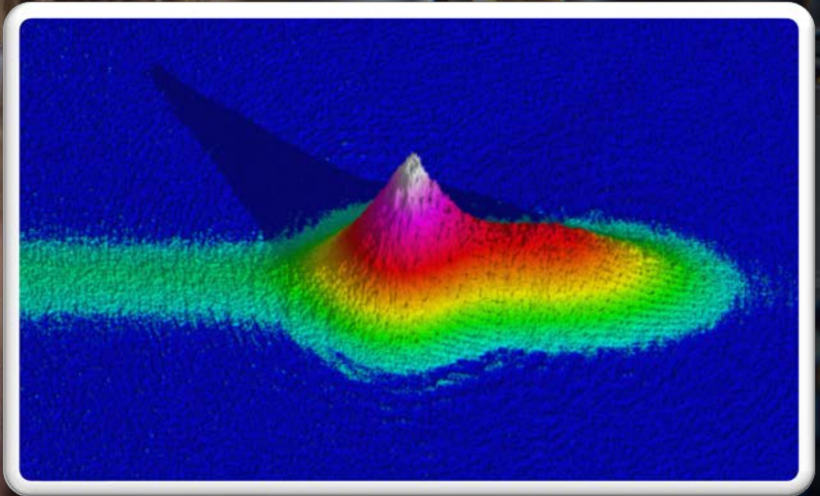
Continuous sources of ultracold strontium:

Towards continuous atom lasers



Shayne Bennetts

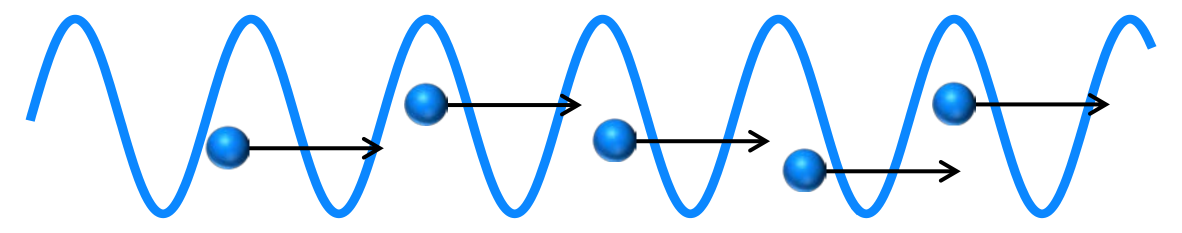
Florian Schreck's group / University of Amsterdam

www.strontiumbec.com

TVLBAI Workshop
April 4, 2024

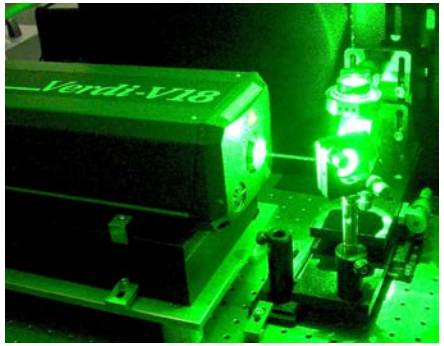
Why Lasers?

Laser beam



Light

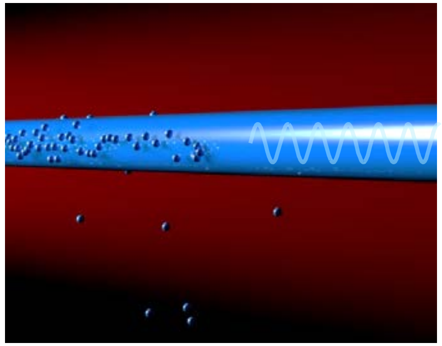
Optical laser



Laser interferometer

Matter

Atom laser



Atom interferometer

Advantages of laser beams

Better

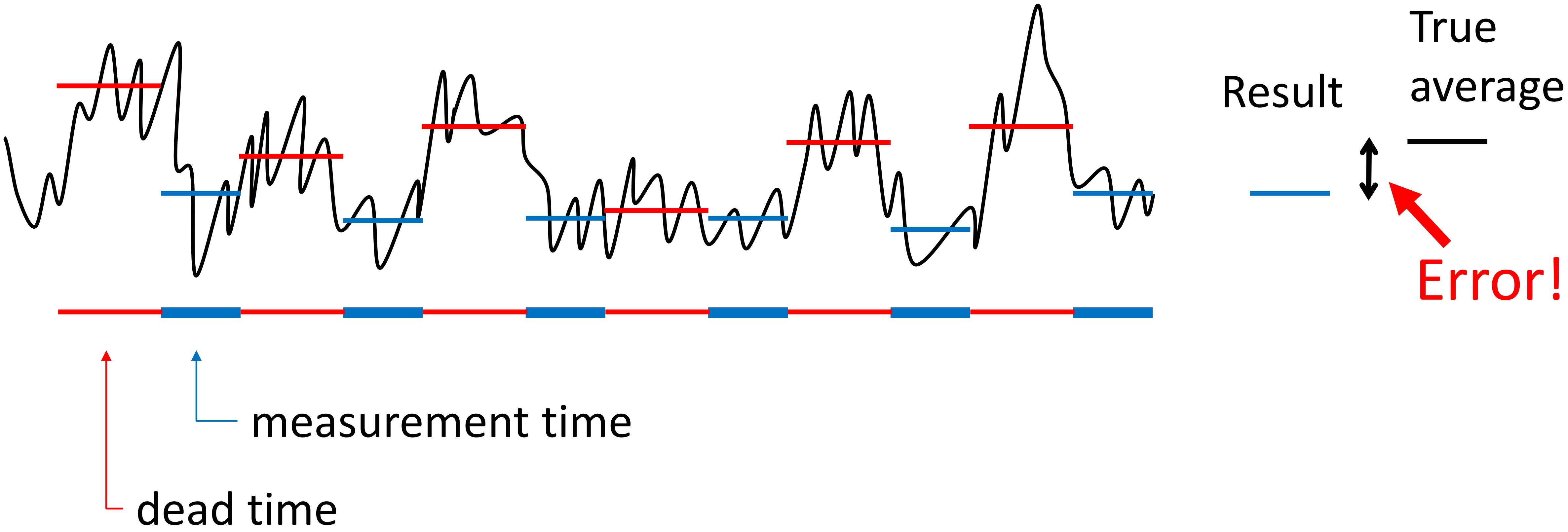
- brightness
- divergence
- coherence

…Potential for squeezing

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

Why continuous?

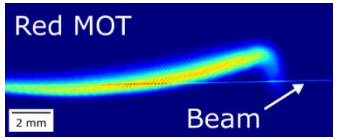
The problem with pulsed measurements (Dick efect):



An “ideal” source of ultracold atoms

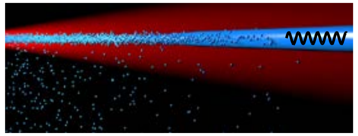
- High flux for **signal**
- Low temperature for **coherence**
- Continuous/high rep rate for **bandwidth** and Dick effect

Continuous guided beam



Continuous BEC

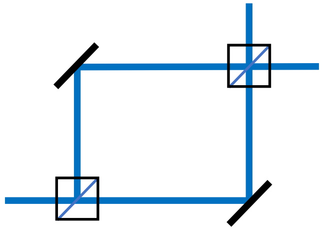
Continuous atom laser



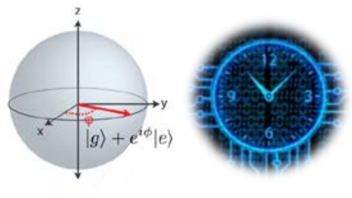
Towards an “ideal” source

Applications:

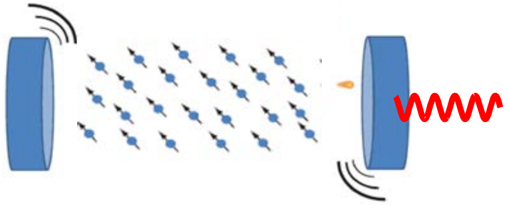
Atom Interferometry



Continuous optical clocks



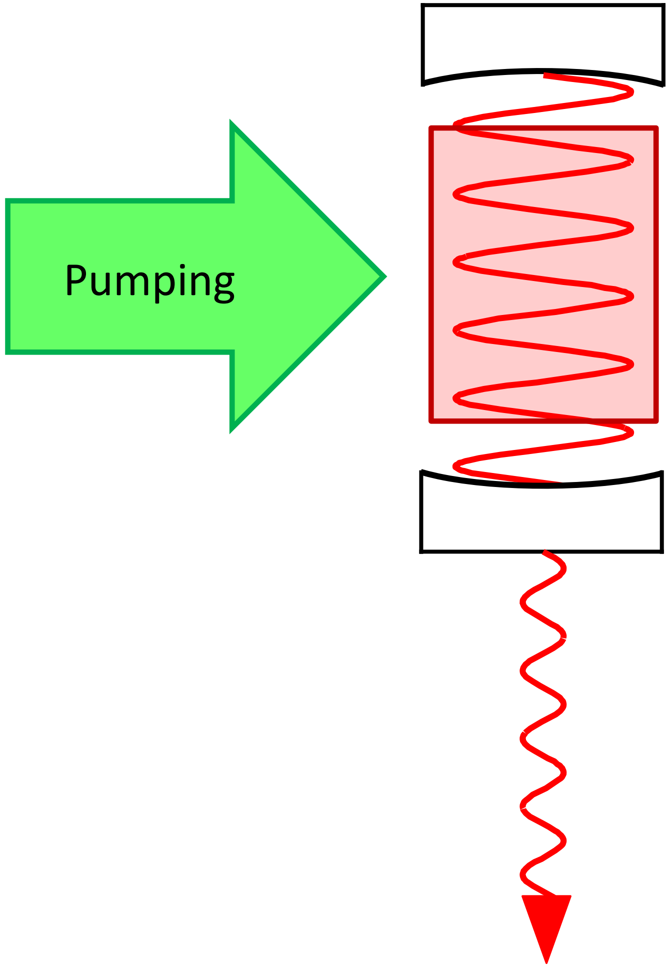
Superradiant optical clocks



...

Concept: Continuous atom lasers?

