

4th Meeting on
Clustering as a window
on the hierarchical structure of quantum matters

28 May 2020

Ultracold atom study of exotic phenomena
bridging different hierarchies

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Outline

1. Quantum Gas Mixture with Unequal Mass
Novel features
2. Experimental system
Creation of ultracold Er, Li, Yb atoms
3. Other possibility
 $SU(4)$ singlet

Outline

1. Quantum Gas Mixture with Unequal Mass

Novel features

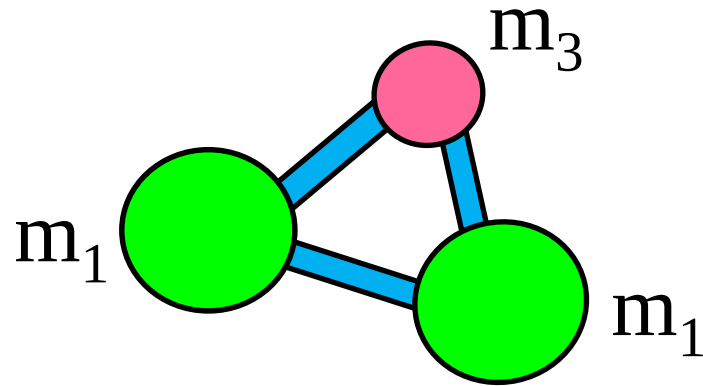
2. Experimental system

Creation of ultracold Er, Li, Yb atoms

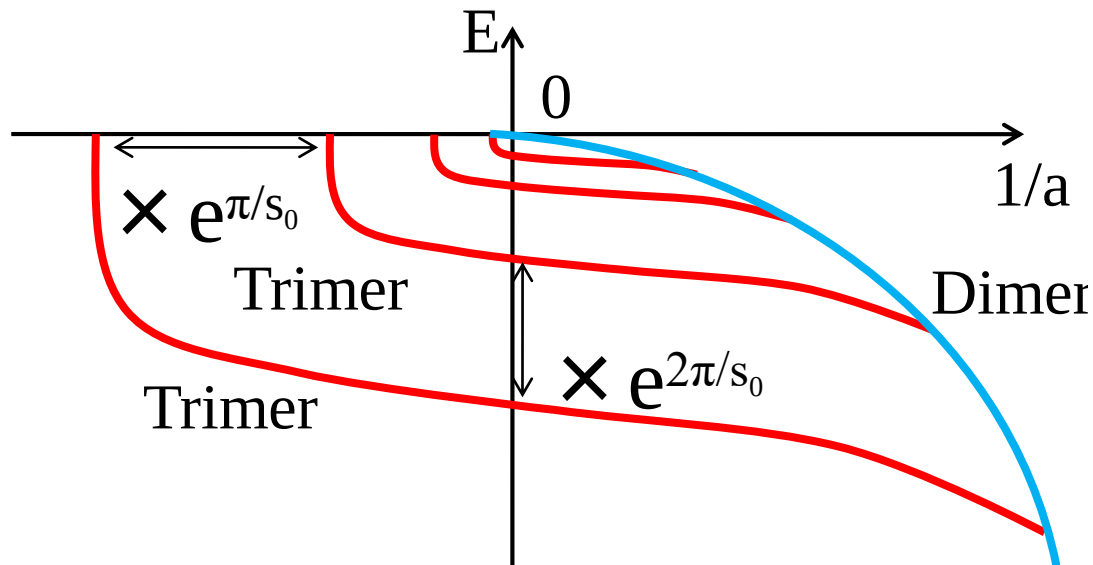
3. Other possibility

$SU(4)$ singlet

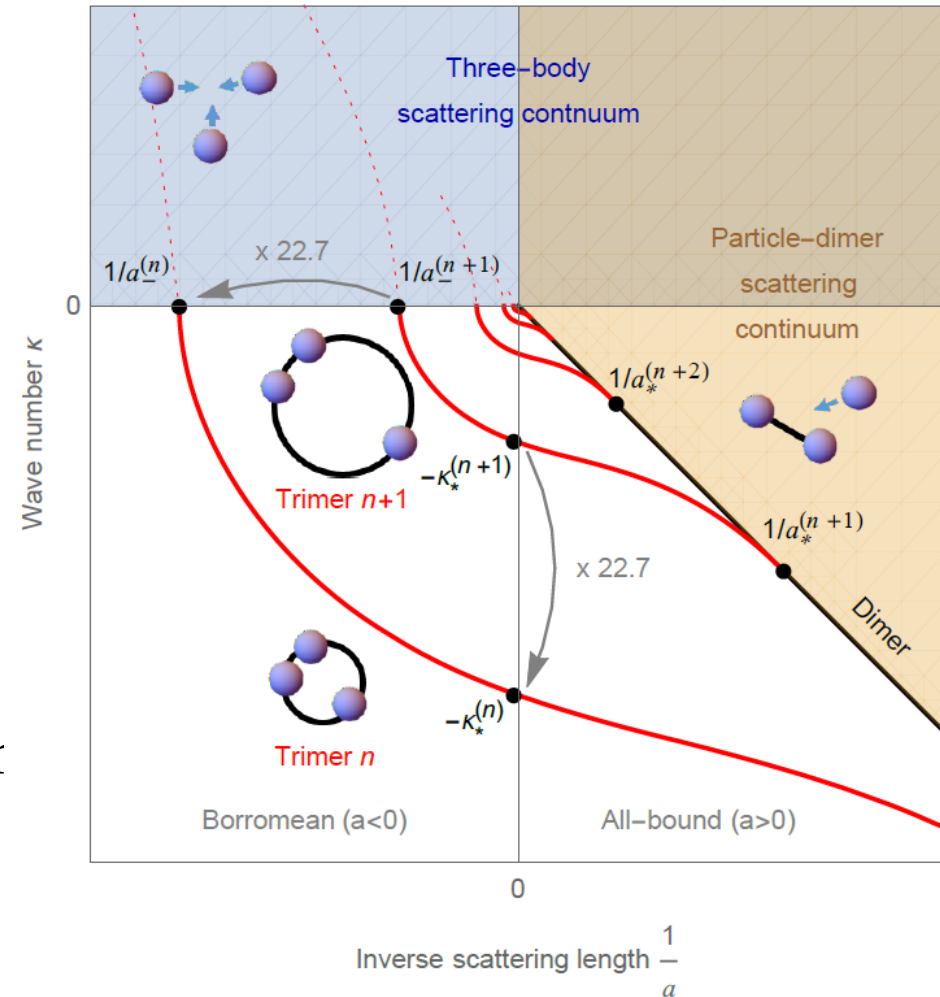
Efimov Trimer



[Amado and Noble, Efimov, Ovchinnikov and Sigal]



Identical Boson: $e^{\pi/s_0} \cong 22.7$



[P. Naidon and S. Endo,
Rep. Prog. Phys. 80,056001(2017)]

