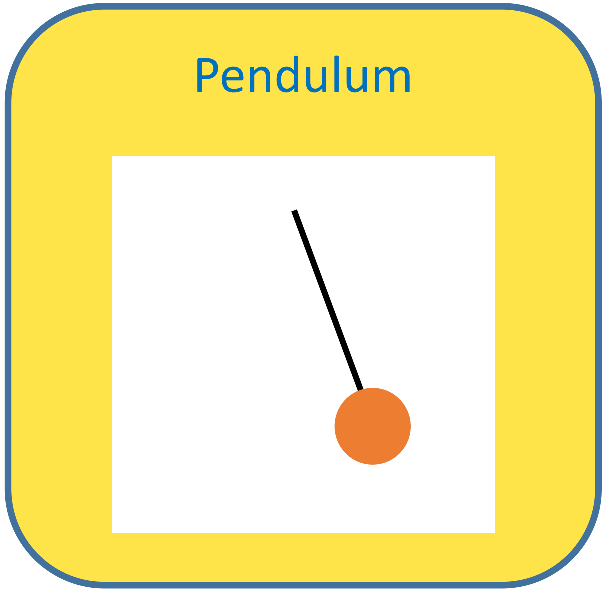
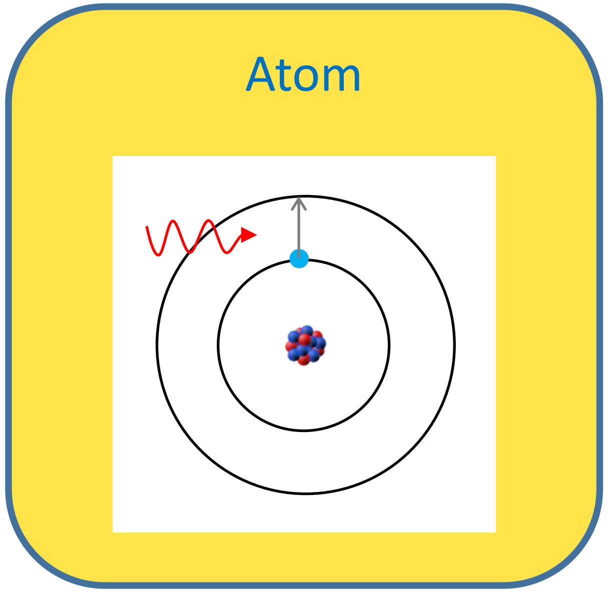
Continuous-wave BECs and superradiant clocks

Florian Schreck
University of Amsterdam

Classical vs. quantum sensors

Task: build the best clock in the world





Highest accuracy

High transition frequency ⟶ optical transitions

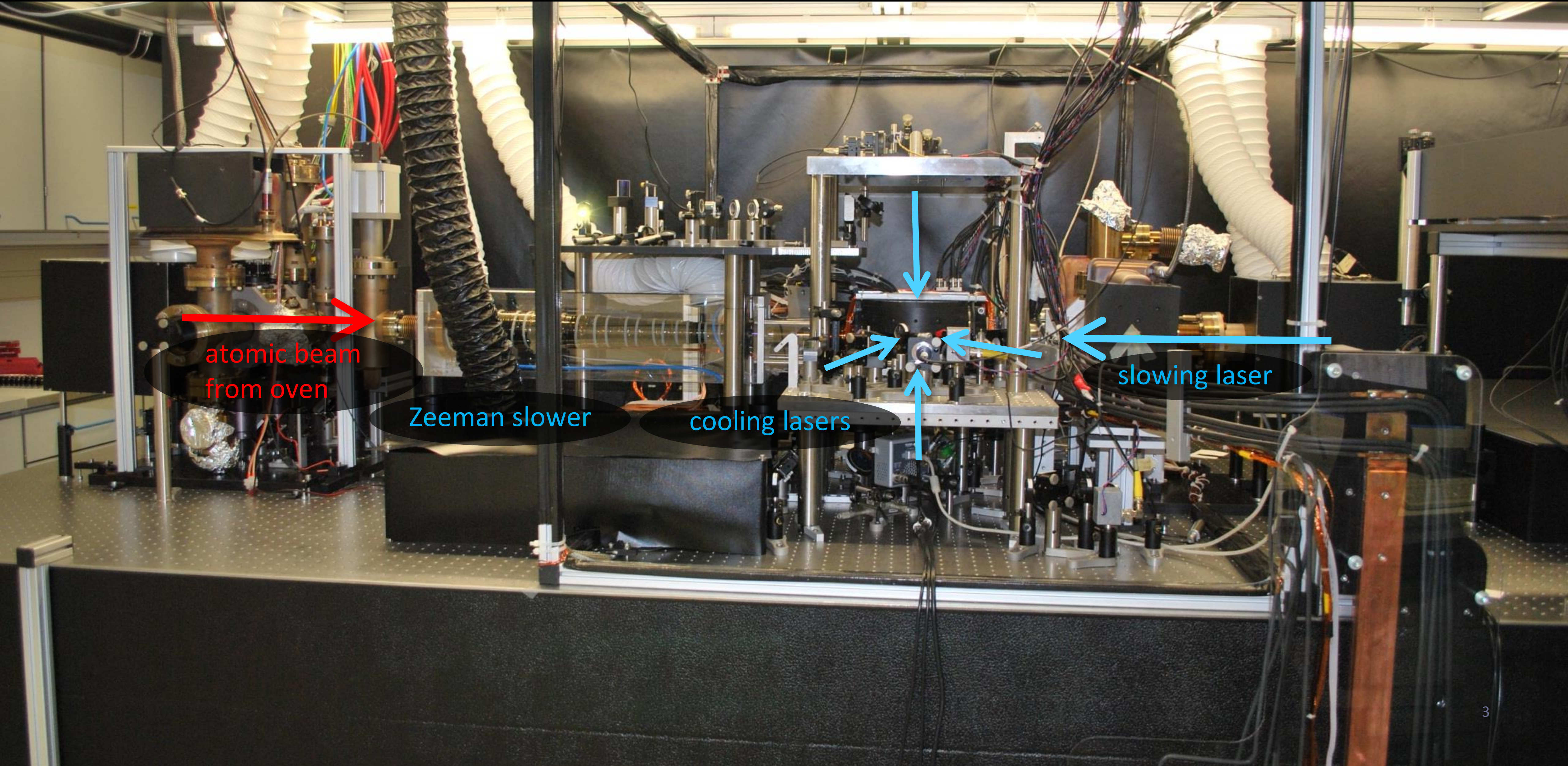
Narrow transition ⟶ mHz linewidth

Large signal ⟶ use many atoms

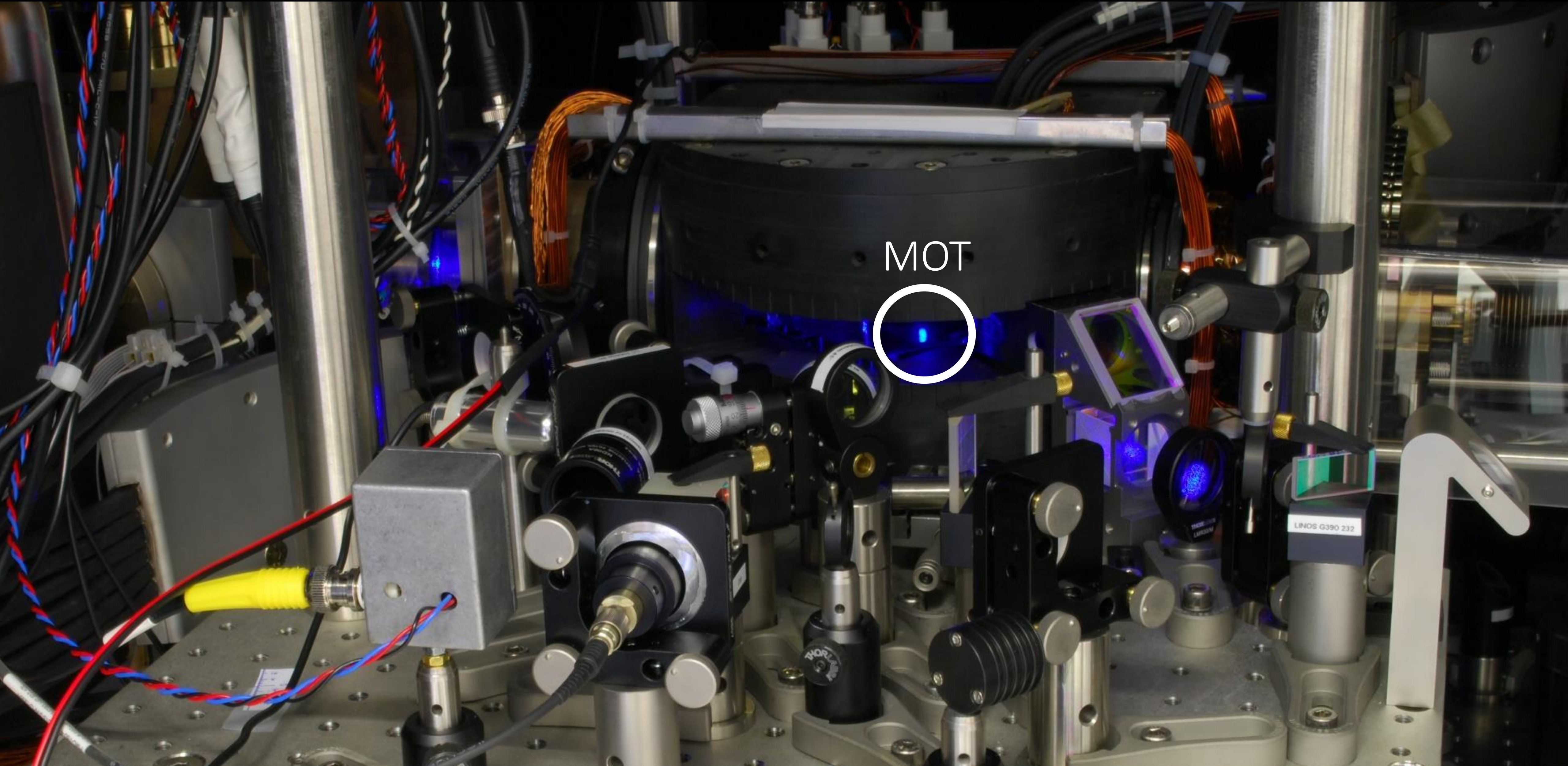
Undisturbed by other atoms ⟶ use gas of atoms

No Doppler shift ⟶ cool atoms to standstill

Laser cooling

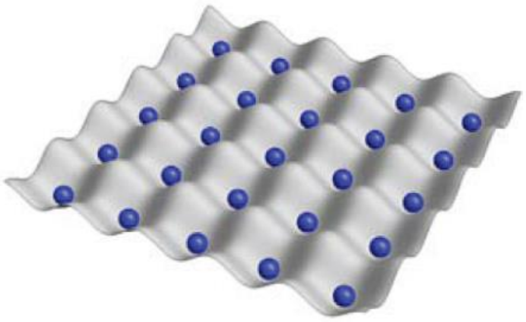


Magneto-optical trap of strontium

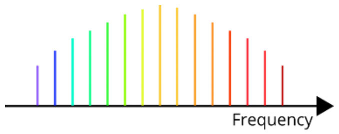


Optical clock scheme

Frequency reference
ultracold Sr atoms in lattice



Clockwork
optical frequency comb

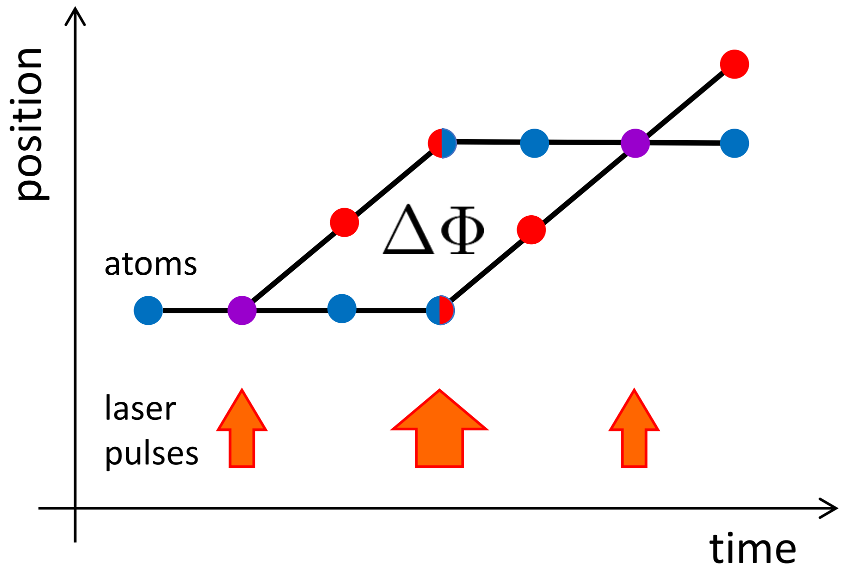


translates optical frequency
into microwave frequency

laser

Atom interferometry

Atom interferometer

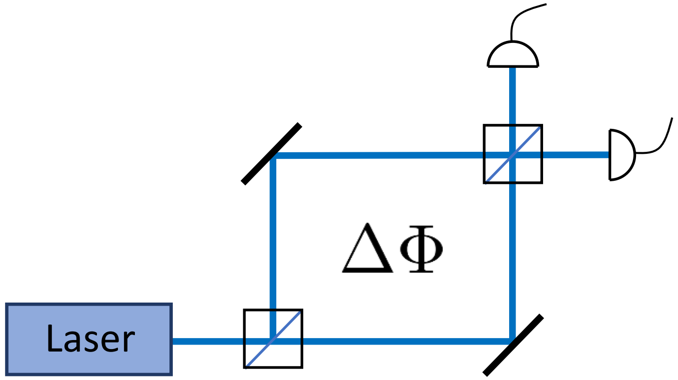


Detection of

- acceleration (gravity, gravity gradient)
- rotation

Also profits from ultracold atoms

Laser interferometer



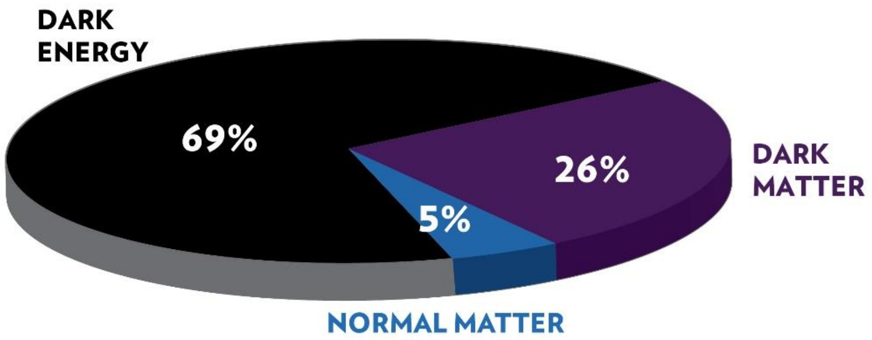
Gravitational wave detection

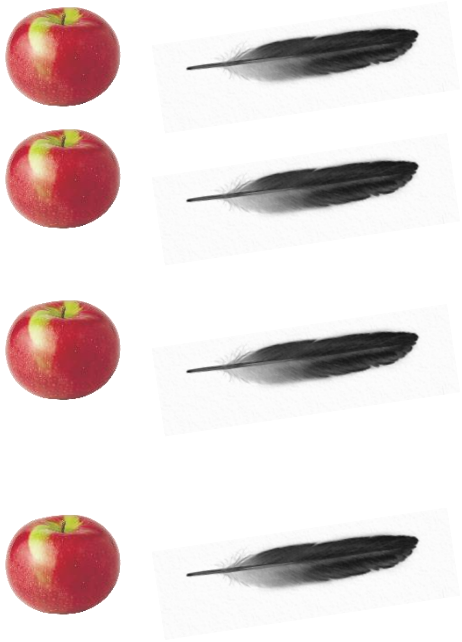
The Virgo collaboration/CCO 1.0

Applications

Fundamental science

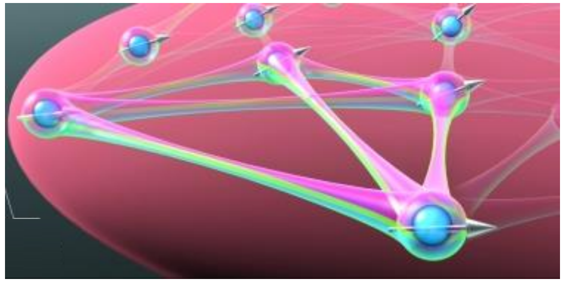
- Beyond Standard Model physics
- Tests of relativity
- Do fundamental constants change?
- Dark matter searches
- QED tests





Explore many-body physics

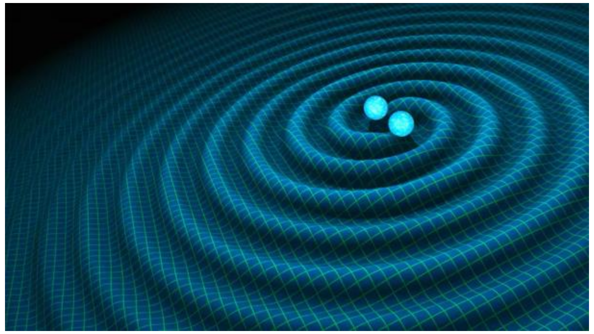
happening in quantum sensors:
spin models, gauge fields,…



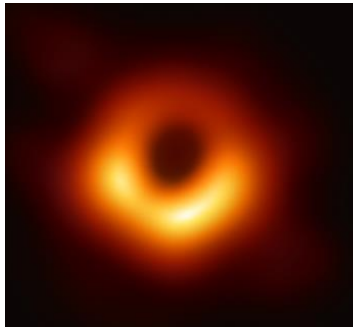
Jun Ye, Ana-Maria Rey groups, JILA

Astronomy

- Infrasound gravitational wave detectors
- Very-long baseline interferometry



NASA



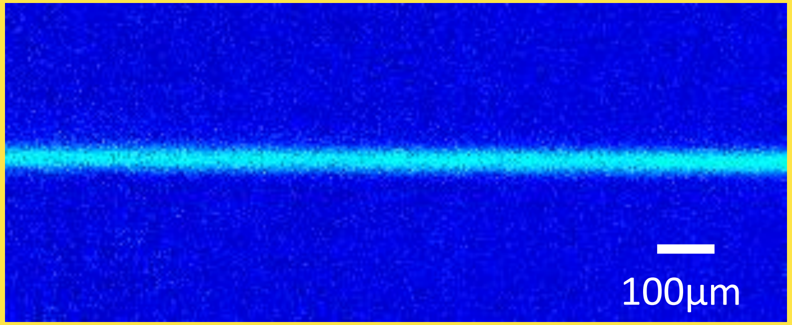
Event Horizon Telescope

Society

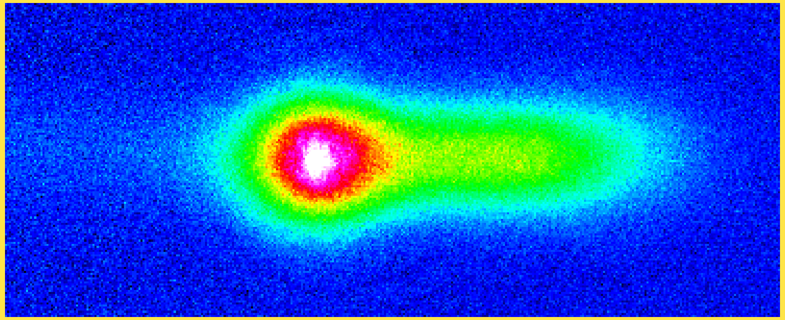
- Network synchronization
- Navigation
- Underground exploration

Outline

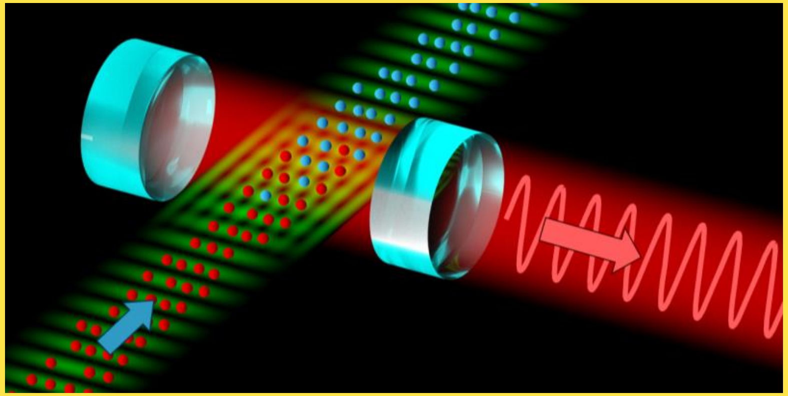
μK Sr beam in the dark



Continuous-wave BEC

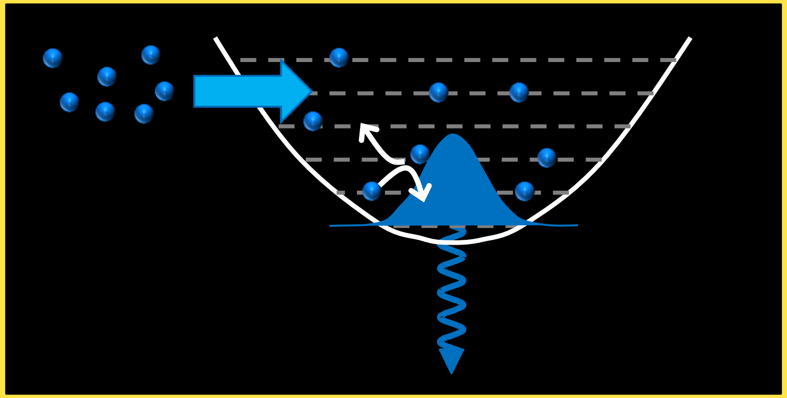


Superradiant clock



frequency & time

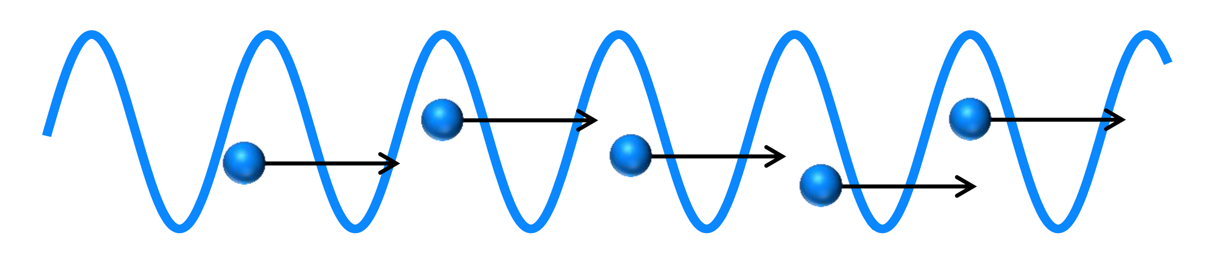
Continuous-wave atom laser



acceleration & rotation

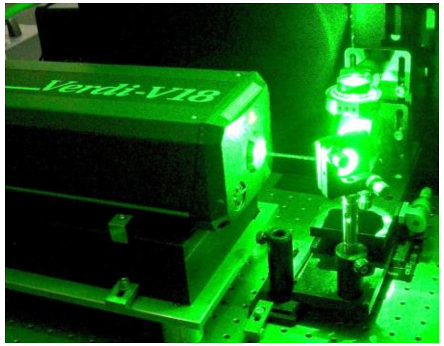
Optical and atom lasers

Laser



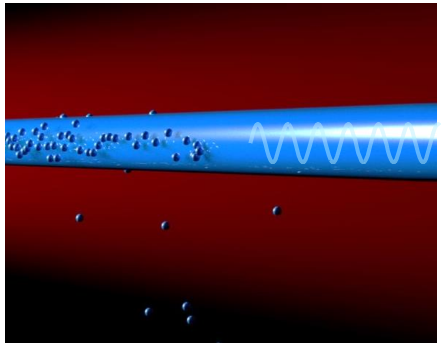
Light | **Matter**

Optical laser



Laser interferometer

Atom laser



Atom interferometer

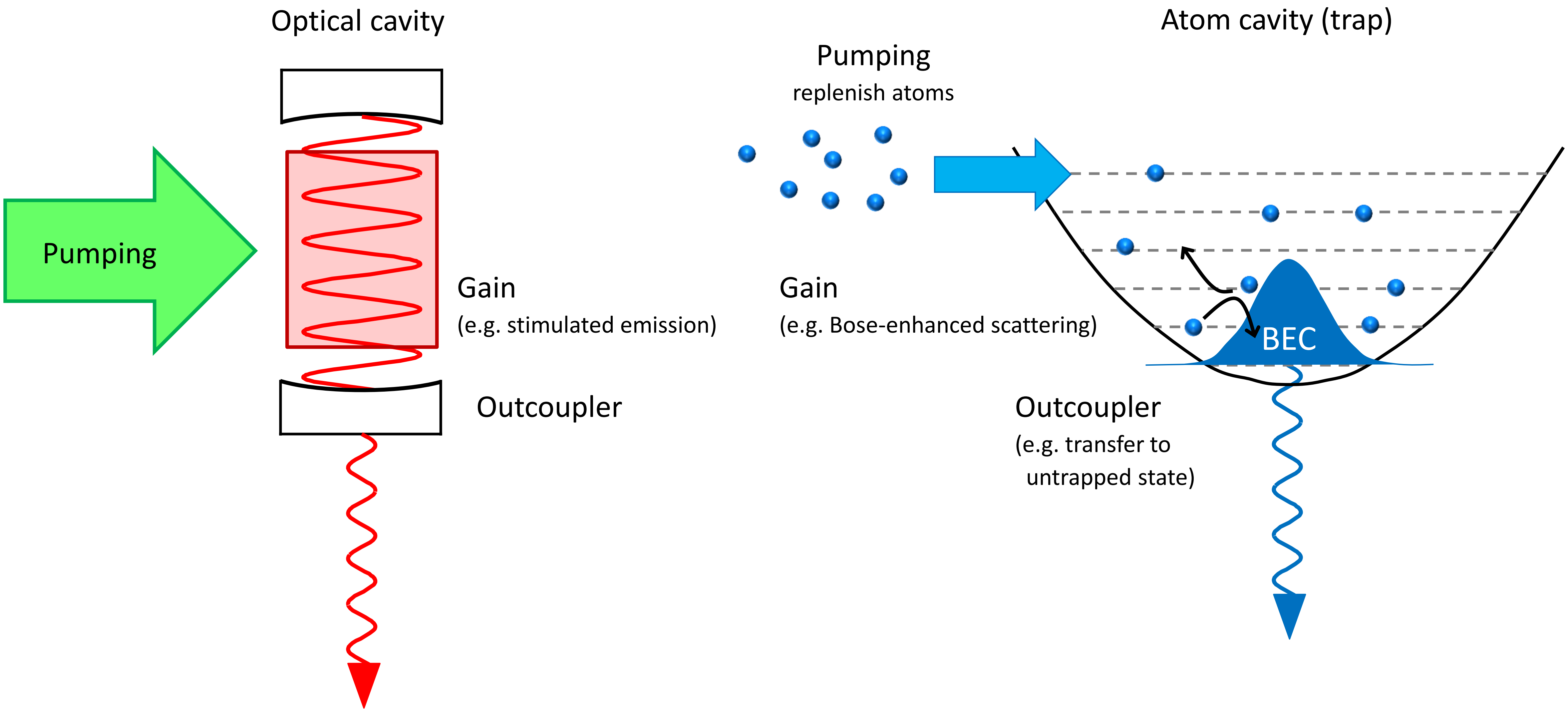
Advantages of lasers

Better
- brightness
- divergence
- spatial mode structure
- coherence

Potential for squeezing

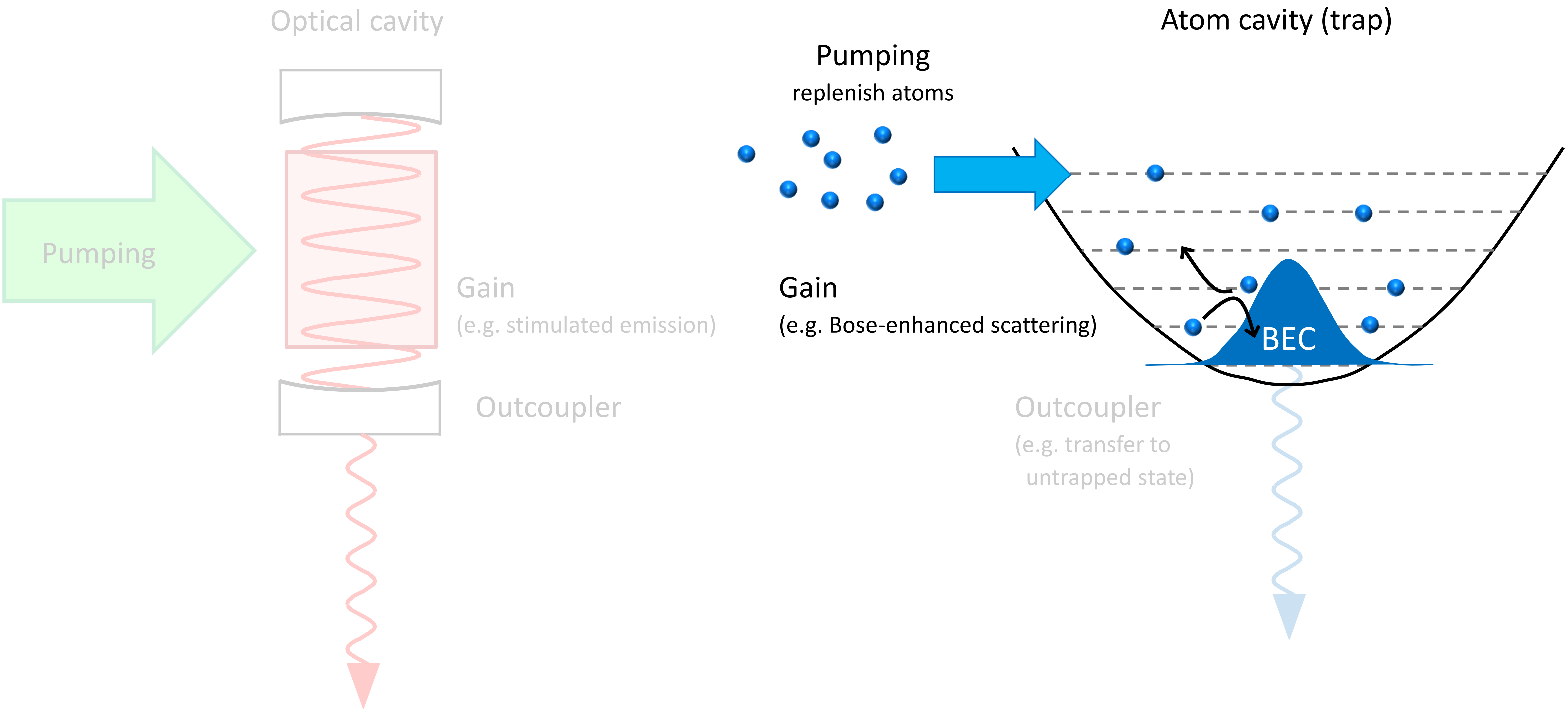
N.P. Robins et al., *Atom lasers: Production, properties and prospects for precision inertial measurement*, Phys. Rep. 529, 265 (2013)

