THE UNIVERSITY OF CHICAGO

Magnetism, Rotons, and Beyond: Engineering atomic systems with lattice shaking.

Colin V. Parker

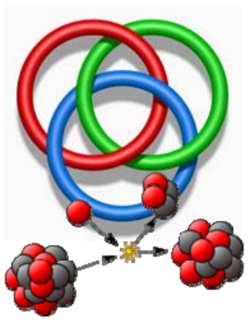
James Franck Institute and Dept. of Physics

University of Chicago

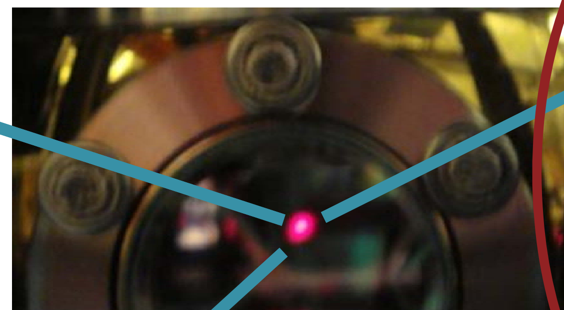
Quantum simulation with cold atoms

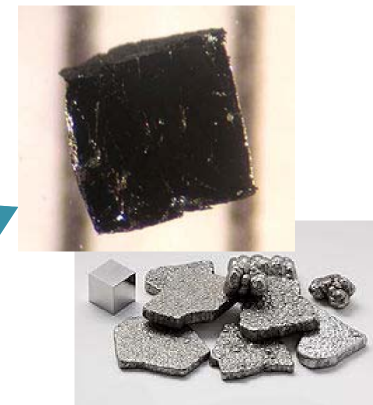
THE UNIVERSITY OF CHICAGO

Chin Lab

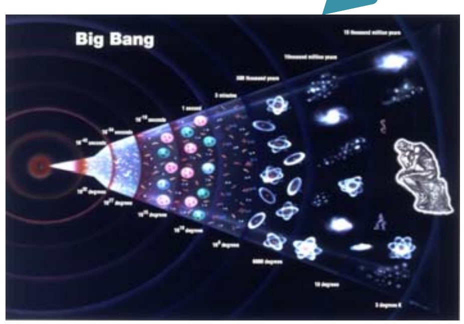


Nuclear Physics:
Efimov Trimers
(see *PRL* **113** 240402)





Condensed Matter:
Superfluids, Magnets and more
(current topic)

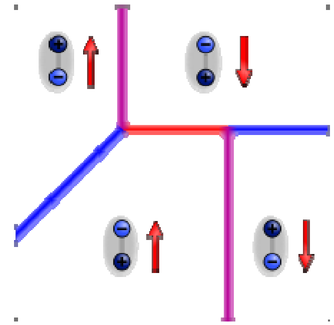


Cosmology:
Sakharov Oscillations
(see *Science* **341** 1213)

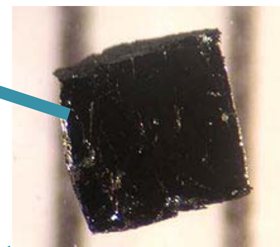
Image Credit: Wikipedia/Chin Lab

Variety in condensed matter systems

Superconductivity

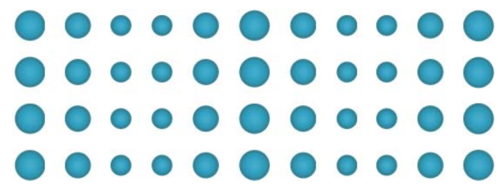


Multiferroics



Topological
Insulation

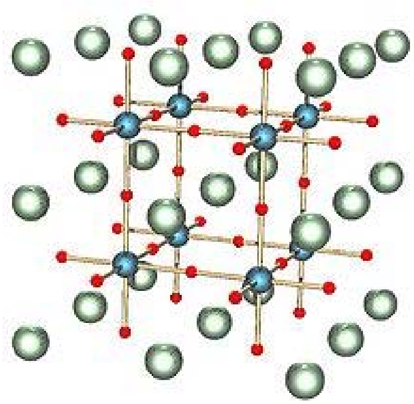
Magnetism
(ferro-/anti-ferro)



Density wave
(charge/spin)

Image Credit: Wikipedia

Where does the variety come from?



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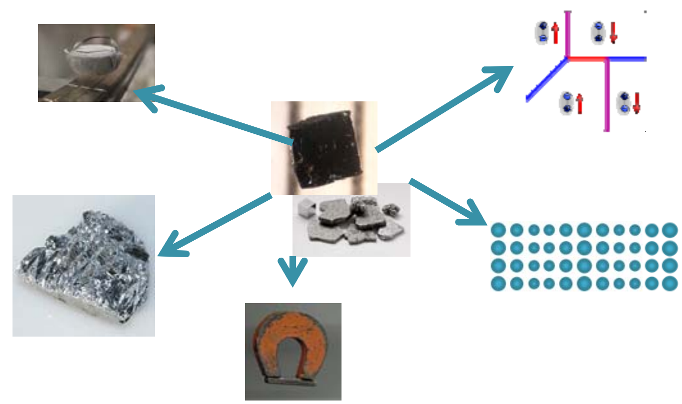


Single Particle Dispersion

Particle-Particle Interactions

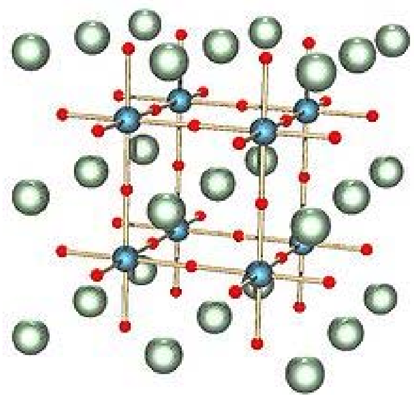
$H =$ [ ] $+$ [ ]

Lattice Phonons

$+$ [ ]

Image Credit: Wikipedia

Where does the variety come from?



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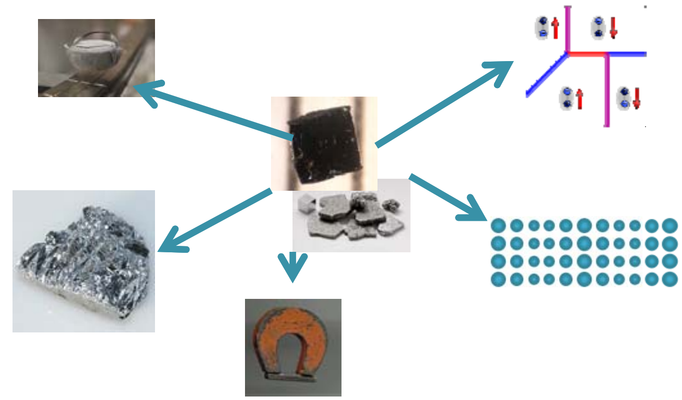

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Single Particle Dispersion

Particle-Particle Interactions

$$H = \boxed{} + \boxed{}$$

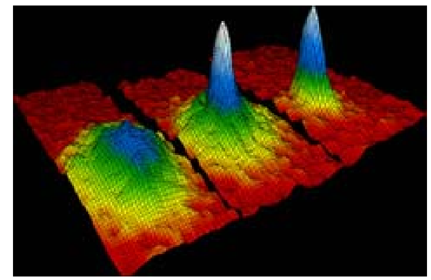
$V(q) = V$

Image Credit: Wikipedia

Dispersion – Simple Cases

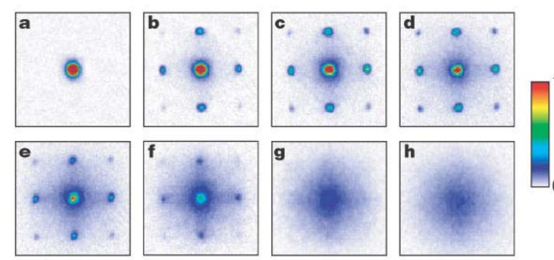
$H =$ [ ] $+$ [ ] → $V(q) = \mathrm{V}$

Free Particle: Normal Gas, Superfluid, BEC-BCS crossover



Anderson *et al Science* **269** 198 (1995)
Davis *et al PRL* **75** 3969 (1995)

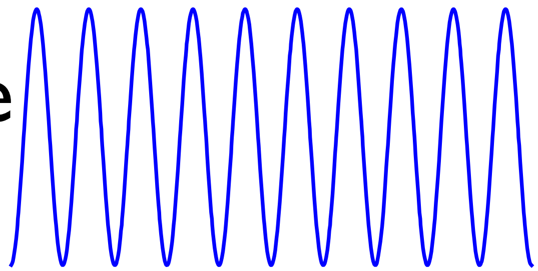
Square/Cubic Lattice: Mott Insulator



Greiner *et al Nature* **415** 39 (2002)

How to create a "designer" dispersion

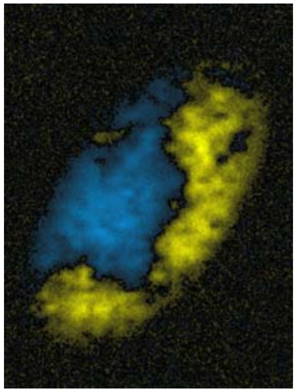
- Simple optical lattices have only one parameter (depth of potential)
- More complicated lattices require higher spatial frequencies

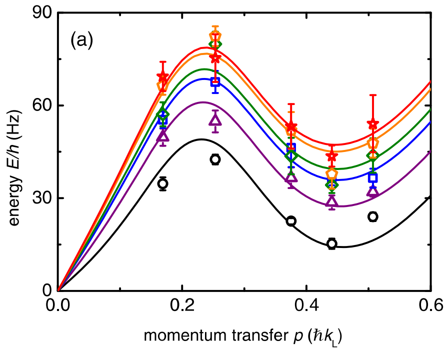


- Accessing the time domain of the lattice is a convenient alternative

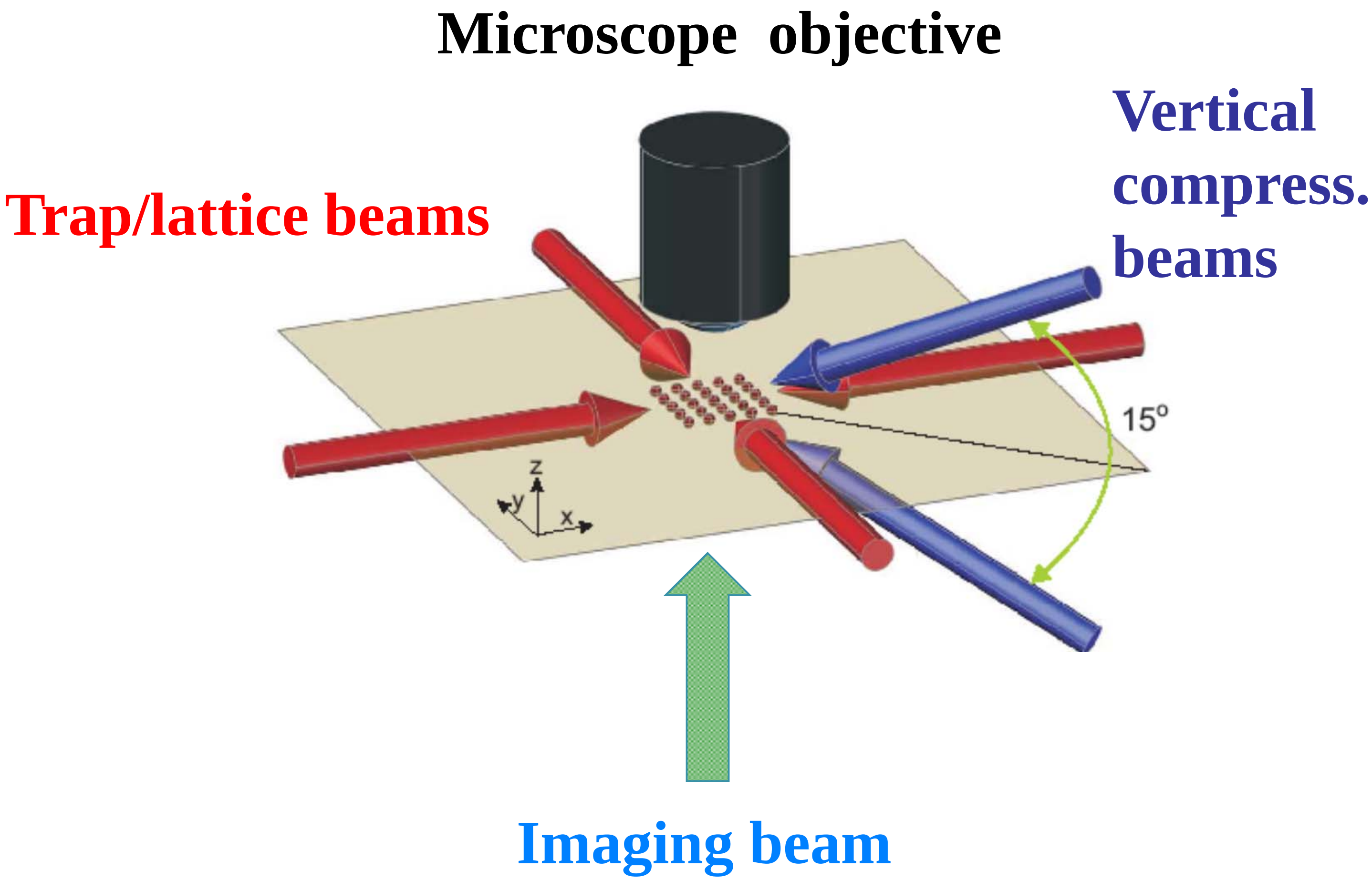
Outline

- Intro
- Ferromagnetism in a single component Bose gas
- Excitations in the ferromagnetic state (roton/maxon)
- NEW! Optical control of scattering length



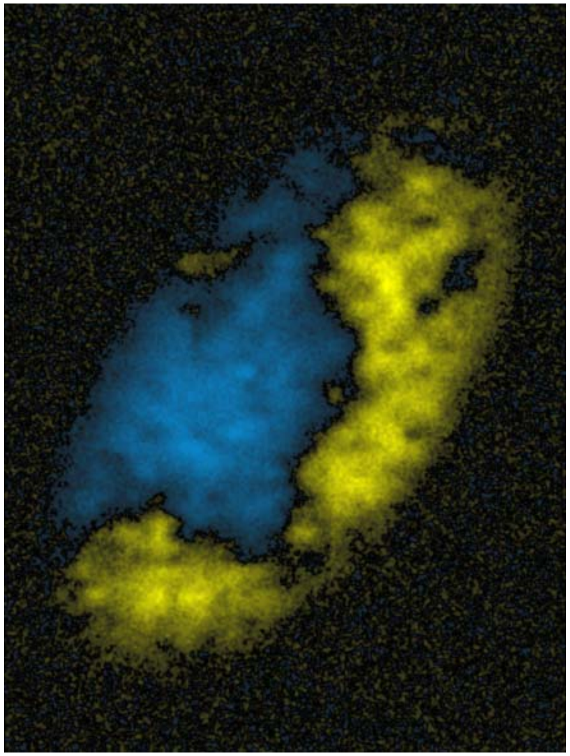


In situ Imaging

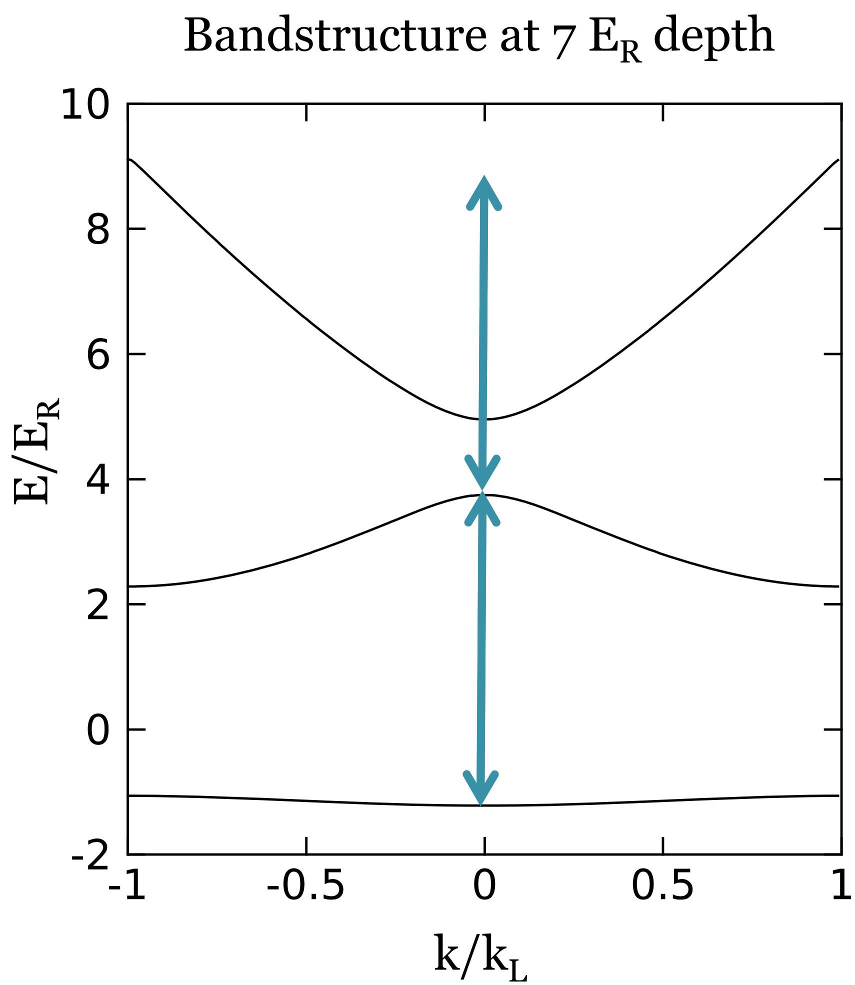


Gemelke et al., Nature (2009)
Single site resolution: M. Greiner Nature (2009), I. Bloch Nature (2010)

