BEC-Light Interactions

(an interacting-atom BEC interacting with coherent light)

Kioloa Workshop 9 February 2006

William D. Phillips,
National Institute of Standards and Technology, Gaithersburg MD, USA
Laser cooling and trapping group: P. Lett, K. Helmerson, T. Porto

Vortex creation by stimulated Raman scattering of optical orbital angular momentum

Changhyun Ryu
Vasant Natarajan
Pierre Cladé
Mikkel F. Andersen

Kris Helmerson

Study of a 2D Mott state using noise correlations

Ian Spielman
Jennifer Strabley
Marco Anderlini

Trey Porto

$upport: NIST, ONR, ARDA/DTO, NASA

Other cool new stuff in Gaithersburg

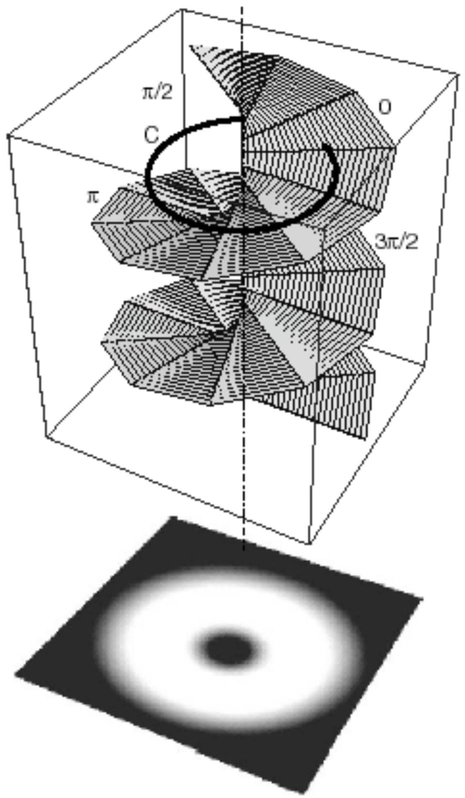
- All optical BEC in Na with a $\lambda = 1\ \mu m$ crossed dipole trap in the horizontal plane: high efficiency evaporation, multiple BECs, atomic waveguides,…Paul Lett *et al*.

- A lattice of double-well potentials: coherent splitting of atoms into double wells, state dependent addressing, …Trey Porto *et al*.

Orbital Angular Momentum of Light

Light can have orbital angular momentum along its direction of propagation!

$$\mathbf{L}_{\text{field}} = \frac{1}{4\pi c}\int \mathbf{r}\times(\mathbf{E}\times\mathbf{B})d^3r$$

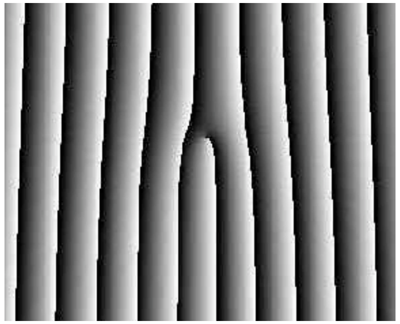


Laguerre-Gaussian Beams:

$$\mathrm{LG}_0^1(\rho,\theta) \propto \frac{1}{\mathrm{w}_0^2}\rho\exp(-\rho^2/\mathrm{w}_0^2)\exp(\mathrm{i}\theta)$$

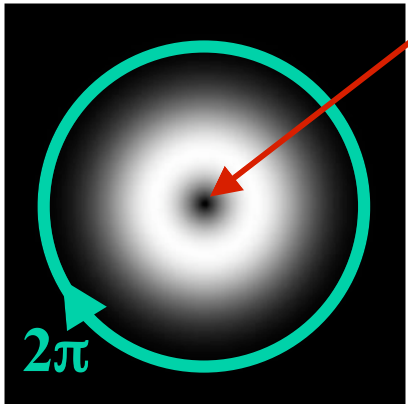
A photon in an LG_0^1 mode has an orbital angular momentum of **h**

Creating a Laguerre-Gaussian Beam



Diffract a lowest-order Gaussian beam with a hologram like this…

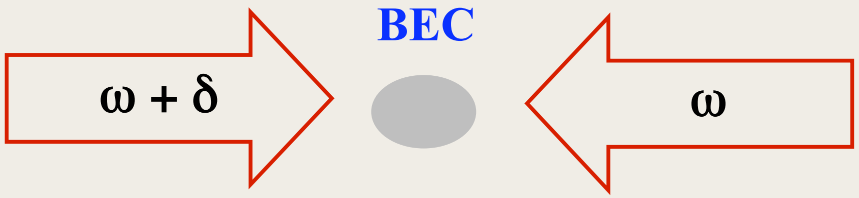
singularity



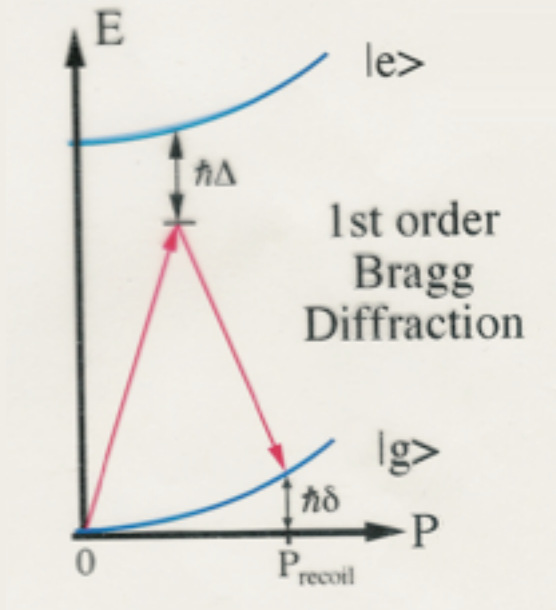
…and the diffracted beam will be a LG beam with this spatial intensity profile, and with angular momentum = **h** per photon.

Reminder:

Bragg diffraction imparts linear momentum



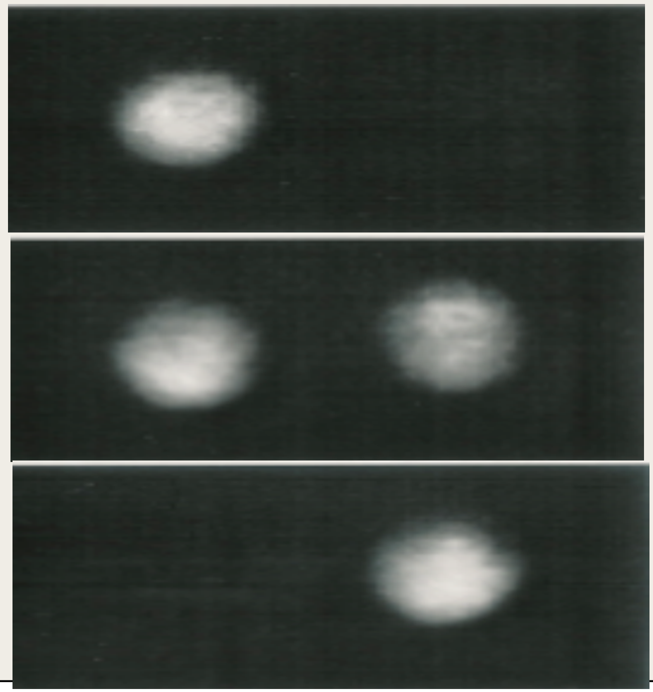
Both beams are TEM_{00} (lowest order Gaussian)



no pulse

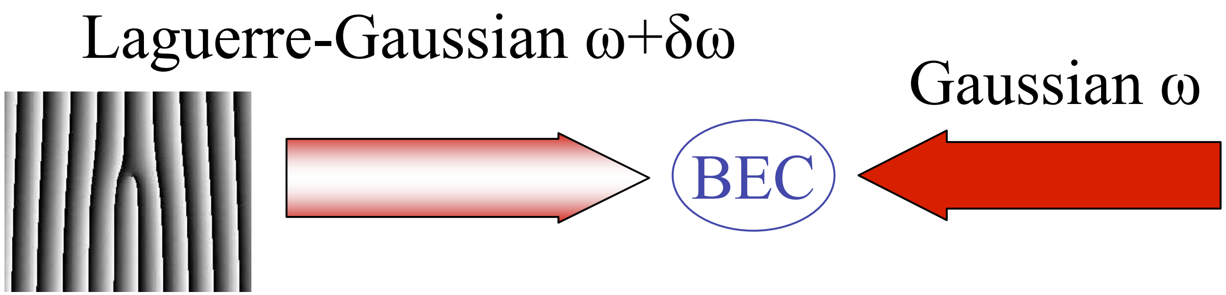
π/2 pulse

π pulse



M. Kozuma, L. Deng, E. Hagley, J. Wen, R. Lutwak, K. Helmerson, S. Rolston, WDP (PRL1999)

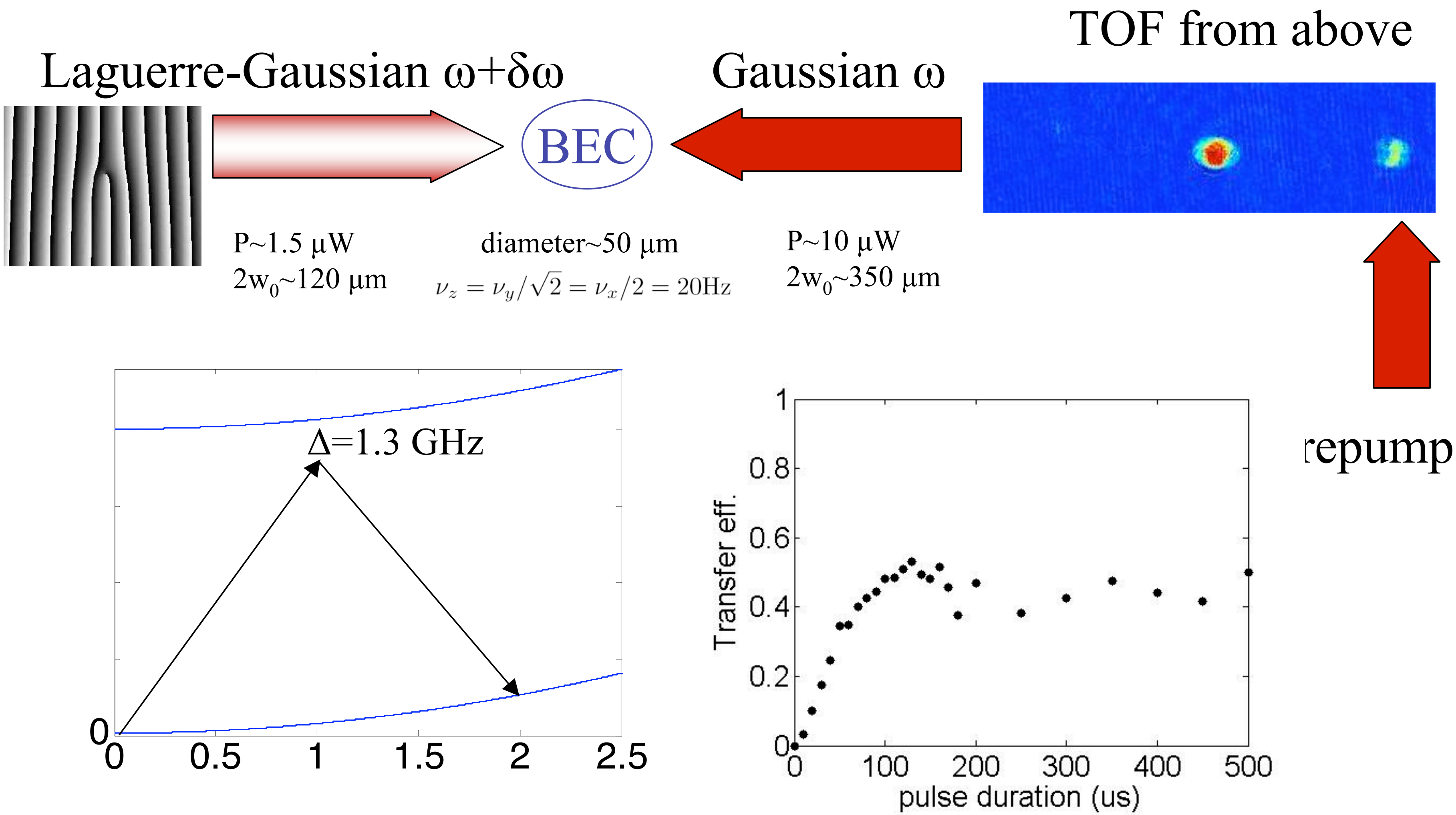
Bragg diffraction with one LG and one Gaussian imparts linear AND angular momentum



