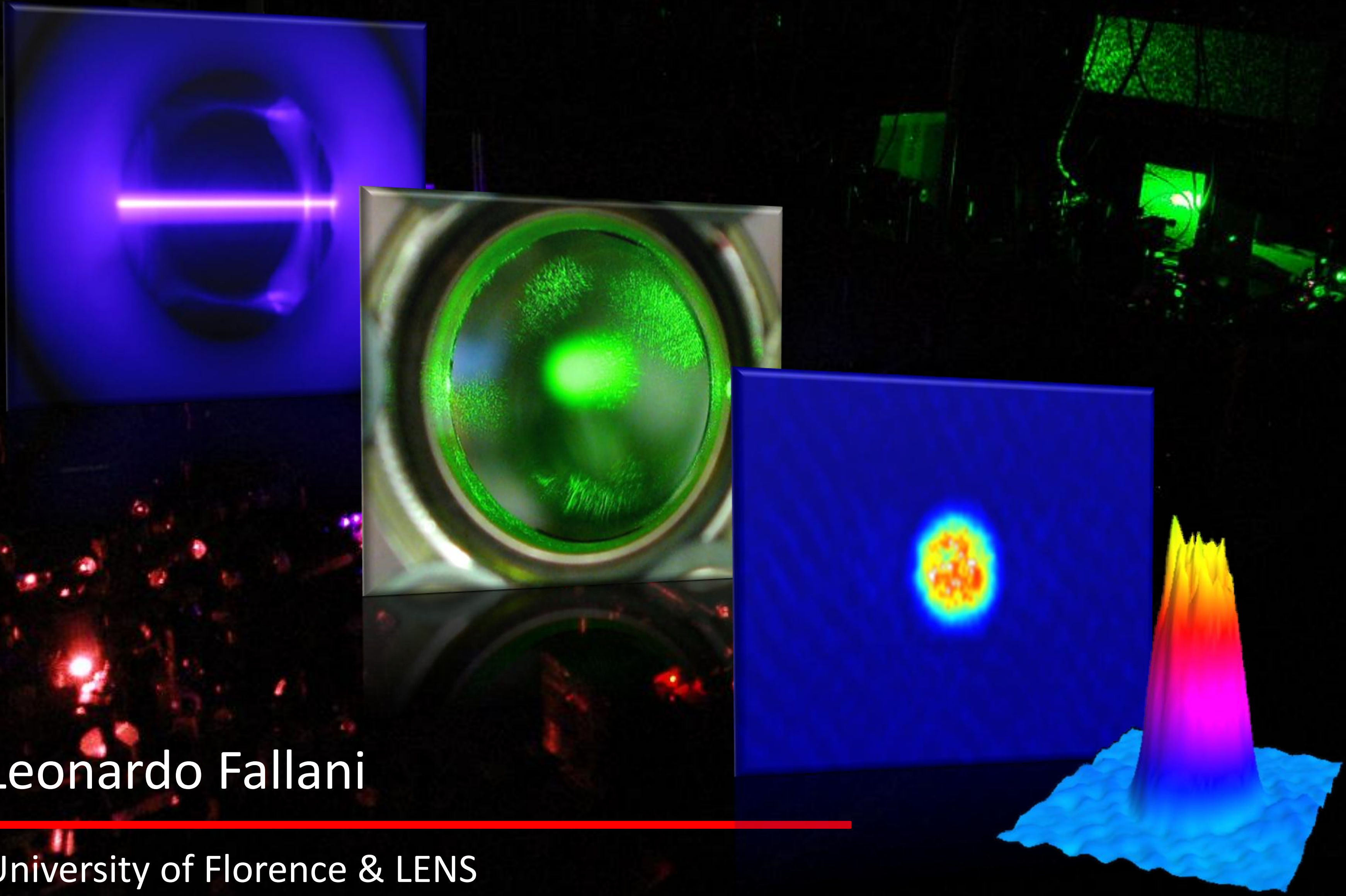
Ytterbium quantum gases in Florence



Leonardo Fallani

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Credits

Marco Mancini

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Funding from EU FP7 Projects AQUTE, NAMEQUAM
and IIT Istituto Italiano di Tecnologia

Introduction

Bose-Einstein condensation of Ytterbium

Current and future work

Introduction

Bose-Einstein condensation of Ytterbium

Current and future work

Alkaline atoms

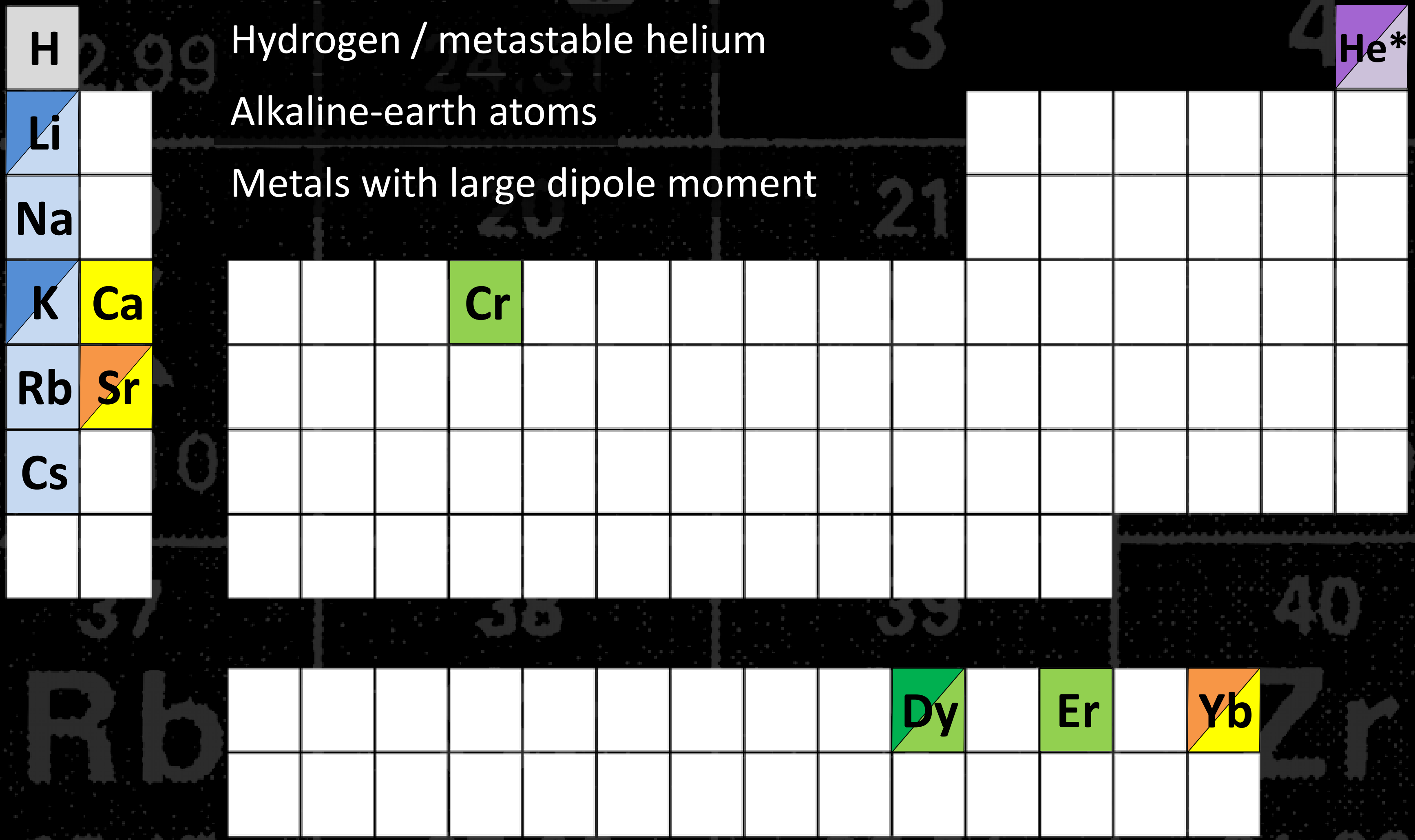
BEC/FG table

Alkaline atoms

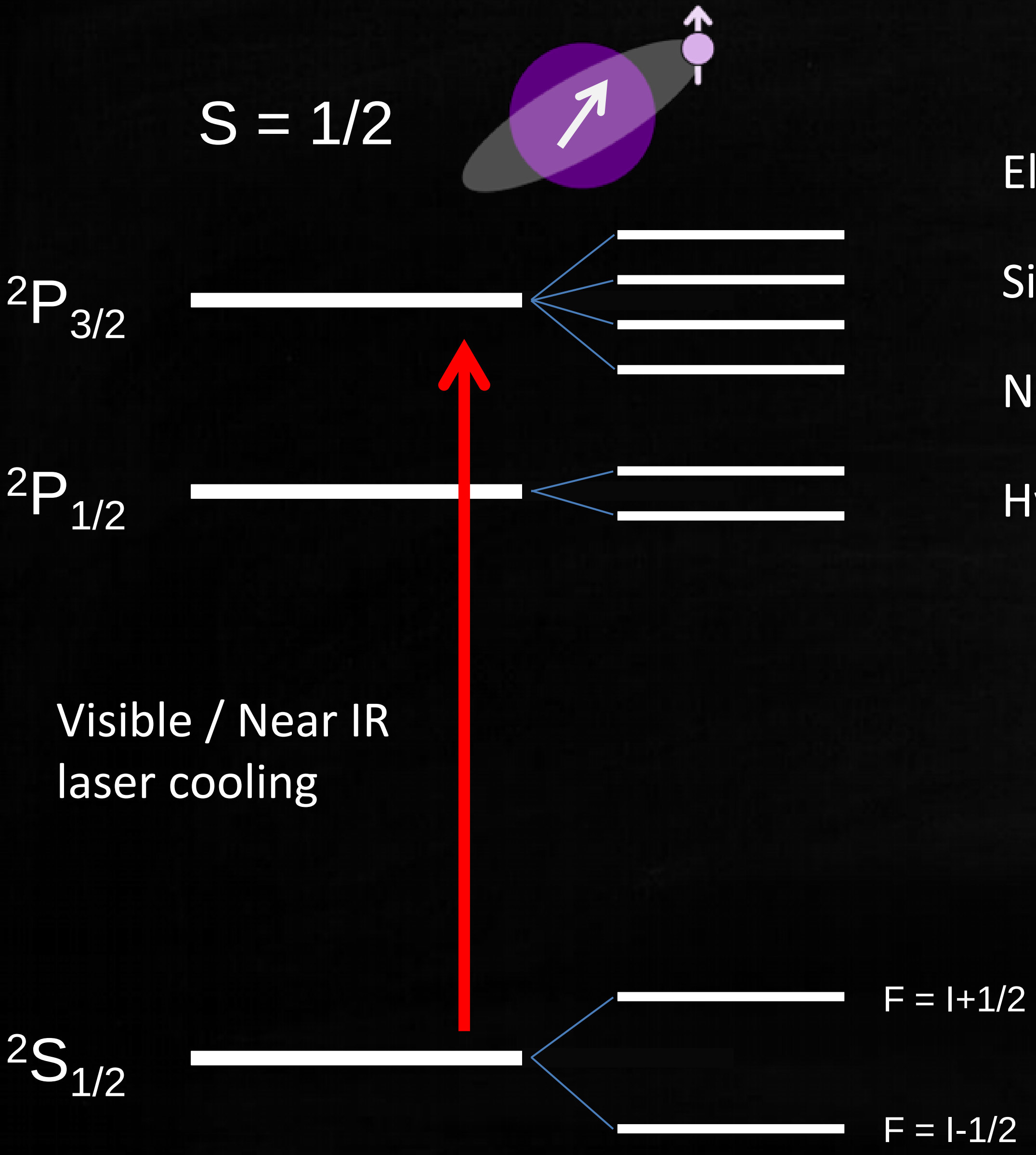
Hydrogen / metastable helium

Alkaline-earth atoms

Metals with large dipole moment



Alkaline atoms



$S = 1/2$

$^2P_{3/2}$

$^2P_{1/2}$

Visible / Near IR
laser cooling

$^2S_{1/2}$

F = I+1/2

F = I-1/2

Electronic configuration [...]1s

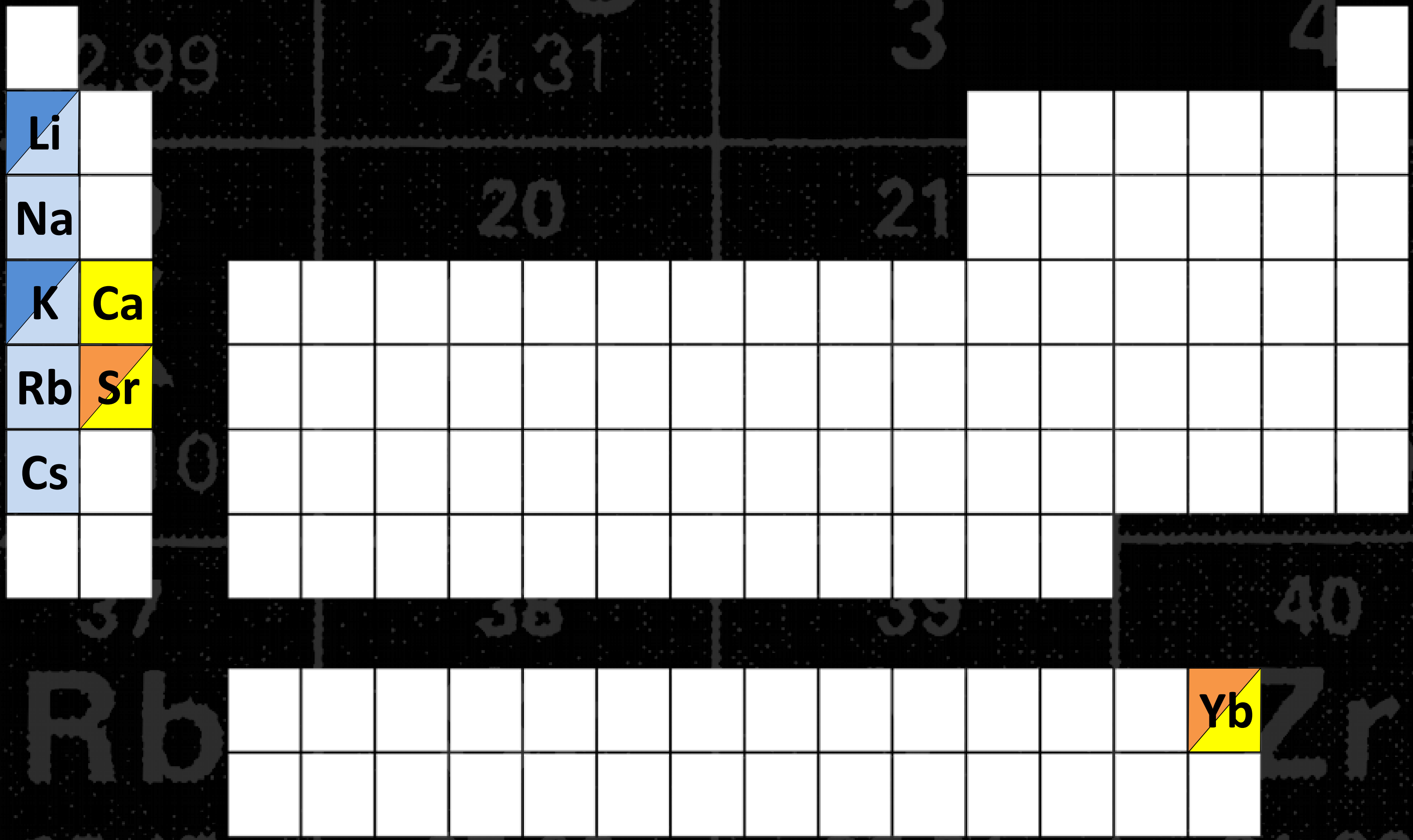
Single-electron structure

Non-zero nuclear spin I

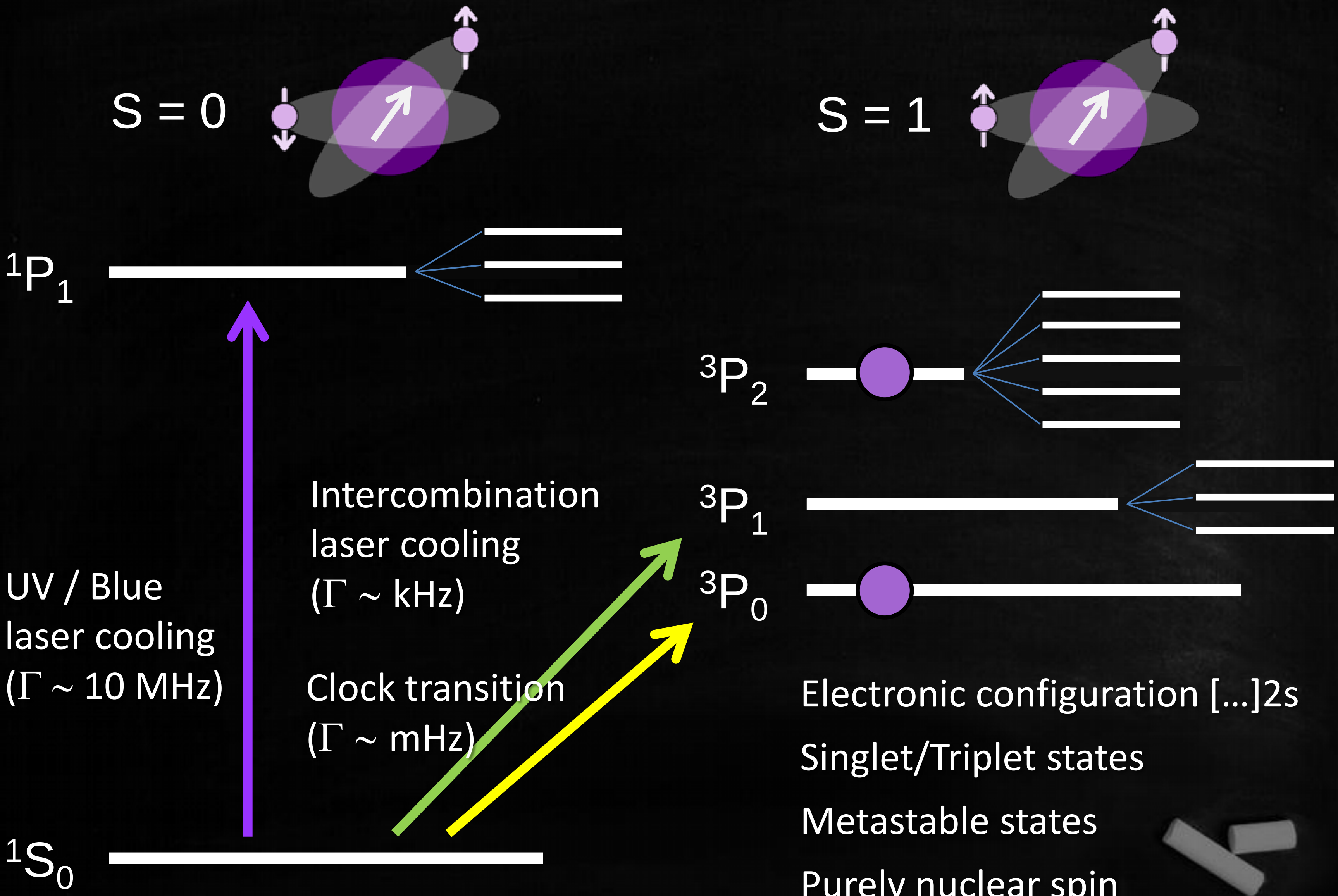
Hyperfine interaction $\mathbf{I} \cdot \mathbf{J} \neq 0$

