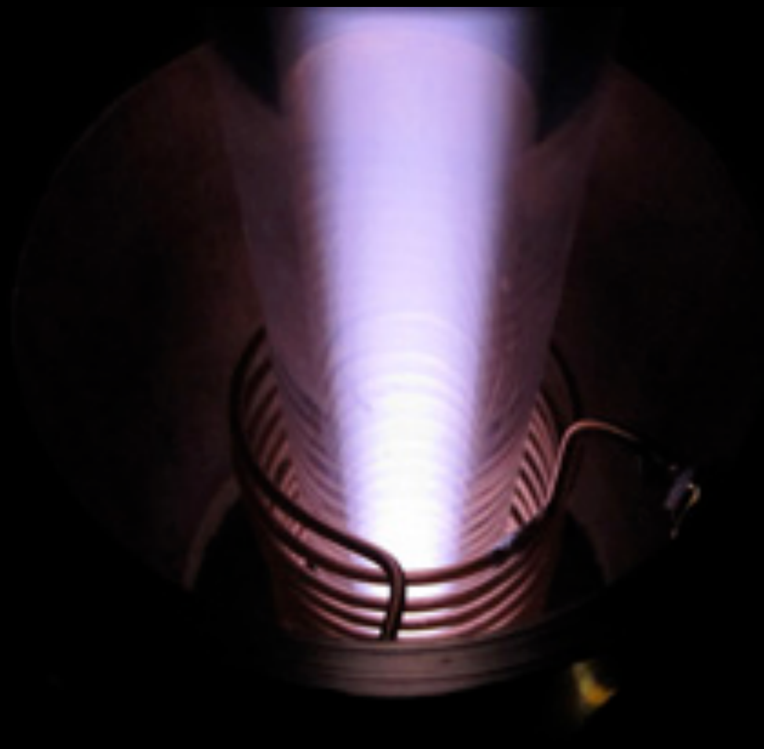
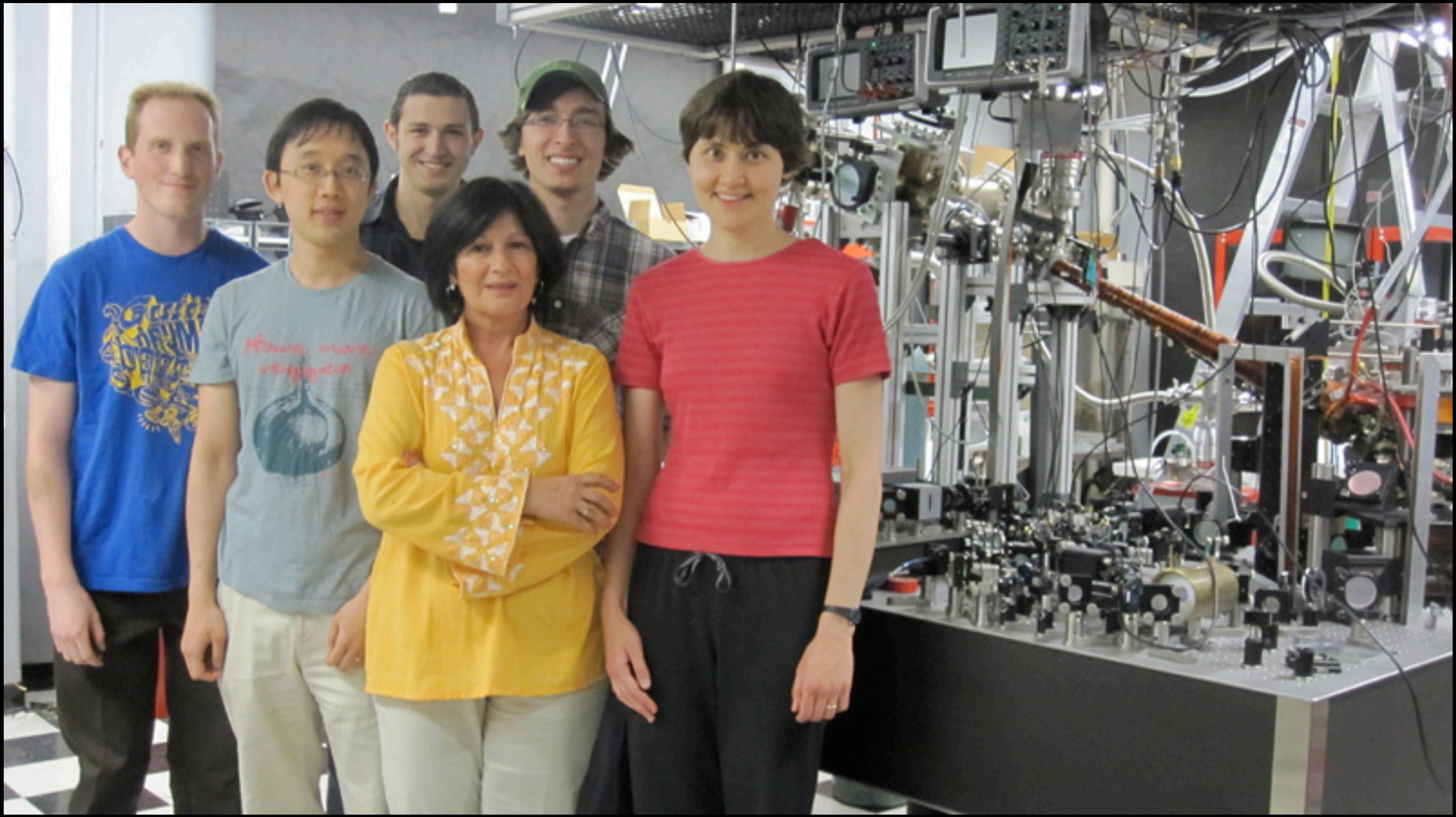
Instrument Development for the XENON Dark Matter Search:

An Atom Trap Trace Analysis System to Measure Ultra-low Krypton Contamination in Xenon



Luke Goetzke
Columbia University
June 2011

Acknowledgements



(left to right) Sam Gordon, Tae-Hyun Yoon, Chris Stevens, Professor Elena Aprile, Luke Goetzke, Professor Tanya Zelevinsky (not present, Claire Allred)

Many thanks to the NSF and Columbia University for the MRI grant that enables this ongoing research

