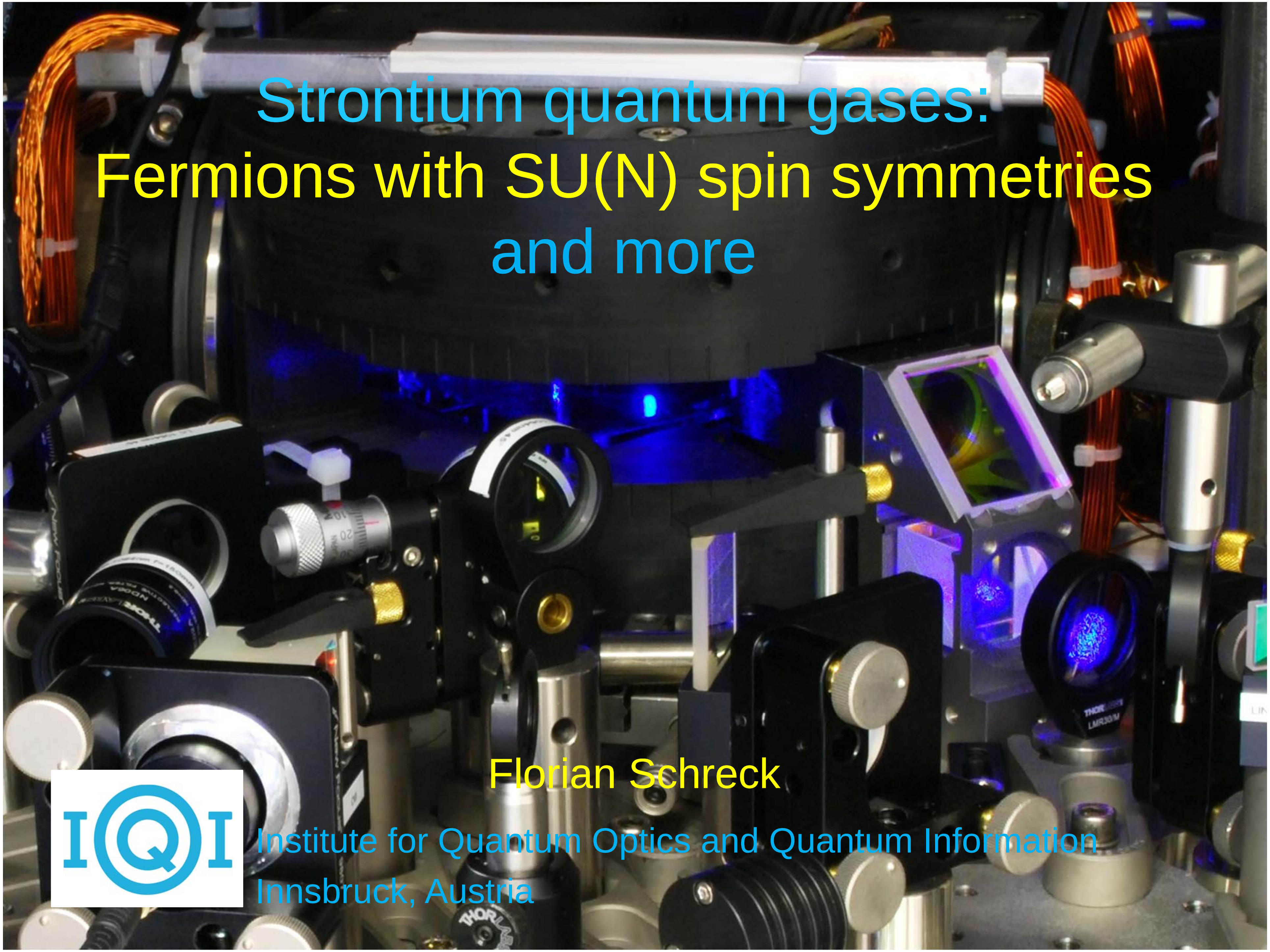
Strontium quantum gases: Fermions with SU(N) spin symmetries and more

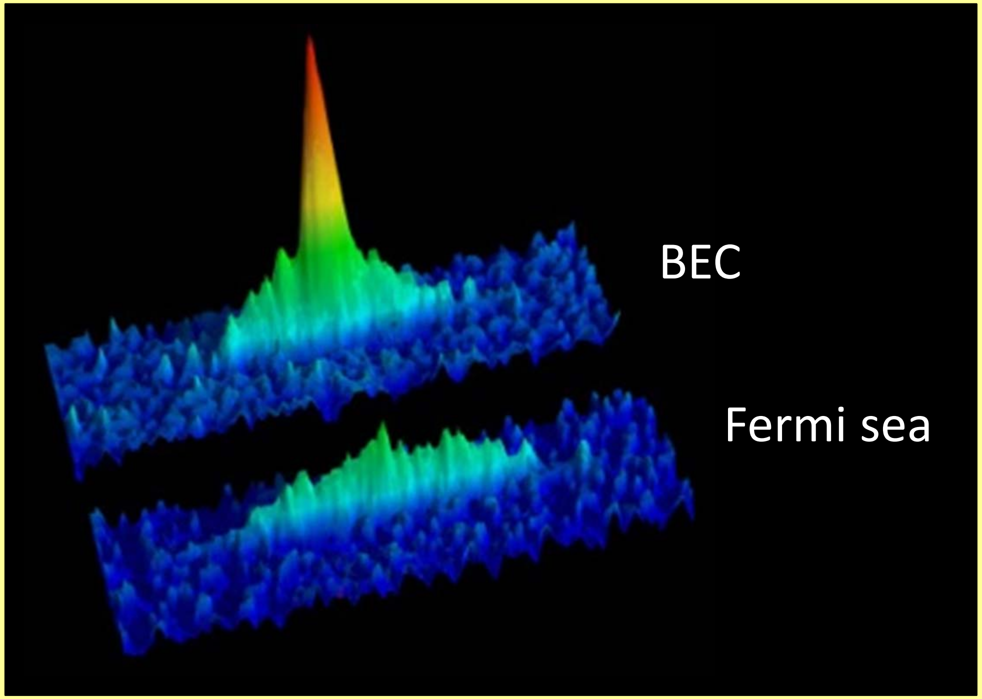


Florian Schreck

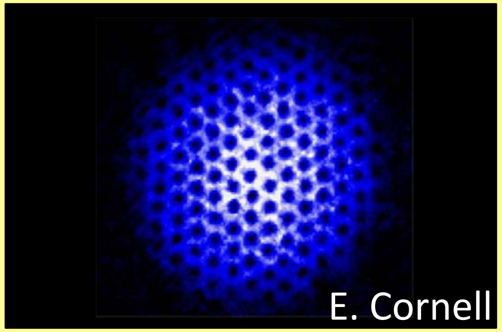
Institute for Quantum Optics and Quantum Information
Innsbruck, Austria

Ultracold quantum gases

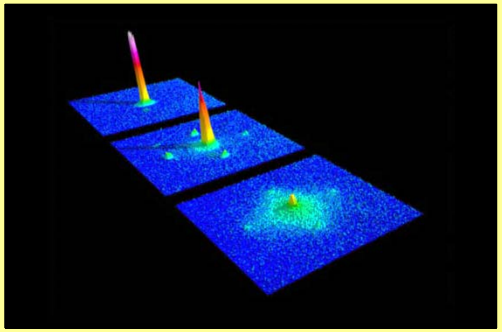
At ultracold temperatures…



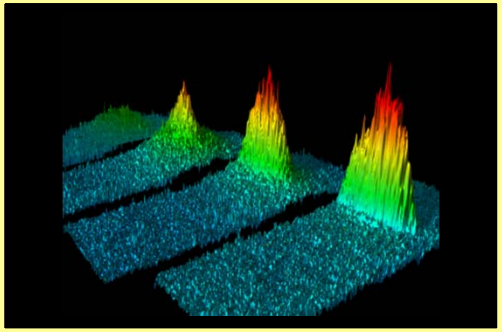
…quantum behavior dominates.



Vortices



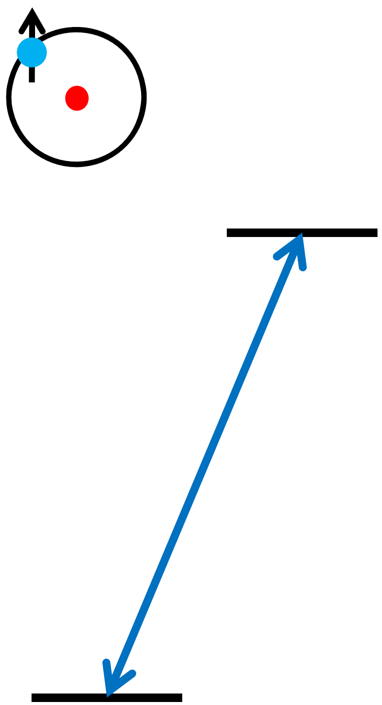
Lattice gas

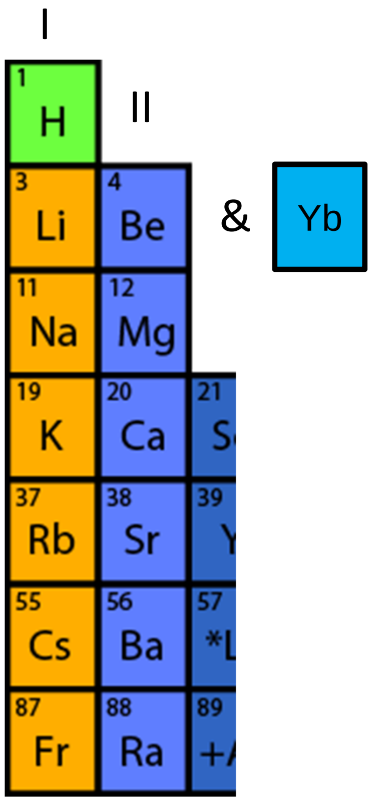


molecular BEC

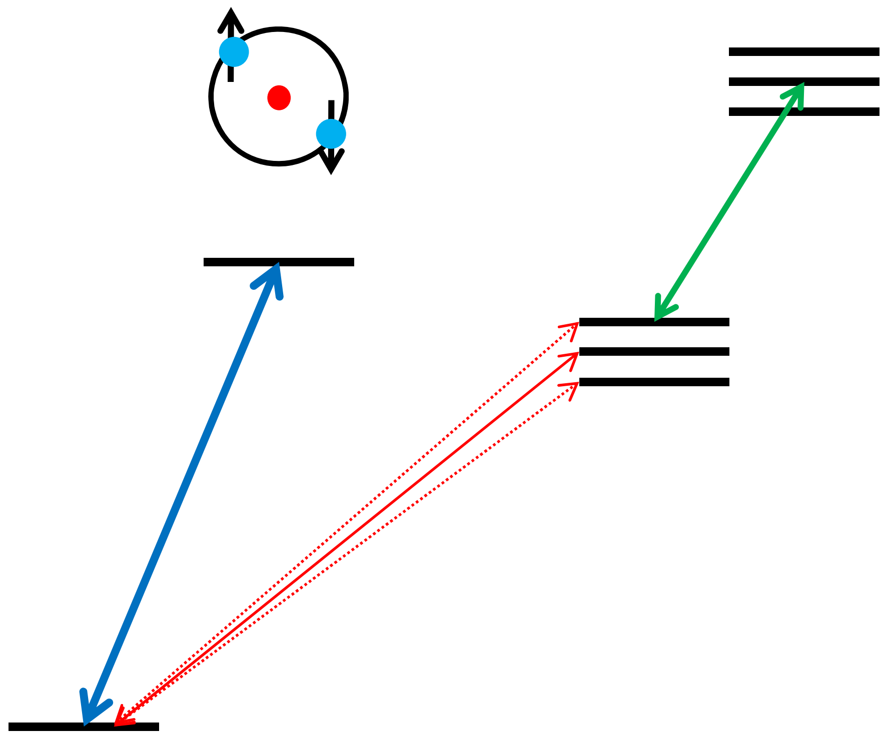
Alkaline-earth elements

Alkali atoms:
one valence electron

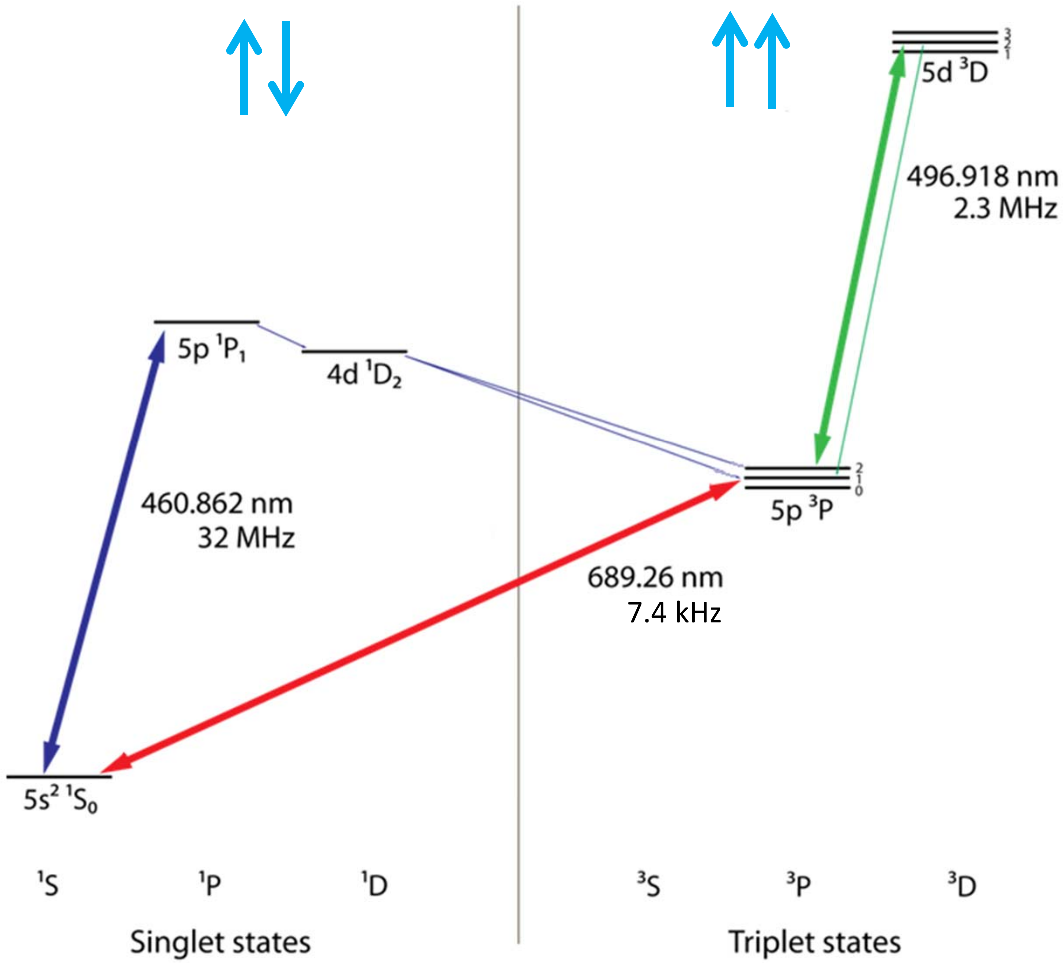




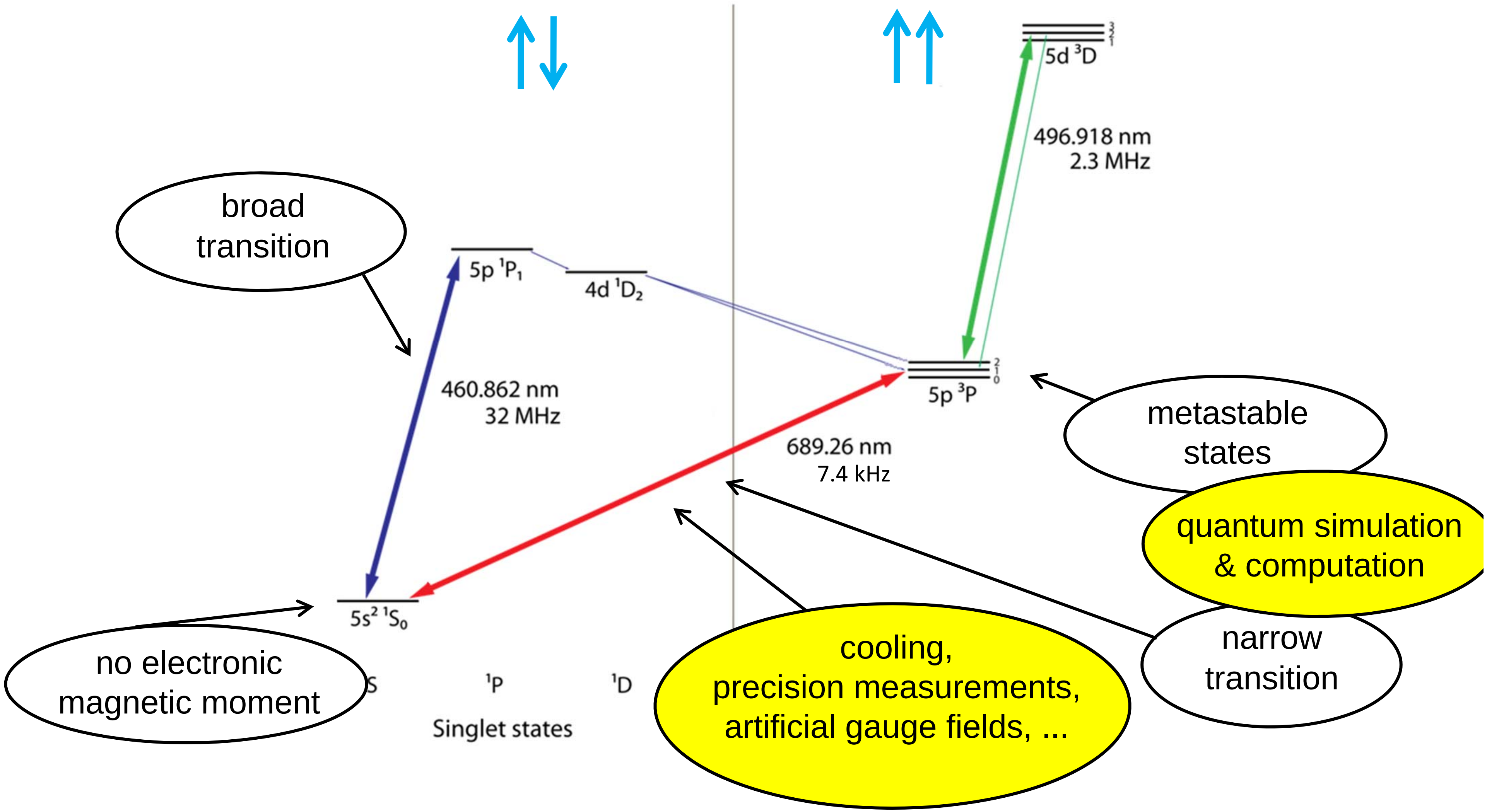
Alkaline-earth (like) atoms:
two valence electrons



Strontium level scheme



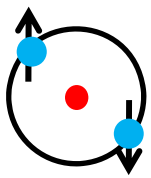
Strontium level scheme



Bosons and Fermions

Bosons

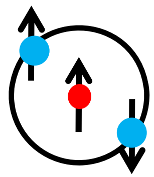
^{84}Sr, ^{86}Sr, ^{88}Sr



no nuclear spin

Fermion

^{87}Sr



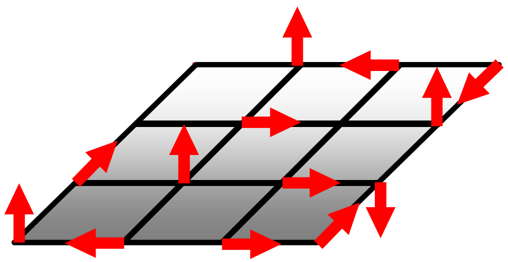
nuclear spin I = 9/2

quantum simulation
& computation

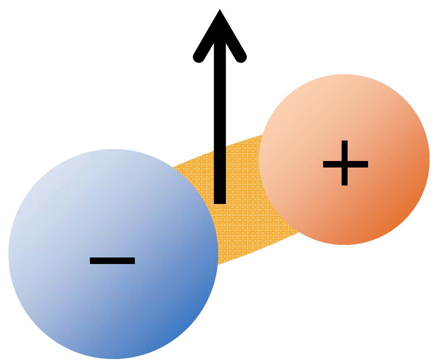
Opportunities

SU(*N*) magnetism

Hermele, Gurarie, and Rey 2009

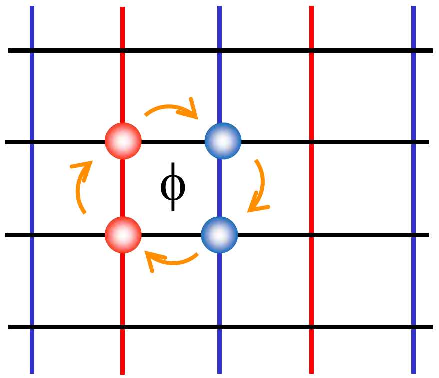


RbSr ground-state molecules



Artificial gauge fields

Gerbier and Dalibard 2010
Cooper 2011

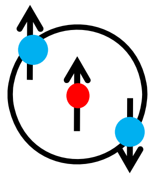


Many other possibilities:

- Quantum computation
- Precision measurement
- Rydberg atoms
- Laser cooling to BEC
- Continuous BEC
- …

SU(N) spin symmetry

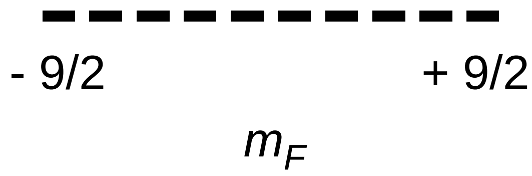
Fermionic ^{87}Sr:



nuclear spin I = 9/2

$^1S_0$

F = 9/2

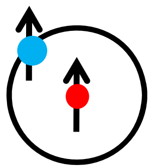


electronic and nuclear spin NOT coupled

→ scattering properties independent of nuclear spin orientation but for fermionic statistics

leads to SU(*N*) spin symmetry! (N=1...10)

Alkali atoms:



electronic and nuclear spin are coupled

→ scattering properties dependent on nuclear spin orientation

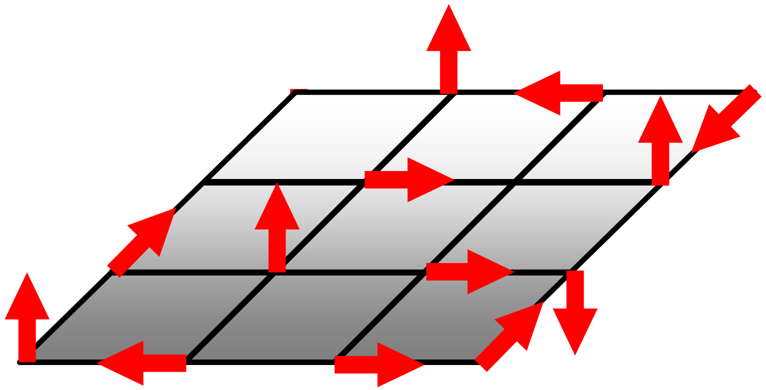
reduced spin symmetry!

SU(N) interaction

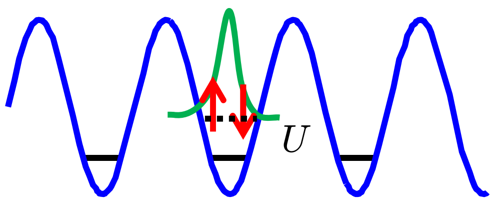
Enter regime dominated by SU(N) symmetric interaction:

Feshbach resonance?   not available

Load ^{87}Sr into lattice!