Alkaline-earth atoms

Alkali atoms



Alkaline-earth atoms



S = 0

S = 1

$^1P_1$

$^3P_2$

$^3P_1$

$^3P_0$

$^1S_0$

UV / Blue
laser cooling
($\Gamma \sim$ 10 MHz)

Intercombination
laser cooling
($\Gamma \sim$ kHz)

Clock transition
($\Gamma \sim$ mHz)

Electronic configuration [...]2s

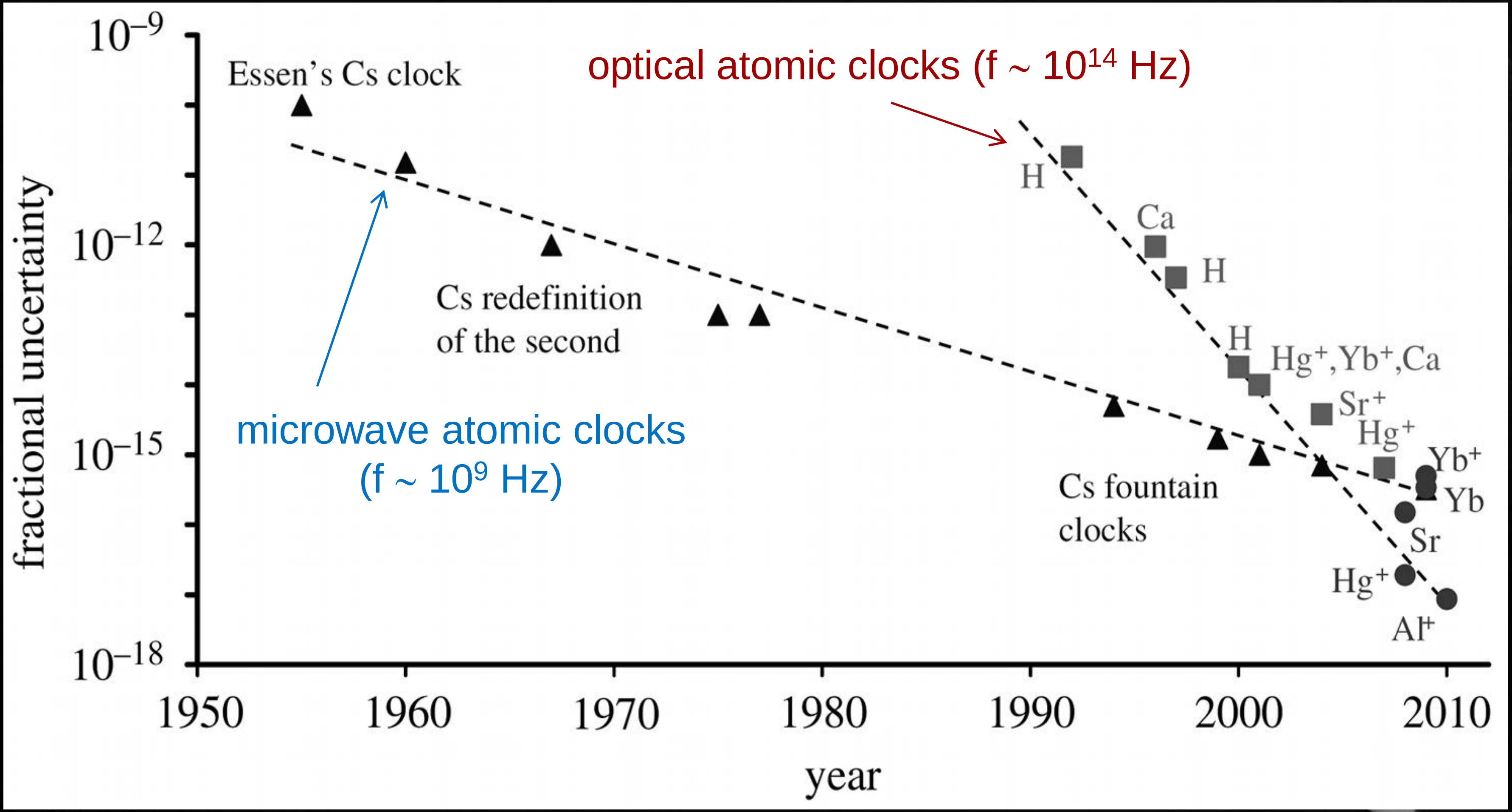
Singlet/Triplet states

Metastable states

Purely nuclear spin

Optical clocks

Optical clocks based on $^1S_0 - {}^3P_0$ transition in alkaline-earth atoms (and ions)

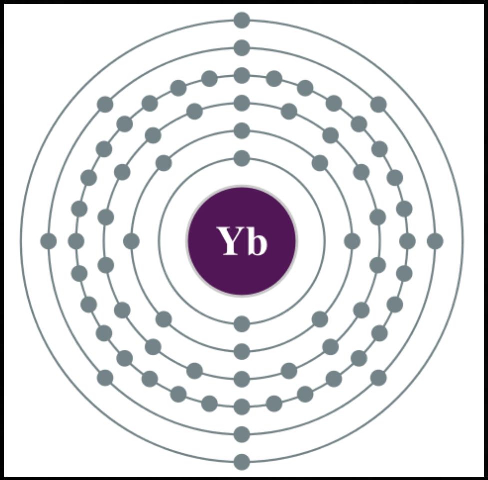


optical atomic clocks (f ~ 10^{14} Hz)

microwave atomic clocks (f ~ 10^9 Hz)

The Ytterbium family

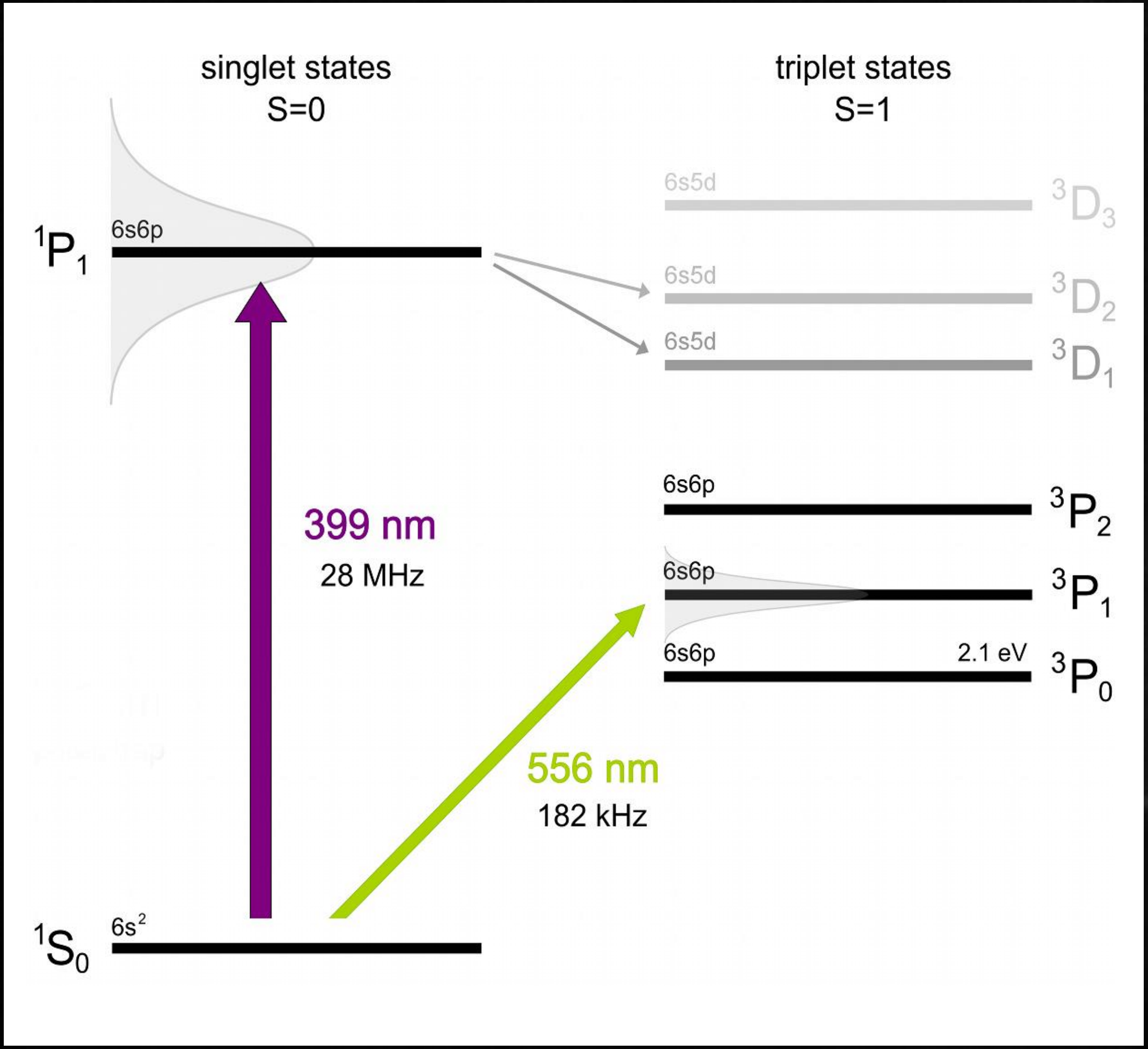
http://periodictable.com



Natural Ytterbium comes in seven stable isotopes:

^{168}Yb	0.13%	I=0	boson
^{170}Yb	3.04%	I=0	boson
^{171}Yb	14.28%	I=1/2	fermion
^{172}Yb	21.83%	I=0	boson
^{173}Yb	16.13%	I=5/2	fermion
^{174}Yb	31.83%	I=0	boson
^{176}Yb	12.76%	I=0	boson

Ytterbium levels



Ytterbium interactions

At ultralow temperatures short-range interactions between neutral atoms are completely described by s-wave scattering

s-wave scattering lengths (in a_0 units)

	^{168}Yb	^{170}Yb	^{171}Yb	^{172}Yb	^{173}Yb	^{174}Yb	^{176}Yb
^{168}Yb	252	117	89	65	39	2	-359
^{170}Yb		64	36	-2	-81	-518	209
^{171}Yb			-3	-84	-578	429	142
^{172}Yb				-600	418	200	106
^{173}Yb					200	139	80
^{174}Yb						105	54
^{176}Yb							-24

Kitagawa *et al., PRA 77, 012719 (2008)*

Isotope tuning of the interactions

Introduction

Bose-Einstein condensation of Ytterbium

Current and future work

The experimental setup

European Laboratory for
Non-Linear Spectroscopy

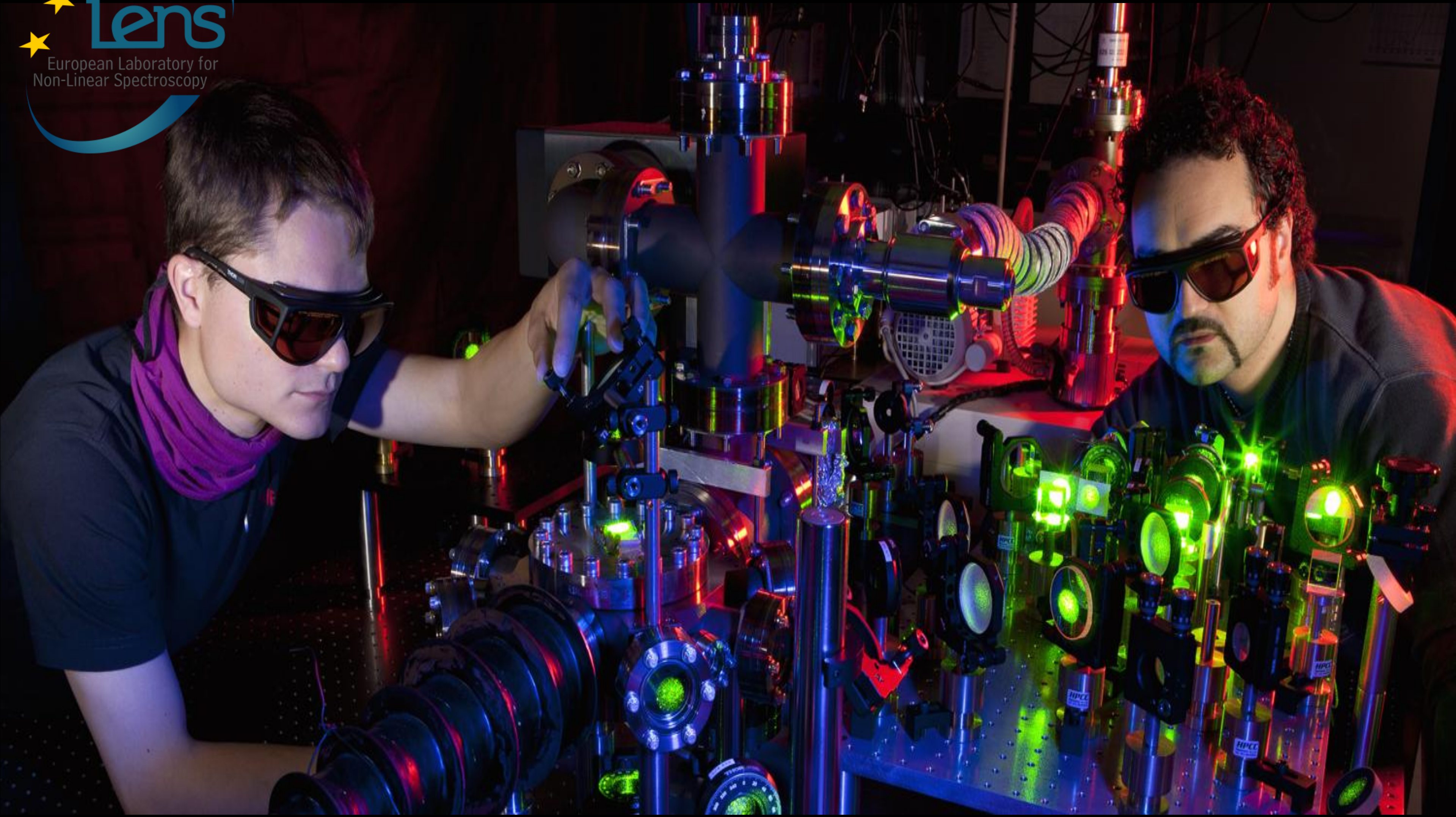
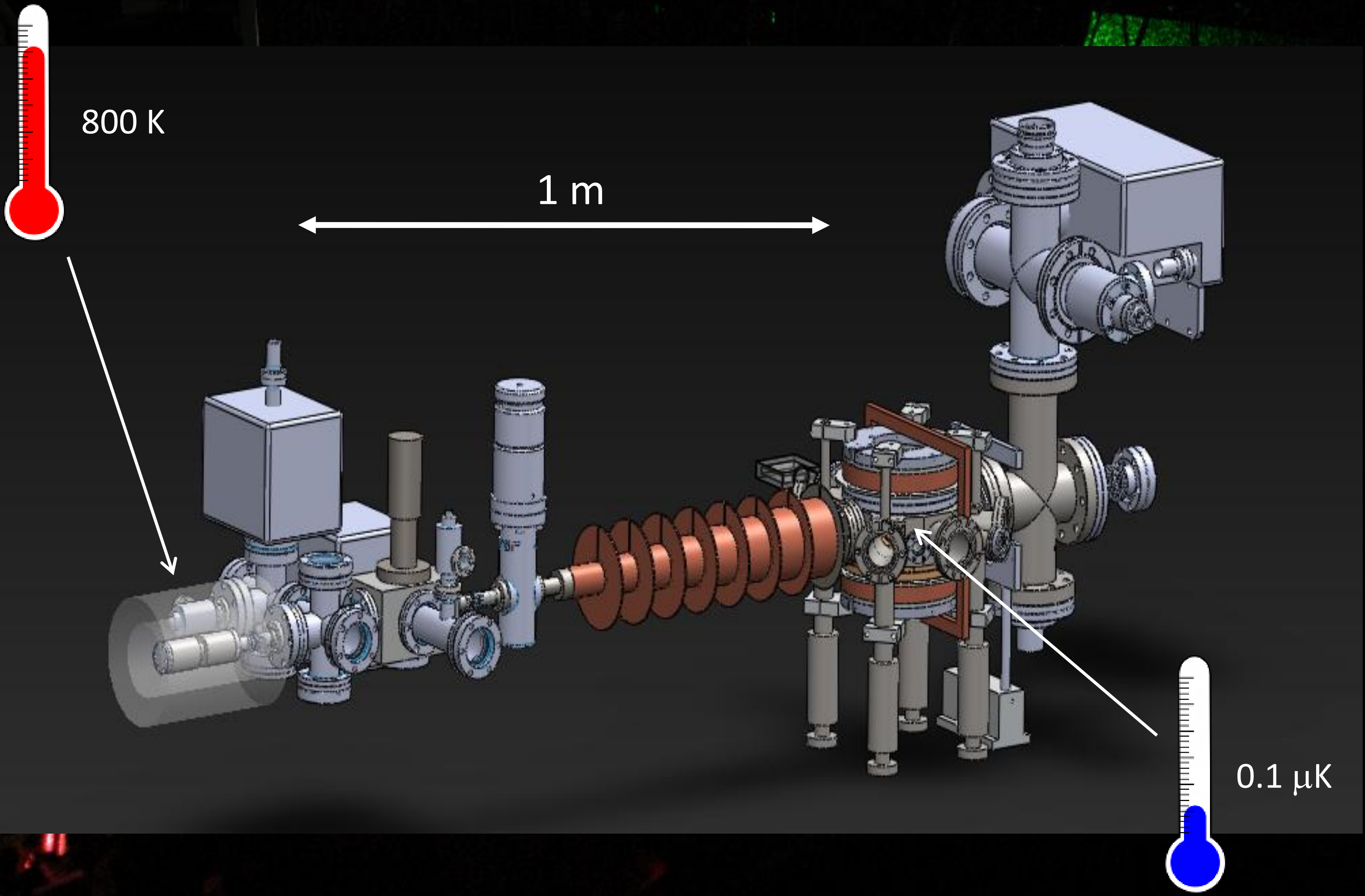
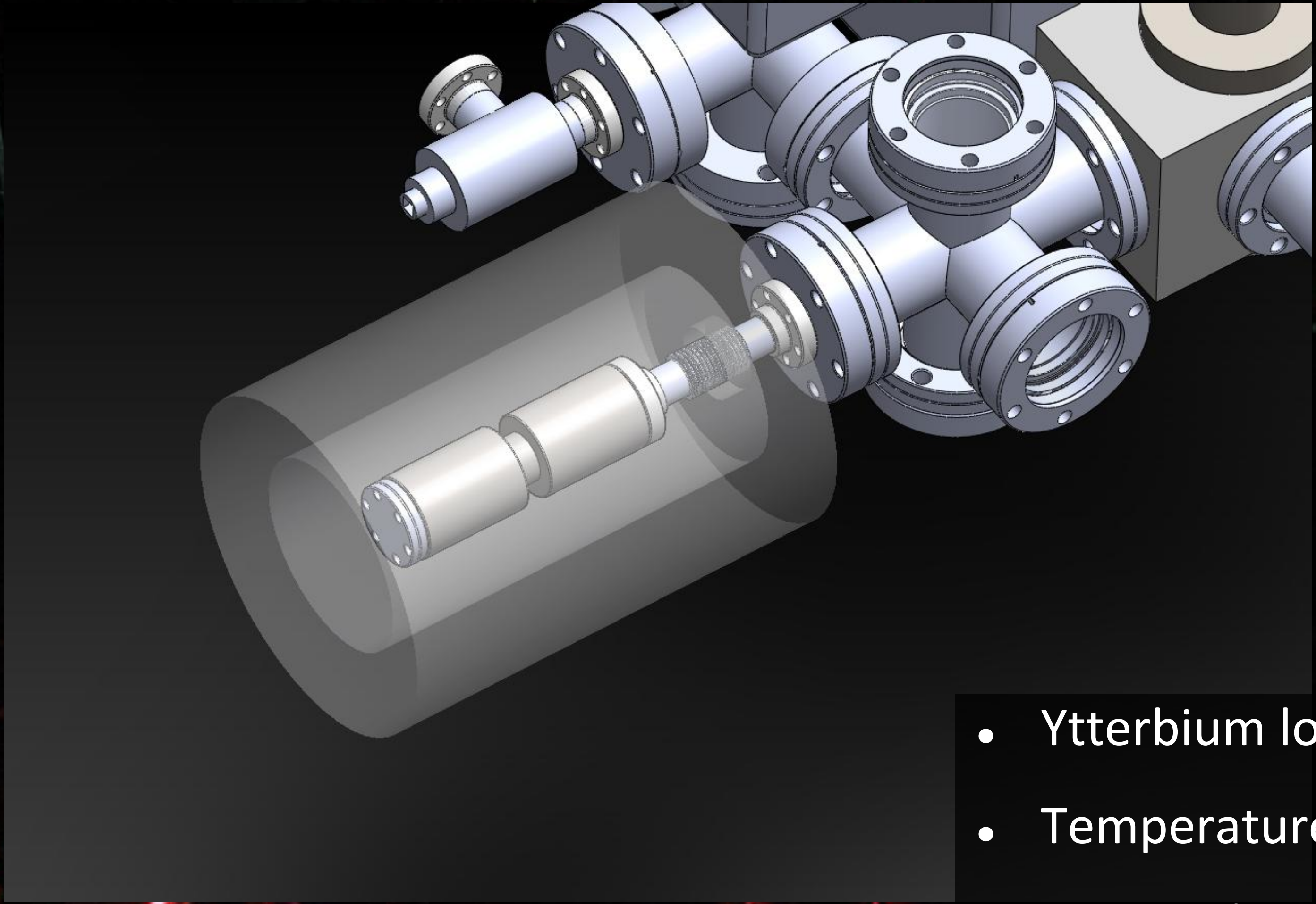


