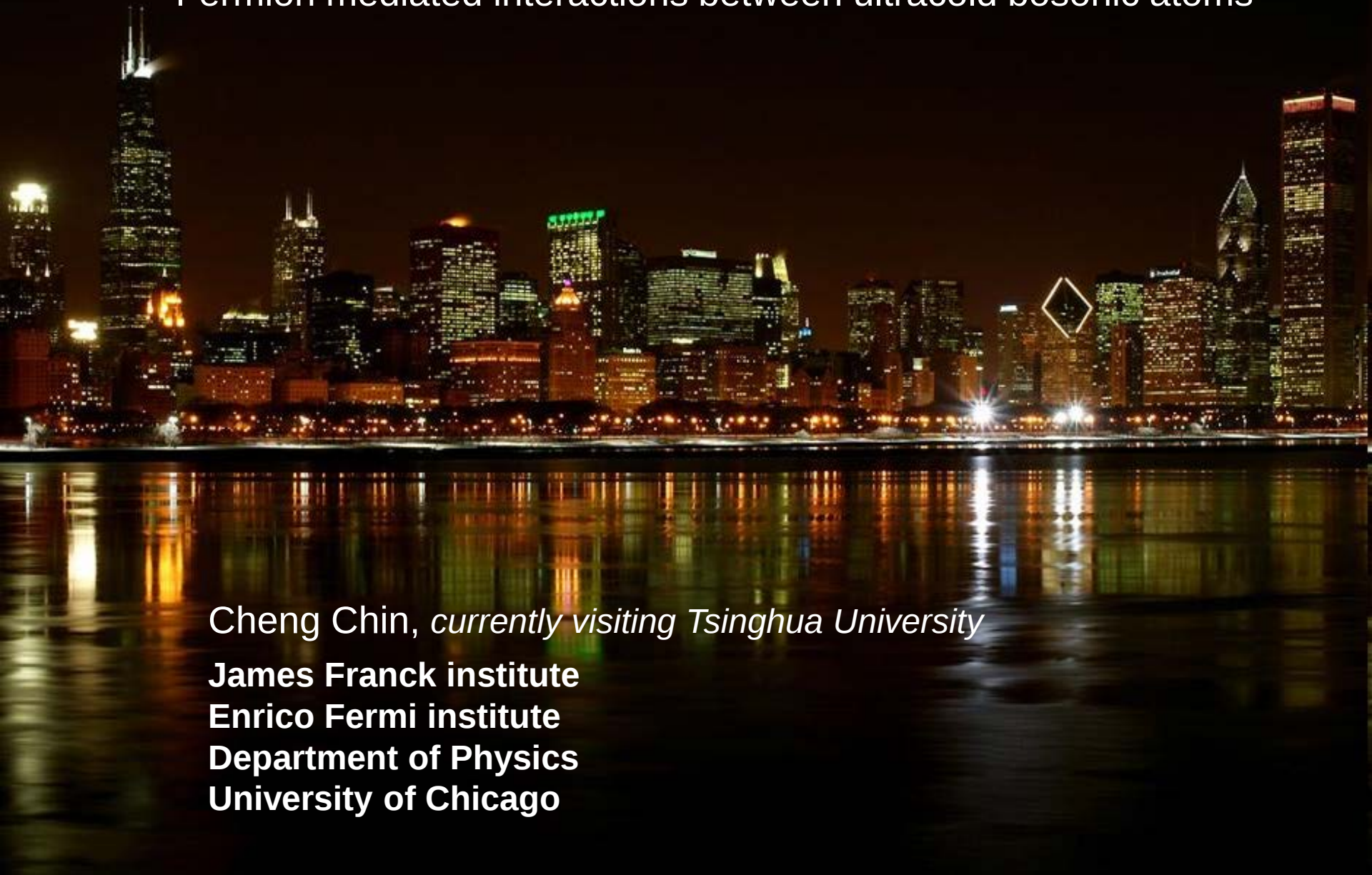


Fermion mediated interactions between ultracold bosonic atoms



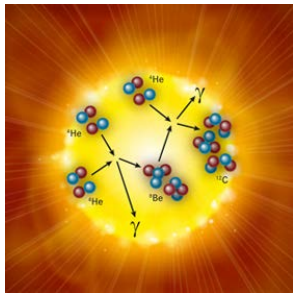
Cheng Chin, *currently visiting Tsinghua University*

**James Franck institute
Enrico Fermi institute
Department of Physics
University of Chicago**

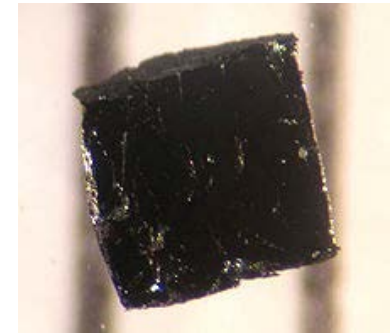
Cold Atom Research at UChicago



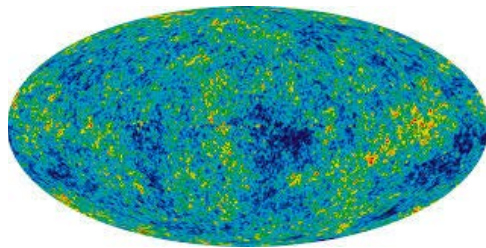
THE UNIVERSITY OF
CHICAGO



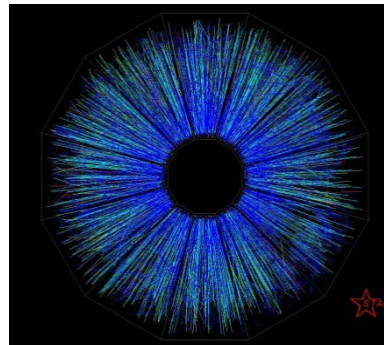
Nuclear Physics:
Feshbach molecules
Efimov physics



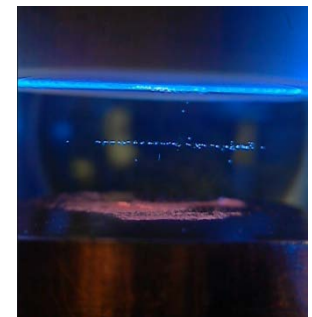
Condensed Matter:
Quantum criticality
Exotic excitations



Cosmology
Sakharov oscillations
Kibble mechanism
Inflation

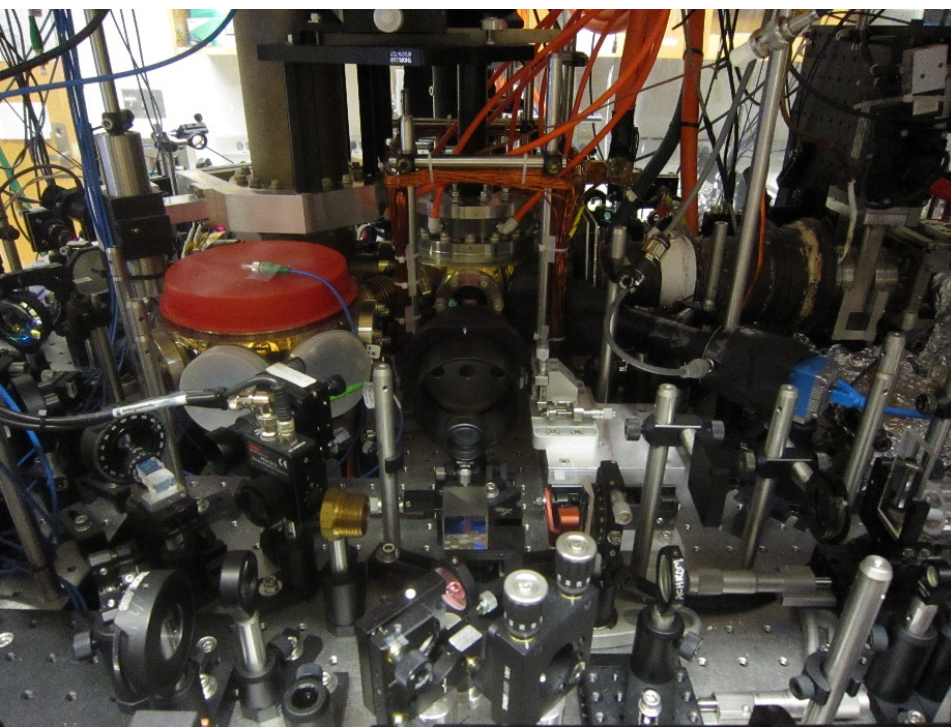
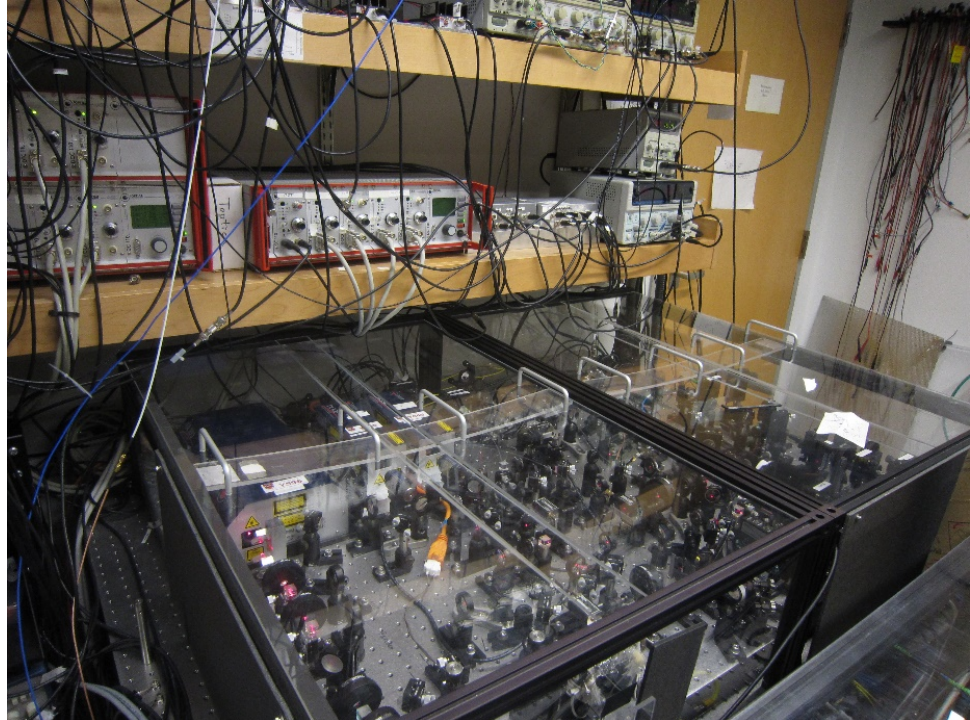


Particle Physics
Jet formation
Pattern
recognition

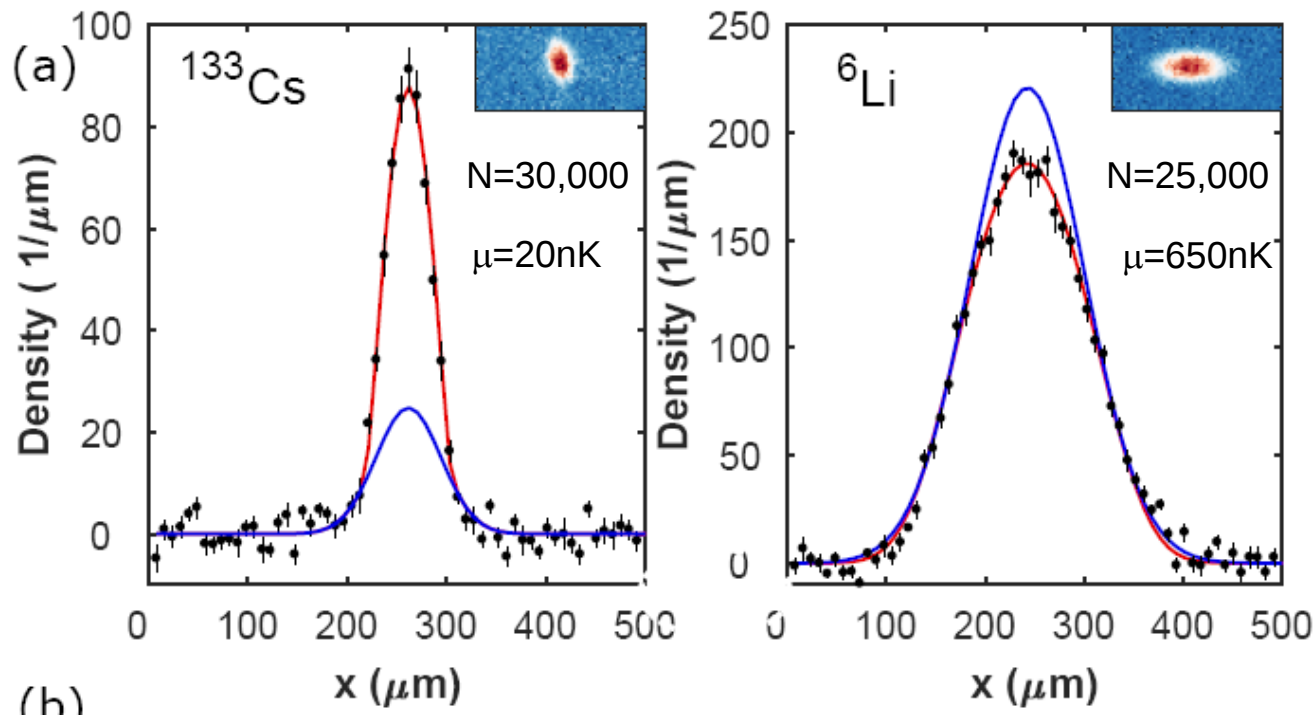
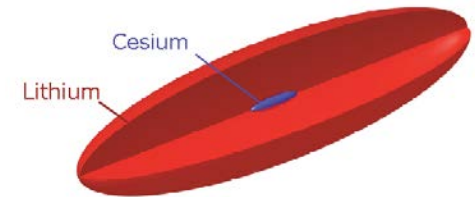