Creating an atom laser



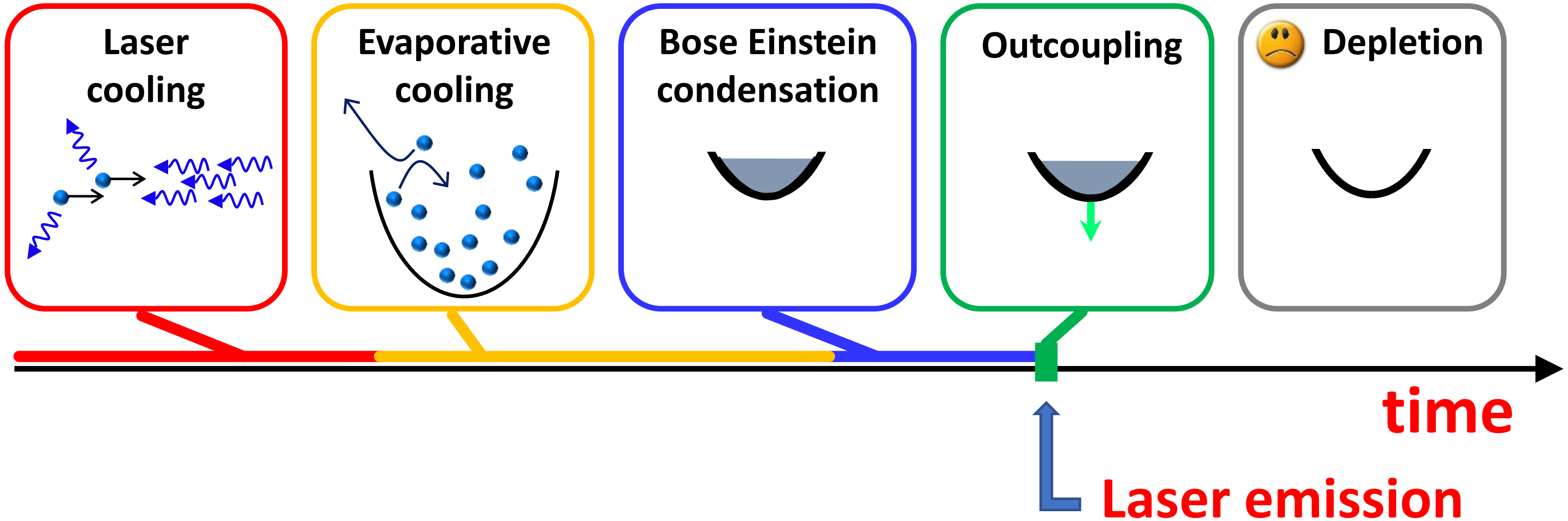
N.P. Robins et al., *Atom lasers: Production, properties and prospects for precision inertial measurement*, Phys. Rep. 529, 265 (2013)

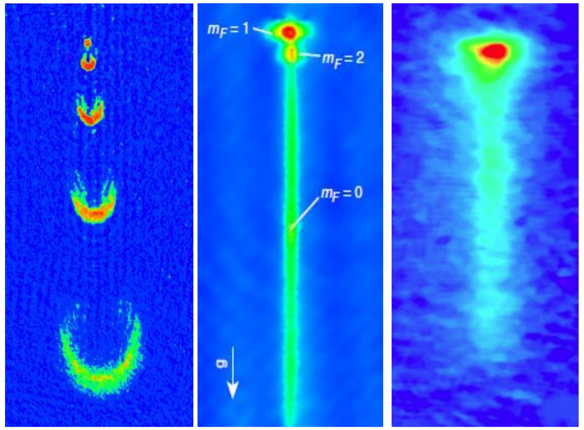
Continuous-wave BEC



N.P. Robins et al., *Atom lasers: Production, properties and prospects for precision inertial measurement*, Phys. Rep. 529, 265 (2013)

State-of-the-art: *pulsed* atom laser





MIT 1997 | Munich 1999 | NIST 1999

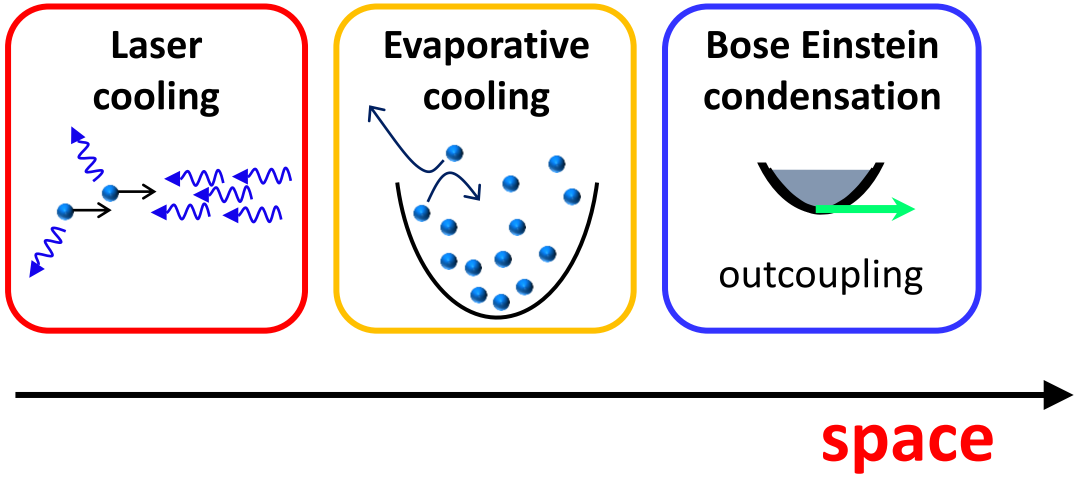
Quasi-continuous mode of operation:

- BEC creation takes seconds
- BEC decays by e.g. molecule formation
- atom laser pulse << 1s

Bad for precision measurement:

- Loss of phase coherence
- Pulsed operation introduces noise (Dick effect)
- Low average flux

Our goal: *continuous* atom laser



Challenges

- Poor laser cooling performance of alkalis and chromium
- BEC incompatible with laser cooling

Steps towards goal

Periodically replenish BEC	Ketterle group, Science **296**, 2193 (2002)
Continuous evaporation	Guéry-Odelin group, PR A **72**, 033411 (2005) Raithel group, PR A **73**, 033622 (2006)
Pumping mechanism	Close group, nature physics **4**, 731 (2008)
Continuous trap loading	Pfau, Griesmaier group, New J. Phys. **15** 093012 (2013) Klempt group, J. Phys. B **48**, 165301 (2015)

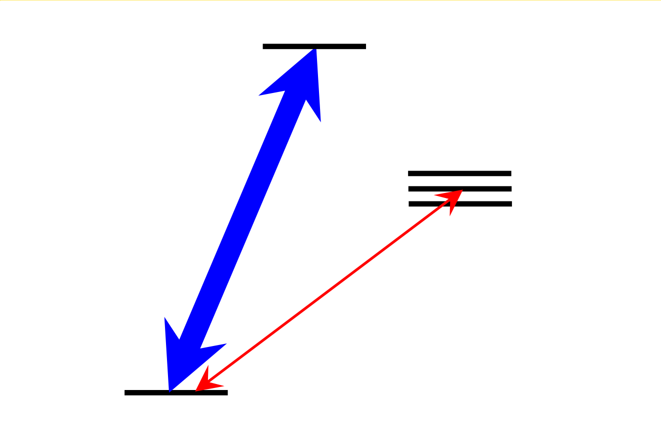
Our tricks

Strontium

Goals of baseline experiment

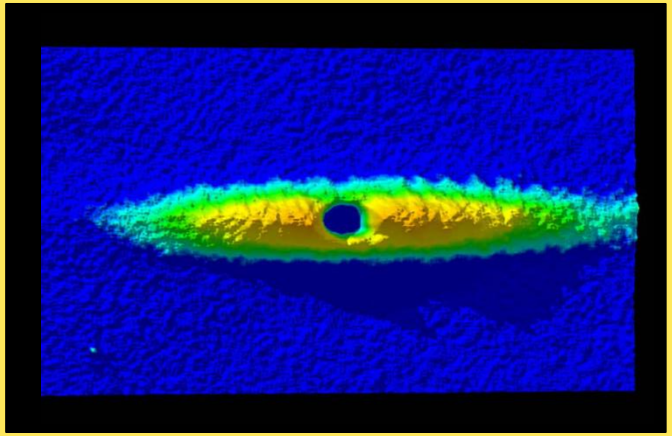
- BEC by removing entropy from gas using only laser cooling
- BEC in thermal contact with laser cooled gas

