Experiments with large mass-imbalance ultracold atom mixtures

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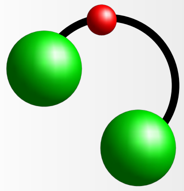
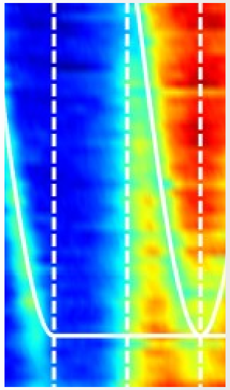
CLUSHIQ2020, Beppu – 2020/01/23-24

Summary

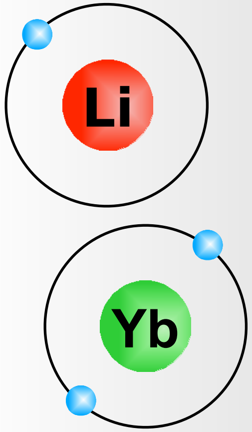


Large mass-imbalance ultracold atom systems in mixed dimensions as gateway to new Efimov clusters states

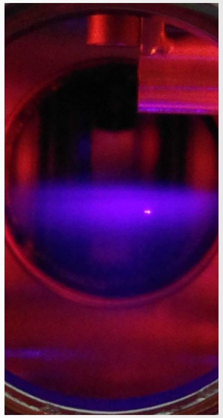


Observed the formation of 2D-3D Fermi-Bose mixed dimensional system

FS, N. Mizukami, P. Yu, S. Koibuchi, A. Bouscal, Y. Takahashi, Phys. Rev. A 98, 051602(R) 2018.



Demonstrated and characterized first ^{7}Li-^{173}Yb quantum degenerate mixture

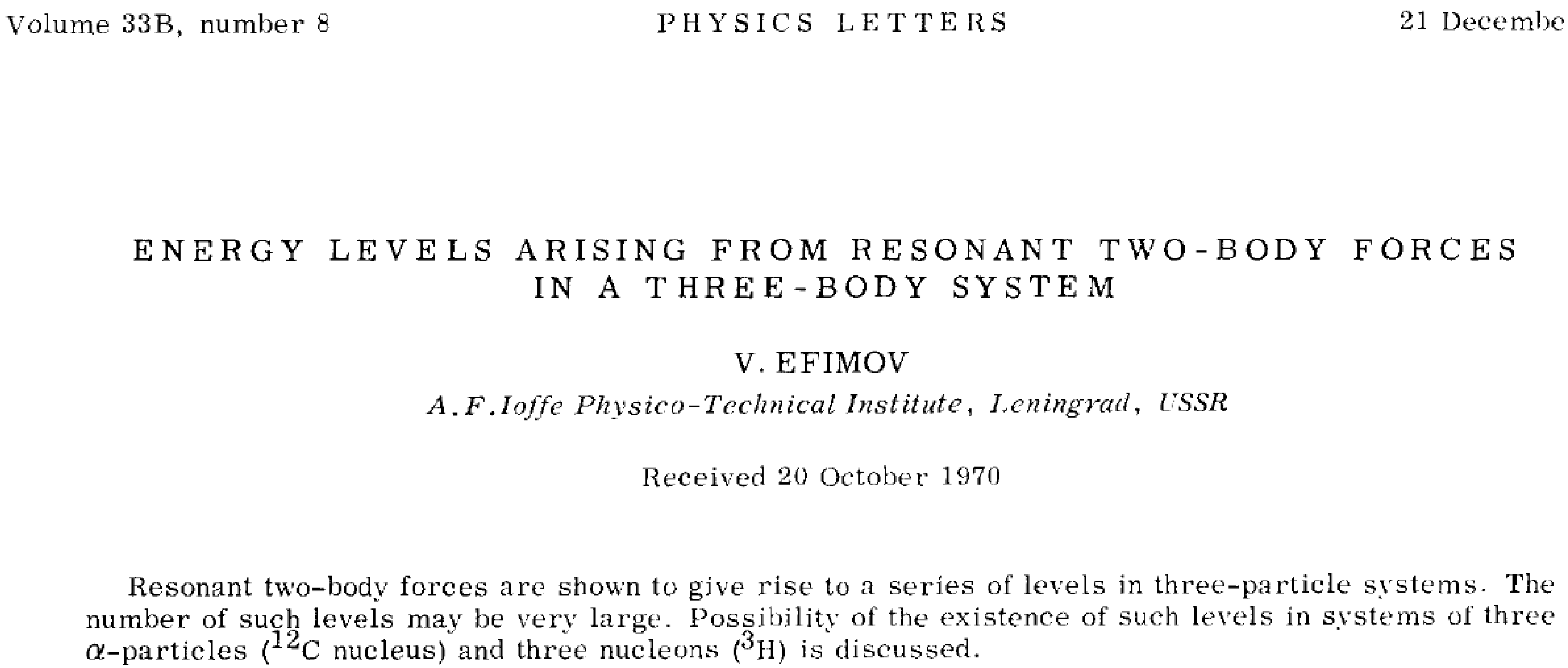


Work towards a new mixture in mixed dimensions with tunable interactions

Outline

- Introduction
  - Efimov cluster states
  - p-wave superfluidity in mixed dimensions
- Proof-of-principle experiments
  - Formation of ^{7}Li-Yb quantum degenerate mixtures
  - 2D-3D and 0D-3D mixed dimensional systems
- A large mass-imbalance quantum mixture with tunable interactions
  - Physics of Er-Li atomic mixtures
  - State of the experiment
- Summary (again)

Efimov cluster states – origins


Volume 33B, number 8 PHYSICS LETTERS 21 December 1970

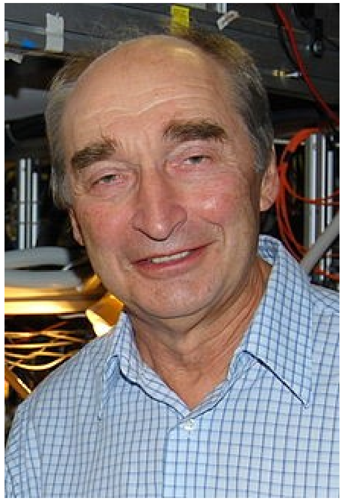
ENERGY LEVELS ARISING FROM RESONANT TWO-BODY FORCES IN A THREE-BODY SYSTEM

V. EFIMOV

A.F.Ioffe Physico-Technical Institute, Leningrad, USSR

Received 20 October 1970

Resonant two-body forces are shown to give rise to a series of levels in three-particle systems. The number of such levels may be very large. Possibility of the existence of such levels in systems of three α-particles (^{12}C nucleus) and three nucleons (^3H) is discussed.