Optical cavity



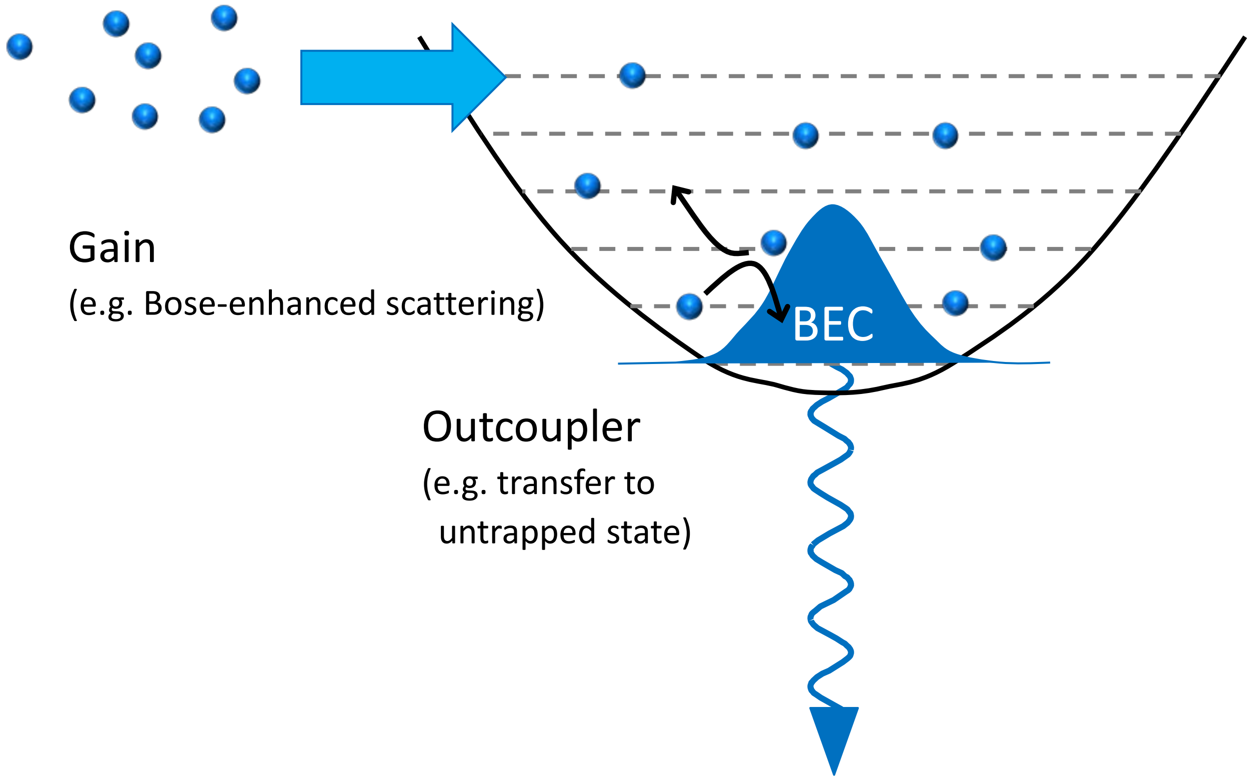
Pumping

Gain
(e.g. stimulated emission)

Outcoupler

Atom cavity (trap)

Pumping
replenish atoms

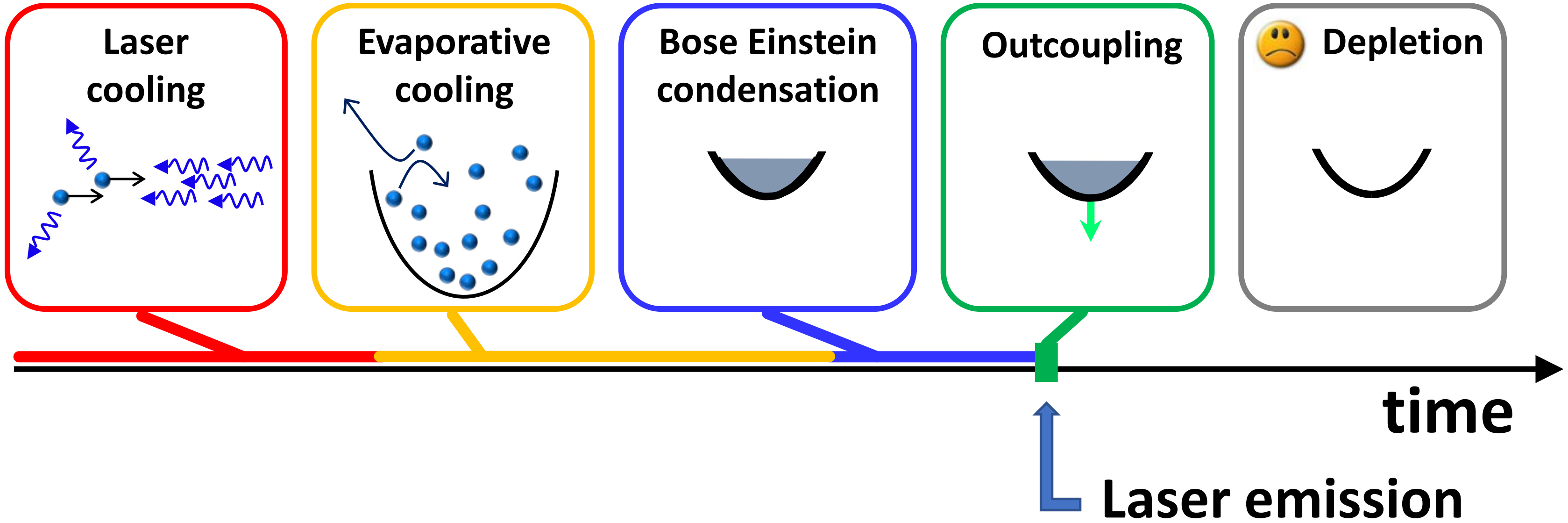


Gain
(e.g. Bose-enhanced scattering)

Outcoupler
(e.g. transfer to
untrapped state)

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

How to make a *pulsed* atom laser?



