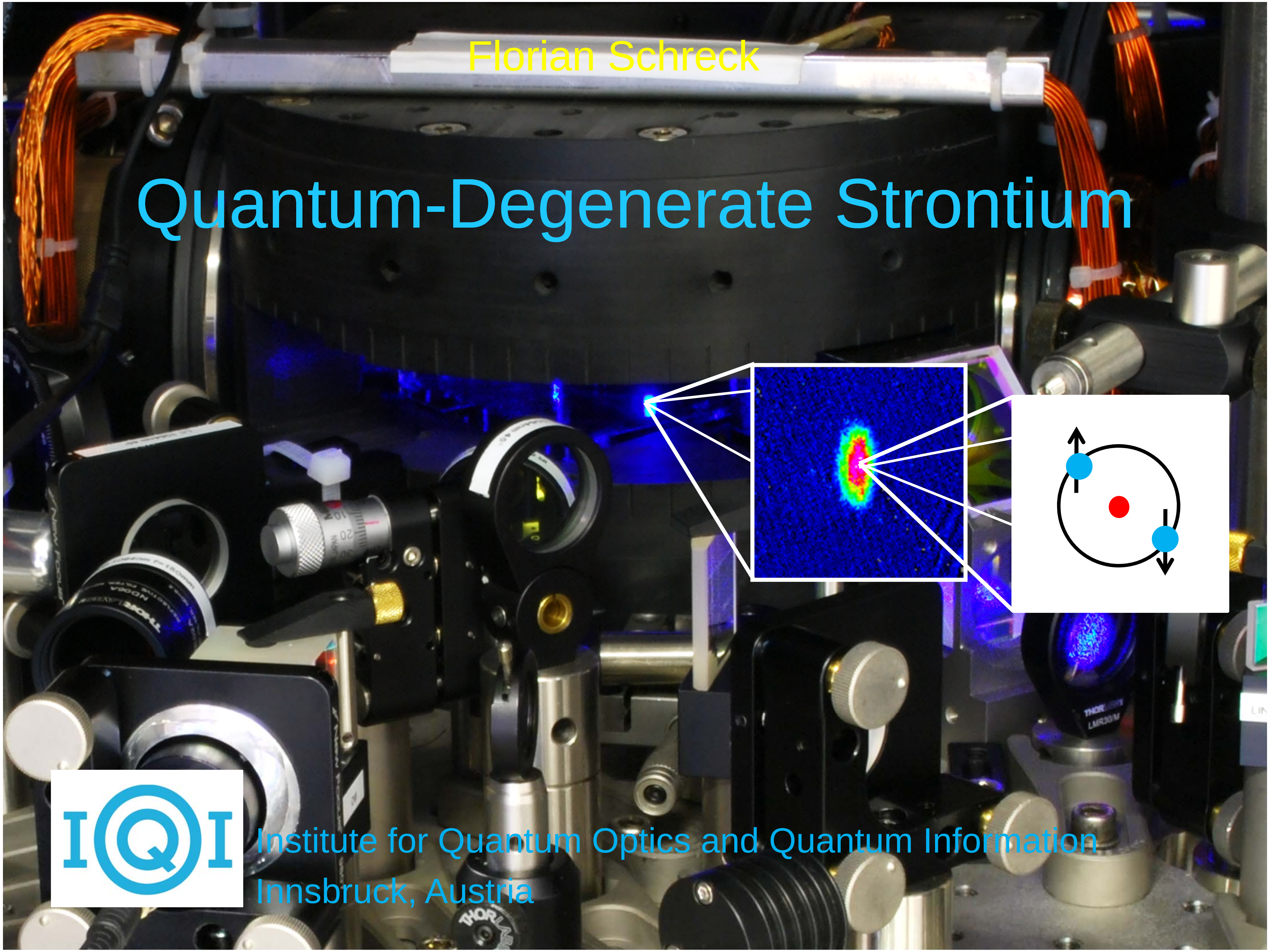
Florian Schreck

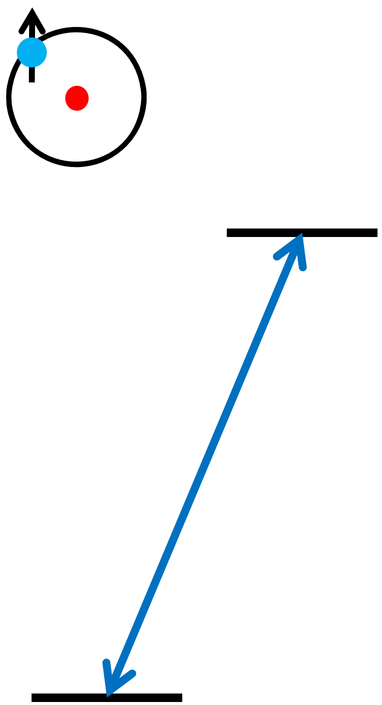
Quantum-Degenerate Strontium

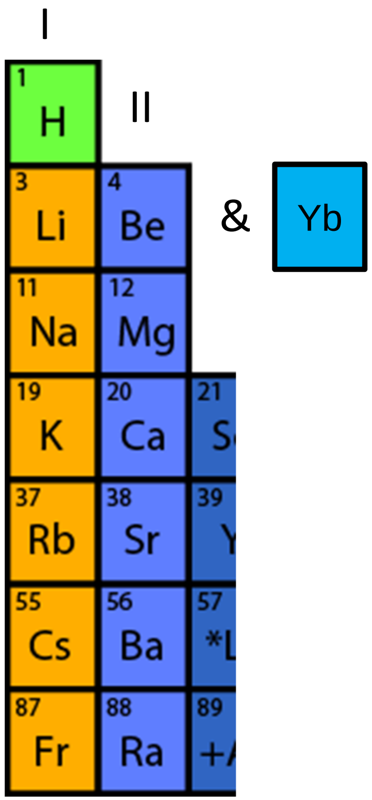


IQI
Institute for Quantum Optics and Quantum Information
Innsbruck, Austria

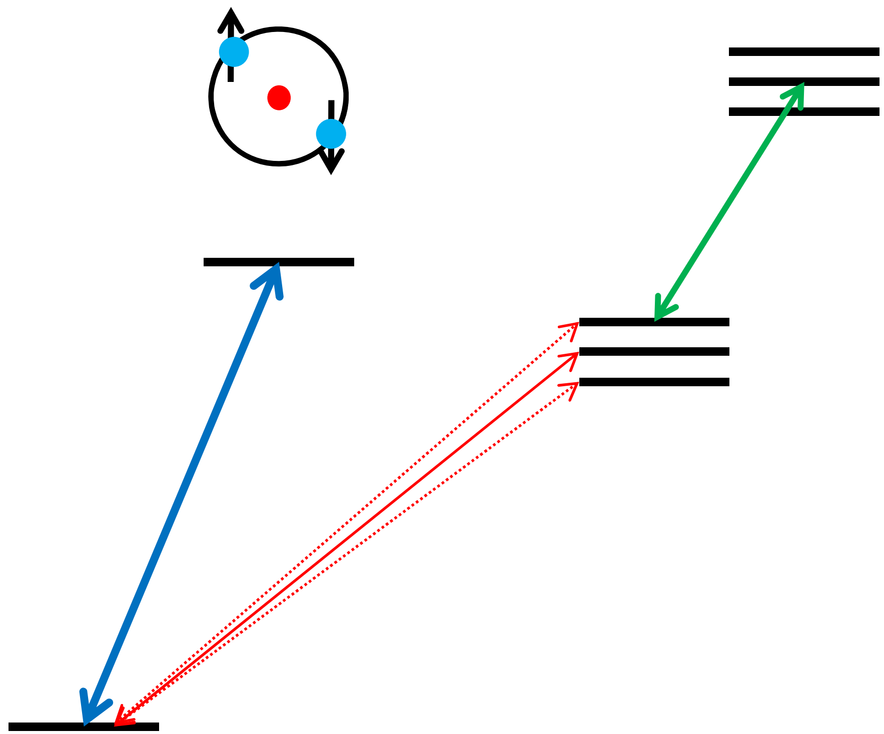
Alkaline-earth elements

Alkali atoms:
one valence electron





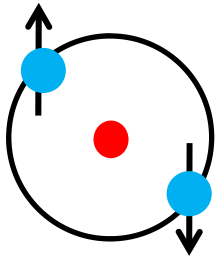
Alkaline-earth (like) atoms:
two valence electrons



Overview

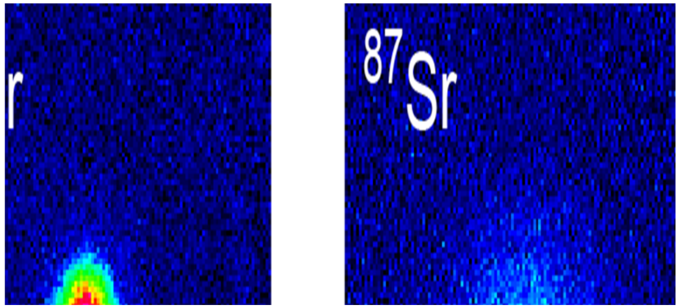
What‘s new?

Properties and opportunities
of alkaline-earth elements



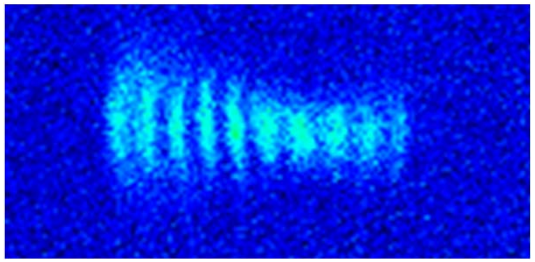
Achieving quantum degeneracy:

BECs and Fermi sea of strontium

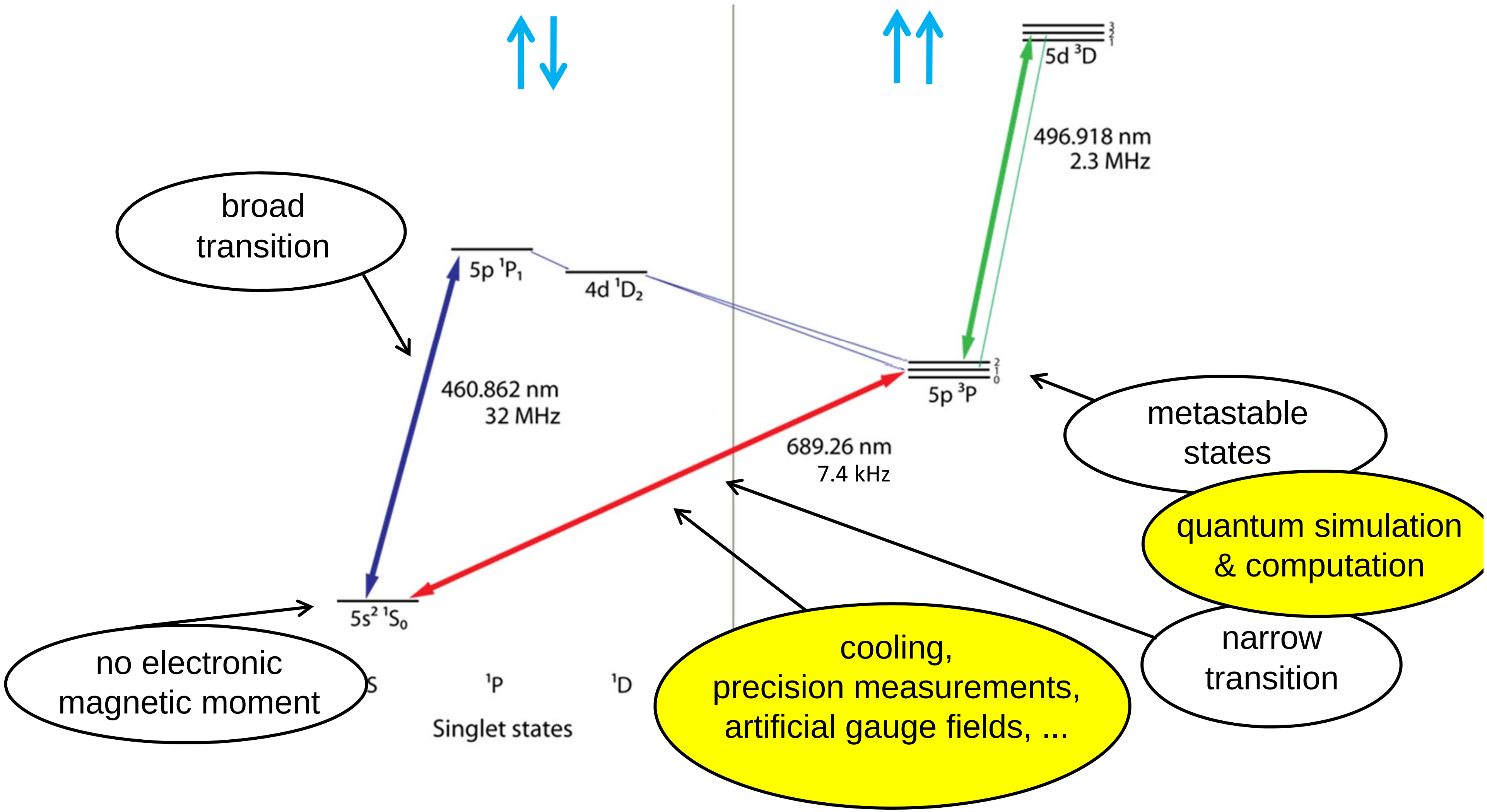


New tools for new quantum gases:

nuclear spin manipulation of ^{87}Sr



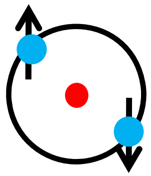
Strontium level scheme



Bosons and fermions

Bosons

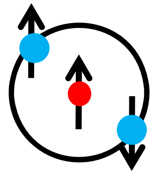
^{84}Sr, ^{86}Sr, ^{88}Sr



no nuclear spin

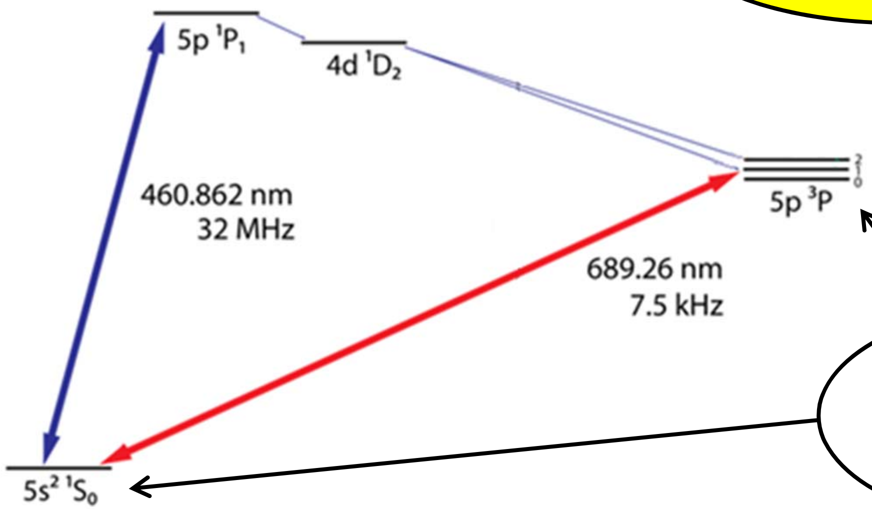
Fermion

^{87}Sr



nuclear spin I = 9/2

quantum simulation & computation

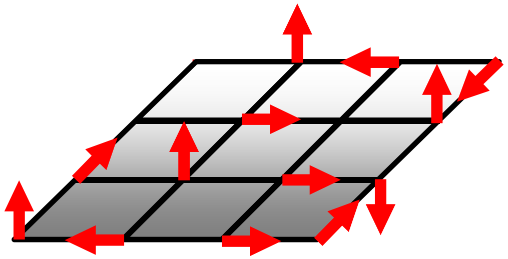


electronic and nuclear spin **not coupled**

Opportunities

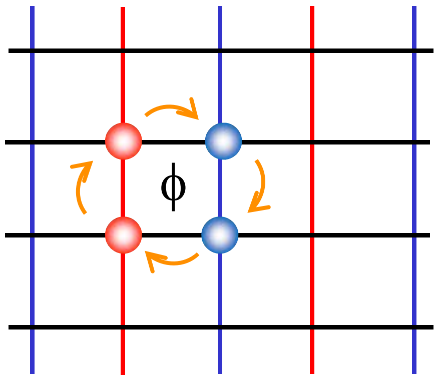
SU(*N*) magnetism

Hermele, Gurarie, and Rey 2009



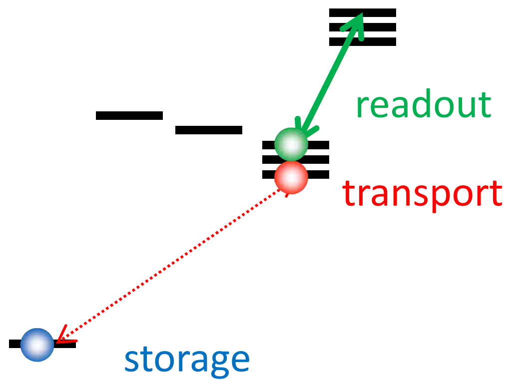
Artificial gauge fields

Gerbier and Dalibard 2010
Cooper 2011

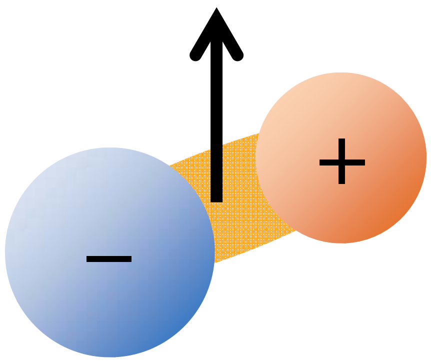


Quantum computation schemes

Stock, Babcock, Raizen, and Sanders 2008
Daley, Boyd, Ye, and Zoller 2008

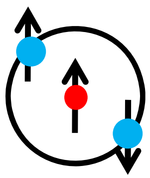


RbSr ground-state molecules



SU(*N*) magnetism

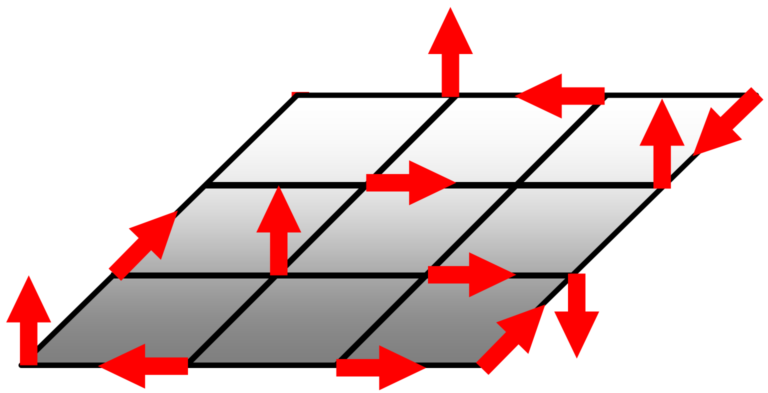
Fermionic alkaline-earth atom (e.g. ^{87}Sr):



electronic and nuclear spin NOT coupled
→ scattering properties independent of nuclear spin orientation
but for fermionic statistics

leads to SU(*N*) spin symmetry!

^{87}Sr on lattice: study SU(*10*) magnetism



Ground state of SU(∞) is chiral spin liquid

Hermele *et al.*, PRL **103**, 135301 (2009)
Gorshkov *et al.*, nature physics **6**, 289 (2010)

Artificial gauge fields

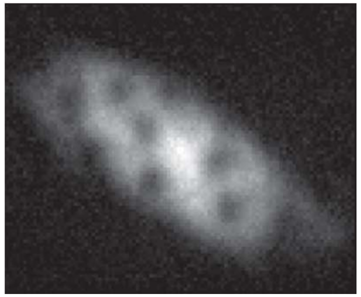
Example:

Quantum simulation of charged particles in strong magnetic fields
to observe e.g. quantum Hall effect

Challenge:

We work with **neutral** atoms $\longrightarrow$ need to simulate effect of B-field on electrons

Ian Spielman‘s group using rubidium:



- B-field proportional to **length** of sample

nature 426, 628 (2009)

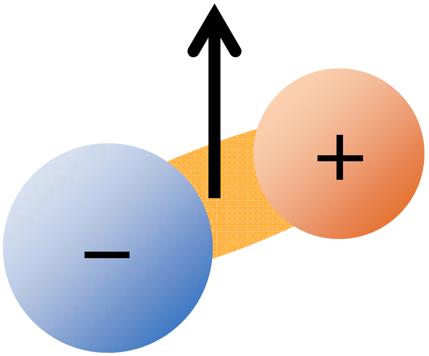
Alkaline-earth:

- B-field proportional to **surface** of sample
- lattice geometry

Gerbier and Dalibard, New J. Phys. **12,** 033007 (2010)
Cooper, PRL **106**, 175301 (2011)
Górecka, Grémaud, and Miniatura, arXiv:1105.3535

RbSr ground-state molecules

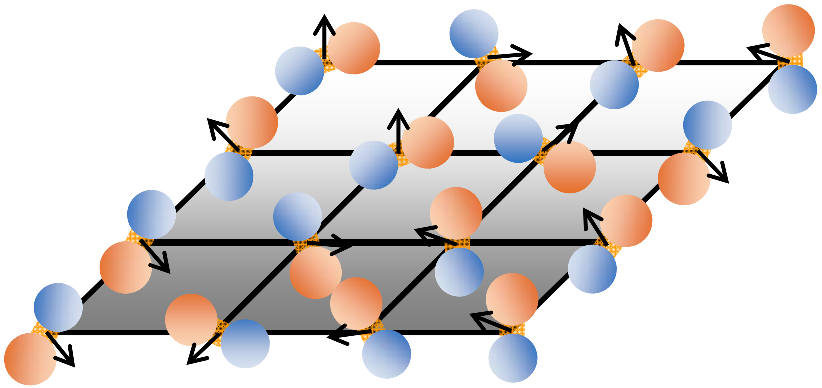
RbSr ground-state molecules



Have electric (1.5 Debye) **and** magnetic (1 μB) dipole moment

(So far only electric **or** magnetic dipole moment)

Leads to anisotropic, long-range interactions that are **spin dependent**!



Simulation of lattice-spin models

Micheli *et al.*, nature physics **2**, 341 (2006)

Overview

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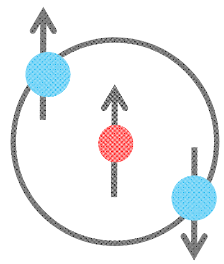
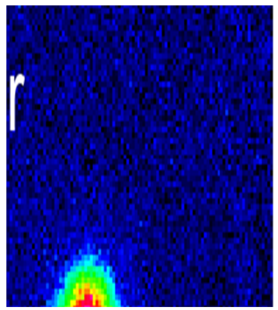
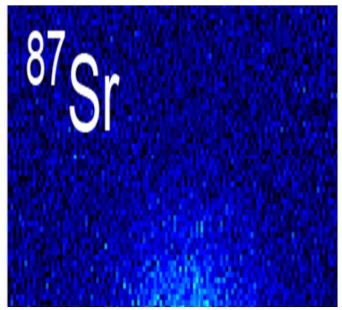


Achieving quantum degeneracy:

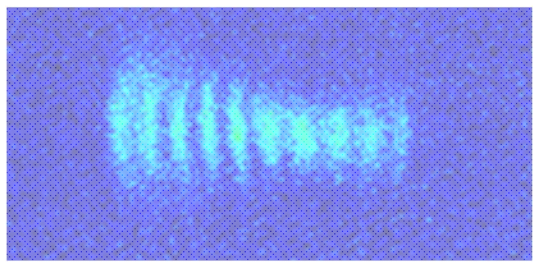
BECs and Fermi sea of strontium





New tools for new quantum gases:

nuclear spin manipulation of ^{87}Sr



Towards high phase-space density

2000: ^{88}Sr at phase-space density of 0.1

PHYSICAL REVIEW A, VOLUME 61, 061403(R)

Optical-dipole trapping of Sr atoms at a high phase-space density

Tetsuya Ido,[1] Yoshitomo Isoya,[1] and Hidetoshi Katori[1,2]

2006: cooling of ^{88}Sr/ ^{86}Sr mixture to phase-space density of 0.06

PHYSICAL REVIEW A **73**, 023408 (2006)

Cooling of Sr to high phase-space density by laser and sympathetic cooling in isotopic mixtures

G. Ferrari, R. E. Drullinger, N. Poli, F. Sorrentino, and G. M. Tino*

New approach

Bosonic strontium isotopes:

Isotope	Natural abundance	Scattering length	
~~^{88}Sr~~	82.58 %	-2 a_0	no collisions
~~^{86}Sr~~	9.86 %	+800 a_0	inelastic collisions
^{84}Sr	0.56 %	?	

New approach

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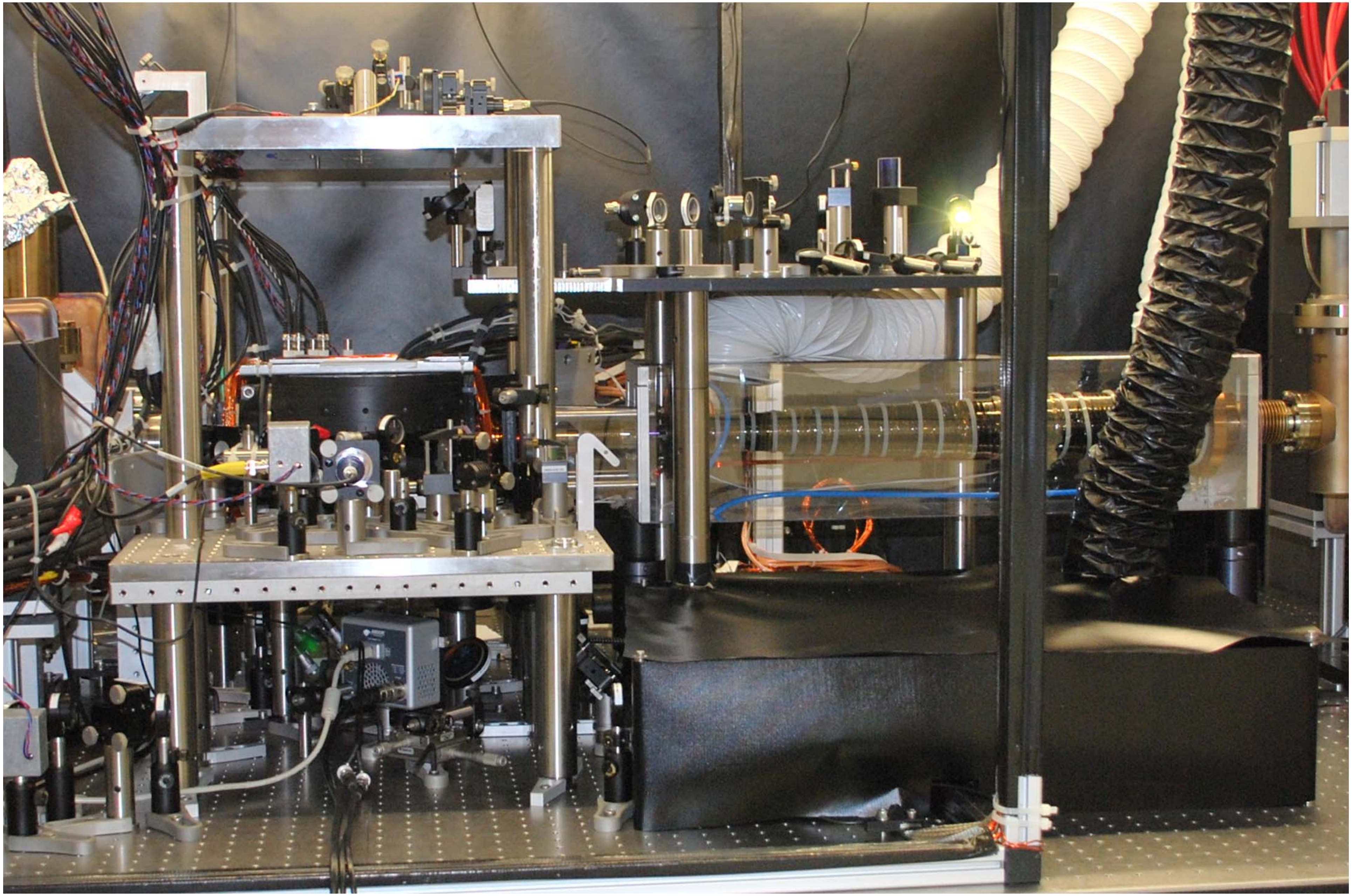
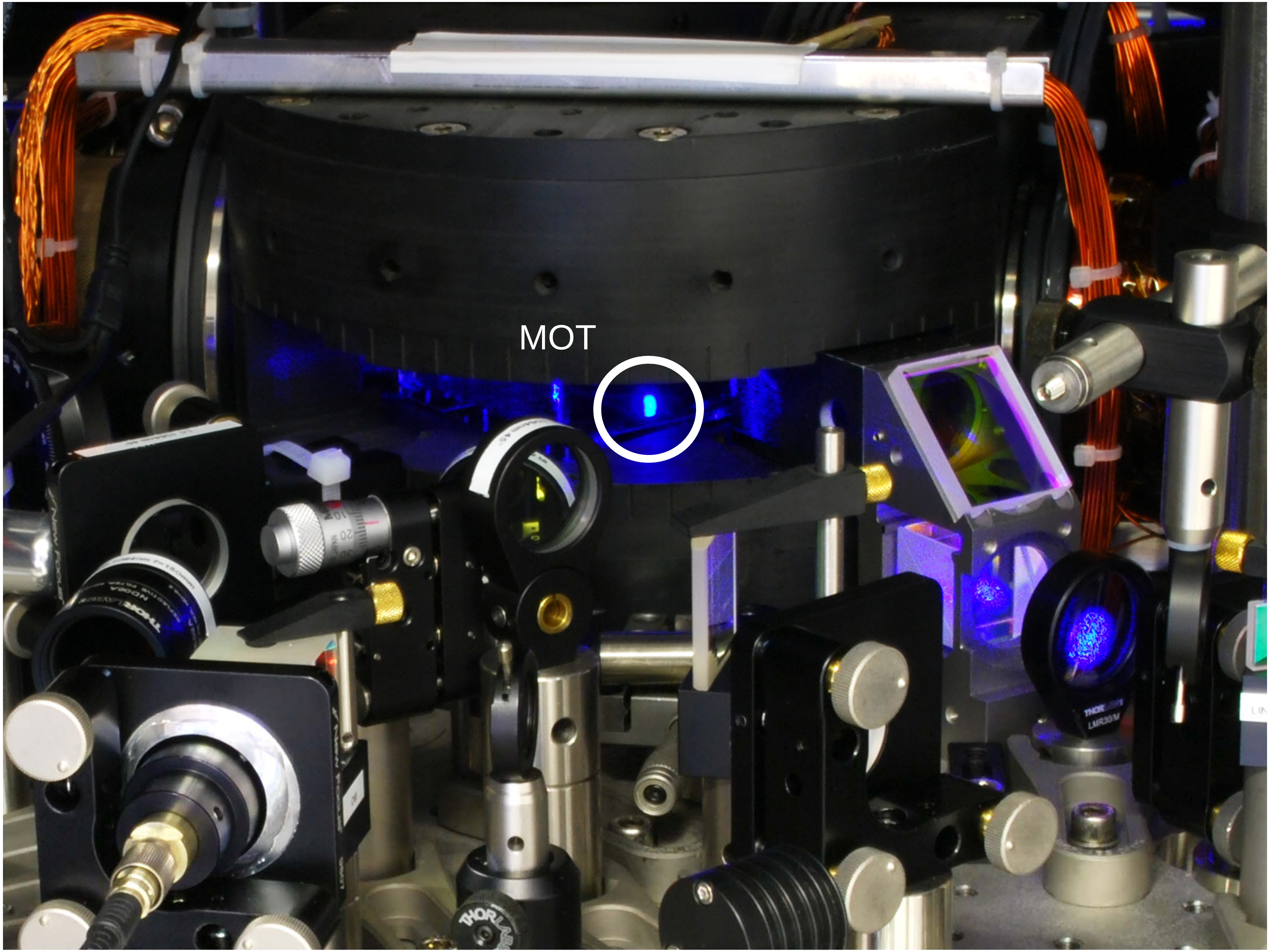
~~^{86}Sr~~	9.86 %	+800 a_0	inelastic collisions
^{84}Sr	0.56 %	+124 a_0	by Roman Ciurylo using PRL **95**, 223002