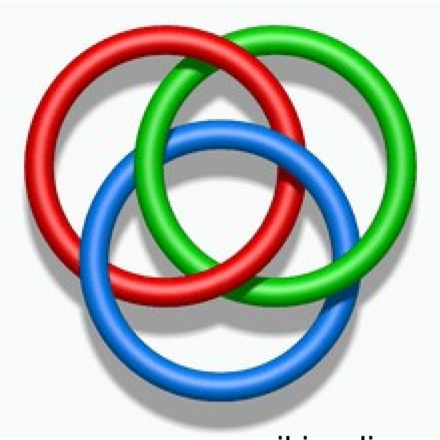


wikipedia.org

- Efimov (PhD 1966) studied the three-body problem in nuclear systems
- Wanted to explain, e.g., triton (p-n-n) and Hoyle state of ^{12}C
- Found stabilization of two nearly binding particles by third particle
- Difficult to test in (fermionic) nuclear systems

Efimov cluster states – universality

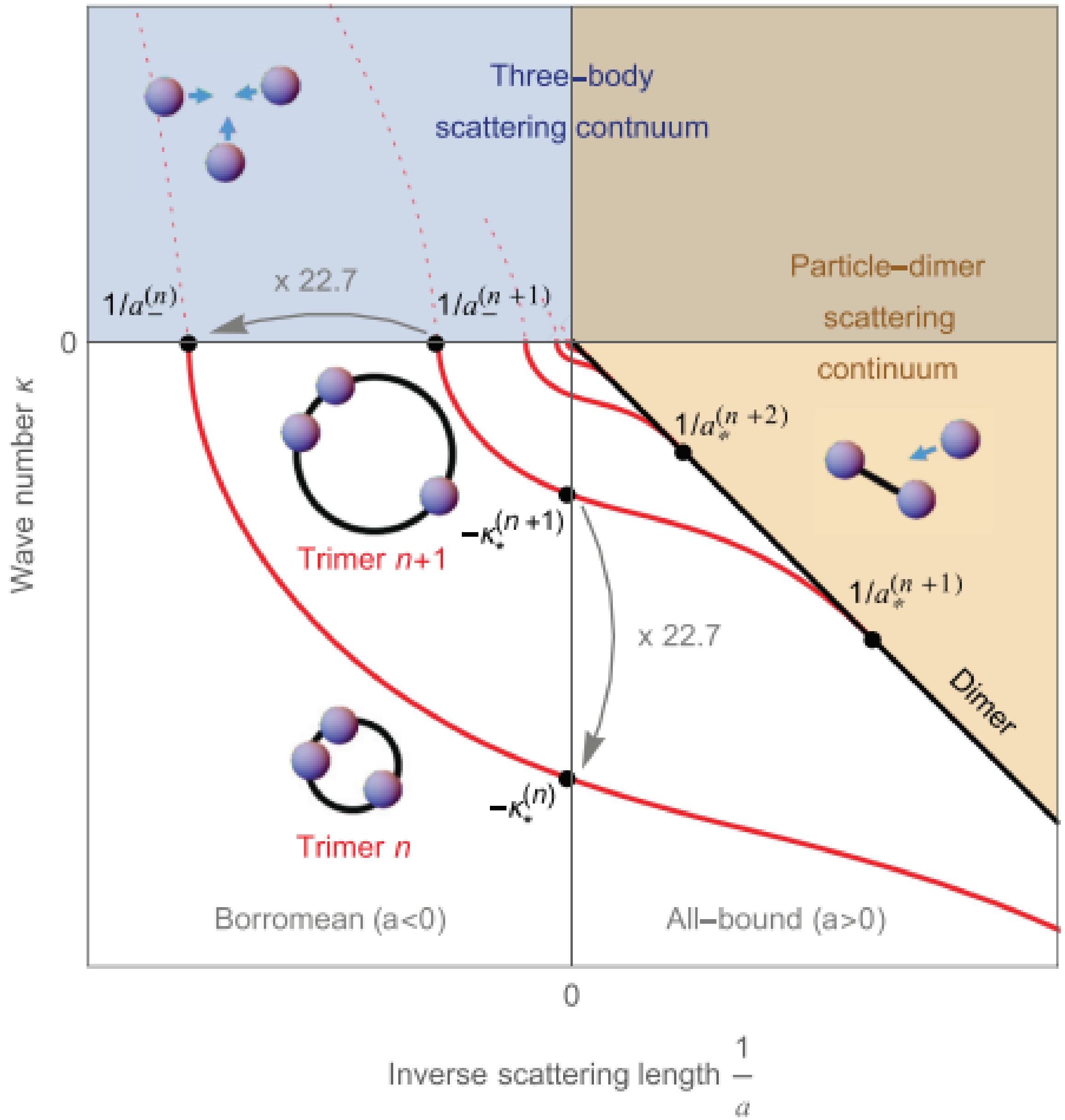
- Basic ingredients (three identical bosons in 3D)
  - Short-range interactions (potential decays faster than $1/r^3$)
  - Near-resonant two-body *s*-wave attractive interaction
- *Universality* of low-energy physics
  - Irrelavance of interaction details at low energy (large wave function)
  - Efimov physics occurs at separations larger than interaction range
- Efimov effect is ubiquitous to many physical systems
  - Nuclear physics (halo nuclei)
  - High-energy physics (QCD - triton)
  - Condensed matter (magnons)
  - Molecular physics ($^{4}He_3$ molecule)
  - Atomic physics (^{133}Cs, ^{39}K, ^{6}Li, ^{41}K-^{87}Rb)



wikipedia.org

Review by P. Naidon and S. Endo, Rep. Prog. Phys. 80, 056001 (2017)