Laser cooling

Evaporative cooling

Bose Einstein condensation

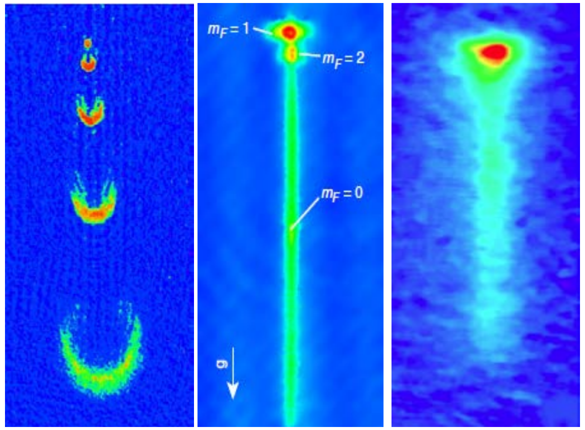
Outcoupling

☹ **Depletion**

time

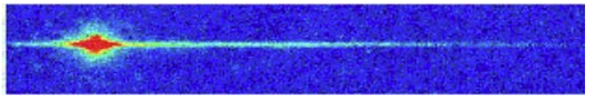
Laser emission

Free falling atom lasers



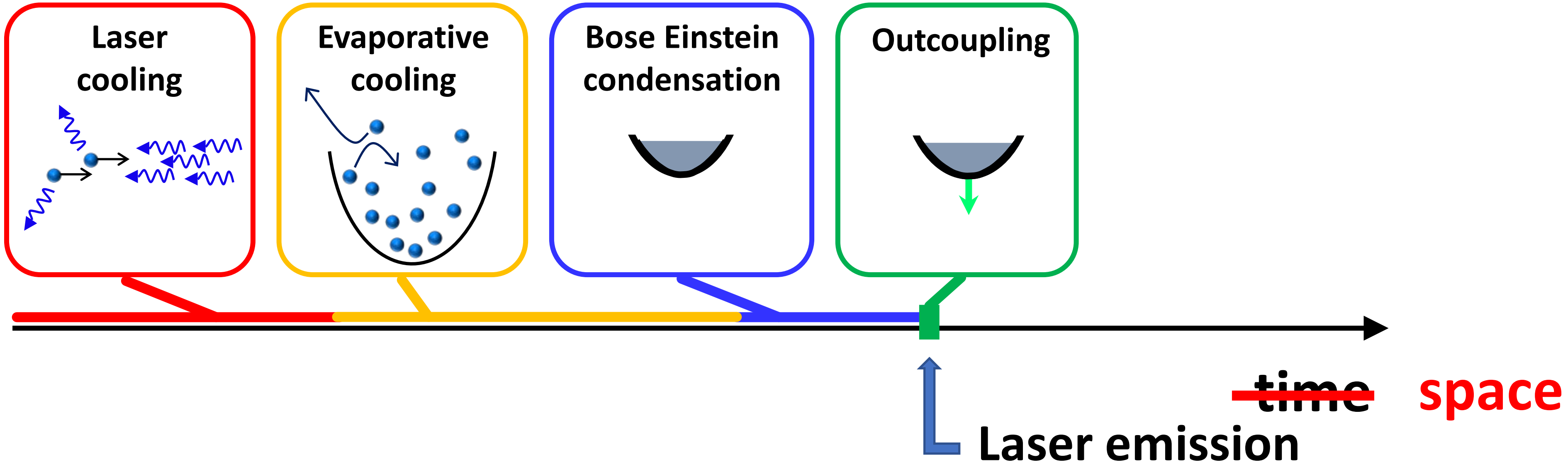
MIT 1997 LMU 1999 NIST 1999

Guided atom laser



Institut d'Optique 2006

Our goal: *continuous* atom lasers



Laser cooling

Evaporative cooling

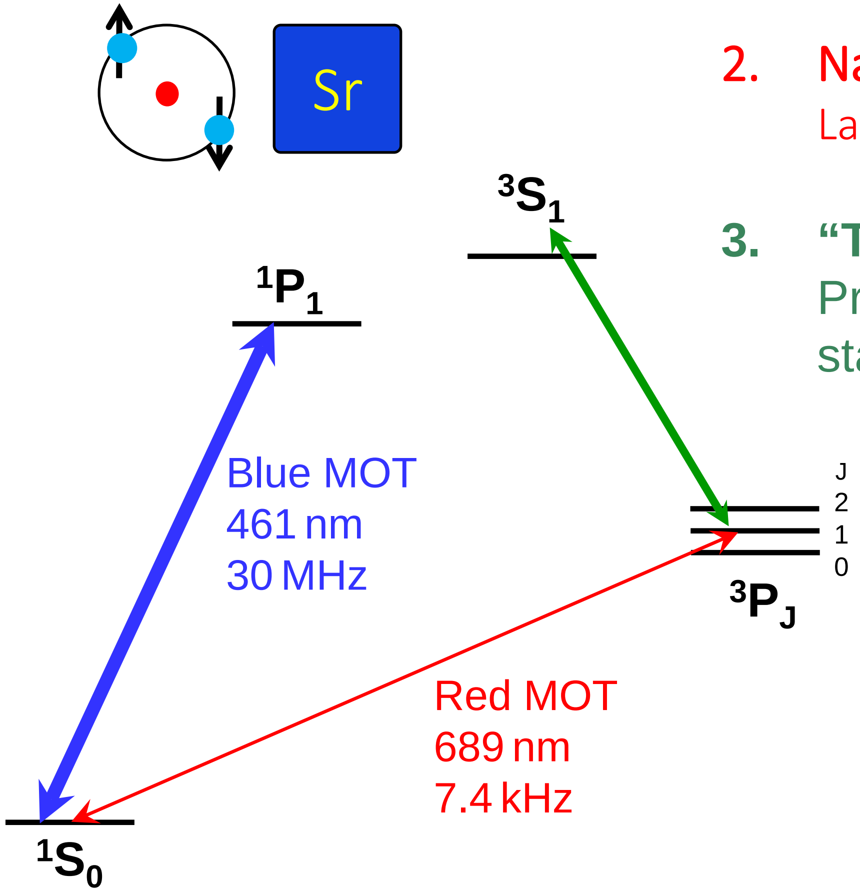
Bose Einstein condensation

Outcoupling

~~time~~ space

Laser emission

Why strontium? – Our tool set

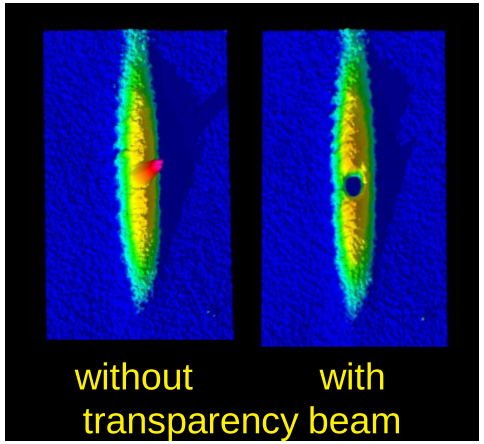


1. **Broad 30MHz "Blue MOT" transition**
   Enables efficient slowing of an atomic beam

2. **Narrow 7.4kHz "Red MOT" transition**
   Laser cooling to high phase-space density

3. **"Transparency beam"**
   Protect from red photons Stark shift excited state with "transparency beam"

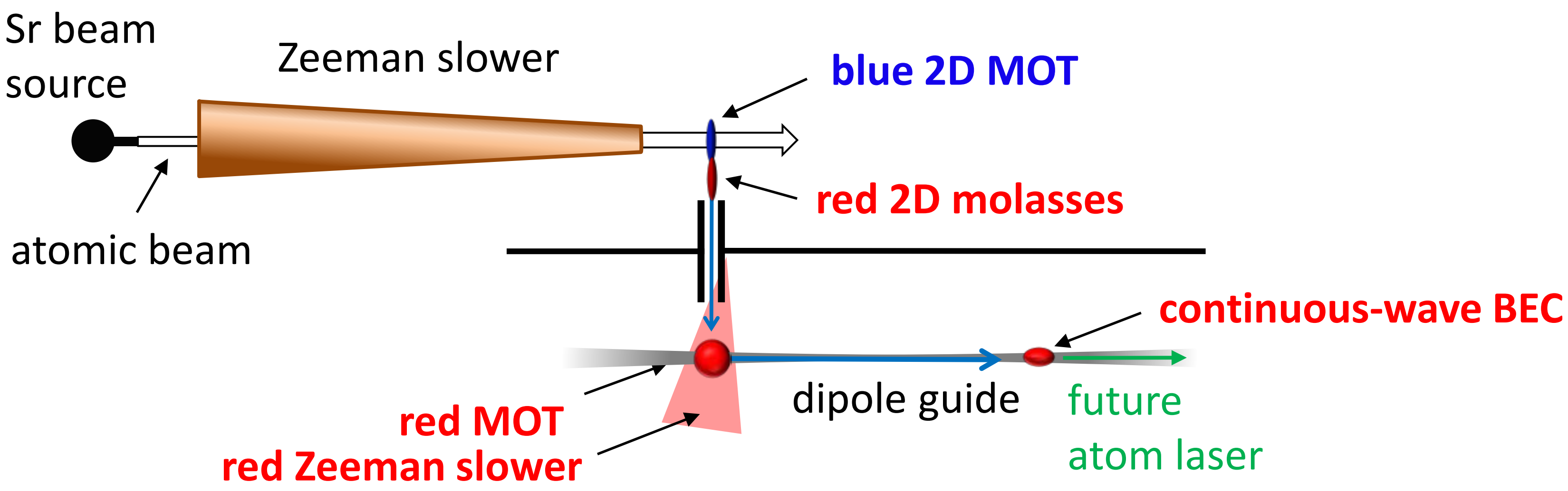
- High flux ✓
- High PSD ✓
- Protect from near-resonant red light ✓

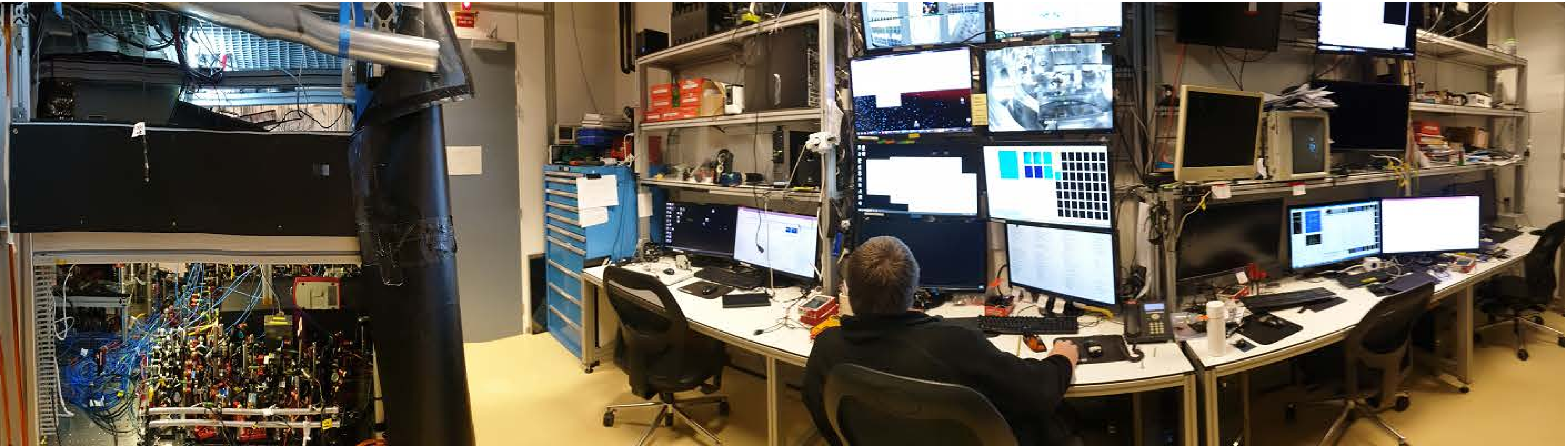


Stellmer et al.,
PRL **110**, 263003 (2013)

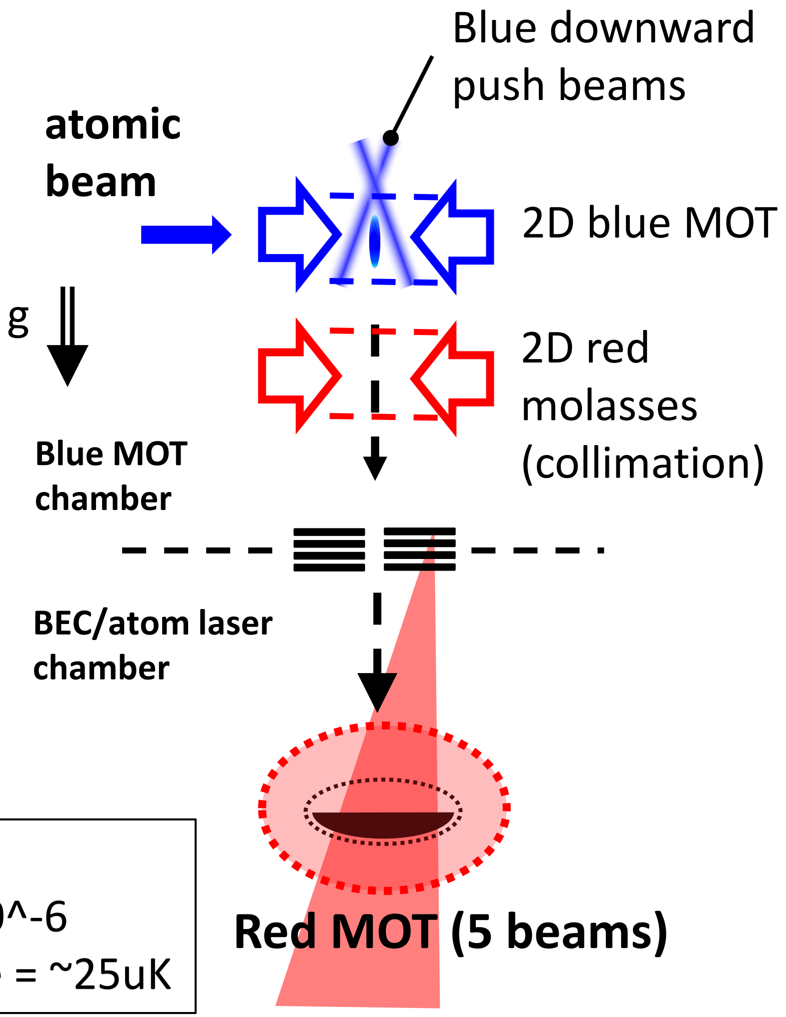
…Scattering cross section is only good for 84Sr (0.5% abundance☹)

