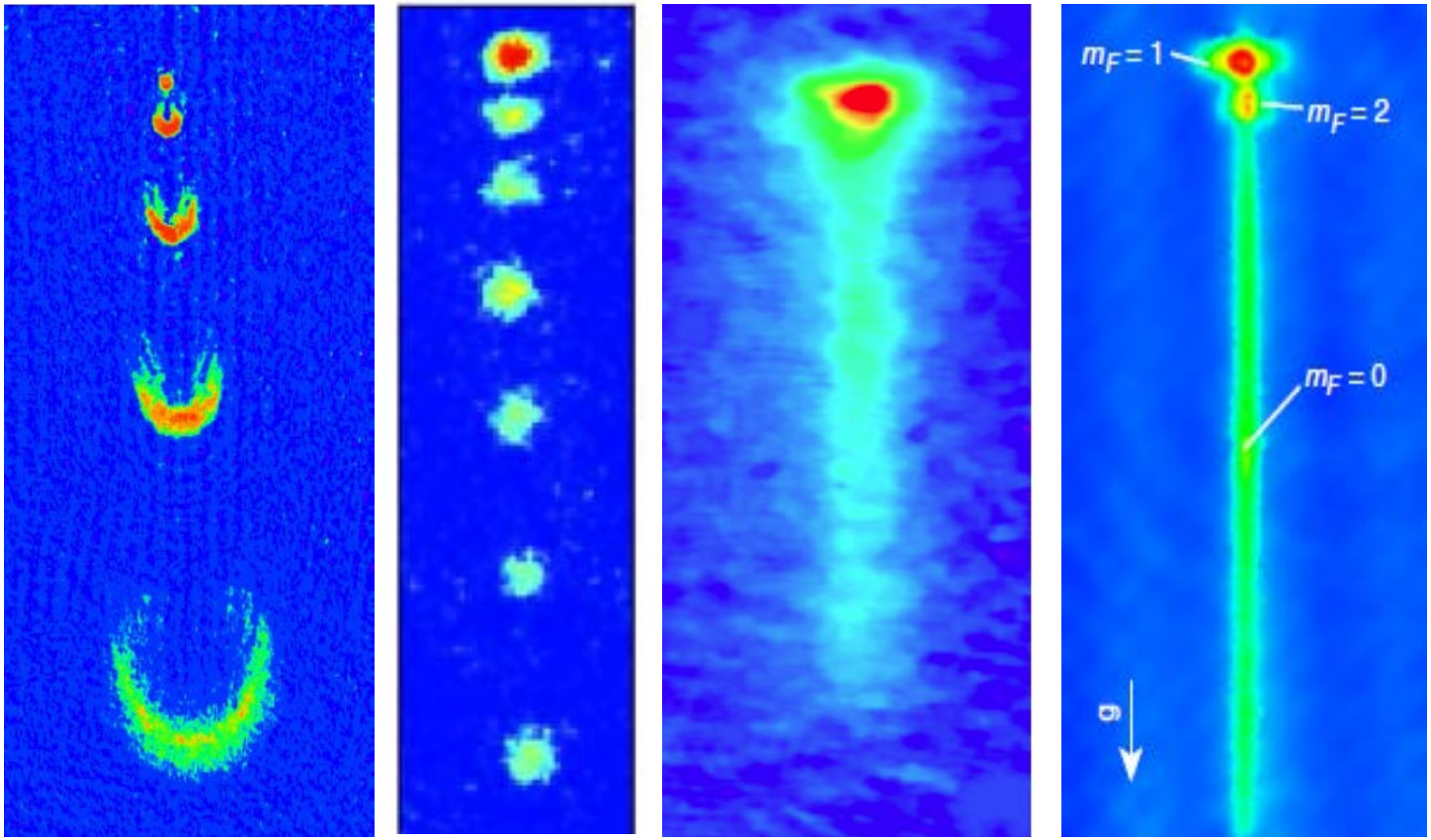
Atom lasers



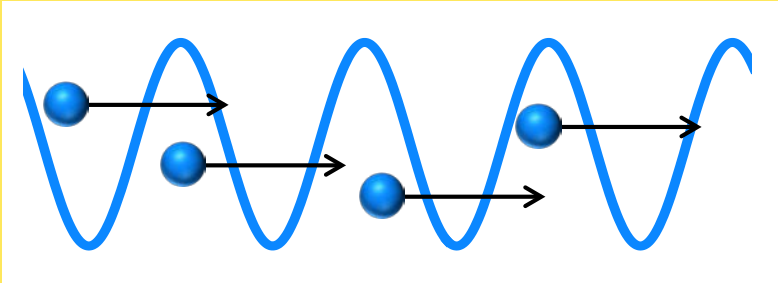
MIT 1997 | Yale 1998 | NIST 1999 | Munich 1999

FOMO summer school 2016

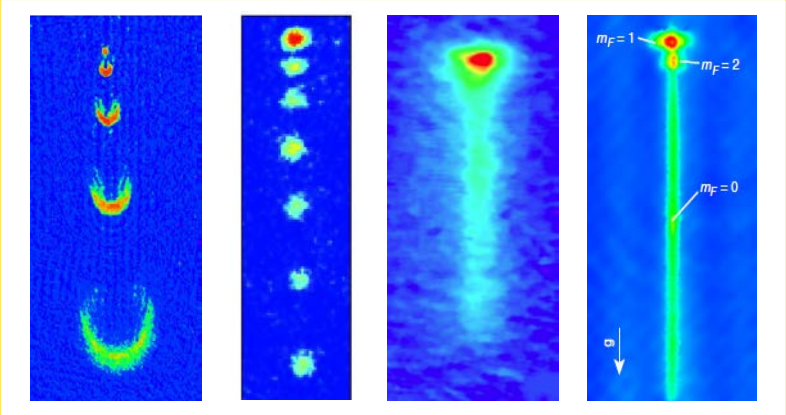
Florian Schreck, University of Amsterdam

Overview

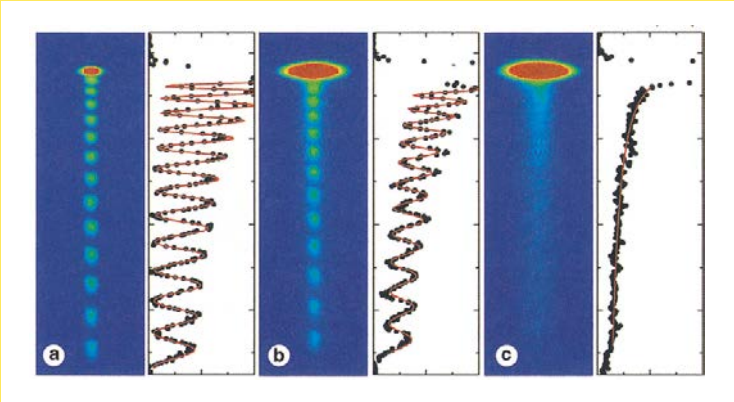
What? Why?



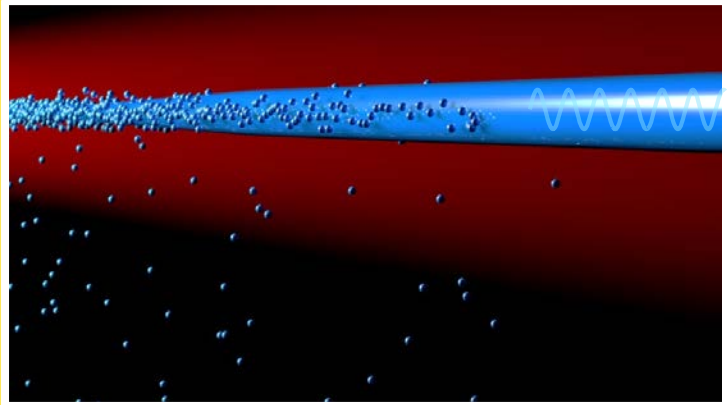
Pulsed atom lasers



Experiments with atom lasers

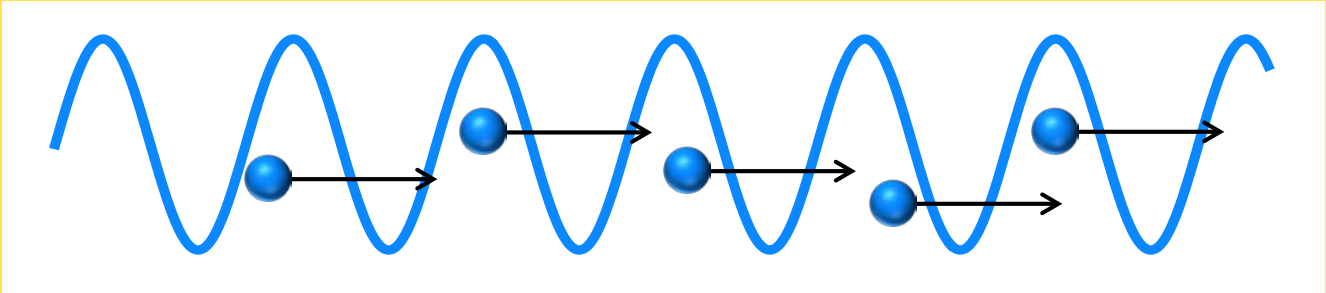


Continuous atom lasers



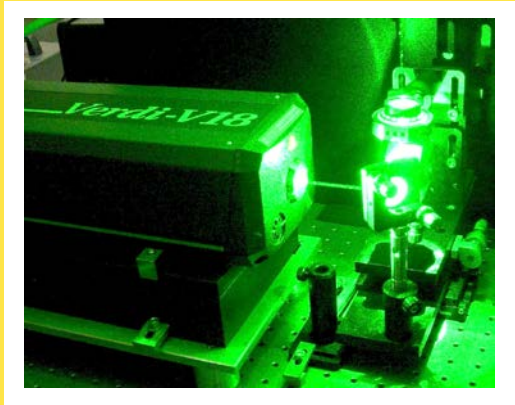
What is an atom laser?

Laser



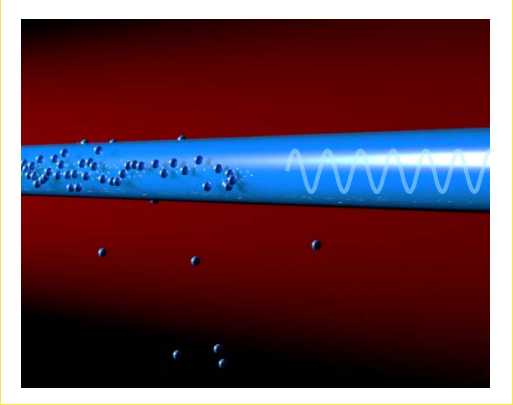
Light

Optical laser



Matter

Atom laser

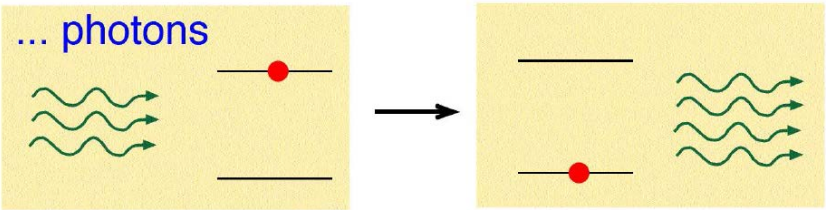


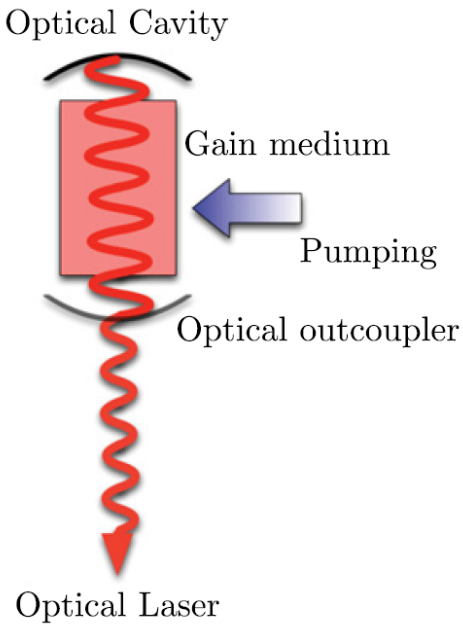
LASER

Light Amplification by Stimulated Emission of Radiation

Optical laser

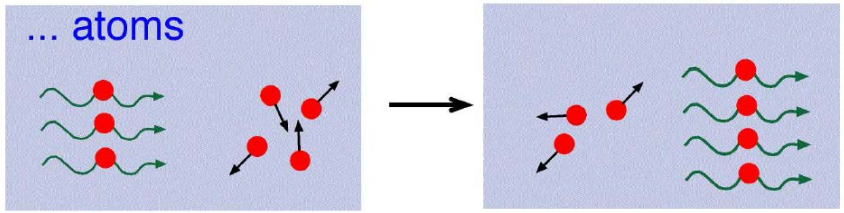
Stimulated emission

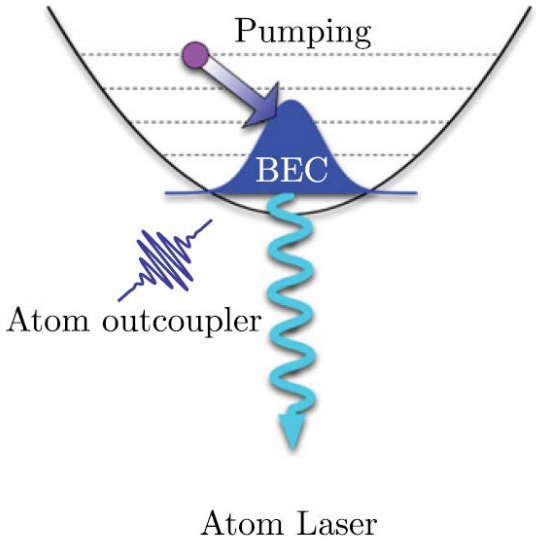




Atom laser

Stimulated scattering





Propagating Matterwave Amplification by Stimulated Scattering of Atoms
PMASSA

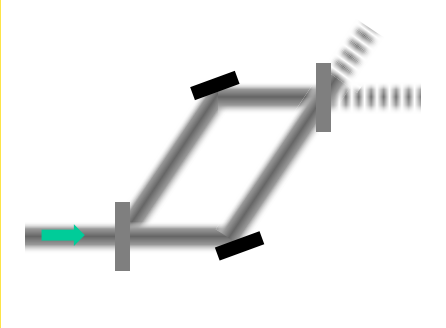
Figure from [1] N.P. Robins, P.A. Altin, J.E. Debs, J.D. Close, Physics Reports 529, 265 (2013)

Atom laser vs. thermal beam

	Atom laser	Thermal beam
Radial coherence	1 mode macroscopically occupied	many mode very weakly occupied
Longitudinal coherence	monochromatic = extremely small velocity spread	white = large velocity spread
Velocity	mm/s to cm/s	m/s to km/s
Correlation $g_2(0)$ probability to find two atoms at once * normalization	1	2
Source area	1...100 µm diameter	0.1...10 mm diameter
Divergence	Heisenberg limited	typically several degrees
Flux	10^5 to 10^7 atoms/s	Zeeman slowed: 10^{11} atoms/s
Brightness flux of atoms per source size / velocity spreads in each dimension	10^{24} atoms s^2 m^{-5}	10^{16} atoms s^2 m^{-5} (Rb 2D MOT)

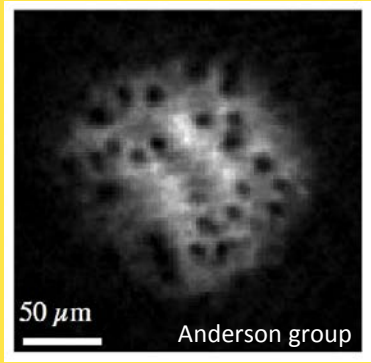
Why atom lasers?

Precision measurement



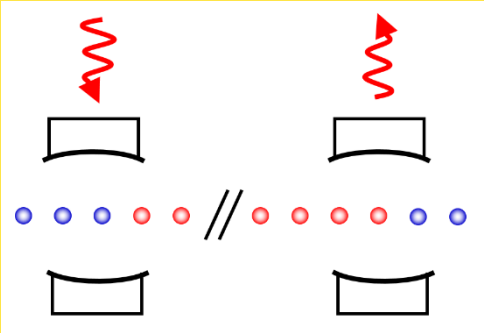
- Atom interferometry
- Superradiant mHz-linewidth laser

Studies of quantum mechanics



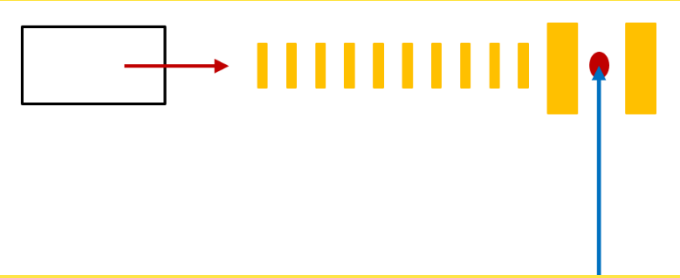
- Dissipative driven systems
- Quantum turbulence

Quantum technology



- Conversion into chain of atoms
  → Quantum FIFO memory

Technology



- Cold e^- or ion sources
- Perpetual sympathetic cooling reservoir
- Lithography

Why atom lasers for interferometry?

Disadvantages compared to standard MOT based atom interferometers

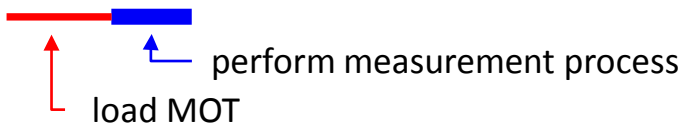
- higher experimental complexity
- lower flux

Advantages

- Higher brightness: higher flux of usable atoms, e.g. atoms within flat region of Bragg beams
- Possibility of squeezing: trade atom-number stability for phase stability
- No Dick effect: if continuous atom laser used

The Dick effect

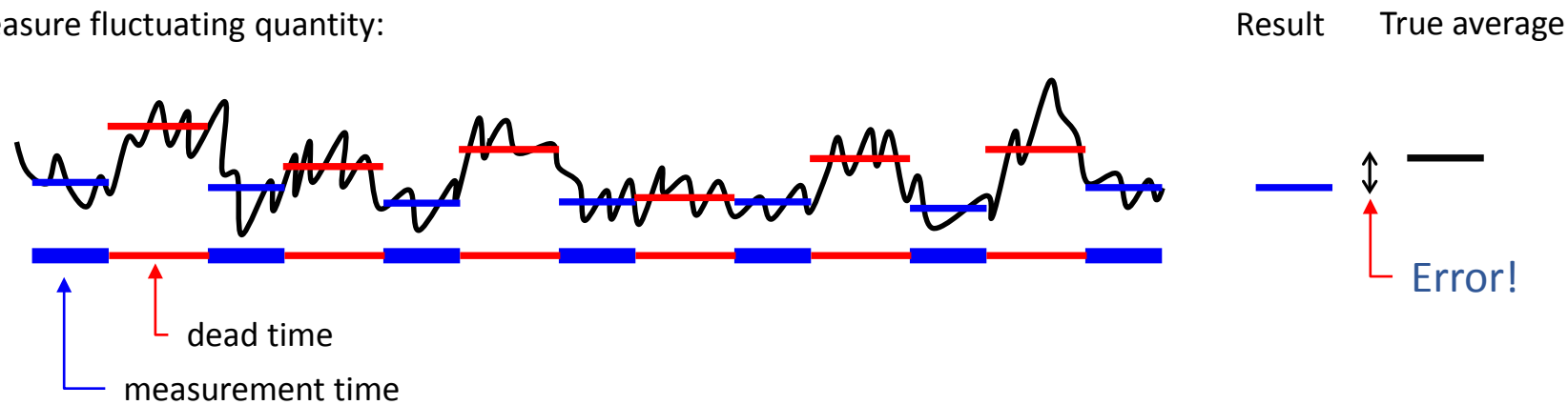
Traditional atom interferometers work in pulsed mode



To measure quantity of interest with high precision, we need to average many measurements.

We cannot resolve fast fluctuation of quantity of interest.

Measure fluctuating quantity:



Dick effect

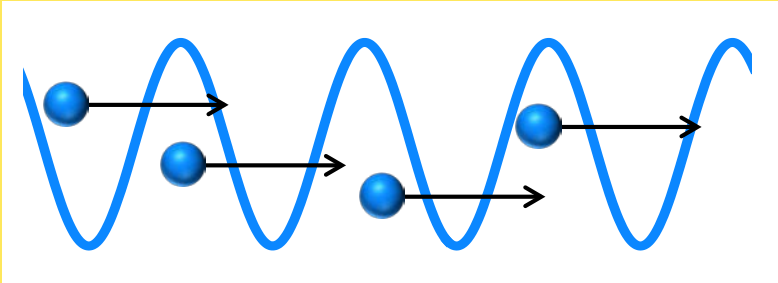
noise with same frequency as measurement repetition frequency is sampled incorrectly

Remedies

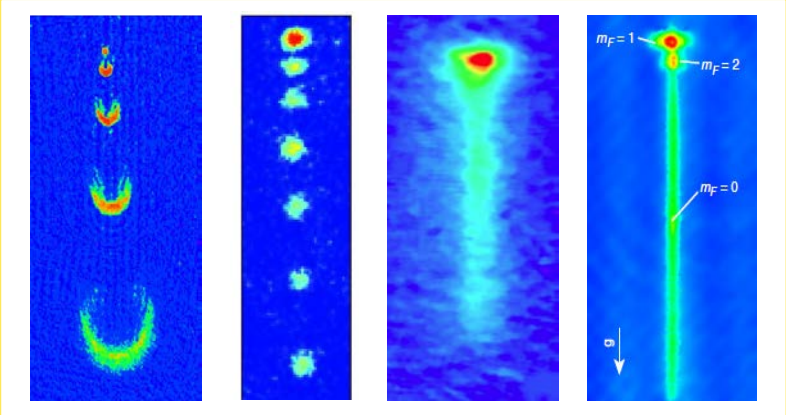
- alternate two measurement devices and average results
- measure continuously → use continuous atom laser

Overview

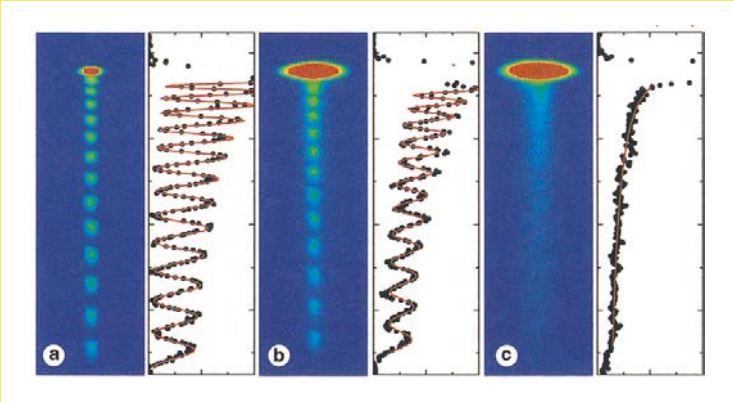
What? Why?



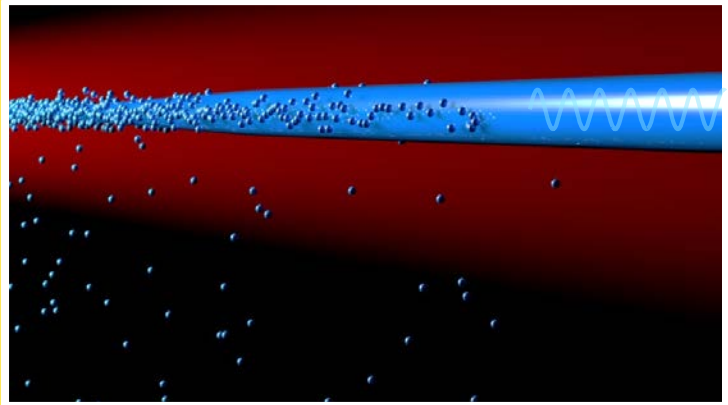
Pulsed atom lasers



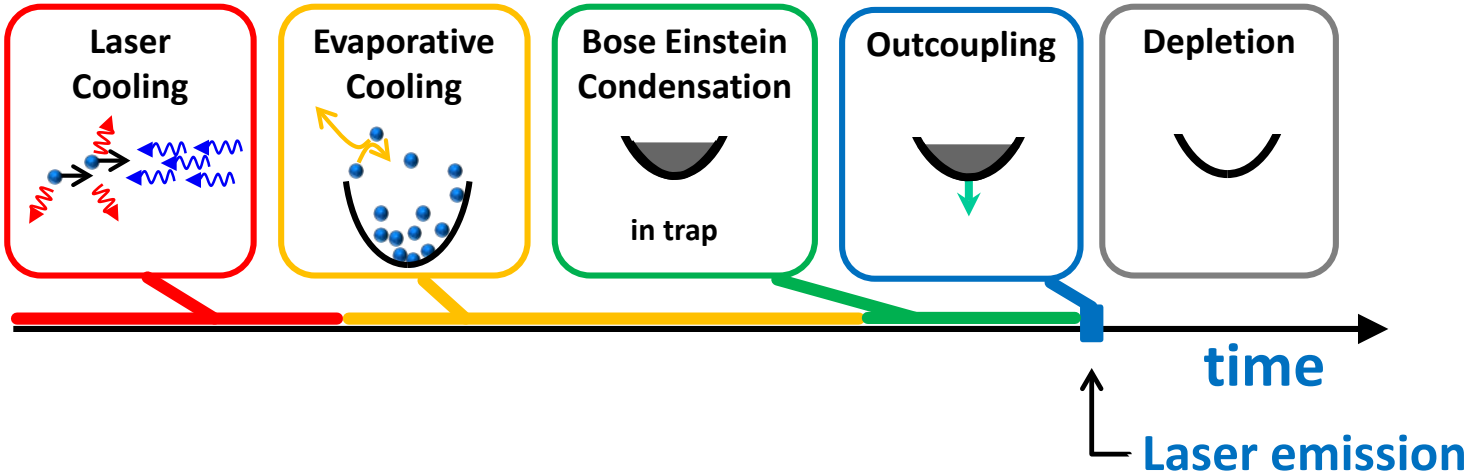
Experiments with atom lasers

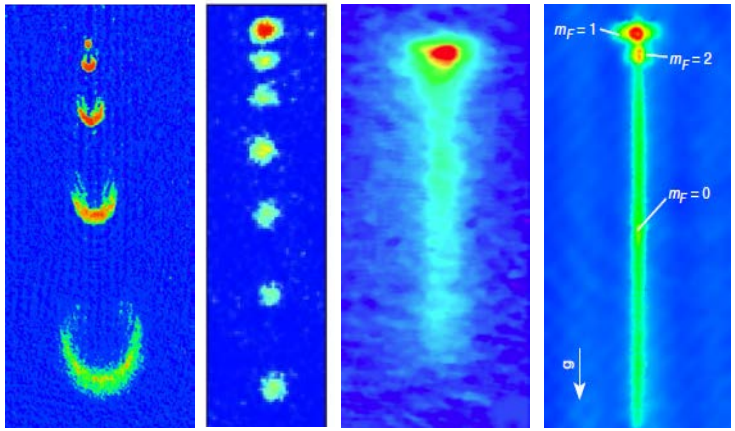


Continuous atom lasers



State-of-the-art: pulsed atom laser





MIT 1997 | Yale 1998 | NIST 1999 | Munich 1999

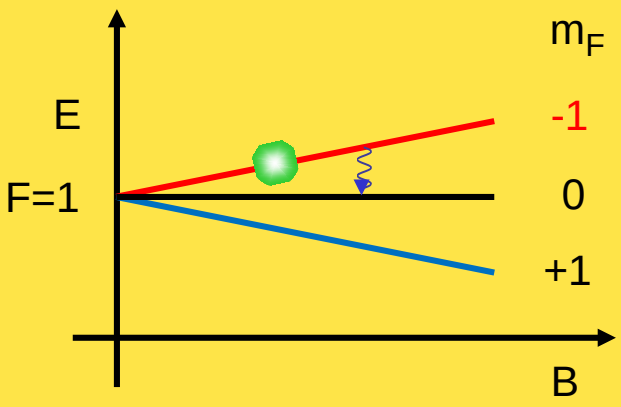
Outcoupling mechanisms

- radiofrequency outcoupling
- Raman outcoupling
- spilling from dipole trap
- outcoupling from lattice

Radiofrequency outcoupling

Starting point:
atoms in magnetic trap

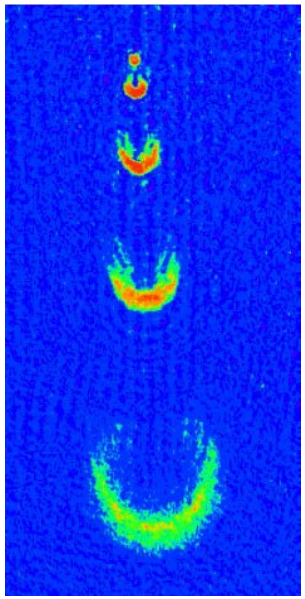
Outcoupling to non-magnetic state



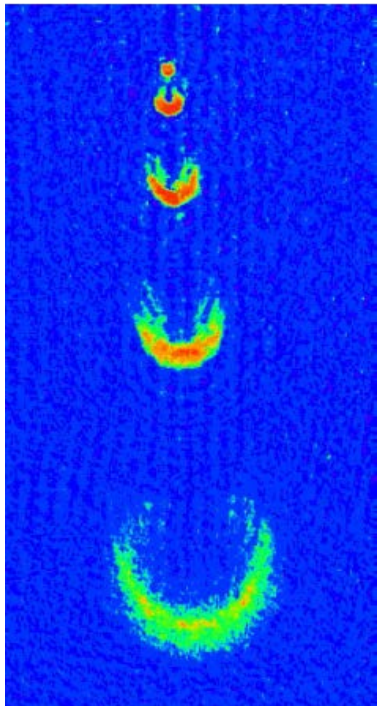
First realization

Ketterle group, PRL 78, 582 (1997)

short radiofrequency pulses



Why this pulse shape?

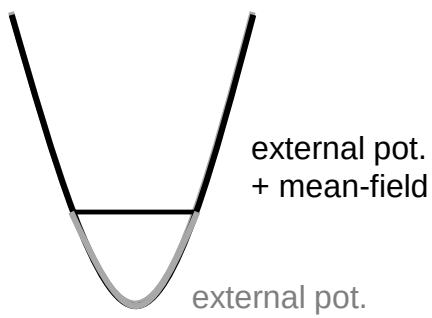


Magnetic field was unstable
→ short pulses used to broaden Fourier width
→ rf pulse addresses all atoms, irrespective of position in trap
→ each pulse creates “copy” of BEC in $m_F = 0$ state

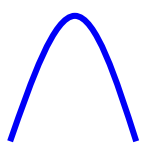
Each copy falls and expands under influence of mean-field interactions

Trapped BEC

Potential

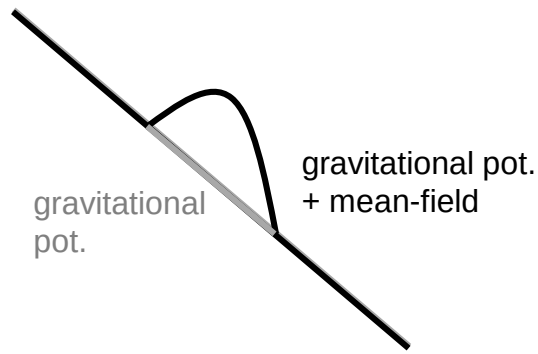


BEC density



Outcoupled m_F=0 BEC

Potential



BEC density

trapped

outcoupled

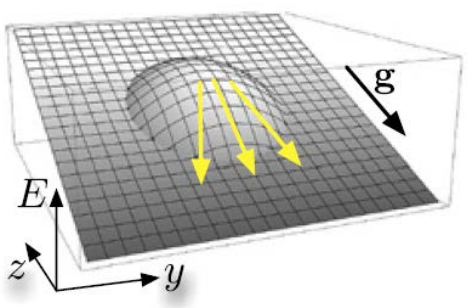
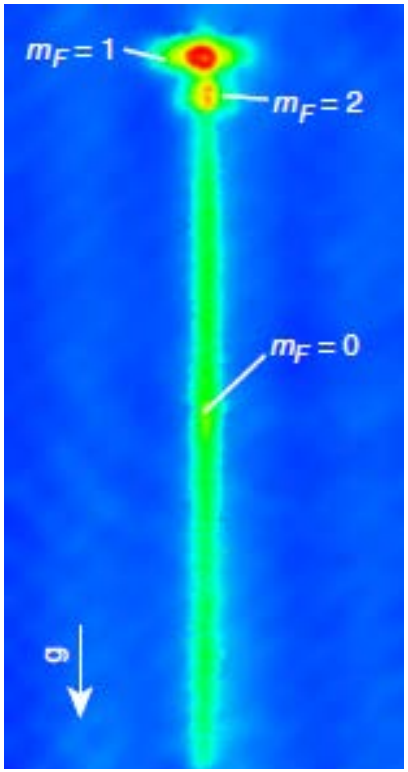


Figure from [1]

Continuous radiofrequency outcoupling

Very stable magnetic fields allow continuous outcoupling

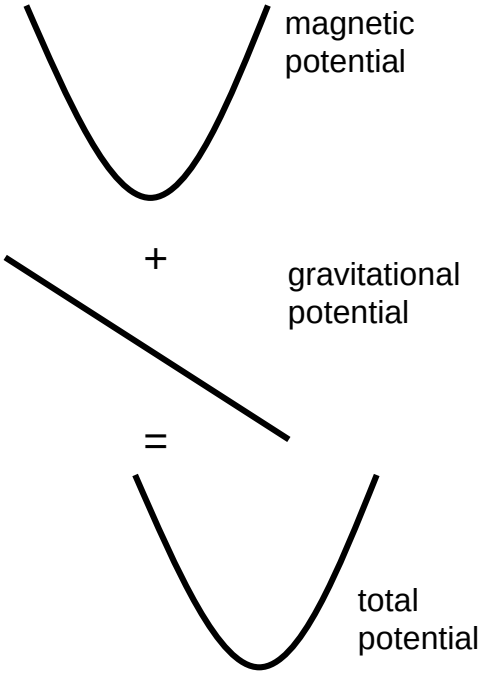
I. Bloch, T.W. Hänsch, T. Esslinger, PRL 82, 3008 (1999)



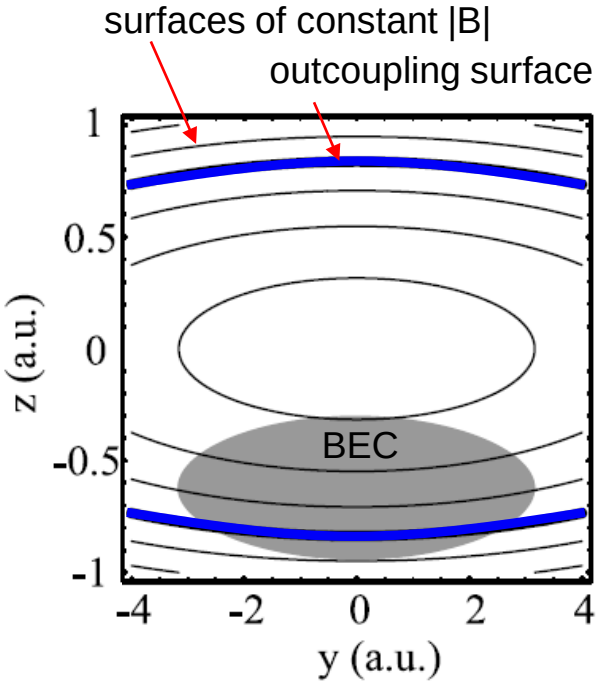
continuous radiofrequency has narrow Fourier width
→ outcoupling occurs at specific locations

Where?

Consider gravitational sagging:



Select outcoupling surface by rf frequency



Continuous radiofrequency outcoupling

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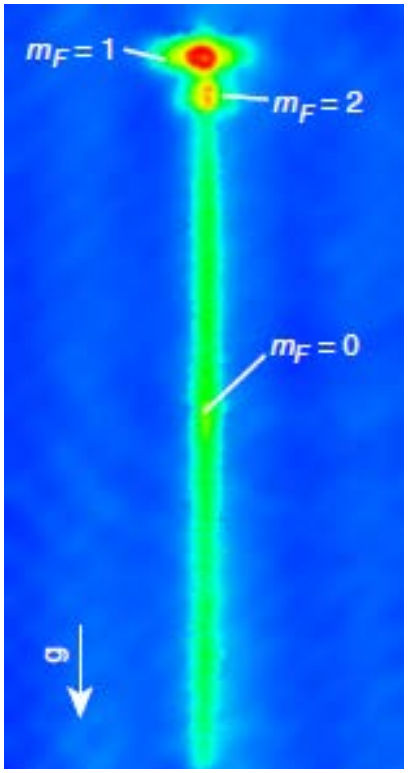
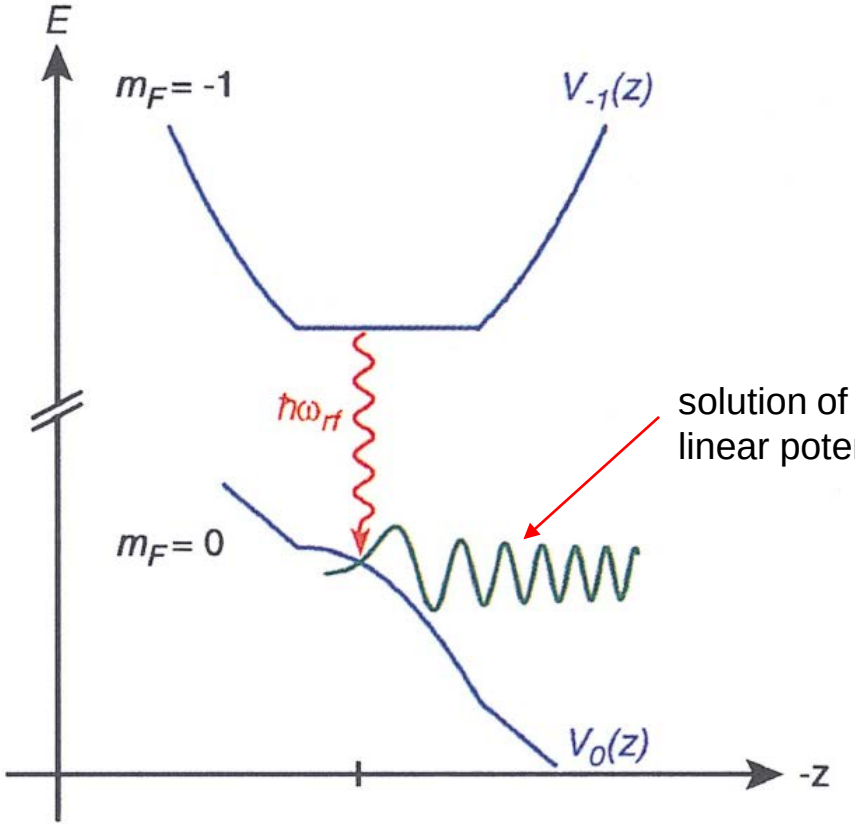




solution of Schrödinger eqn. in linear potential = Airy function

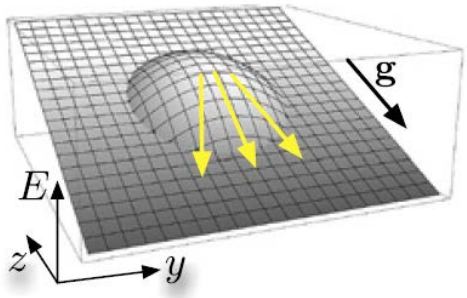
Figure from Bloch, Hänsch, Esslinger, *Atom lasers and phase coherence of atomic Bose gases*, RIKEN review 33 (2001)

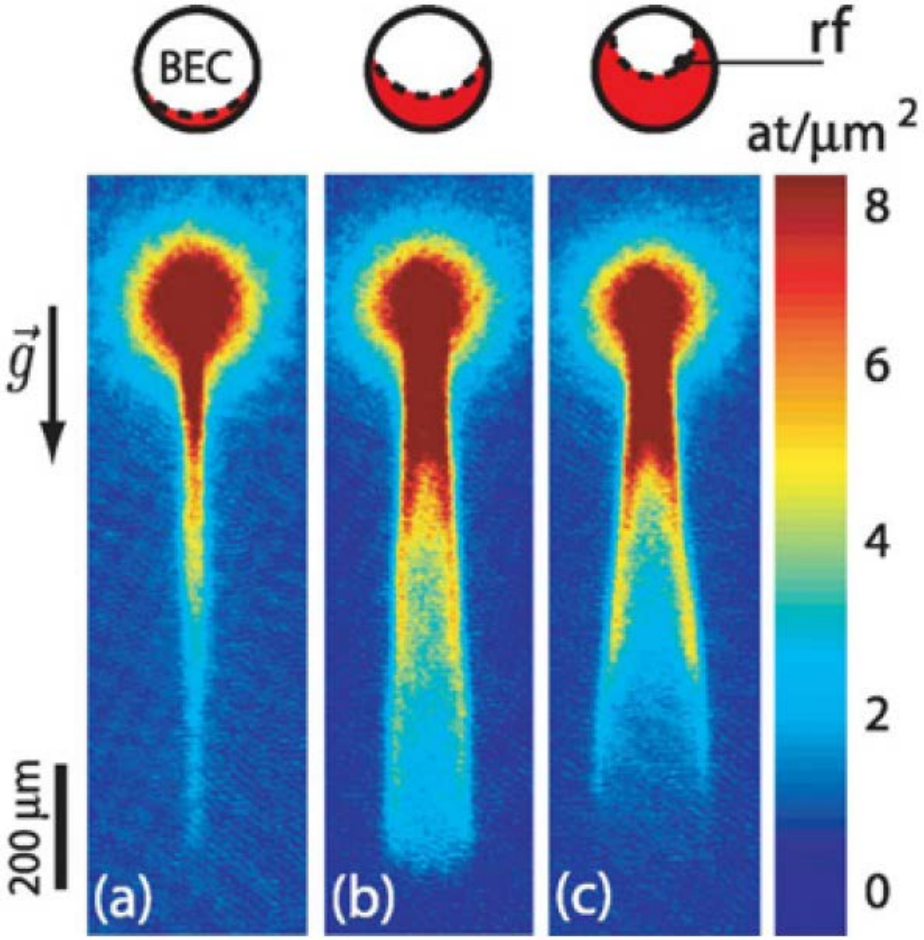
Spatial mode

Mean-field influences expansion
→ spatial mode depends on outcoupling surface

Esslinger group, PRA 72, 063618 (2005)