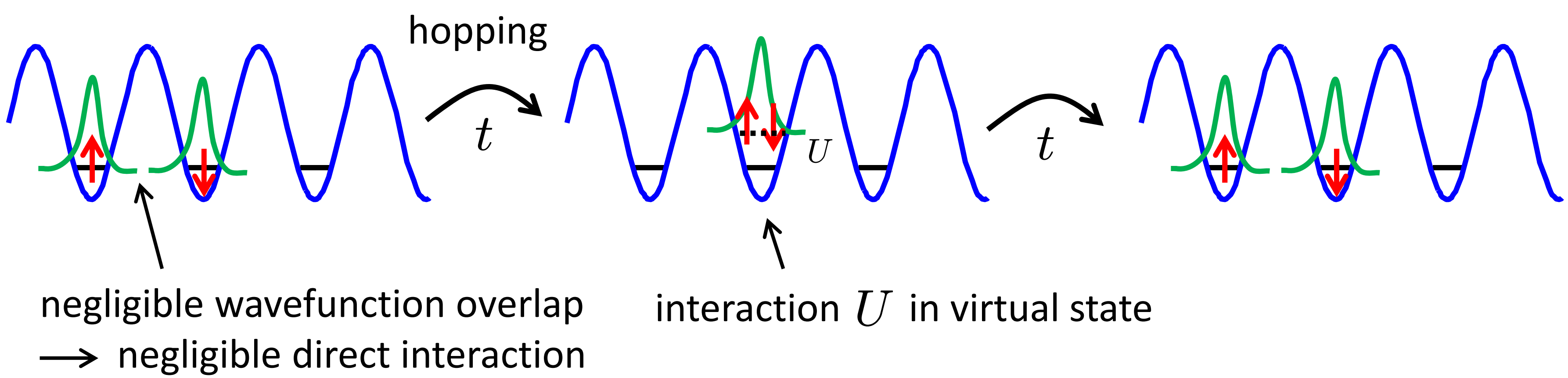
Two atoms on same site experience significant mean-field shift U



SU(N) super-exchange

Interaction between sites:

Super-exchange interaction:



SU(N) magnetism (simplest case):

Heisenberg Hamiltonian

$$\hat{H} = -J_{\mathrm{ex}}\frac{1}{2}\sum_{<i,j>}\vec{\hat{S}}_i \cdot \vec{\hat{S}}_j \quad ; \quad J_{\mathrm{ex}} = \pm 4\frac{t^2}{U}$$

SU(N) spins

super-exchange interaction

Properties of SU(N) spins:

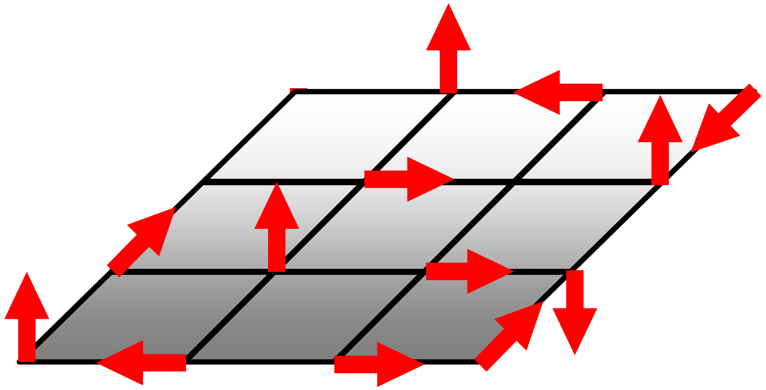
- for strong interactions: singlet energetically favorable
  singlet has to be composed of N spins!

  link to **QCD**: baryons are SU(3) color singlets

- spin fluctuations scale with N (unlike large classical spin!)

SU(N) magnetism

SU(N) magnetism:



for N>3 classical ground state highly frustrated

→ interesting quantum phases expected

M. Cazallila, A. Ho, M. Ueda (2009)

A.V. Gorshkov, M. Hermele, V. Gurarie, C. Xu, P.S. Julienne, J. Ye, P. Zoller, E. Demler, M.D. Lukin, A.M. Rey (2010)

- Analytical methods available for $N \to \infty$

Hermele, Gurarie, Rey (2009)

Rich phase diagram predicted,
including **valence bond solid** or **chiral spin liquid**

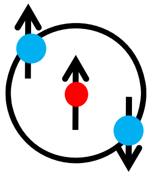
- Numerical methods up to N=3

T. Tóth, A.M. Läuchli, F. Mila, K. Penc (2010)

N=3: quantum and thermal fluctuations favor different phases.

Two-orbital SU(N) physics

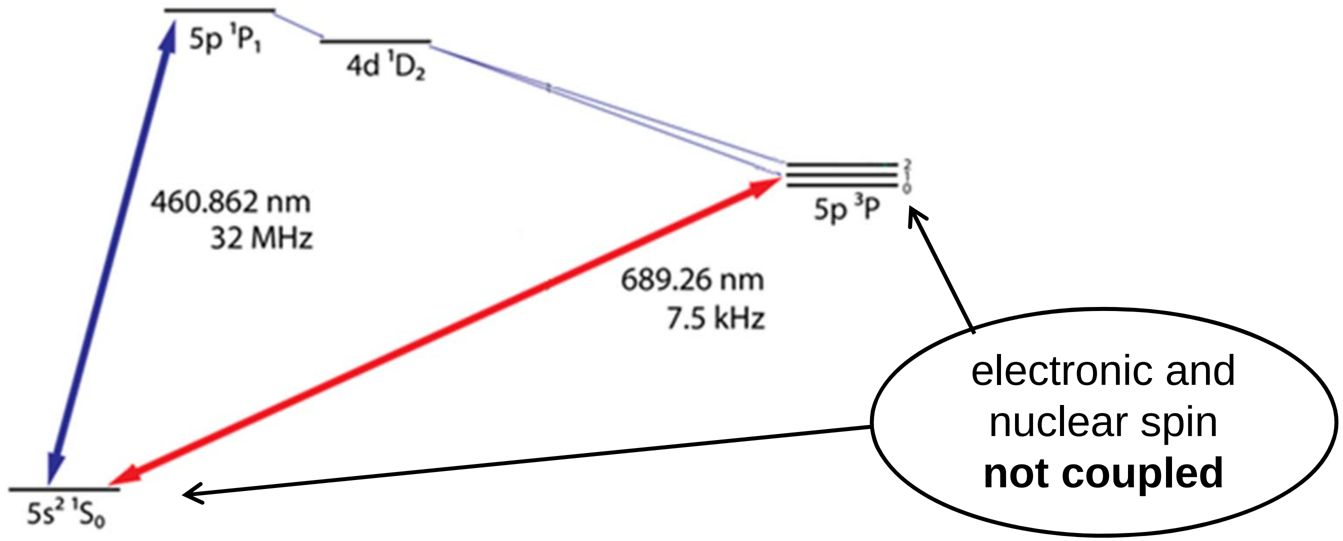
Fermionic two-electron atom (e.g. ^{87}Sr):



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

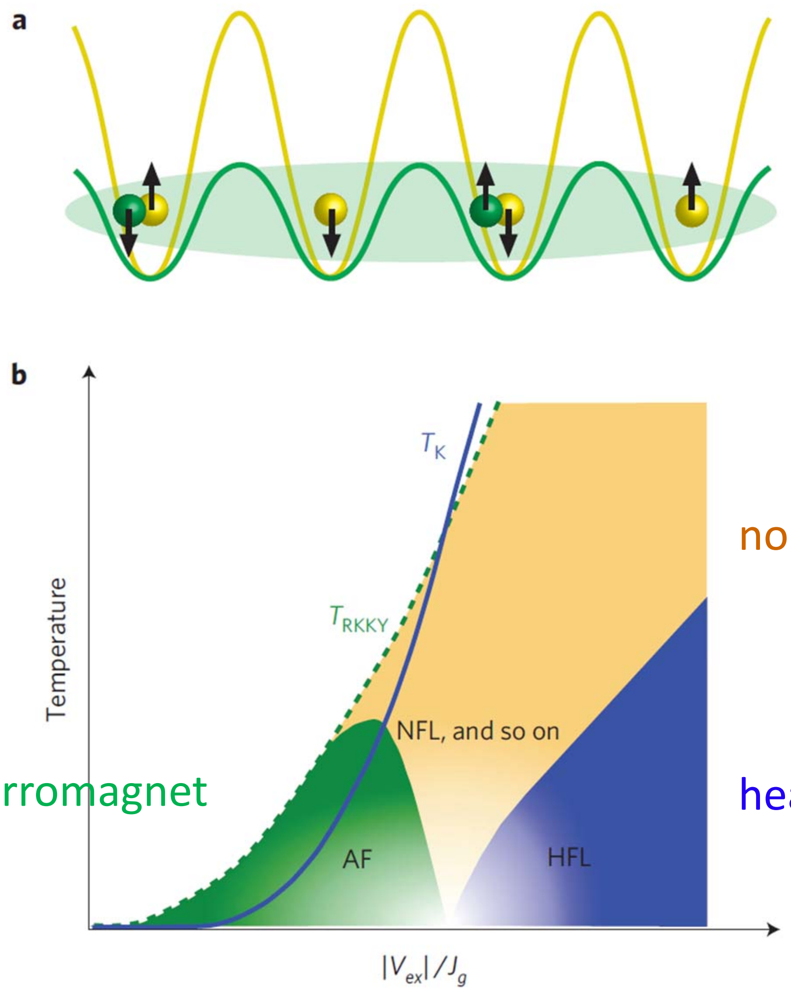
leads to SU(*N*) spin symmetry!

True for two states:



Two-orbital SU(N) magnetism

Two orbital SU(N) magnetism: e.g. Kondo lattice model



non-Fermi-liquid

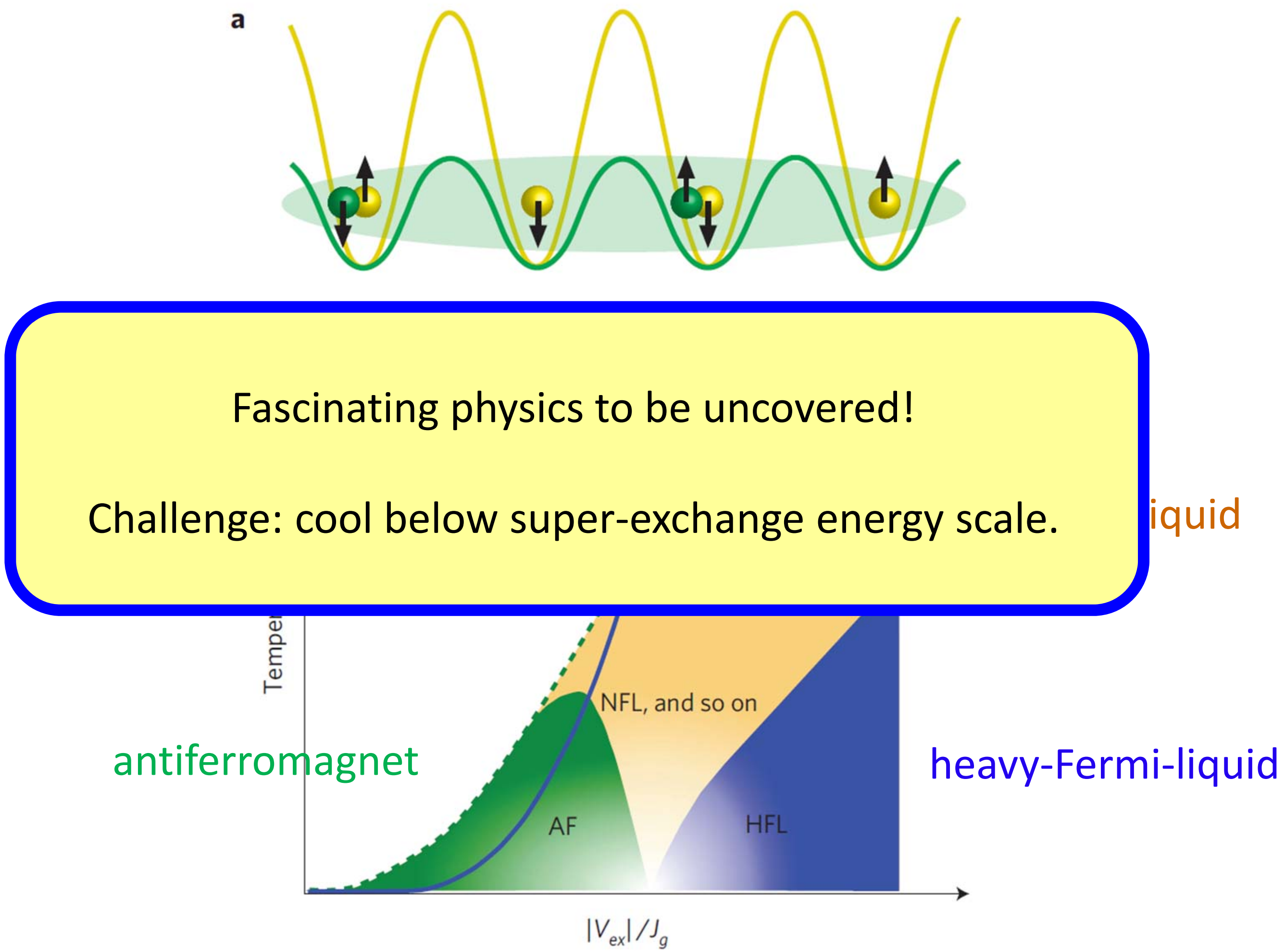
antiferromagnet

heavy-Fermi-liquid

A.V. Gorshkov, M. Hermele, V. Gurarie, C. Xu, P.S. Julienne, J. Ye, P. Zoller, E. Demler, M.D. Lukin, A.M. Rey (2010)

Two-orbital SU(N) magnetism

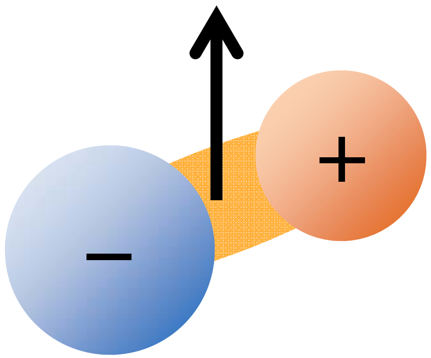
Two orbital SU(N) magnetism: e.g. Kondo lattice model



A.V. Gorshkov, M. Hermele, V. Gurarie, C. Xu, P.S. Julienne, J. Ye, P. Zoller, E. Demler, M.D. Lukin, A.M. Rey (2010)

RbSr ground-state molecules

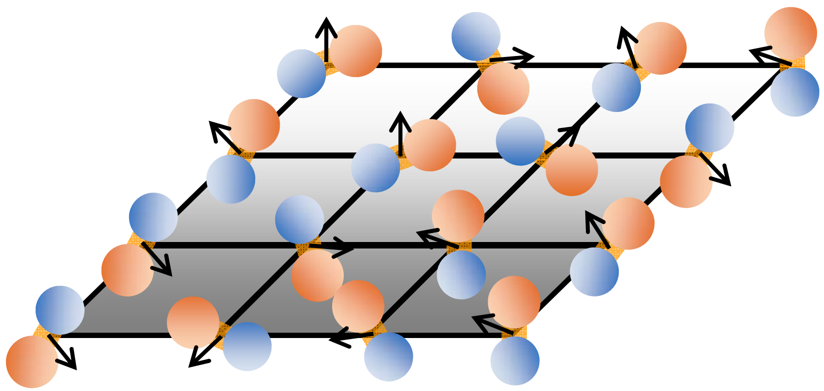
RbSr ground-state molecules



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**!



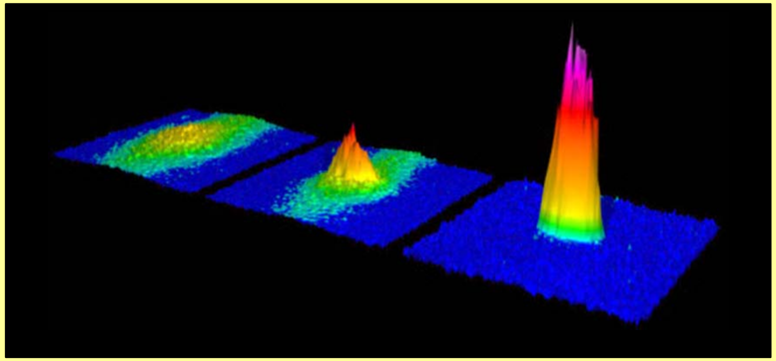
Simulation of lattice-spin models

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

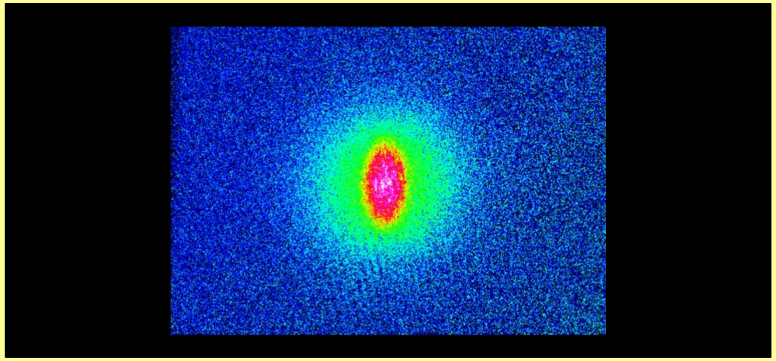
Overview

BEC of strontium

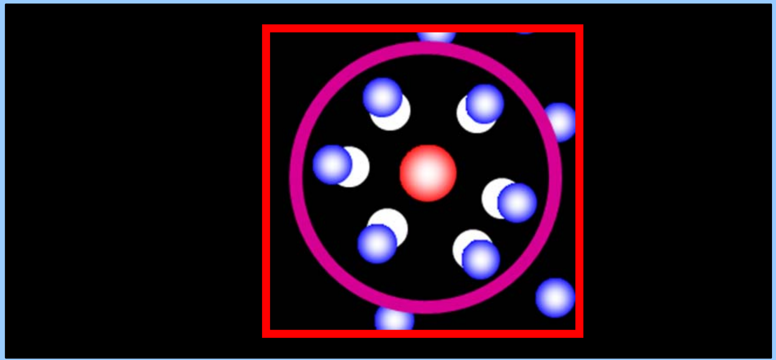
^{87}Sr Fermi gas



Laser cooling to BEC



Strongly-interacting
^{6}Li-^{40}K Fermi mixture



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
~~^{86}Sr~~	9.86 %	+800 a_0
^{84}Sr	0.56 %	?

