Arbitrary positioning and manipulation of ultra-cold atoms with optical tweezers

UC San Diego

Raghav Kansal, Paul Lauria, Chenghui Yu, Julio Barreiro

Department of Physics, UC San Diego

William Lee Research Award

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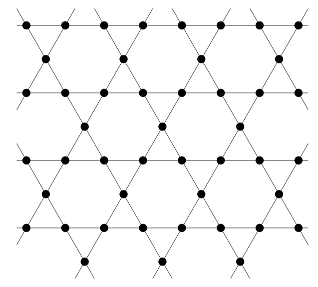
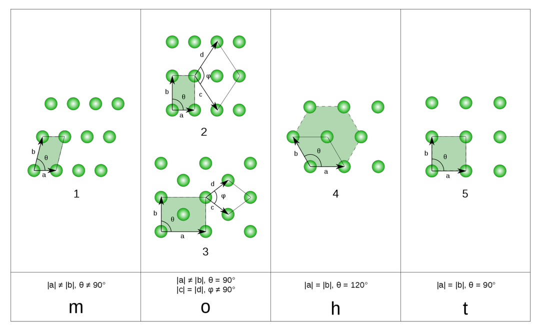
Quantum Simulations

- We want to model complex systems, for which classical algorithms are slow and inefficient, using quantum simulations with ultra-cold atomic strontium gases
- Sr atoms are cooled to a BEC or DFG then arranged in lattices, which we can use to simulate condensed matter and quantum chemistry systems

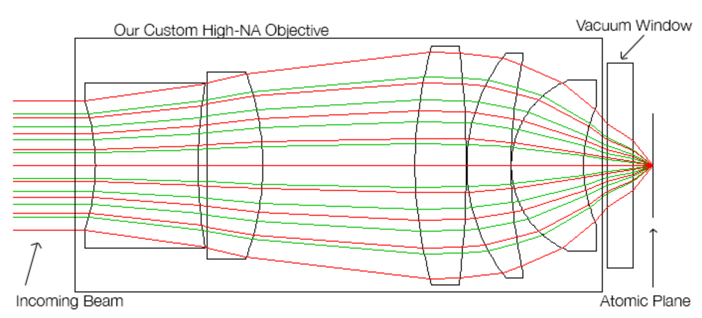




Optical Tweezers

To control atoms with a small confining trap we want an "optical tweezer", a powerful laser beam focused to a sub-micron spot that, depending on the wavelength and the detuning, can apply gradient and radiation force on a polarizable atom to attract (in our case) or repel it.

Multiple tweezers can be produced using multiple beams.

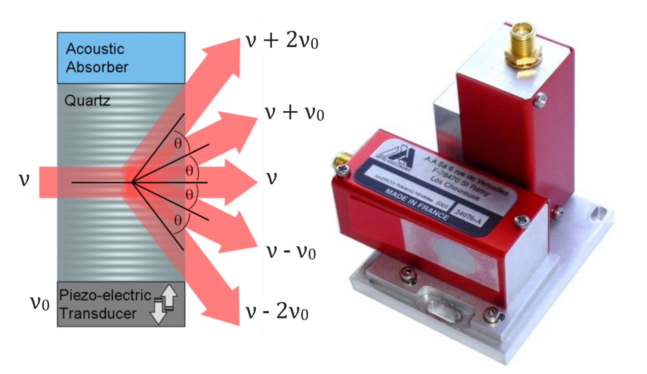


A high numerical aperture (NA) objective focuses a collimated beam to a diffraction-limited spot.

These were implemented using:

(1) acousto-optic deflectors (AODs), for precise and rapid motion;

(2) holography via a digital micromirror device (DMD), for arbitrary 2D lattices.