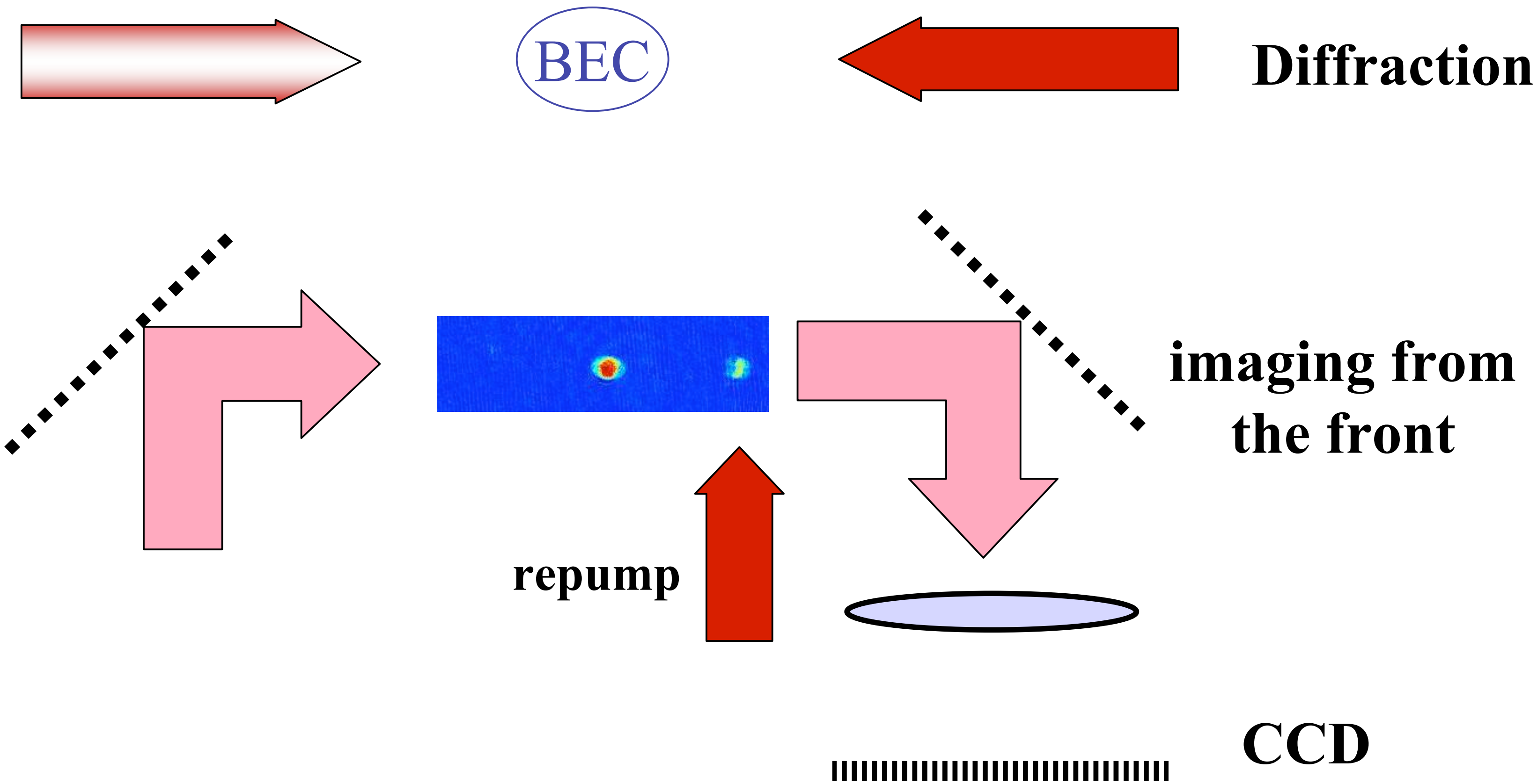
K. P. Marzlin, W. Zhang, and E. M. Wright, PRL 79, 4728 (1997).
E. L. Bolda and D. F. Walls, Phys. Lett. A245, 32 (1998).
R. Dunn, J. I. Cirac, M. Lewenstein, and P. Zoller, PRL, 80, 2972 (1998).
G. Nandi, R. Walser, and W. P. Schleich, Phys. Rev. A69, 063606 (2004).
K.T. Kapale, and J. P. Dowling, PRL 95, 123601 (2005).

(But in general, these treatments imagined changing the internal state of the atoms (rather than the linear momentum) along with the orbital angular momentum.)

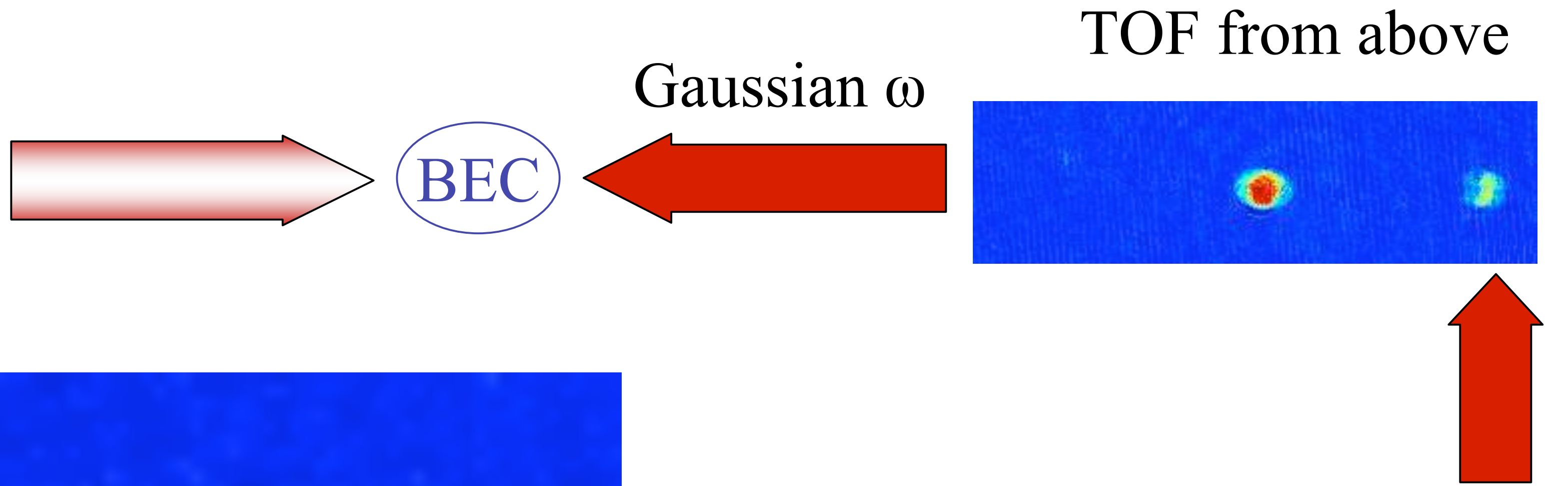
Bragg diffraction with one LG and one Gaussian imparts linear AND angular momentum

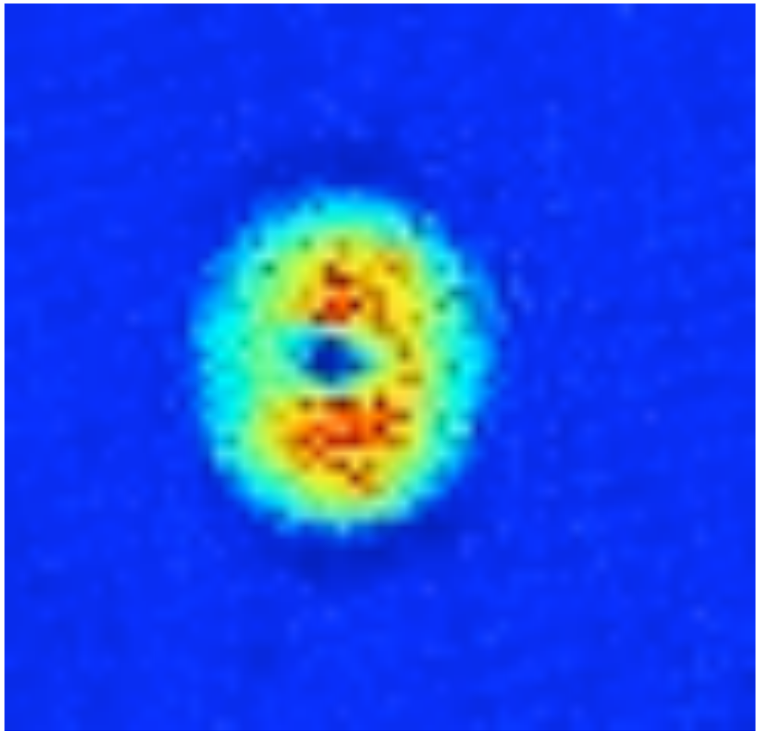


Bragg diffraction with one LG and one Gaussian imparts linear <u>AND</u> angular momentum



From the Front

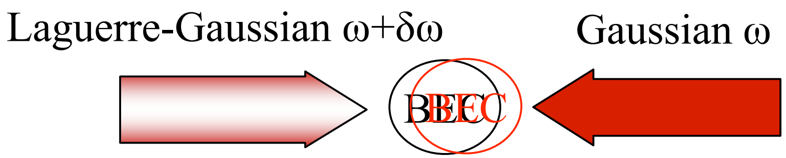


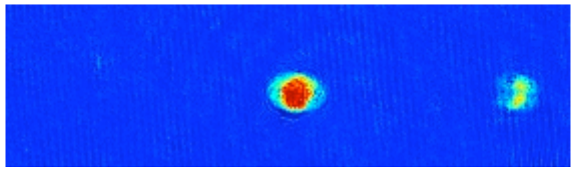


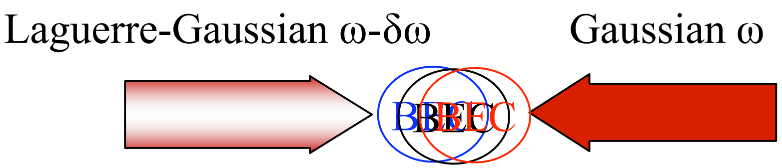
Is this hole a vortex core?