Thermal Levitation

Experimental Setup

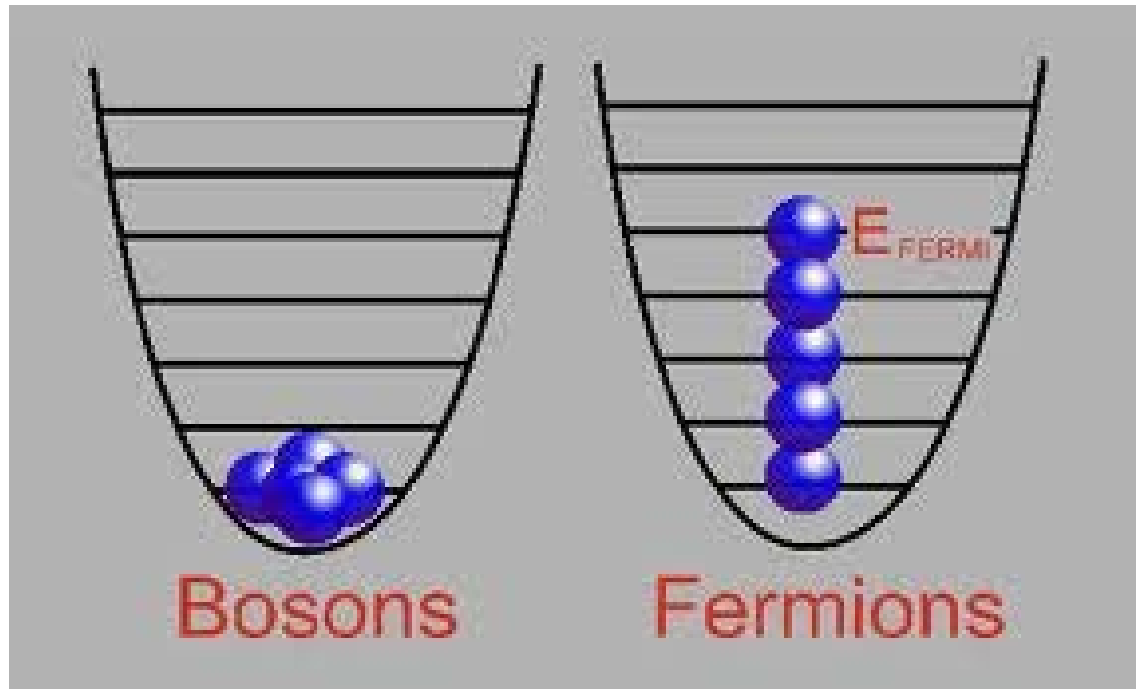


Cs BEC embedded in Li-6 Fermi gas

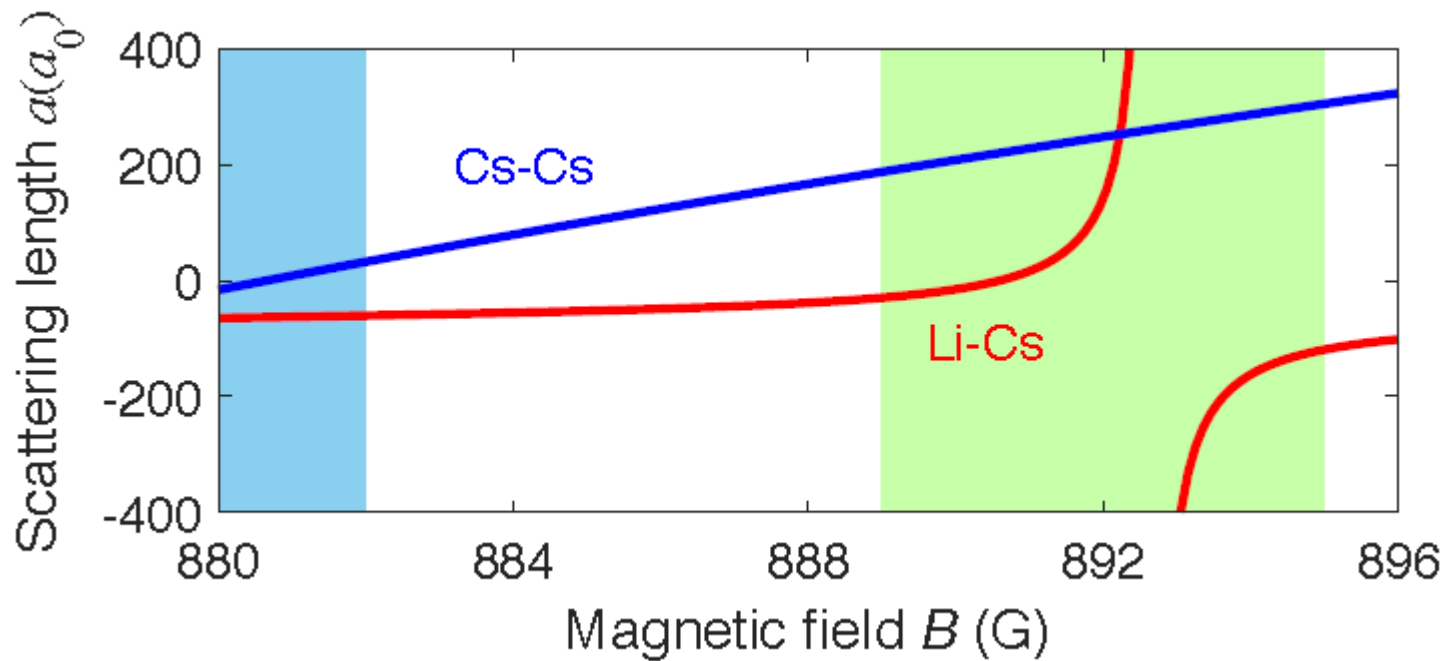


Fermi droplet in BEC, B. DeSalvo, K. Patel, J. Johansen, CC, PRL (2017)

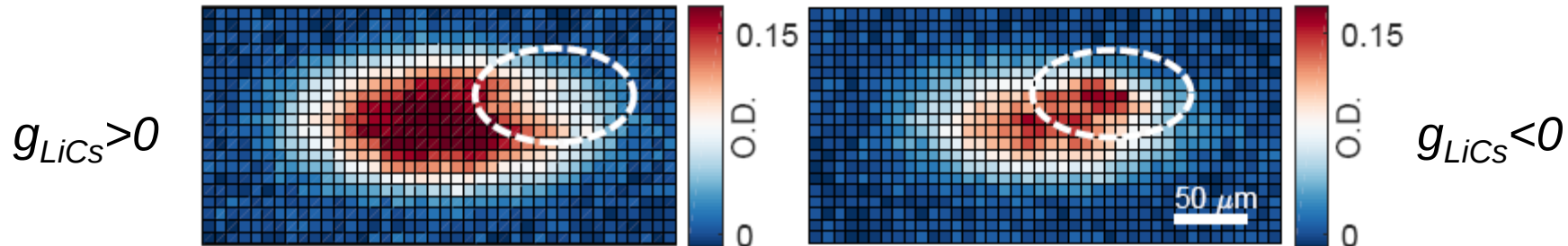
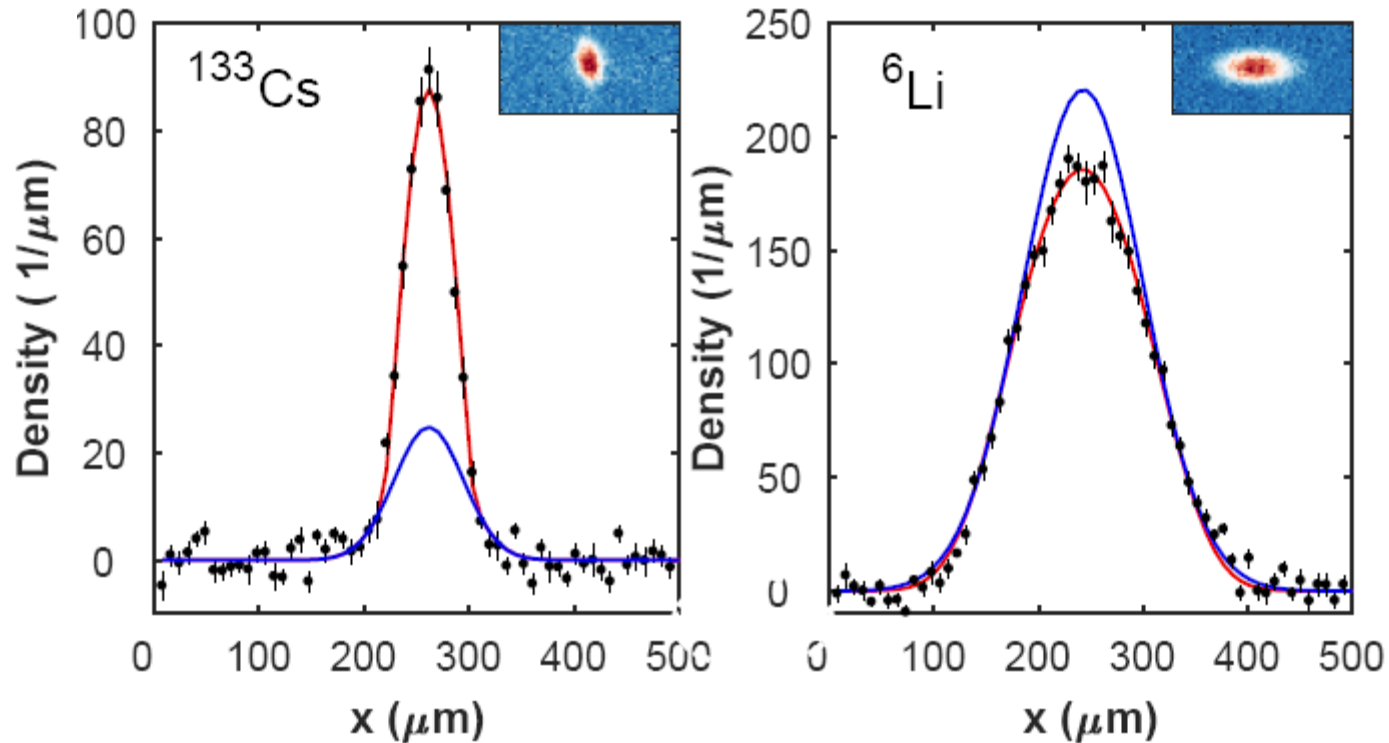
Bosons s. Fermions



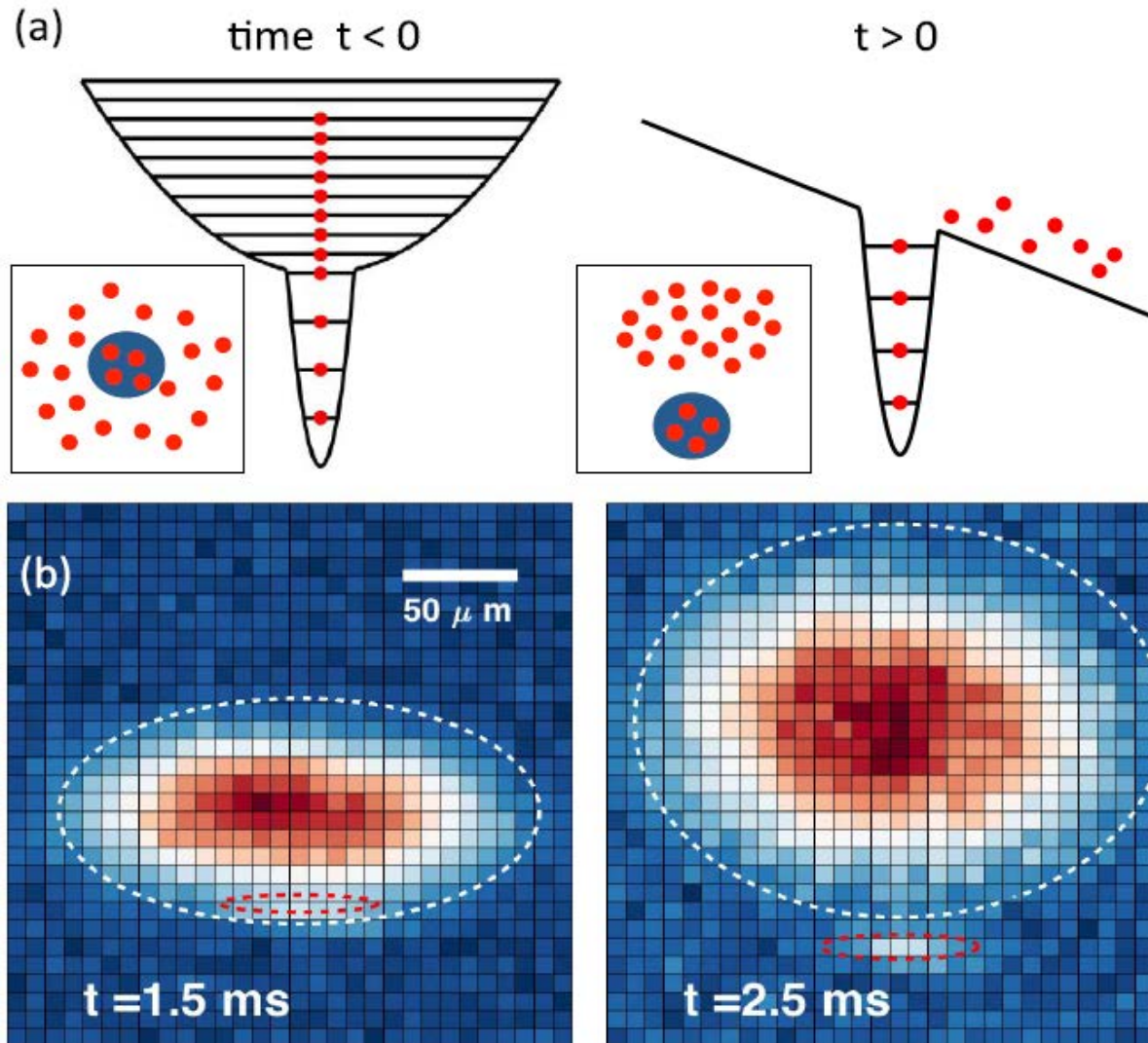
Bose-Fermi mixture with Feshbach resonances