no collisions

inelastic collisions

New approach

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 %	+124 a_0

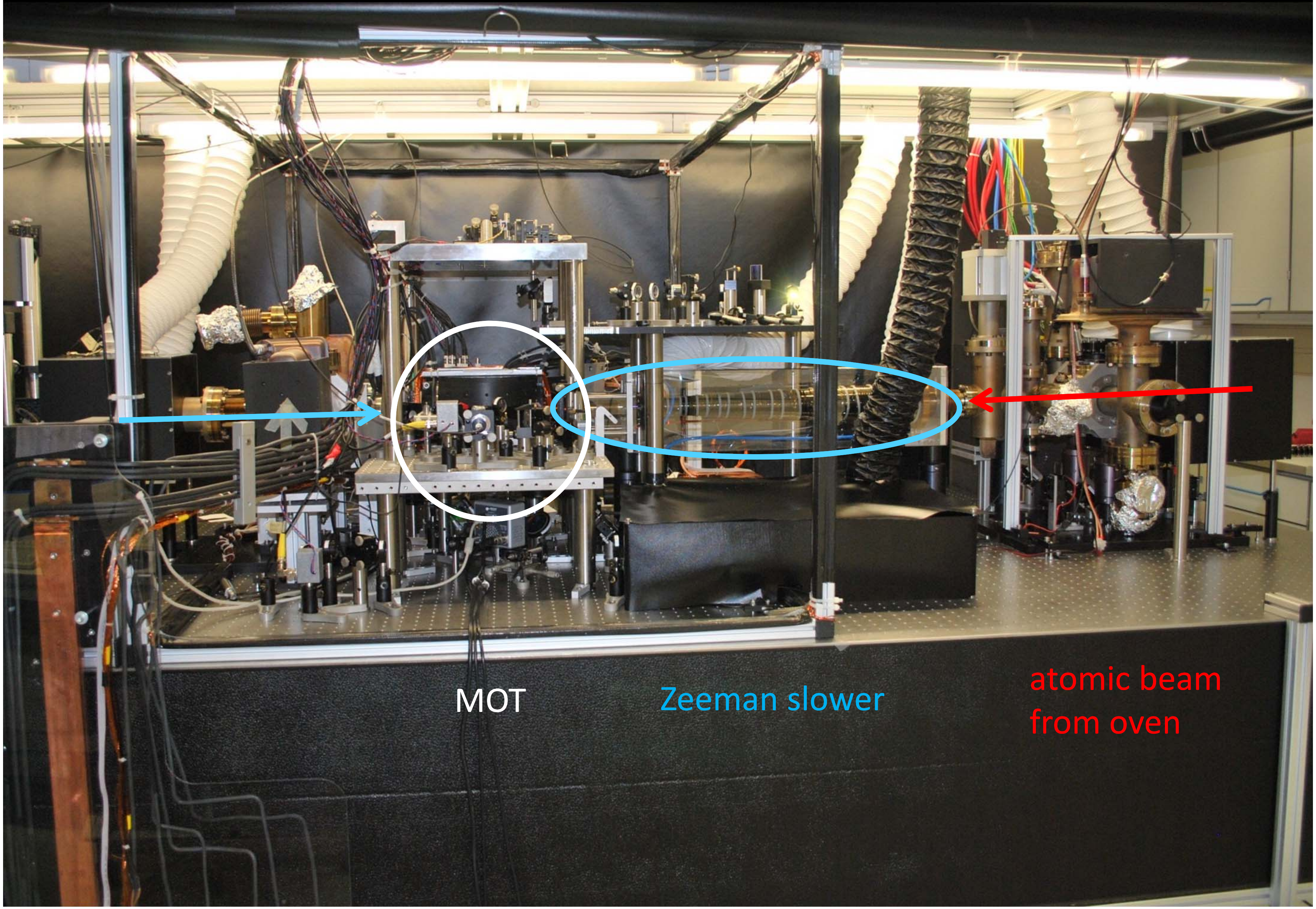
no collisions

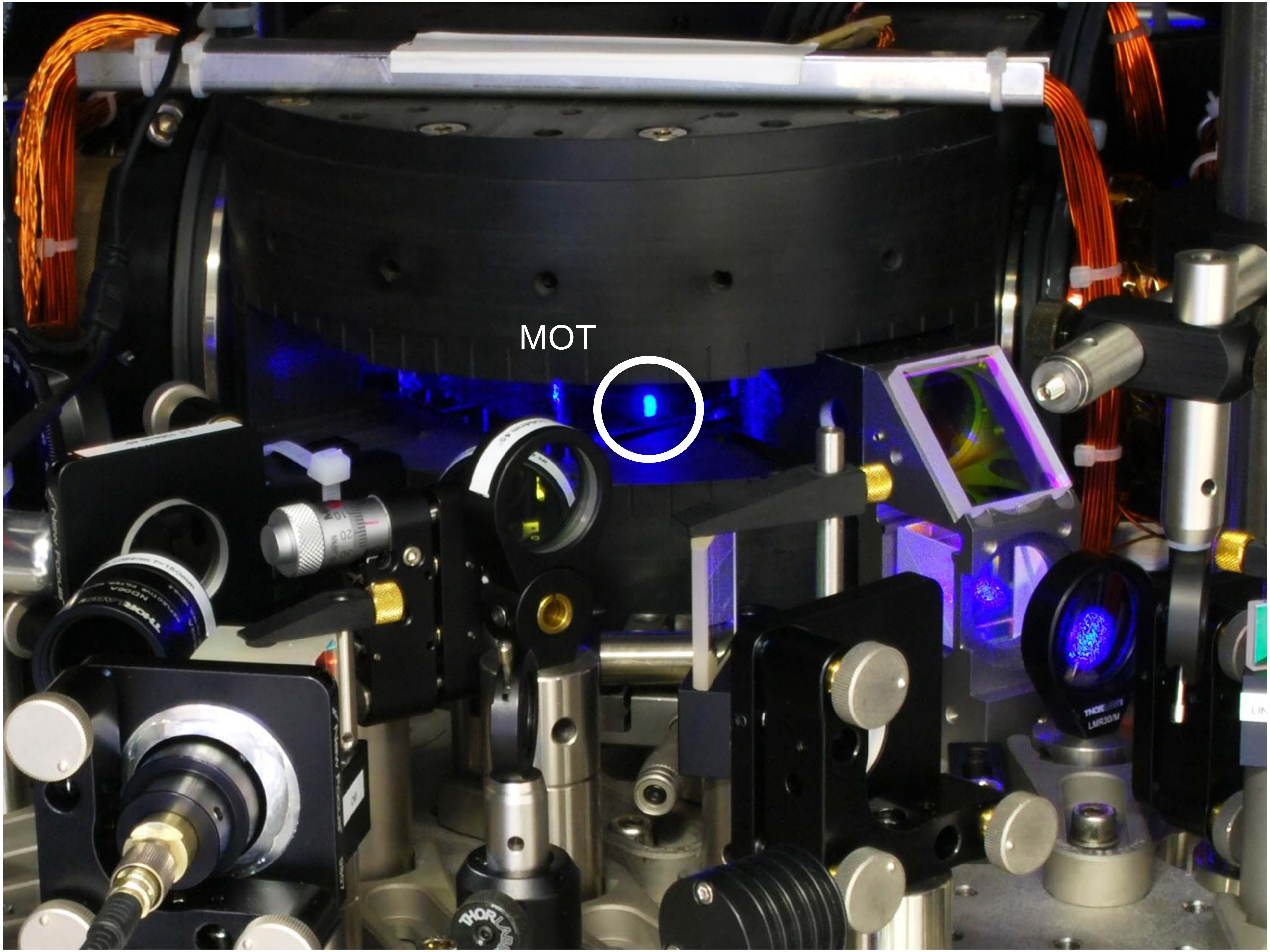
inelastic collisions

by Roman Ciurylo
using PRL **95**, 223002

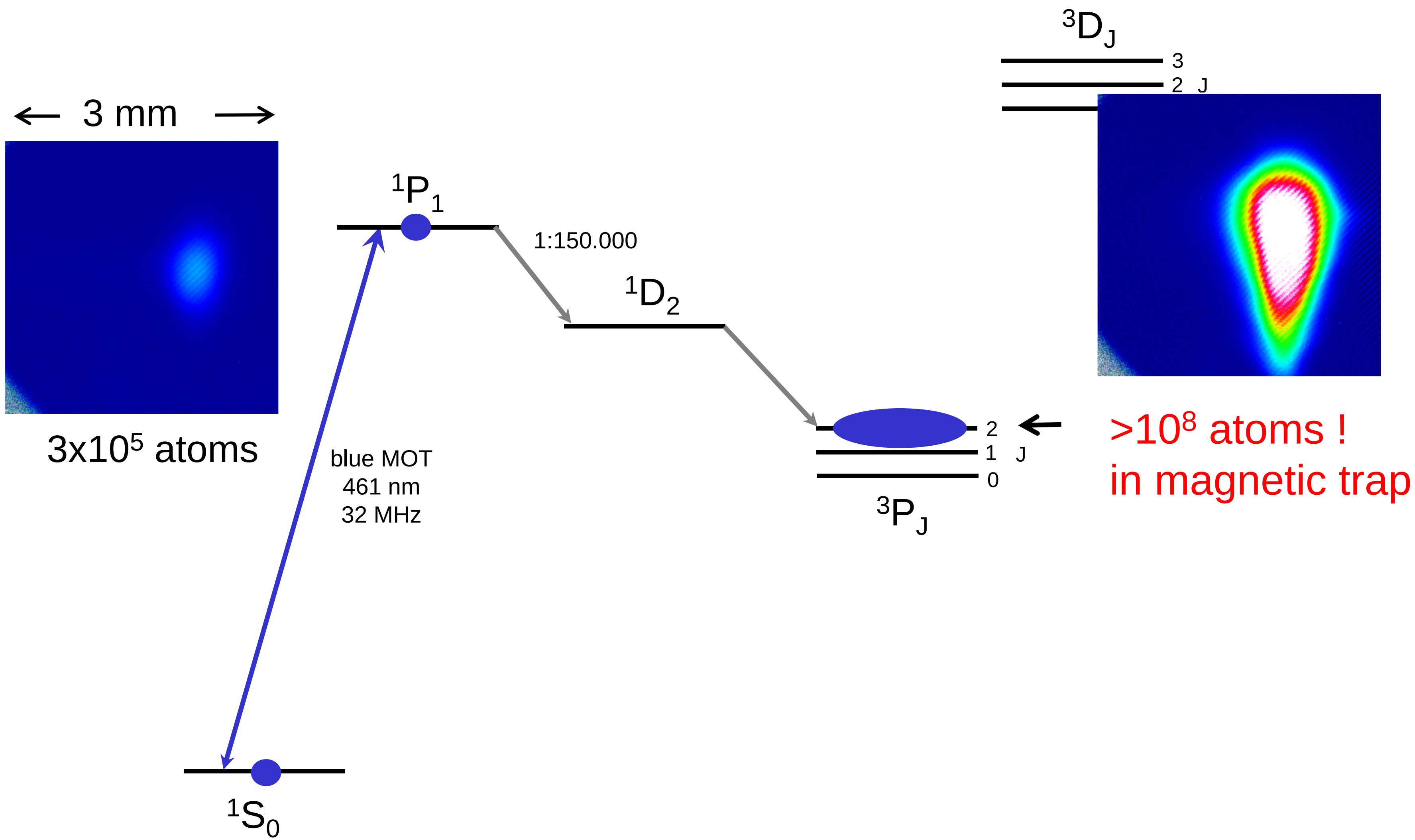
$\Longrightarrow$ Our strategy: use ^{84}Sr

Let's do it!

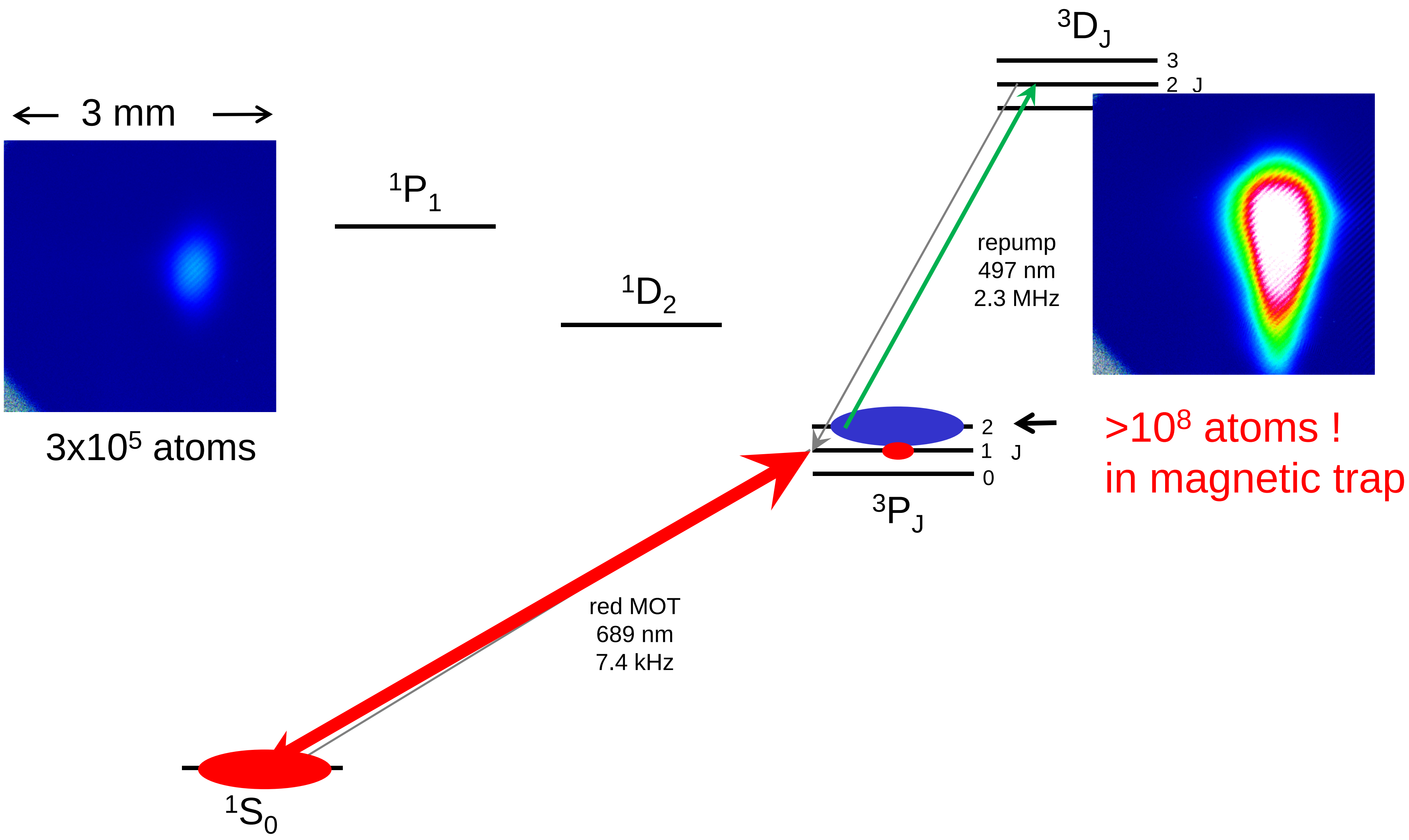



MOT
THORLABS
LMR30/M

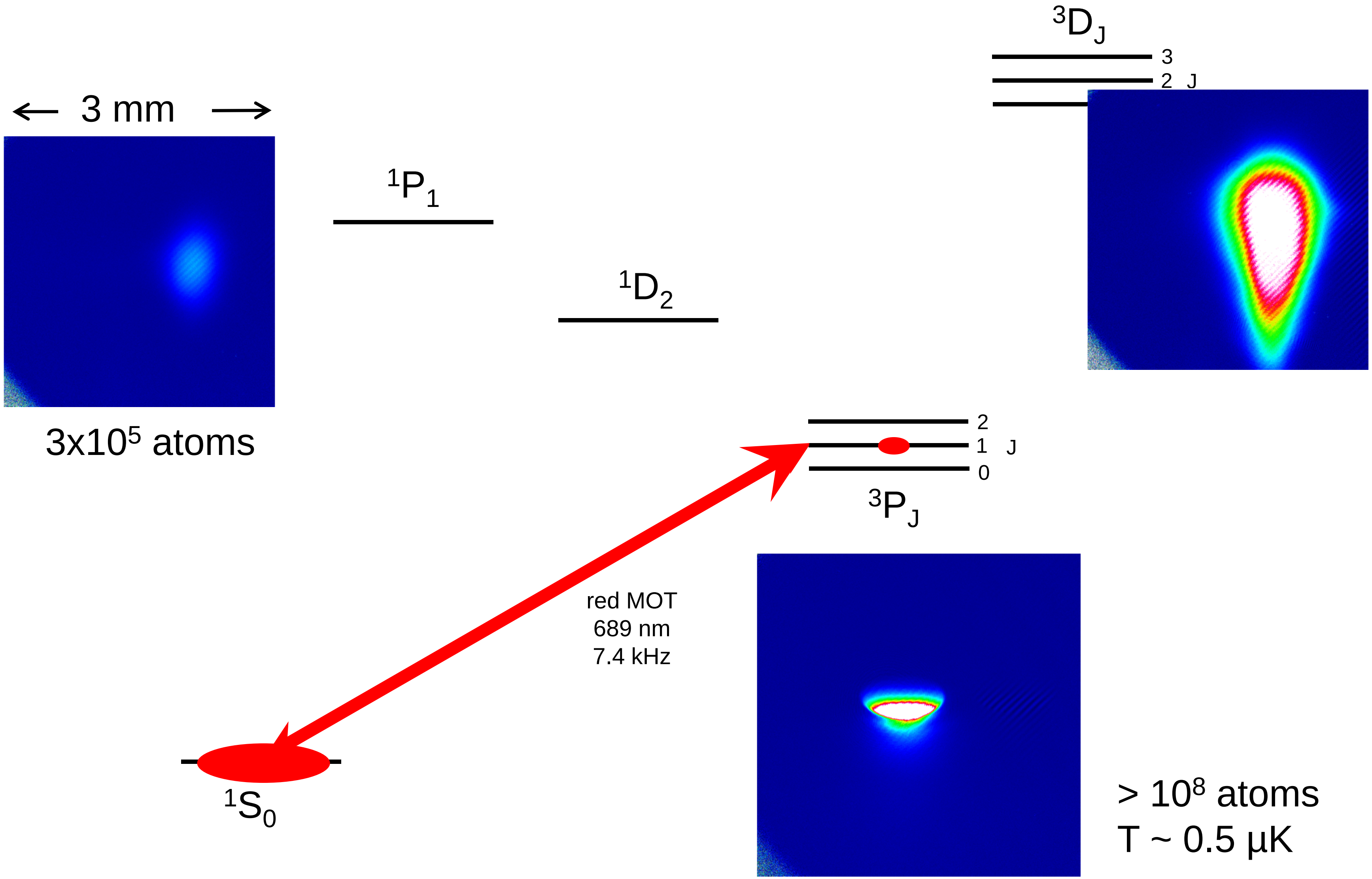
Accumulation in metastable state



Narrow linewidth MOT



Narrow linewidth MOT

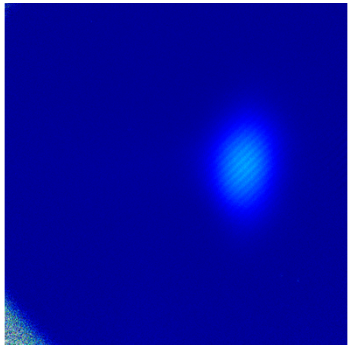


Narrow linewidth MOT

^3D_J

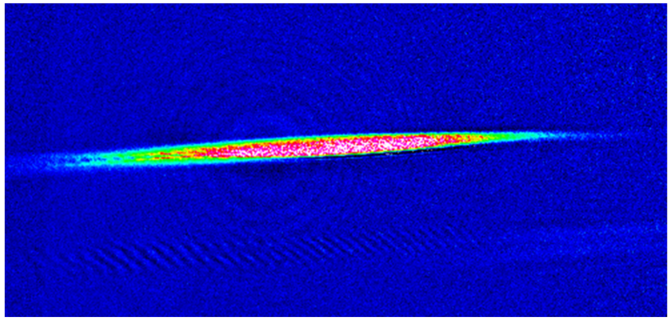
3
2 J

← 3 mm →

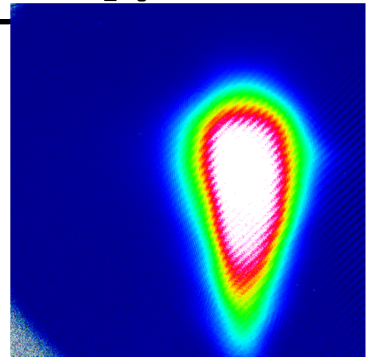


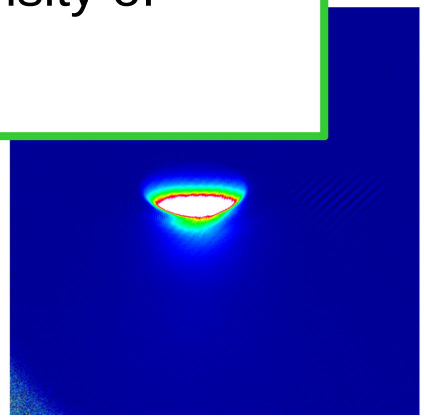
$3x10^5$ atoms

Atoms in dipole trap



$5x10^7$ atoms with
phase-space density of
0.1 !

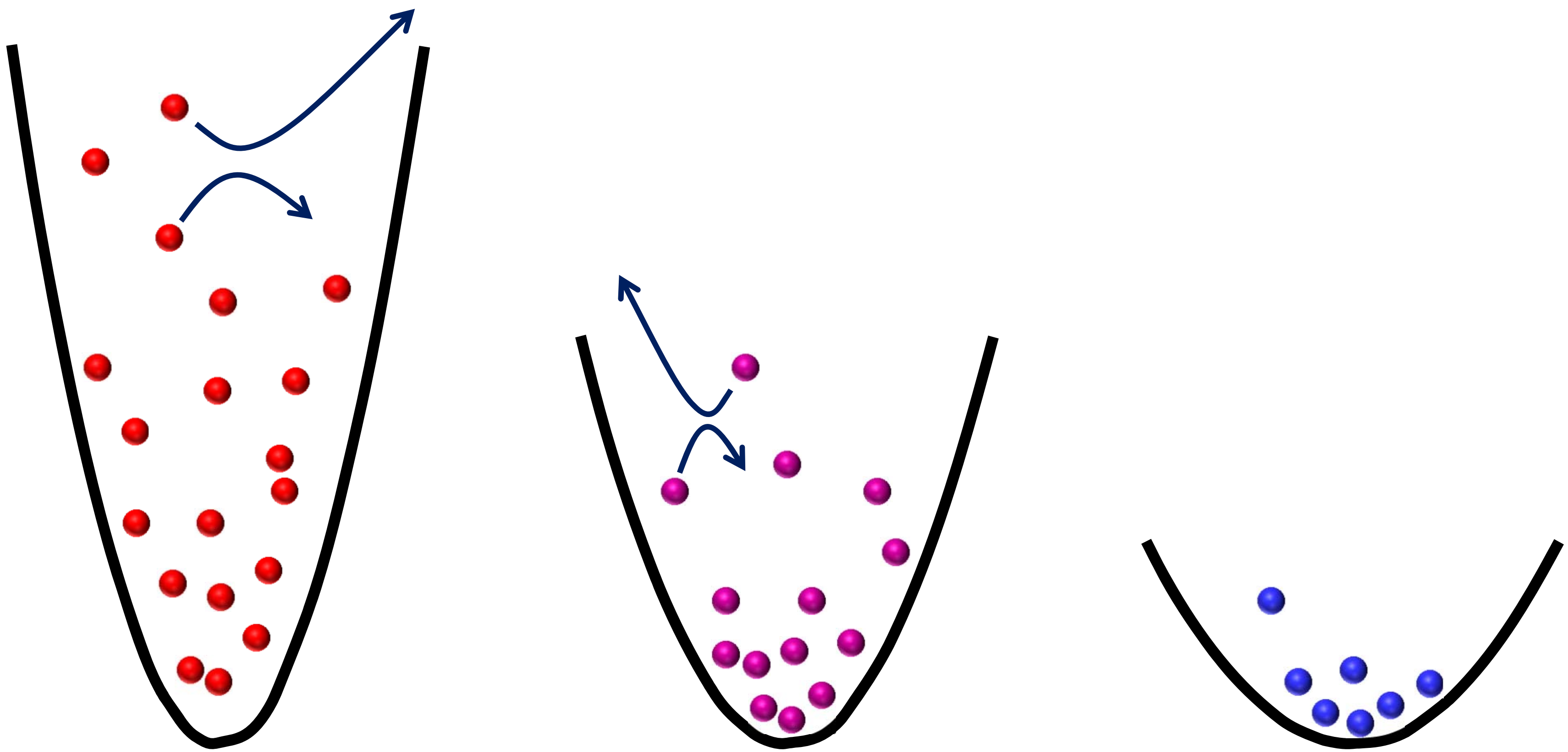




10^8 atoms
T ~ 0.7 µK

$^1S_0$

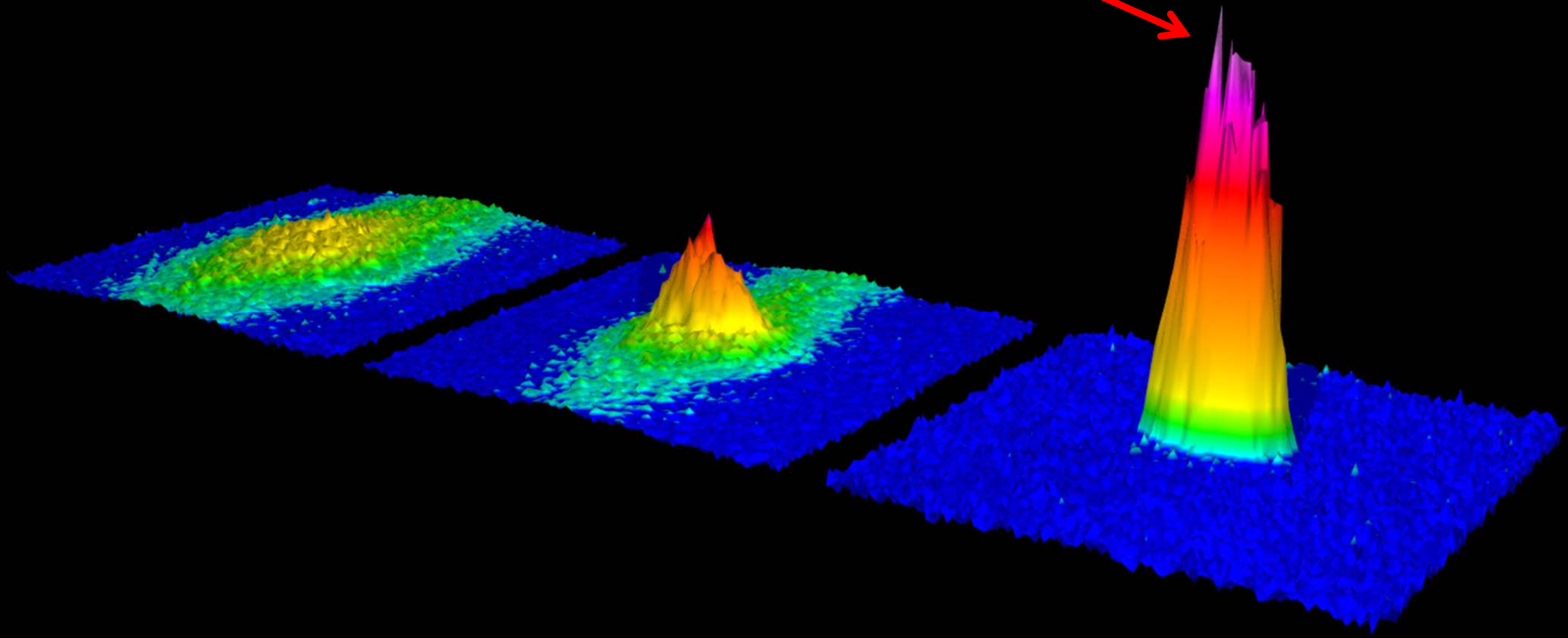
Forced evaporative cooling



Sr BEC!

9/26/2009

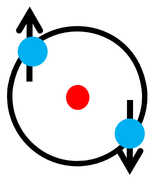
10 million atoms in pure BEC!