Laser cooling
on narrow transition



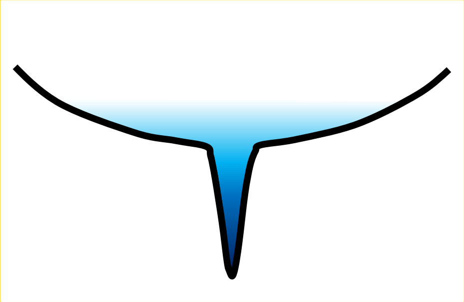
Cool to BEC

Transparency beam



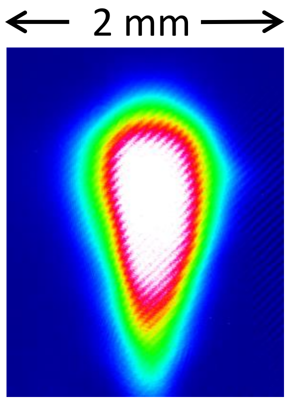
Protect BEC from photons

Dimple trick



Increase
phase-space density

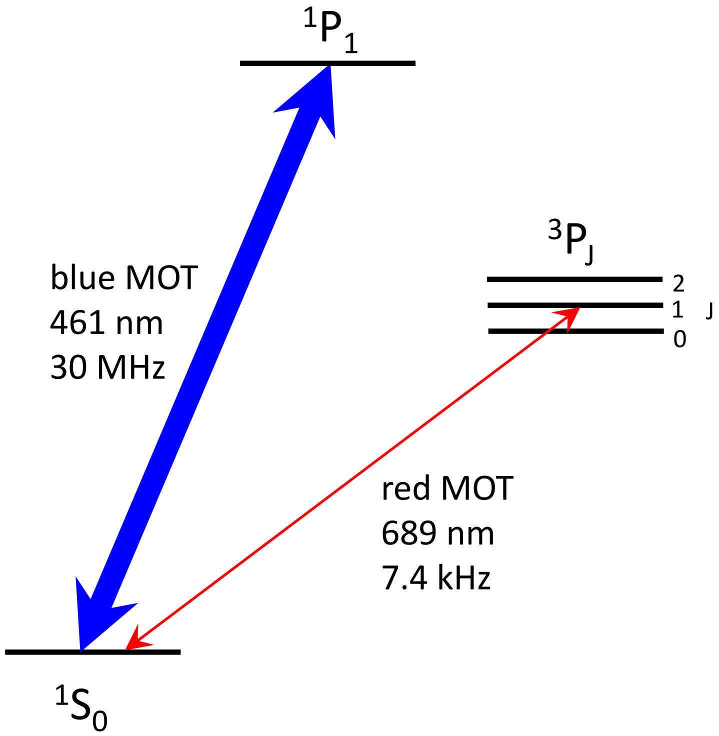
Narrow line cooling

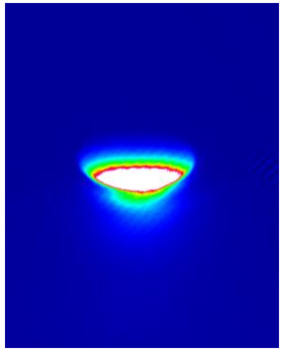


hot blue MOT

T ~ 1 mK

PSD ~ 10^{-10}



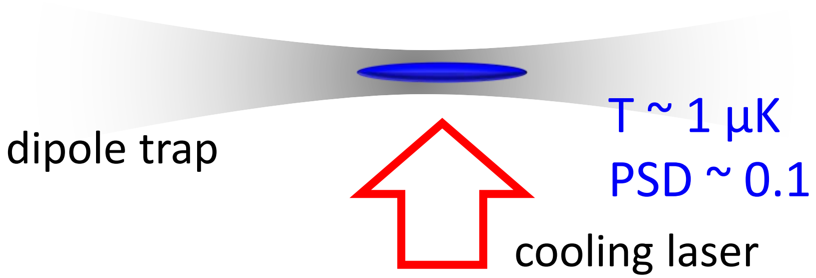


cold red MOT

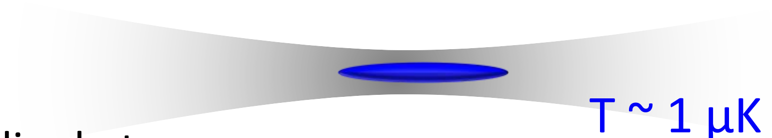
T ~ 1 μK

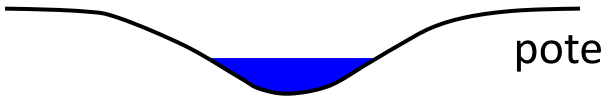
PSD ~ 10^{-3}

Cooling in trap

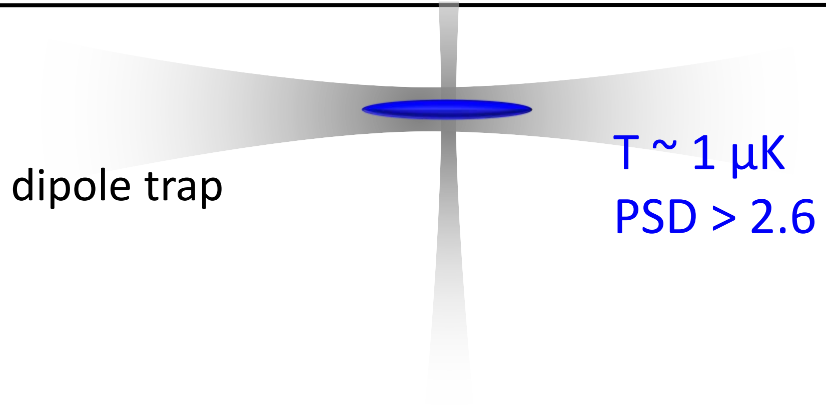


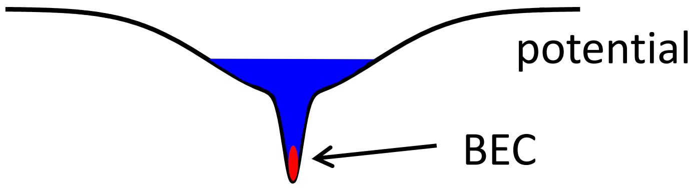
BEC using dimple trick

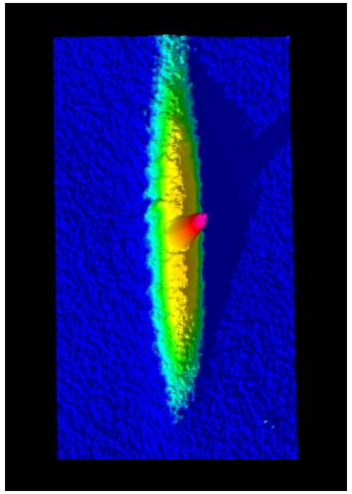




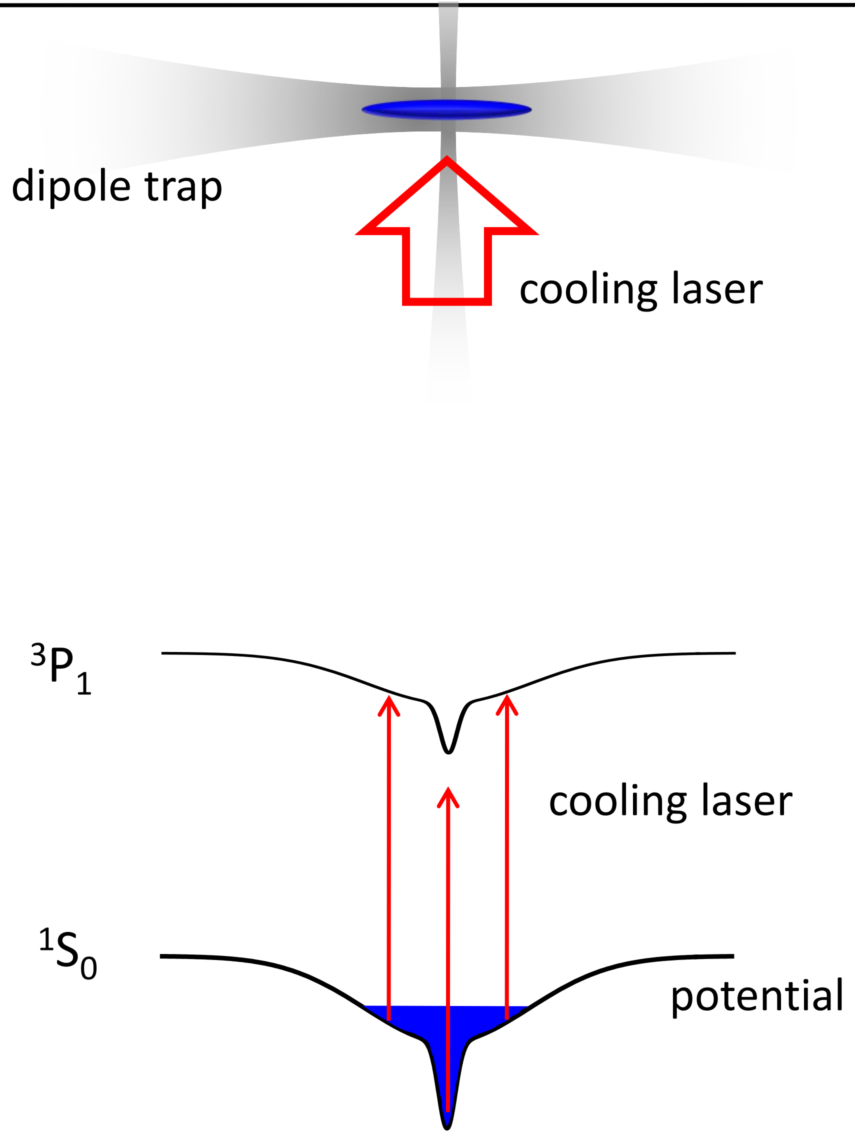
BEC using dimple trick

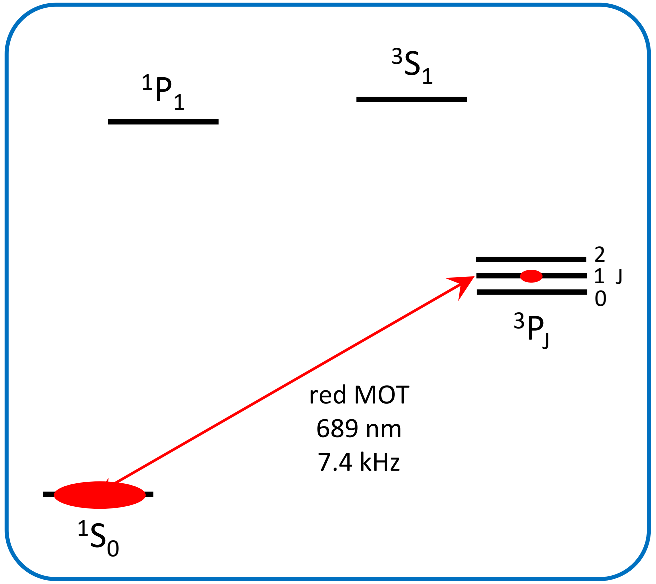


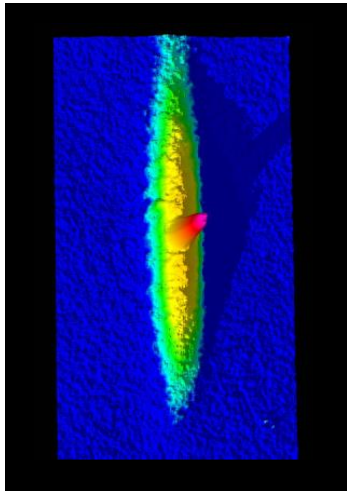




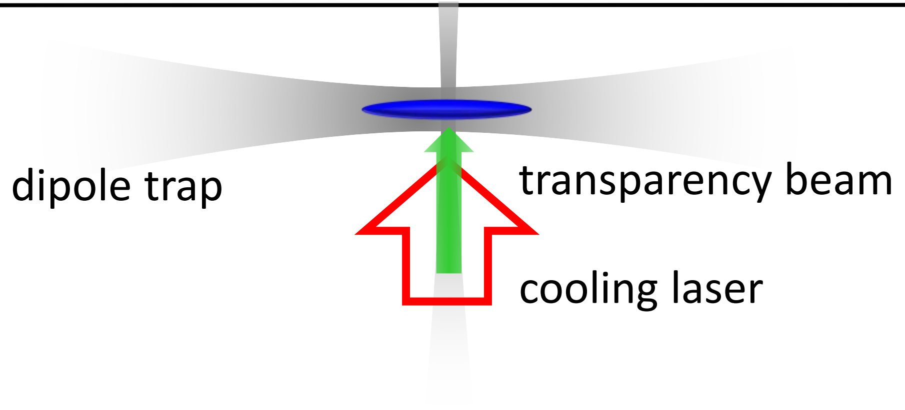
Transparency beam

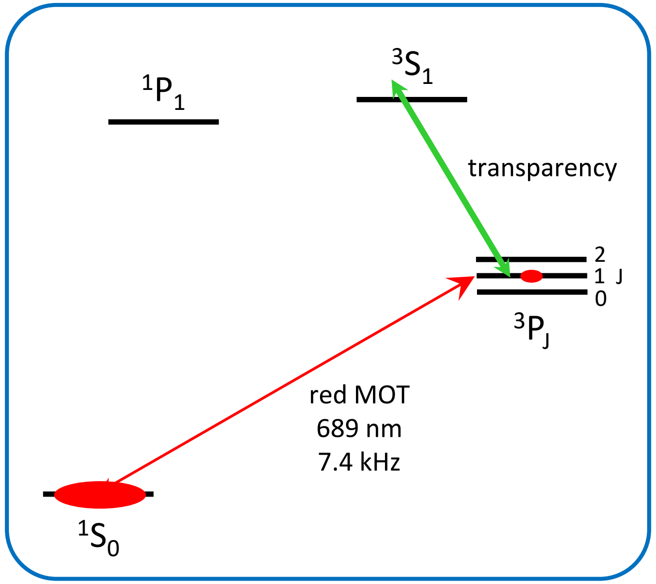


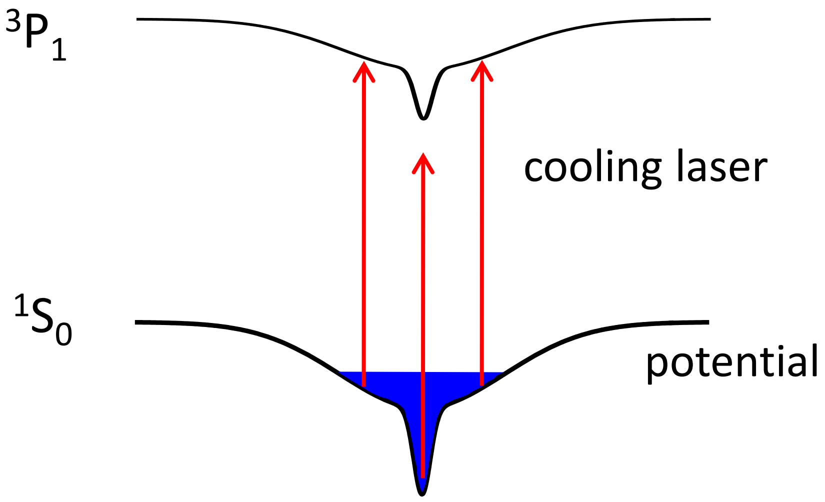


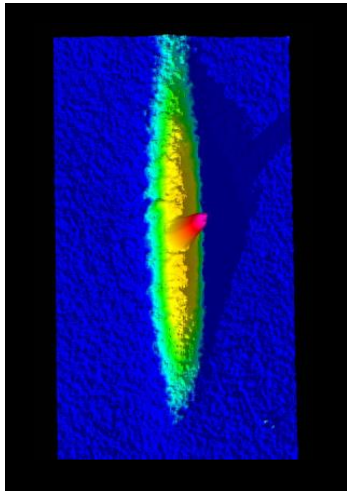


Transparency beam

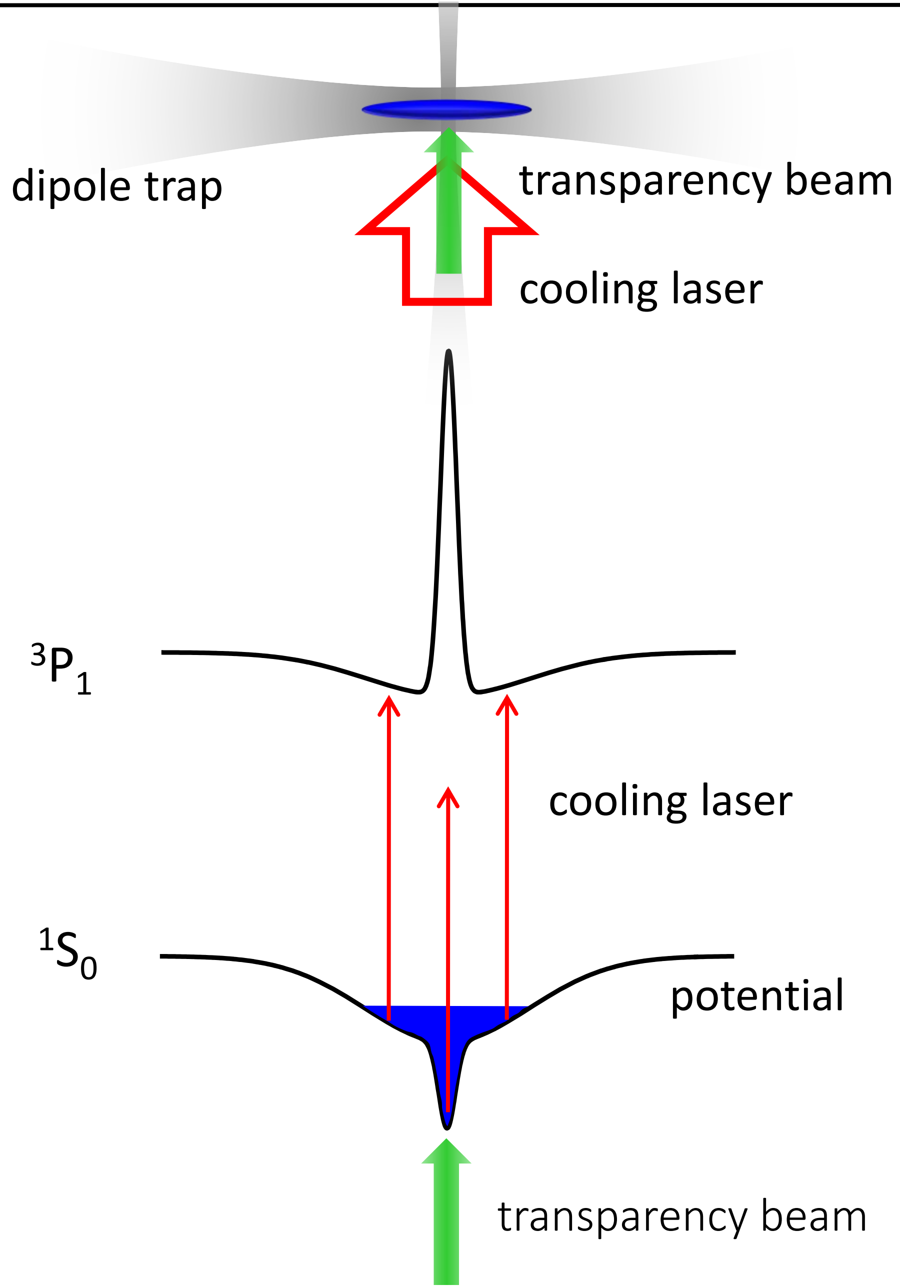


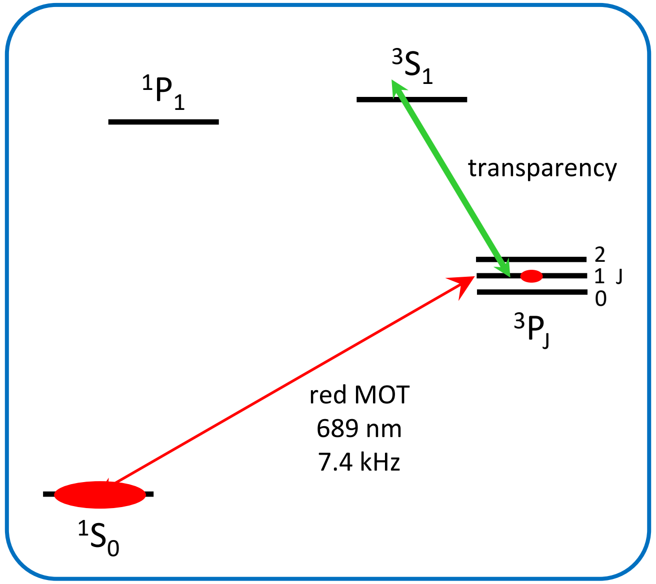


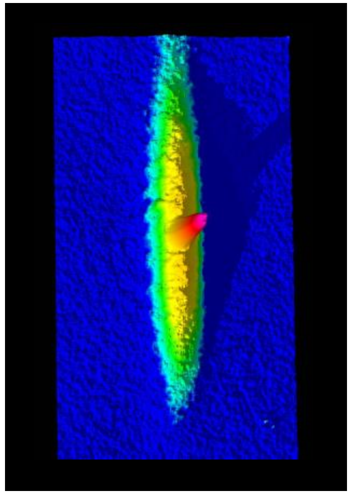




Transparency beam







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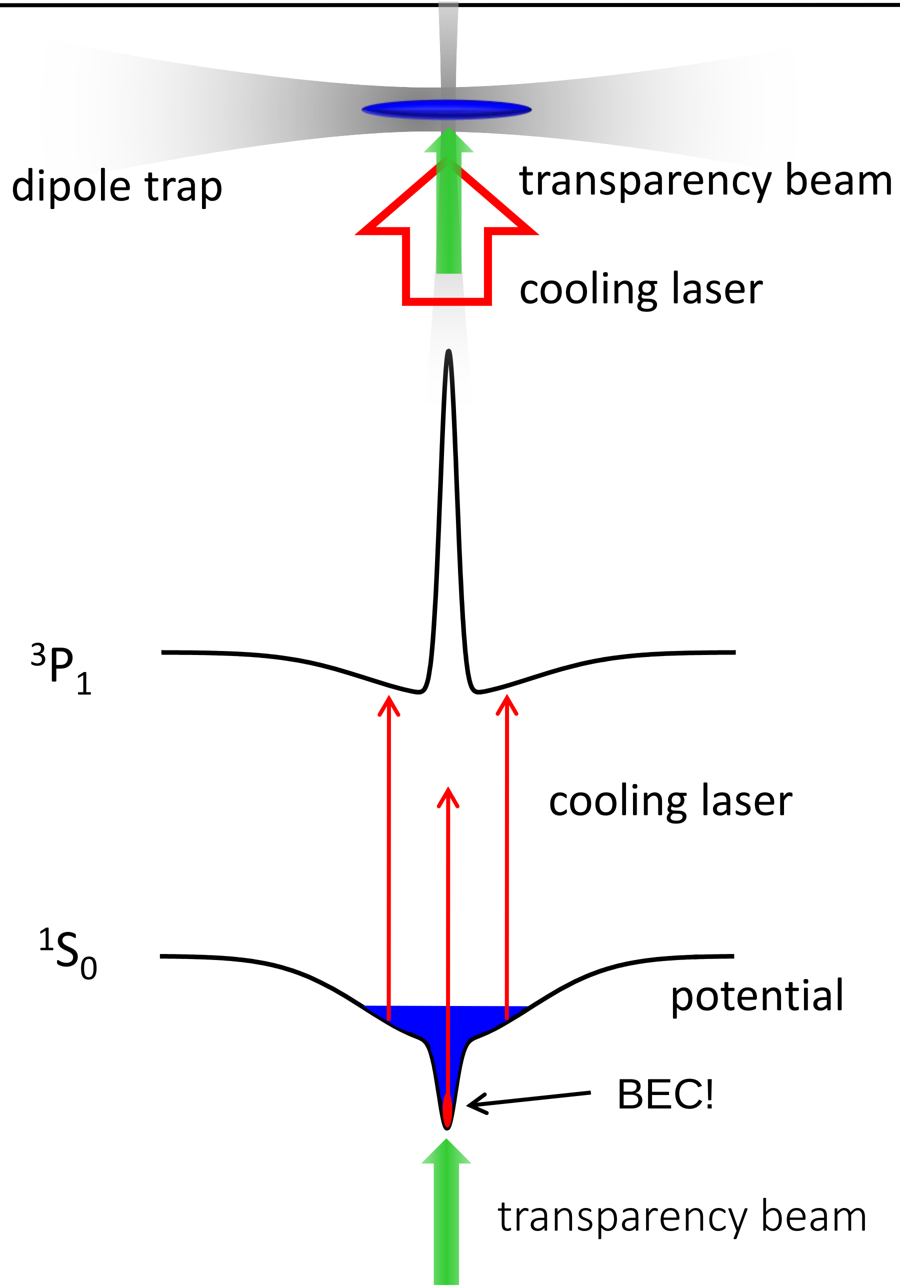
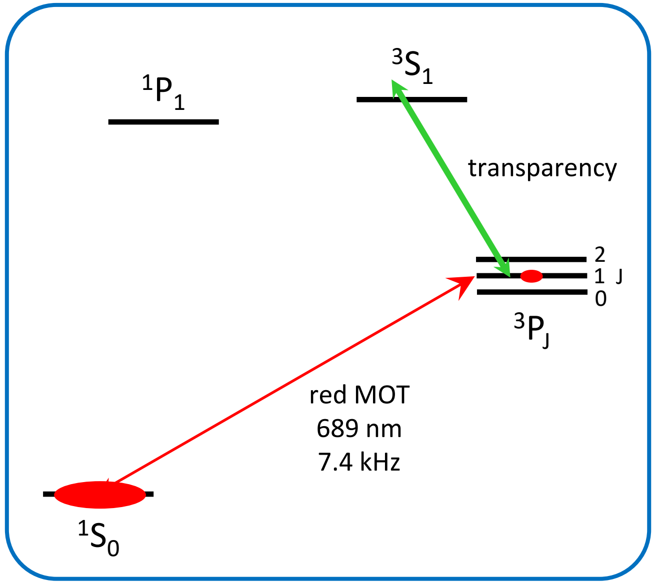
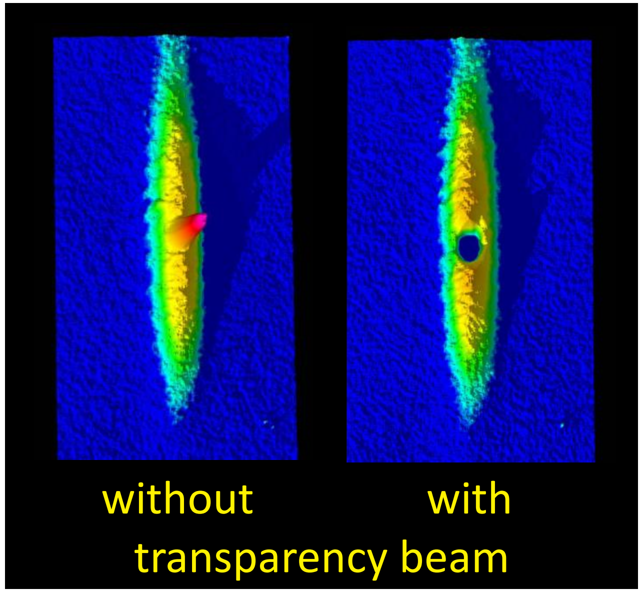
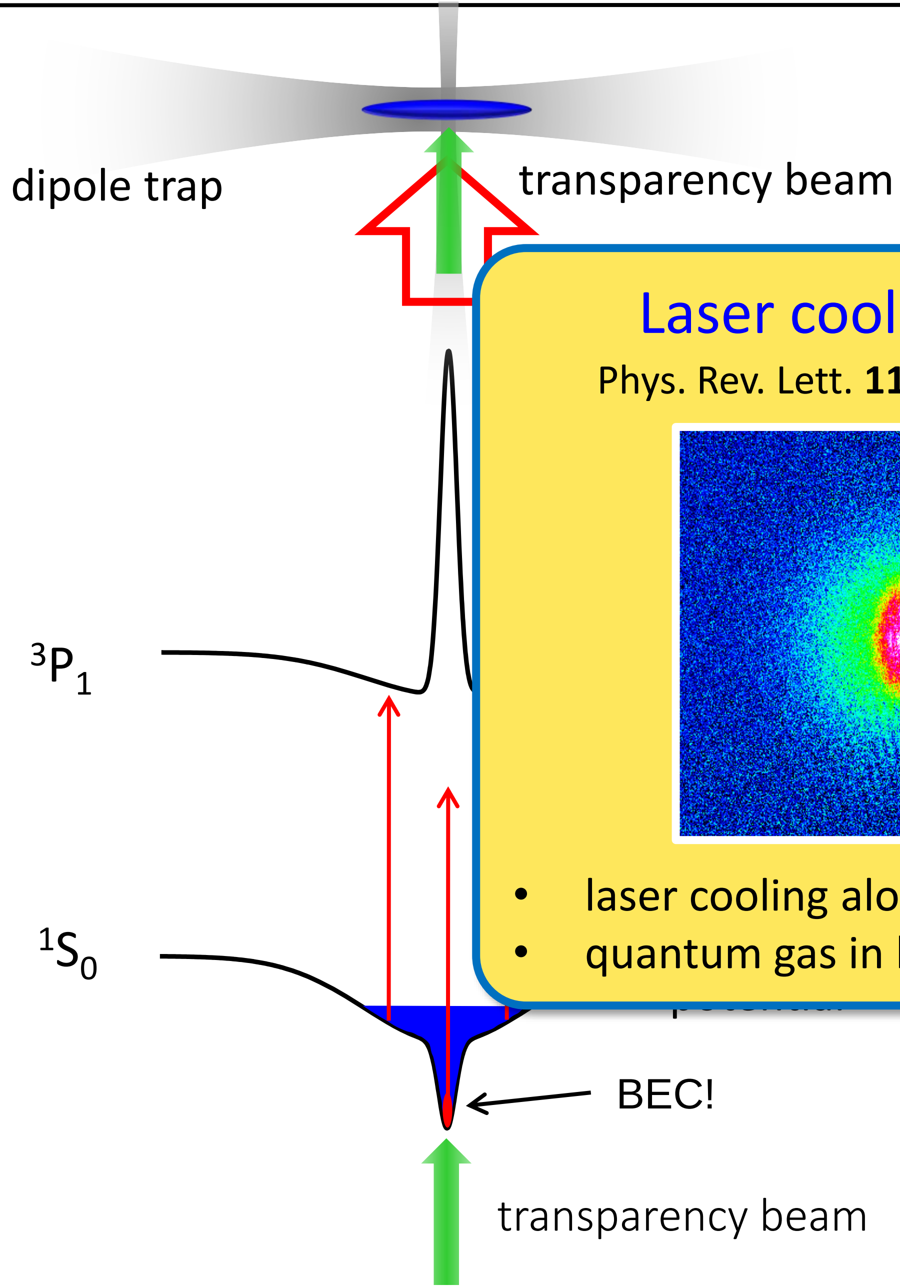
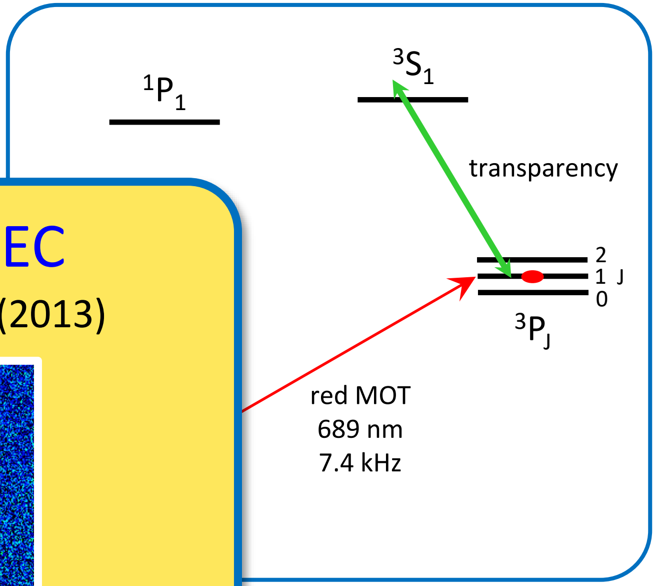






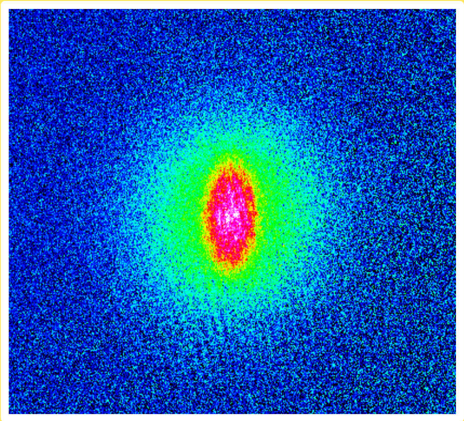
Transparency beam



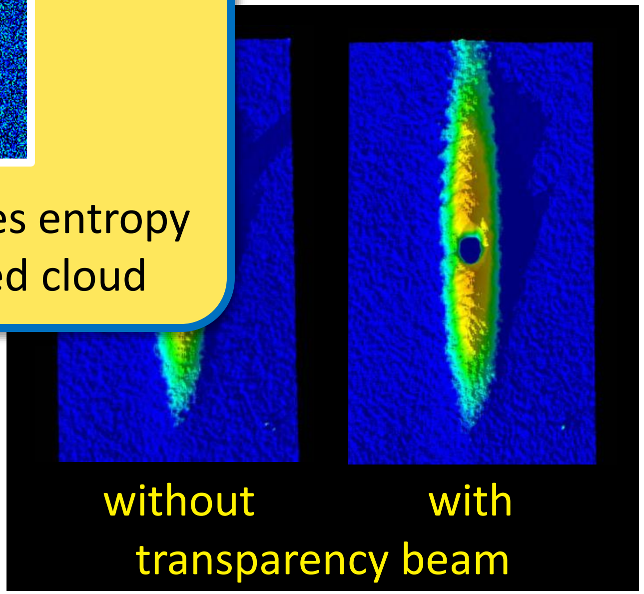


Laser cooling to BEC

Phys. Rev. Lett. **110**, 263003 (2013)



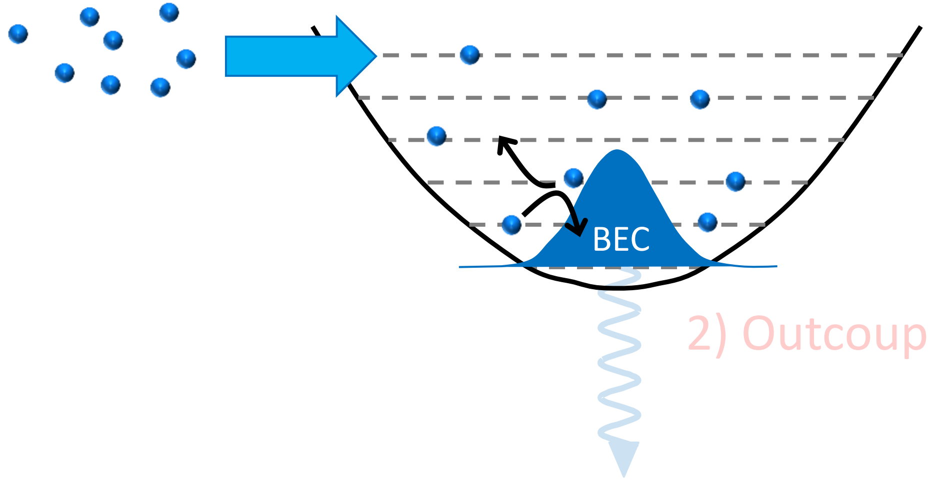
- laser cooling alone removes entropy
- quantum gas in laser cooled cloud



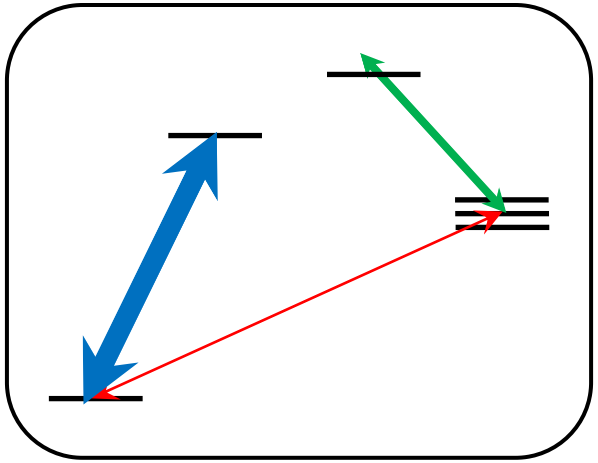
Continuous atom laser

New requirements

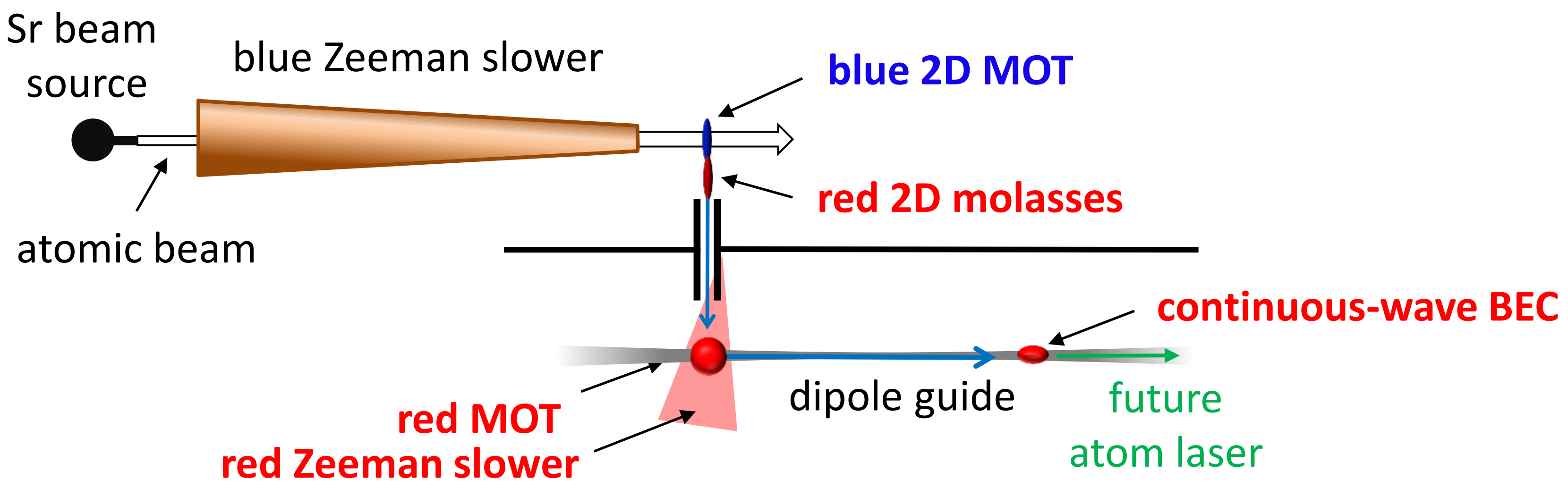
1) Pumping: replenish atoms



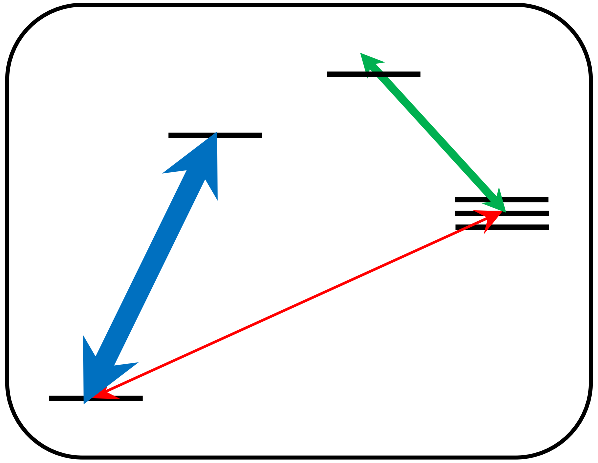
Challenge: BEC not protected from blue photons