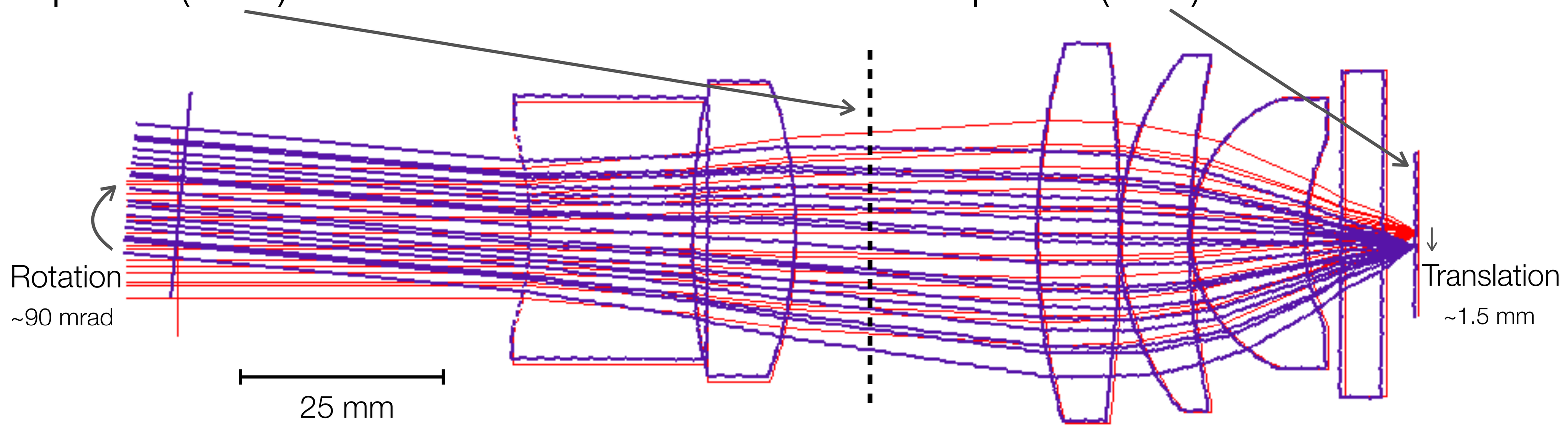


(Left) AODs diffract an input beam based on a radio frequency input waveform.
(Right) Our AA Opto Electronic DTSXY-400 2D AODs, which deflect along both axes.

The DMD is used to reflect light and imprint a phase pattern to create holograms.

Acousto-Optic Deflector (AOD) Optical Tweezers

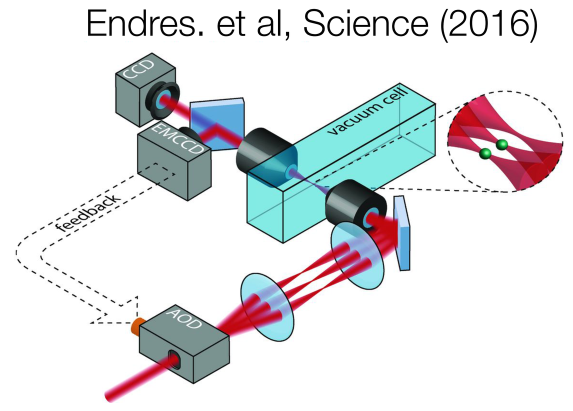
A converging lens (or objective) transforms rotations in its back focal plane (BFP) into translations in its front focal plane (FFP).



Since AODs rotate an input beam, they can be used to control the position of the tweezers.

Multiple input frequencies produce multiple output beams, or tweezers.

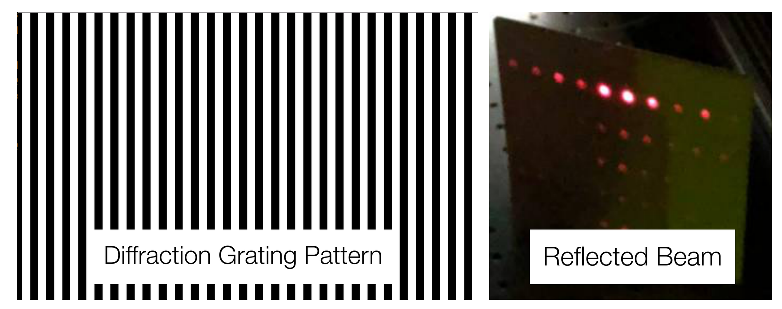
Endres. et al, Science (2016)