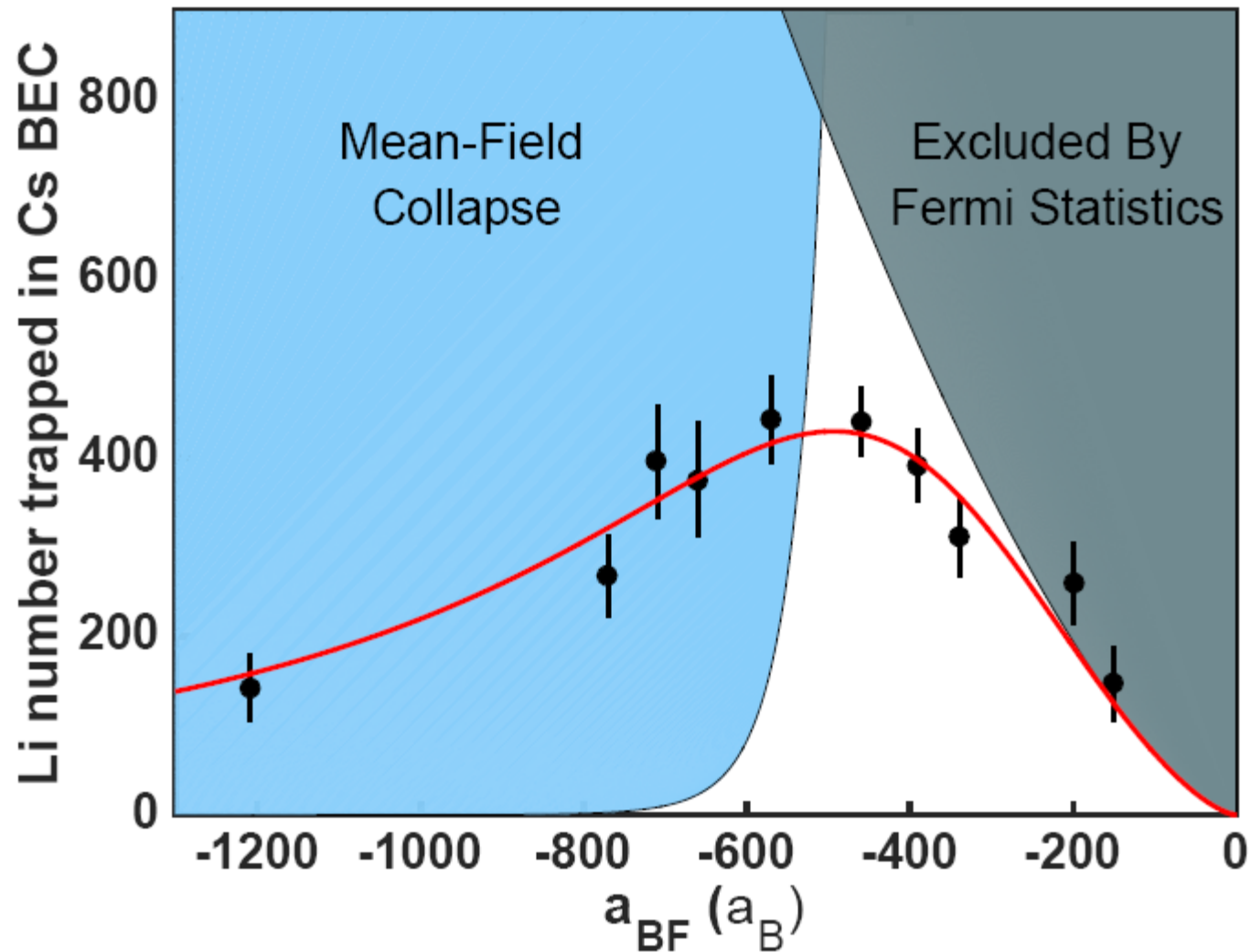
Cs BEC embedded in Li Fermi gas



Degenerate Fermi gas inside a Bose Einstein condensate

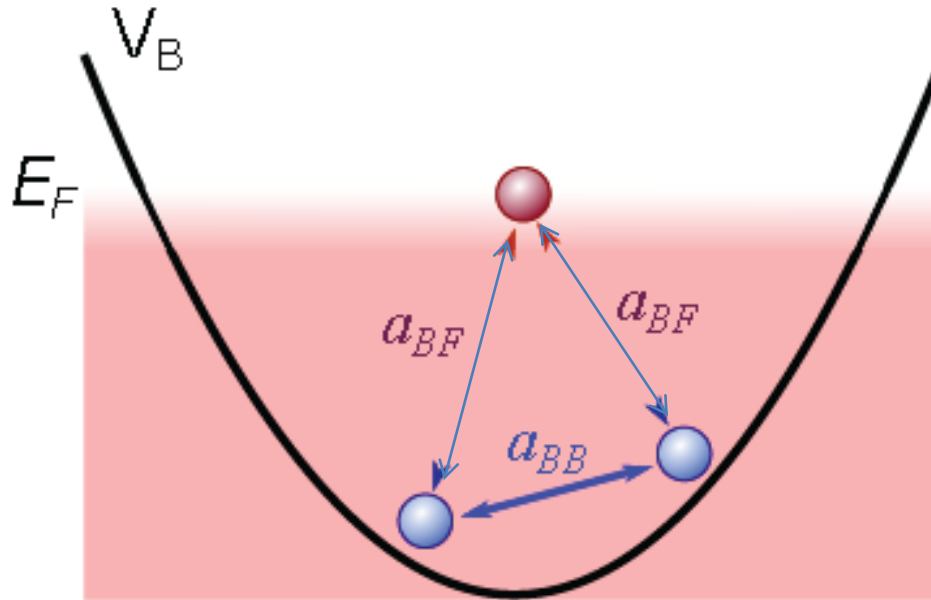


Bose-Fermi droplet



Fermion-mediated (RKKY) interactions

Ruderman-Kittel-Kasuya-Yosida

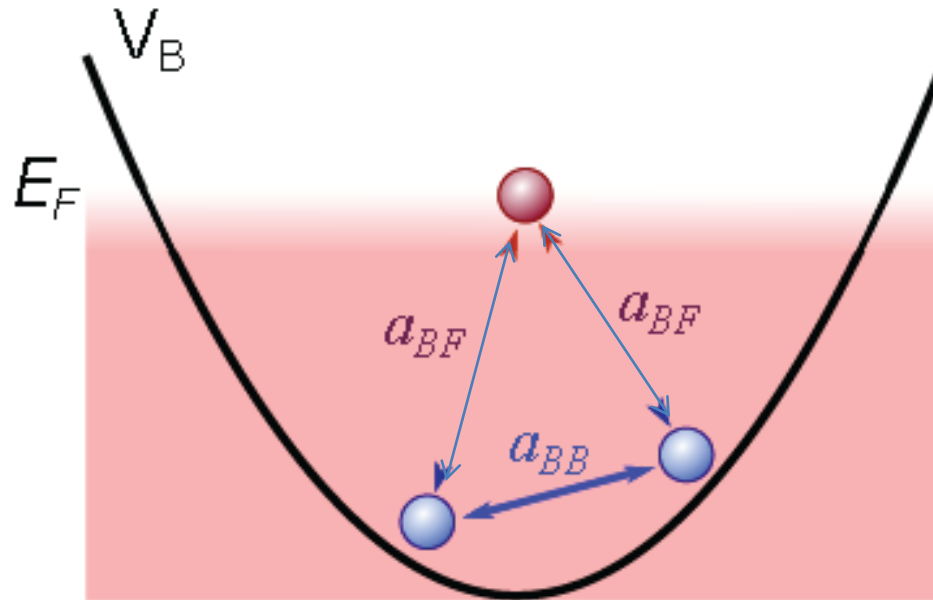


$$V(R) = -2m_F g_{BF}^2 \hbar^2 \frac{\sin 2k_F R - 2k_F R \cos 2k_F R}{(2k_F R)^4}$$

Cold atom RKKY, De and Spielman, APB 2014

Fermion-mediated (RKKY) interactions

Ruderman-Kittel-Kasuya-Yosida



$$E = \frac{\hbar^2}{2m_B} |\nabla \psi_B(r)|^2 + V_{\text{eff}}(r) |\psi_B(r)|^2 + \frac{g_{\text{eff}}}{2} |\psi_B(r)|^4$$

$$g_{\text{eff}} = g_{BB} - \xi \frac{3}{2} \frac{n_F}{E_F} g_{BF}^2$$

Hydrodynamics (Tsurumi et al, JPSU 2000)

Path Integral (Chui et al, PRA 2004)

Diag. Expansion (Santamore et al, PRA 2008)

Scattering (De and Spielman, APB 2014)

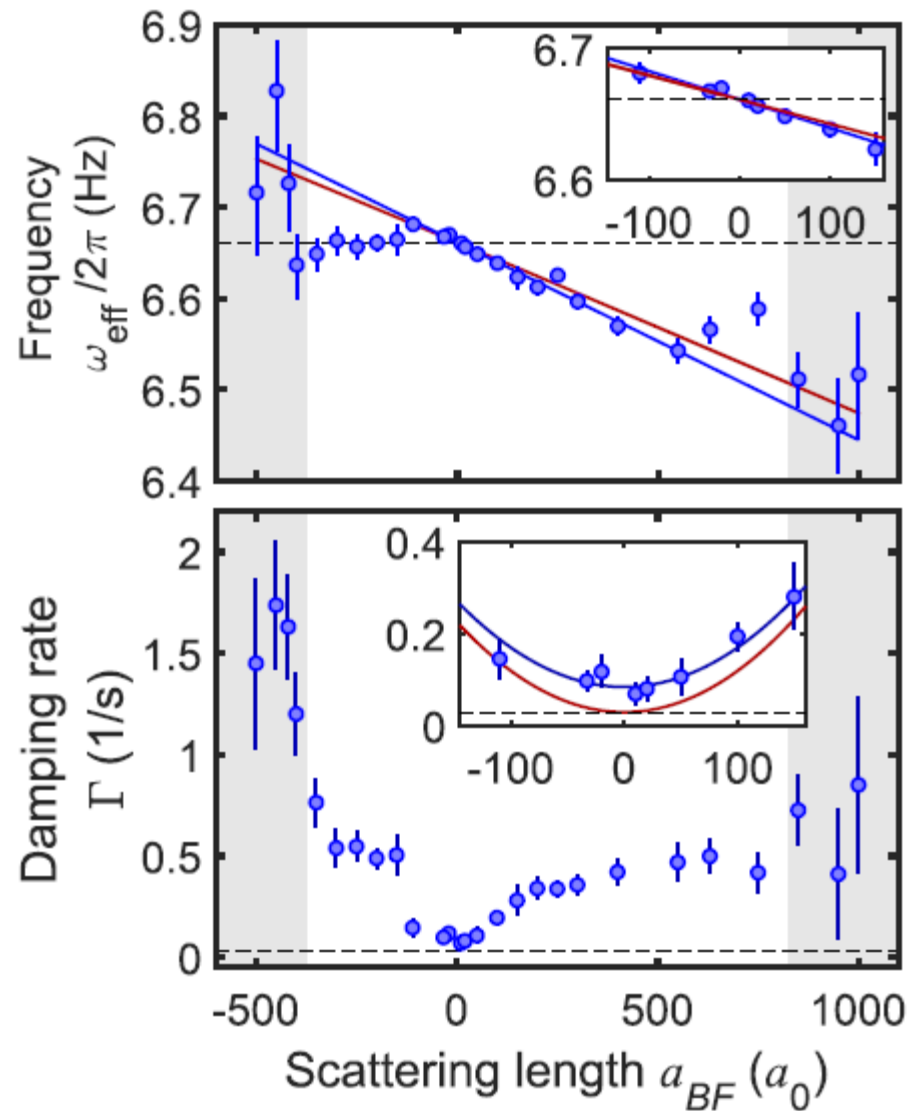
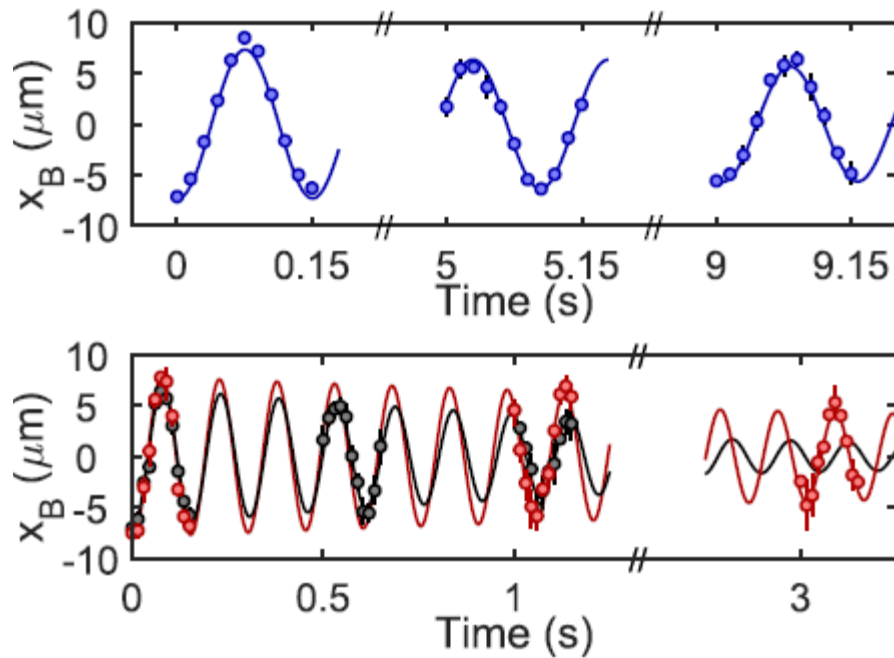
$\xi=1$

