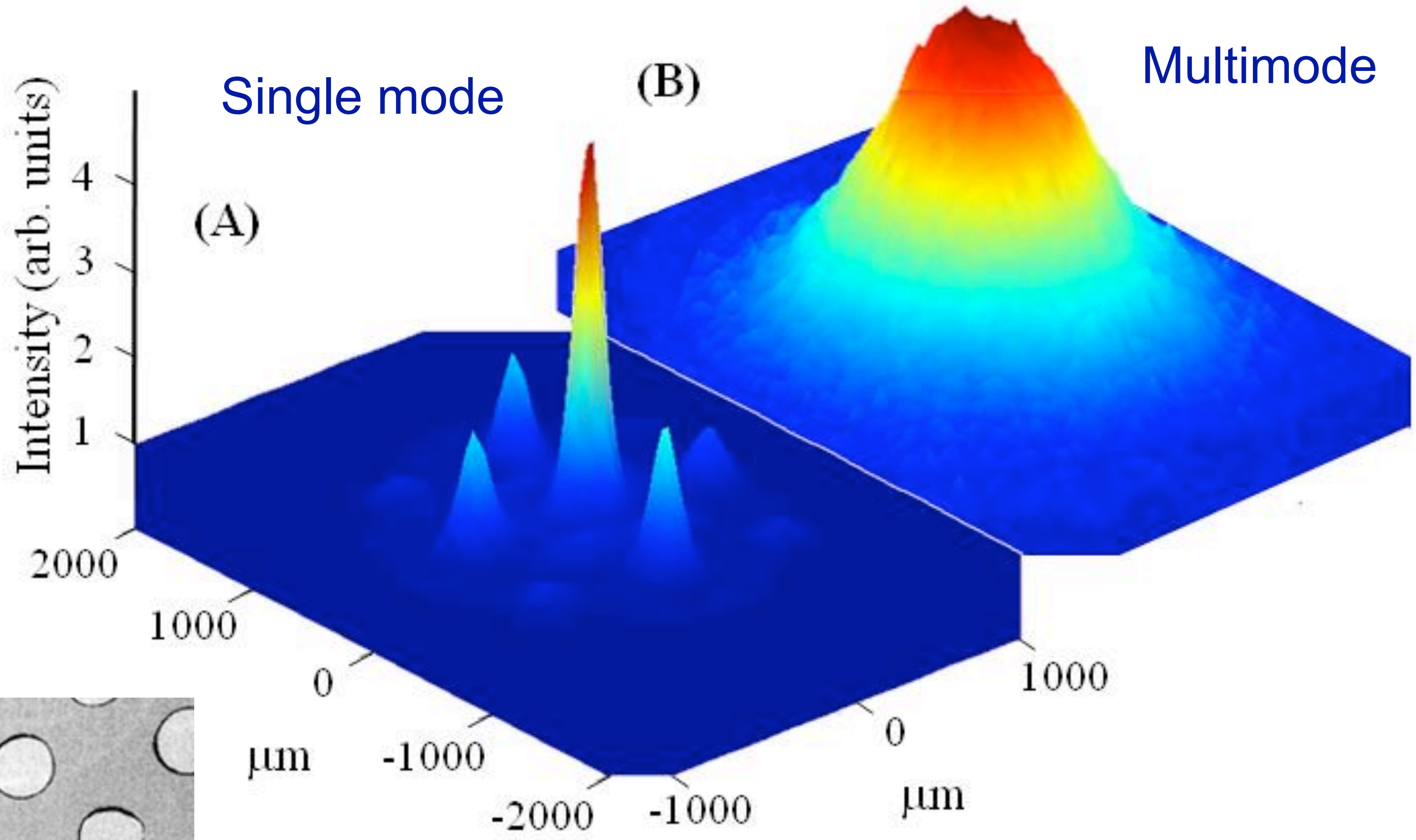
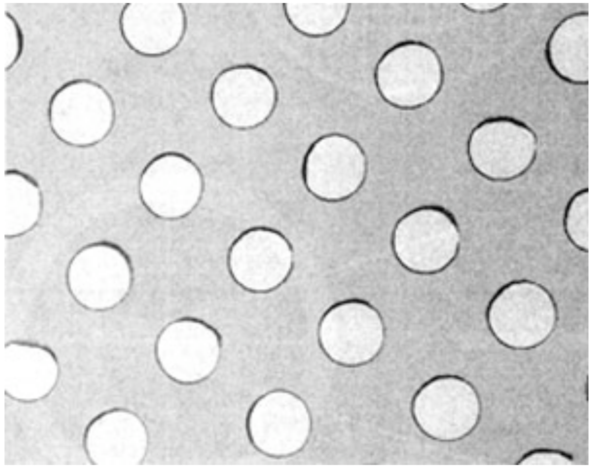
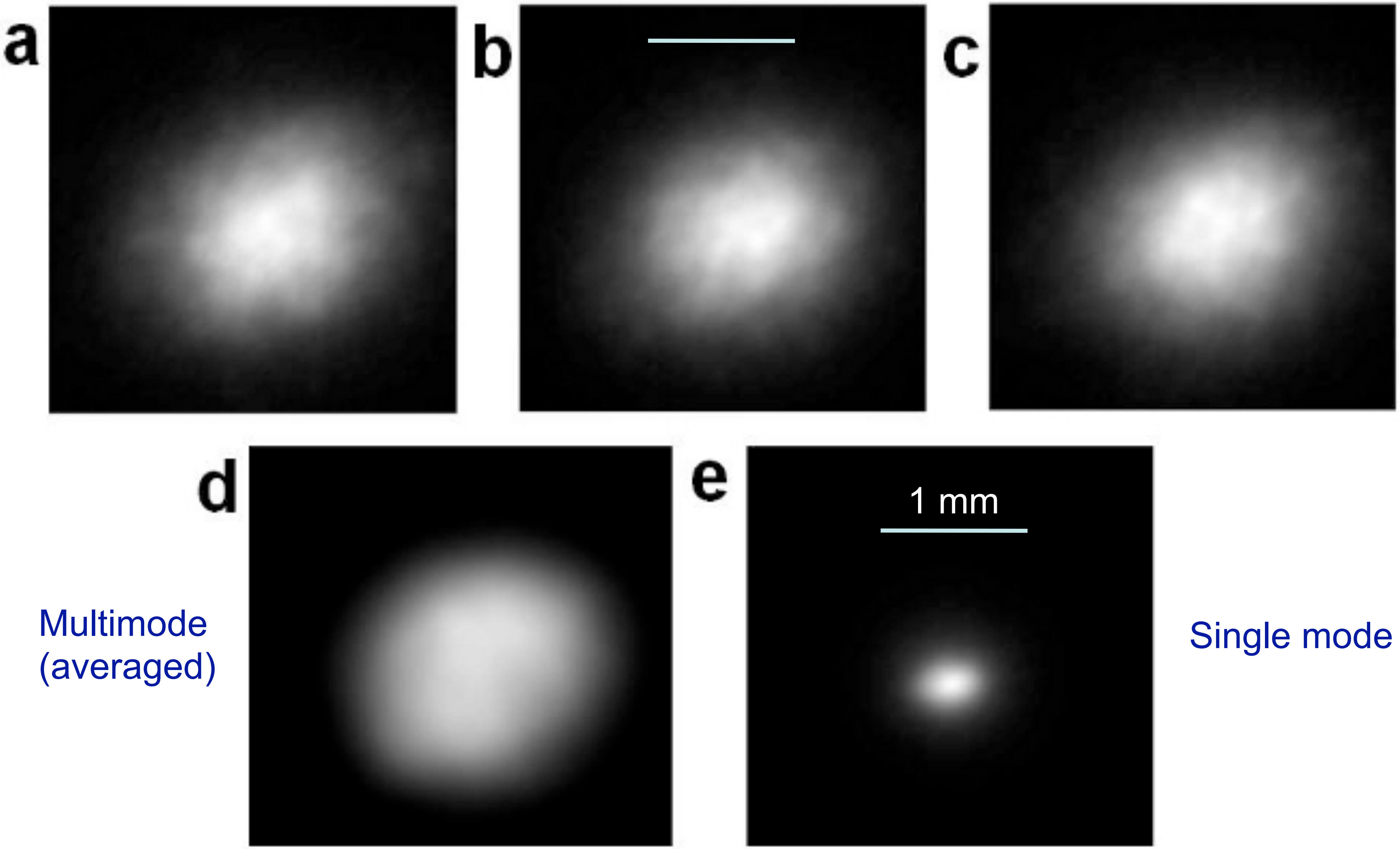




Guided atoms diffracted through Quantifoil R2/2 :
2 micron holes separated by 2 microns in carbon film

Speckle: $g^{(2)}(\tau)$ coherence

Multimode – 3 separate realisations



Multimode (averaged)

Single mode

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$g^{(2)}(\tau)$: guided thermal atoms