Shaking Lattice Ferromagnetism



Near resonant shaking with low heating



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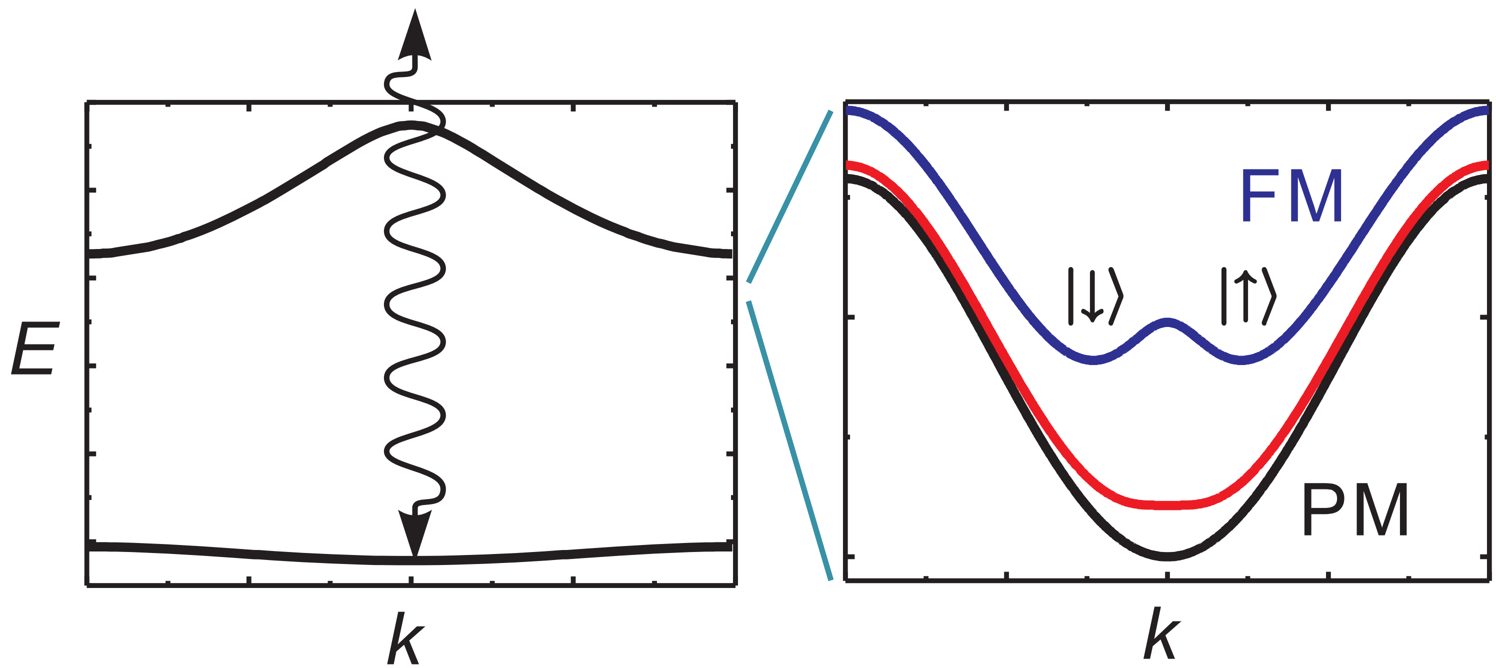
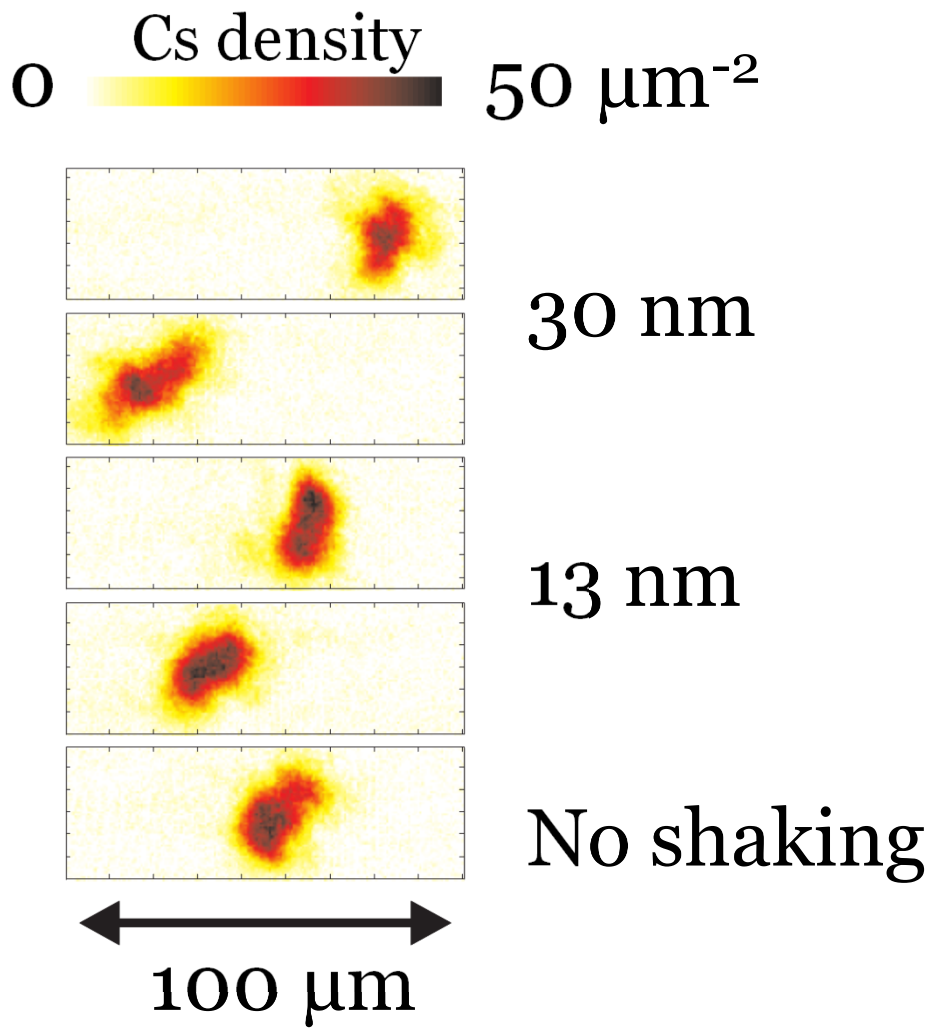


Parker, Ha, Chin - Nat. Phys. (2013)

c.f. Gemelke (PRL 170404 2005), Lignier (PRL 220403 2007), Struck (Science 2011)
Other driven lattices: ETH, MPQ, MIT

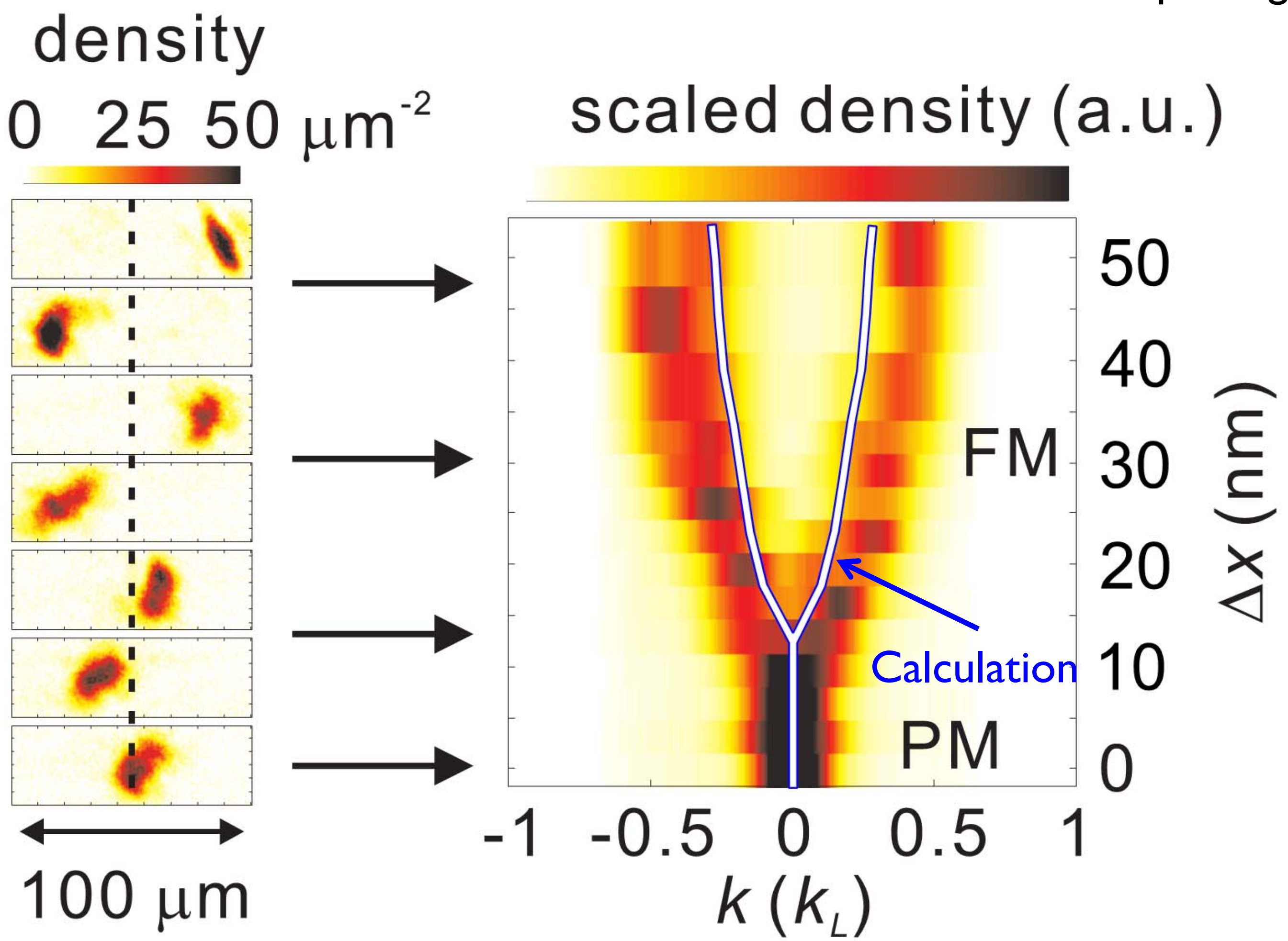
Observation of two minima

30 ms TOF

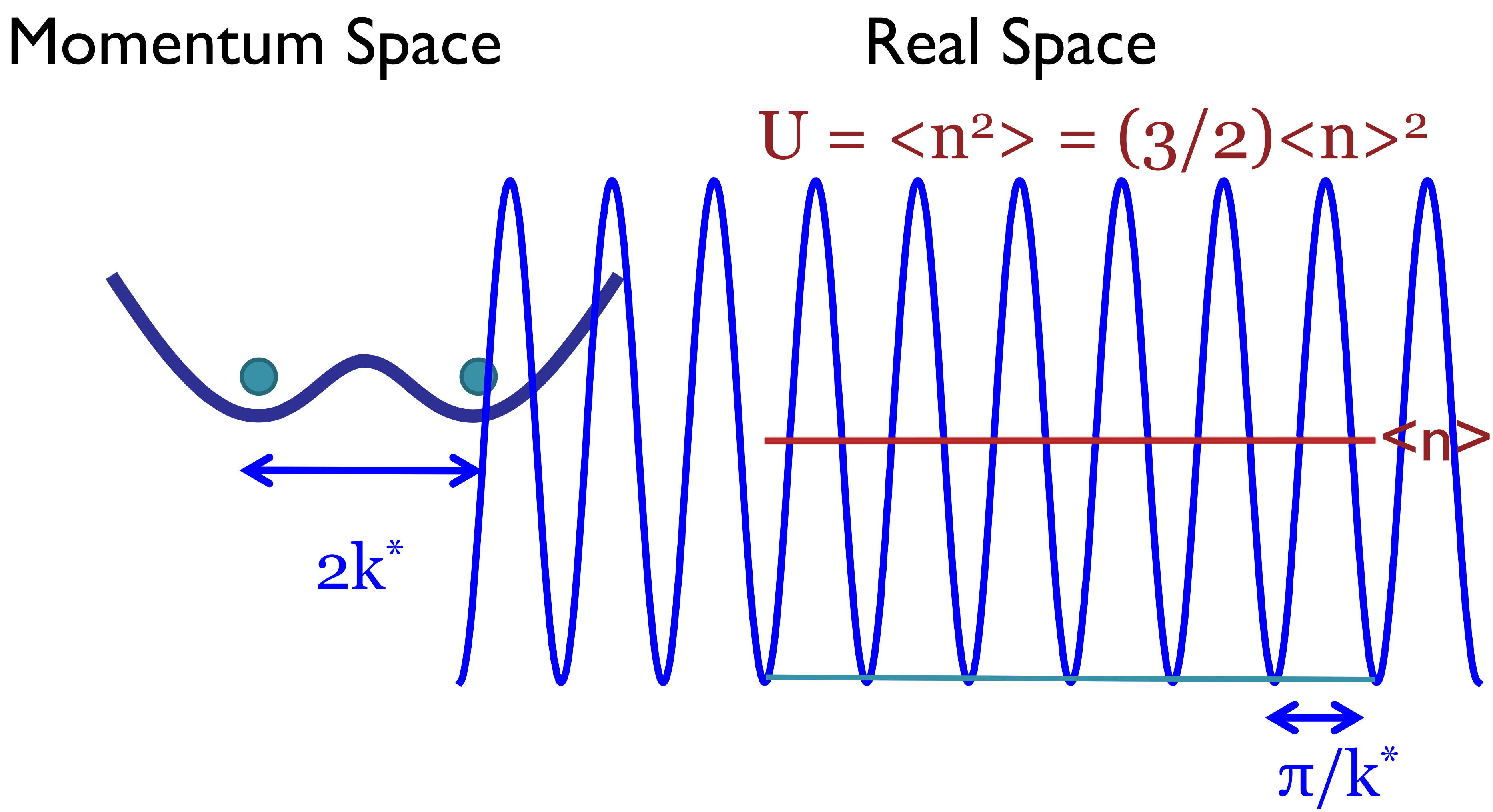


Observation of two minima

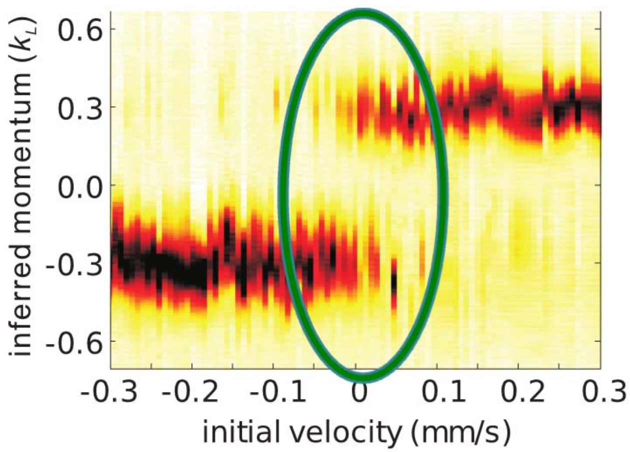
Lattice Spacing: 532 nm



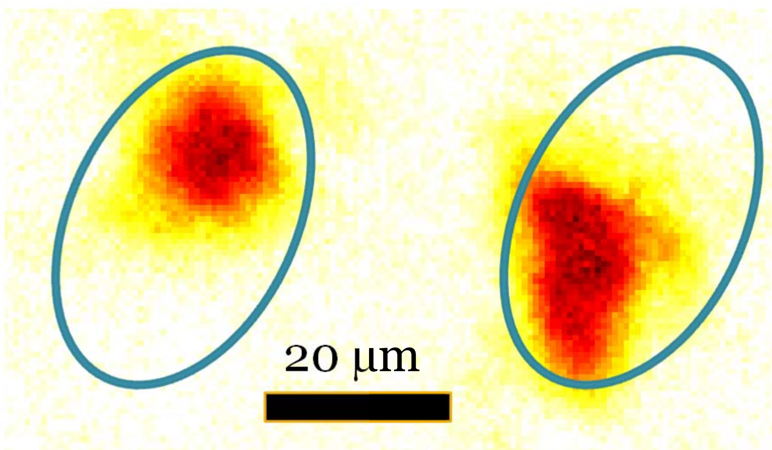
Why does the system avoid pseudo-spin mixtures?



