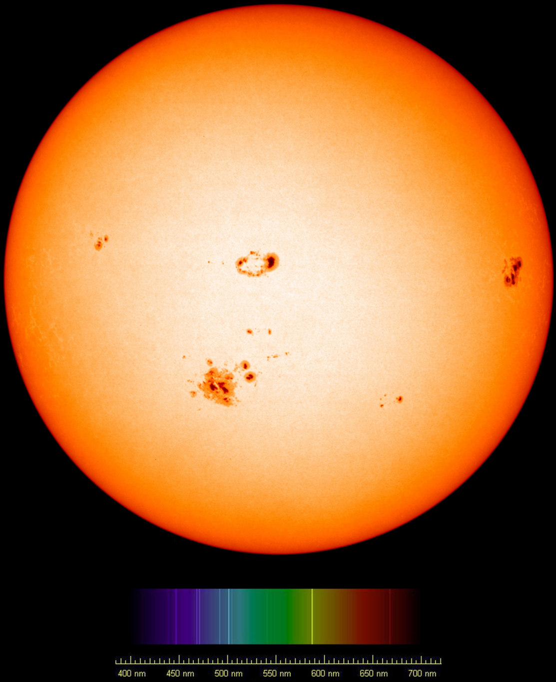
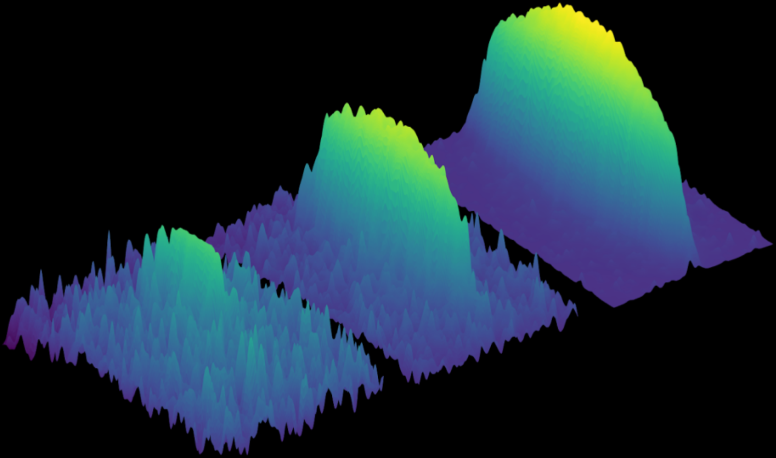
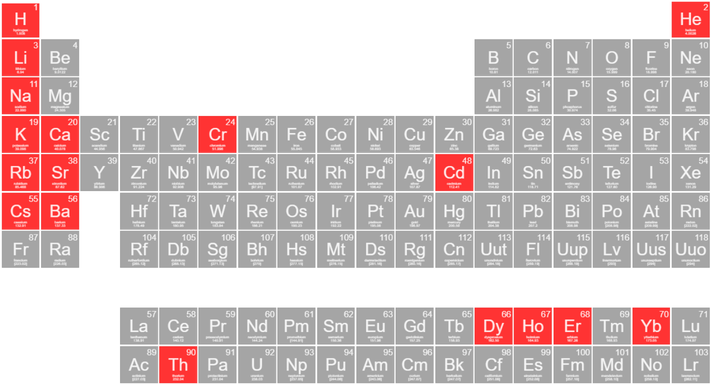