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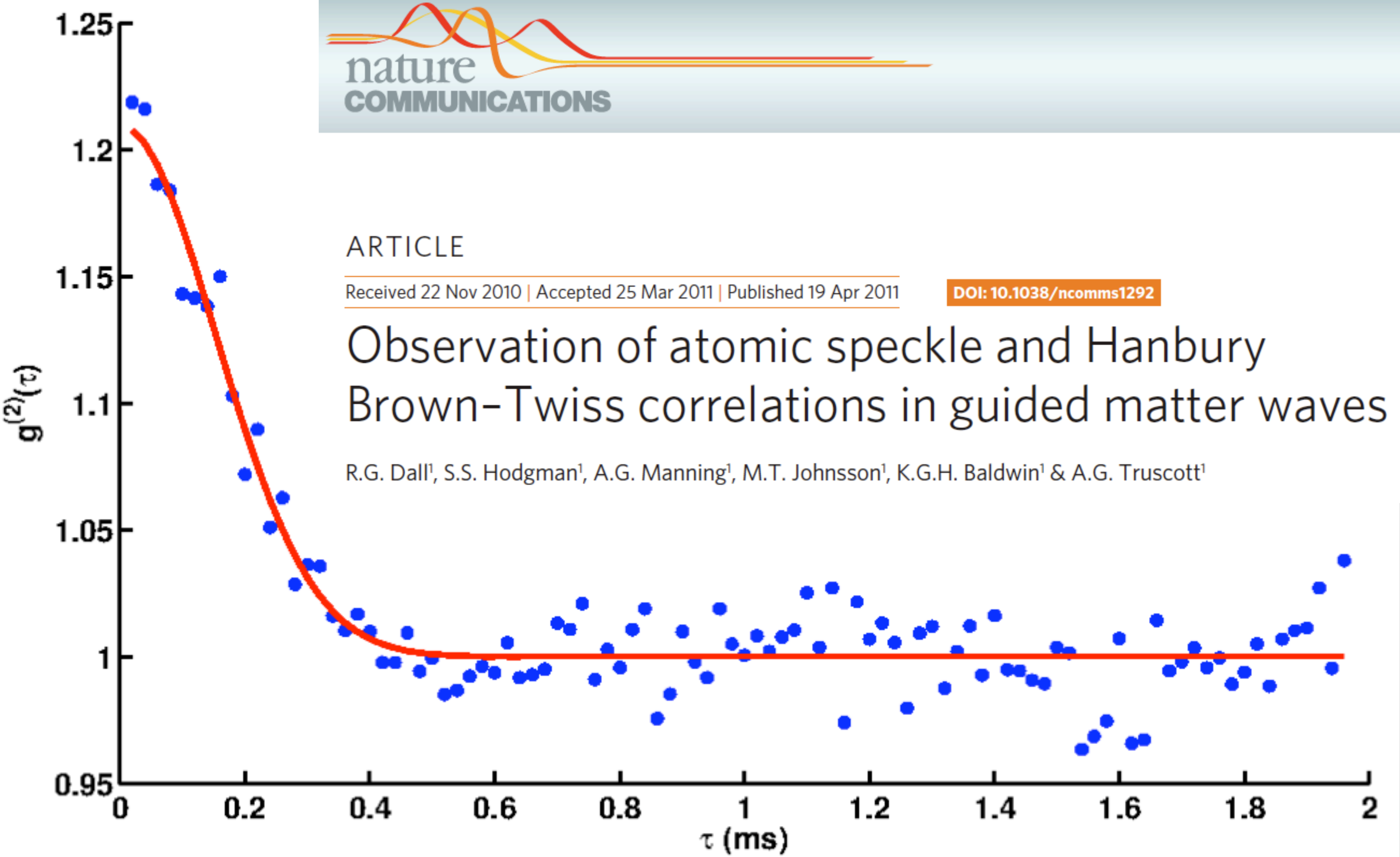


nature COMMUNICATIONS

ARTICLE

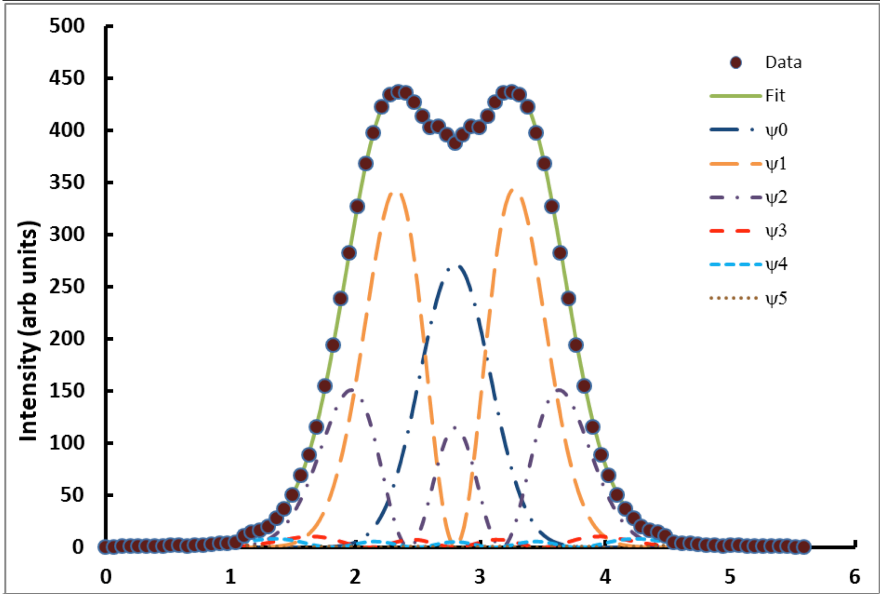
Received 22 Nov 2010 | Accepted 25 Mar 2011 | Published 19 Apr 2011 DOI: 10.1038/ncomms1292

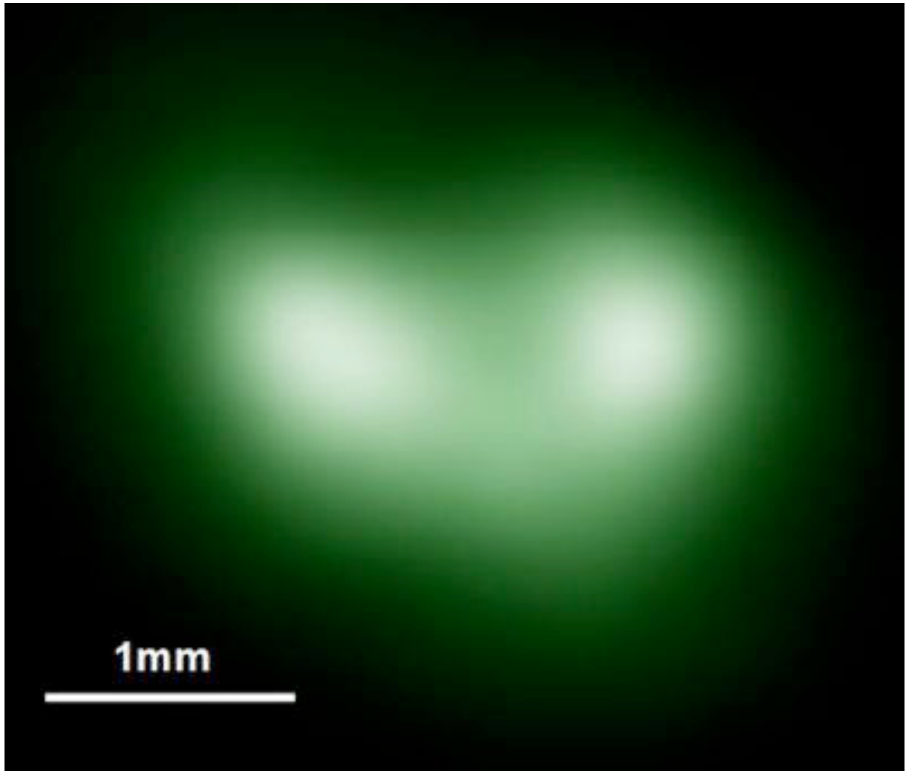
Observation of atomic speckle and Hanbury Brown–Twiss correlations in guided matter waves

R.G. Dall[1], S.S. Hodgman[1], A.G. Manning[1], M.T. Johnsson[1], K.G.H. Baldwin[1] & A.G. Truscott[1]