Xe
XENON
Dark Matter Project

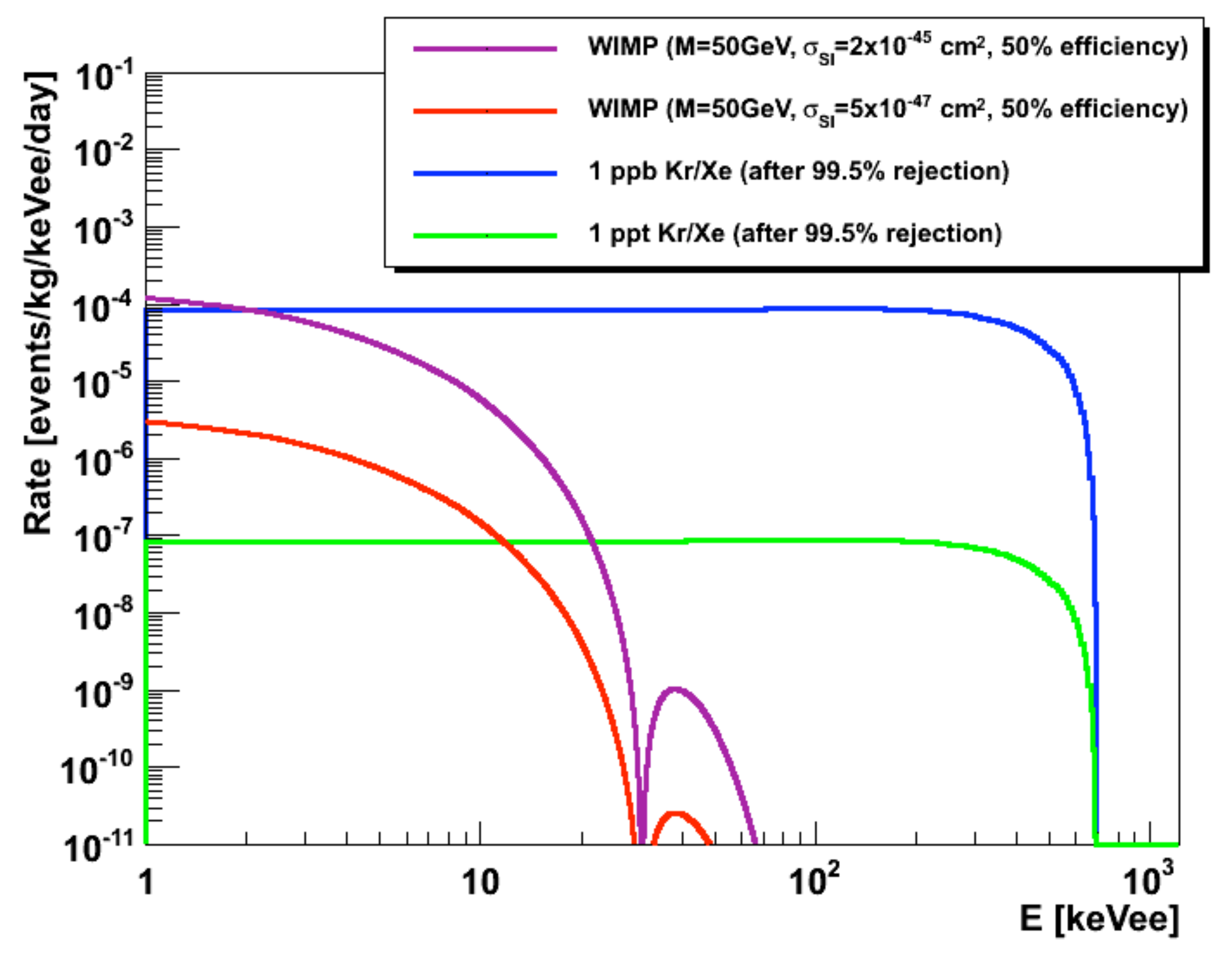
Kr Contamination

Xe extracted from atmosphere ⟶ Kr remains at ppm level in commercial gas

The Problem (for XENON): **^{85}Kr**

- β- emitter (99.6%), Emax = 687 keV
- long-lived, $t_{1/2}$ = 10.76 yr
- irreducible background, scales with the volume

} must be further purified ⟶ cryogenic distillation



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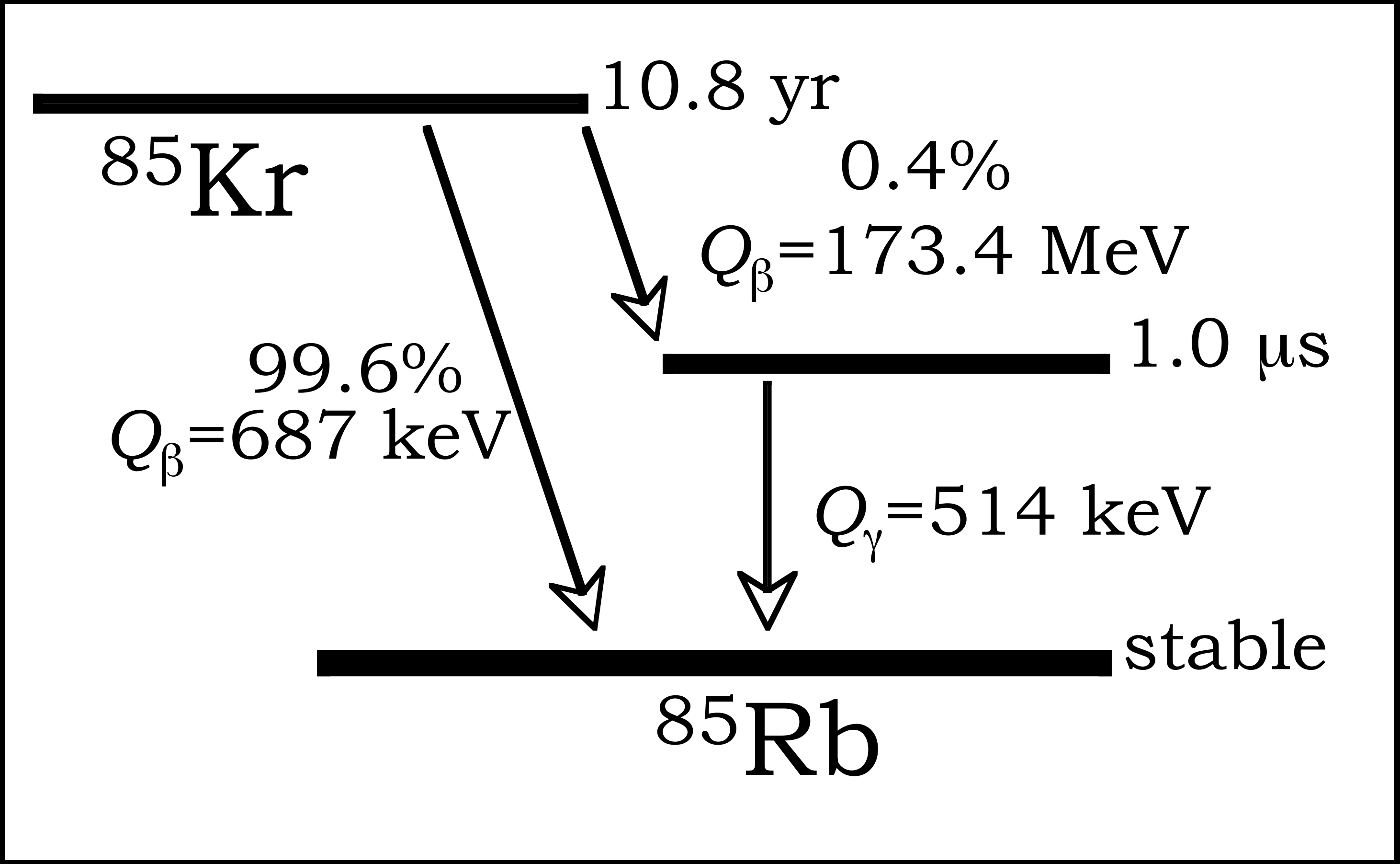
Kr Contamination

The Problem (for me): **^{85}Kr/Kr ~ 2 x 10^{-11}**

- must ensure Kr/Xe ~ 10^{-12} as needed for next generation DM detectors
  ⟶ ^{85}Kr/Xe ~ 10^{-23}
- for 160kg of Xe, this is only ~7,000 ^{85}Kr atoms