See also work by Tom Killian's group: PRL **103**, 200402 (2009)

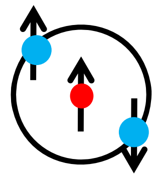
Fermionic ^{87}Sr

Bosonic Sr:



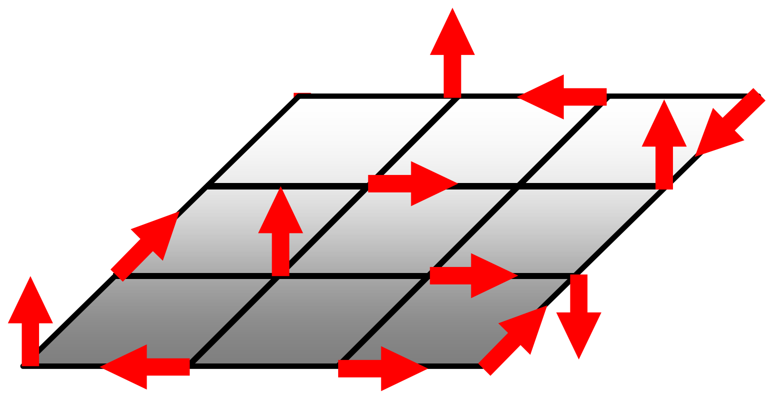
no nuclear spin

Fermionic ^{87}Sr:

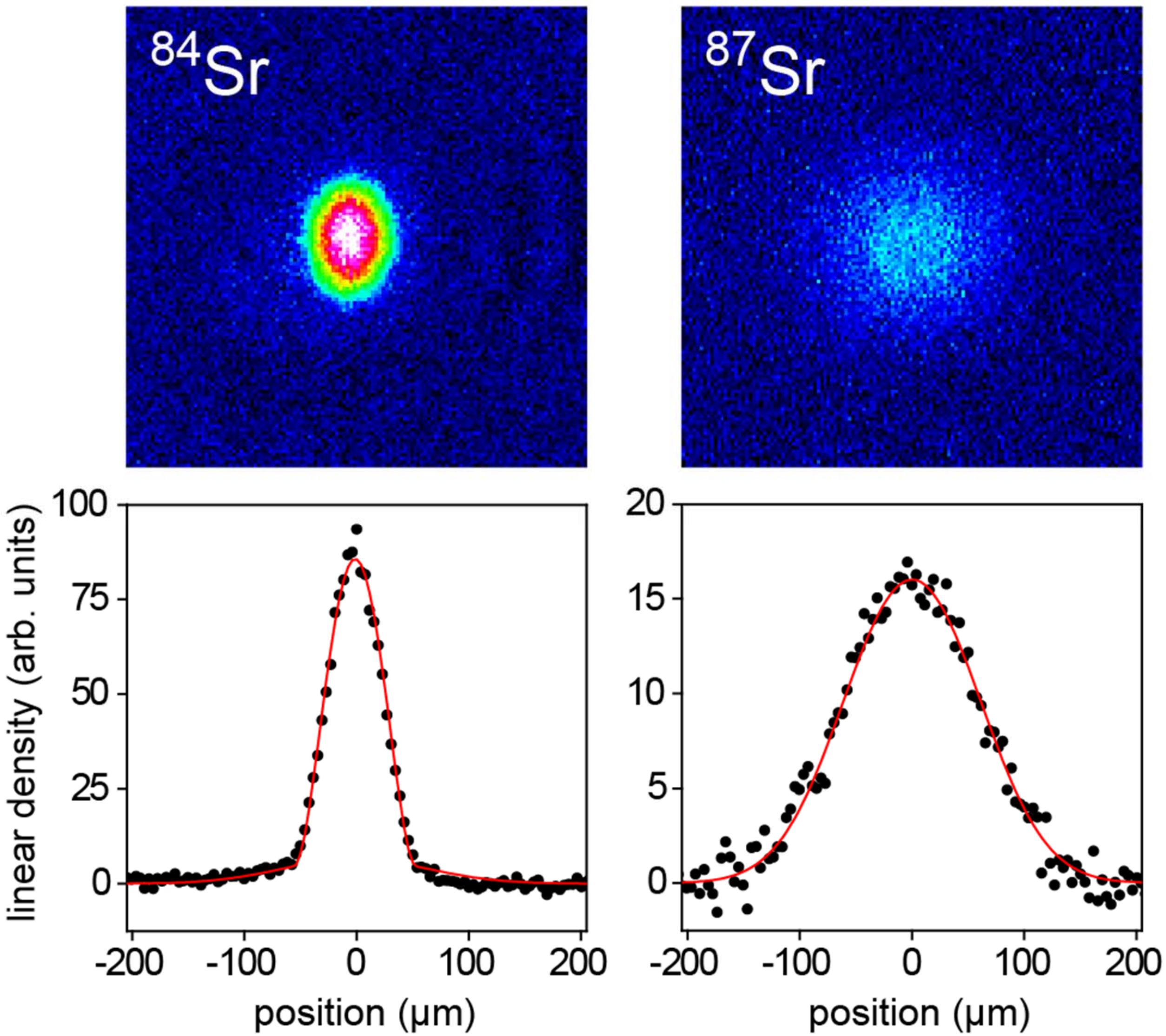


nuclear spin I = 9/2

Quantum computation / simulation

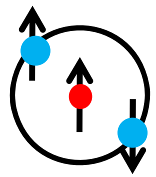


BEC & Fermi sea



^{87}Sr Optical Stern-Gerlach

Fermionic ^{87}Sr:



nuclear spin I = 9/2

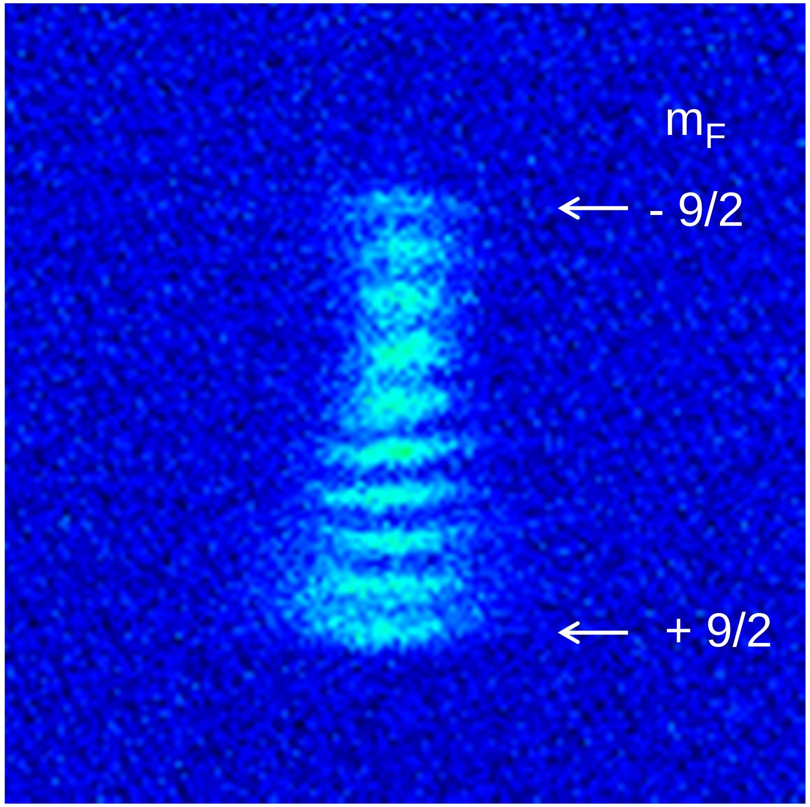
$^1S_0$

F = 9/2

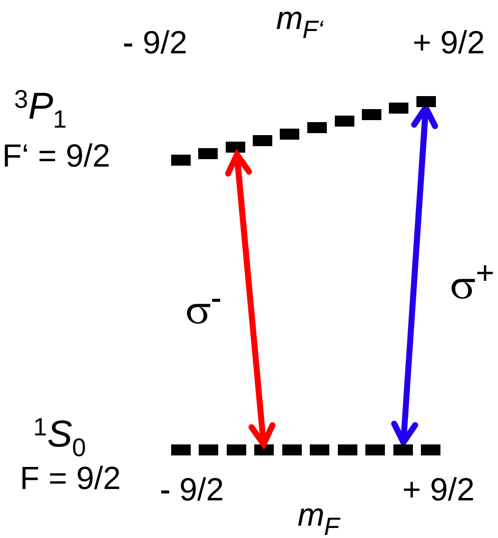
- 9/2 + 9/2

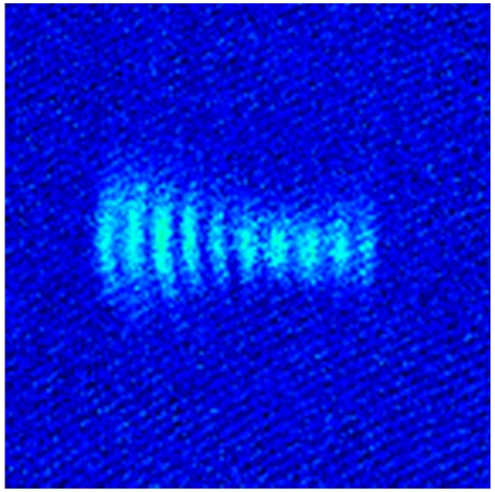
m_F

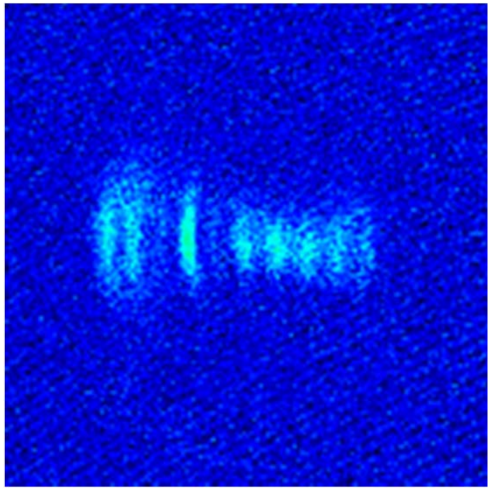
optical Stern-Gerlach

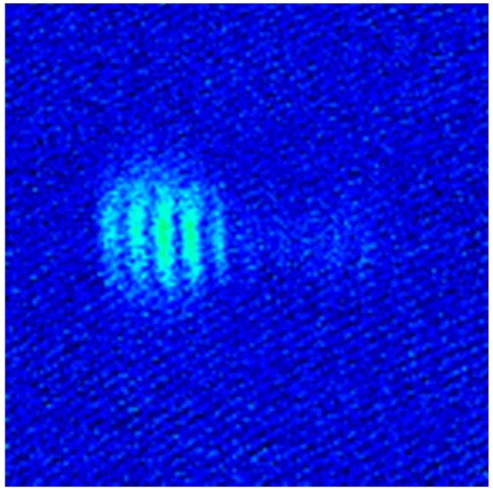


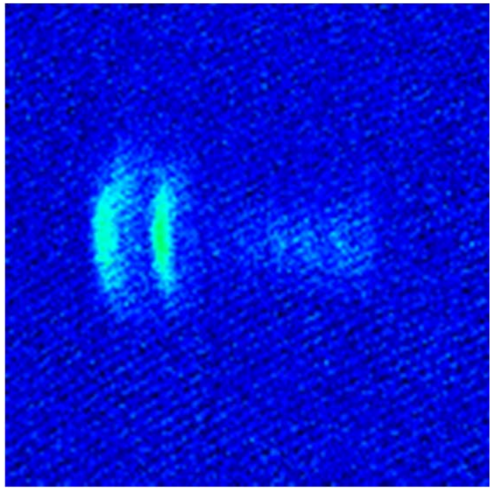
Optical pumping







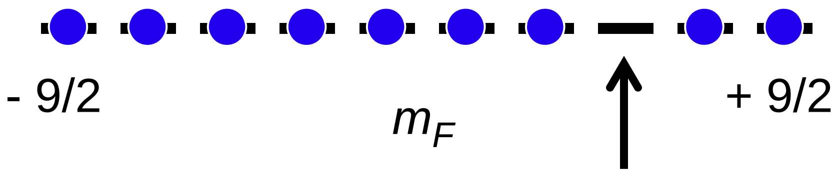


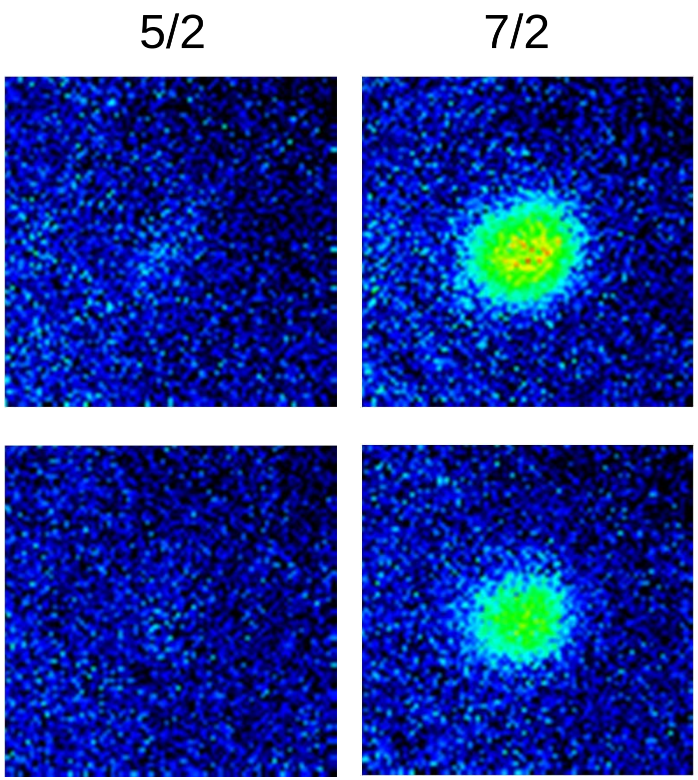


Spin relaxation?

$^1S_0$

F = 9/2





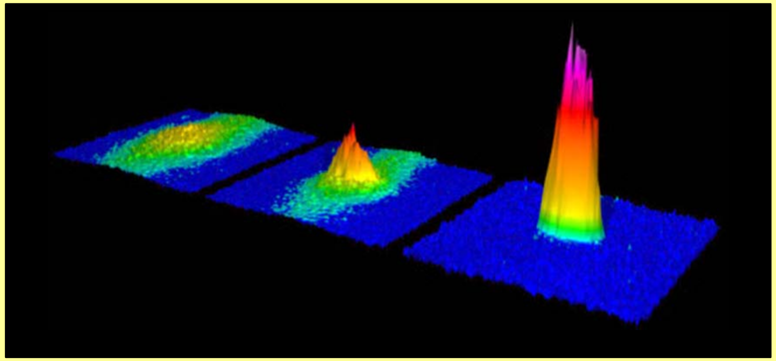
averages of 25 images

No spin relaxation after 1000 collisions!

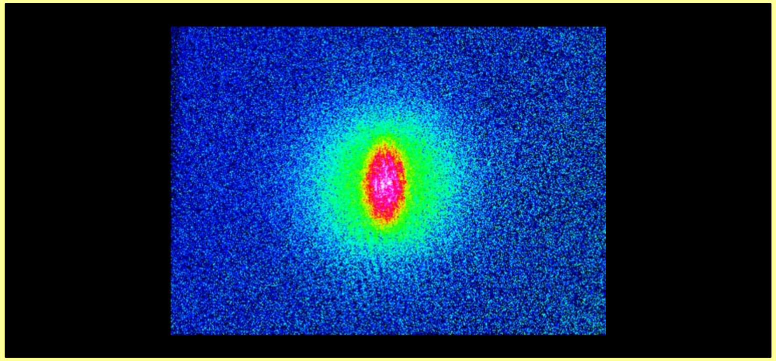
Overview

BEC of strontium

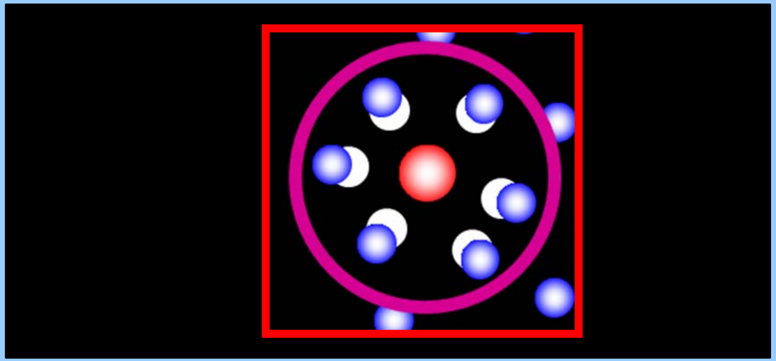
^{87}Sr Fermi gas



Laser cooling to BEC



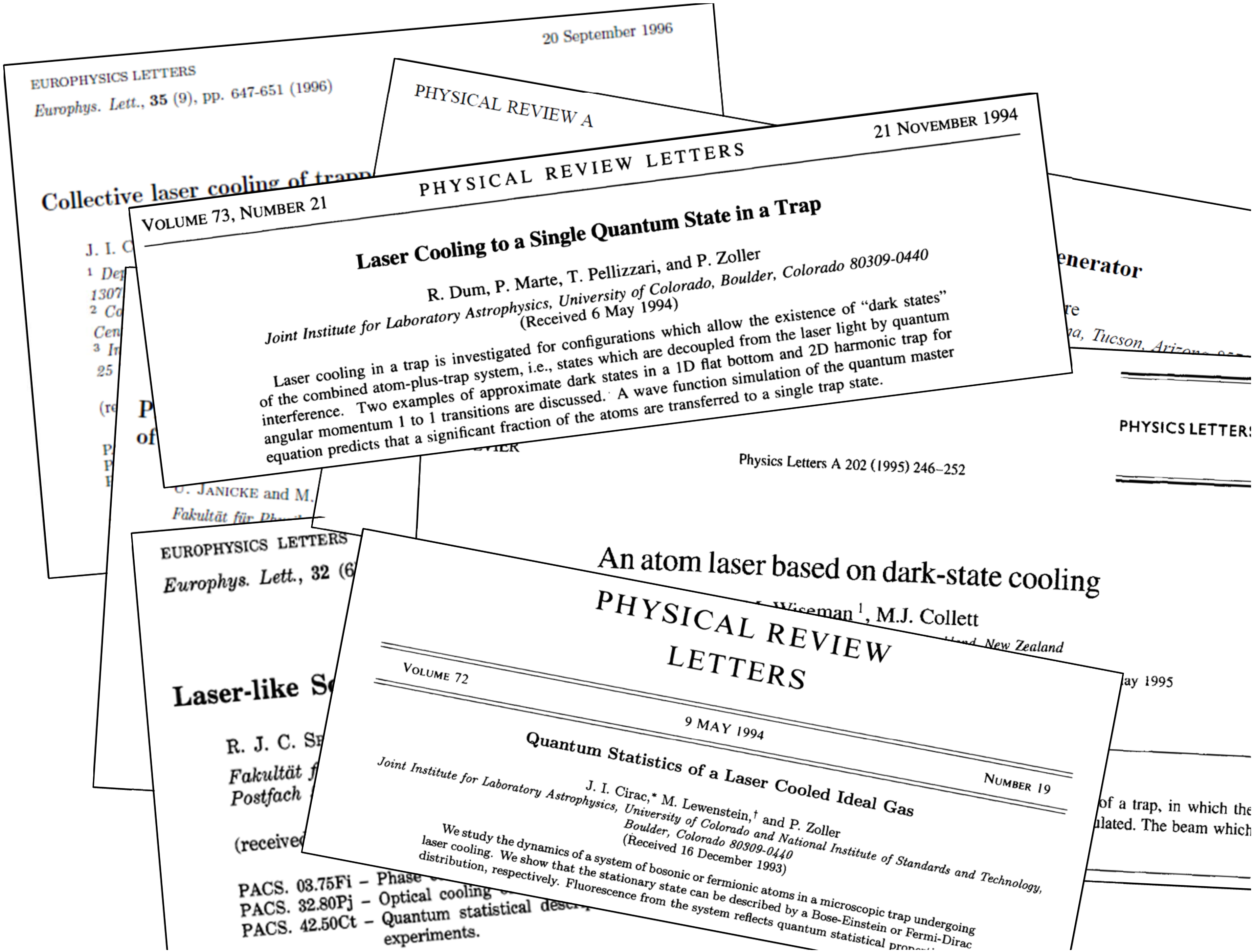
Strongly-interacting
^{6}Li-^{40}K Fermi mixture



A new dog for new tricks: laser cooling to BEC

Why laser cooling to BEC?

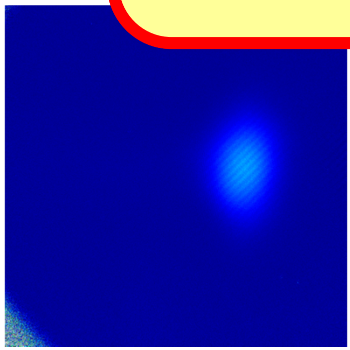
- Shows that evaporative cooling is **not** the only way to BEC
- Laser cooling does not rely on losses
- Easily extended to continuous BEC!


EUROPHYSICS LETTERS
Europhys. Lett., 35 (9), pp. 647-651 (1996)
20 September 1996
Collective laser cooling of trap
PHYSICAL REVIEW A
PHYSICAL REVIEW LETTERS
VOLUME 73, NUMBER 21
21 NOVEMBER 1994
Laser Cooling to a Single Quantum State in a Trap
R. Dum, P. Marte, T. Pellizzari, and P. Zoller
Joint Institute for Laboratory Astrophysics, University of Colorado, Boulder, Colorado 80309-0440
(Received 6 May 1994)
Laser cooling in a trap is investigated for configurations which allow the existence of "dark states" of the combined atom-plus-trap system, i.e., states which are decoupled from the laser light by quantum interference. Two examples of approximate dark states in a 1D flat bottom and 2D harmonic trap for angular momentum 1 to 1 transitions are discussed. A wave function simulation of the quantum master equation predicts that a significant fraction of the atoms are transferred to a single trap state.
enerator
PHYSICS LETTERS
Physics Letters A 202 (1995) 246–252
Fakultät für Ph
EUROPHYSICS LETTERS
Europhys. Lett., 32 (6
An atom laser based on dark-state cooling
M.J. Collett
New Zealand
Laser-like So
R. J. C. S
Fakultät f
Postfach
PACS. 03.75Fi – Phase
PACS. 32.80Pj – Optical cooling
PACS. 42.50Ct – Quantum statistical desc
experiments.
PHYSICAL REVIEW LETTERS
VOLUME 72
9 MAY 1994
NUMBER 19
Quantum Statistics of a Laser Cooled Ideal Gas
J. I. Cirac,* M. Lewenstein,† and P. Zoller
Joint Institute for Laboratory Astrophysics, University of Colorado and National Institute of Standards and Technology, Boulder, Colorado 80309-0440
(Received 16 December 1993)
We study the dynamics of a system of bosonic or fermionic atoms in a microscopic trap undergoing laser cooling. We show that the stationary state can be described by a Bose-Einstein or Fermi-Dirac distribution, respectively. Fluorescence from the system reflects quantum statistical

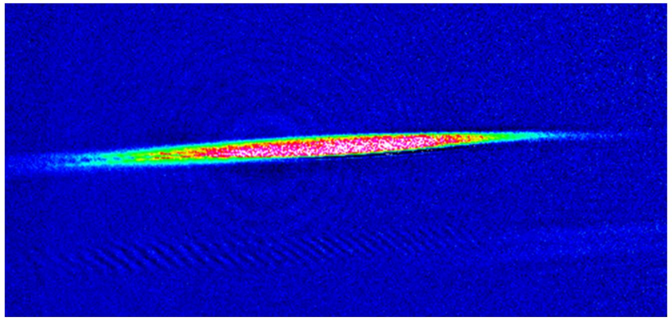
Narrow linewidth MOT

Very high phase-space density has been reached by laser cooling.

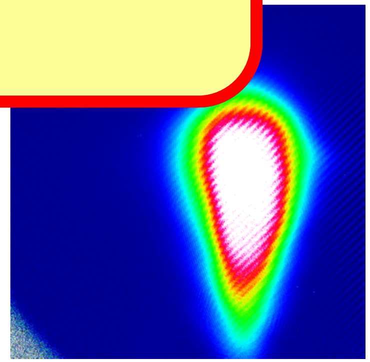
Why not more?

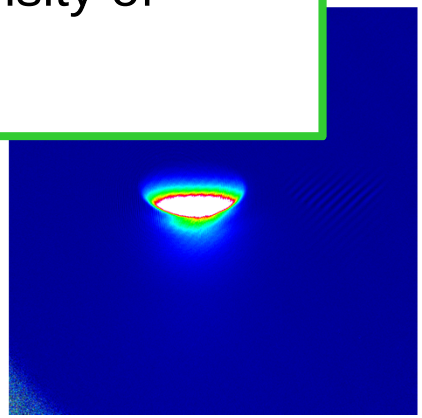


3×10^5 atoms



5×10^7 atoms with
phase-space density of
0.1 !