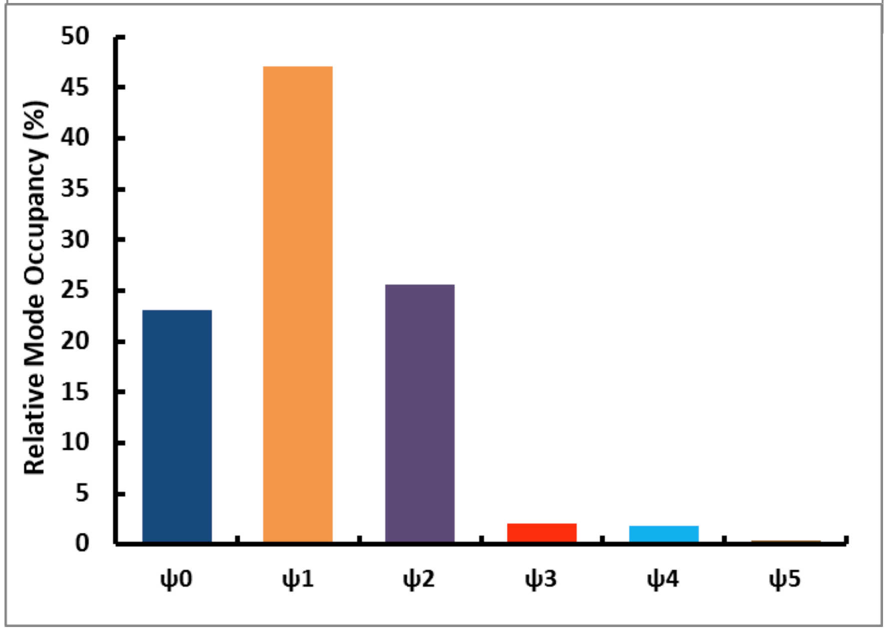
Mode Occupancy

Mode composition





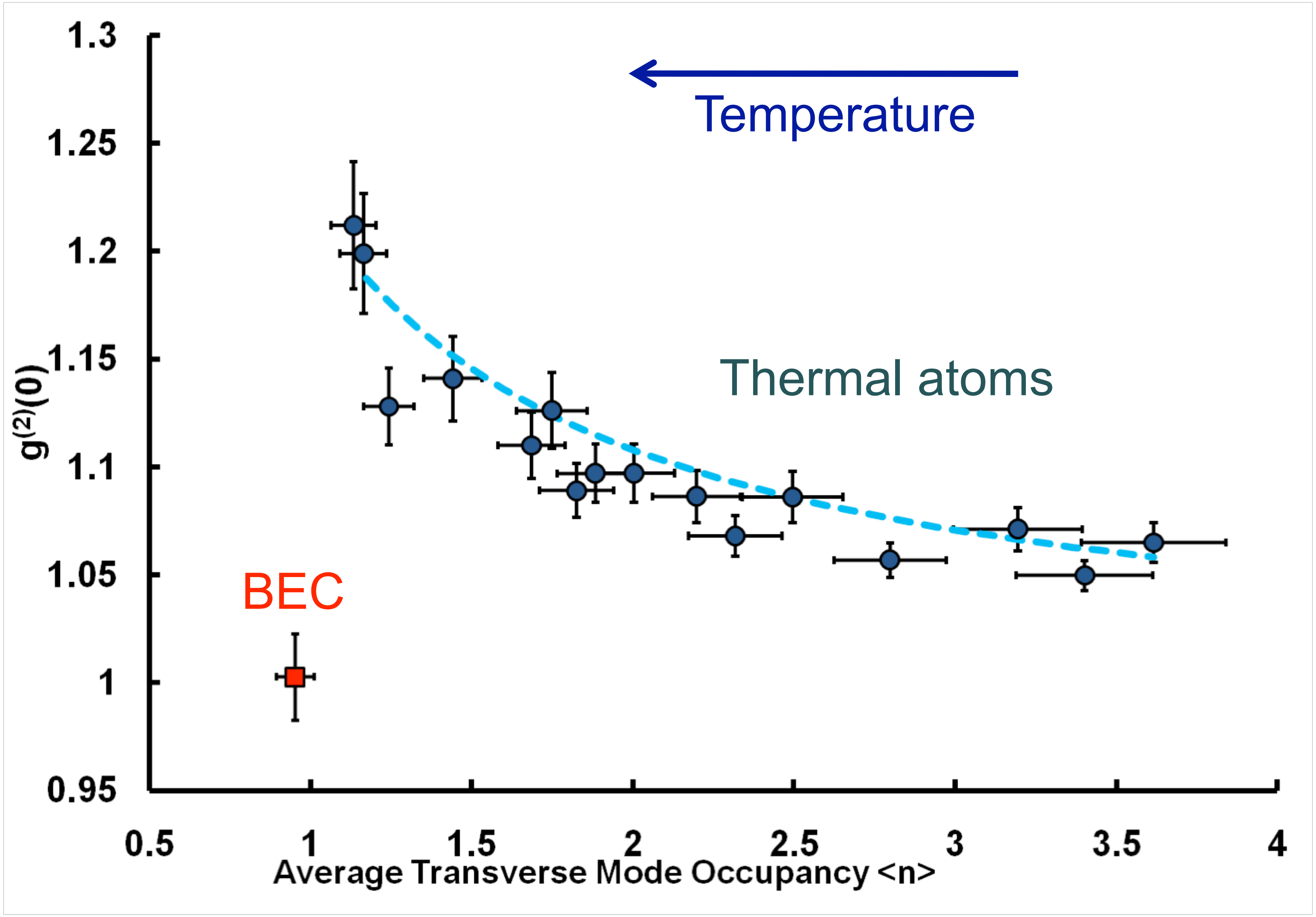
Mainly TEM 01 Spatial profile



Mode occupancy

R.G. Dall, S.S. Hodgman, A.G. Manning and A.G. Truscott, *Optics Letters* **36**, 1131 (2011)

Mode occupancy

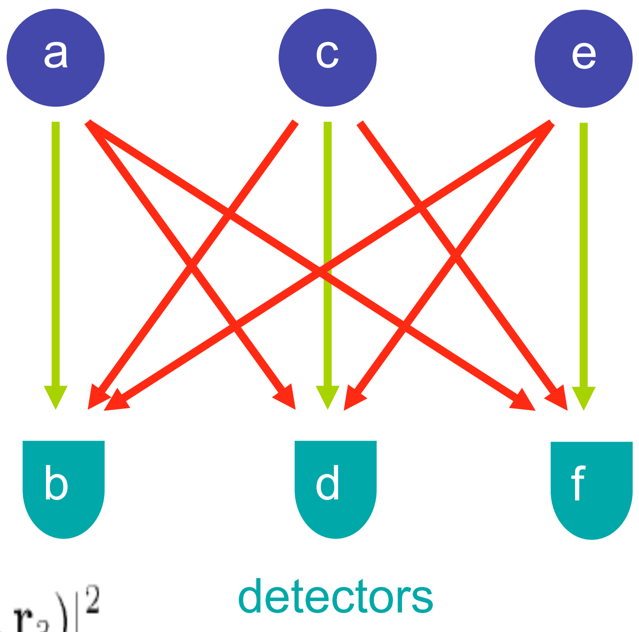


Third Order Correlation Function $g^{(3)}$

- Measures coincidence of particle *triplets*
- Determines coherence to third order

For *random Gaussian events*, correlation functions are a nested series (Glauber)

So in principle, only need to calculate $g^{(1)}$ over the ensemble

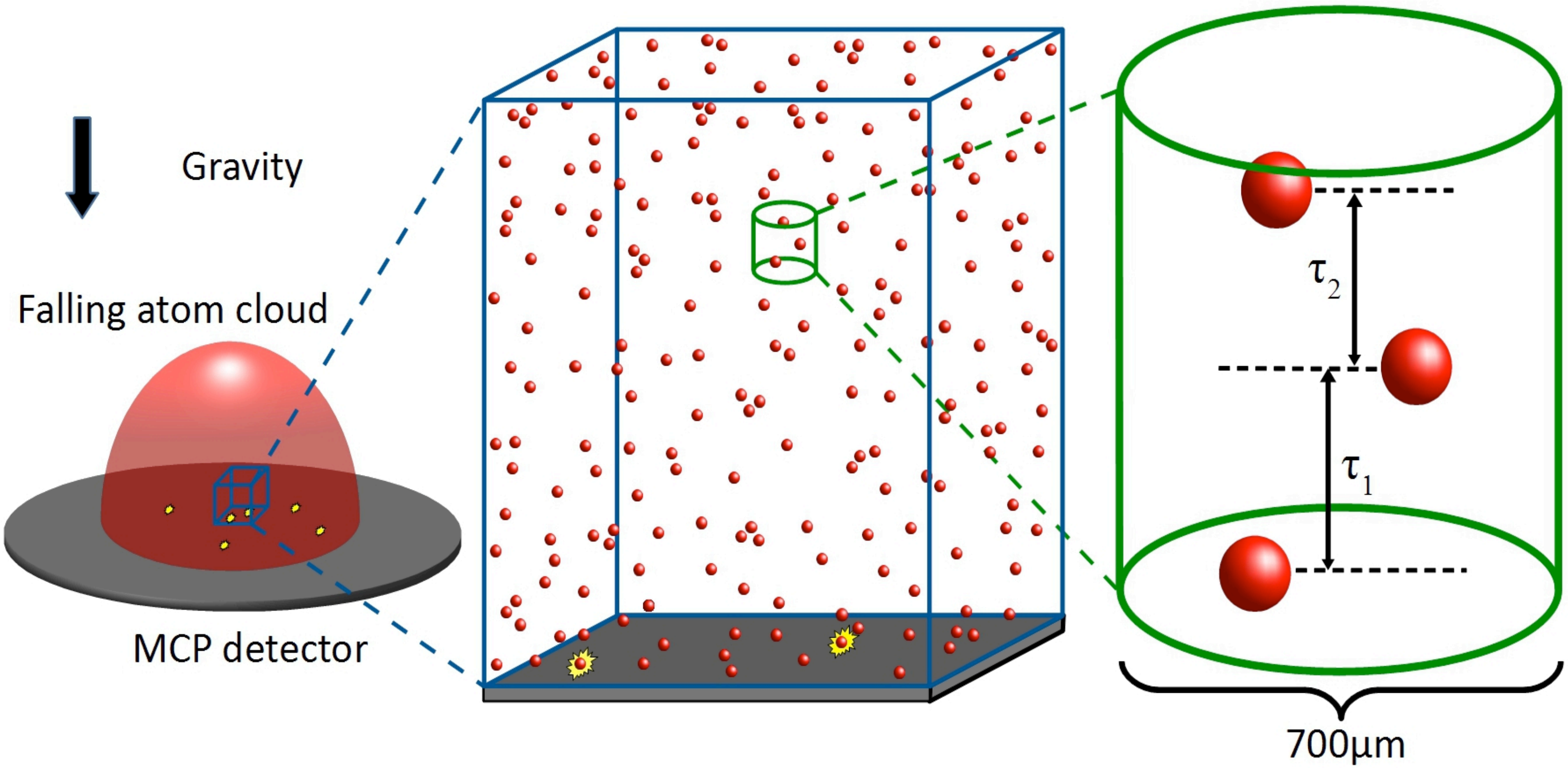


3! = 6 combinations

$$g^{(2)}(\mathbf{r}_1, \mathbf{r}_2) = 1 + |g^{(1)}(\mathbf{r}_1, \mathbf{r}_2)|^2$$

$$\begin{aligned} g^{(3)}(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3) &= 1 + |g^{(1)}(\mathbf{r}_2, \mathbf{r}_3)|^2 + |g^{(1)}(\mathbf{r}_1, \mathbf{r}_2)|^2 + |g^{(1)}(\mathbf{r}_1, \mathbf{r}_3)|^2 \\ &\quad + g^{(1)}(\mathbf{r}_1, \mathbf{r}_2) g^{(1)}(\mathbf{r}_2, \mathbf{r}_3) g^{(1)}(\mathbf{r}_3, \mathbf{r}_1) \\ &\quad + g^{(1)}(\mathbf{r}_2, \mathbf{r}_1) g^{(1)}(\mathbf{r}_3, \mathbf{r}_2) g^{(1)}(\mathbf{r}_1, \mathbf{r}_3). \end{aligned}$$