$=1$

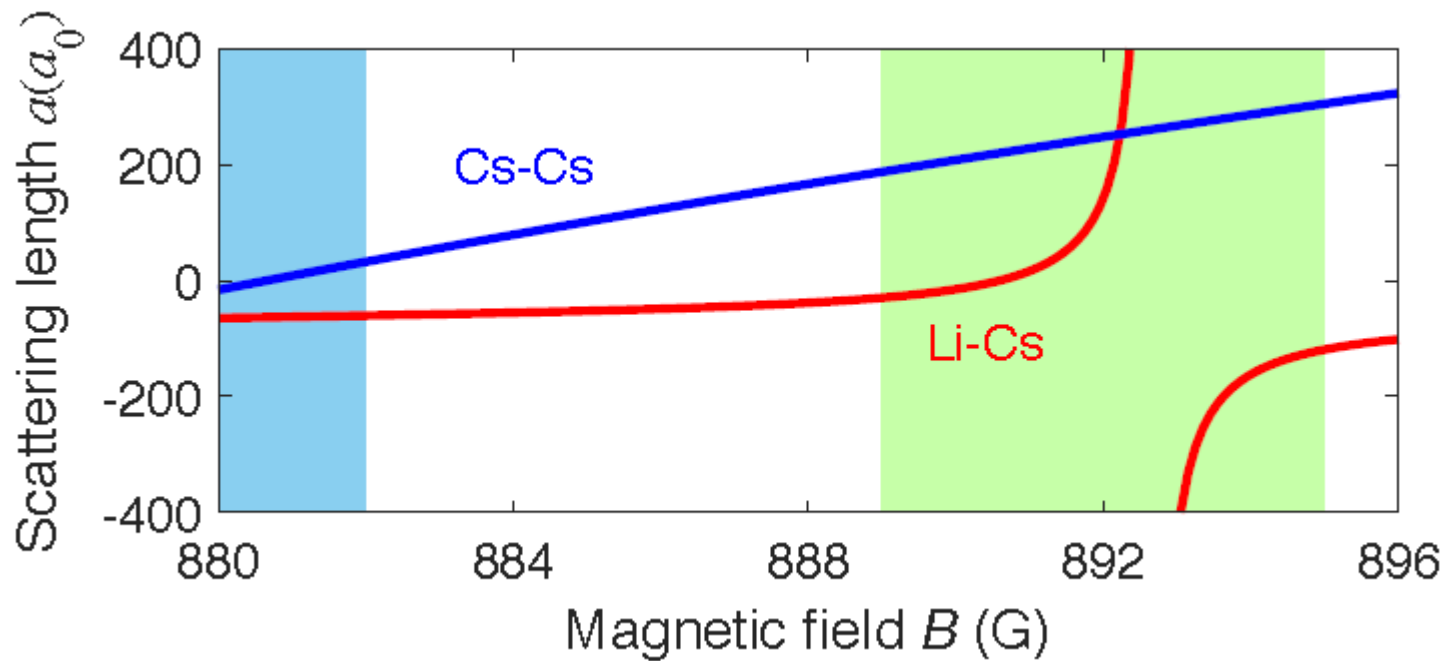
$=1$

$=\pi^3$

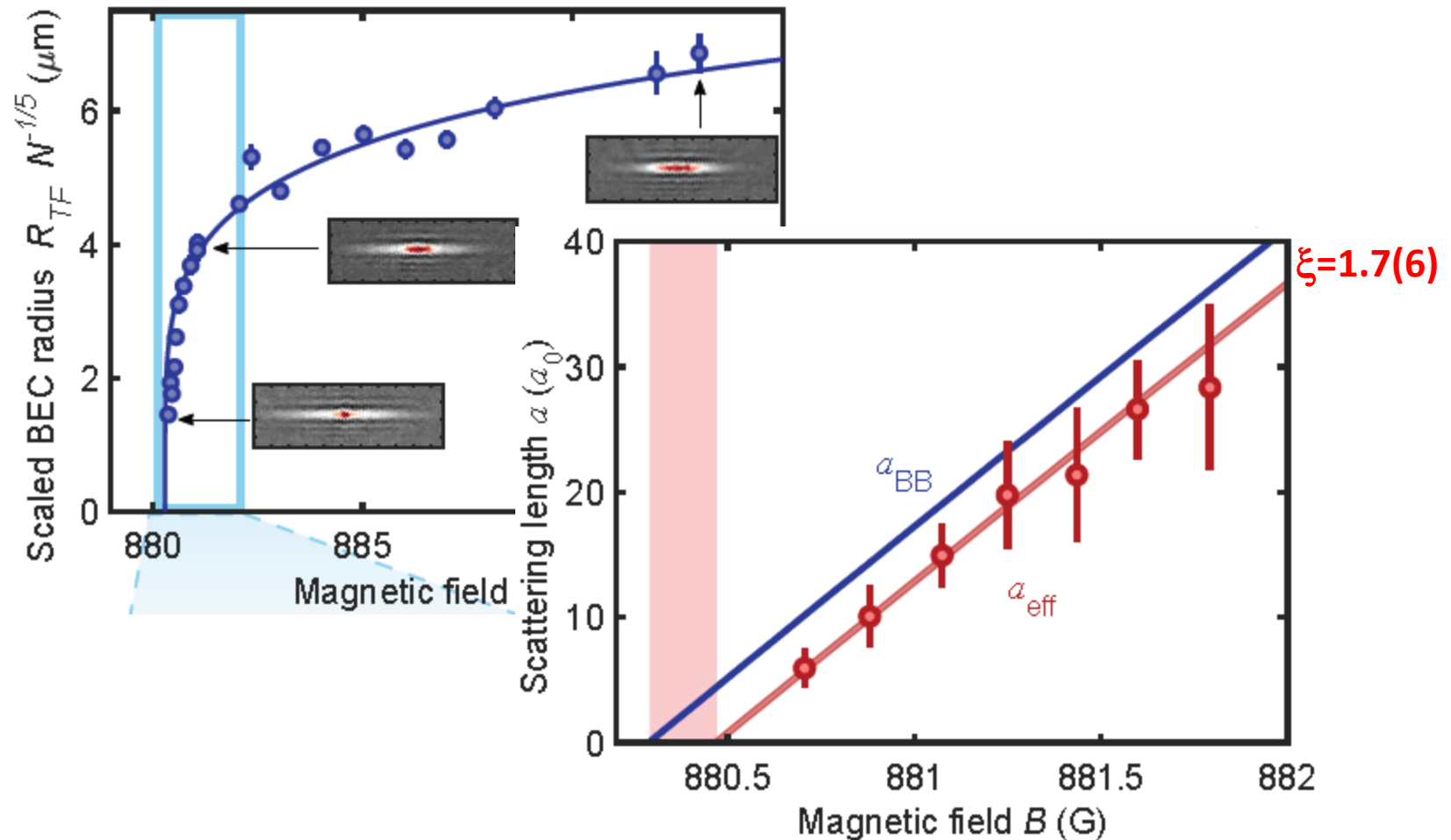
Trap frequency measurement



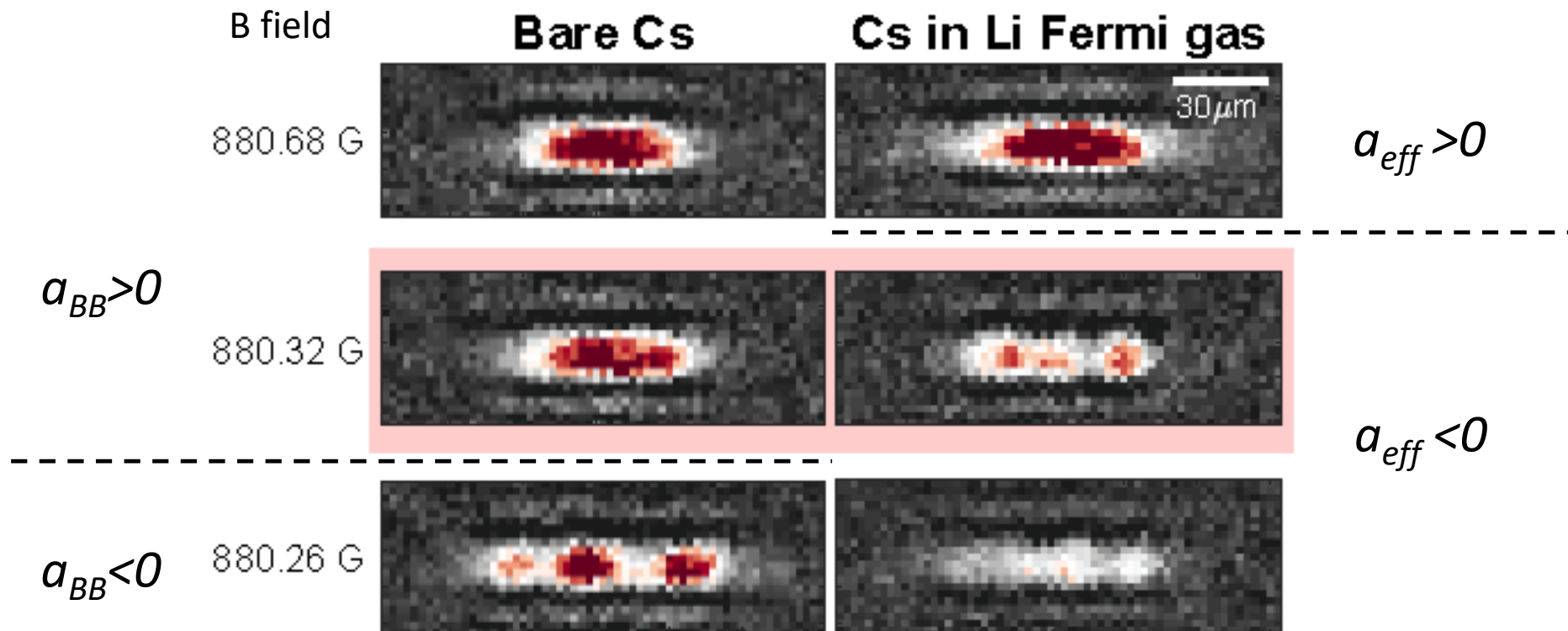
Bose-Fermi mixture with Feshbach resonances



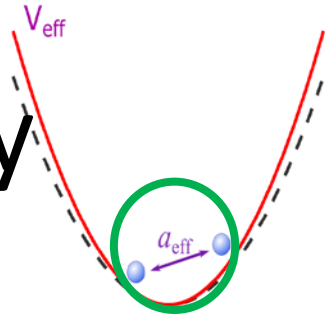
Effective scattering length measurement



Bose-Fermi Solitons with $a_{\text{eff}} < 0$



Fermion induced instability

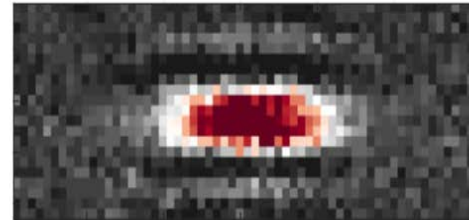


- In field range where a_{Eff} becomes negative, fermions cause BEC collapse
- Striking, qualitative change in the BEC!

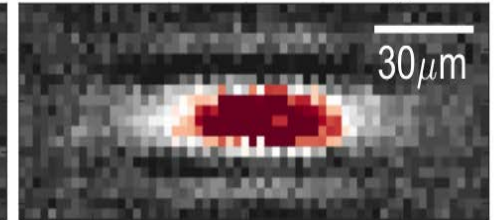
$$a_{\text{Eff}} > 0$$

$$a_{\text{BB}} > 0$$

Bare Cs

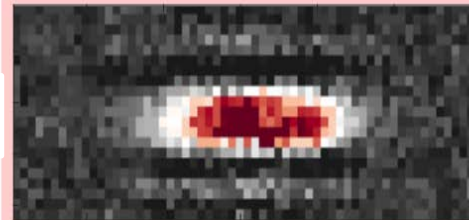


Cs in Li Fermi gas



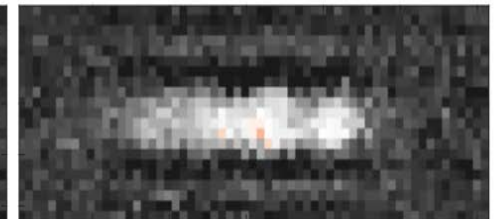
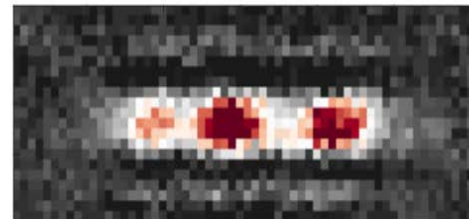
$$a_{\text{Eff}} < 0$$

$$a_{\text{BB}} > 0$$



$$a_{\text{Eff}} < 0$$

$$a_{\text{BB}} < 0$$

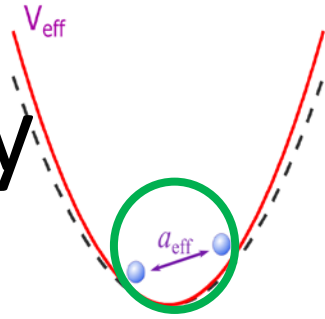


-0.1

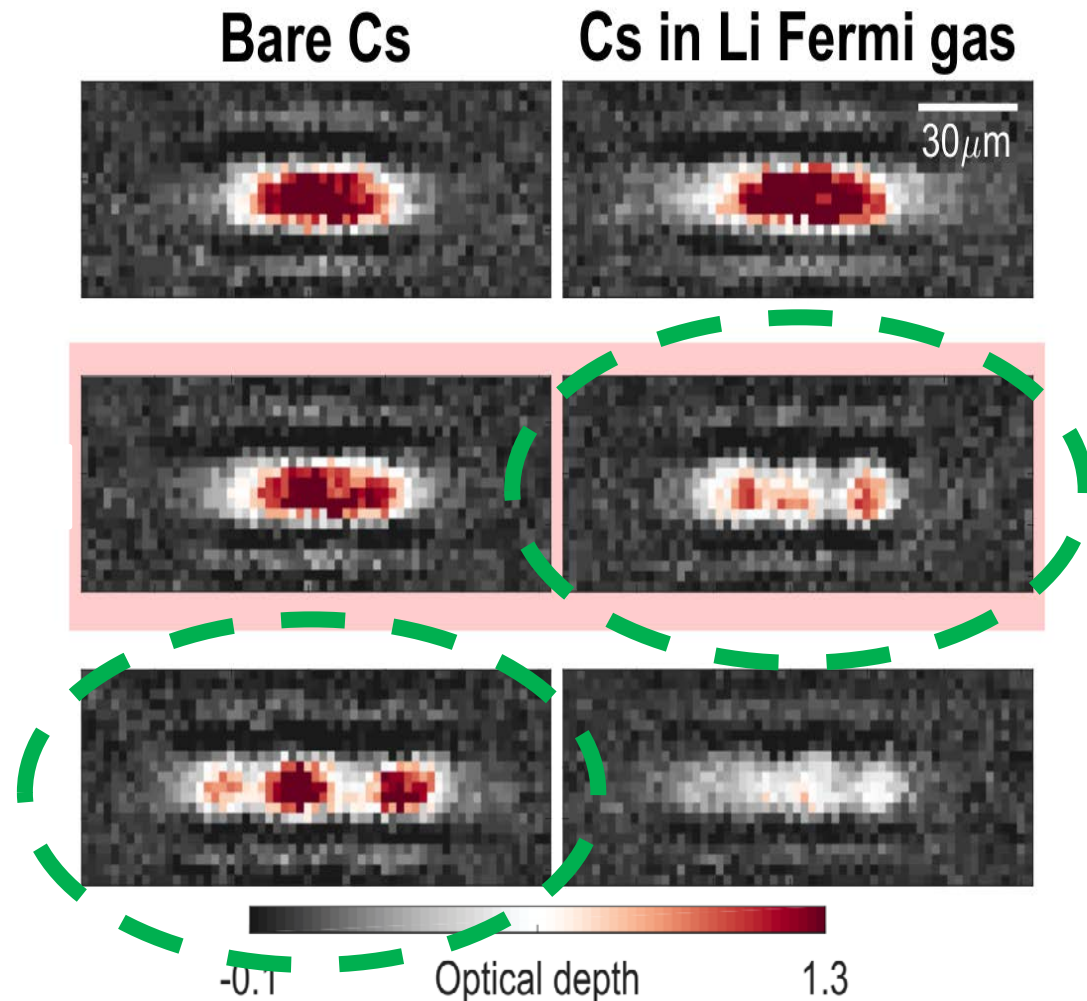
Optical depth

1.3

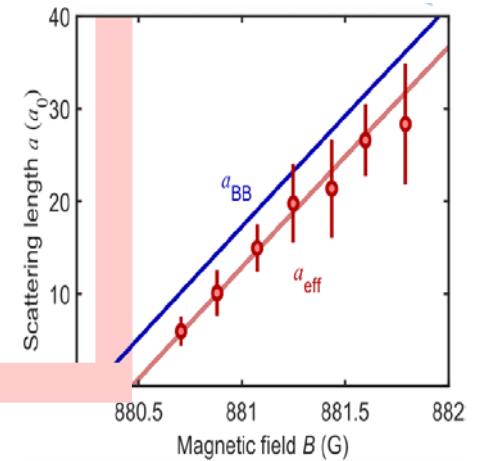
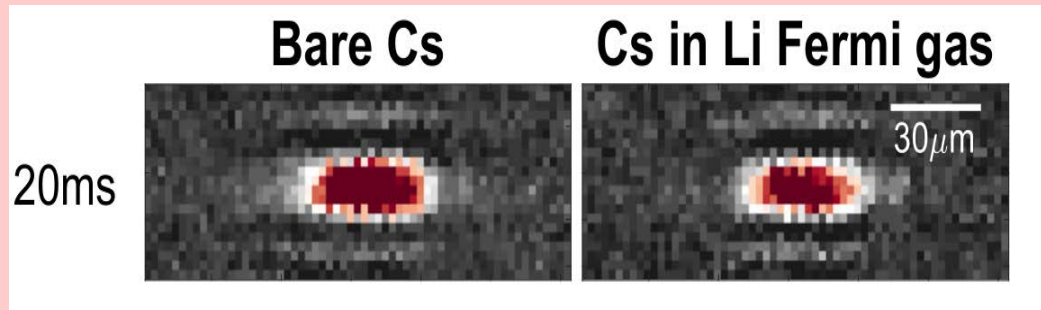
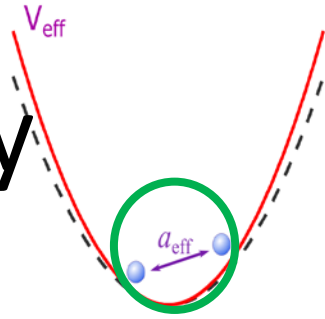
Fermion induced instability