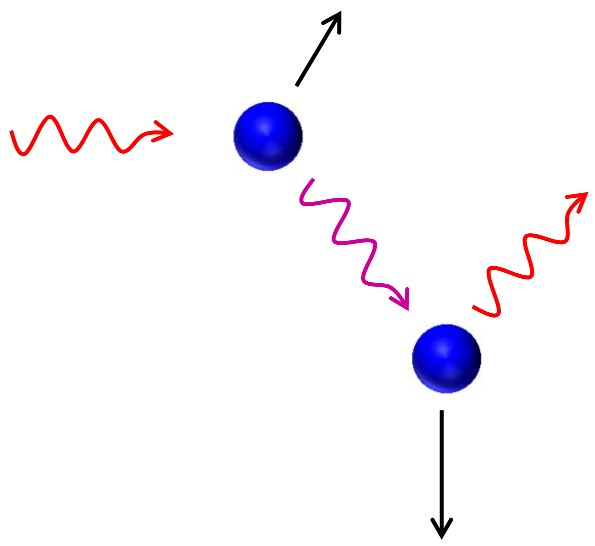


10^8 atoms
$T \sim 0.7\ \mu K$

$^1S_0$

Phase-space density limit

Photon reabsorption

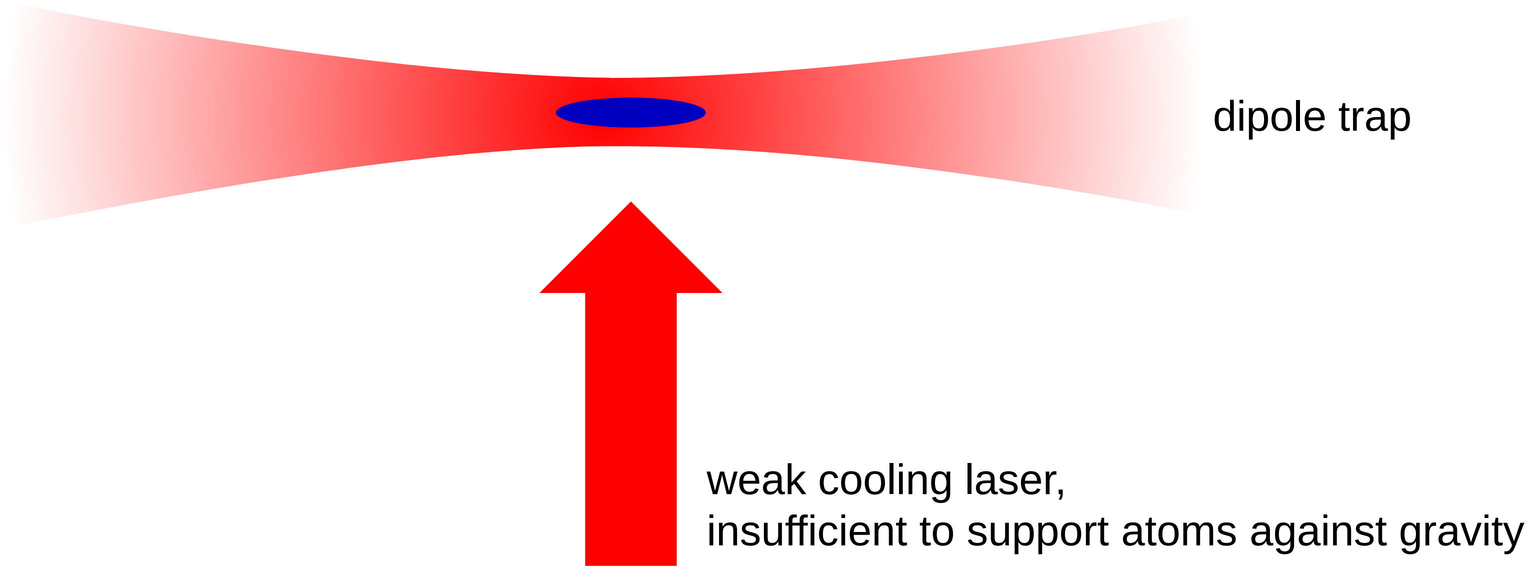


Consequences:

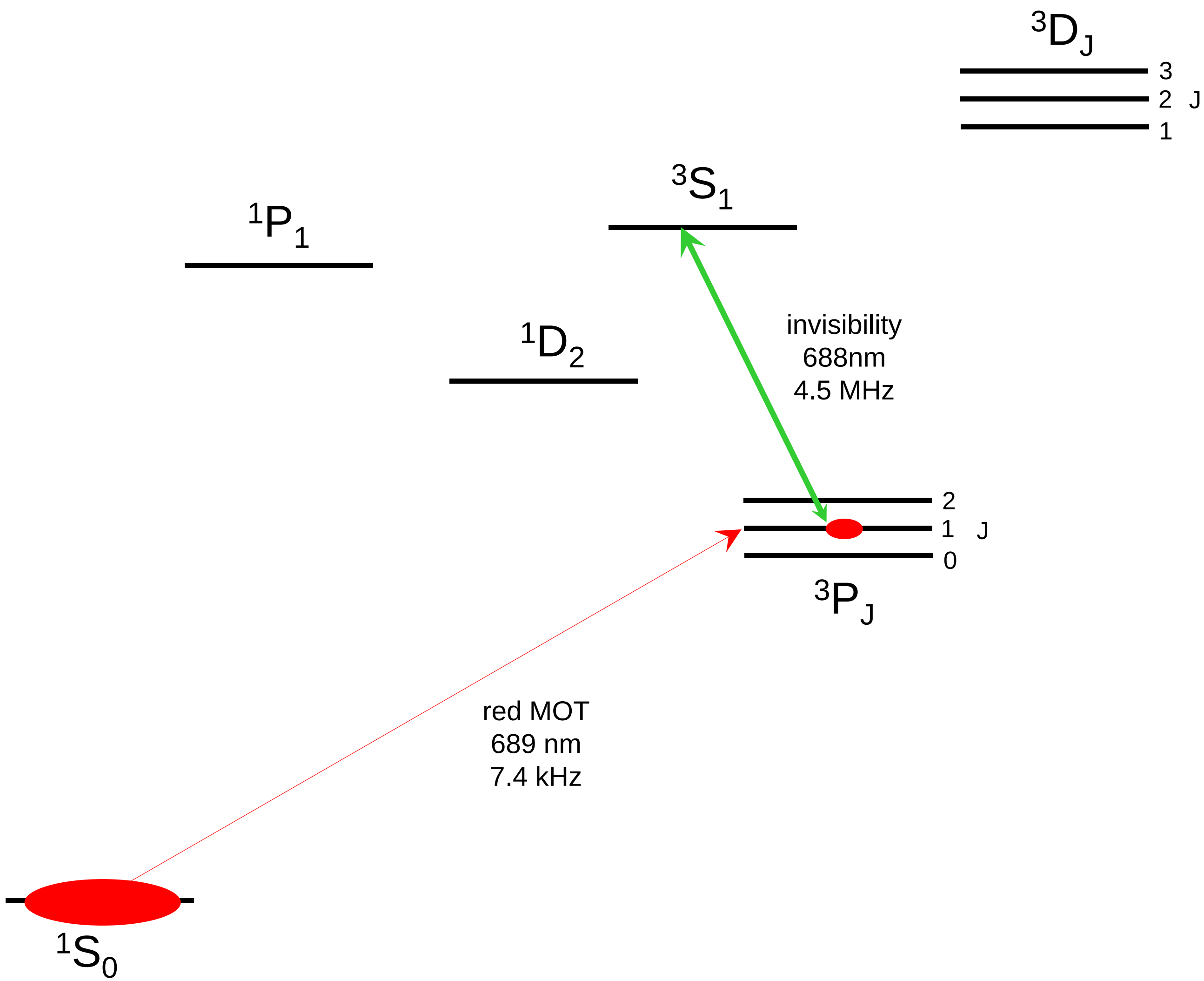
- effective repulsive interaction between atoms $\longrightarrow$ density limit
- widens frequency spectrum of photons $\longrightarrow$ can not cool as well

Another bad effect: light-assisted collisions $\longrightarrow$ heating

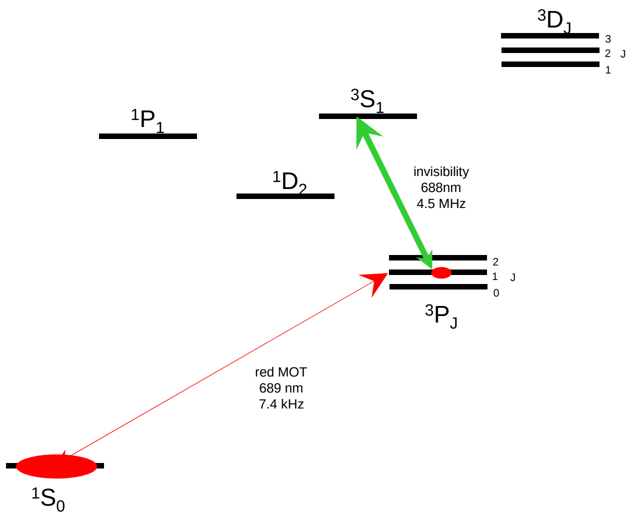
Highest phase-space density reached by laser cooling sample in dipole trap:

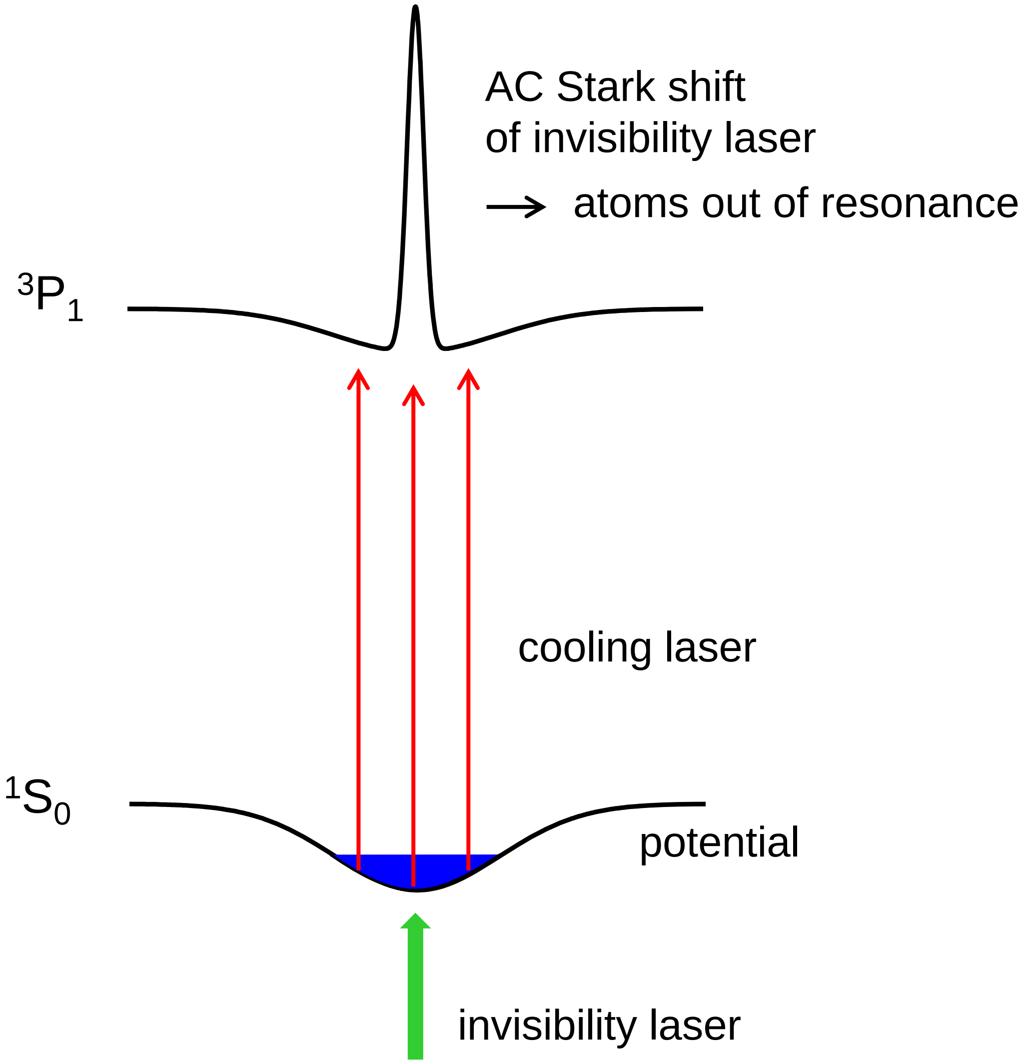


Cap of Invisibility

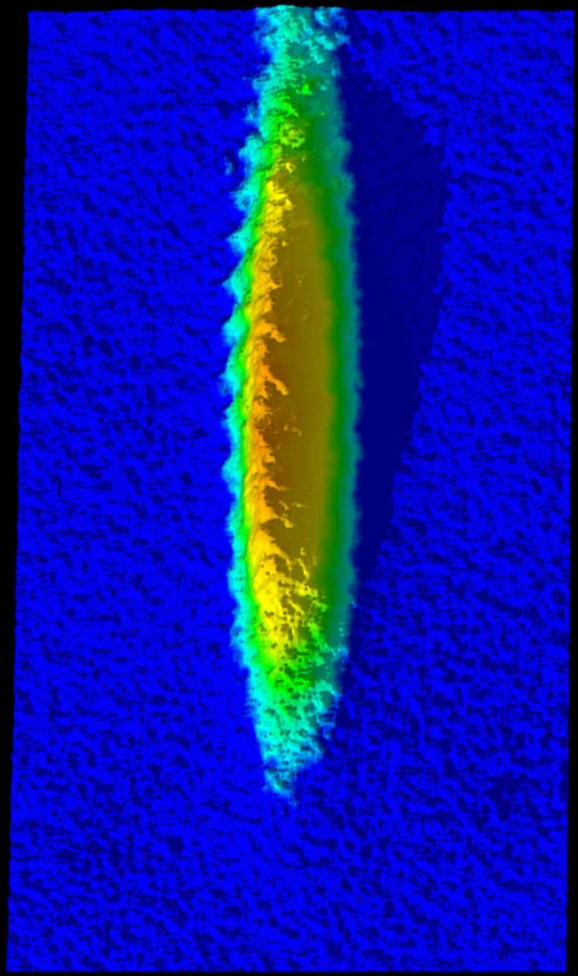


Cap of Invisibility

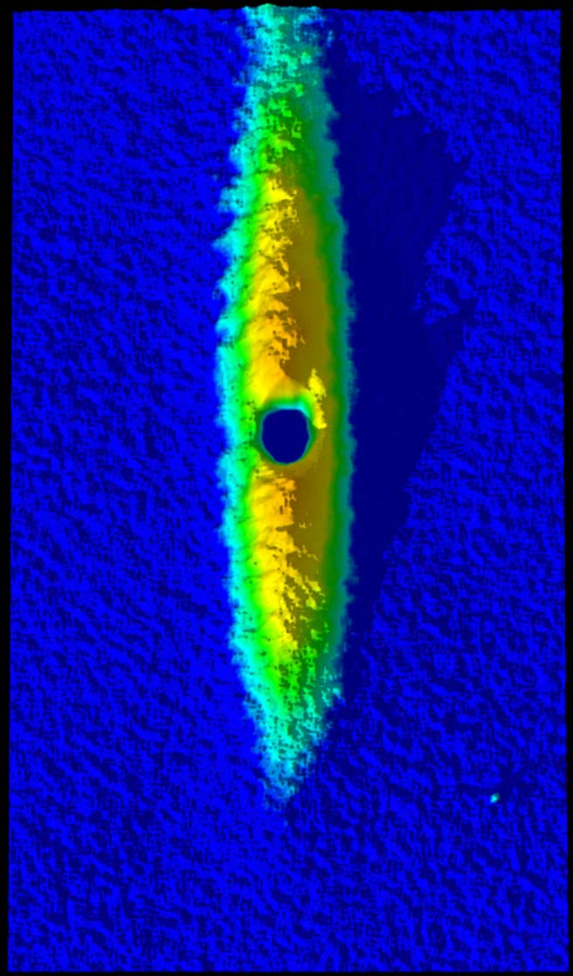




Cap of Invisibility in action

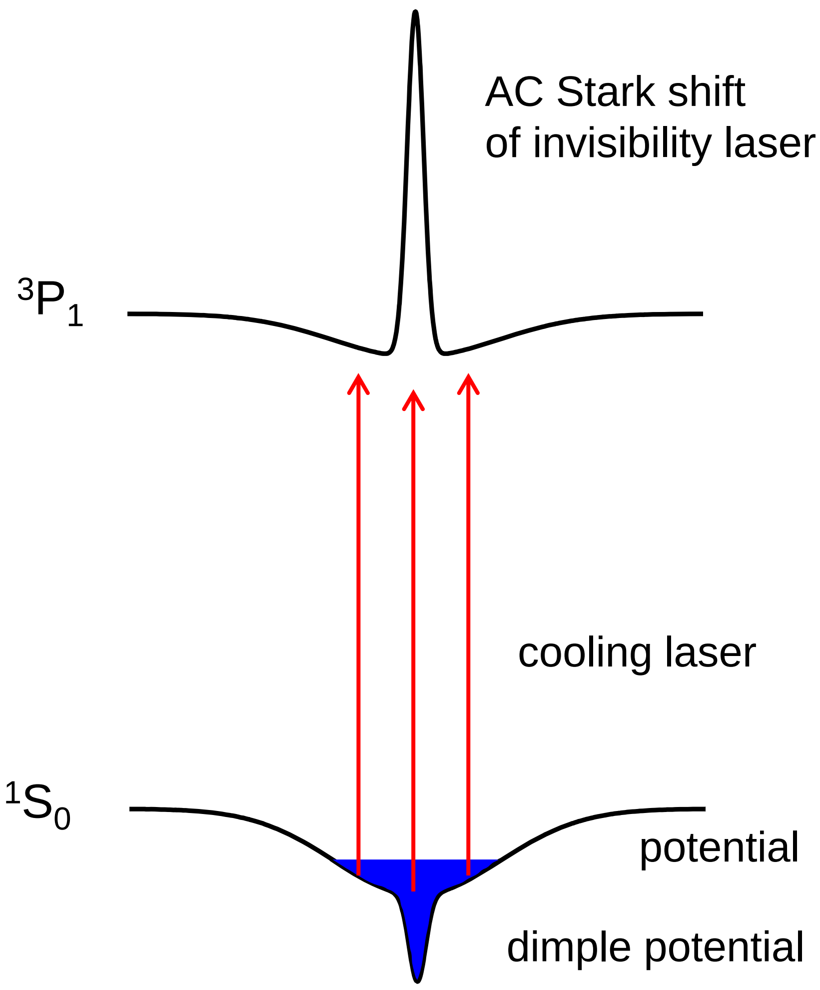


laser cooled atoms

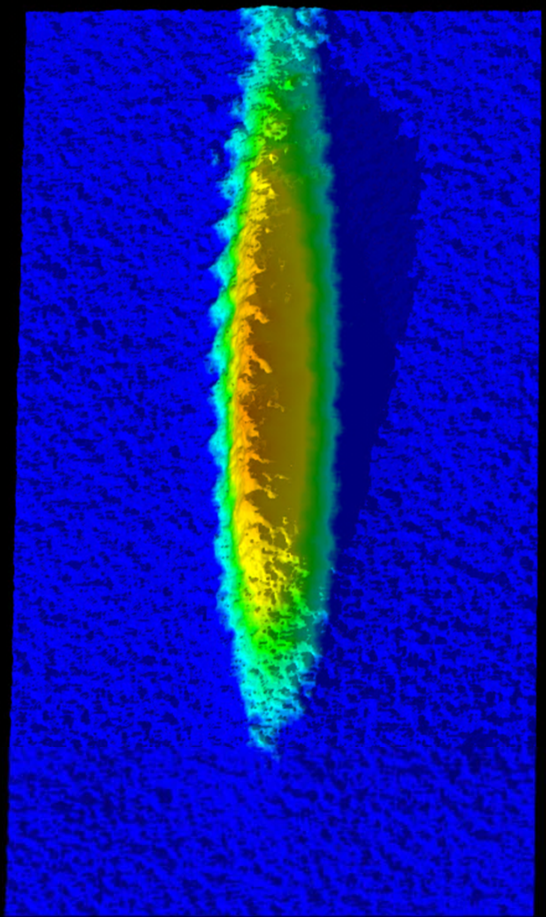


Cap of Invisibility on

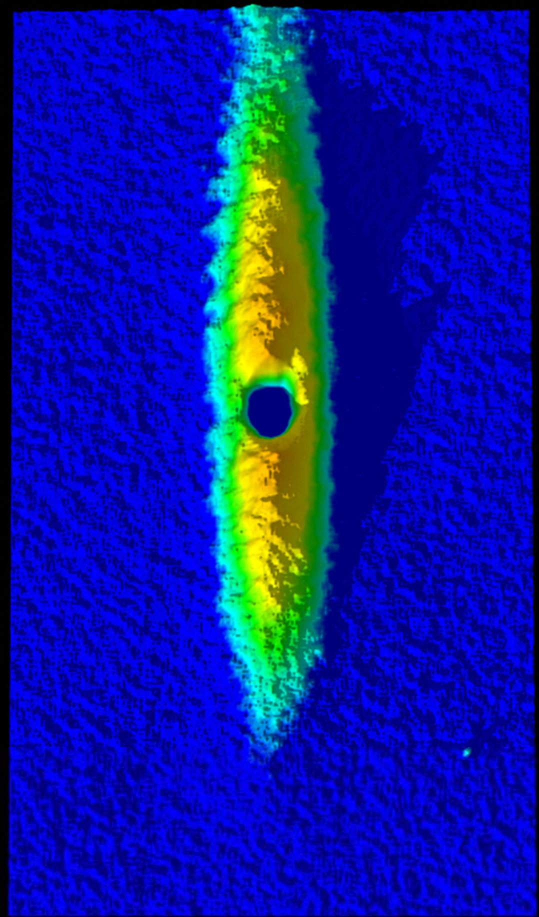
A bit more density…



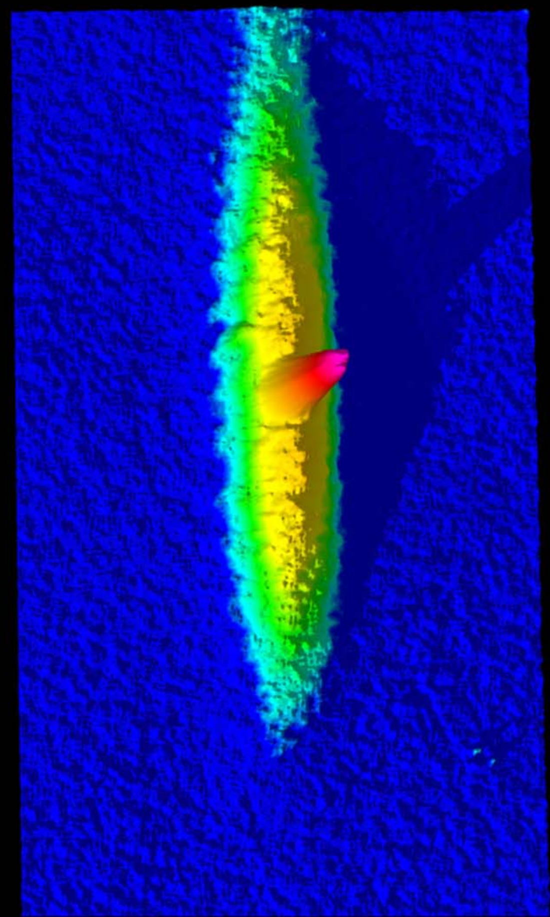
Dimple in action



laser cooled atoms



Cap of invisibility on



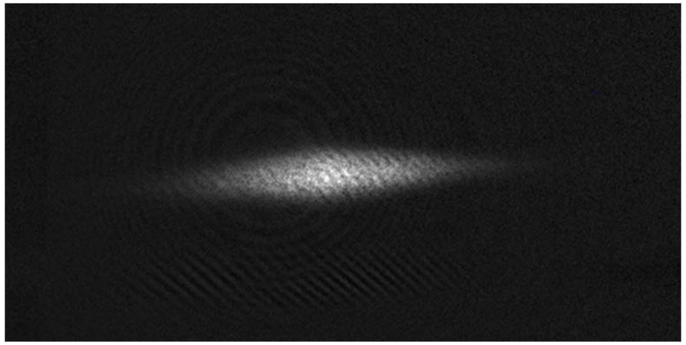
dimple on

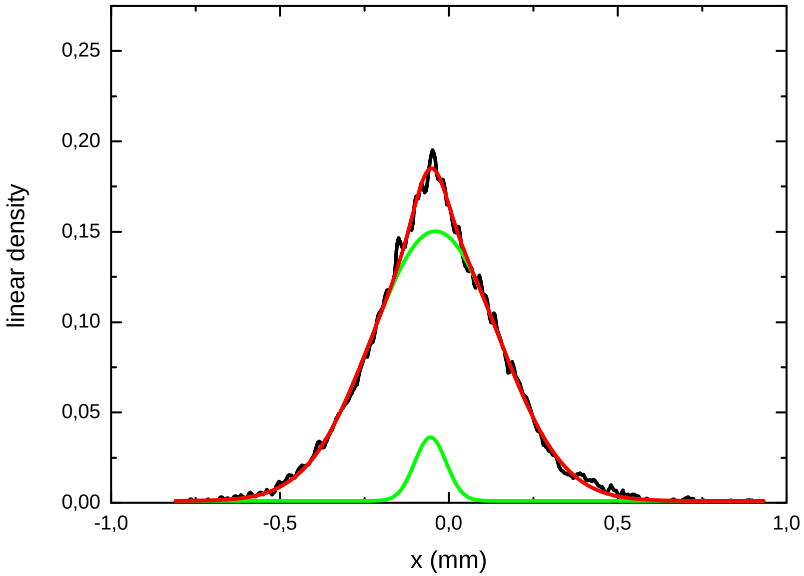
(no invisibility)

Dimple & Invisibility

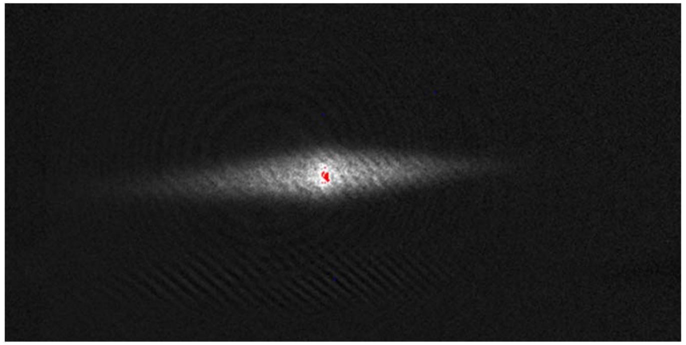
4 ms time of flight images:

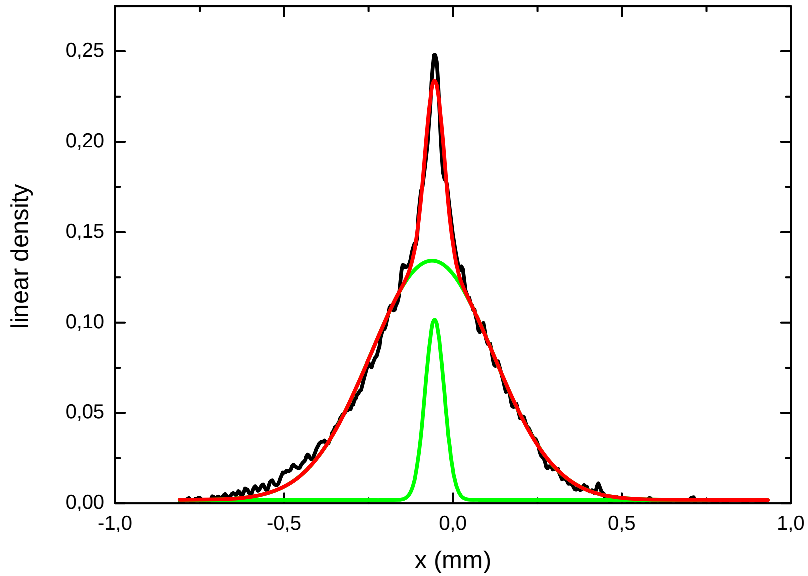
No invisibility laser, weak dimple





invisbility on for 150ms, strong dimple

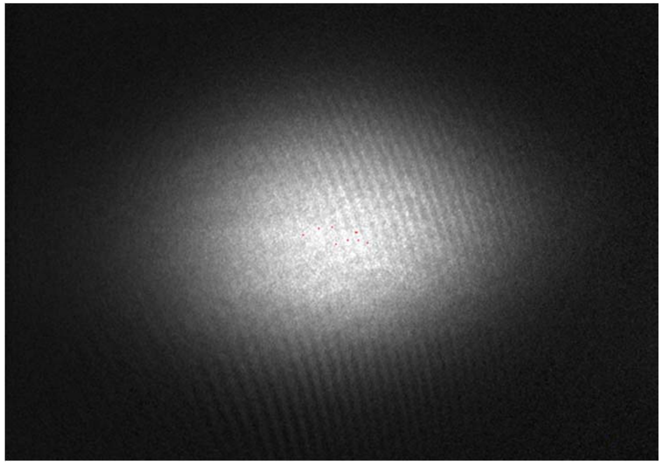


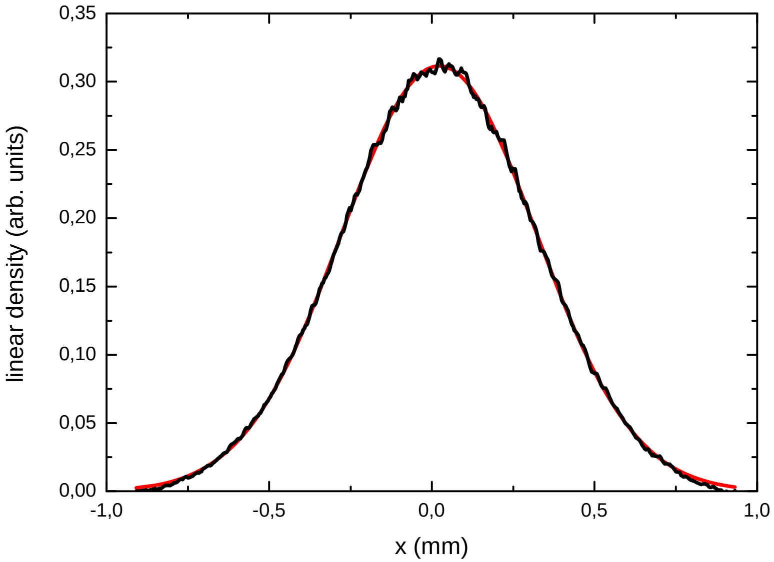


BEC?