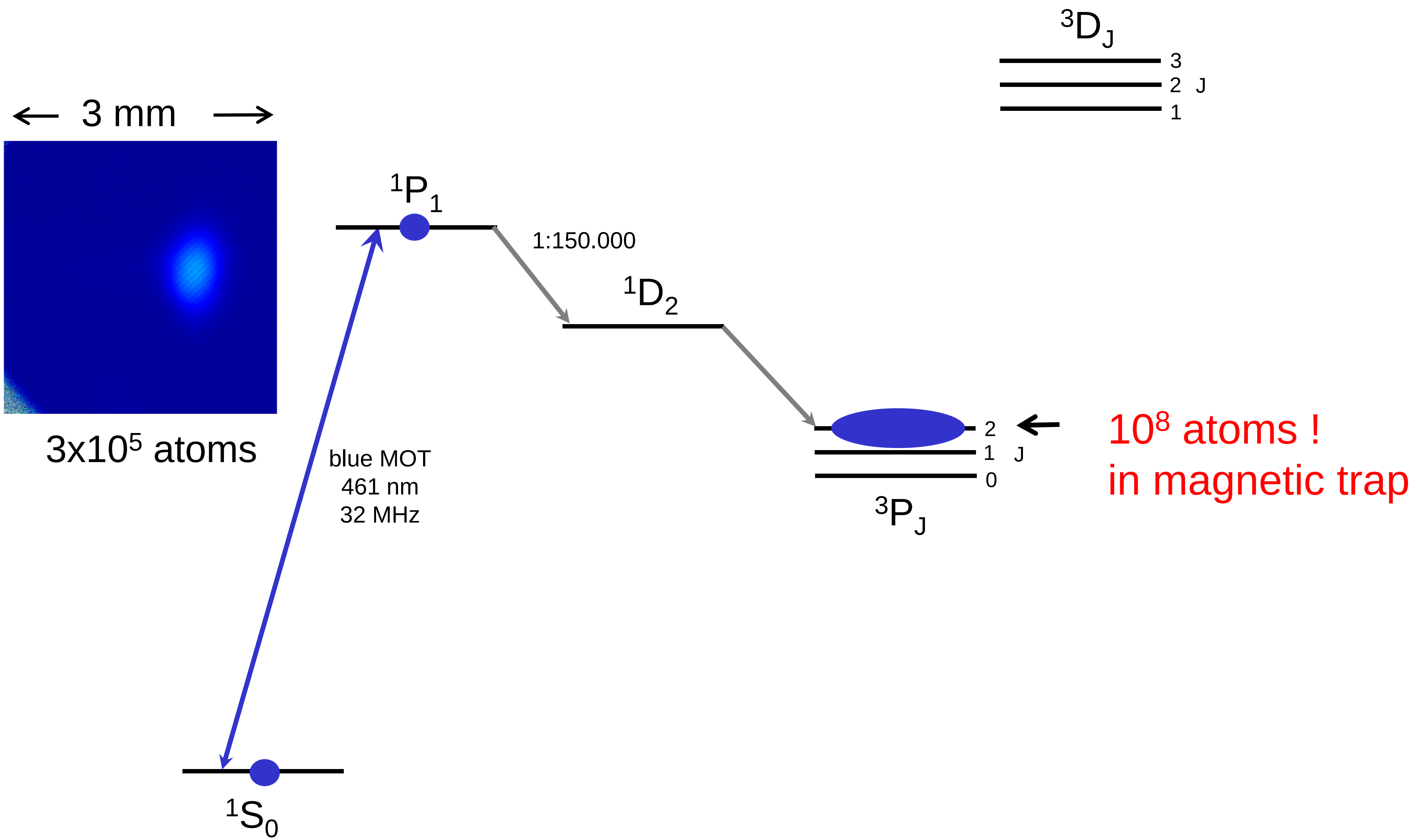
⟹ Our strategy: use ^{84}Sr

Let's do it!

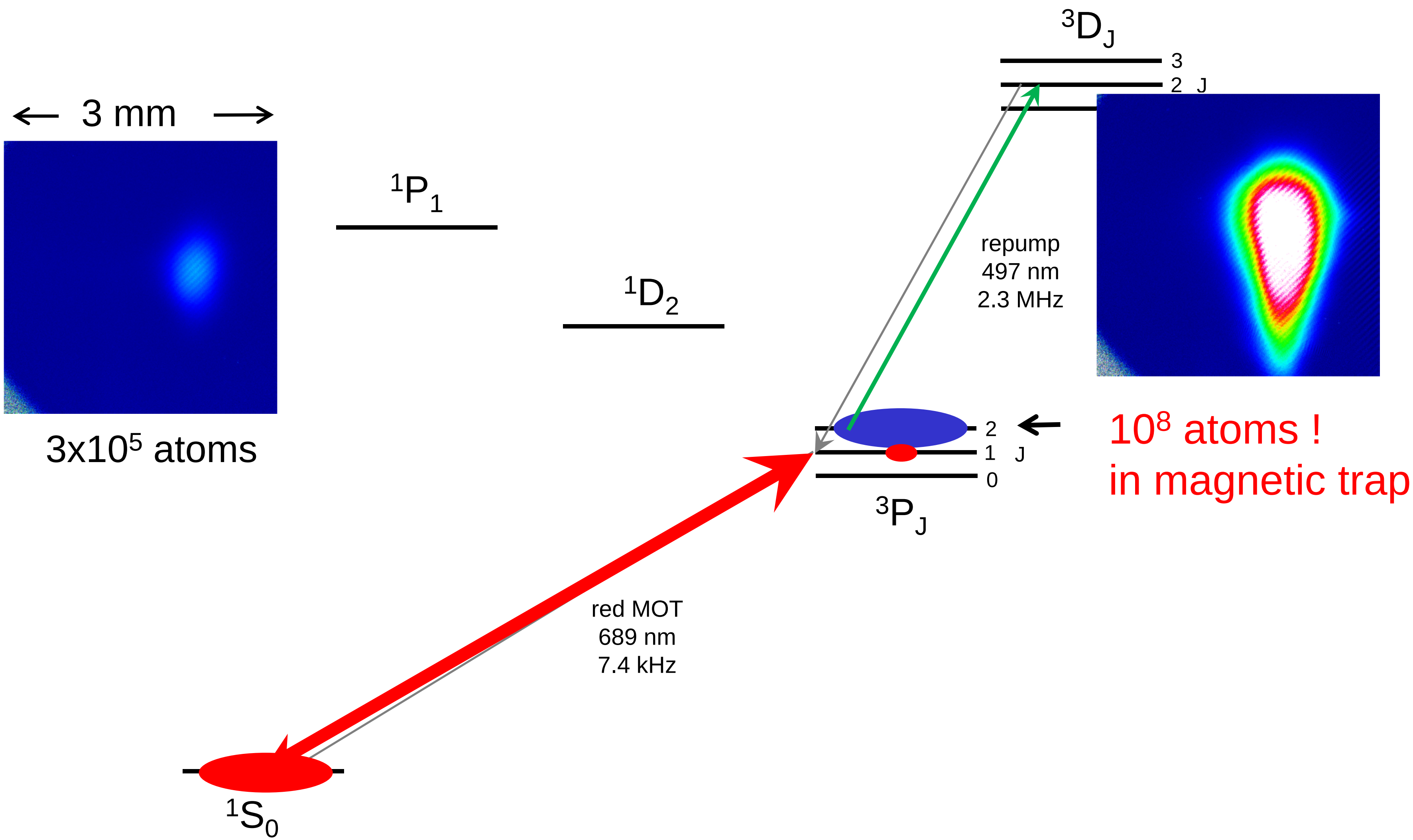



MOT
LMR30/M

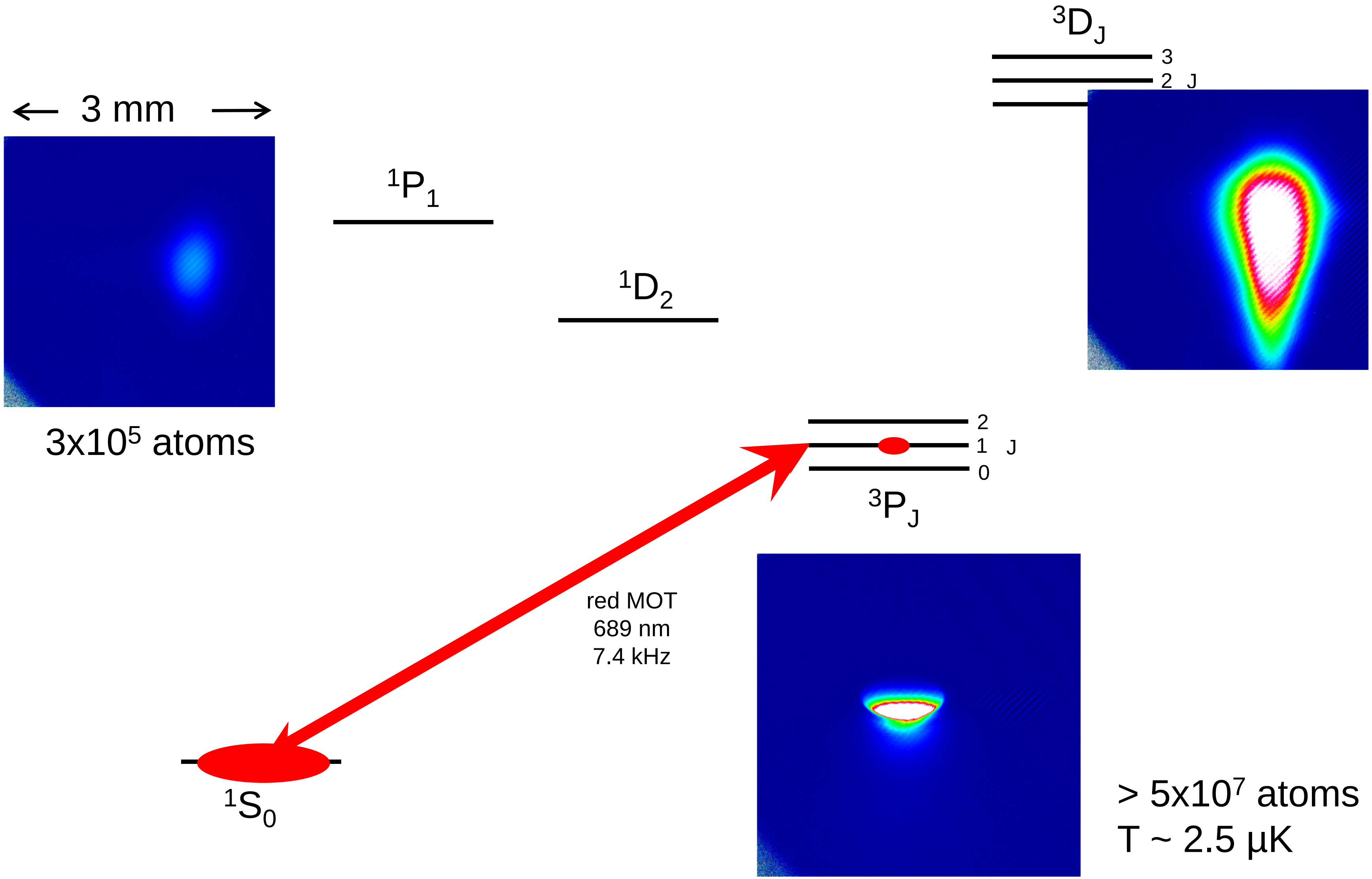
accumulation in metastable state



narrow linewidth MOT

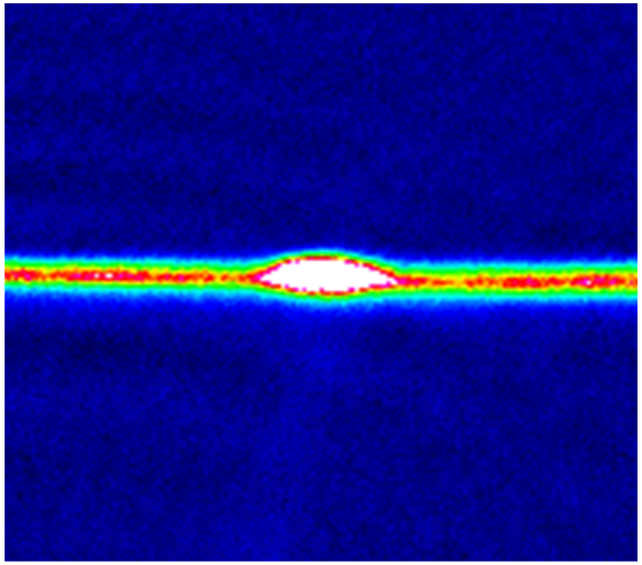


narrow linewidth MOT



narrow linewidth MOT

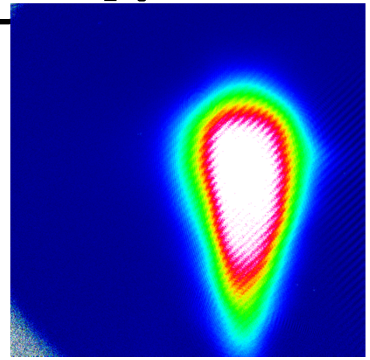
Atoms in dipole trap



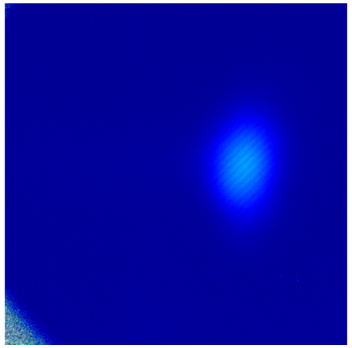
^3D_J

3

2 J



← 3 mm →



3×10^5 atoms

J

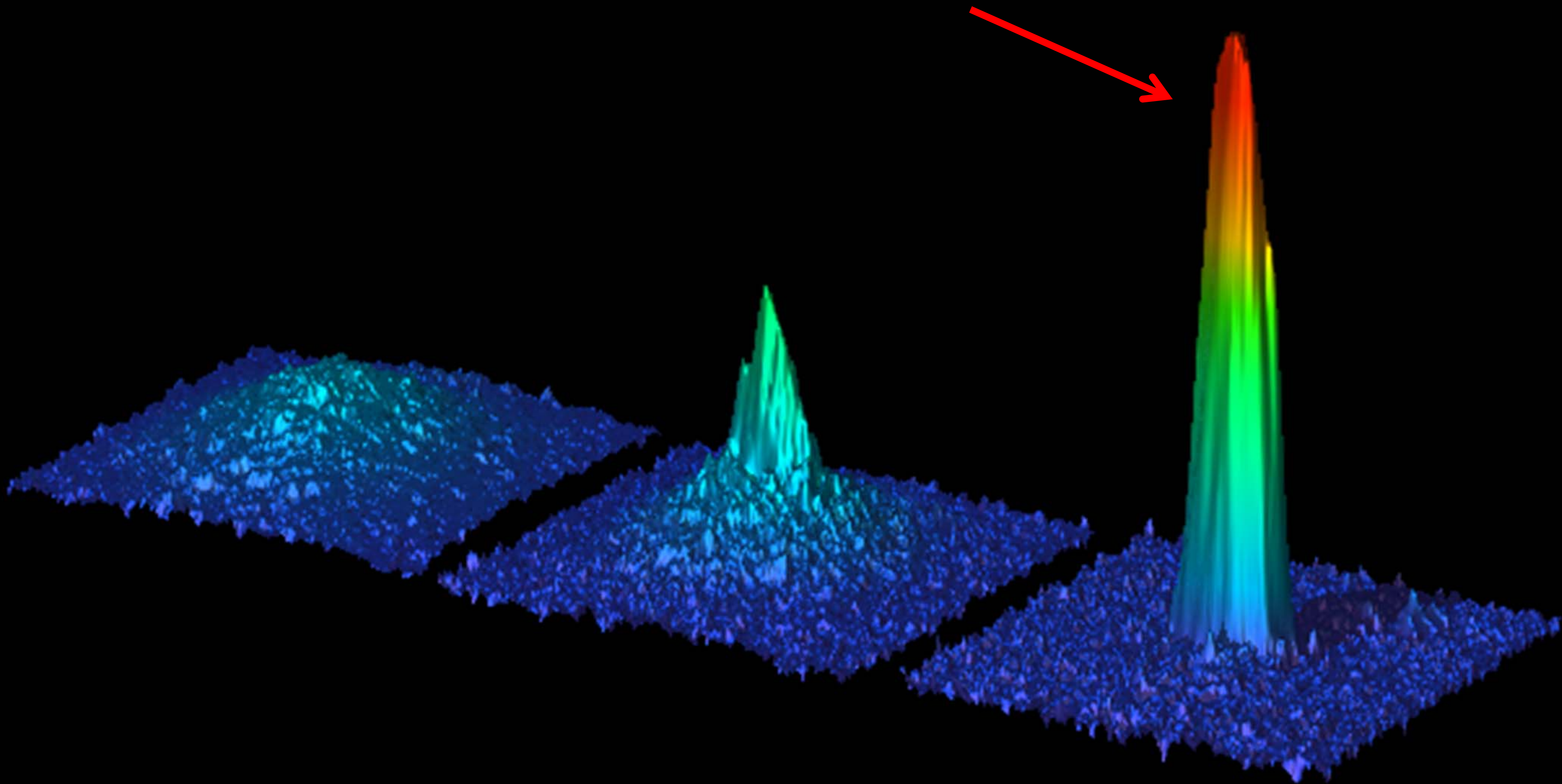
10^6 atoms with
phase-space density of

0.02 !