Unique double-coincidence signature, background-free but rate limited



Method

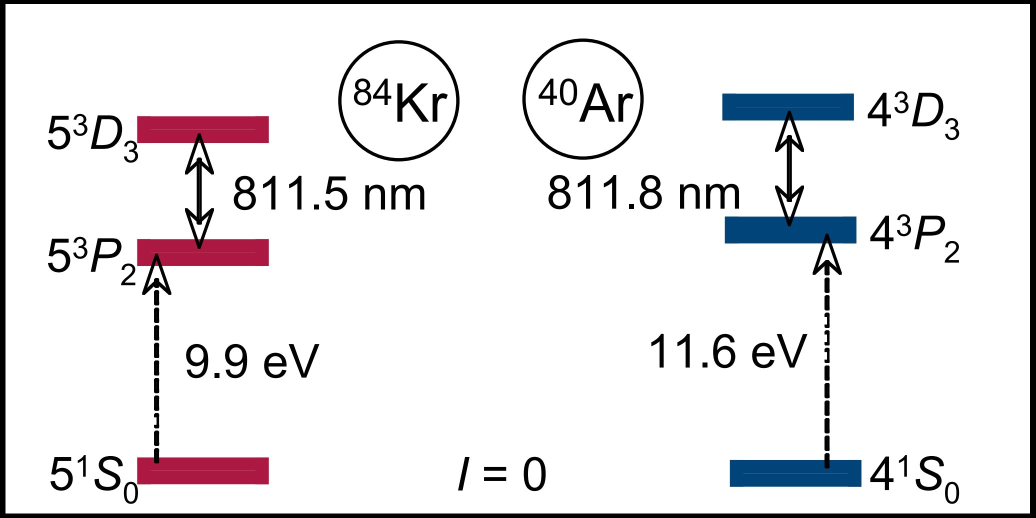
Atom Trap Trace Analysis (ATTA)

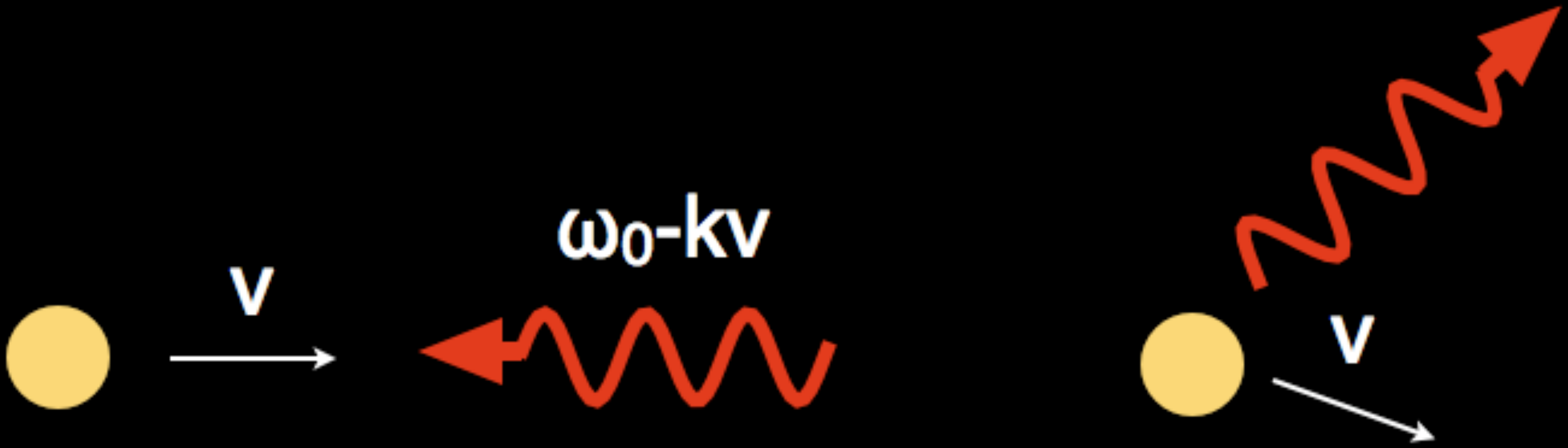
- Developed at Argonne National Lab for radioactive dating[1]
- Traditional laser cooling and trapping techniques employed to count single Kr atoms at a time with extremely high selectivity
- Will be used to measure directly Kr/Xe < 1 ppt level
- ^{84}Kr trapped (^{84}Kr/Kr ~ 0.57), ^{85}Kr inferred from known relative abundance[2]
- Initially calibrated and optimized with Ar to prevent Kr contamination of device

1. C. Y. Chen, *et al.*, *Ultrasensitive Isotope Trace Analyses with a Magneto-Optical Trap,* Science 286, 1139 (1999)
2. X. Du, *et al.*, *An atom trap system for practical 81Kr dating*, Rev. Sci. Inst. 10, 3224 (2004)

Principle of Operation

Laser Trapping Basics



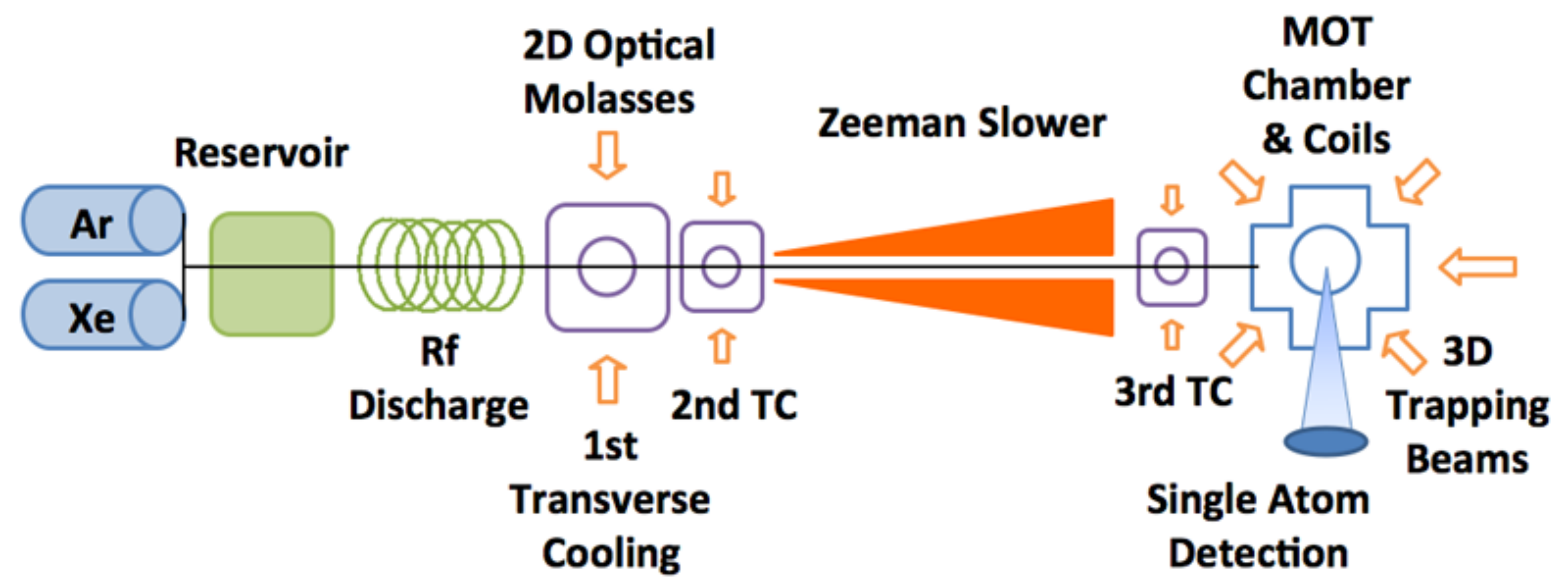


- Spectroscopy: Extremely narrow bandwidth laser with frequency locked to an atomic transition (isotope specific)
- Doppler “cooling”: Laser red-shifted so that atoms moving towards the laser source will preferentially absorb. Absorption of laser light + isotropic spontaneous emission = effective force

Principle of Operation

Traditional magneto-optical techniques

- Optical molasses: counter-propagating, red-shifted beams produce viscous force, reducing transverse velocity and increasing forward flux
- Zeeman Slower: 1D spatially varying magnetic field counteracts Doppler shift, allowing atoms to stay in resonance with coaxial laser as they slow down
- Magneto-Optical Trap (MOT): quadrupole magnetic field, 3 pairs of counter-propagating red-shifted beams