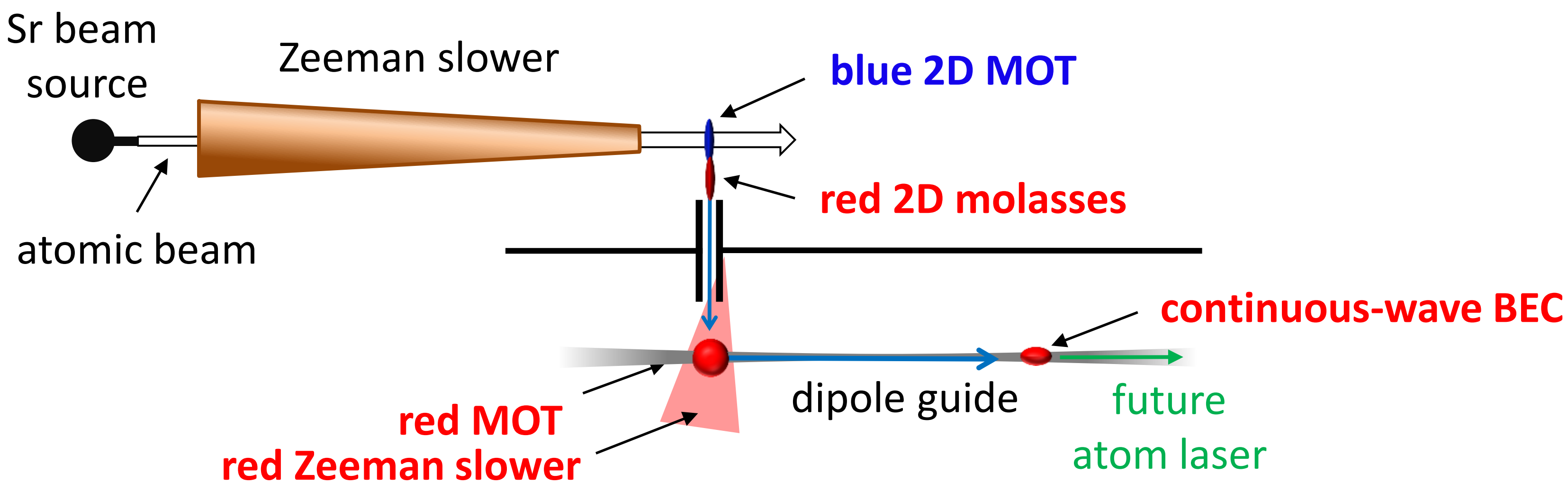
Blue stray light protection

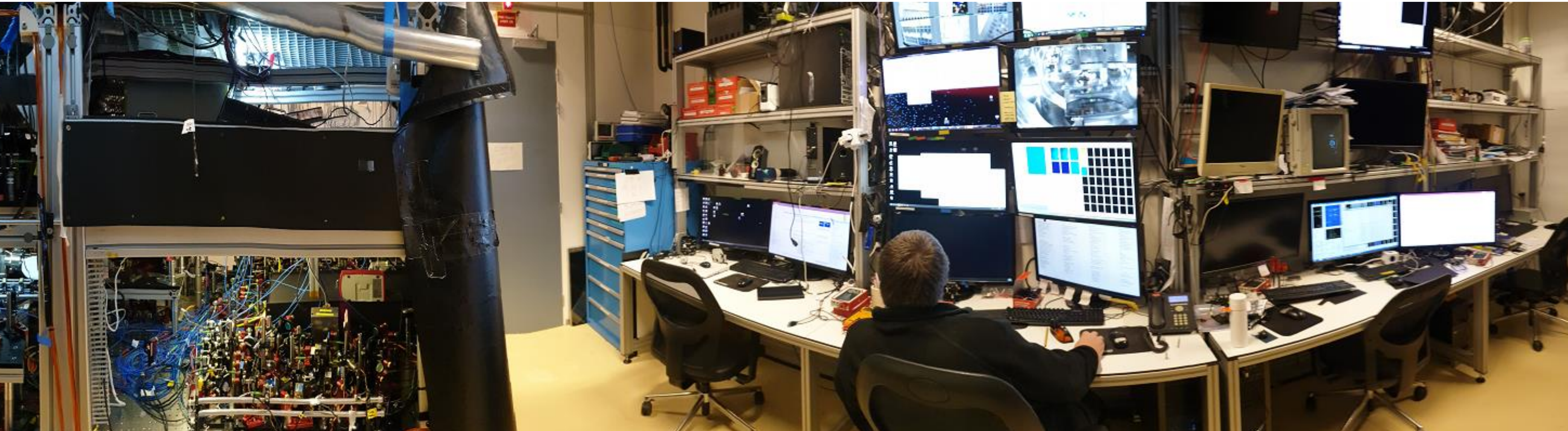


Challenge: BEC not protected from blue photons



Design and construction





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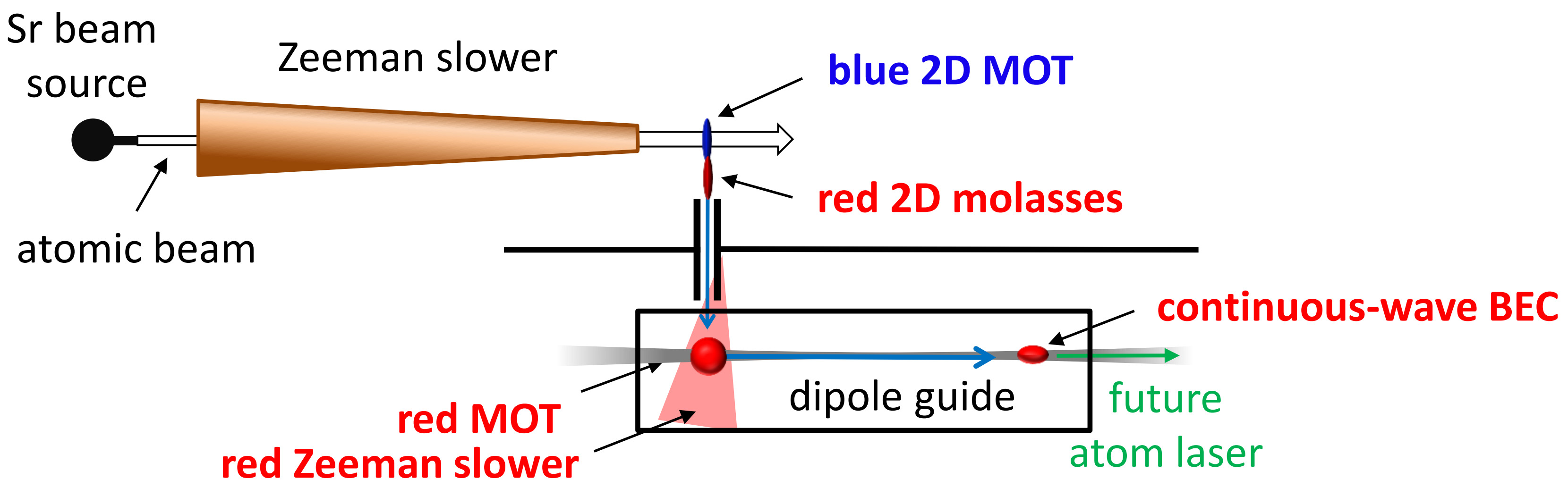
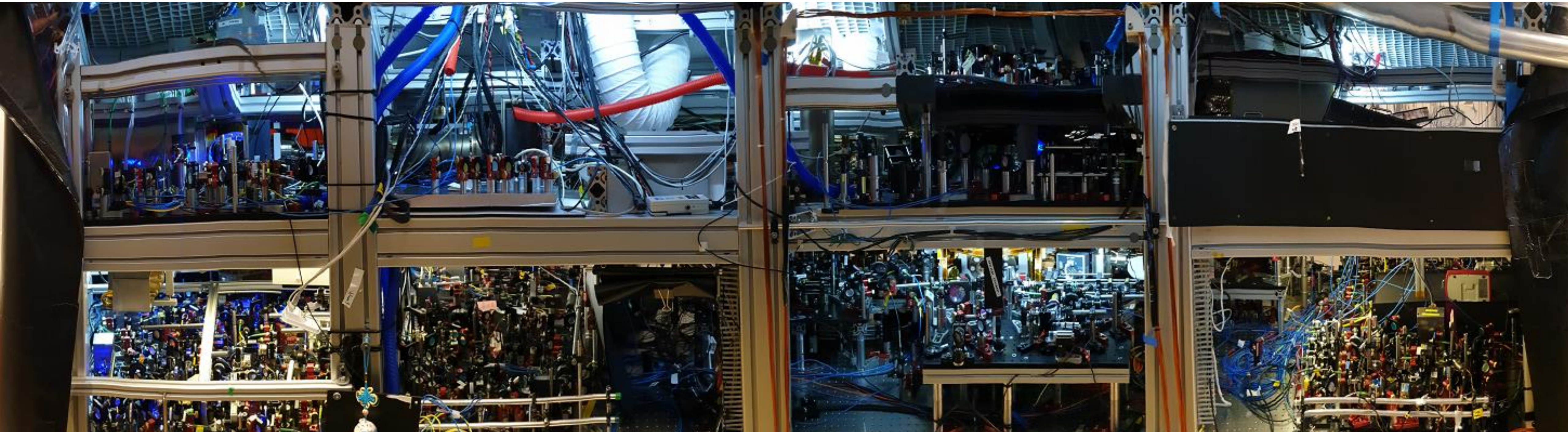
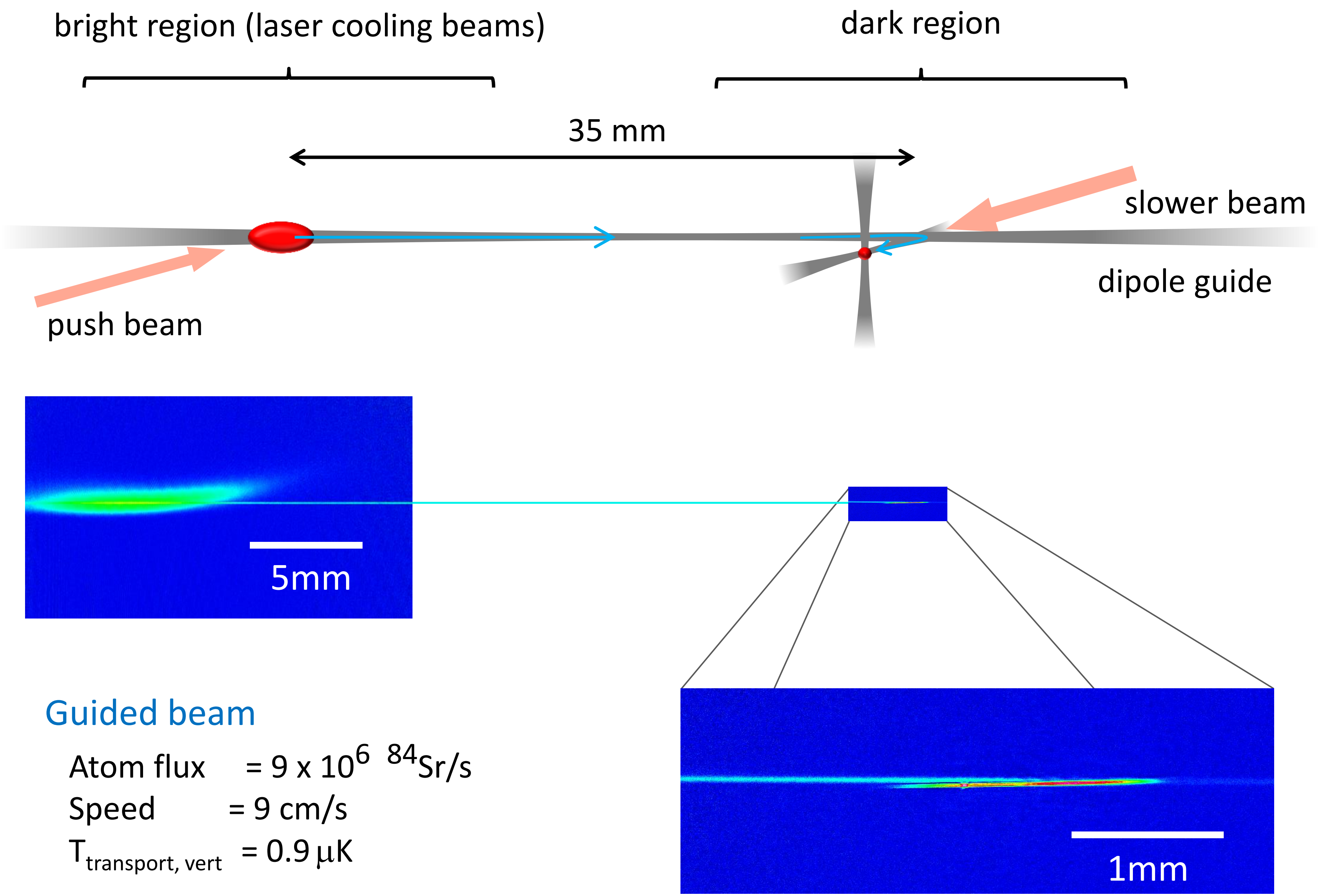




Dipole guide to darkness



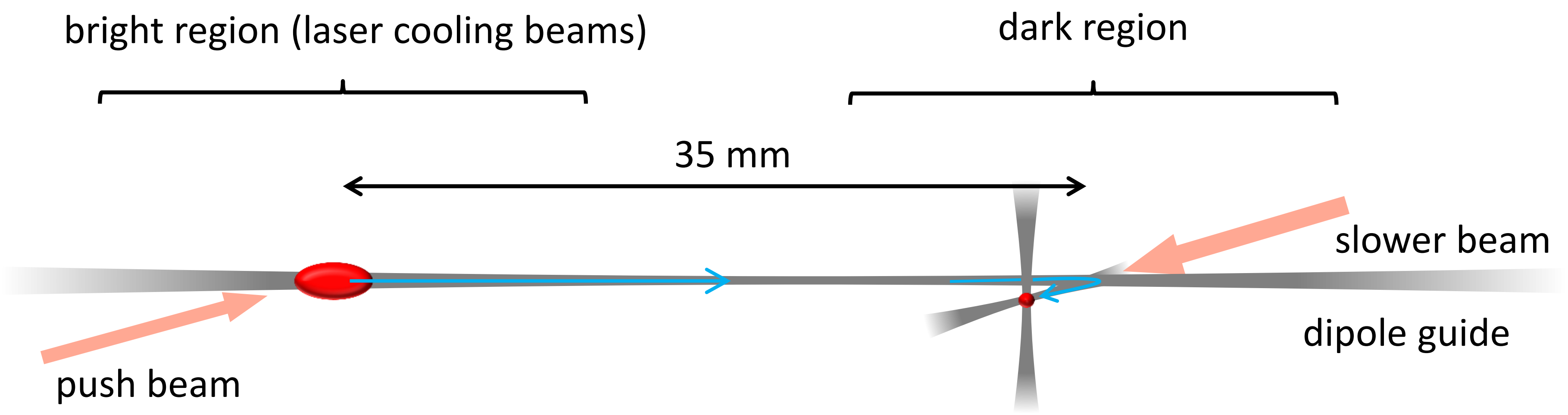
Guided beam

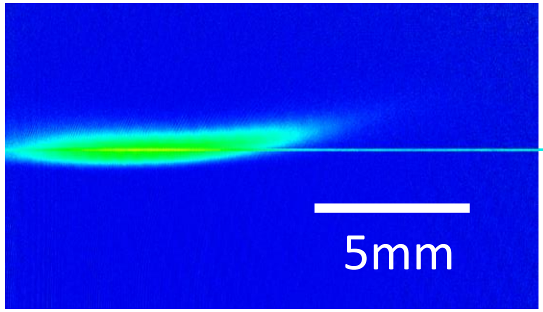
Atom flux = 9×10^6 $^{84}Sr/s$

Speed = 9 cm/s

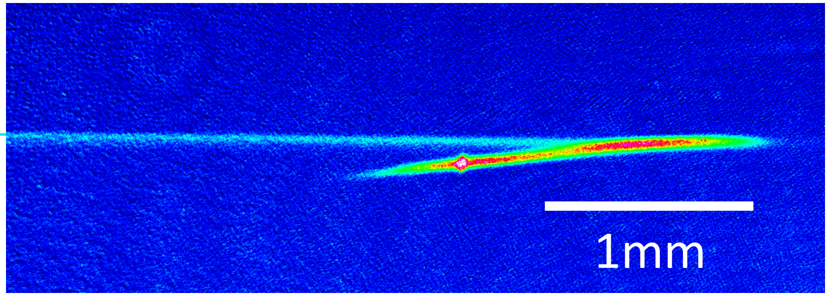
$T_{transport, vert}$ = 0.9 μK

Dipole guide to darkness

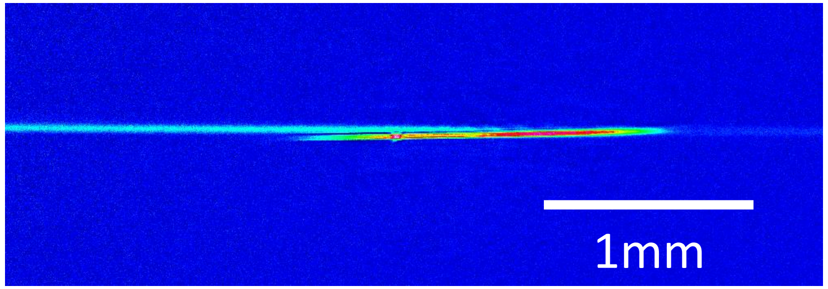




Top View



Side View

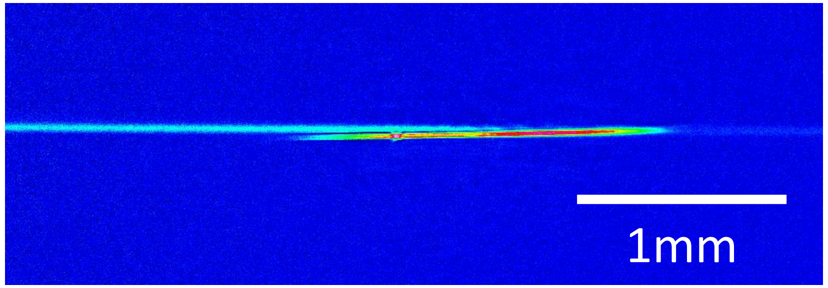


Guided beam

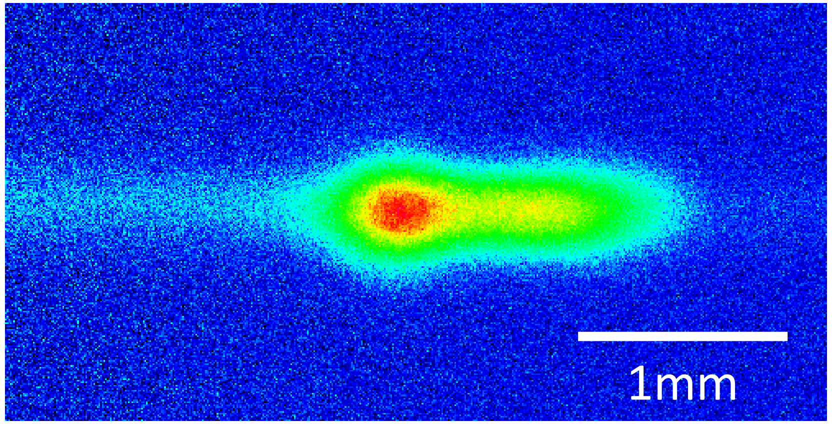
Atom flux = 9×10^6 ^{84}Sr/s
Speed = 9 cm/s
$T_{transport, vert}$ = 0.9 μK

BEC in steady-state?

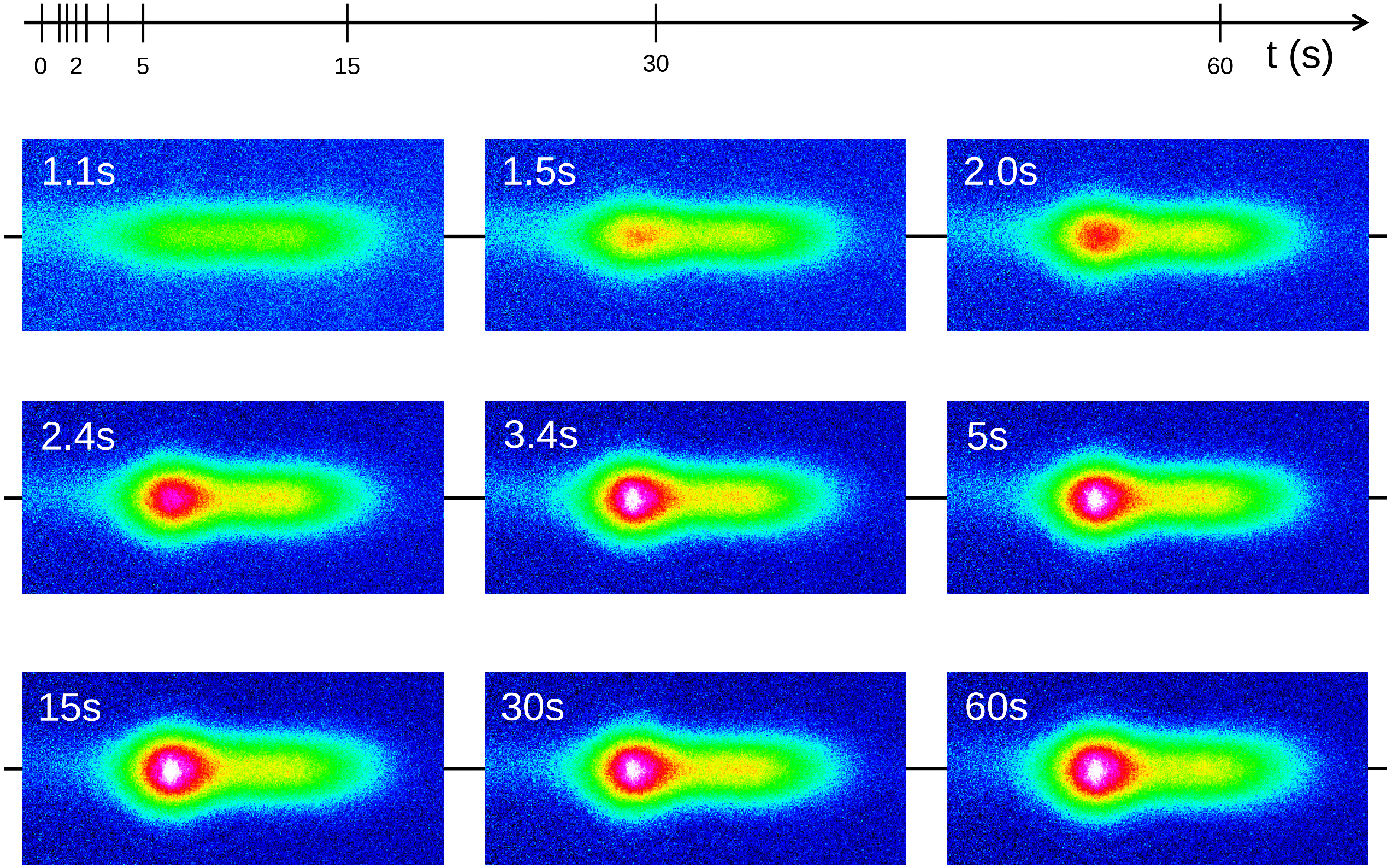
In situ



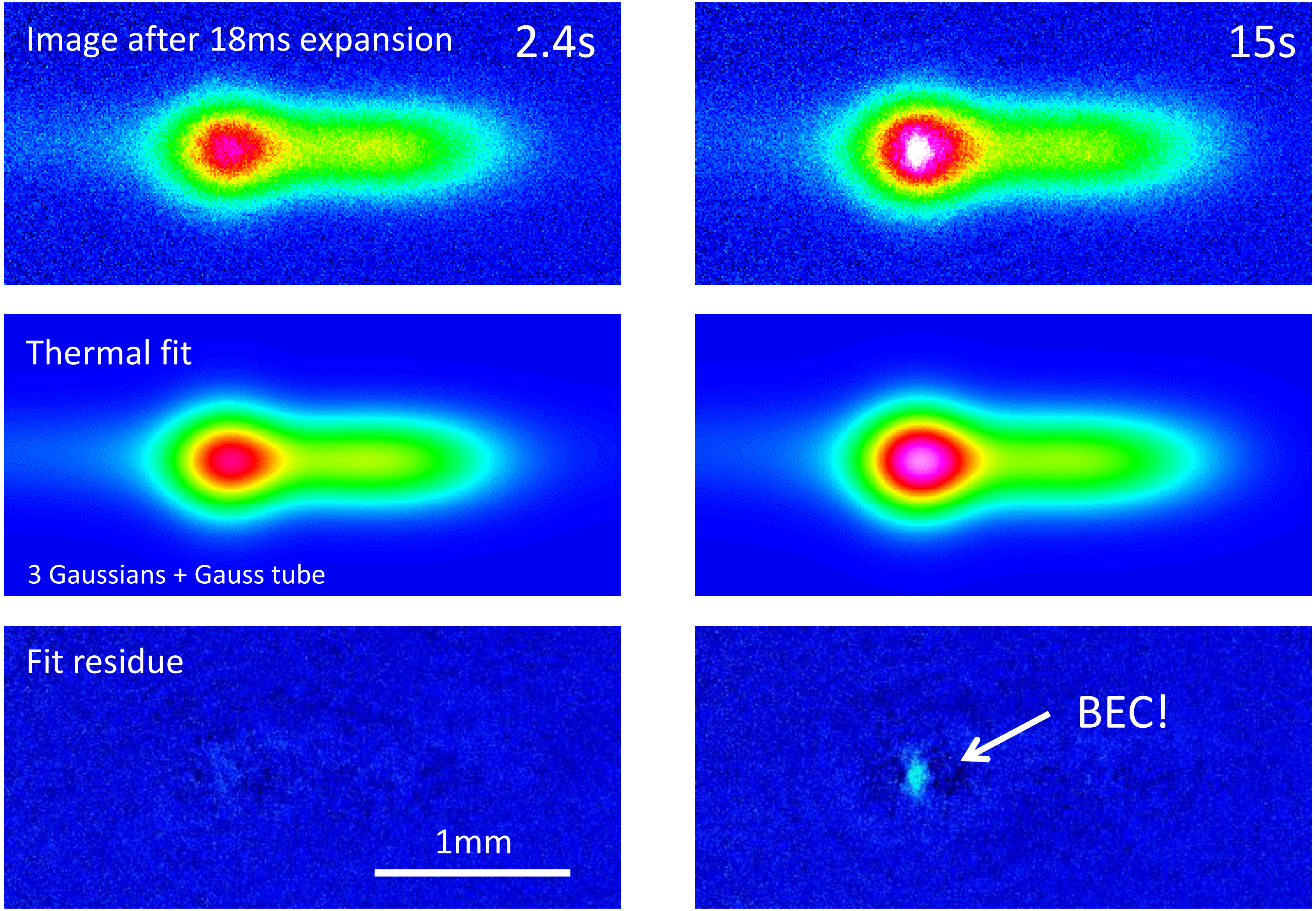
18 ms expansion



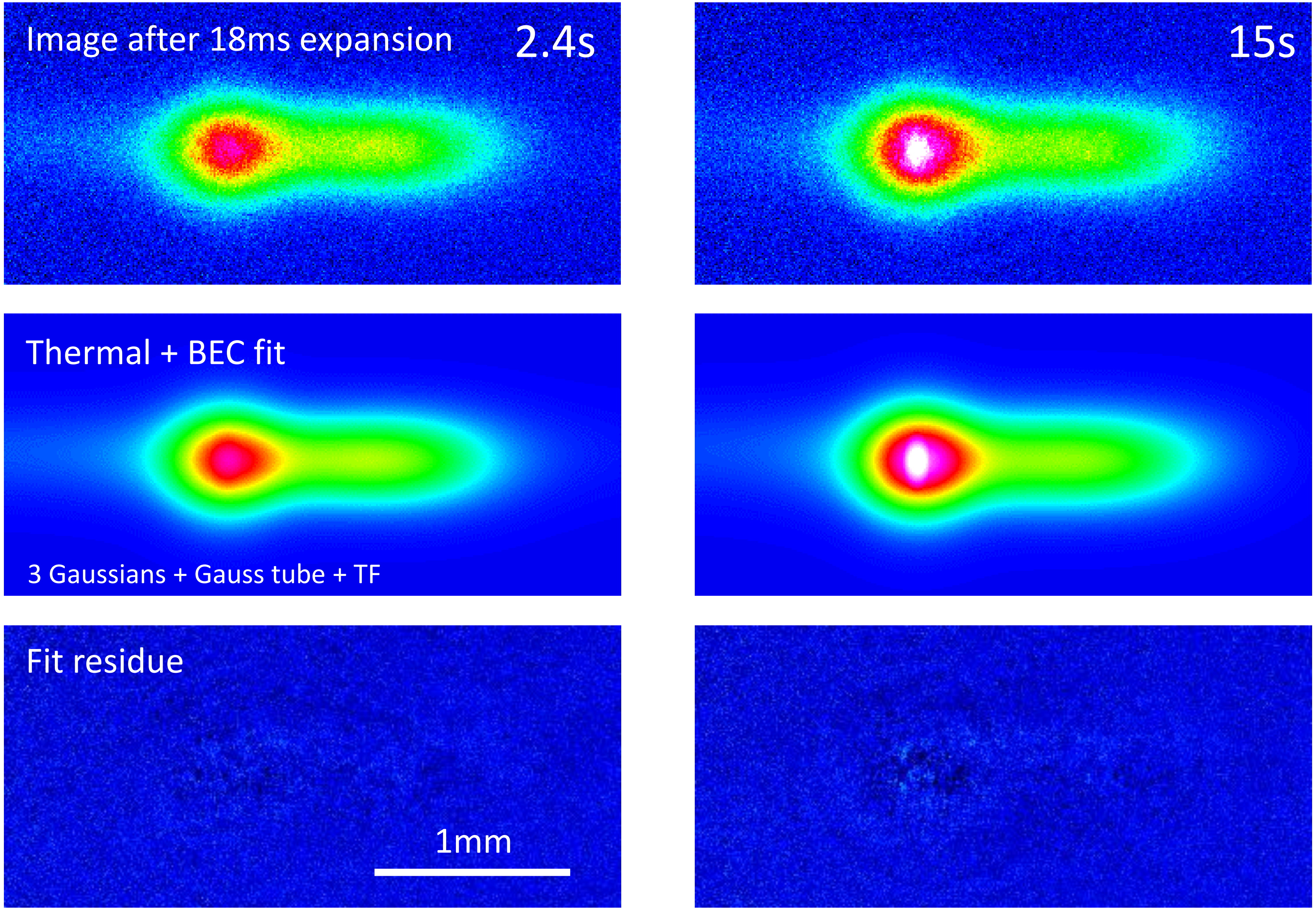
BEC in steady-state?



BEC detection

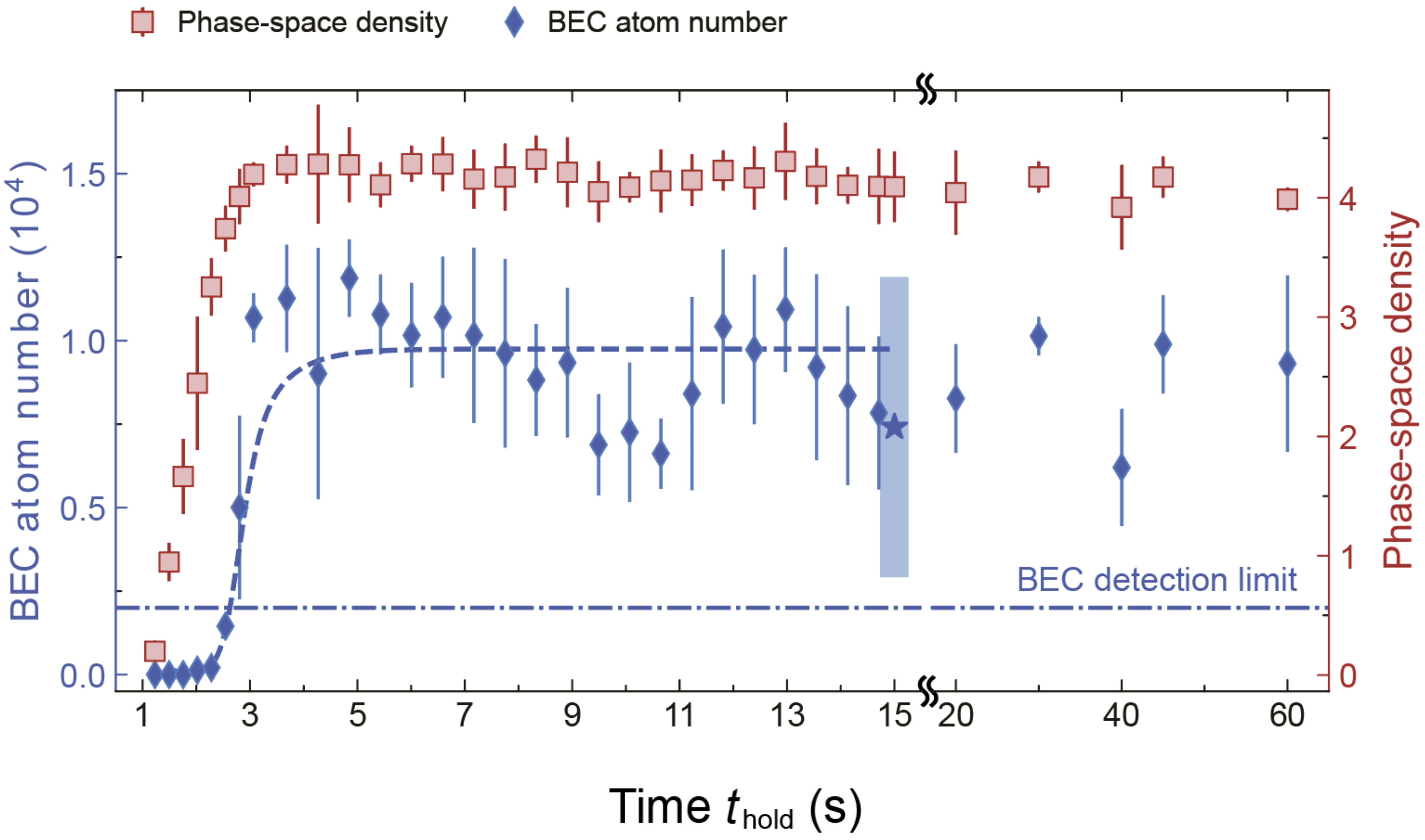


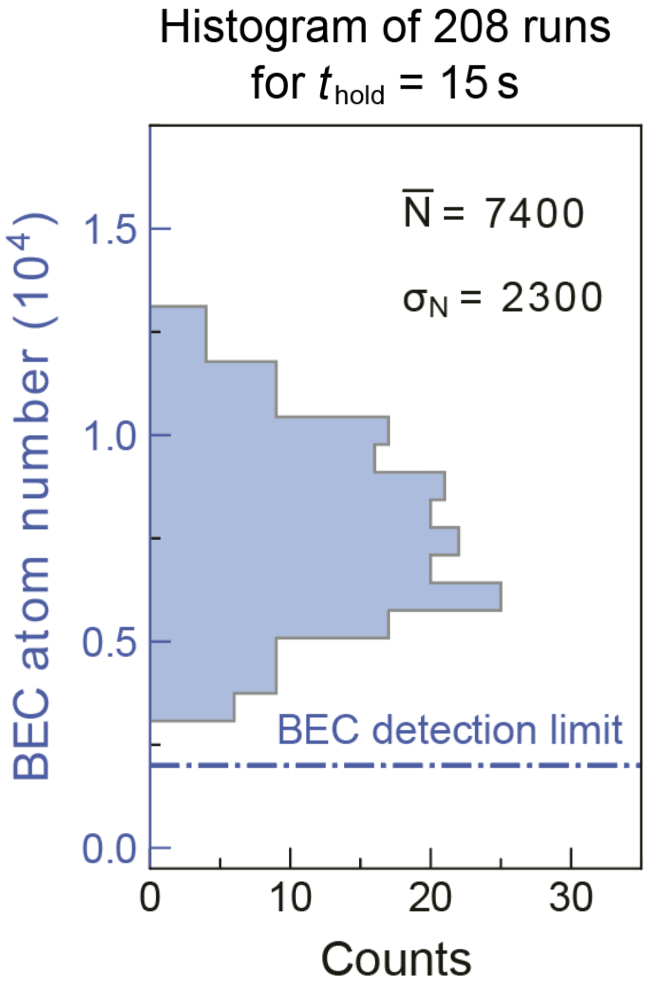
BEC detection



BEC formation

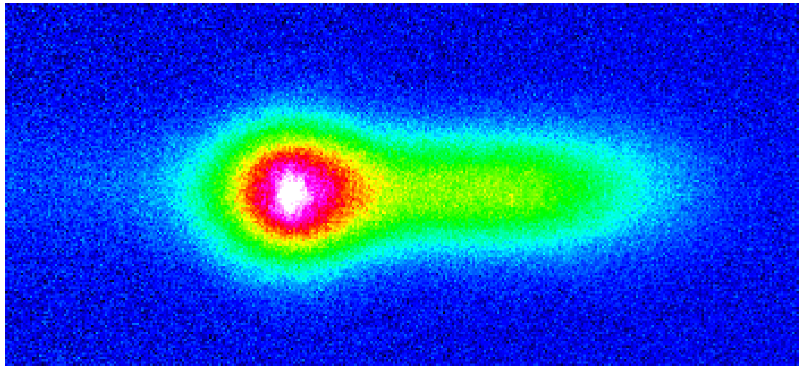
arXiv:2012.07605





Characterization of steady-state

arXiv:2012.07605



BEC: $N = 7.4(2.4) \times 10^3$ ^{84}Sr atoms
Replenishment rate 10^5 atoms/s

Dimple: $N = 6.9(4) \times 10^5$ $T_{vertical} = 1.08(3)\,\mu K$

Reservoir: $N = 7.3(1.8) \times 10^5$
Loading rate $1.1(4) \times 10^6$ atoms/s

- Model assuming thermalized gas does not describe data.