Aspect group, PRL 96, 070404 (2006)

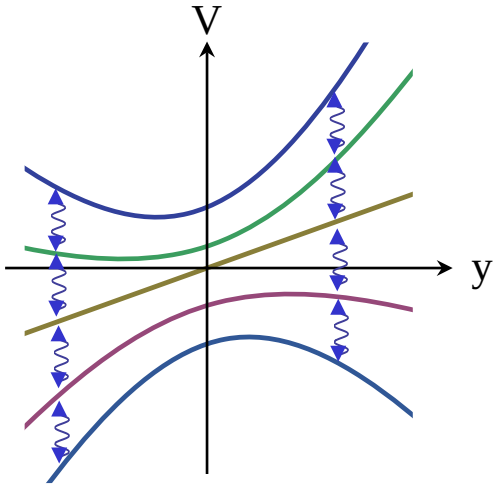




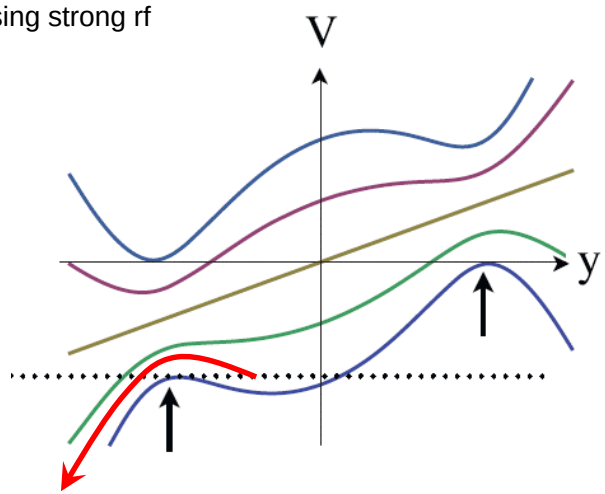
Aspect group, PRL 96, 070404 (2006)

High-flux outcoupling

Uncoupled states



Rf dressed states
using strong rf

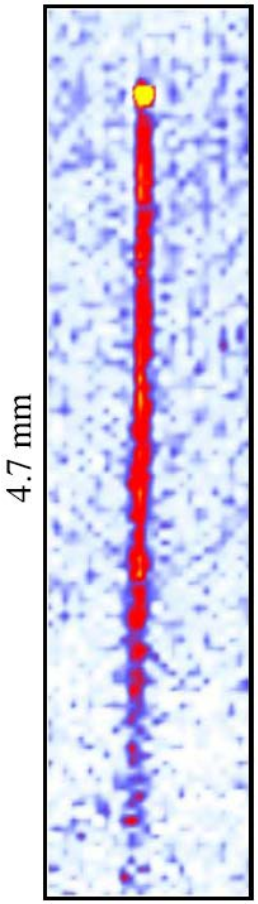


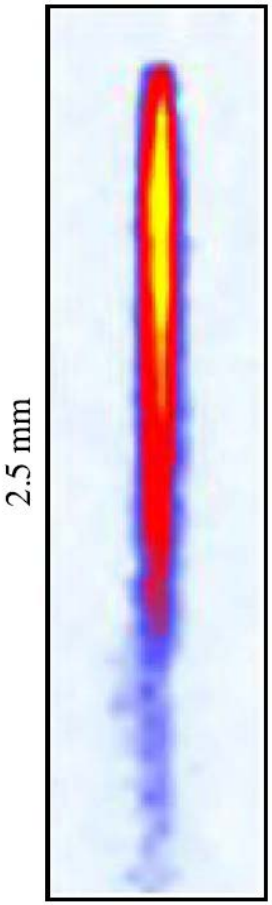
spilling

Klitzing group, New J. Phys. 16, 033036 (2014)

well-collimated

high-flux
4 x 10^7 atoms/s

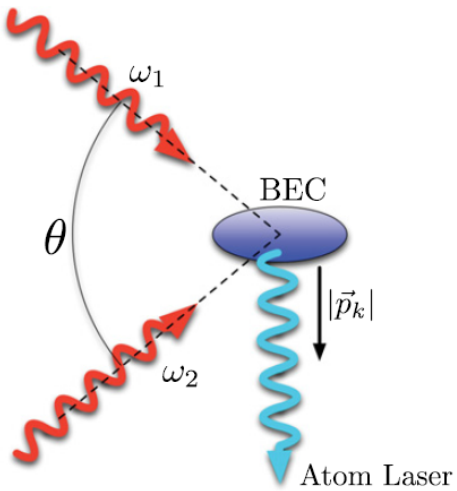


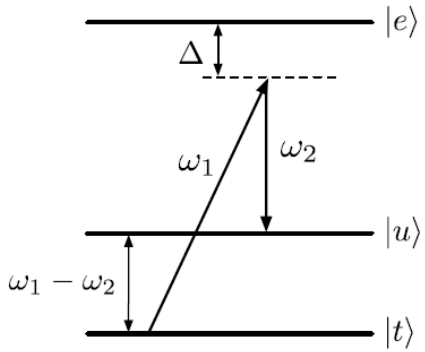


Raman outcoupling

Starting point:
atoms in magnetic or dipole trap

Raman transition imparts momentum
and changes internal state

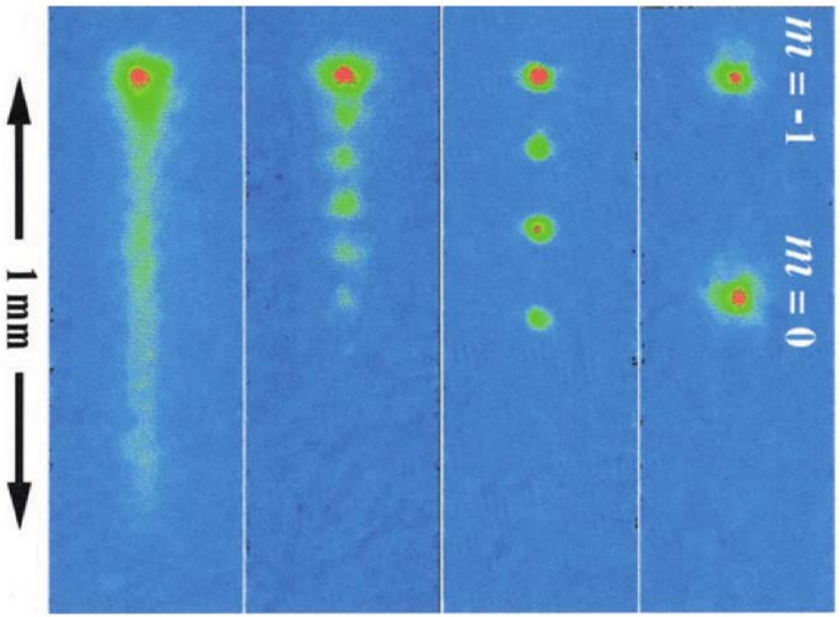




First realization

Phillips group, Science 283, 5408 (1999)

Here: pulsed operation
(required by time-orbiting-potential magnetic trap)



20 kHz repetition rate: “quasi-continuous”

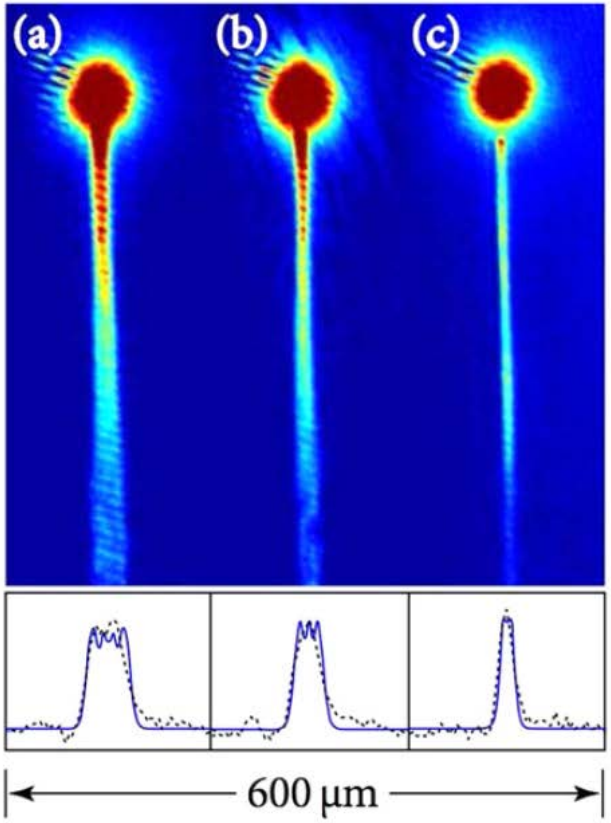
Radiofrequency vs. Raman outcoupling

Raman outcoupling imparts momentum to atom laser
→ less distortion of spatial mode by mean-field potential

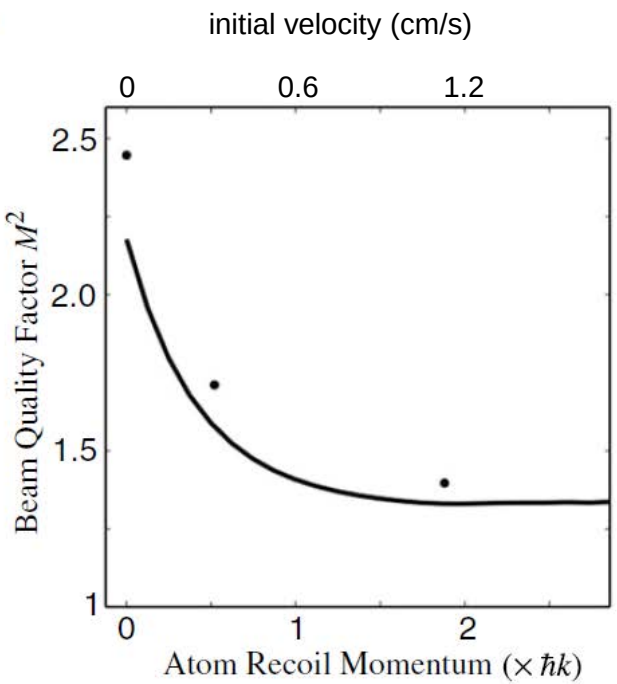
Close group, PR A 77, 063618 (2008)

	RF	Raman	
Initial velocity:	0 cm/s	0.3 cm/s	1.1 cm/s

A



B



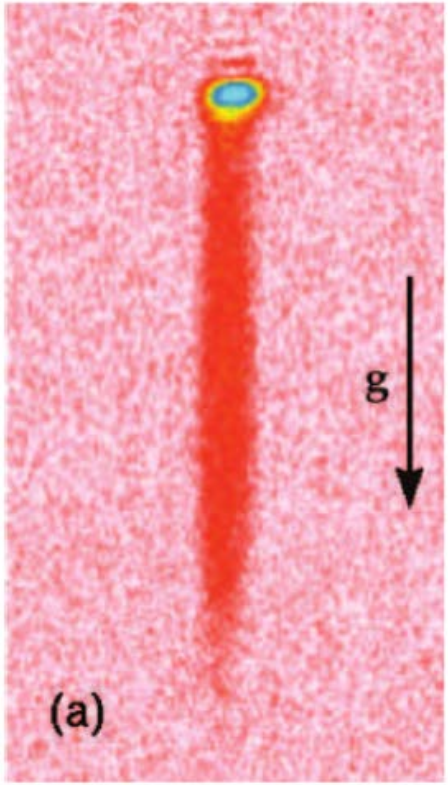
Outcoupling by spilling

Starting point:
atoms in dipole trap

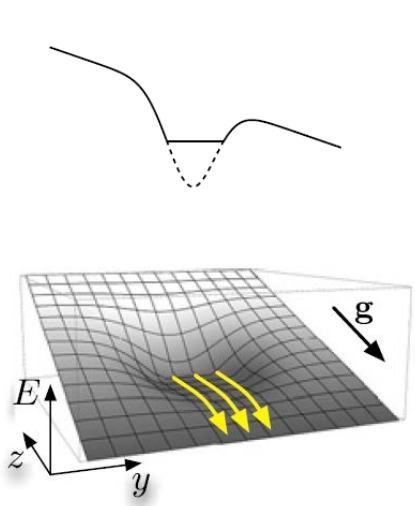
Gradually reduce intensity of dipole trap beam

First realization

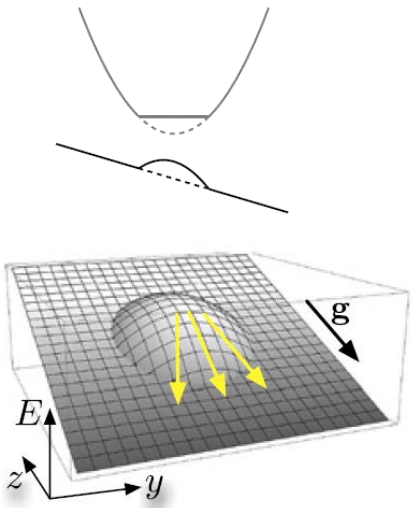
Weitz group, PRL 91, 240408 (2003)



Spilling from dipole trap



Rf outcoupling



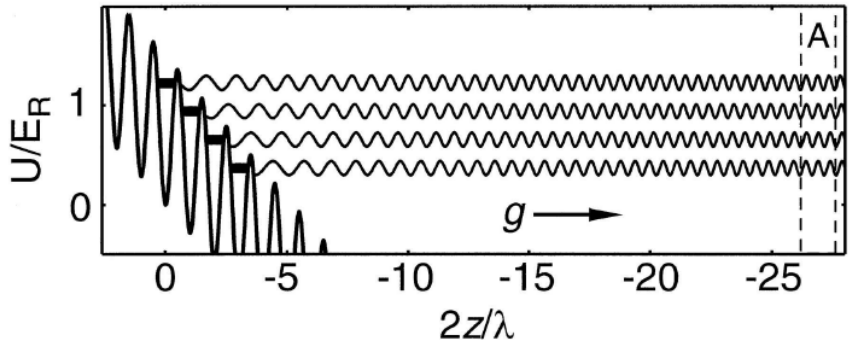
No repulsive mean-field potential
→ better beam quality

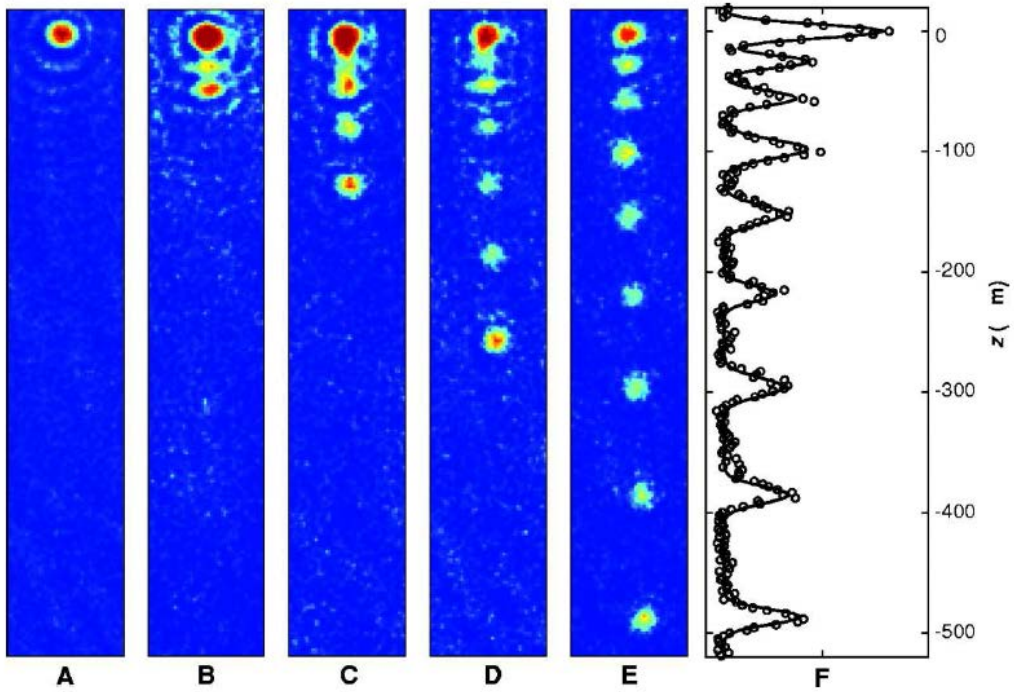
Figures from [1]

Outcoupling from lattice

1D optical lattice+Gravity

Kasevich group, Science 282, 1686 (1998)



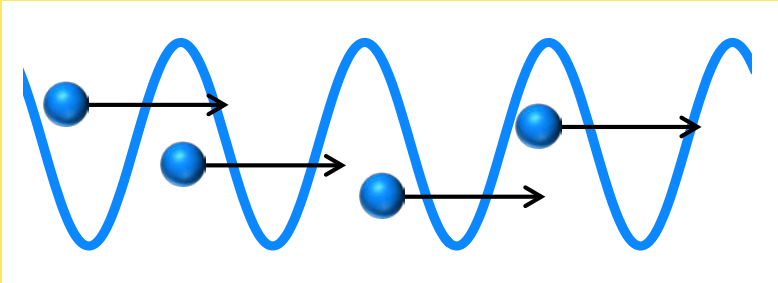


Interference of many Airy functions leads to atom laser pulses

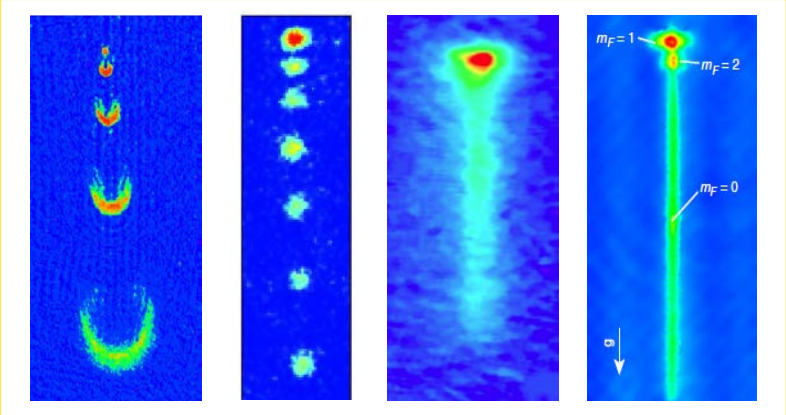
(= Bloch oscillations in lattice with partial Bragg reflection)

Overview

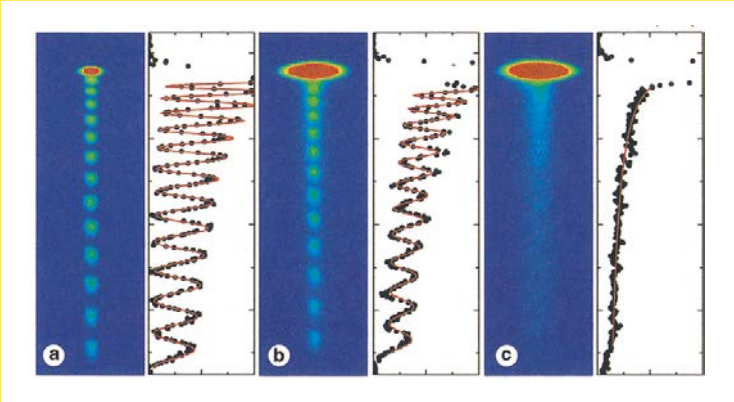
What? Why?



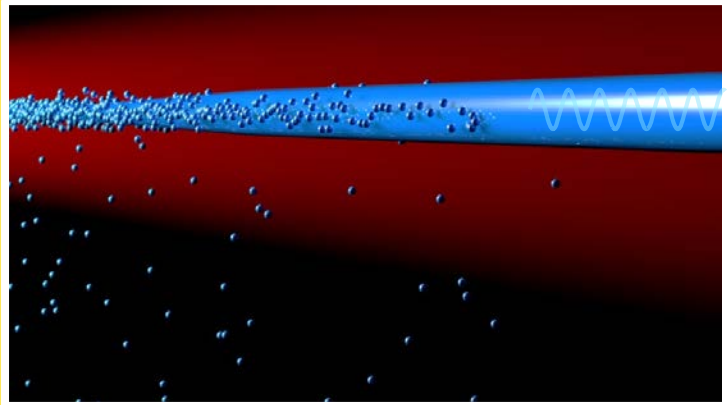
Pulsed atom lasers



Experiments with atom lasers

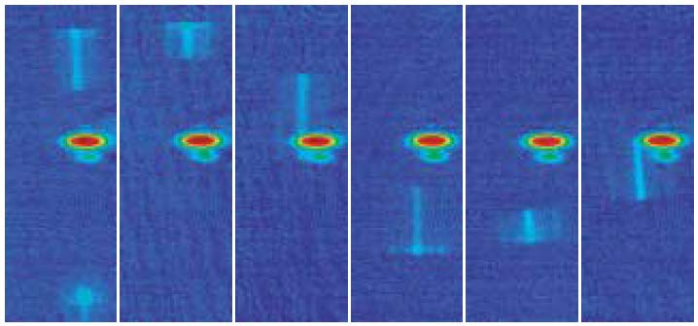


Continuous atom lasers

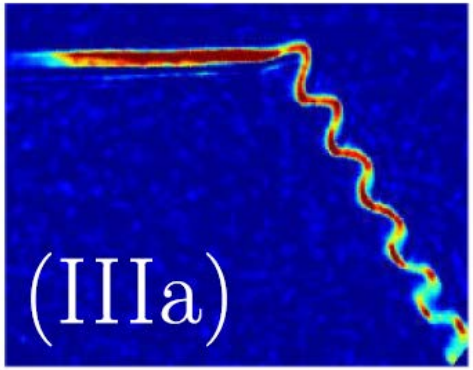


Experiments with atom lasers

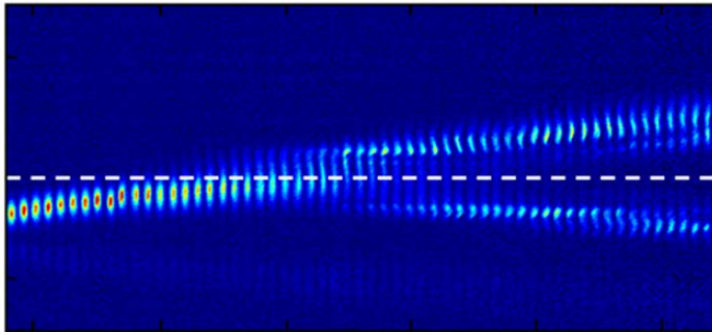
Magnetic mirror & resonator



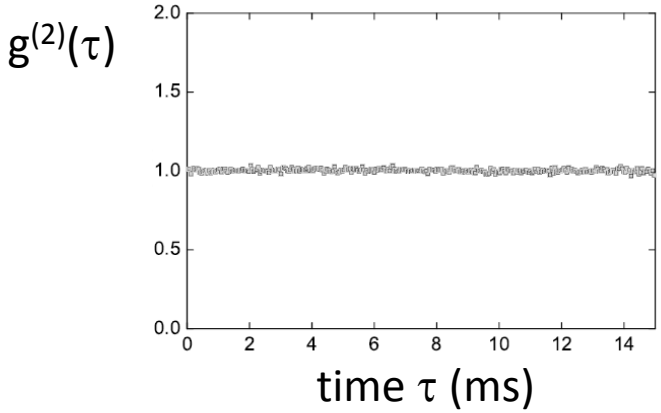
Guided atom lasers



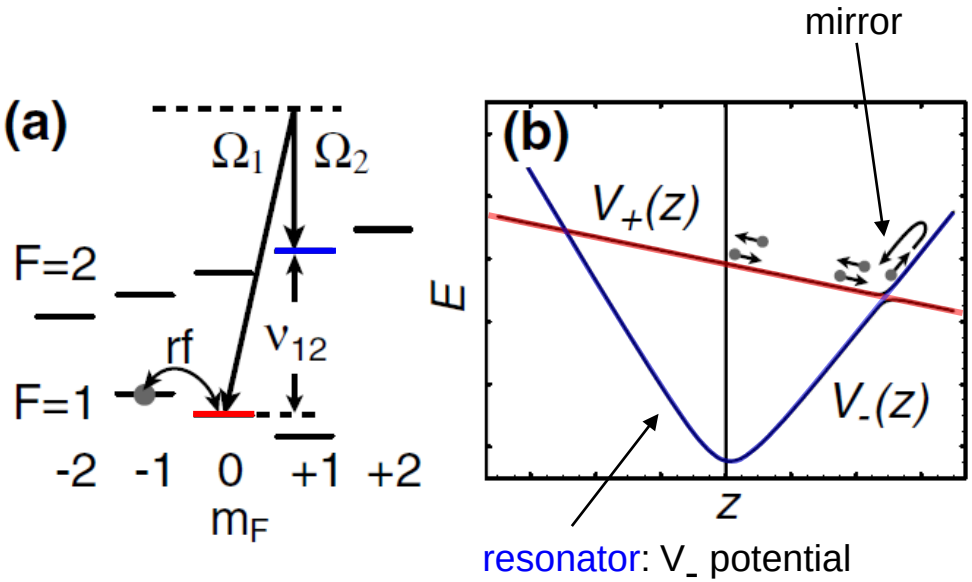
Bragg mirrors and resonator



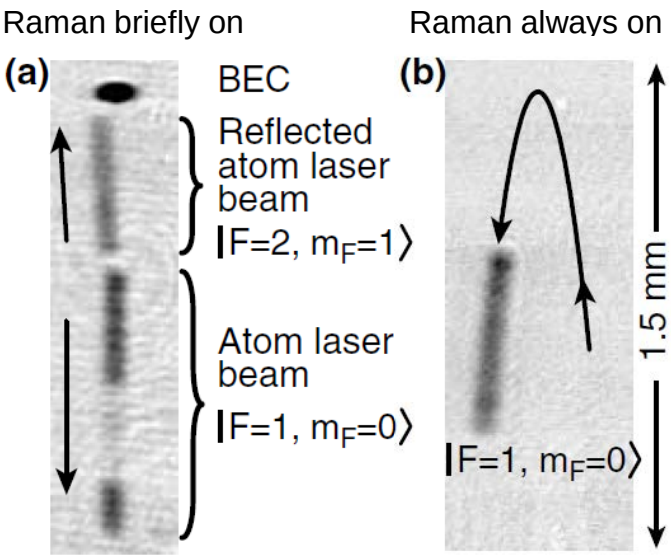
Coherence and correlations



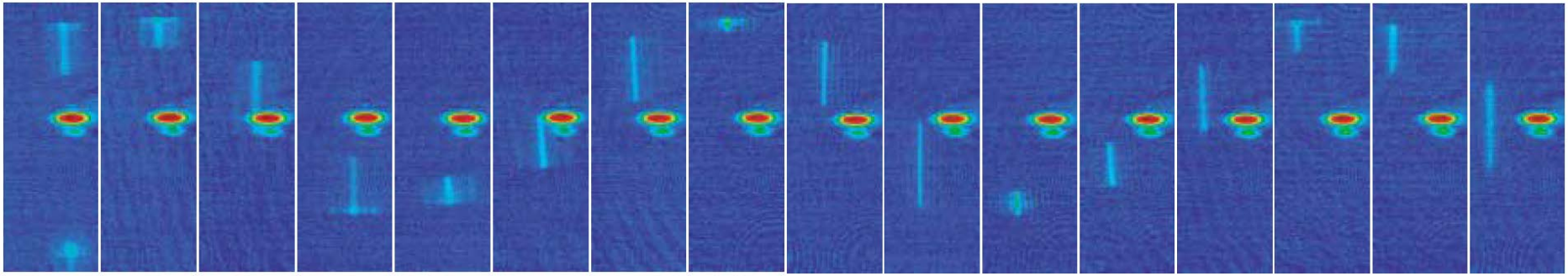
Atom laser mirror and resonator



Esslinger group, PRL 87, 030401 (2001)



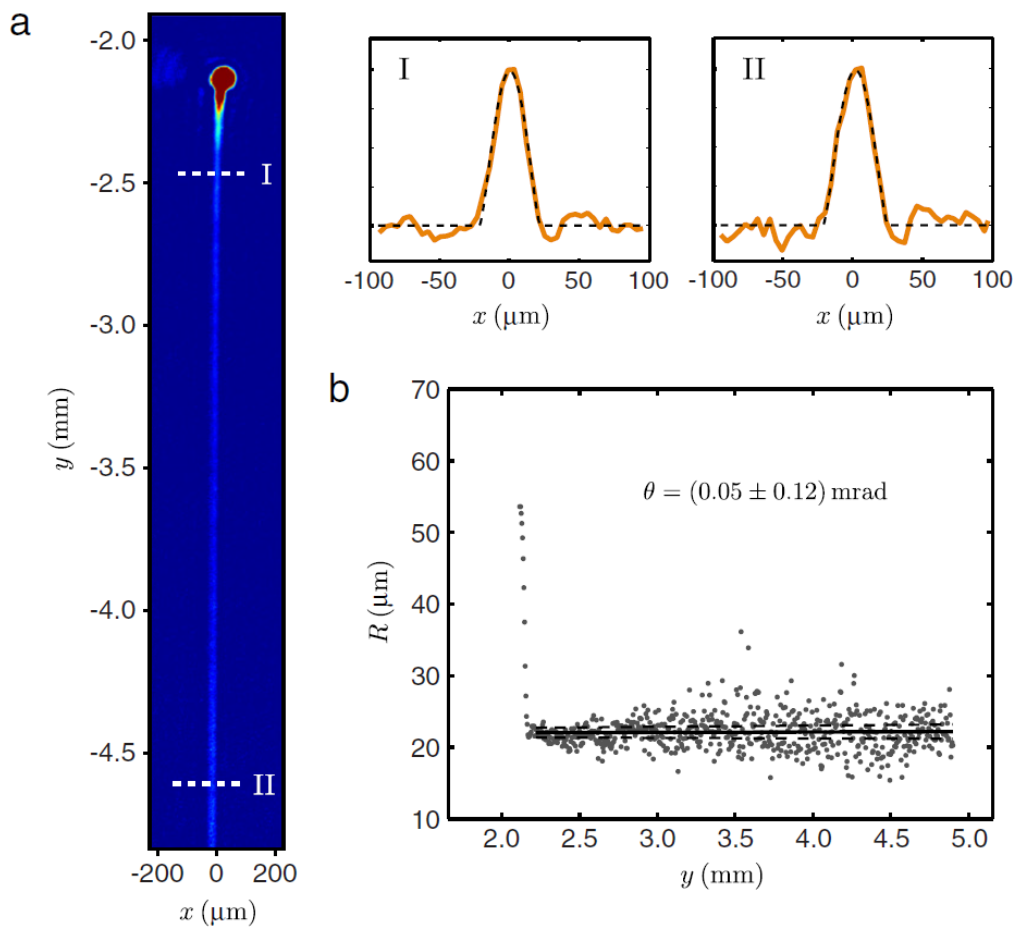
Raman briefly on → load atom laser into resonator → oscillations in resonator



Guided atom lasers

Starting point: BEC in crossed beam dipole trap

Atom laser beam confined in vertical dipole trap → improved spatial beam profile

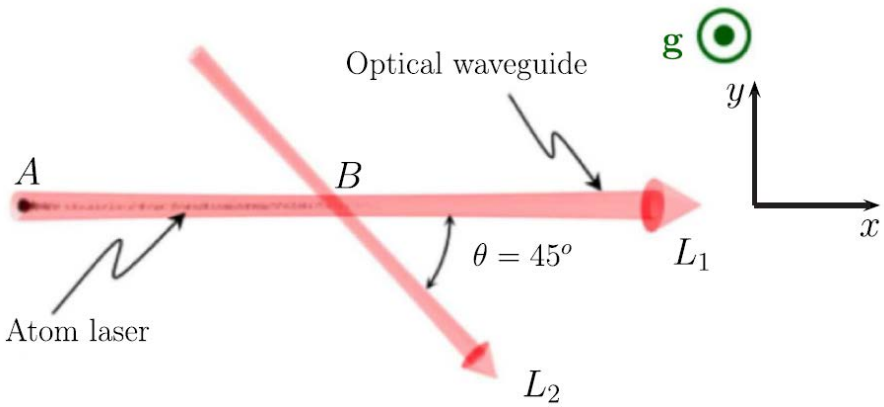


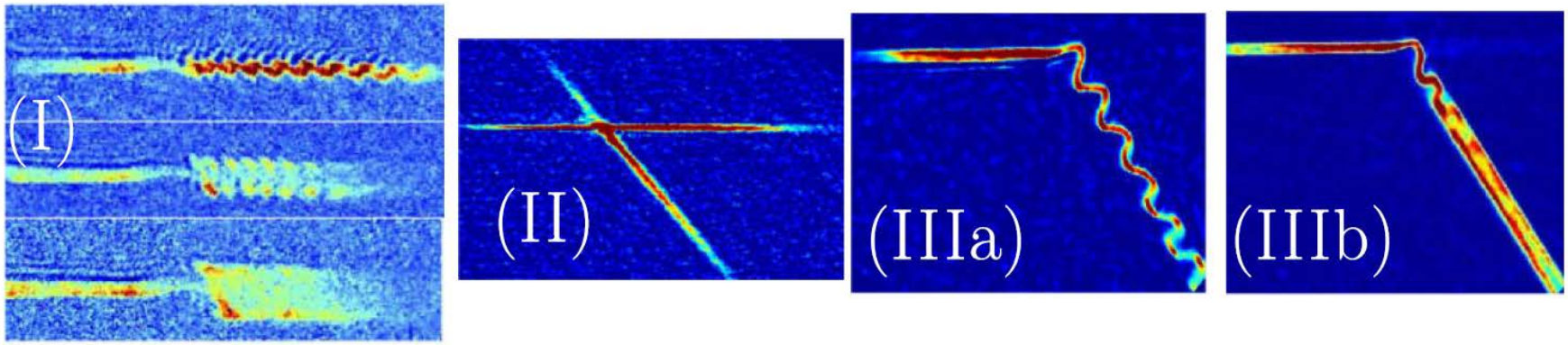
P.A. Altin, Ph.D. thesis, The Australian National University (2012)

Atom laser beam splitter

Optically guided beam splitter

Guéry-Odelin group, PRL 109, 030403 (2012)



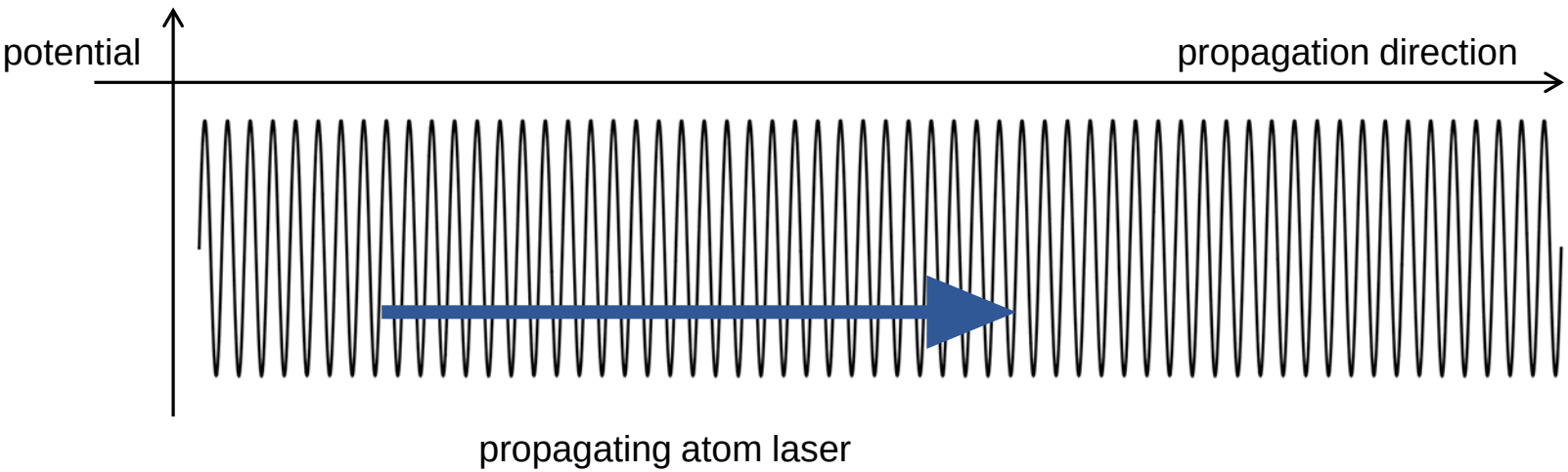


power laser L_2 / power laser L_1

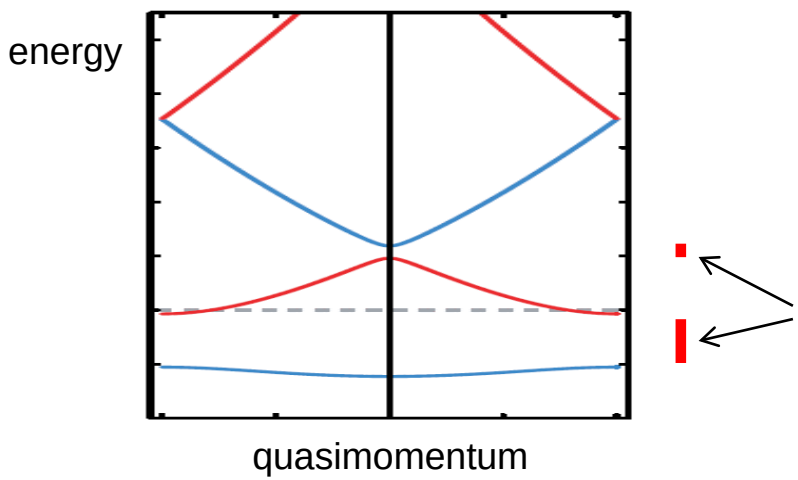
Atom laser Bragg mirror

Guéry-Odelin group, EPL 103, 50006 (2013)

Lattice potential



Band structure



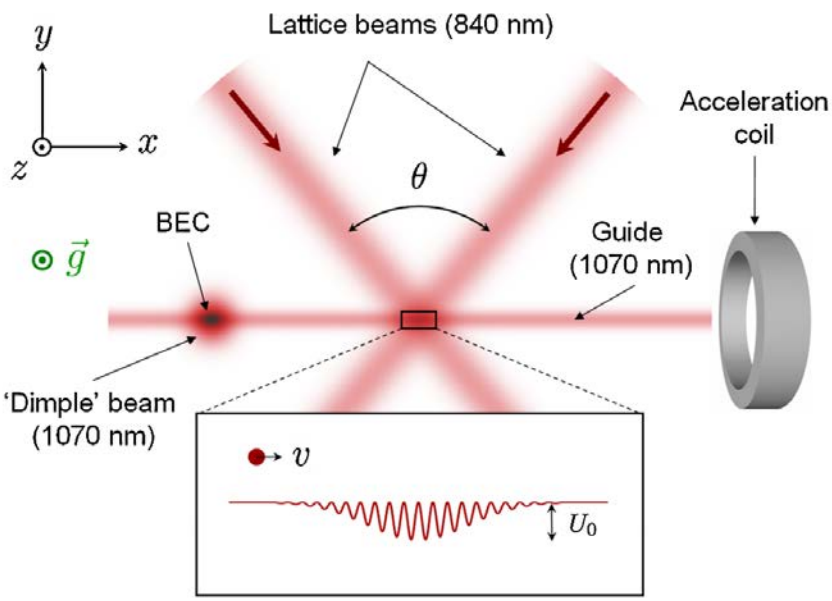
forbidden bands

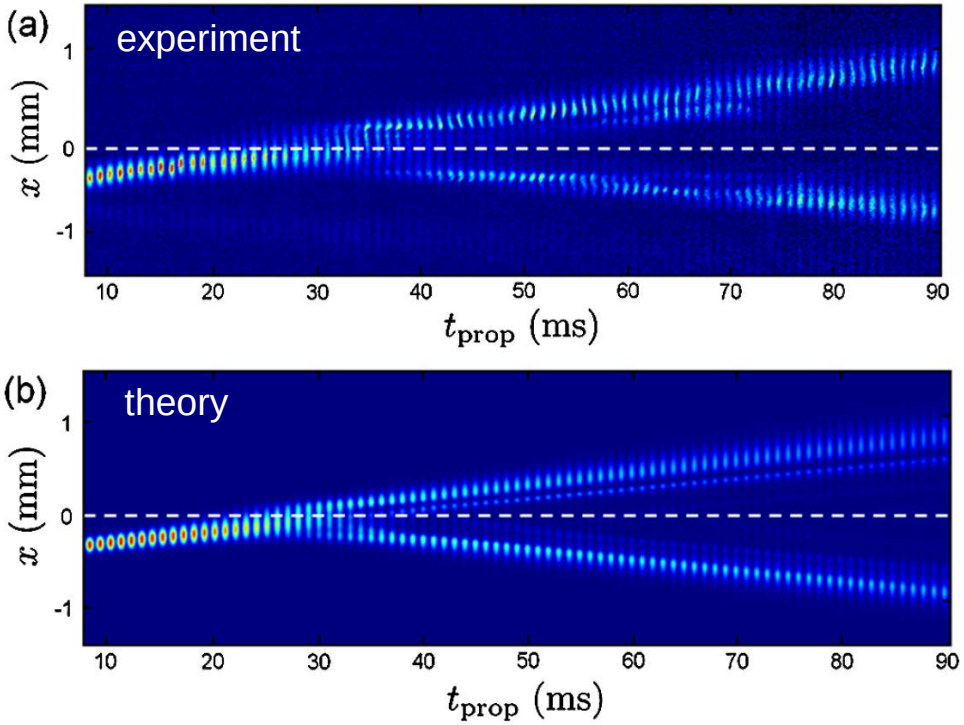
→ no propagating matter wave at these energies