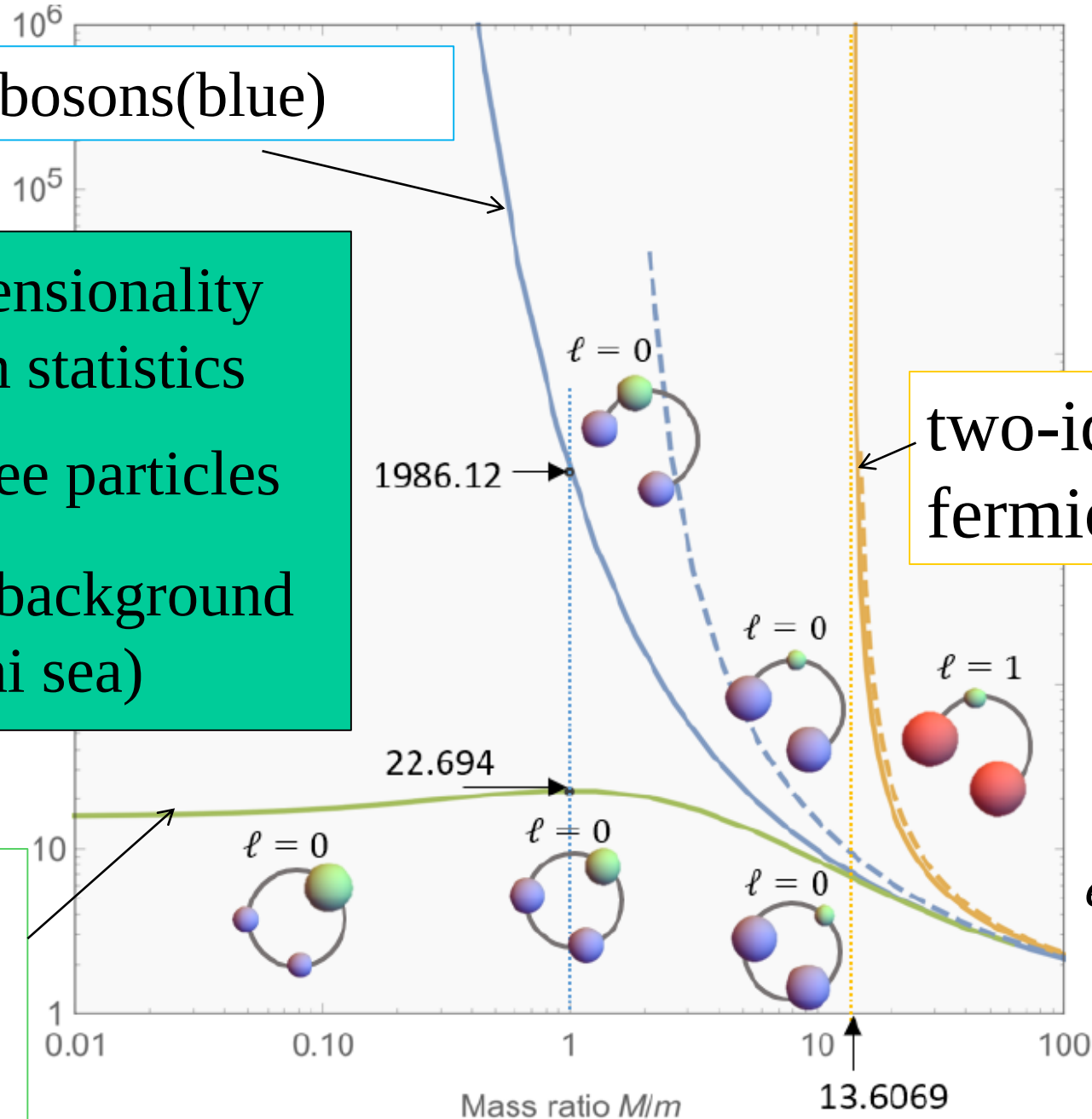
two-identical bosons(blue)

(Mixed) dimensionality
quantum statistics

More than three particles

Many-body background
(BEC, Fermi sea)

two-identical
bosons(green)
(3-resonant
interaction)



two-identical
fermions(red)

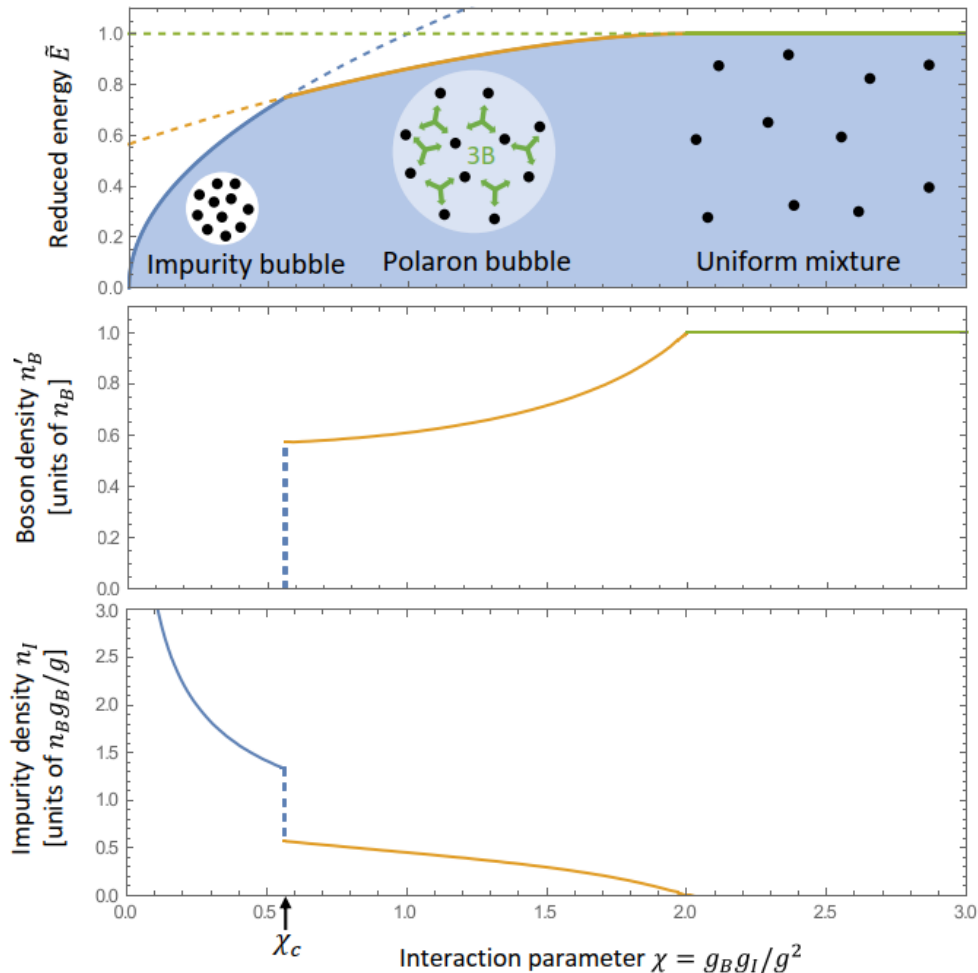
LiErEr

$$e^{\pi/s_0} \cong 4 \sim 6$$

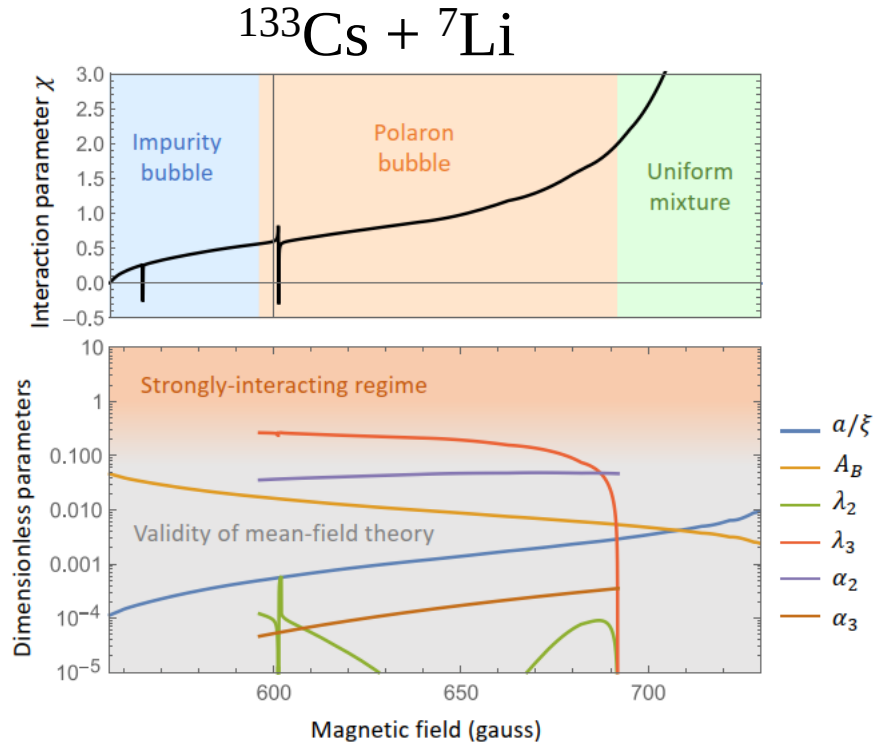
$$\frac{M_{Er}}{M_{Li}} \cong 28$$

Polaron bubble stabilised by medium-induced three-body interactions

”P. Naidon, arXiv:2001.08352”



g_B : boson repulsion
 g_I : impurity repulsion
 g : impurity-boson repulsion



Similar behavior for
 $^{174}\text{Yb} + ^7\text{Li}$

p-wave Superfluidity

fermion attraction mediated via BEC in mixed dimension

”PRL**117**,245302 (2016) , PRA **94**, 063631(2016), NJP**19**, 115011 (2017), arXiv:1809.04812”