Photo by Marco De Pas

The experimental setup

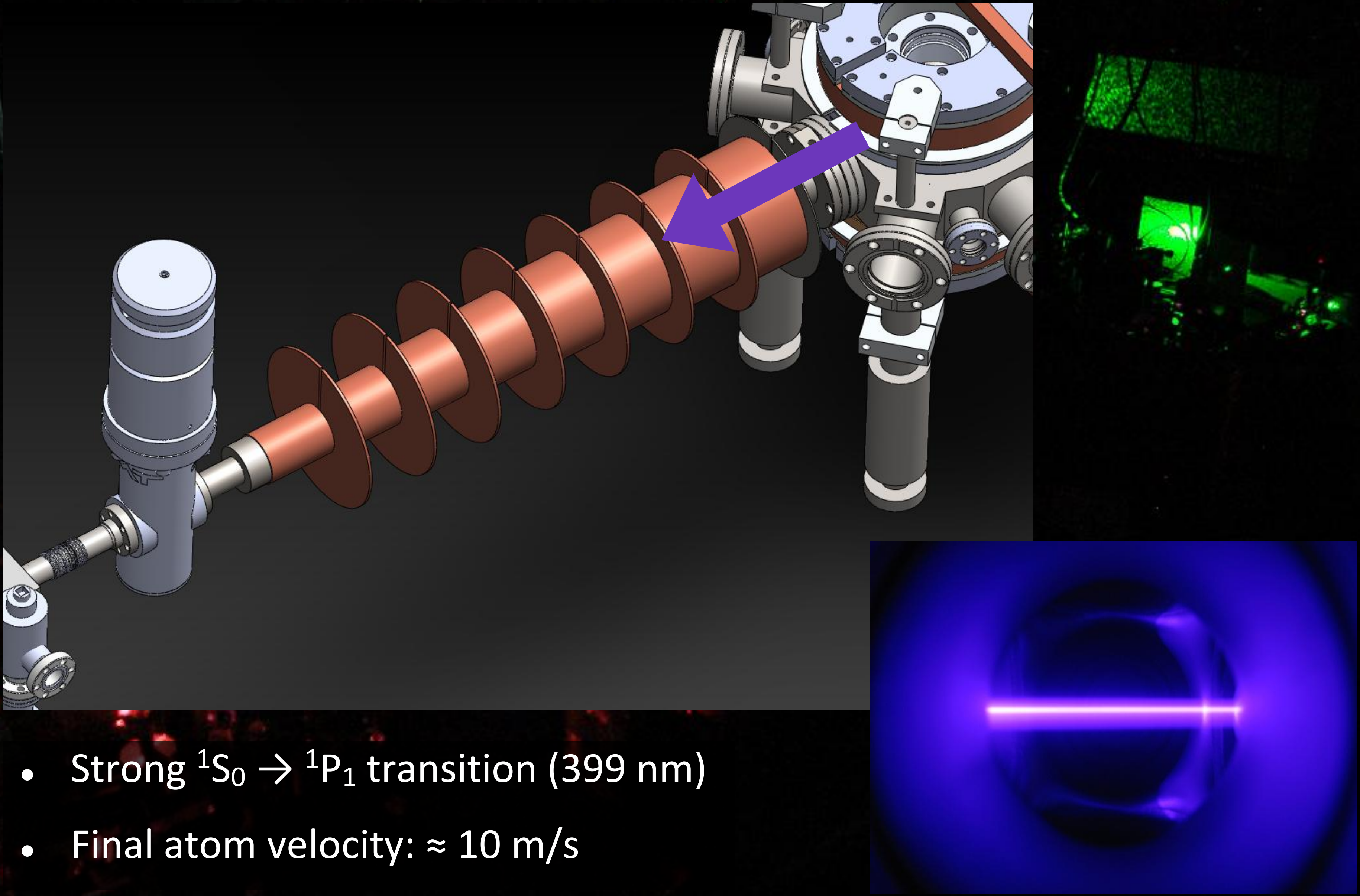


The experimental setup



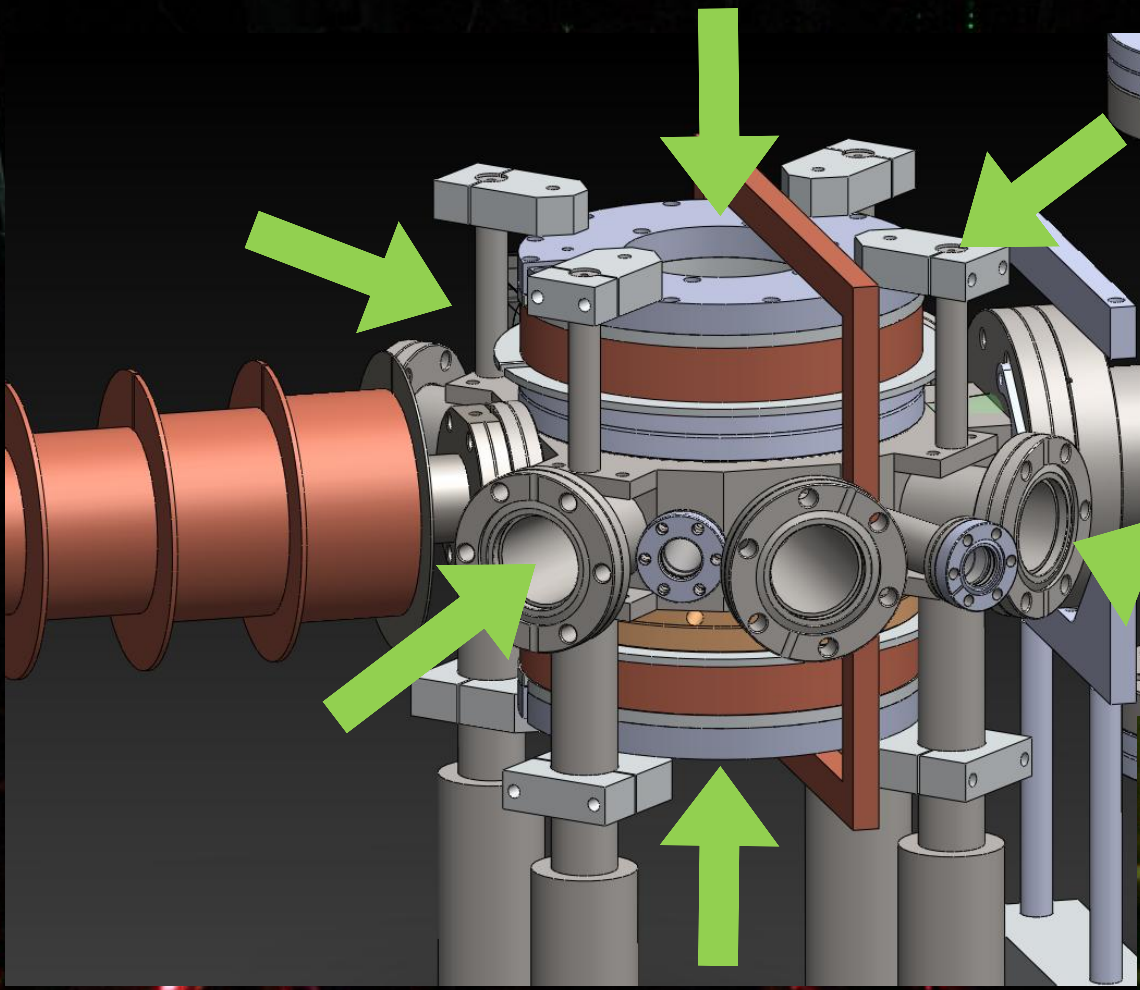
- Ytterbium loaded: 7 g
- Temperature: 800 K
- Atom velocity: ≈ 330 m/s
- Beam diameter: 5 mm

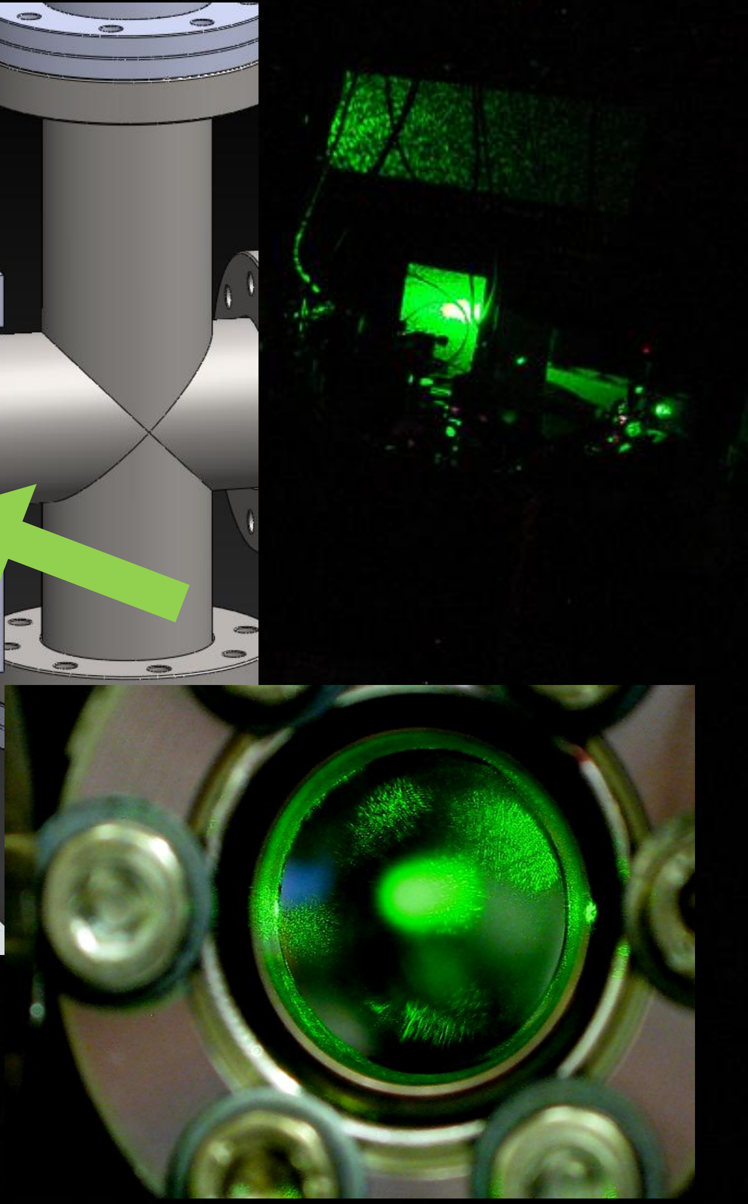
Slowing the atomic beam



- Strong $^1S_0 \rightarrow {}^1P_1$ transition (399 nm)
- Final atom velocity: ≈ 10 m/s

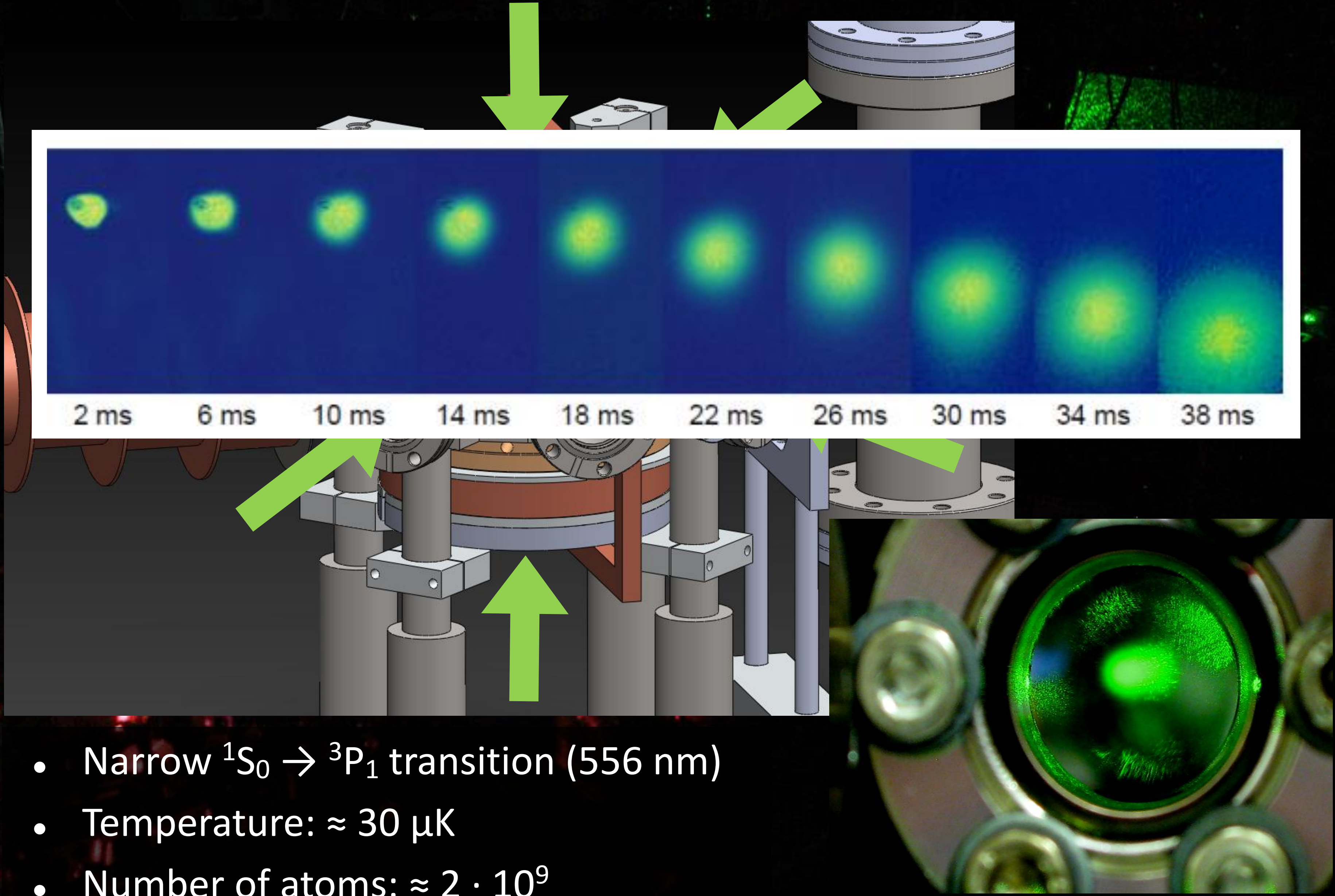
The green MOT





- Narrow $^1S_0 \rightarrow {}^3P_1$ transition (556 nm)
- Temperature: ≈ 30 µK
- Number of atoms: ≈ $2 \cdot 10^9$