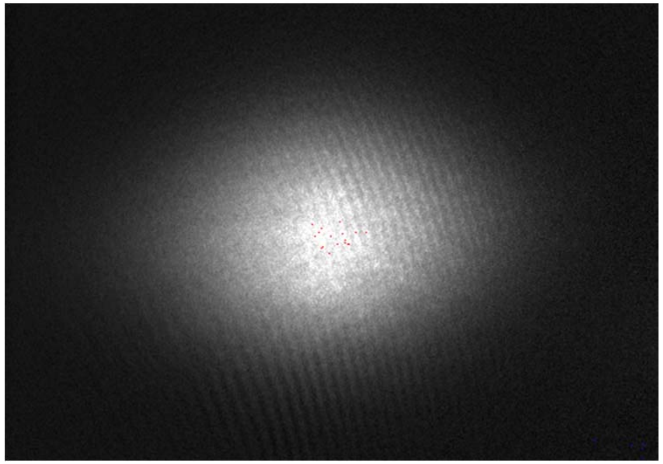
24 ms time of flight images:

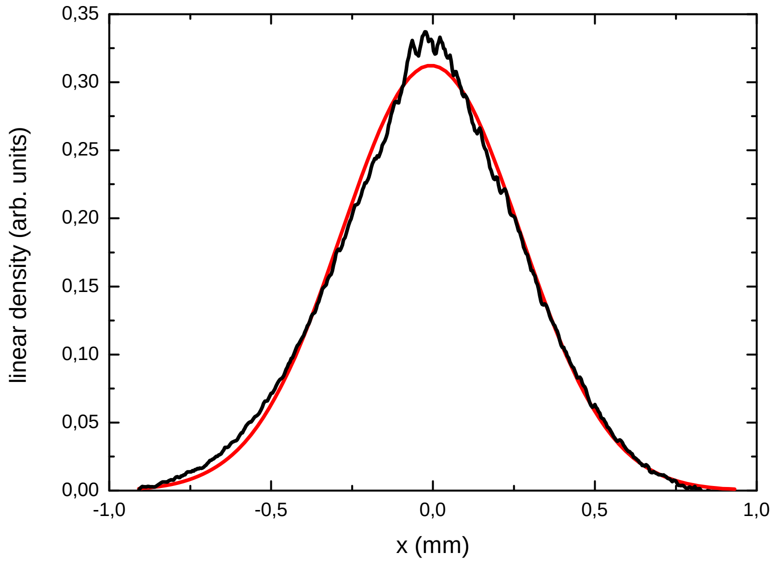
No invisibility laser, weak dimple





invisbility on for 150ms, strong dimple

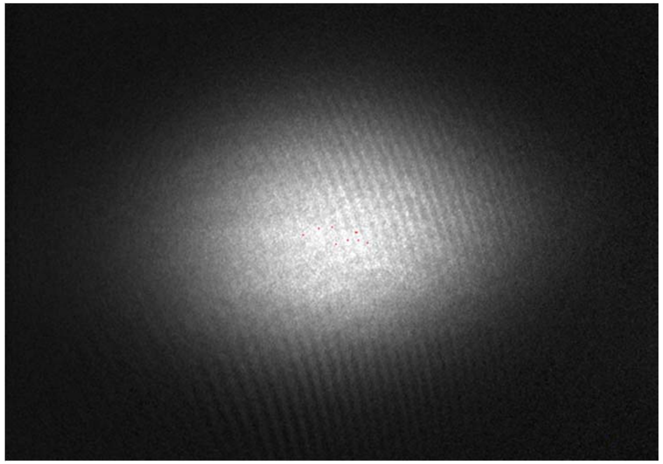


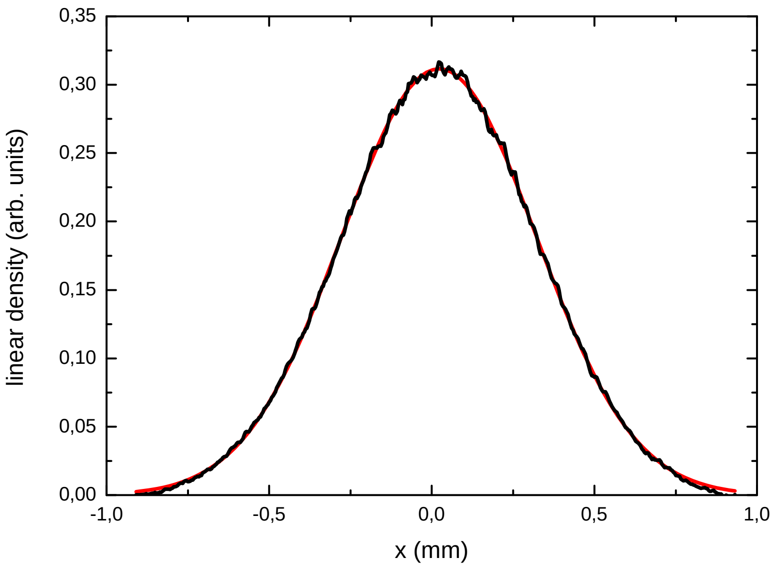


BEC?

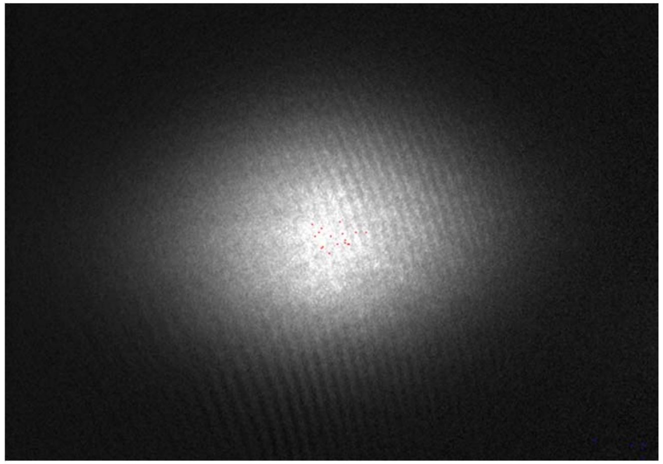
24 ms time of flight images:

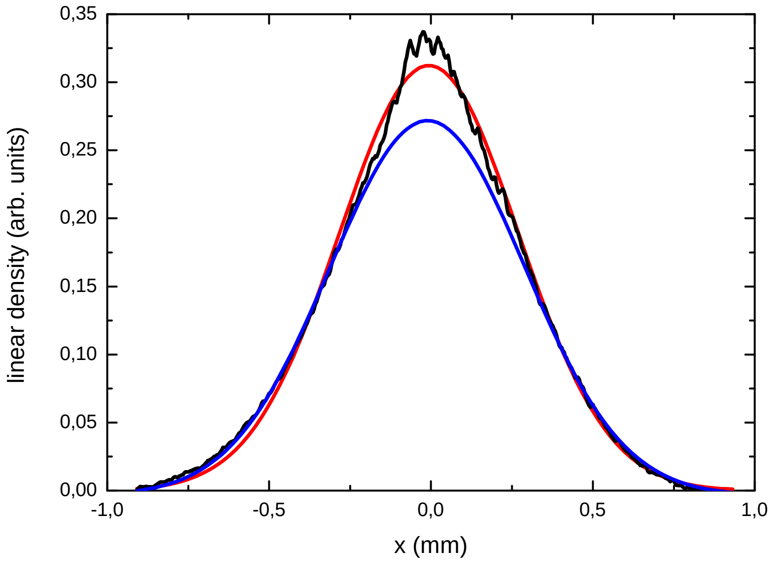
No invisibility laser, weak dimple





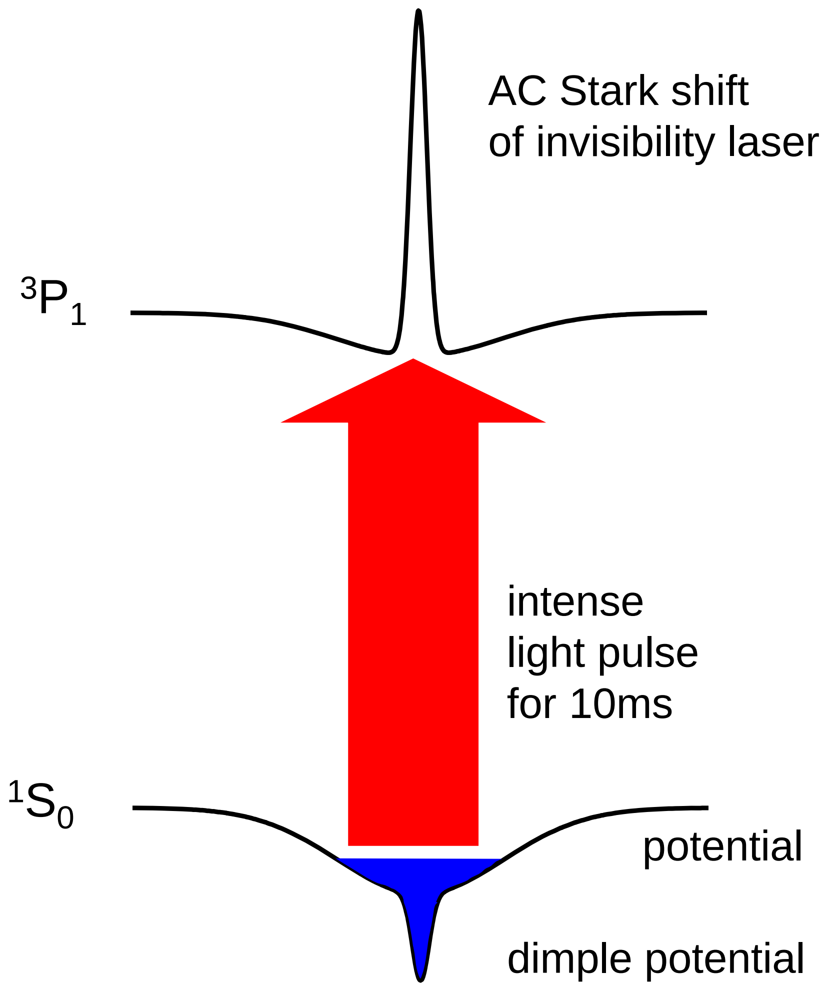
invisbility on for 150ms, strong dimple





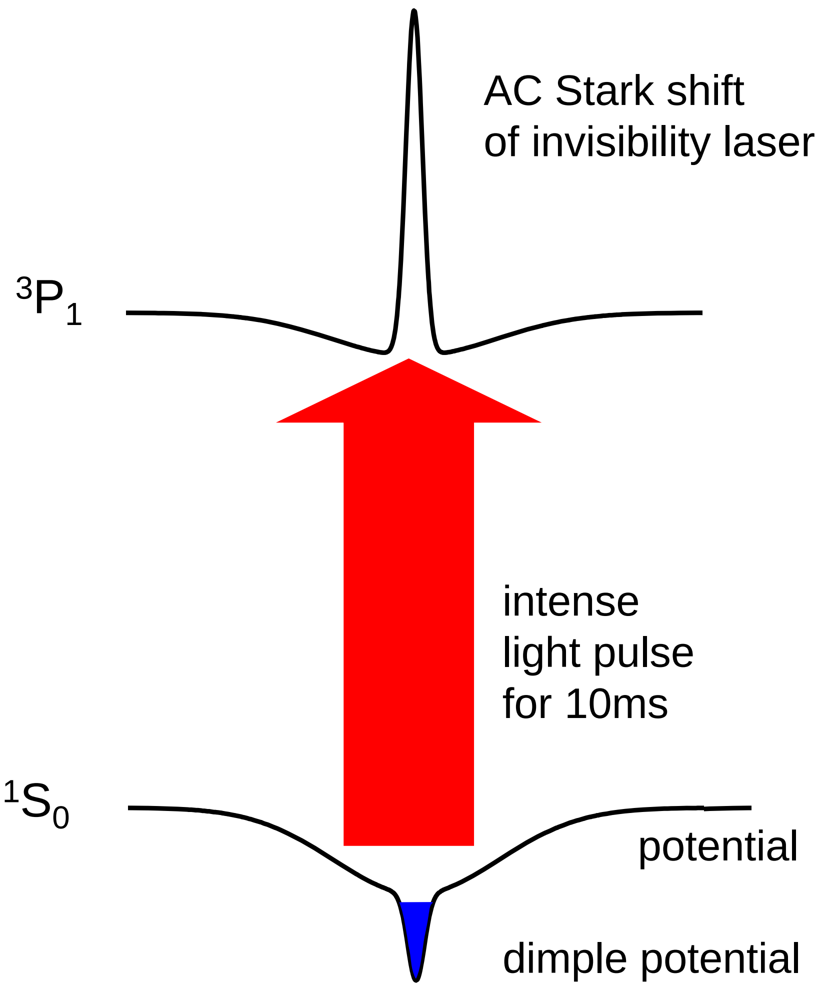
BEC?

Remove reservoir to see more clearly:

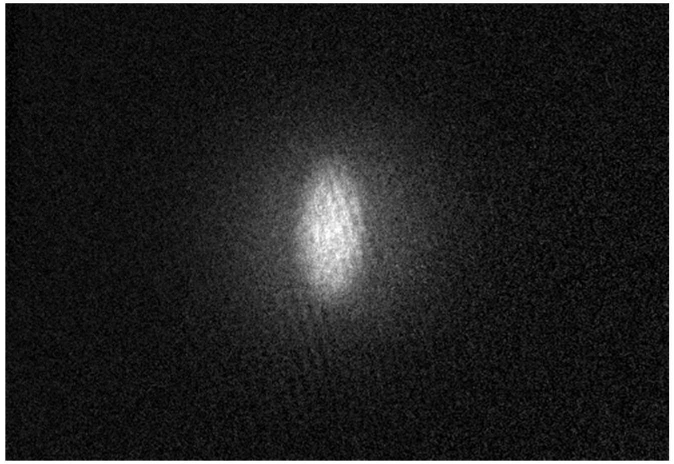


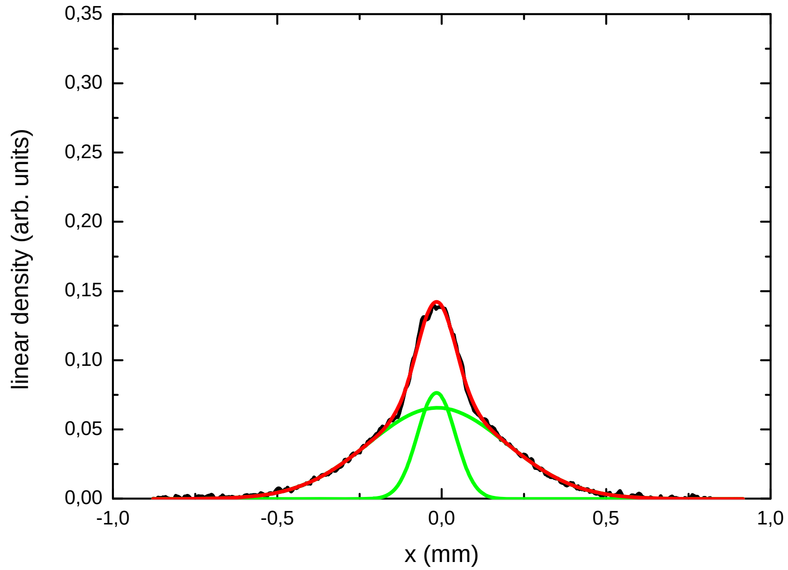
BEC!

Remove reservoir to see more clearly:



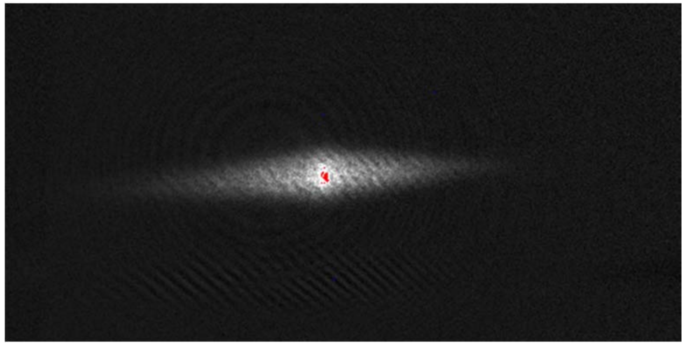
atoms from invisibility area
24ms TOF





Determine T,N

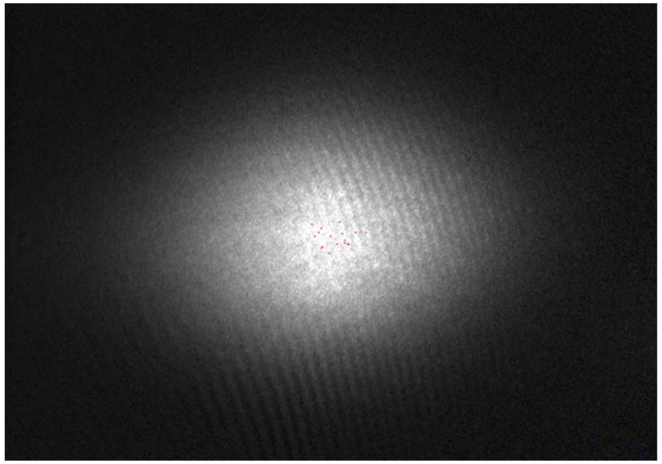
4ms time of flight:



Double Gauss fit gives:

- N reservoir
- N dimple
- T reservoir
- T dimple

24ms time of flight:

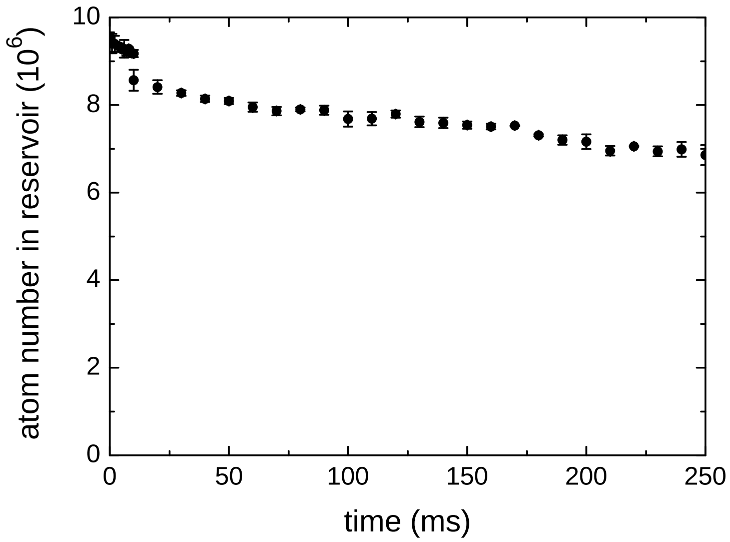


Gauss/BEC fit gives:

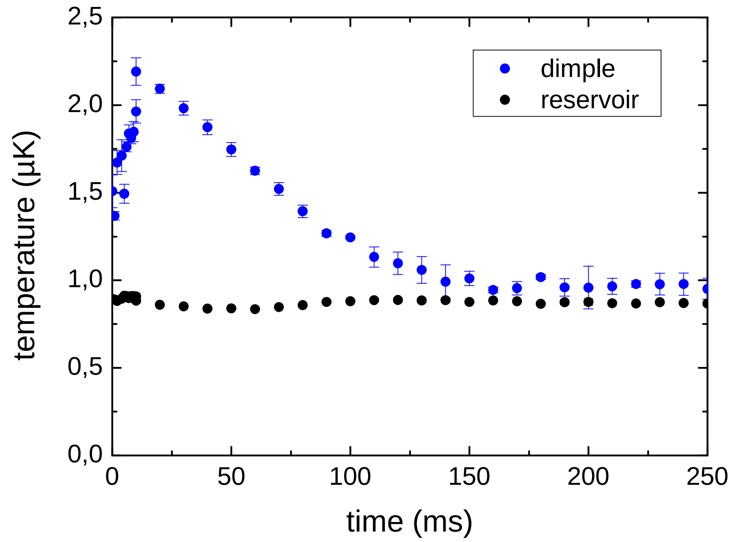
- N thermal
- N BEC

Dimple loading

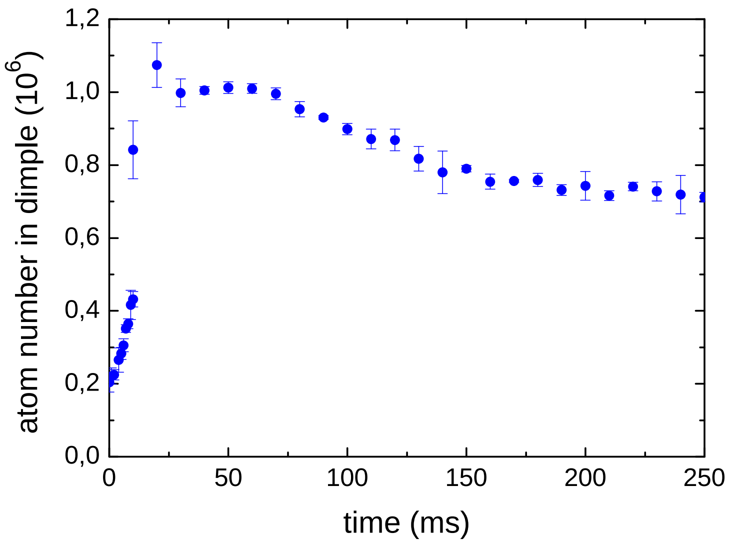
Reservoir atom number reduced:



Dimple thermalizes with reservoir:

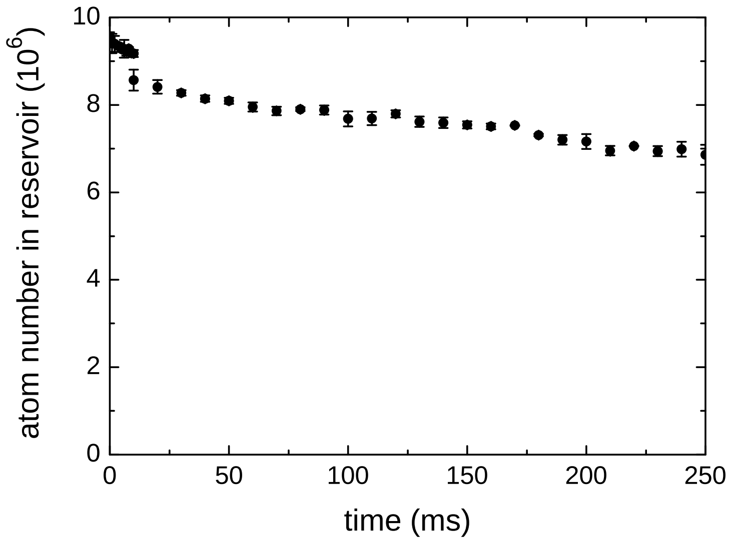


Dimple fills up on 10ms time scale:

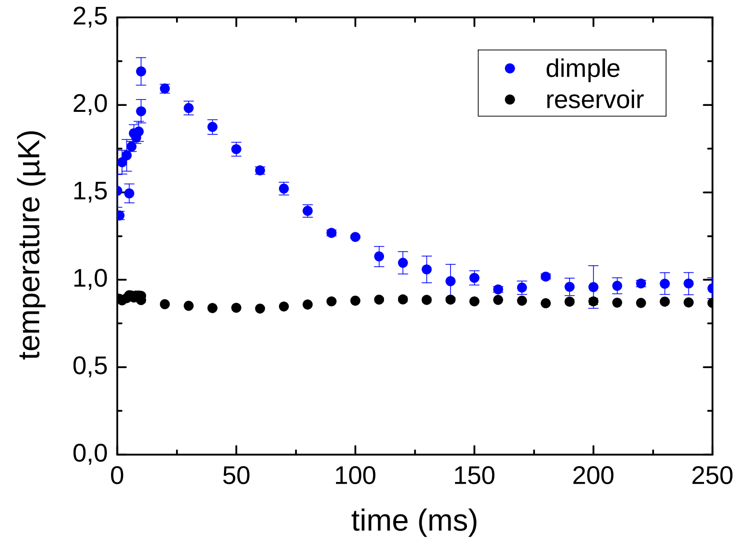


BEC formation

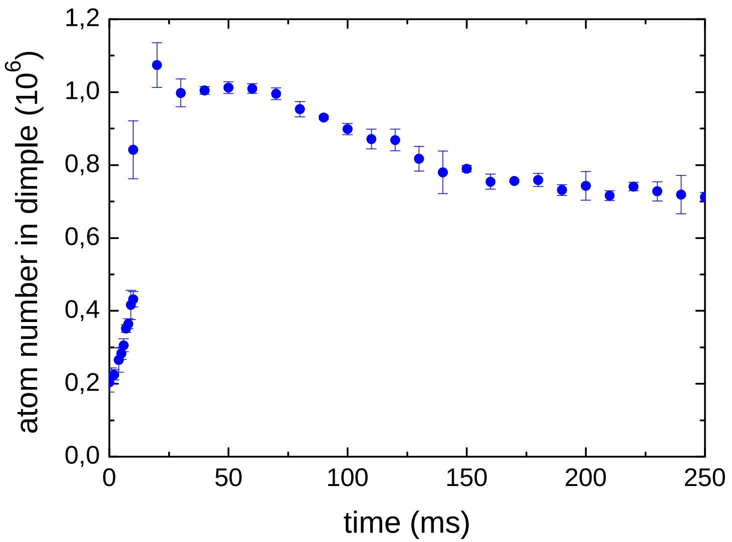
Reservoir atom number reduced:



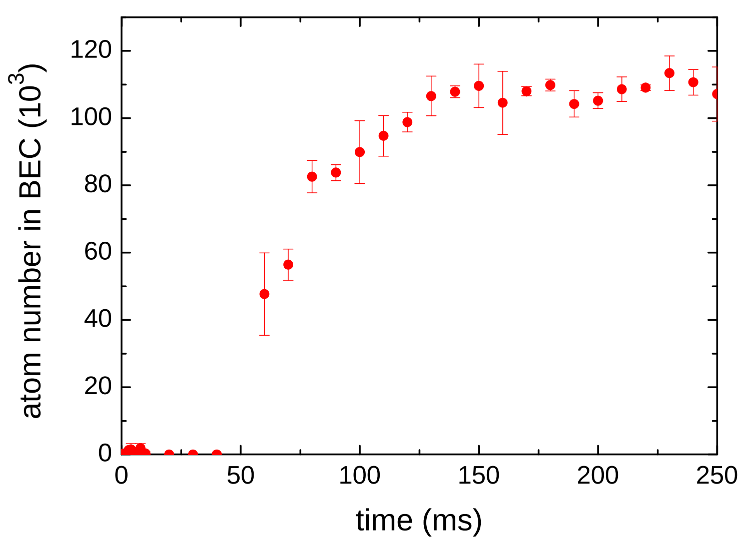
Dimple thermalizes with reservoir:



Dimple fills up on 10ms time scale:

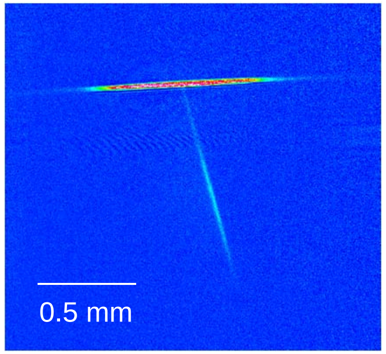


BEC forms on thermalization time scale:



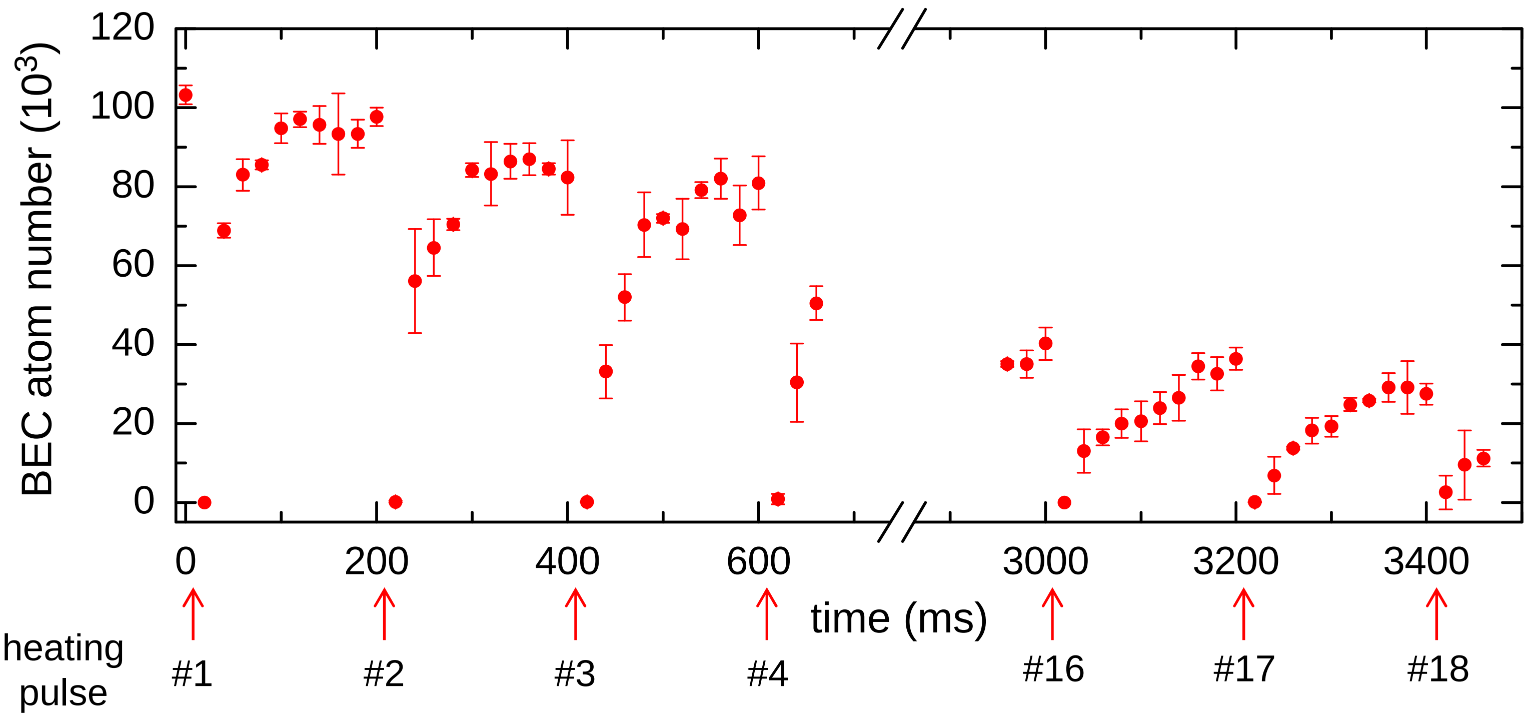
Demonstrate laser cooling power

Repeatedly destroy BEC by heating and removing atoms:



in-situ image

50 thousand atoms coupled out
by briefly increasing dimple potential



Demonstrate laser cooling power

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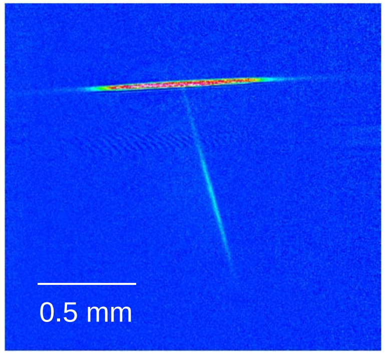
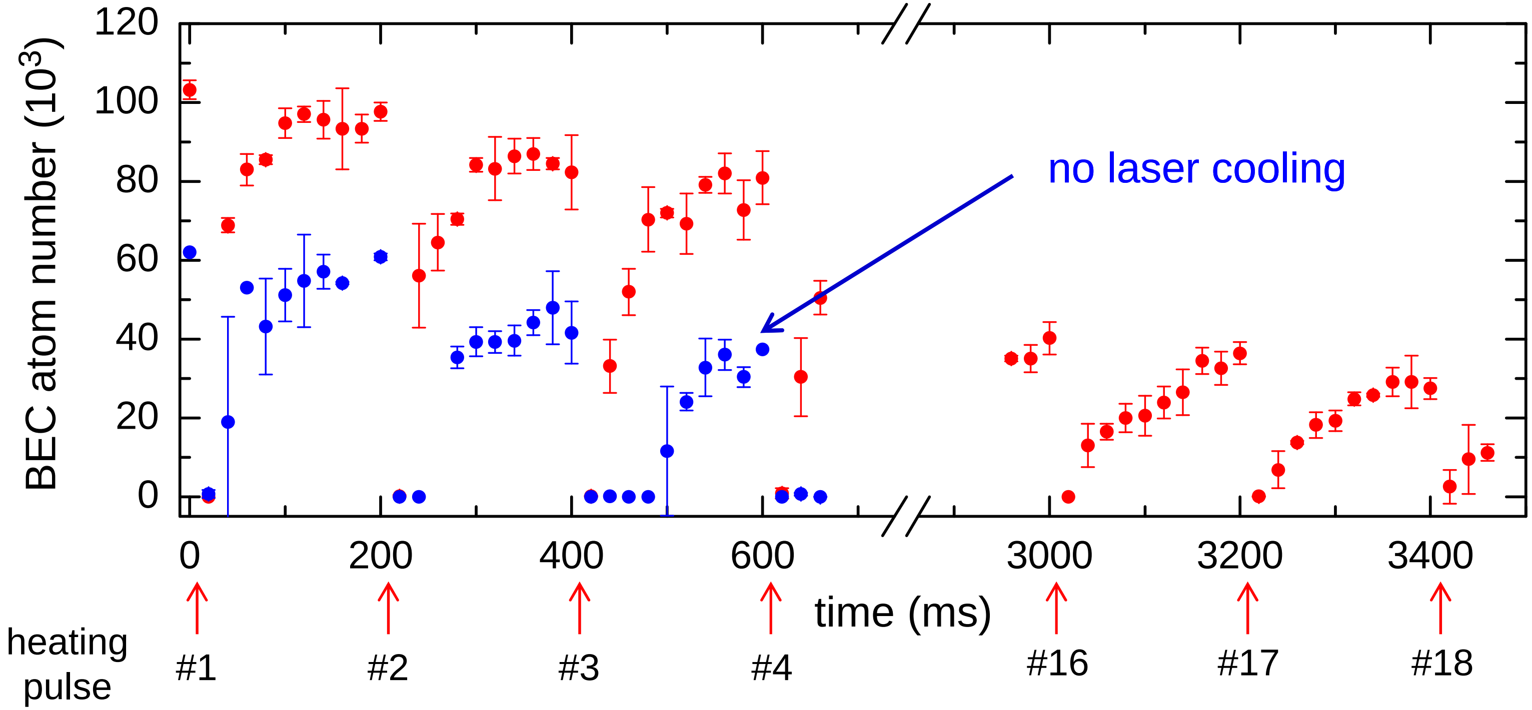


in-situ image

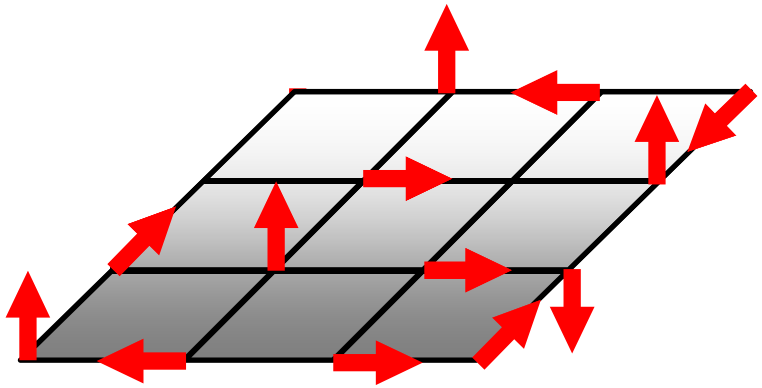
50 thousand
by briefly inc

Can we create continuous BEC?

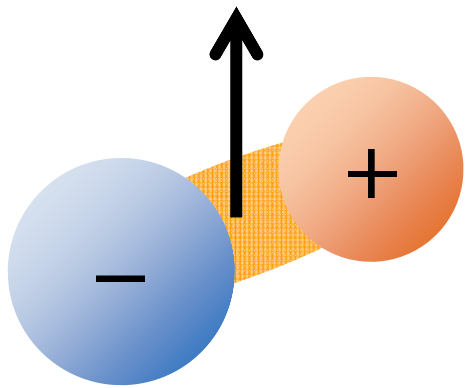


Future research

Quantum simulation



RbSr molecules



Strontium team

Former members:

Bo Huang

Meng Khoon Tey

Start 2010

Austrian ministry of science

FWF Der Wissenschaftsfonds.

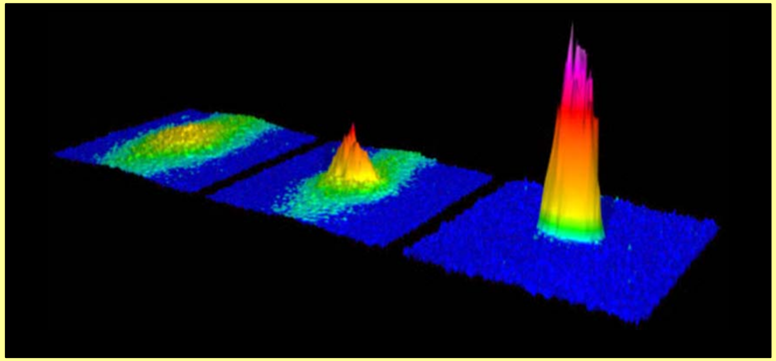
ÖAW Austrian Academy of Sciences

iSENSE Integrated Quantum Sensors

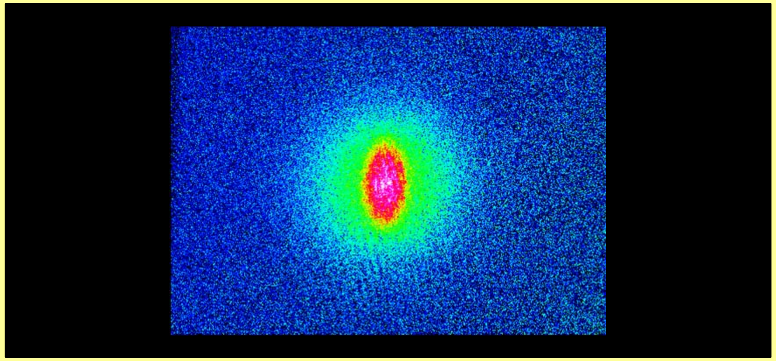
Overview

BEC of strontium

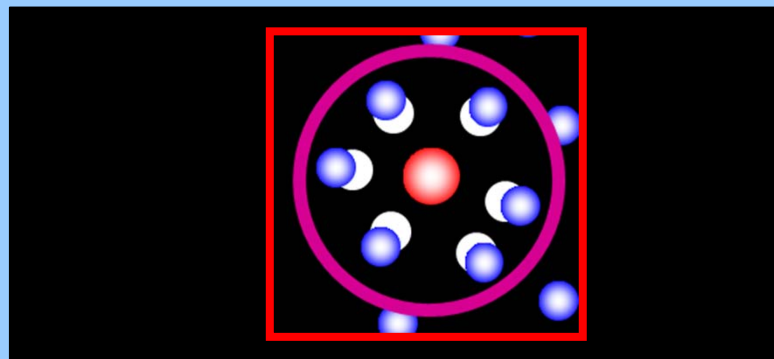
^{87}Sr Fermi gas



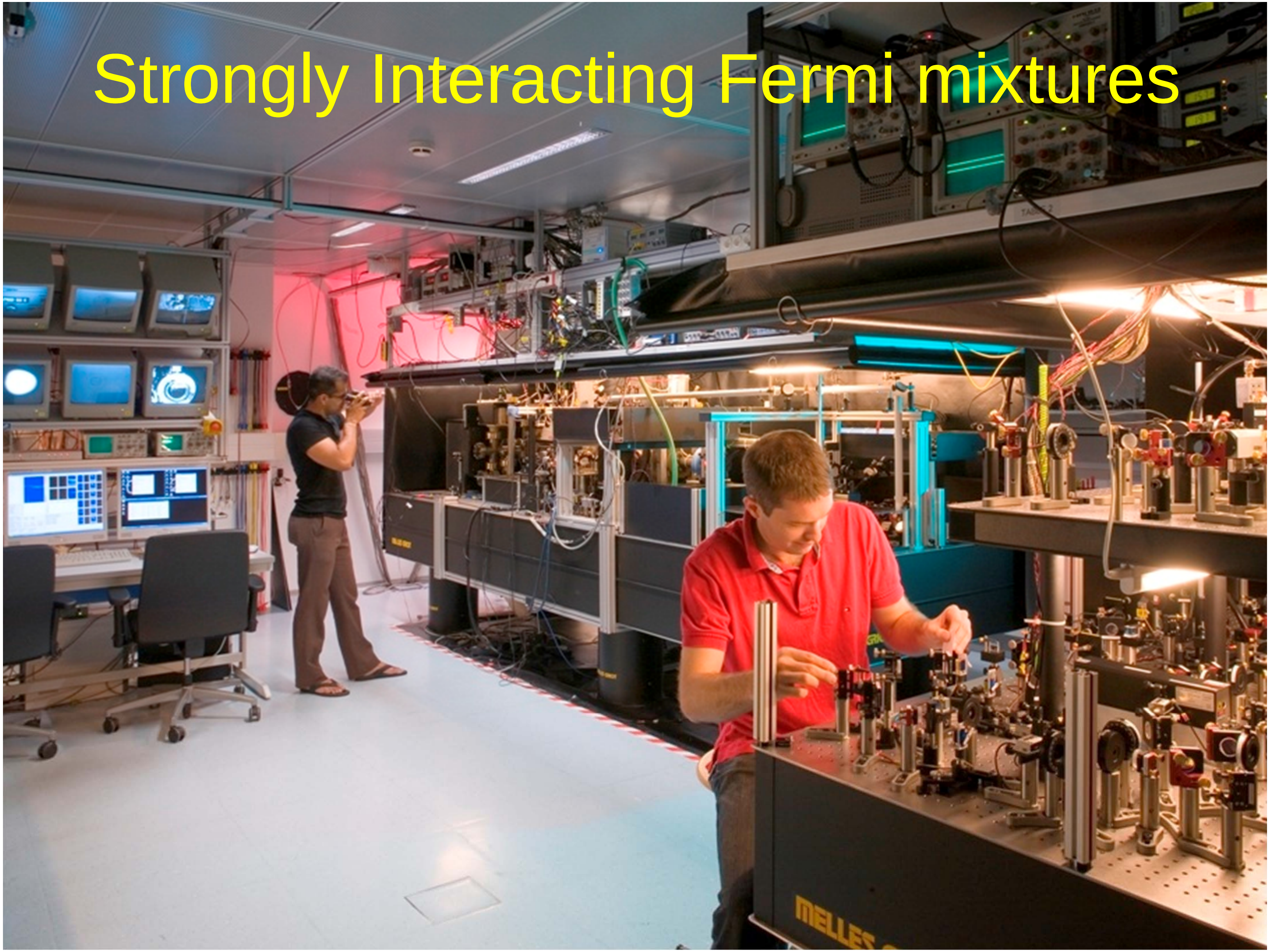
Laser cooling to BEC



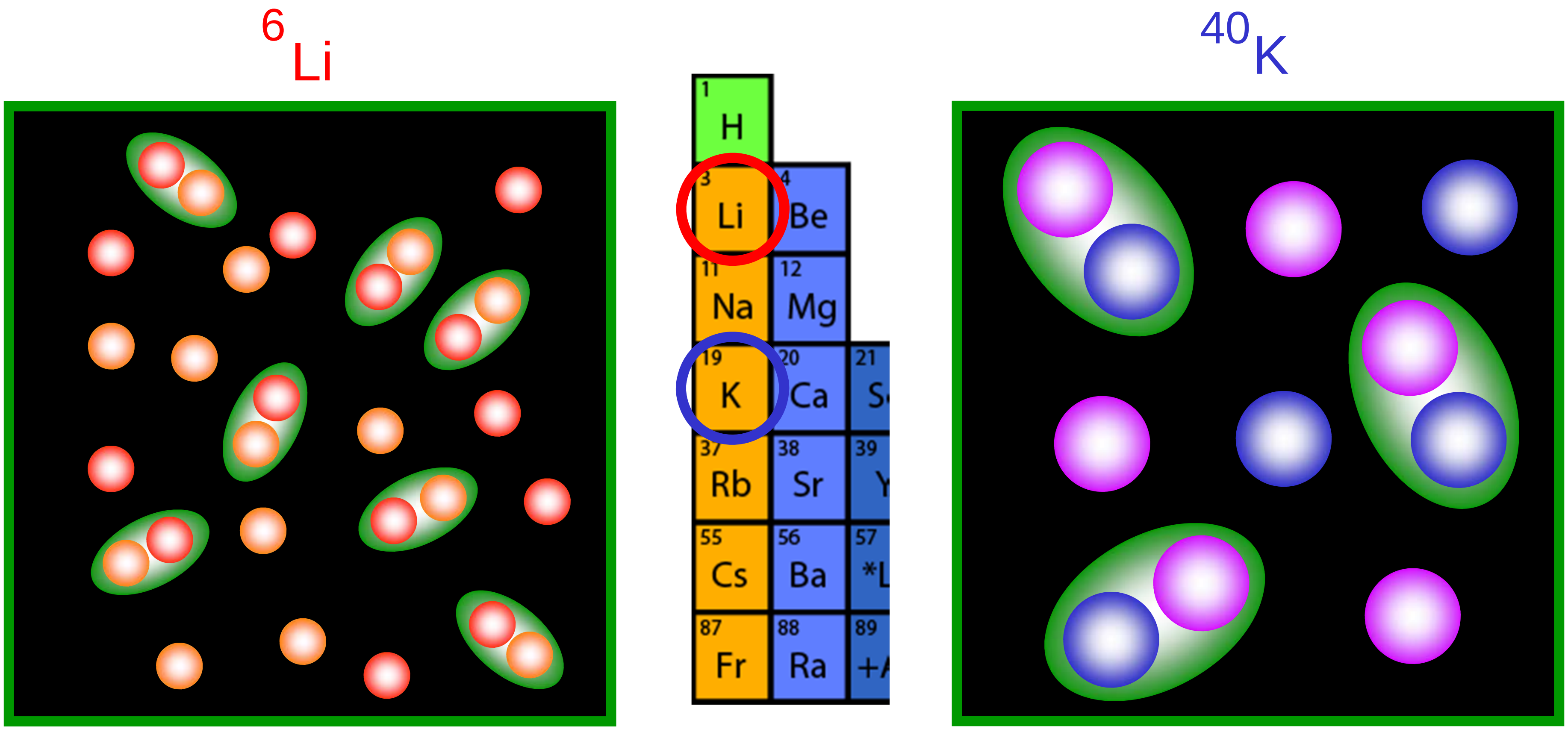
Strongly-interacting
^{6}Li-^{40}K Fermi mixture