Can we still prepare a multi-state mixture?

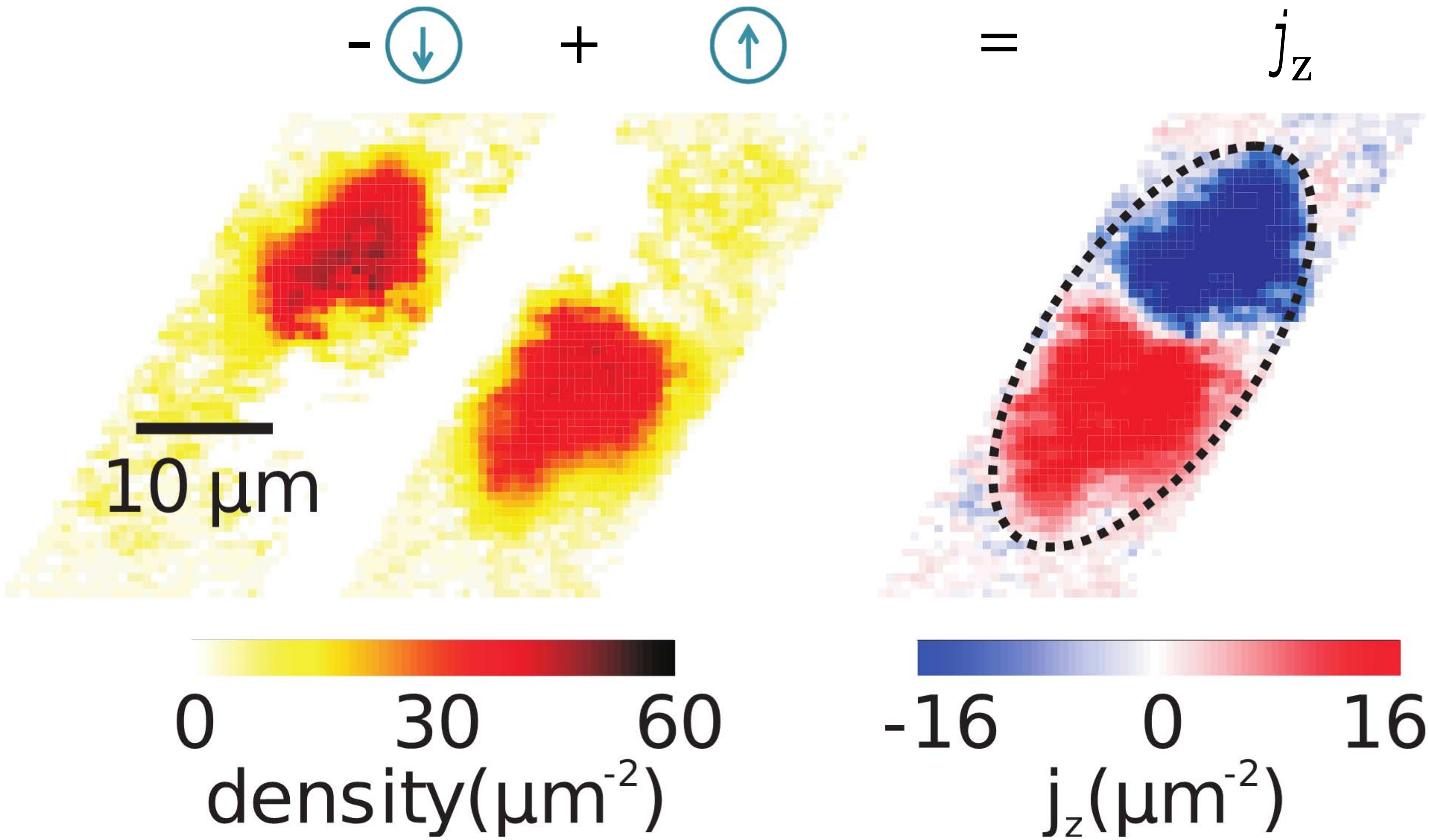


30 ms TOF



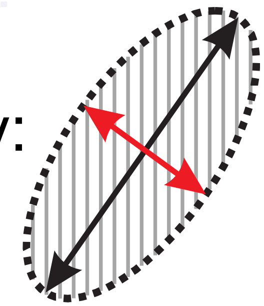
Parker, Ha, Chin - Nature Physics (2013)

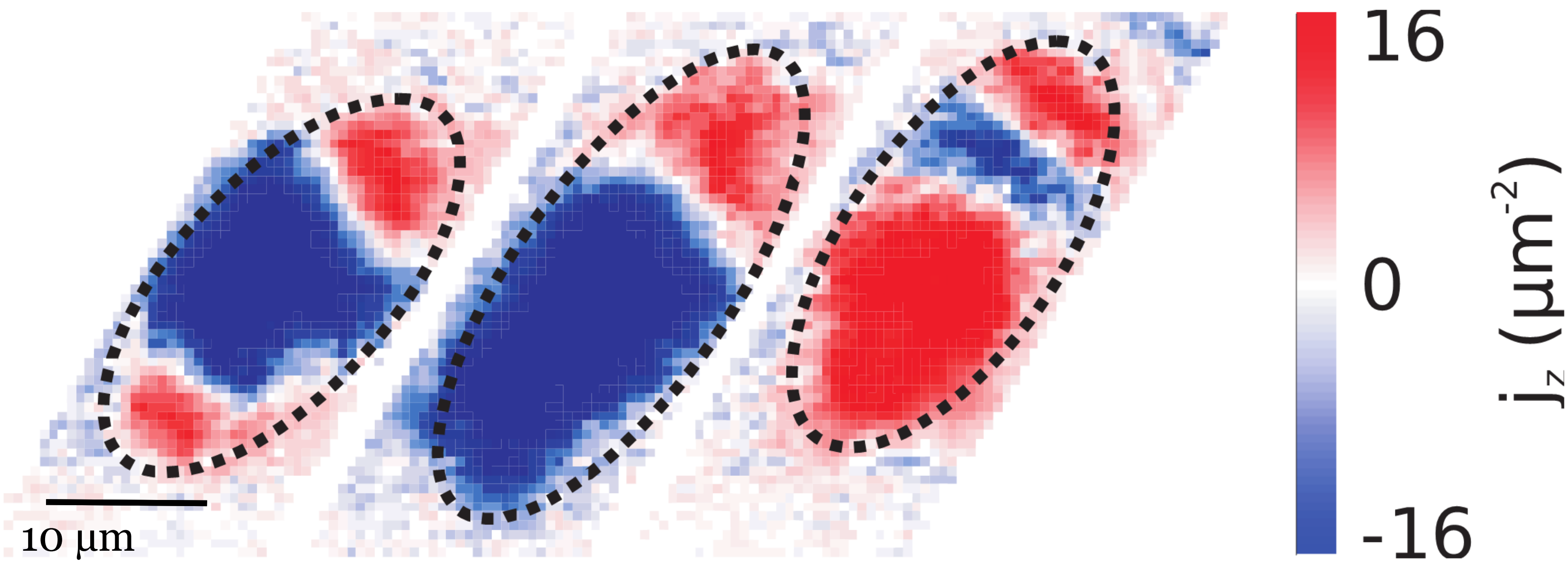
Domain reconstruction



Domain gallery

Geometry:

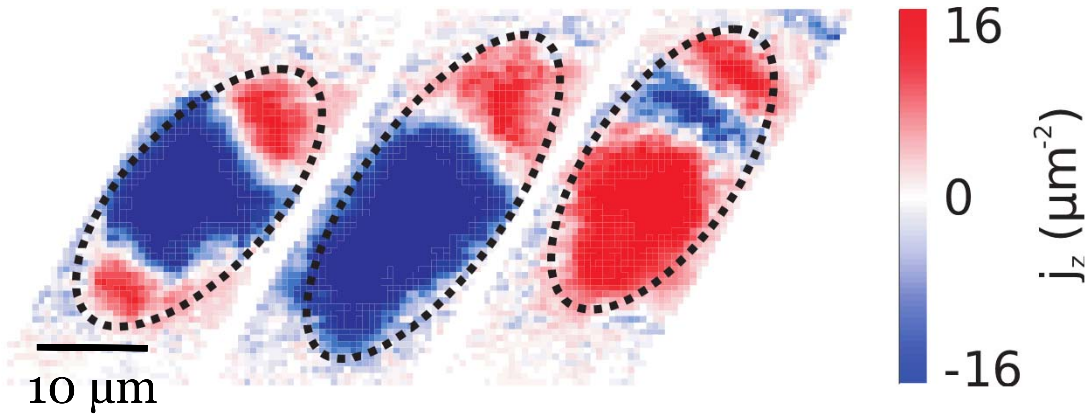




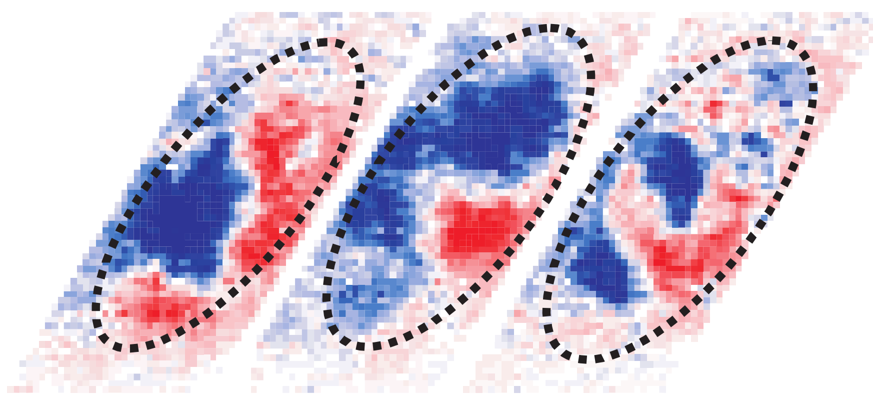
Parker, Ha, Chin - Nature Physics (2013)

Domain size and ramping speed

100 ms ramping



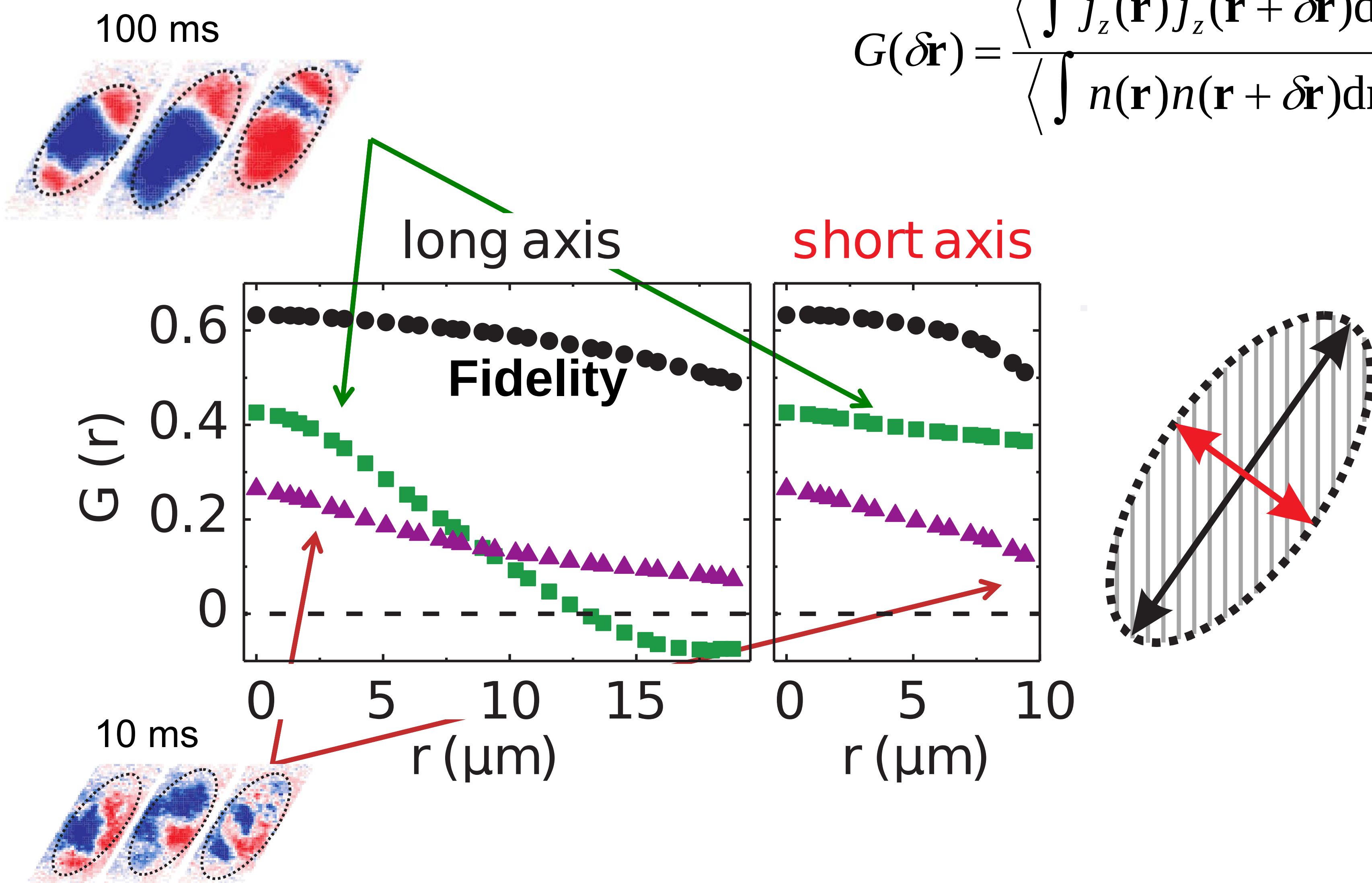
10 ms ramping



Parker, Ha, Chin - Nature Physics (2013)

Correlation length

$$G(\delta\mathbf{r}) = \frac{\left\langle \int j_z(\mathbf{r}) j_z(\mathbf{r}+\delta\mathbf{r}) \mathrm{d}\mathbf{r} \right\rangle}{\left\langle \int n(\mathbf{r}) n(\mathbf{r}+\delta\mathbf{r}) \mathrm{d}\mathbf{r} \right\rangle}$$