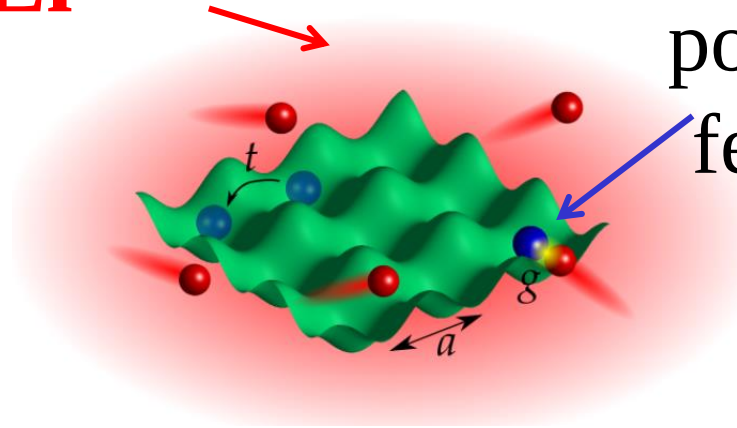
$$V_{\text{ind}}(i, j) = -g^2 \frac{n_0 m_B}{\pi} \frac{e^{-\sqrt{2}|\mathbf{r}_i - \mathbf{r}_j|/\xi_B}}{|\mathbf{r}_i - \mathbf{r}_j|}$$

$$g = 2\pi a_{\text{BF}}/m_r$$

$$m_r = mm_{\text{B}}/(m + m_{\text{B}})$$

^7Li boson (3D)

polarized
fermion
(2D)



Quantum Disentangled Liquid (like MBL)

Two different kind of fermions with large mass ratio

“T. Grover and M. P. A. Fisher, J. Stat. Mech.: Theor. Exp. (2014) P10010.”

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Periodic Table of the Elements

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Legend:

- Atomic Number
- Symbol
- Name
- Atomic Mass

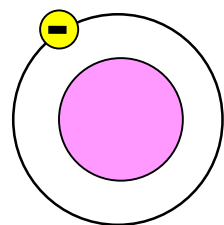
Highlighted Elements:

- Lithium (Li) - Atomic Number 3, Atomic Mass 6.941
- Erbium (Er) - Atomic Number 68, Atomic Mass 167.26
- Ytterbium (Yb) - Atomic Number 70, Atomic Mass 173.04

The periodic table displays elements from Hydrogen (1) to Oganesson (118) in the main body, and the Lanthanide and Actinide series at the bottom. Elements are color-coded by groups: IA (light blue), IIA (orange), IIIA (teal), IVA (blue), VA (light blue), VIA (teal), VIIA (purple), and VIIIA (purple). Transition metals (groups 3-10) are yellow, and post-transition metals (groups 11-12) are light green. Nonmetals (groups 13-18) are various shades of blue and purple. Lanthanides and actinides are pink.

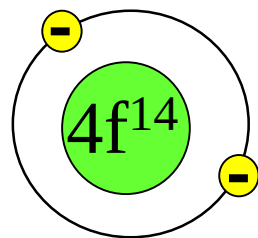
Quantum Gas Mixtures with Unequal Mass

Lithium(Li) : [He] 2s¹ : light



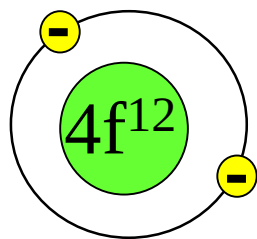
Mass number	6	7
Abundance[%]	7.5	92.5
Bose or Fermi	F	B

Ytterbium(Yb) : [Xe]4f¹⁴6s² : heavy



Mass number	168	170	171	172	173	174	176
Abundance[%]	0.13	3.1	14.3	21.9	16.1	31.8	12.7
Bose or Fermi	B	B	F	B	F	B	B

Erbium(Er) : [Xe]4f¹²6s² : heavy

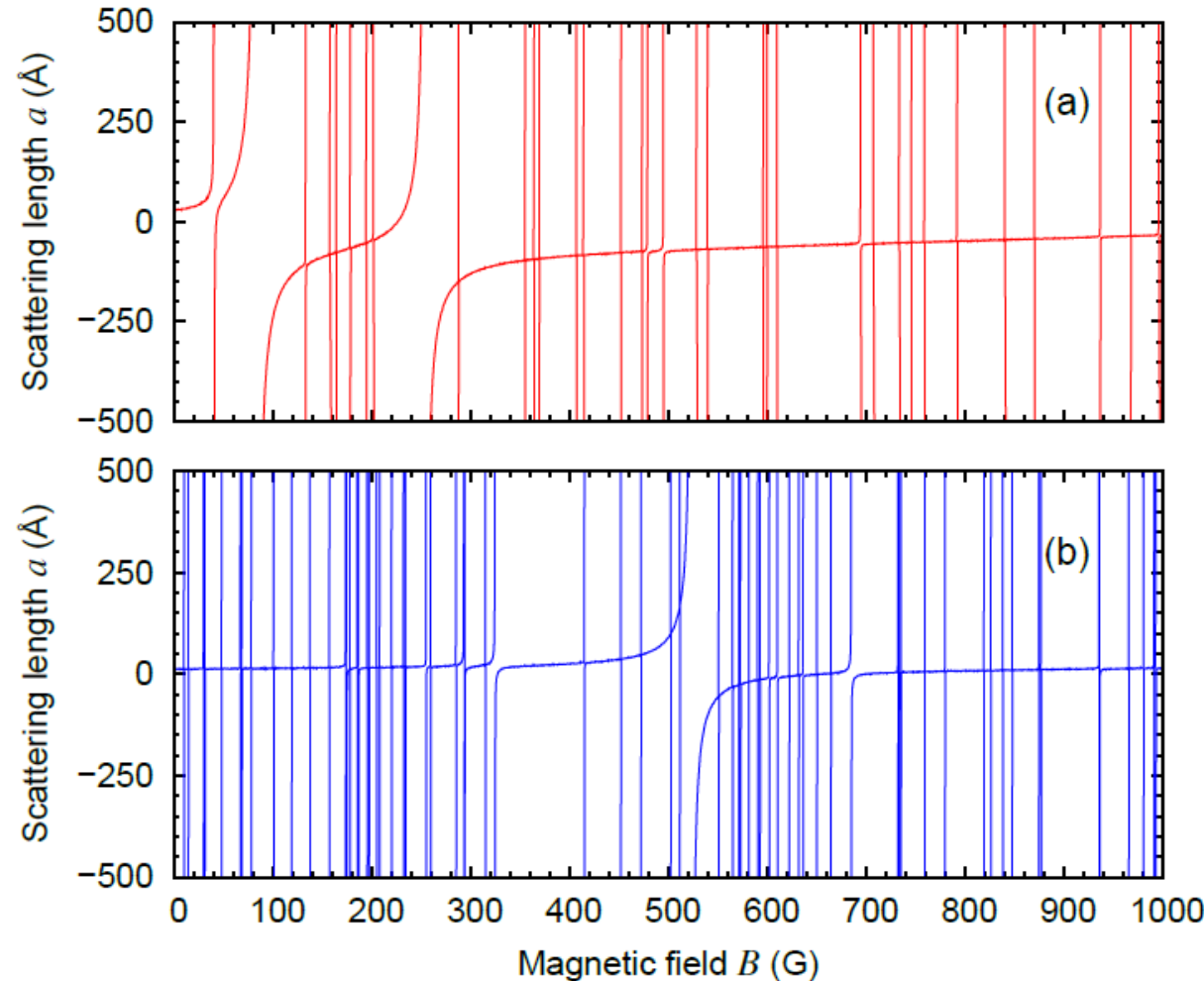


Mass number	162	164	166	167	168	170
Abundance[%]	0.1	1.6	33.5	22.9	27.0	14.9
Bose or Fermi	B	B	B	F	B	B

Magnetically tunable Feshbach resonances in **Li+Er**

[M. L. Gonzalez-Martinez and Piotr S. Zuchowski, Phys. Rev. A **92**, 022708(2015)]