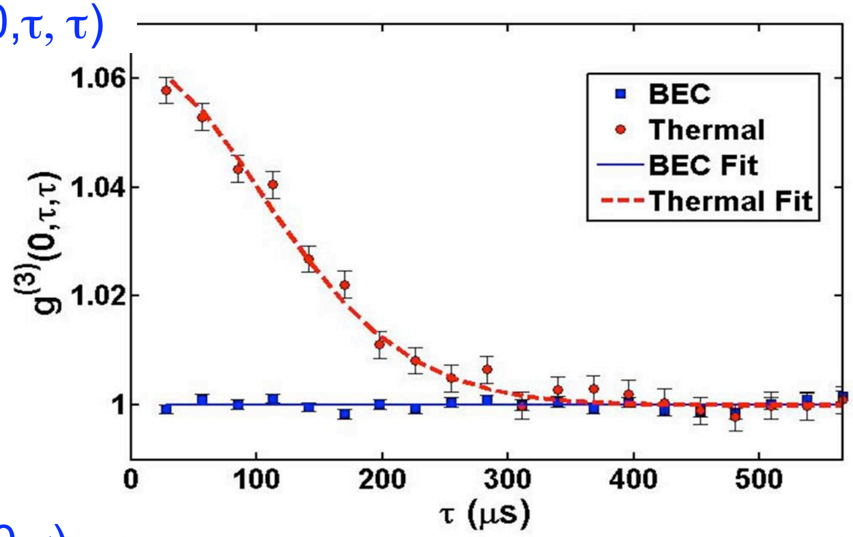
Third order: 3 atom bunching



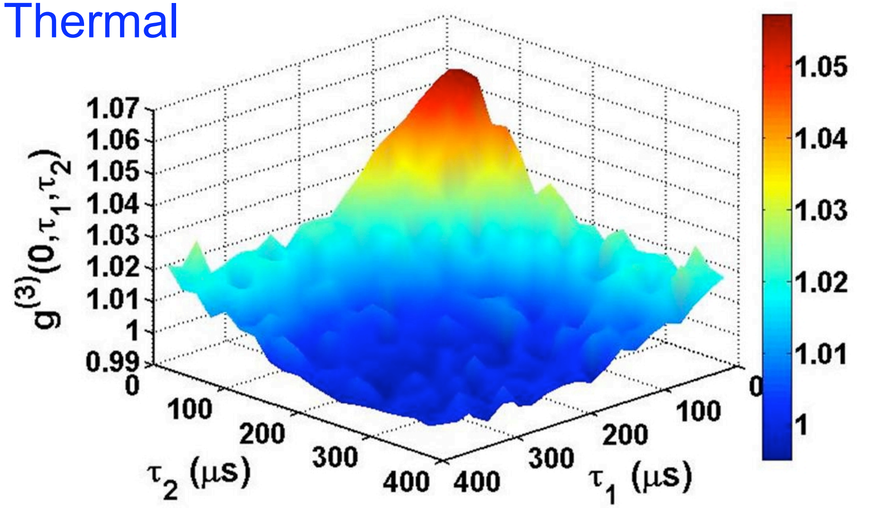
$g^{(3)}$ - the probability of detecting a third atom following the detection of an atom pair

$g^{(2)}$ and $g^{(3)}$ for atoms

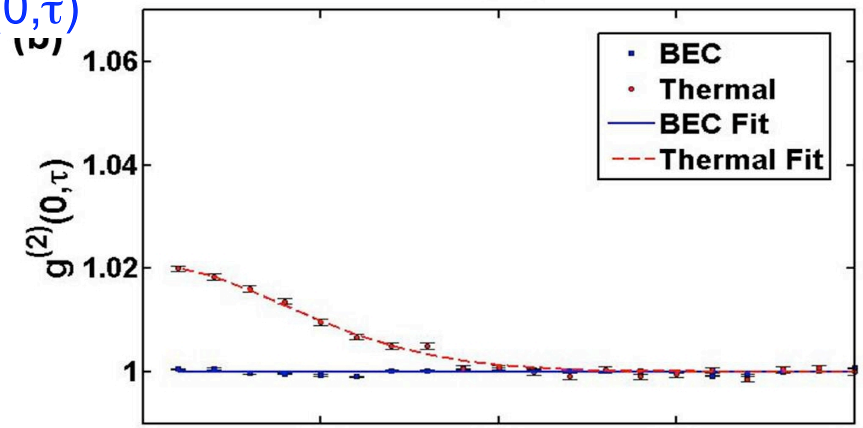
$g^3(0,\tau,\tau)$



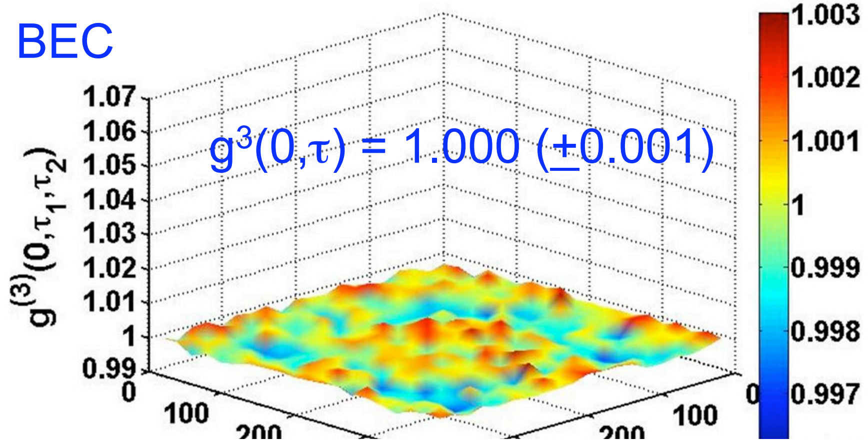
Thermal



$g^2(0,\tau)$



BEC



$g^3(0,\tau) = 1.000\ (\pm 0.001)$

Science

AAAS

Direct Measurement of Long-Range Third-Order Coherence in Bose-Einstein Condensates