  Model assuming enhanced occupation of higher trap states fits data.

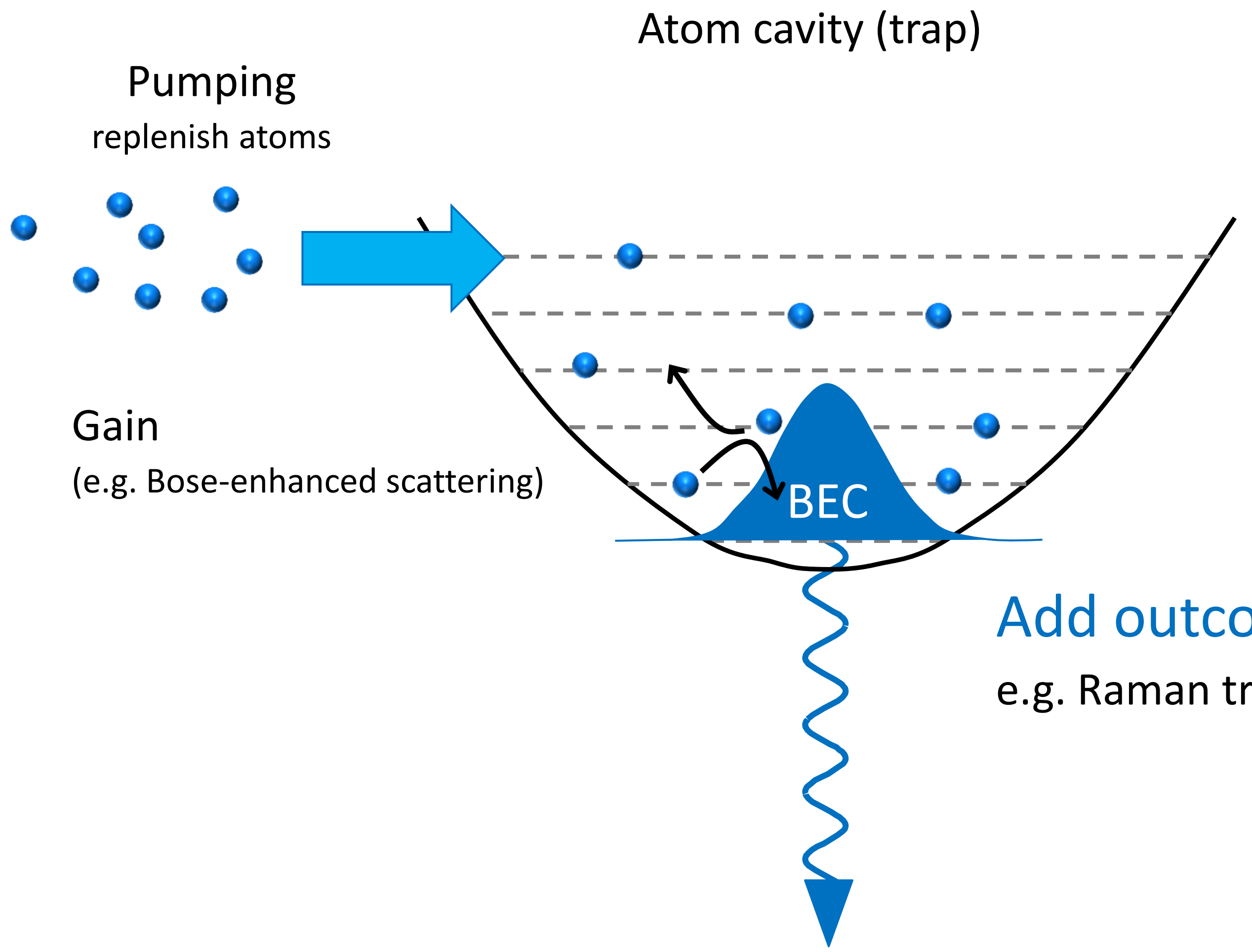
  Signature of driven, dissipative nature of system?

- Future direction: driven-dissipative many-body physics

  BEC purity oscillations — Phys. Rev. Lett. 88, 170403 (2002), Phys. Rev. A 93, 033617 (2016)
  new critical exponents — Phys. Rev. Lett. 110, 195301 (2013)
  unusual quantum phases, especially in lower dimensions — Phys. Rev. Lett. 118, 085301 (2017)

Driven-dissipative BECs created with
exciton-polaritons — Rev. Mod. Phys. 82, 1489 (2010)
magnons — Nat. Phys. 4, 198 (2008)
photons — Nature 468, 545 (2010)

Creating an atom laser: method 1



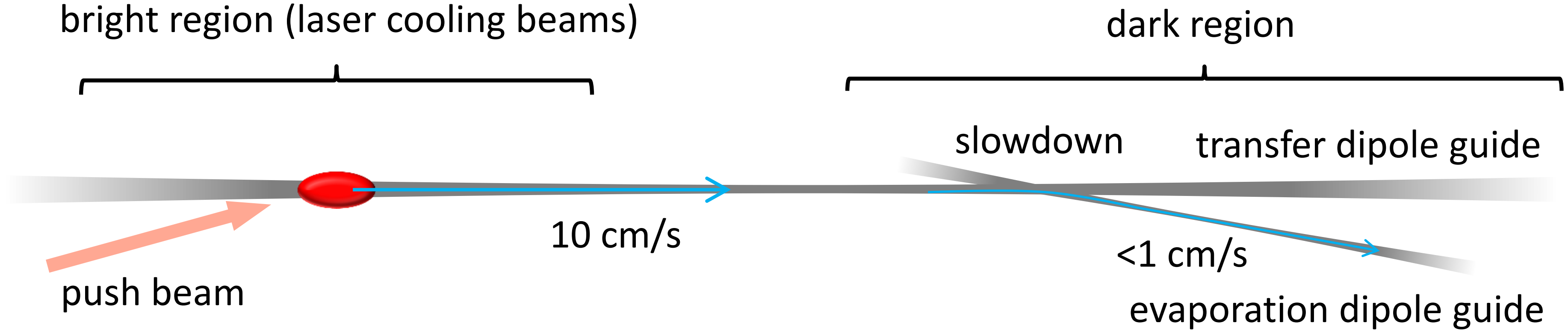
Add outcoupling mechanism

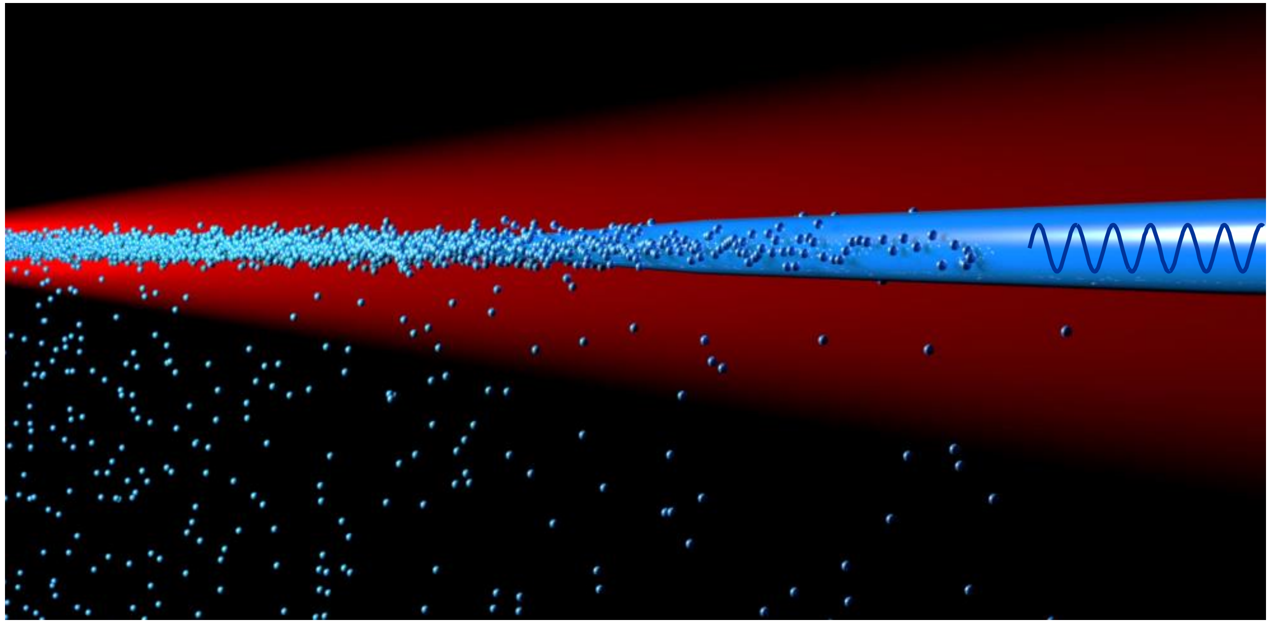
e.g. Raman transfer to untrapped, metastable state

N.P. Robins et al., *Atom lasers: Production, properties and prospects for precision inertial measurement*, Phys. Rep. 529, 265 (2013)

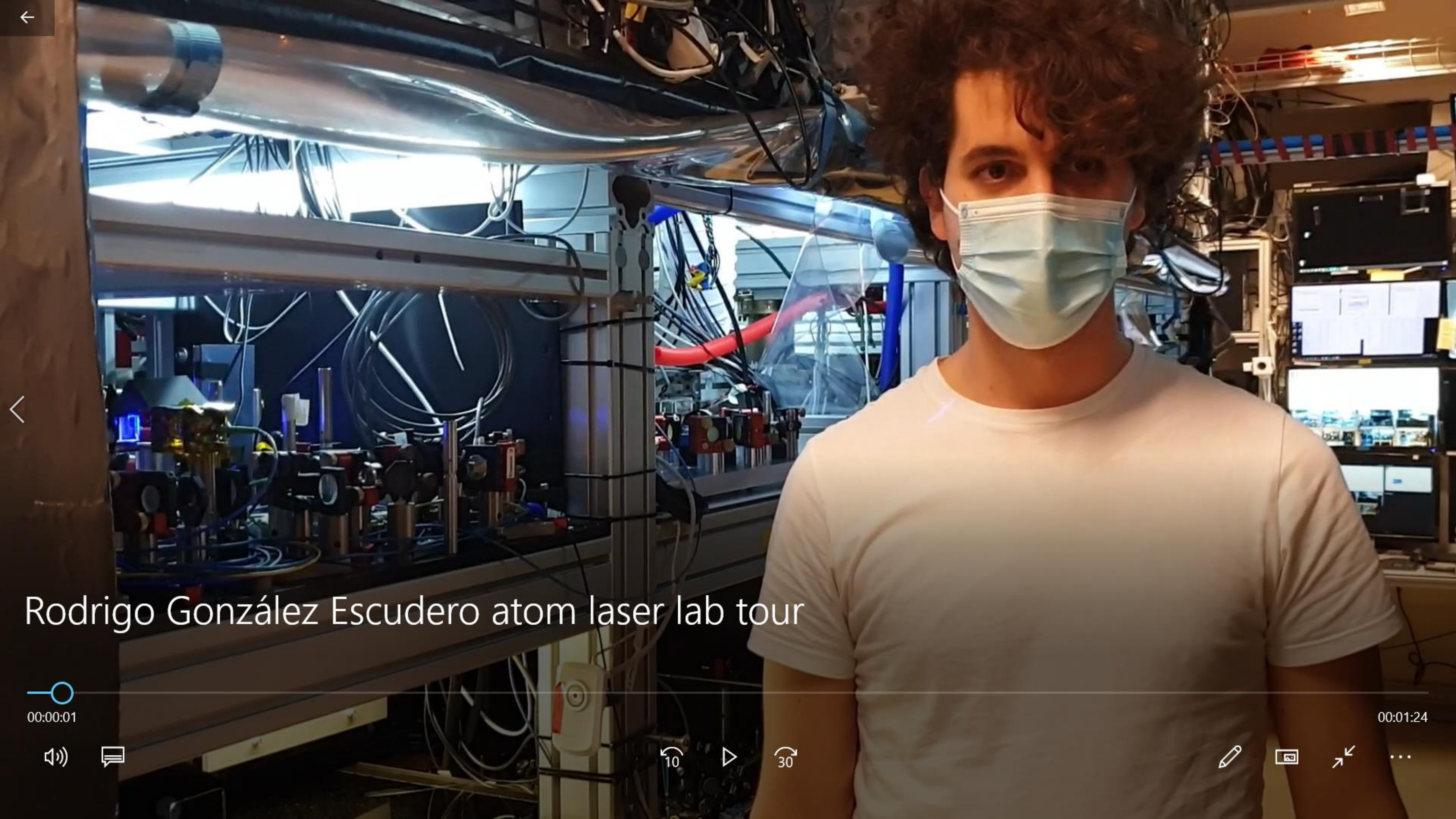
Creating an atom laser: method 2

Add evaporative cooling, e.g.



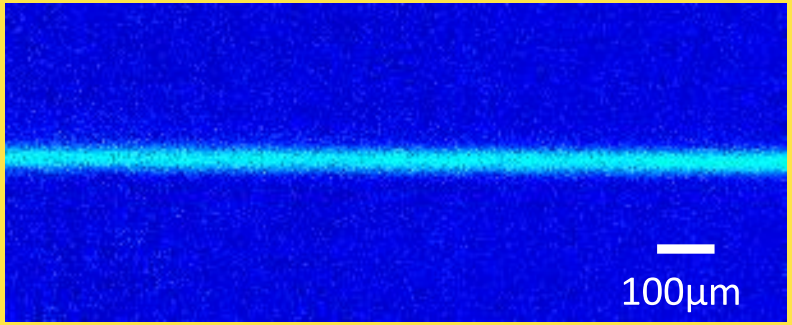


Slowdown using e.g. Sisyphus optical lattice decelerator, Phys. Rev. A 100, 023401 (2019)
Enhance Sr laser cooling scheme, e.g. Katori group, Phys. Rev. A 103, 023331 (2021)

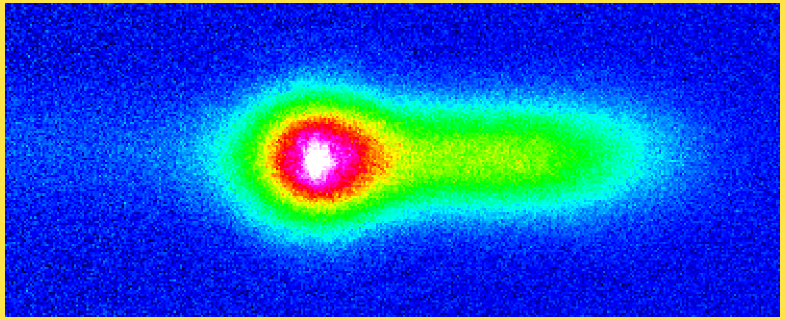

Rodrigo González Escudero atom laser lab tour
00:00:01
00:01:24
10
30

Outline

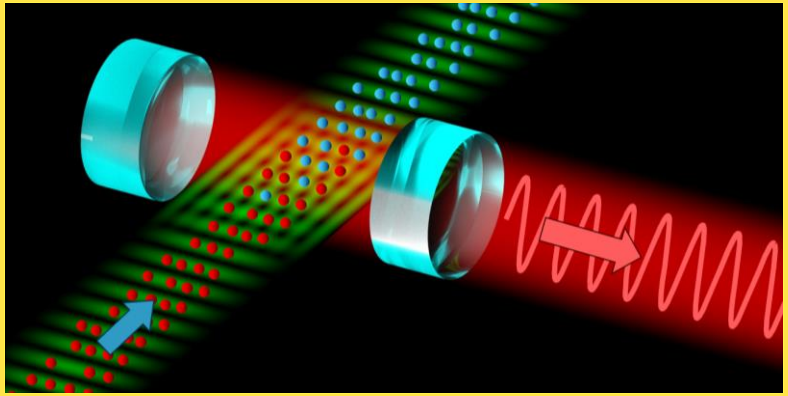
μK Sr beam in the dark



Continuous-wave BEC

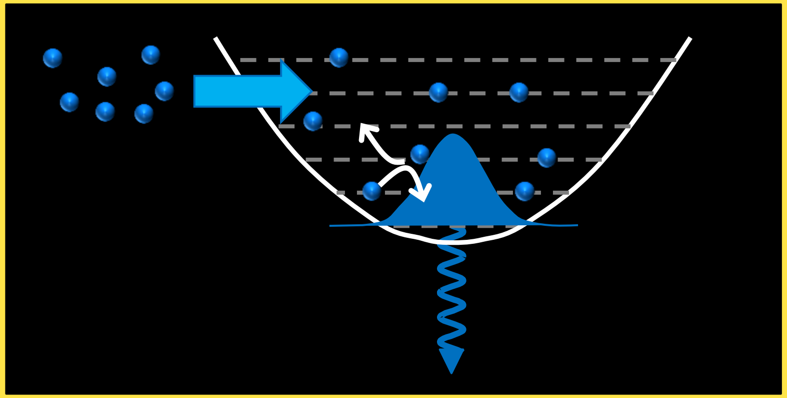


Superradiant clock



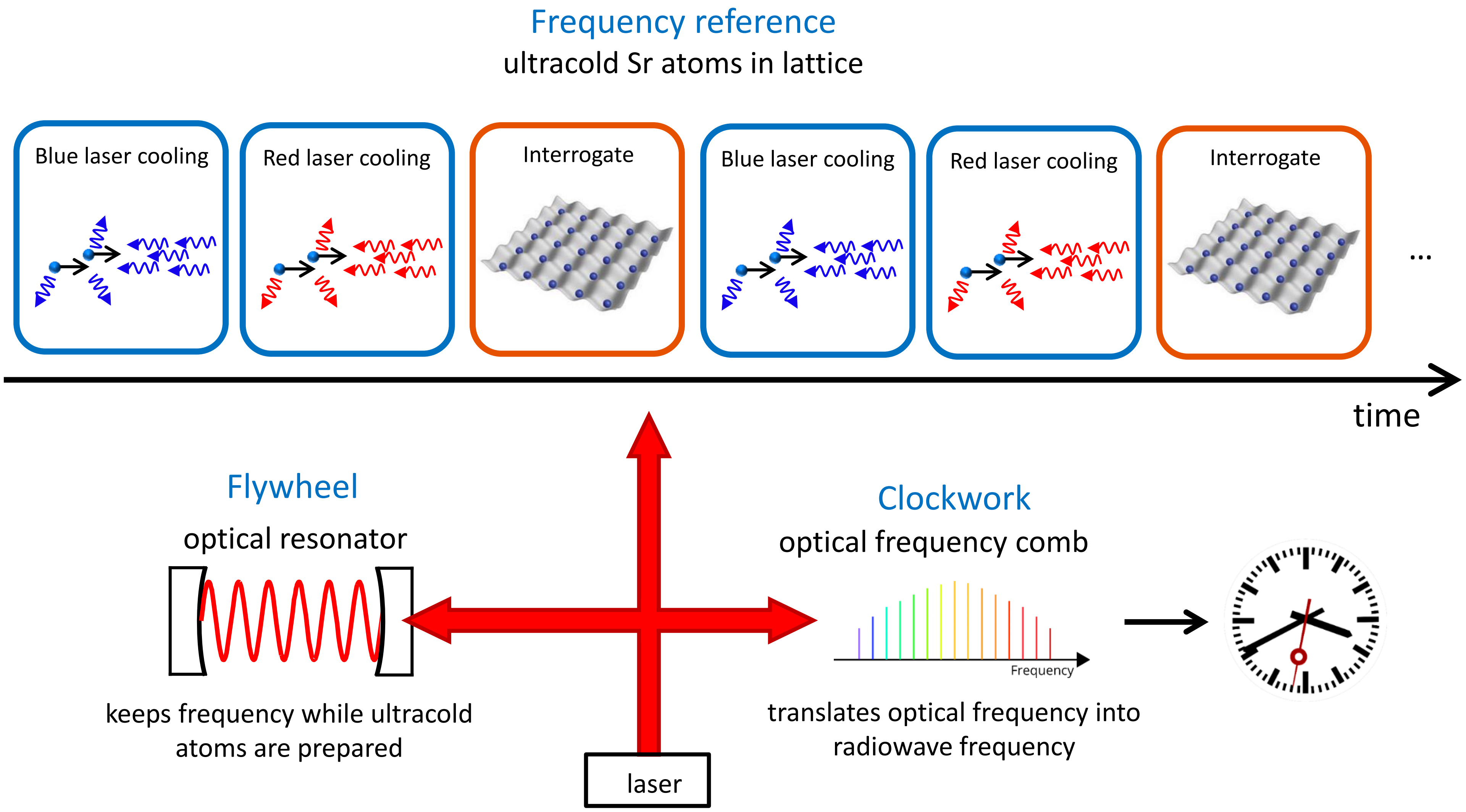
frequency & time

Continuous-wave atom laser

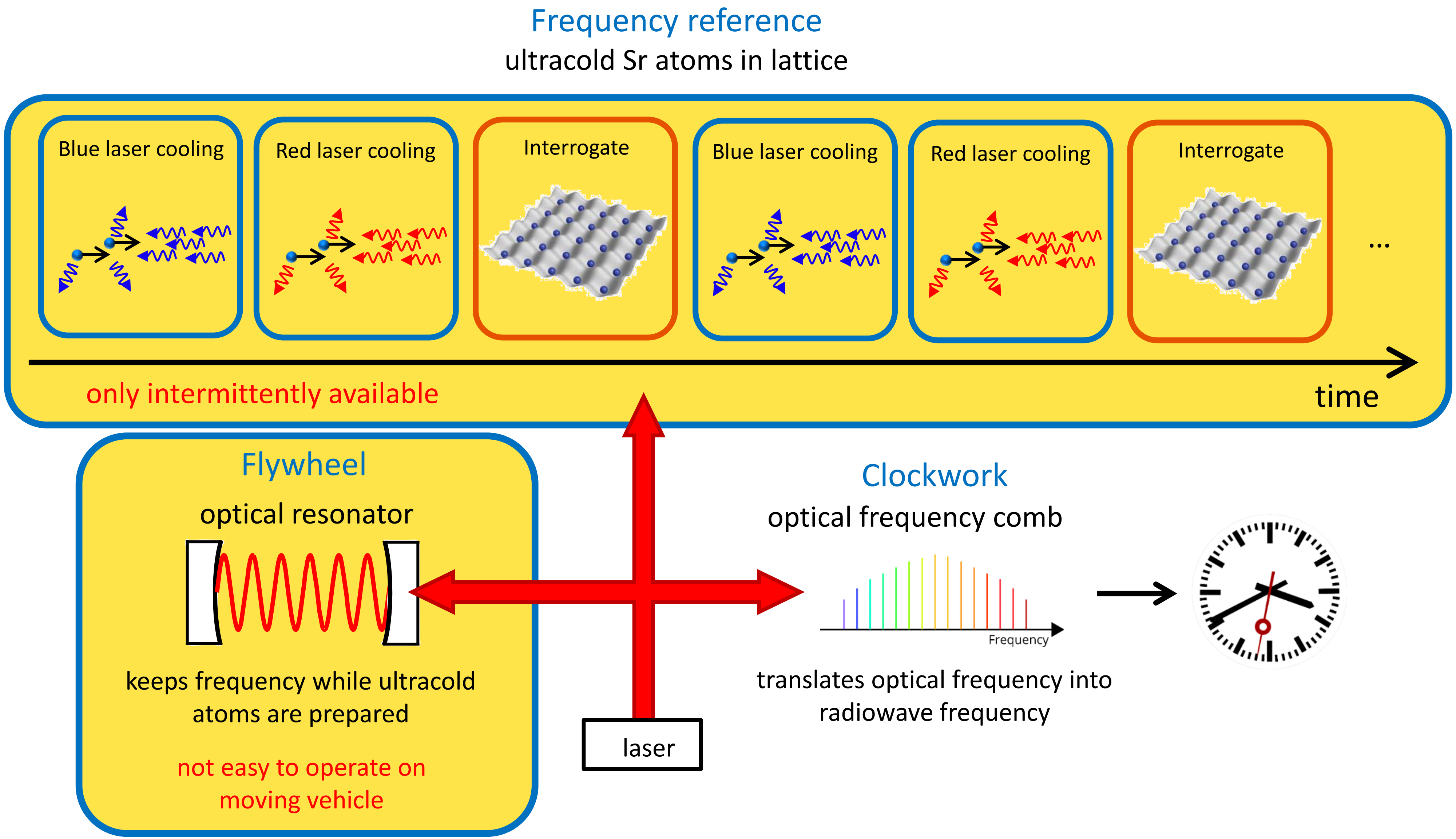


acceleration & rotation

Optical lattice clock scheme

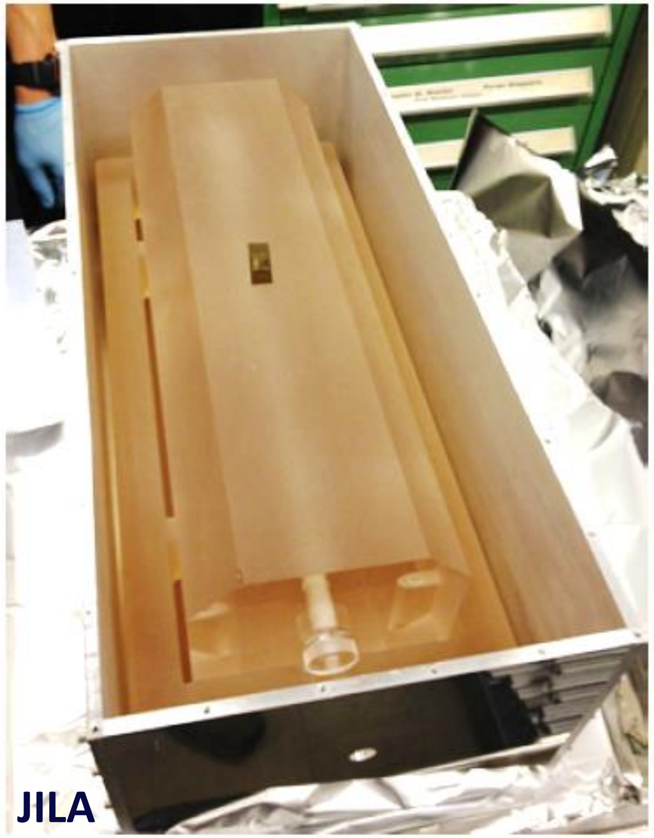


Challenges


Frequency reference
ultracold Sr atoms in lattice
Blue laser cooling
Red laser cooling
Interrogate
Blue laser cooling
Red laser cooling
Interrogate
...
only intermittently available
time
Flywheel
optical resonator
keeps frequency while ultracold atoms are prepared
not easy to operate on moving vehicle
laser
Clockwork
optical frequency comb
Frequency
translates optical frequency into radiowave frequency