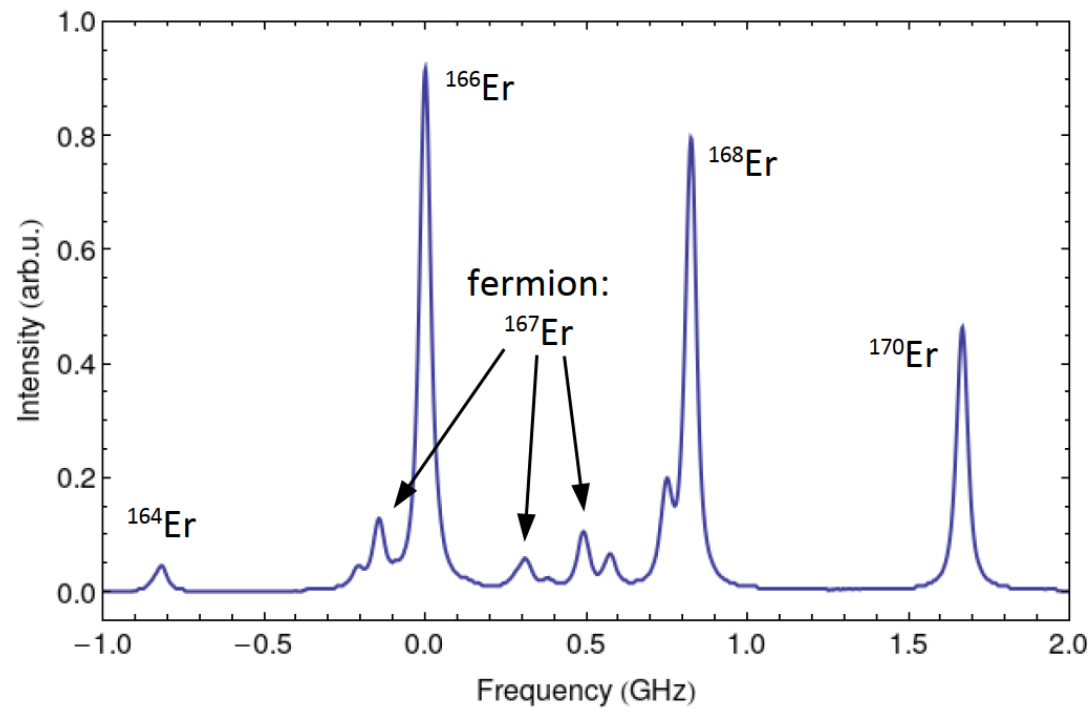
$^{166}\text{Er}(\text{b})$
 $+^6\text{Li}(\text{f})$



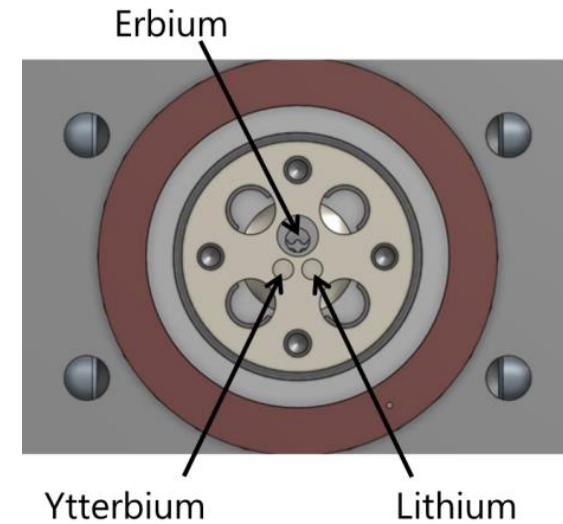
$^{166}\text{Er}(\text{b})$
 $+^7\text{Li}(\text{b})$