Efimov cluster states – scaling

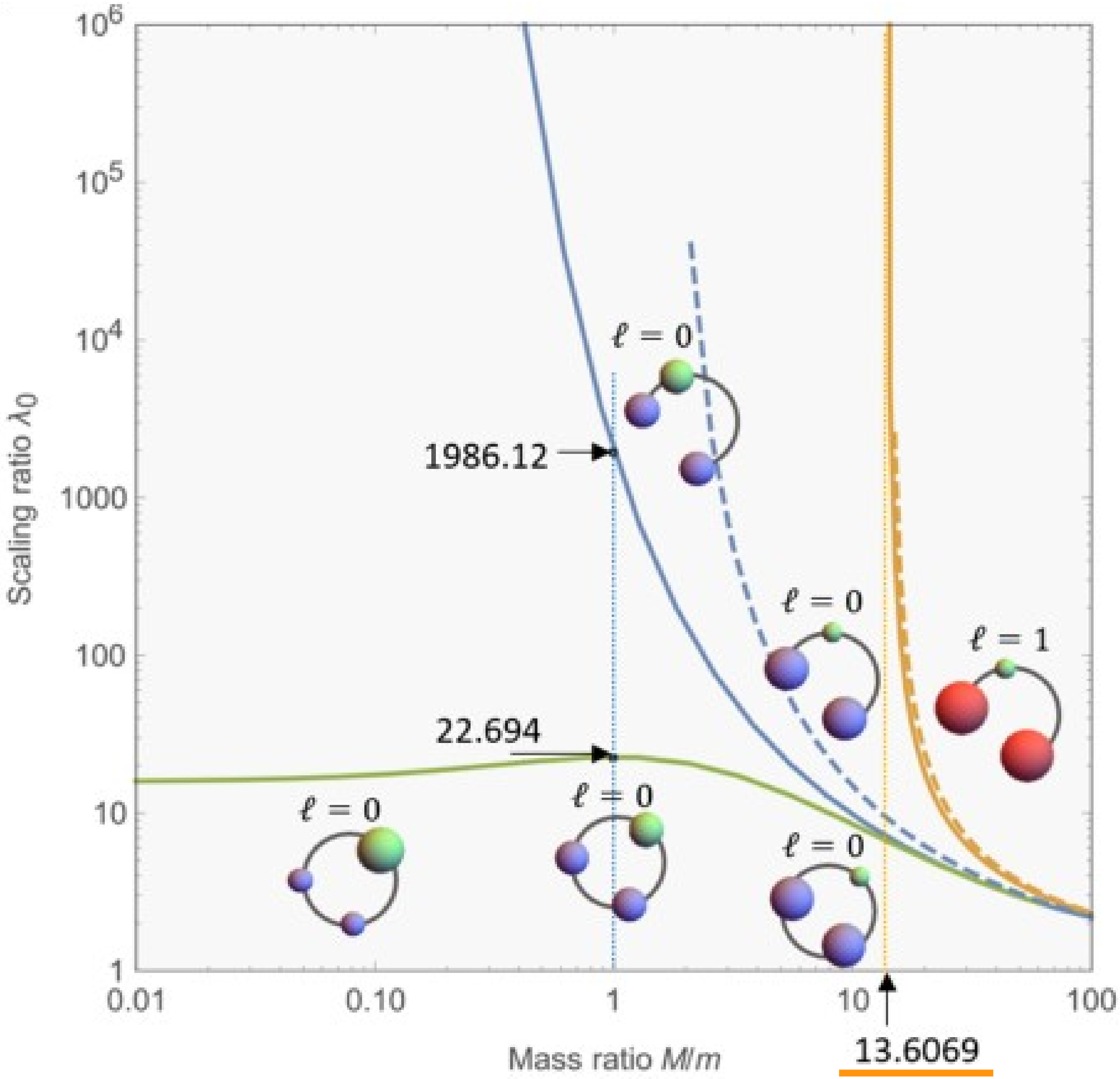


P. Naidon and S. Endo, Rep. Prog. Phys. 80, 056001 (2017)

- Infinite number of three-body bound states
- Scaling factor $\lambda_0 \approx 22.694$
- Energy scaling $E/(\lambda_0)^{2n}$
- Deviation of ground-state and first excited-state trimer from universal spectrum

► Difficulty to observe series of Efimov trimers due to large scaling factor

Efimov physics beyond three identical bosons



Two identical bosons and one particle (all resonant)

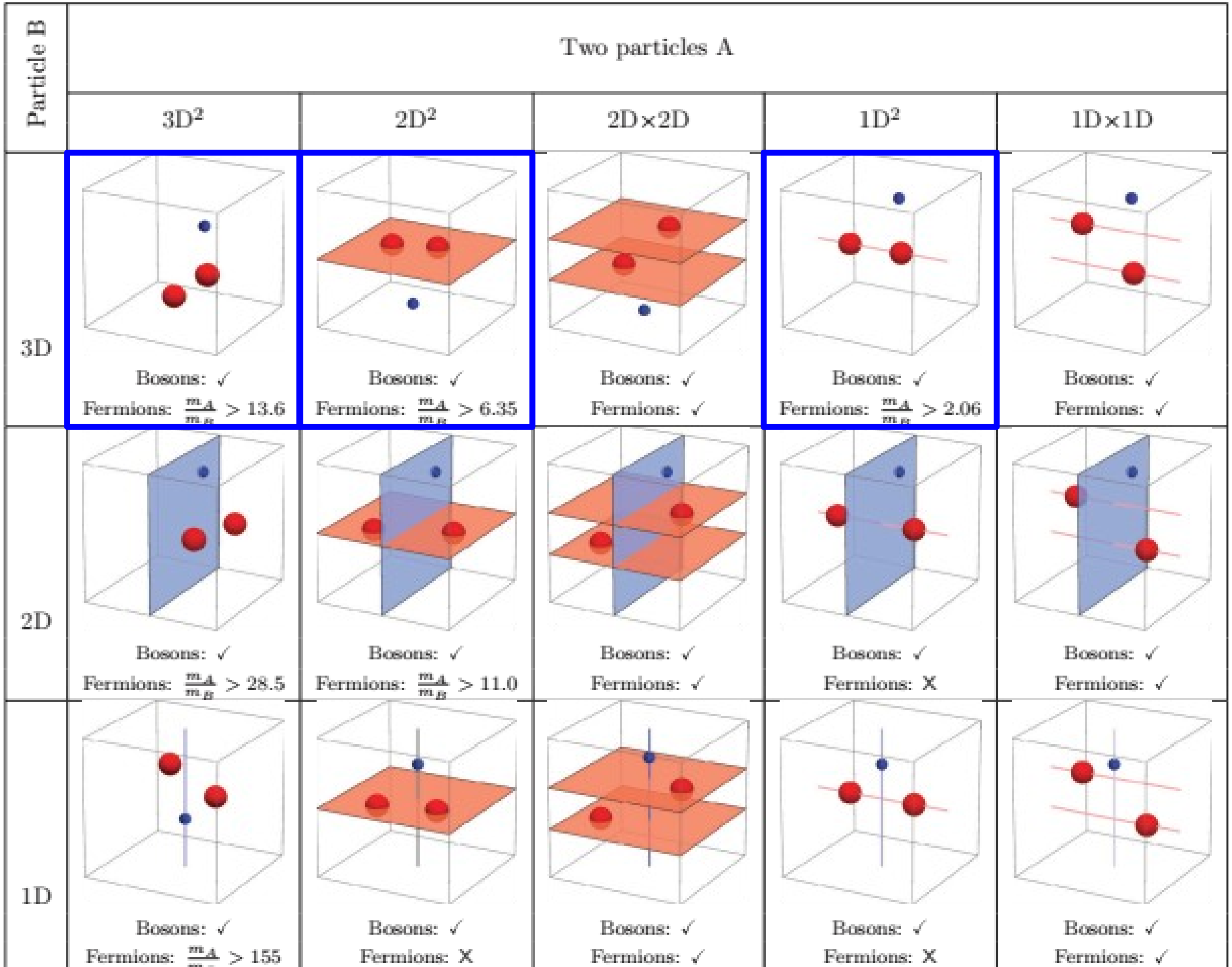
Two identical **bosons** resonant with one particle