The green MOT

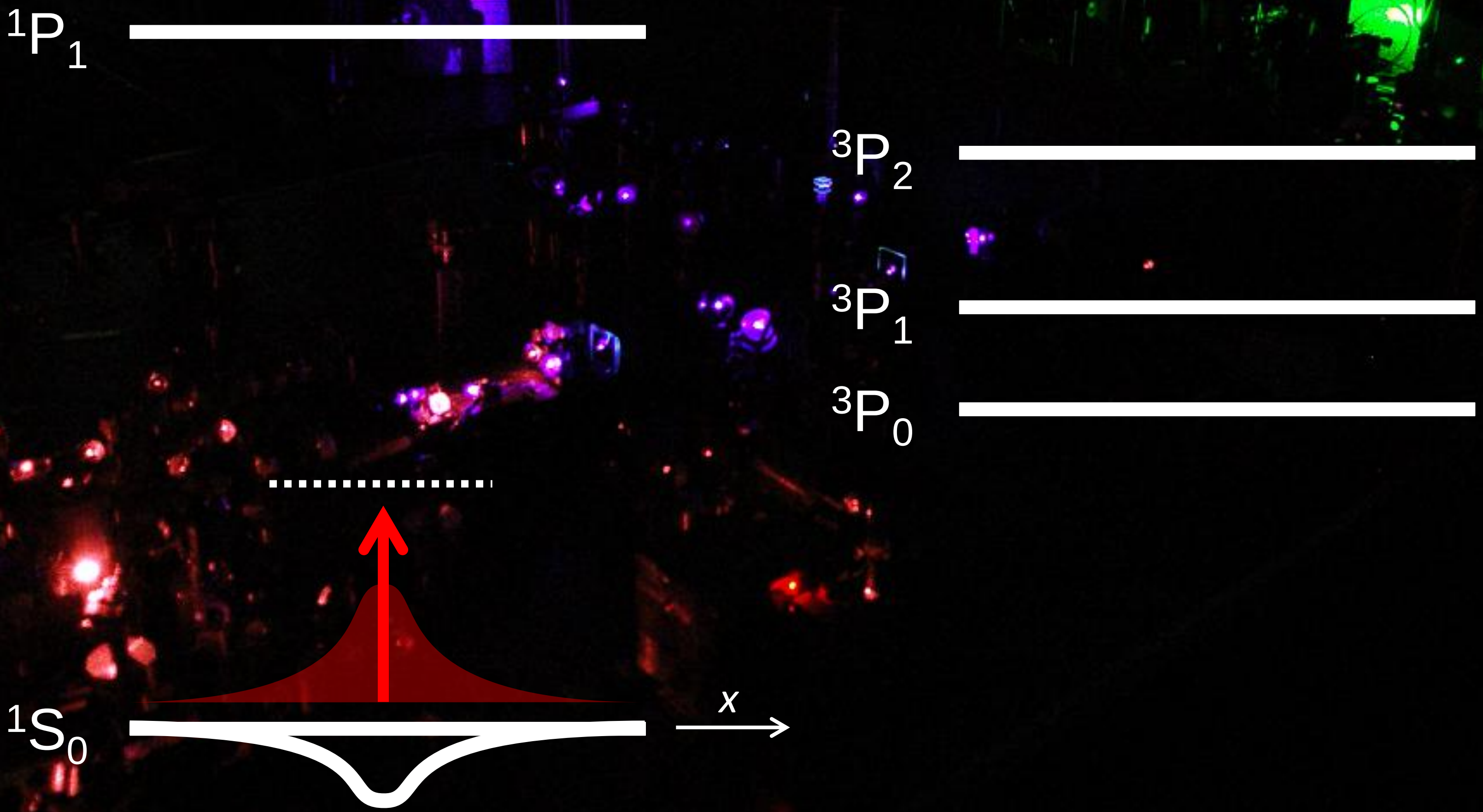


- Narrow $^1S_0 \rightarrow {}^3P_1$ transition (556 nm)
- Temperature: ≈ 30 µK
- Number of atoms: $\approx 2 \cdot 10^9$

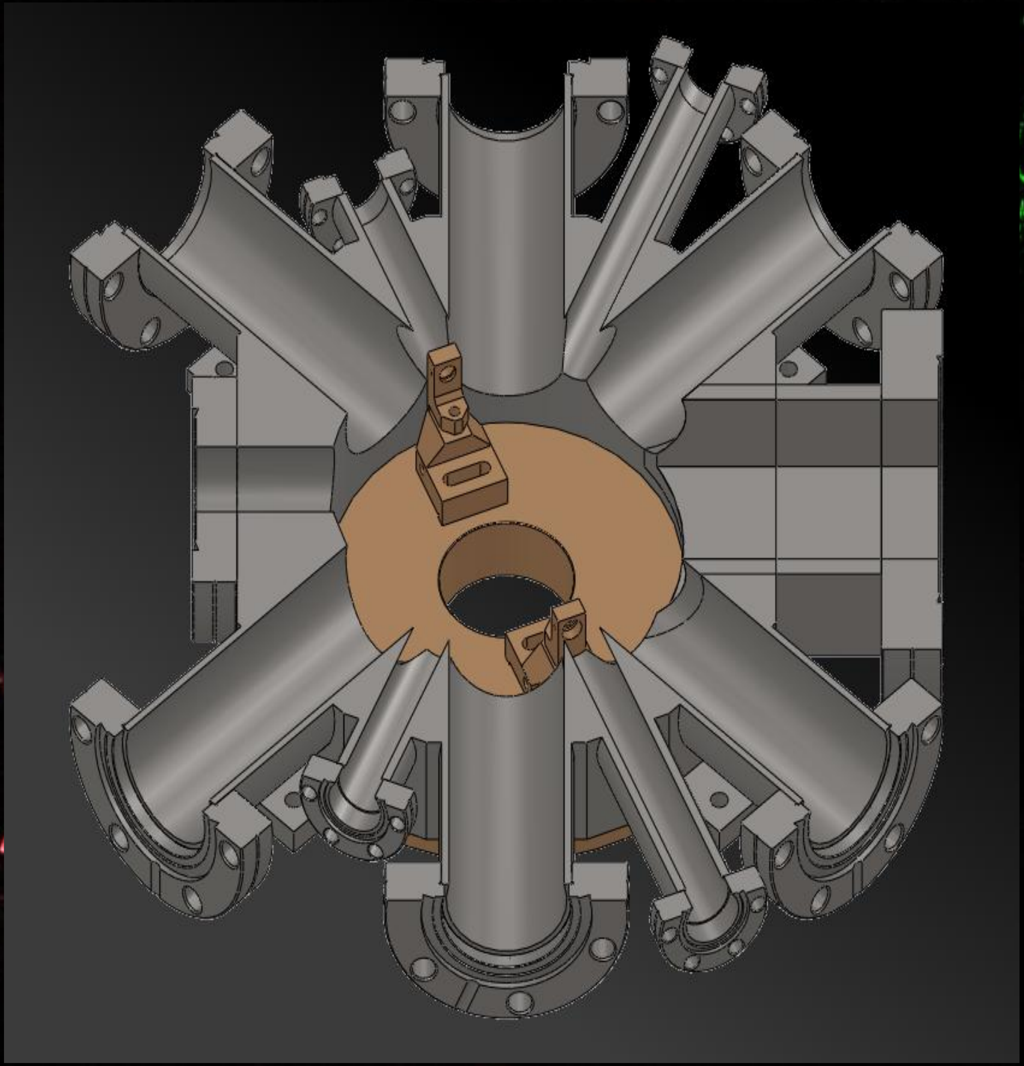
Optical trapping

Diamagnetic ground state: no magnetic trapping

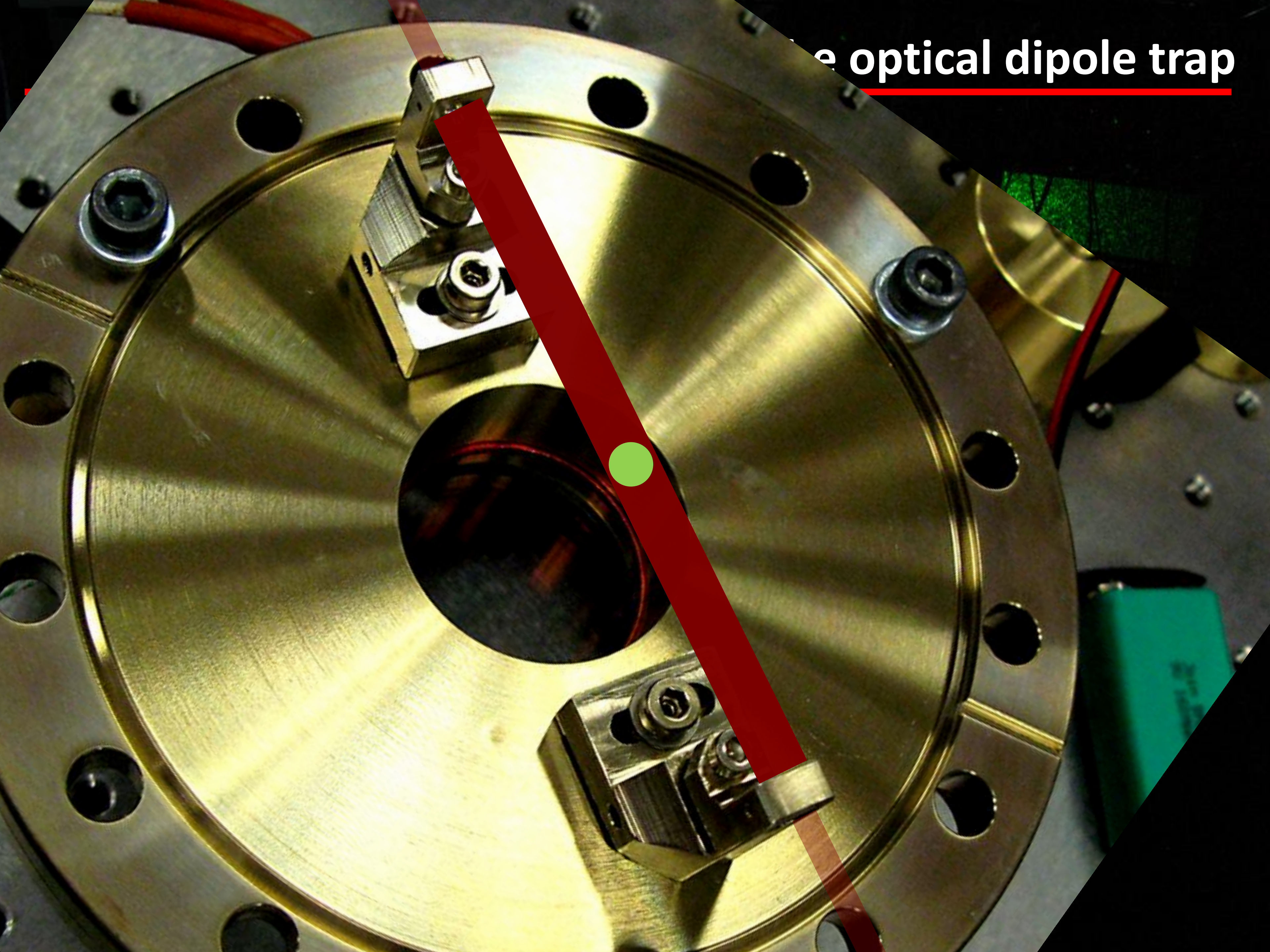
Optical trap: spatially-dependent ac-Stark shift induced by off-resonant light