Design and construction





A steady-state narrow line MOT



Blue downward push beams

atomic beam

2D blue MOT

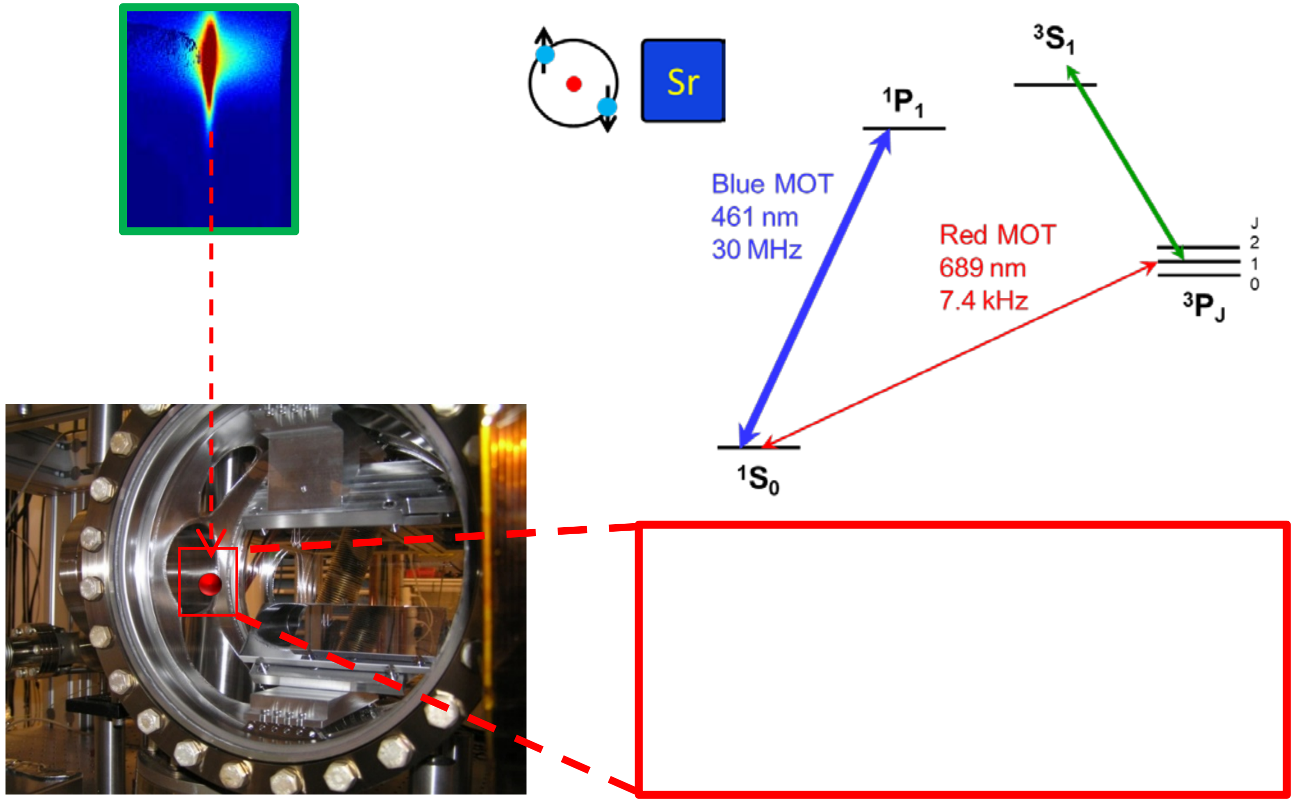
g

2D red molasses (collimation)

Blue MOT chamber

BEC/atom laser chamber

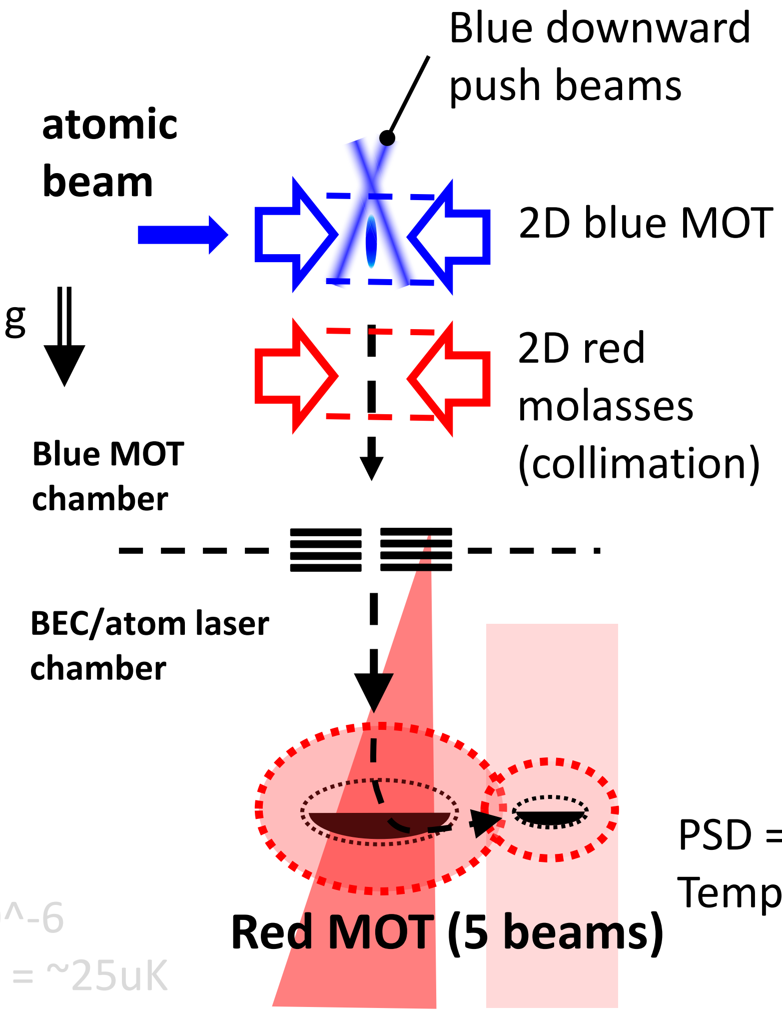
Red MOT (5 beams)



MOT I:
PSD = 2.8x10^-6
Temperature = ~25uK

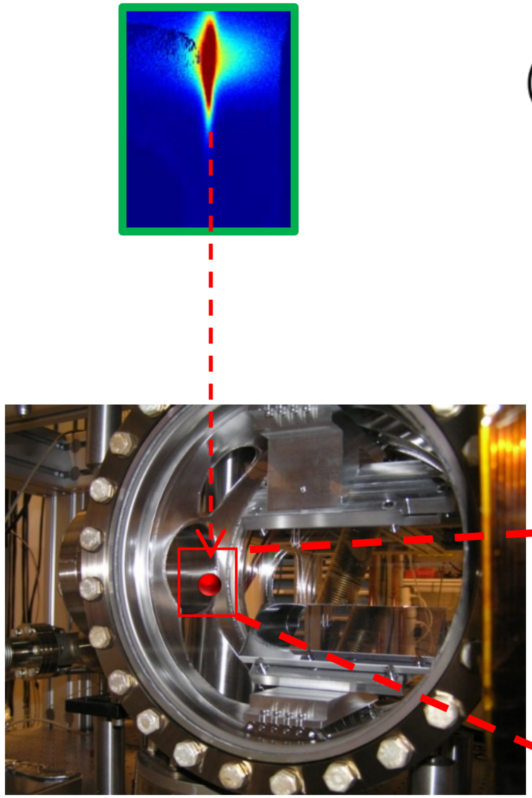
Phys. Rev. Lett. **119**, 223202 (2017)

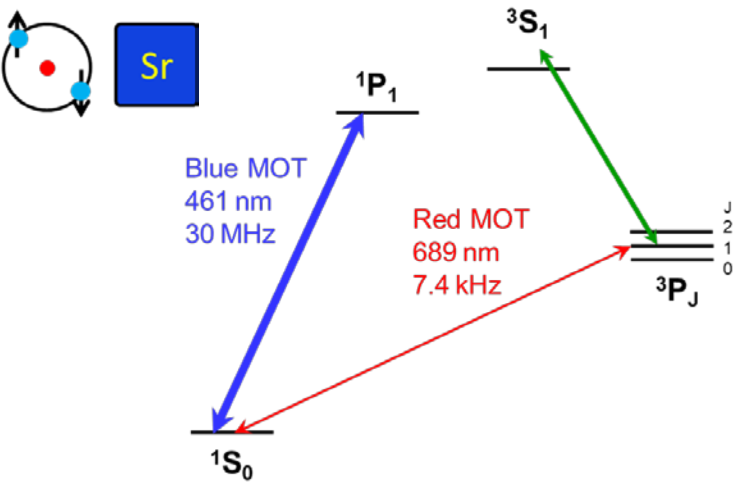
A steady-state narrow line MOT



PSD = 1.3x10^-3 (88Sr), 4.5x10^-5 (84Sr)
Temperature = 1.6uK (88Sr)

MOT I:
PSD = 2.8x10^-6
Temperature = ~25uK

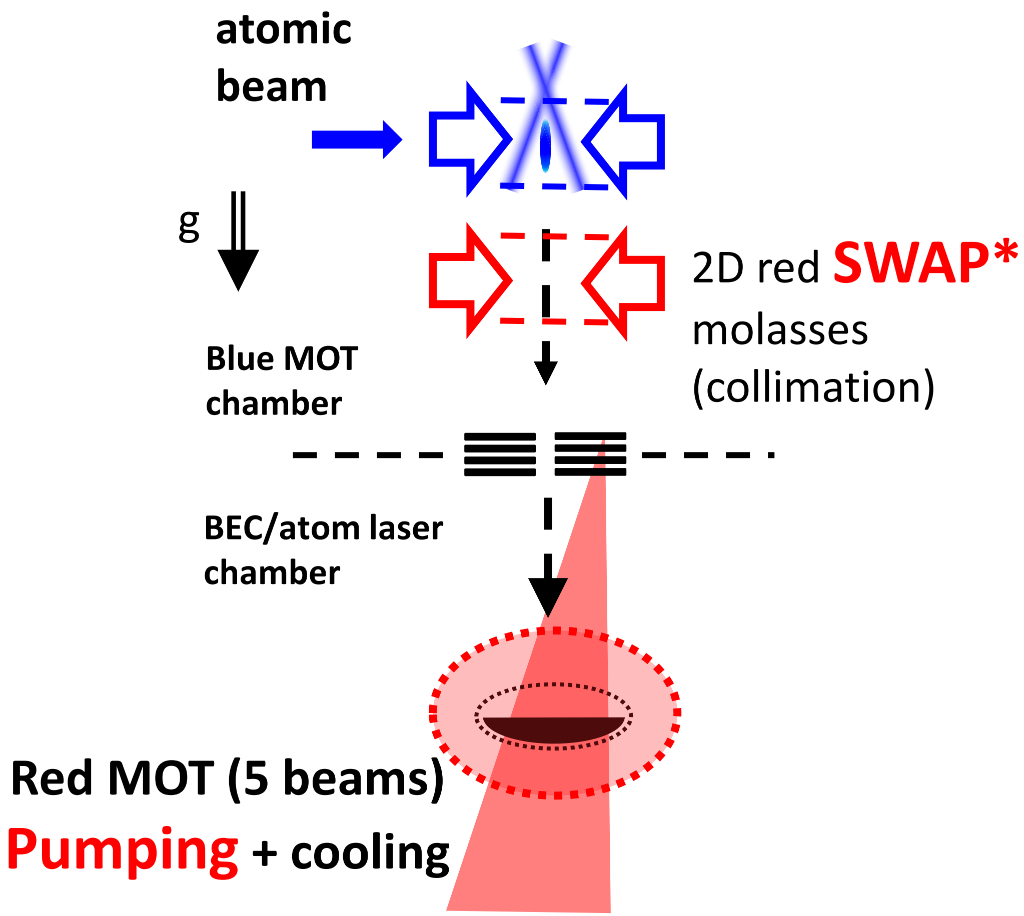




Steady-state MOT with record phase-space density

Phys. Rev. Lett. **119**, 223202 (2017)