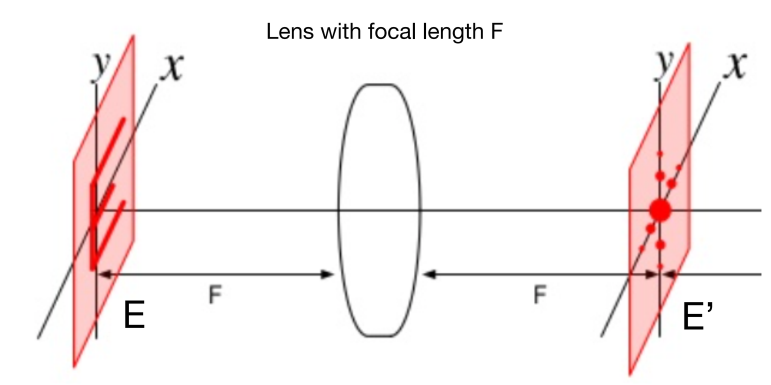
Holographic Optical Tweezers (HOTs)

Holography produces a desired image by the transmission/ reflection of a beam through/off an interference pattern.

A diffraction grating is a simple example of a hologram:



Fourier optics:
(FT ≡ Fast Fourier Transform)



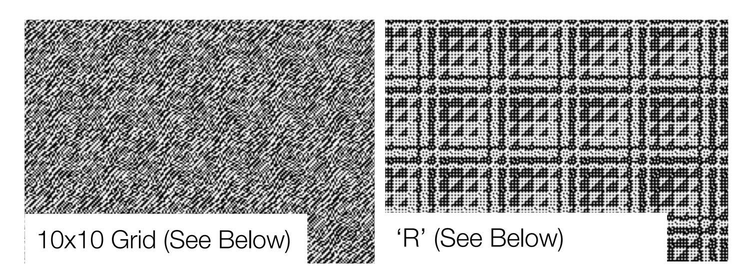
$$E'(\vec{r}') = FT\{E\} = \sum_m^M C_m \delta(\vec{r}' - \vec{r}'_m) = A'(\vec{r}')e^{i\varphi'(\vec{r}')}$$

$$E(\vec{r}) = FT^{-1}\{E'\} = \sum_m^M A_m e^{i\frac{2\pi}{\lambda f}\vec{r}\cdot\vec{r}'_m} = A(\vec{r})e^{i\varphi(\vec{r})}$$

After performing the GSA and binarizing, ϕ(r) is displayed on the DMD.

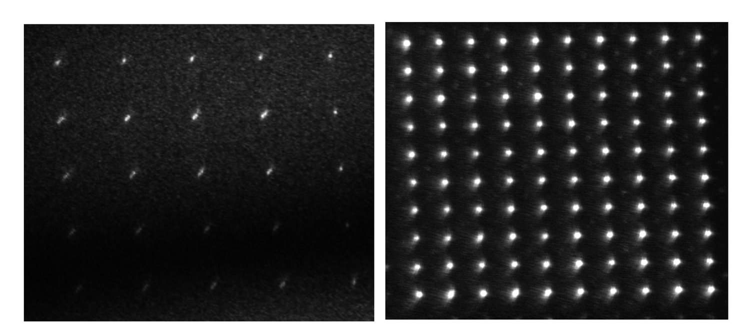
Producing HOTs:

1. The desired discrete interference patterns (here an array of spots) are numerically calculated and generated based off Fourier optics; this is known as computer generated holography (CGH)



Examples of binarized interference patterns. Output holograms are labeled.