400 nm
450 nm
500 nm
550 nm
600 nm
650 nm
700 nm



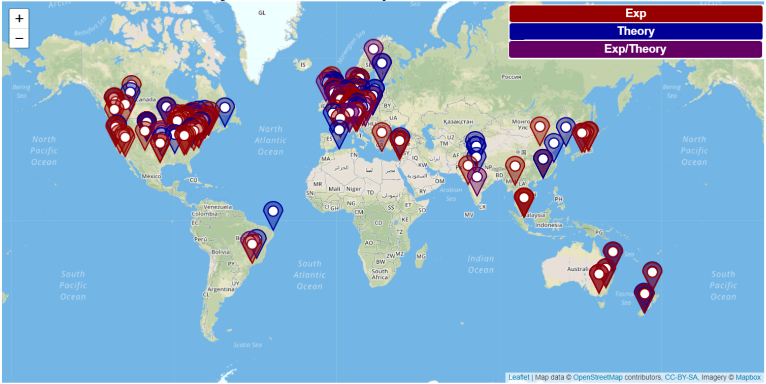
The cold atom zoo[1]



[1] everycoldatom.com

The world of ultracold atoms[2]

Every Cold Atoms Experiment in the World



[2] everycoldatom.com

Metrology & many-body physics with ultracold Helium

He* BEC group, LPC

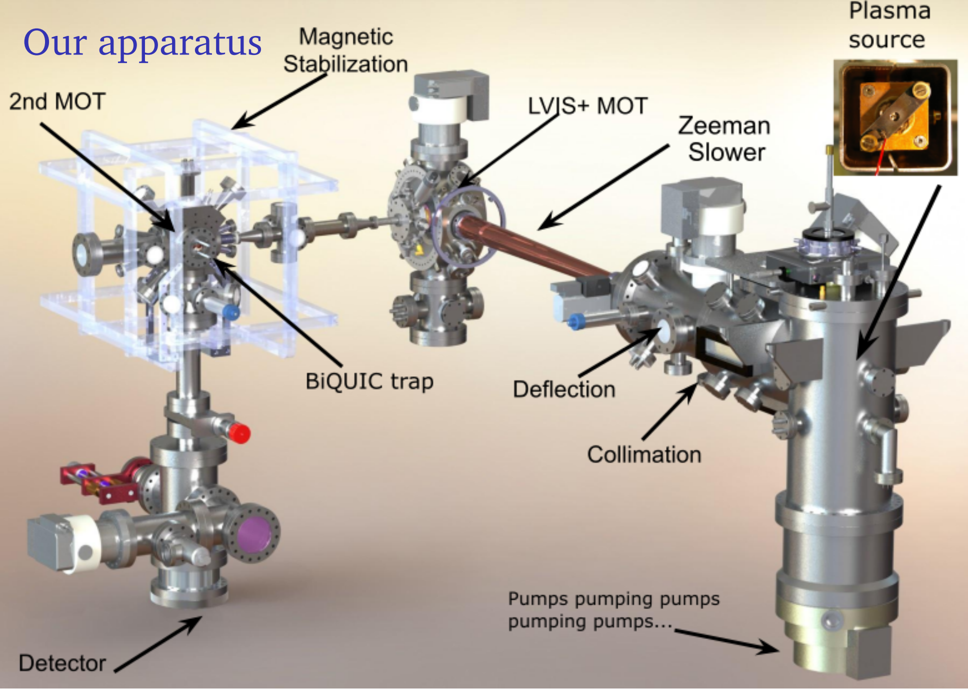
What good are BECs?

They're excellent testbeds for fundamental physics.

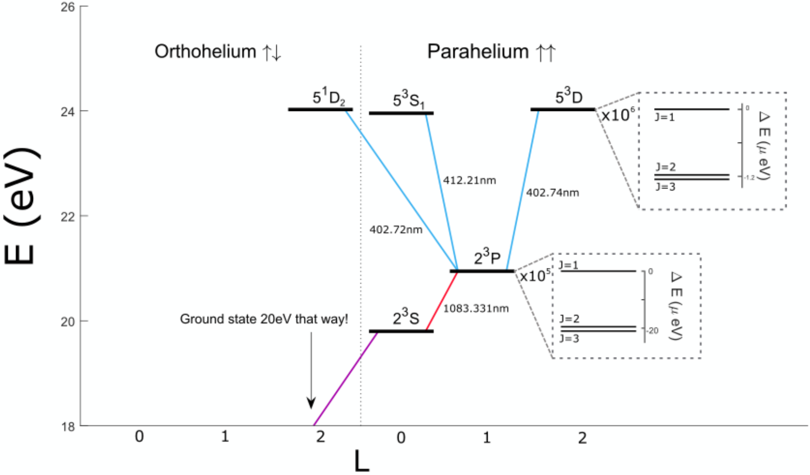
They exhibit controllable macroscopic coherent phenomena.