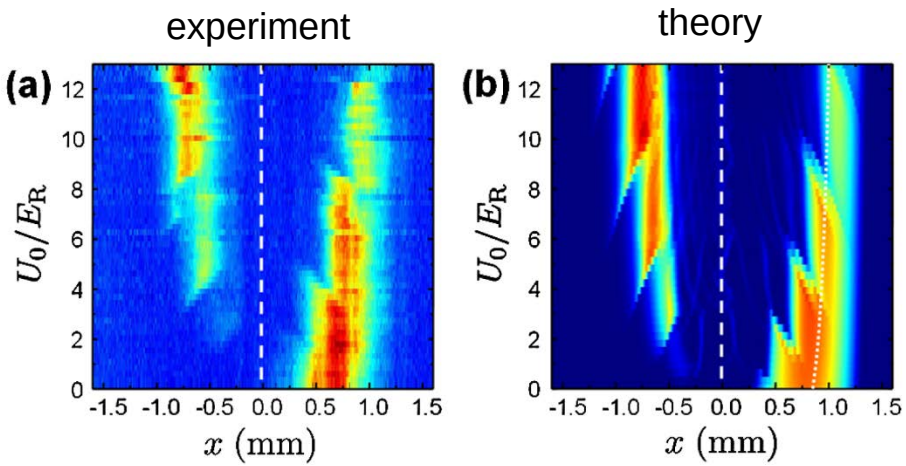
→ energy dependent mirror

Atom laser Bragg mirror

Guéry-Odelin group, PRL 107, 230401 (2011)

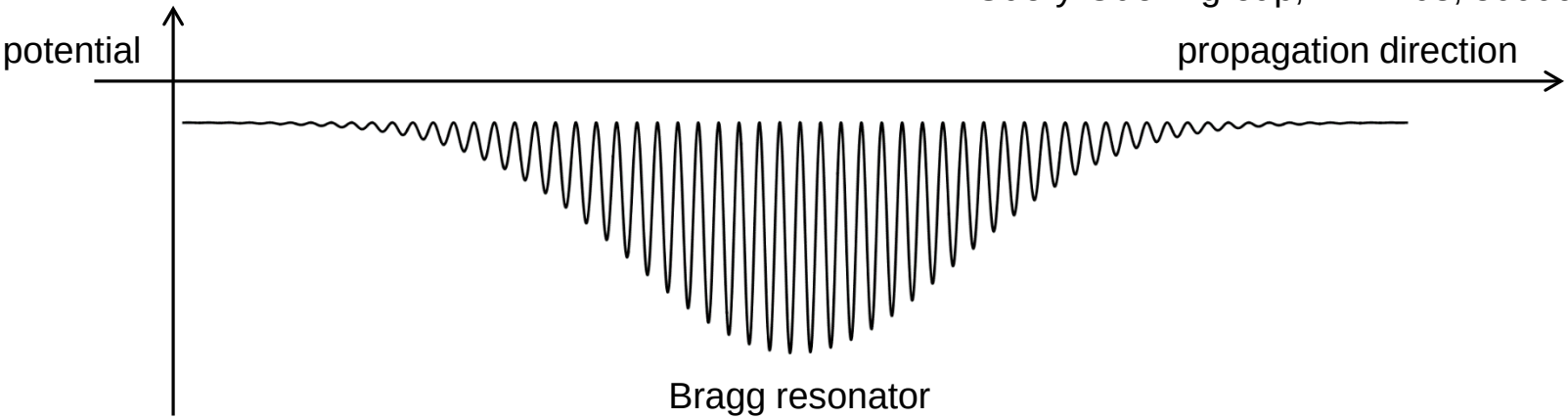


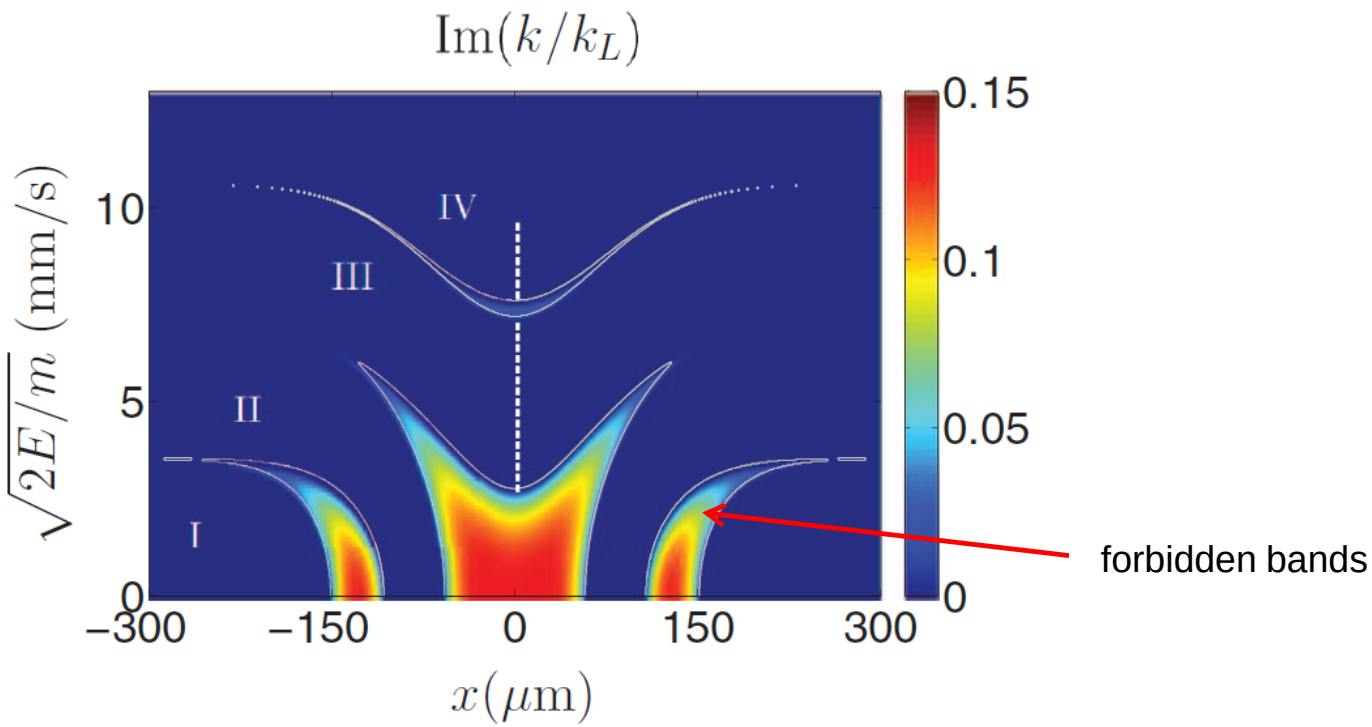




Atom laser Bragg cavity

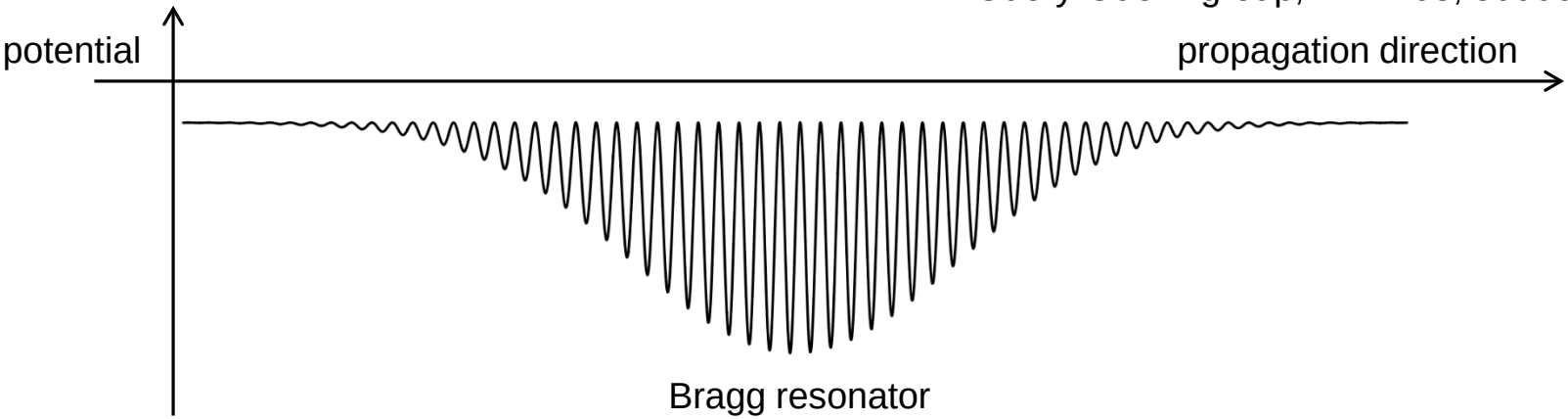
Guéry-Odelin group, EPL 103, 50006 (2013)

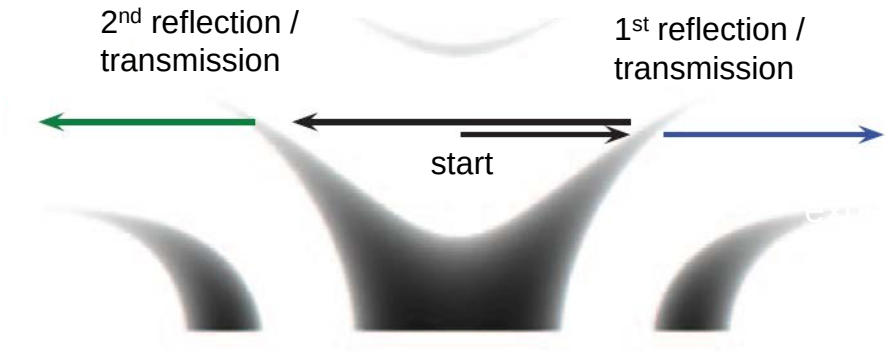




Atom laser Bragg cavity

Guéry-Odelin group, EPL 103, 50006 (2013)



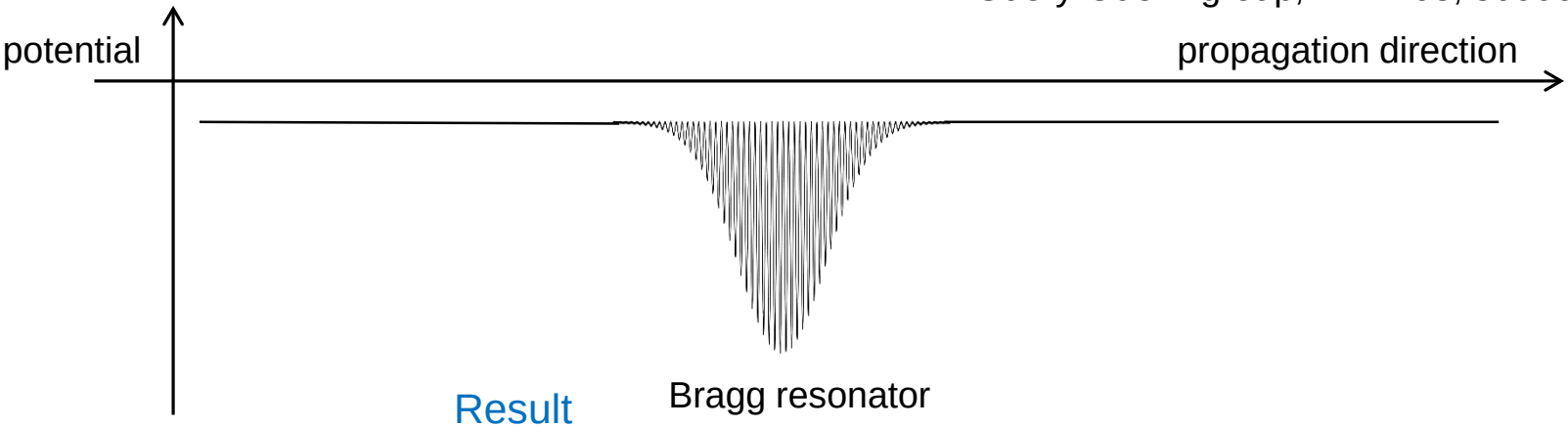


Procedure

1) Give atom laser velocity of 9.4mm/s using B-field gradient
2) Adiabatically ramp up resonator (in 0.1ms)
3) Let atom laser evolve
4) Image

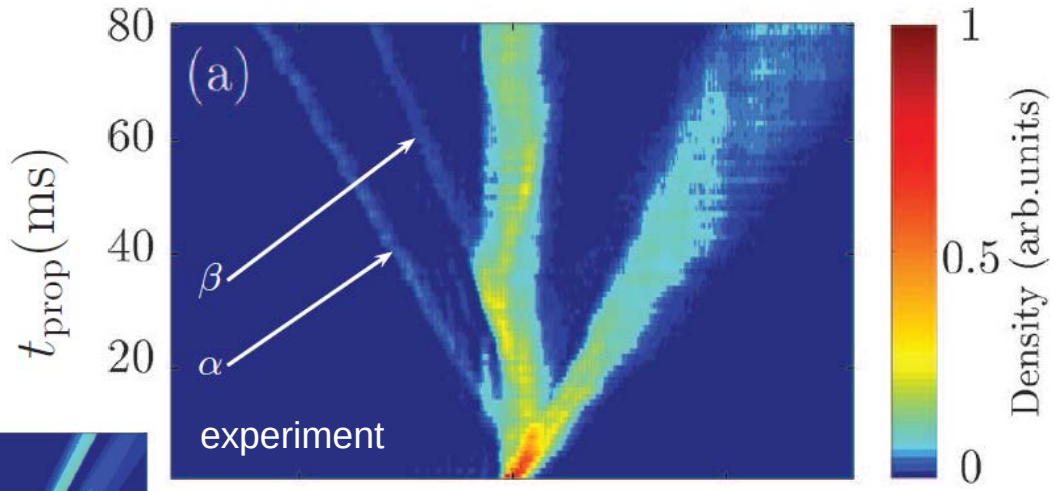
Atom laser Bragg cavity

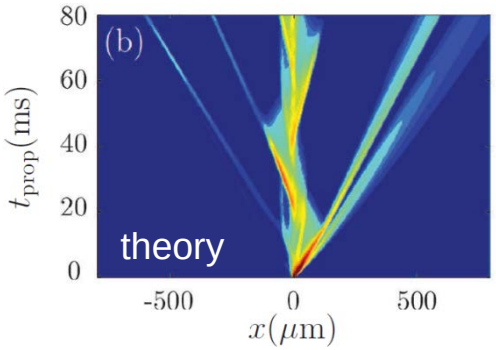
Guéry-Odelin group, EPL 103, 50006 (2013)



Bragg resonator

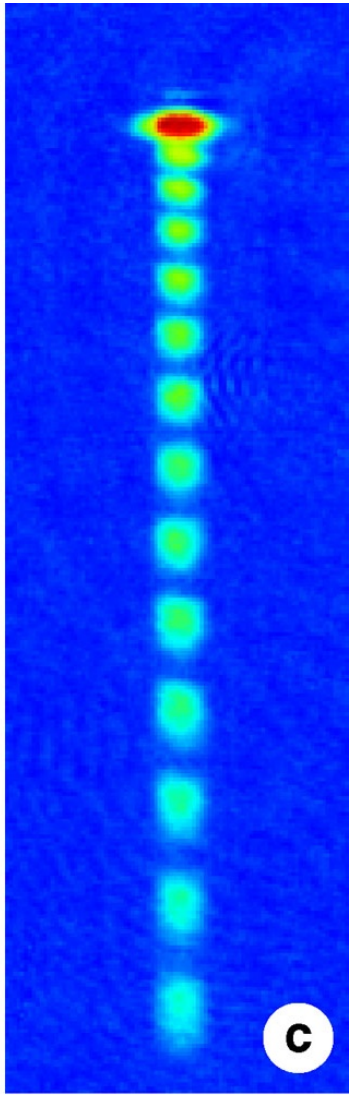
Result



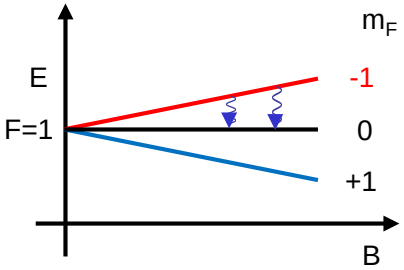


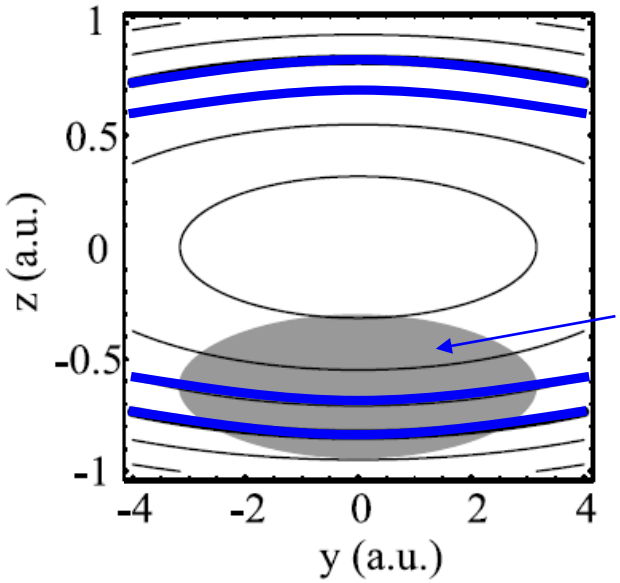
Interfering two atom lasers

Esslinger group, Riken Review No. 33, 6 (2001)



Outcoupling with two radiofrequencies

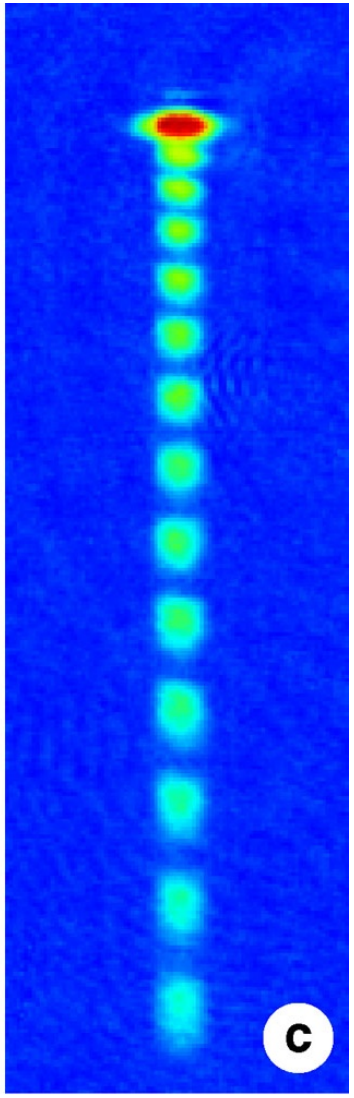


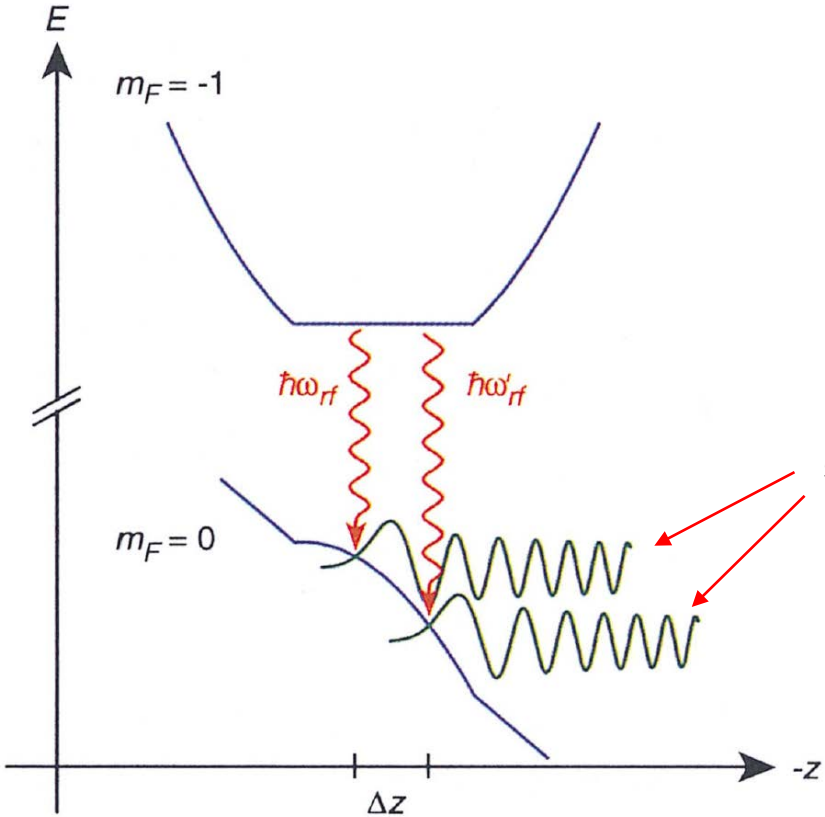


surfaces of constant |B|

BEC, displaced by gravity

Interfering two atom lasers





solutions of Schrödinger eqn. in linear potential = Airy function

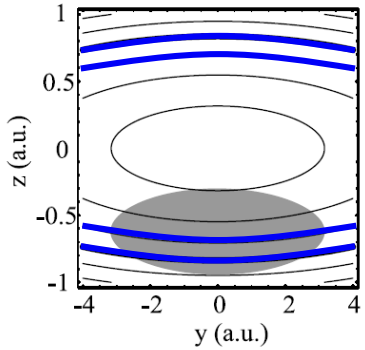
Interference of atom laser beams:

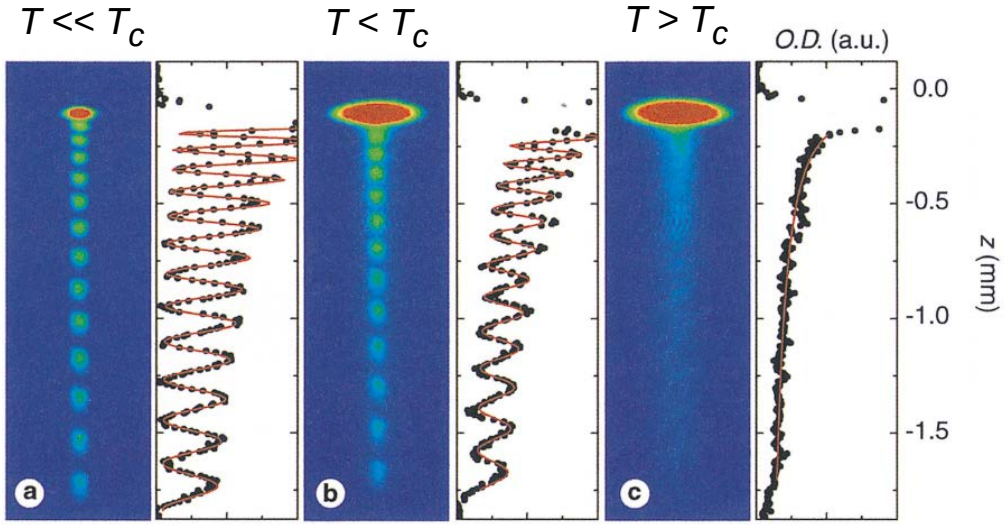
$$n(z,t) \propto \frac{1}{\sqrt{|z|}} \left\{ 2 + 2V \cos\left(q\sqrt{|z|} + \Delta E t/\hbar \right) \right\}$$

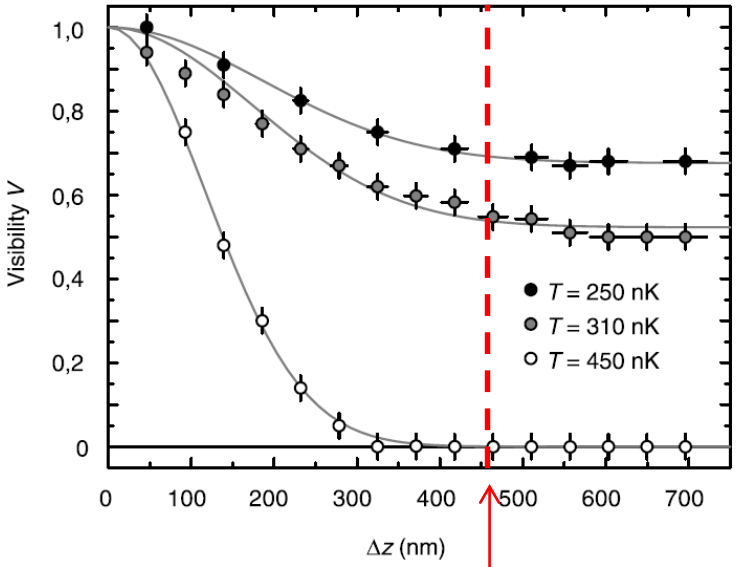
Spatial coherence of source BEC

Esslinger group, Riken Review No. 33, 6 (2001)

Choose distance between outcoupling surfaces by selecting rf frequencies

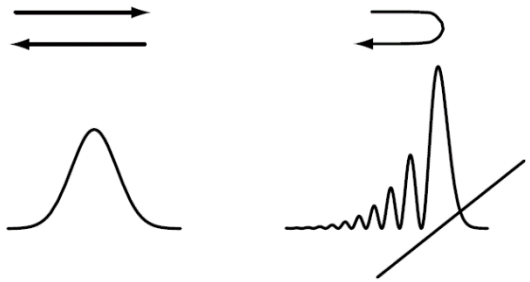






Temporal coherence of atom laser

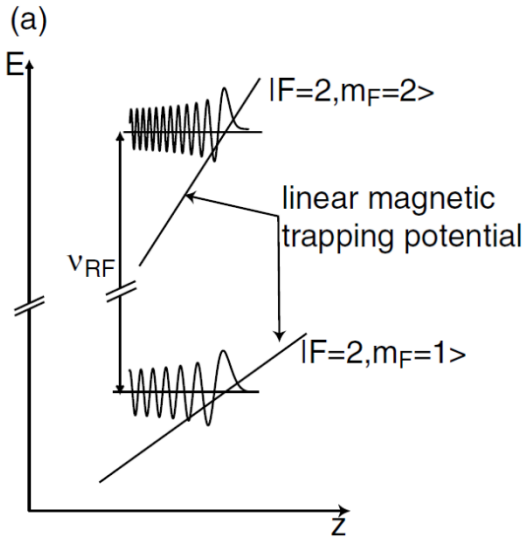
Atom laser reflecting on mirror:
in and outgoing wave packets interfere

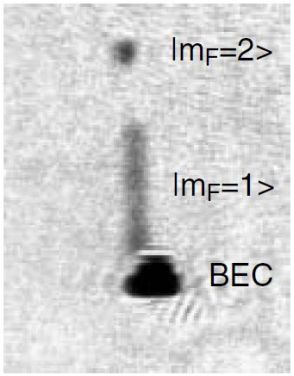


Fringes would smear out if no temporal coherence
→ measure fringes to measure coherence

Fringes have spacing of 150 nm → too small to be imaged

Perform spectroscopy
exploit variation in wavefunction overlap

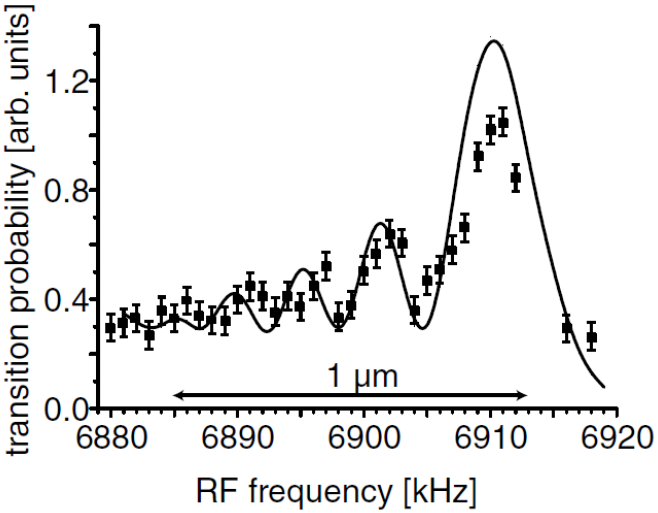




Esslinger group, PRL 87, 16040 (2001)

Measurement procedure

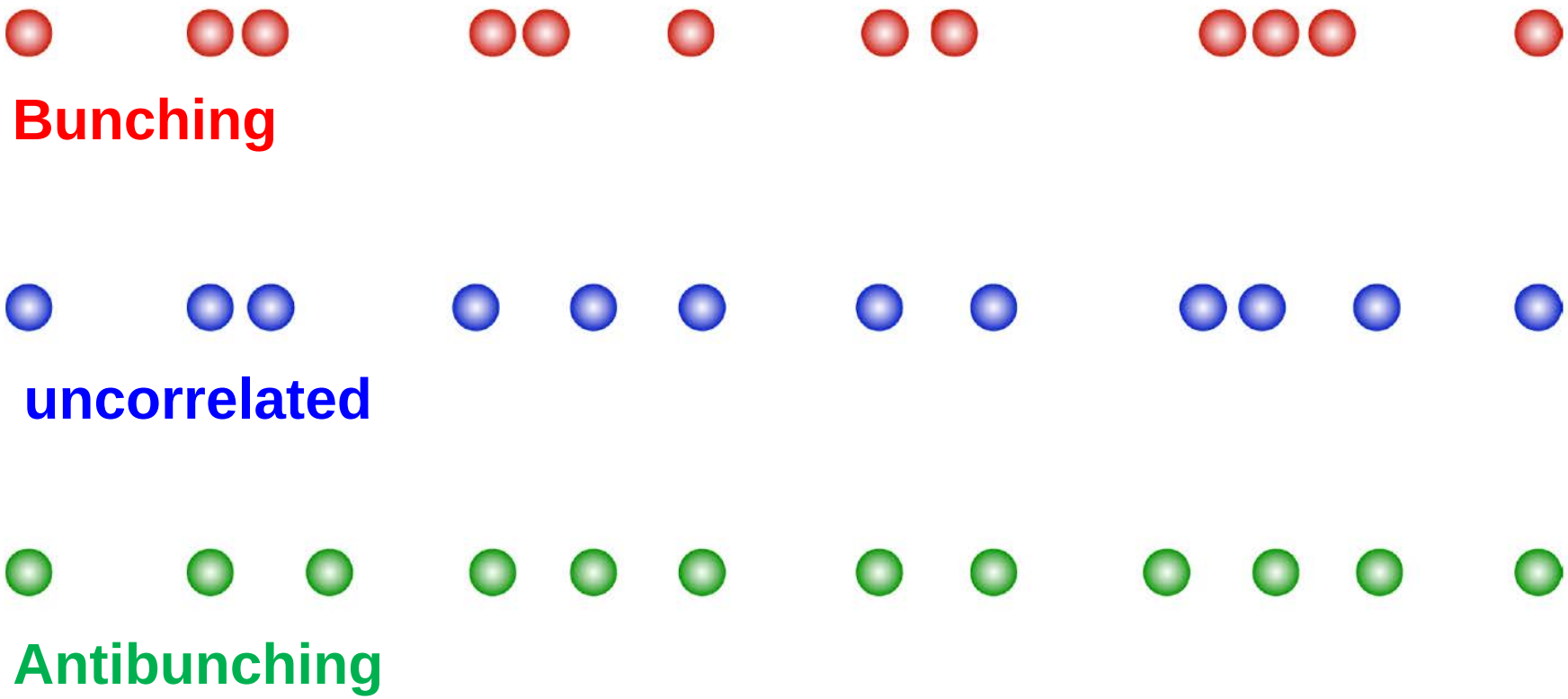
1) Prepare atom laser in F=2, m_F=1
2) Reflect laser on magnetic mirror
3) Couple atoms to F=2, m_F=2 states with various turning points, determined by rf. Transfer probability given by overlap integral.
4) Separate m_F=1 and m_F=2 by letting them oscillate in their different potentials
5) Detect atoms, count m_F=1 and m_F=2



→ atom laser linewidth ~700 Hz

Spatial correlations

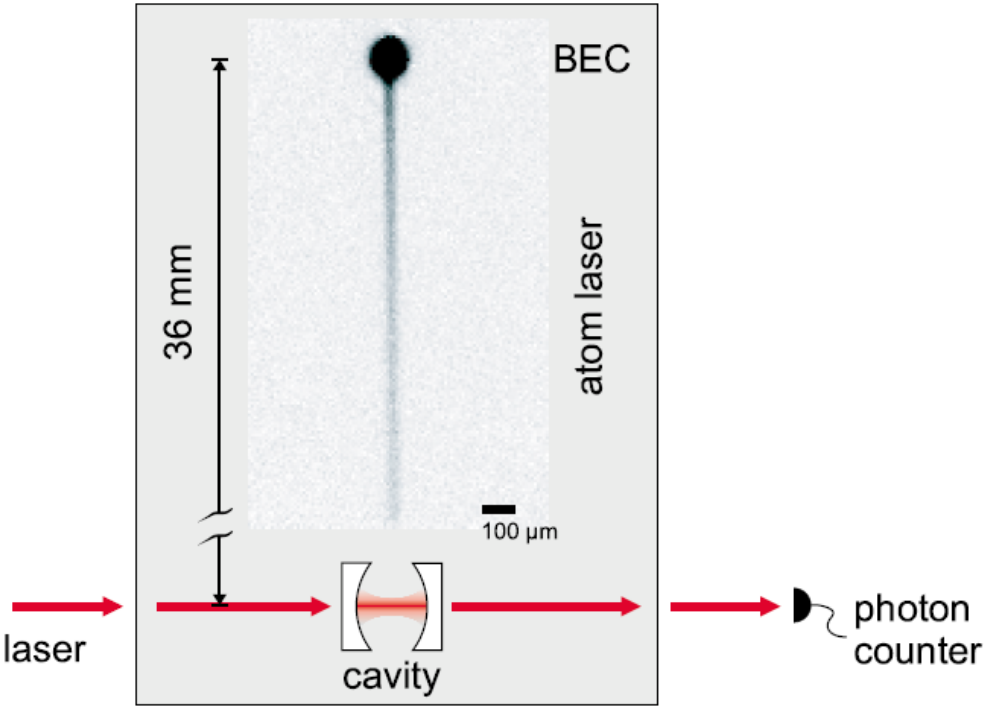
1D atomic beams with same density, but different spatial correlations:



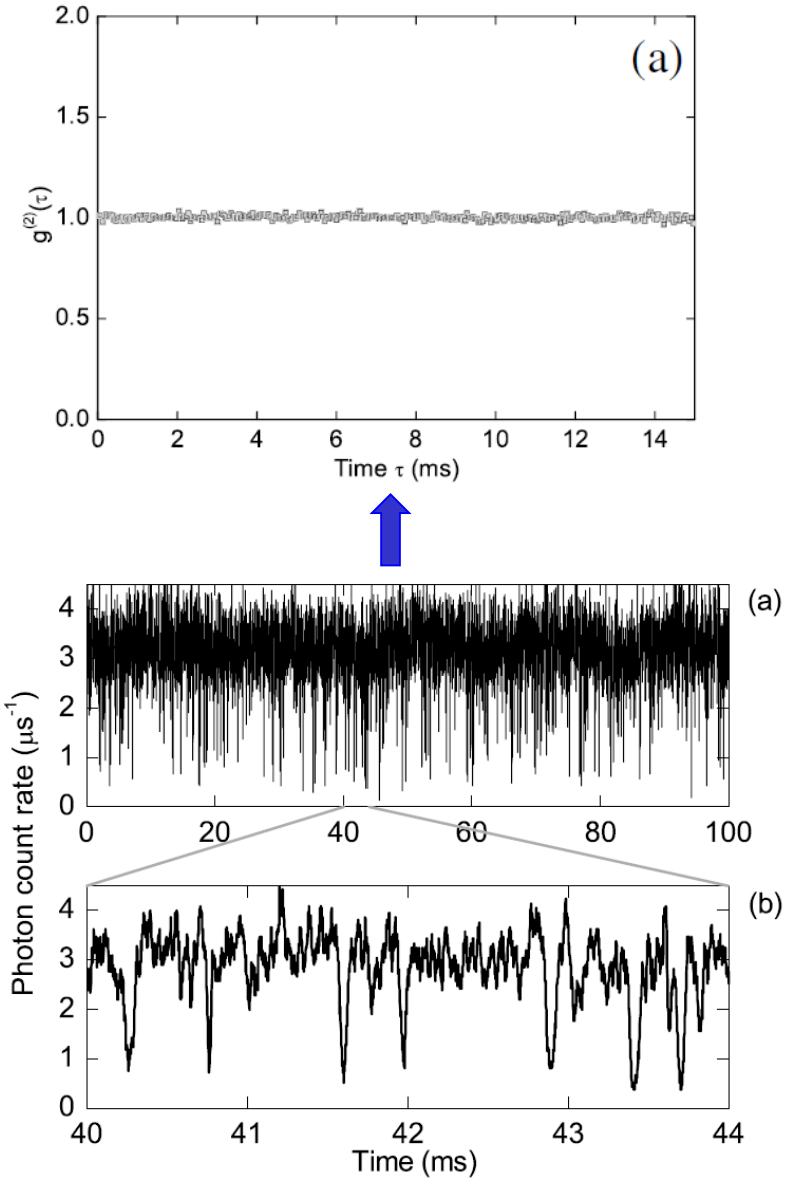
Correlations contain interesting information about quantum system.
They can e.g. be used to distinguish different quantum phases.

Correlation function of atom laser

Esslinger group, PRL 95, 090404 (2005)

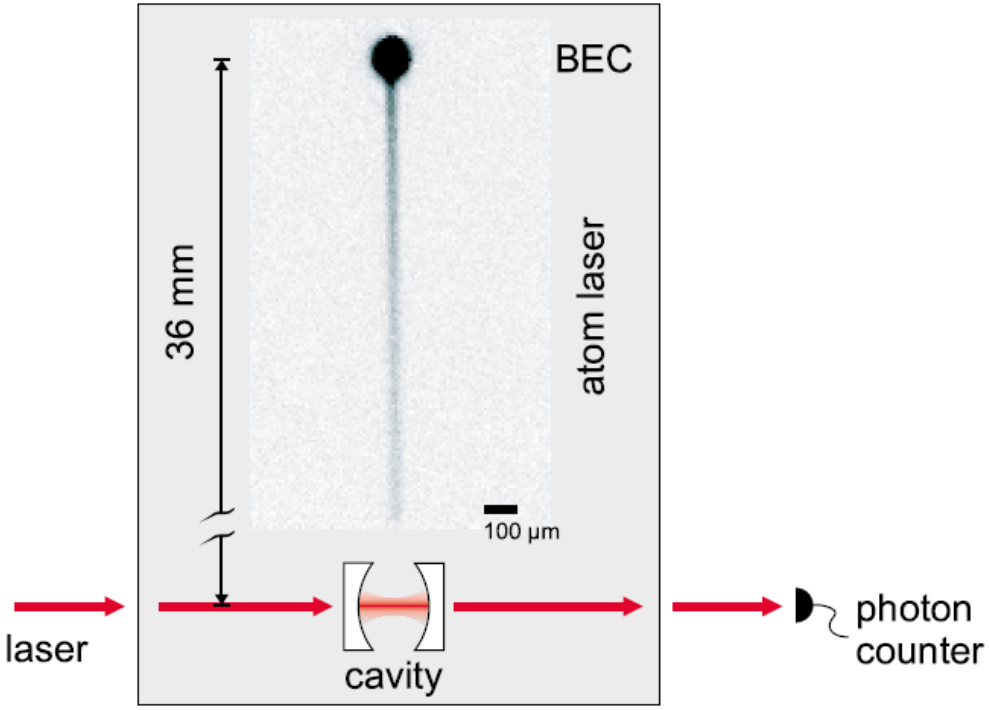


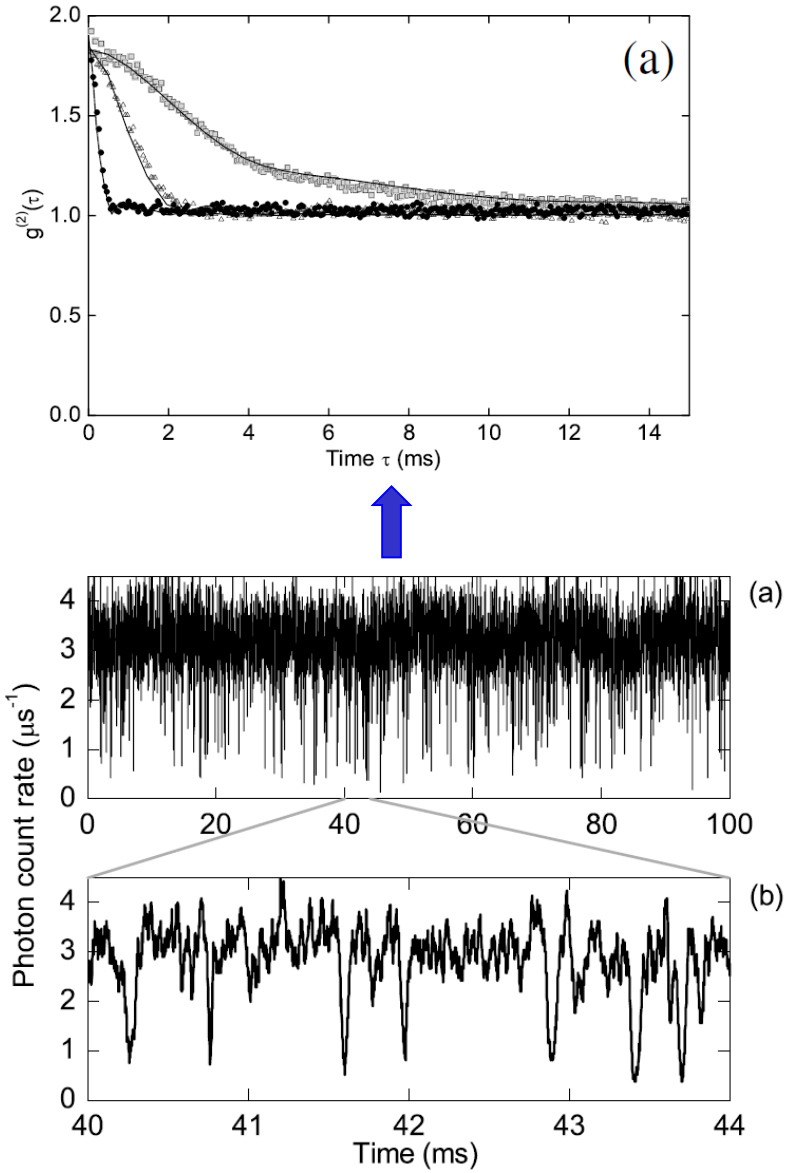
$g^{(2)}(\tau)$ = likelyhood to detect a 2nd photon a time τ after having detected a 1st photon



Correlation function of “thermal” beam

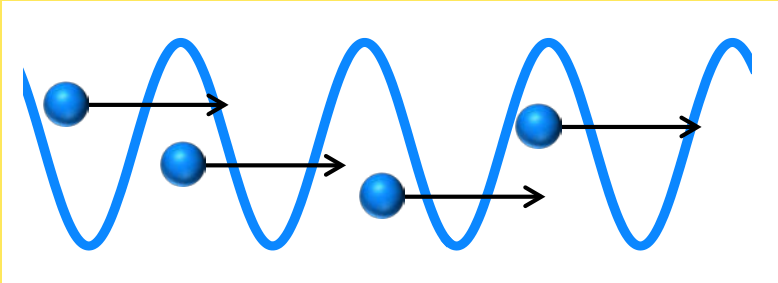
Use noisy radiofrequency for outcoupling to simulate thermal beam.