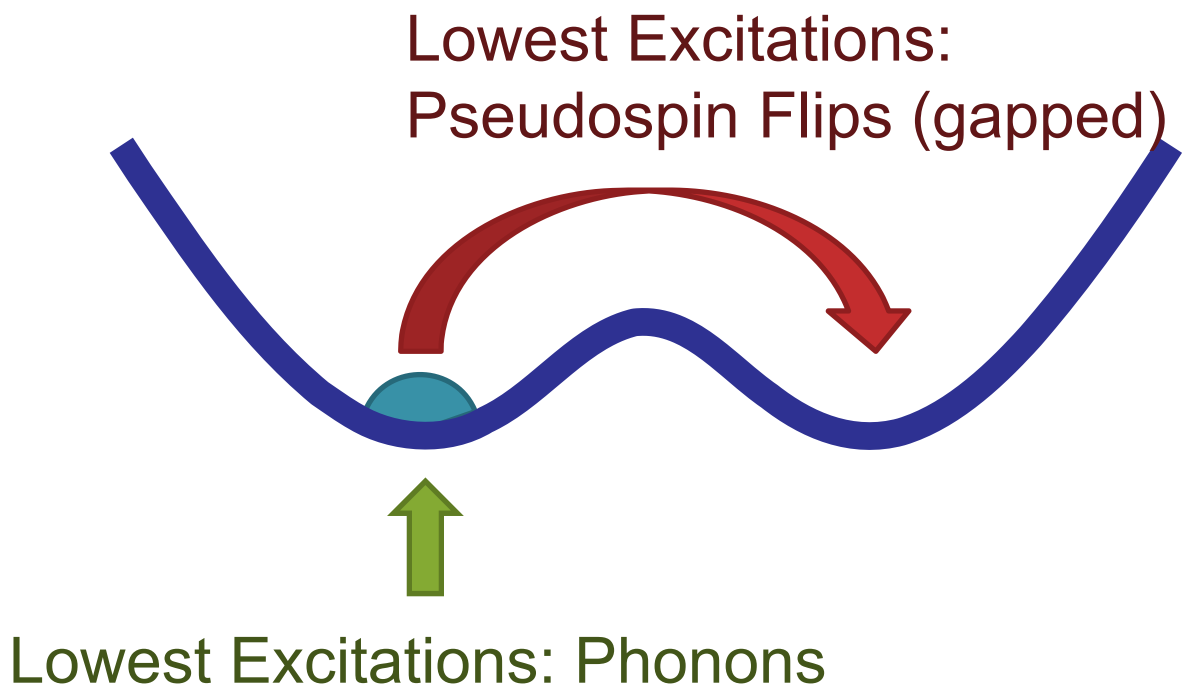


Summary - Ferromagnetism

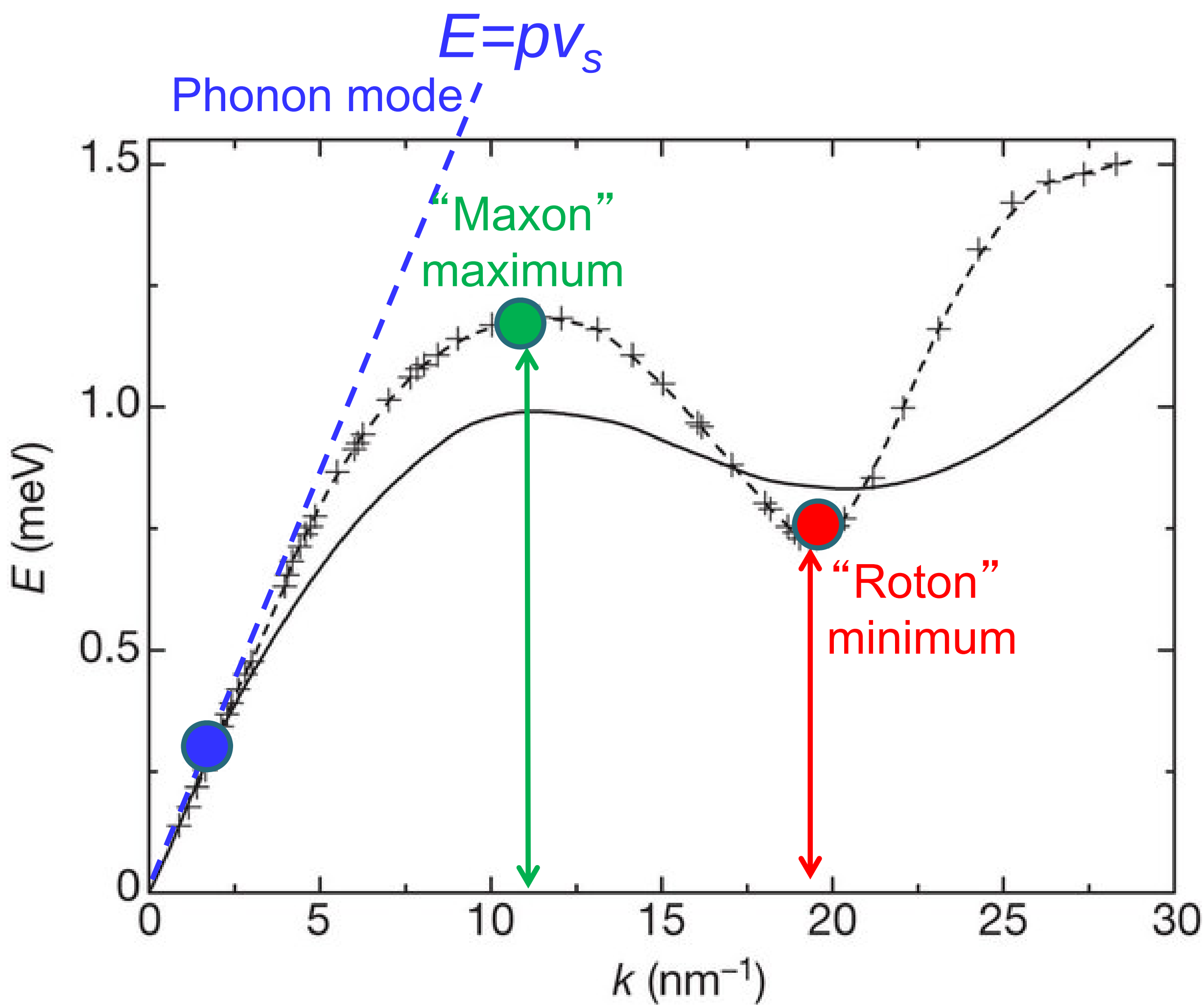
- Modifying only the dispersion we create an effective ferromagnet in a single-component gas.
- Domain formation at long length scales (of order the system size)
- Dynamics considerably faster than heating timescales

Excitations: Roton/Maxon

Excitations of the double-well dispersion



Roton-maxon excitations (He II)



Landau (1941, 47)

Neutron Scattering: Henshaw and Woods (1961)

Reference: Glyde, H. R. *Excitations in Liquid and Solid Helium* (Clarendon, 1994)

Similar Proposals/Experiments

Theory proposals:

•Resonantly-interacting gases:

Yunomae, Yamamoto, Danshita, Yokoshi, Tsuchiya, PRA (09); Cormack, Schumayer, Hutchinson, PRL (11); Rota, Tramonto, Galli, Giorgini, PRB (13).

•Dipolar gases:

Santos, Shlyapnikov, Lewenstein, PRL (03); O'Dell, Giovanazzi, Kurizki, PRL (03); Wilson, Ronen, Bohn, Pu, PRL (08).

•Rydberg-excited condensates:

Henkel, Nath, Pohl, PRL (10).

•Dilute 2D Bose gases:

Fischer PRA(06), Nogueira, Kleinert, PRB (06).

•Spinor condensates:

Cherng, Demler, PRL (09); M. Matuszewski, PRL (10).

•Spin-orbit coupled condensates:

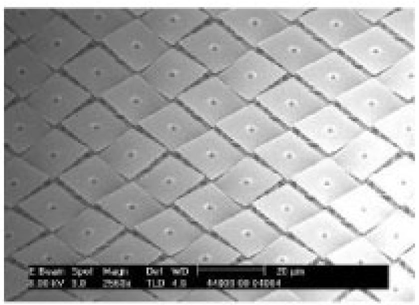
Higbie, Stamper-Kurn, PRL (02); Zheng, Li, PRA (12); Martone, Li, Pitaevskii, Stringari, PRA (12); Zheng, Yu, Cui, Zhai, J. Phys. B (13).

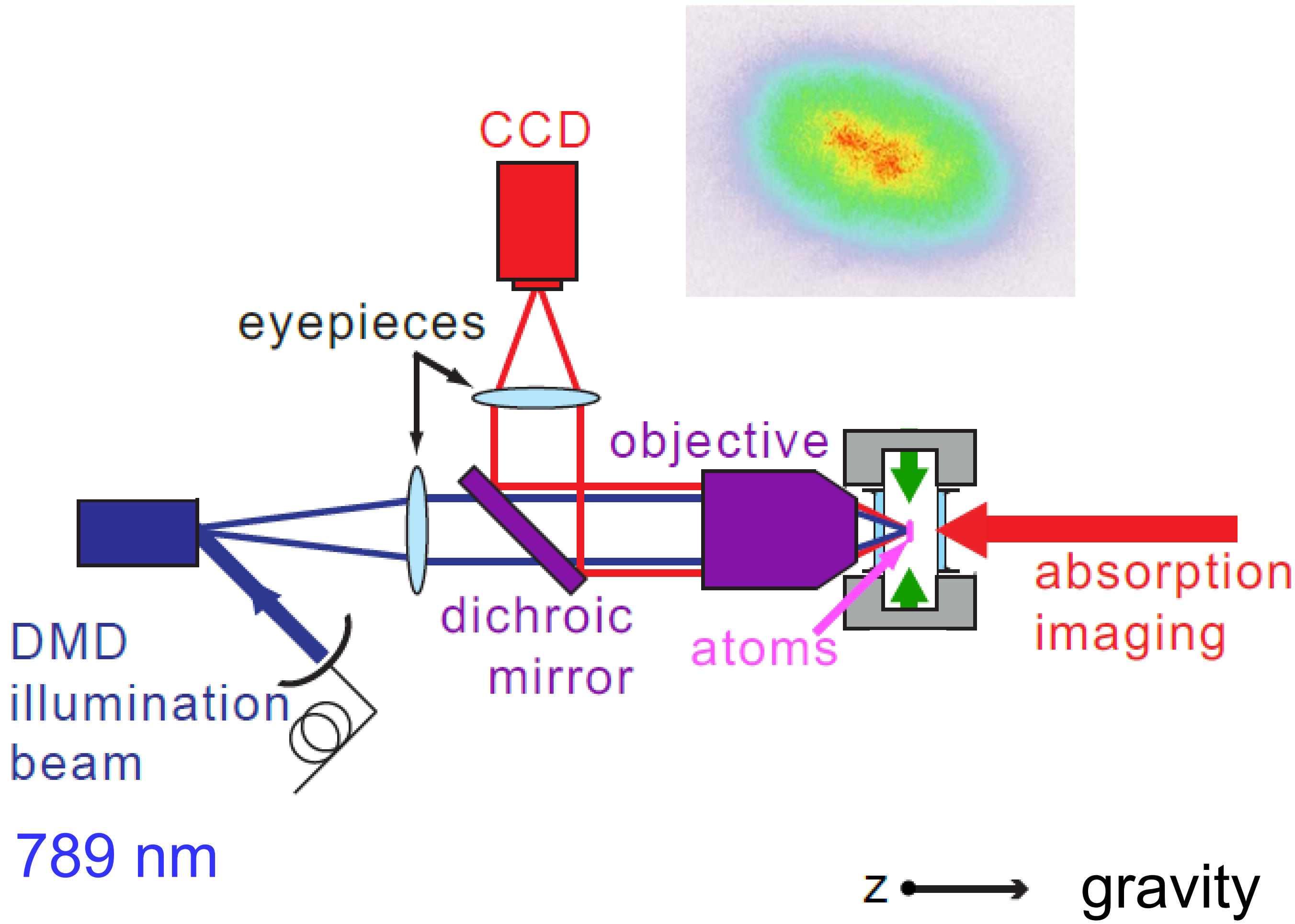
Experimental observation:

•Cavity mediated systems (Roton-type mode softening):

Mottl et. al., Science (12)

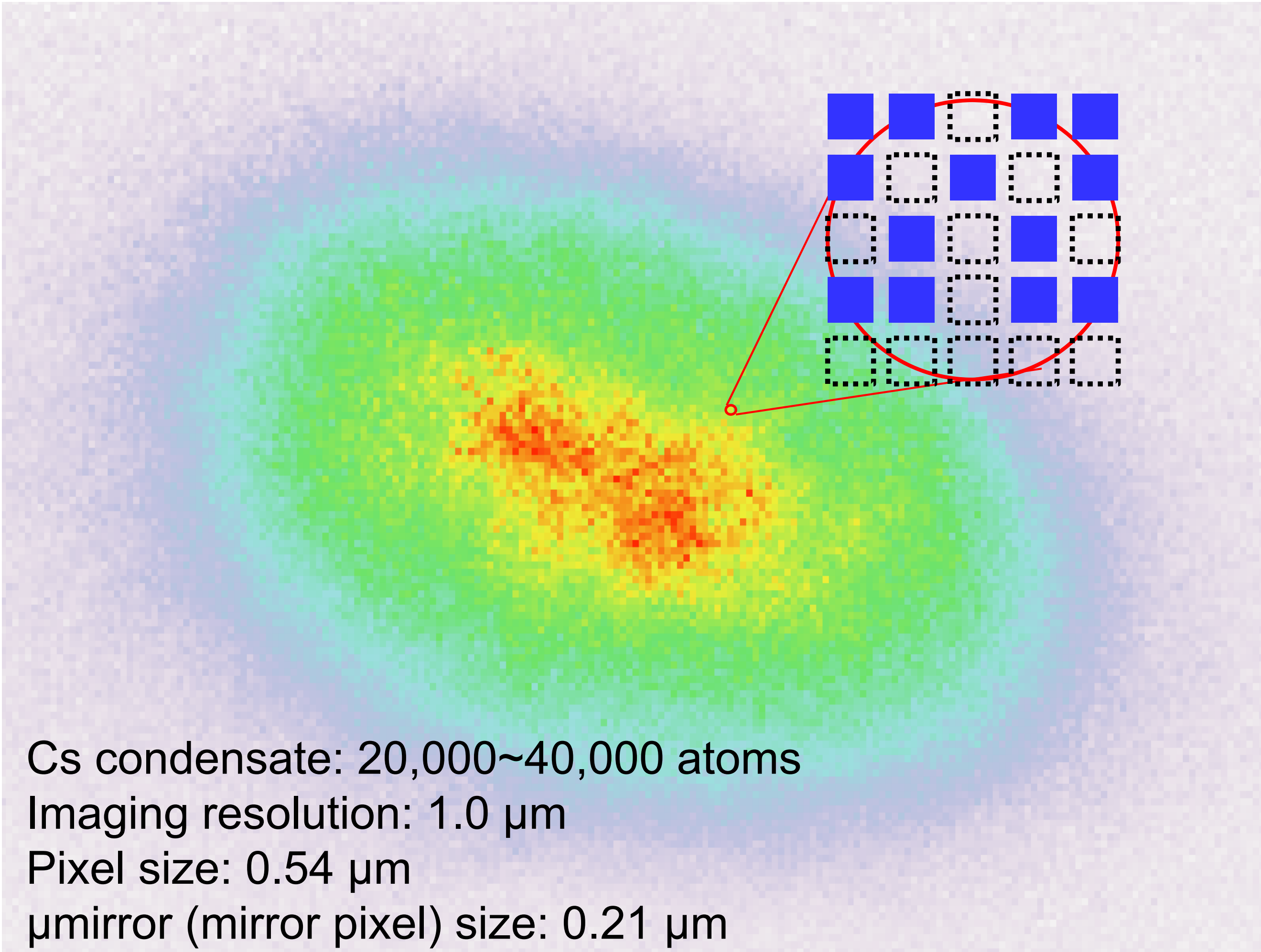
Digital Micromirror Device Projection



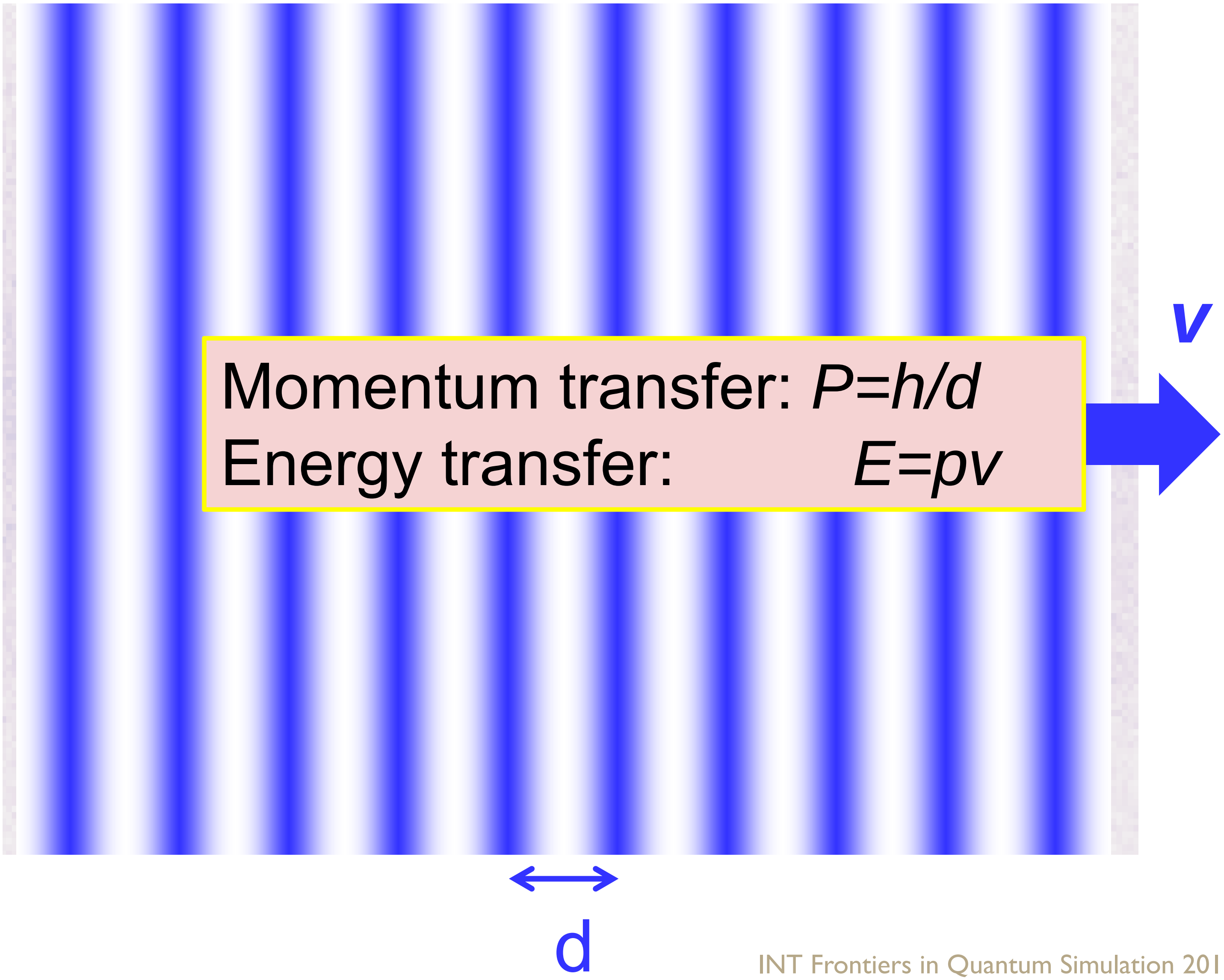


Projection optics: Heinzen group (UTexas), Greiner group (Harvard), Bloch group (Munich), Esslinger group (ETH) , Hadzibabic group(Cambridge), Dalibard group (ENS)…