Ultrastable resonators

Ultralow expansion glass cavity

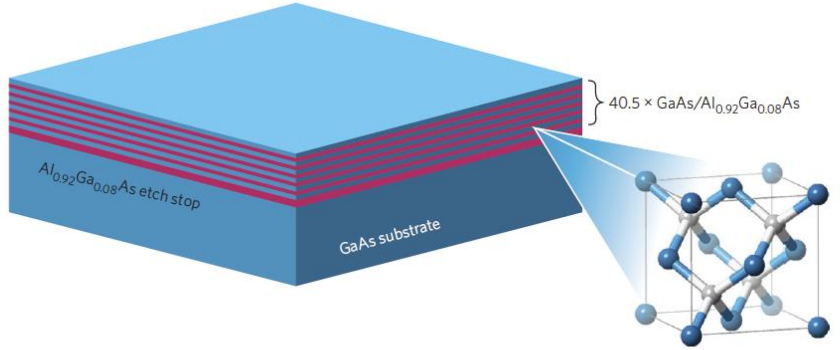


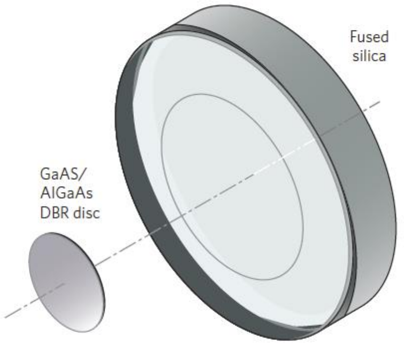
Limit: thermal length changes of spacer

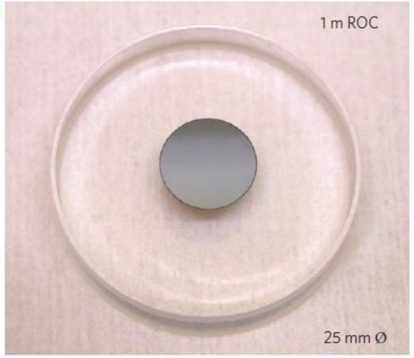
Silicon monocrystal cavity

Limit: thermal noise in coatings

Crystalline mirror coatings







PTB, 8 × 10^{-17} fractional laser frequency instability with a long room-temperature cavity, Optics Lett. 40, 2112 (2015)

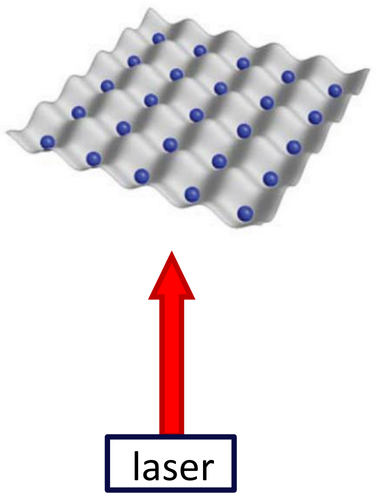
PTB, JILA: *1.5 µm Lasers with Sub-10 mHz Linewidth*, Phys. Rev. Lett. 118, 263202 (2017)

Aspelmeyer group, *Tenfold reduction of Brownian noise in high-reflectivity optical coatings*, Nature photonic 7, 644 (2013)

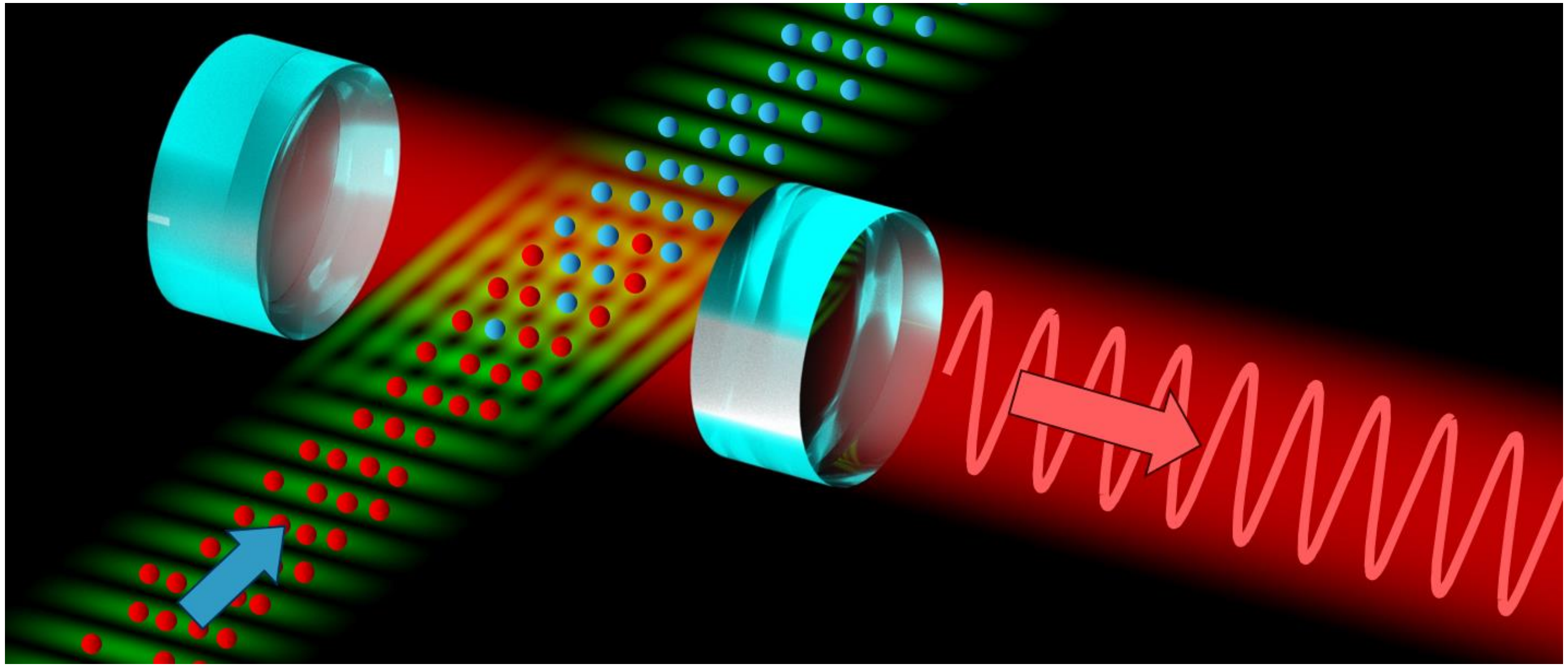
Superradiant clock

Passive clock

ultracold Sr atoms in lattice



Active, superradiant clock

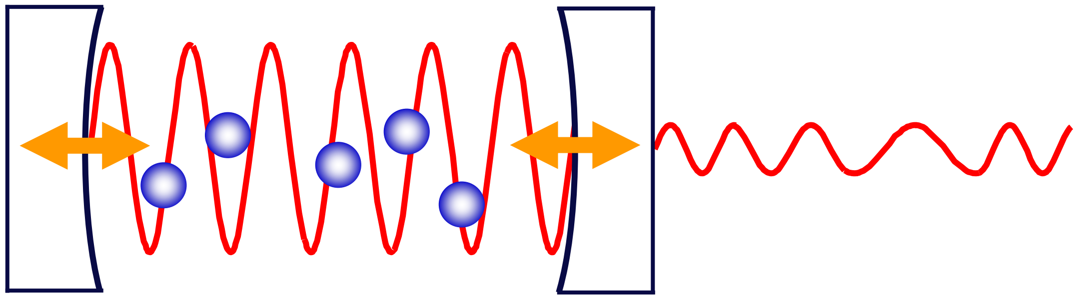


Continuous ultracold strontium beam in

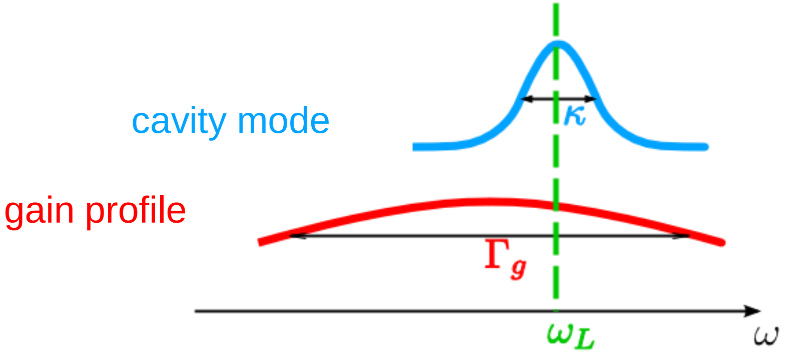
Clock laser beam out

Comparison to standard laser

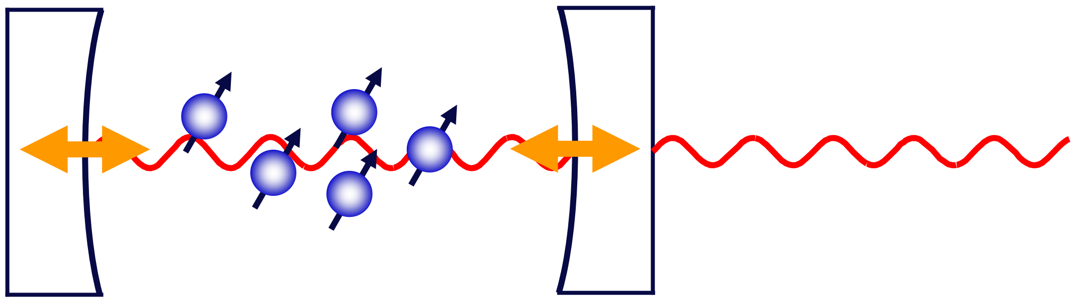
Standard laser: frequency stability from length of cavity



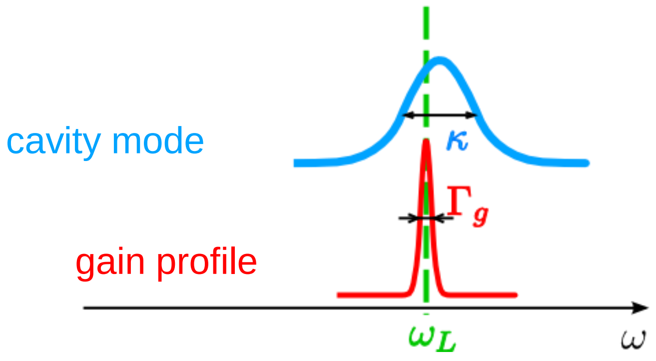
good-cavity regime: $\kappa \ll \Gamma_g$



Superradiant clock laser: frequency stability from ensemble spin of atoms

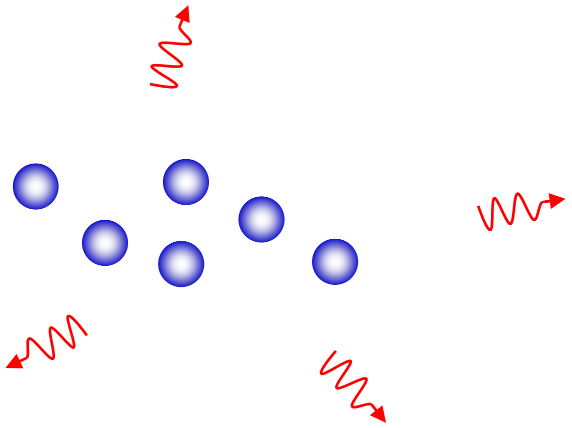


bad-cavity regime: $\kappa \gg \Gamma_g$



Active optical clock

Goal: photons from mHz linewidth transition



Challenges:
- minutes of excited state lifetime
- emission into 4π

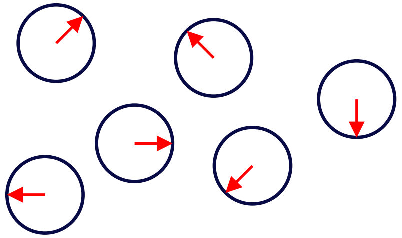
Solution: enhance emission into single mode by superradiance

Jingbiao Chen, arXiv:physics/0512096 (2005), Chinese Science Bulletin **54**, 348 (2009)

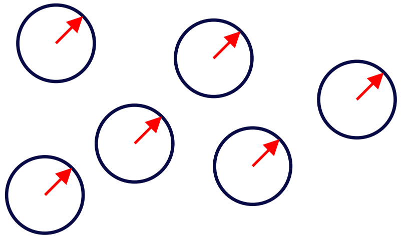
D. Meiser, J. Ye, D. R. Carlson, M. J. Holland, PRL **102**, 163601 (2009)

Phased array of N emitters

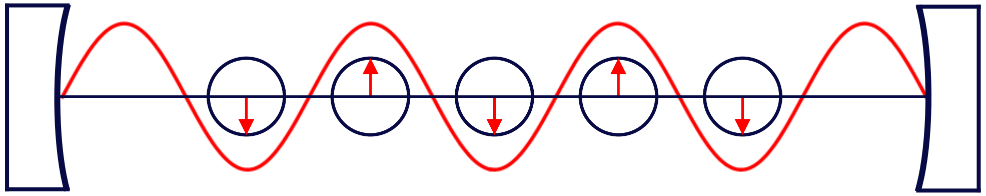
Closer spaced than wavelength
Random phase



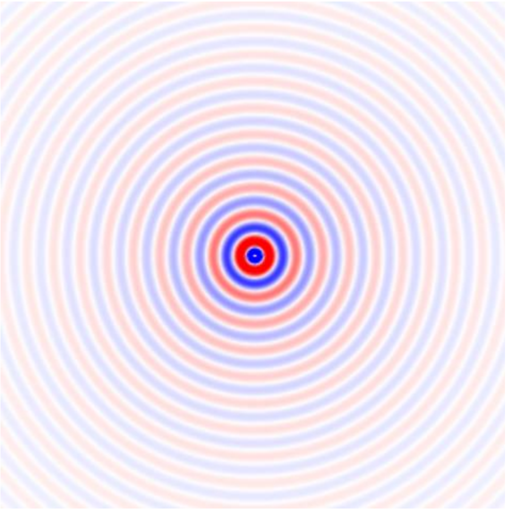
Closer spaced than wavelength
Same phase



Spaced wavelength/2 along axis
Alternating phase



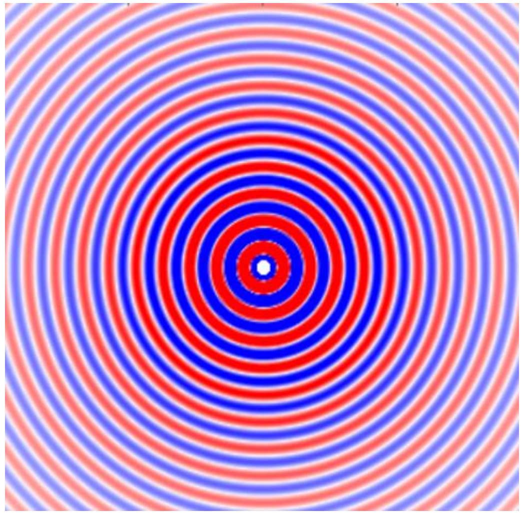
Electric field



Random interference

E-field ~ Sqrt(N)

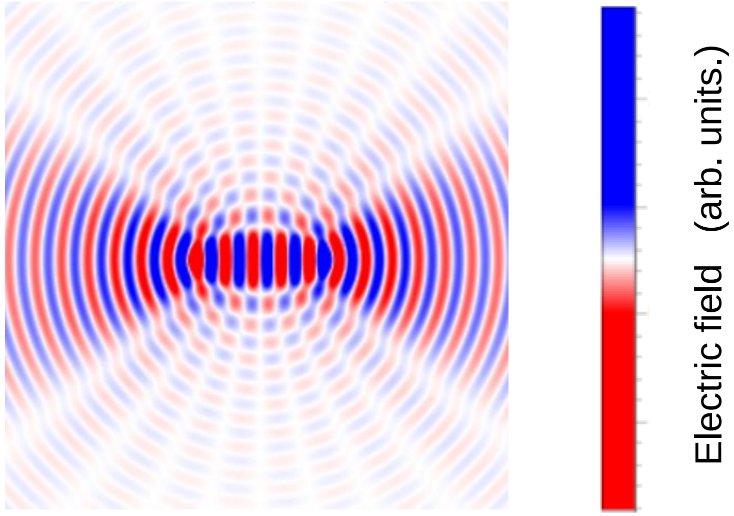
Power ~ N



Constructive interference

E-field ~ N

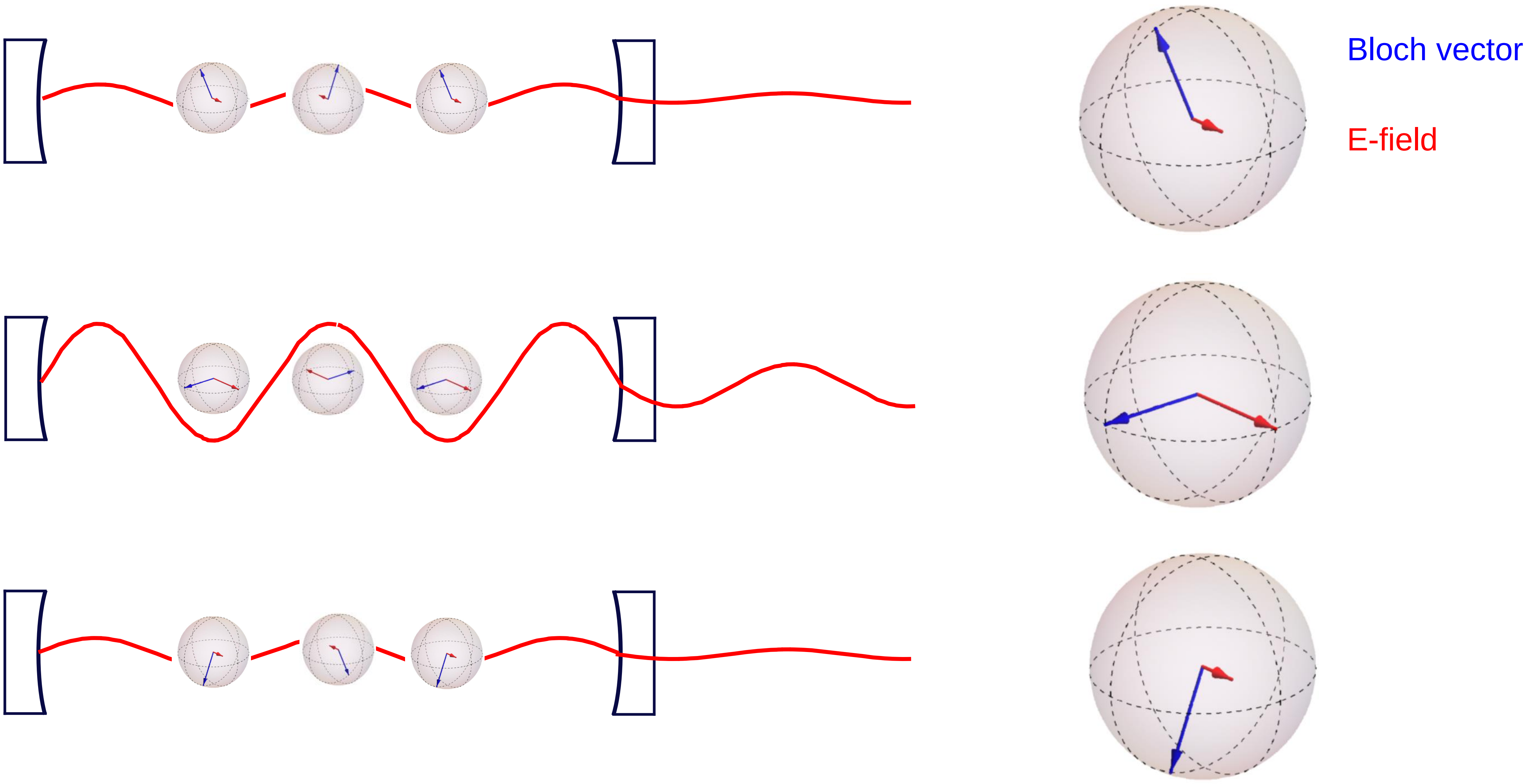
Power ~ N^2



Constructive interference along axis

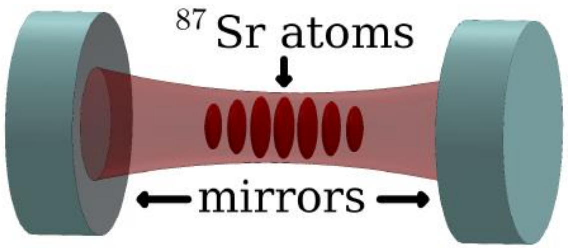
Power along axis ~ N^2

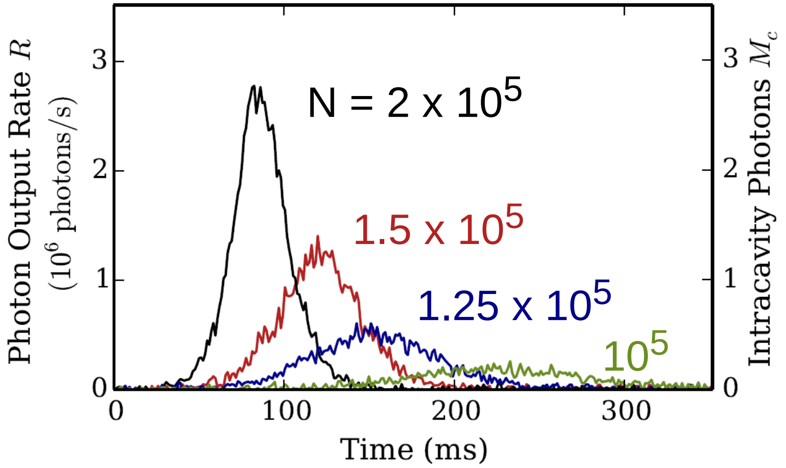
How is superradiance established?

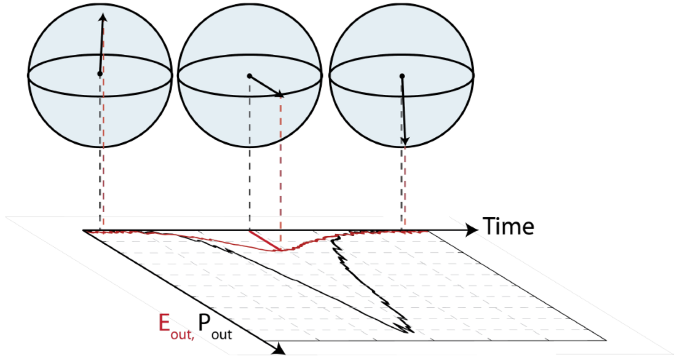


Superradiant lasers

James Thompson group, JILA: pulsed superradiance Rb Raman transition, Nature, **484**, 78 (2012)
pulsed superradiance on Sr mHz transition, Science Advances, **2**, e1601231 (2016)





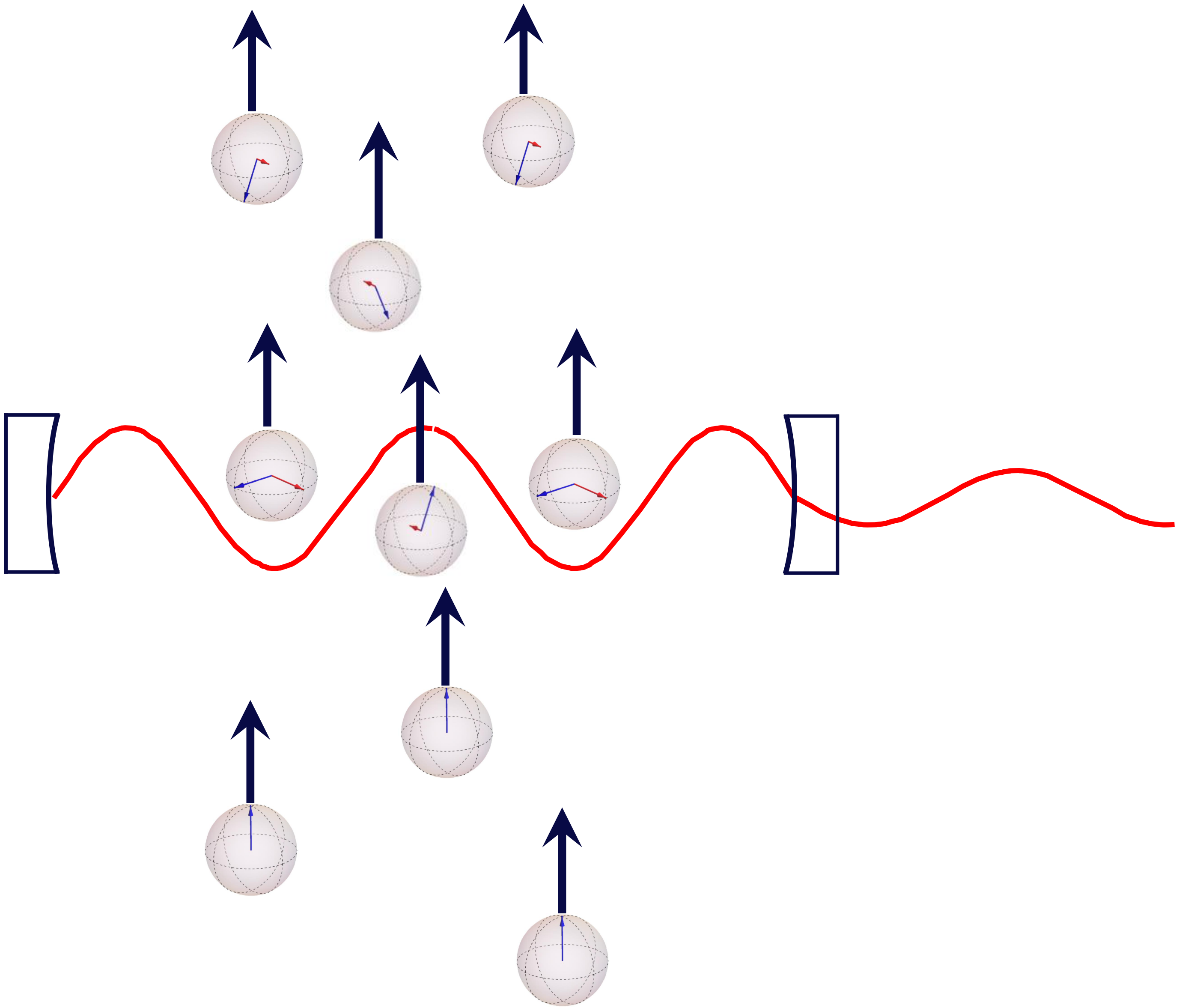


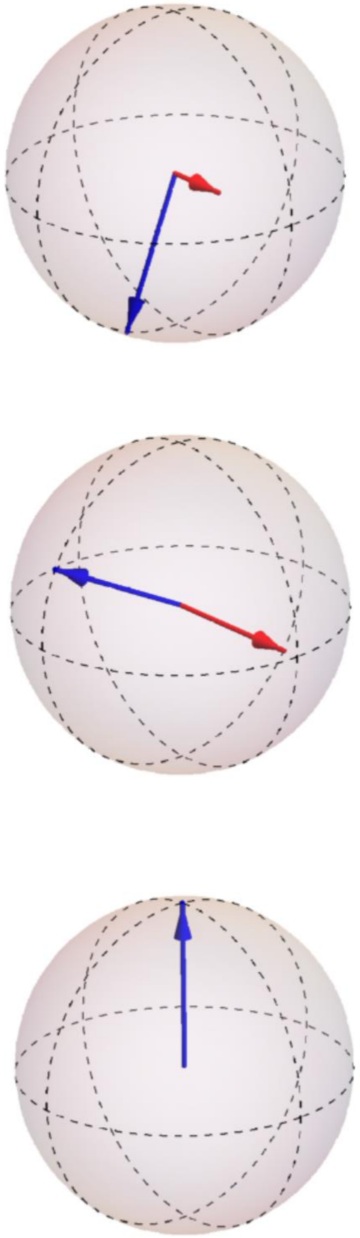
Andreas Hemmerich group (Hamburg): pulsed Ca superradiance on 379-Hz transition, PRL **123**, 103601 (2019)

Jan Thomsen group (Copenhagen): pulsed Sr superradiance on kHz transition, PR A **101**, 013819 (2020)

Related: Jingbiao Chen group (Beijing): continuous Cs bad-cavity laser on 1.8-MHz transition, IEEE Trans. Ultrason. Ferroelectrics. Freq. Contr. **65**, 1958 (2018)

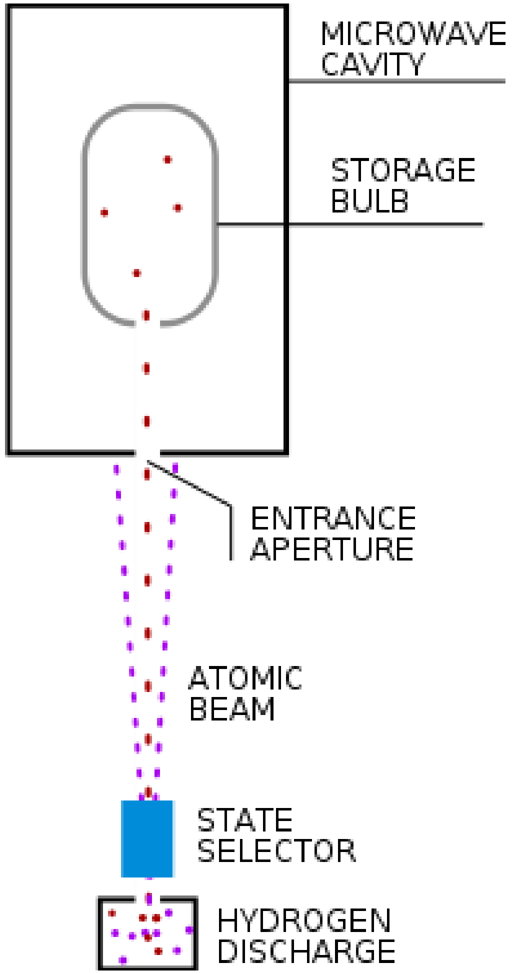
How can superradiance be maintained?