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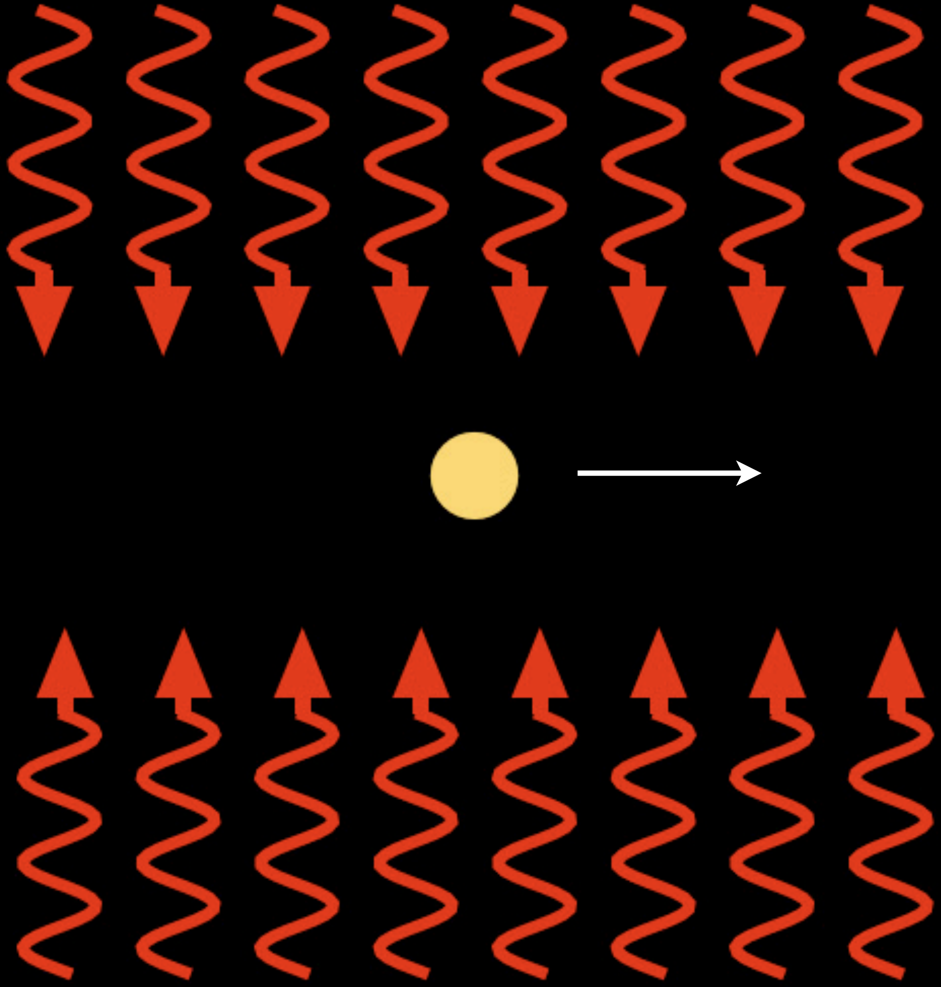
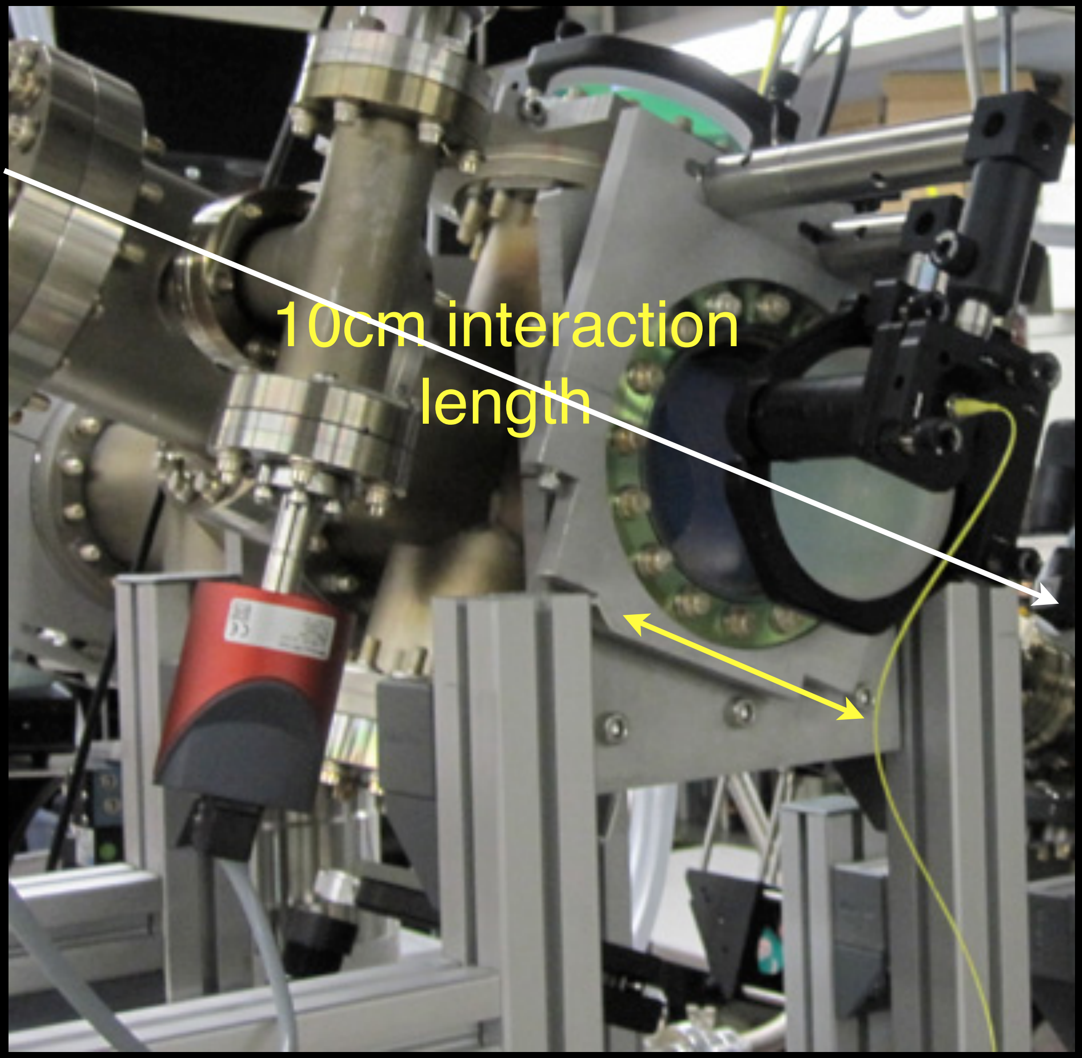
Principle of Operation

Traditional magneto-optical techniques

- **Optical molasses**: counter-propagating, red-shifted beams produce viscous force, reducing transverse velocity and increasing forward flux