S. S. Hodgman, *et al.*

Science **331**, 1046 (2011);
DOI: 10.1126/science.1198481

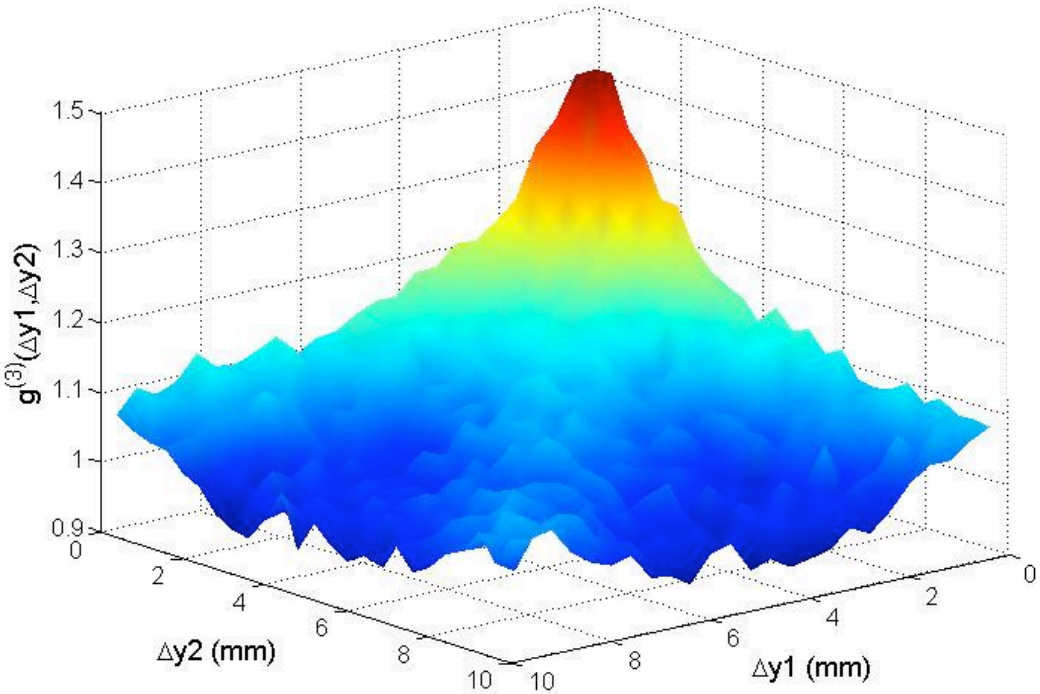
Model comparisons with data

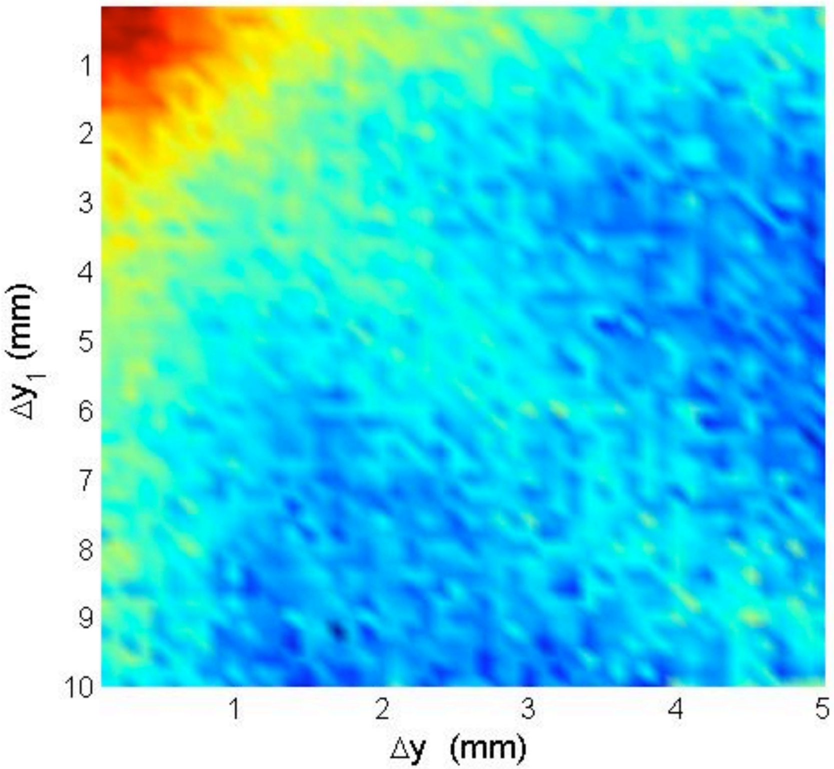
	Experiment	Theory
$g^{(2)}(0, \tau)$ max.	1.022(2)	1.025(5)
$g^{(2)}(0, \tau)$ width (μs)	90(10)	80(20)
$g^{(3)}(0, \tau_1, \tau_2)$ max.	1.061(6)	1.075(15)
$g^{(3)}(0, \tau_1, \tau_2)$ width (μs)	120(10)	100(20)
$[g^{(3)}(0,0,0) - 1]/[g^{(2)}(0,0) - 1]$	2.8(3)	3.0(3)

Model based on:

"Theory for a Hanbury Brown Twiss experiment with a ballistically expanding cloud of cold atoms," J. Viana Gomes, A. Perrin, M. Schellekens, D. Boiron, C. I. Westbrook and M. Besley, *Phys. Rev. A* **74**, 053607 (2006).

Spatial $g^{(3)}(\Delta y_1, \Delta y_2)$





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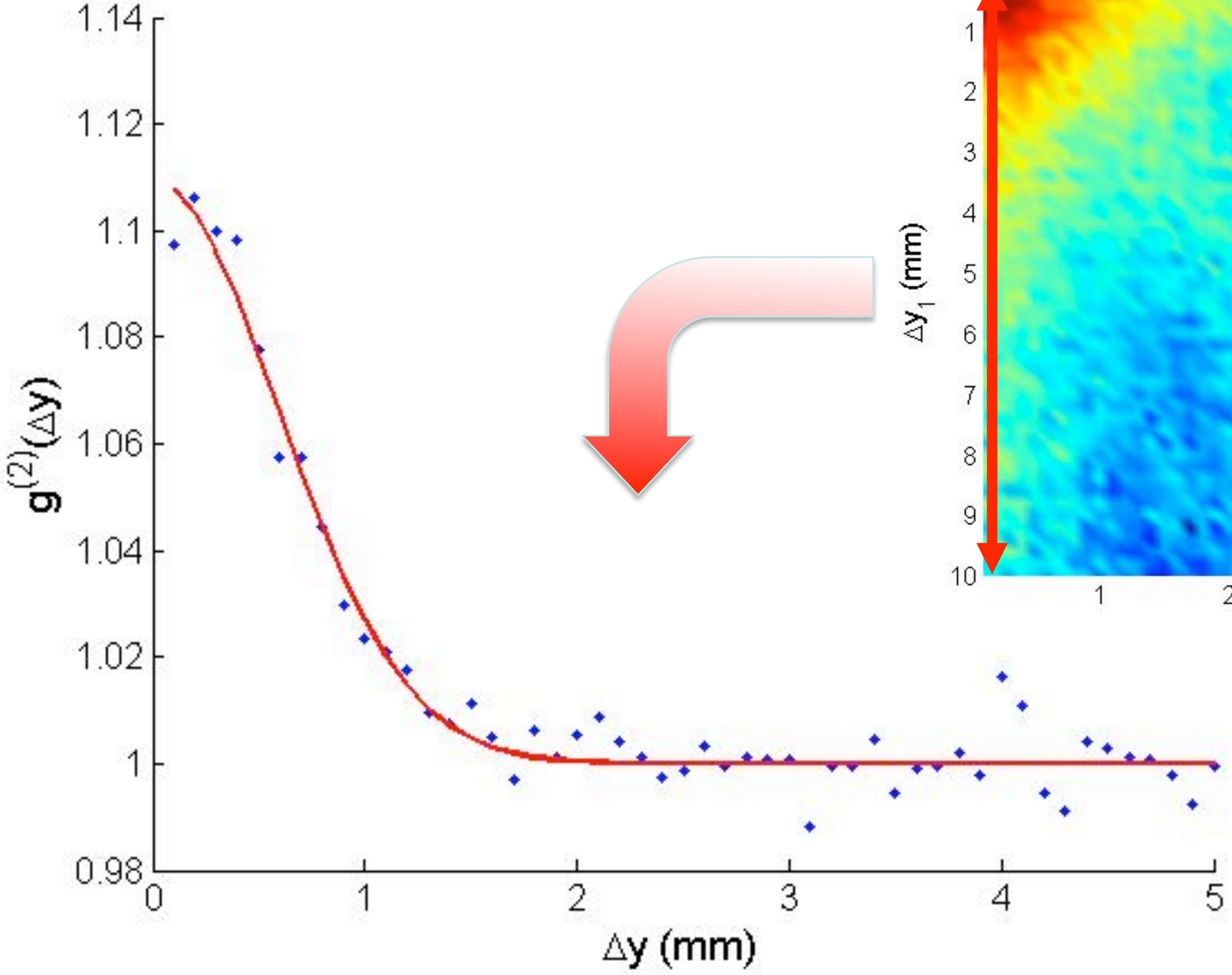
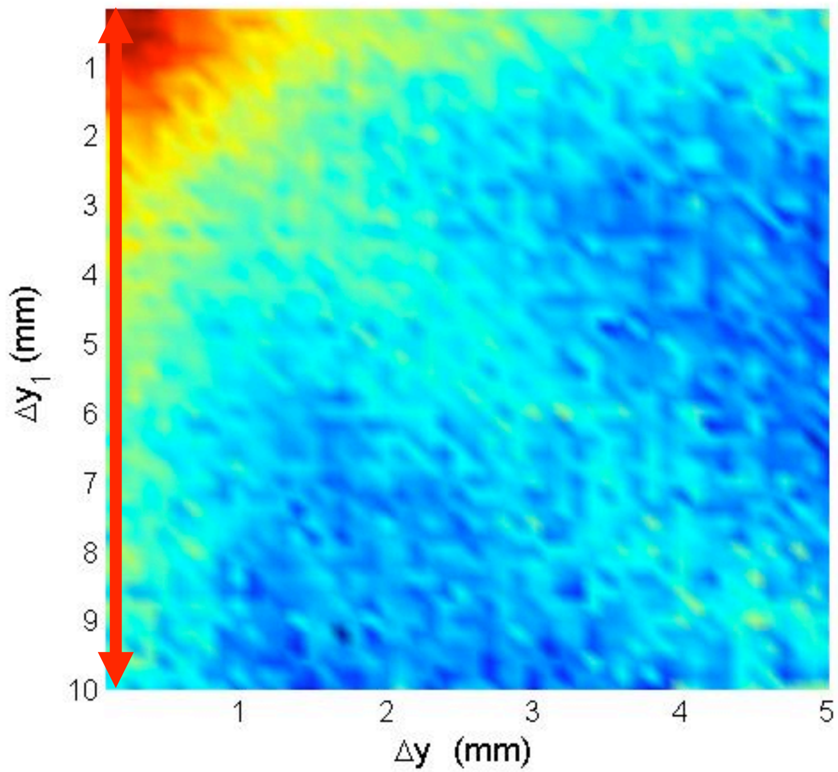
Spatial $g^{(2)}(\Delta y)$