Two identical **fermions** resonant with one particle ($l = 1$)

► Large variety of particle combinations and scaling ratios possible

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

Efimov physics beyond three dimensions – mixed dimensions



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

Previous experiments on Efimov physics with ultracold atoms

Single species experiments

- 2002 – Grimm (Innsbruck): ^{133}Cs, ground Efimov state
- 2009 – Inguscio (Florence): ^{39}K, first two Efimov states
- 2009 – Hulet (Rice): ^{7}Li, first two Efimov states
- 2014 – Grimm (Innsbruck): ^{133}Cs, second Efimov trimer

Mixture experiments

- 2013 – Jin (JILA): ^{87}Rb(B)-^{40}K(F)^{87}Rb(B) loss coefficient peak
- 2014 – Chin (Chicago) & Weidemüller (Heidelberg):
  ^{6}Li(F)^{133}Cs(B)^{133}Cs(B), series of three Efimov bound states
- 2015 – Inouye (Tokyo): ^{87}Rb(B)-^{41}K(B)^{87}Rb(B) loss coefficient peak

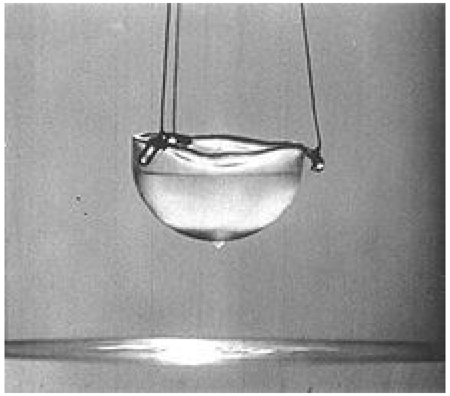
Missing experimental confirmation

- Effect of mixed dimensions (first 2D-3D experiments at LENS, 2010)

Bonus fact: p-wave superfluidity

- 1972: Discovery of superfluidity in ^{3}He by Lee, Osheroff and Richardson (Nobel Prize 1996)
- ^{3}He is a fermion $\rightarrow$ no s-wave coupling possible

► Superfluidity caused by p-wave Cooper pairs



wikipedia.org

It is hard to find a well controllable system to study p-wave superfluidity.

P-wave superfluidity with ultracold atoms in mixed dimensions

- 2009 – Nishida: 2D Fermi gas within 3D other species Fermi gas
- 2016 – Wu, Bruun: 2D Fermi gas embedded in 3D BEC
- 2017, 2018: Further refinements and detailed calculations for ^{7}Li-^{173}Yb
- Mechanism: Increased critical temperature due to Fermion pairing via Bogoliubov phonon mediated interactions

Elements for a large mass-imbalance ultracold mixture

Periodic Table of the Elements

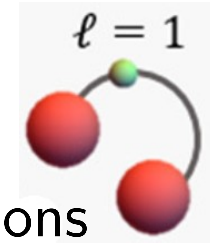
Number
Symbol
Name
Mass

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H Hydrogen 1.008																	2 He Helium 4.003
2	3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
3	11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
4	19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.798
5	37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.293
6	55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
7	87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [278]	110 Ds Darmstadtium [281]	111 Rg Roentgenium [280]	112 Cn Copernicium [285]	113 Nh Nihonium [286]	114 Fl Flerovium [289]	115 Mc Moscovium [289]	116 Lv Livermorium [293]	117 Ts Tennessine [294]	118 Og Oganesson [294]

Lanthanide Series	57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.243	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

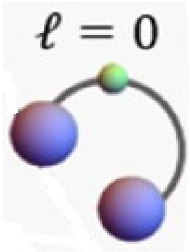
http://sciencenotes.org

Properties of a large mass-imbalance Yb-Li mixture



Mass ratio ^{173}Yb (boson) : ^{7}Li (fermion) $= 24.7 \gg 13.6$

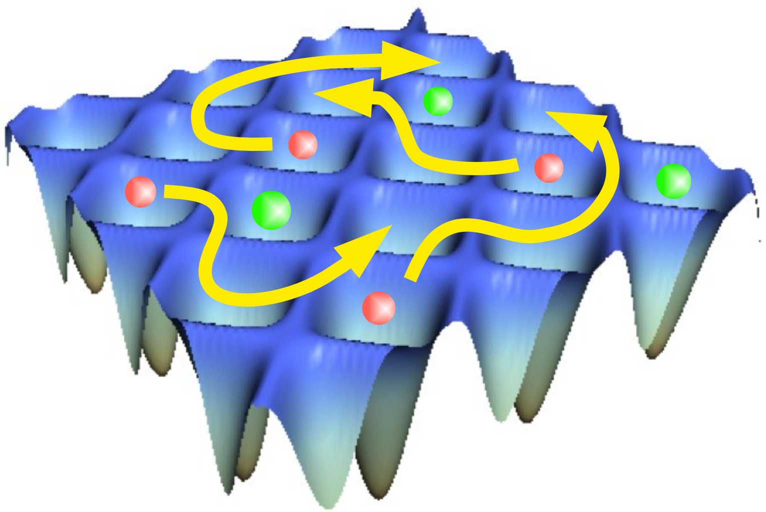
- Mass ratio $> 13.6 \rightarrow$ Possibility of Efimov states involving fermions
- Expected scaling ratio for ^{173}Yb-^{173}Yb-^{7}Li trimer: $\lambda_0 \approx 8.9 \ll 22.7$
- Also possible: all bosonic case, ^{174}Yb-^{174}Yb-^{7}Li $\rightarrow \lambda_0 \approx 4.4$



Further advantage of large mass imbalanced mixture:

- Effective depth of optical lattice

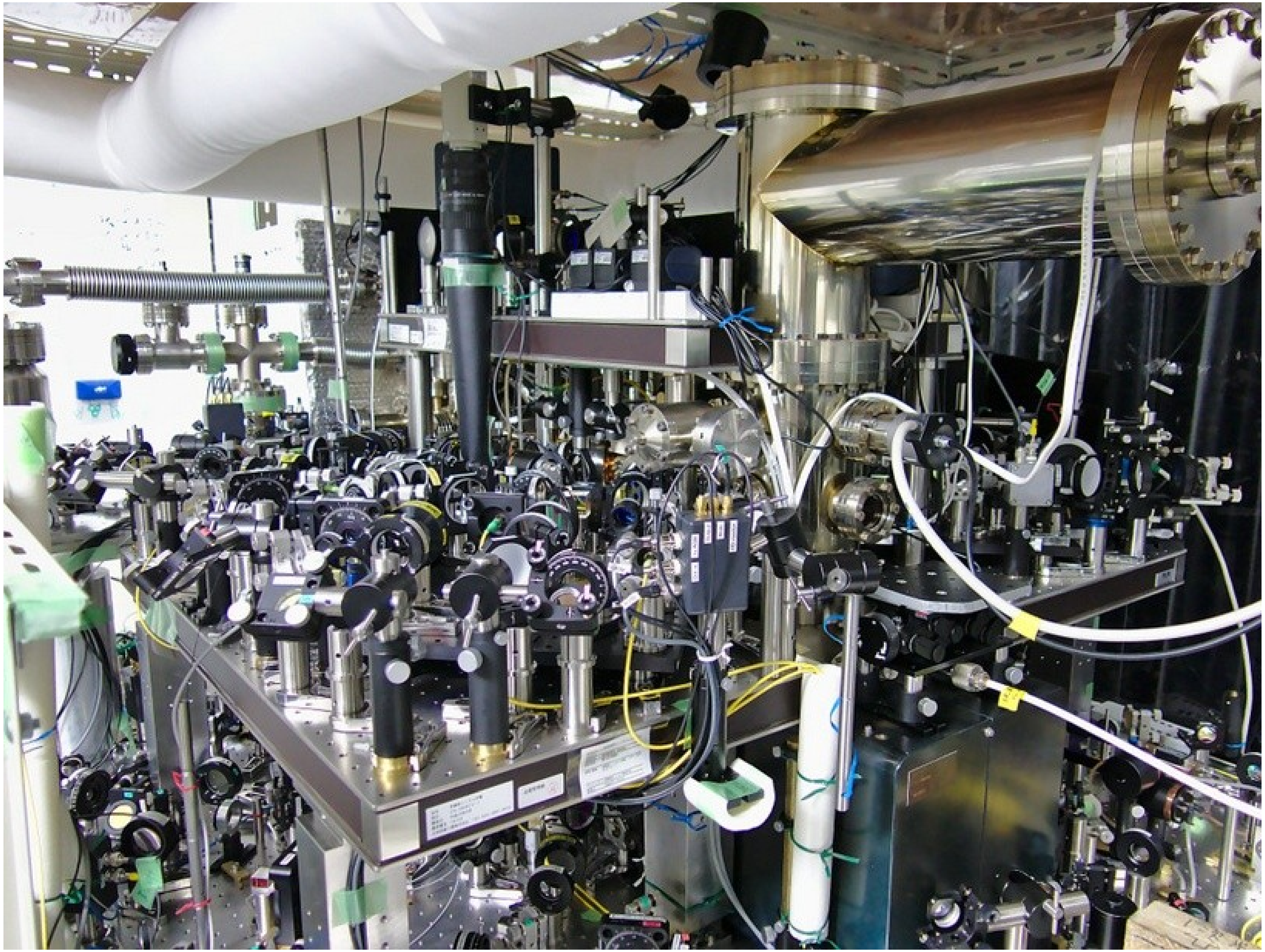
$$\frac{V_{\rm lat}}{E_R} = \frac{2\,m}{\hbar^2 k^2}\frac{3\pi c^2}{2\omega_0^3}\frac{\Gamma}{\Delta}\frac{2P}{\pi\omega_0^2}$$