1D



2D

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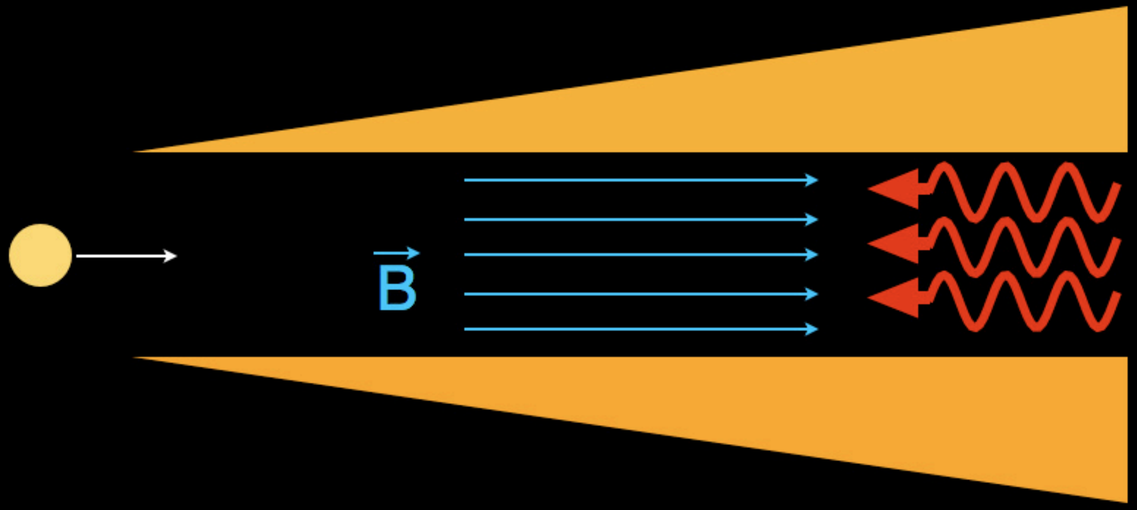
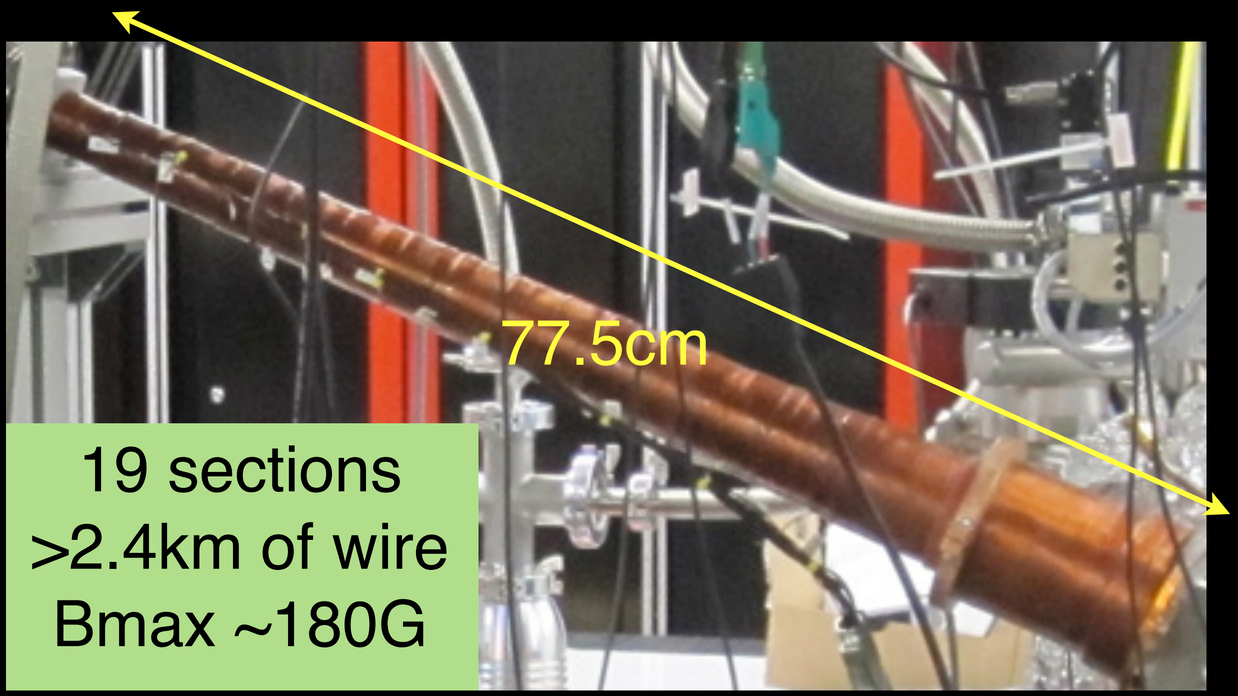
Principle of Operation

Traditional magneto-optical techniques

- Optical molasses: counter-propagating, red-shifted beams produce viscous force, reducing transverse velocity and increasing forward flux
- **Zeeman Slower:** 1D spatially varying magnetic field counteracts Doppler shift to the energy levels, allowing atoms to stay in resonance with coaxial laser as they slow down

Magnetic field causes Zeeman shift in energy level





19 sections
>2.4km of wire
Bmax ~180G

Principle of Operation

Traditional magneto-optical techniques

- Optical molasses: counter-propagating, red-shifted beams produce viscous force, reducing transverse velocity and increasing forward flux
- Zeeman Slower: 1D spatially varying magnetic field counteracts Doppler shift, allowing atoms to stay in resonance with coaxial laser as they slow down
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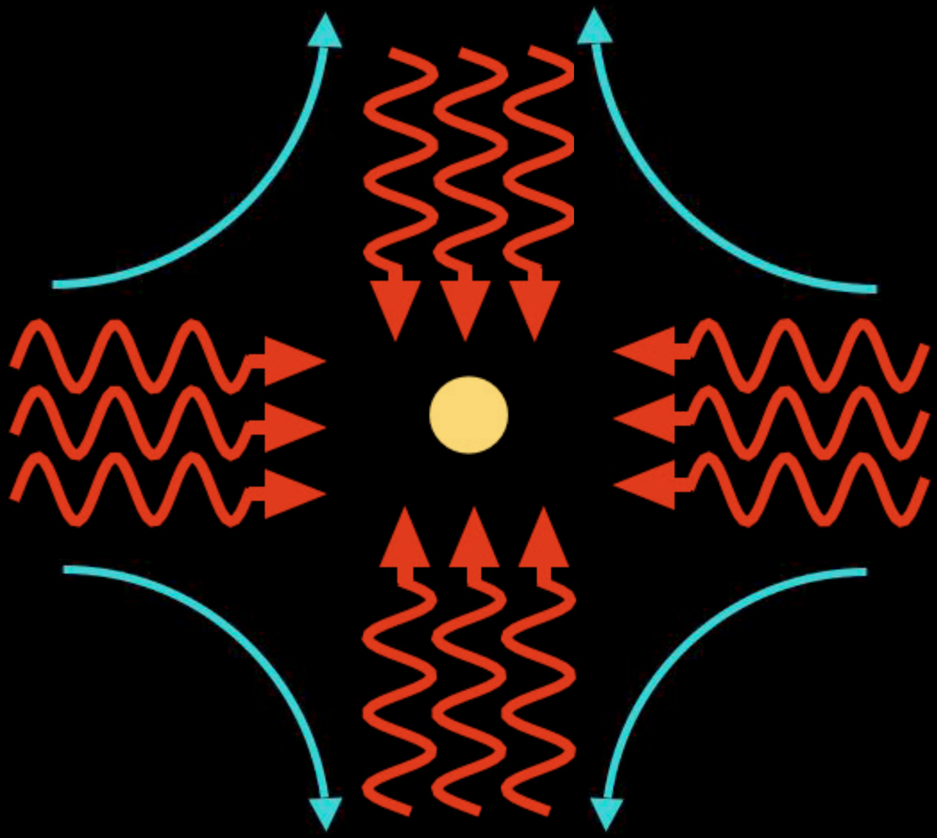