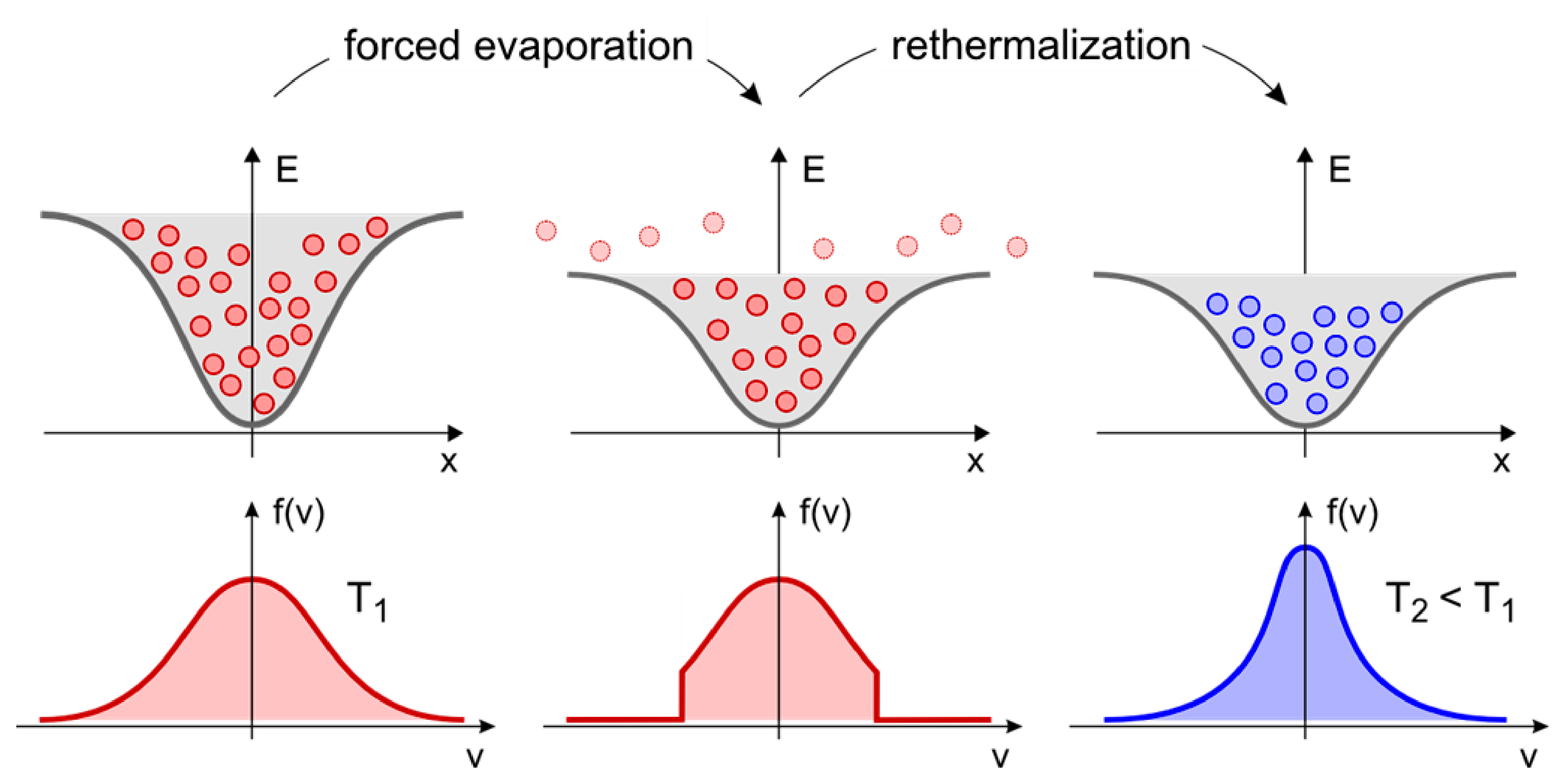
The optical dipole trap



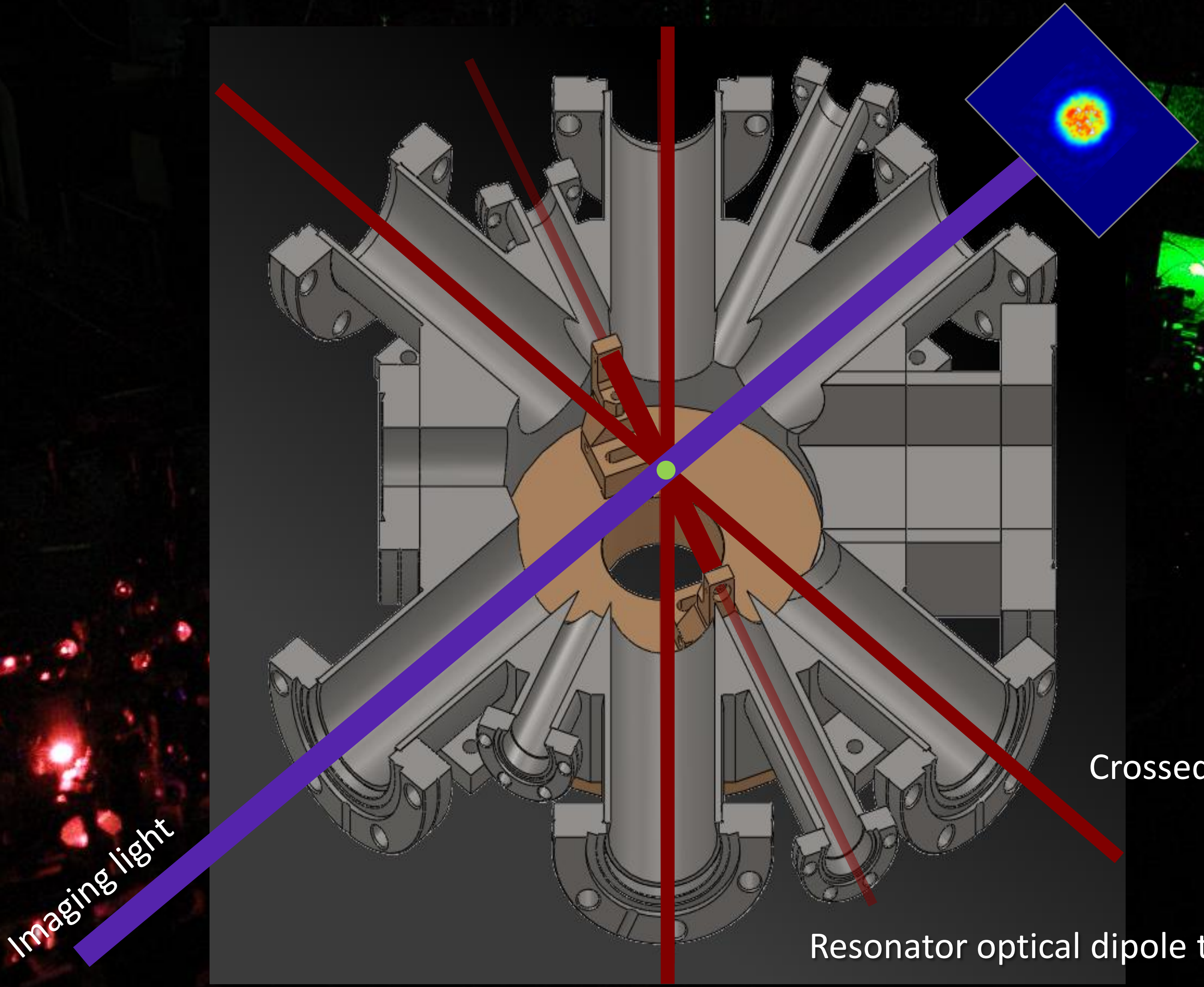
e optical dipole trap



Evaporative cooling



The optical dipole trap



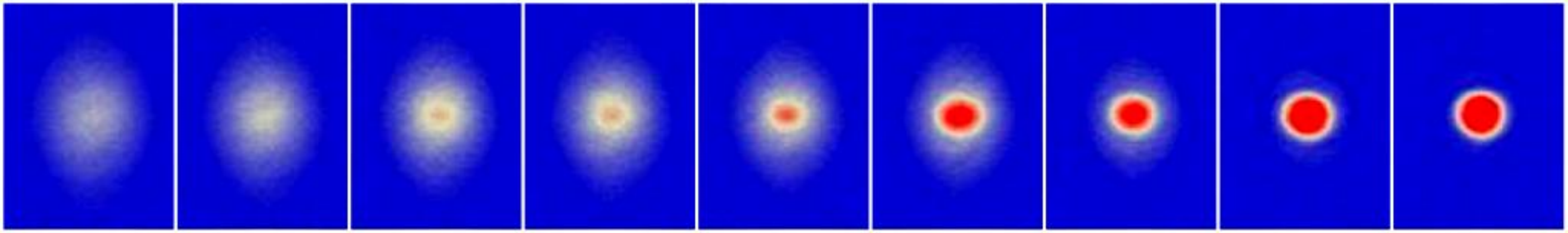
Crossed dipole trap

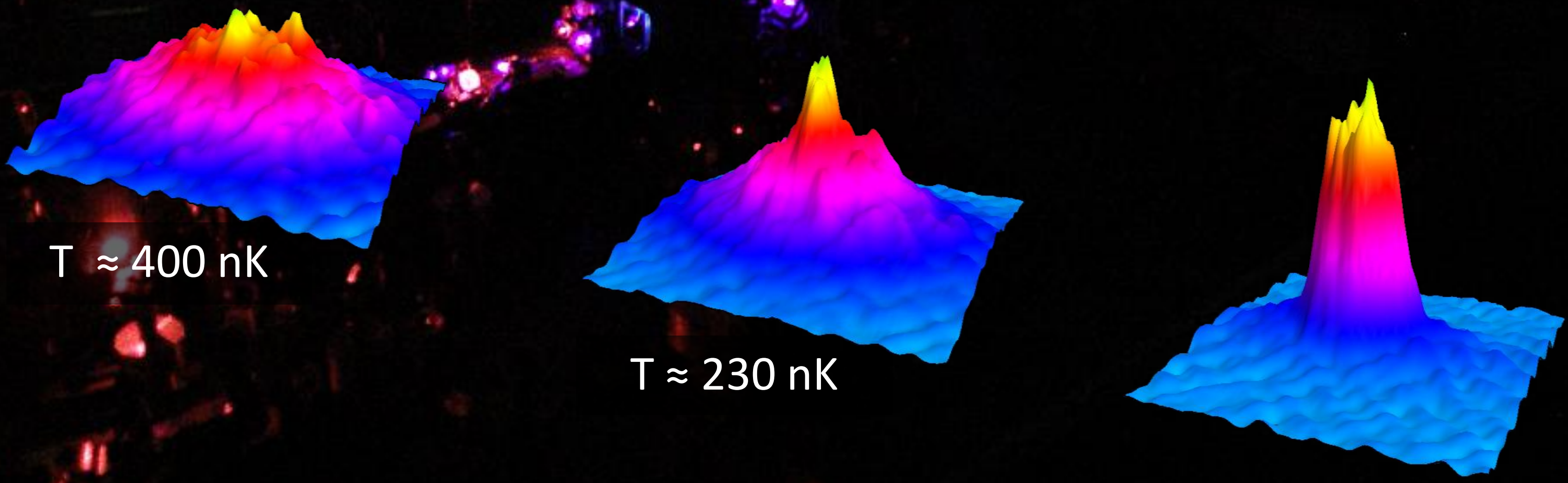
Resonator optical dipole trap

First ^{174}Yb BEC in Florence

Time-of-flight images: momentum distribution

lower temperature ⟶

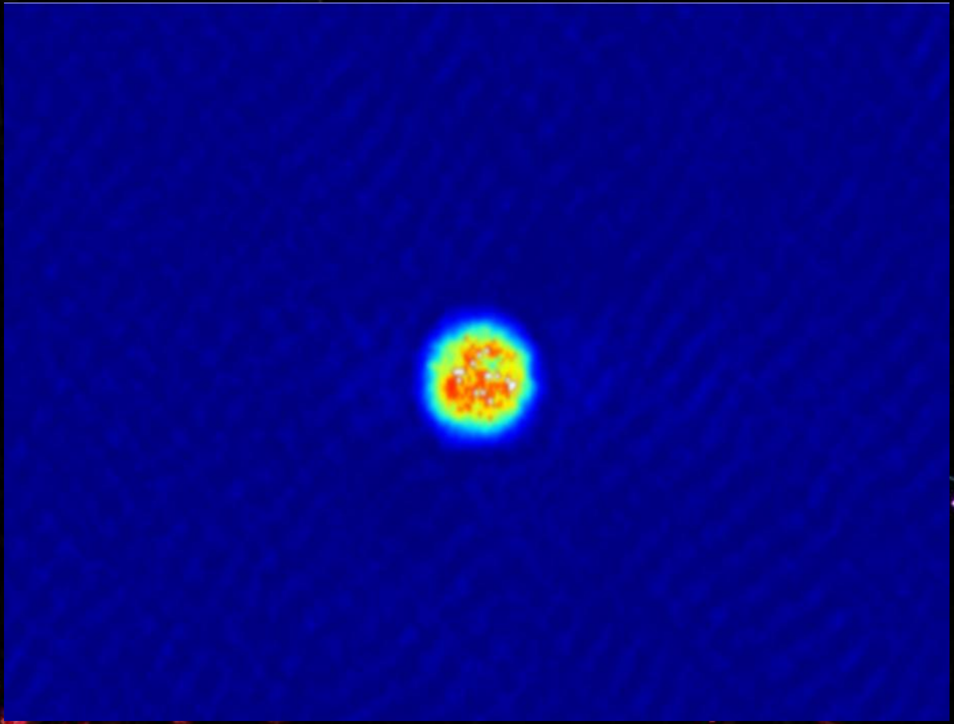


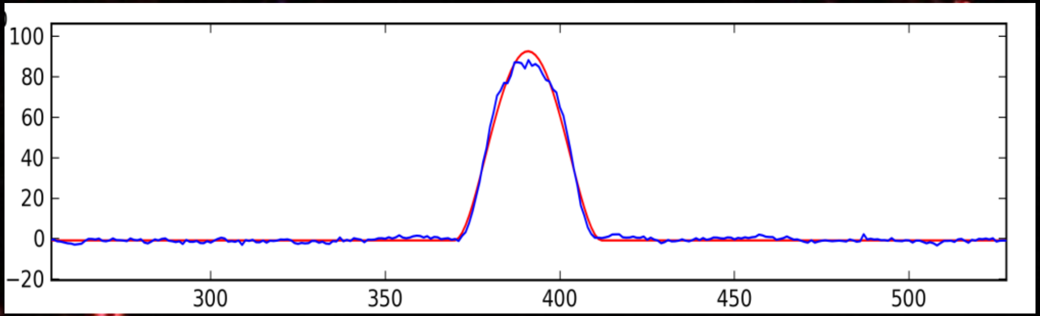


T ≈ 400 nK

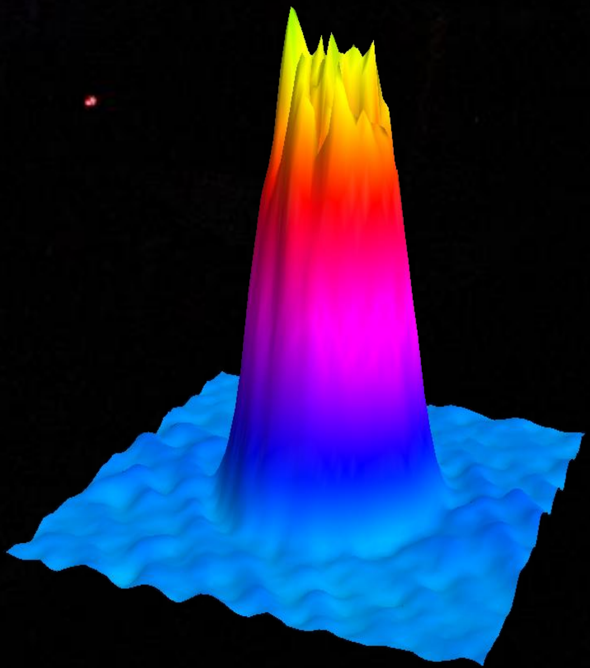
T ≈ 230 nK

First ^{174}Yb BEC in Florence



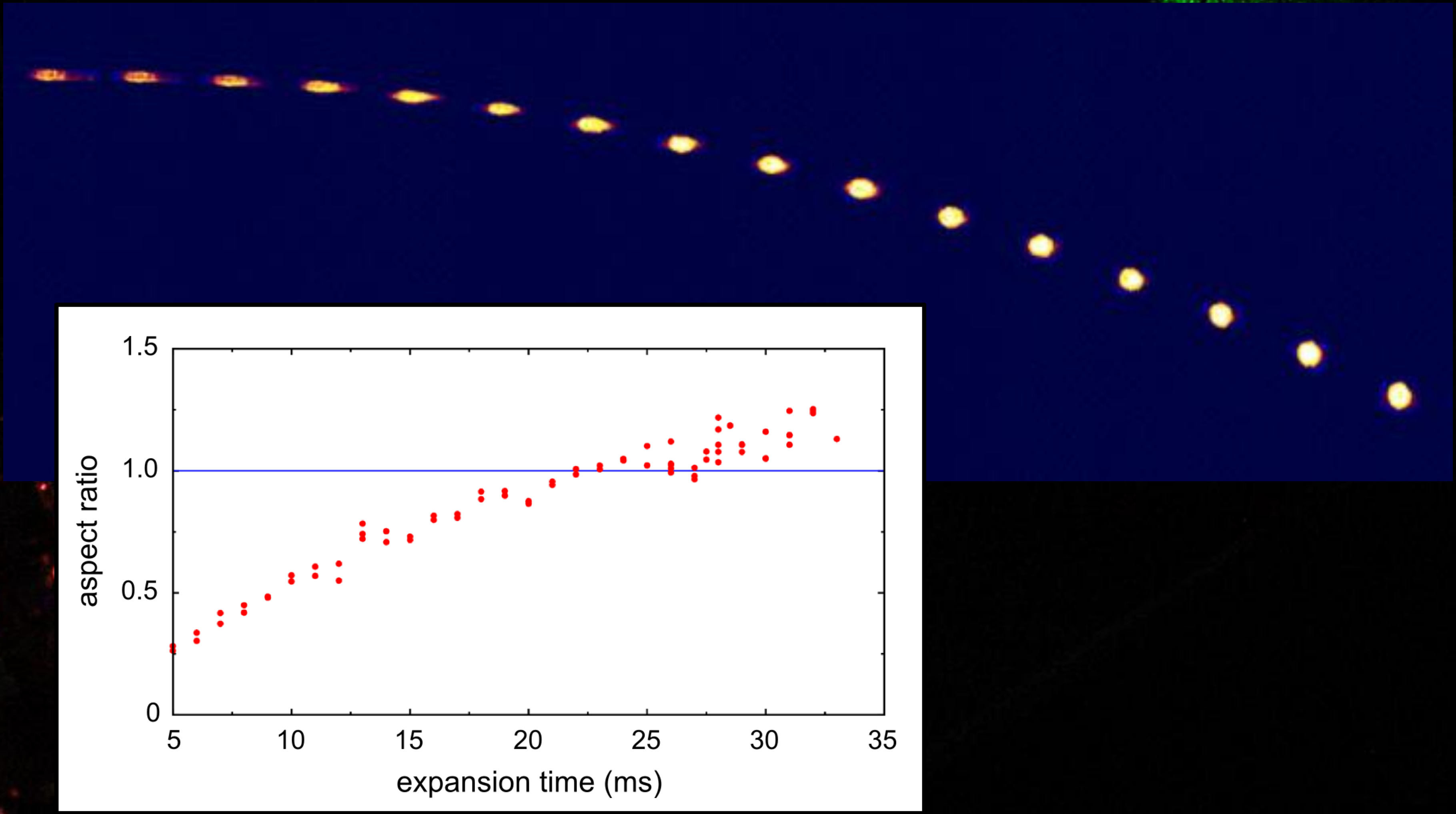


almost pure ^{174}Yb BEC
with N = 4×10^{5} atoms



First ^{174}Yb BEC in Florence

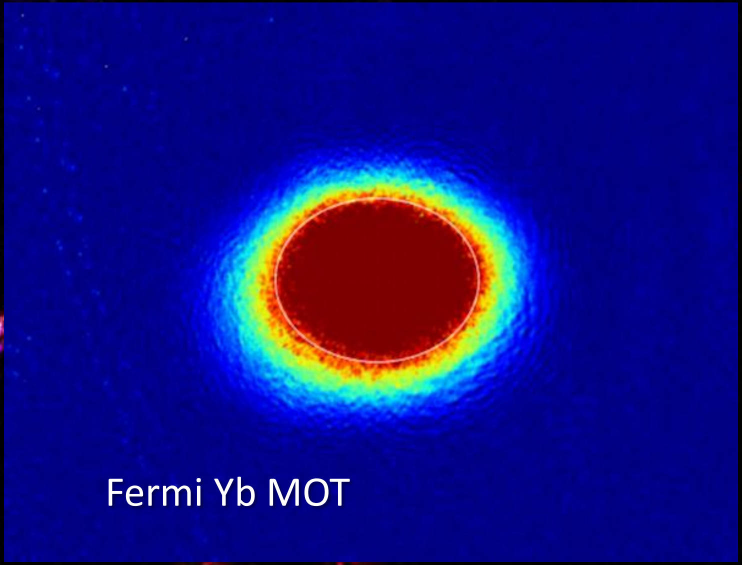
Time-of-flight measurement of anisotropic BEC expansion



Fermionic ^{173}Yb under cooling

Laser cooling and trapping of fermionic ^{173}Yb demonstrated.

Evaporative cooling in progress.



Fermi Yb MOT

Introduction

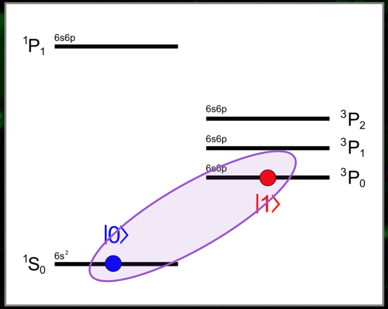
Bose-Einstein condensation of Ytterbium

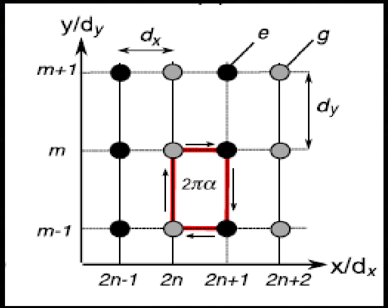
Current and future work

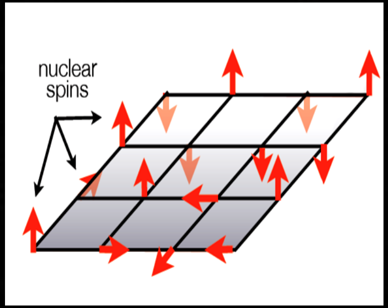
Why Ytterbium?

Three examples:

- Quantum information
- Synthethic gauge potentials
- SU(N) physics





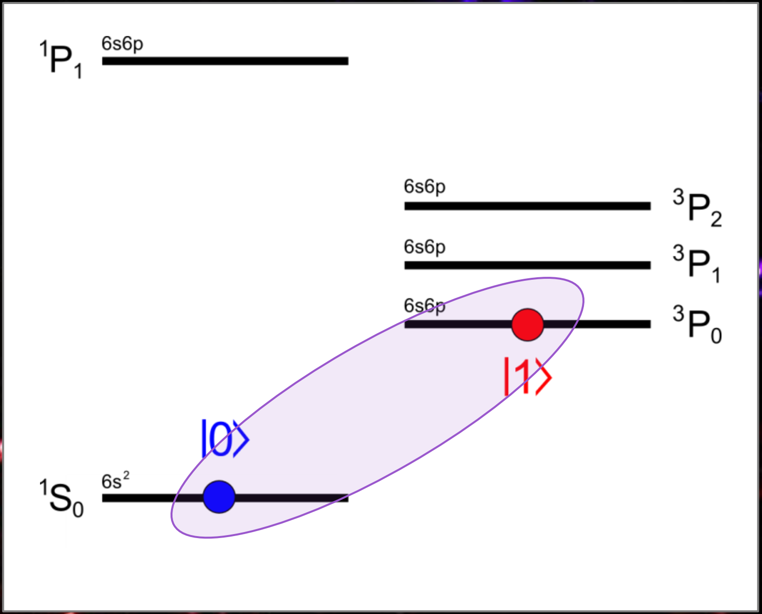


Quantum information with long-lived qubits

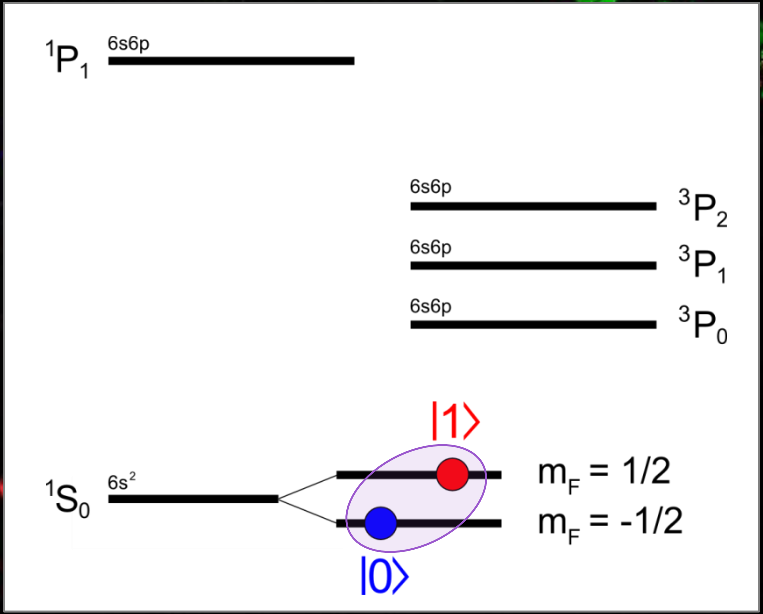
Two-electron atoms offer possibilities of encoding quantum information with long coherence times