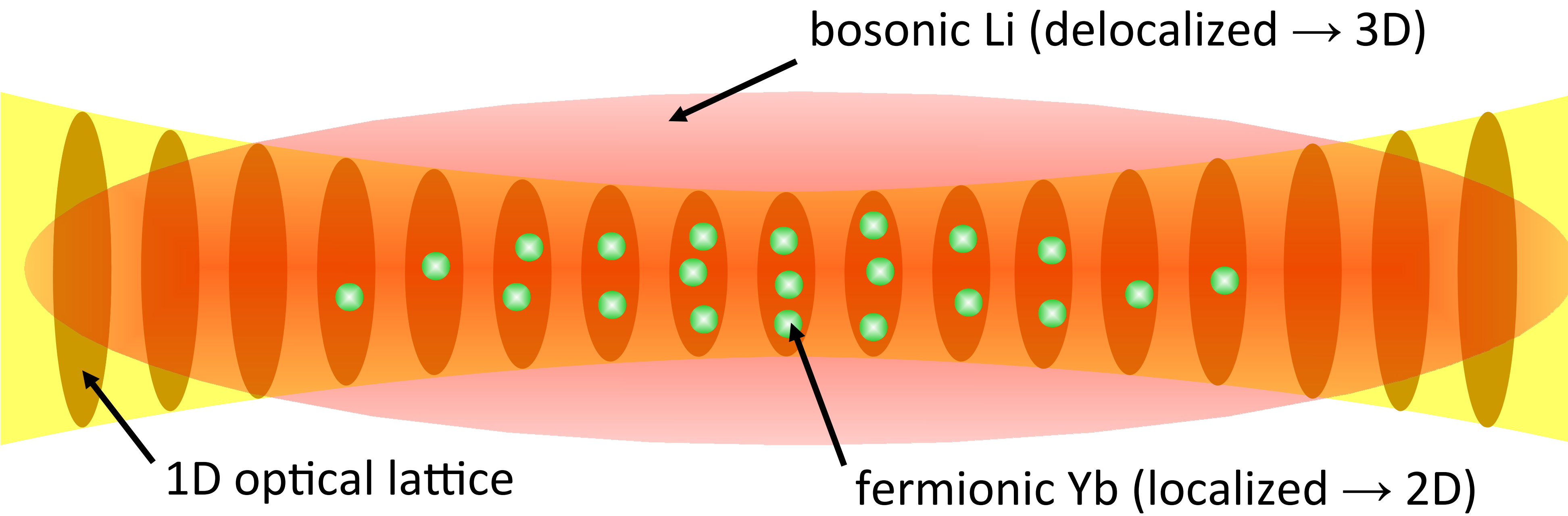
► Heavy Yb localized in optical lattice

► Light Li is still unconstrained in 3D

The Kyoto Li-Yb mixture machine



^{7}Li-Yb in mixed dimensions

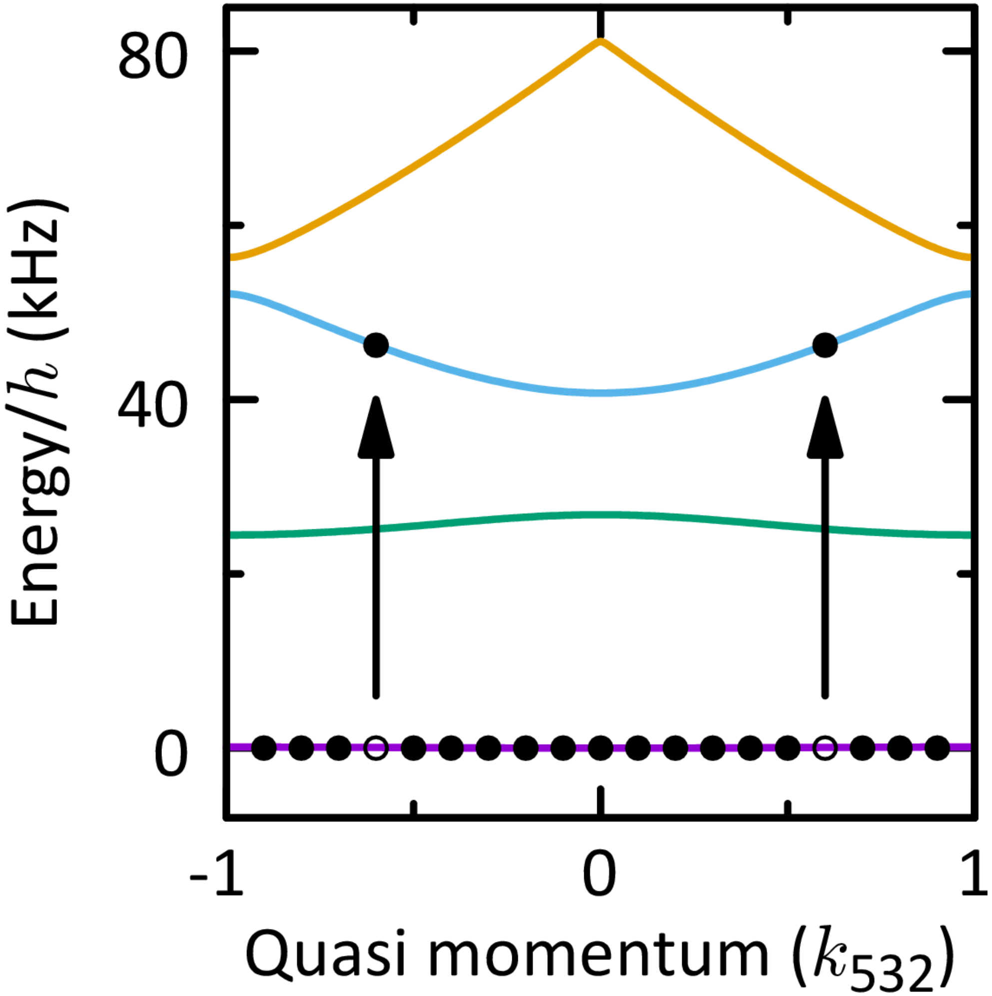


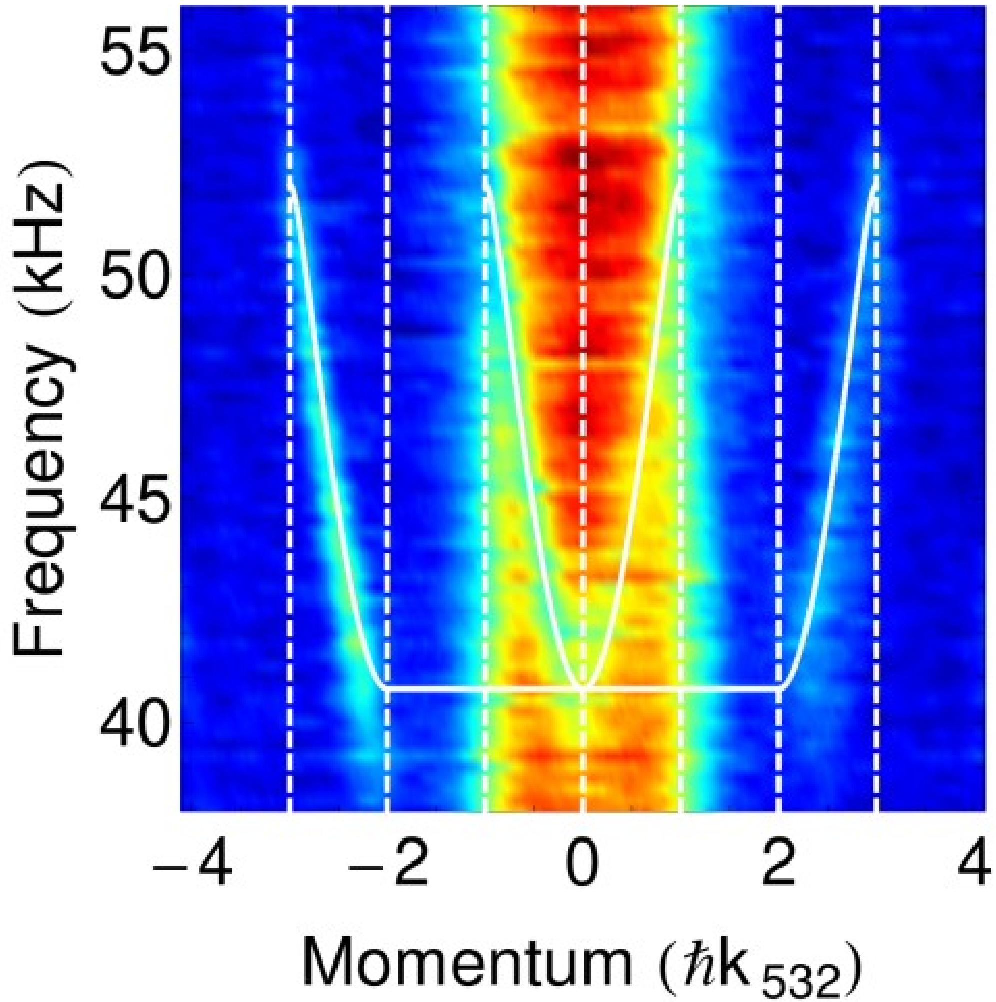
- Create 2D fermionic system in 3D bosonic
- Use optical lattice ($\lambda = 532$ nm) to localize species selectively only Yb
- Typical lattice depths:

$$U_{\mathrm{Yb}} = 15\,E_R^{\mathrm{Yb}} \qquad E_R^{\mathrm{Yb,Li}} = \frac{\hbar^2\,k_{532}}{2\,m_{\mathrm{Yb,Li}}}$$

$$U_{\mathrm{Li}} = 0.7\,E_R^{\mathrm{Li}}$$

Band structure of 3D ^{7}Li – 2D ^{173}Yb mixture

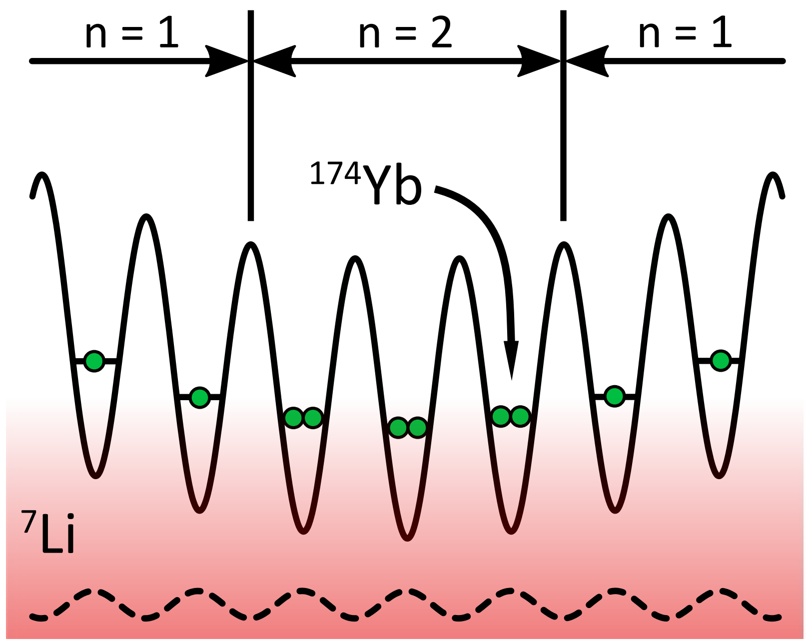


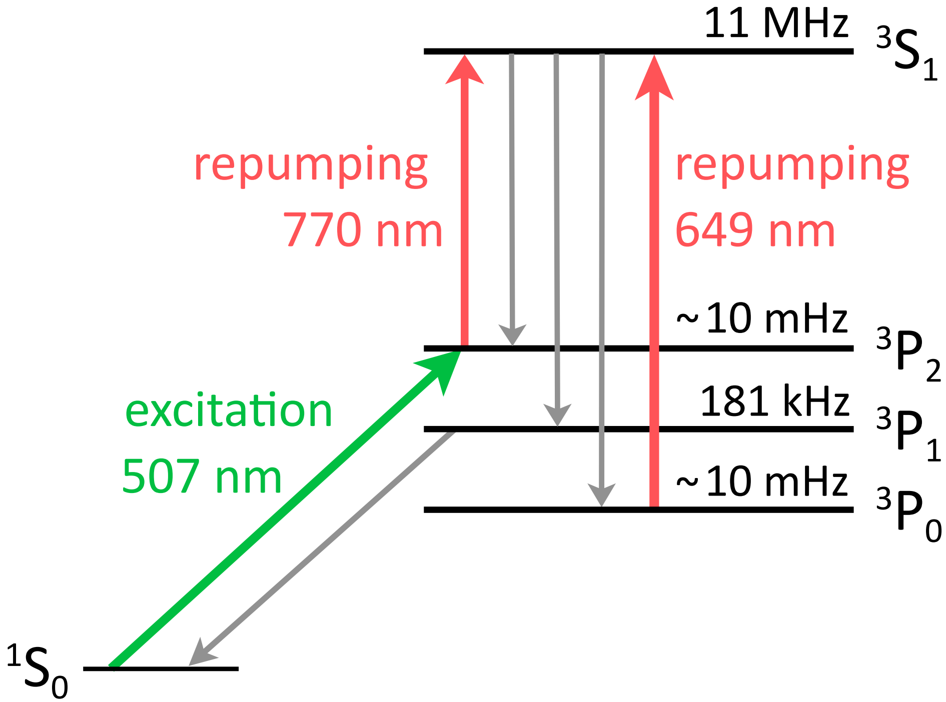


- Periodic modulation of lattice depth to cause ^{173}Yb interband excitations
- Good agreement with expected band structure for $U_{\mathrm{Yb}} = 14\, E_R^{\mathrm{Yb}}$

Yb intercombination line high-resolution spectroscopy

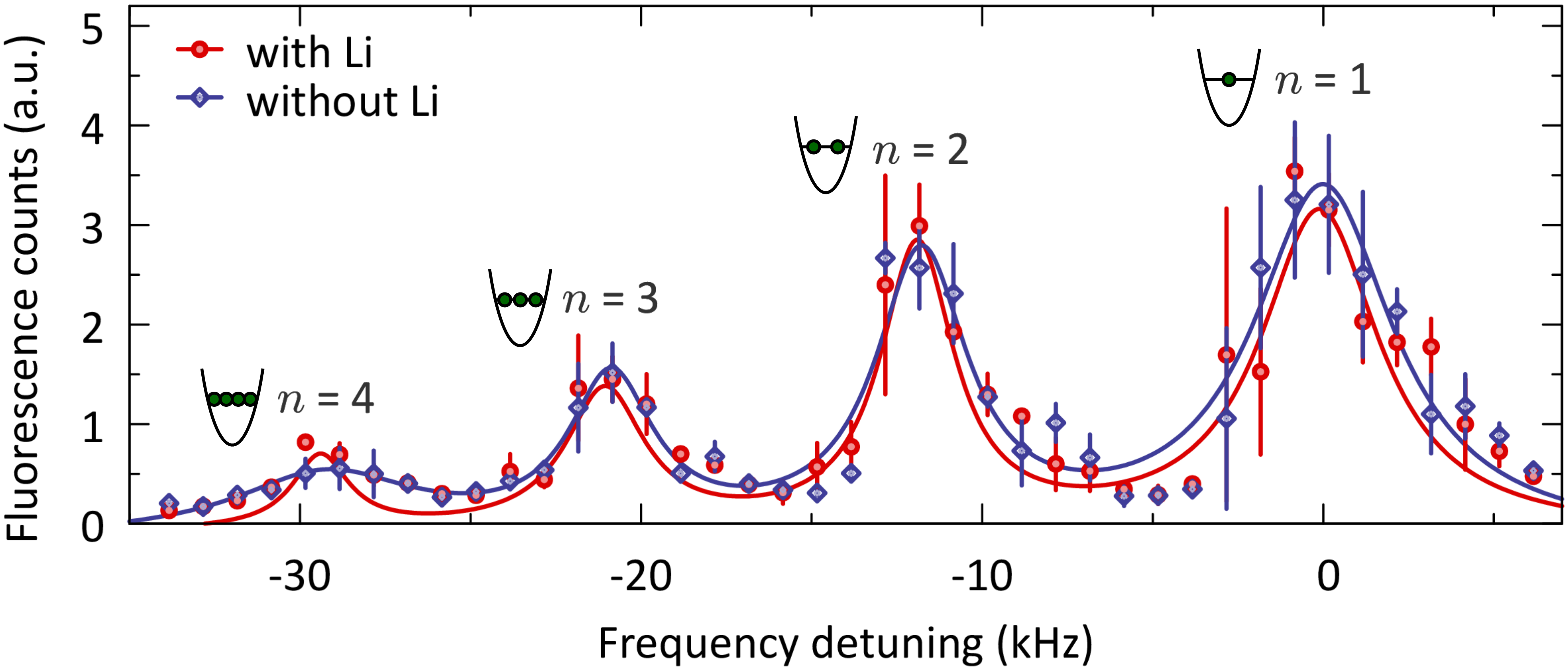
- Use narrow-linewidth transition to probe Yb Mott-Insulator structure