They're rich resources for engineering 'large' quantum states.

Our apparatus

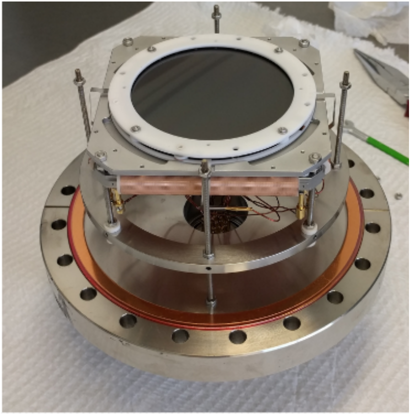


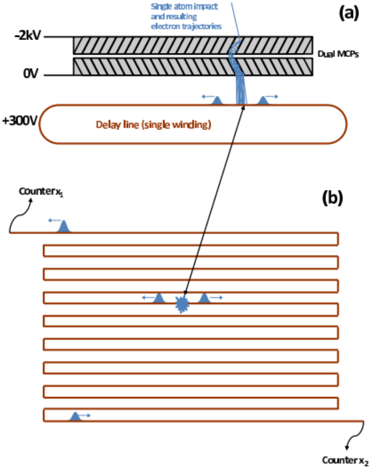
Helium



20eV gap to metastable $2^3\mathrm{S}_1$ allows single-atom detection and laser accessibility.

Single-atom detection





The MCP-DLD harnesses the unique ability of He* for 3D single-atom momentum resolution

Metrology I: Transition spectroscopy

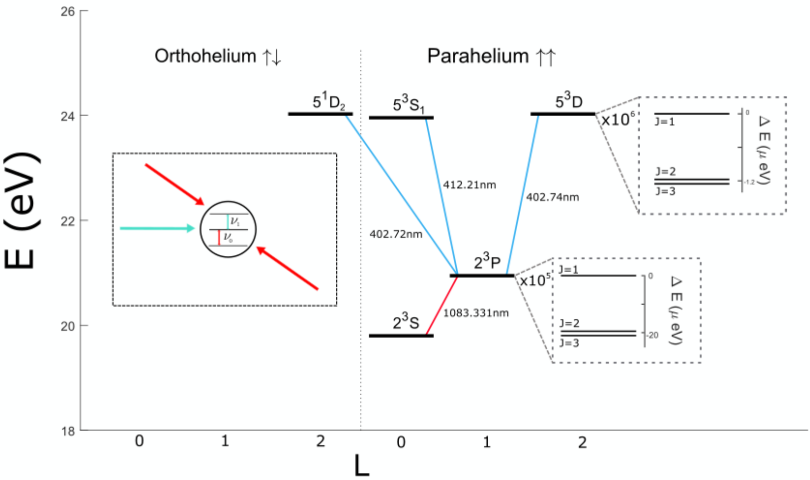
Motivation

Spectroscopy built modern physics.

But, there are unresolved issues, like the proton radius puzzle.