Review paper: A. Daley, arXiv:1106.5712

electronic qubits



nuclear qubits

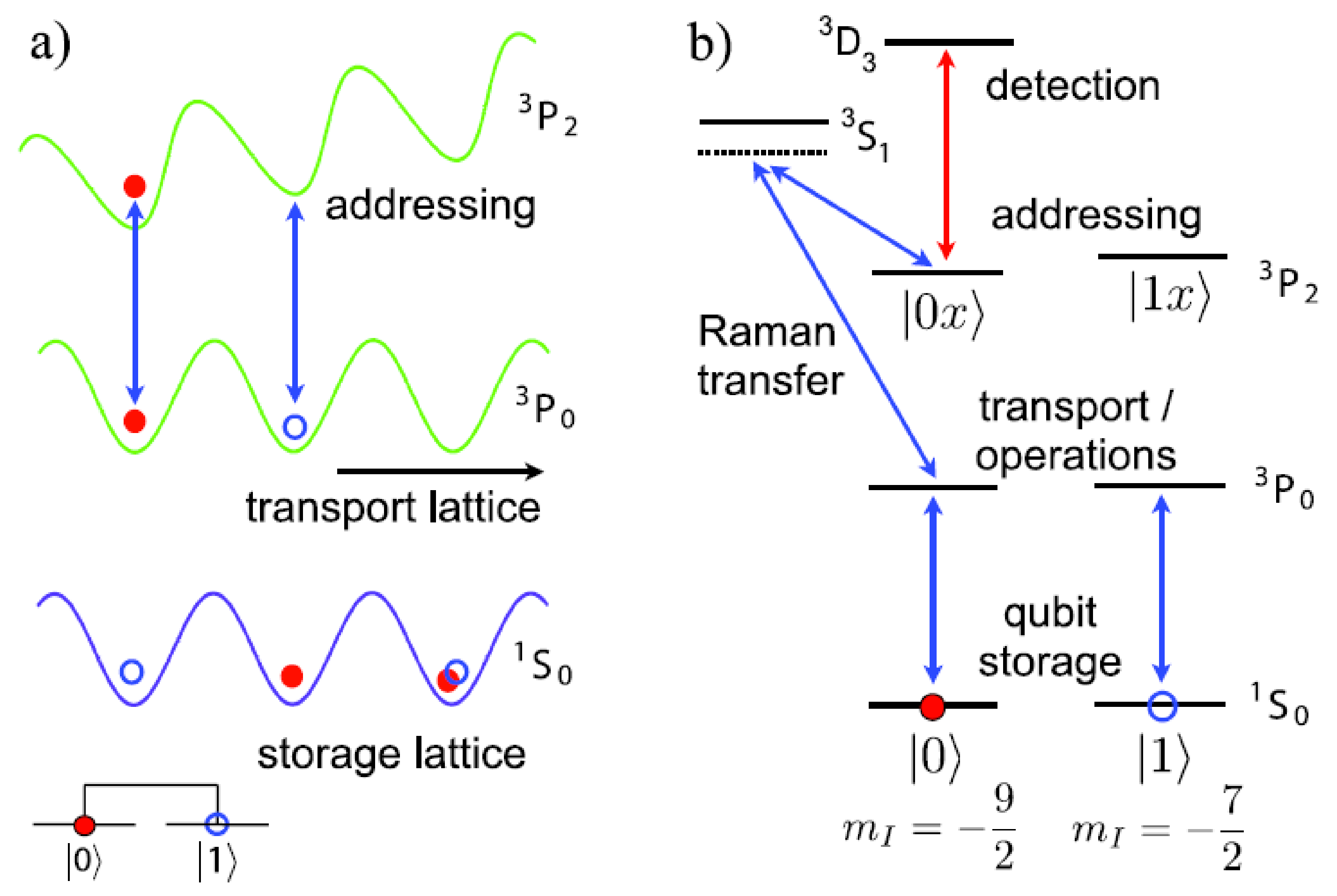


- ultra-narrow clock transition
- long coherence times

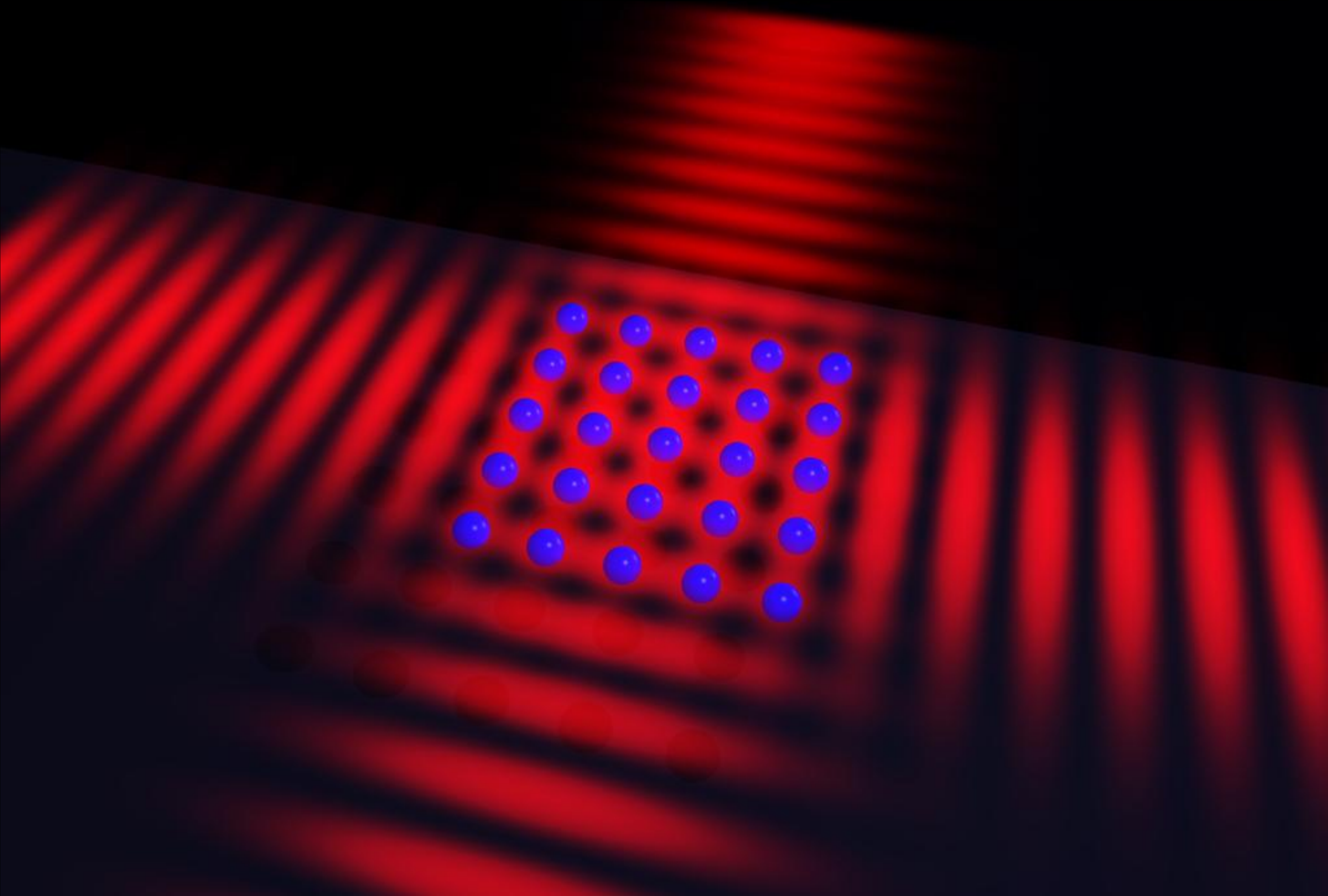
- no hyperfine interaction
- low coupling to magnetic fields

Quantum information with long-lived qubits

Quantum computing with alkaline-earth-metal atoms
A. Daley, M. M. Boyd, J. Ye, P. Zoller, PRL **101**, 170504 (2008)



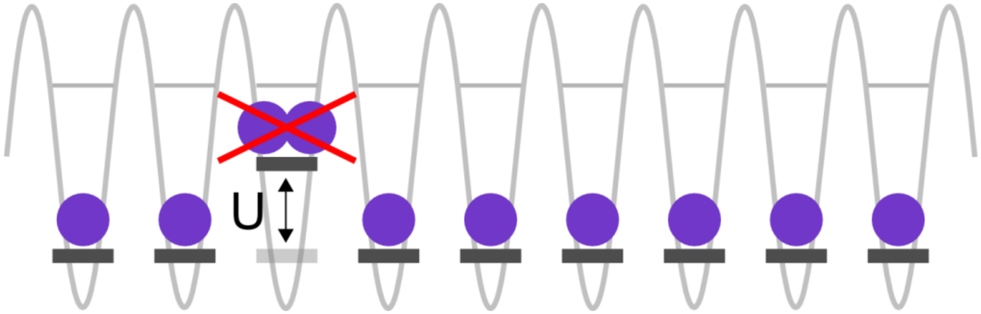
Optical lattices



Optical lattices

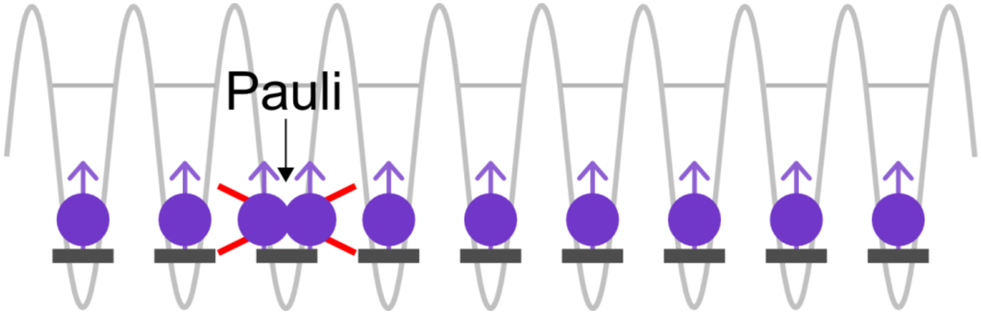
strong repulsive interactions
between bosons

MOTT INSULATOR



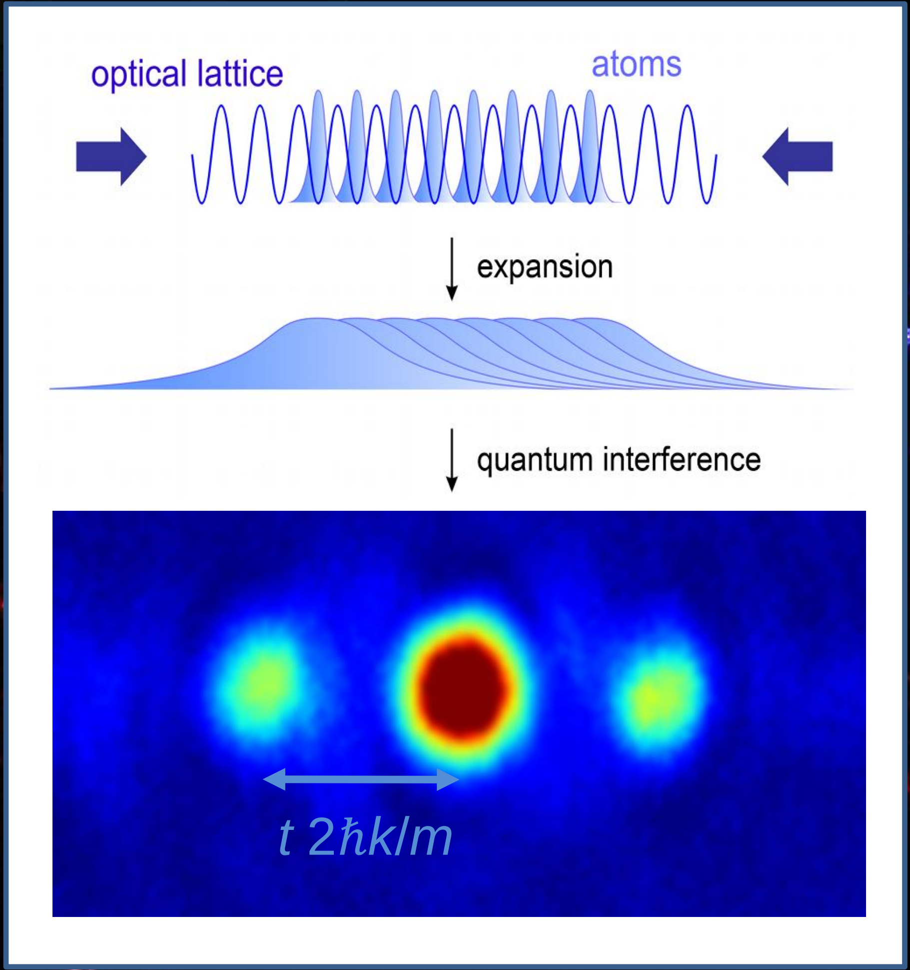
spin polarized fermions

BAND INSULATOR

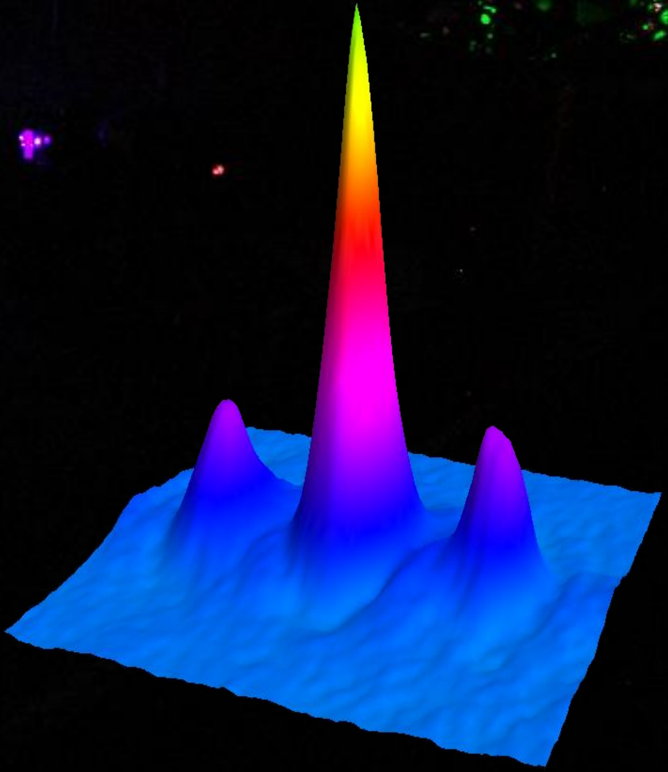


^{174}Yb BEC in optical lattice

1D optical lattice



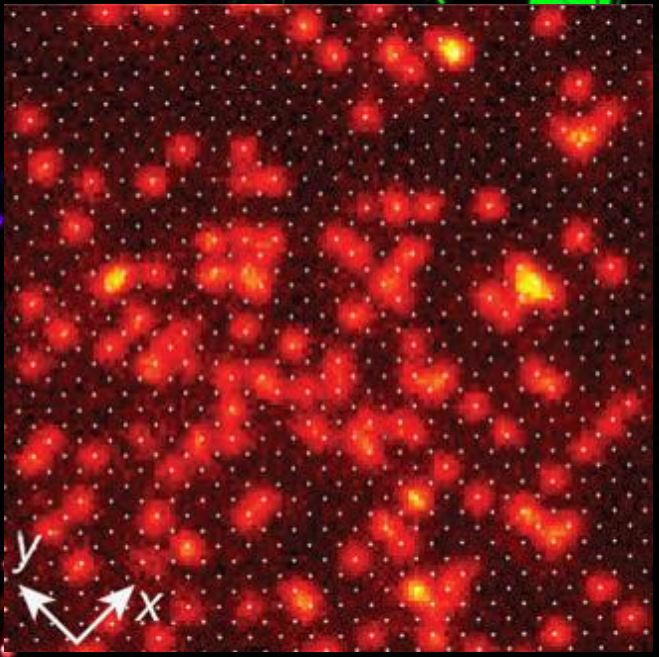
Imaging of momentum distribution after 30 ms of free expansion



Future plans

Single-site high-resolution imaging

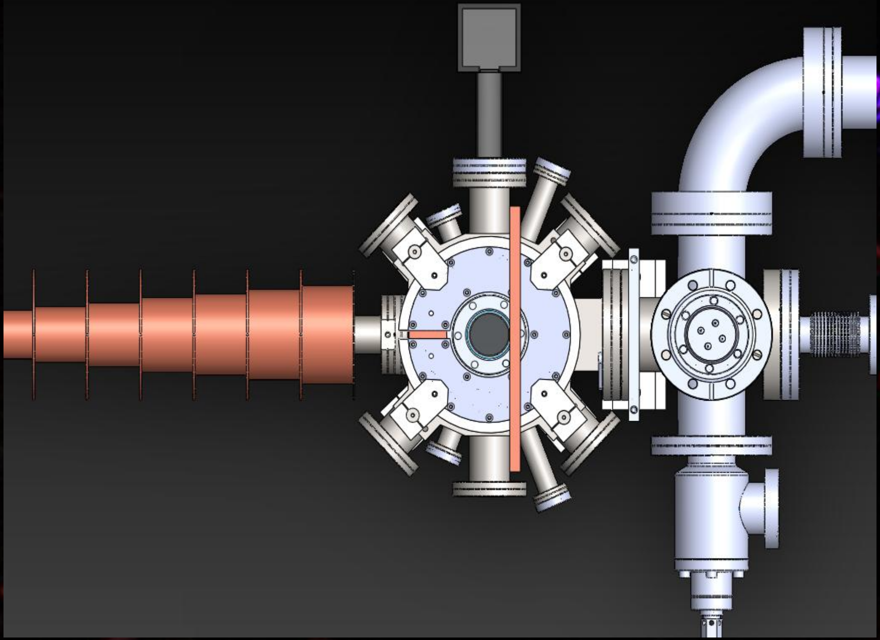
W. S. Bakr et al.,
Science 329, 547 (2010).