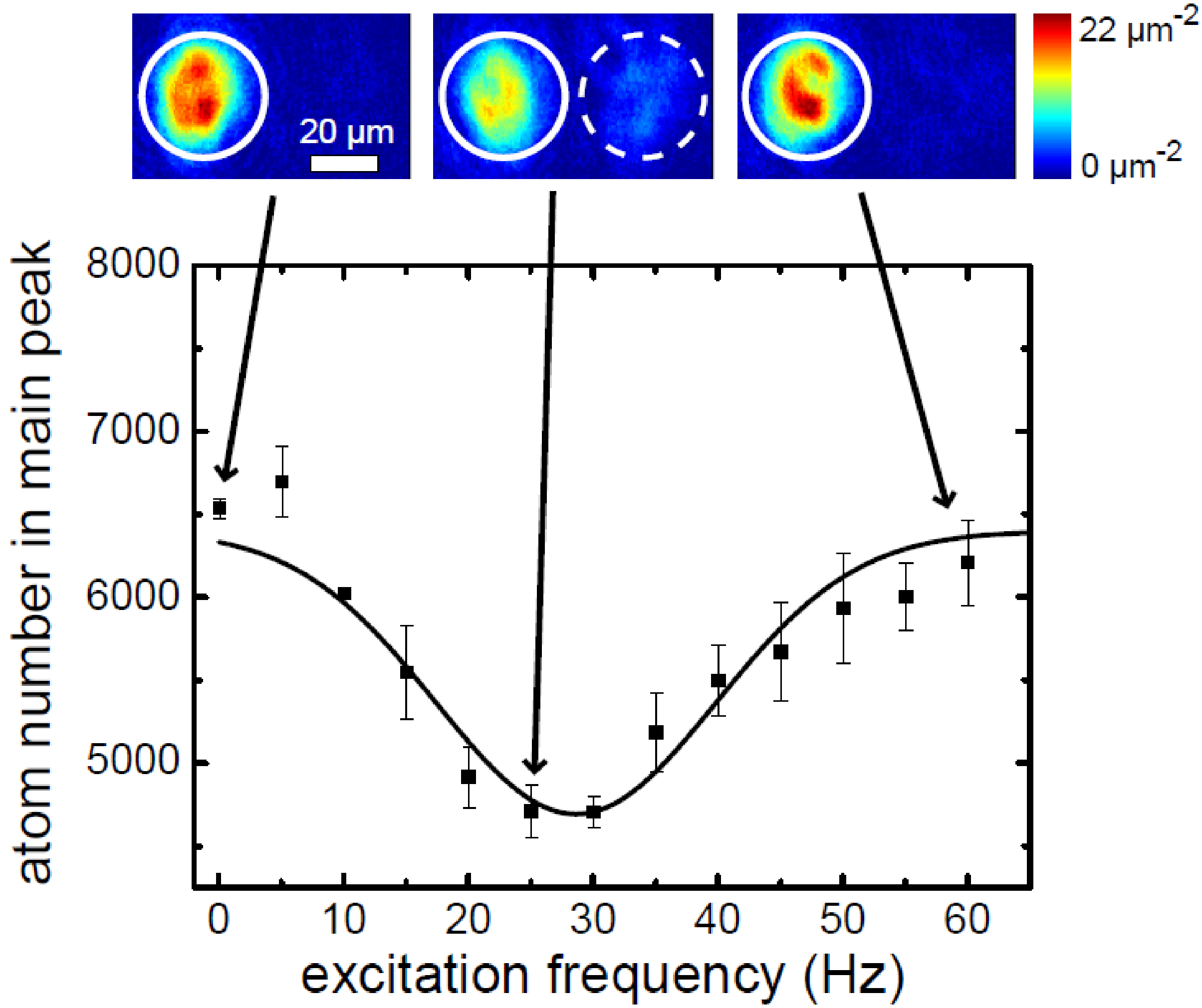
DMD/Imaging


Cs condensate: 20,000~40,000 atoms
Imaging resolution: 1.0 μm
Pixel size: 0.54 μm
μmirror (mirror pixel) size: 0.21 μm

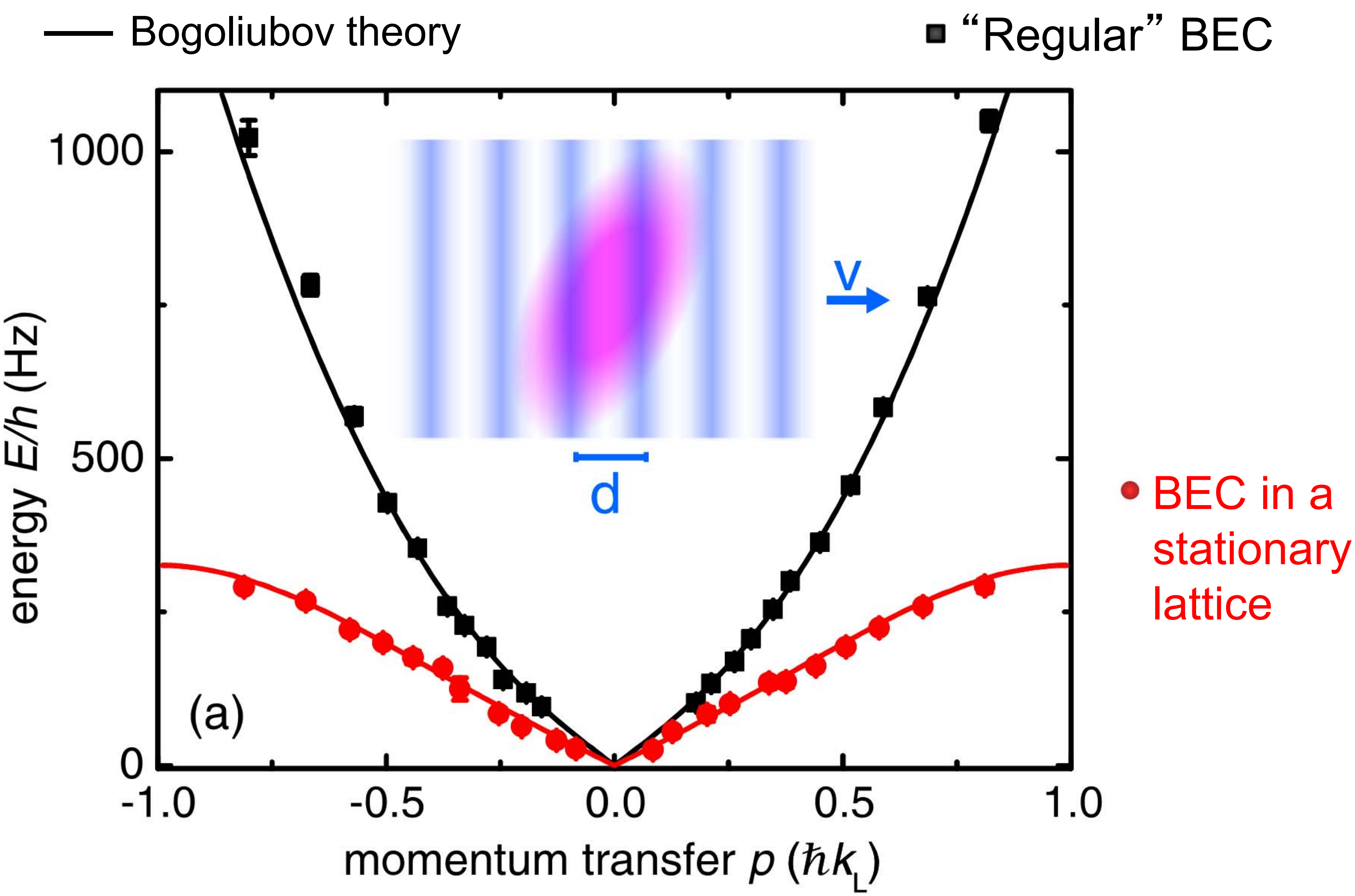
(Raman) Bragg Spectroscopy



Typical frequency (energy) spectrum

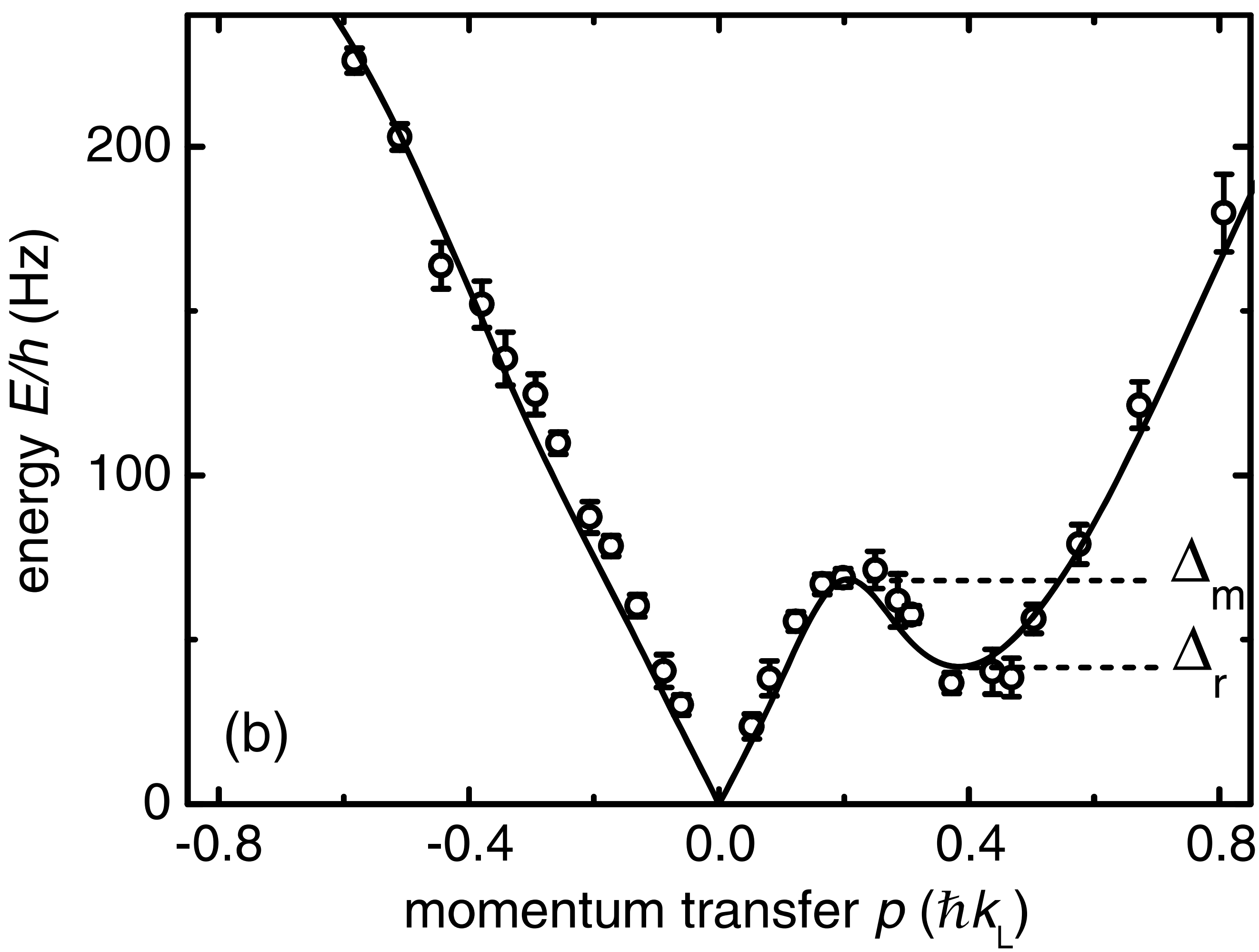


Warm-up exercise (w/o shaking)



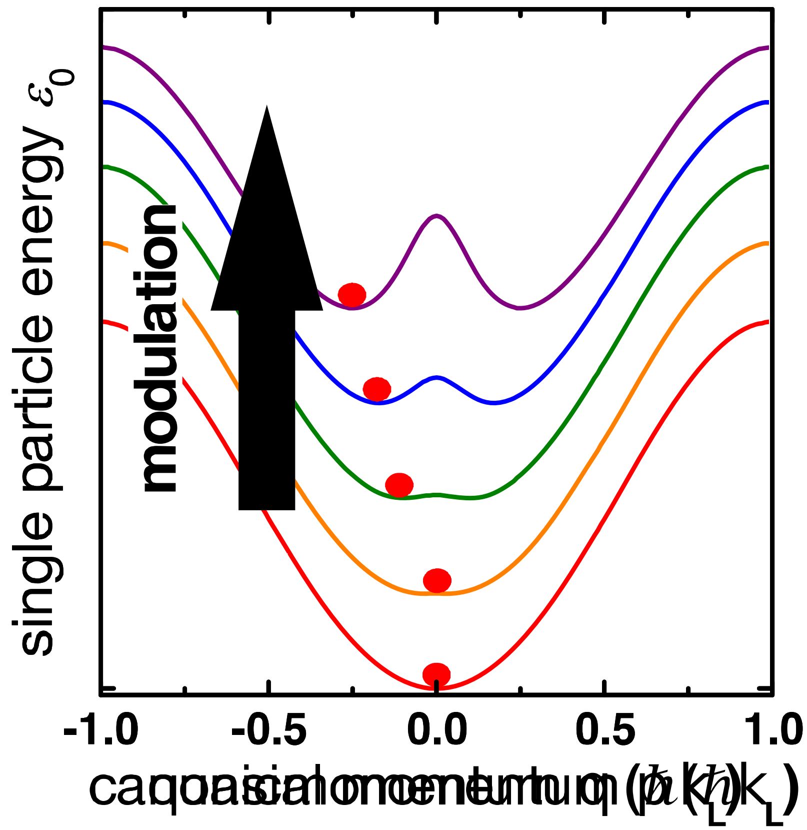
Ha, Clark, Parker, Anderson, Chin – PRL 114 055301 (2015)