Helium is simple enough that we can move towards testing QED; isotope shifts

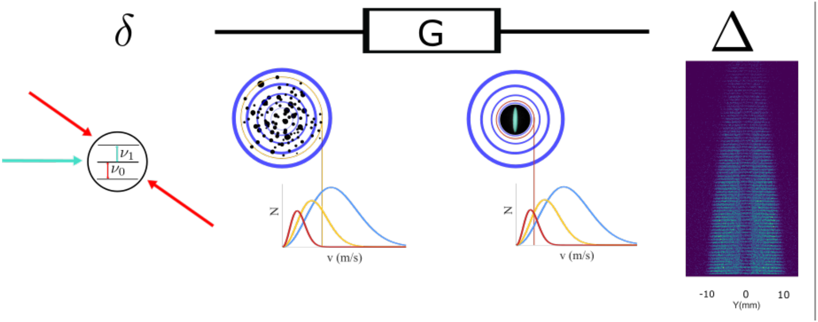
On needles in haystacks



Measured $2\mathrm{L} \leftrightarrow 5D$ intervals disagree with predictions.

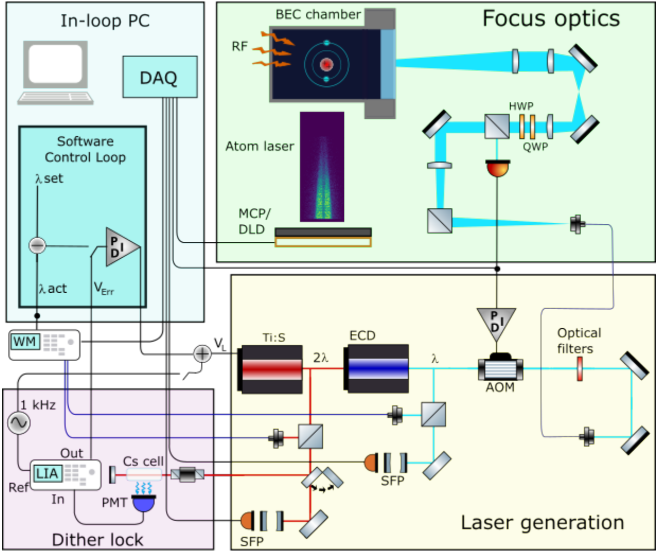
Measurement method

New technique for ultracold, low-background, highly sensitive spectroscopy with multilevel transitions.

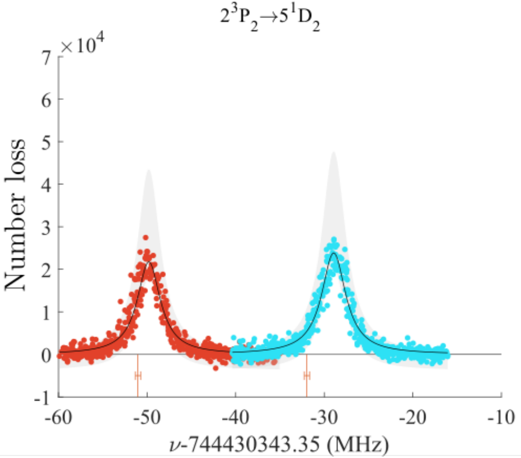


Small changes in phase space density $n\lambda_{dB}^3 = n\hbar/\sqrt{2\pi m k_B T}$ measured with number changes at a fixed temperature.

Experimental schematic

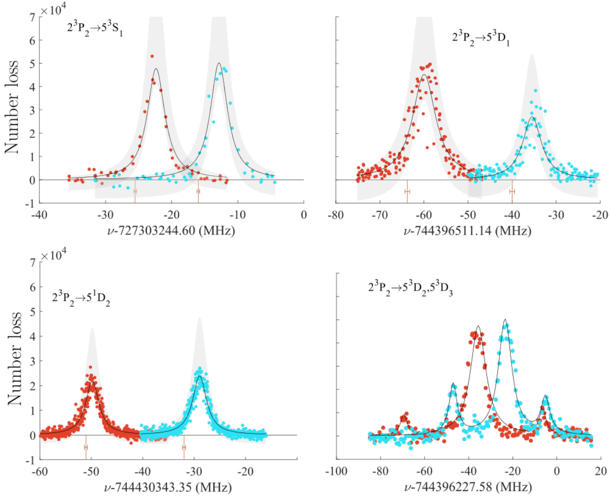


Transition spectra



First measurement to constrain both singlet-tripled and $2L - 5D$ intervals.