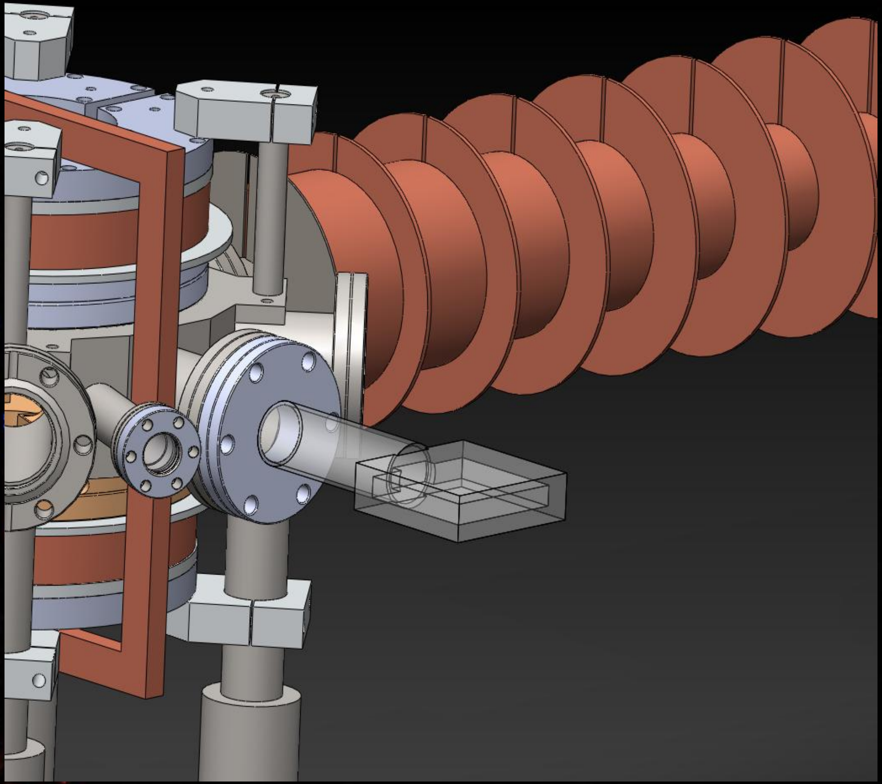


J. F. Sherson et al.,
Nature 467, 68 (2010).

Future plans

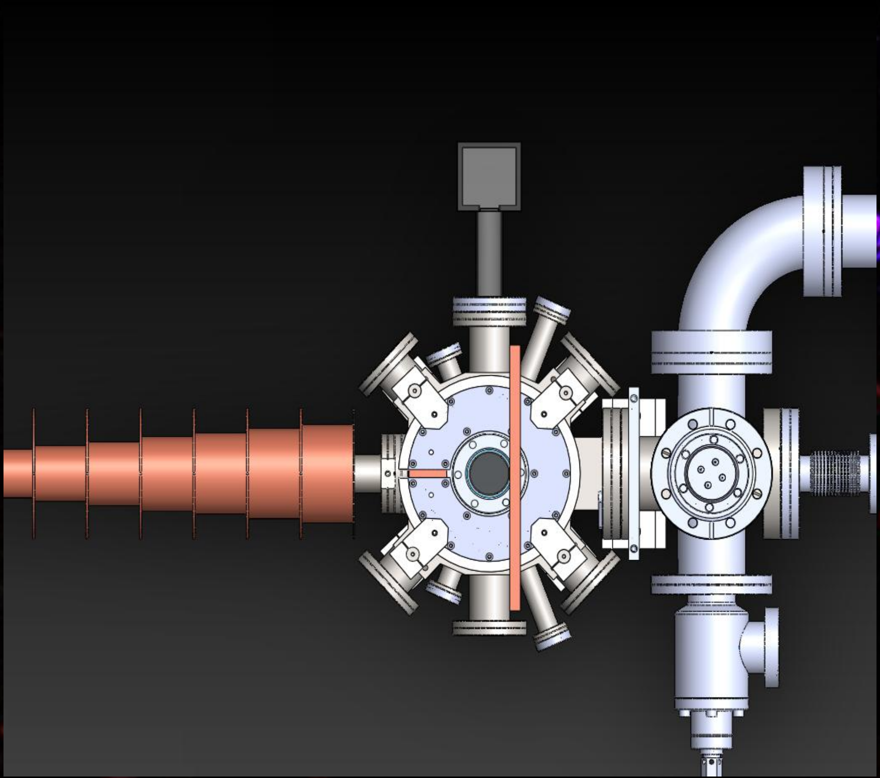
Glass cell with large optical access
for high-resolution imaging

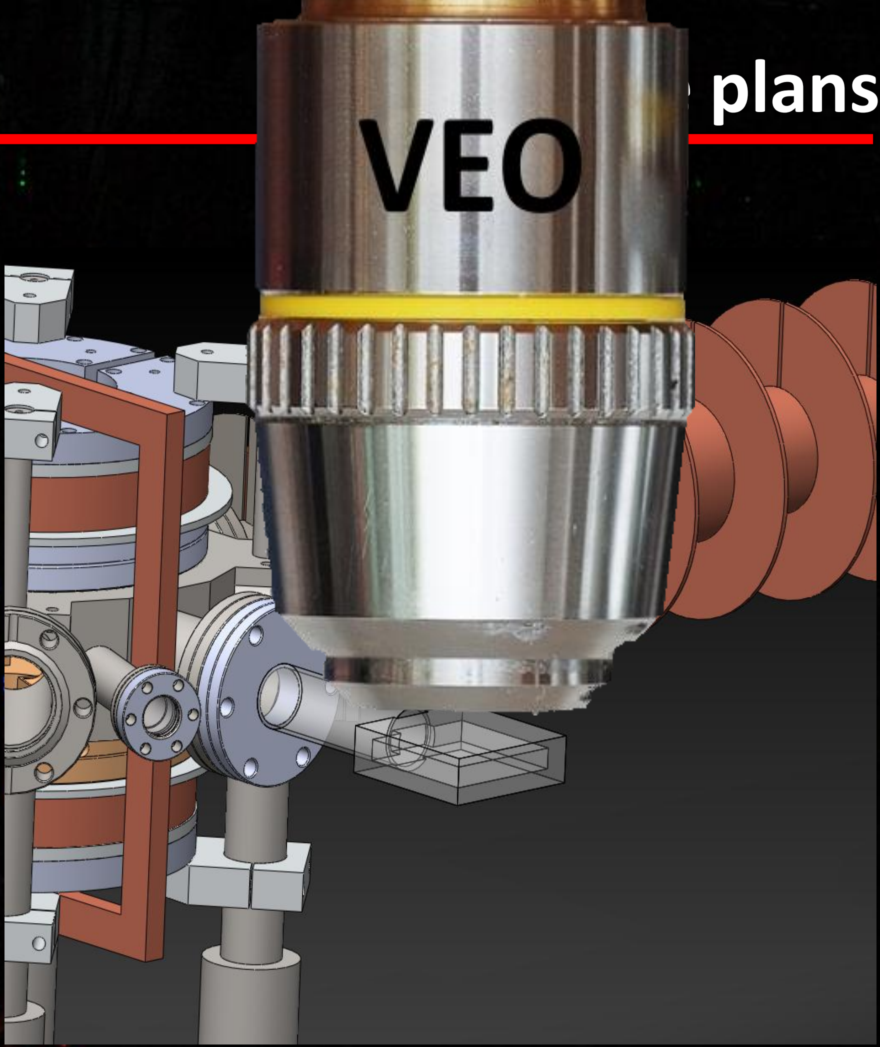




plans

Glass cell with large optical access
for high-resolution imaging

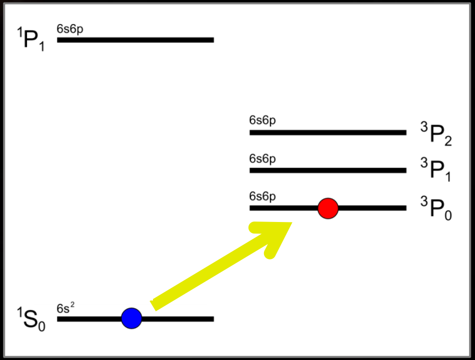


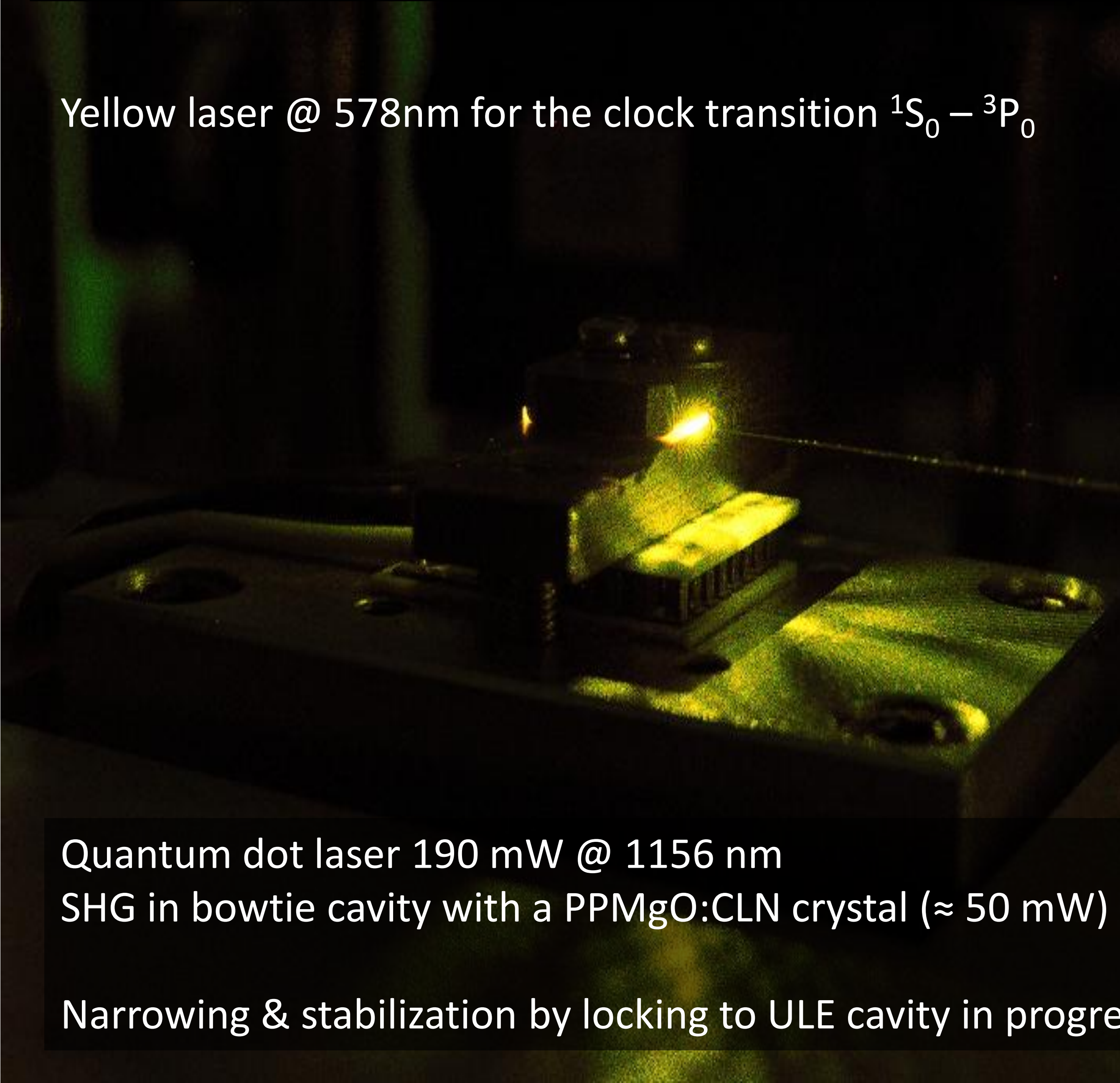


VEO = Very Expensive Objective!

Excitation of the $^3P_0$ state

Yellow laser @ 578nm for the clock transition $^1S_0 - {}^3P_0$





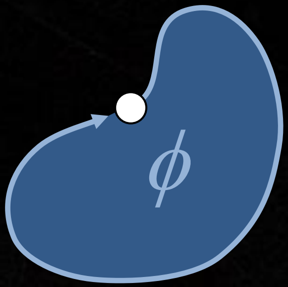
Quantum dot laser 190 mW @ 1156 nm
SHG in bowtie cavity with a PPMgO:CLN crystal (≈ 50 mW)

Narrowing & stabilization by locking to ULE cavity in progress

Synthetic gauge potentials

Abelian gauge potentials → Artificial magnetic field
QHE (integer and fractional)

$$\hat{H} = \frac{1}{2m}\left(\mathbf{p} - q\mathbf{A}\right)^2$$



Aharonov-Bohm geometric phase for
the closed loop of an electron in a magnetic field

$$\psi \rightarrow e^{i\phi}\psi$$

$$\phi = 2\pi\frac{\Phi}{\Phi_0} \qquad \Phi_0 = \frac{h}{e}$$

Non-Abelian gauge potentials → Non-Abelian anyons
Fractional statistics
Topological insulators

$$|\psi\rangle \rightarrow \hat{U}|\psi\rangle$$

U unitary transformation
of a multi-component wavefunction

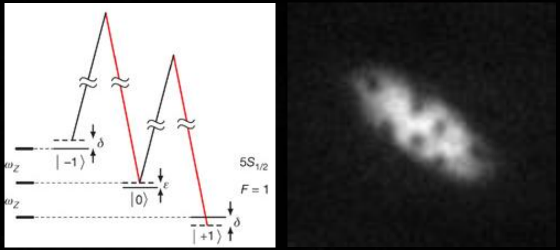
Synthetic gauge potentials

Different ways to produce artificial (Abelian) gauge potentials

J. Dalibard et al., Rev. Mod. Phys. **83**, 1523 (2011)

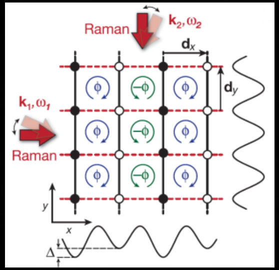
- Rotating traps
- Optical dressing in multilevel atoms

  Y.-J. Lin et al., Nature **462**, 628 (2009).



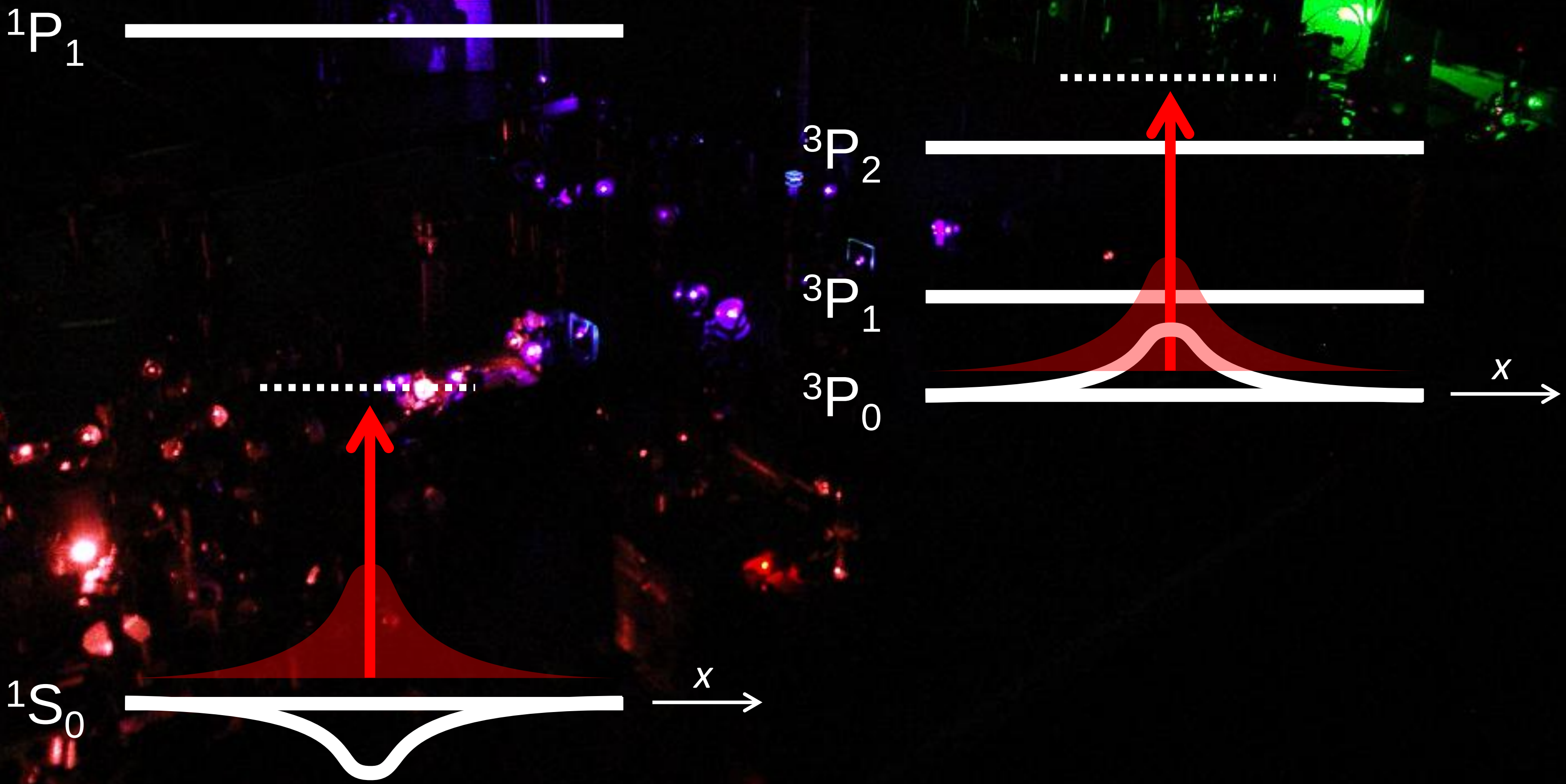
- Laser-assisted tunnelling in state-dependent lattices

  M. Aidelsburger at al., Phys. Rev. Lett. **107**, 255301 (2011).



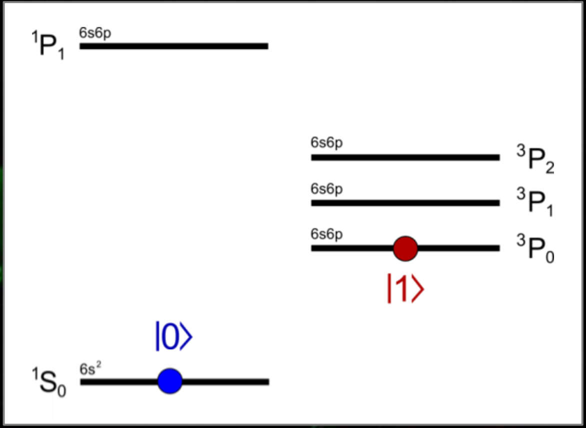
State-dependent optical trapping

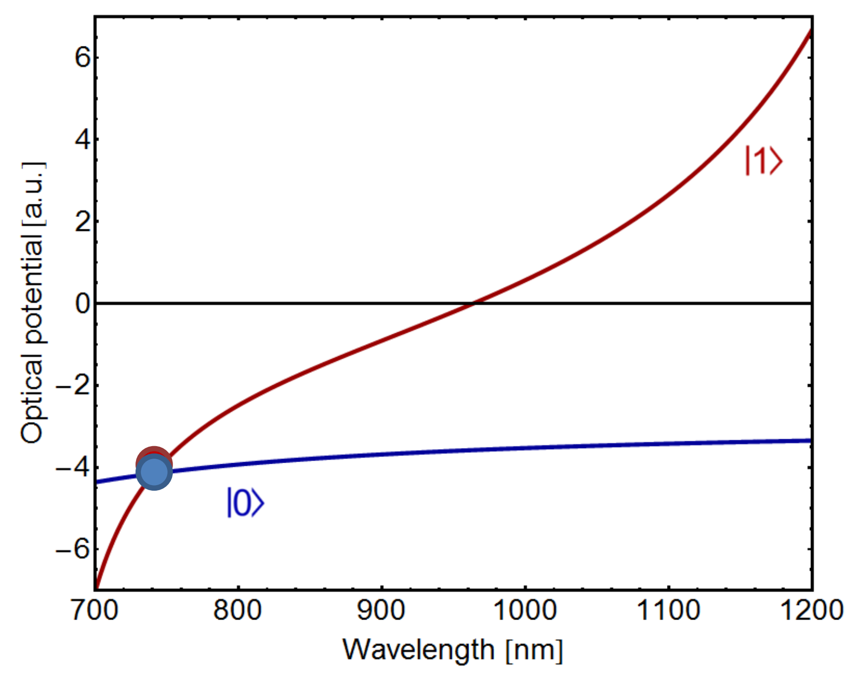
Spatially-dependent ac-Stark shift induced by off-resonant light