Er-Li-Yb Oven

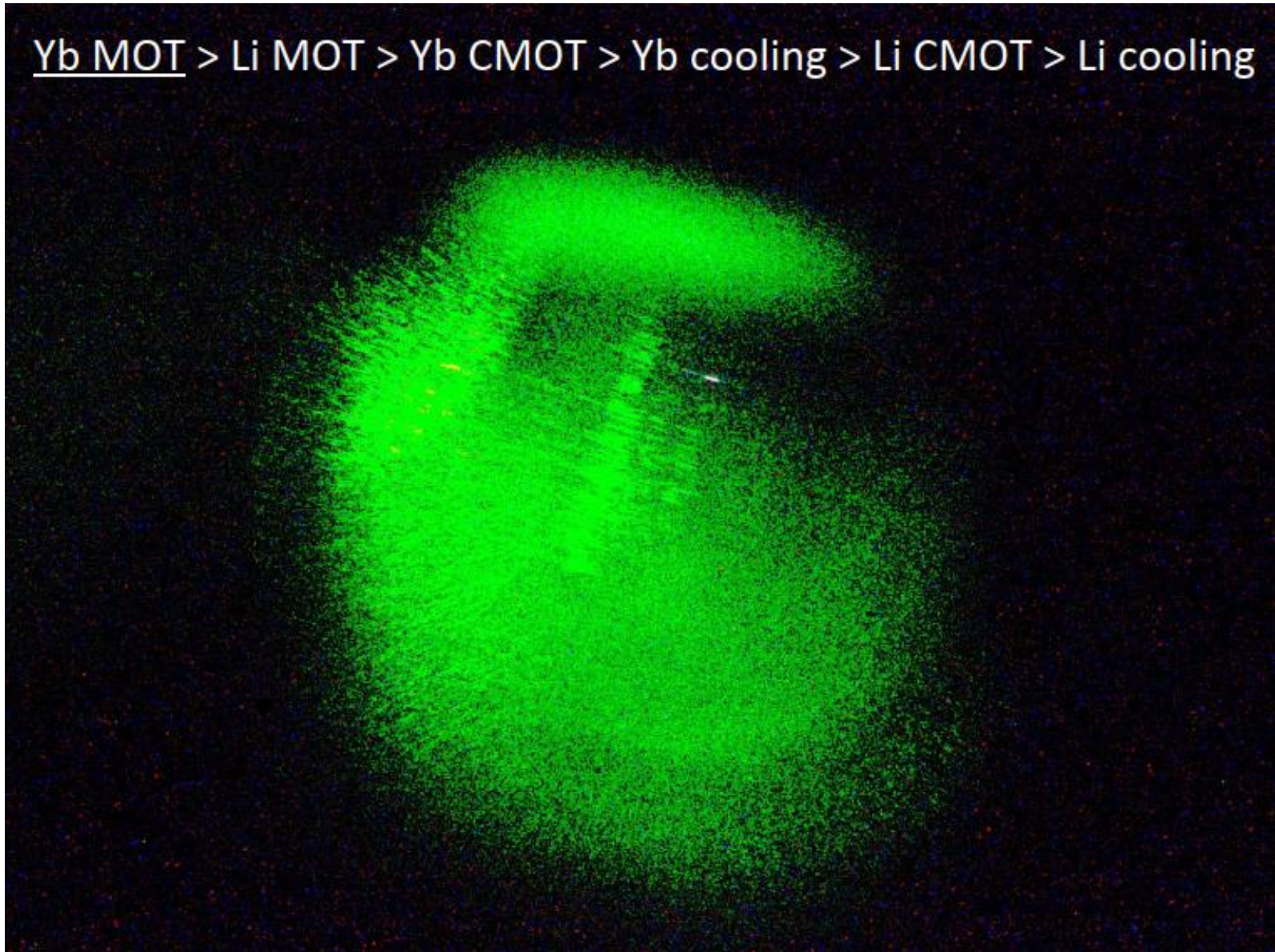
high temperature
Er oven



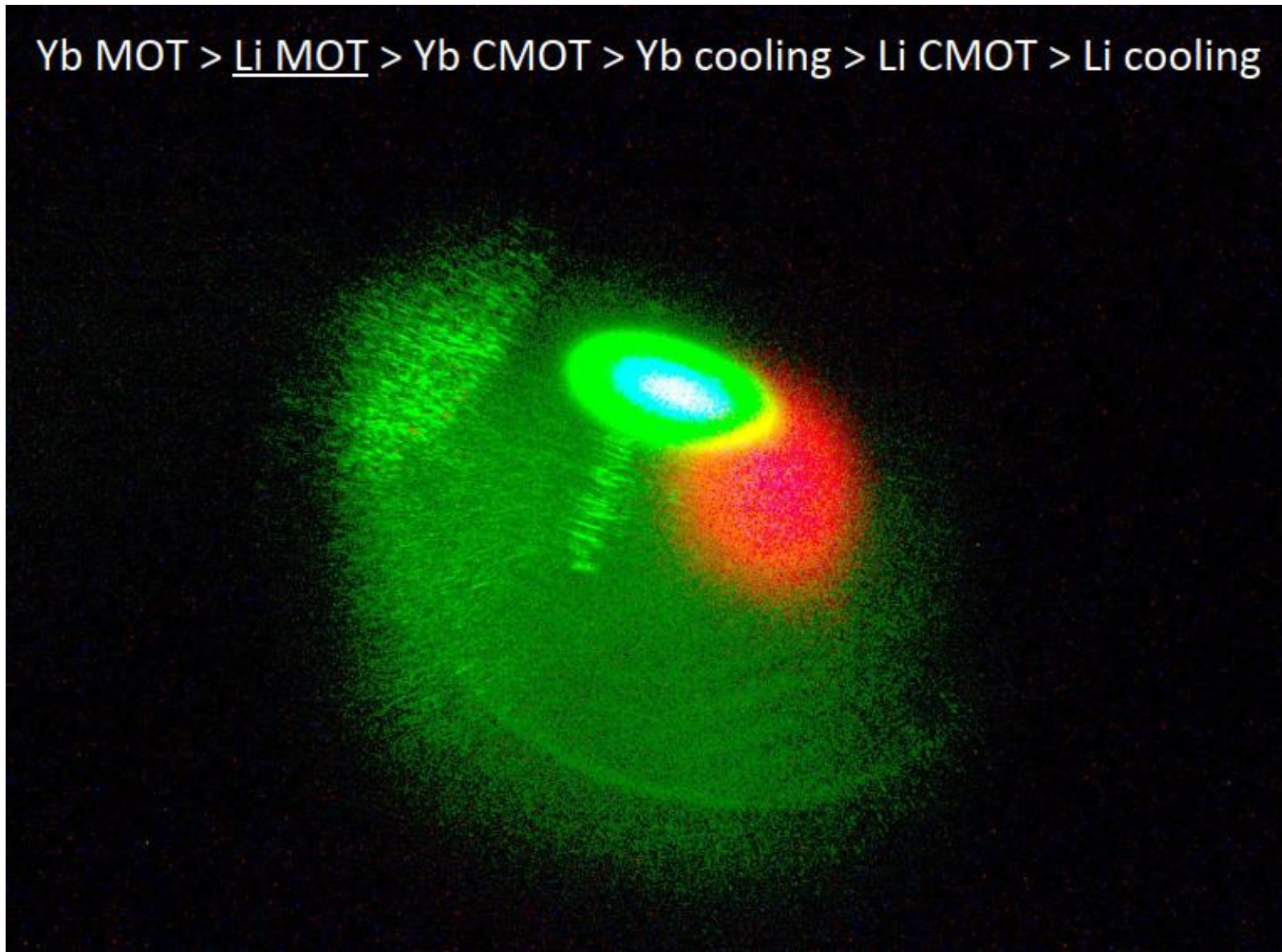
ion pump



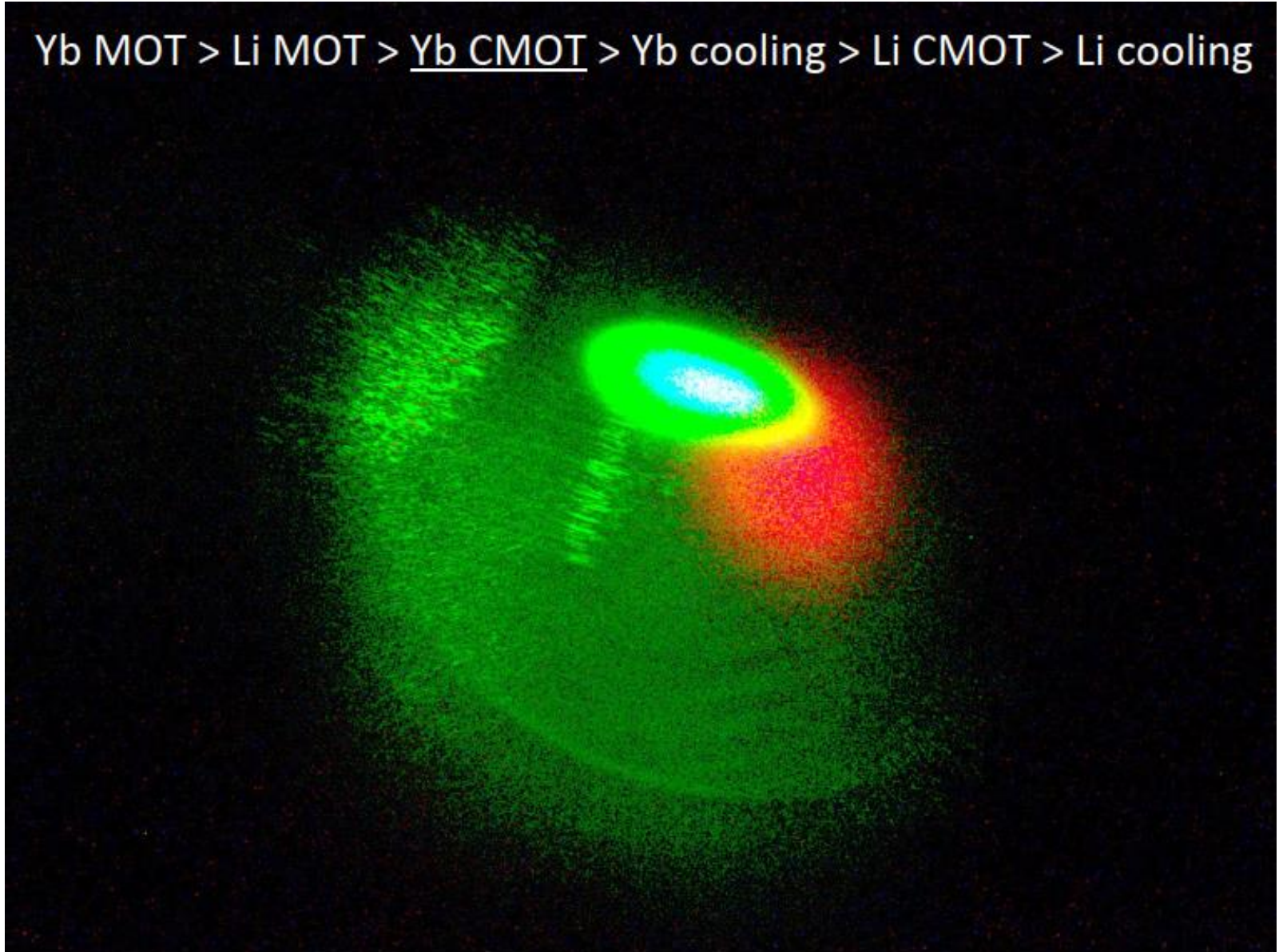
Yb MOT > Li MOT > Yb CMOT > Yb cooling > Li CMOT > Li cooling



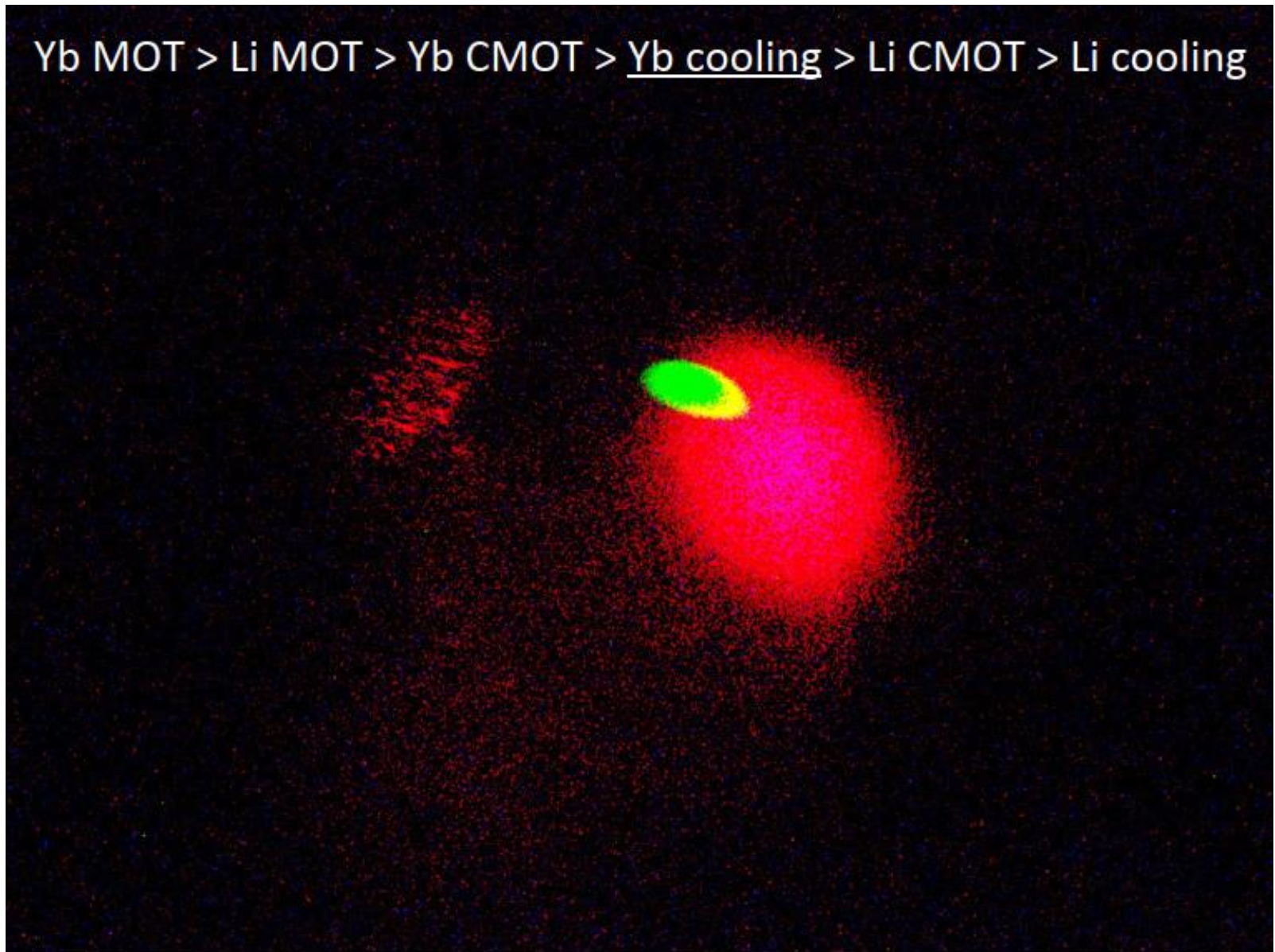
Yb MOT > Li MOT > Yb CMOT > Yb cooling > Li CMOT > Li cooling