Transition spectra



First resolution of sub-level transitions to the 5^3D states.

Spectroscopic results

$\vert e\rangle$	ν_{obs} (MHz)	$\nu_{obs} - \nu_{theory}$ (MHz)
$5^3\mathrm{S}_1$	727303247.812(0.143)	3.212
$5^3\mathrm{D}_1$	744396515.588(0.224)	4.448
$5^3\mathrm{D}_2$	744396235.844(0.282)	8.264
$5^3\mathrm{D}_3$	744396204.115(0.341)	-4.245
$5^1\mathrm{D}_2$	744430345.471(0.047)	2.121

New method provides sub-MHz precision, sufficient for test of QED

Systematics & past results

$\lvert e\rangle$	ν_{obs} (MHz)	$\nu_{obs} - \nu_{old}$[3] (MHz)
5^3S_1	727303247(4)	13713(201)
5^3D_1	744396515(20)	13575(168)
5^3D_2	744396235(20)	13855(168)
5^3D_3	744396204(20)	13886(168)
5^1D_2	744430345(20)	N/A

Accuracy limited by wavemeter (High Finesse WS-8).

We correct previous measurements, adding five lines to NIST.

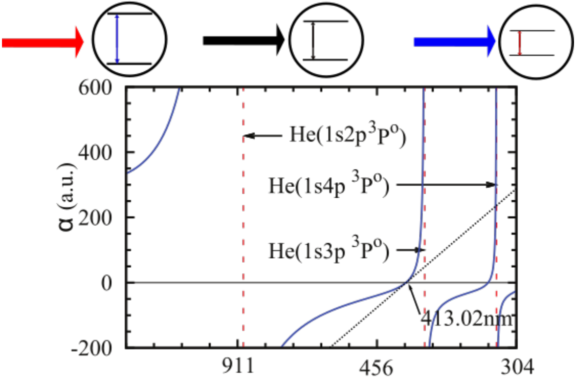
[3] Martin, New Wavelengths for Some Helium (He i) Lines, Journal of the Optical Society of America Vol. 50, Issue 2, pp. 174-176 (1960)

Metrology II: Tuneout

Tuneout wavelengths[4]

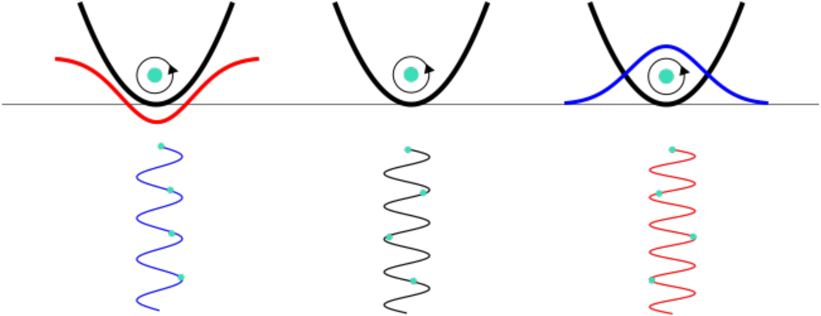
The dynamic polarizability determines the level shift in response to an AC field:

$$U_L = -\frac{\alpha(\nu)}{2}\langle\mathcal{E}^2\rangle$$



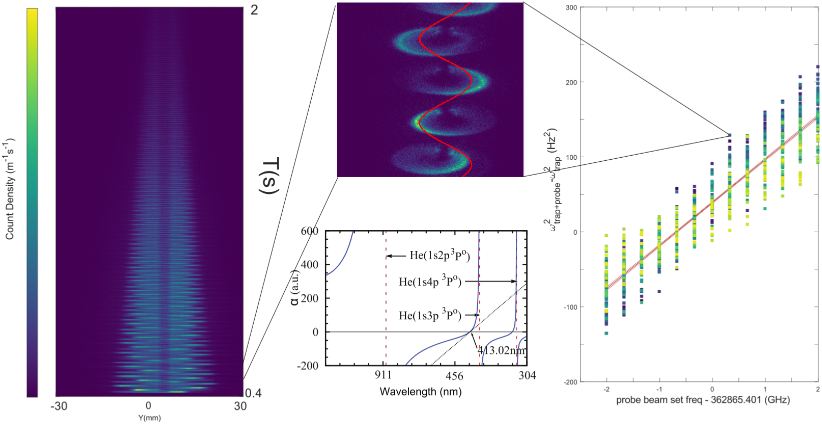
[4]Henson et al, PRL 115 (2015)

Hybrid trap response function



$$
\begin{aligned}
F &= -\nabla(U_L + U_B) \\
&= \sqrt{m\partial_x \left(\alpha(\nu)|\mathcal{E}| + \mu|B|\right)}x \\
\implies \omega &= \sqrt{\omega_B^2 + \omega_E^2}
\end{aligned}
$$

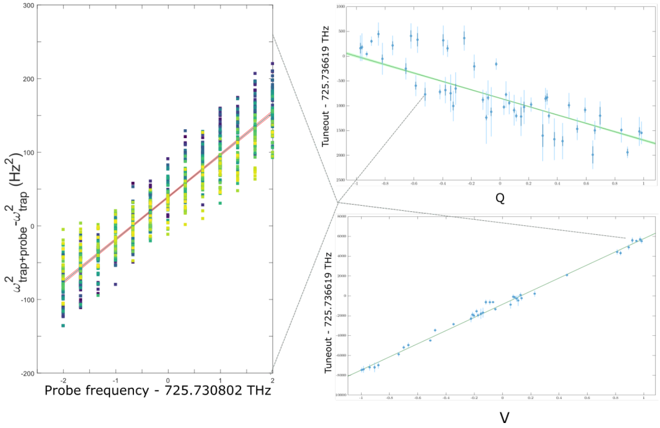
Determining the Tuneout wavelength



Change in fitted trap frequency^2 is proportional to polarizability; fit the scan to fix the Tuneout

Determining the Tuneout wavelength

Sufficient sensitivity to resolve polarization dependence!



Multiparameter fit on the Stokes sphere to obtain the value...

Results... coming soon!

Many-Body physics I: Quantum depletion

What is depletion?

Thermodynamics forbids a pure condensate. Instead, they coexist with a 'depleted' population:

$$|\Psi\rangle = \psi_0 + \hat{\delta\psi}, \text{ where } \psi_0 = \sqrt{N_0}e^{i\theta}$$

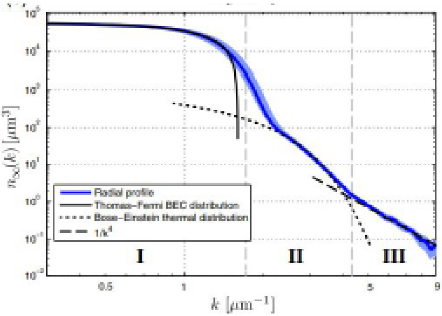
The Gross-Pitaevskii equation describes the dynamics of the condensed fraction:

$$i\hbar\frac{\partial\psi_0}{\partial t} = \left(-\frac{\hbar^2}{2m}\nabla^2 + V + g|\psi_0|^2\right)\psi_0$$

Quantum depletion is the 'quantum correction' to ψ_0, whose amplitude scales with the *gas parameter* $\sqrt{na_s^3}$

What does depletion look like?