A fermionic steady-state narrow line MOT



atomic beam

g

Blue MOT chamber

2D red **SWAP*** molasses (collimation)

BEC/atom laser chamber

Red MOT (5 beams)

Pumping + cooling

Performance:

^{87}Sr fermionic MOT :	^{88}Sr bosonic MOT:
Loading = 1.31 x $10^7 atom/s$	Loading = 2.3x $10^8 atom/s$
Lifetime = 4.84 s	Lifetime = 4.6 s
$T_{average} = 12.0\ \mu K$	$T_{average} = 11.4\ \mu K$

MOT comparison:

- Flux ratio: Loading (^{88}Sr)/Loading (^{87}Sr) $= 17$
- Abundance ratio: Abundance (^{88}Sr)/Abundance(^{87}Sr) $= 11.8$

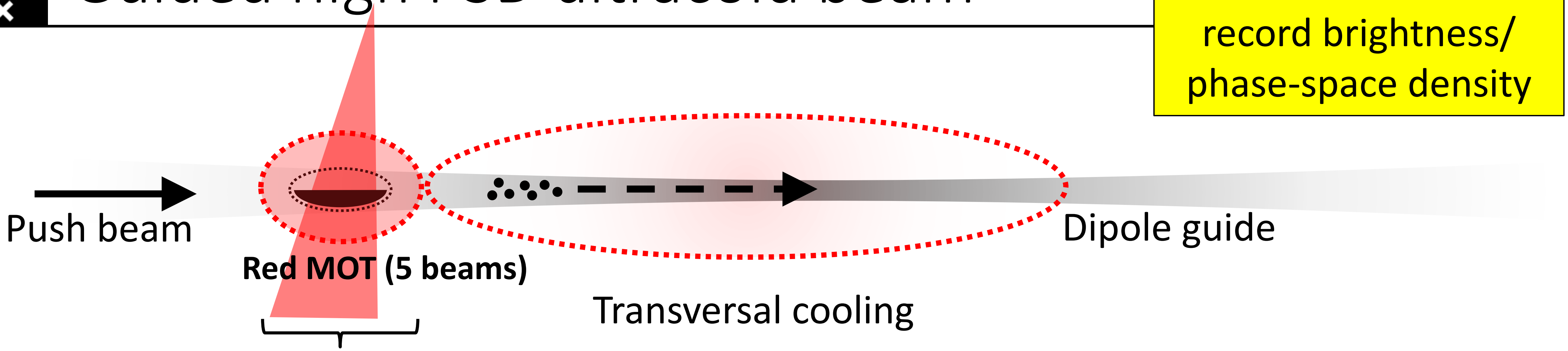
Phys. Rev. Research. **3**, 033159 (2021)

*__SWAP cooling__ (Thompson and Holland groups at JILA):
PRA **98** 023404 (2018)
PRA **99** 063421 (2019)

Fermionic MOT similar performance as bosonic MOT

Guided high PSD ultracold beam

Atomic beam with
record brightness/
phase-space density



Push beam

Red MOT (5 beams)

Bright region

Transversal cooling

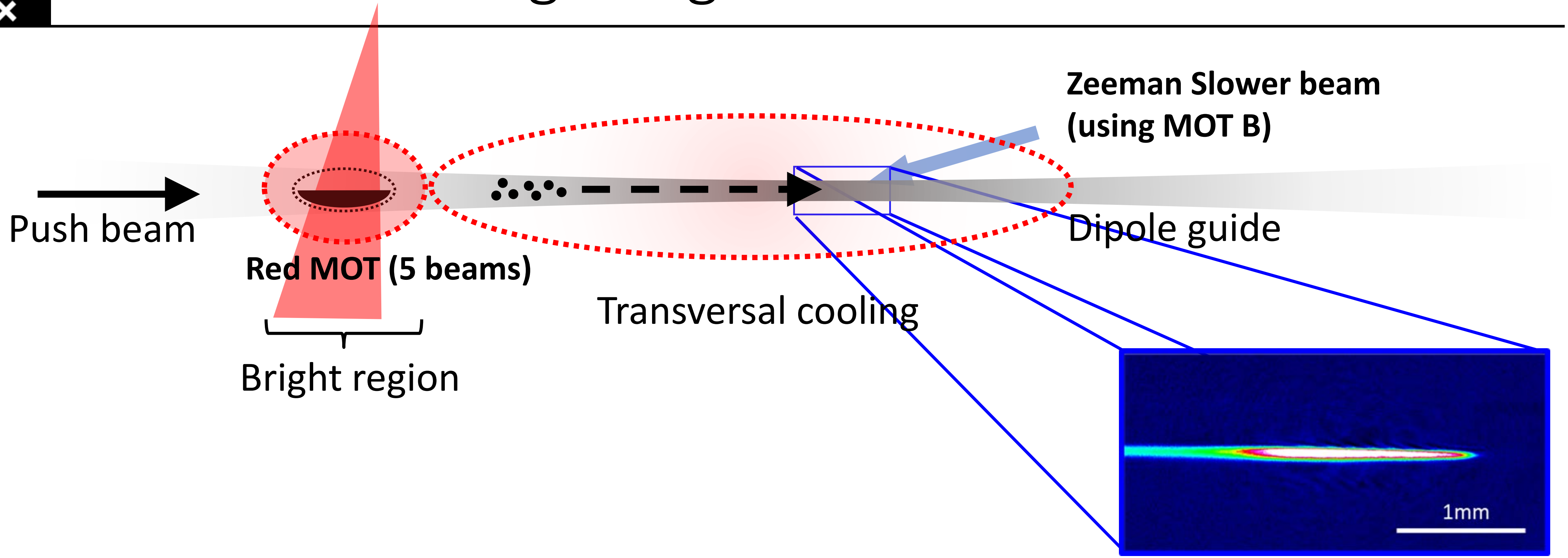
Dipole guide

Flux (88Sr/s):	3 x 10^7
PSD (88Sr):	1.5 x 10^-4
Velocity:	8cm/s
Temperature (radial):	1uK

Dark Spots imaged along the waveguide

Phys. Rev. Applied **12**, 044014 (2019)