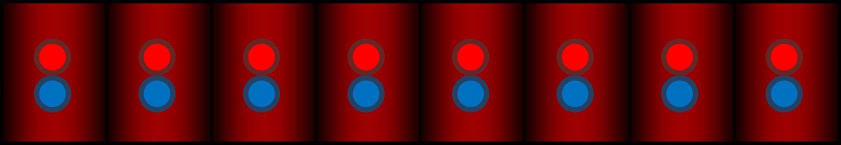
Synthetic gauge potentials

State-dependent potentials for Ytterbium

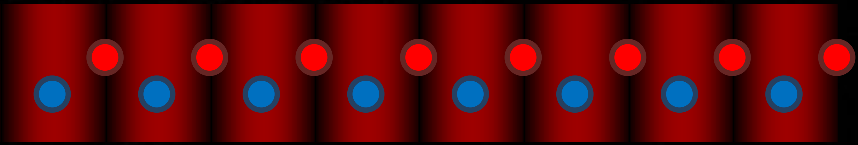




Magic wavelength 760nm



Antimagic wavelength 1120nm

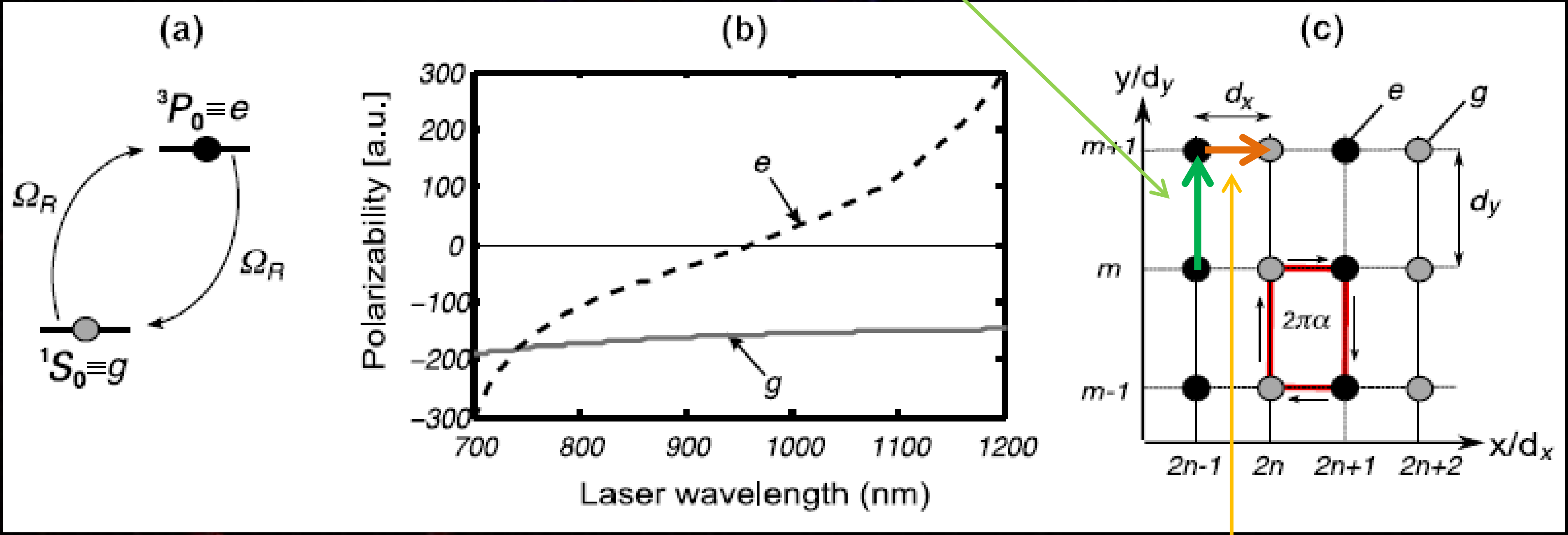


Synthetic gauge potentials

Laser-assisted tunnelling in state-dependent potentials

D. Jaksch and P. Zoller, New J. Phys. **5**, 56 (2003)

F. Gerbier and J. Dalibard, New J. Phys. **12**, 033007 (2010)



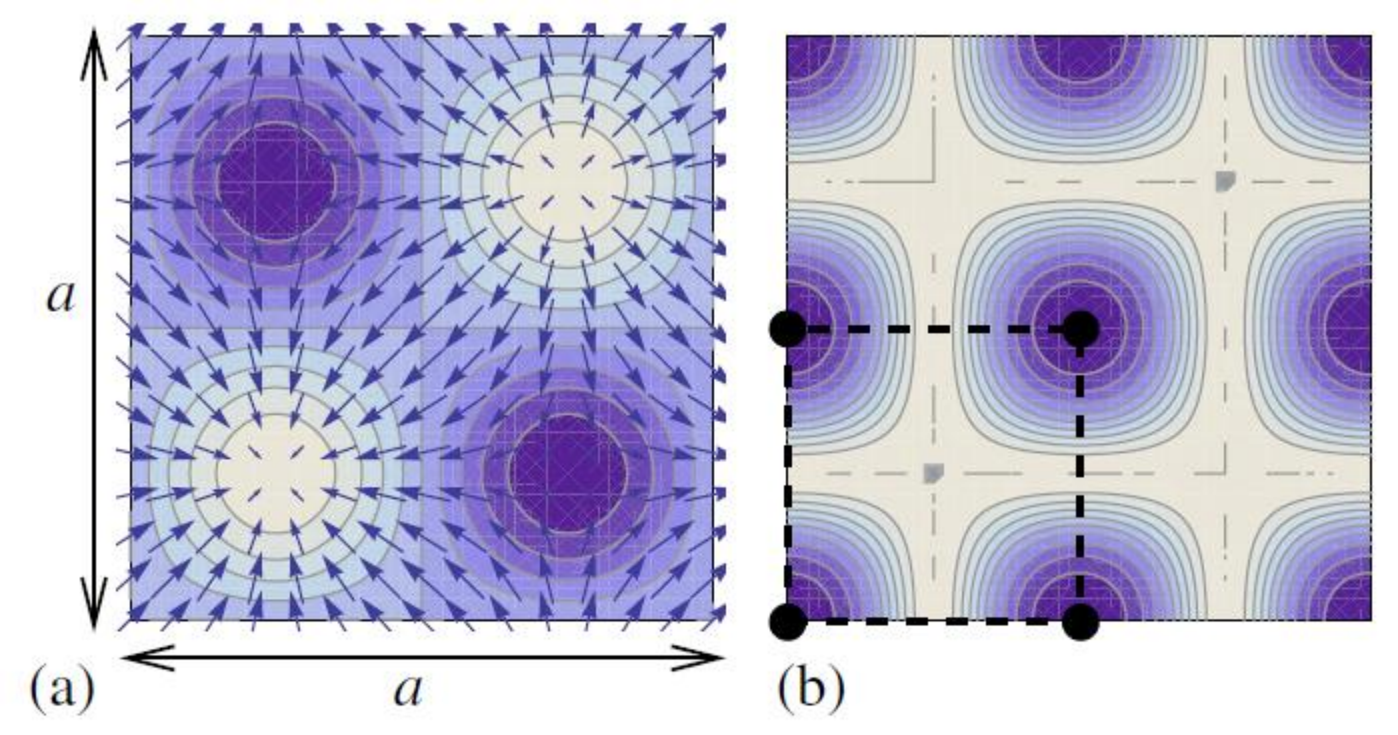
Ordinary tunnelling: J

Laser-assisted tunnelling: J exp(ikx)

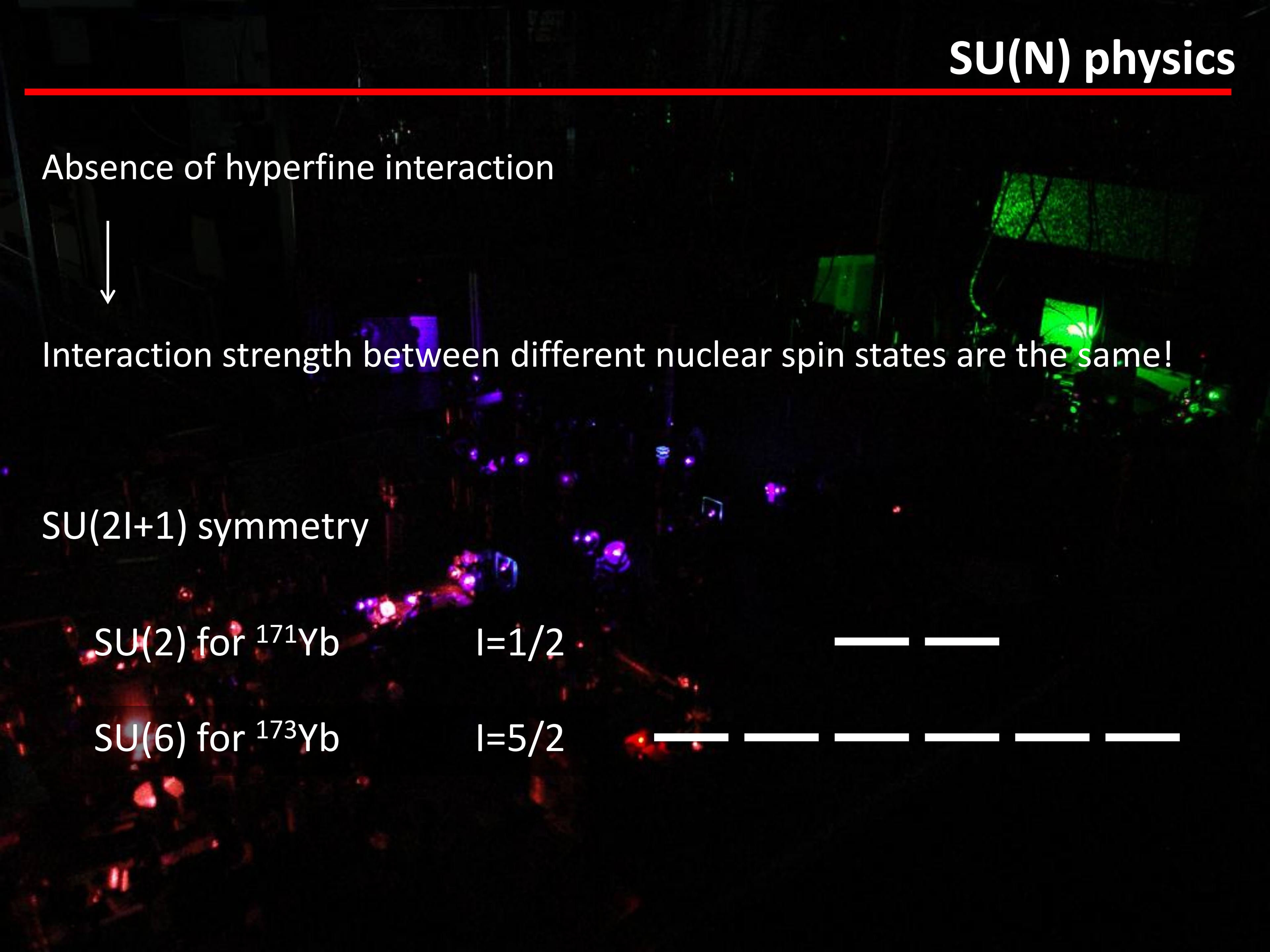
Synthetic gauge potentials

Optical flux lattices

N. Cooper, PRL **106**, 175301 (2011)



SU(N) physics



Absence of hyperfine interaction

↓

Interaction strength between different nuclear spin states are the same!

SU(2I+1) symmetry

SU(2) for ^{171}Yb I=1/2 — —

SU(6) for ^{173}Yb I=5/2 — — — — — —

SU(N) magnetism

Example: interacting fermions (repulsive) on a square lattice

Fermi-Hubbard model

$$\hat{H} = t \sum_{<ij>,\alpha=1,\dots,N} \left(\hat{f}^{\dagger}_{i,\alpha}\hat{f}_{j,\alpha} + h.c.\right) + U \sum_{i,\alpha,\beta} \hat{f}^{\dagger}_{i,\alpha}\hat{f}_{i,\alpha}\hat{f}^{\dagger}_{i,\beta}\hat{f}_{i,\beta}$$

$\downarrow$ U >> t

SU(N) symmetric Heisenberg model

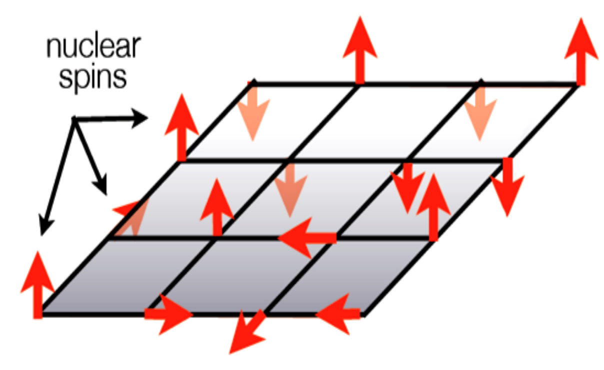
$S_{\alpha\beta}(\boldsymbol{r}) = f^{\dagger}_{\boldsymbol{r}\alpha} f_{\boldsymbol{r}\beta}$ SU(N) spin

$$\mathcal{H} = J \sum_{\langle \boldsymbol{r}\boldsymbol{r}'\rangle} S_{\alpha\beta}(\boldsymbol{r}) S_{\beta\alpha}(\boldsymbol{r}')$$

$$J = \frac{2t^2}{U}$$

superexchange interaction

Independent of spin projection α!

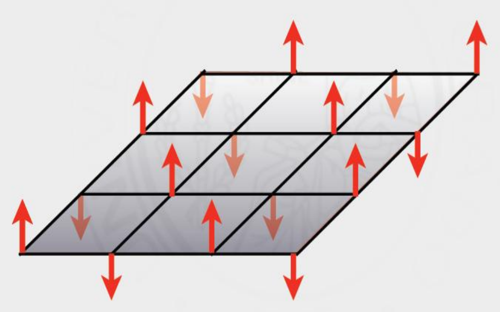


SU(N) magnetism

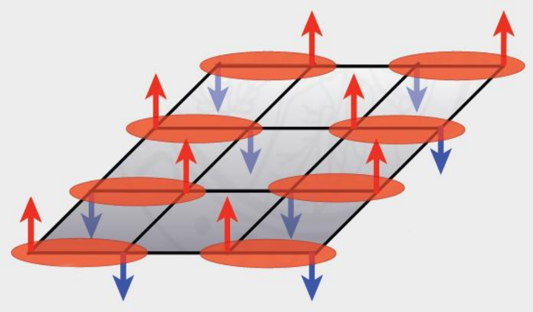
Increased symmetry ⟶ Exotic ground states, Topological excitations

Possible ground states (phase diagram largely unknown):

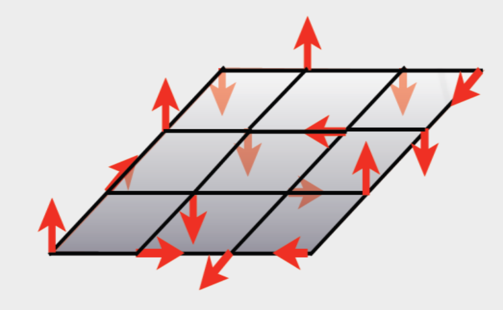
Neel state



Valence Bond Solids



Chiral Spin Liquids

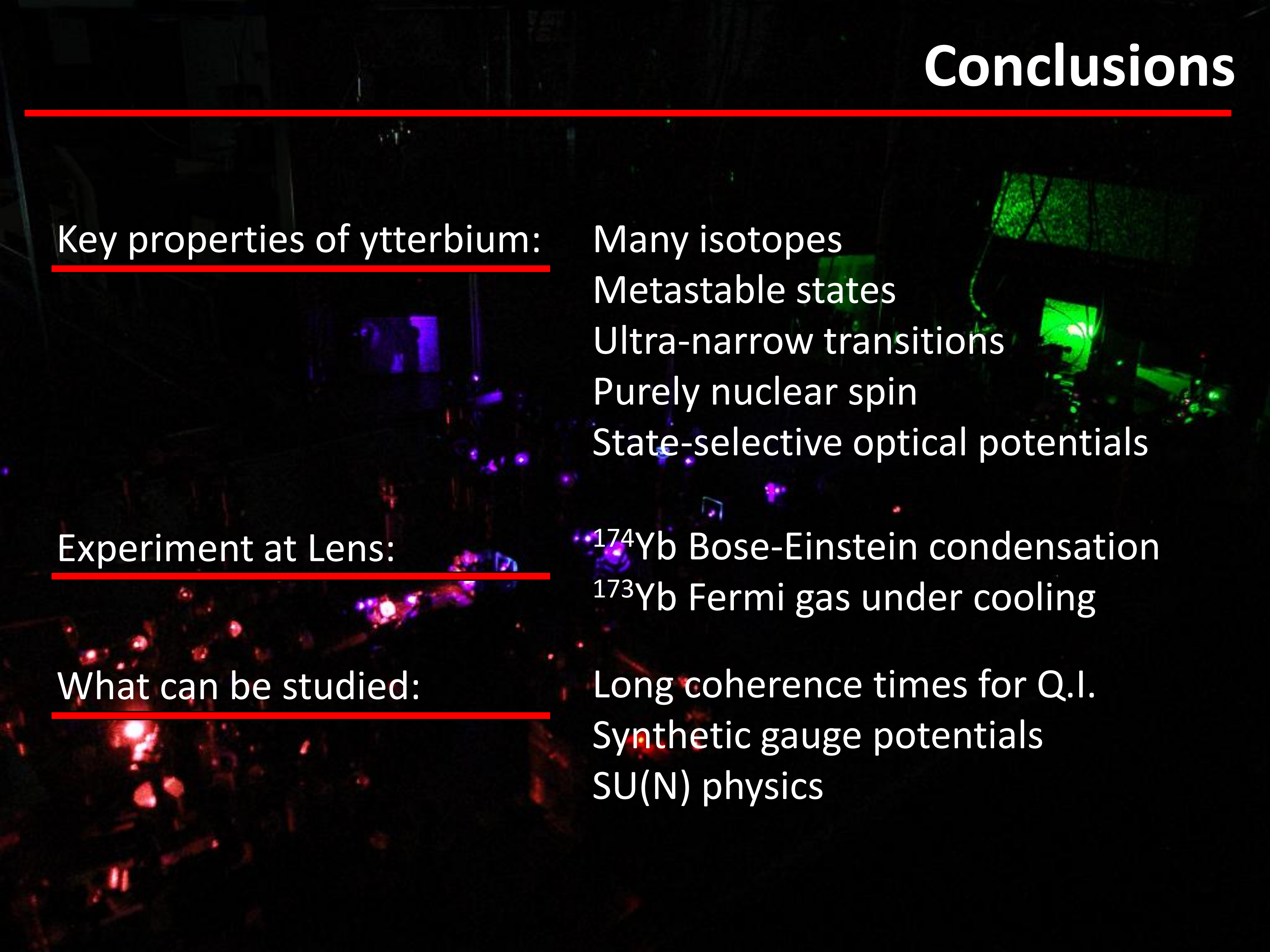


Figures from V. Gurarie
KITP “Beyond Standard Optical Lattices“ (2010) online talk

Non-Abelian excitations
Fractional statistics

Some references to SU(N):

M. A Cazalilla et al., New J. Phys. **11**, 103033 (2009).
M. Hermele et a., Phys. Rev. Lett. **103**, 135301 (2009).
A. V. Gorshko et al., Nature Physics **6**, 289 (2010).



Conclusions

Key properties of ytterbium:

- Many isotopes
- Metastable states
- Ultra-narrow transitions
- Purely nuclear spin
- State-selective optical potentials

Experiment at Lens:

- ^{174}Yb Bose-Einstein condensation
- ^{173}Yb Fermi gas under cooling

What can be studied:

- Long coherence times for Q.I.
- Synthetic gauge potentials
- SU(N) physics