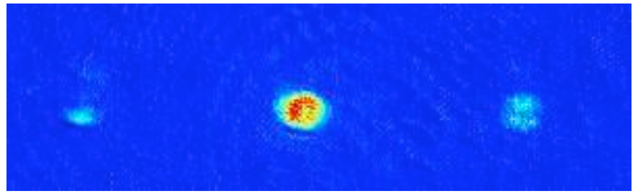
Or is it just a hole in the diffracted BEC because the diffracting beam has a hole?

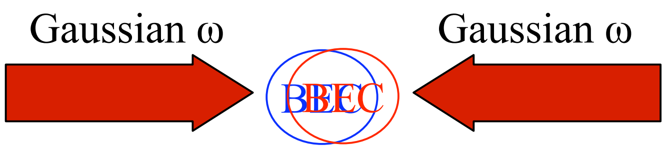
Do the Atoms Rotate?

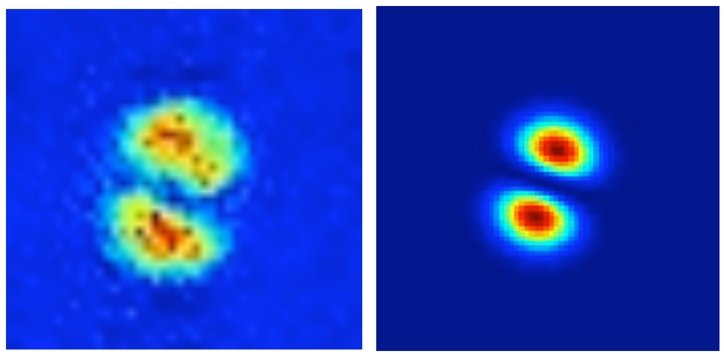










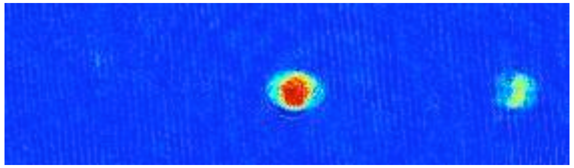


Superpose left- and right-going
condensates and image selectively

Does the phase of the vortex correlate with the phase of the LG beam?

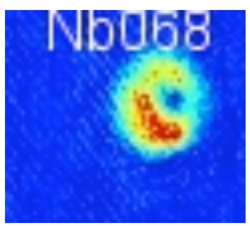
Laguerre-Gaussian ω+δω

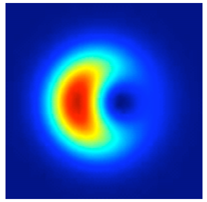
Gaussian ω

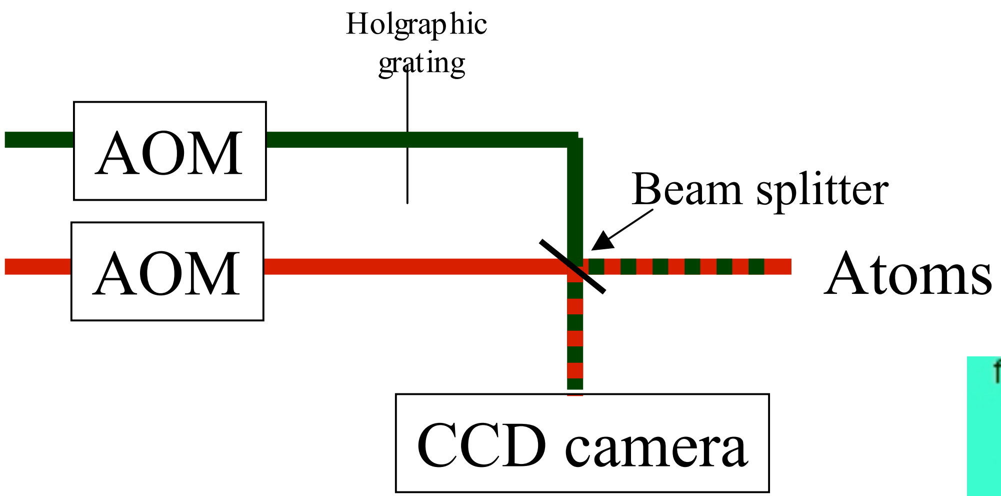


Gaussian ω+ δω

Gaussian ω



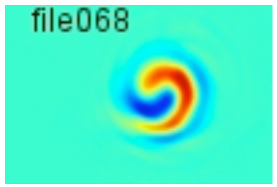




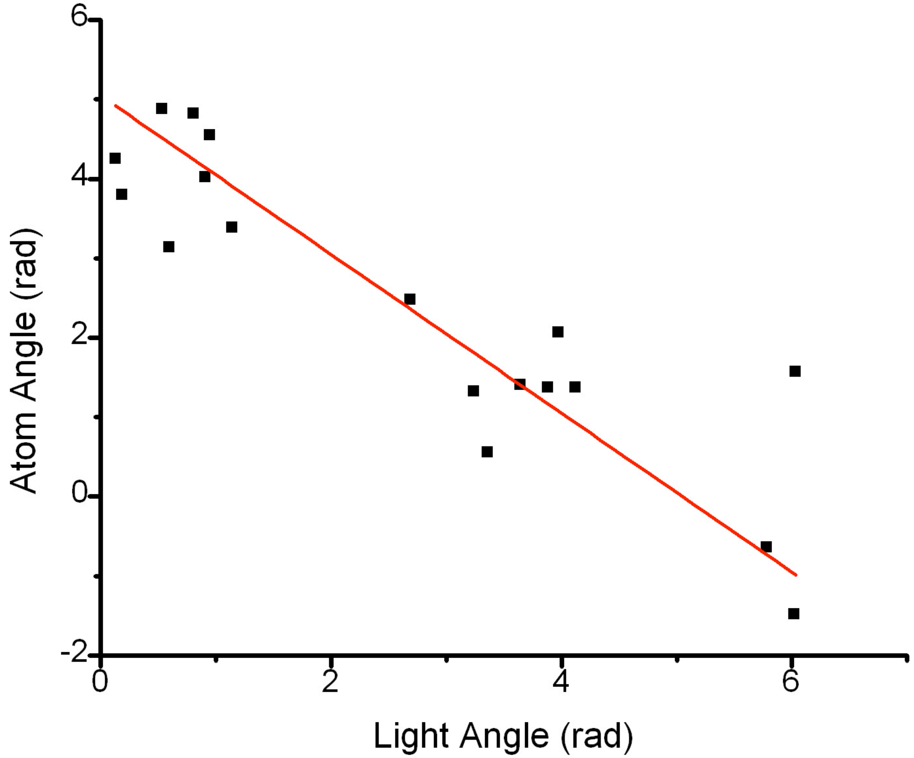
VOLUME 83, NUMBER 13 PHYSICAL REVIEW LETTERS 27 SEPTEMBER 1999

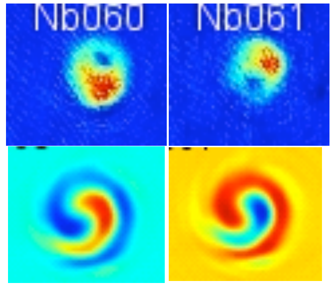
Vortices in a Bose-Einstein Condensate

M. R. Matthews, B. P. Anderson,* P. C. Haljan, D. S. Hall,† C. E. Wieman, and E. A. Cornell*
JILA, National Institute of Standards and Technology and Department of Physics, University of Colorado, Boulder, Colorado 80309-0440