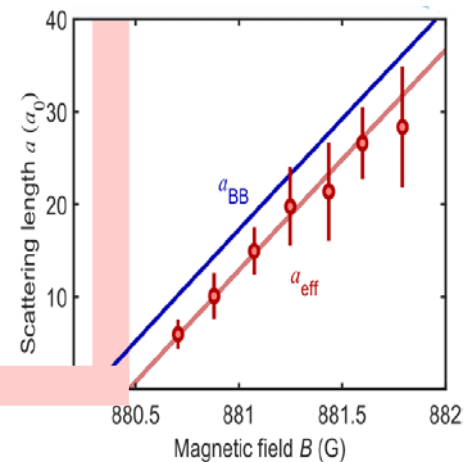
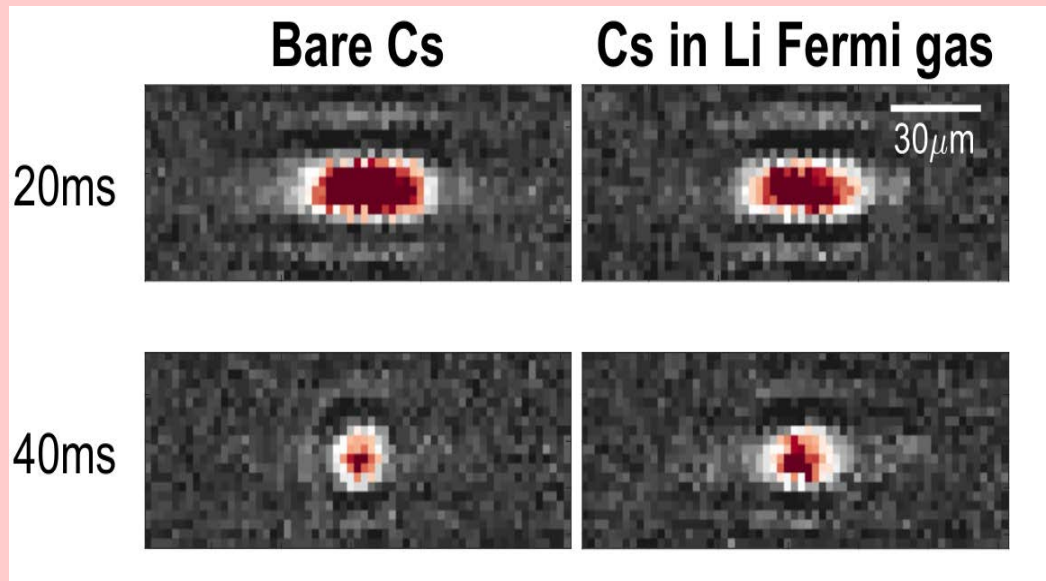
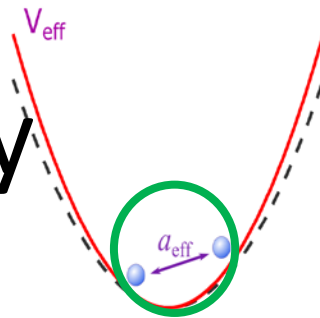
- In field range where $a_{\text{Eff}} < 0$, fermions cause BEC collapse
- Striking, qualitative change in the



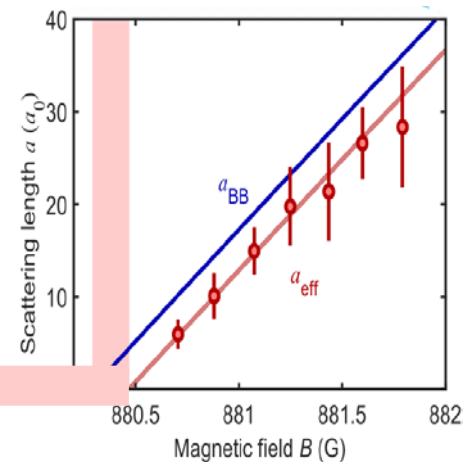
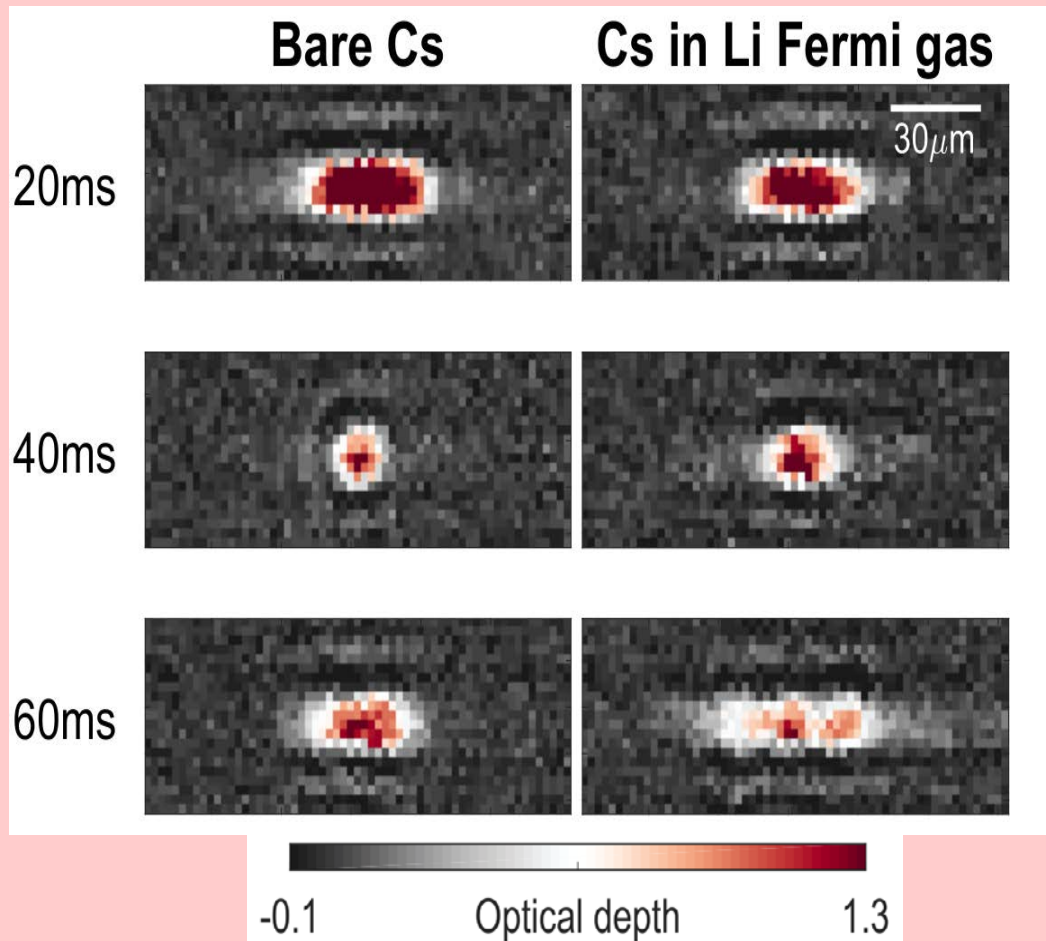
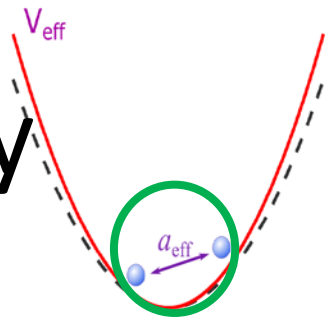
Fermion induced instability



Fermion induced instability



Fermion induced instability



Conclusion

Fermion mediated interactions between bosons

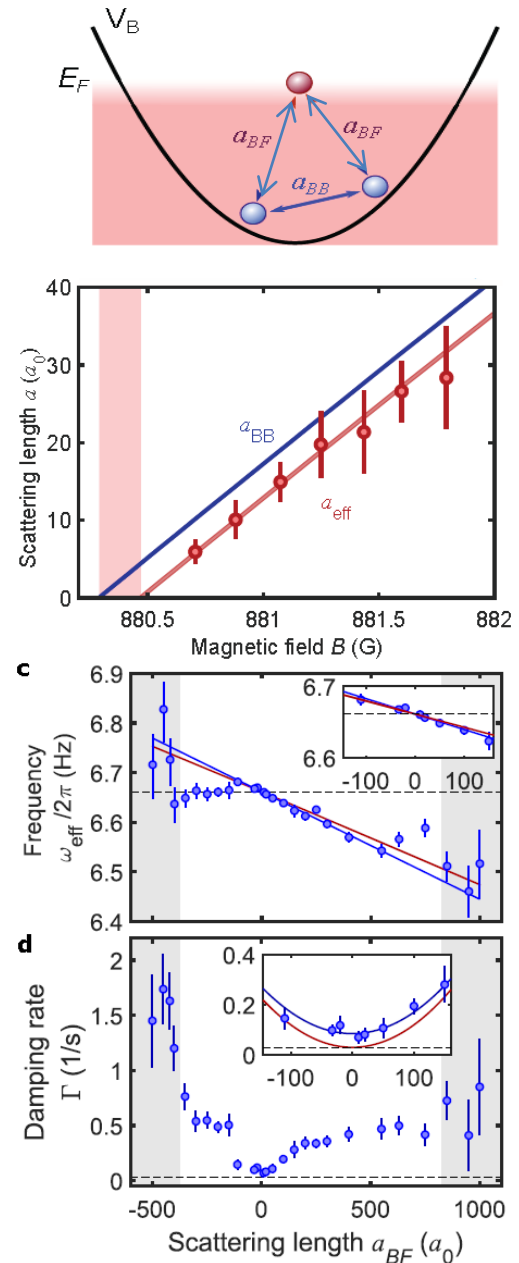
- Long range RKKY interaction at 1 micron scale
- Effective attractive interactions at short range

$$g_{\text{eff}} = g_{BB} - \xi \frac{3}{2} \frac{n_F}{E_F} g_{BF}^2 \quad \xi = 1.7 \quad (6)$$

- Mediated interactions lead to Bose-Fermi soliton train
- Novel collective oscillation and damping behavior

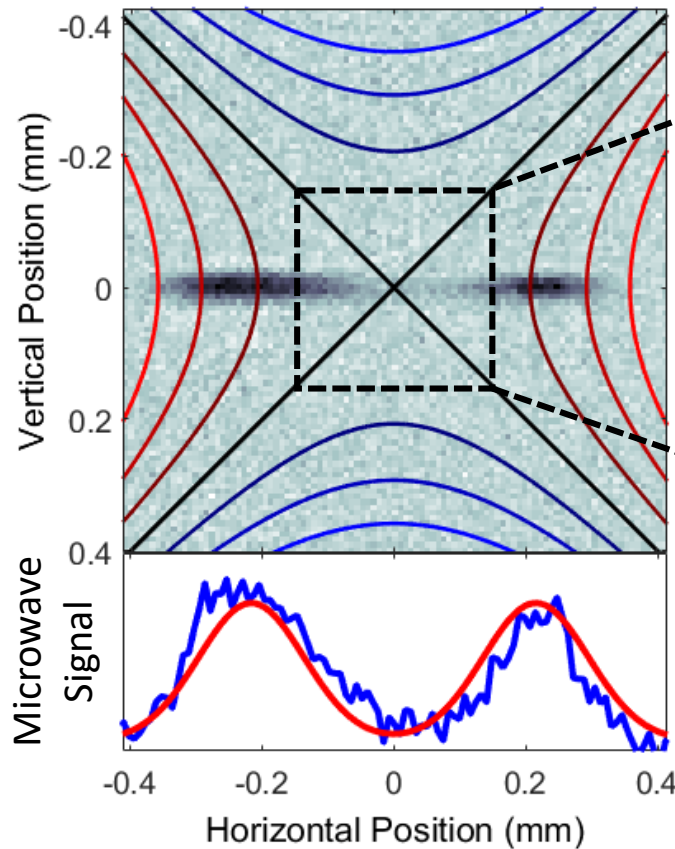
Future

- Collision thin to hydrodynamic behavior
- Demonstration of long range interactions
- New quantum phases in Bose-Fermi mixtures



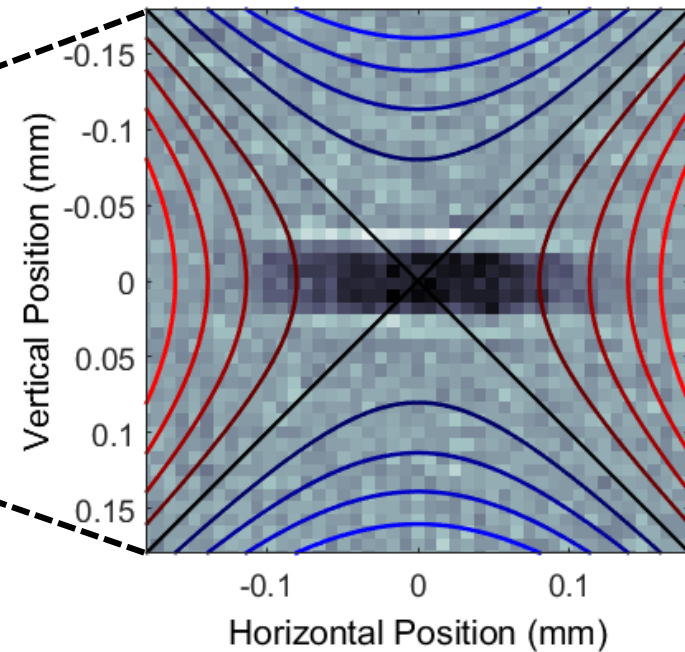
Magnetometry

Calibration Shot



Calibration shot: contours spaced by 20 mG @ 893 G

Atom Loss Shot

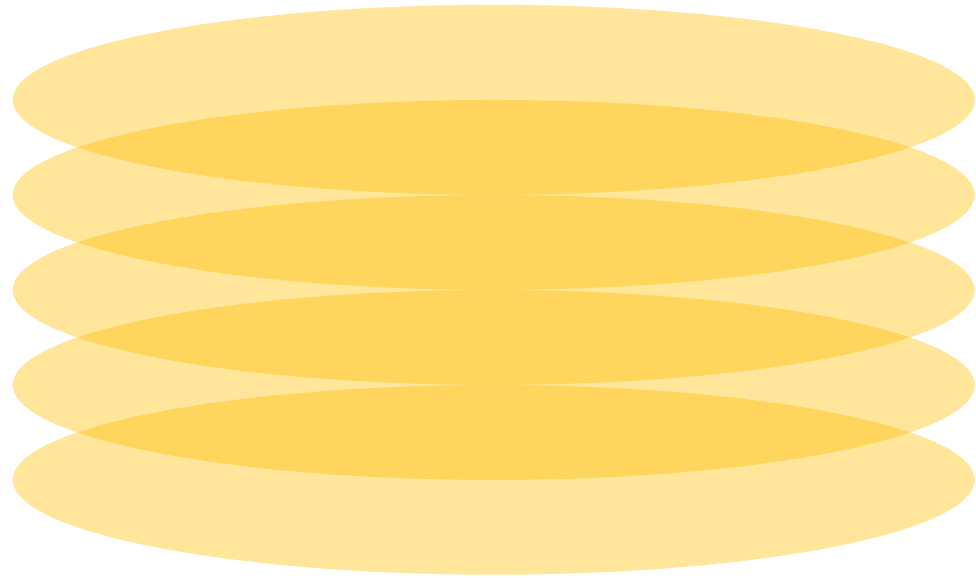


3 parts per million!