Zeeman slowing the guided beam



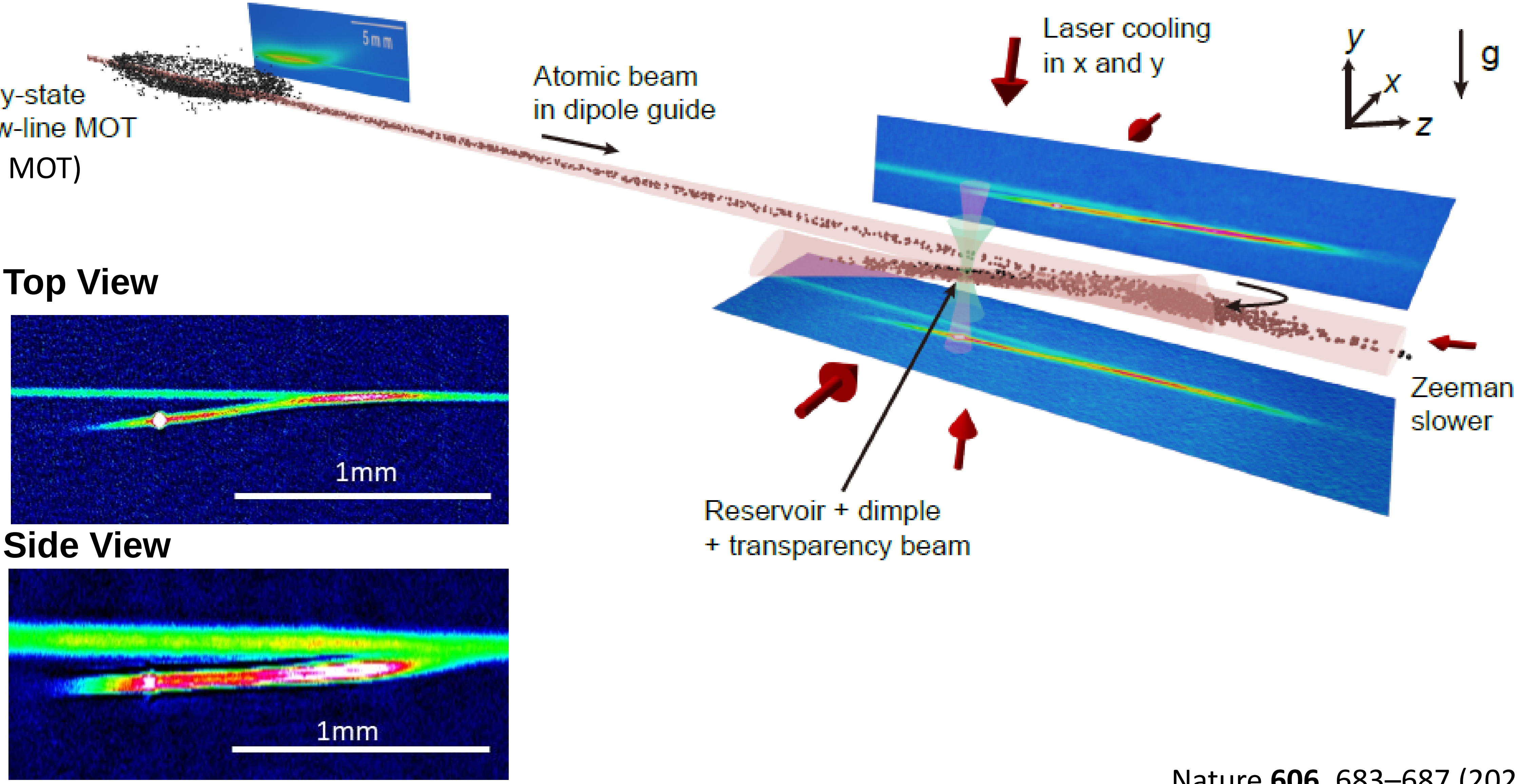
N : 2 x 10^6 ^{84}Sr

Temperature$_{radial}$: 0.95 ± 0.05 uK

Temperature$_{axial}$: 6 ± 2 uK

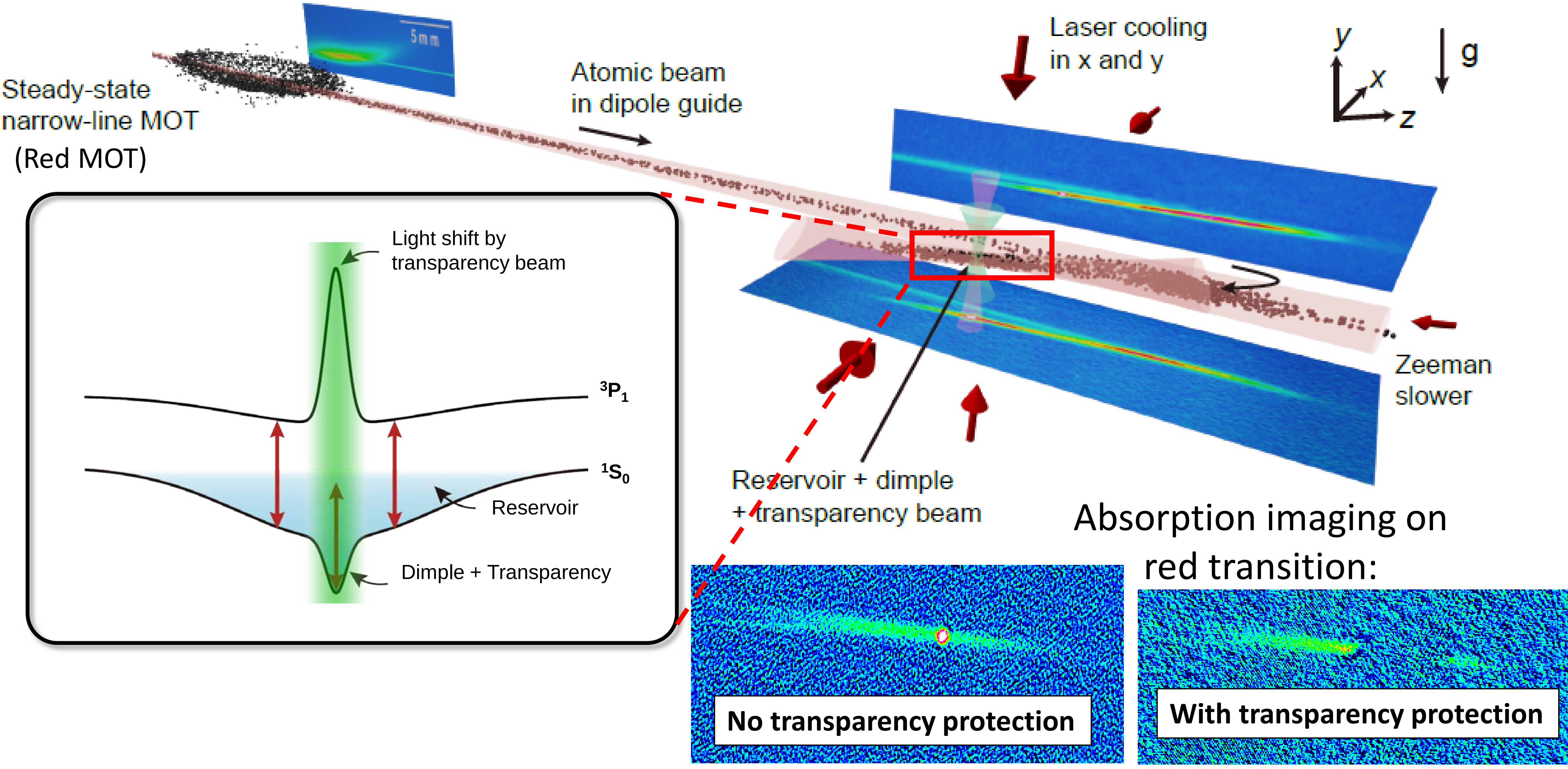
But not a great spot for a BEC…fast incoming atoms ☹

Continuous Bose-Einstein condensation

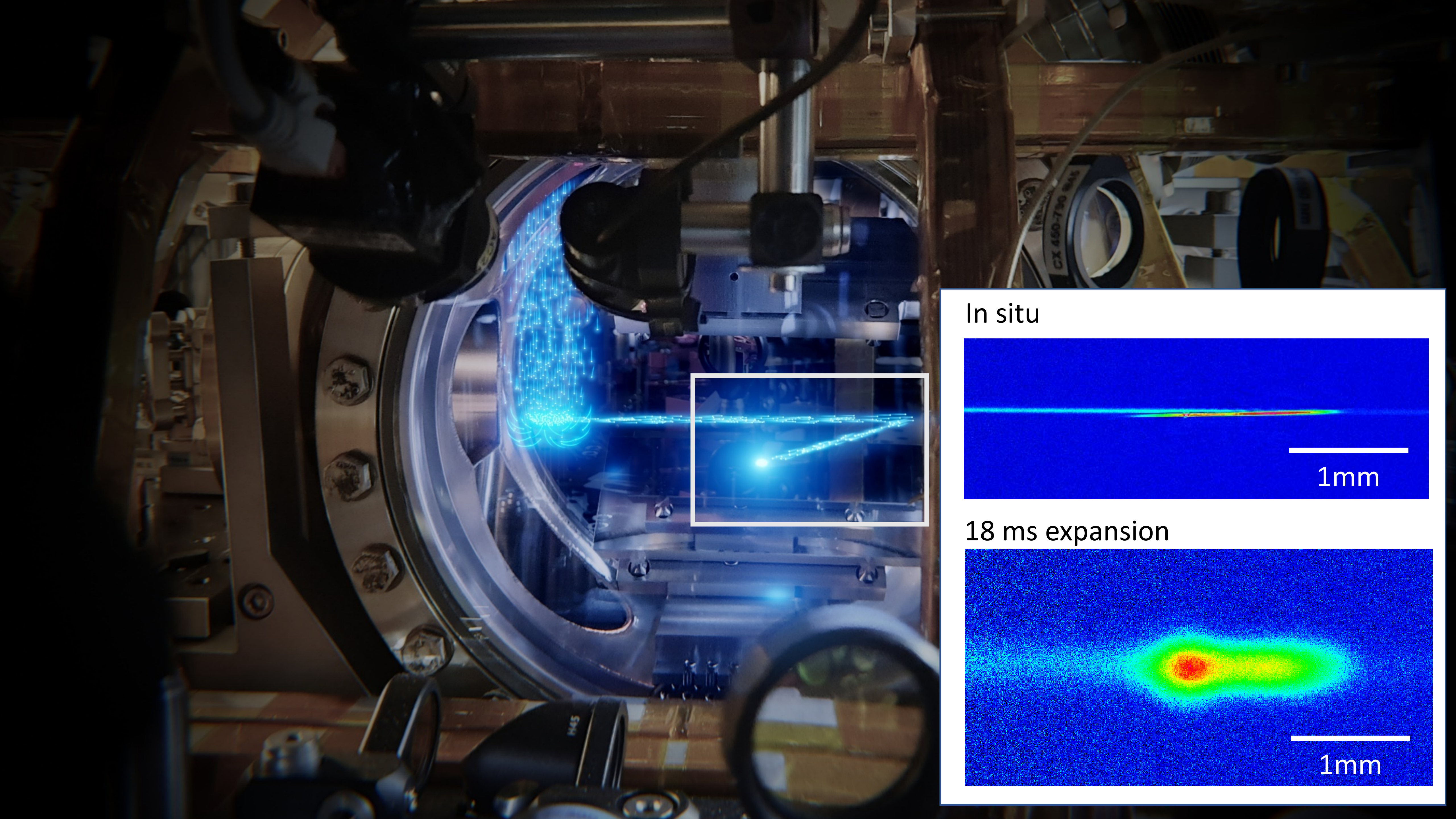


Nature **606**, 683–687 (2022)