2. The iterative Gerchberg-Saxton algorithm (GSA) improves the uniformity of spots for non-ideal input beams.

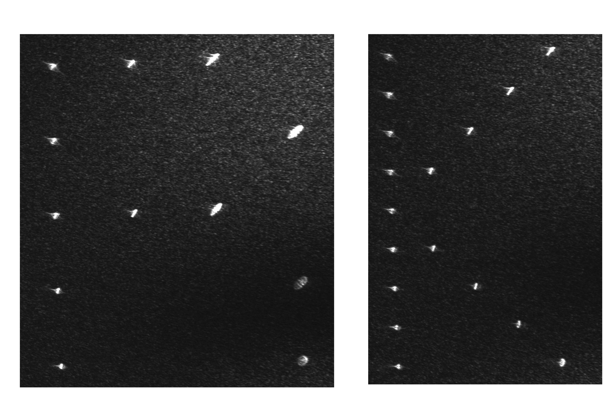


Without GSA With GSA

3. Patterns are binarized and displayed on a DMD with 1080x1920 ~3μm mirrors/pixels.

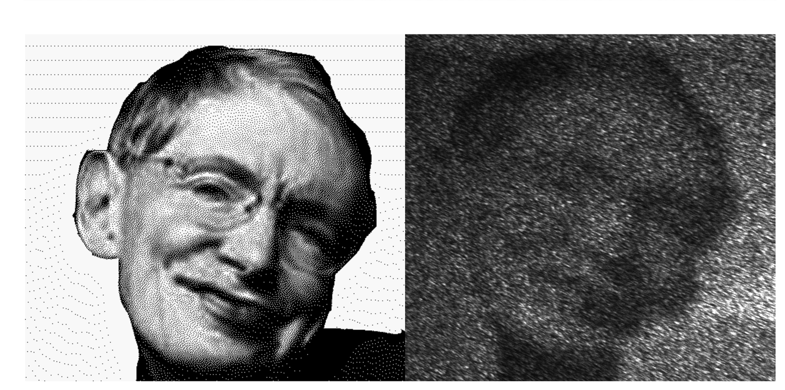
4. DMD imprints interference phase pattern on a reflected beam, which after focusing through a lens, produces the desired holograms

Through CGH, arbitrary uniform HOTs were produced, ideal for quantum simulation experiments:

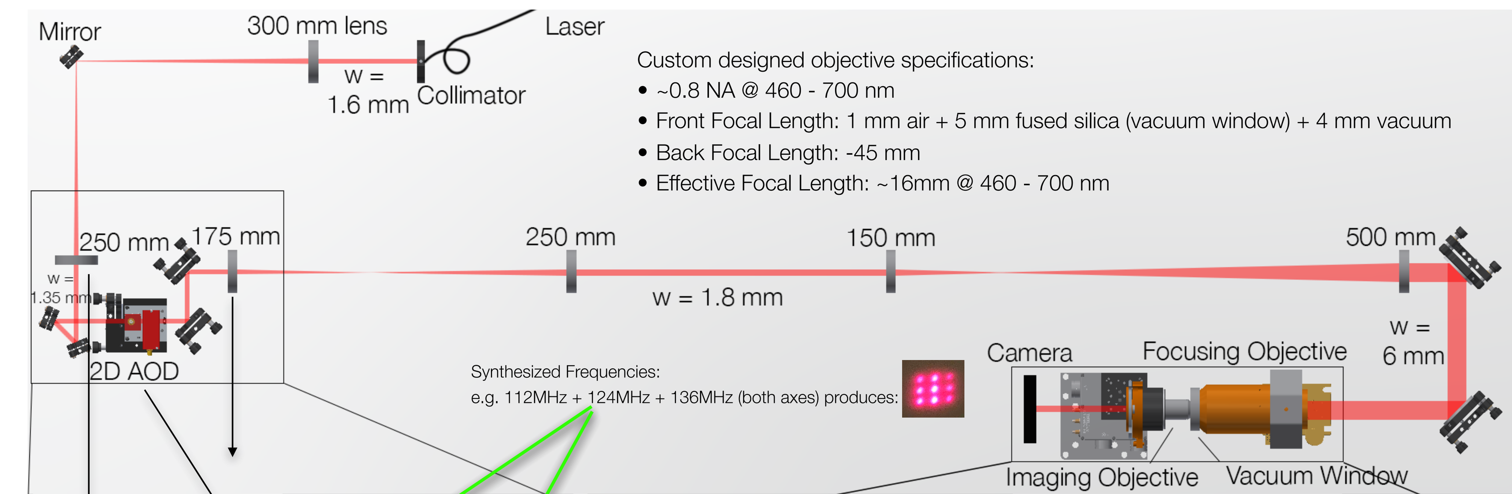


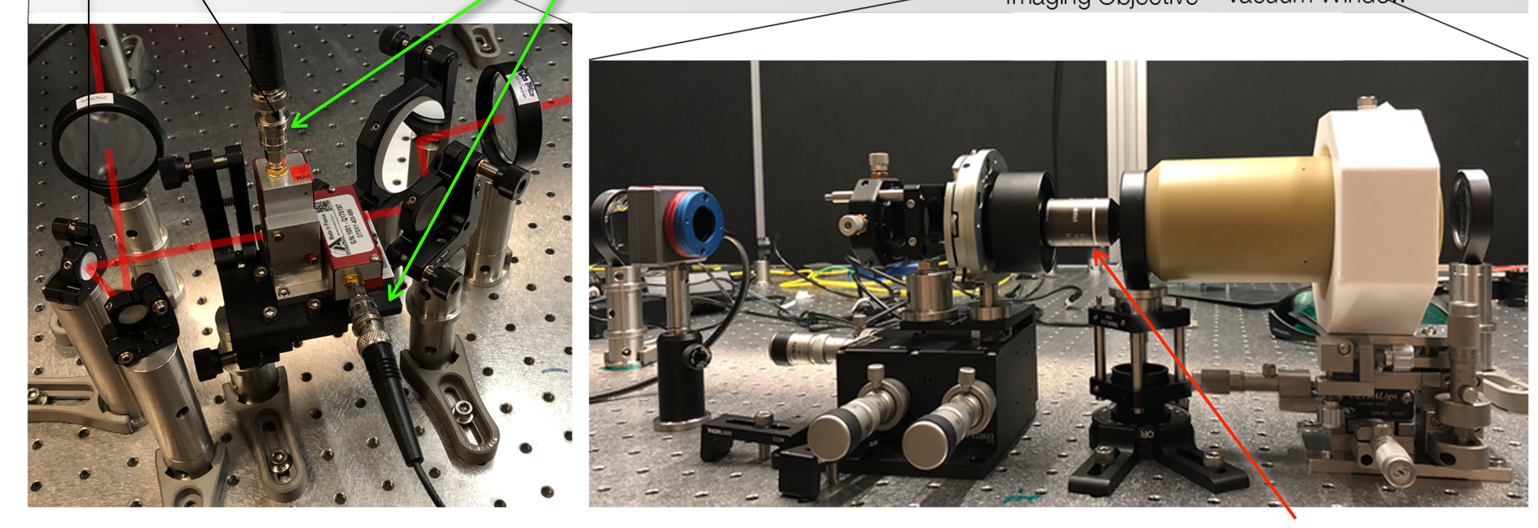
They work best with monochrome images, like those needed for our discrete lattices.

Holograms can produce arbitrary continuous images as well:

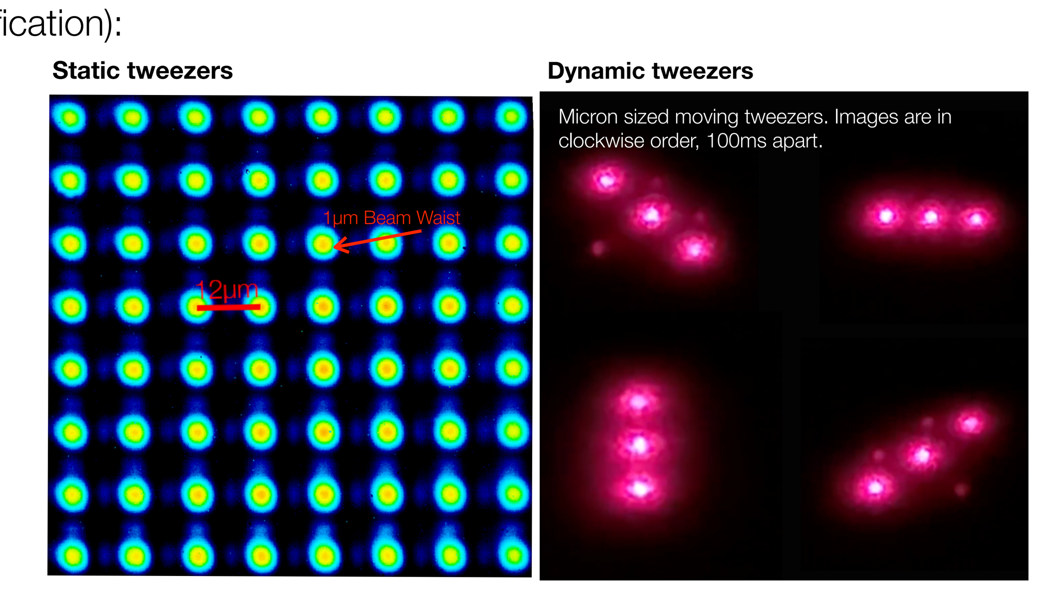


Characterization of AOD Tweezers





With the setup above, the following were produced and imaged with the second objective (~50x magnification):