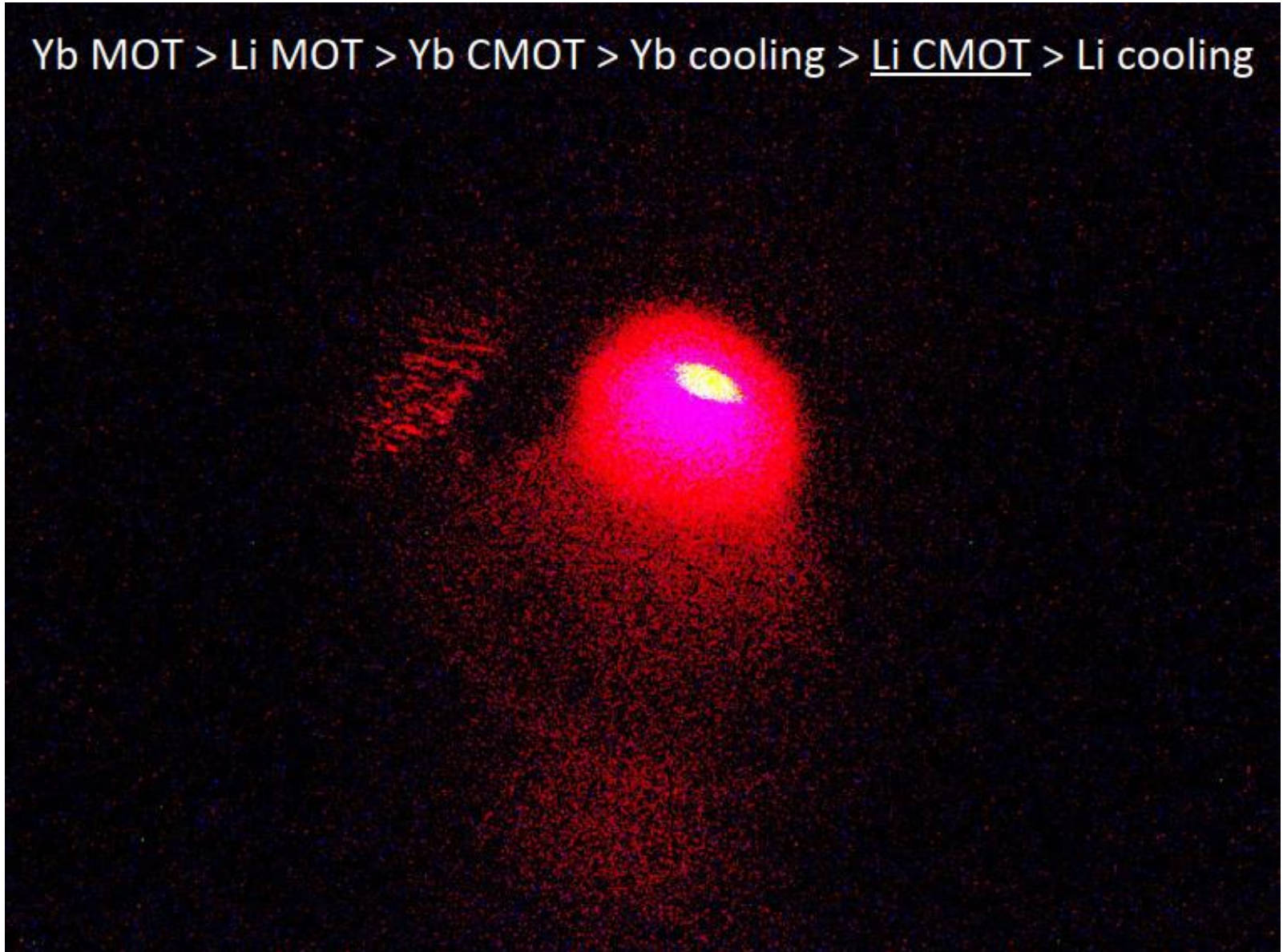
Yb MOT > Li MOT > Yb CMOT > Yb cooling > Li CMOT > Li cooling



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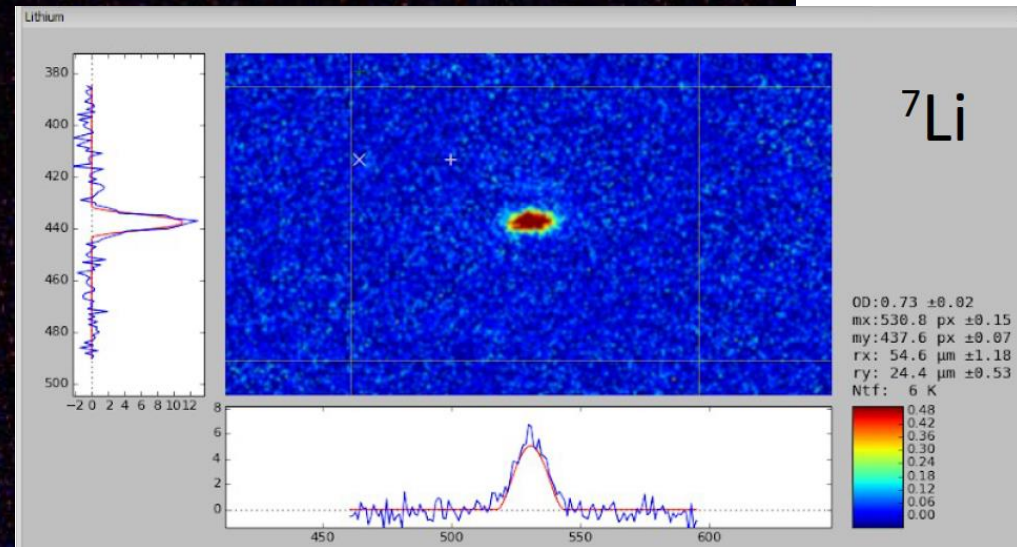
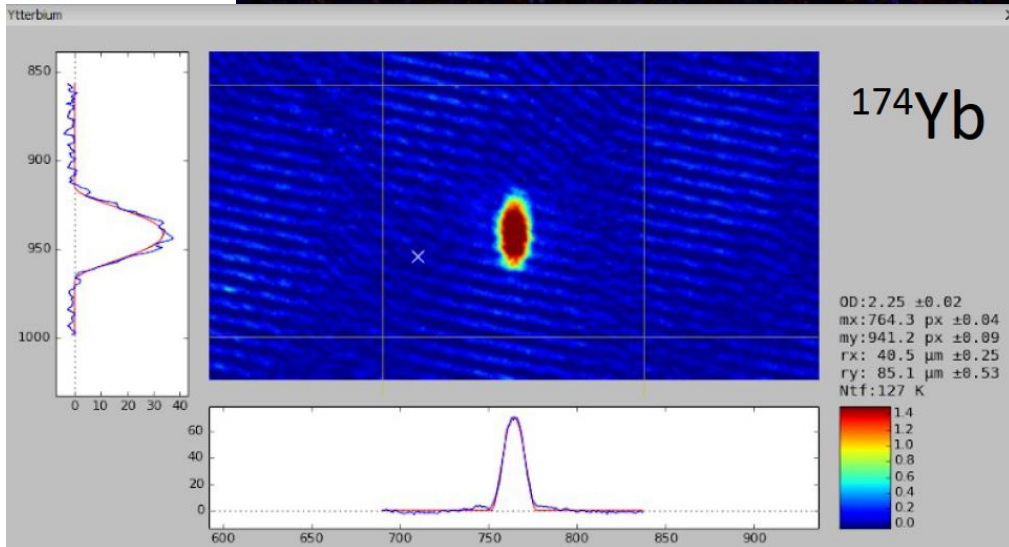
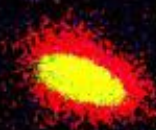