$^1S_0$

> 5×10^7 atoms
T ~ 2.5 μK

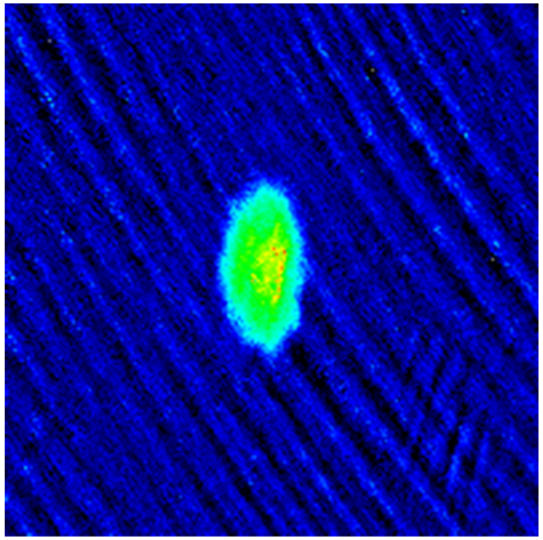
1.5 x 10^5 atoms in pure BEC!



See also work by Tom Killian's group

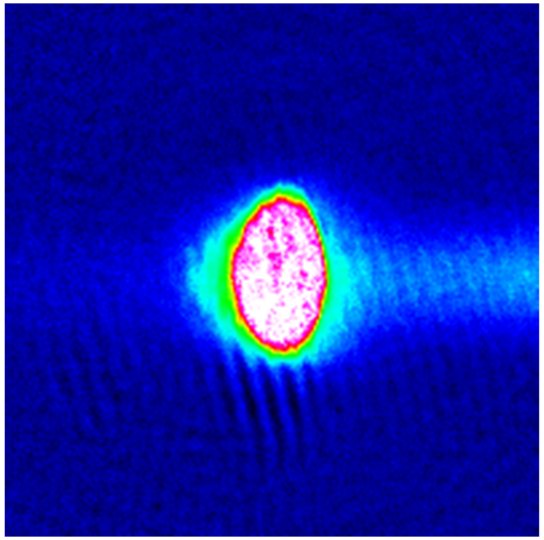
^{84}Sr BEC today

2009:

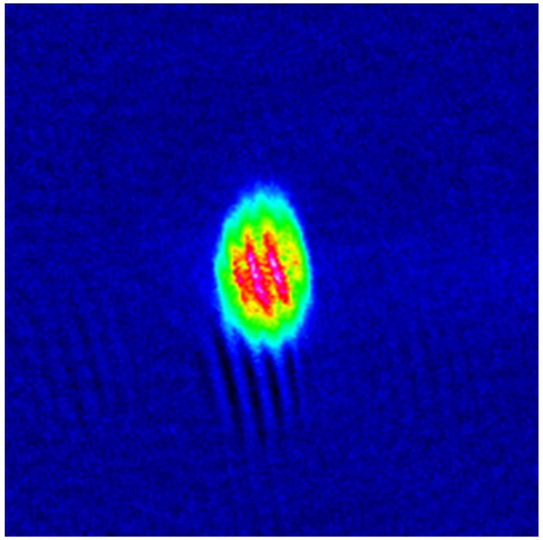


1.5 x 10^5 atoms

2011:



imaged on resonance



imaged off resonance

4 x 10^6 atoms

a 25-fold improvement!

Reasons:

- larger dipole trap
- intercombination line laser with narrower linewidth
- better dipole trap loading

strontium bosons

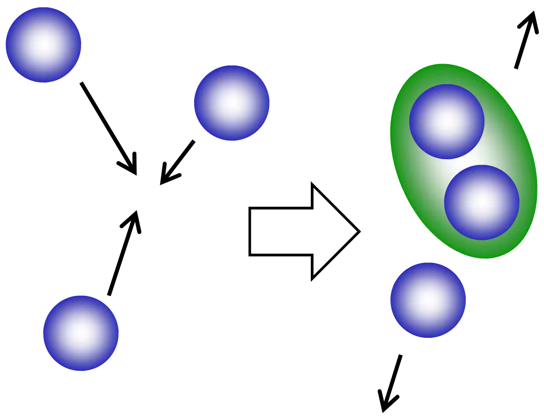
Bosonic strontium isotopes:

Isotope	Natural abundance	Scattering length	
^{88}Sr	82.58 %	-2.5 a_0	no collisions
^{86}Sr	9.86 %	800 a_0	inelastic collisions
^{84}Sr	0.56 %	123 a_0	✓

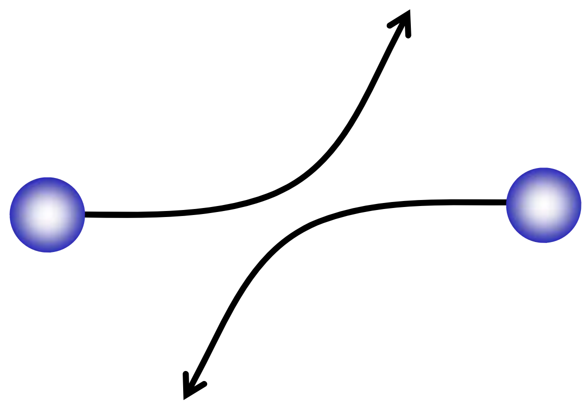
strategy for ^{86}Sr BEC

Need: inelastic collision rate Γ_{inel} << elastic collision rate Γ_{el}

inelastic collisions:
3-body process
$\Gamma_{inel} \sim n^2$

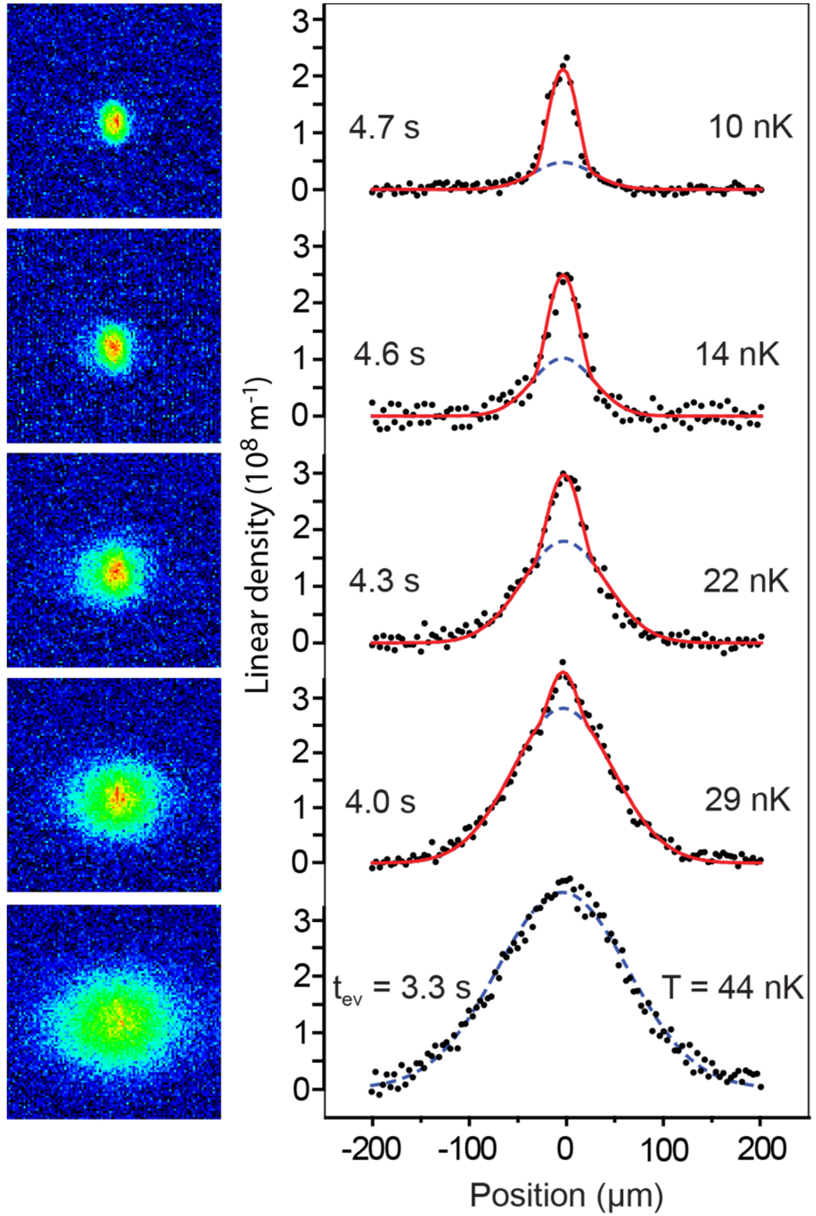


elastic collisions:
2-body process
$\Gamma_{el} \sim n$



Improve elastic to inelastic collision ratio by lowering density
→ large volume dipole trap

^{86}Sr BEC



5000 atoms in BEC

strontium bosons

Bosonic strontium isotopes:

Isotope	Natural abundance	Scattering length
^{88}Sr	82.58 %	-2 a_0
^{86}Sr	9.86 %	800 a_0
^{84}Sr	0.56 %	123 a_0

no collisions

inelastic collisions

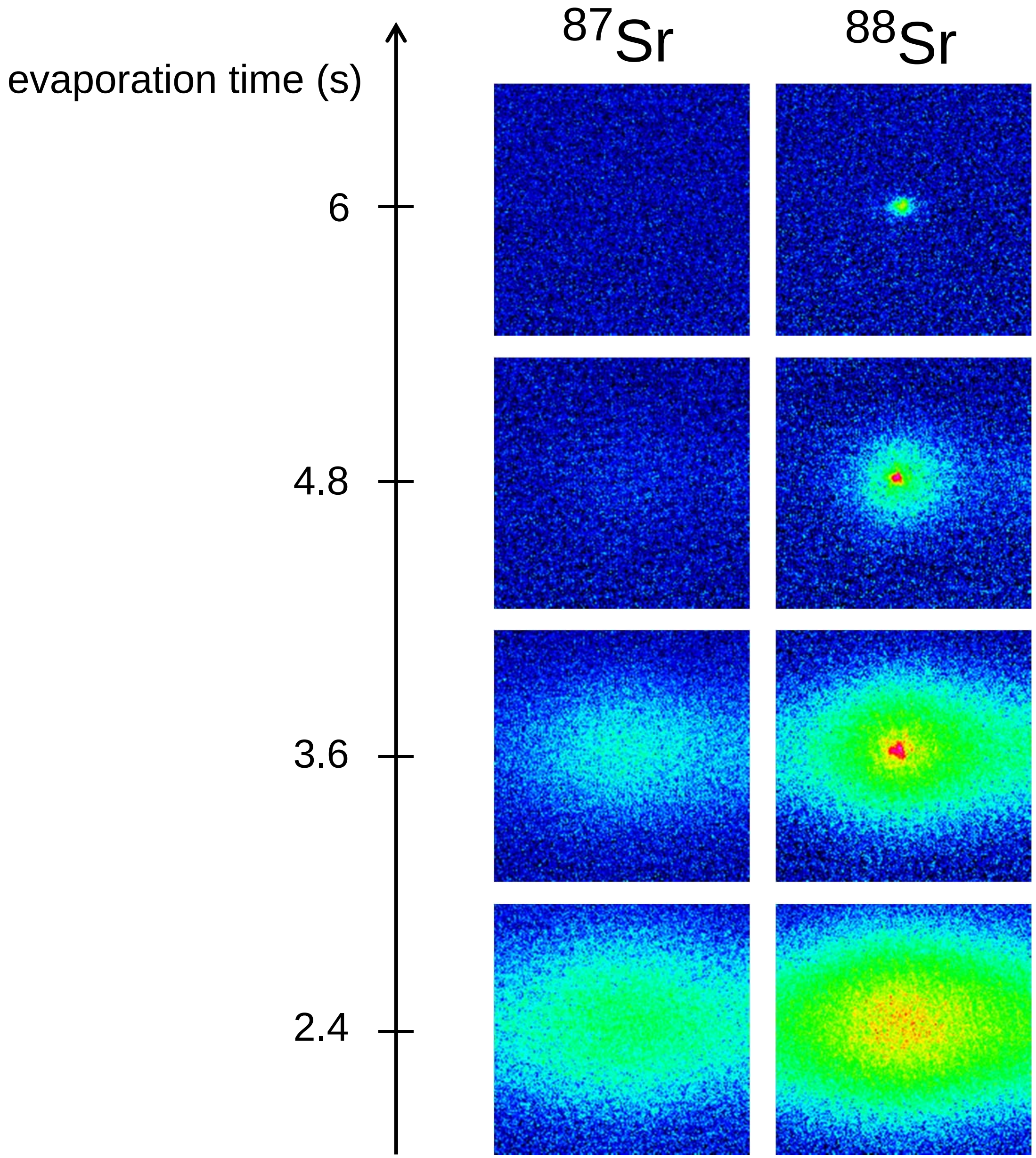
✓

✓

Tom Killian's group (2010):
use sympathetic cooling with ^{87}Sr

$a_{87\text{-}88} = 55\ a_0$

^{88}Sr BEC



5000 atoms in BEC

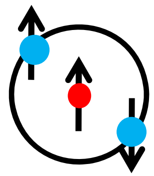
$a_{88} = -2\ a_0$

BEC limited to
finite atom number

$N_{critical} = 5000$

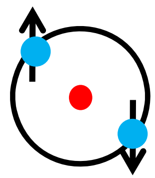
Fermionic ^{87}Sr

Fermionic ^{87}Sr:



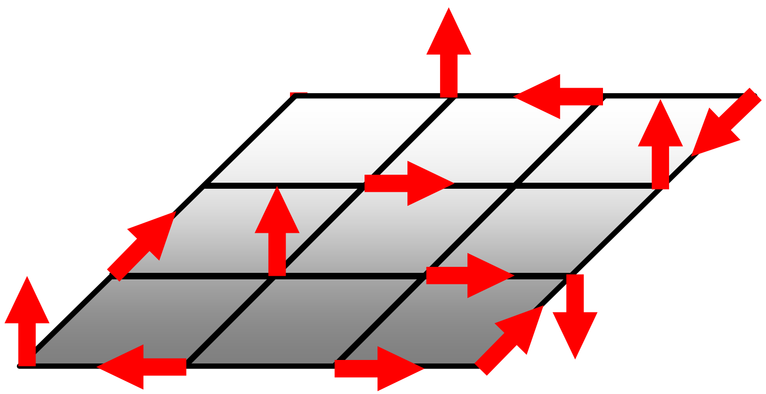
nuclear spin I = 9/2

Bosonic Sr:



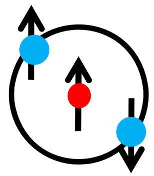
no nuclear spin

Quantum computation / simulation



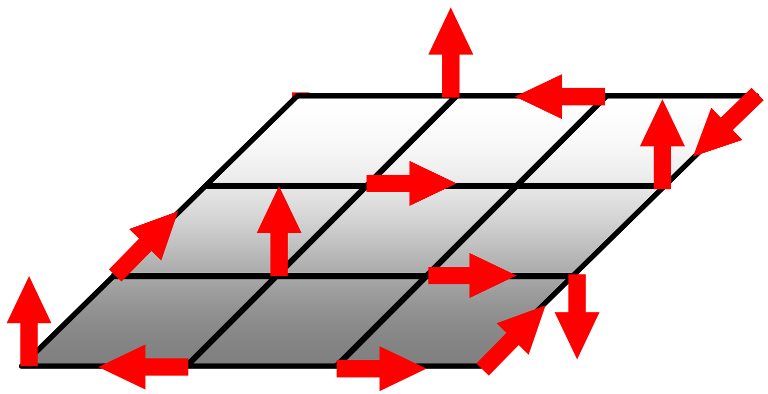
Fermionic ^{87}Sr

Fermionic ^{87}Sr:



nuclear spin I = 9/2

Quantum computation / simulation



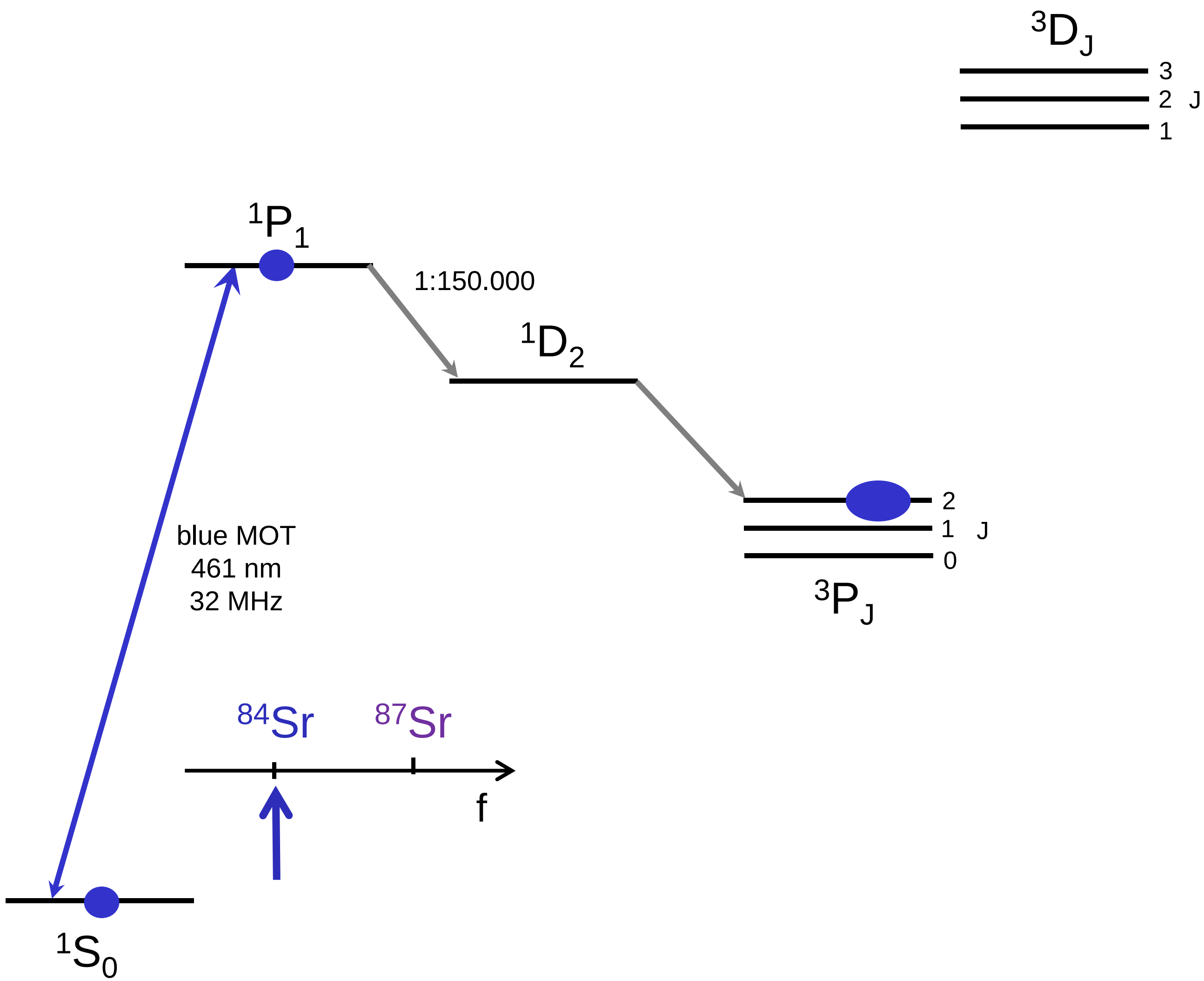
Challenge:

identical fermions don‘t collide
at ultracold temperatures

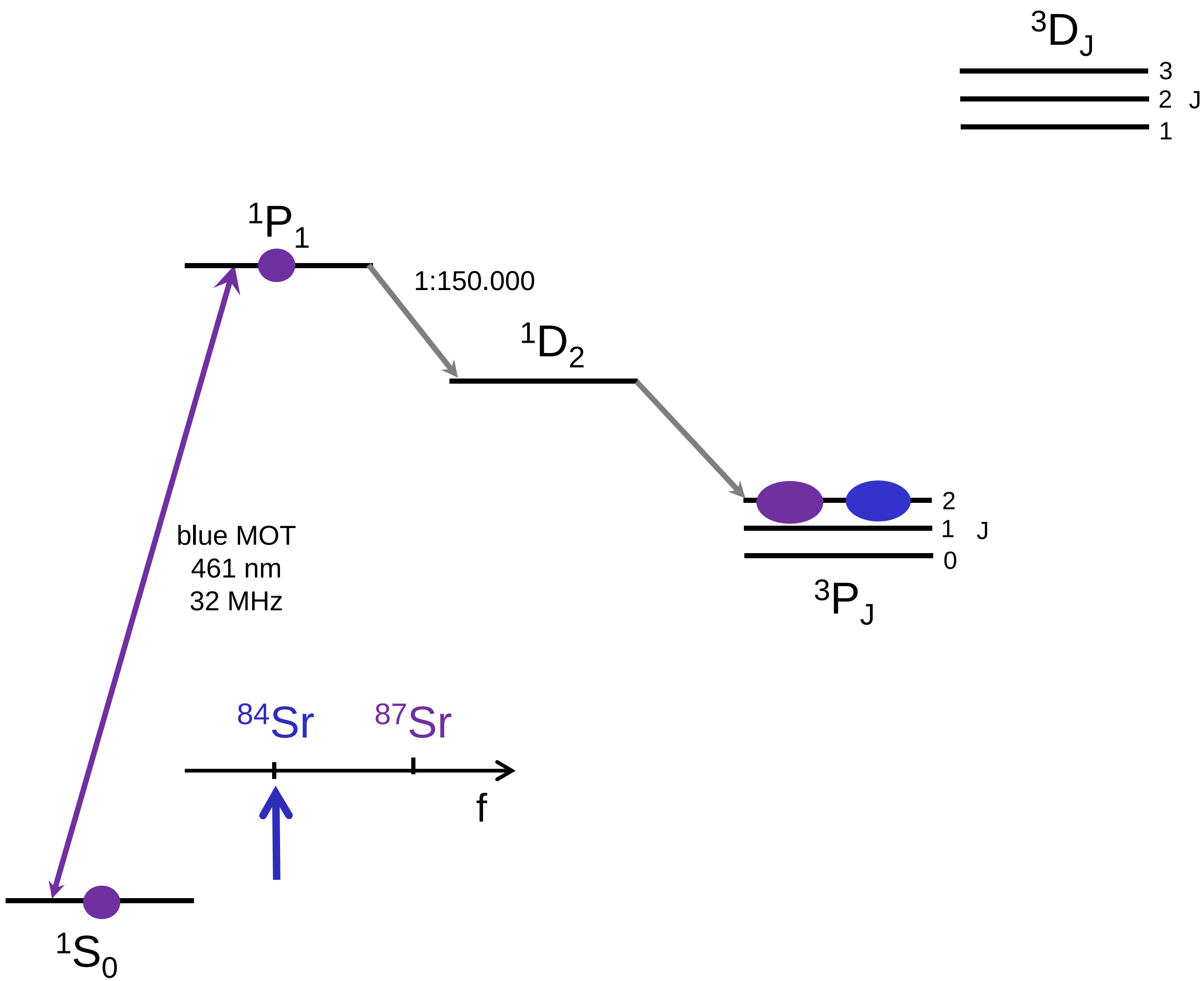
Solutions:

- ^{87}Sr in spin mixture
  Tom Killian‘s group
- ^{87}Sr in single spin state & ^{84}Sr
  our group