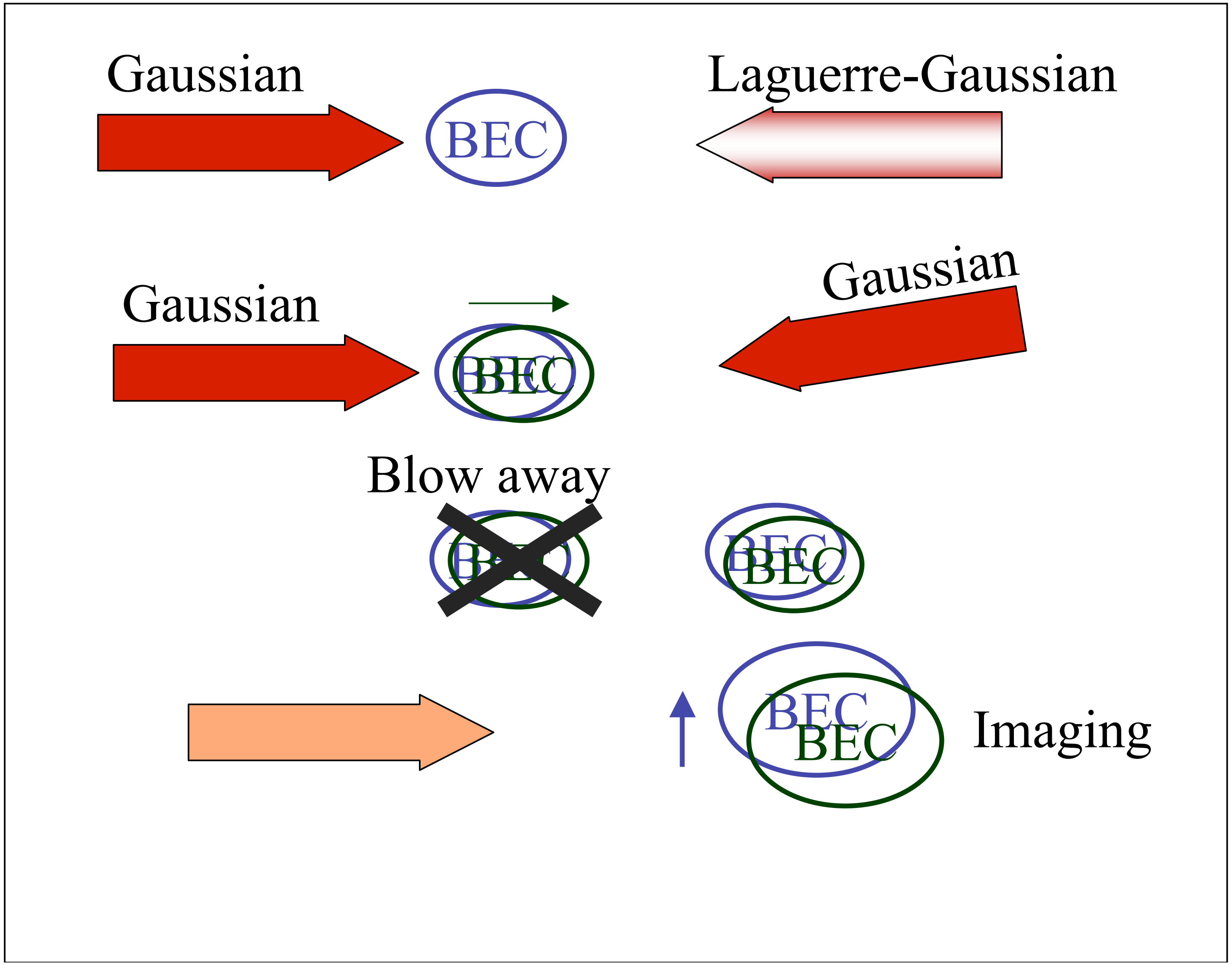


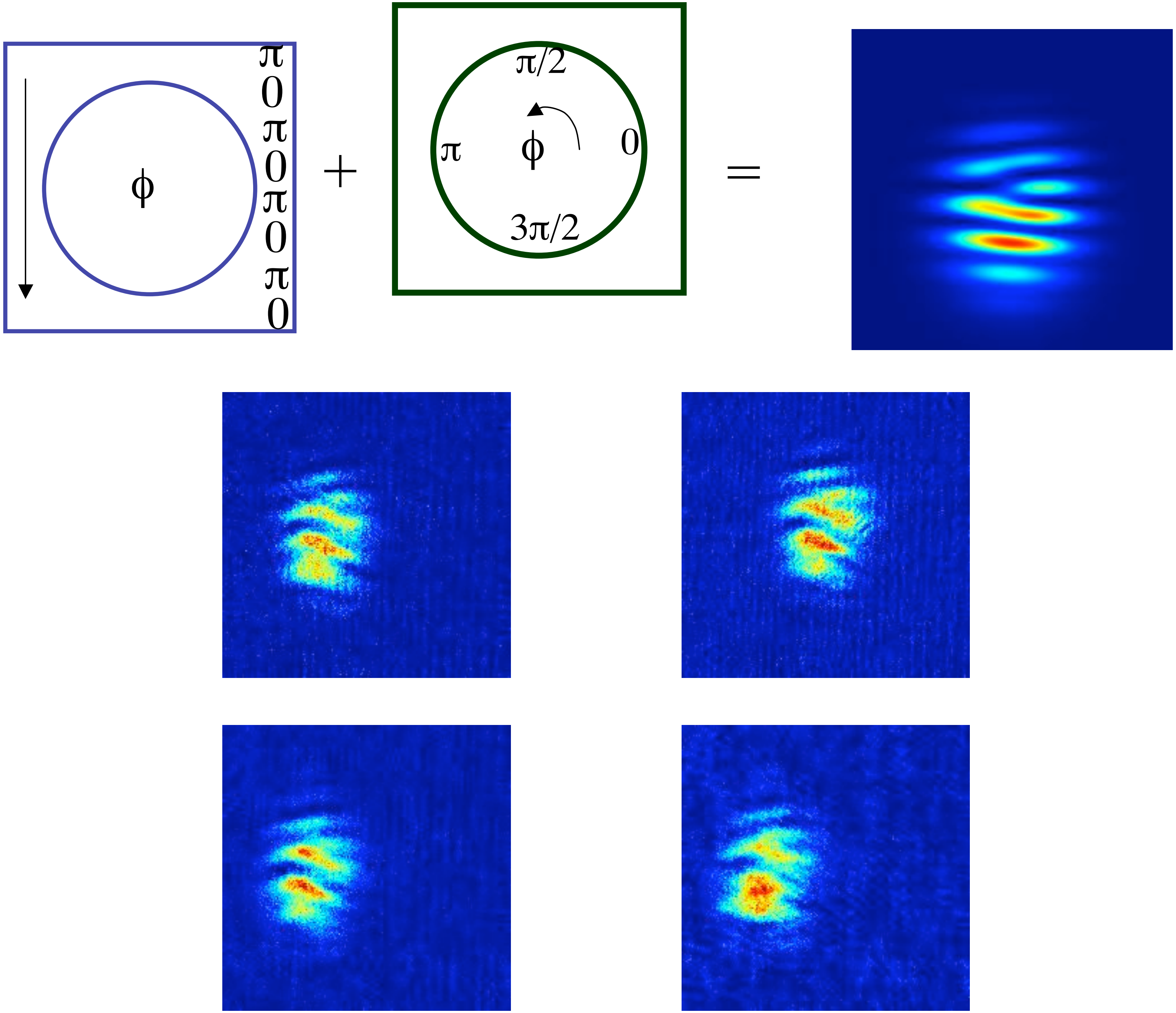
Yes





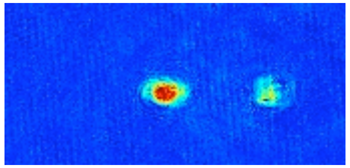
Another way to look at the phase of the vortex



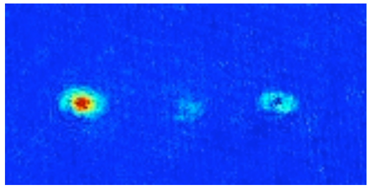

π
0
π
0
π
0
π
0
φ
+
π/2
π
φ
0
3π/2
=

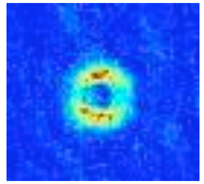
Higher Charge

Laguerre-Gaussian ω+δω **Gaussian ω**



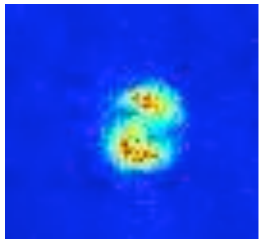
Laguerre-Gaussian ω+3δω **Gaussian ω**

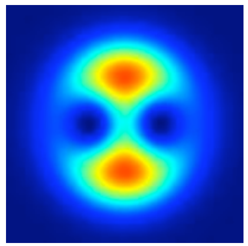




(this does a 1st order Bragg scattering from 2**h***k* to 4 **h***k*)

Gaussian ω+2δω **Gaussian ω**





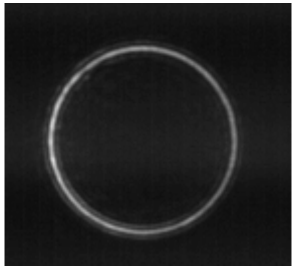
(This 2nd order Bragg scattering interferes the original condensate with the charge-2 (2**h**) vortex)

Perspectives

- **This is a new way to create vortex states in a BEC**

1

- **This method should be effective in producing persistent currents in a toroidal trap.**

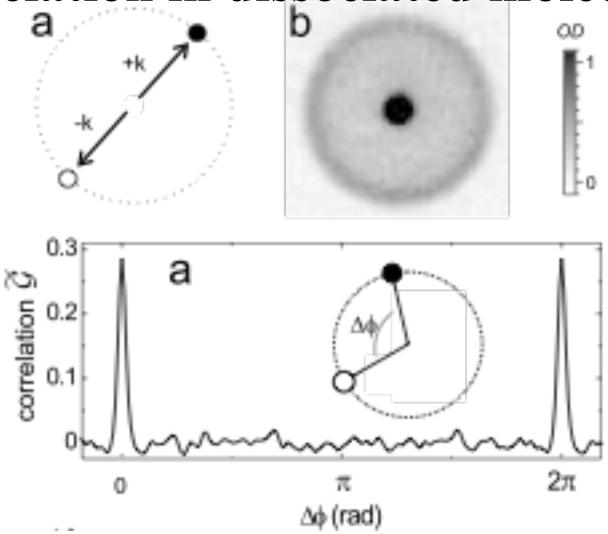


- **Can this be used to create cat states of rotation?**

Mott transition and noise correlations

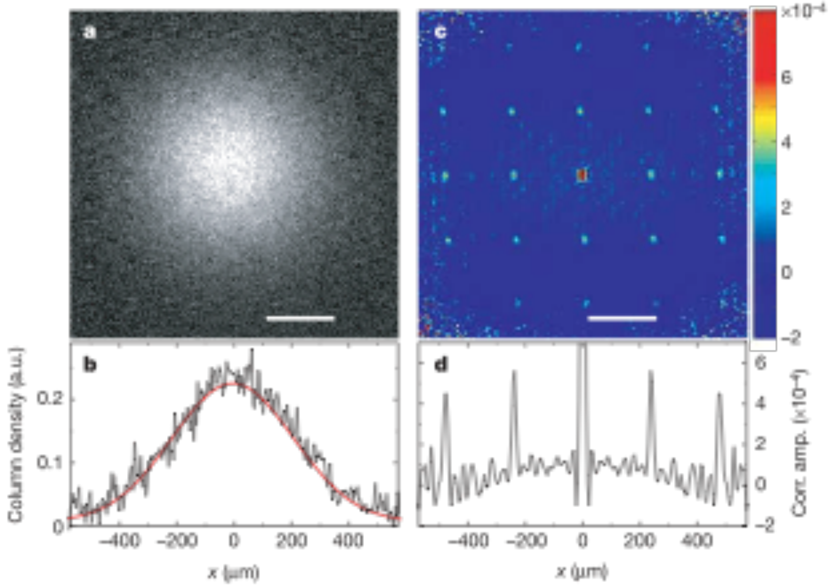
Recent, related experiments

Jin Group:
Correlation in dissociated molecules



Greiner, Regal, Stewart, and Jin PRL **94**, 110401 (2005)

Bloch Group
Correlation in Mott insulator state

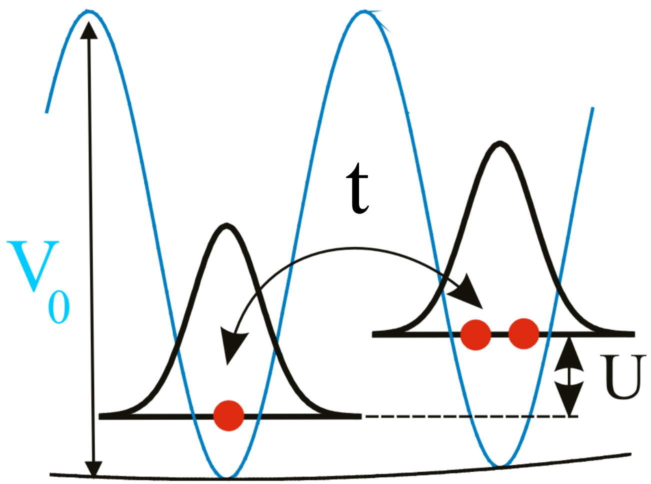


Fölling et al., Nature **434**, 481-484 (2005)

Also: Hanbury Brown, and Twiss experiments:

- Aspect group with He*
- Esslinger group with Rb

Bose Hubbard Model



***t* ... tunneling**

***U* ... onsite interaction**

$$H = -t\sum_{\langle i,j\rangle} b_i^\dagger b_j + \tfrac{1}{2}U\sum_i n_i(n_i - 1) + \mu(i)$$

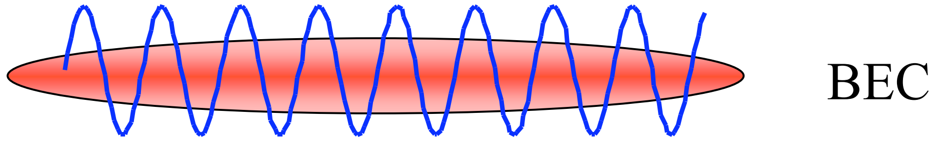
Both *t* and *U* change with the lattice depth: *t* is strongly dependent and *U* is weakly dependent.