Yb MOT > Li MOT > Yb CMOT > Yb cooling > Li CMOT > Li cooling

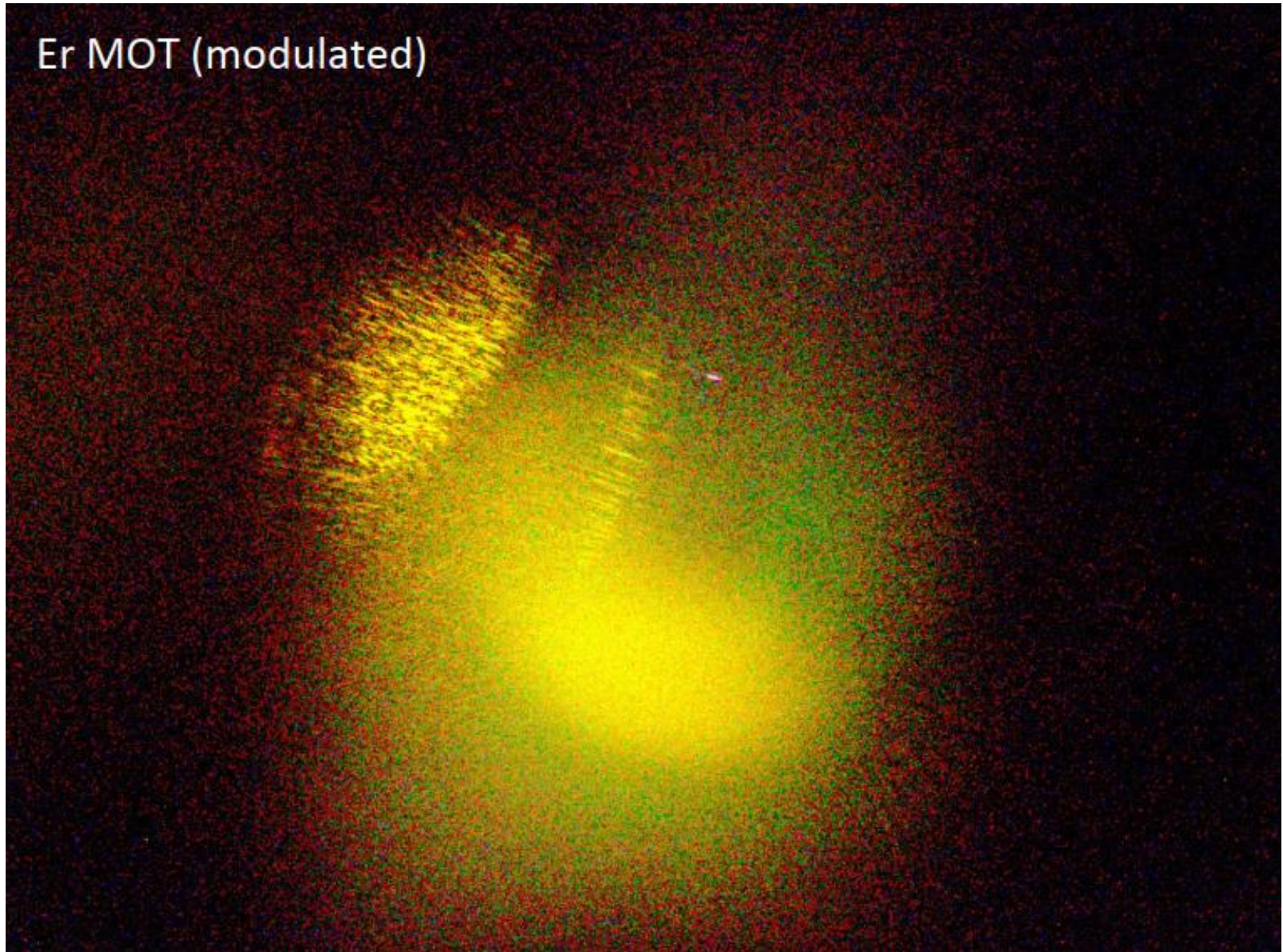


Yb MOT > Li MOT > Yb CMOT > Yb cooling > Li CMOT > Li cooling

Successfully Reproduce ^{174}Yb - ^7Li Quantum Degenerate Mixture

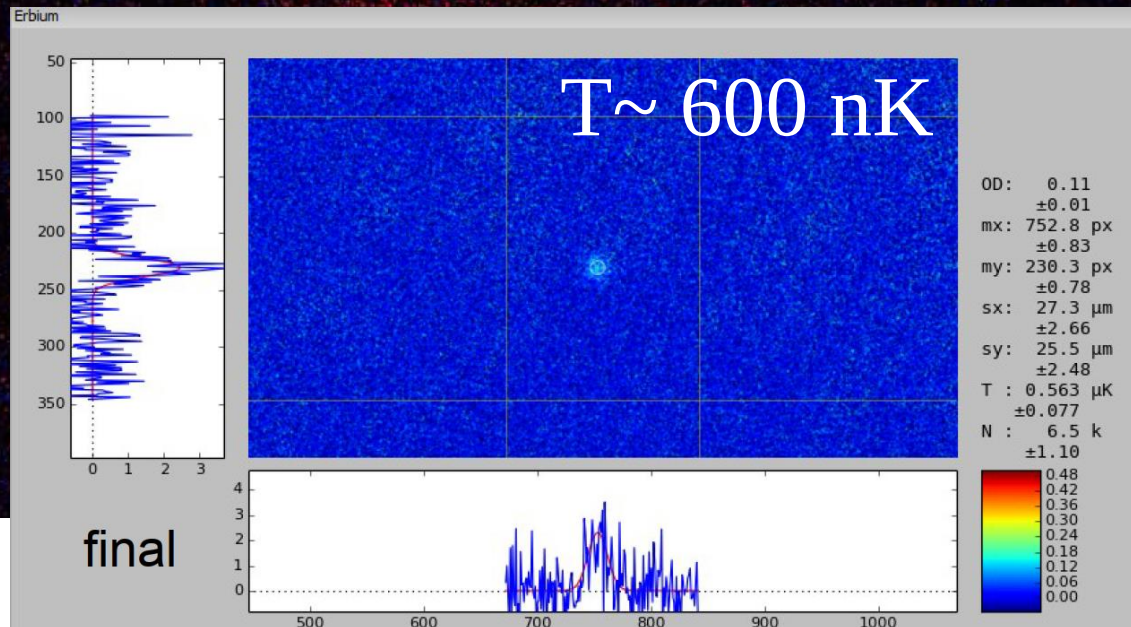


Er MOT (modulated)



Er CMOT (cooling phase, -2Γ)

Successfully Creating Ultracold ^{168}Er



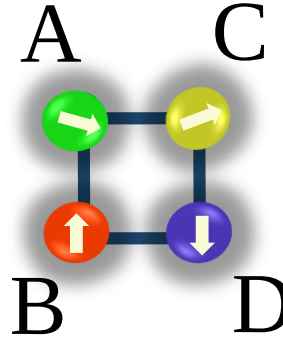
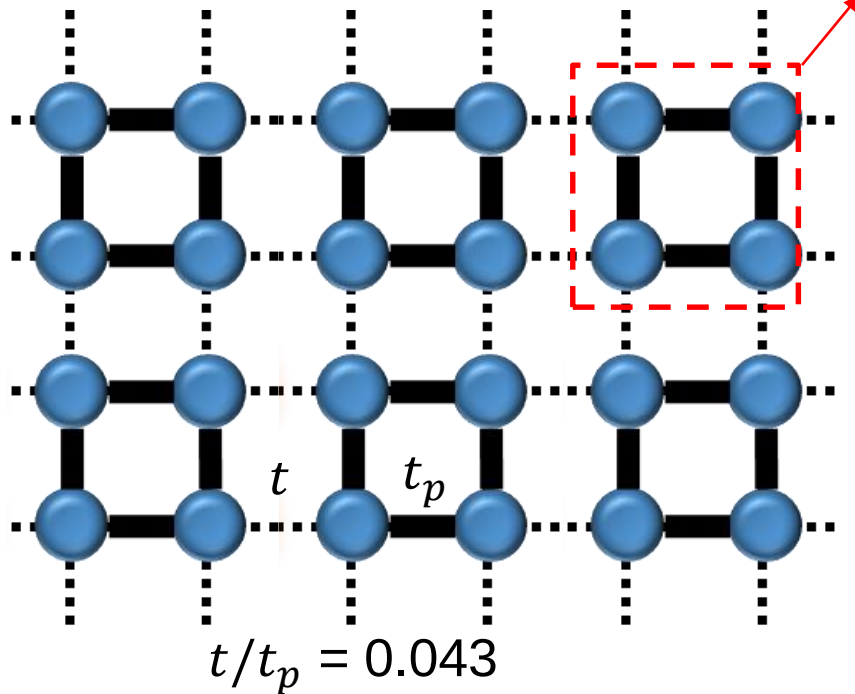
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 $SU(4)$ singlet