Atom loss shot: contours spaced by 3 mG @ 893 G

Oscillating Time-Averaged Optical Trap

- 10 W @ 1064 nm
- Elliptical beam: $33\mu\text{m} \times 350\mu\text{m}$
- Can be modulated or moved vertically by changing an AOM frequency
- Additional beam from the same MOPA perpendicular to this, 10 W, $370\mu\text{m}$ diameter



Oscillating Time-Averaged Optical Trap

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Group Members

Cs BEC

Q Matter
Synthesizer

Li-Cs mixture

Postdocs



Jiazhong Hu Mickey McDonald

Brian DeSalvo

Grads



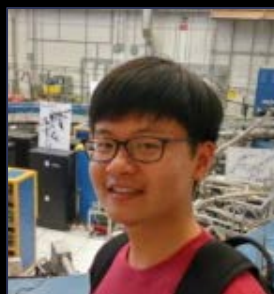
Lei Feng



Jonathan Trisnadi



Krutik Patel



Zhendong
Zhang

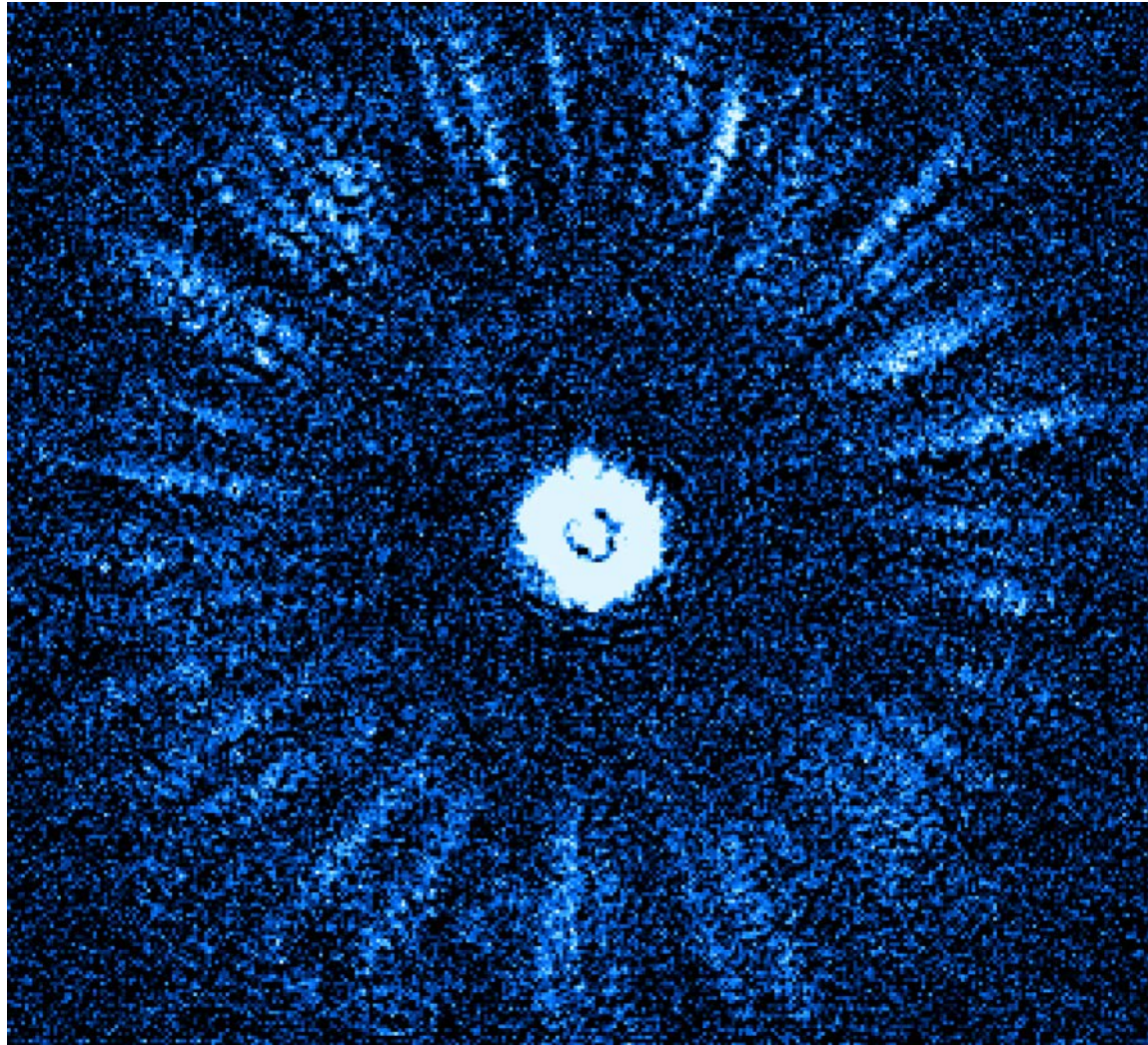


Kai-Xuan
Yao



Geyue Cai

Bose fireworks

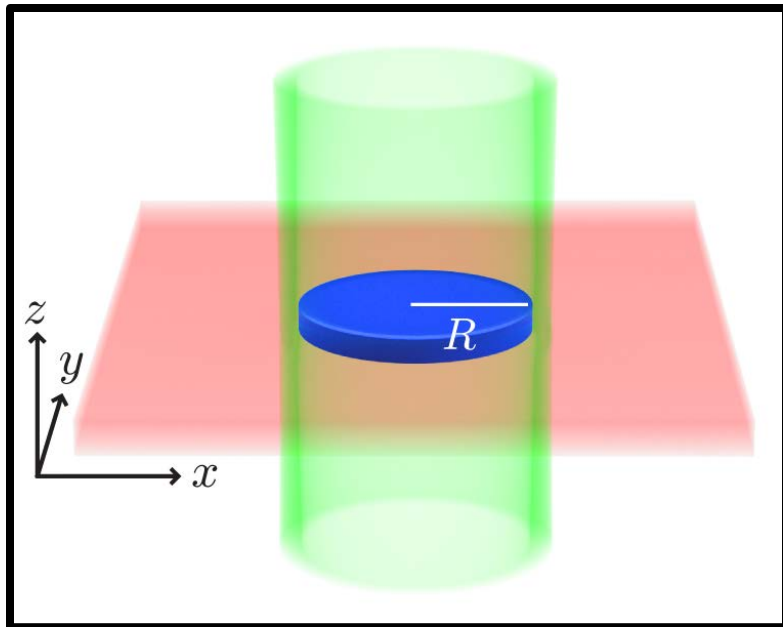


Logan Clark

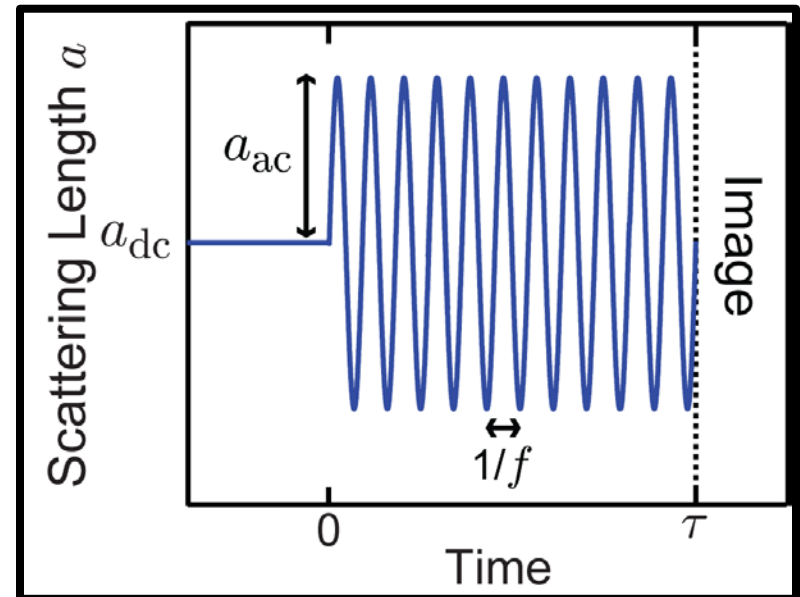
Nature 551, 356 (2017)

Oscillate scattering length $a(t)$

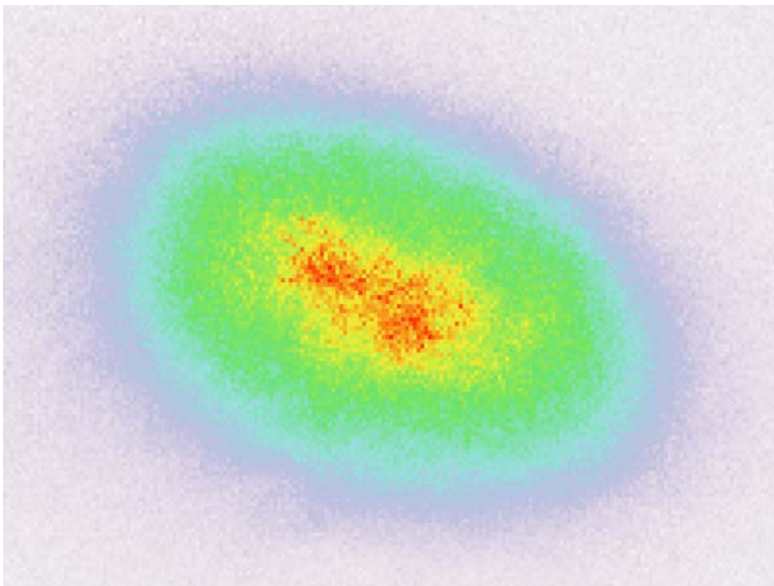
Step 1: Create thin, homogeneous Bose-Einstein condensates



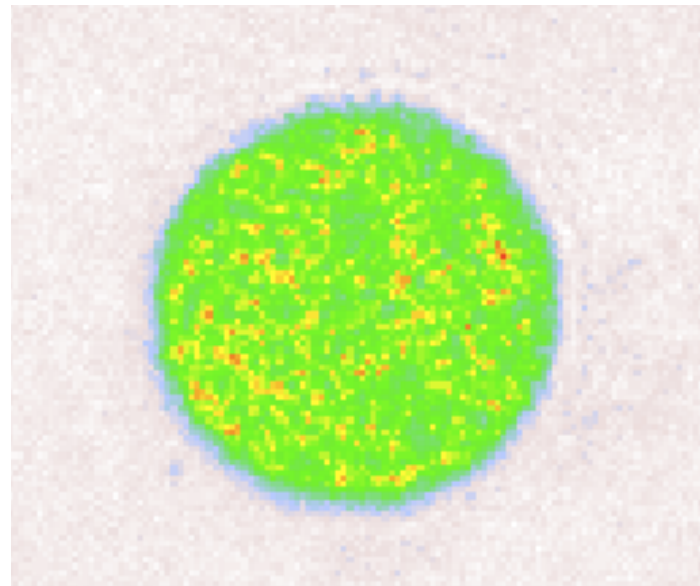
Step 2: Modulate the interaction strength