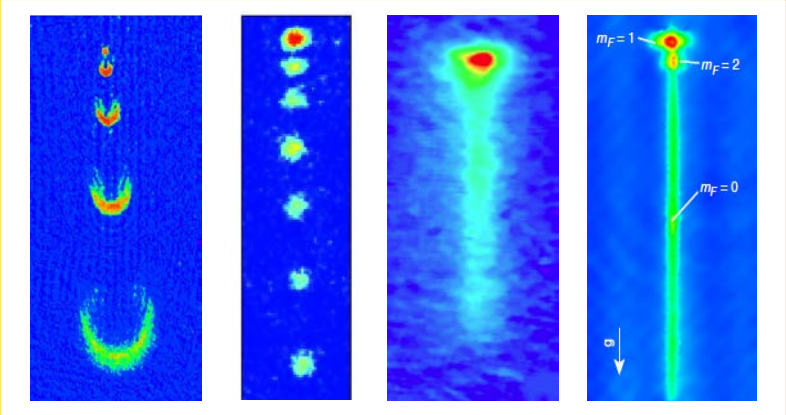


Overview

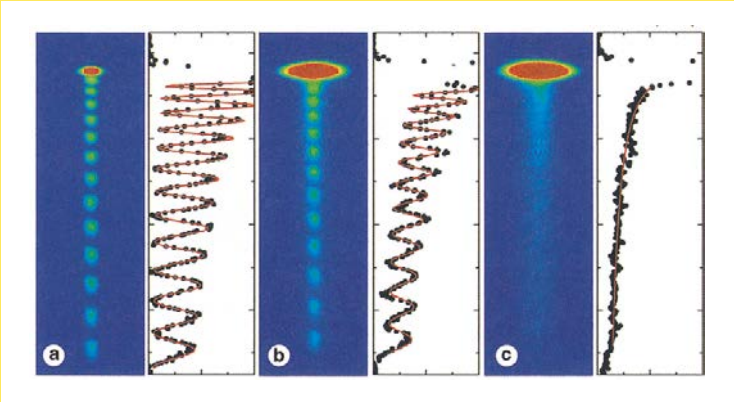
What? Why?



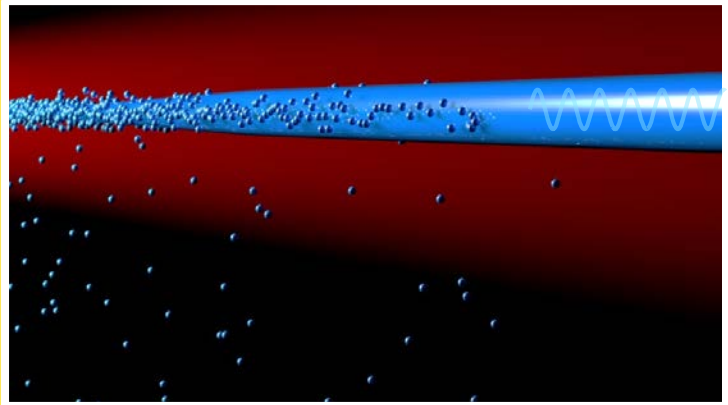
Pulsed atom lasers



Experiments with atom lasers

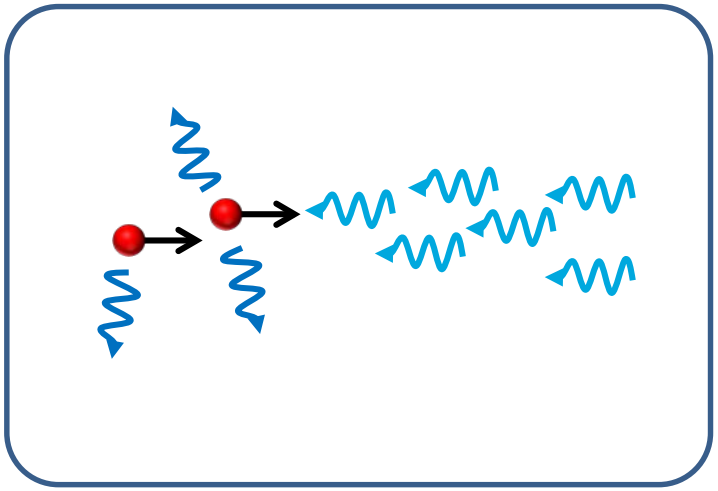


Continuous atom lasers

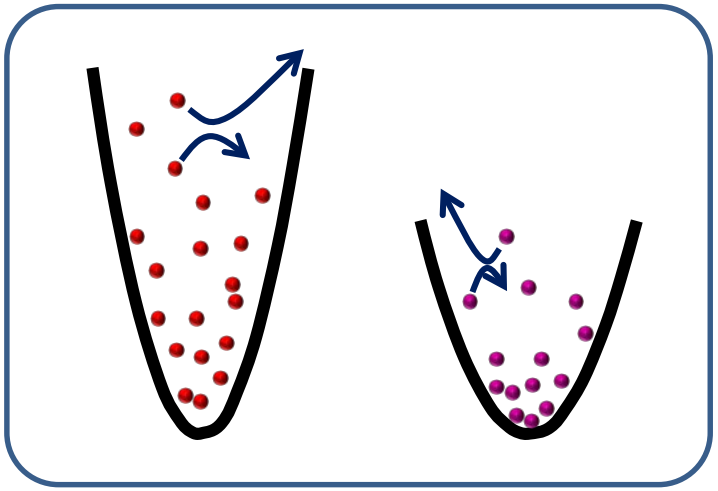


Cooling steps

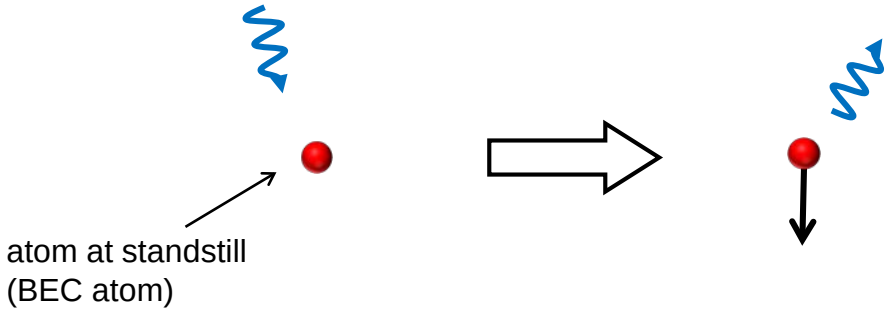
Step 1: laser cooling



Step 2: evaporative cooling



Not easy to combine:

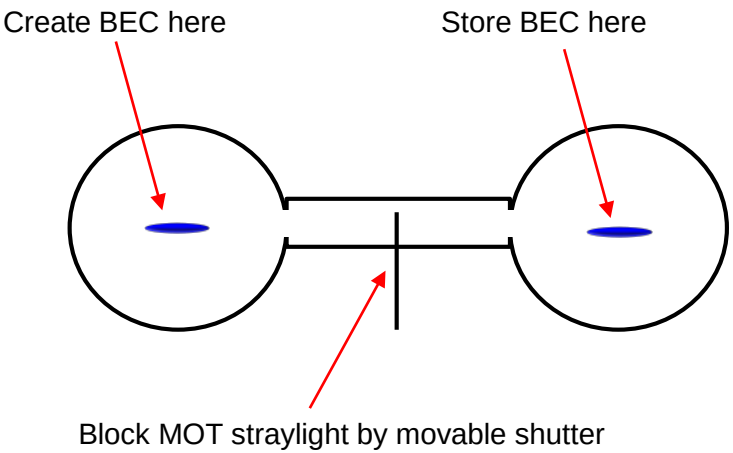


Laser cooling photons can heat up quantum gas

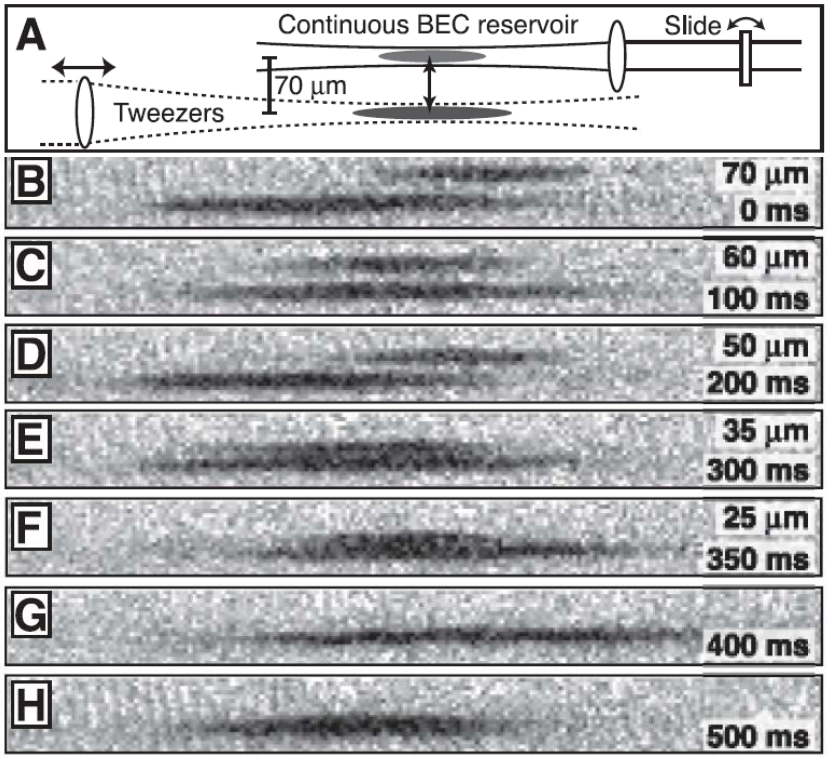
Perpetual BEC

Ketterle group, Science 296, 2193 (2002)

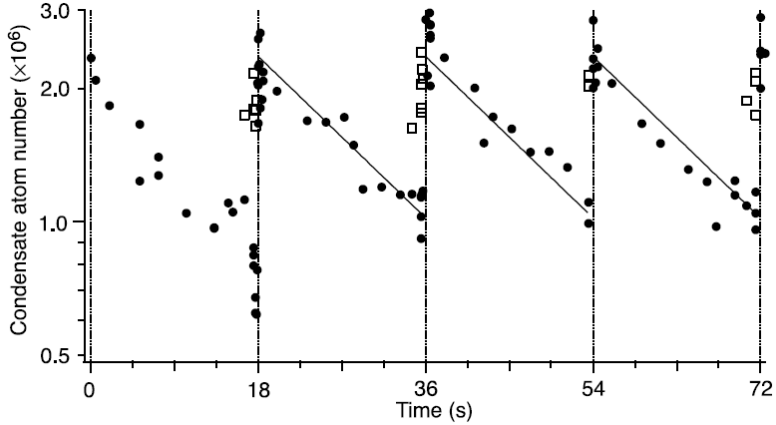
Separate vacuum chamber in BEC production chamber and BEC storage chamber (“science chamber”)



Transport and merging



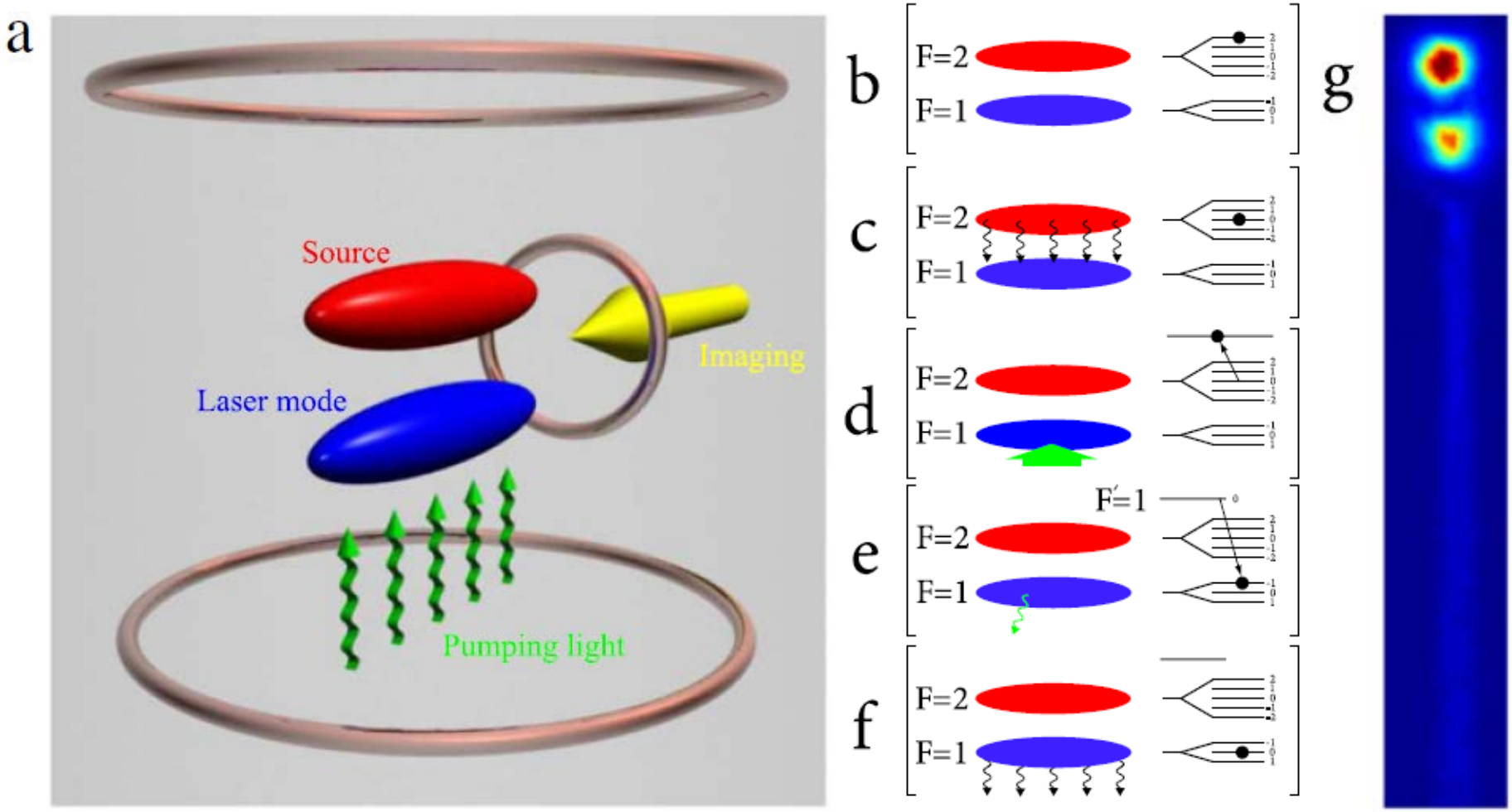
Atom number in stored BEC



It should be possible to outcouple continuous atom laser (~10^5 atoms/s, phase jump when merging)

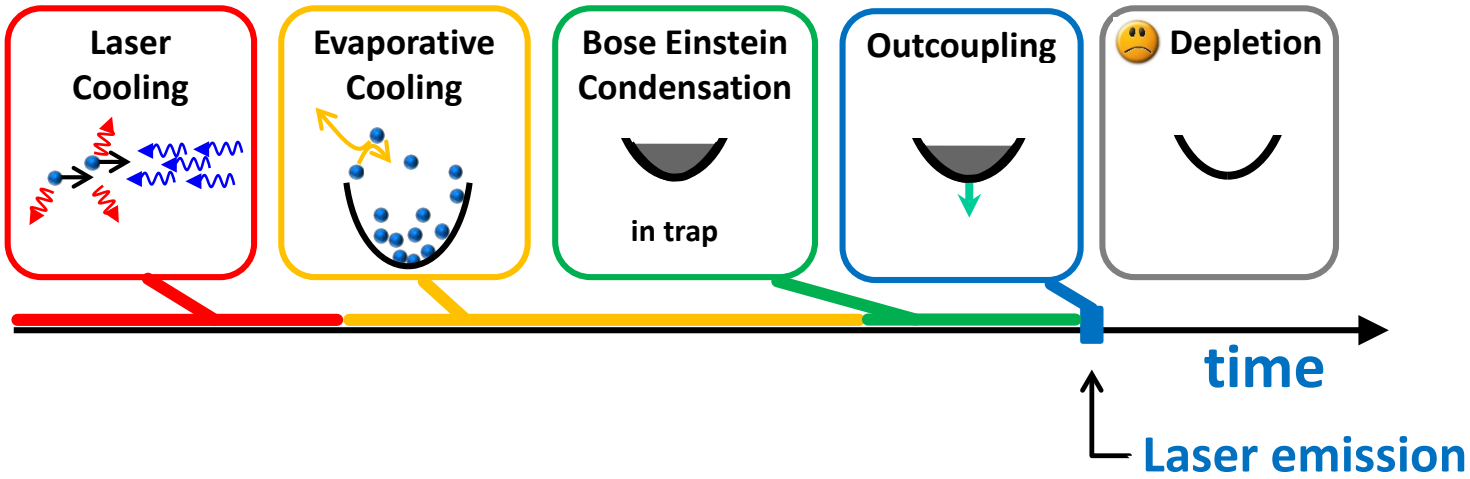
Atom laser with pumping mechanism

Close group, Nature Phys. 4, 731 (2008)

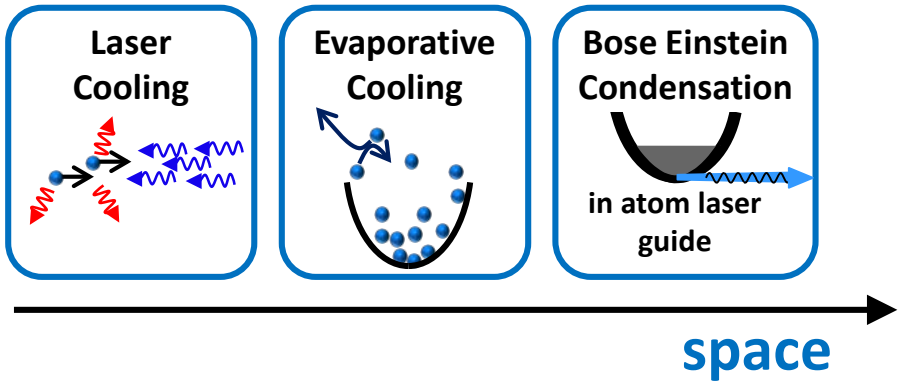


Creating continuous atom laser

State-of-the-art: pulsed atom laser

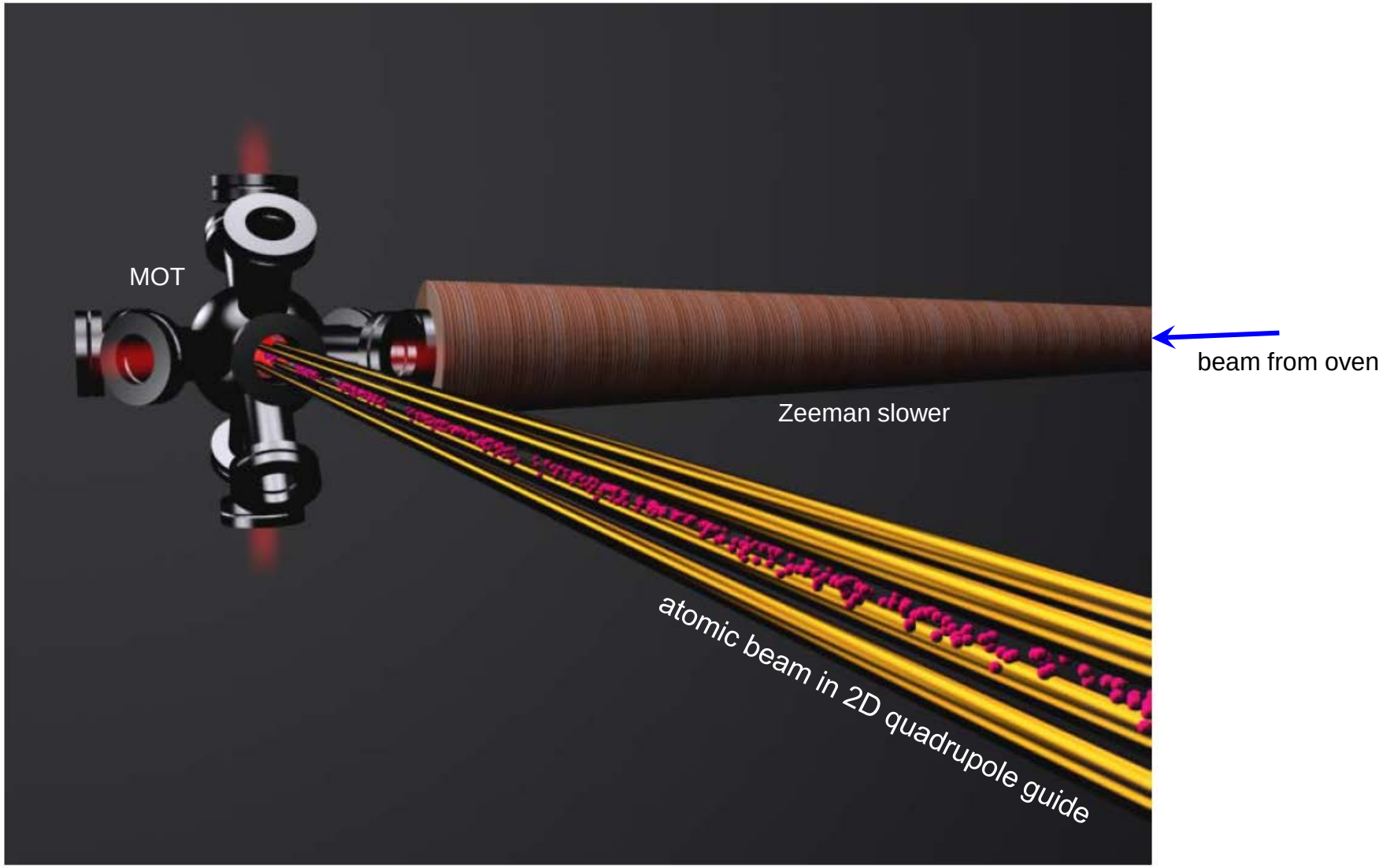


Vision: time → space : perpetual atom laser

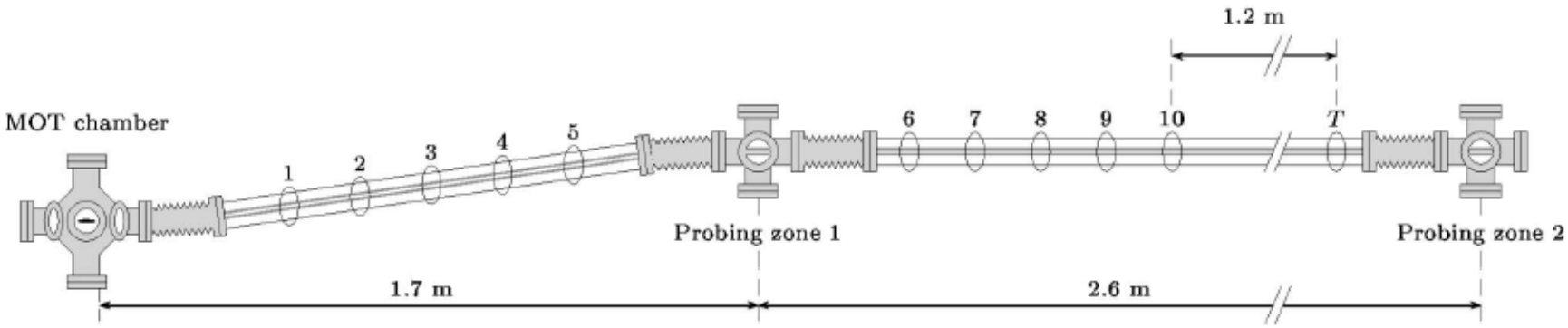


Evaporative cooling of guided atoms

Guéry-Odelin group, PR A 72, 033411 (2005)



Evaporative cooling of guided atoms



Operating procedure

Every 100ms

- accumulate 10^9 atoms in MOT
- push those atoms into magnetic guide

Reduce forward velocity by climbing hill
Let packets of atoms overlap to form beam

Perform evaporation while beam drifts along guide

detect atoms by fluorescence

determine

- flux
- forward velocity
- radial temperature

Phase-space density evolution

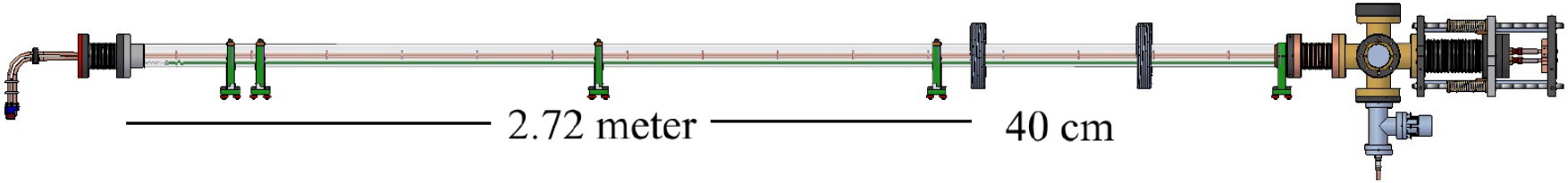
MOT: 10^{-5}

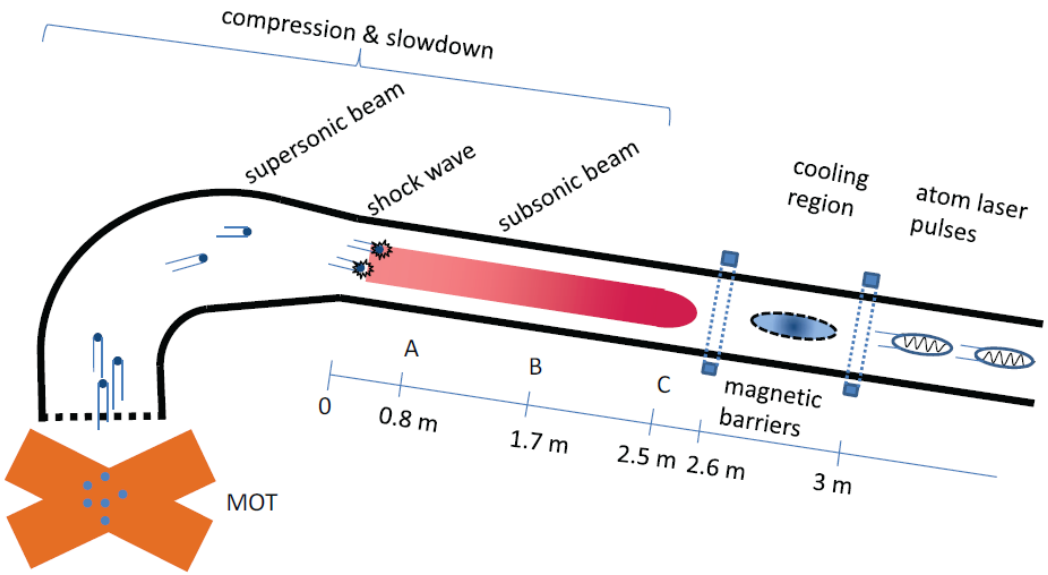
start guide: 10^{-7} → end guide: 10^{-6}

factor 10 increase

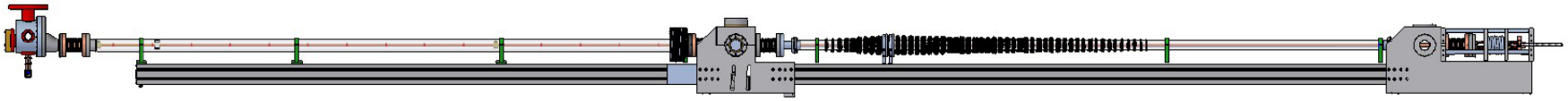
Continuous loading of magnetic trap

Vogels group, PhD thesis Louise Kindt (2011)





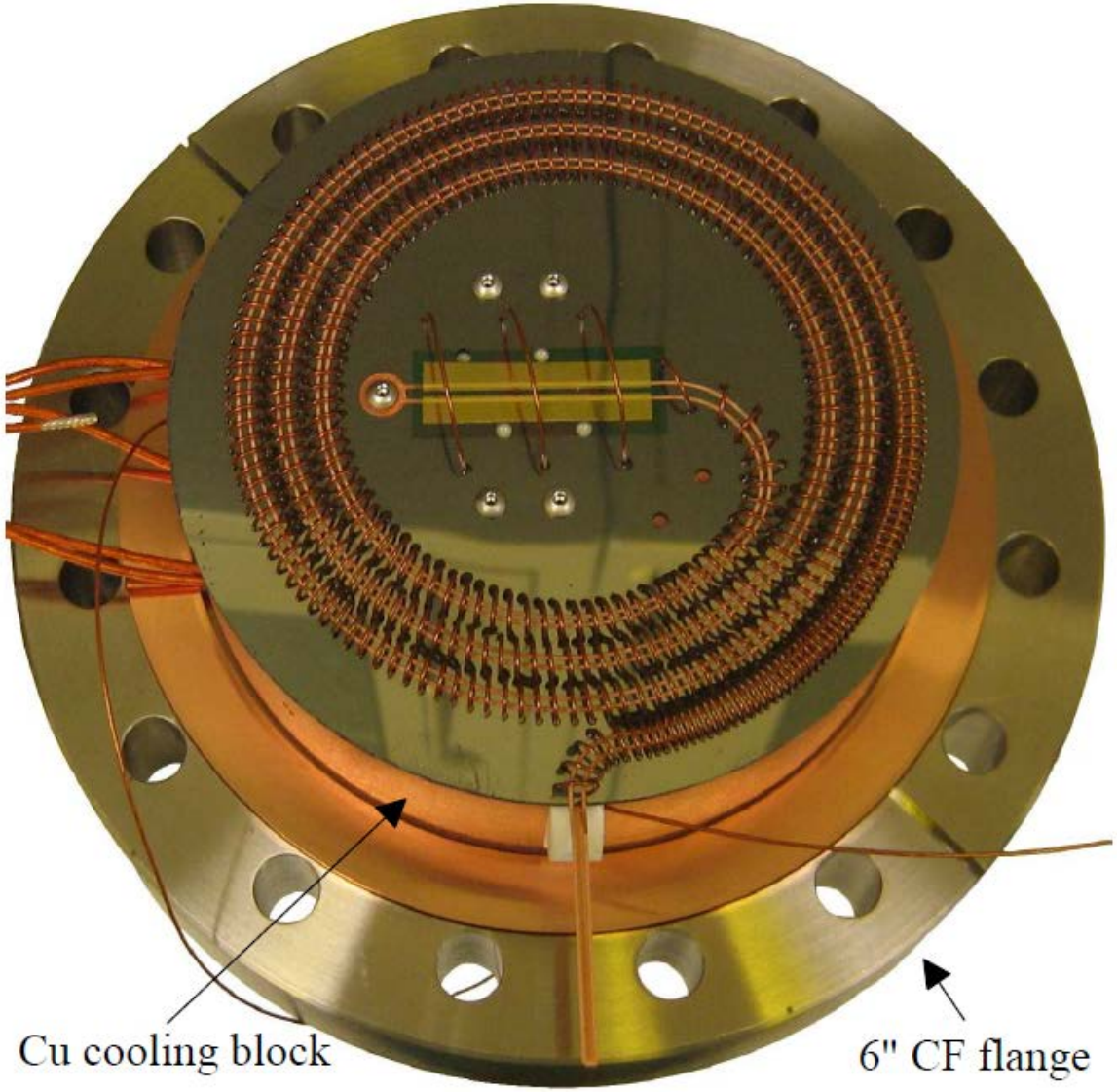
Plan: add 8m quadrupole guide for evaporative cooling



Compact magnetic guide

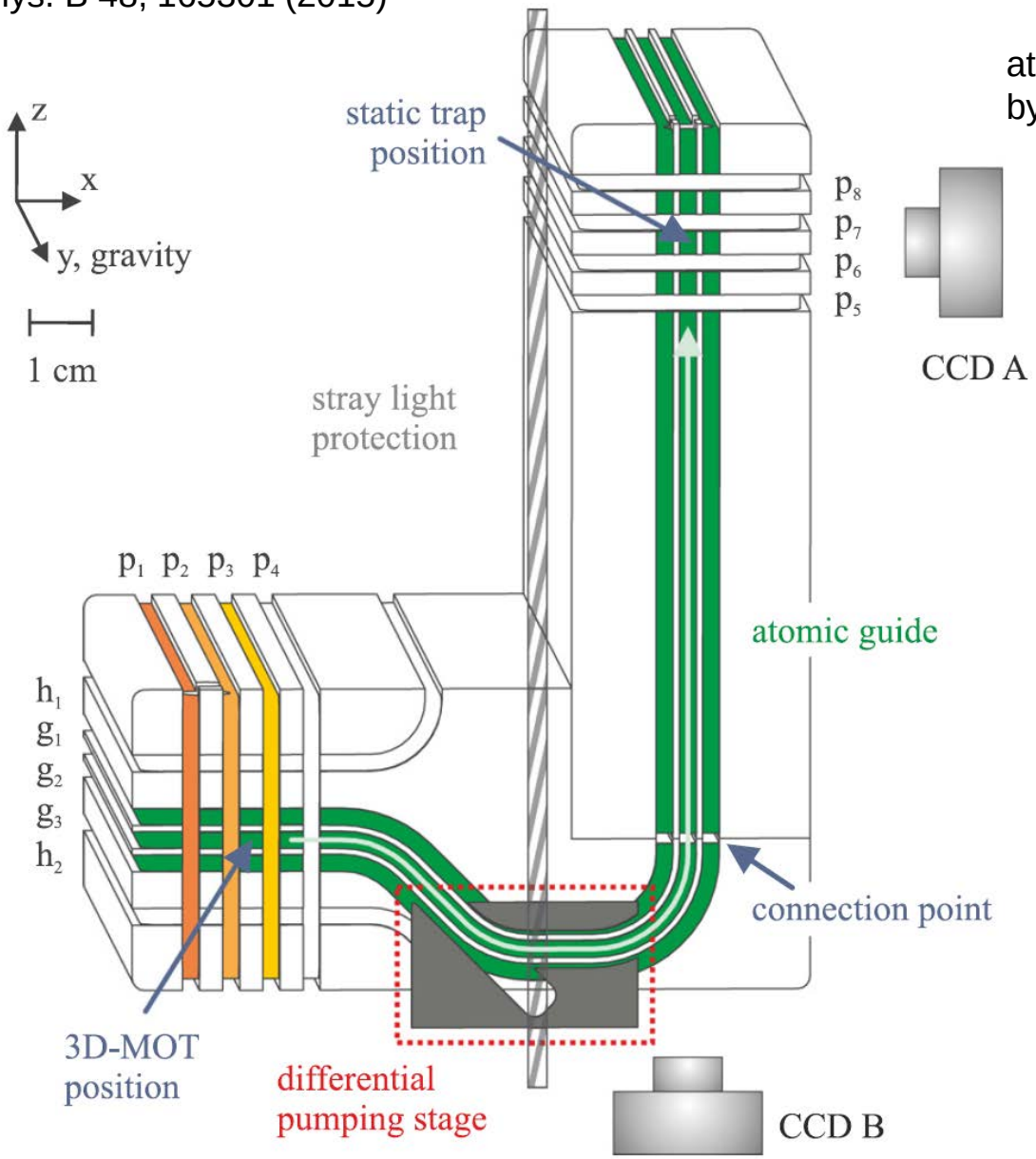
Bend guide into the form of a spiral

Raithel group, arXiv:1202.0479



Continuous loading of magnetic trap

Klempt group, J. Phys. B 48, 165301 (2015)

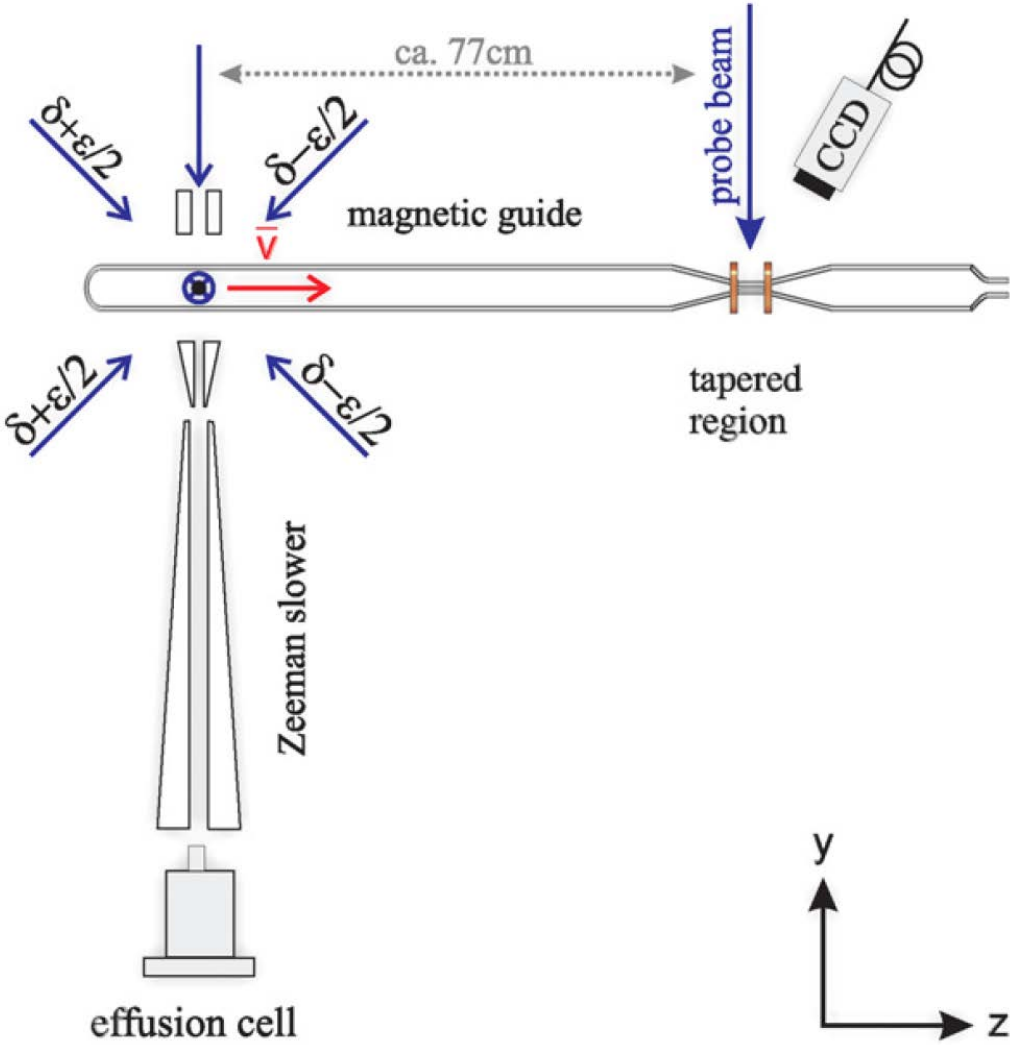


atoms accumulate in trap by elastic collisions

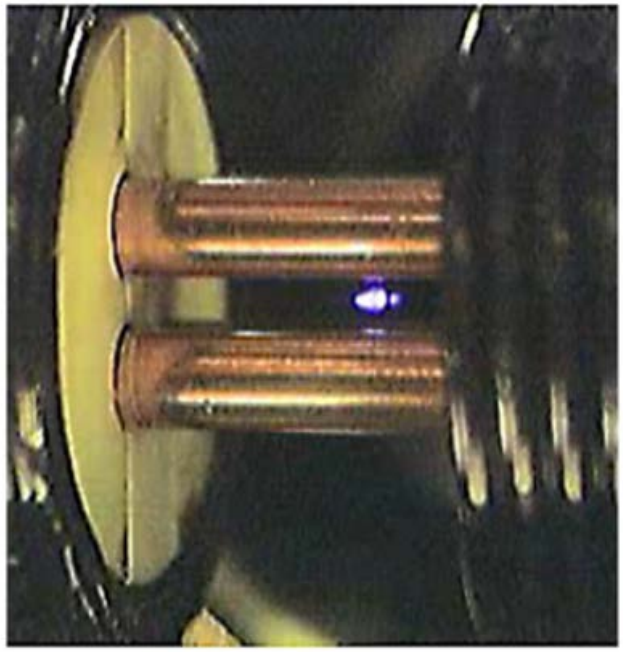
$N = 4 \times 10^7$
$T = 0.1\,\mathrm{mK}$
$PSD = 10^{-7}$

High-flux source of guided atoms

Pfau group, J. Phys. B 42, 145306 (2009)