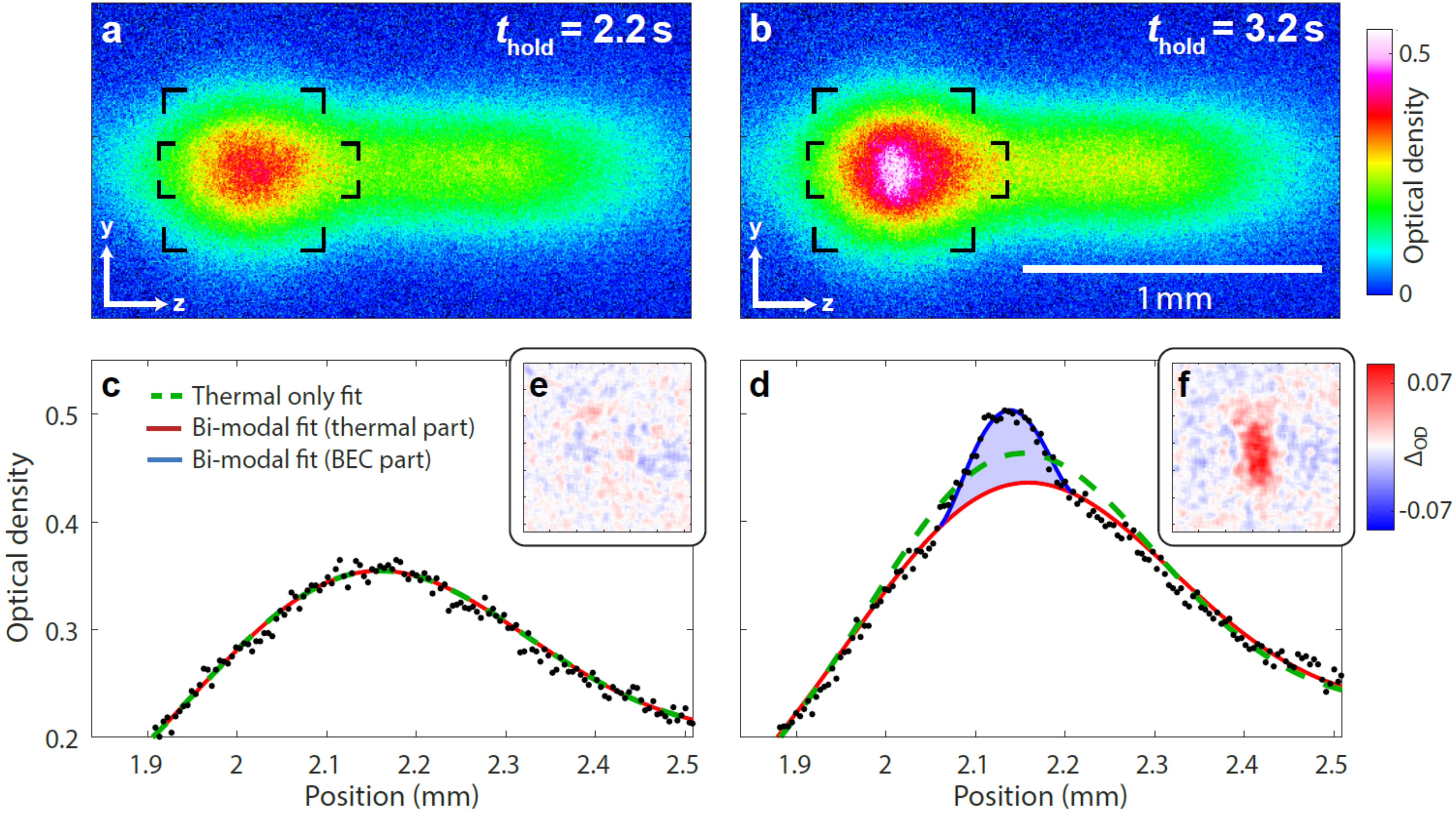
Continuous Bose-Einstein condensation



Absorption imaging on red transition:

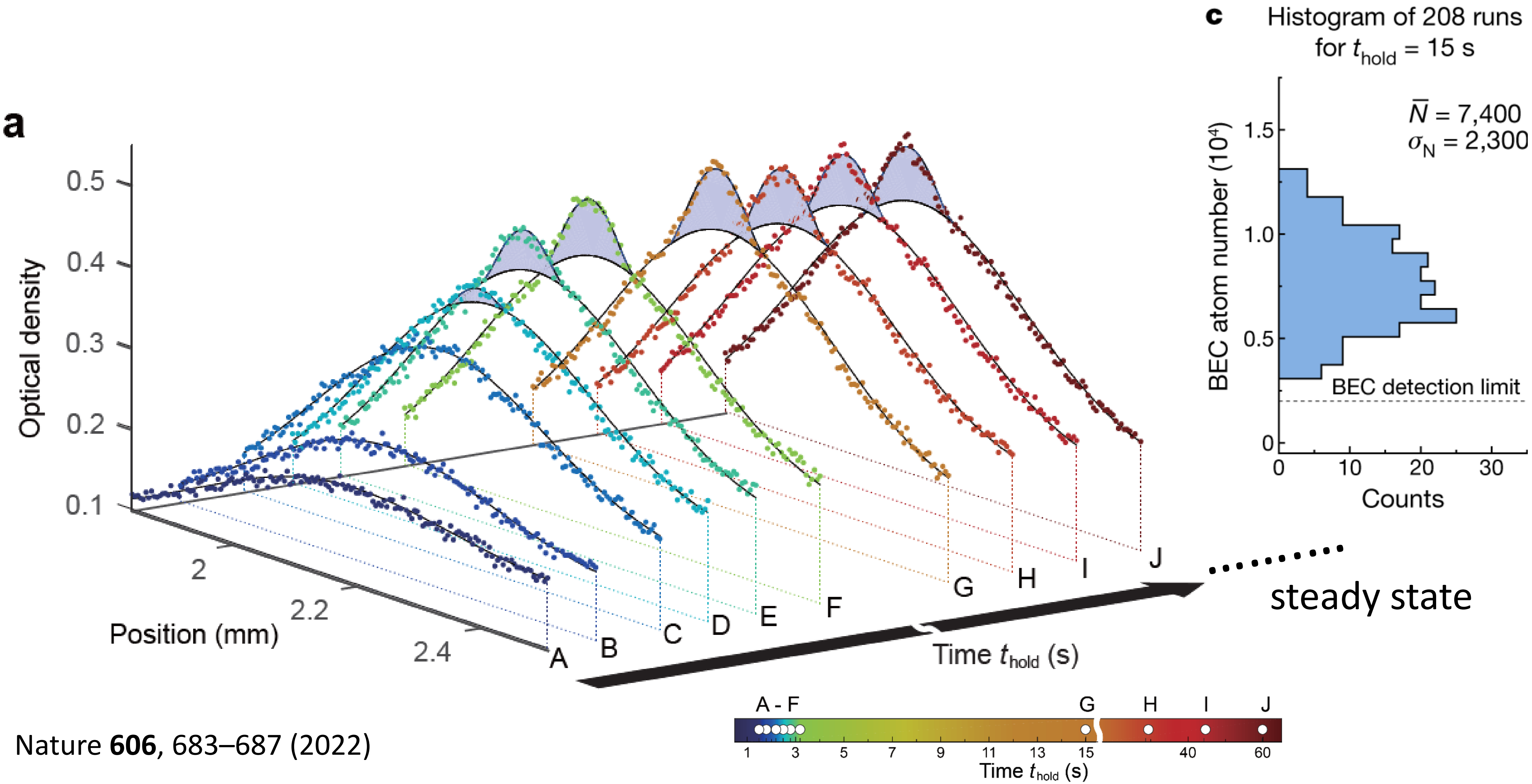

In situ
1mm
18 ms expansion
1mm

Continuous **Bose-Einstein condensation**



Nature **606**, 683–687 (2022)

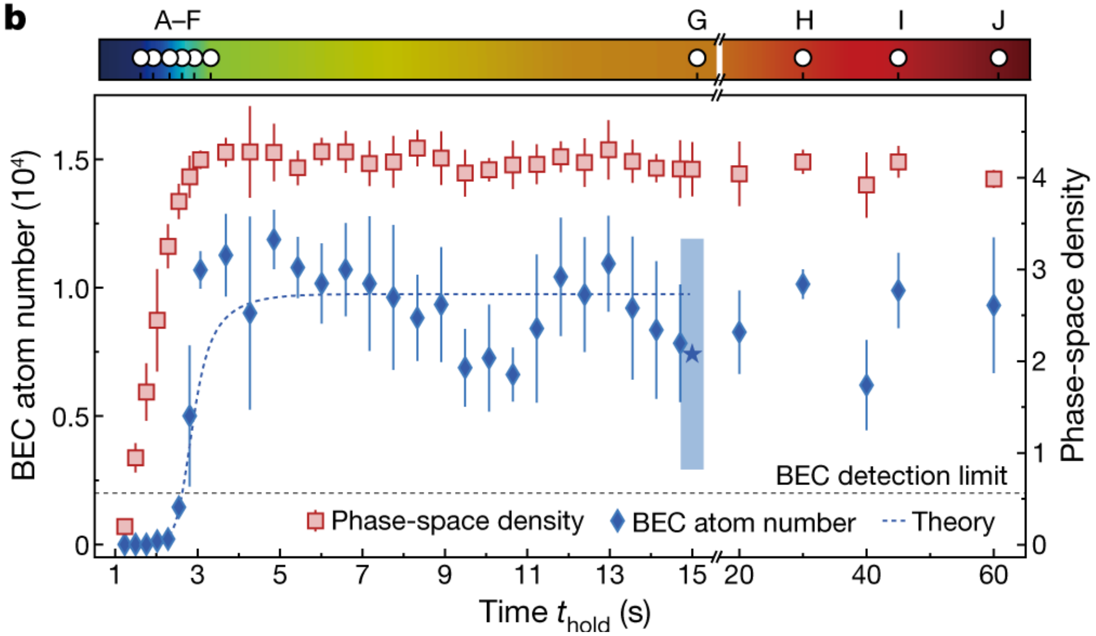
Continuous Bose-Einstein condensation



steady state

Nature **606**, 683–687 (2022)

Estimating potential output flux



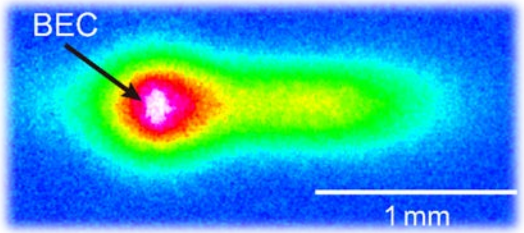
Fitted steady-state gain
(potential atom laser output):

250,000 atoms/second !

Nature **606**, 683–687 (2022)

Continuous Bose-Einstein condensation

First matter-wave analog of a CW laser



BEC number:	7.4(2.4) x 10^3 ^{84}Sr atoms
Stimulated gain:	2.4(5) x 10^5 atoms/s
Dimple number:	6.9(4) x 10^5 ^{84}Sr atoms
Dimple temperature:	T_{vertical} = 1.08(3) µK
Reservoir number:	7.3(1.8) x 10^5
Reservoir loading:	1.1(4) x 10^6 atoms/s

Chun-Chia Chen, Shayne Bennetts
Rodrigo González Escudero, Benjamin Pasquiou,
Florian Schreck

C.-C. Chen et al. Nature ***606****, 683–687 (2022)*

Next steps:

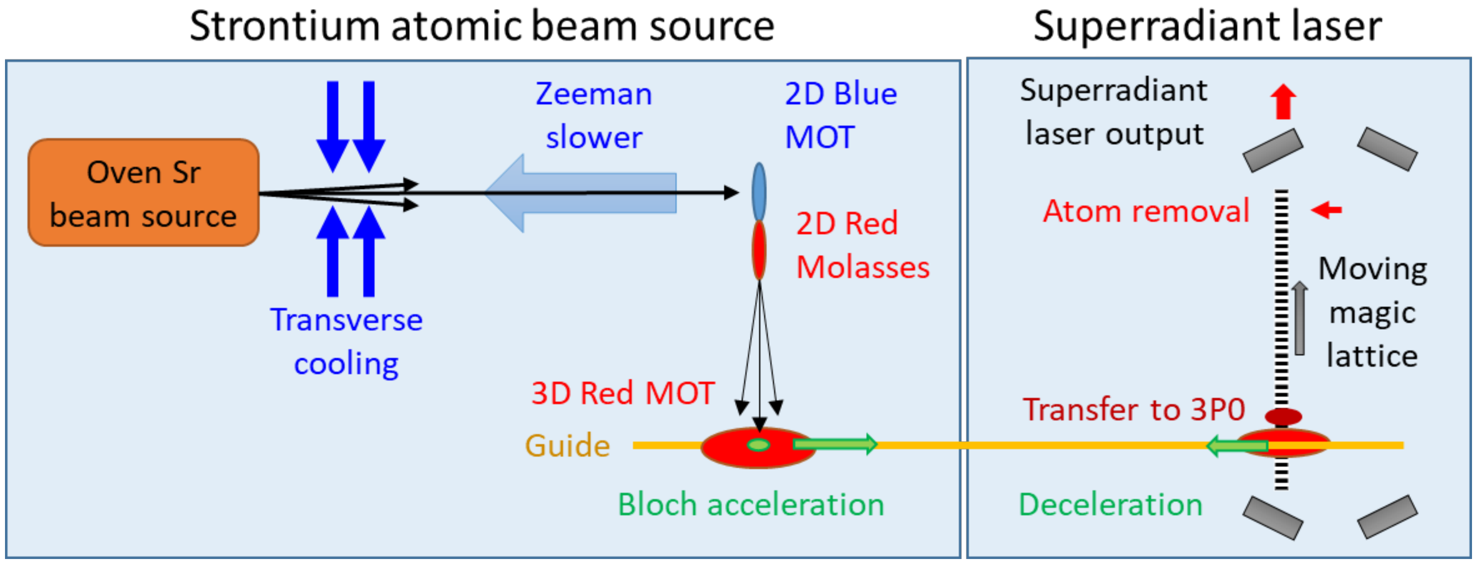
Outcoupling a continuous atom laser

- Change reservoir trap closer to magic improving cooling
- Use 679nm dimple trap to compensate trap for 3P0
- Coherent transfer of BEC atoms to un-trapped 3P0
- Momentum kick from state transfer outcouples atoms

Junyu He

- **CW atom laser by waveguide evaporation?**
- **Improved BEC purity and flux?**
    - Better cooling, reduced trap light shift variation

mHz superradiance: Continuous active optical clocks


Strontium atomic beam source

Superradiant laser

Oven Sr beam source

Transverse cooling

Zeeman slower

2D Blue MOT

2D Red Molasses

3D Red MOT

Guide

Bloch acceleration

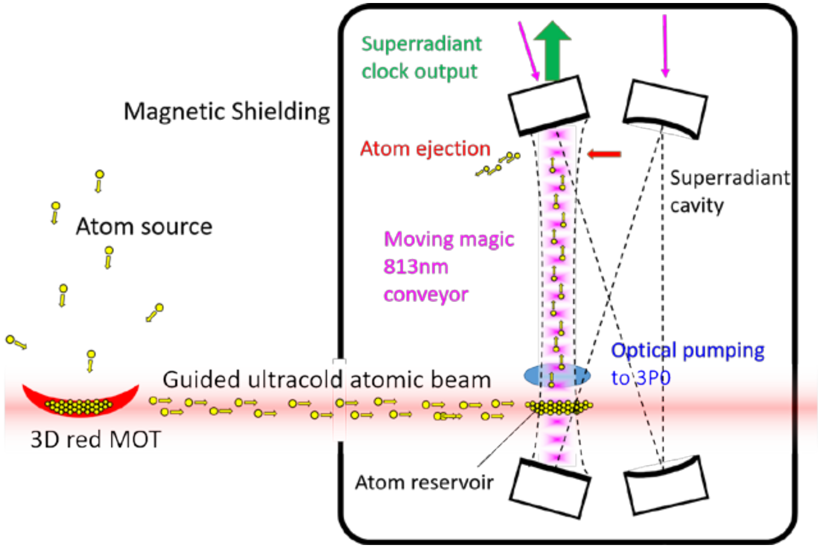
Superradiant laser output

Atom removal

Moving magic lattice

Transfer to 3P0

Deceleration


Superradiant clock output

Magnetic Shielding

Atom ejection

Superradiant cavity

Atom source

Moving magic 813nm conveyor

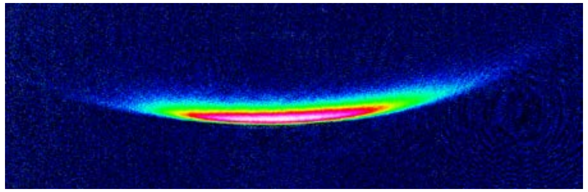
Optical pumping to 3P0

Guided ultracold atomic beam

3D red MOT

Atom reservoir

- New machine, smaller, simpler
- Guided ultracold beam continuously loads ultracold atoms into a magnetically and optically shielded (nom ~10k) finesse cavity.
- Able to reach 200G uniform B field for 88Sr operation or operate on 87Sr.



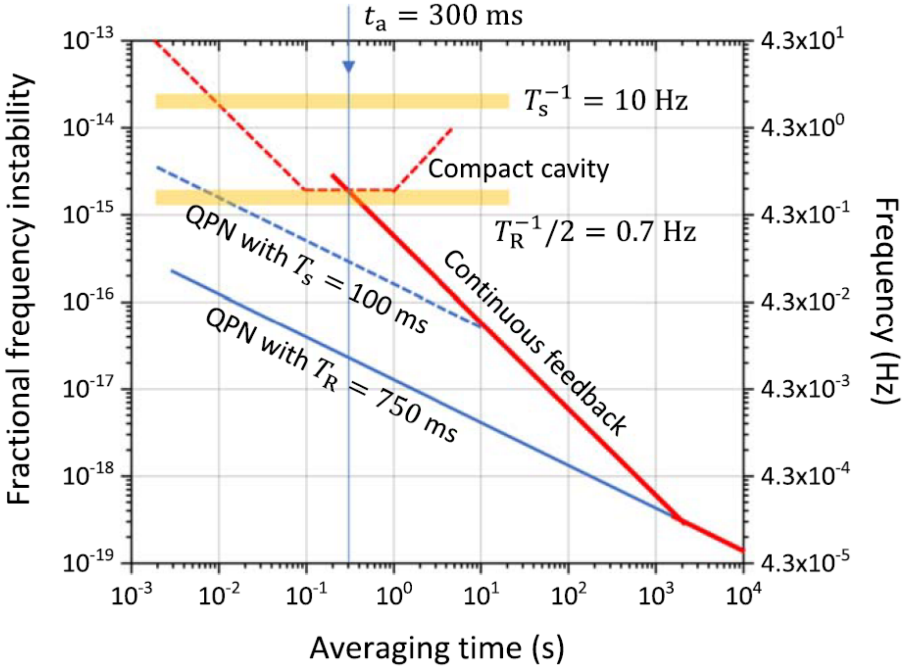
Status:

Now: Steady-state red MOT

Next: Transfer atoms to cavity

Sheng Zhou

Continuous passive optical clocks

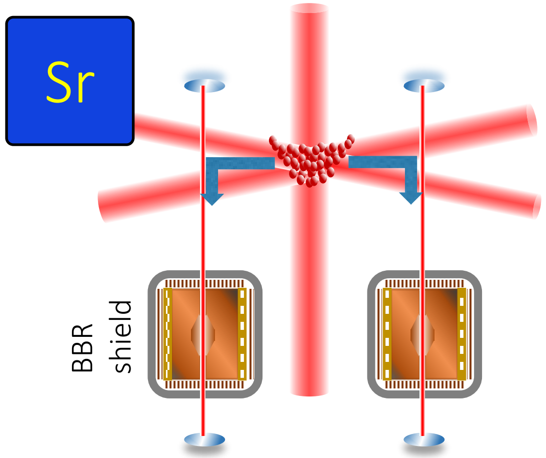


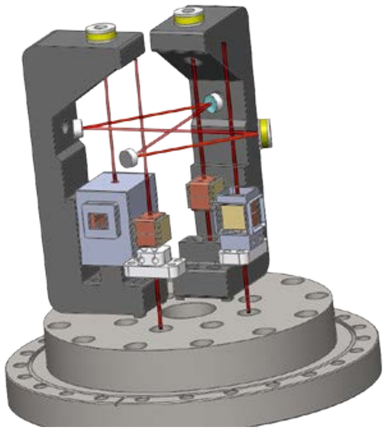
H. Katori, *Appl. Phys. Express* **14** 072006 (2021)

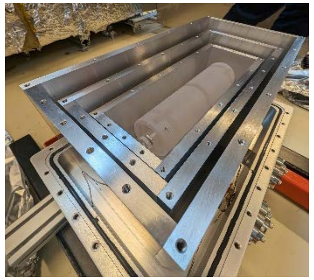
R. Takeuchi et al., *Appl. Phys. Express* **16** 042003 (2023)

Zero dead time passive optical clock

Sr







Sumit Sarkar
András Gácsbaranyi
Scott Wolzak

Use a steady-state red MOT to supply atoms to an array of optical lattice clocks operating on different time scales

New project: Continuous near degenerate ytterbium applications

Yb

ACADEMIA SINICA

IAMS **Taiwan**

Chun-Chia Chen
Shayne Bennetts

Our team

PhD, postdoc & research assistant
positions available

atomlaser
clocks
RbSr
Sr tweezer

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(PI)

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(PI)

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(PhD)

Shayne Bennetts
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Klaasjan van Druten
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Sheng Zhou
(PhD)

Junyu He
(postdoc)

Camila Beli Silva
(PhD)

Florian Schreck
(PI)

Alex Urech
(PhD)

Jiří Minář
(theory postdoc)

Benedikt Heizenreder
(PhD)

Sumit Sarkar
(postdoc)

Yu Chih Tseng
(PhD)

Digvijay
(PhD student)

erc
iqClock
Quantum Flagship
MoSaiQC | ITN
NWO
VENI & VICI
NWA Startimpuls II QuNav
Programme QuSim 2.0
Zwaartekracht QCS
Quantum Delta the Netherlands
QuSoft
Quantum.Amsterdam

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Funding

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iqClock

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MoSaiQC | ITN

MARIE CURIE ACTIONS

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101080166 (AQuRA project).

AQuRA

erc

NWO
VENI & VICI
NWA Startimpuls II QuNav

MINISTRY OF EDUCATION
教育部

Quantum Delta
the Netherlands

QUANTUM
Sensing
metrology