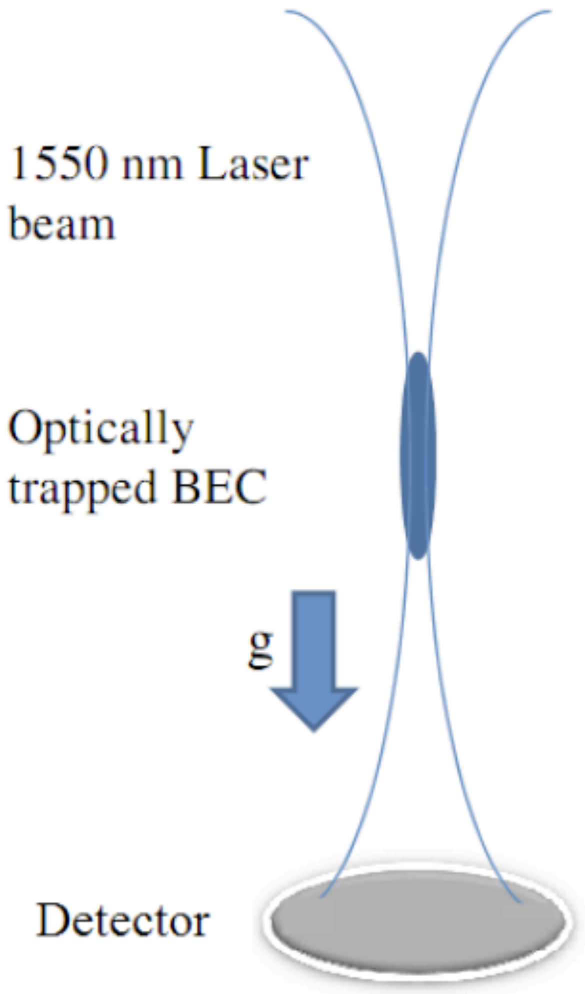
Optical Dipole Trap

Using an optical dipole trap has many advantages

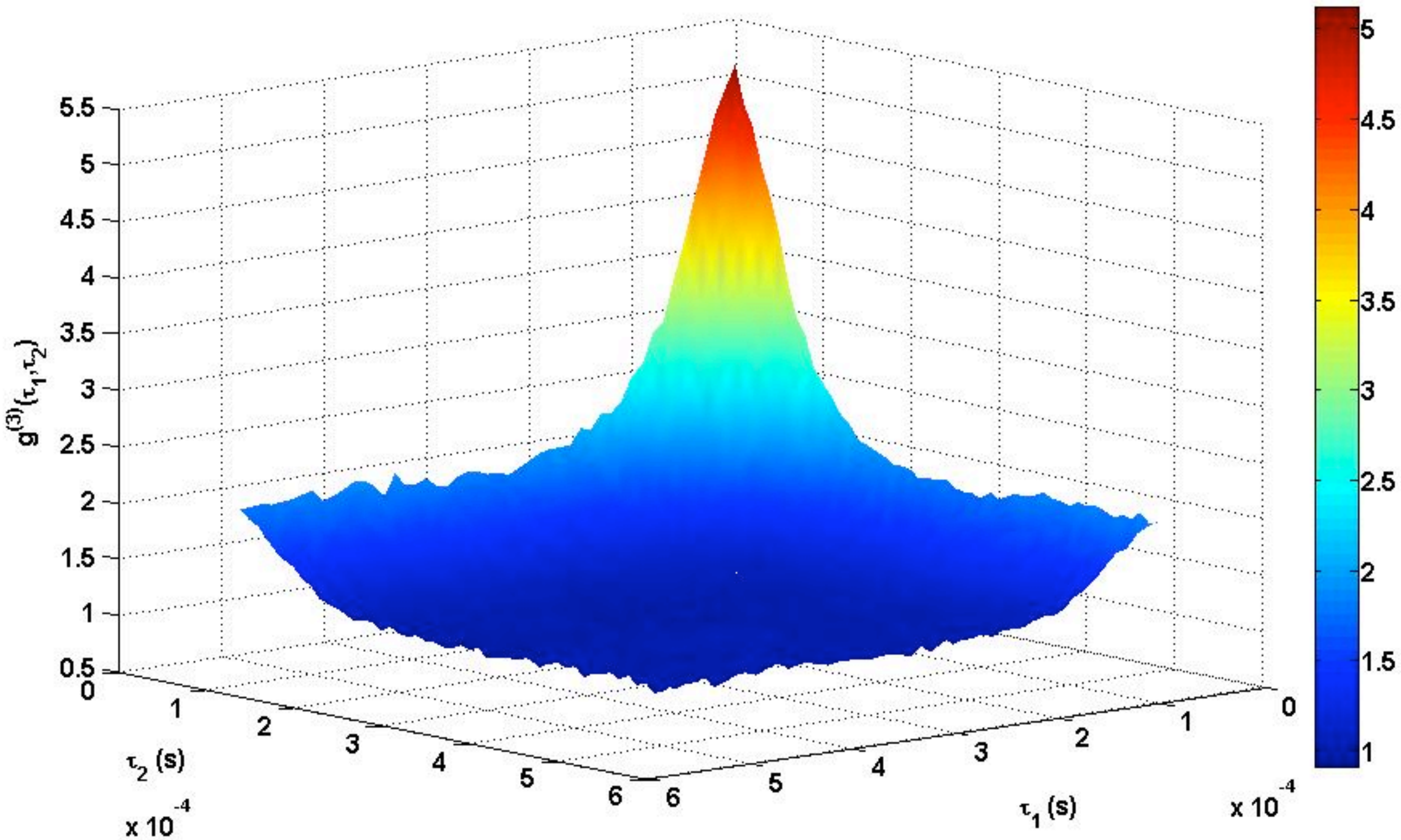
- Tighter trap
  $= 2\pi$ (2.4k, 1.8k, 17) Hz

compared to magnetic trap
$= 2\pi$ (550, 50, 550) Hz

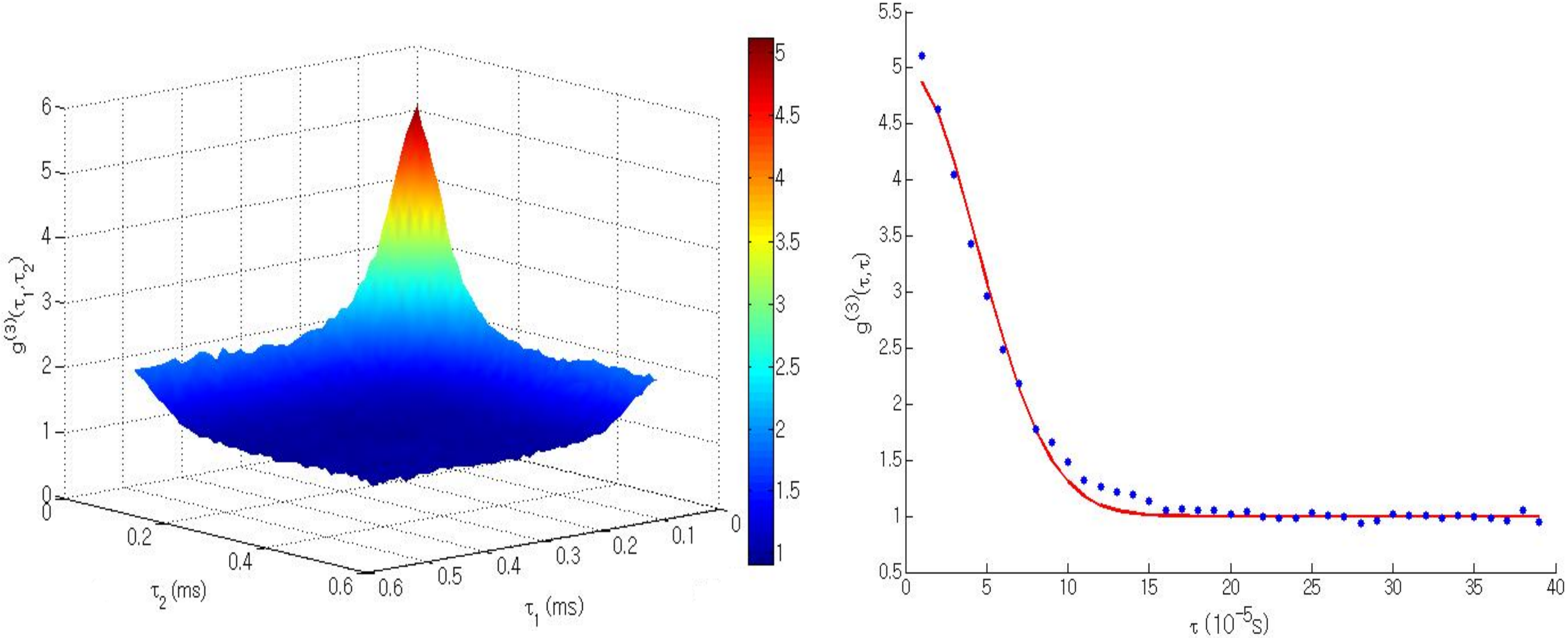
- Thus, increase correlation length
- Smaller number (10^4 compared to 10^6 in magnetic trap - saturation)
- Loads colder atoms
- Fine control over evaporation ramp