BEC in harmonic trap vs circular well trap



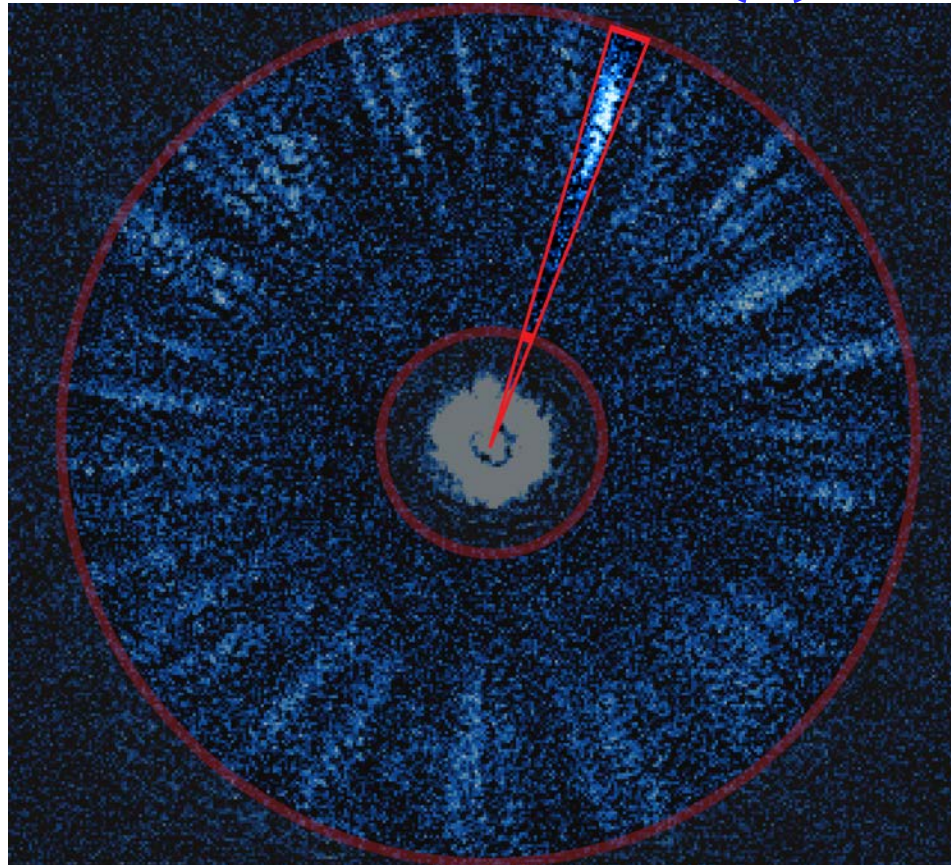
Harmonic



Circular well

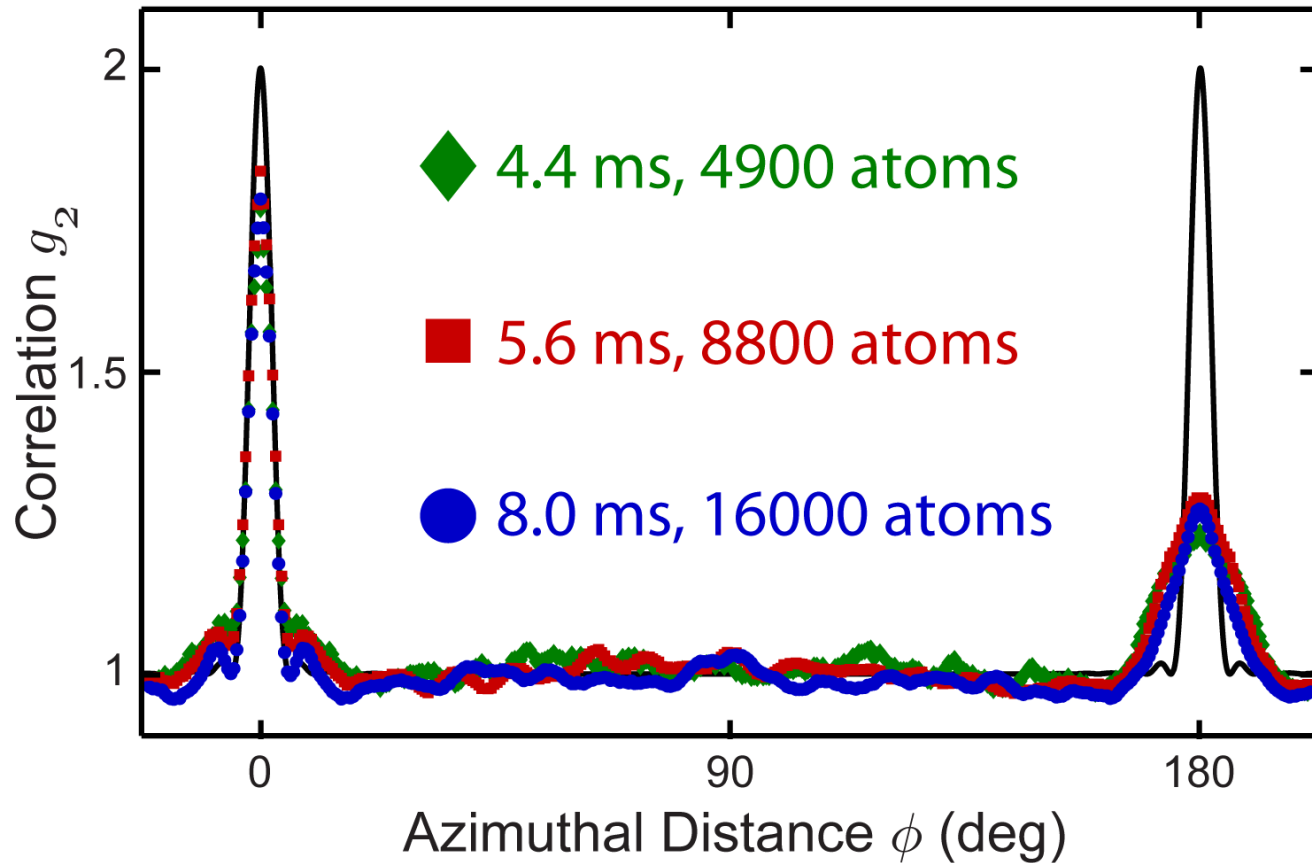
Same color code

$N(\theta)$

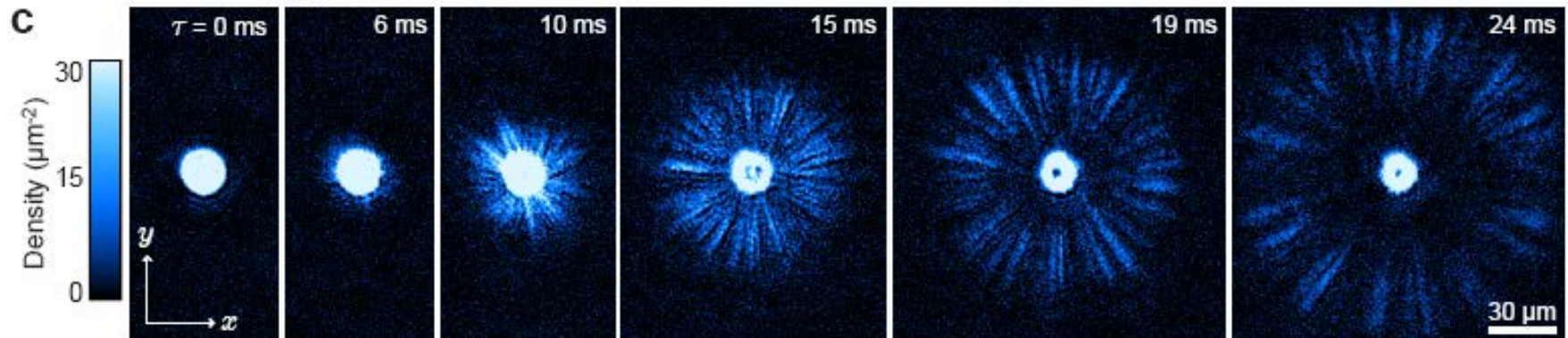


$$g_2(\phi) = \frac{\langle \int d\theta N(\theta) (N(\theta + \phi) - \delta(\phi)) \rangle}{\langle \int d\theta N(\theta) \rangle^2}$$

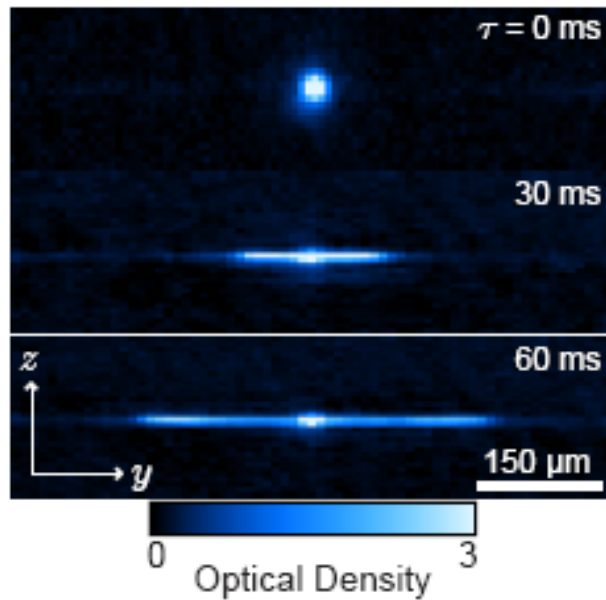
Mode structure and occupation



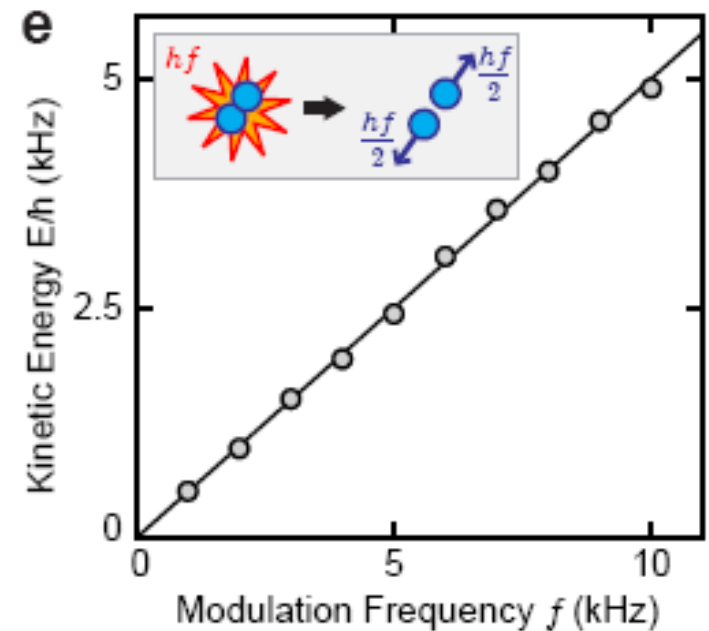
Top view



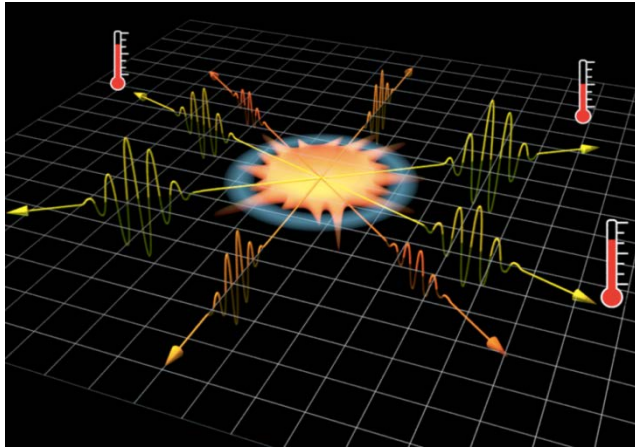
Side view



Jet energy



Quantum simulation of Unruh effect



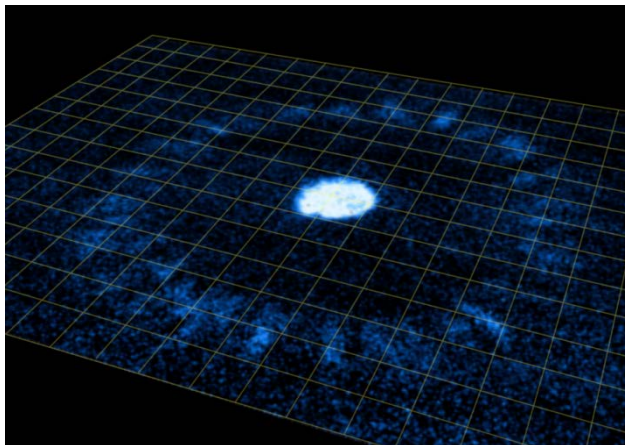
Unruh radiation

$$R_A |\text{vac}\rangle = |\text{thermal}\rangle$$

Unruh temperature $T_U = \frac{\hbar A}{2\pi k_B c}$

$$T = 1\mu\text{K} \text{ when } A = 2.5 \times 10^{14} \text{ m/s}^2$$

$$A = \frac{\pi \omega c}{2 \ln \coth(g\tau)}$$



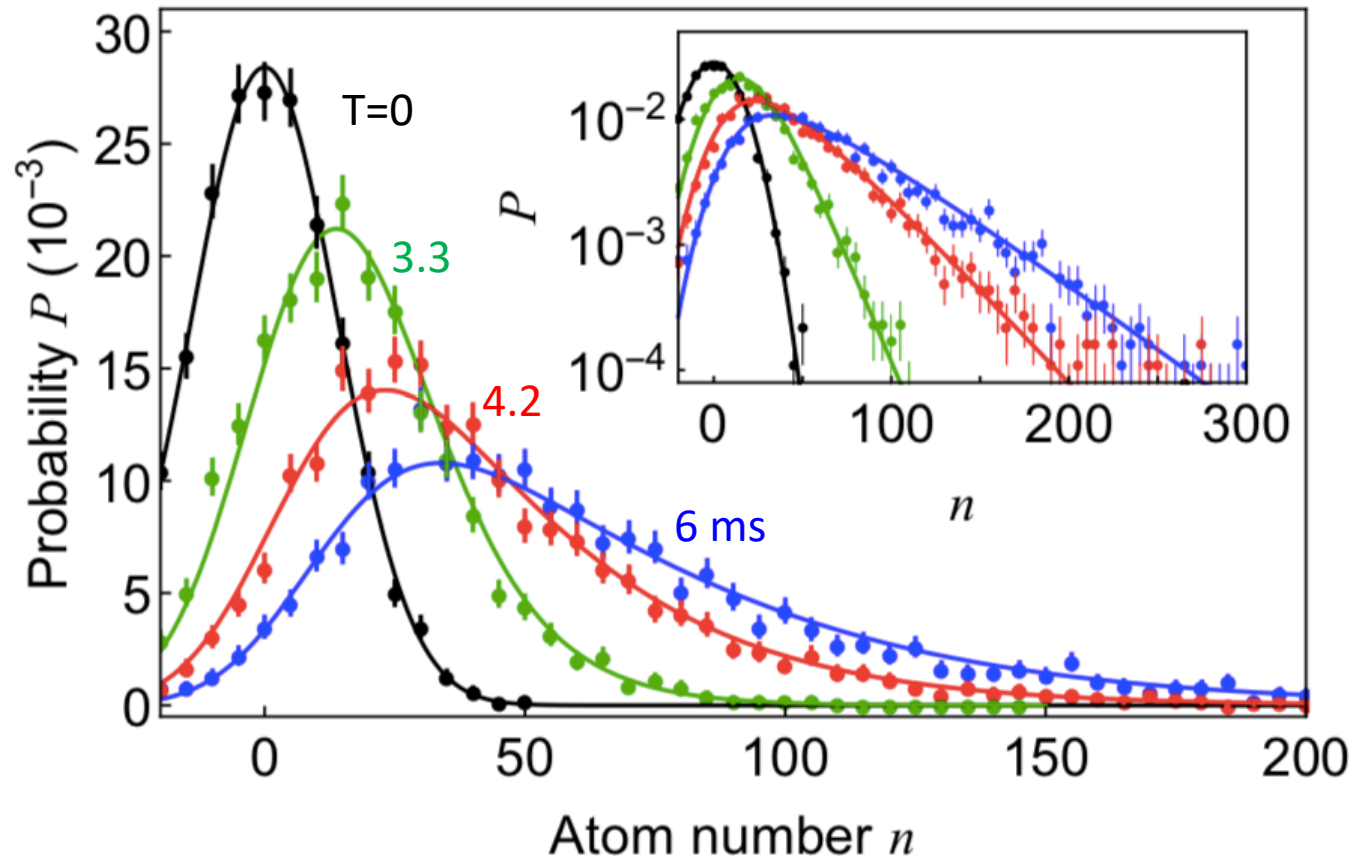
Quantum simulation of frame transformation

$$\hat{R}_A \Psi_0 = \hat{U}(\tau) \Psi_0$$

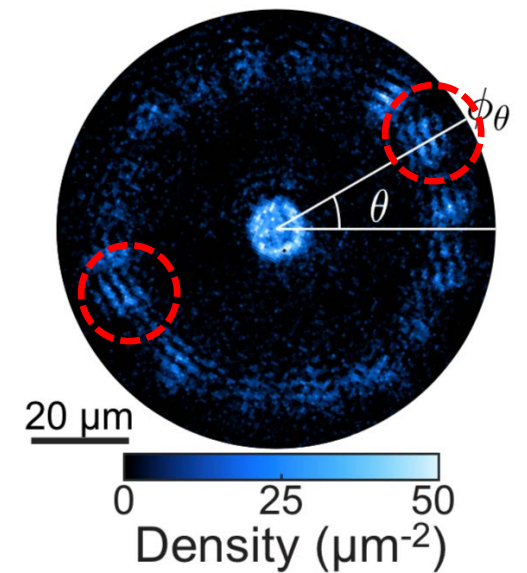
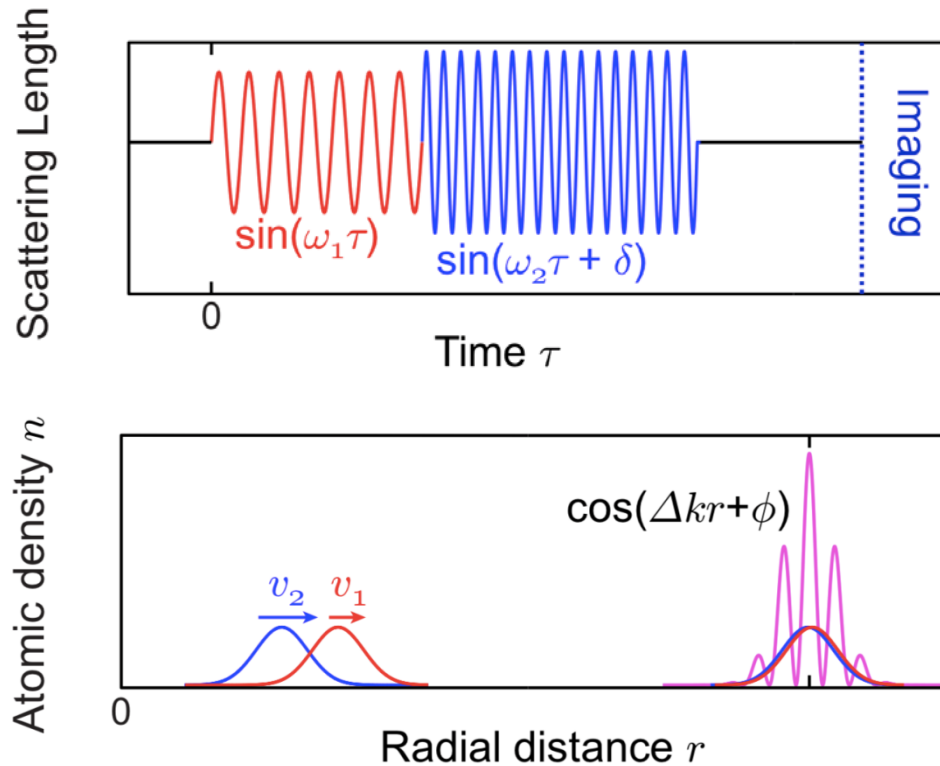
$U(\tau) = e^{-iH\tau/\hbar}$: evolution operator