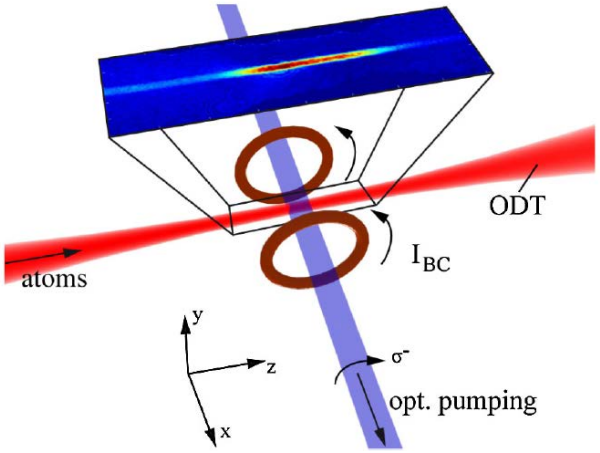


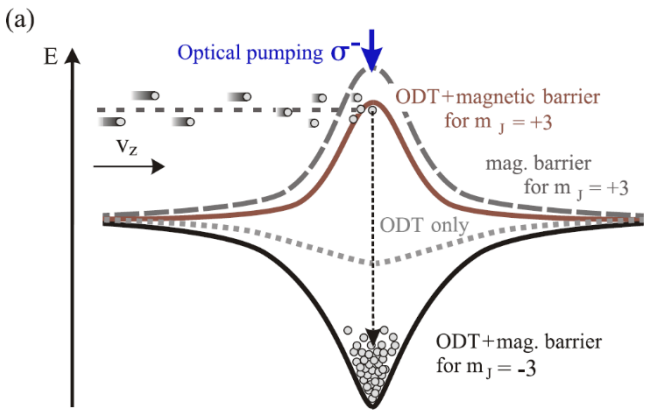
Atoms in probe region

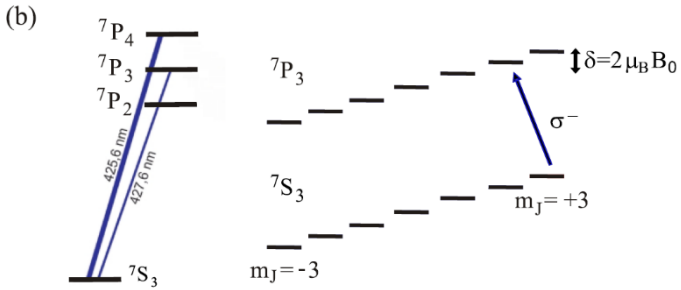


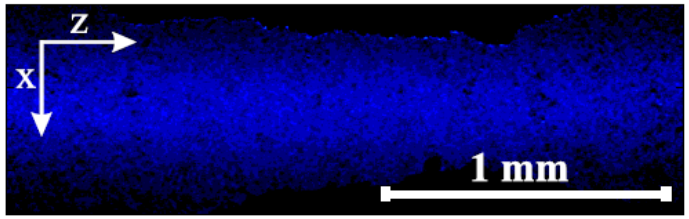
Continuous loading of optical trap

Pfau group, PRL 106, 163002 (2011)

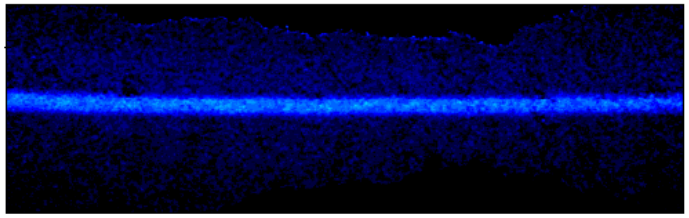




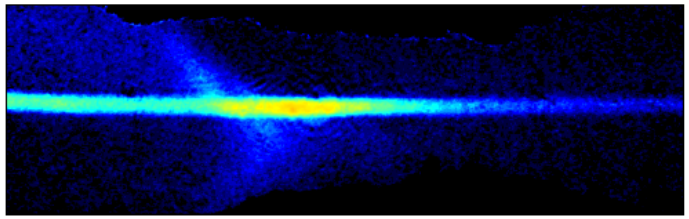




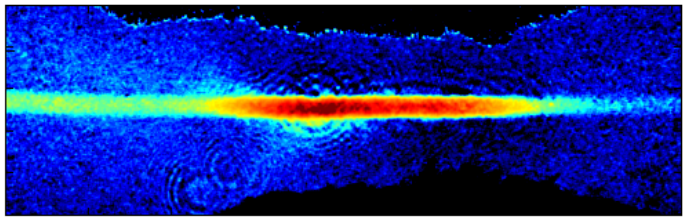
magnetic guide



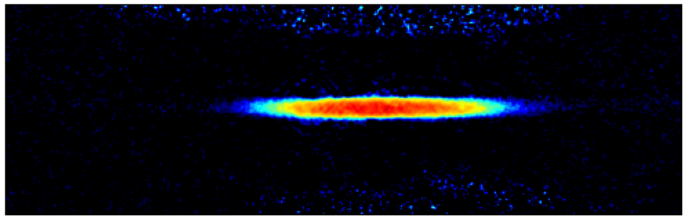
+ optical guide



+ magnetic barrier



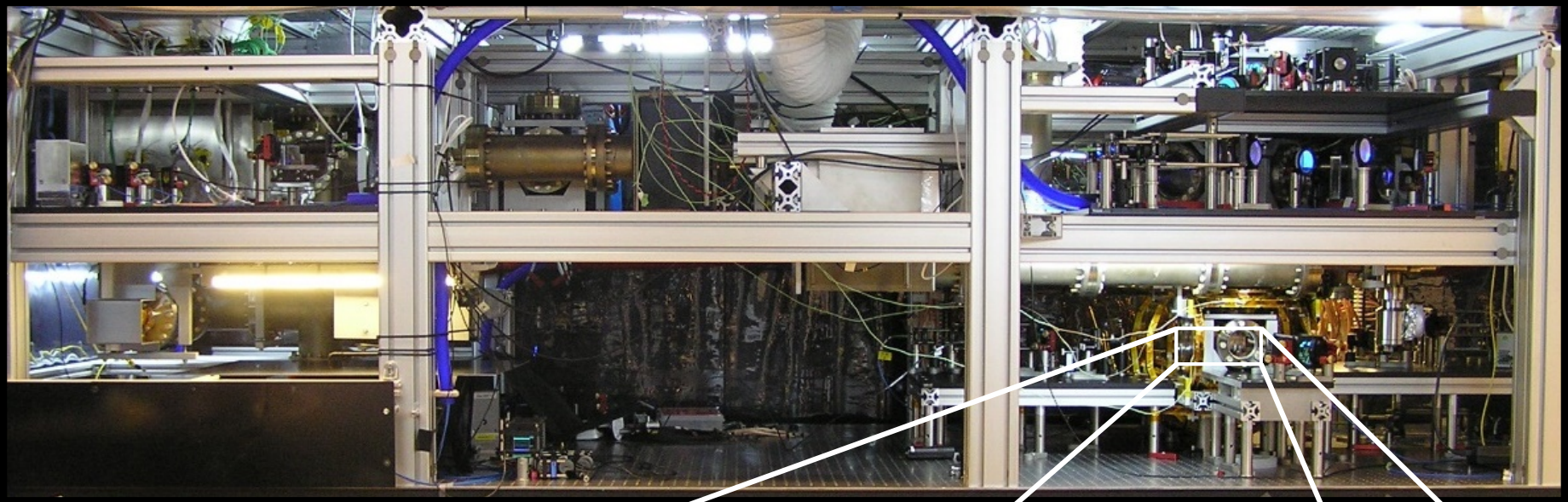
+ optical pumping

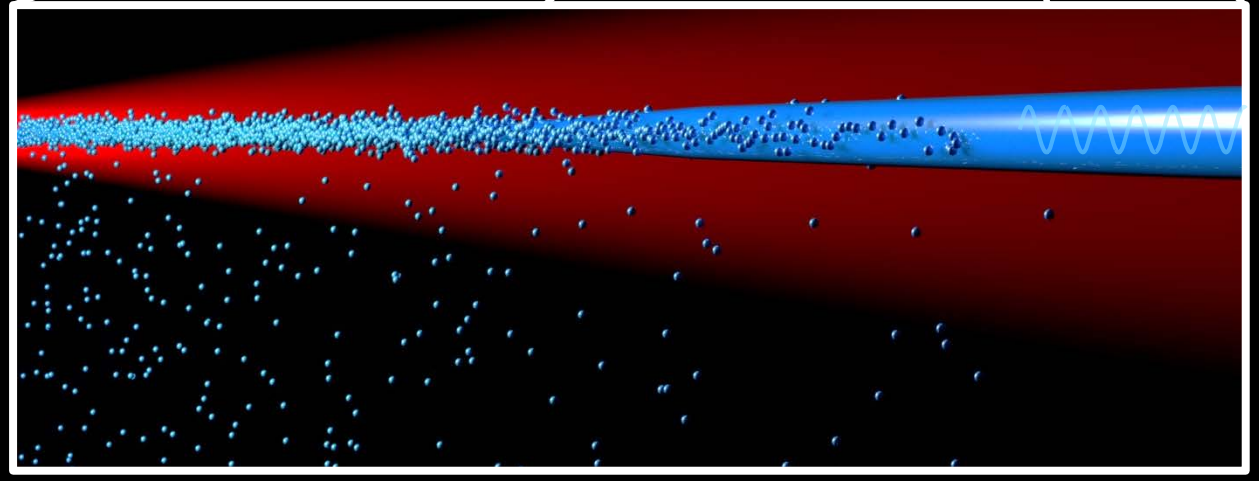


only trapped atoms

$N = 2 \times 10^5$
$T = 0.2\,\mathrm{mK}$
$PSD = 3 \times 10^{-6}$

Building a perpetual atom laser

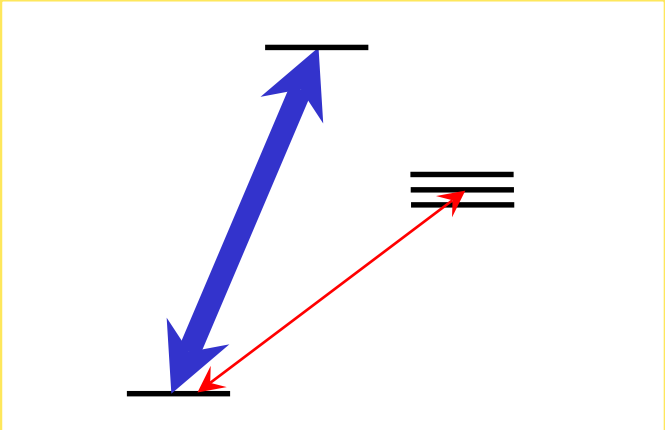




Our new tricks

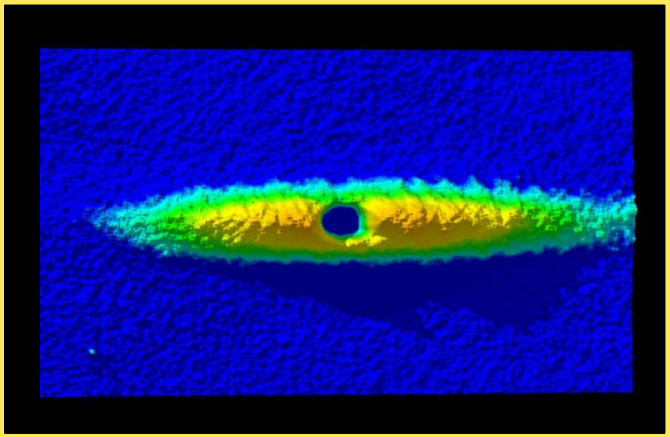
Strontium

Laser cooling
on narrow transition



Phase-space density = 0.1

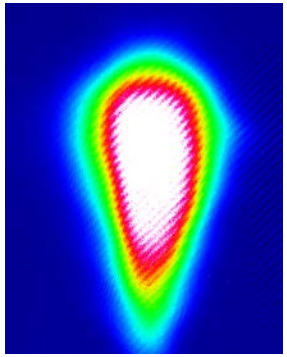
Transparency beam



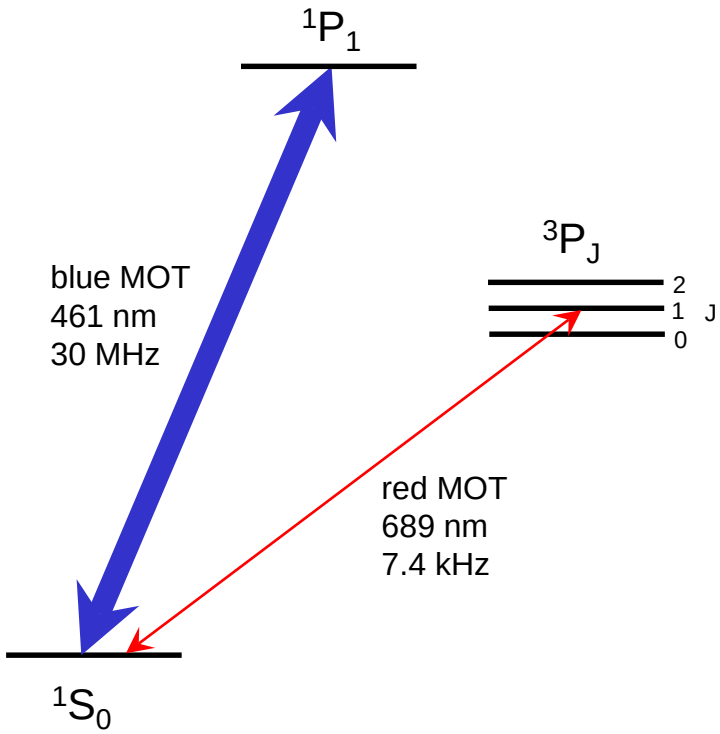
BEC in thermal cloud

Narrow line cooling

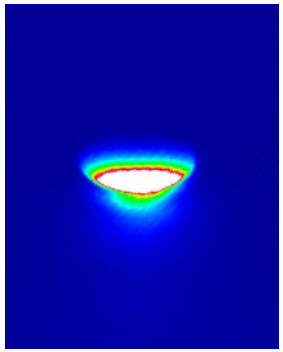
hot blue MOT
T ~ 1 mK
PSD > 10^{-6}



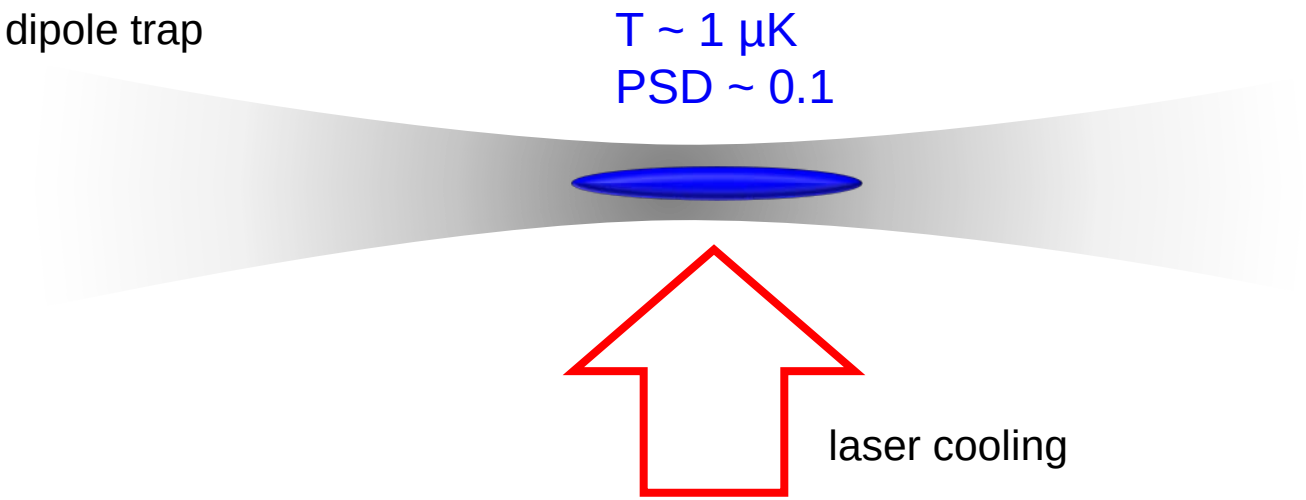
← 2 mm →



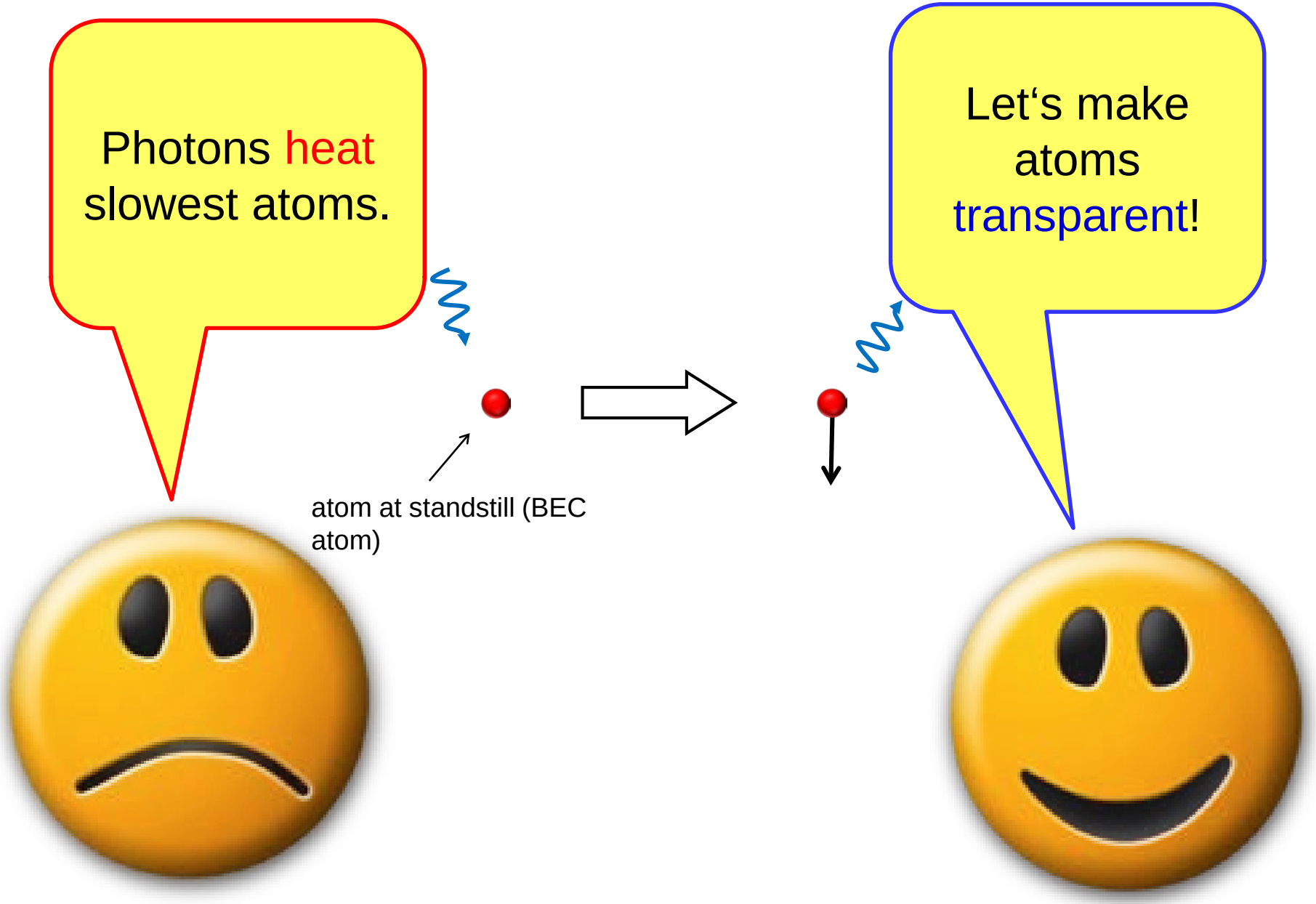
cold red MOT
T ~ 1 μK
PSD ~ 0.1



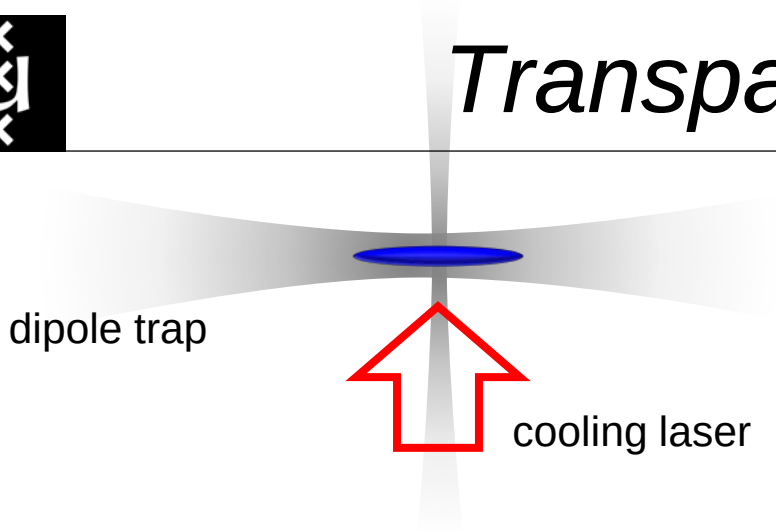
Dipole trap

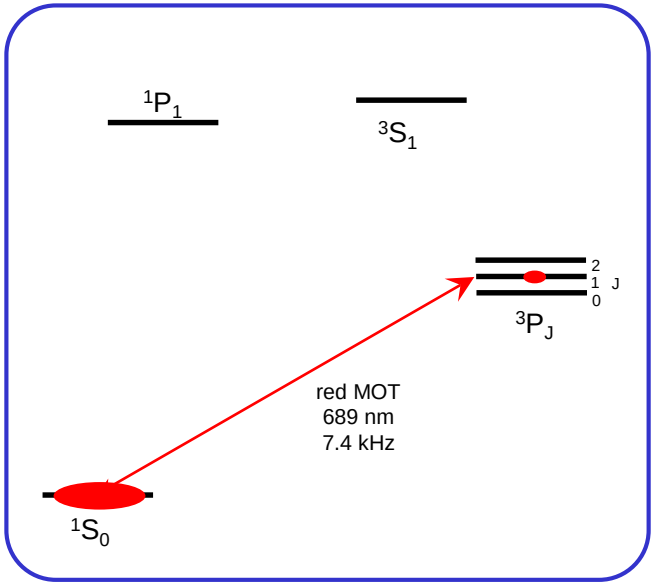


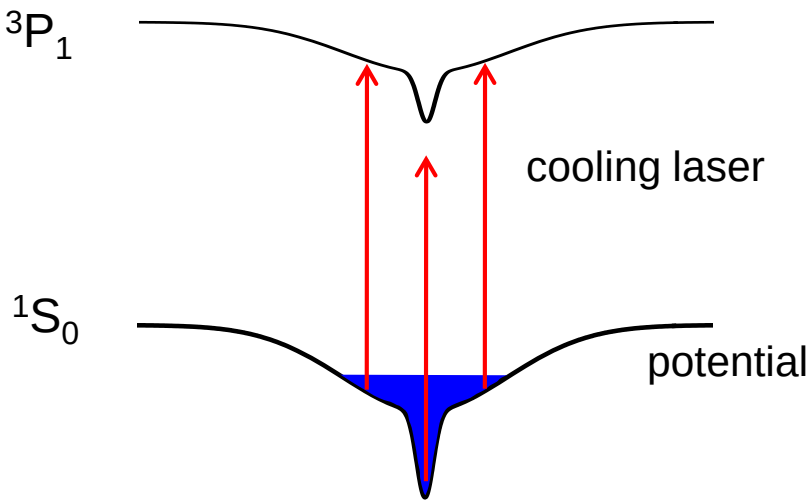
Why not more?


Photons heat slowest atoms.
Let‘s make atoms transparent!
atom at standstill (BEC atom)