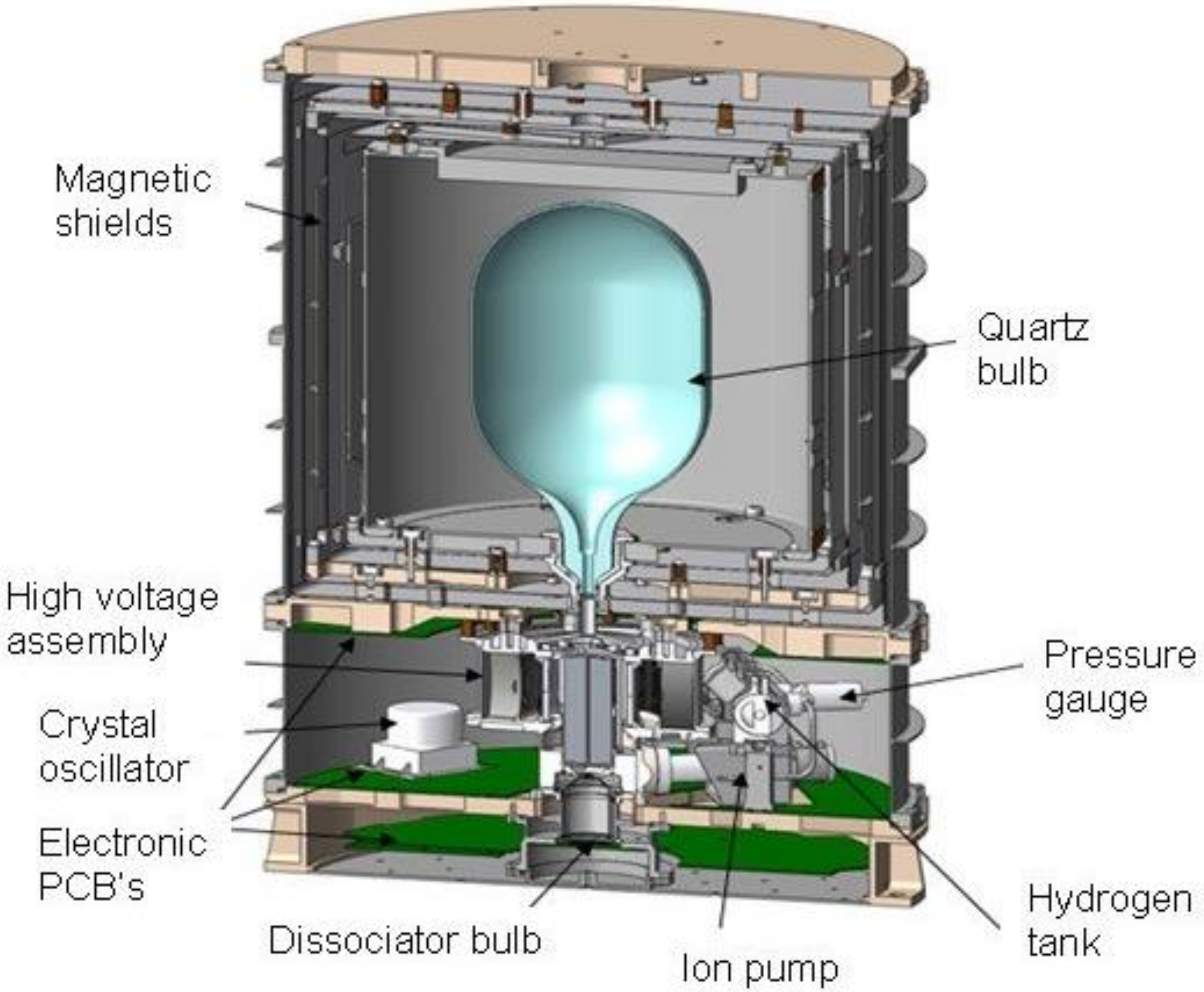




Hydrogen maser

Continuous superradiant microwave emission, used as frequency reference





Continuous superradiant Sr lasers

Version 1

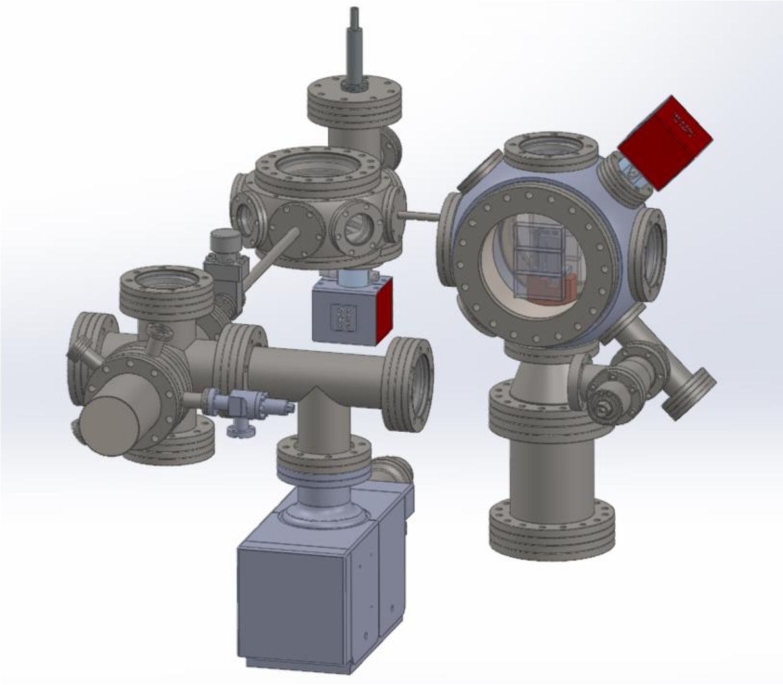
kHz transition

hot atomic beam

Version 2

mHz transition

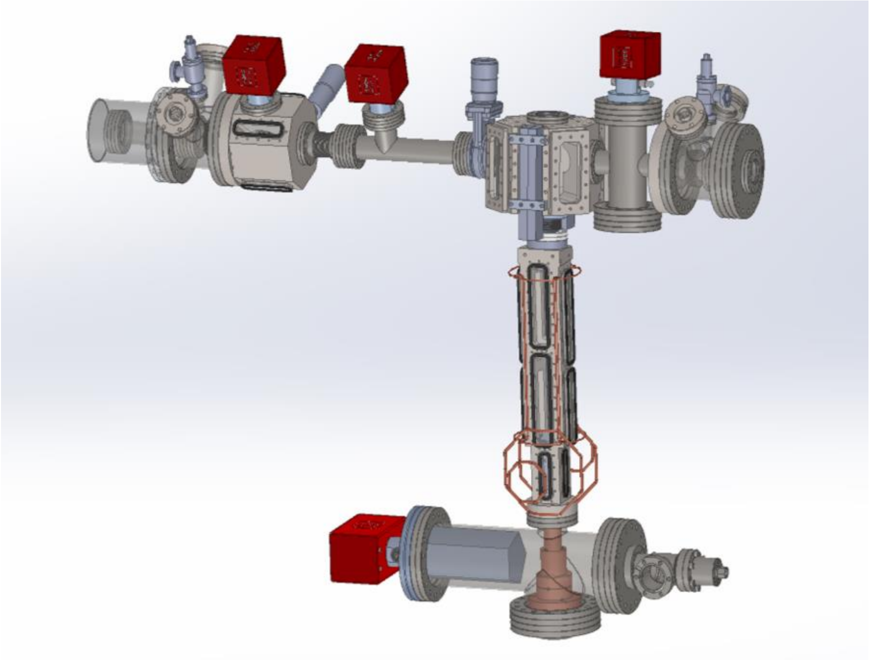
continuous ultracold beam
from periodically refilled reservoir



Version 3

mHz transition

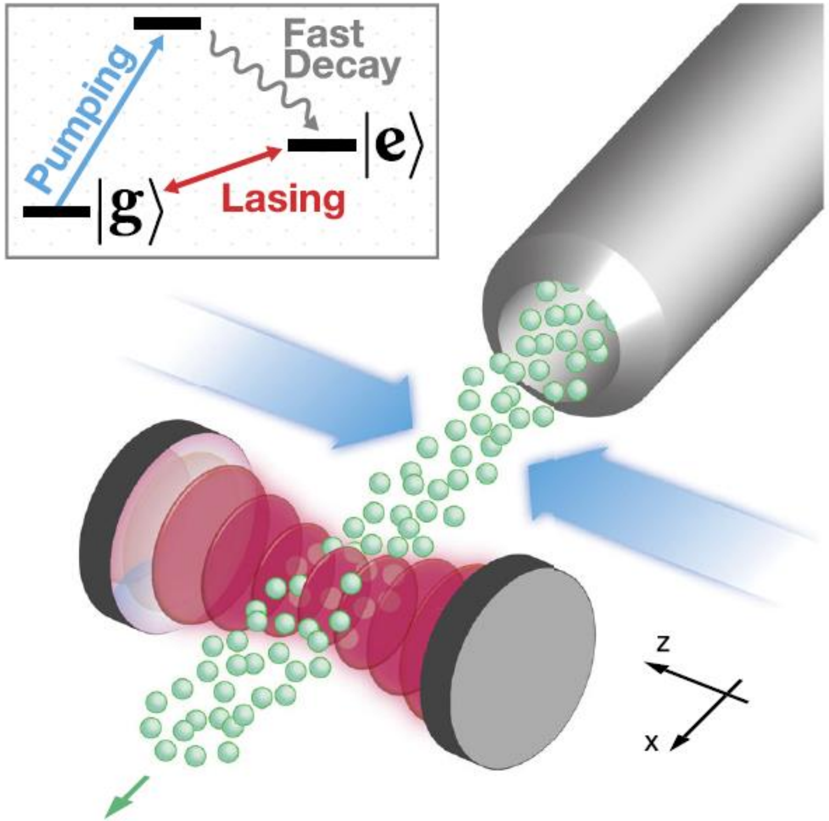
continuous ultracold beam



V1: kHz-transition superradiant Sr laser

Jingbiao Chen
Active Optical Clock
arXiv:physics/0512096 (2005), Chinese Science Bulletin **54**, 348 (2009)

H. Liu, S. B. Jäger, X. Yu, S. Touzard, A. Shankar, M. J. Holland, and T. L. Nicholson
Rugged mHz-Linewidth Superradiant Laser Driven by a Hot Atomic Beam
PRL **125**, 253602 (2020)



Key requirements

- sufficient atom flux
  - ~ 10^{12} atoms/s through cavity mode
  - ~ 10^{5} atoms in cavity mode
- low velocity along cavity
  - ~ 0.4 m/s

Expected performance V1.1

- Linewidth ~ 100 Hz
- Power ~ 100 nW

V1: kHz-transition superradiant Sr laser

Jingbiao Chen
Active Optical Clock
arXiv:physics/0512096 (2005), Chinese Science Bulletin **54**, 348 (2009)

H. Liu, S. B. Jäger, X. Yu, S. Touzard, A. Shankar, M. J. Holland, and T. L. Nicholson
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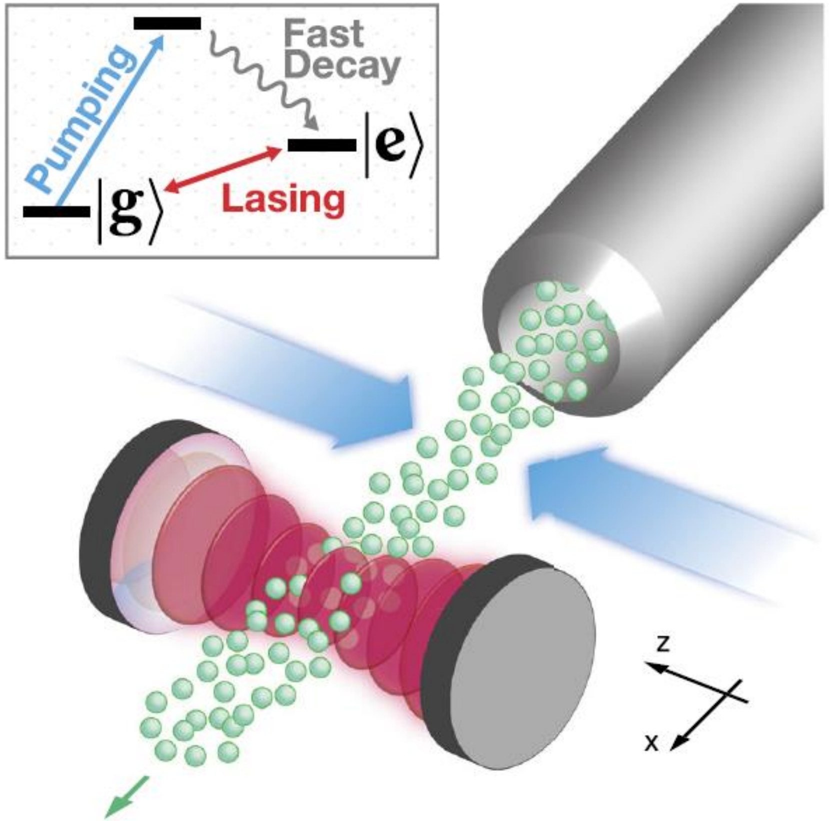

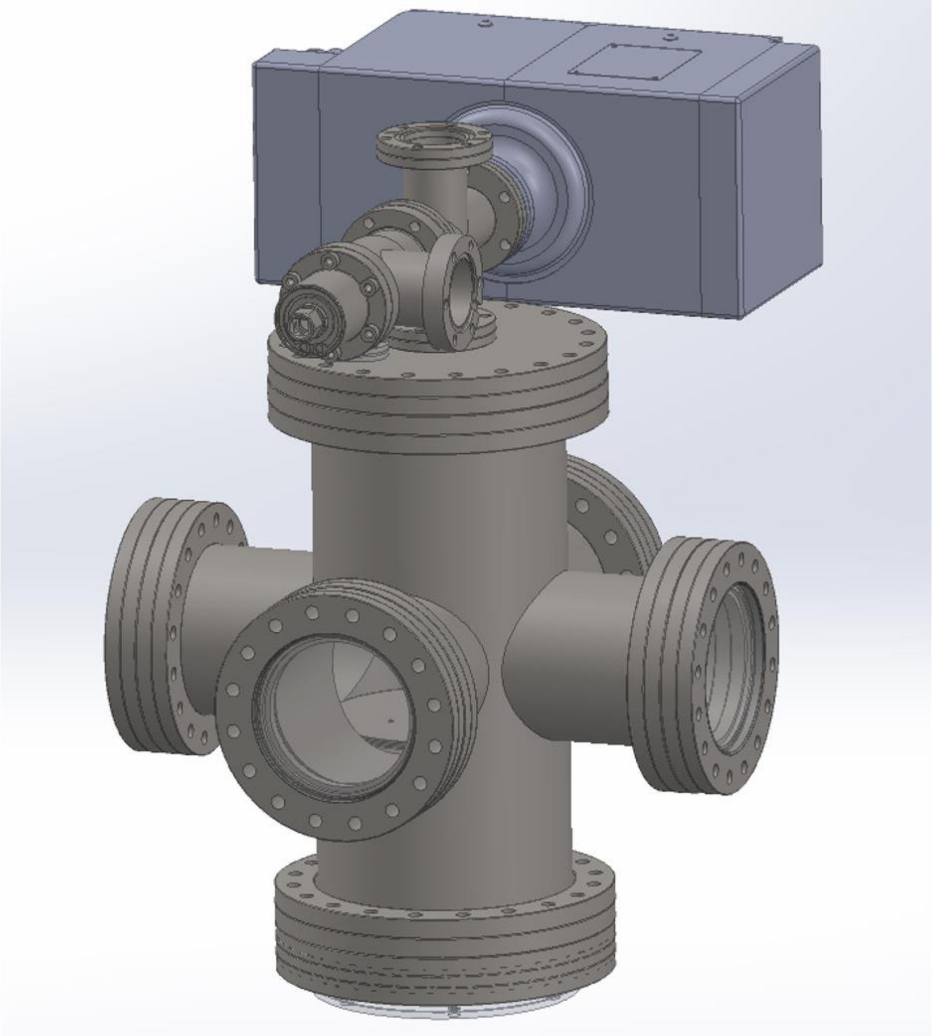

V1: kHz-transition superradiant Sr laser

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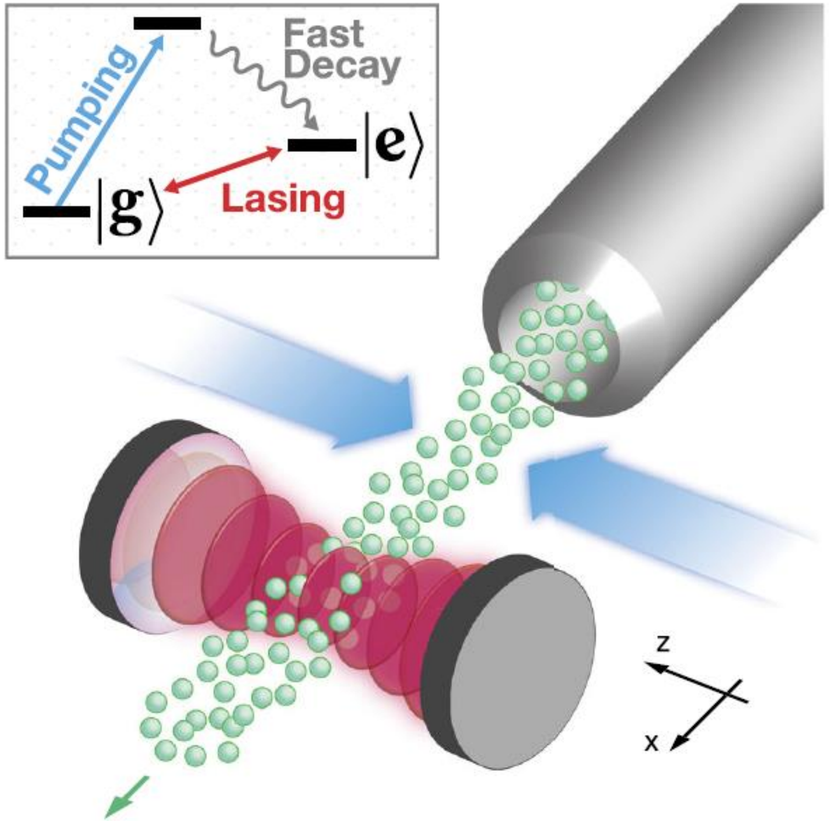
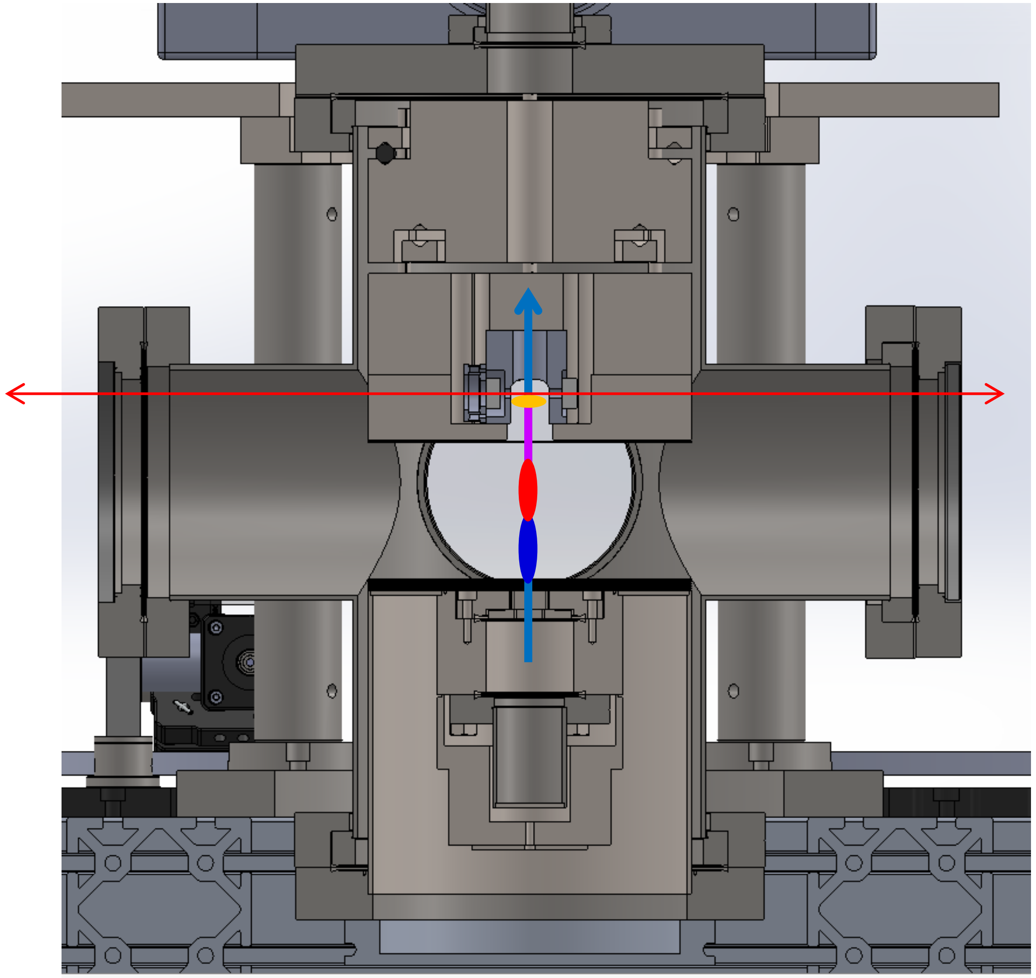




V1: kHz-transition superradiant Sr laser

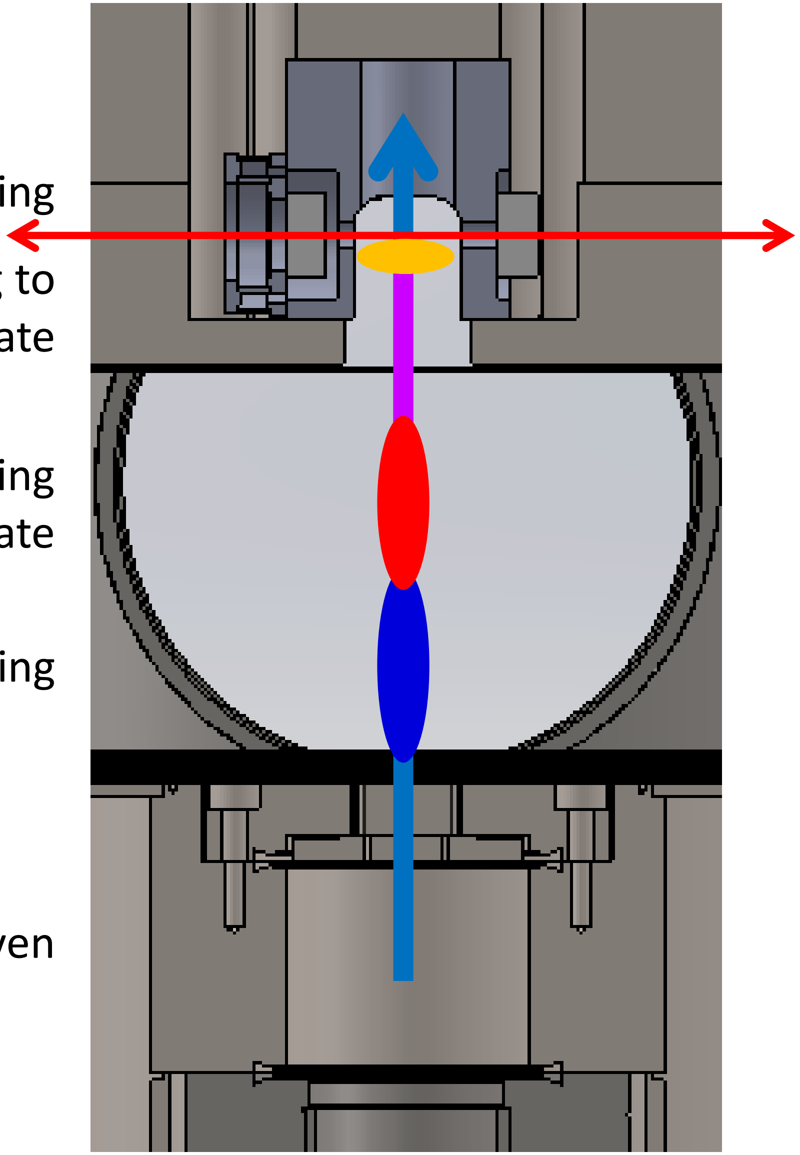
Cavity for superradiant lasing

Optical pumping to
upper lasing state

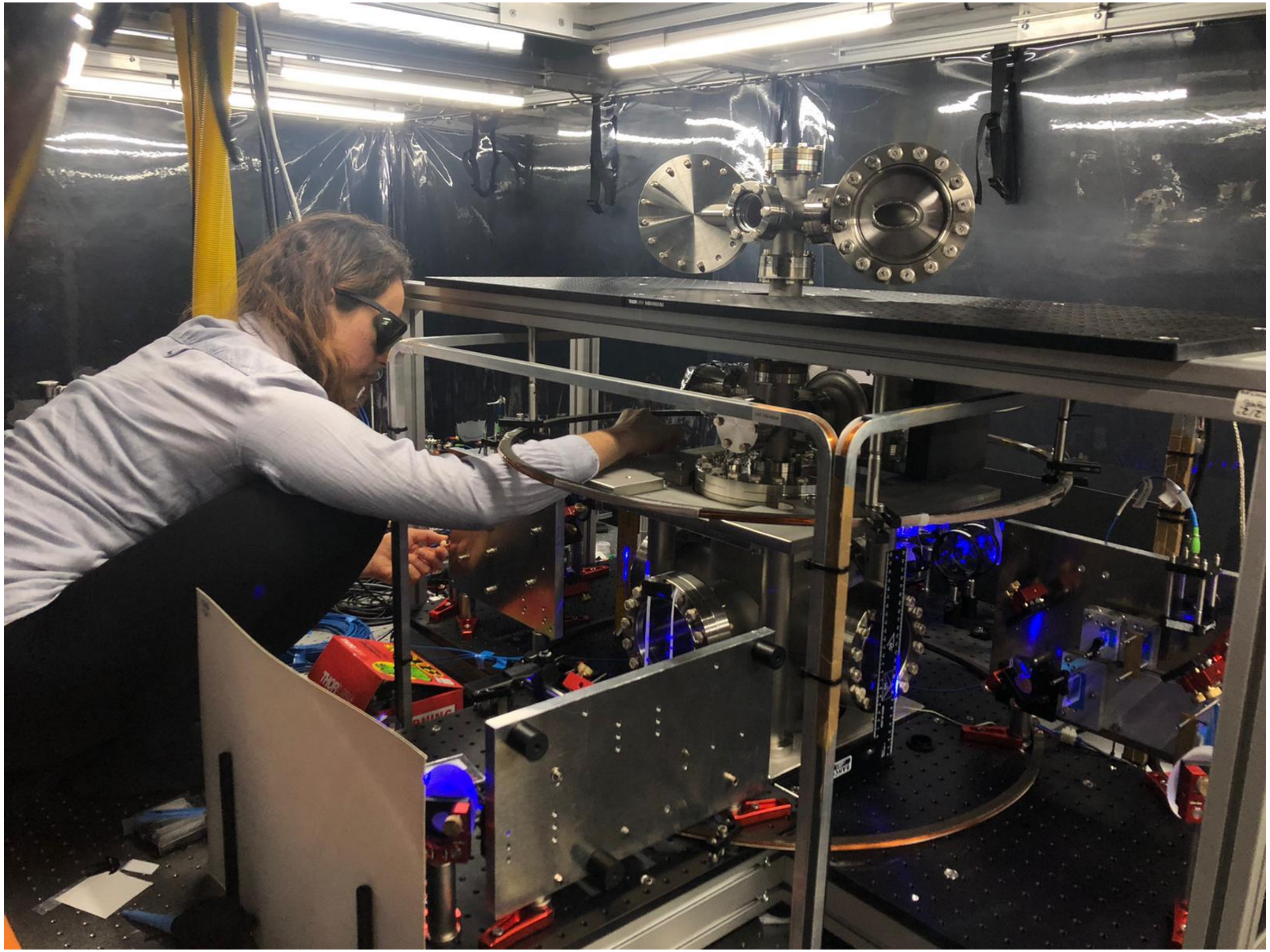
Velocity selective optical pumping
to metastable state