$$H = \sum_k g_k a_k^+ a_{-k}^+ + h.c.$$

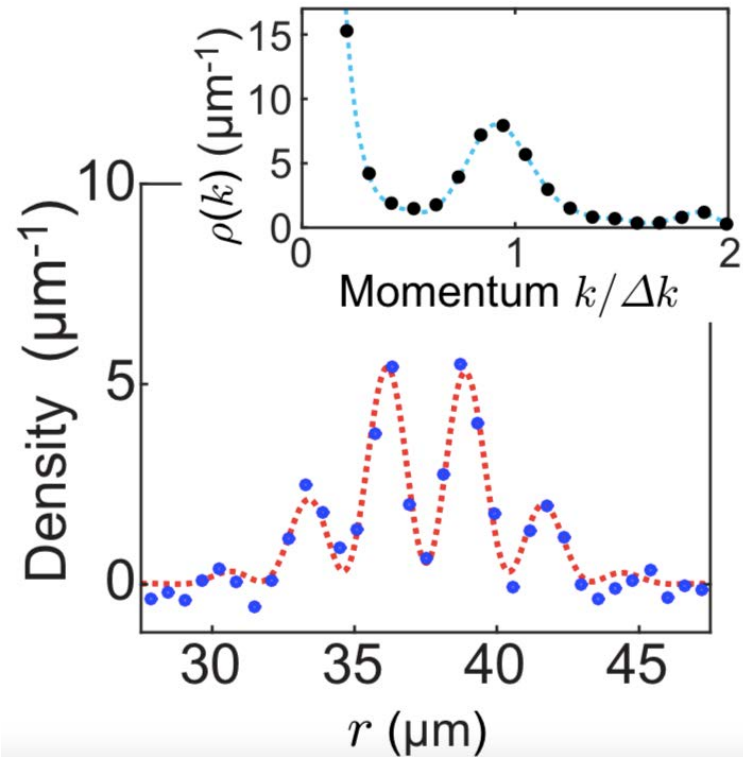
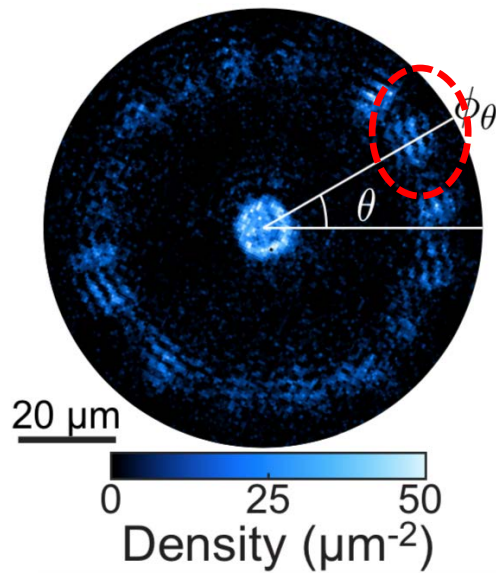
Atom number statistics (*2-degree slice*)



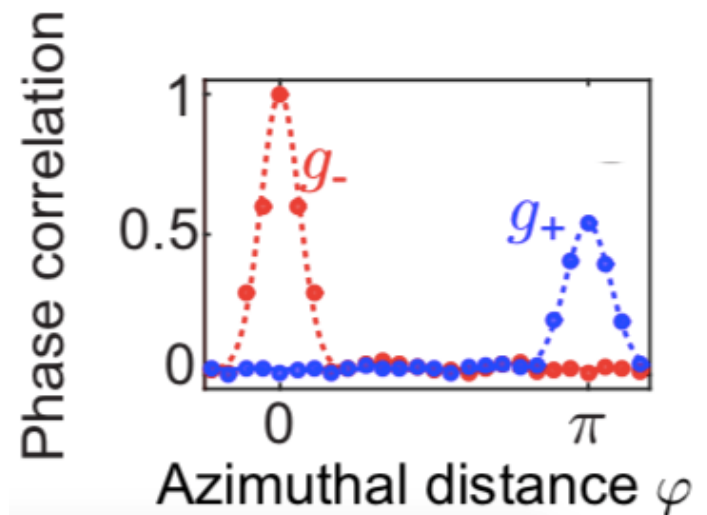
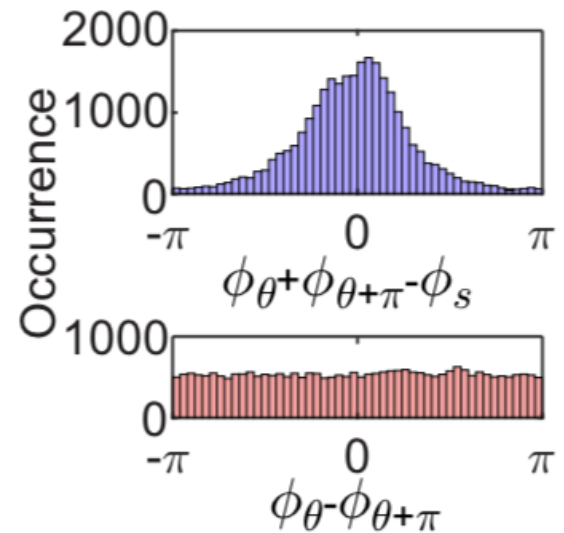
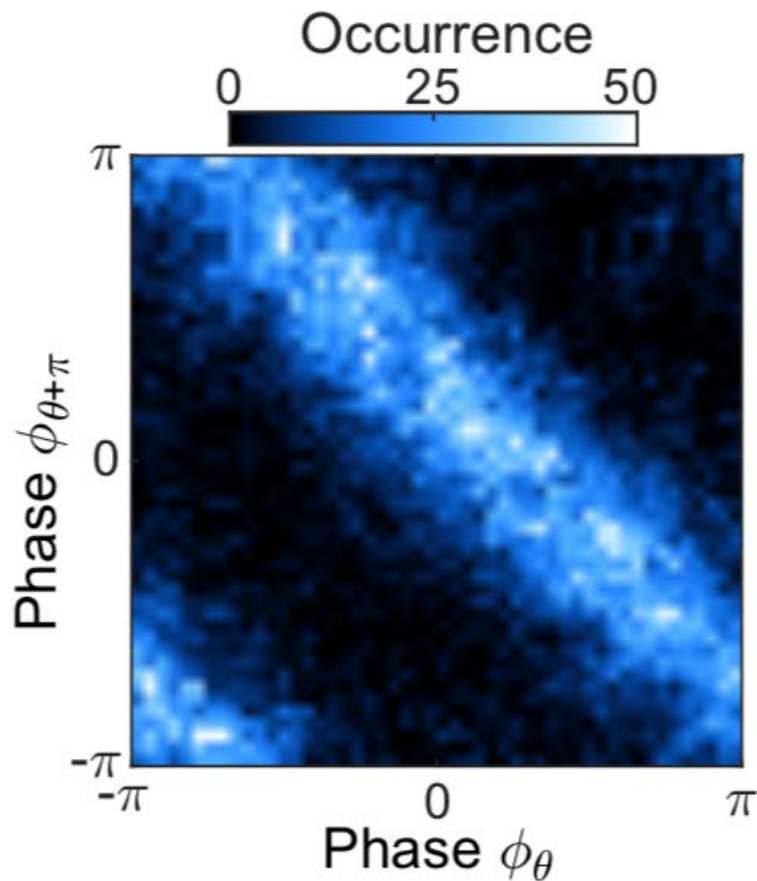
Interference of matterwave radiations



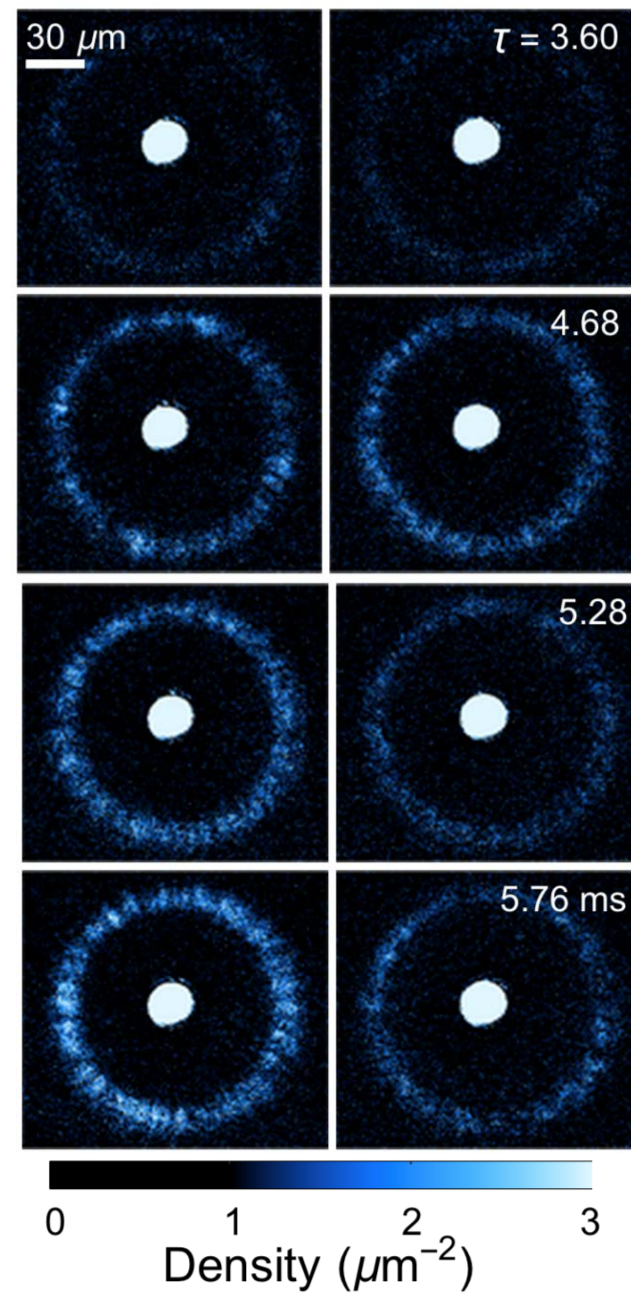
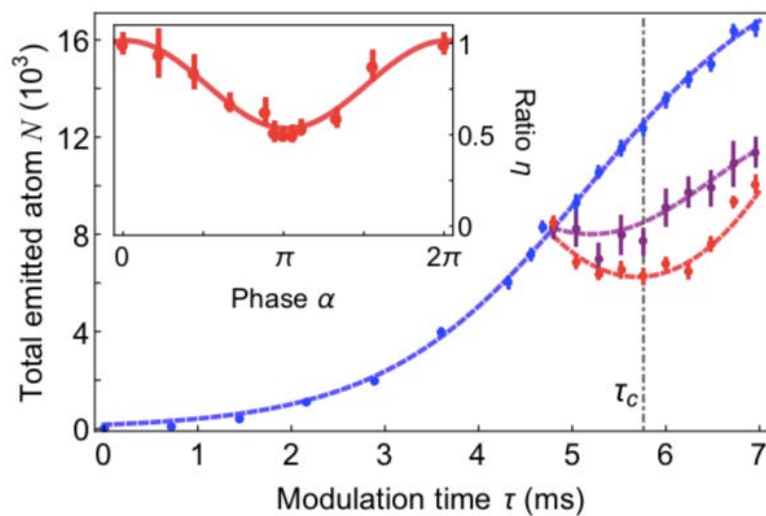
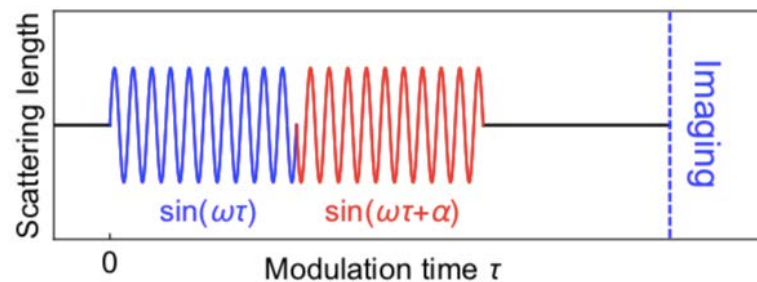
Angular correlation pattern of matterwave interference



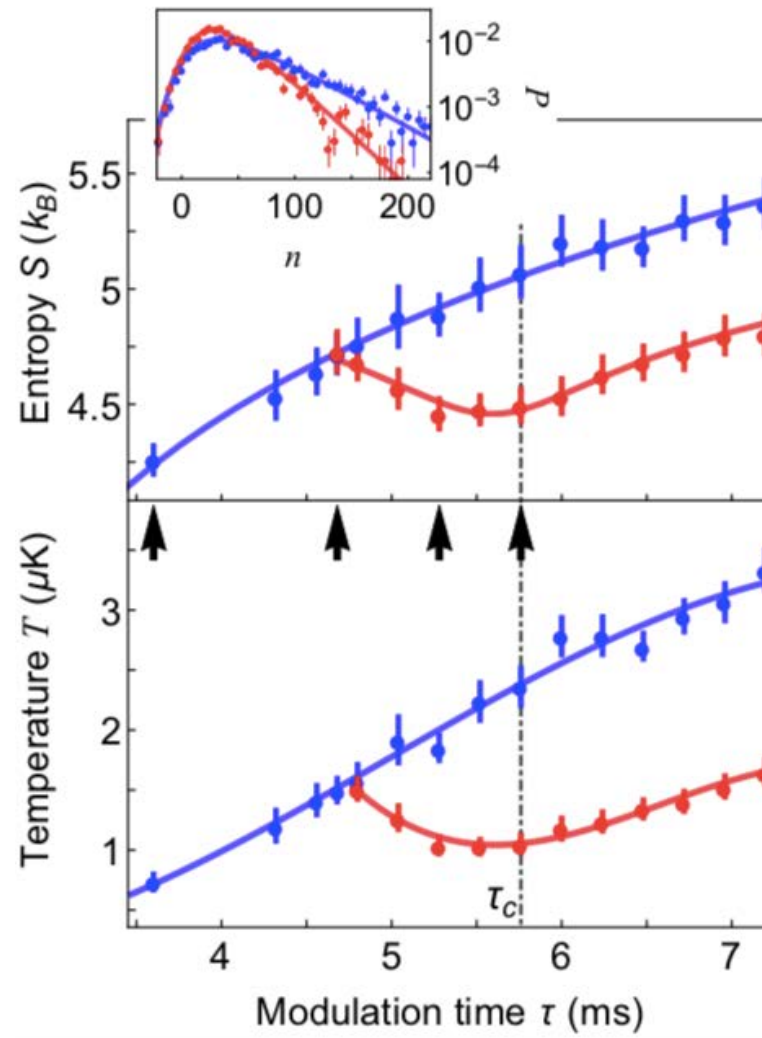
Phase correlations of matterwave fields



Time reversal of matterwave radiation field



Reversal of heating and entropy reduction (from local measurement)



Recent works

Bose fireworks:

- Matterwave HHG 1803.01786
- Density waves 1807.08718
- Simulation of Unruh effect 1807.07504

Shaken lattices

- Inflation NPhys (2018)
- Density dependent gauge field PRL(2018)

Bose-Fermi mixture

- Fermion droplet in BEC PRL (2017)
- Fermi-mediated interactions 1808.07856

Super-resolution imaging 1807.02906

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Li-Cs mixture

Postdocs



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Grads



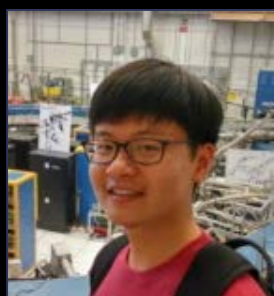
Lei Feng



Jonathan Trisnadi



Krutik Patel



**Zhendong
Zhang**



**Kai-Xuan
Yao**



Geyue Cai