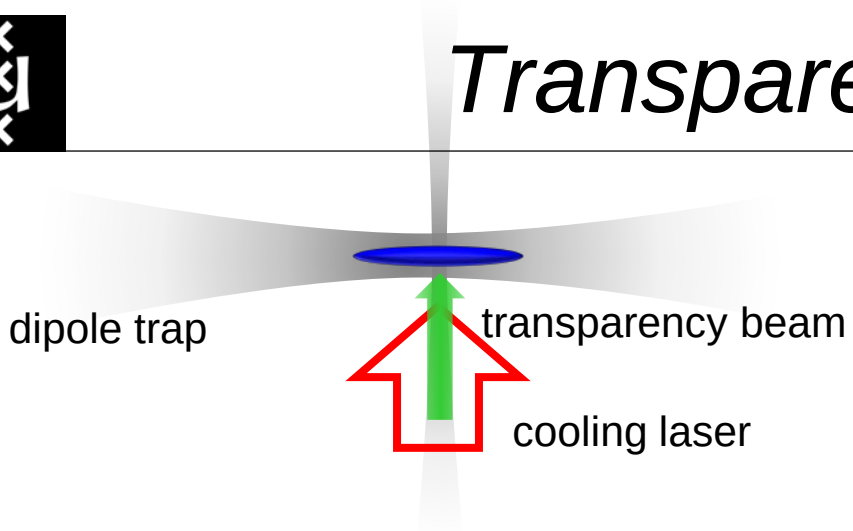
Transparency beam

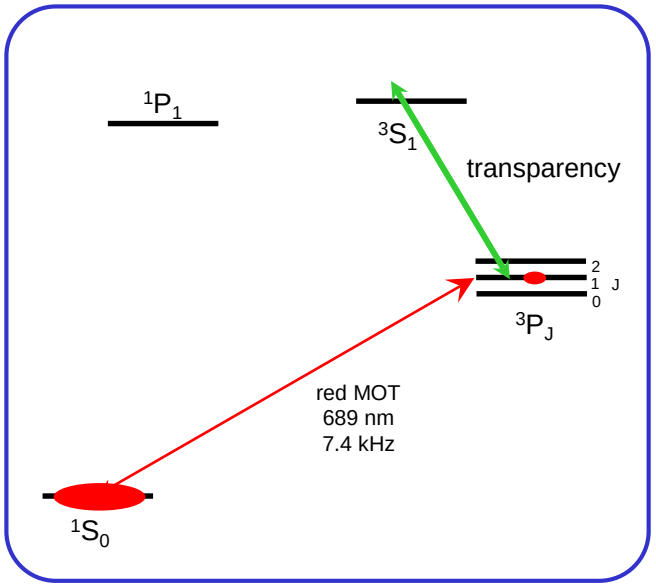


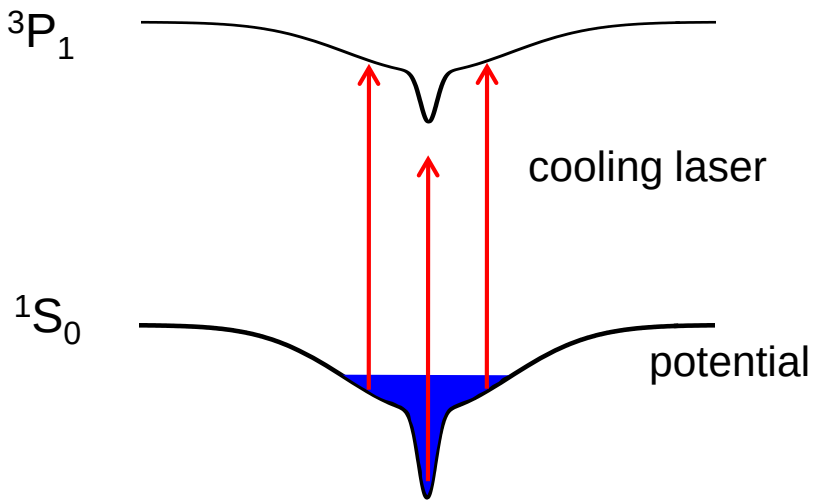




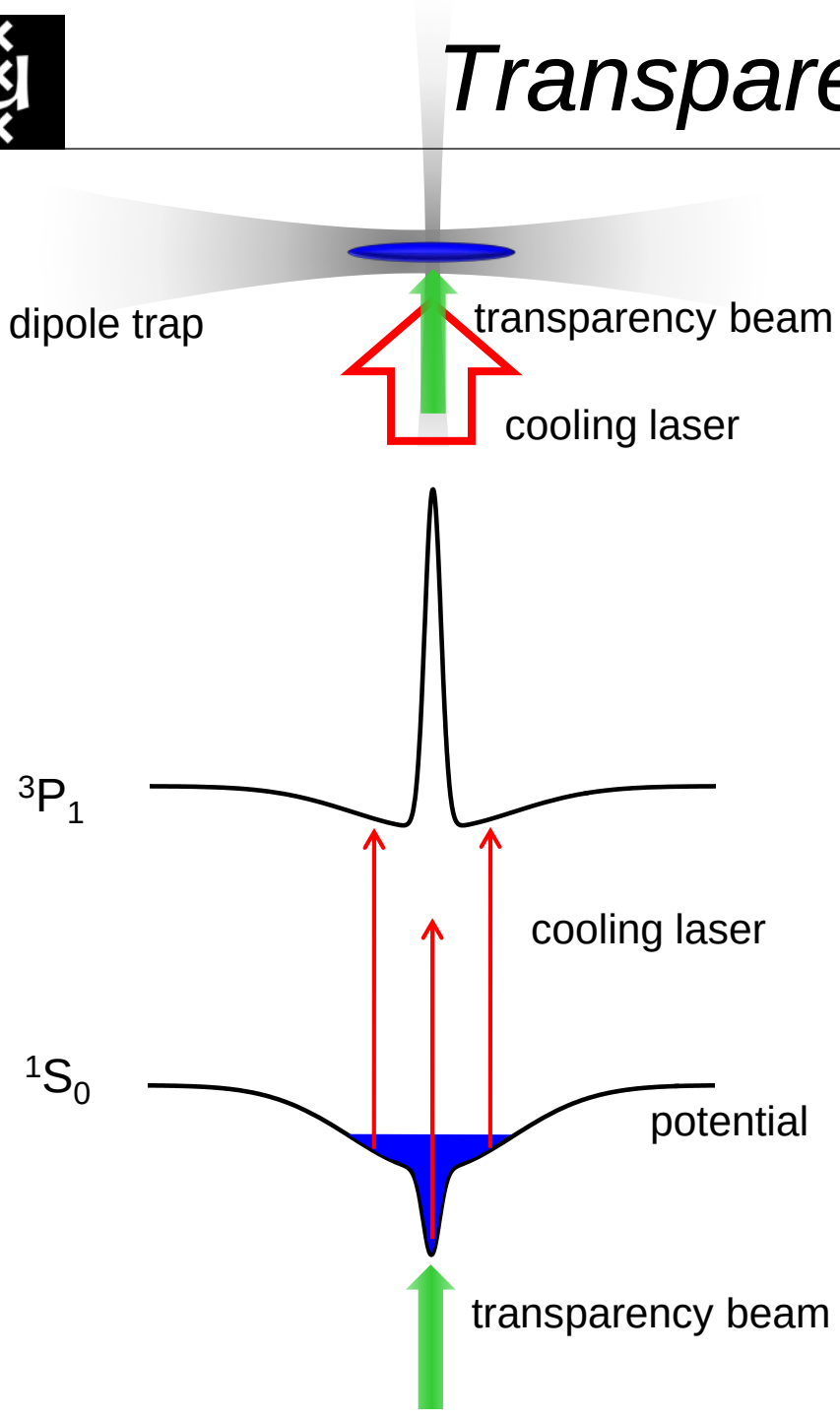
Transparency beam

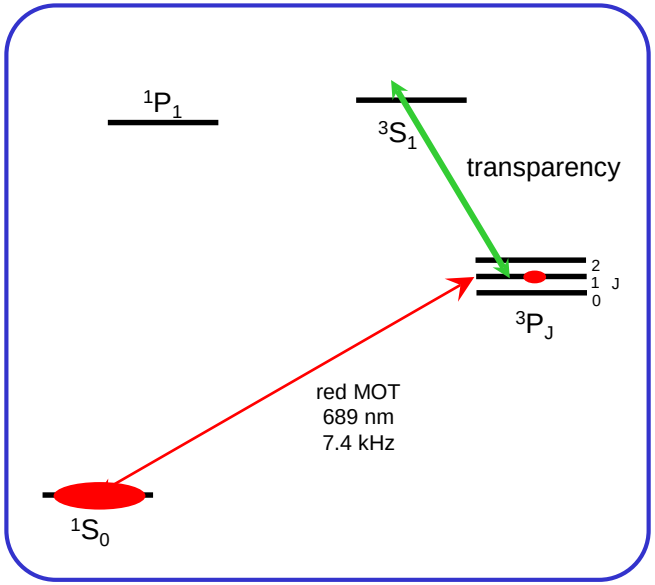




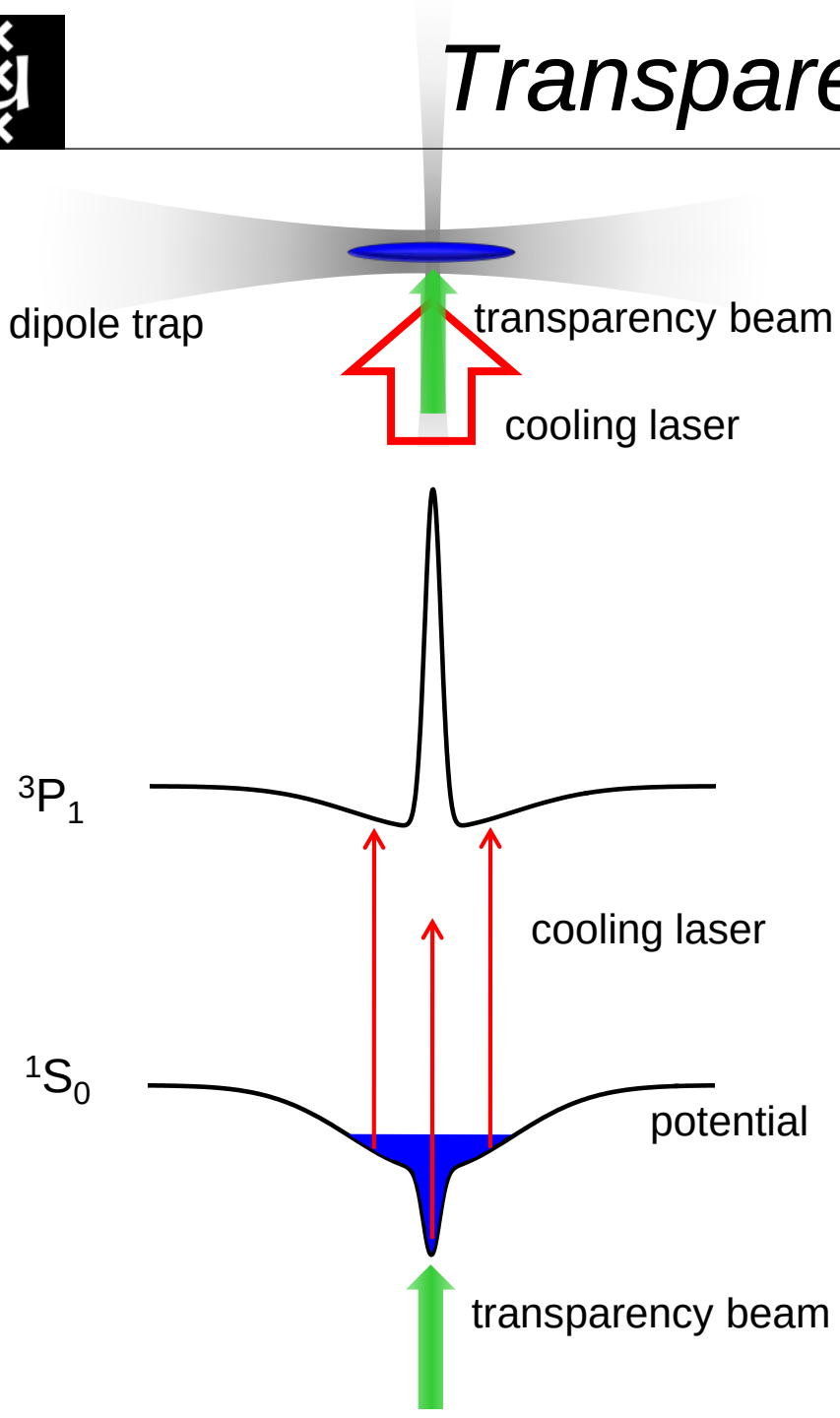


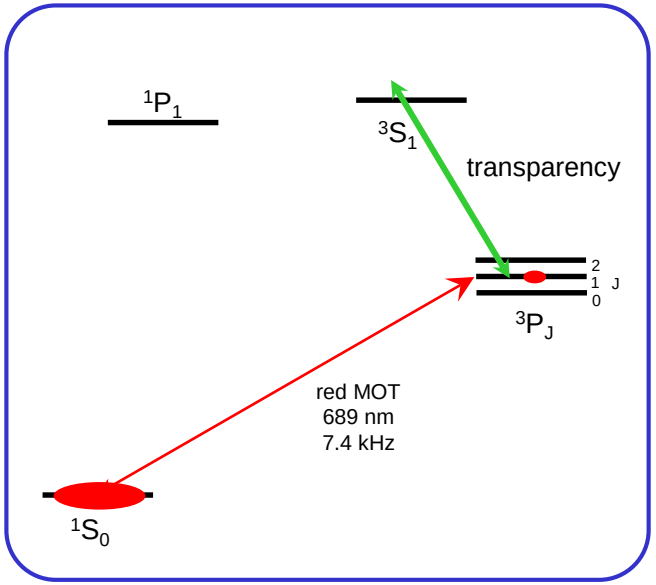
Transparency beam

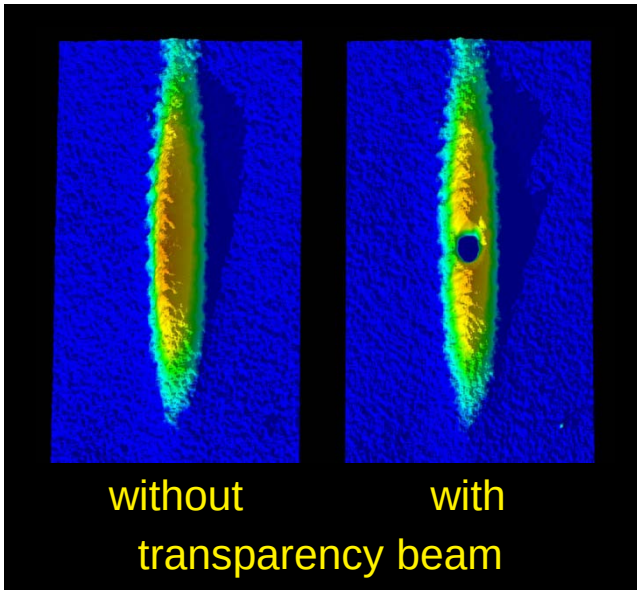




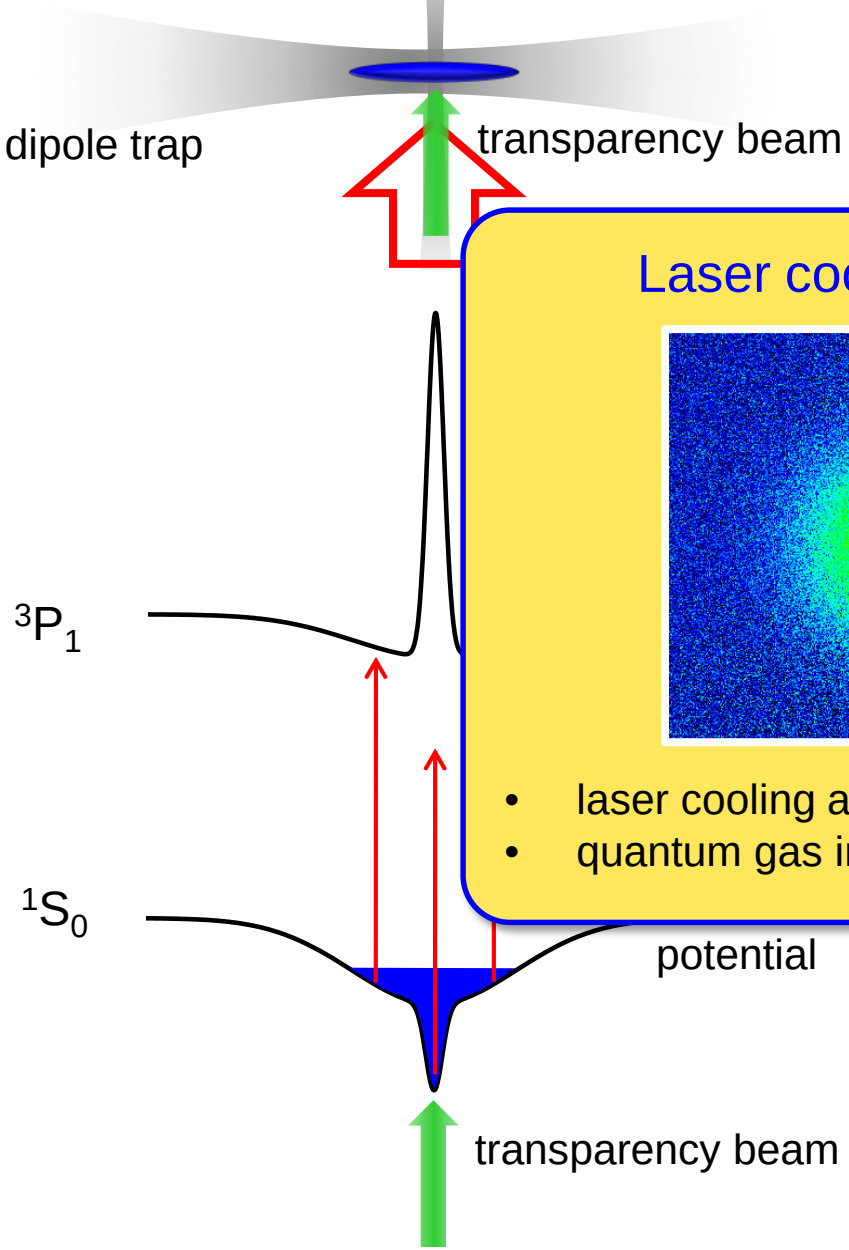
Transparency beam

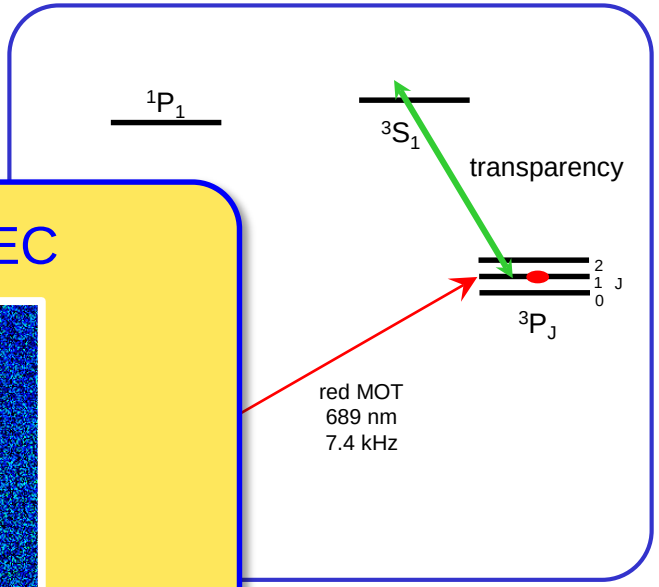




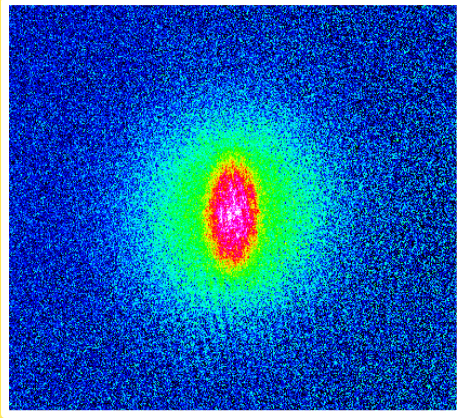


Transparency beam

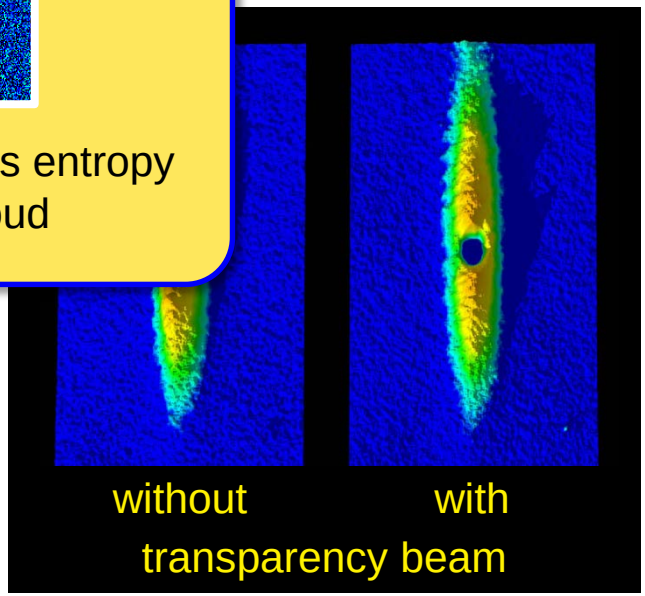




Laser cooling to BEC



- laser cooling alone removes entropy
- quantum gas in thermal cloud

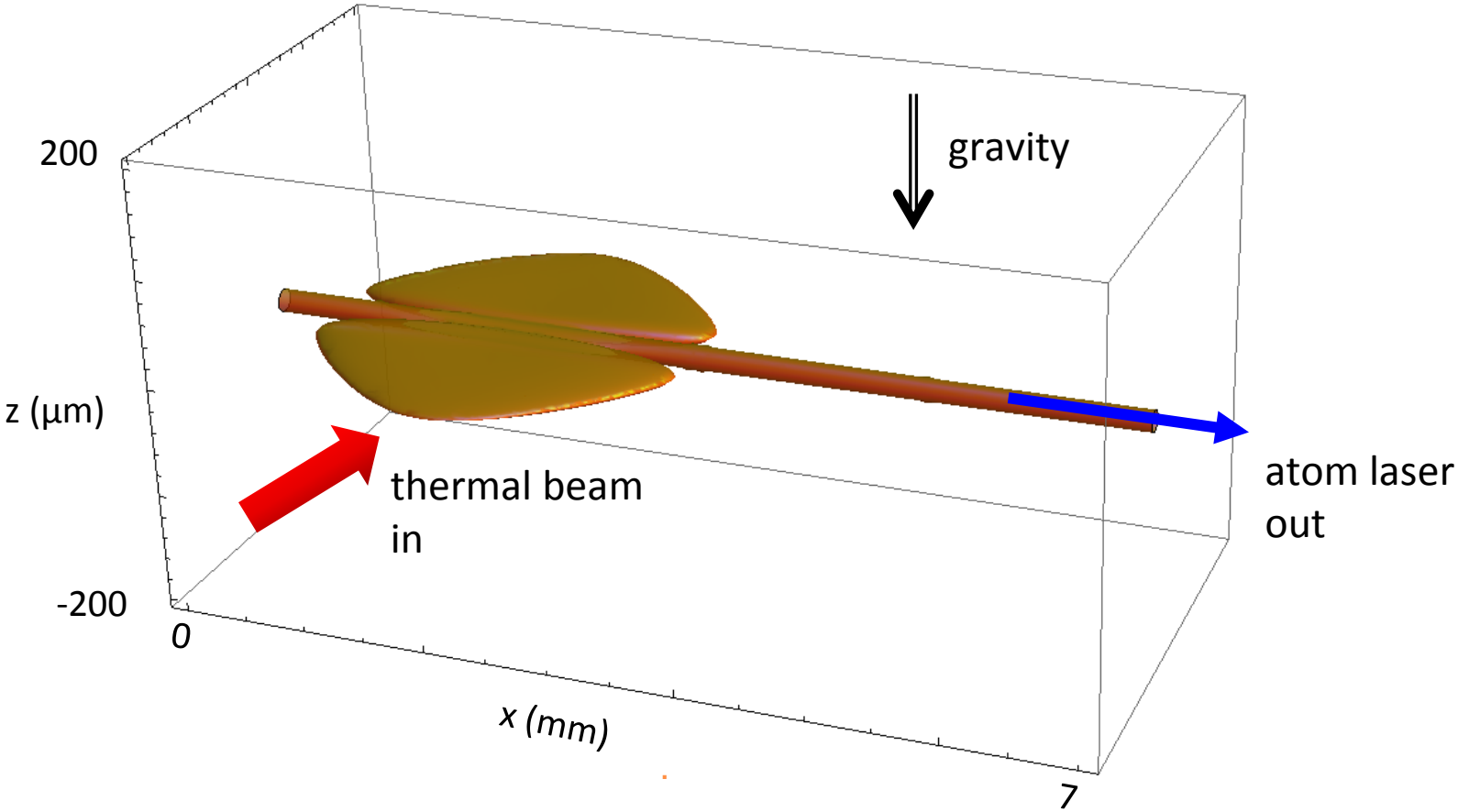


Perpetual atom laser

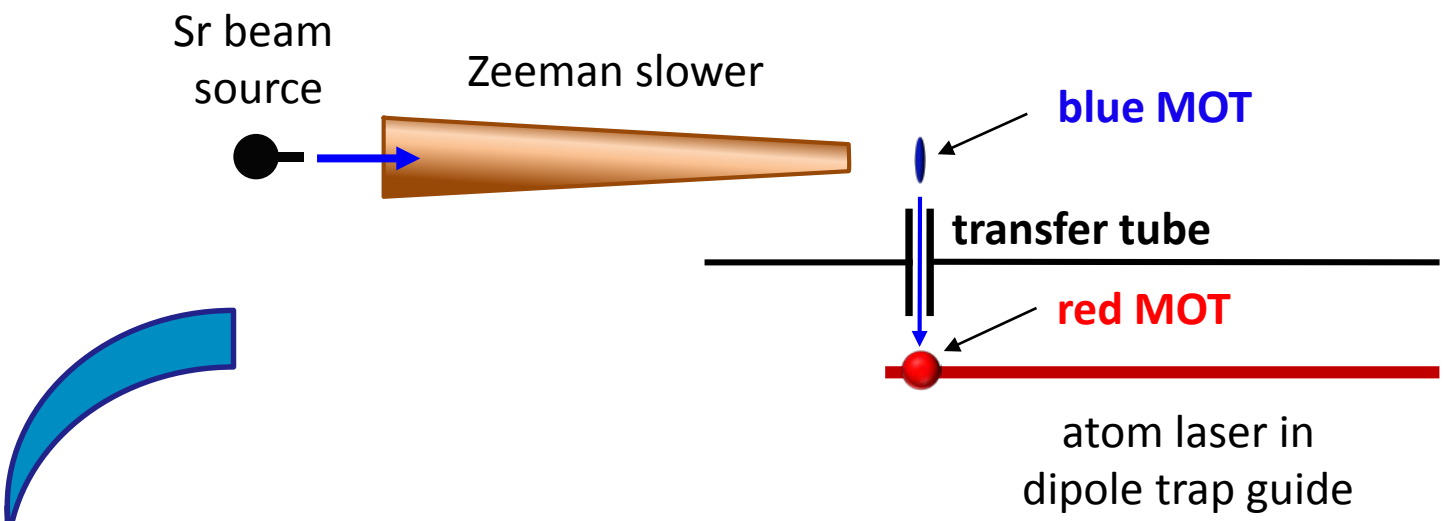
Requirements:

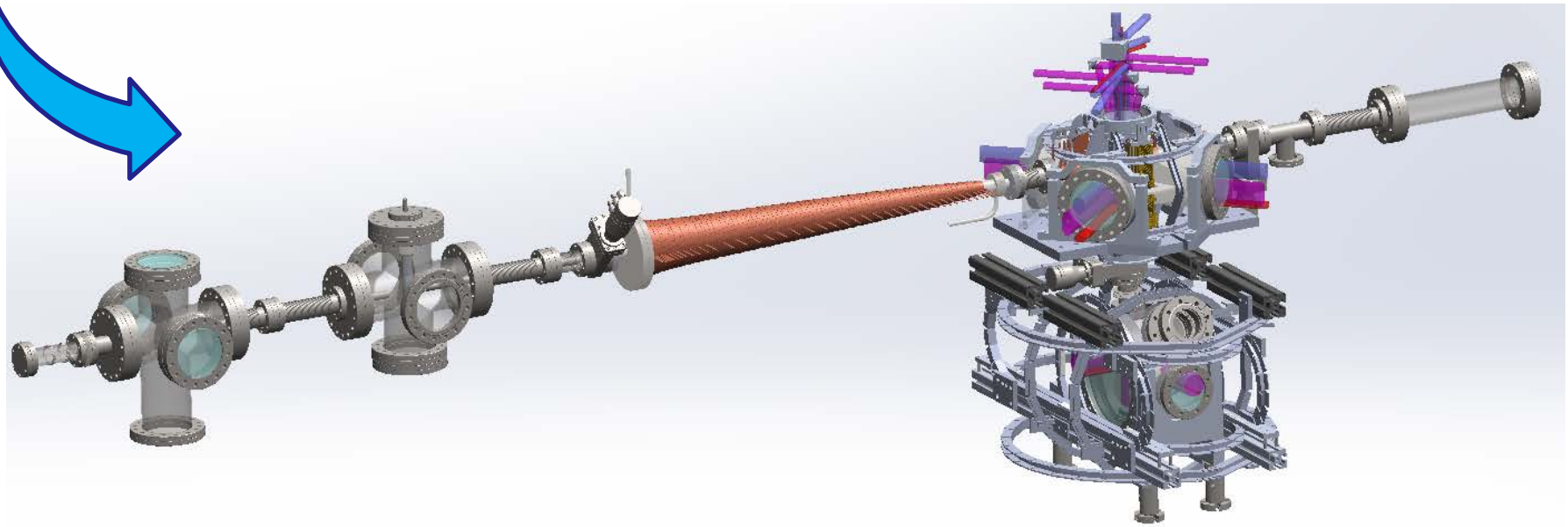
1) Outcouple atom laser beam
2) Replenish reservoir

Potential landscape for perpetual atom laser:

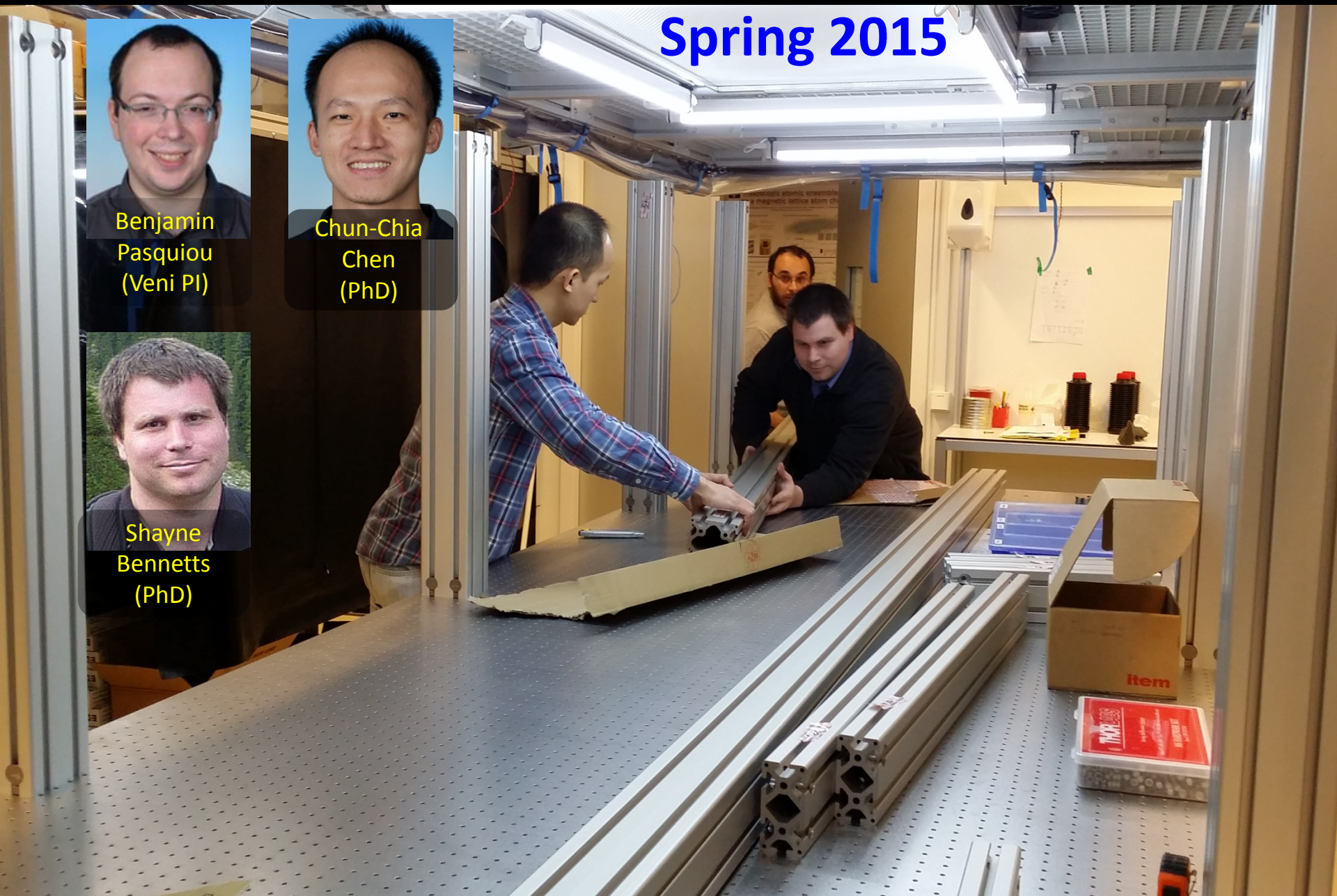


Operation principle and design



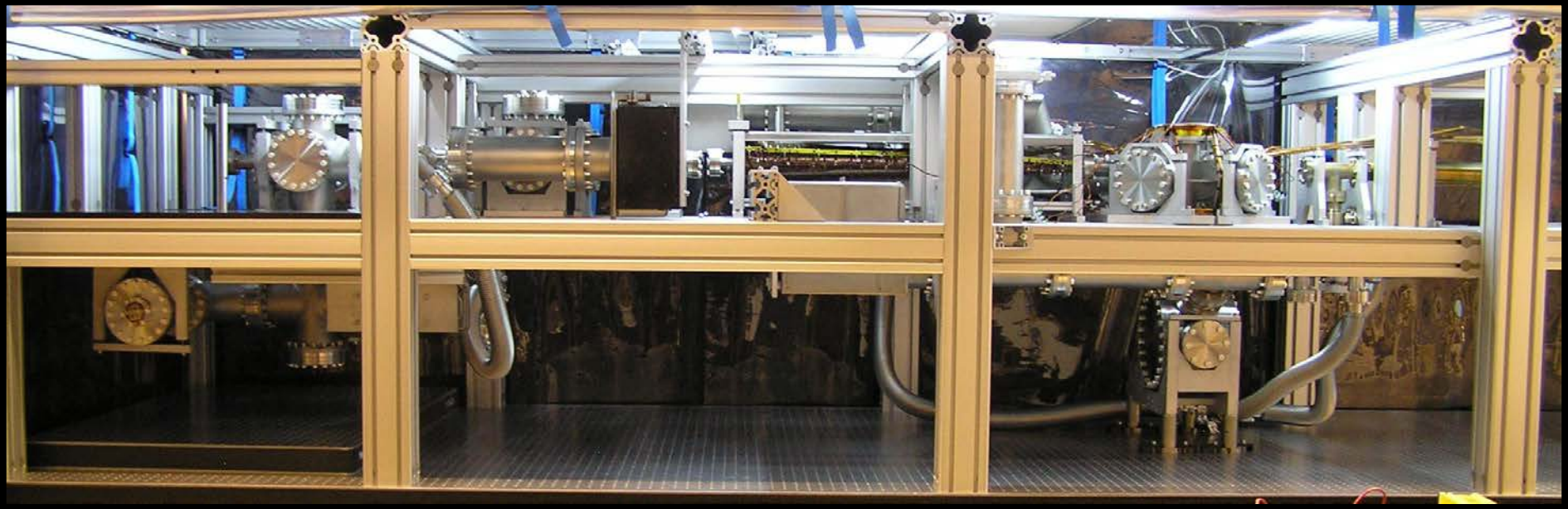


Building our perpetual atom laser



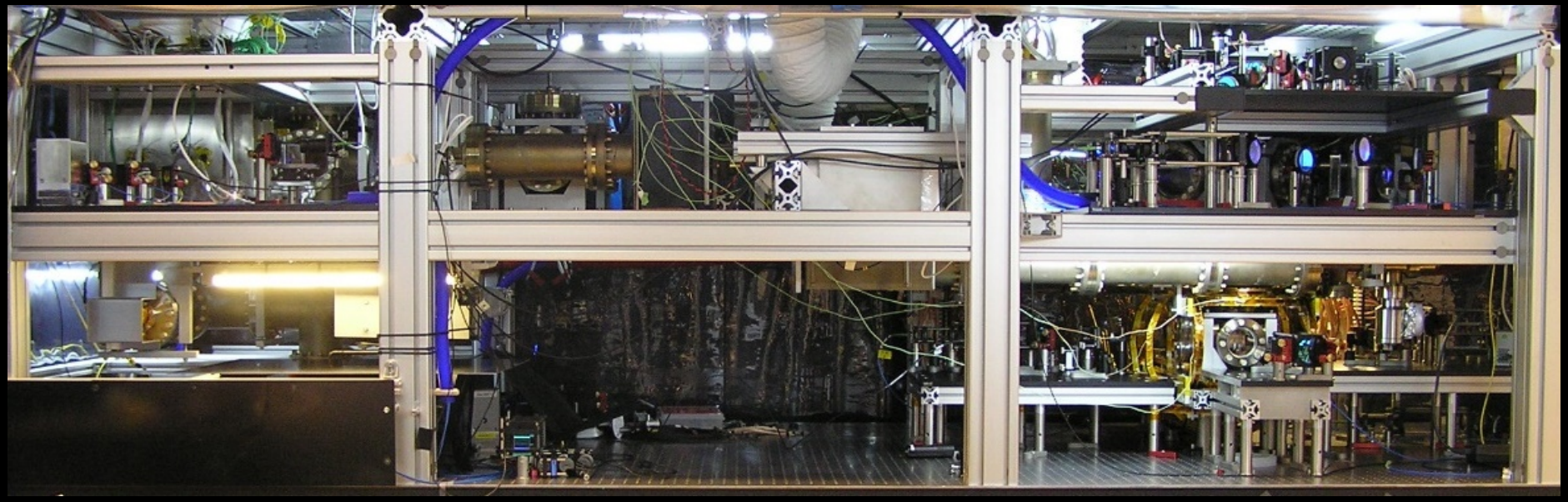
Building our perpetual atom laser

Summer 2015



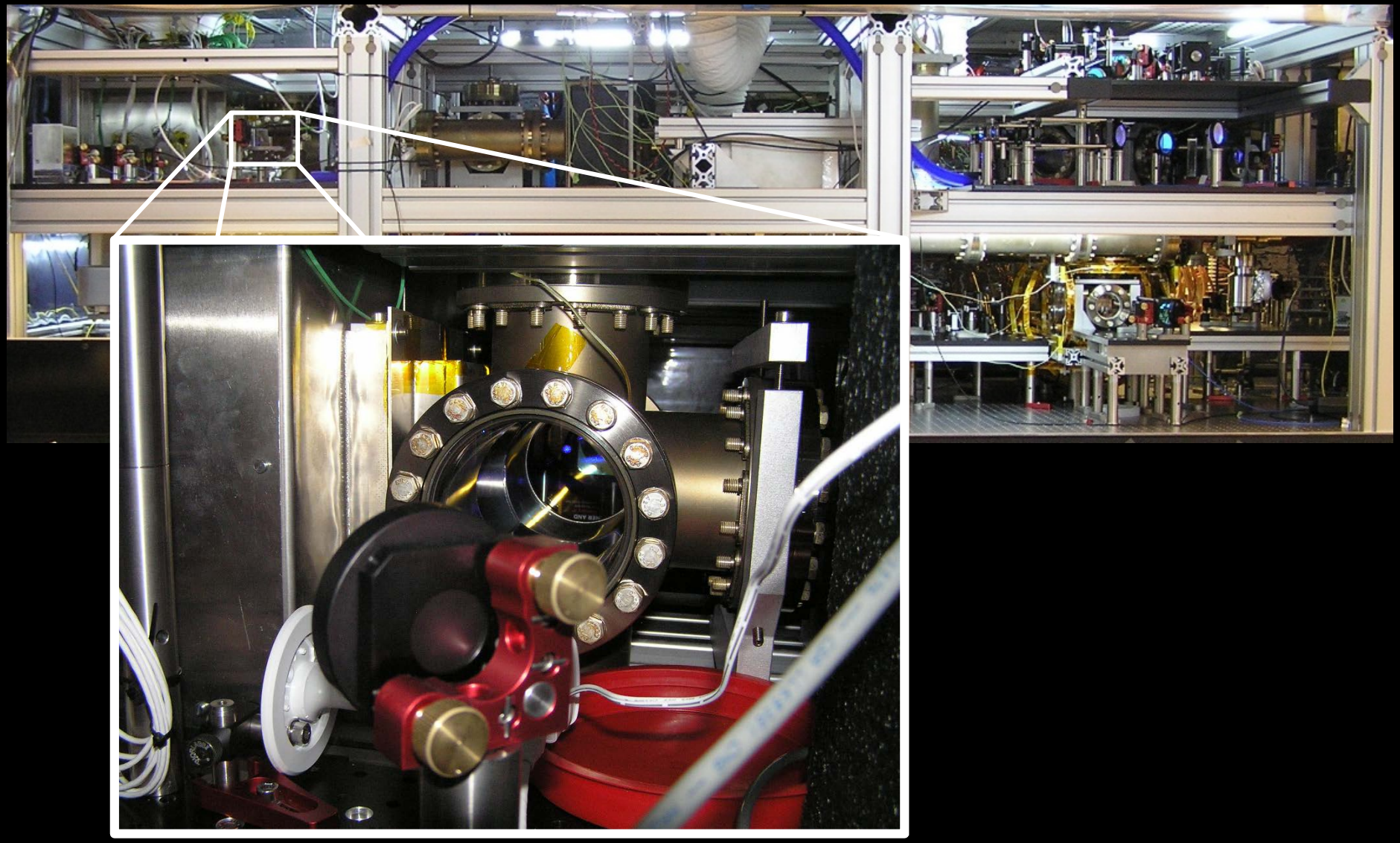
Building our perpetual atom laser

Winter 2015/16



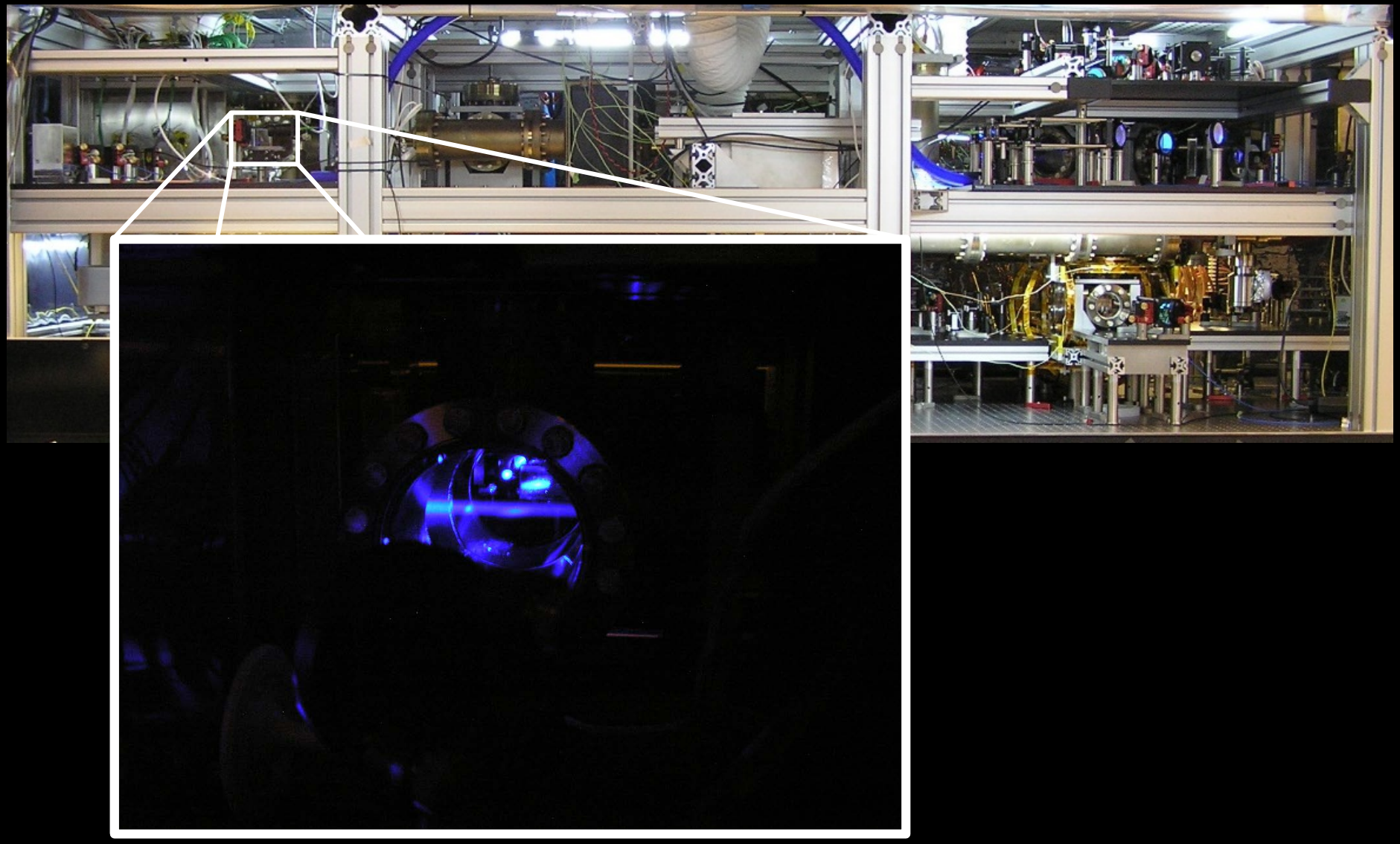
Booting up our atom laser

Spring 2016

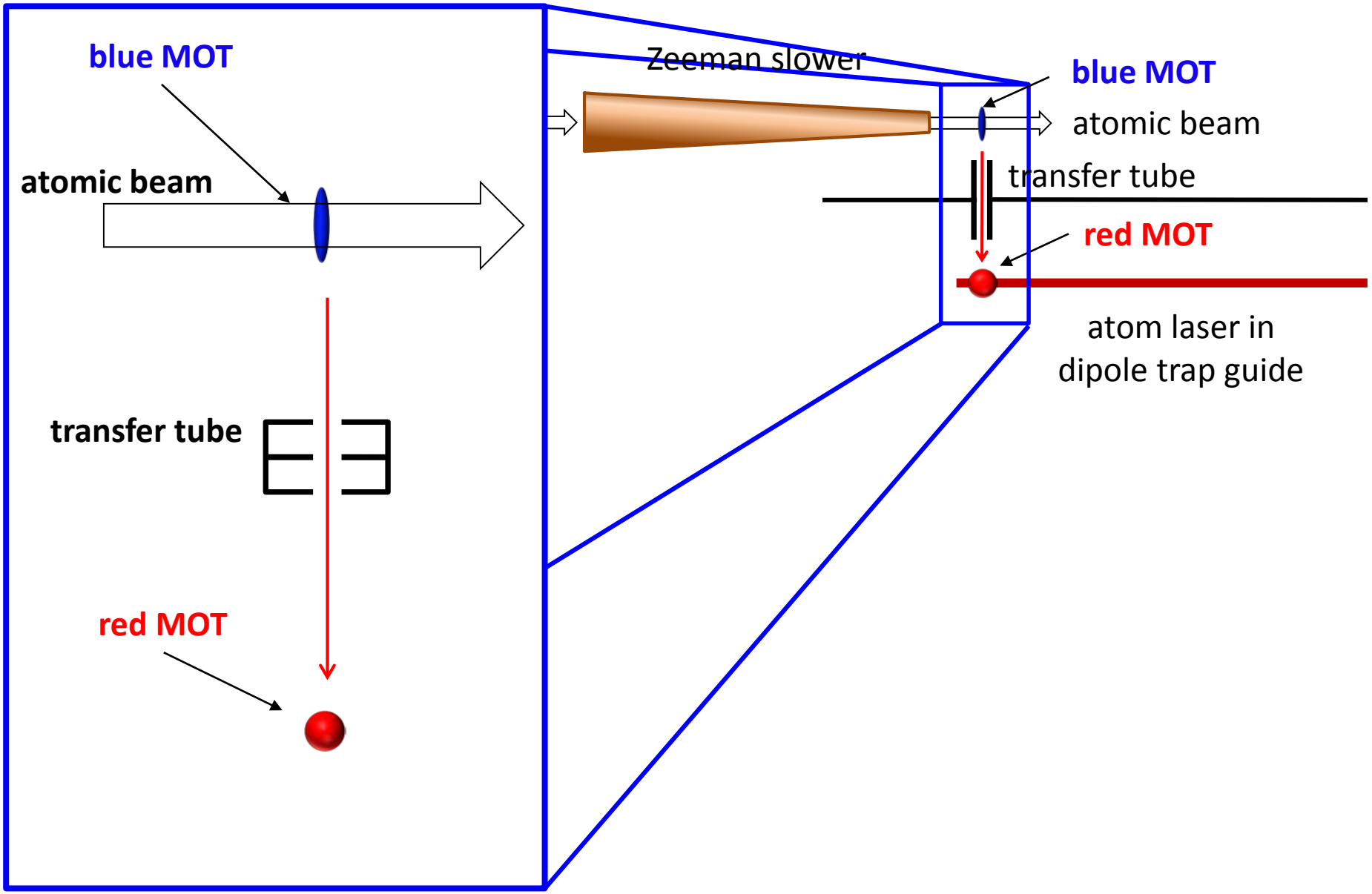


Booting up our atom laser

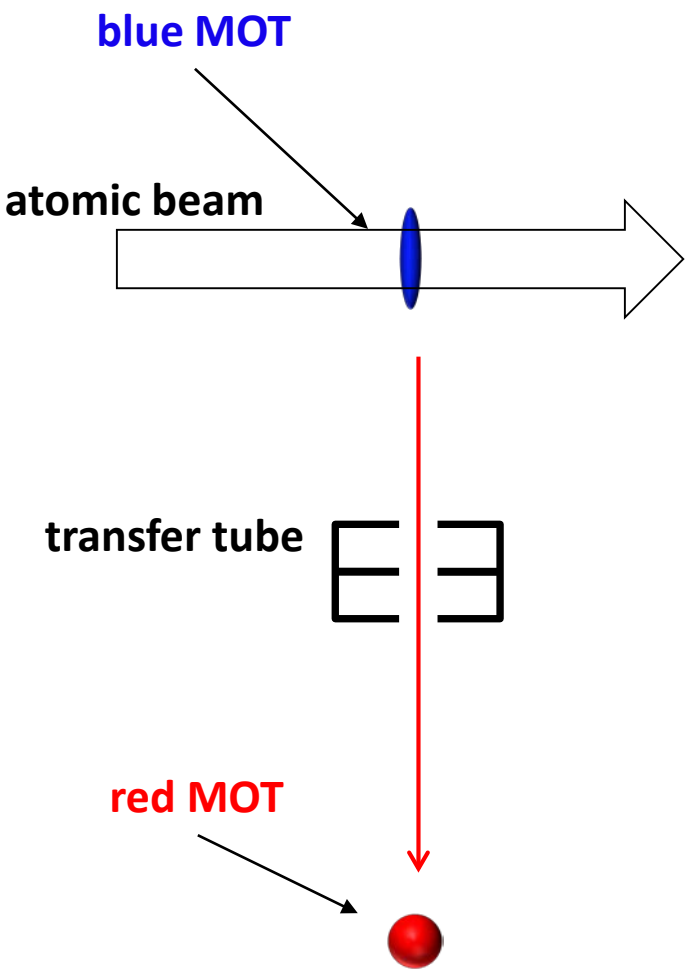
Spring 2016



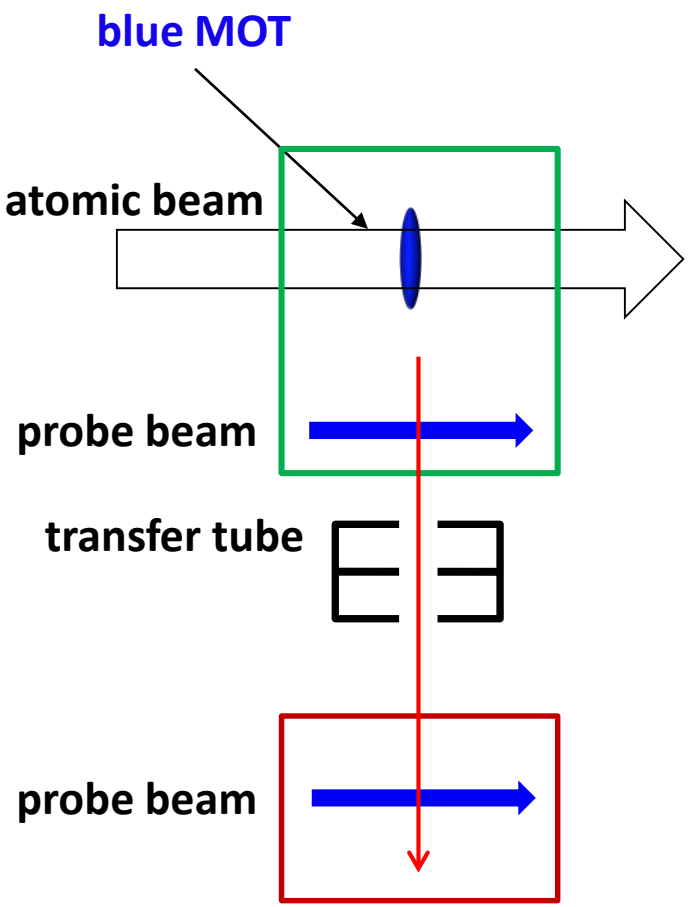
Booting up the atom laser

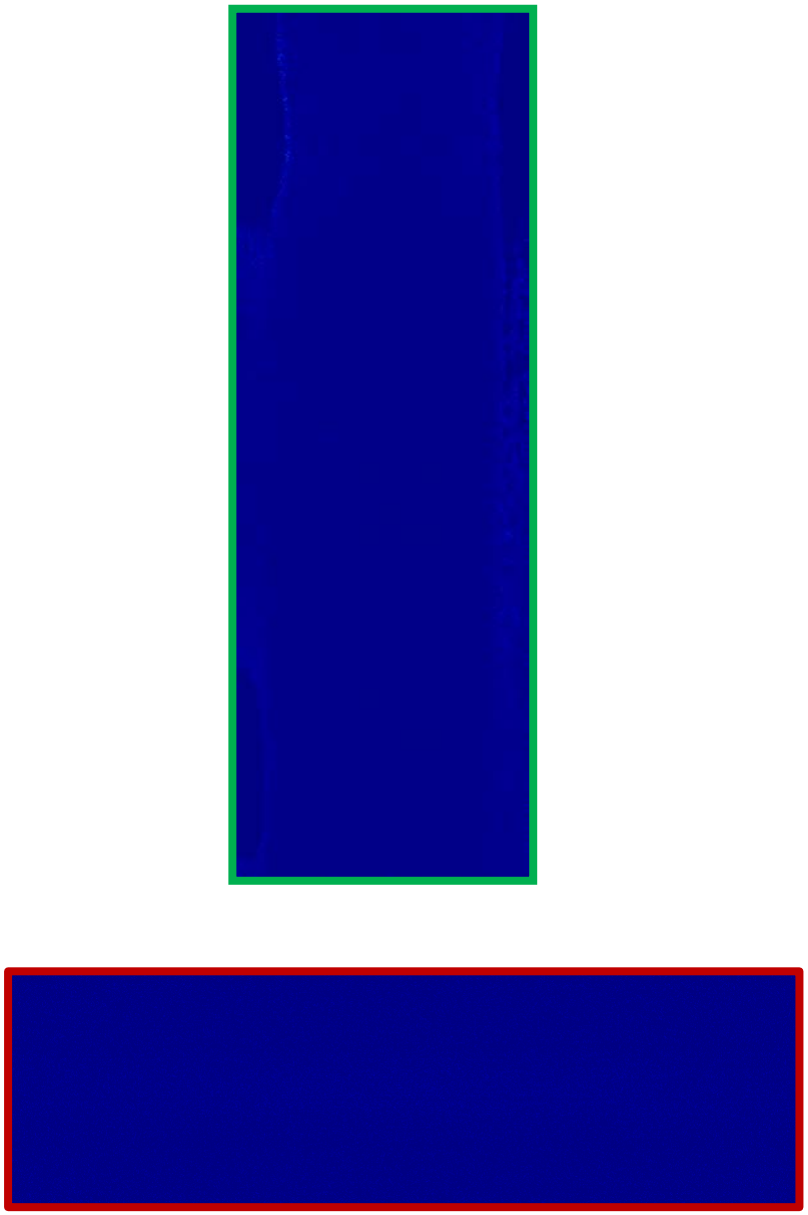


Atom transfer

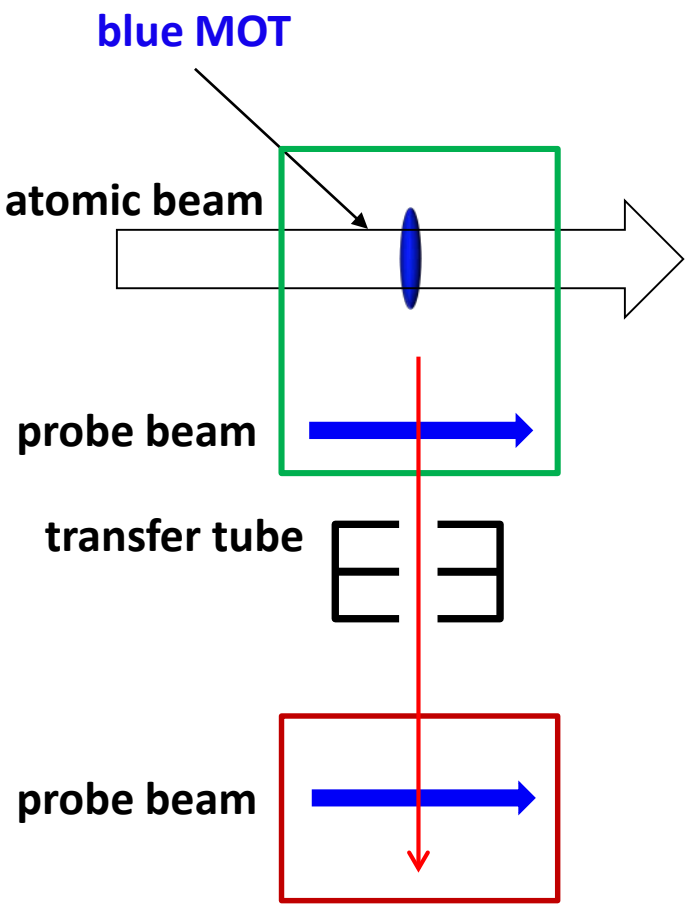


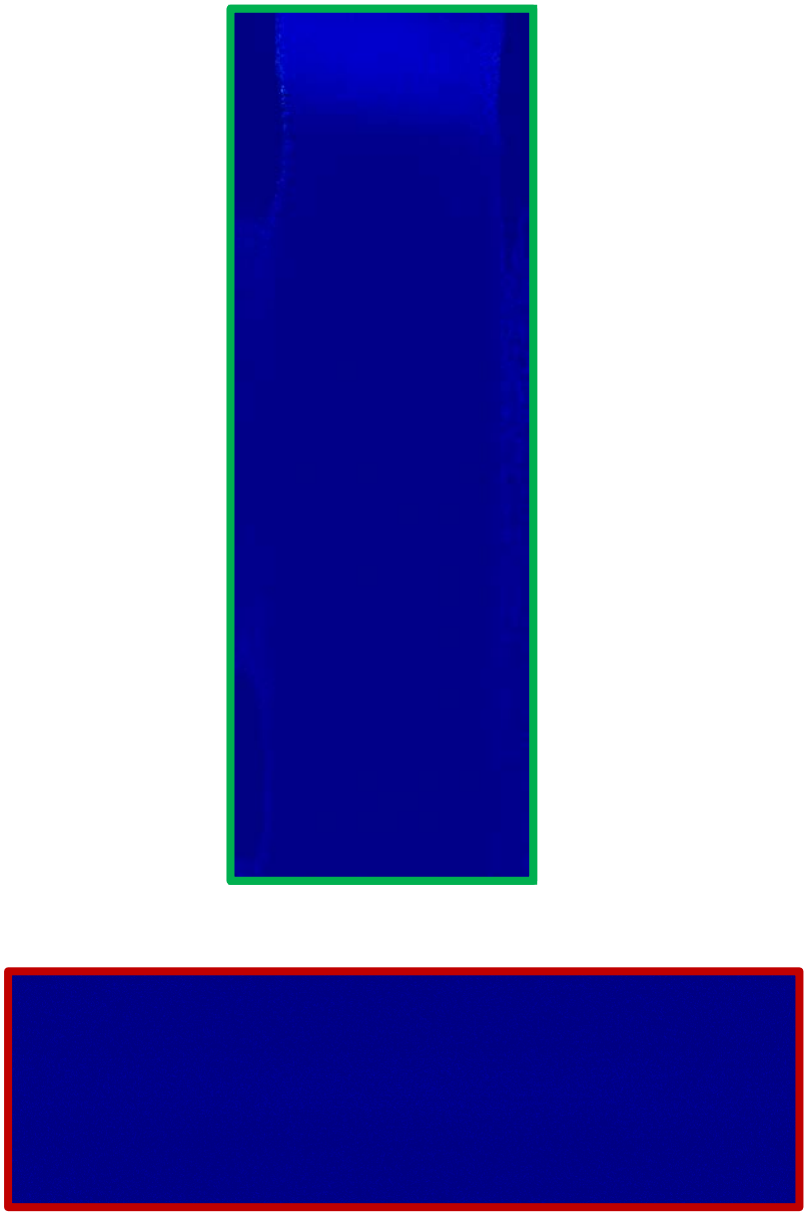
Fluorescence images



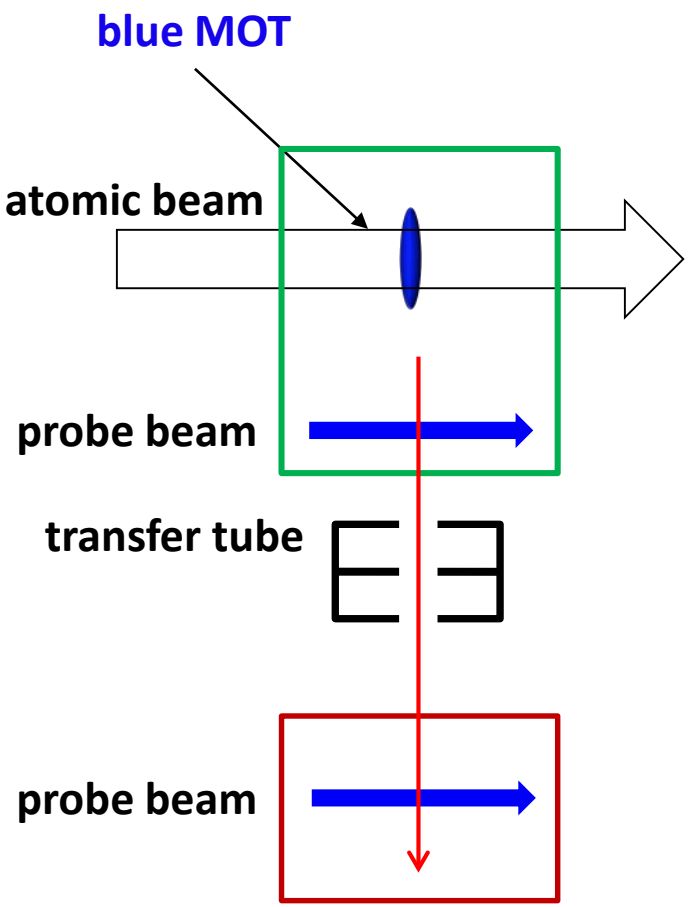


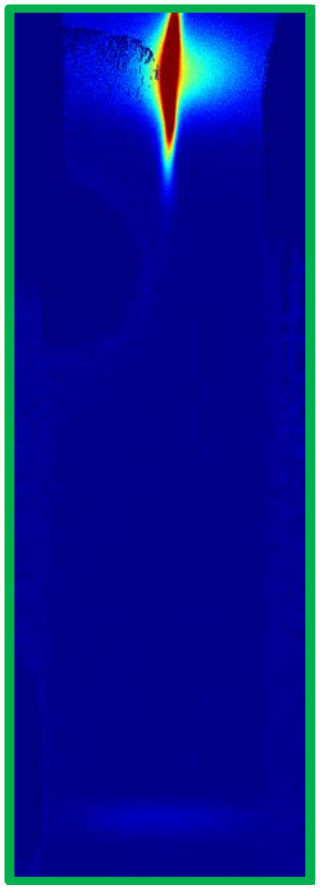
Zeeman slower on

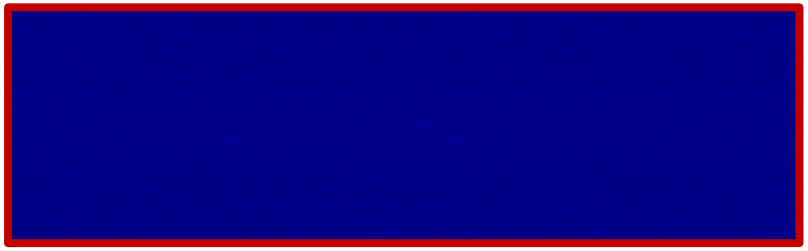




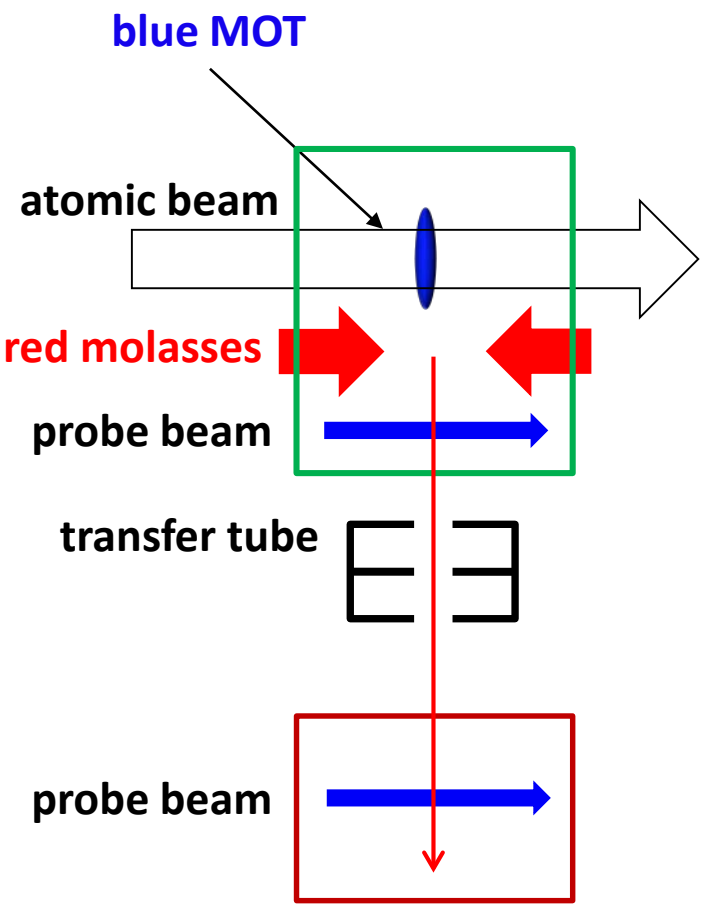
Blue MOT on

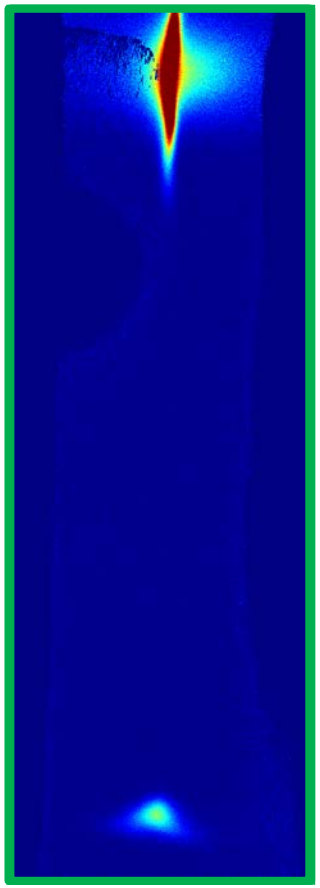


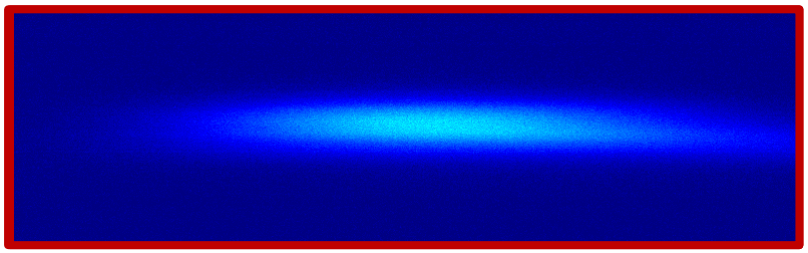




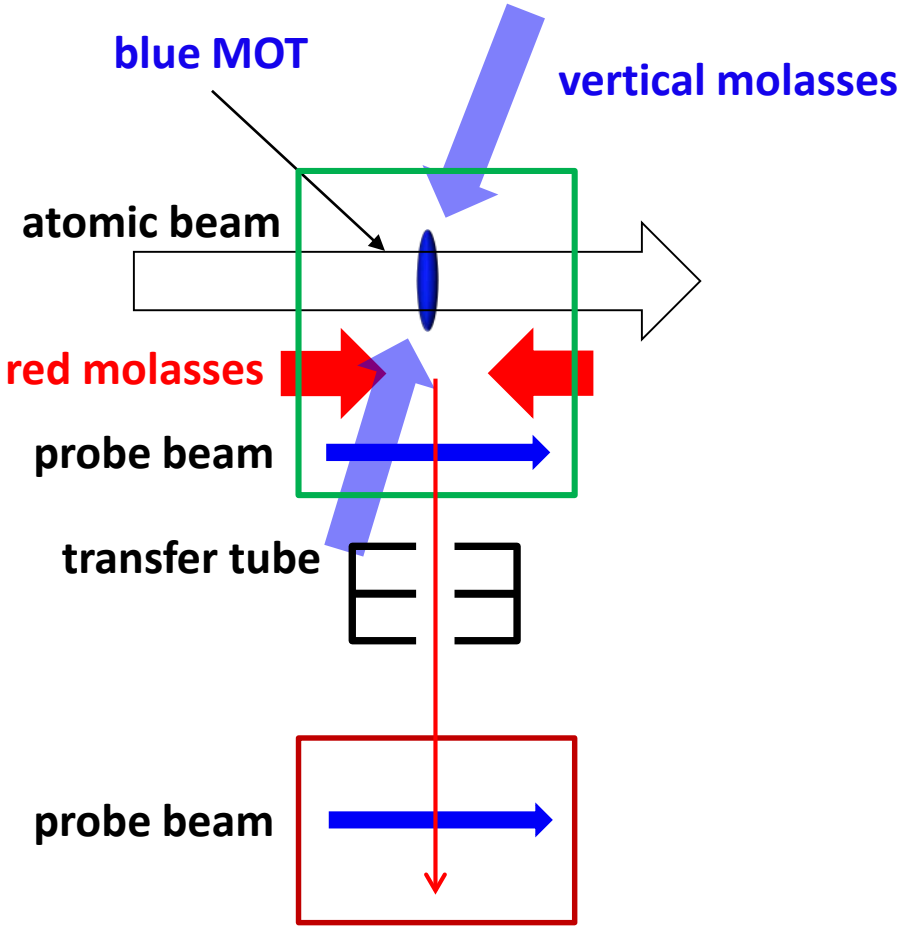
Get colder

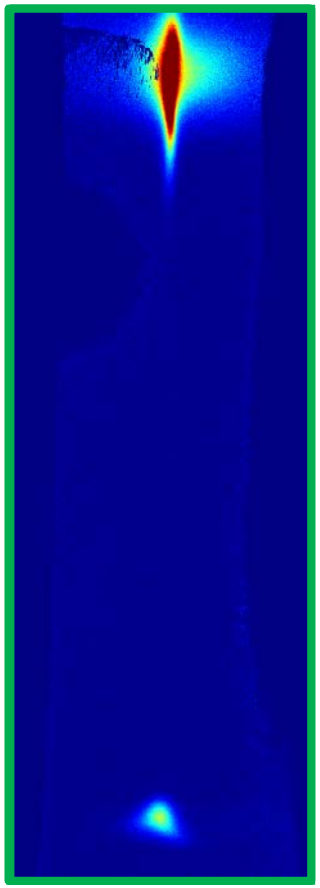

blue MOT
atomic beam
red molasses
probe beam
transfer tube
probe beam

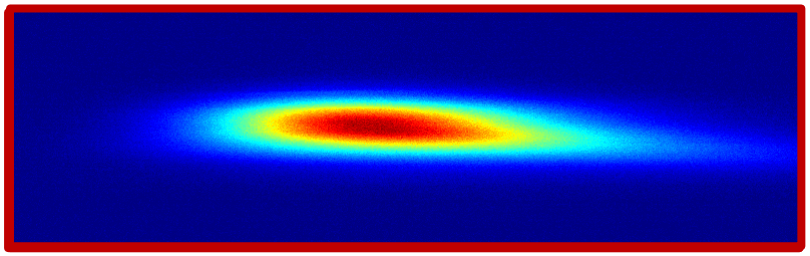




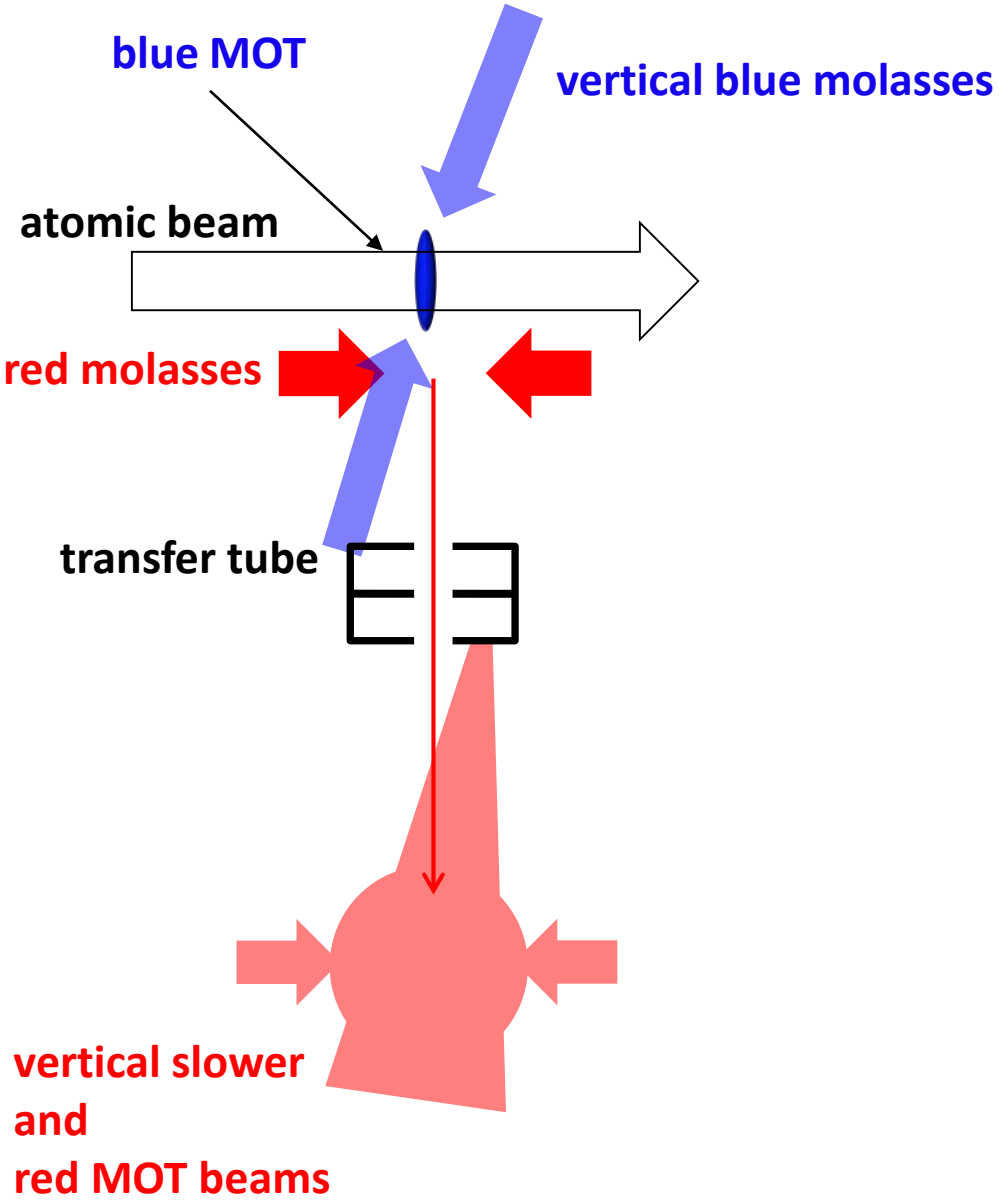
Get slower


blue MOT
vertical molasses
atomic beam
red molasses
probe beam
transfer tube
probe beam

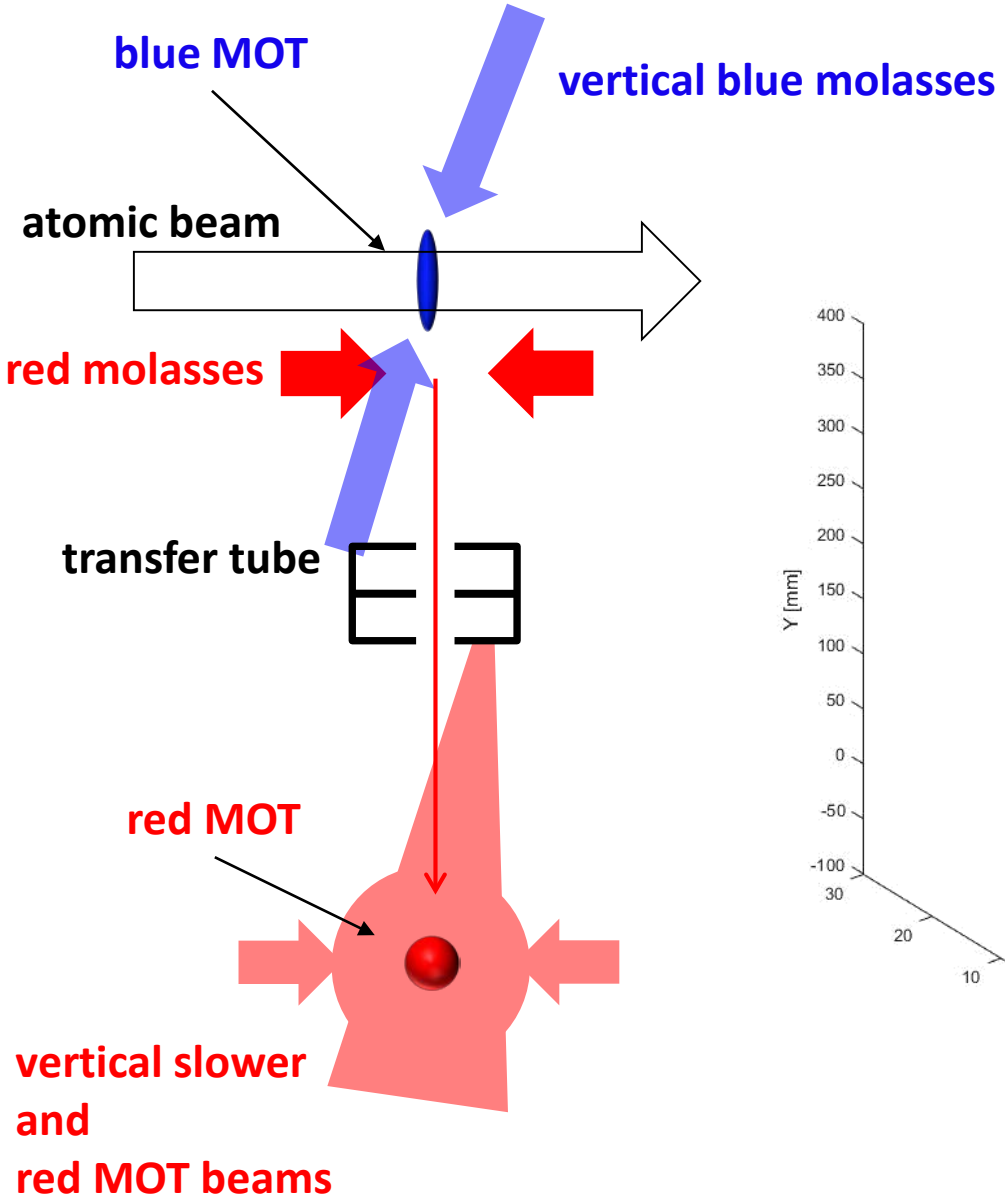


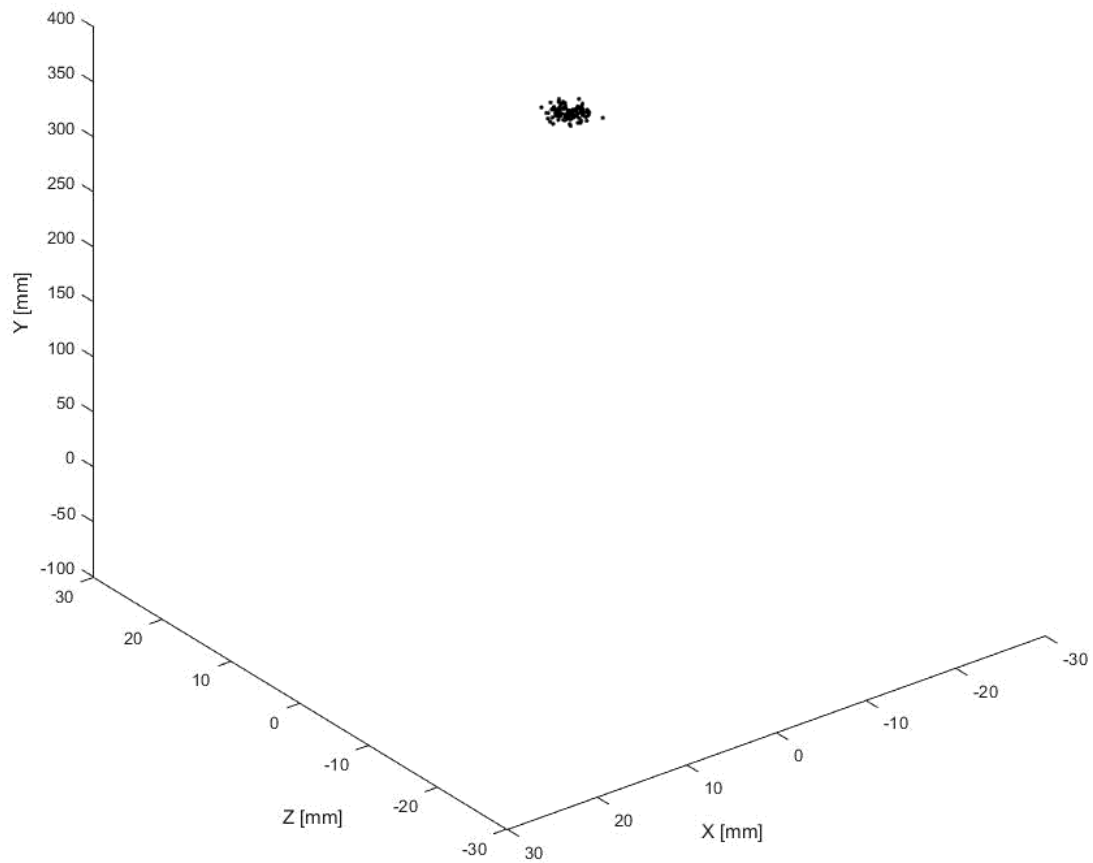


Capture atoms

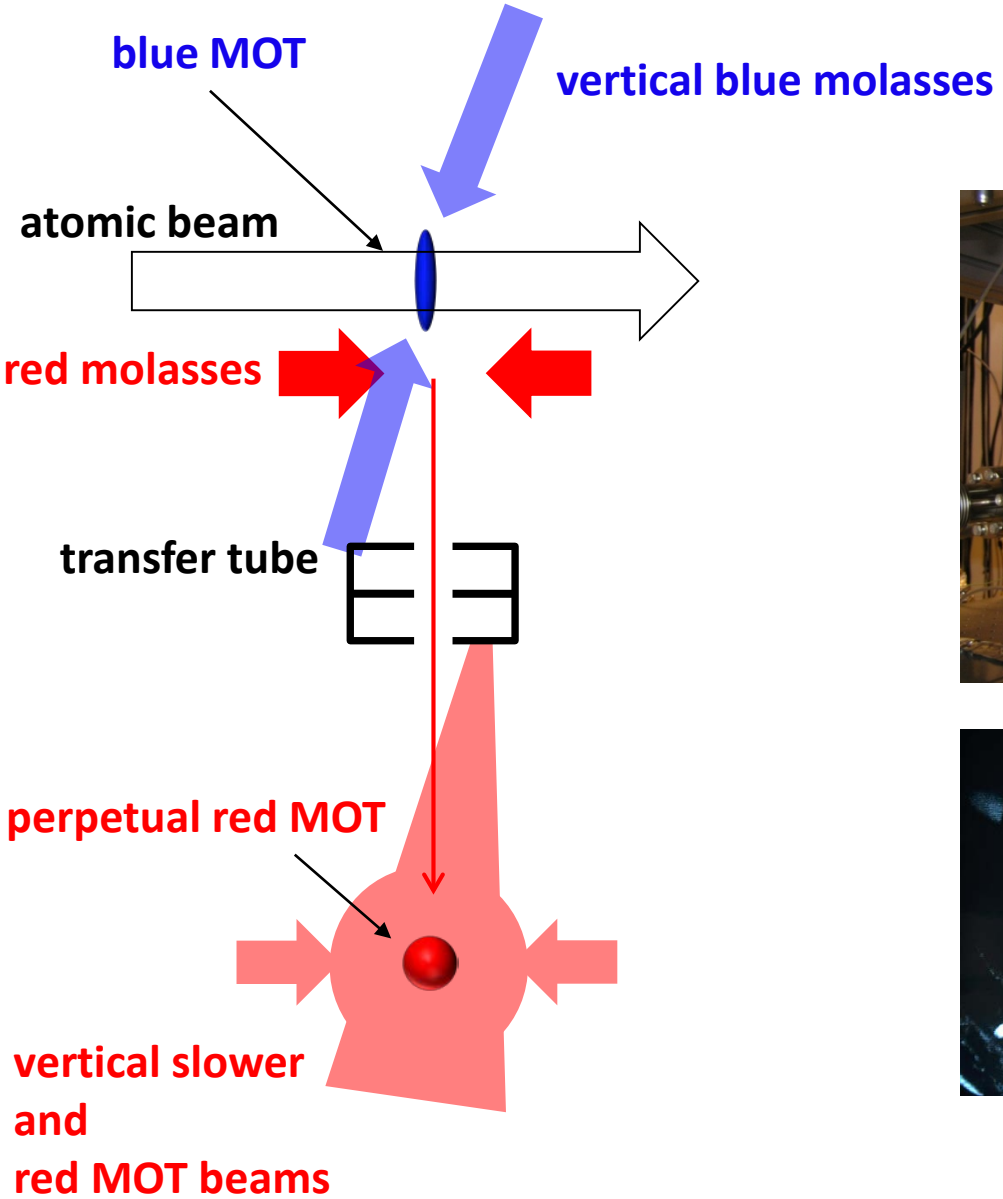


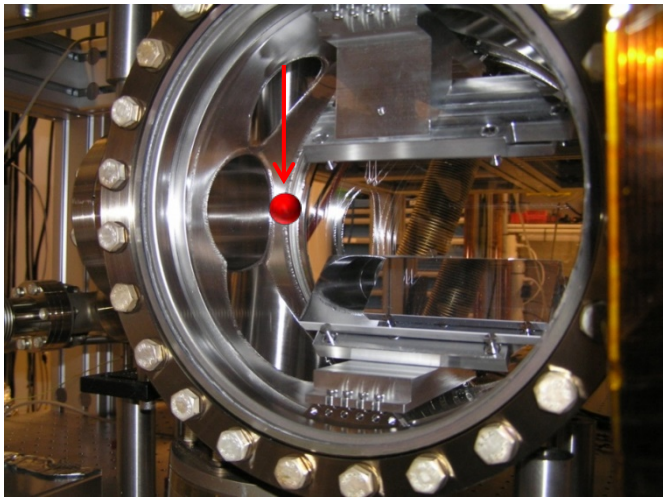
Capture atoms

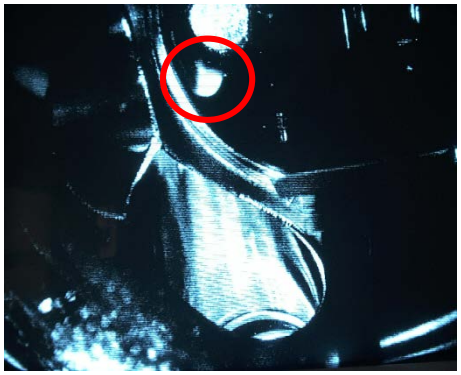


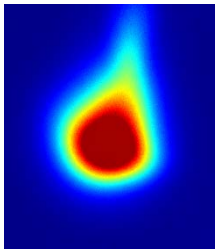


Perpetual red MOT



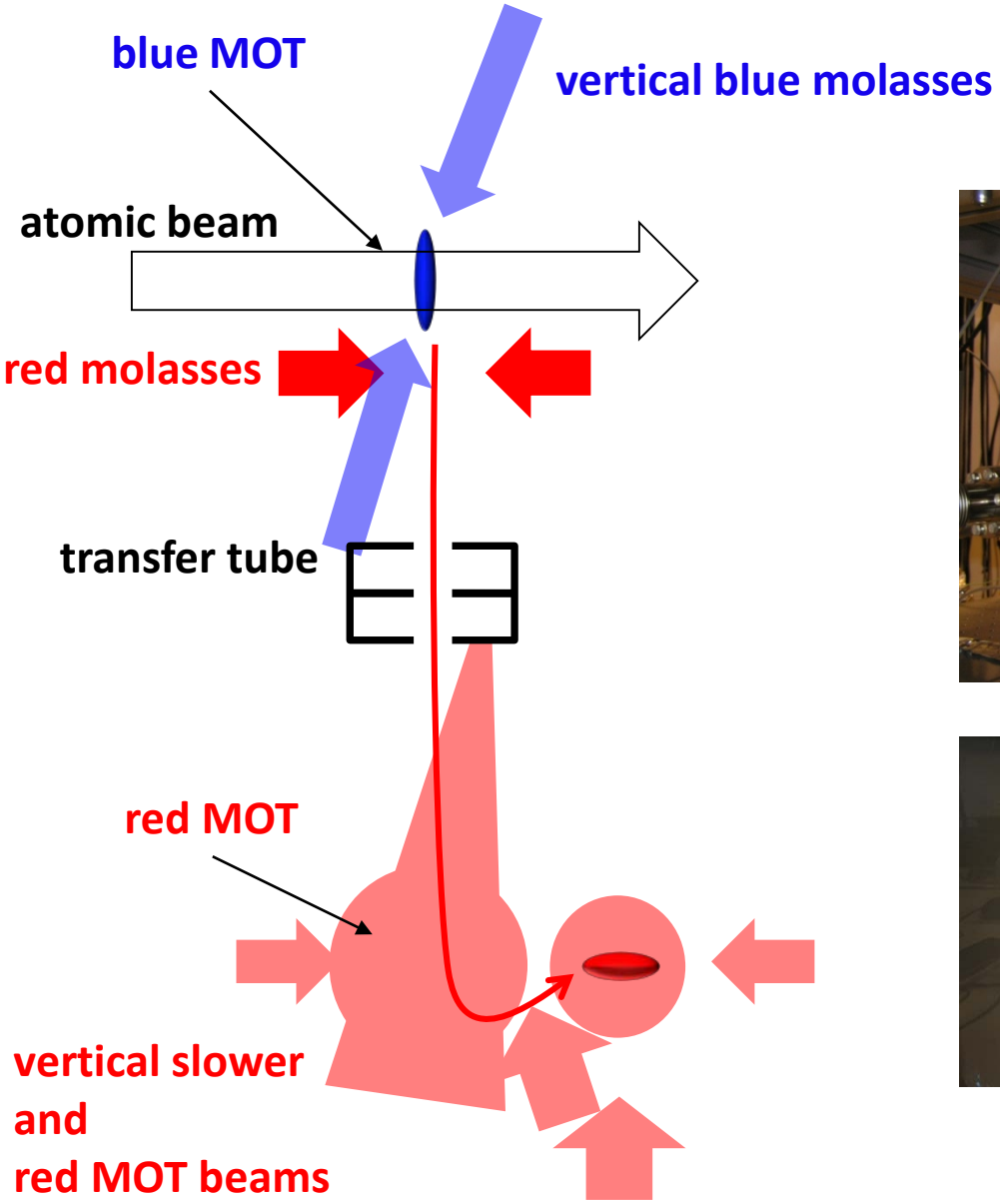


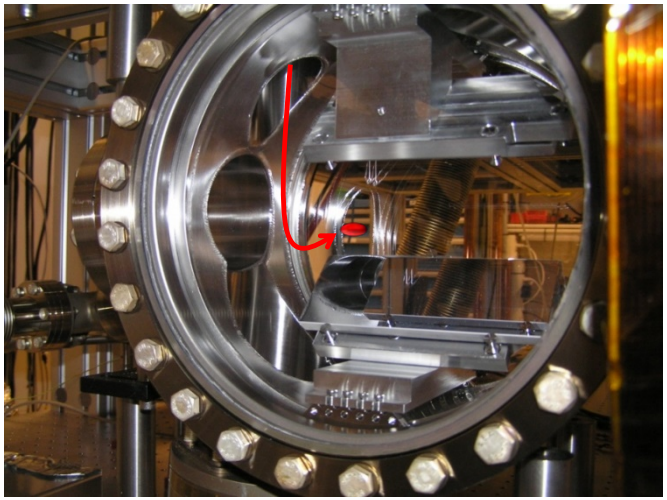


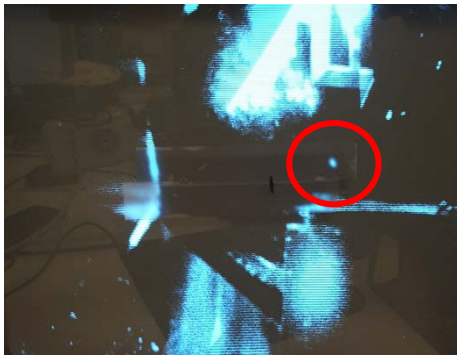


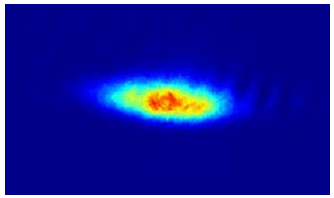
N = 10^9 ^{88}Sr
Flux = 10^8 ^{88}Sr/s
T = 50 μK

Perpetual narrow-line MOT







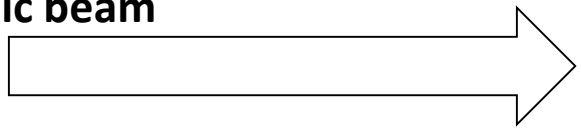


N = 10^7 ^{88}Sr
T = 3 μK
flux = 10^7 ^{88}Sr/s
= 10^5 ^{84}Sr/s

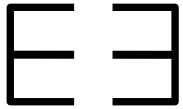
(oven T= 410°C, design 540°C)