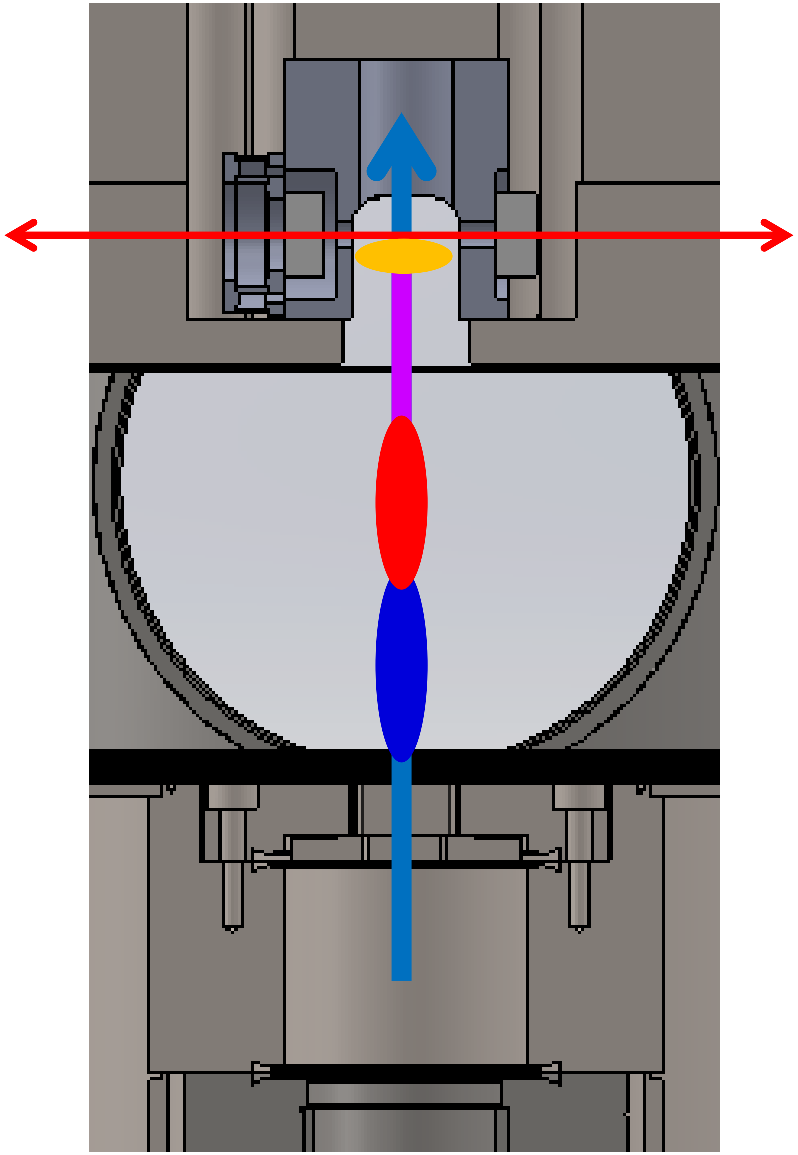
Transversal cooling

Beam oven



V1: kHz-transition superradiant Sr laser





Continuous superradiant Sr lasers

Version 1

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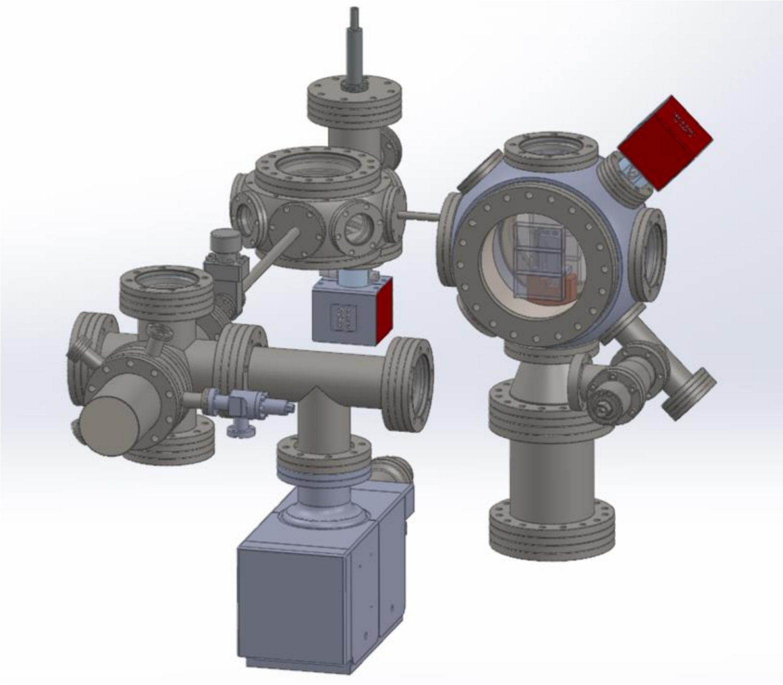
Version 2

mHz transition

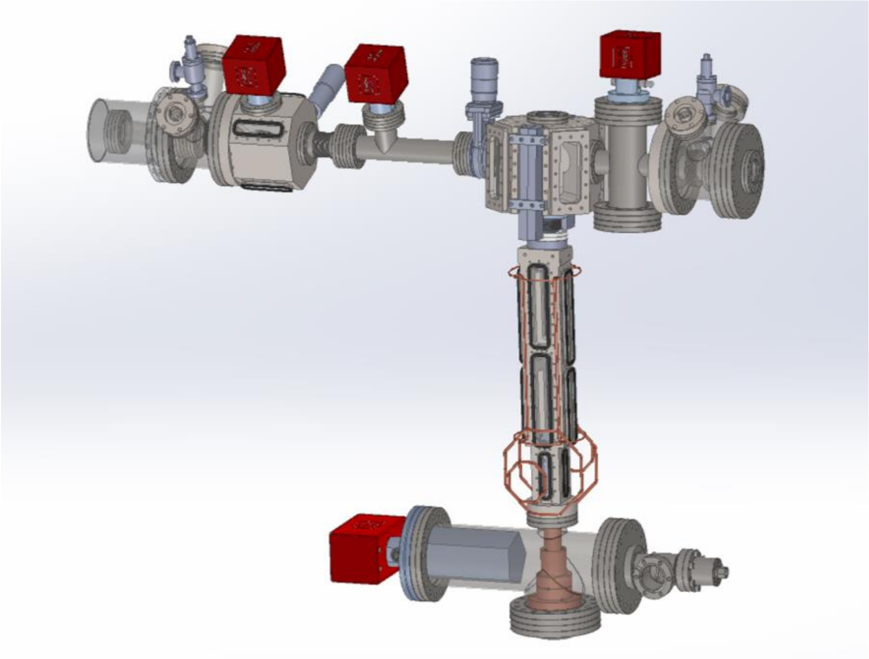
continuous ultracold beam
from periodically refilled reservoir



Version 3

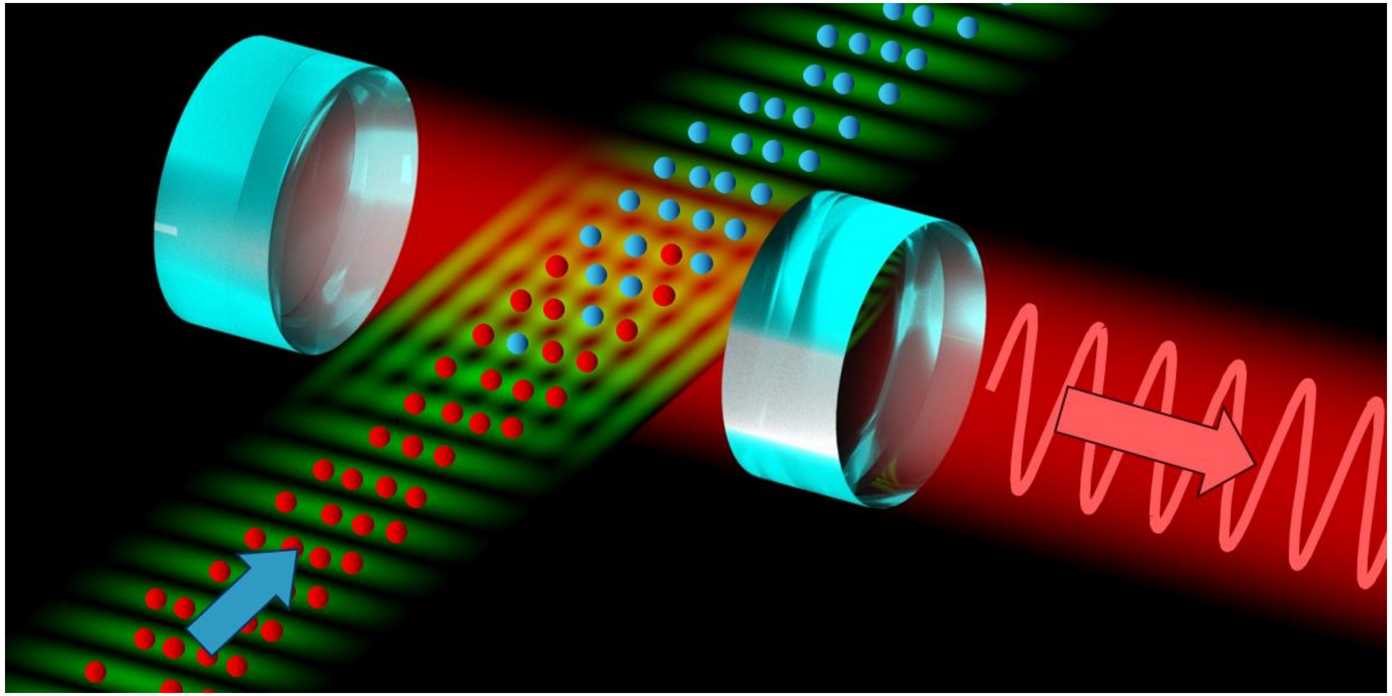
mHz transition

continuous ultracold beam



Continuous mHz-transition superradiant lasers

D. Meiser, J. Ye, D. R. Carlson, M. J. Holland,
Prospects for a Millihertz-Linewidth Laser
PRL **102**, 163601 (2009)



Continuous ultracold strontium beam in — Clock laser beam out

Key requirements

- confine atoms along cavity

  μK temperature beam

- protect superradiant ensemble from laser cooling photons

- sufficient atom flux

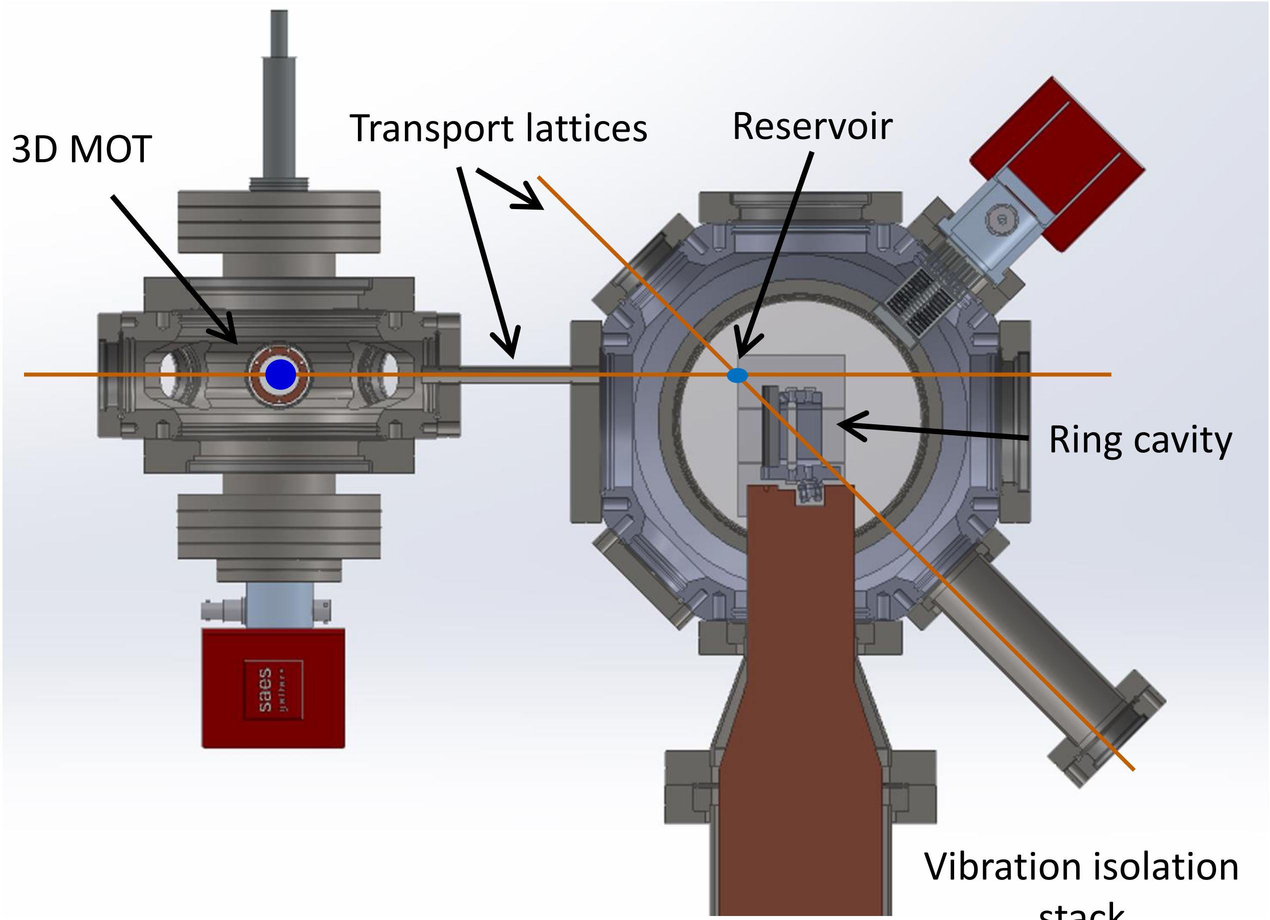
  ~ 10^5 ^{87}Sr or 10^6 ^{88}Sr atoms in cavity mode

Expected performance V2.1

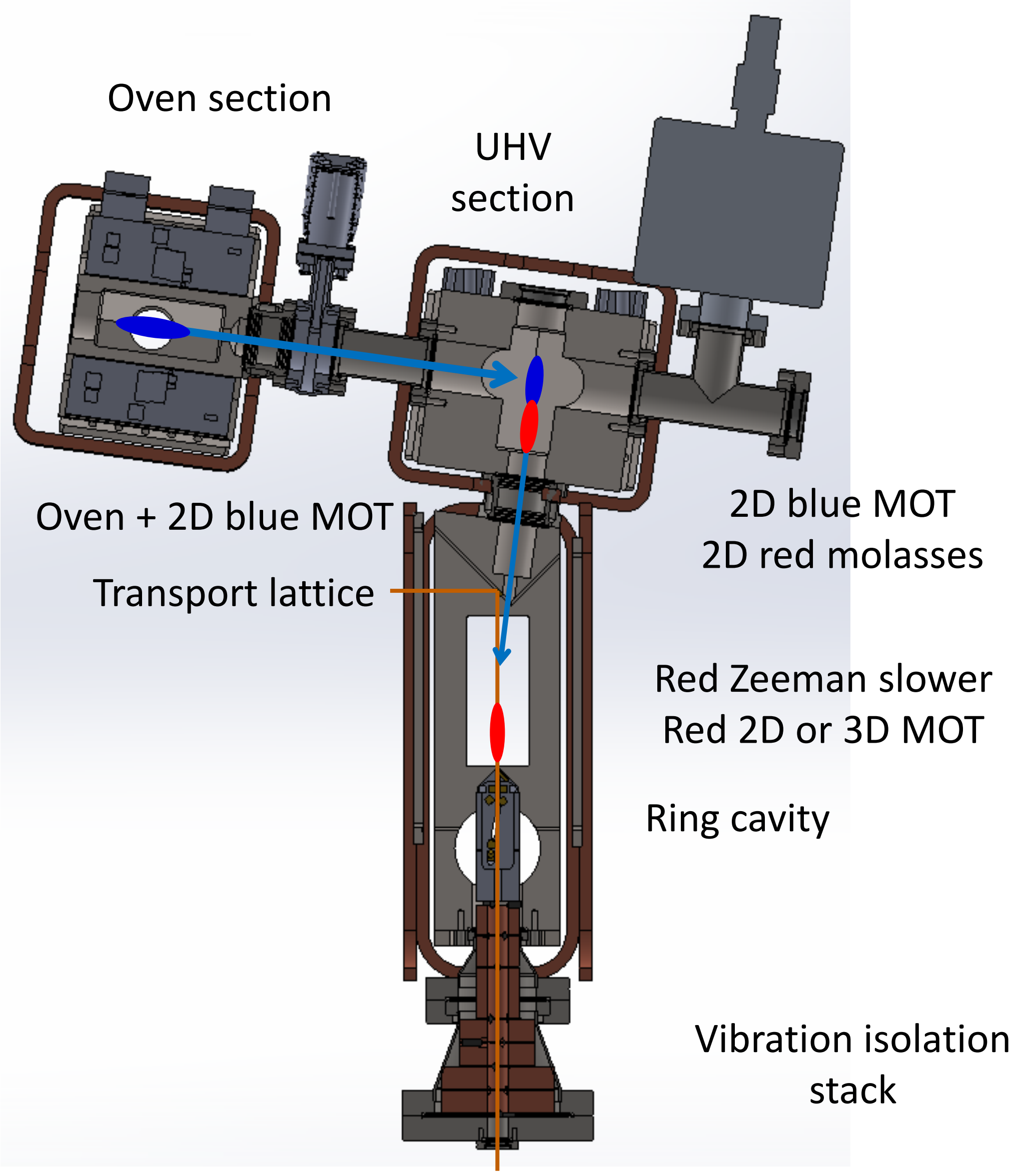
- Linewidth ~ mHz
- Power ~ 1 pW

Continuous mHz-transition superradiant lasers

V2 continuous ultracold beam from periodically refilled reservoir



V3 continuous ultracold beam




Francesca Famá iqClock lab tour
00:00:04
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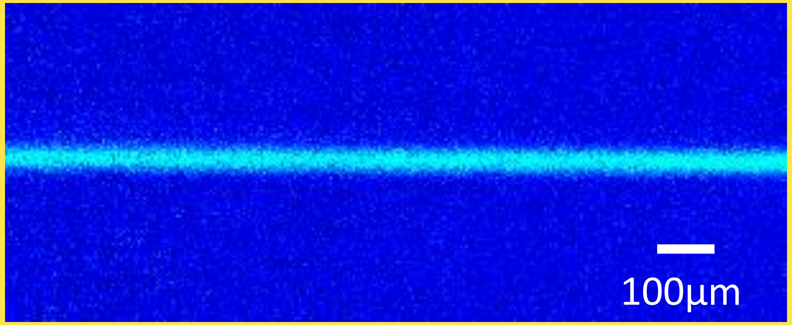
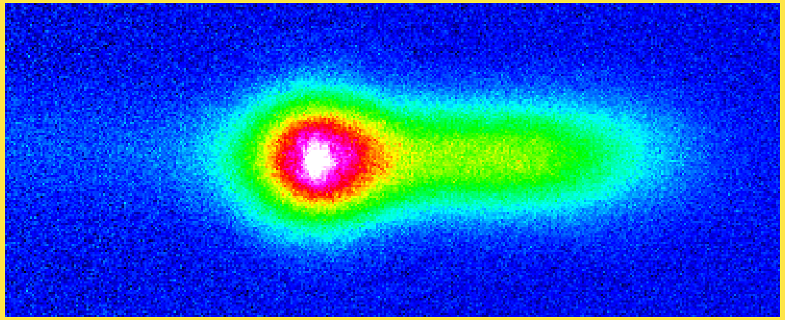
Summary

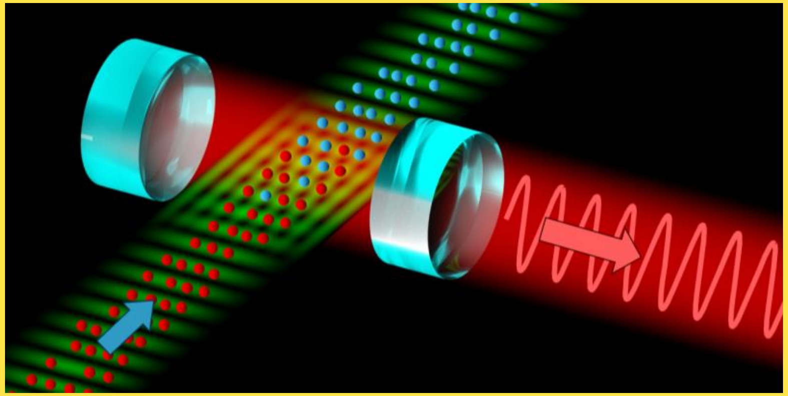
µK Sr beam in the dark



Continuous-wave BEC

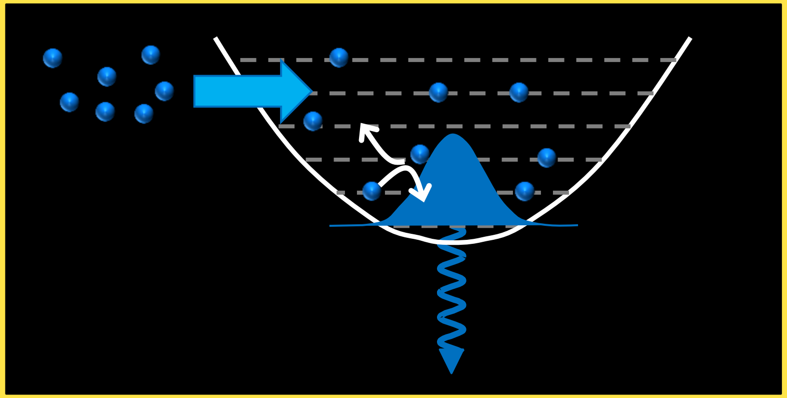


Superradiant clock



frequency & time

Continuous-wave atom laser



acceleration & rotation

iqClock – integrated quantum clock

Main objectives

- bring optical clocks from lab to society
- kick-start European optical clock industry

Industry partners

Te2v	Teledyne e2v
Toptica	Toptica
NKT	NKT Photonics
Acktar	Acktar
Chronos	Chronos
BT	British Telecom

Collaboration

Murray Holland group
Travis Nicholson group

Academic partners

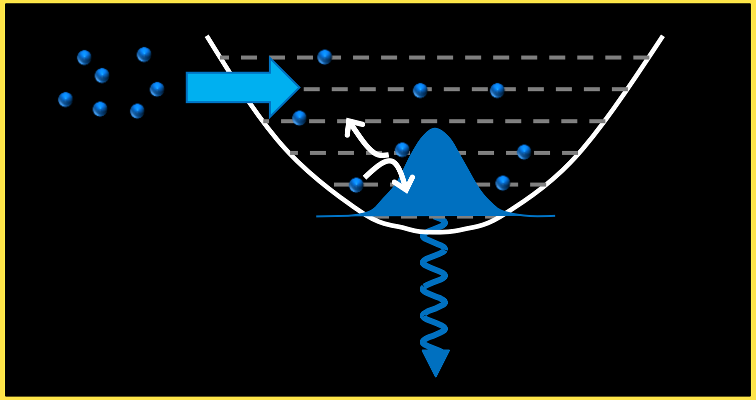
UvA	University of Amsterdam
UoB	The University of Birmingham
UMK	Nicolaus Copernicus University
UCPH	Copenhagen University
TUW	Technical University of Vienna
UIBK	University of Innsbruck

Our projects

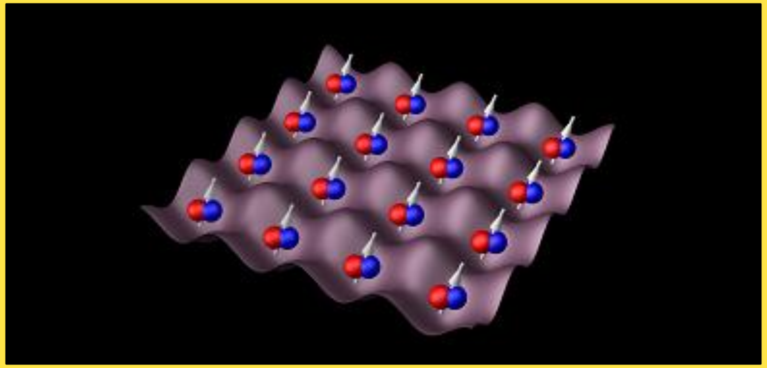
Quantum sensing

Quantum simulation

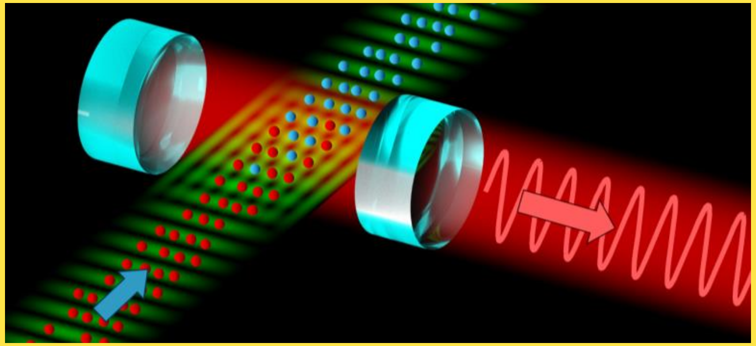
Continuous atom laser



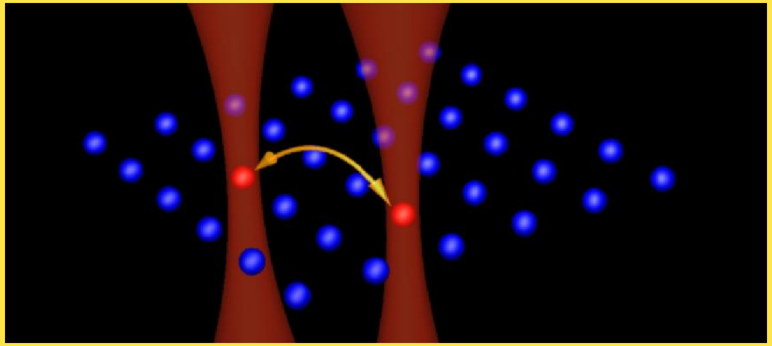
RbSr molecules



Superradiant clock



Rydberg coupled Sr atoms



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Quantum Flagship

iqClock

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T. L. Nicholson
groups

NWO

Quantum Delta the Netherlands

Quantum Software Consortium

QuSoft

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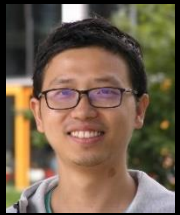

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erc
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