Creation of ^{87}Sr-^{84}Sr mixture



Creation of ^{87}Sr-^{84}Sr mixture

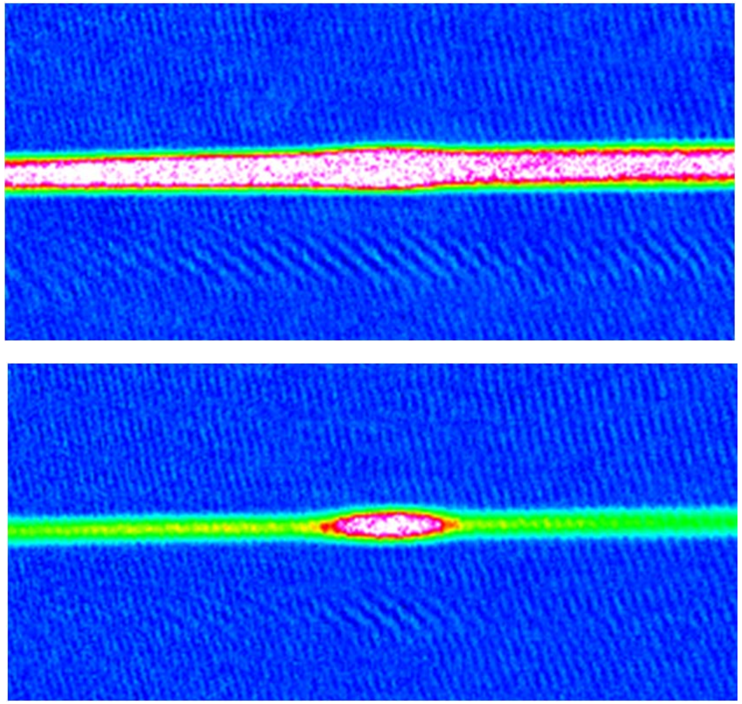


narrow linewidth MOTs

^3D

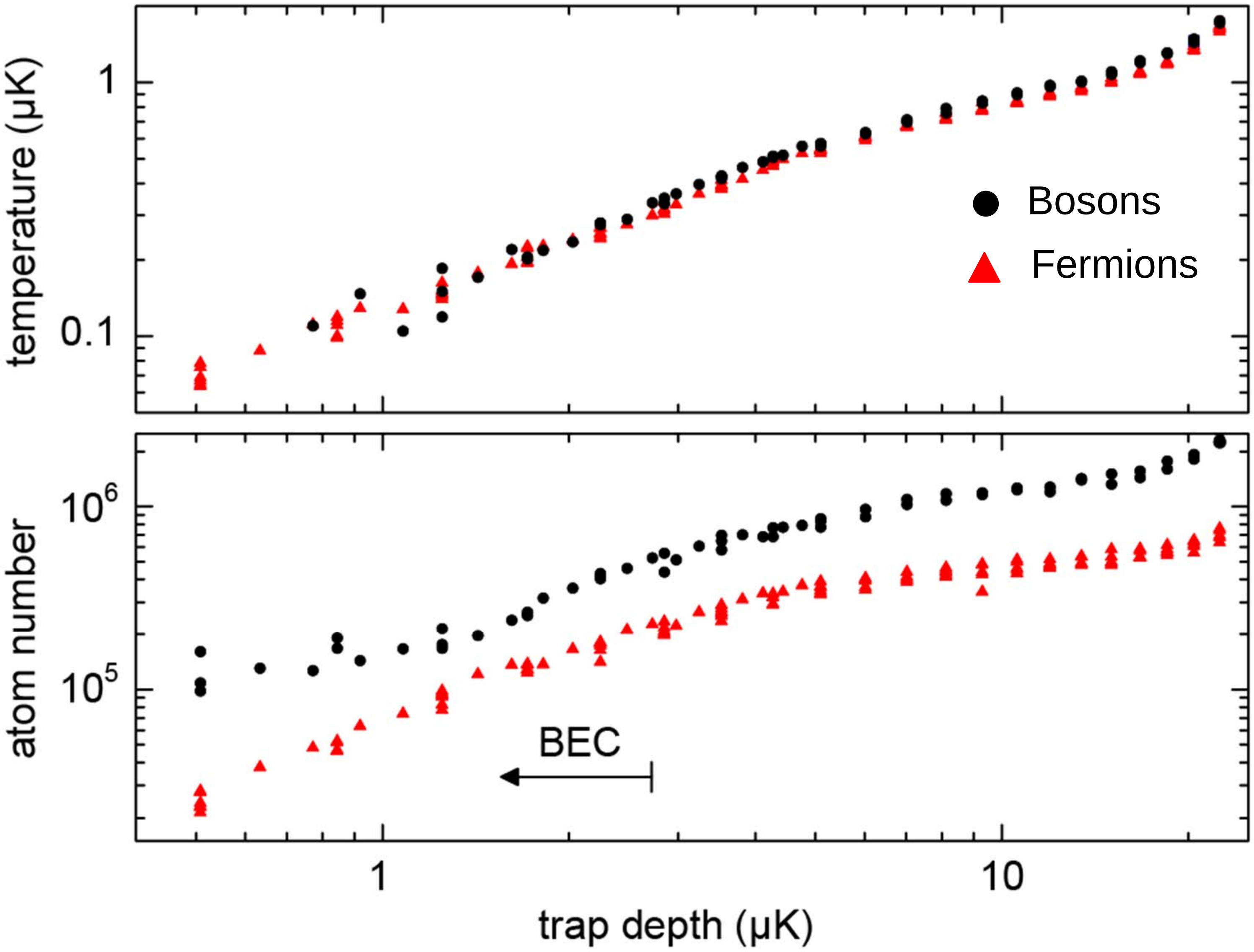
3
2 J
1

Atoms in dipole trap

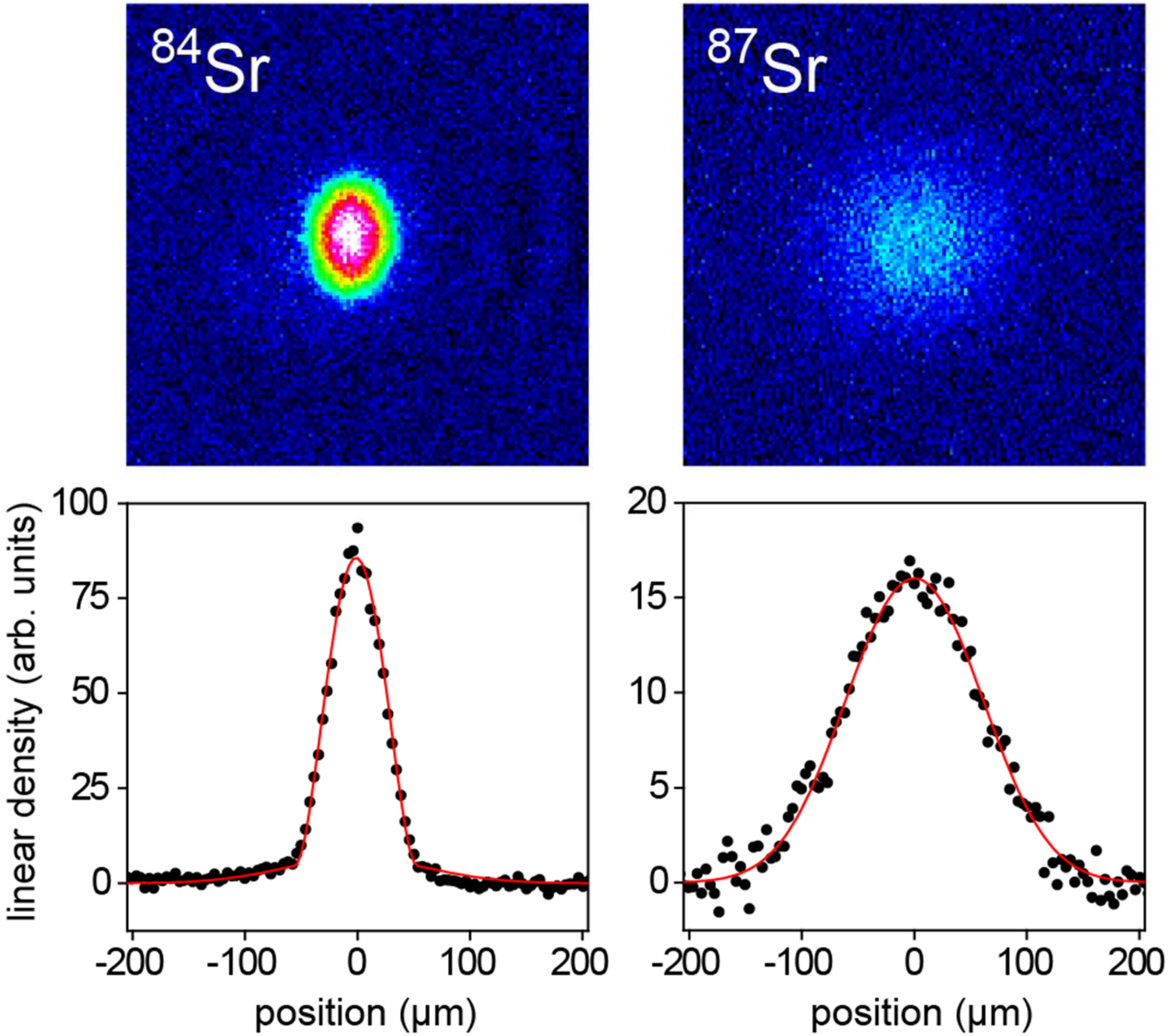


$^1S_0$

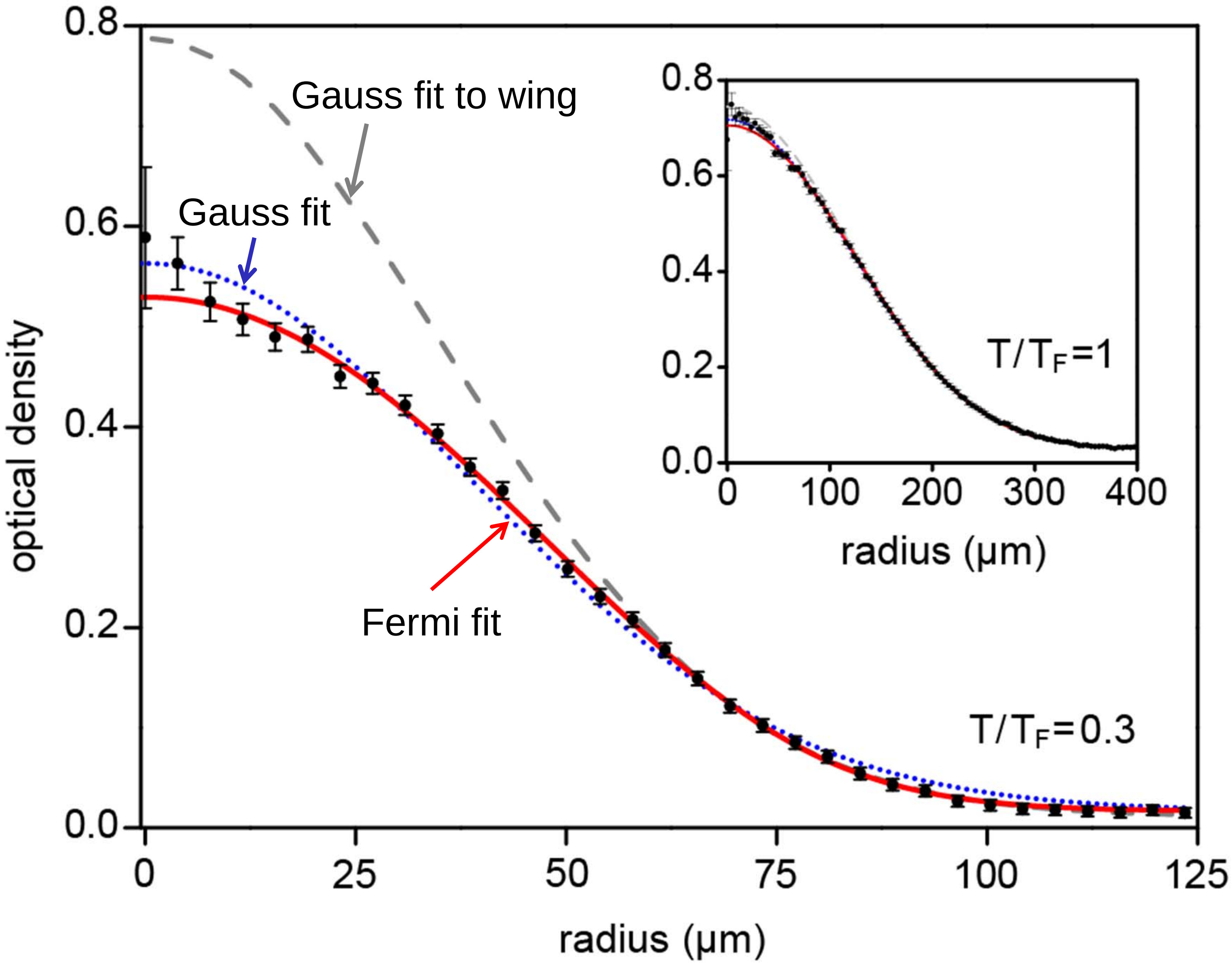
Evaporation



BEC & Fermi sea



Degenerate Fermi Gas of ^{87}Sr



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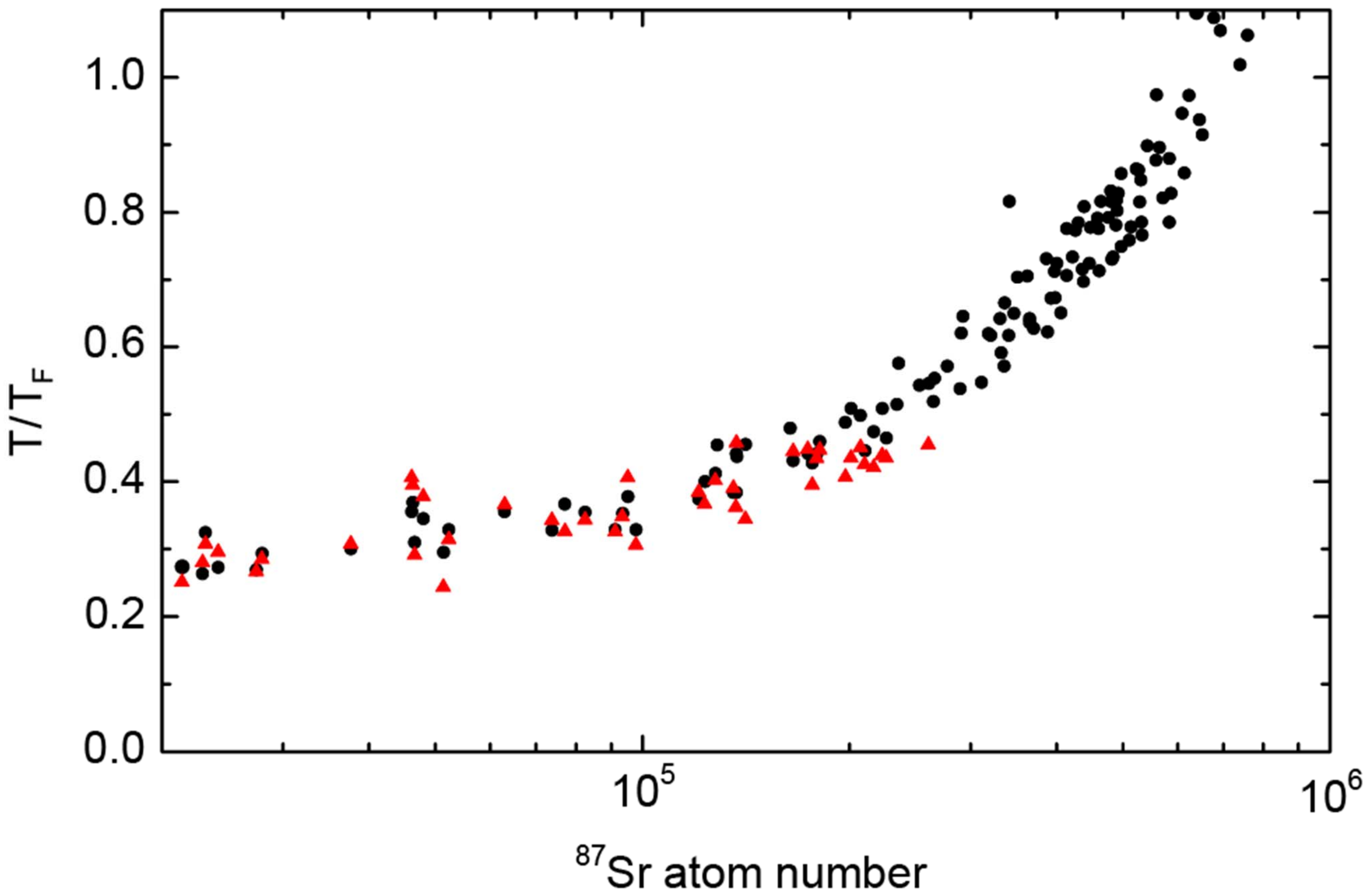
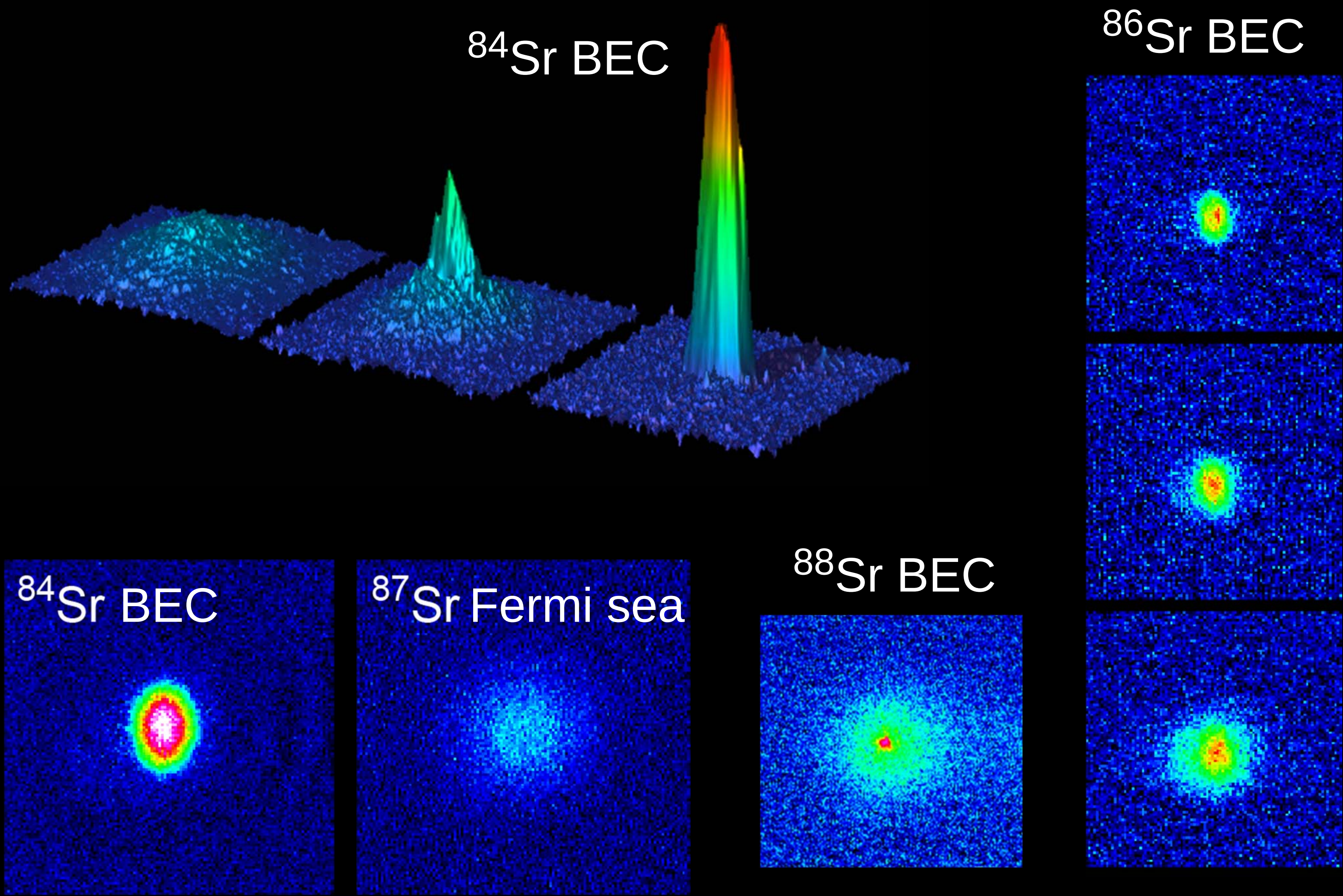


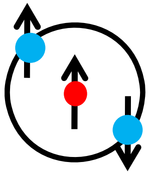
Quantum Degenerate Strontium



Tools!