Roton dispersion measurement



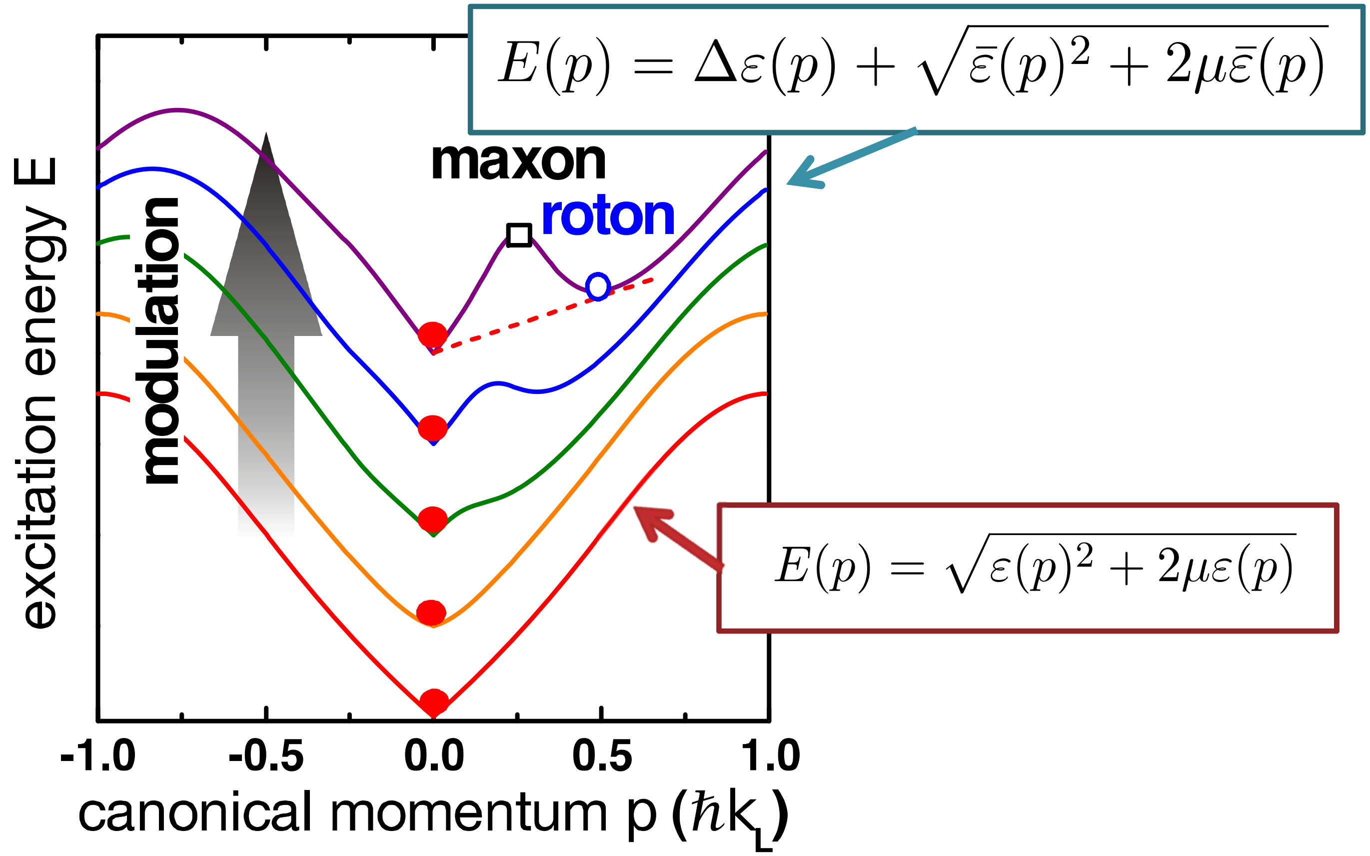
Ha, Clark, Parker, Anderson, Chin – PRL (2015) (soon)

Dispersion – Calculations



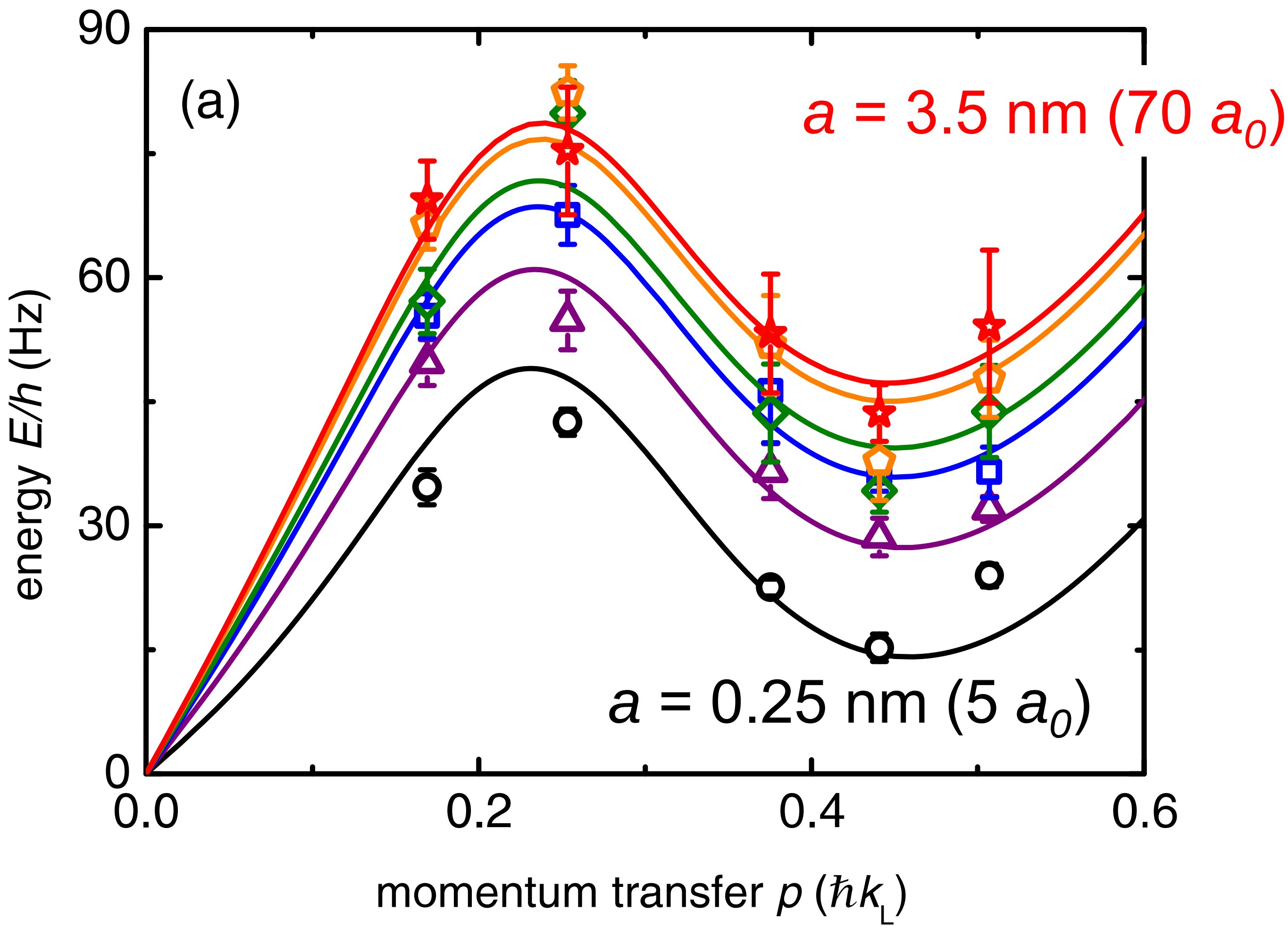
Parker, Ha, Chin - Nature Physics (2013)
Ha, Clark, Parker, Anderson, Chin – PRL 114 055301 (2015)

Dispersion – Calculations



Parker, Ha, Chin - Nature Physics (2013)
Ha, Clark, Parker, Anderson, Chin – PRL 114 055301 (2015)

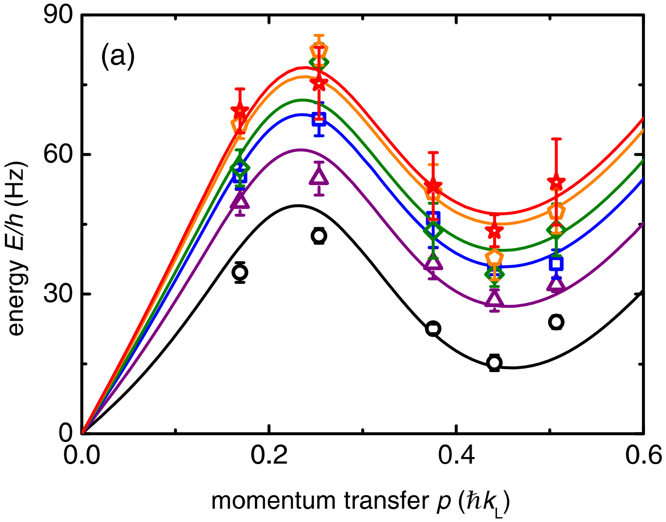
Roton depends on interactions

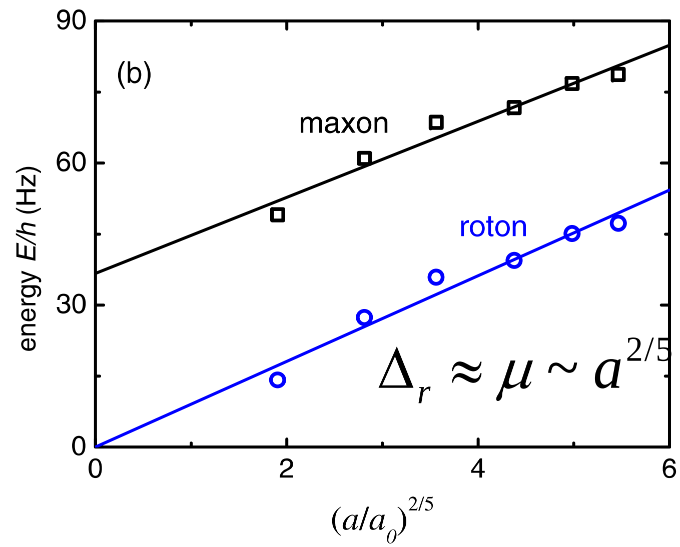


Ha, Clark, Parker, Anderson, Chin – PRL 114 055301 (2015)

Interaction scales as expected

$$\Delta_m \approx C + a^{2/5}$$

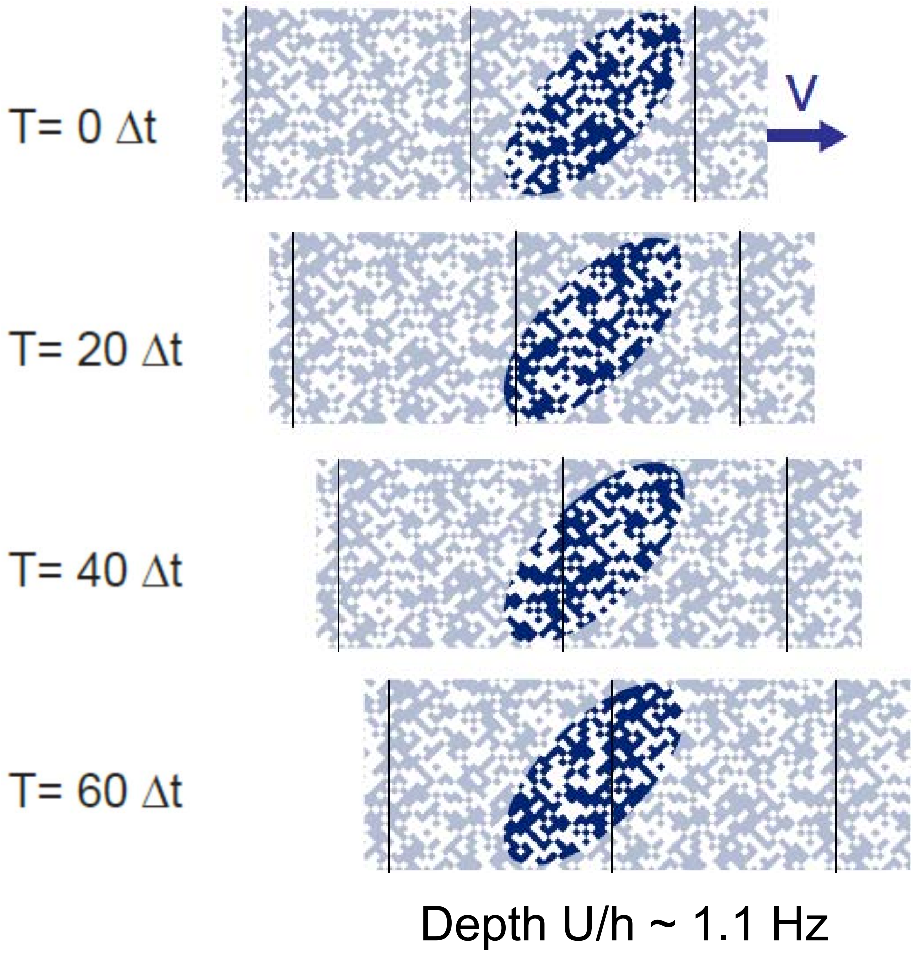


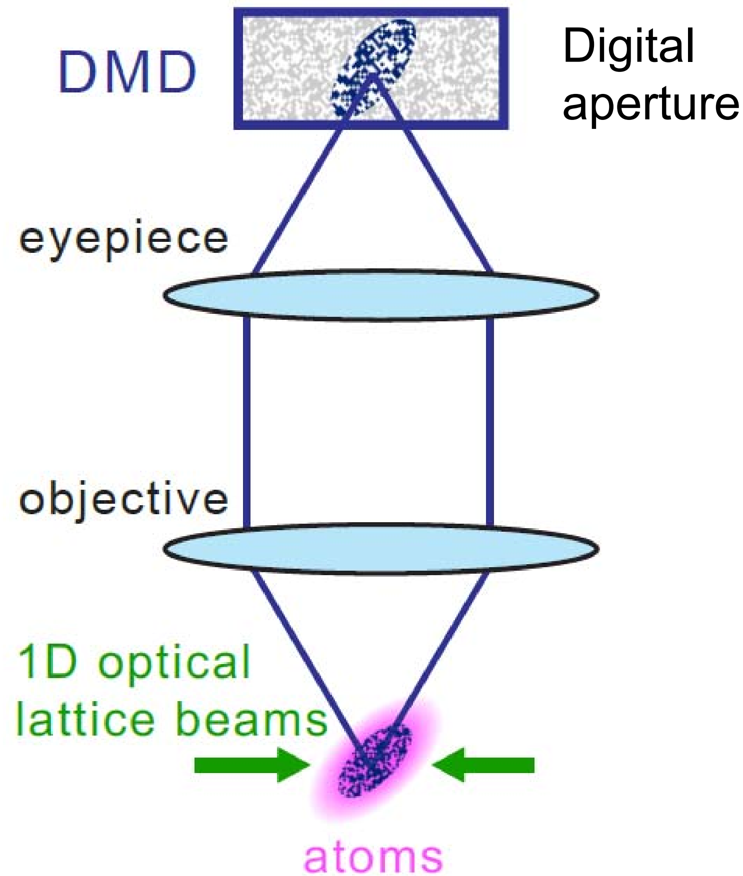


$$\Delta_r \approx \mu \sim a^{2/5}$$

Ha, Clark, Parker, Anderson, Chin – PRL 114 055301 (2015)