New $g^{(3)}$ measurement

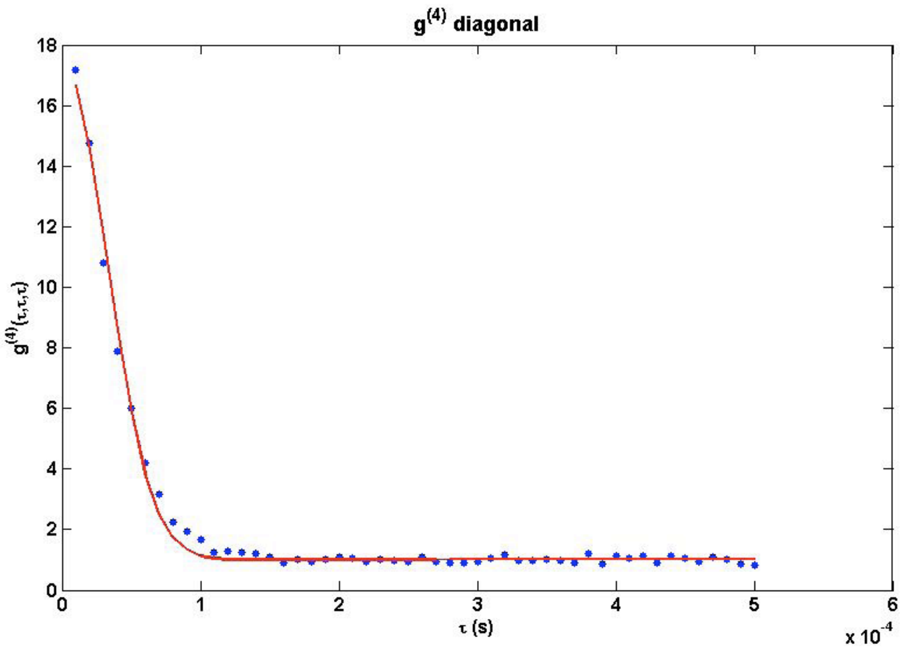


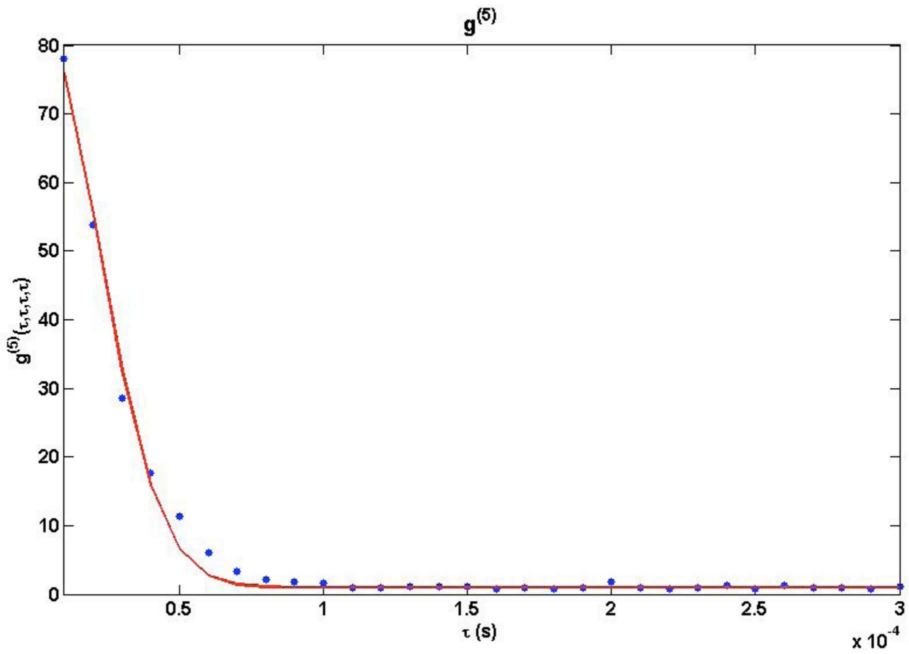
World record enhancement



Maximum $g^{(3)} \sim 5$ (theoretical maximum $3! = 6$)

$g^{(4)}$ and $g^{(5)}$

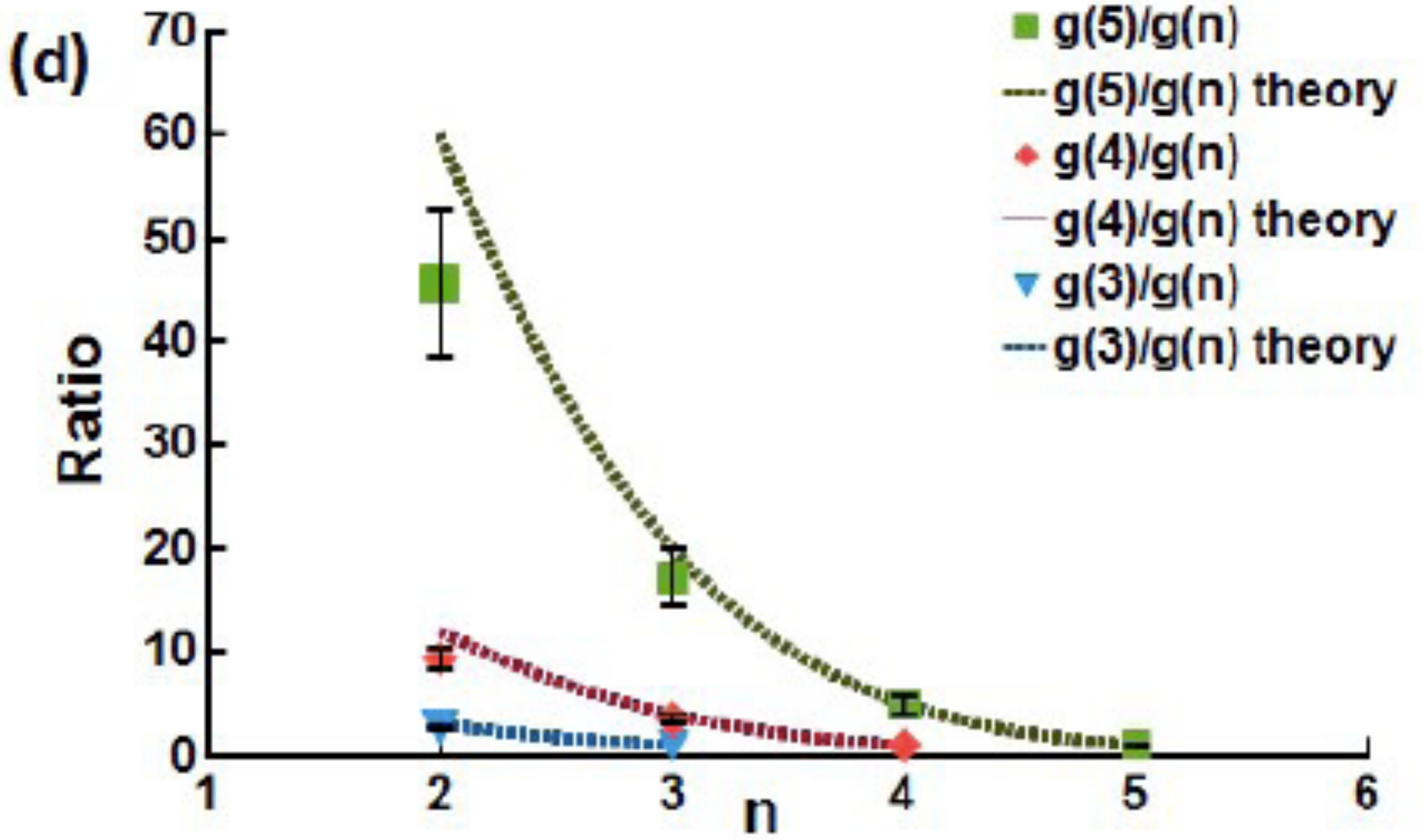




$g^{(4)}$
maximum ~18
(c.f. 4! = 24)

$g^{(5)}$
maximum ~ 80
(c.f. 5! = 120)

Higher Order Correlations



Summary

- We have guided near single-mode (BEC) and multi-mode (thermal) matter waves in a focused laser beam
- For multi-mode guiding, we have imaged atomic speckle for the first time
- The second order correlation function for multi-mode (thermal) guiding yielded atom bunching: $g^{(2)}(\tau) > 1$
- For the single-mode (BEC): $g^{(2)}(\tau) = 1$

The Future

- Correlations can be used as a diagnostic of the coherence of matter wave devices
- Applications might include squeezed atom interferometry, atom holography
- Correlations can lead to entanglement
- Studies of entanglement enable investigation of fundamental questions in quantum mechanics, such as the Einstein-Podolsky-Rosen paradox

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Optics in 2011

Highlights of Optics during the year

Published in

Optics and Photonics News, The Optical Society, December 2011

Characterizing Atom Sources with Quantum Coherence

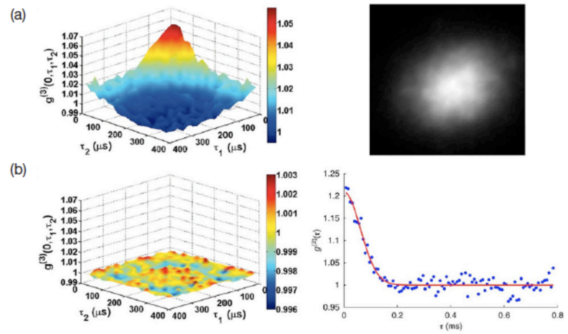
S.S. Hodgman, R.G. Dall, A.G. Manning, M.T. Johnsson, K.G.H. Baldwin and A.G. Truscott

Researchers can characterize atom sources by coherence properties, viewed by a wave or particle picture, by using quantum optics as an analogy. For example, first-order coherence measures amplitude fluctuations related to fringe visibility in an interferometer. Second-order coherence measures intensity variations as manifested in laser light speckle.

Hanbury Brown and Twiss (HBT) demonstrated that incoherent sources are characterized by photon bunching in the particle picture, whereby the second-order correlation function exceeds unity for short arrival times between pairs of photons (coherence time).[1] In contrast, a coherent source—e.g., a laser—has a correlation function value of unity for all times; and per Glauber's quantum theory, this is expected to be true to all orders of the correlation function.[2]

Previous experiments by this group of researchers observed atom bunching for thermal (incoherent) sources of bosonic atoms (anti-bunching for fermions), and a second-order correlation function unity value, i.e., an equal probability for all arrival times, for Bose-Einstein condensates (BECs) by analogy with coherent optical sources.

We have used a new approach to measure the temporal third-order correlation function for both thermal and BEC ensembles of atoms. Our results demonstrate atom bunching for ultracold metastable helium atoms sourced from a 1 μK thermal ensemble, where the observed 6 percent bunching enhancement is less than the theoretical maximum (n! for nth order coherence) due to the finite resolution of the detector. By contrast, we measured a unity (within 0.1 percent) third-order correlation value for the BEC, thereby demonstrating that a BEC is coherent to a higher order and confirming Glauber's hypothesis.[3]



(Left) Third-order correlation function for thermal atoms, 6 percent bunching enhancement (a) and a Bose-Einstein condensate, unity value, within 0.1 percent (b). (Right) Image of atomic speckle (top) and second-order correlation function (bottom) for multimode guided atoms, 21 percent bunching enhancement.