Fermionic ^{87}Sr

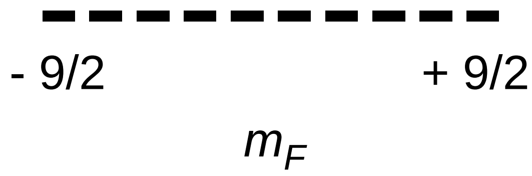
Fermionic ^{87}Sr:



nuclear spin I = 9/2

$^1S_0$

F = 9/2



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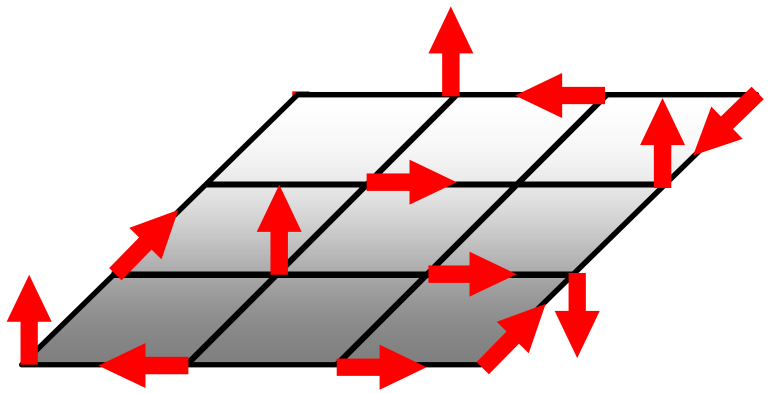
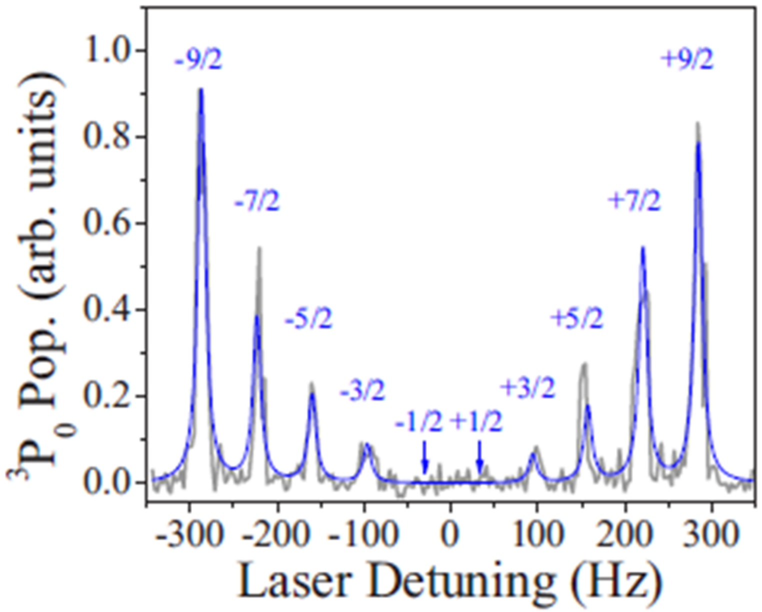
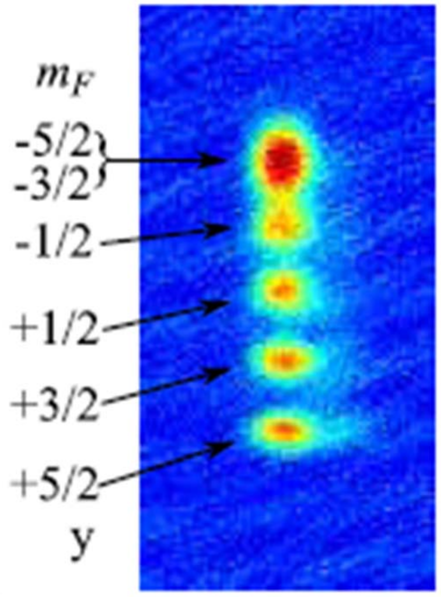


m_F - state detection

Alkalis: e.g. magnetic Stern-Gerlach separation
not possible with alkaline-earths

Alkaline-earths:





Ye group (Sr, 2007):
spectroscopy
(using ‚clock‘ – transition)

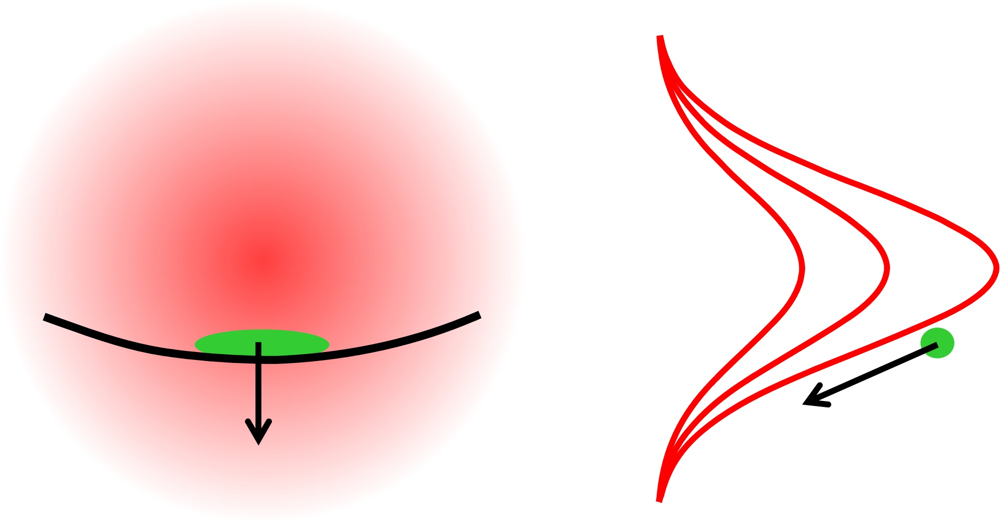
Takahashi group (Yb, 2010):
optical Stern-Gerlach separation

Mlynek (He* beam, 1992)

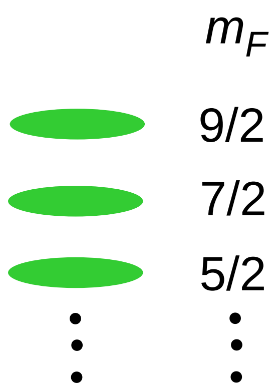
Optical Stern-Gerlach

Working principle:

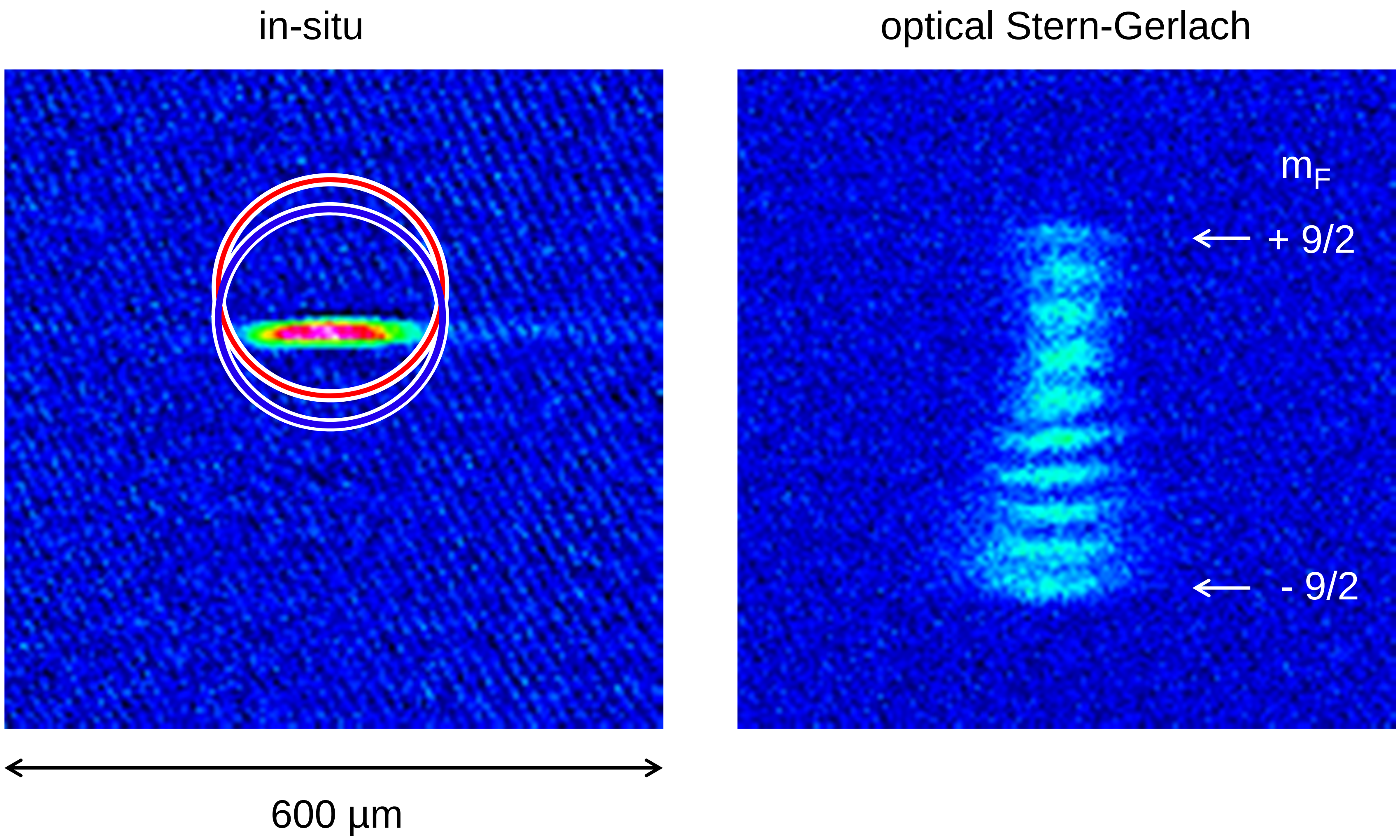
accelerate atoms using m_F - state dependent light shift gradient



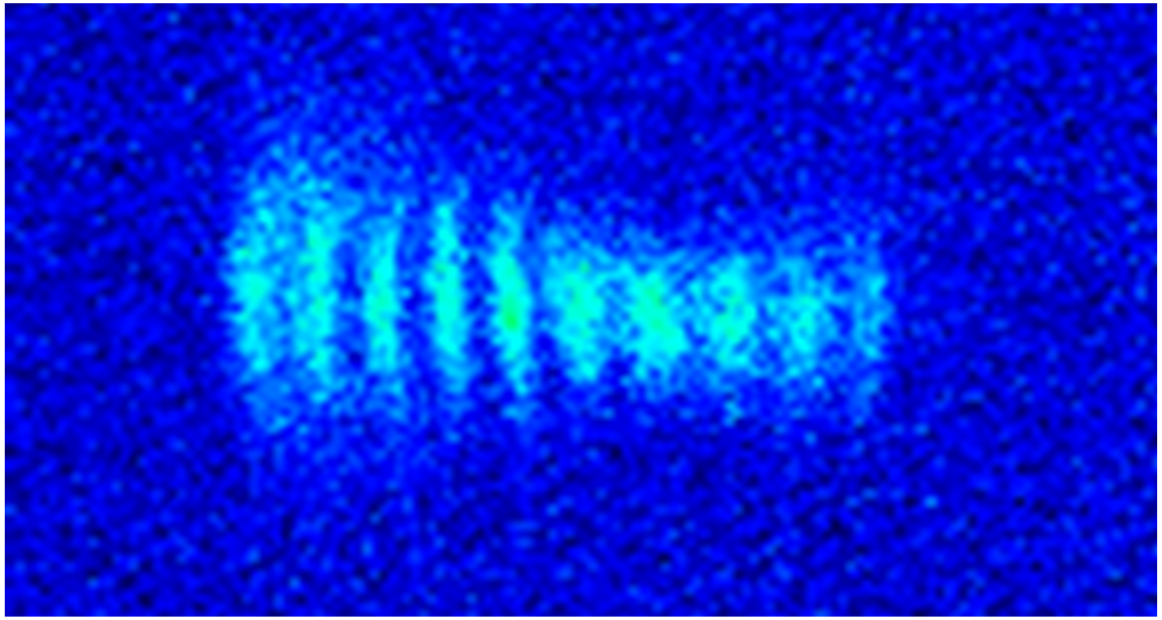
After flight:

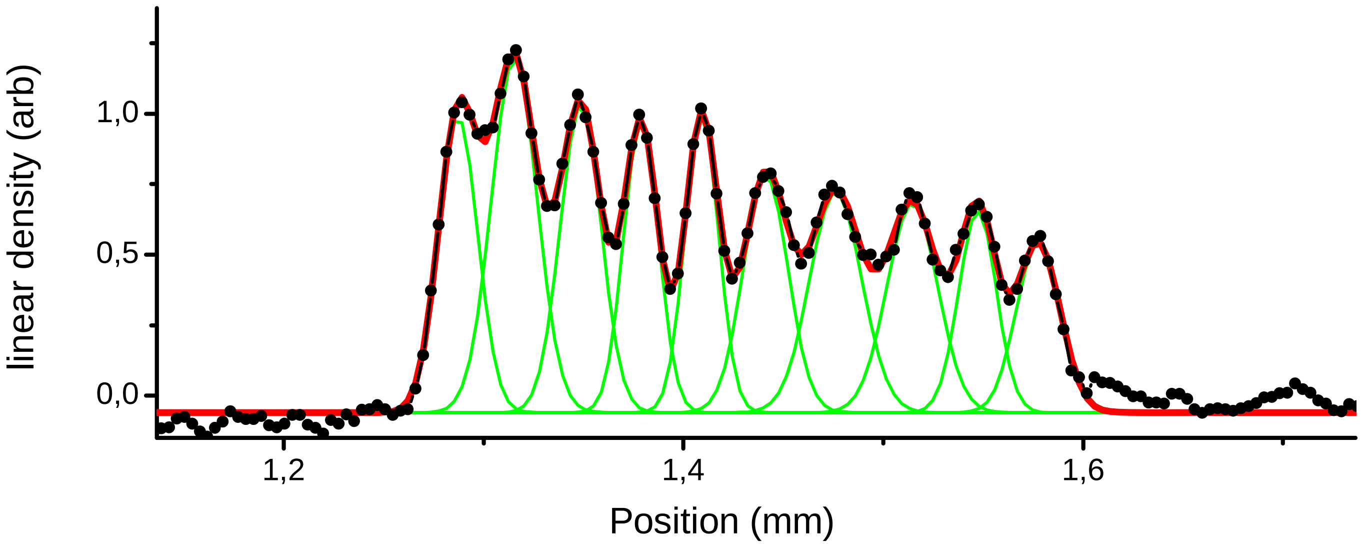


^{87}Sr Optical Stern-Gerlach

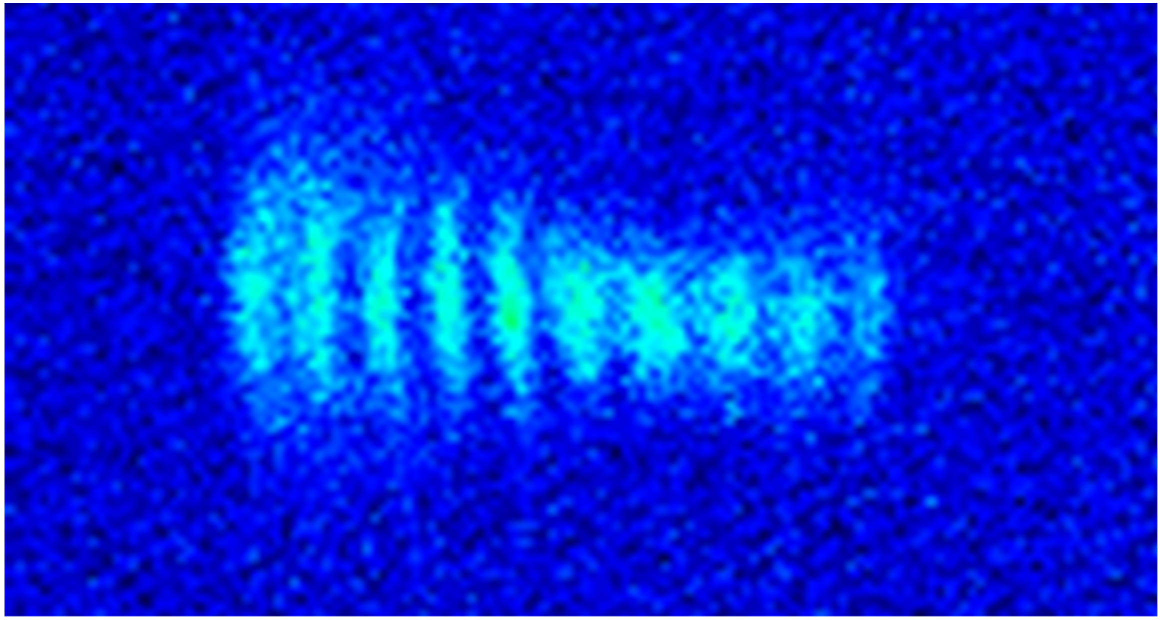


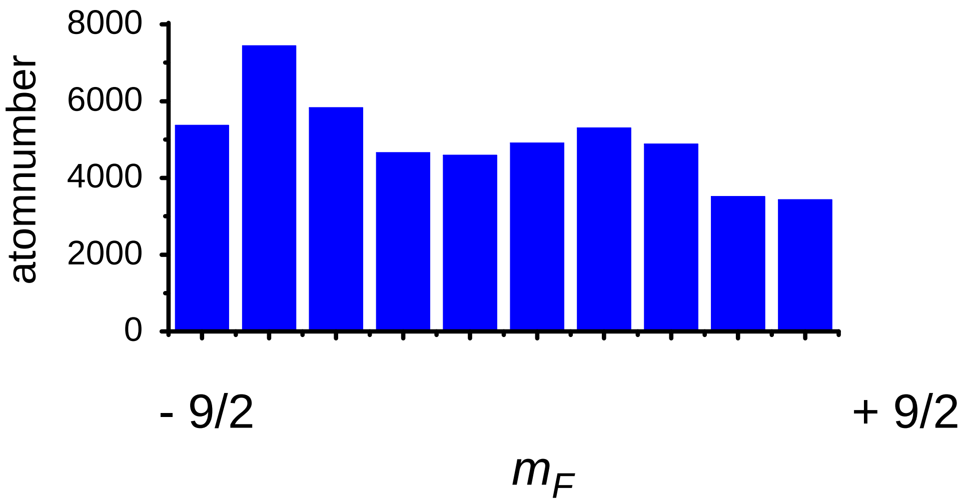
^{87}Sr Optical Stern-Gerlach



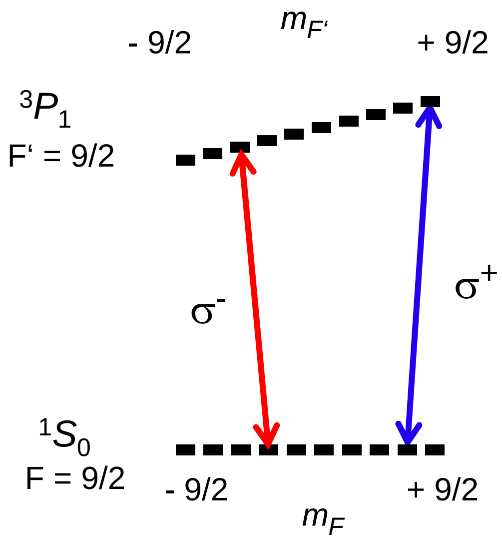


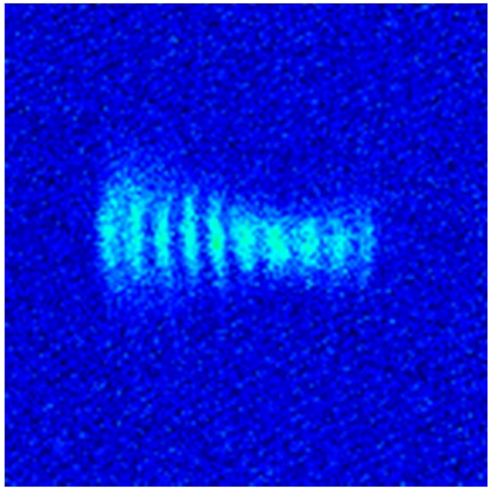
^{87}Sr Optical Stern-Gerlach

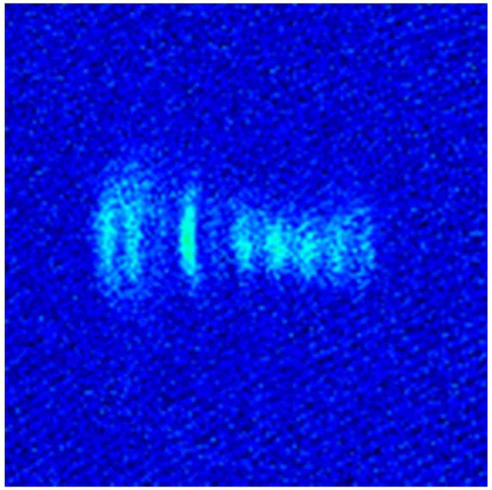


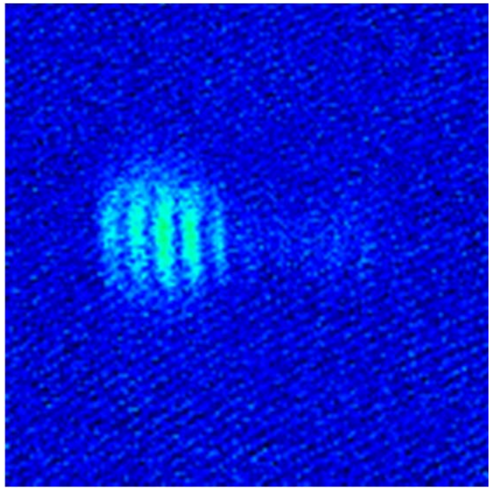


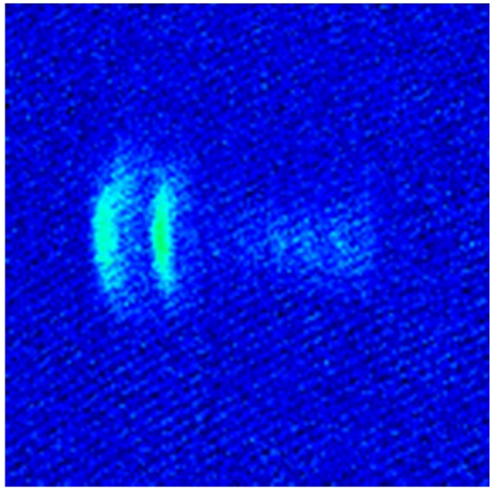
Optical pumping



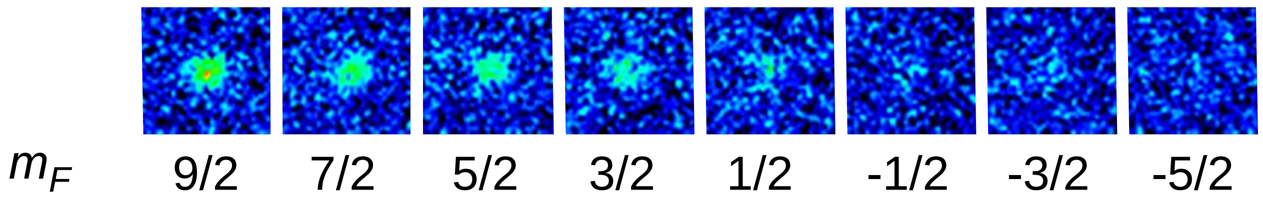


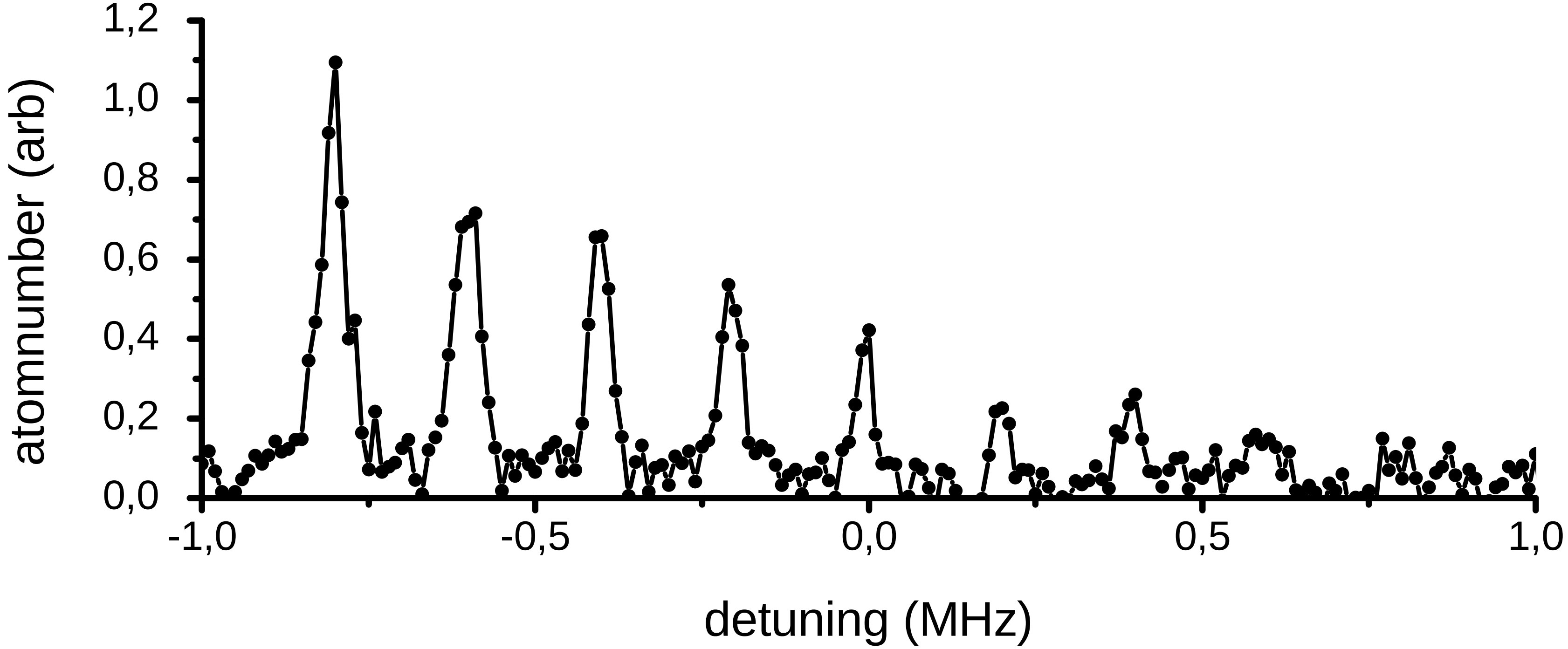






State resolved absorption imaging

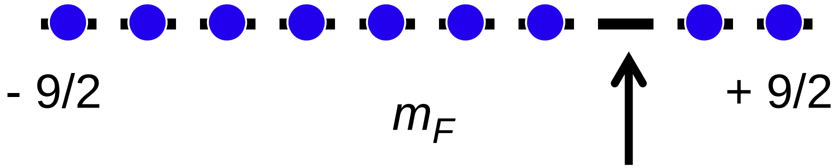




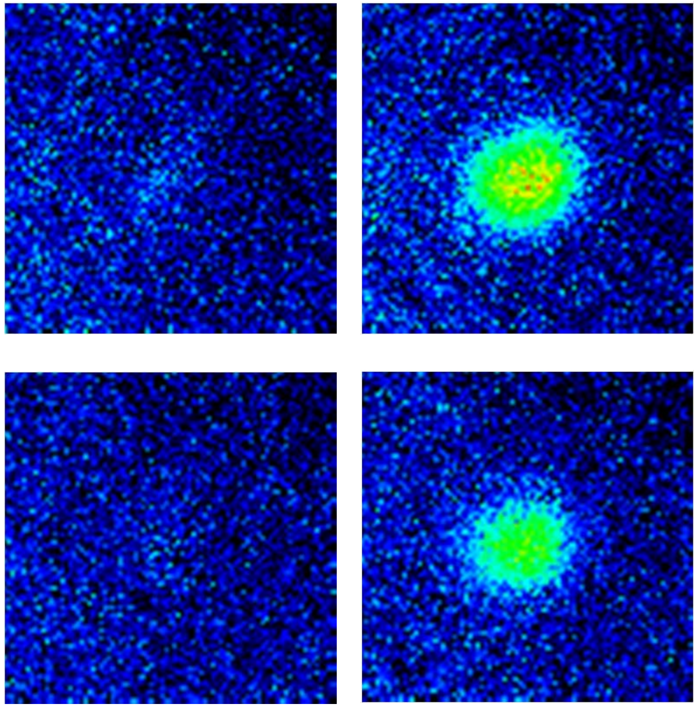
Spin relaxation?

$^1S_0$

F = 9/2



	5/2	7/2
t = 0 s		
t = 10 s		

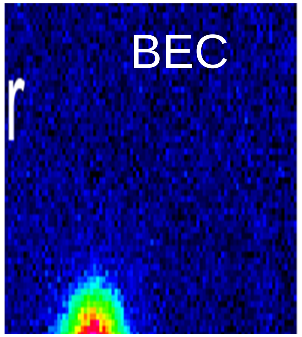


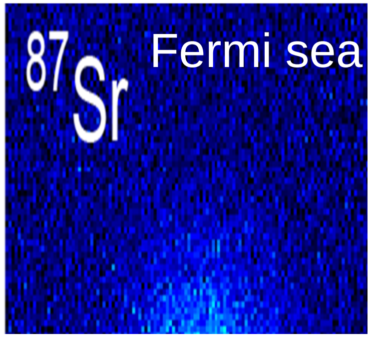
averages of
25 images

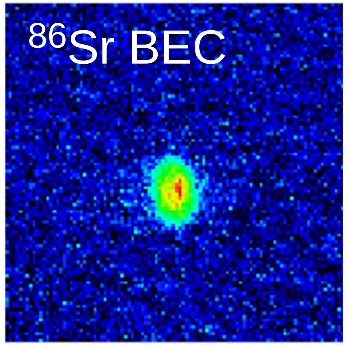
No spin relaxation after 1000 collisions!

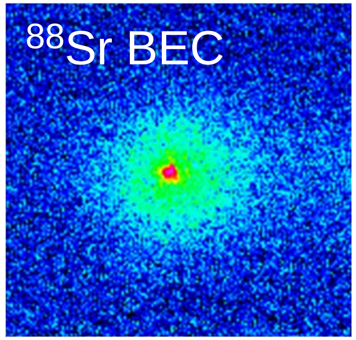
Summary

Achieved quantum degeneracy with all isotopes

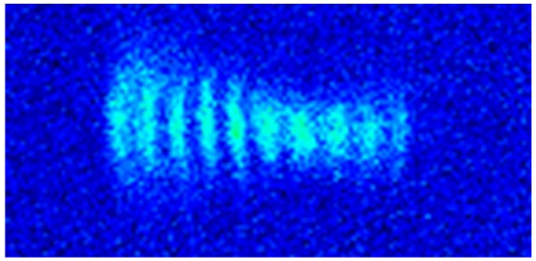








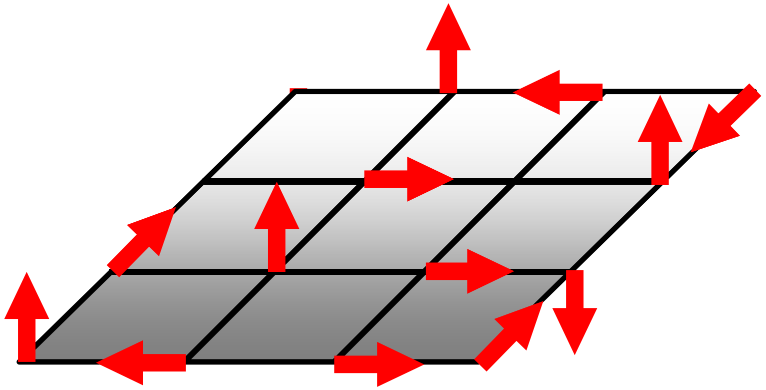
Nuclear spin manipulation of ^{87}Sr



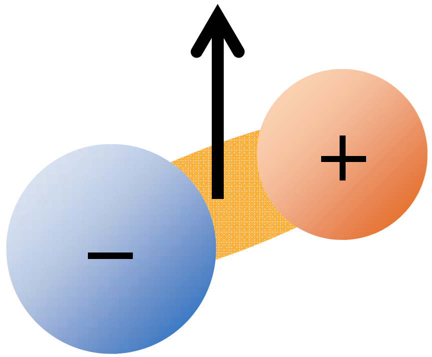
The future

Two interconnected research lines:

Quantum computation / simulation



SrRb ground state molecules



The team

Former members:

Bo Huang

Meng Khoon Tey

Start 2010

Austrian ministry of science

FWF Der Wissenschaftsfonds.

ÖAW Austrian Academy of Sciences

iSENSE Integrated Quantum Sensors