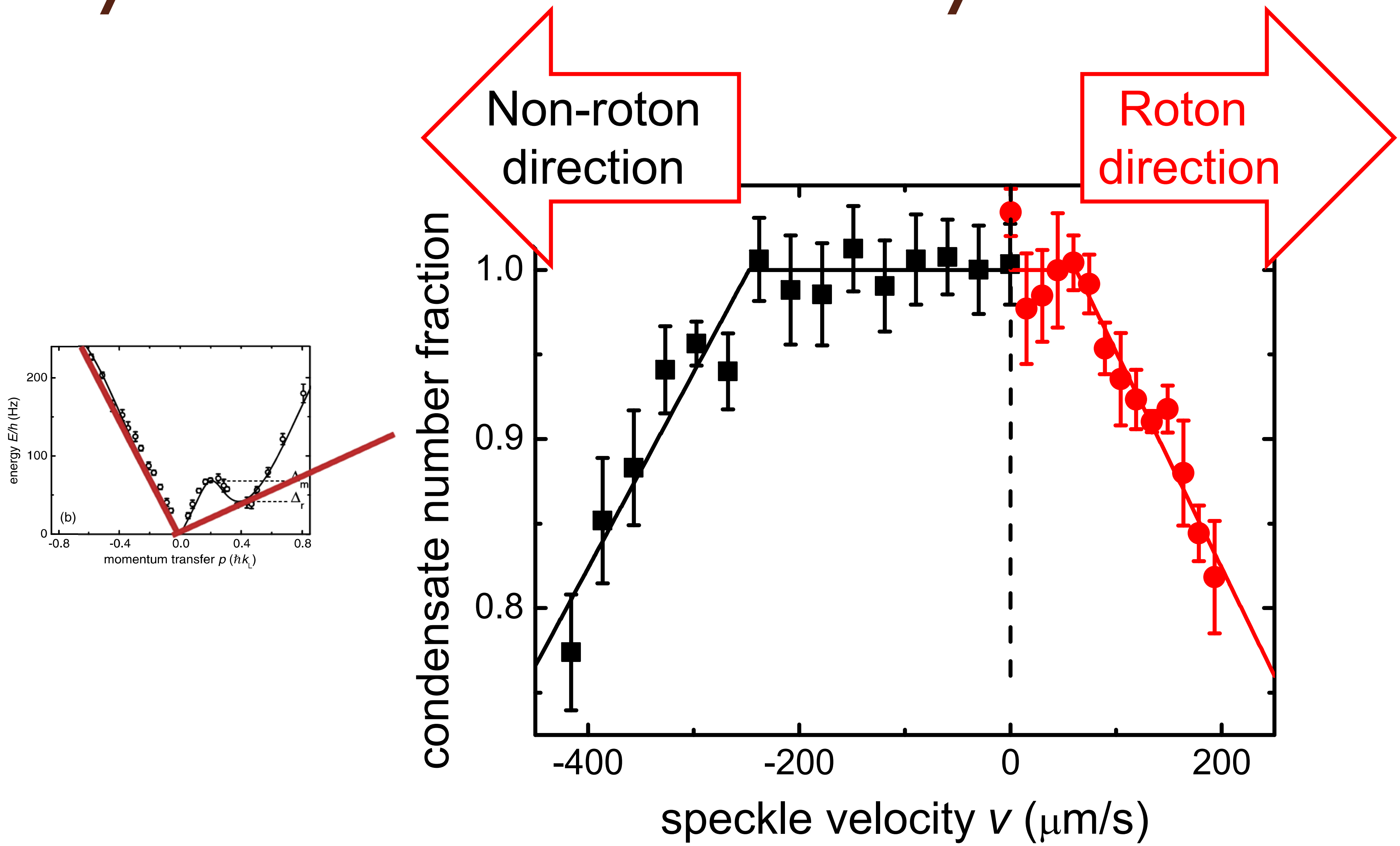
Critical Velocity Measurement



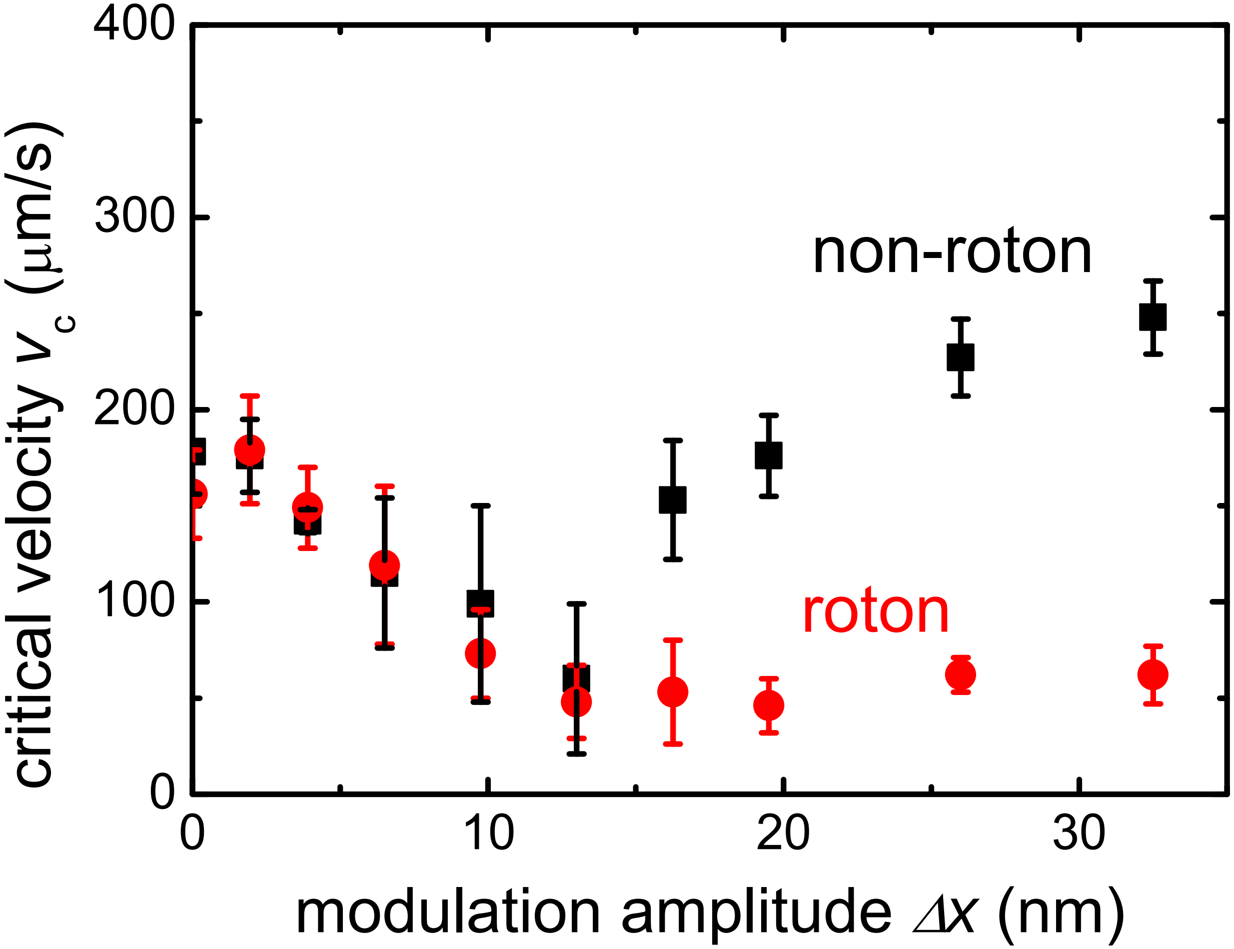


Ha, Clark, Parker, Anderson, Chin – PRL 114 055301 (2015)

Asymmetric critical velocity!

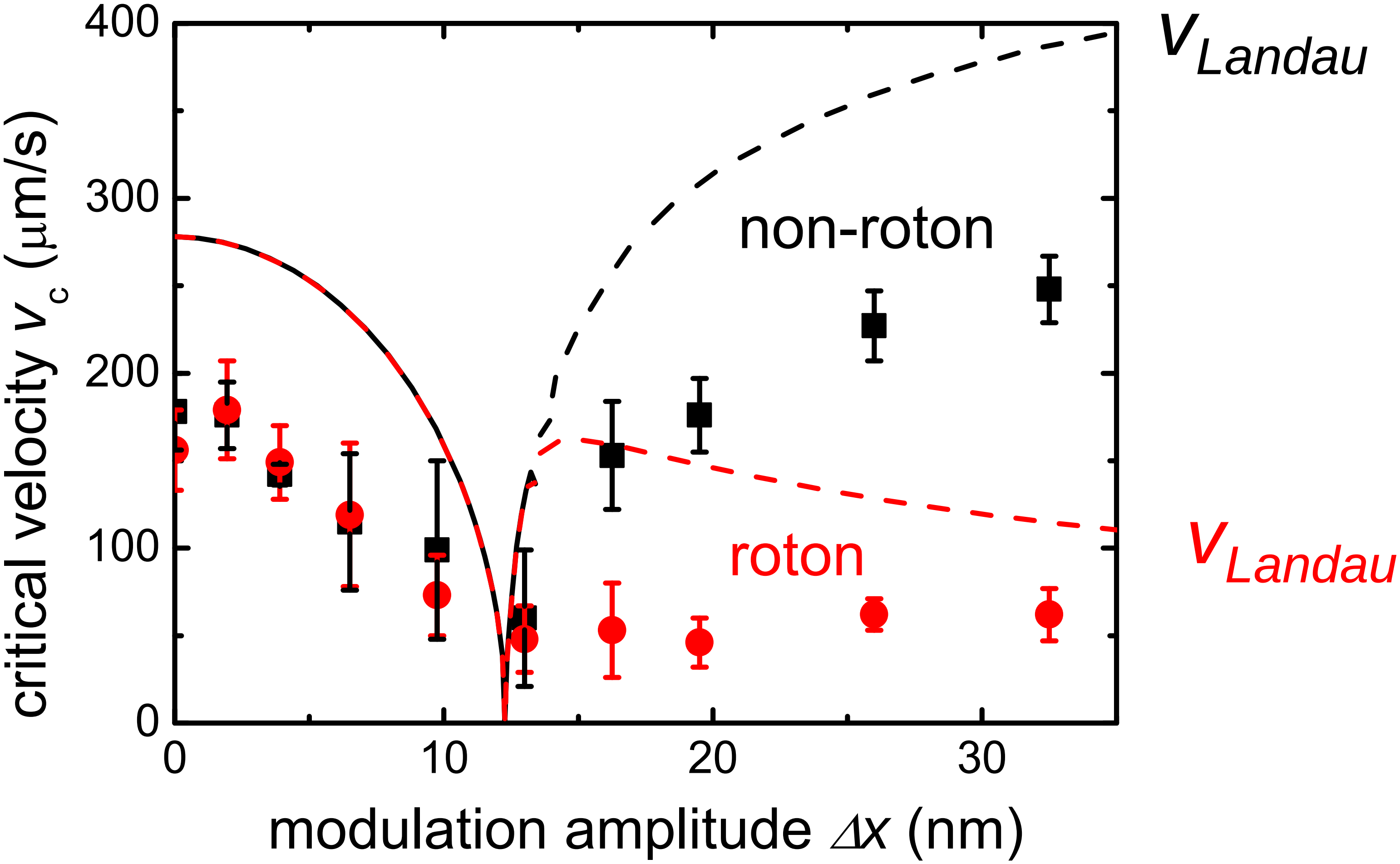


Superfluid critical velocity



Ha, Clark, Parker, Anderson, Chin – PRL 114 055301 (2015)

Superfluid critical velocity



Ha, Clark, Parker, Anderson, Chin – PRL 114 055301 (2015)

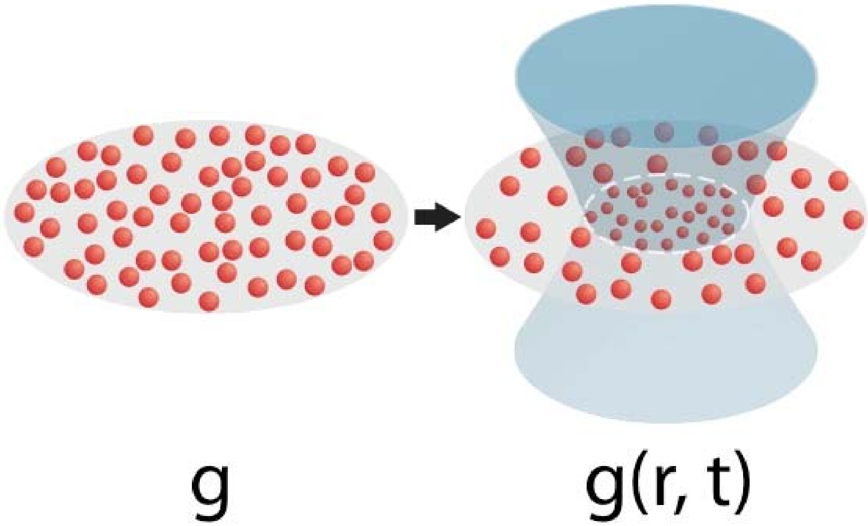
Summary - Roton

- Excitations of the effective ferromagnetism turn out to be phonon-maxon-roton
- Roton properties driven by interaction
- Landau criterion qualitatively explains critical velocity (strong suppression with roton)
- Exotic behavior, but still a single component gas with simple interactions

Optical Control of Scattering Length

Motivation

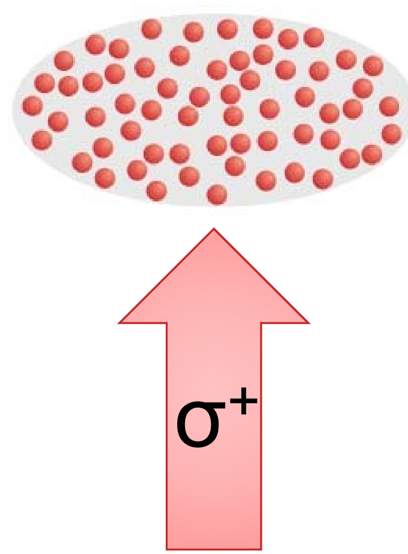
- For Cs, already good control of scattering length
- Want optical control for:
    - Spatially varying interactions
    - Fast modulation of interactions



New Approach: Vector Light Shift

- Cs ideal:
  - Large $6p^{1/2}$-$6p^{3/2}$ fine structure splitting
    - Allows vector light shift at large detuning
  - Many Feshbach resonances available
    - Can choose sensitivity in terms of a(B)

$$B = B_{physical} + B_{eff}$$



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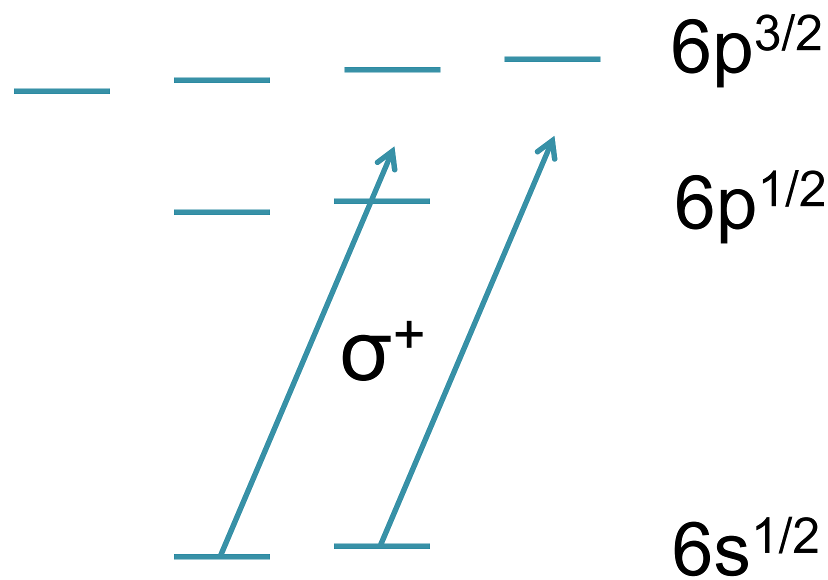
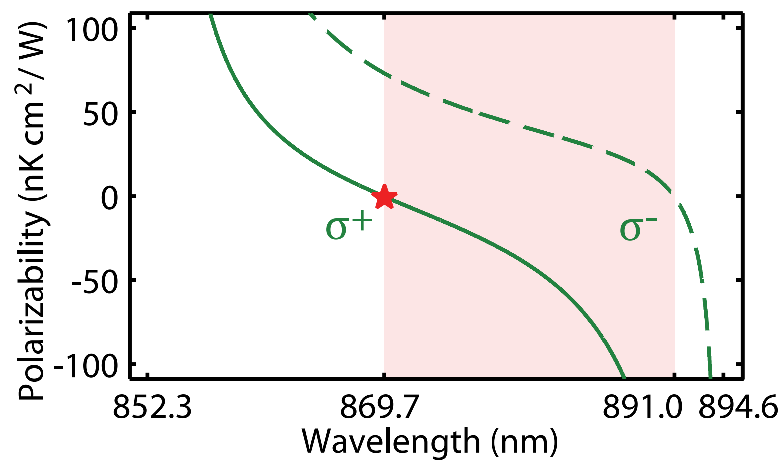
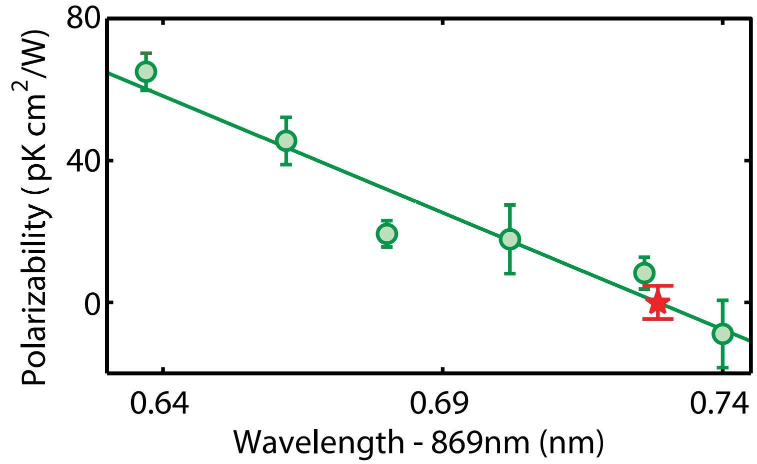