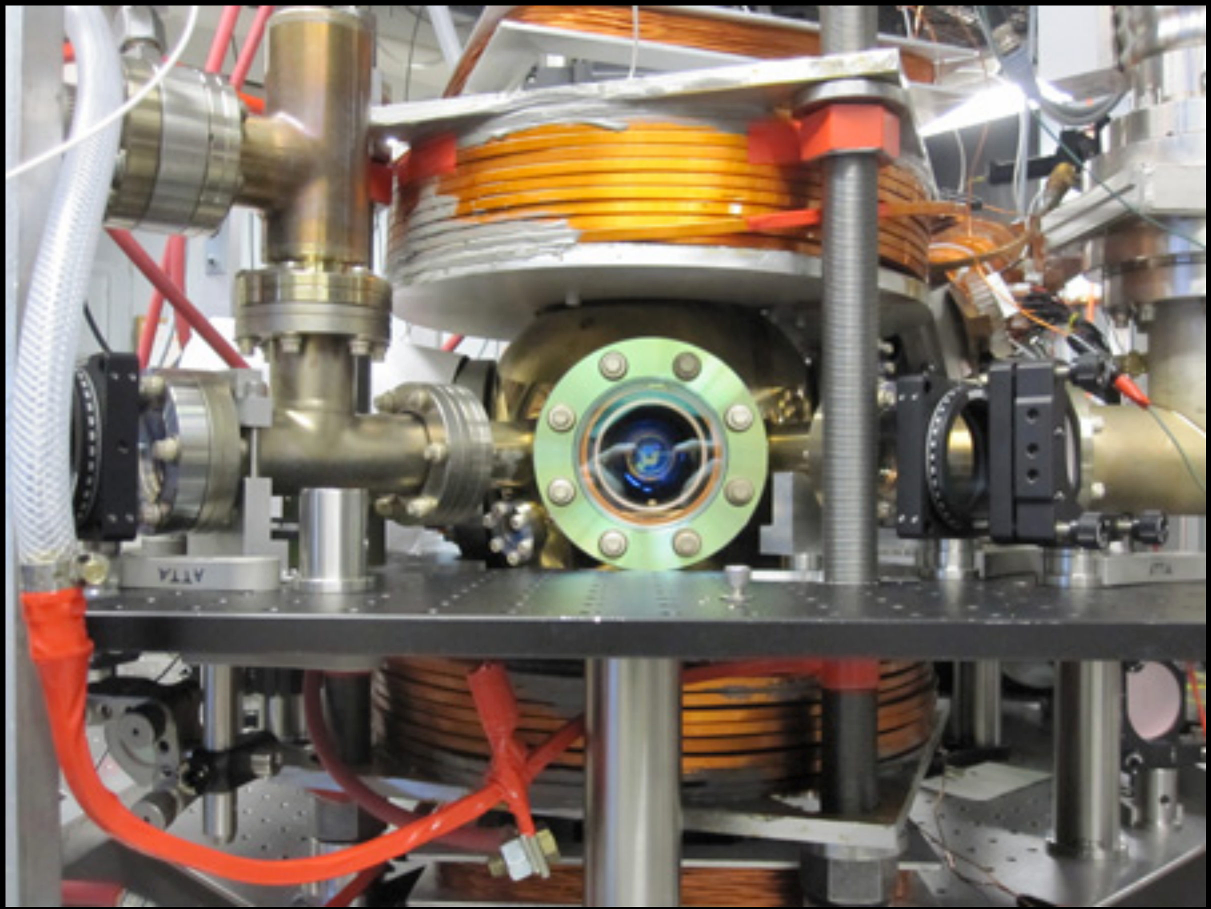

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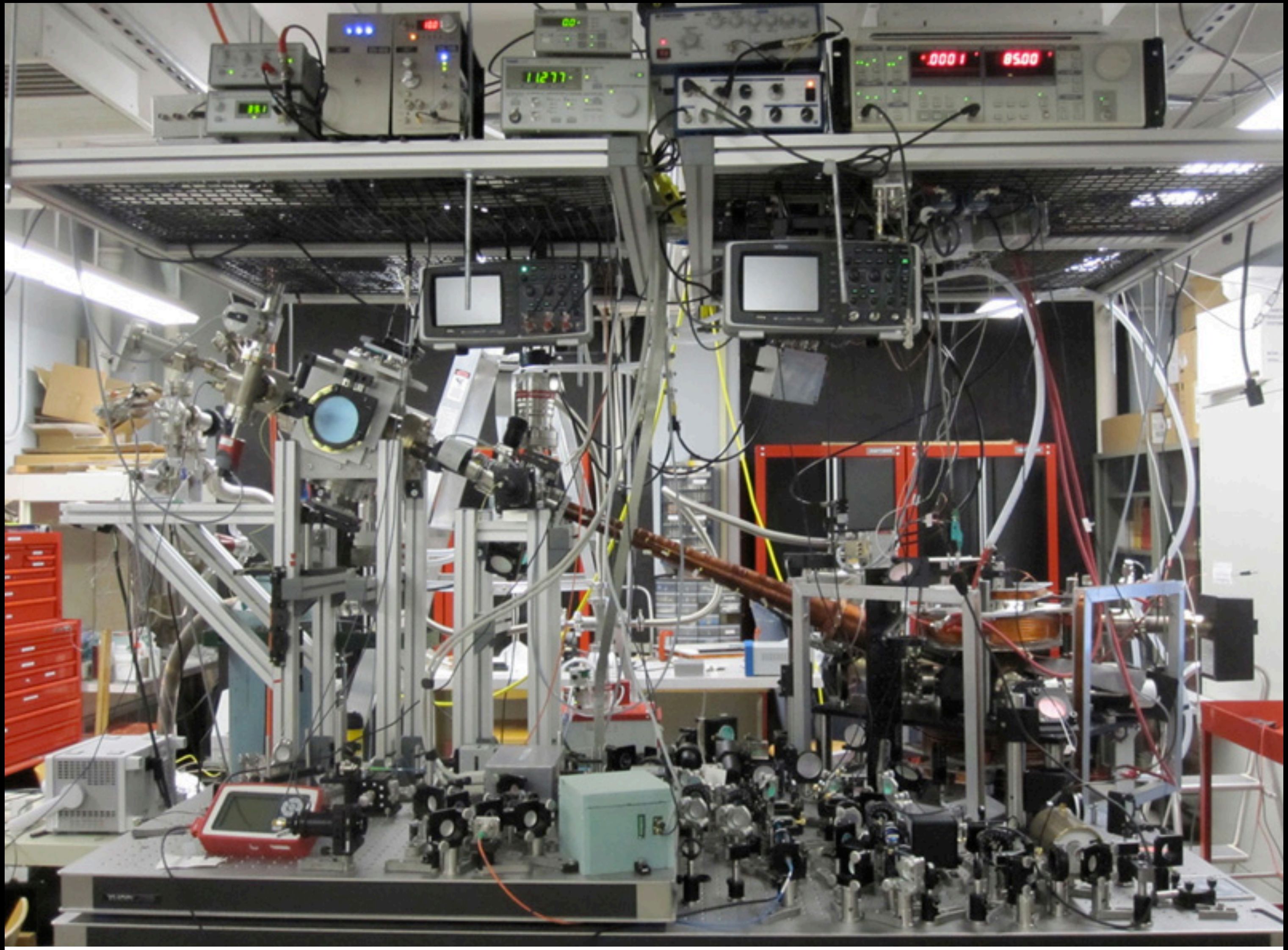
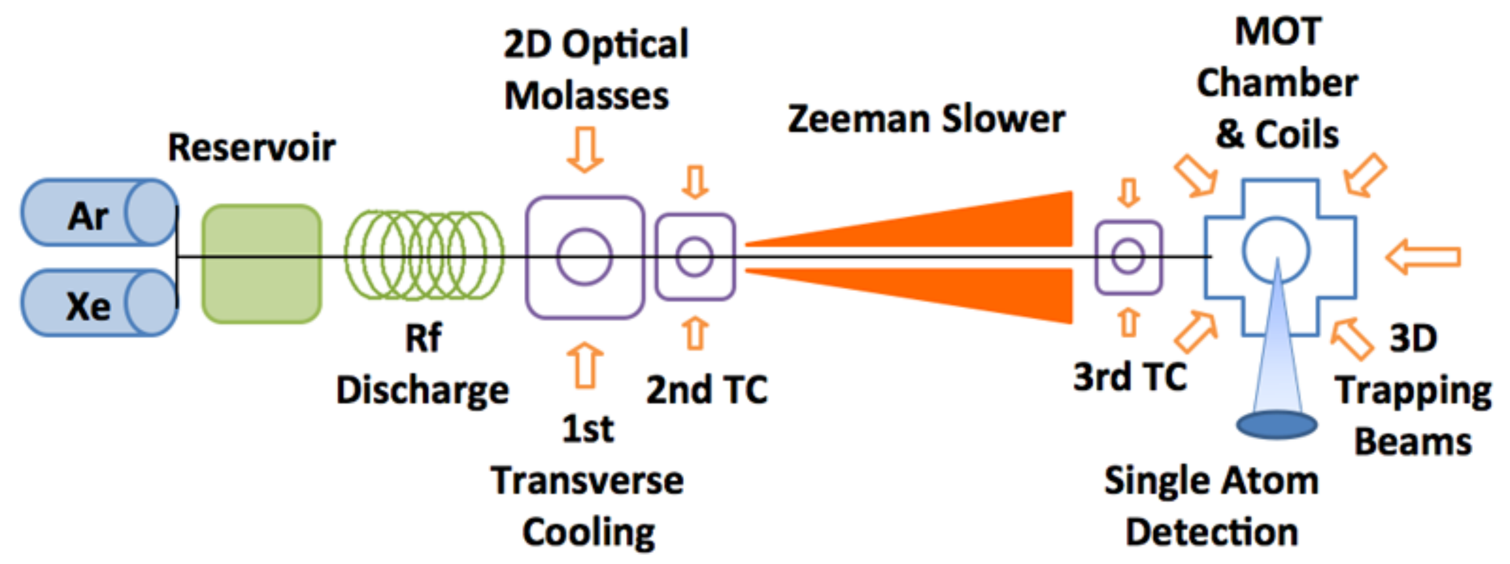
Principle of Operation