Slide:Courtesy of Peter Zoller

“Superfluid”-Mott insulator phase transition

D. Jaksch et al., PRL '99

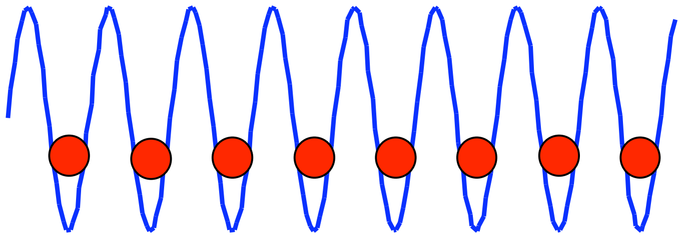
- “superfluid” phase



tunneling >> on site interaction

- Mott insulator

(commensurate filling)



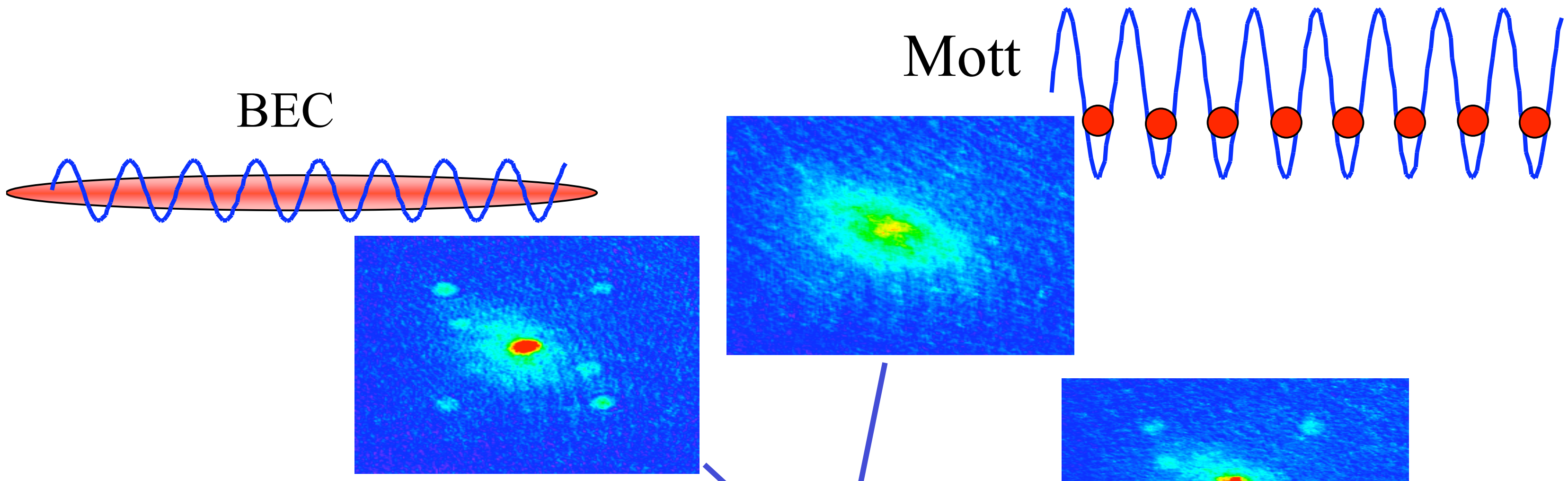
"Fock states"

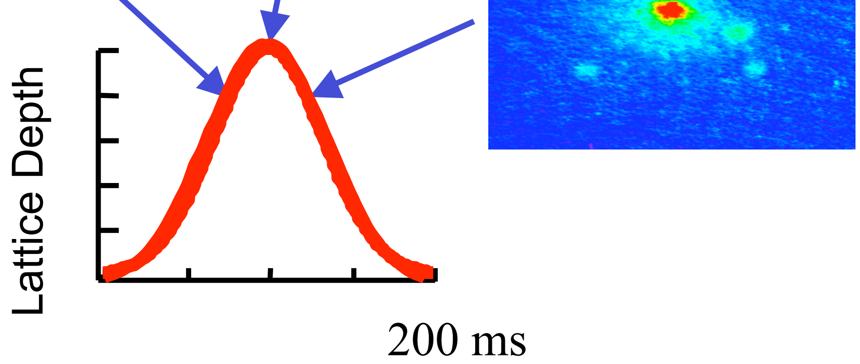
tunneling << on site interaction

Transition is achieved when laser parameters are changed adiabatically with respect to t, U.

Mott transition in a 3D optical lattice

Gaithersbug group: Phil. Trans. R. Soc. Lond. A **361**, 1417 (2003)



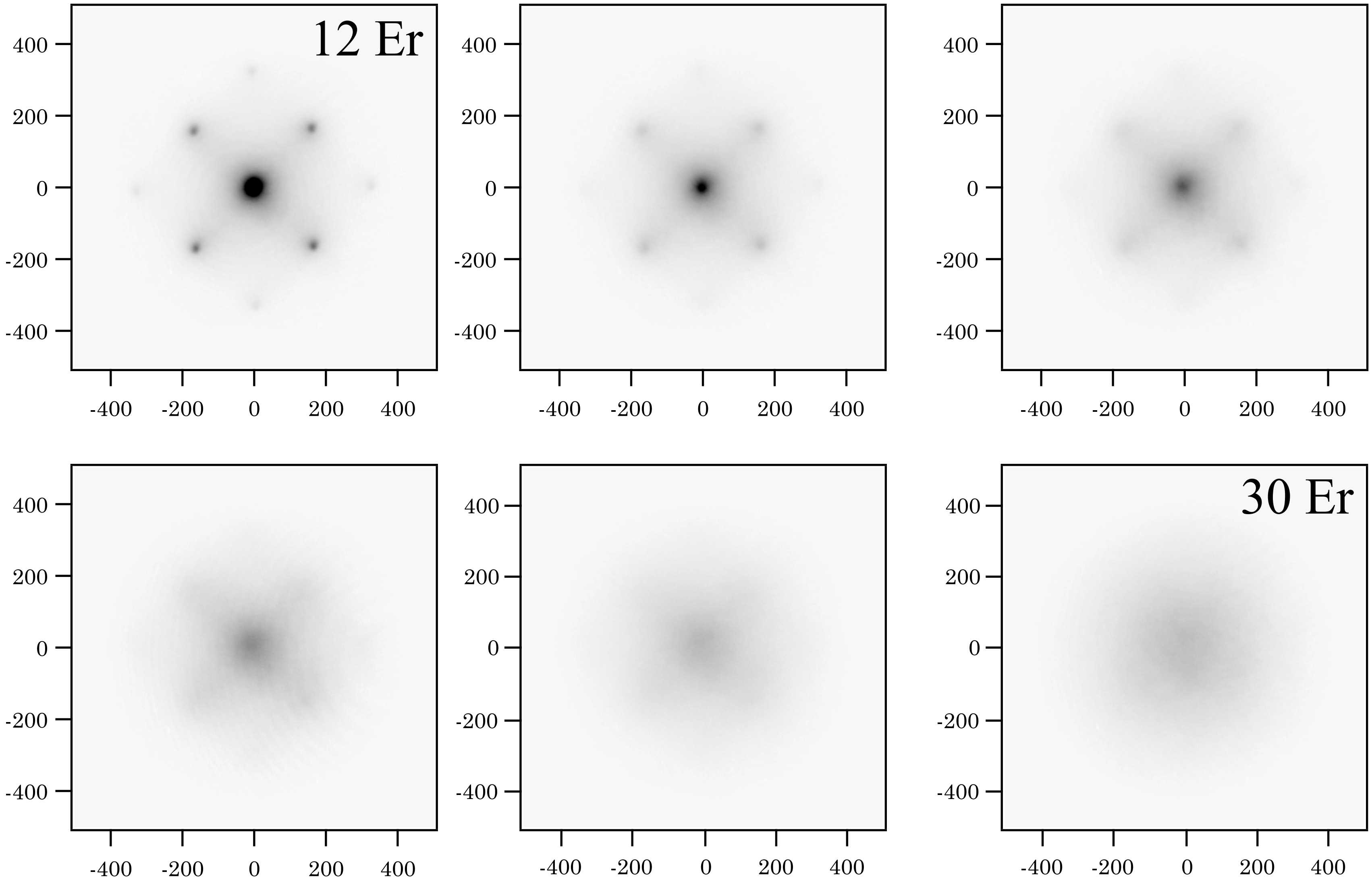


Lattice is deepened adiabatically; repulsive interactions localize atoms.

Similar, earlier work in Munich:
Greiner et al. Nature **415**, 39, (2002).

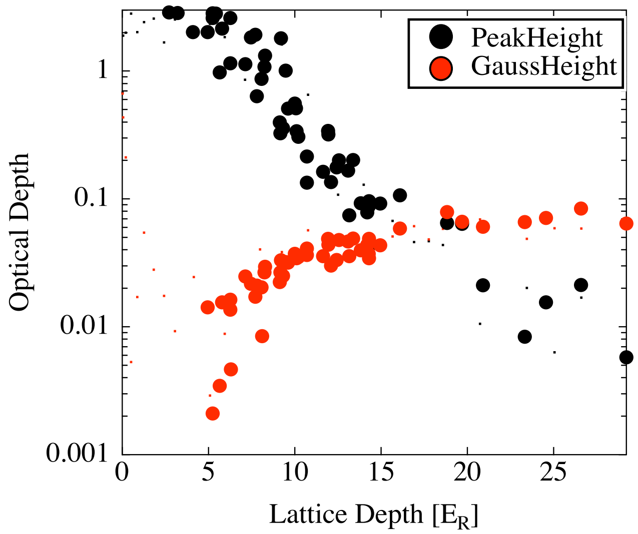
New at NIST-deep pancakes+2D square lattice

2D Mott transition (disappearing diffraction)