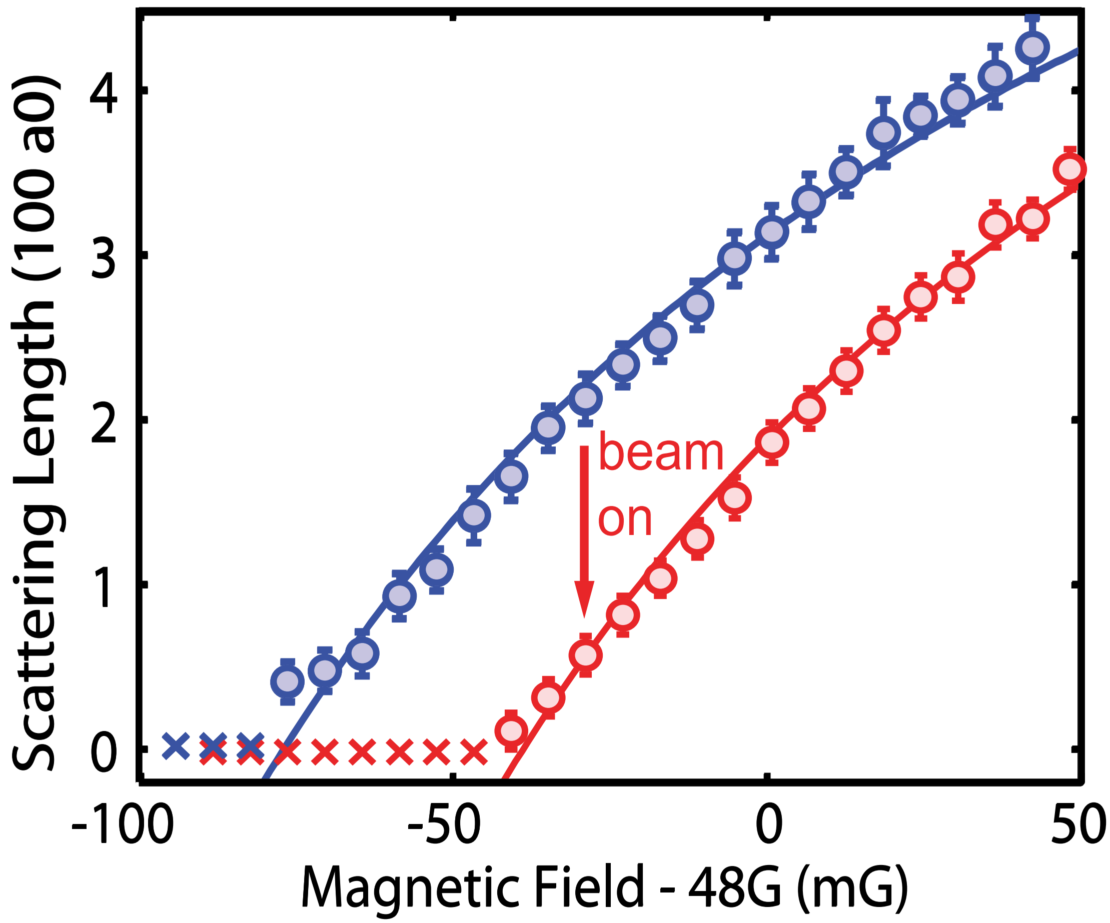
Caveat: We want minimal scalar shift

- Adjust detuning so that polarizability is zero for the entrance channel |3,3> state
- Molecular state still experiences a light shift, which changes scattering length
- Polarization is very sensitive

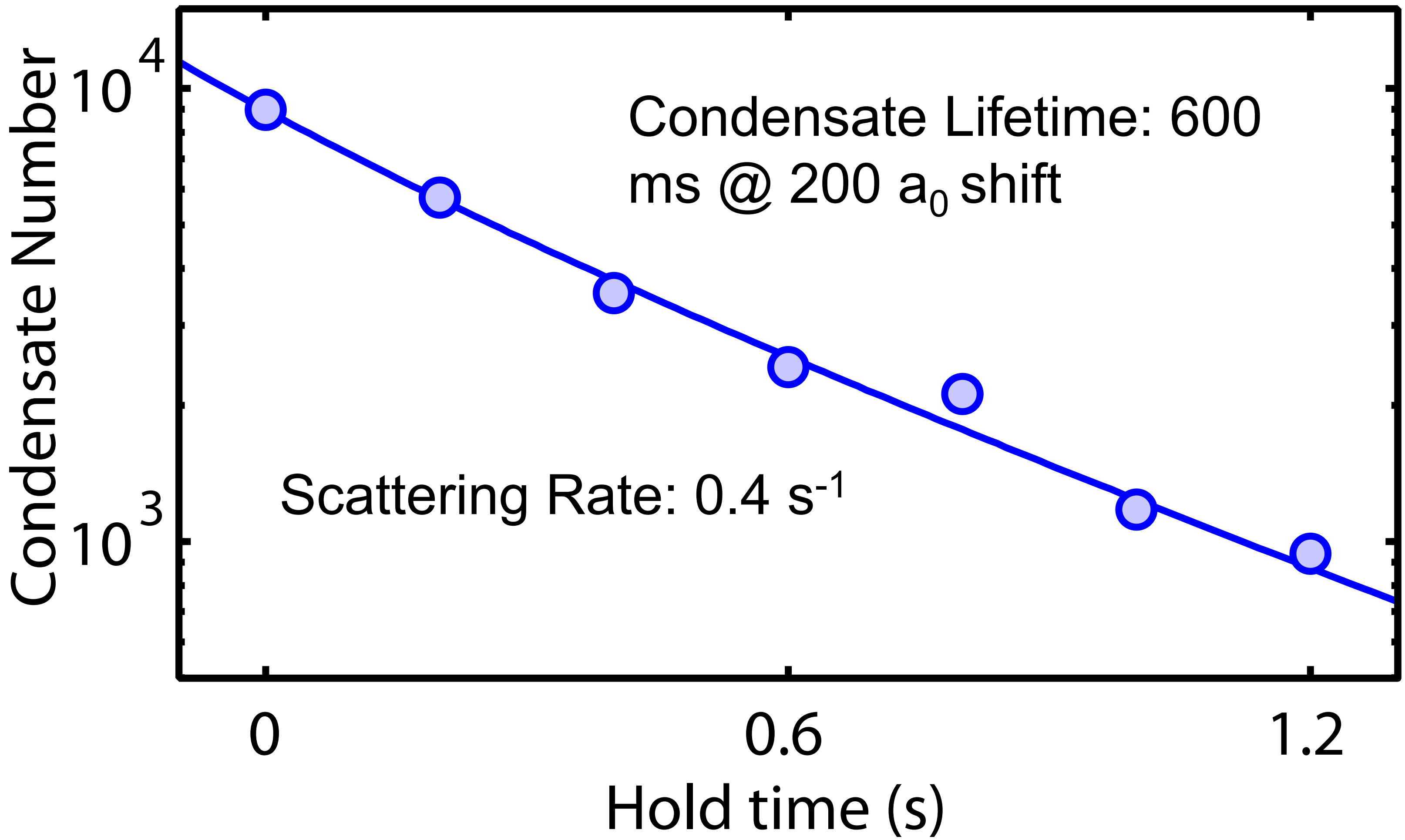




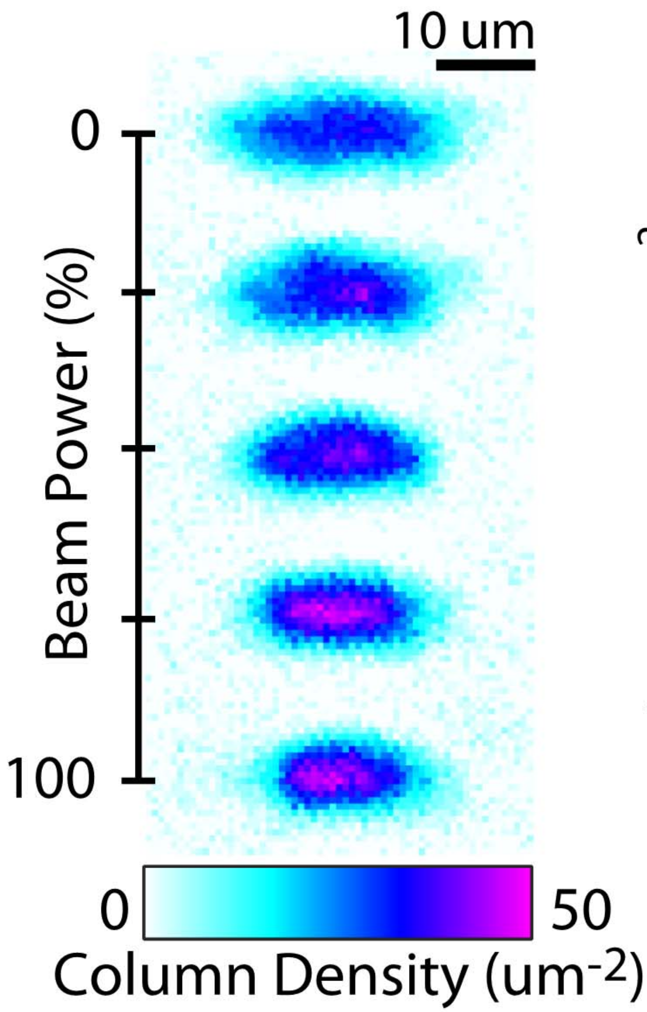
Scattering Length Change Near 48 G

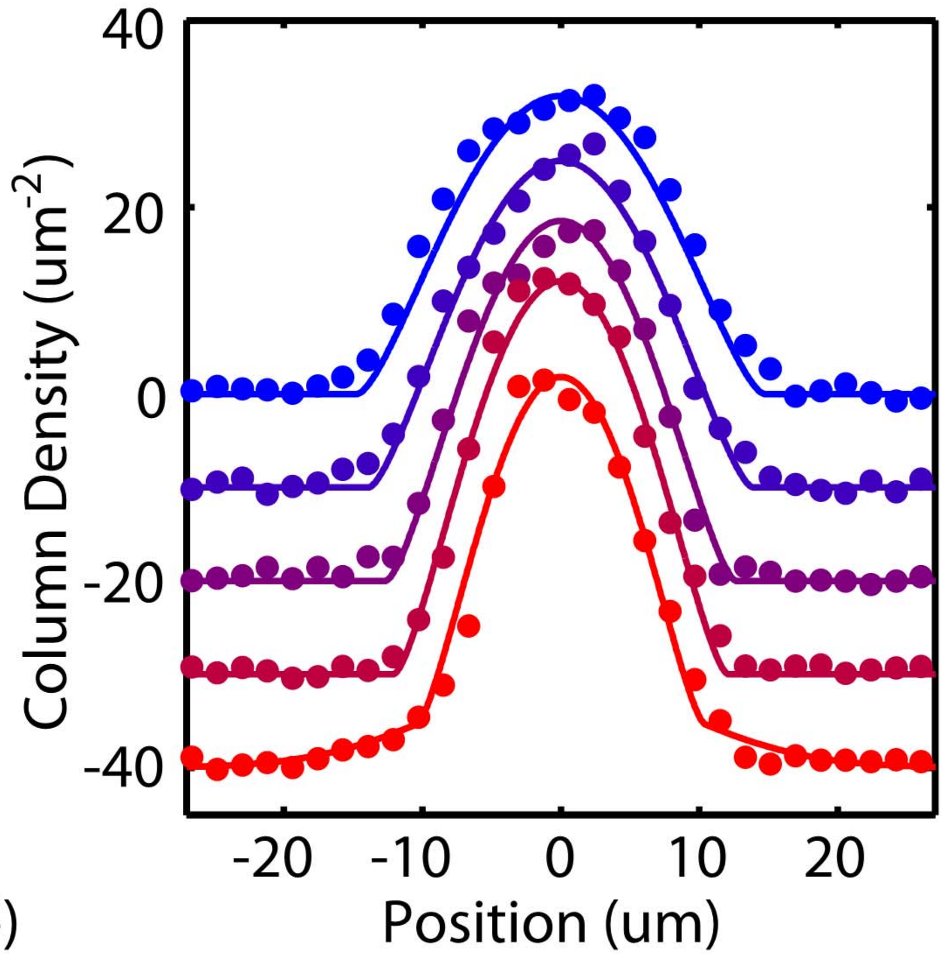


Heating Rate: Low

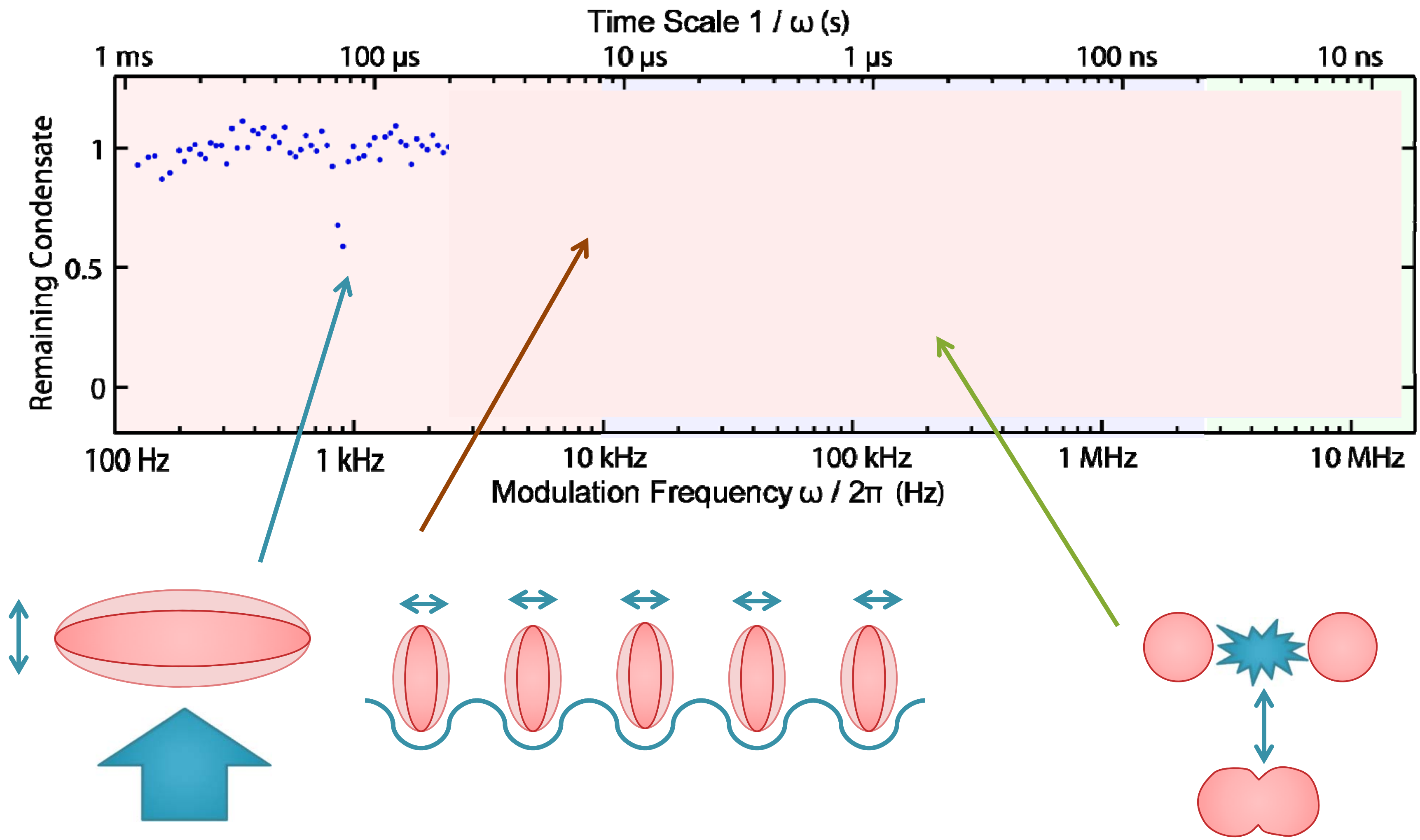


Cloud Size Change





Rich Dynamics



Chicago cold atom group:

PI

Cheng Chin

Postdoc

CVP

Undergrad

Paloma Ocola

Collaborators:

Brandon Anderson

Jason Ho (Ohio State)

Sayan Choudhury, Erich Mueller (Cornell Univ.)

Hui Zhai (Tsinghua Univ.)

Graduate Students

Li-Chung Ha

Logan Clark

Jacob Johansen

Gustaf Downs

Lei Feng