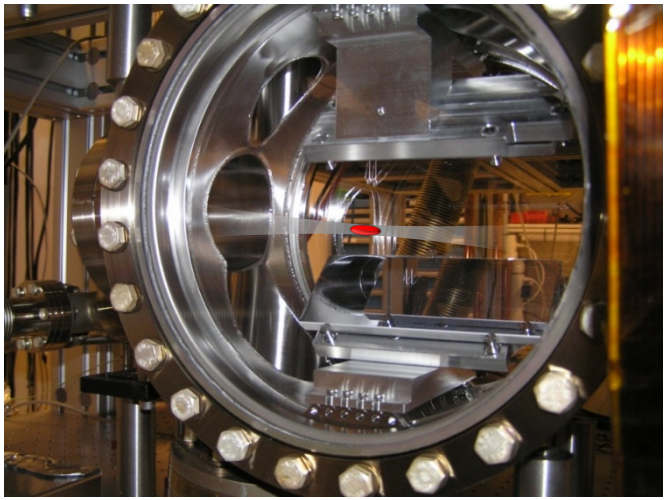
Time-sequential BEC

atomic beam



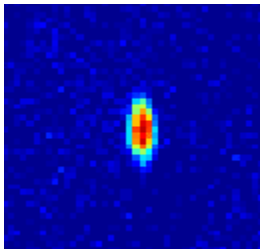
transfer tube





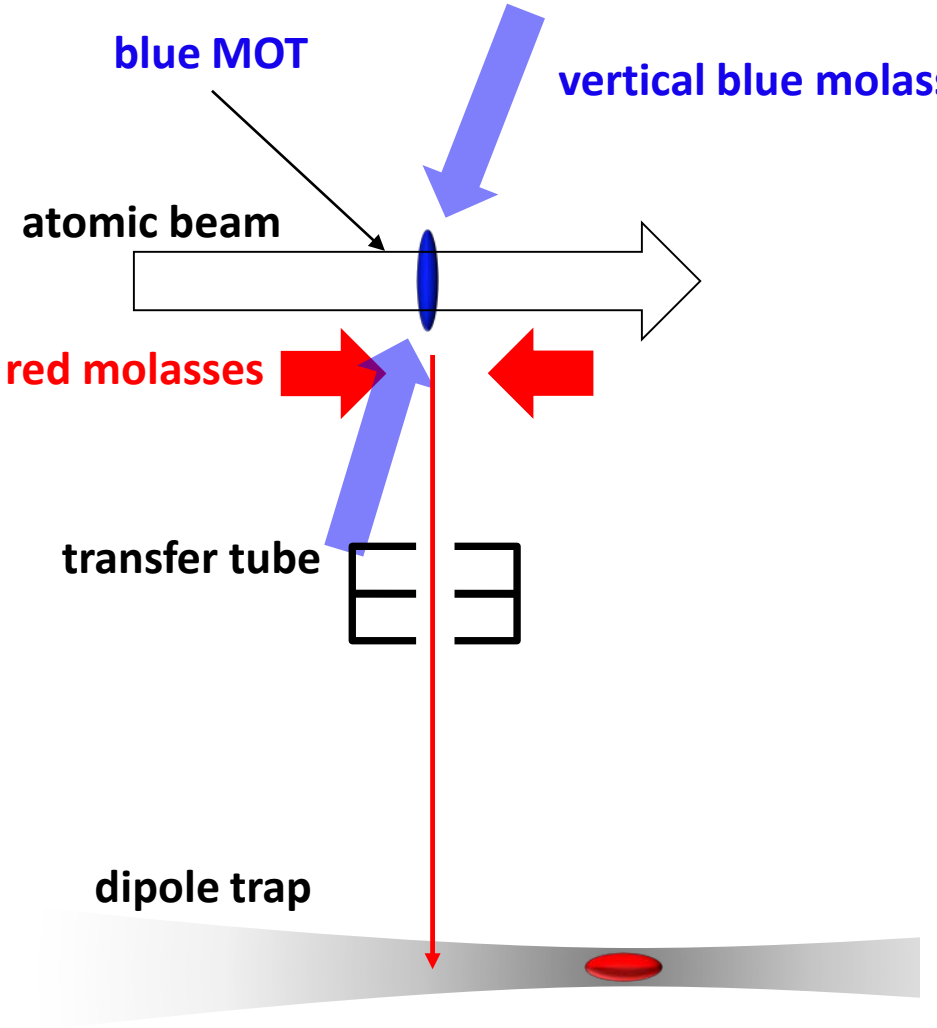
Time-sequentially created BEC

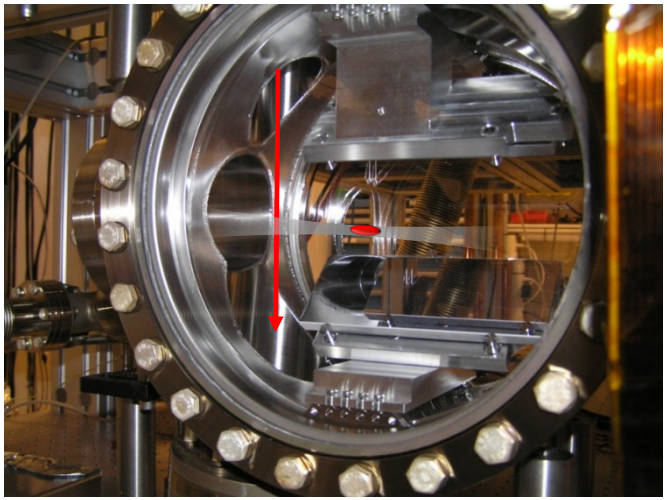
dipole trap



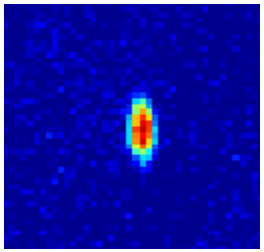
BEC lifetime
without blue light: 7s

Stray-light protected BEC





Time-sequentially created BEC



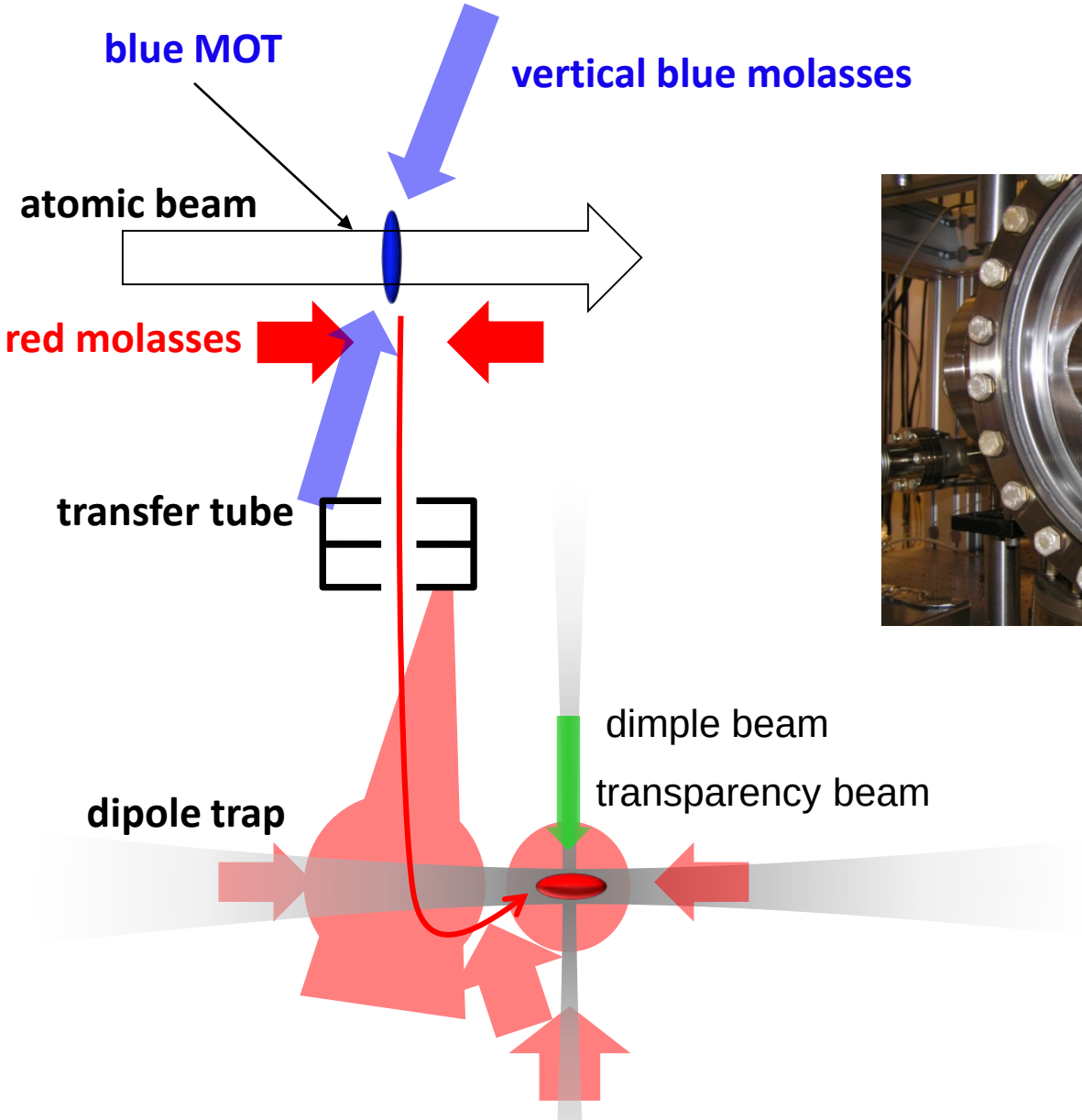
BEC lifetime

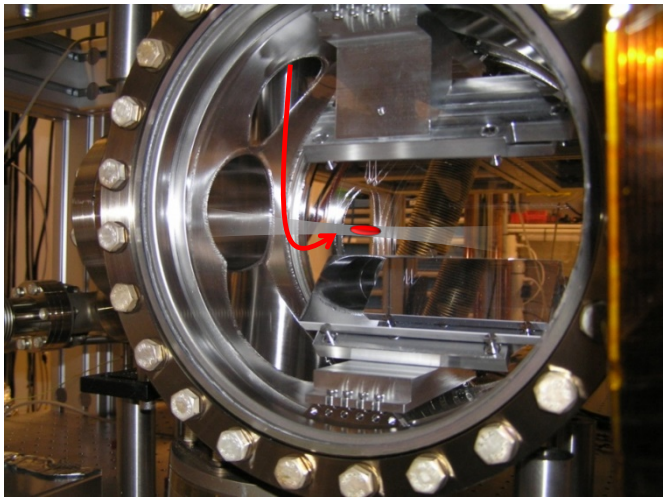
without blue light: 7s

with blue light: 6s

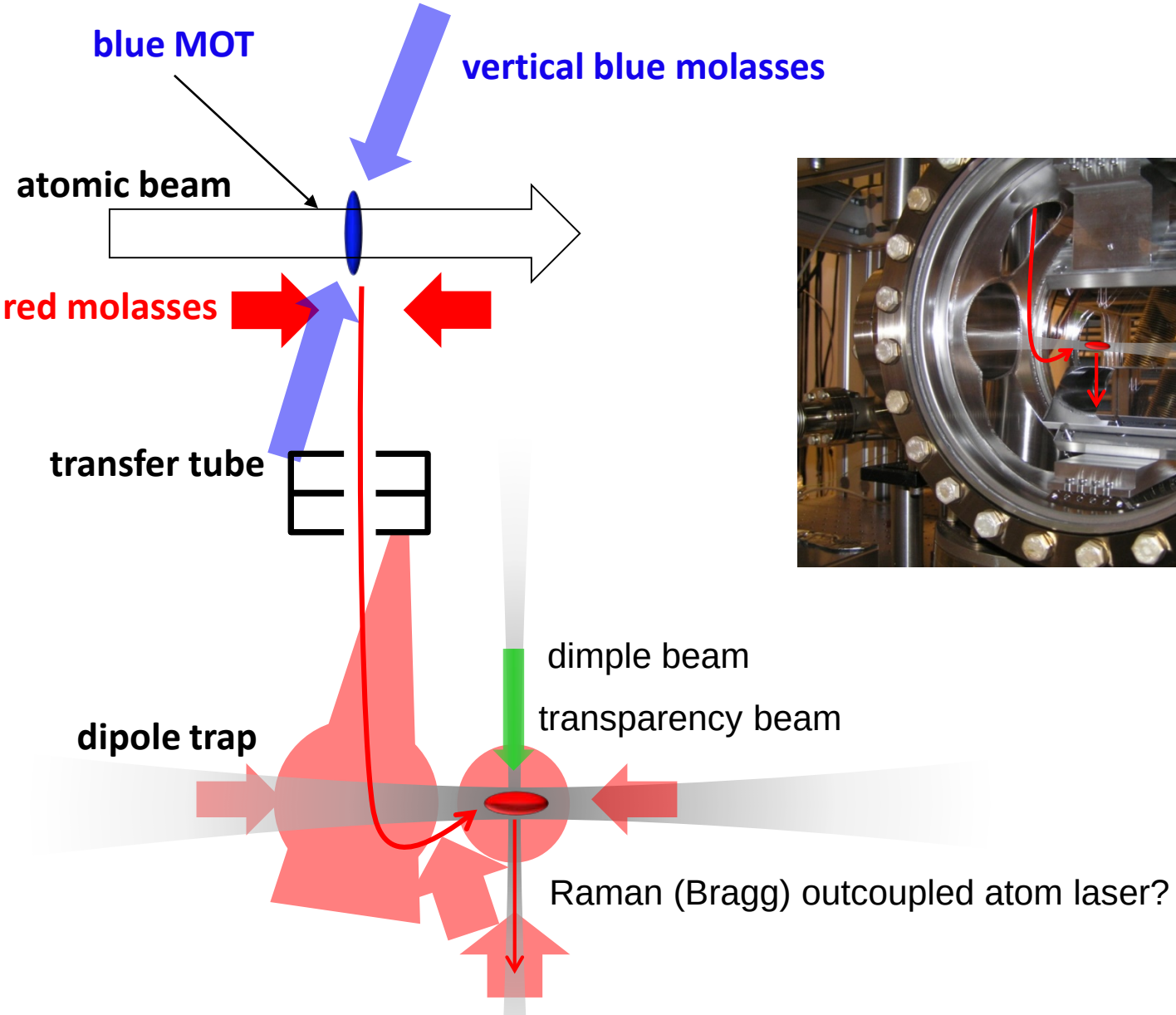
Straylight protection works!

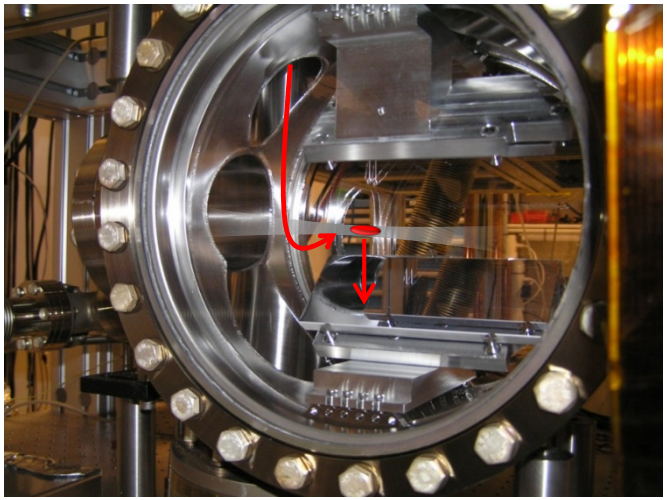
Towards perpetual BEC



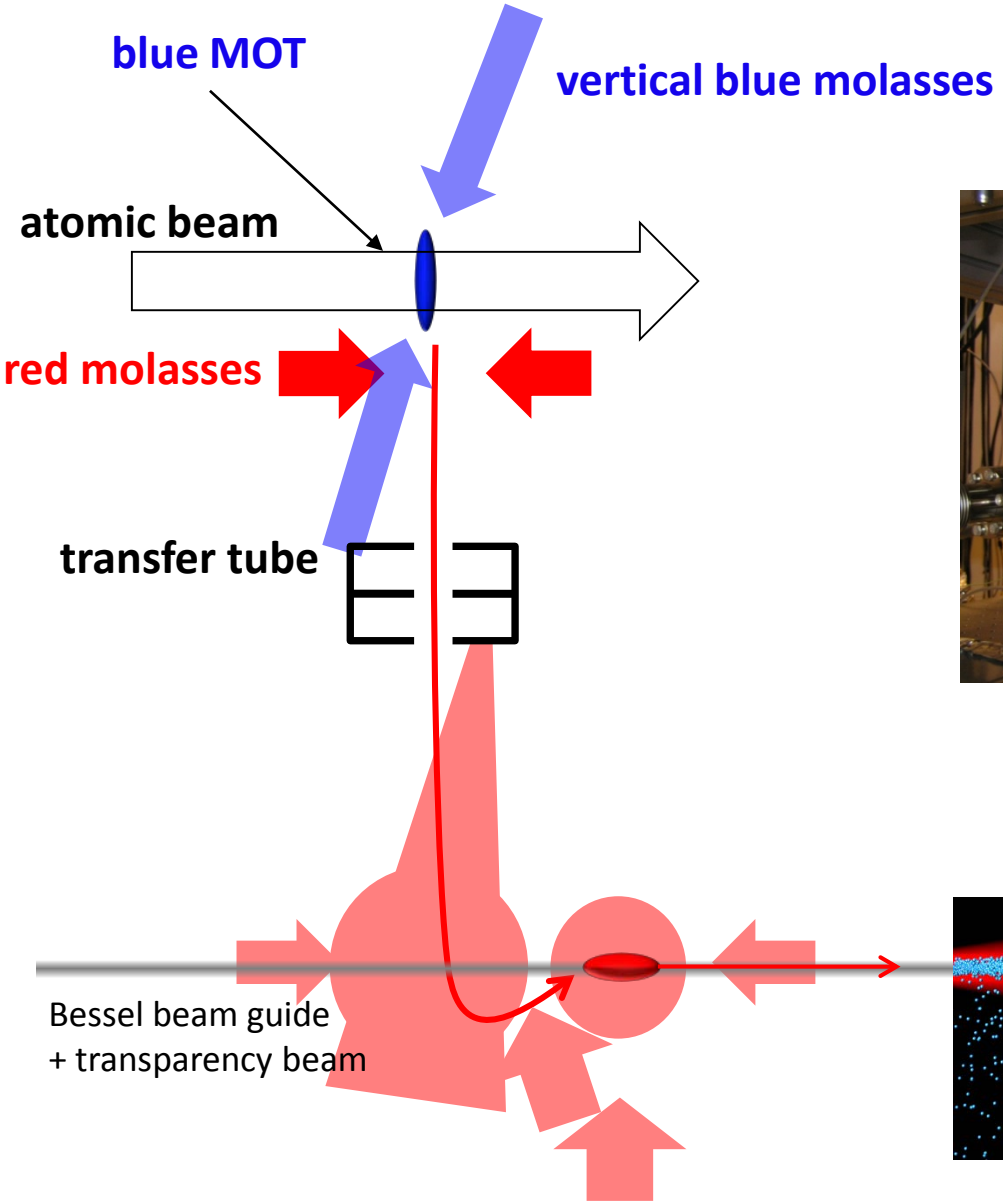


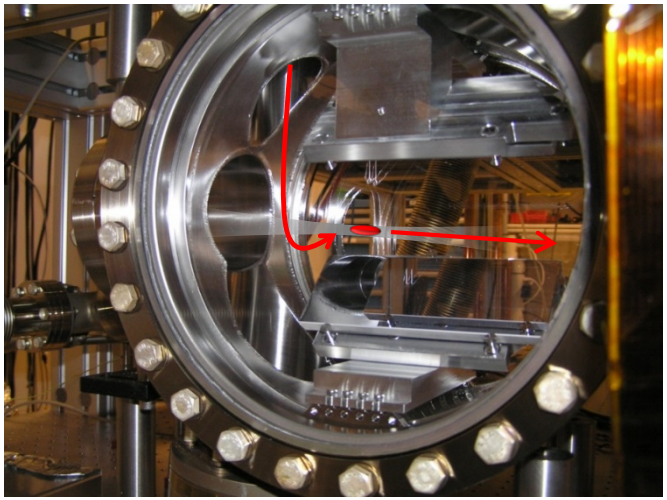
Towards perpetual atom laser

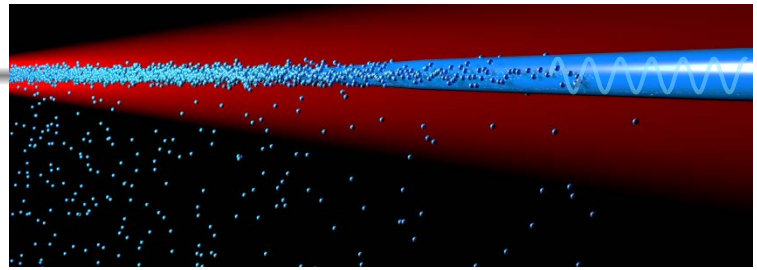




Towards perpetual atom laser

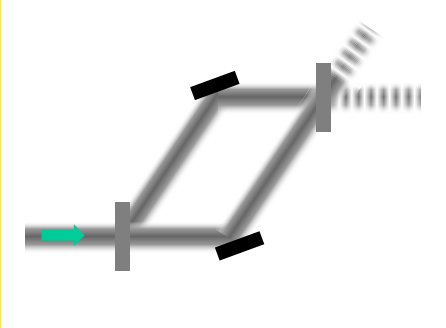






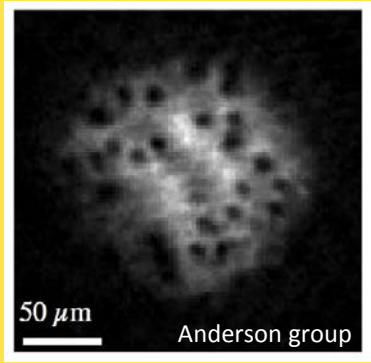
Why atom lasers?

Precision measurement



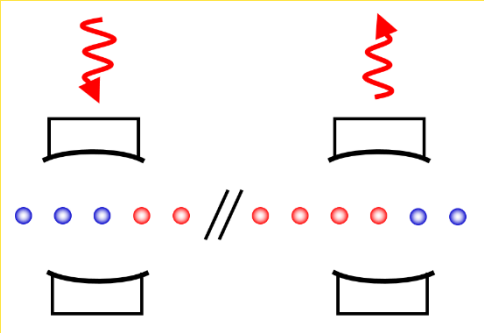
- Atom interferometry
- Superradiant mHz-linewidth laser

Studies of quantum mechanics



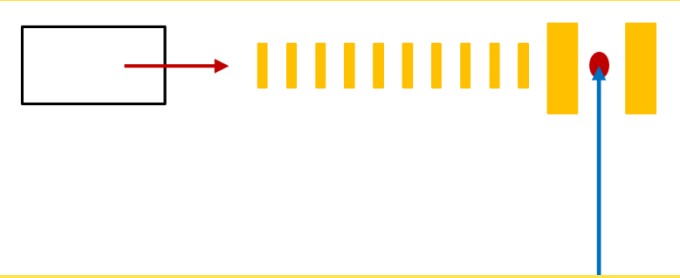
- Dissipative driven systems
- Quantum turbulence

Quantum technology



- Conversion into chain of atoms
  → Quantum FIFO memory

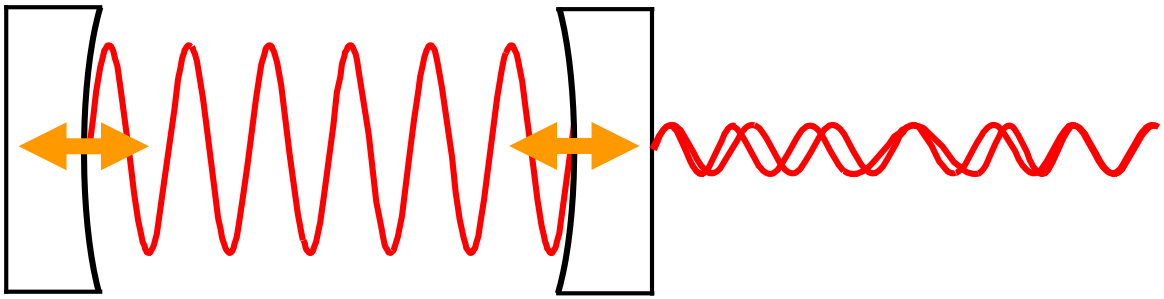
Technology



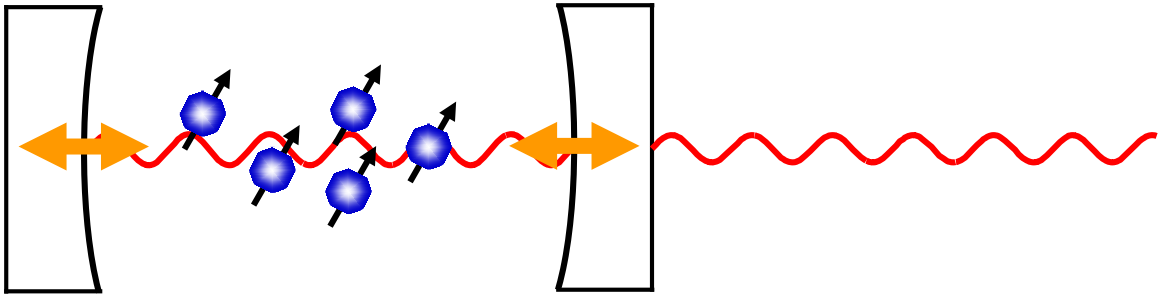
- Cold e^- or ion sources
- Perpetual sympathetic cooling reservoir
- Lithography

mHz-linewidth superradiant laser

Normal clock laser: frequency stability from length of cavity



Superradiant clock laser: frequency stability from ensemble spin of atoms



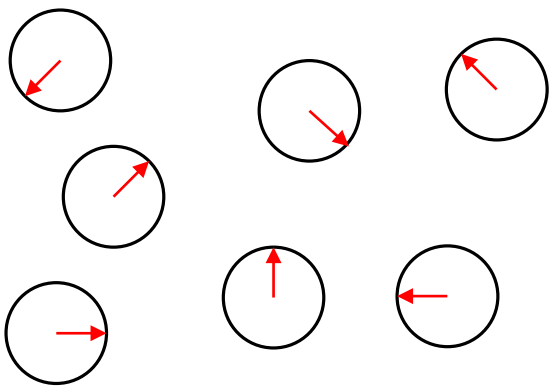
Need very longlived excited state to conserve spin orientation for long time.

→ Sr mHz-linewidth clock transition. Minutes lifetime.

How do we get sufficient flux of photons from such a long-lived state?

Phased antennas

Emission of *N* antennas with random phase:

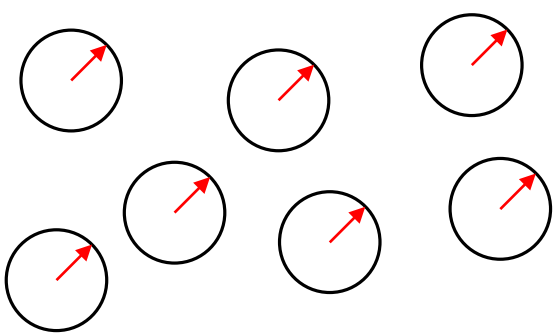


Electric fields interfere randomly

Total power is *N* times power of one antenna

Power scales with *N*

Emission of *N* antennas with same phase, closer spaced than wavelength



Electric fields interfere constructively

Electric field scales with *N*

Total power scales with N^2

Superradiance

Consider emission of *N* excited state atoms such that it cannot be known which atom emitted a photon

e.g. - all atoms within volume λ^3
- couple all atoms to same cavity mode

After one emission event, superposition state results of all combinations of one atom in ground state and all other in excited state

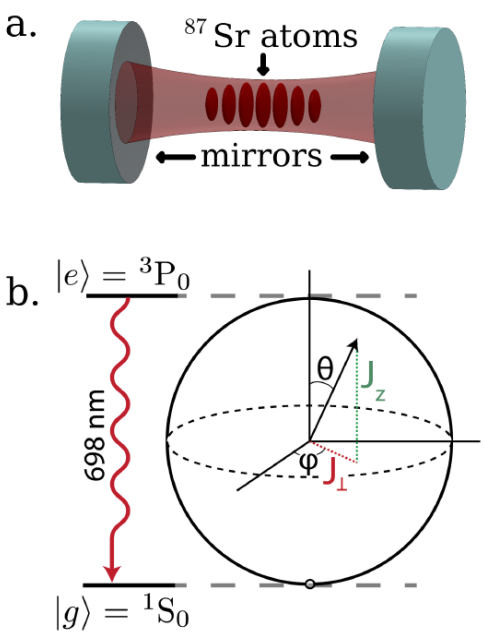
This is a Dicke state.
It will emit with higher probability into same mode as first photon.

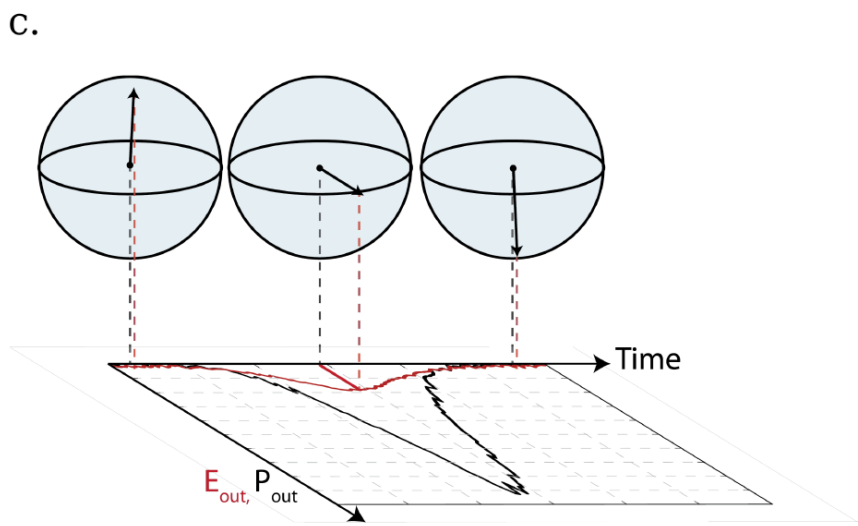
Even stronger entanglement.
Even higher emission probability, just like for phased antennas.

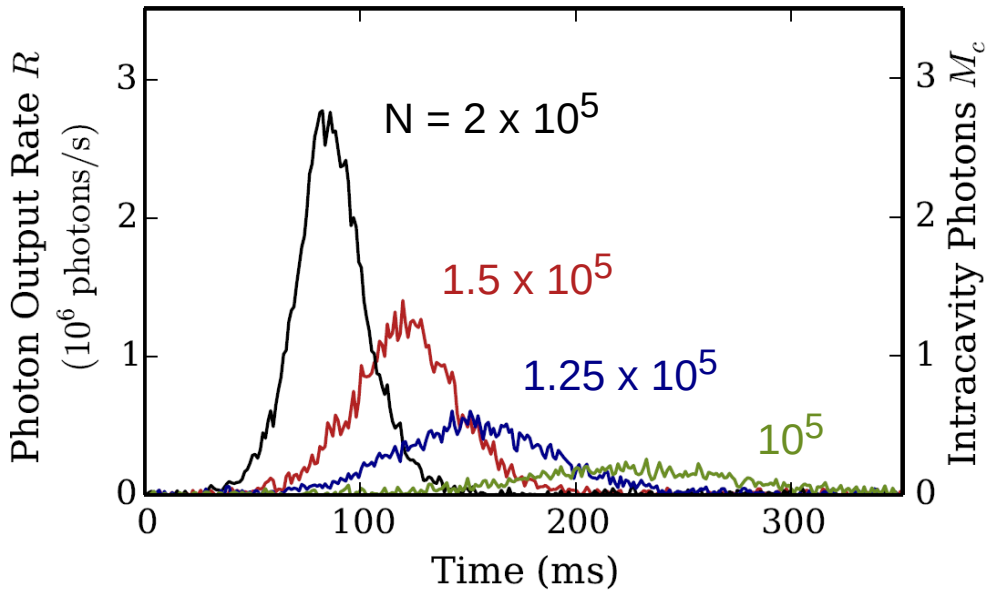
A superradiant flash of light is the result.

Pulsed superradiant laser

Thompson group, arXiv:1603.05671



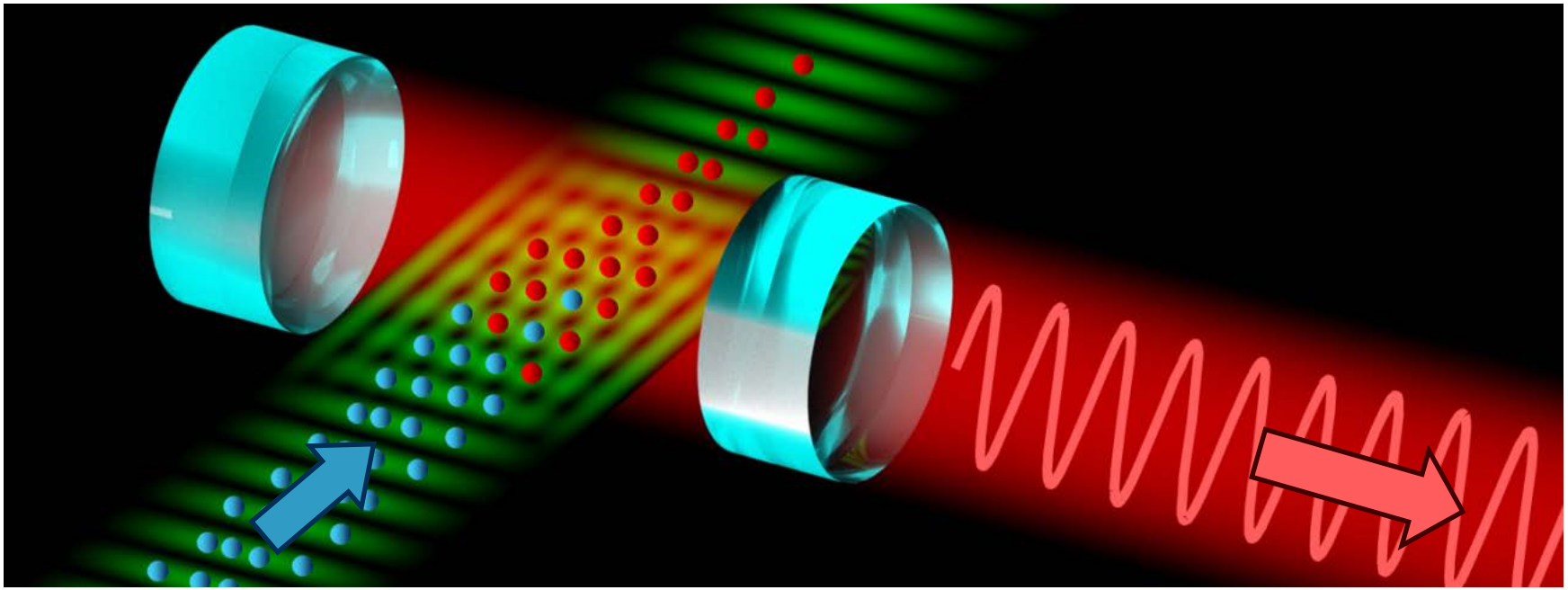




mHz-linewidth laser

For continuous laser beam:

- ovecome Doppler broadening by confinement in lattice (Lamb-Dicke regime)
- repump atoms to metastable state
- continuously cool atoms
- replenish lost atoms



strontium atom laser beam in

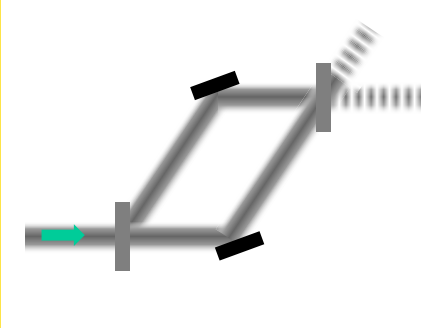
optical clock laser beam out

Theory:

Optical lattice laser, J. Chen, Chinese Science Bulletin 54, 348 (2009), on arXiv 2005.
Prospects for a Millihertz-Linewidth Laser, Meiser et al., PRL **102**, 163601 (2009).

Why atom lasers?

Precision measurement



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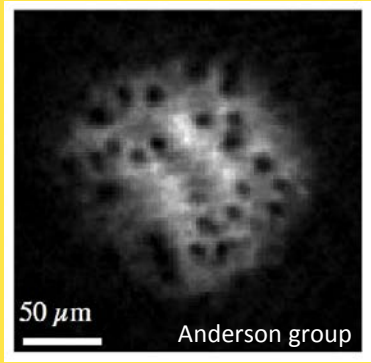
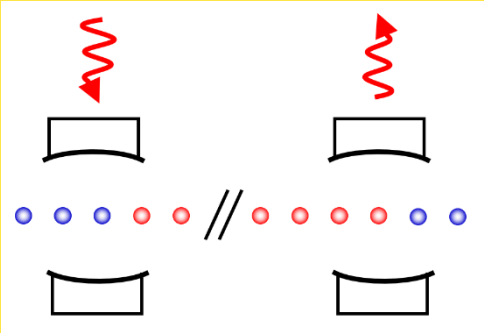
- Superradiant mHz-linewidth laser

Studies of quantum mechanics



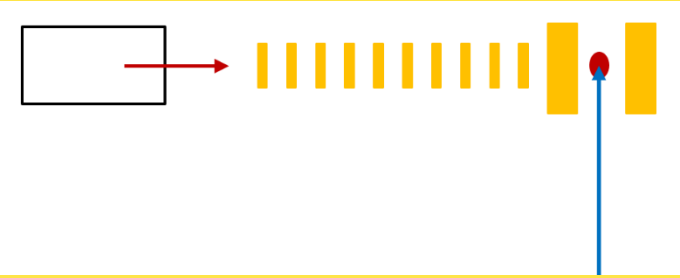
- Dissipative driven systems
- Quantum turbulence

Quantum technology



- Conversion into chain of atoms
  → Quantum FIFO memory

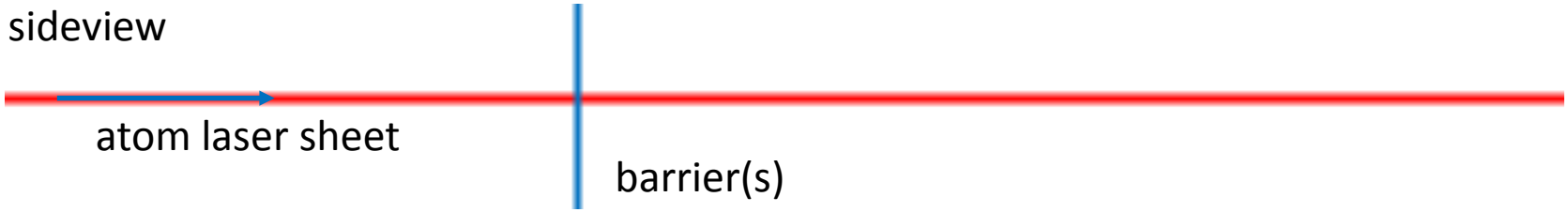
Technology



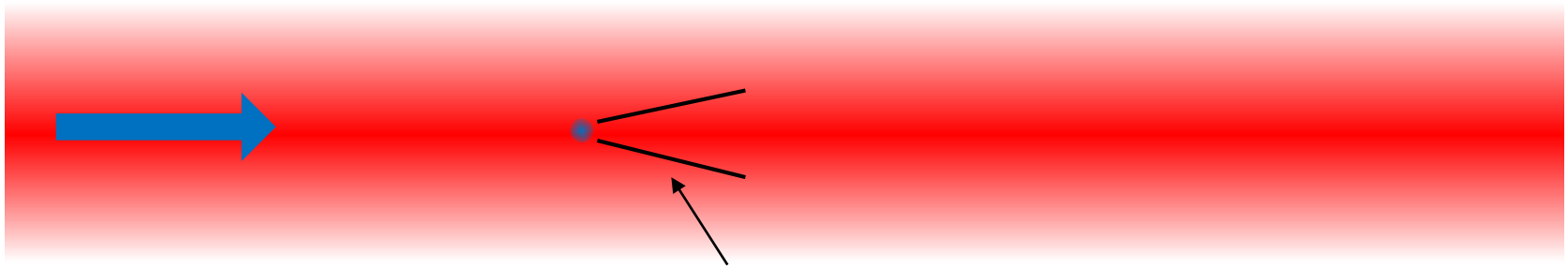
- Cold e^- or ion sources
- Perpetual sympathetic cooling reservoir
- Lithography

Quantum turbulence

sideview

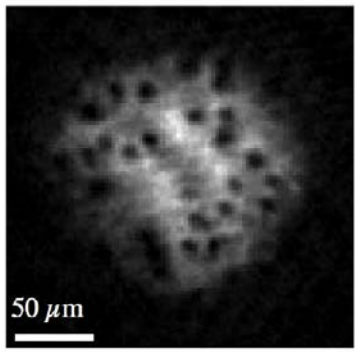


topview

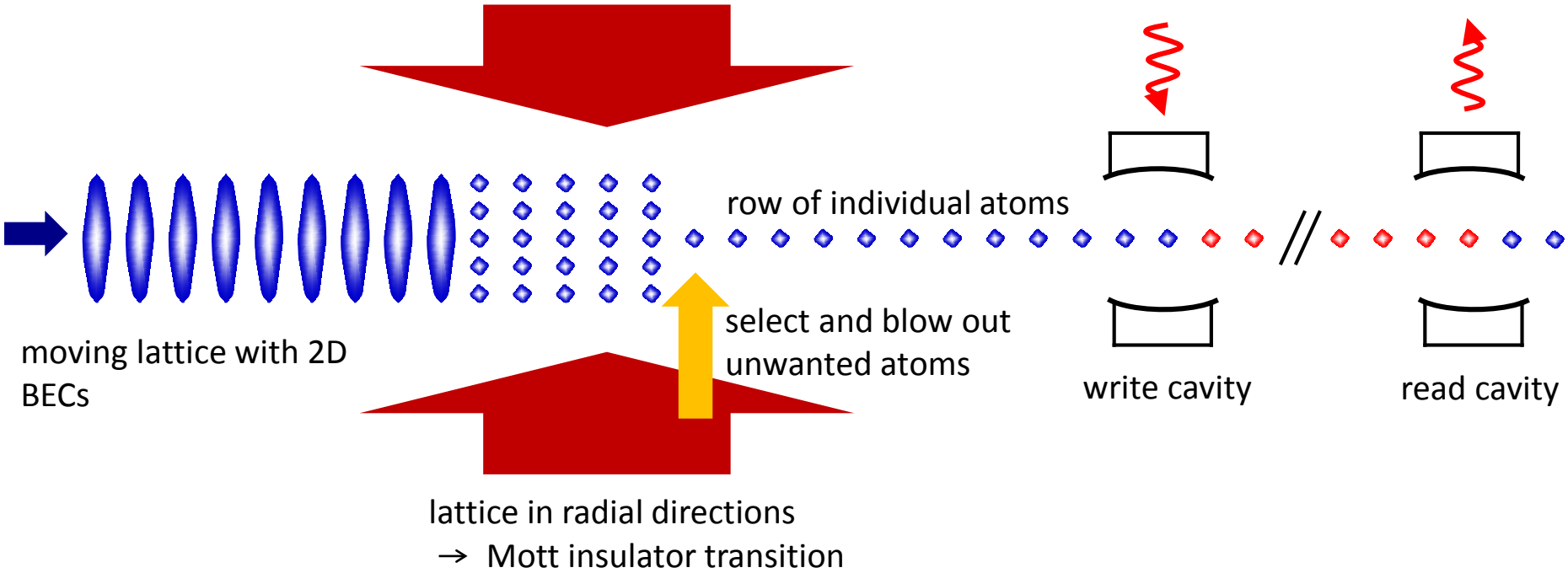


Mach cones, vortices,…

similar to Anderson group,
arXiv:1303.4764



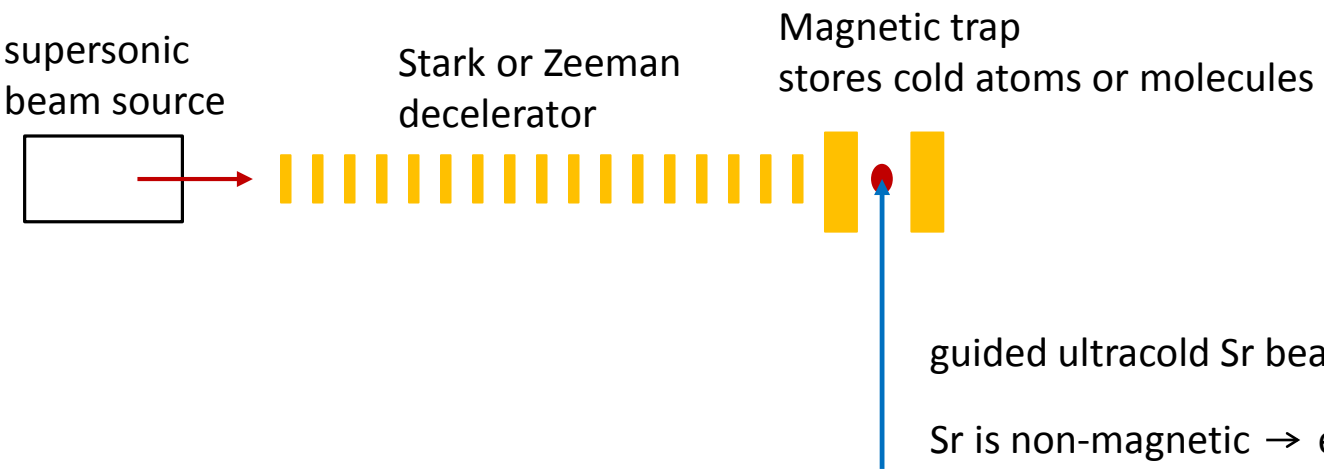
Quantum FIFO memory



- Create infinite row of individual atoms
- Store quantum information in atoms using cavity
- Retrieve quantum information later using second cavity

Sympathetic cooling

Goal: ultracold gas or quantum gas of atoms or molecules without laser cooling transition



guided ultracold Sr beam

Sr is non-magnetic → enters magnetic trap region without accelerating

Sr evaporates after colliding with target species

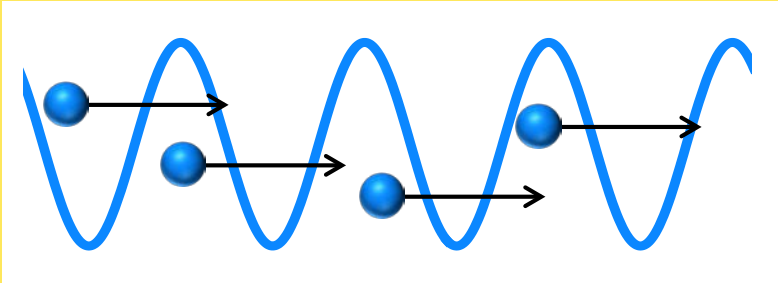
Target species cooled

Usages

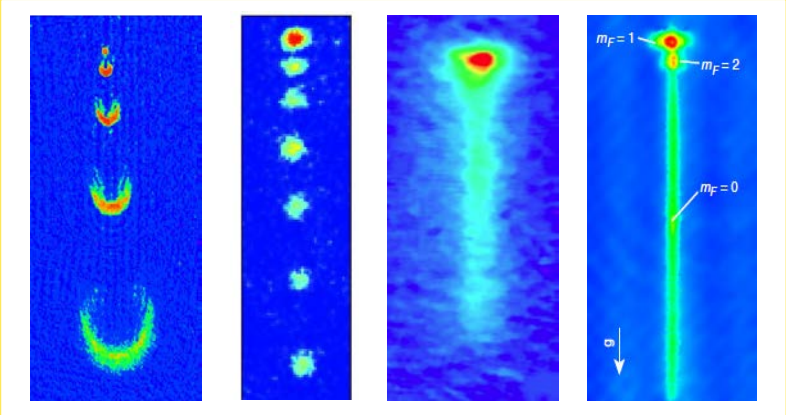
- precision spectroscopy of target species
- ultracold chemistry
- Few- and many-body physics

Summary

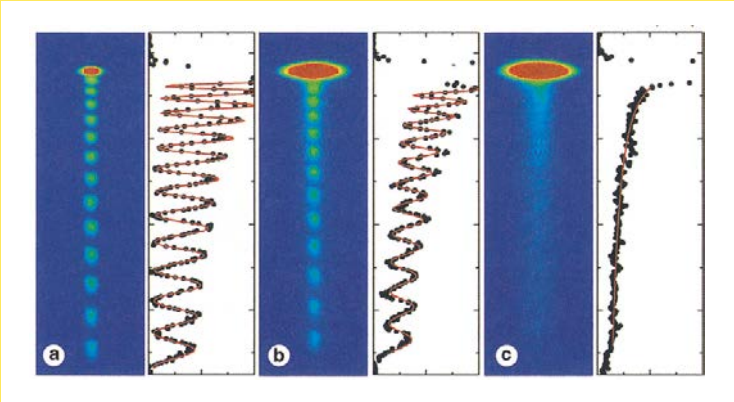
What? Why?



Pulsed atom lasers



Experiments with atom lasers



Continuous atom lasers