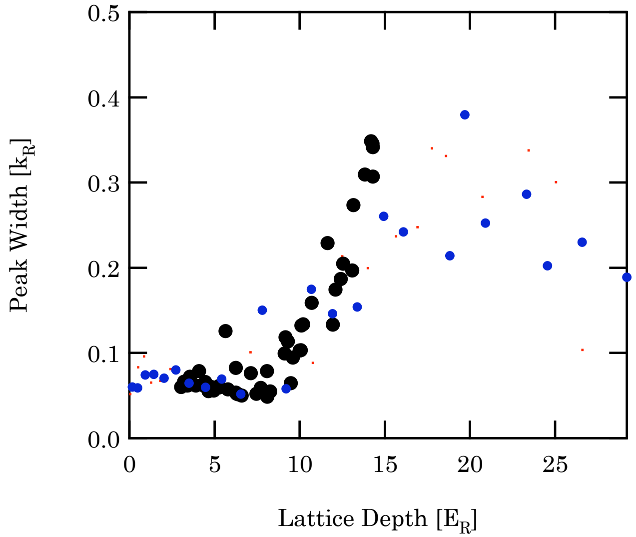


Extracted data from absorption

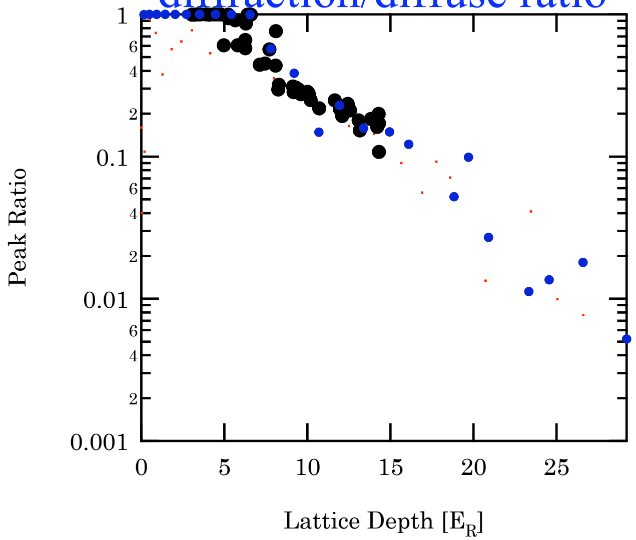
height



width

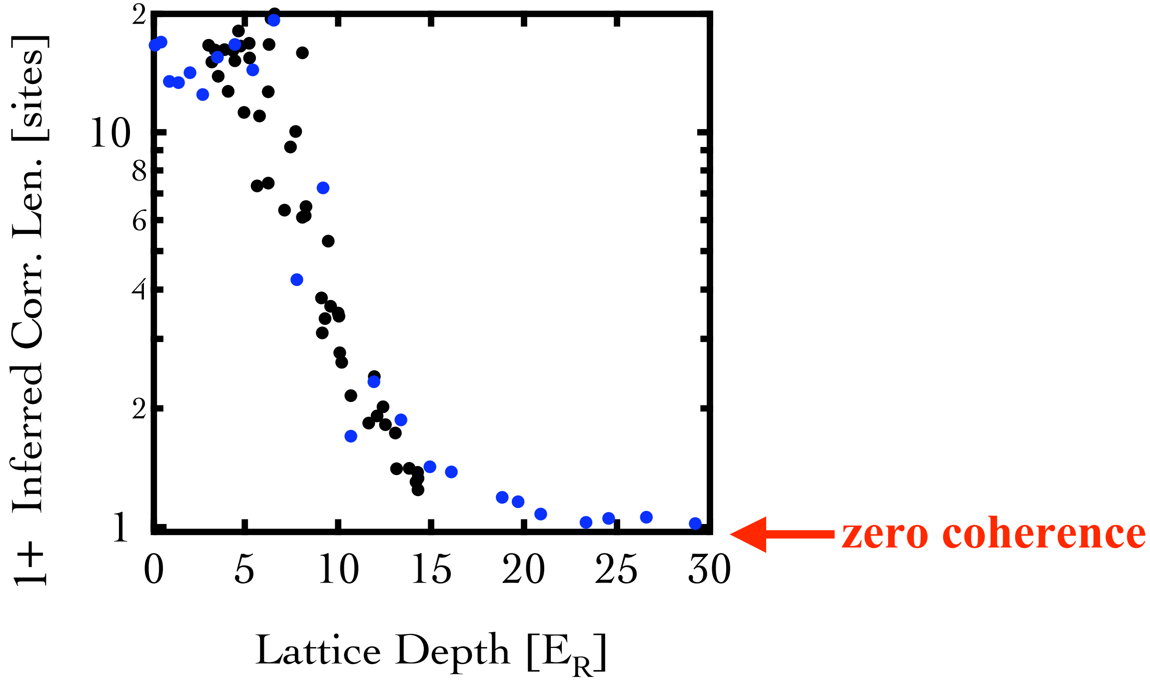


diffraction/diffuse ratio

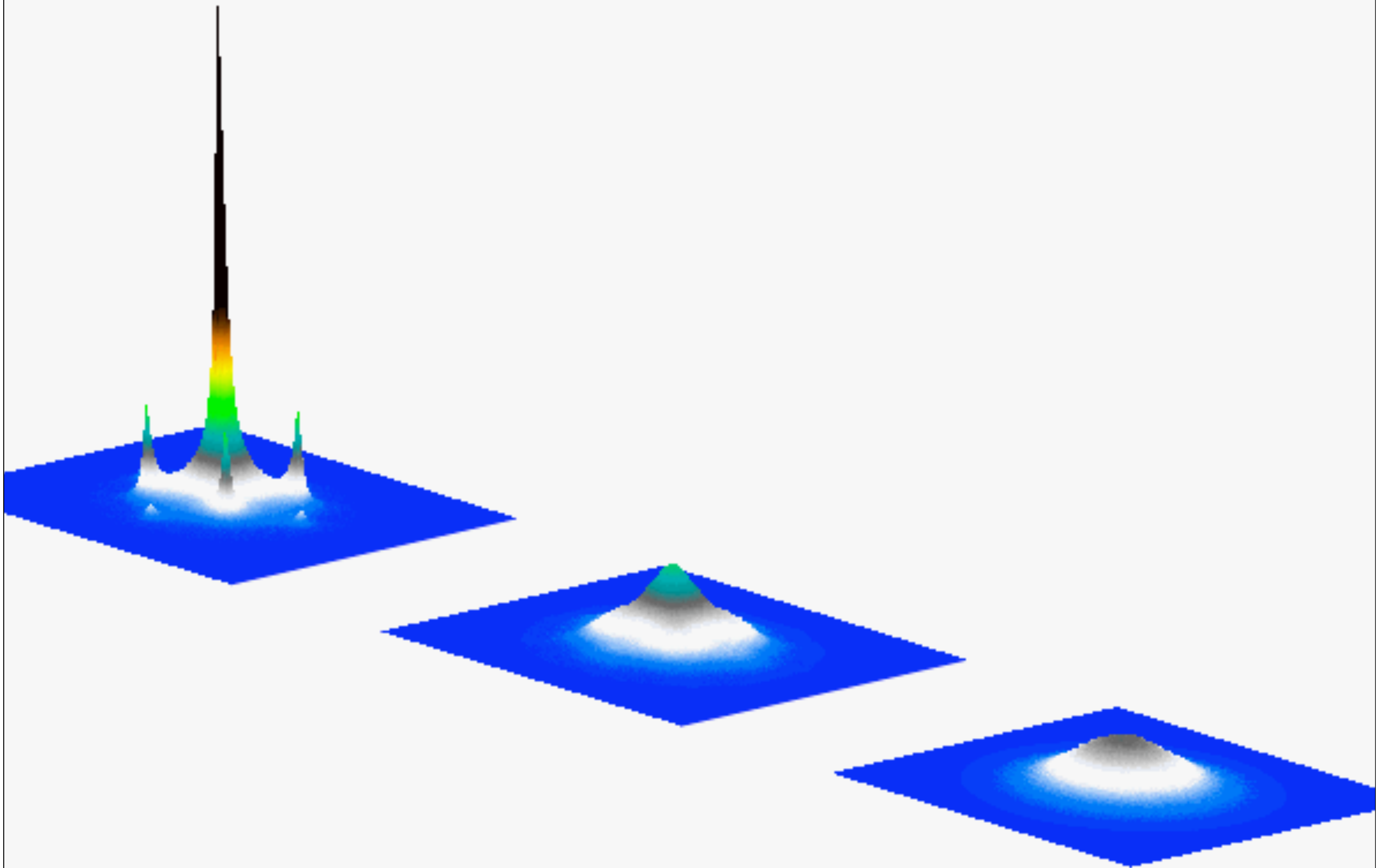


These data give indications about the loss of phase coherence among the lattice sites.

First-order coherence vs. lattice depth

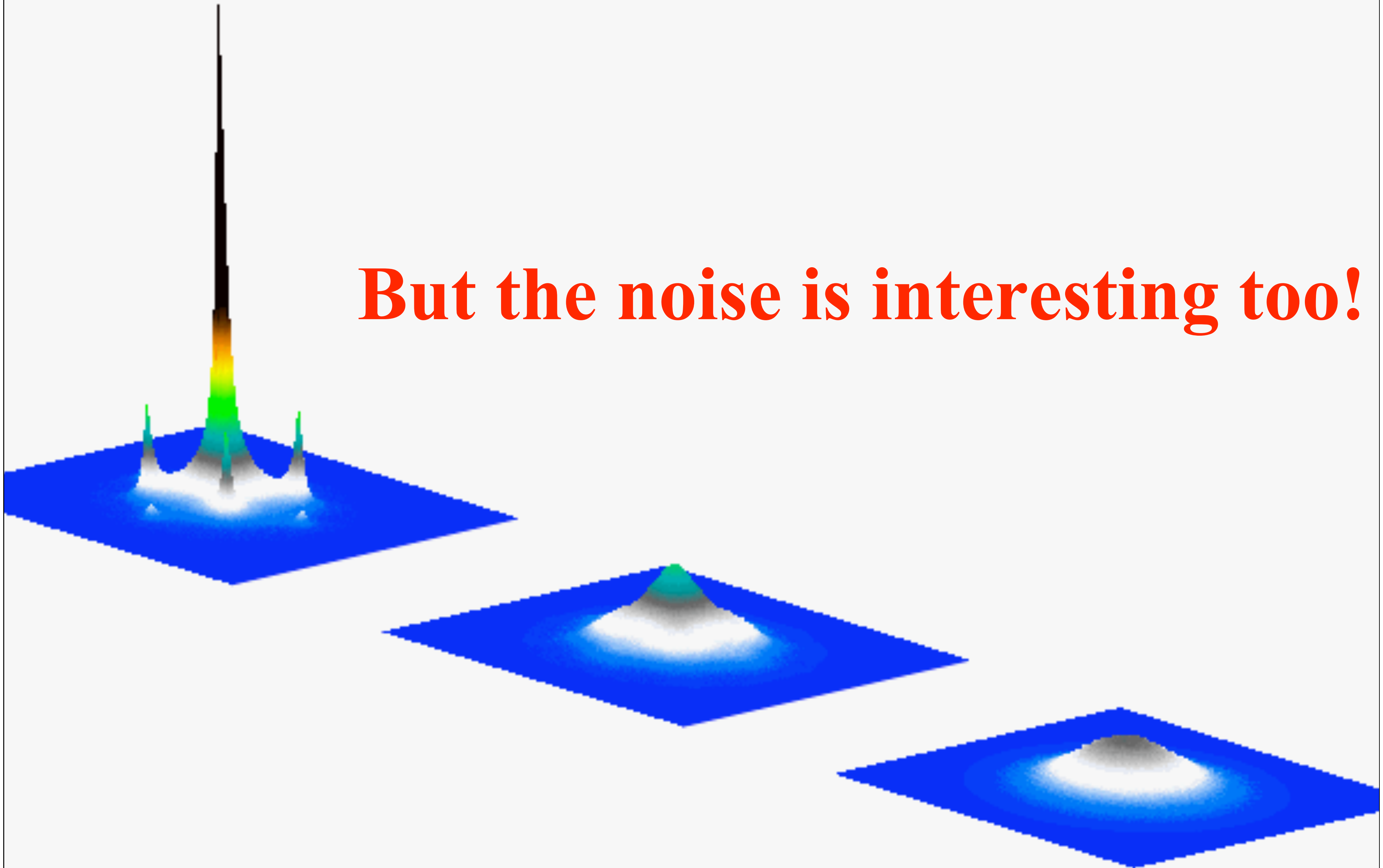


The data are really nice and clean.