The depleted fraction is populated by bosons in quasiparticle modes, whose asymptotic momentum density scales with k^{-4}:

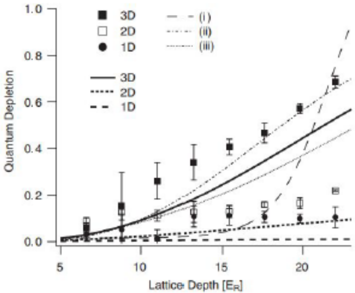


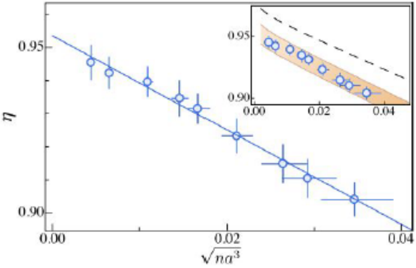
But... This shouldn't be visible![5]

[5]Chang et al, PRL 117 (2016)

Quantum depletion in the wild

- First observation in an optical lattice[6]
- More recently observed in a homogenous trap[7]





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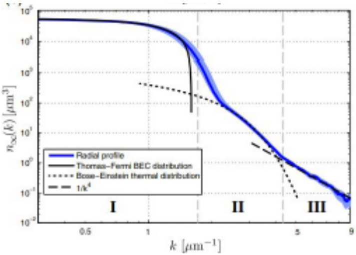
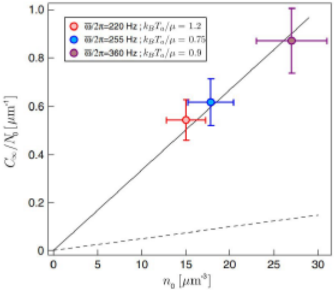
[6] Xu et al, PRL 96 (2006)
[7] Lopes et al, PRL 119 (2017)

Quantum depletion in far-field

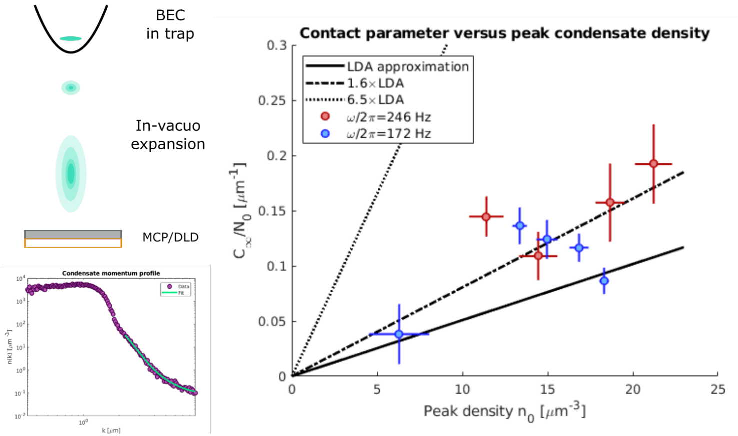
- Far-field anomaly reported by Palaiseau lab[8]
- MCP-DLD resolves six orders of magnitude in momentum density





[8] Chang et al, PRL 117 (2016)

Results (preliminary)



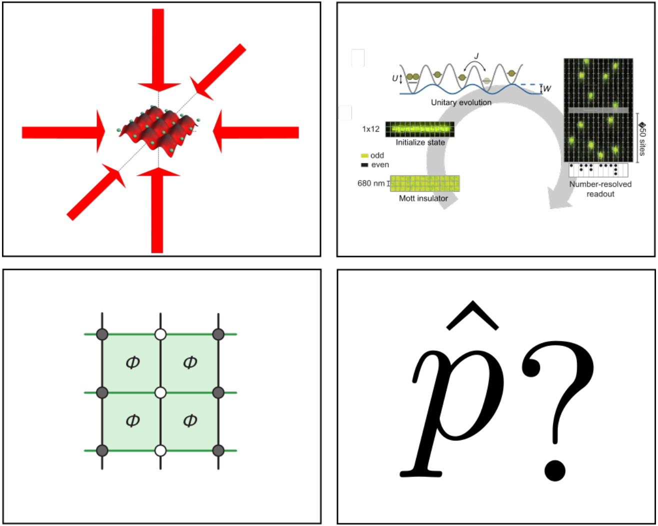
Depleted population fraction scales as $C_\infty / N_0 \propto n_0$, where the asymptotic momentum density is $n(k) = \frac{C_\infty}{(2\pi)^2 k^4}$