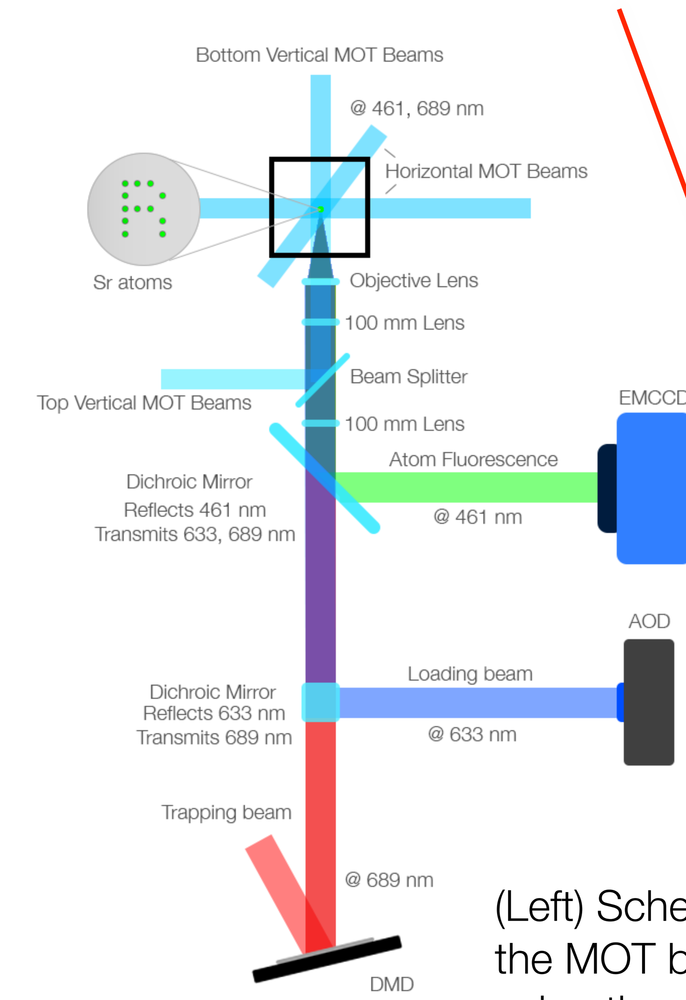


CCD Image

Video frames of white screen projection

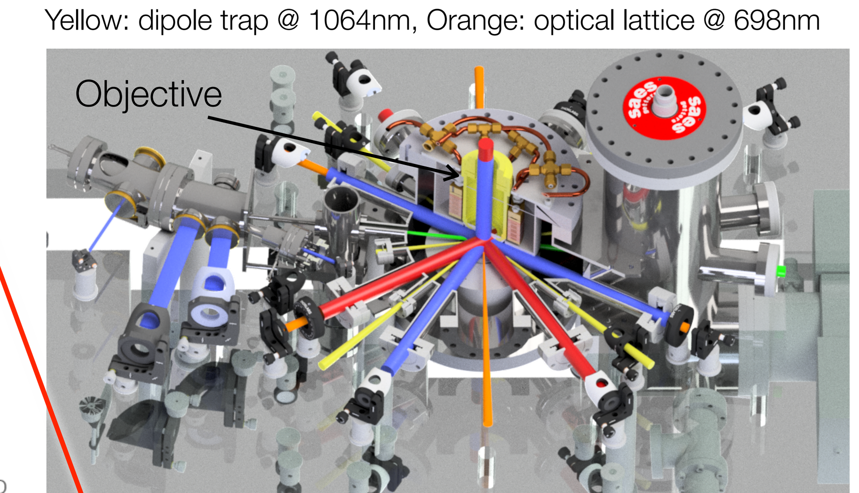
What's Next

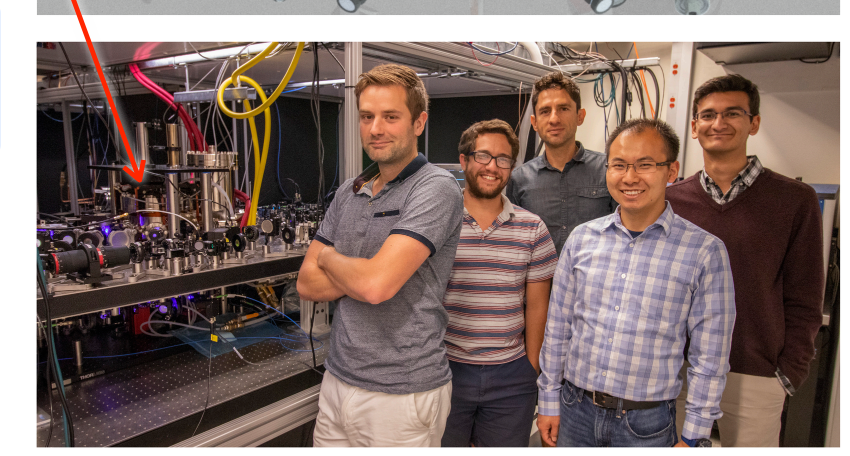
Integrating the HOTs, AOD tweezers, and atomic imaging system with our magneto-optical trap (MOT) beams (for initial cooling) in our vacuum chamber.



Rendering of setup for cooling atoms into which the tweezers will be integrated:
(Vacuum chamber in half-cut view)

Blue: MOT beams @ 461nm, Red: MOT @ 689nm
Yellow: dipole trap @ 1064nm, Orange: optical lattice @ 698nm





(Left) Schematic of final setup. To come out collimated, the MOT beam is focused onto the BFP of the objective using the second 100mm lens, which also forms a relay telescope focused on the BFP for the other beams.

References:

D. Barredo et al. An atom-by-atom assembler of defect-free arbitrary 2D atomic arrays. *Science* **354**, 1021 (2016).
M. Endres et al. Atom-by-atom assembly of defect-free one-dimensional cold atom arrays. *Science* **354**, 1024 (2016)
F. Nogrette et al. Single-atom trapping in holographic 2D arrays of microtraps with arbitrary geometries. *Phys. Rev. X* **4**, 021034 (2014)
D. Stuart and A. Kuhn. Single-atom trapping and transport in DMD-controlled optical tweezers. *New J. Phys.* **20**, 023013 (2018)