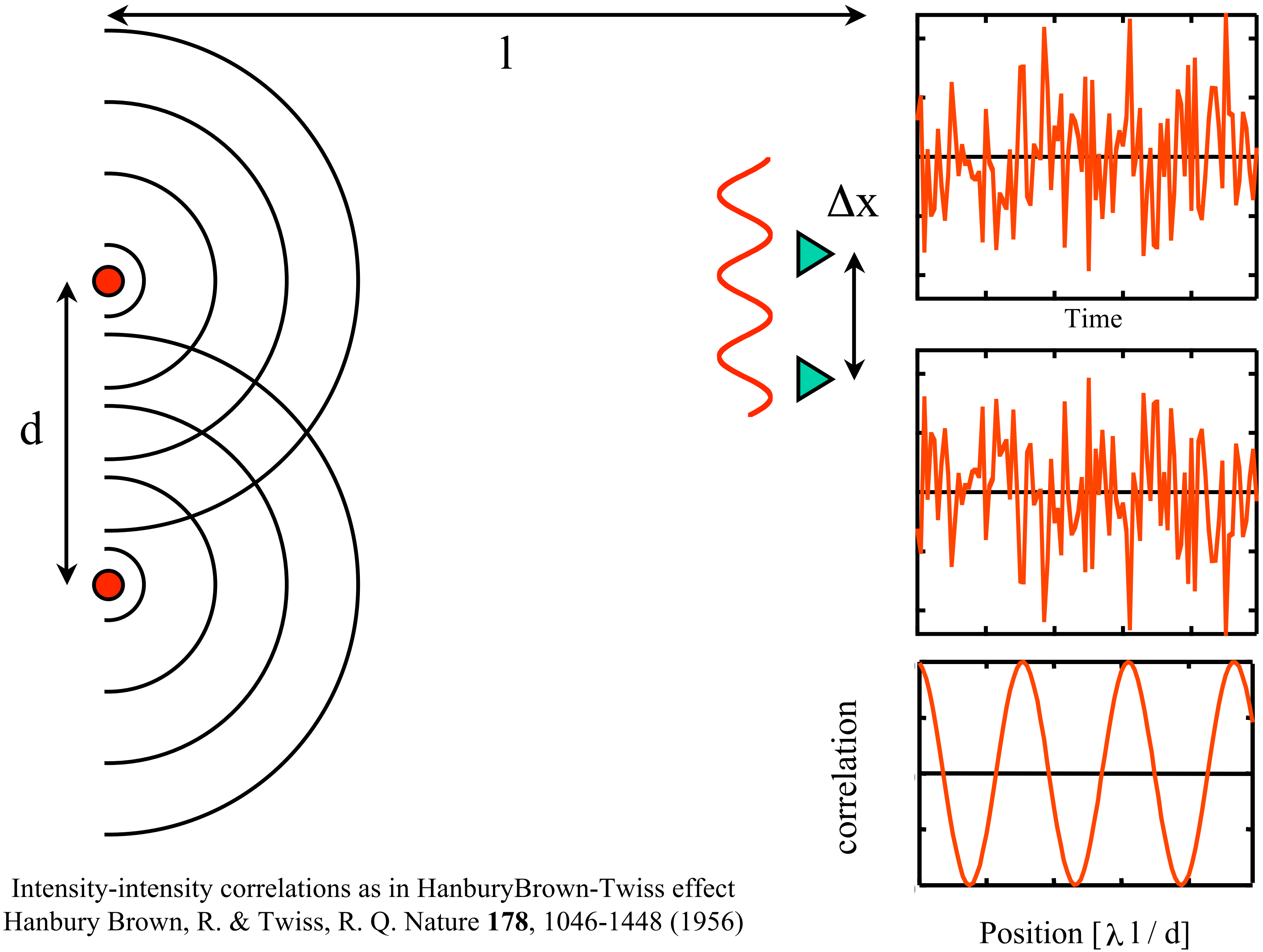


The data are really nice and clean.

But the noise is interesting too!

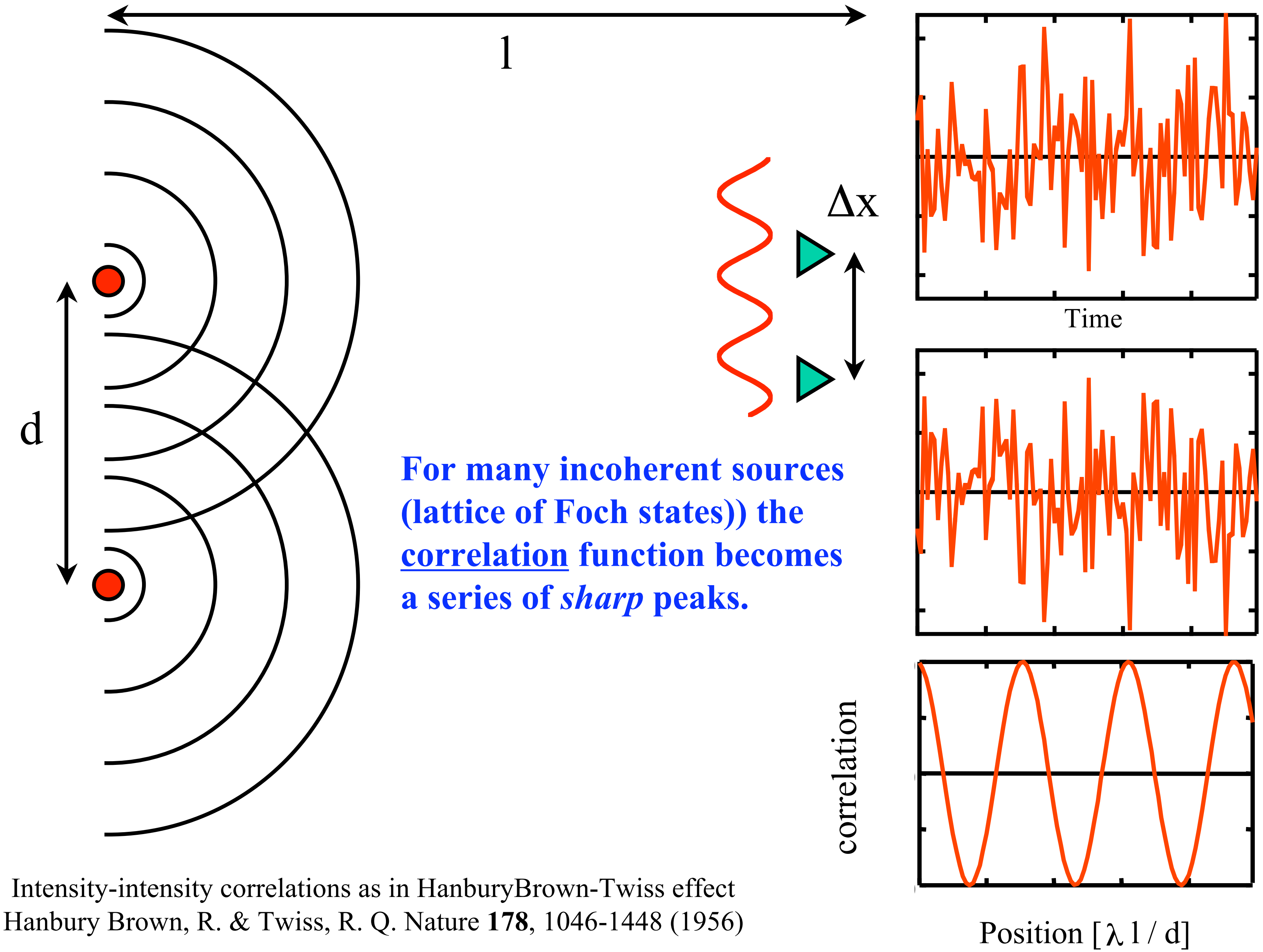


What can we learn from the noise on these images?



Intensity-intensity correlations as in HanburyBrown-Twiss effect
Hanbury Brown, R. & Twiss, R. Q. Nature **178**, 1046-1448 (1956)

What can we learn from the noise on these images?

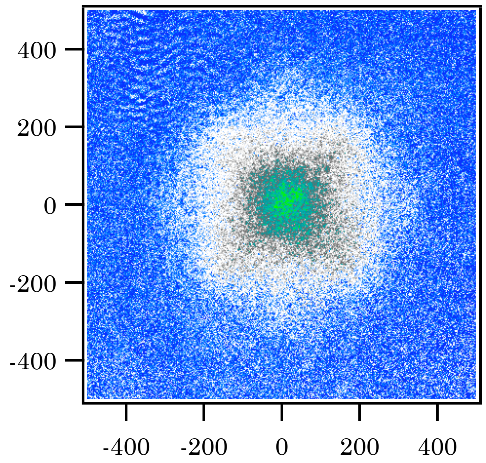


For many incoherent sources (lattice of Foch states)) the <u>correlation</u> function becomes a series of *sharp* peaks.