Many-Body physics II: Towards an optical lattice

Motivation: Quantum simulation

- Large-scale engineering requires accurate and efficient simulation.
- In general, simulating large quantum systems is intractable.
- Digital quantum computers would help, but are too small and noisy.
- Quantum simulators directly realize the Hamiltonian of a system of interest.

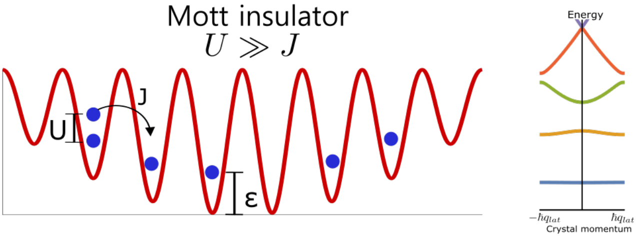
Optical lattices[9]

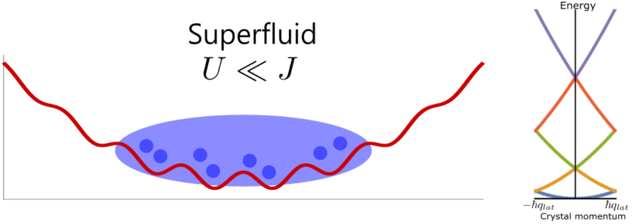


[9] Rispoli et al, arxiv.org/abs/1812.06959, Aidelsburger et al, Nat Phys 11 (2015)

The Bose-Hubbard model

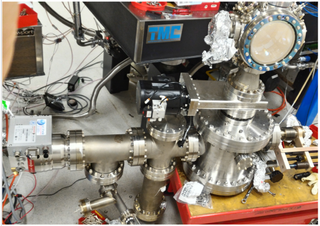
$$\hat{H} = -J \sum_{\langle ij \rangle} (\hat{b}_i^\dagger \hat{b}_j + \text{c.c.}) + U \sum_i \hat{n}_i(\hat{n}_i - 1) + \sum_i \epsilon_i \hat{n}_i$$



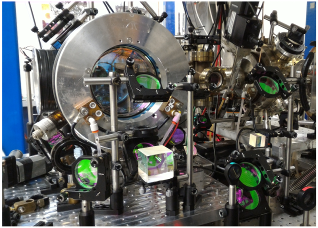


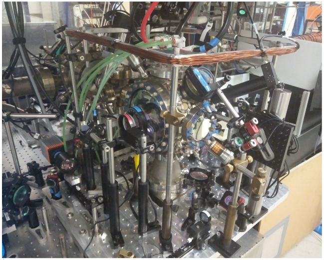
Building in progress...

Vacuum system construction

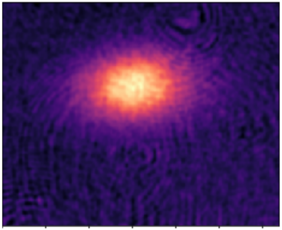


Magneto-Optical trap build





Absorption imaging the new magnetic trap!



Coming soon...

What happens during the trap switch-off?

Can we find the forbidden $2^3\mathrm{S}_1 \rightarrow 3^3\mathrm{S}_1$ transition?

Did we find a crack in the crown jewel of physics?

With thanks to...

- **Fellow students:** Bryce Henson, David Shin, Abbas Hussein, Kieran Thomas, Sam Meng
- **Supervisors:** Andrew Truscott, Sean Hodgman, Ken Baldwin
- **Technical wizards:** Ross Tranter, Colin Dedman
- **Theory support:** Piotr Deuar, Gordon Drake, Li-Yan Tan
- And you!