Quantum Magnetism of $SU(N=6)$ Fermi gas of ^{173}Yb



isolated plaquette lattice

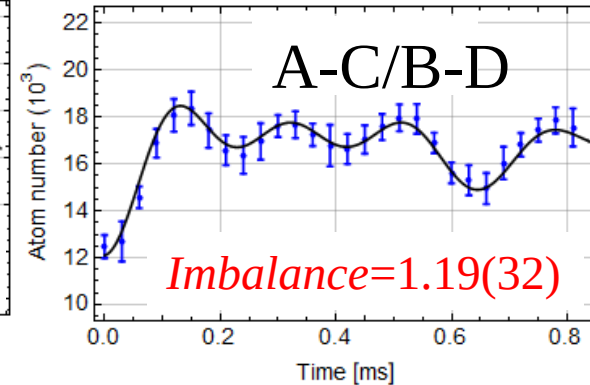
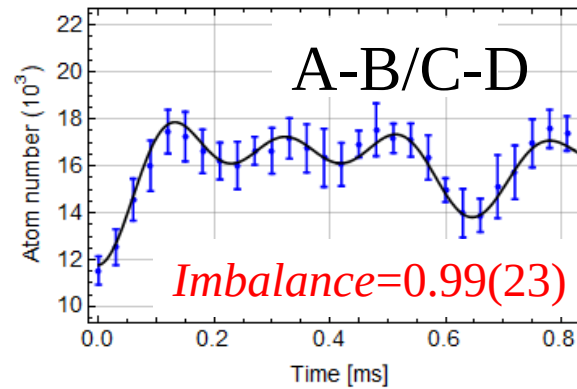


$SU(4)$ singlet: $|SU(4)S\rangle$

$$= \frac{1}{\sqrt{24}} \sum_{\{ijkl\}} c_{1i}^\dagger c_{2j}^\dagger c_{3k}^\dagger c_{4l}^\dagger |0\rangle$$

$$i,j,k,l = A,B,C,D$$

$$1,2,3,4 = \text{purple down, green diagonal down-right, yellow diagonal up-right, red up}$$

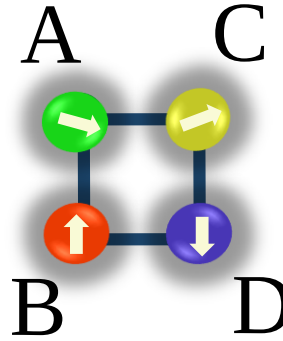
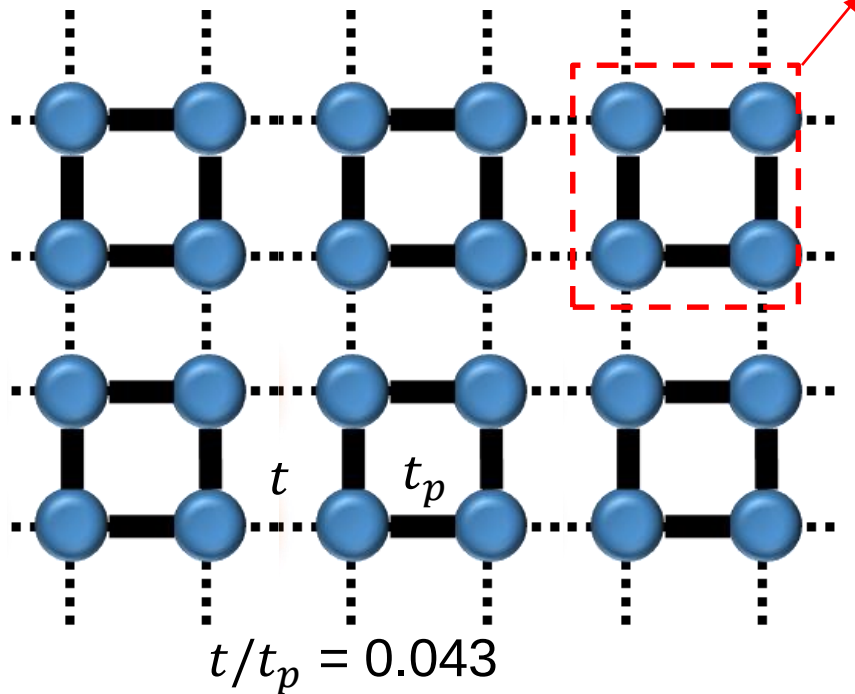


$$|SU(4)S\rangle = \frac{1}{\sqrt{6}} \sum_{\{\sigma,\tau\}} |S_{SU2}^{AB}(\sigma\tau), S_{SU2}^{CD}(\bar{\sigma}\bar{\tau})\rangle = \frac{1}{\sqrt{6}} \sum_{\{\sigma,\tau\}} |S_{SU2}^{AC}(\sigma\tau), S_{SU2}^{BD}(\bar{\sigma}\bar{\tau})\rangle$$

Quantum Magnetism of $SU(N=6)$ Fermi gas of ^{173}Yb



isolated plaquette lattice



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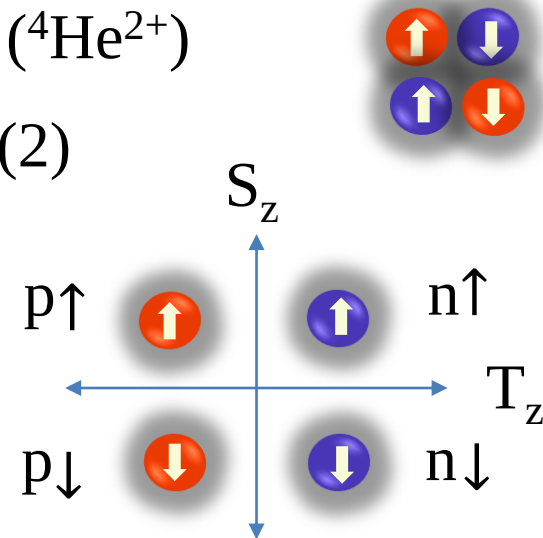
Alpha particle: α ($^4\text{He}^{2+}$)

$SU(4):SU(2) \times SU(2)$

$S(\text{Spin})=0$

$T(\text{Isospin})=0$

(after Y. Kanada)



Summary

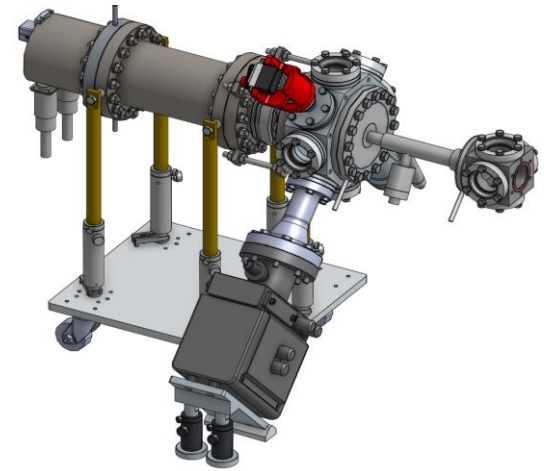
1. Quantum Gas Mixture with Unequal Mass

(b-b, f-f, b-f, f-b) in mixed dimensions

novel Efimov trimer

test of polaron bubble formation

p-wave superfluid

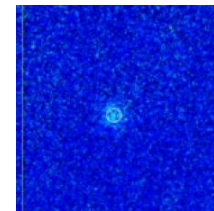


2. Er-Li-Yb Quantum Gas Mixture

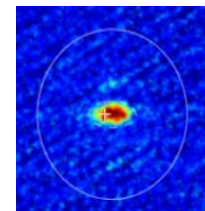
construction of Er-Li-Yb oven

successful creation of ultracold atoms

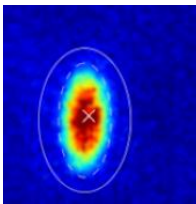
^{168}Er



^7Li



^{174}Yb



3. Other possibilities

realization of SU(4) singlet

Yb(-Li) Rydberg excitation