Implementation





The life of an atom in ATTA

- plasma discharge excites atoms to optically-accessible metastable state Ar* (Kr*), λ = 811nm

- three stages of 2D optical molasses collimate the Ar* (Kr*)

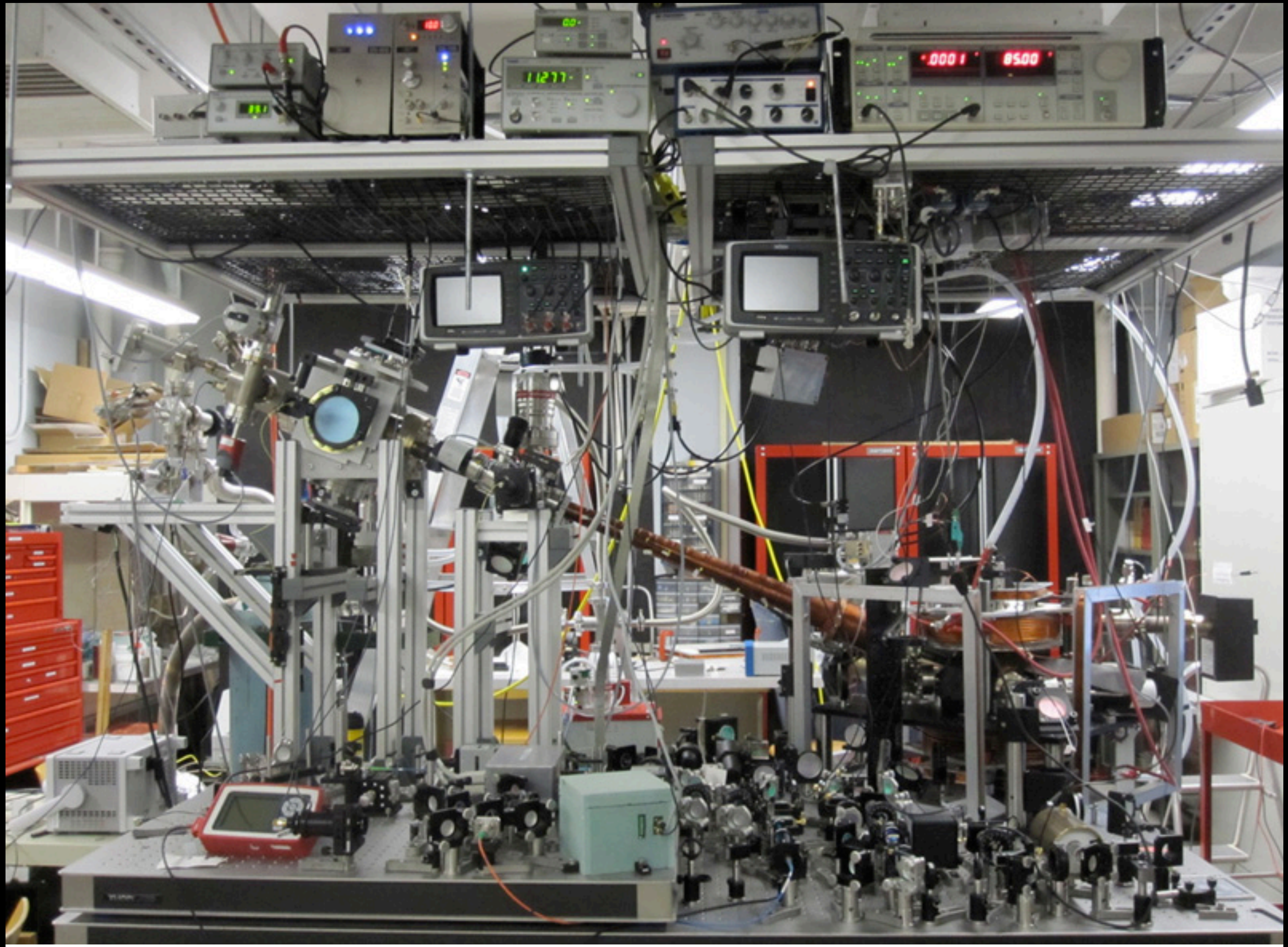
- Zeeman Slower slows atoms from ~245m/s to ~10 m/s

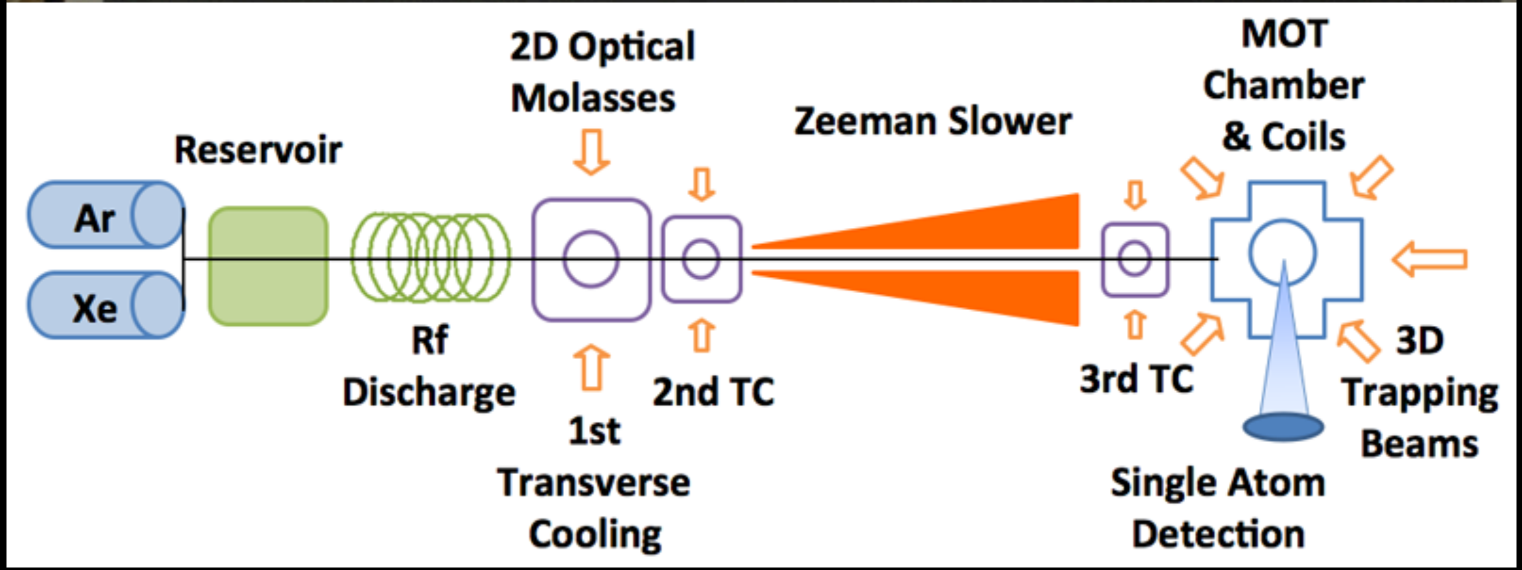
- Magneto-Optical Trap (MOT) traps single atoms