Strongly Interacting Fermi mixtures



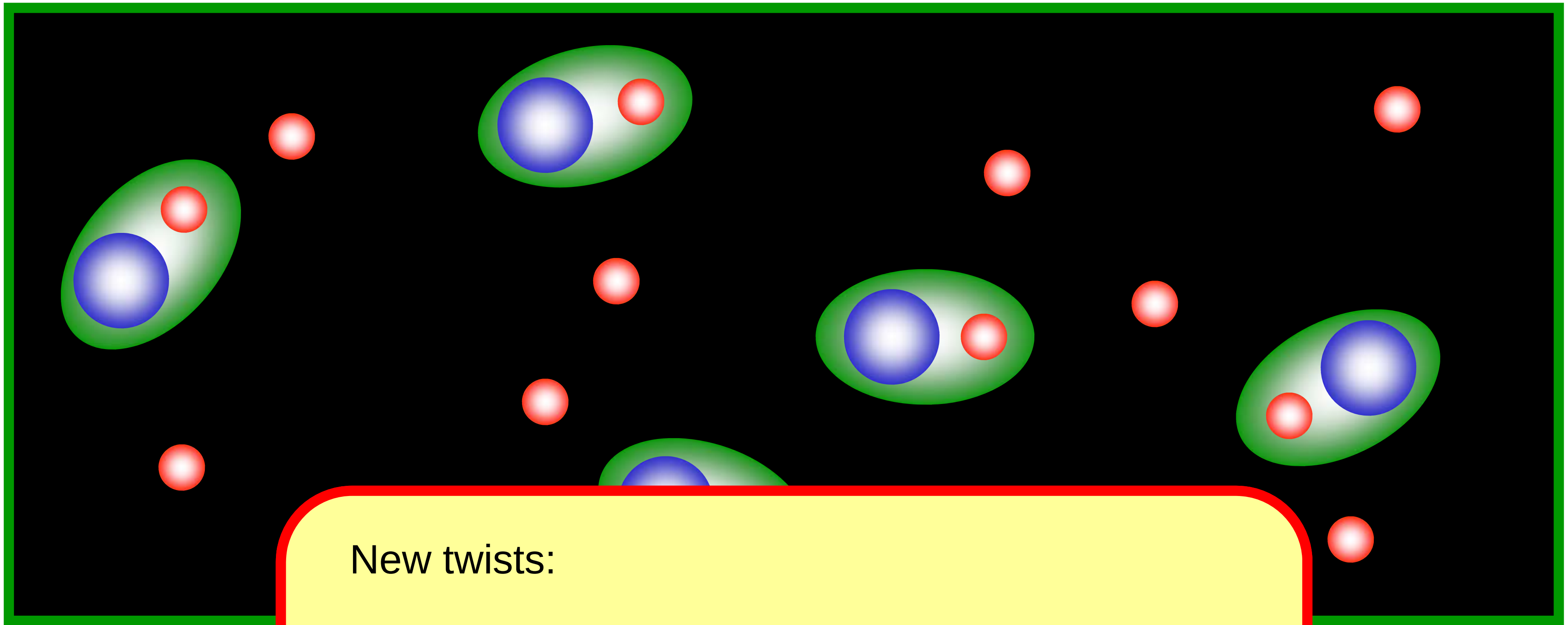
ultracold alkali fermions



BEC-BCS studies: Innsbruck, JILA, MIT, Duke, E.N.S., Rice, Swinbourne, Tokyo

^6Li ^{40}K Fermi-Fermi mixtures

^6Li & ^{40}K



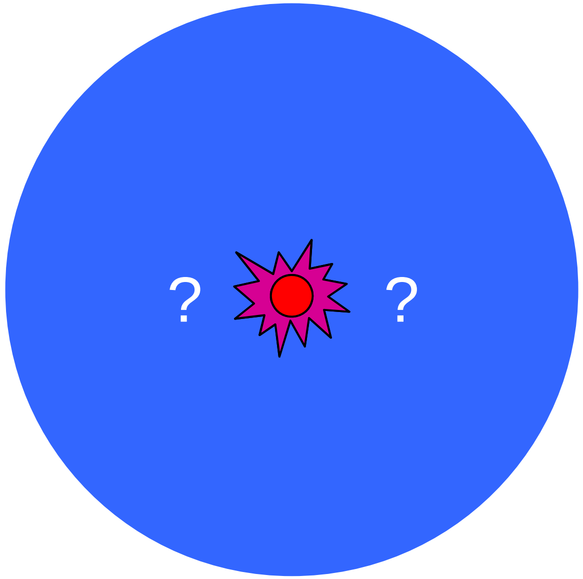
LiK experiment …

New twists:

- Independent trapping
  e.g. ^{40}K in lattice immersed in ^6Li Fermi sea
- Mass ratio

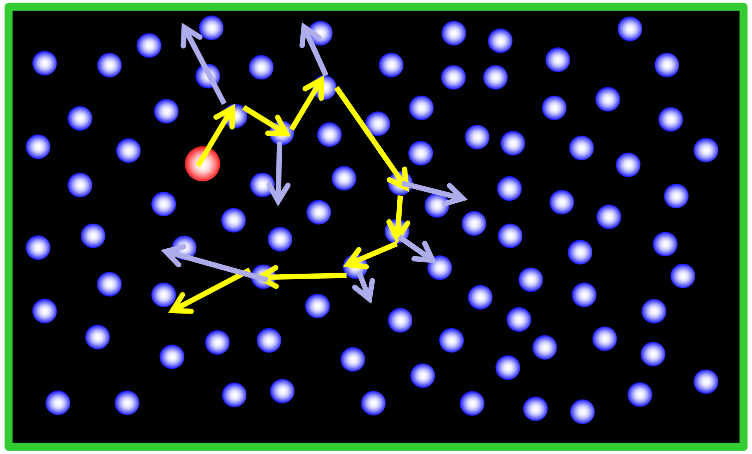
⟶ New few-body and many-body phenomena!

Impurity in a Fermi sea

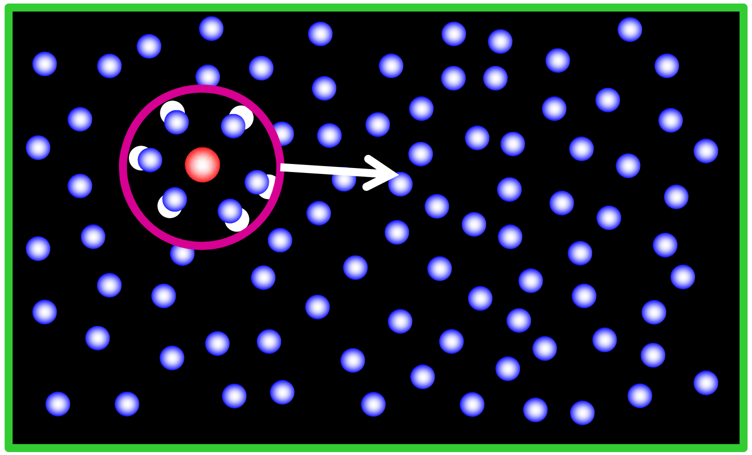


Polarons

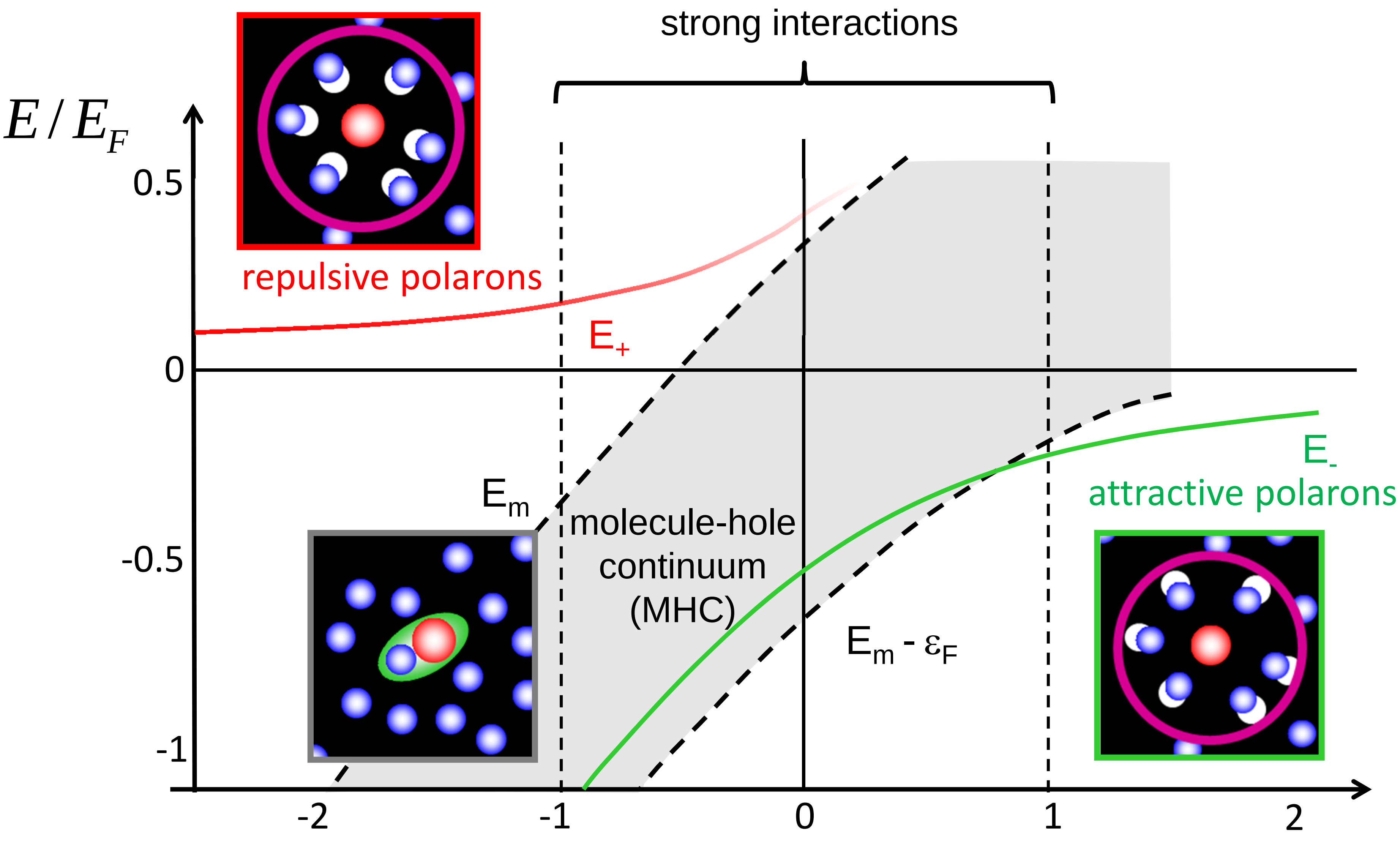
Single ^{40}K impurity scatters with ^{6}Li Fermi sea and excites it



The complex behavior of real particles can be described by simple behavior of quasi-particles, here called polarons:



Many-body energy diagram (T=0)

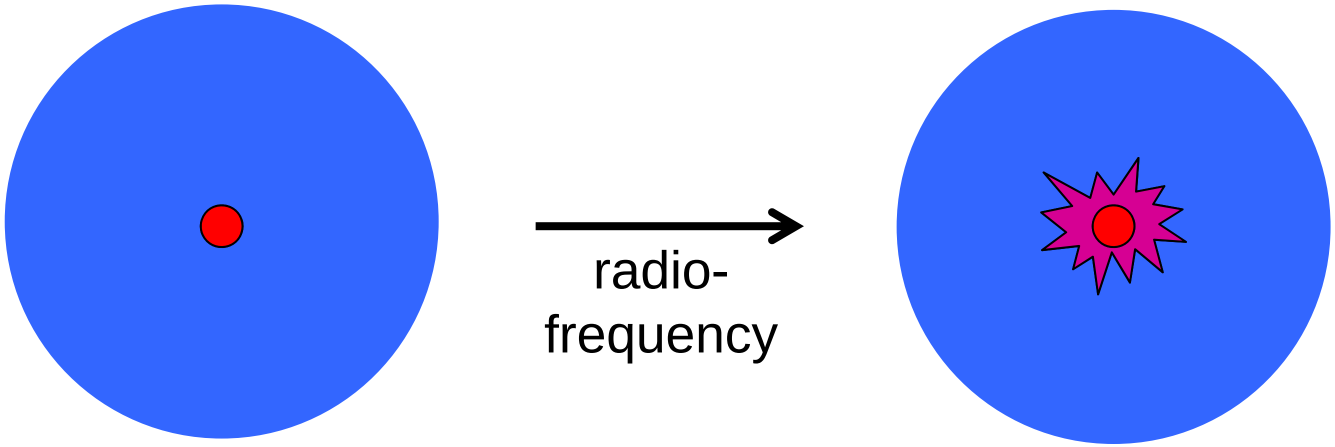


theory: P. Massignan and G. Bruun $-1/k_F a$ studied at ENS and MIT in ^{6}Li

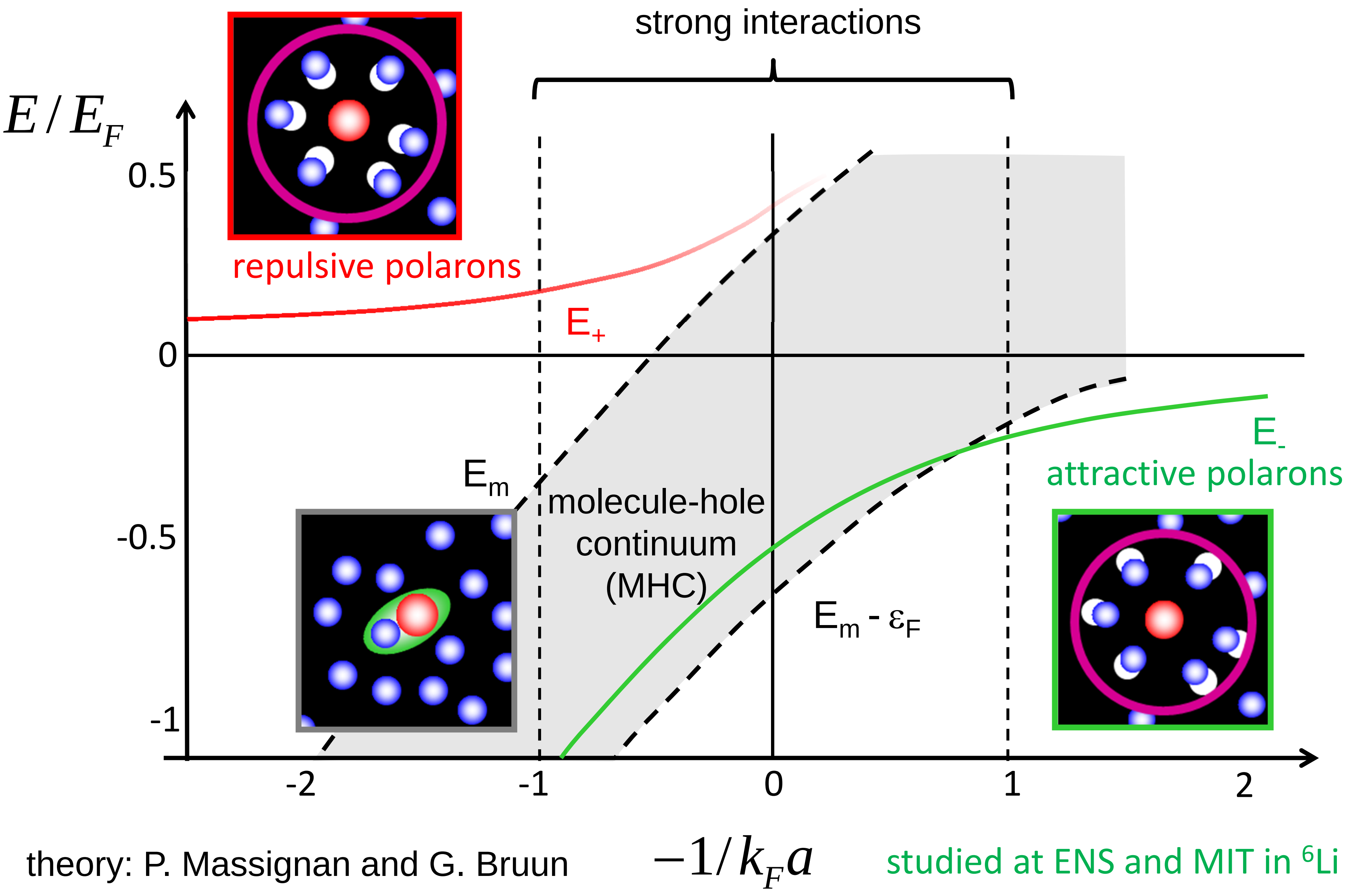
“reverse” rf spectroscopy

K
in non-interacting
spin state

K
in (strongly) interacting
spin state



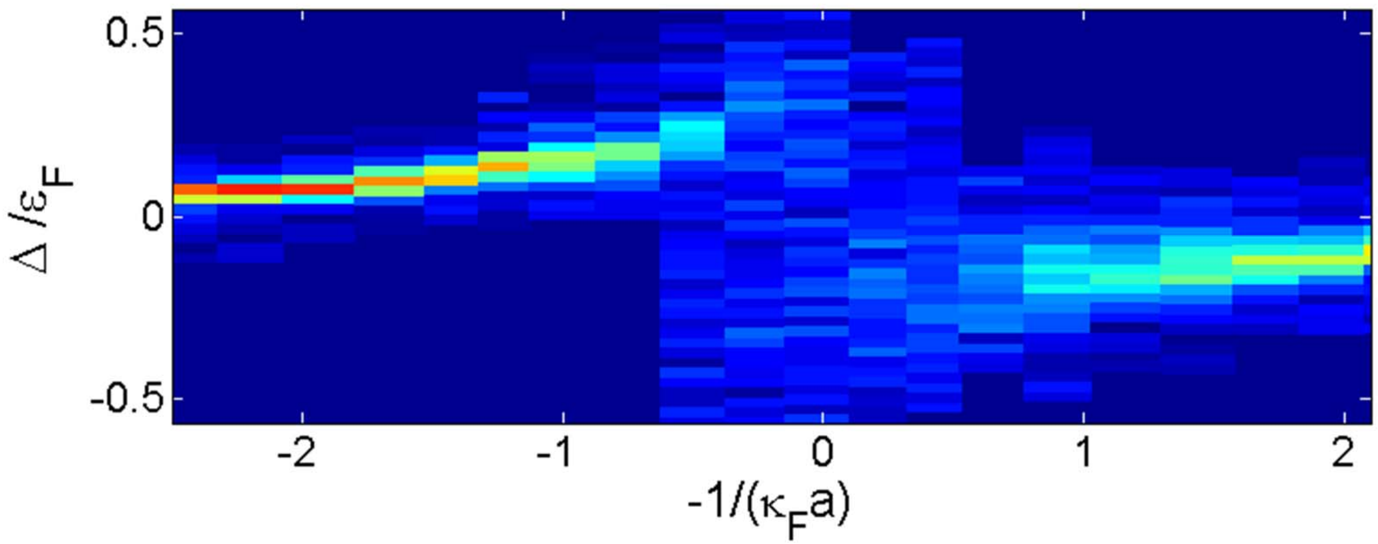
Many-body energy diagram (T=0)



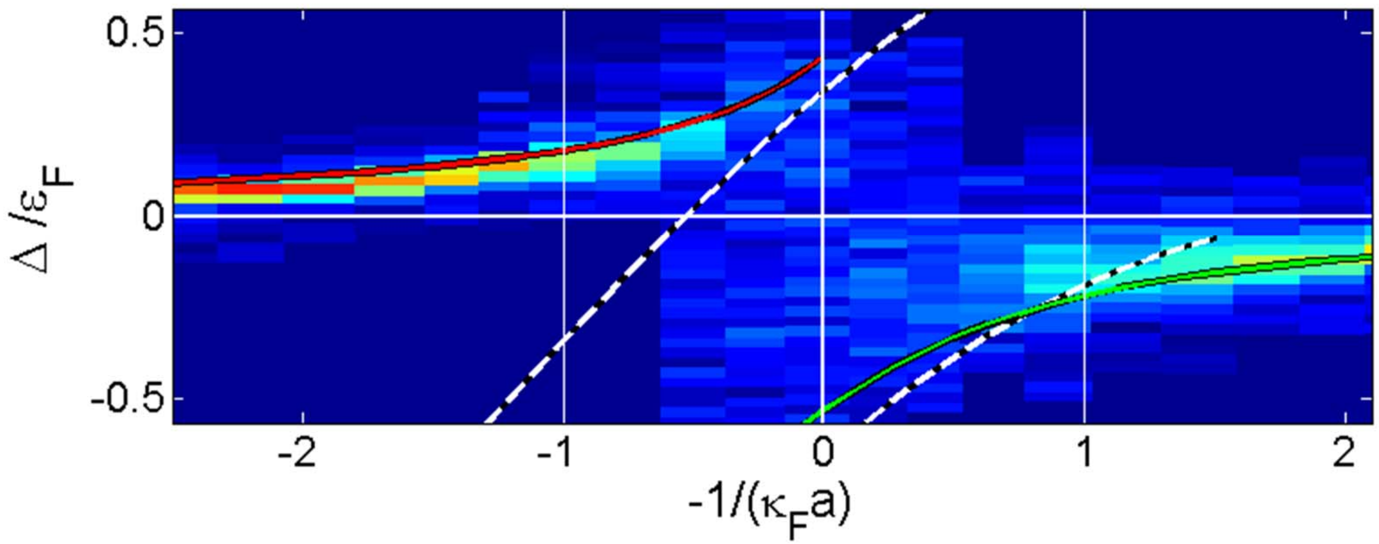
theory: P. Massignan and G. Bruun

studied at ENS and MIT in ^{6}Li

spectral response

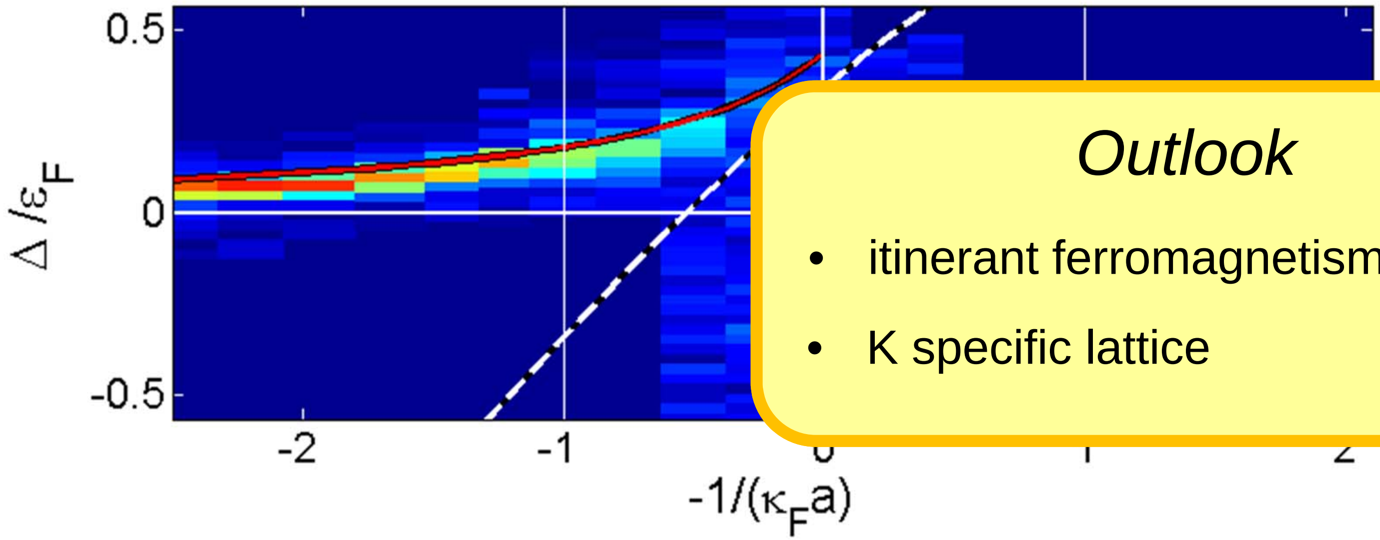


spectral response



Interesting:
Lifetime of repulsive polarons >10x longer than in ^{6}Li

spectral response



Outlook

- itinerant ferromagnetism possible?
- K specific lattice

Interesting:
Lifetime of repulsive polarons >10x longer than in ^{6}Li

Fermi-Fermi team

Thanks!