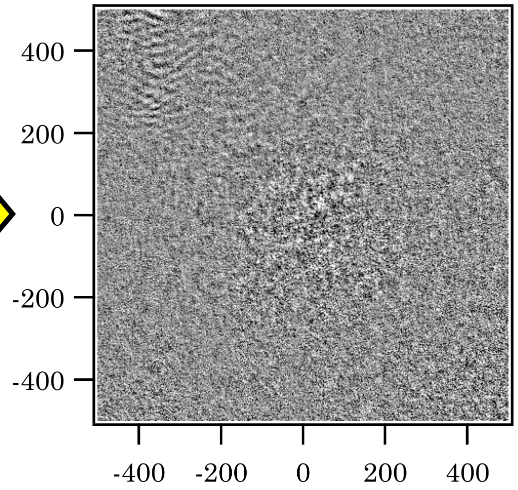
Intensity-intensity correlations as in HanburyBrown-Twiss effect
Hanbury Brown, R. & Twiss, R. Q. Nature **178**, 1046-1448 (1956)

look for noise correlations

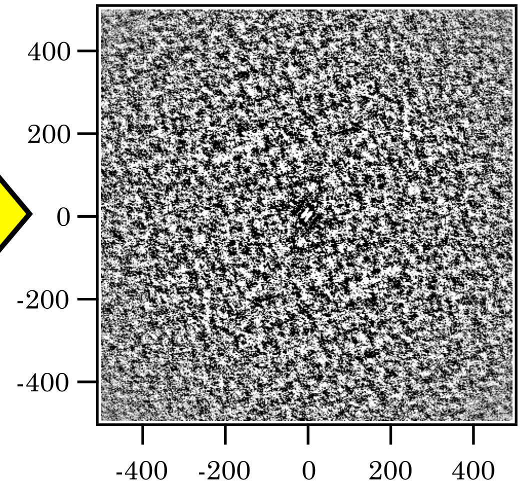
image

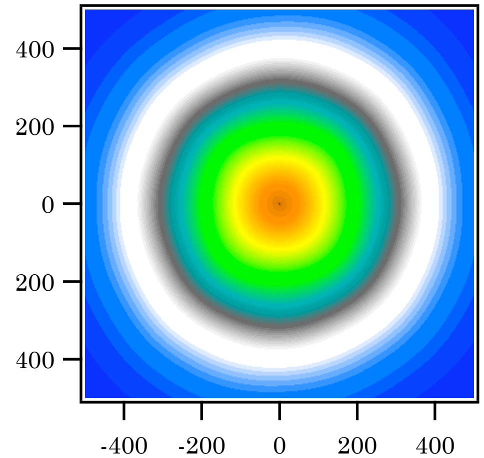


noise



correlation



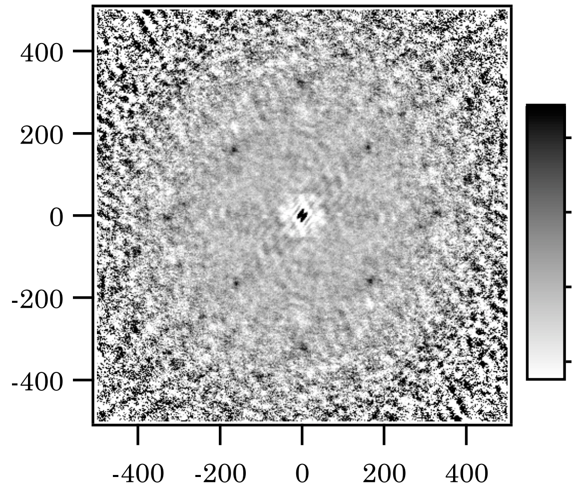


$$\langle I(x,y)\rangle = \langle\Psi|\, n(x,y)\,|\Psi\rangle$$

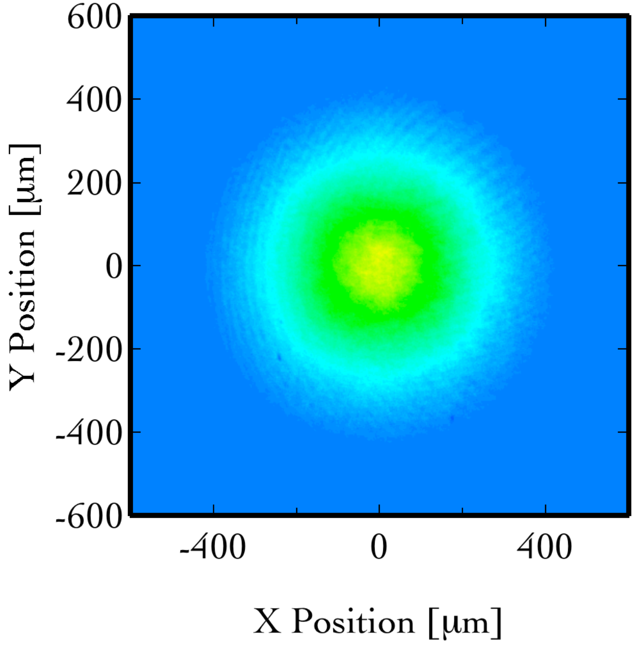
$$\langle \mathrm{ACF}(I)\rangle = \int dxdy\, \langle\Psi|\, n(x,y)n(x+\delta x, y+\delta y)\,|\Psi\rangle$$

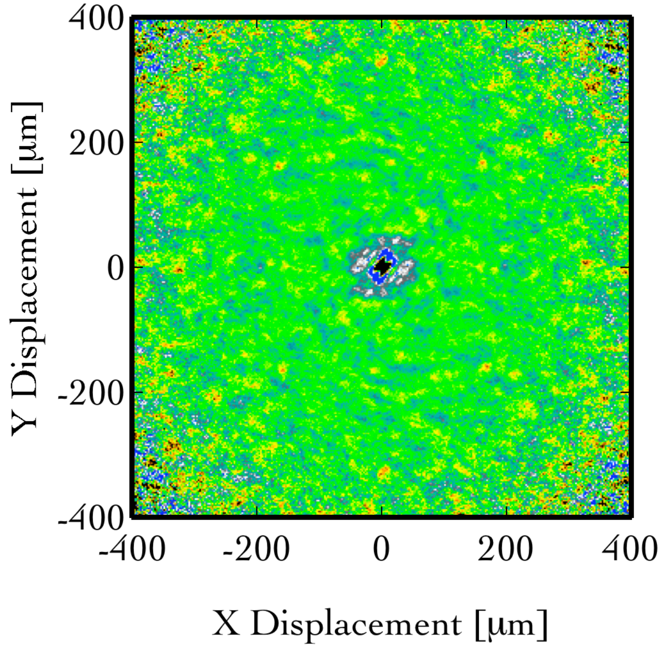
$$S = \frac{\langle \mathrm{ACF}(I)\rangle}{\mathrm{ACF}(\langle I\rangle)} - 1 \approx \left\langle \frac{\mathrm{ACF}(\delta I)}{\mathrm{ACF}(I)}\right\rangle$$

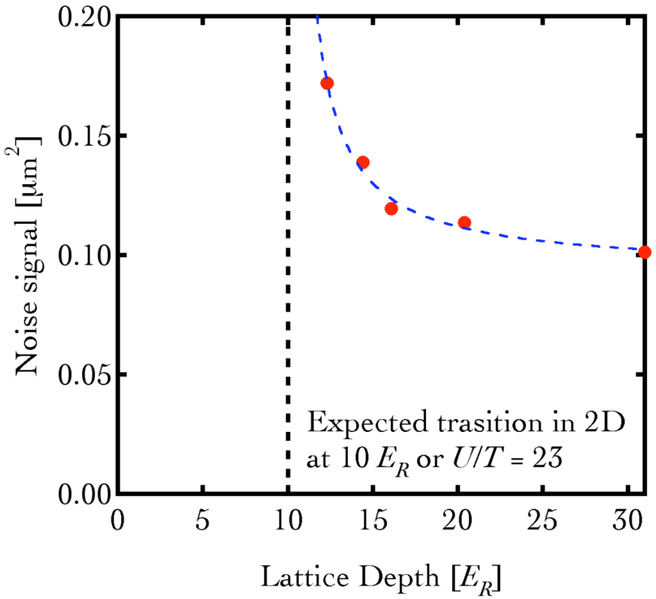
averaged



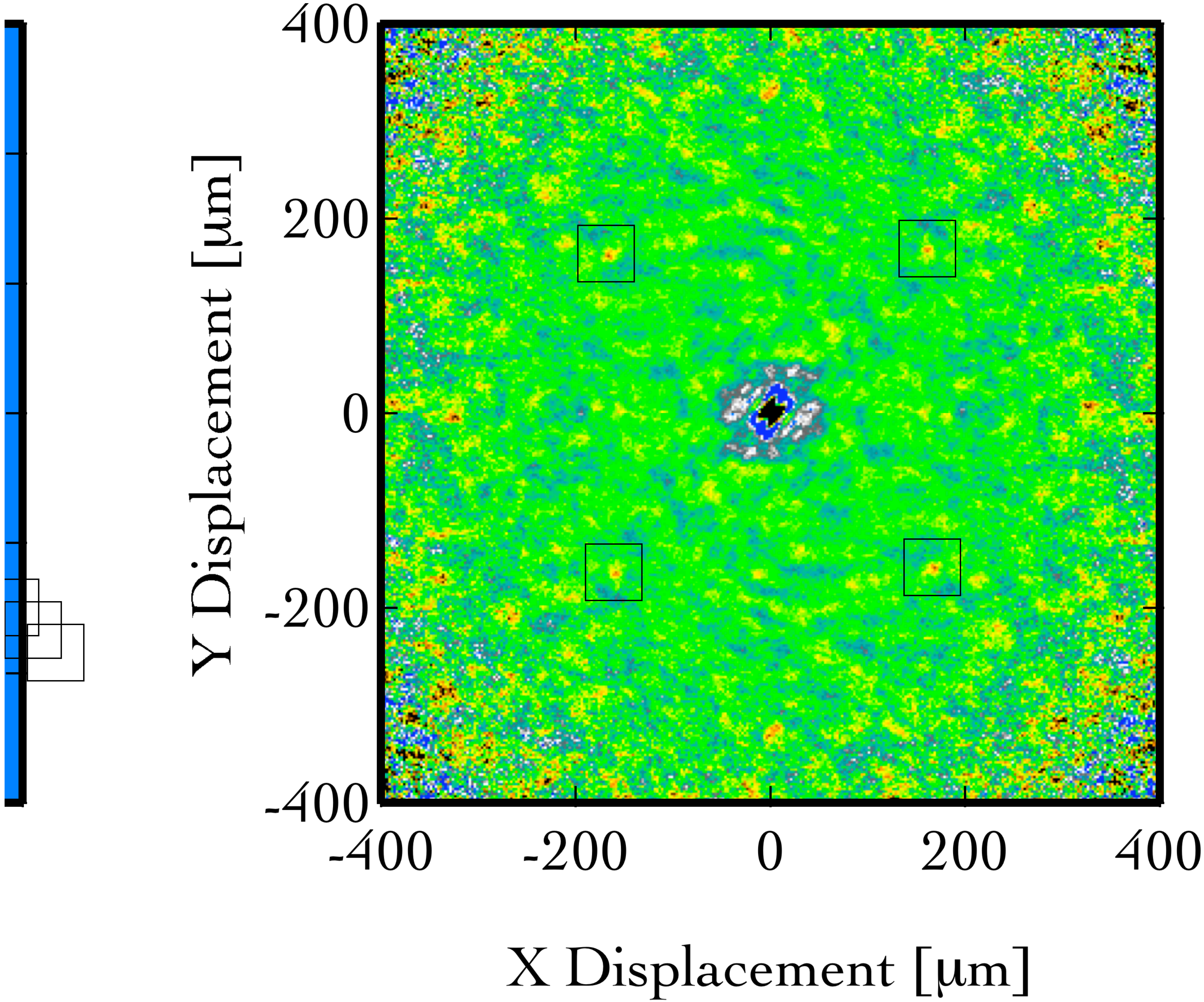
30 E_R Depth







The function of 4 variables: I(x,y)*I(x+Δx, y+Δy), is masked around the values of x,y corresponding to the diffraction peaks. Then, when integrating over x,y to get the autocorrelation F(Δx, Δy), this does not contain the diffraction pattern, but only the (unresolvably narrow) correlation due to the increasingly Fock-like Mott state.



400
200
0
-200
-400
-400
-200
0
200
400
Y Displacement [μm]
X Displacement [μm]

A New Tool

Noise correlations provide a new window into the Mott state--providing a signal that gets narrower as the Mott state becomes more Fock-like, rather than wider. (But the area of the peak goes down as it gets narrower.)

All of this is very preliminary, and we are still learning what to do with this tool.

The End