- fluorescence from trapped atoms imaged with a CCD camera

Principle of Operation

Implementation





Vacuum System

- All stainless steel, high-temp bakeable
- UHV, < 10^{-9} torr base pressure
- during gas flow, ~1 mtorr in source chamber, while MOT pressure remains < ~10^{-8} torr

Laser System

- single diode laser, amplified from ~60mW to >1W
- robustly locked using reference gas cell to 811.7542nm (Ar*), 811.5132nm (Kr*)
- laser frequency detuned for TC, ZS, and MOT

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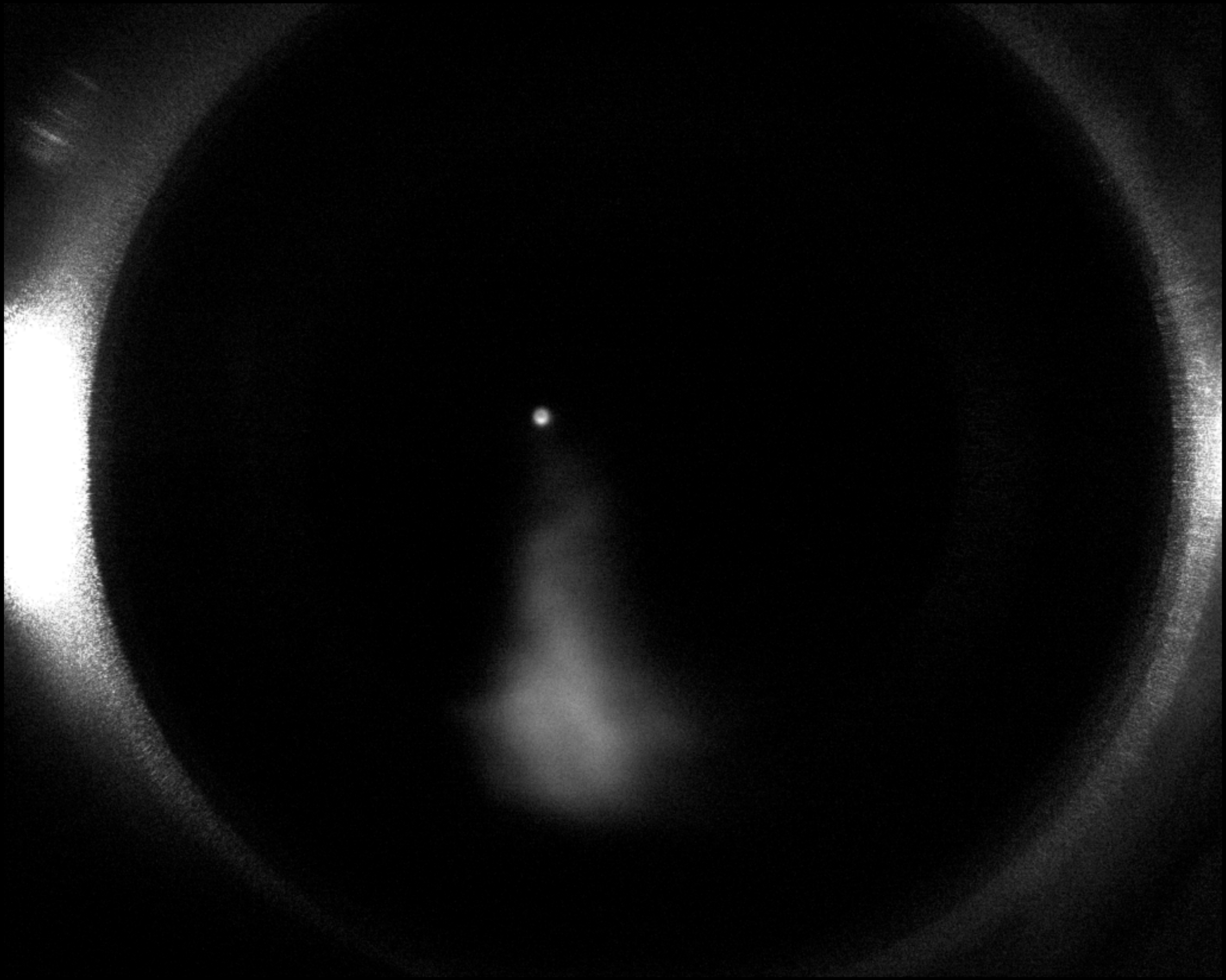
Current Status

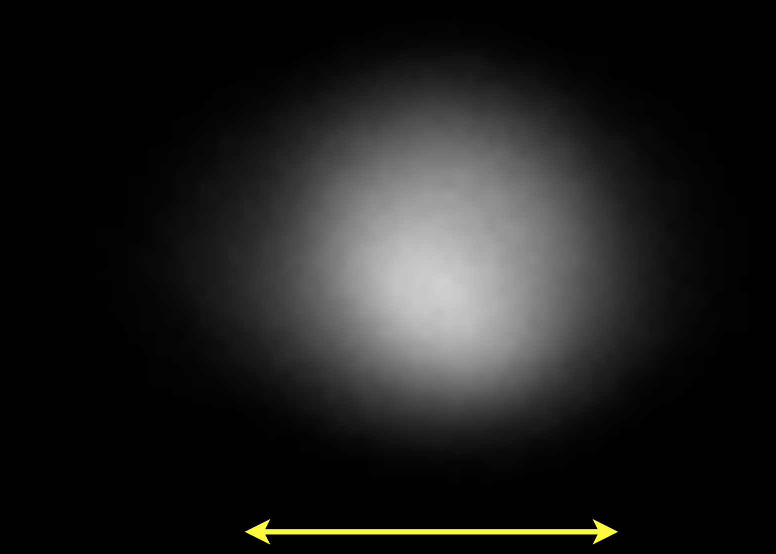
Successfully trapped Ar* atoms in a MOT



Current Status

Successfully trapped Ar* atoms in a MOT

Preliminary Results



$\sim 10^6$ atoms

~ 0.5mm

Density $\sim 1.5*10^{10}$ atoms/cm^3
MOT lifetime ~ 1.5s
Loading Rate $\sim 10^5$/s

Next Steps

- Optimize transverse cooling and loading into MOT
  - Cool input gas to ~140K using pulse tube refrigerator
- Single atom detection using avalanche photodiode (Summer 2011)
  - single atom at a time trapped in MOT for ~1s
- Calibrate loading rate using Xe with known Kr level (Fall 2011)
- Measure Xe from XENON100 experiment (Early 2012)
  - sample size ~1L STP of Xe gas (sample destroyed)
  - measurement time ~hours