We have extended these quantum statistical measurements to atomic de Broglie waves guided within a red-detuned laser beam. The waveguide is capable of supporting the lowest-order mode (BEC, yielding a gaussian transverse spatial profile) or several low-order modes that we are able to selectively control.[4] For multimode guiding, the transverse spatial profile exhibits a structure corresponding to atomic speckle. By adding the speckle images over multiple realizations of the experiment, the spatial profile yields an expected smooth average for independent thermal sources.

To further test the speckle hypothesis, we measured the second-order correlation function for the guided atoms. We detected HBT atom bunching, indicating that multimode guiding is associated with matter-wave speckle.[5] When a BEC is loaded into the guide with up to 65 percent of atoms in the lowest order mode, the atom bunching disappears, a finding that is consistent with the propagation of a coherent matter wave in the lowest-order mode of the guide.

These experiments demonstrate the usefulness of the quantum statistical properties of matter waves as a diagnostic for atomic source coherence properties. By being able to determine the transverse mode occupancy and spatial structure (speckle) for atoms guided by an optical potential, researchers can characterize de Broglie wave fronts for use in atom optics applications such a matter-wave interferometry.

S.S. Hodgman, R.G. Dall, A.G. Manning, M.T. Johnsson, K.G.H. Baldwin (kenneth.baldwin@anu.edu.au) and A.G. Truscott are with the Research School of Physics and Engineering, Australian National University, in Canberra, Australia.

References

1. R.H. Brown and R.Q. Twiss. Nature **177**, 27 (1956).
2. R.J. Glauber. Phys. Rev. **130**, 2529 (1963).
3. S.S. Hodgman et al. Science **331**, 1046 (2011).
4. R.G. Dall et al. Opt. Lett. **36**, 1131 (2011).
5. R.G. Dall et al. Nat. Commun. **2**, 291; doi:10.1038/ncomms1292 (2011).

The Helium Team

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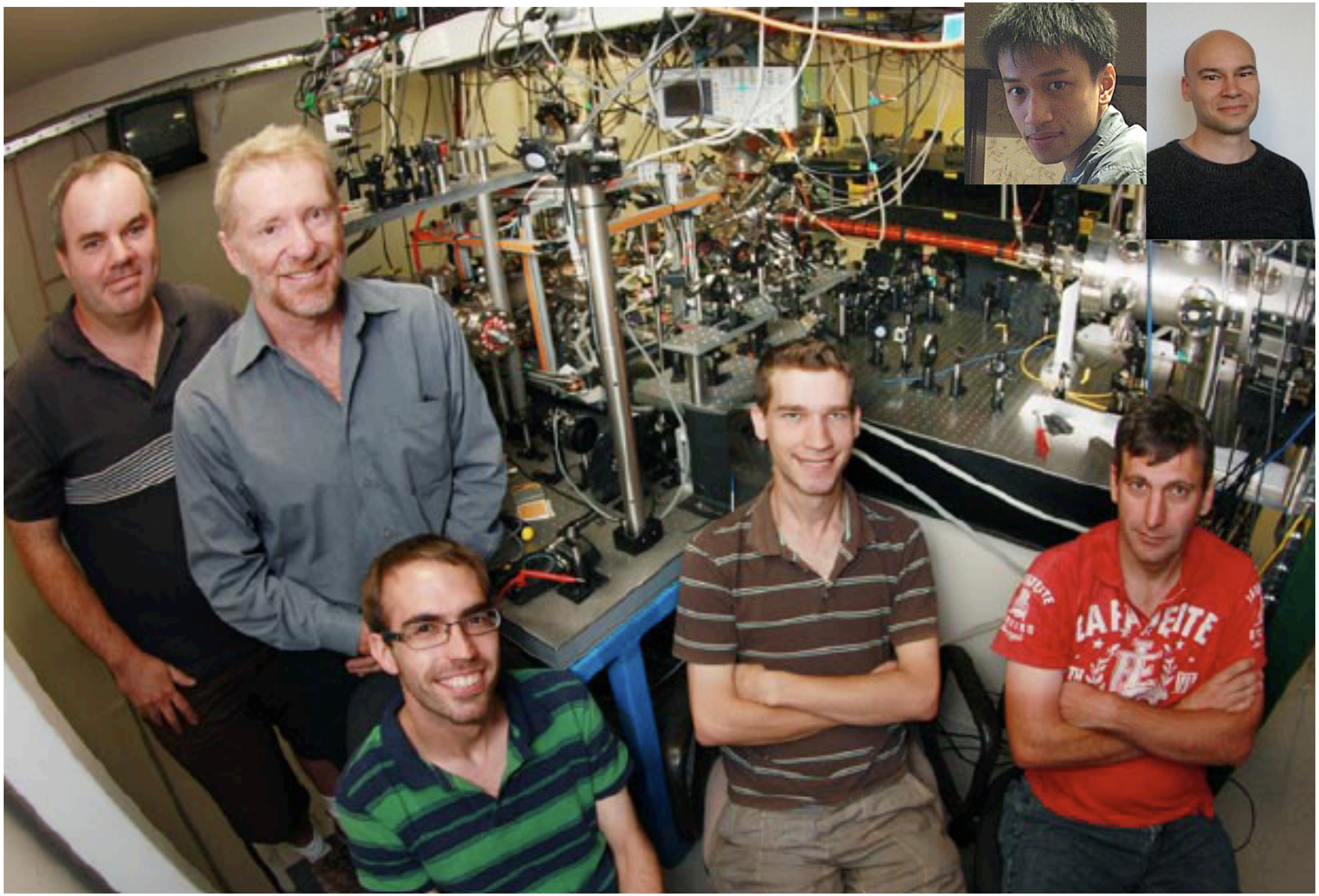
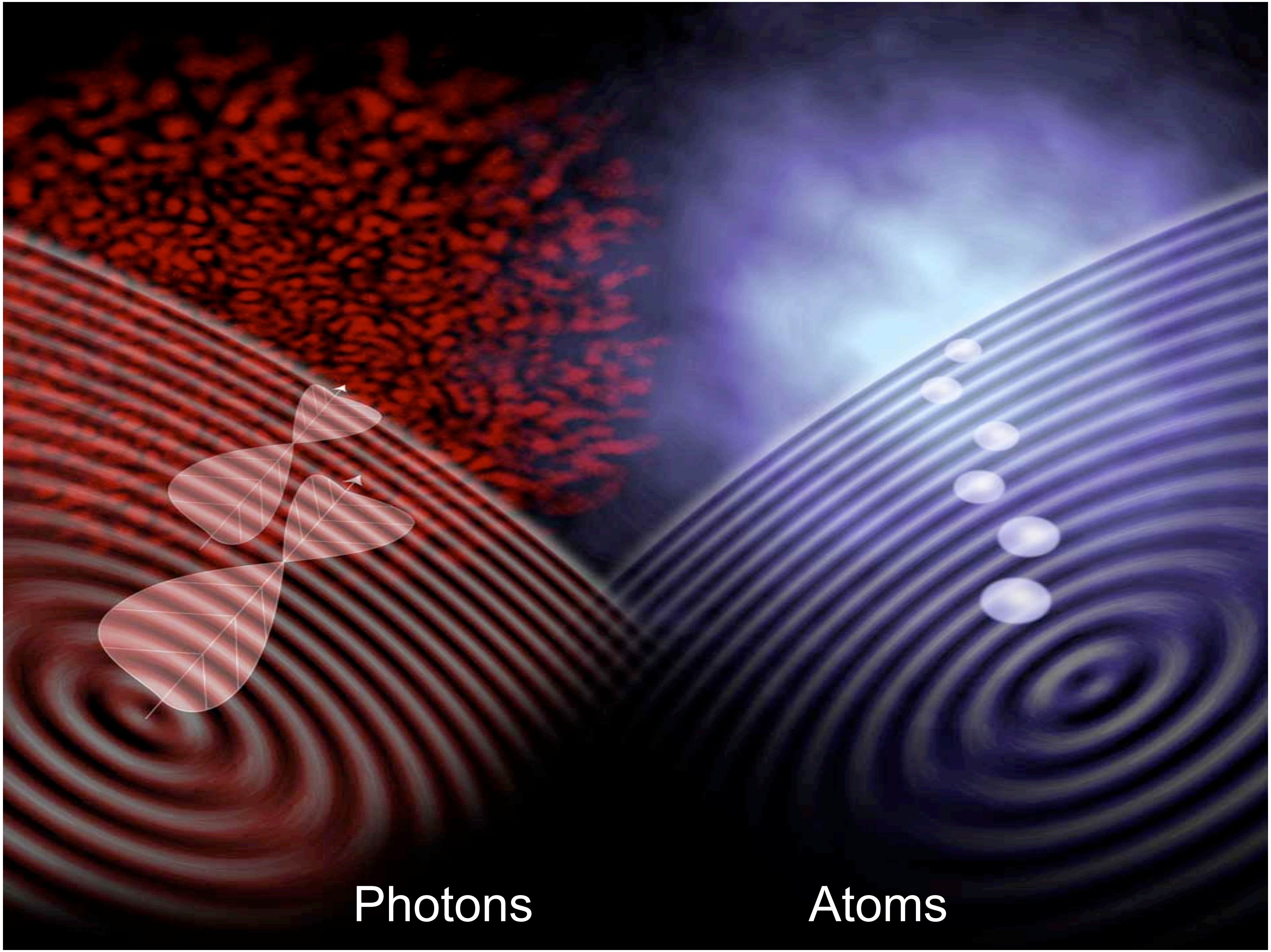
Andrew Truscott KB Ru Gway Wu Mattias Johnsson



Andrew Manning Sean Hodgman Robert Dall


Photons
Atoms


Thank you!
Ultracold Physics: 6,547m Nepal