- Sensitive tool to detect changes in the Yb energy landscape
  - intraspecies: energy shift from multiply occupied lattice sites
  - interspecies: differences in Li-Yb scattering lengths

Spectroscopy of 3D ^{7}Li – 0D ^{174}Yb mixture



- Mott-Insulator structure of ^{174}Yb clearly resolved
- Presence of ^{7}Li does not significantly disturb Yb Mott-Insulator state

► Only very weak Li-Yb interspecies interactions

Where do we go from here?

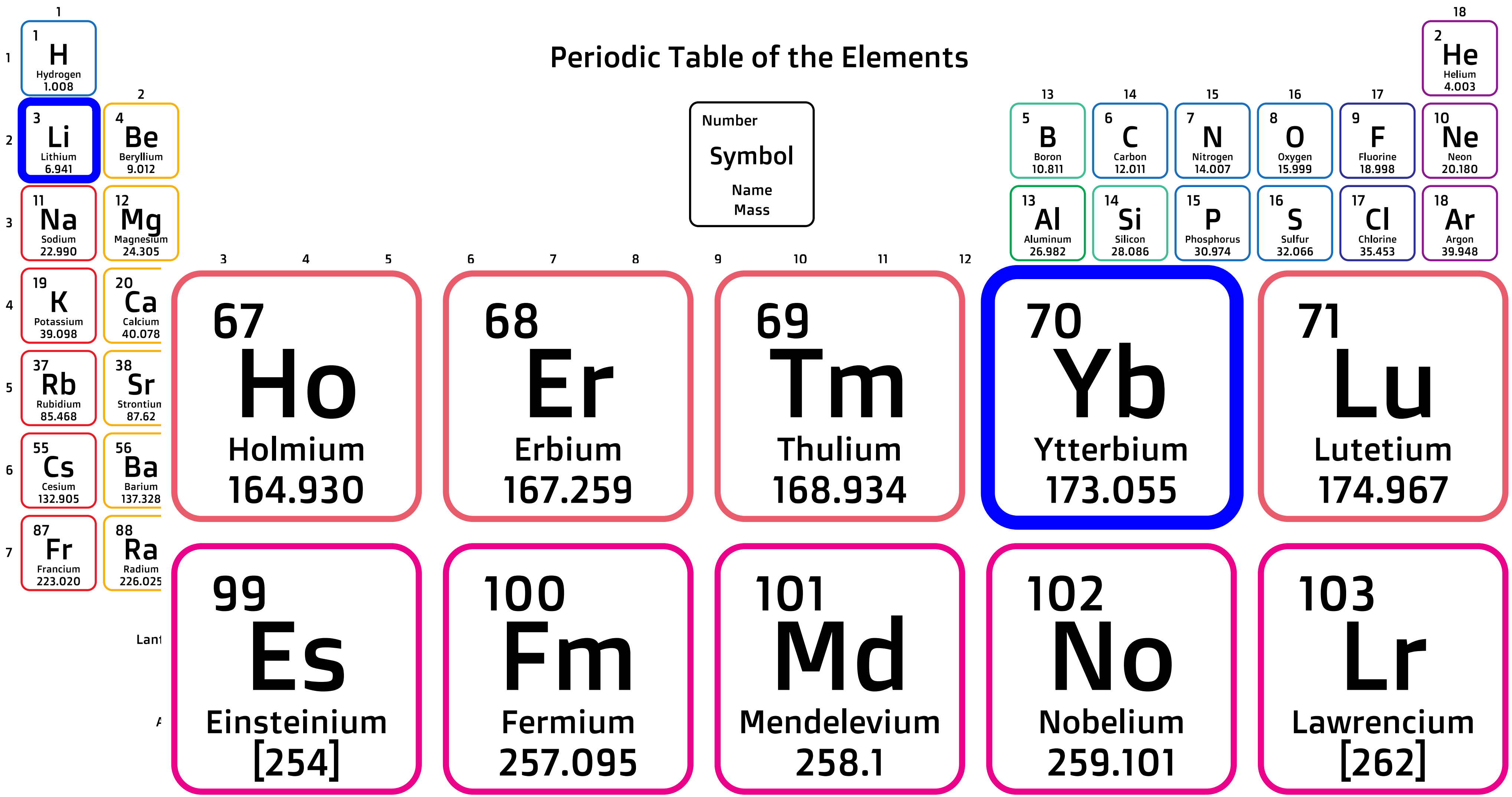
- (Some) requirements for both Efimov and p-wave superfluidity physics

Requirement	State of the art
^{7}Li-^{173}Yb Fermi-Bose mixture	done ✓
2D-3D mixed dimensional system	done ✓
Spin polarized fermions	demonstrated before ✓
Fermion temperature $< 0.1\ T_F$	not impossible ○
Tunable interspecies scattering length	very difficult for Li-Yb ✗

- Problem: No (usable) Li-Yb Feshbach resonances found or predicted

New mixtures

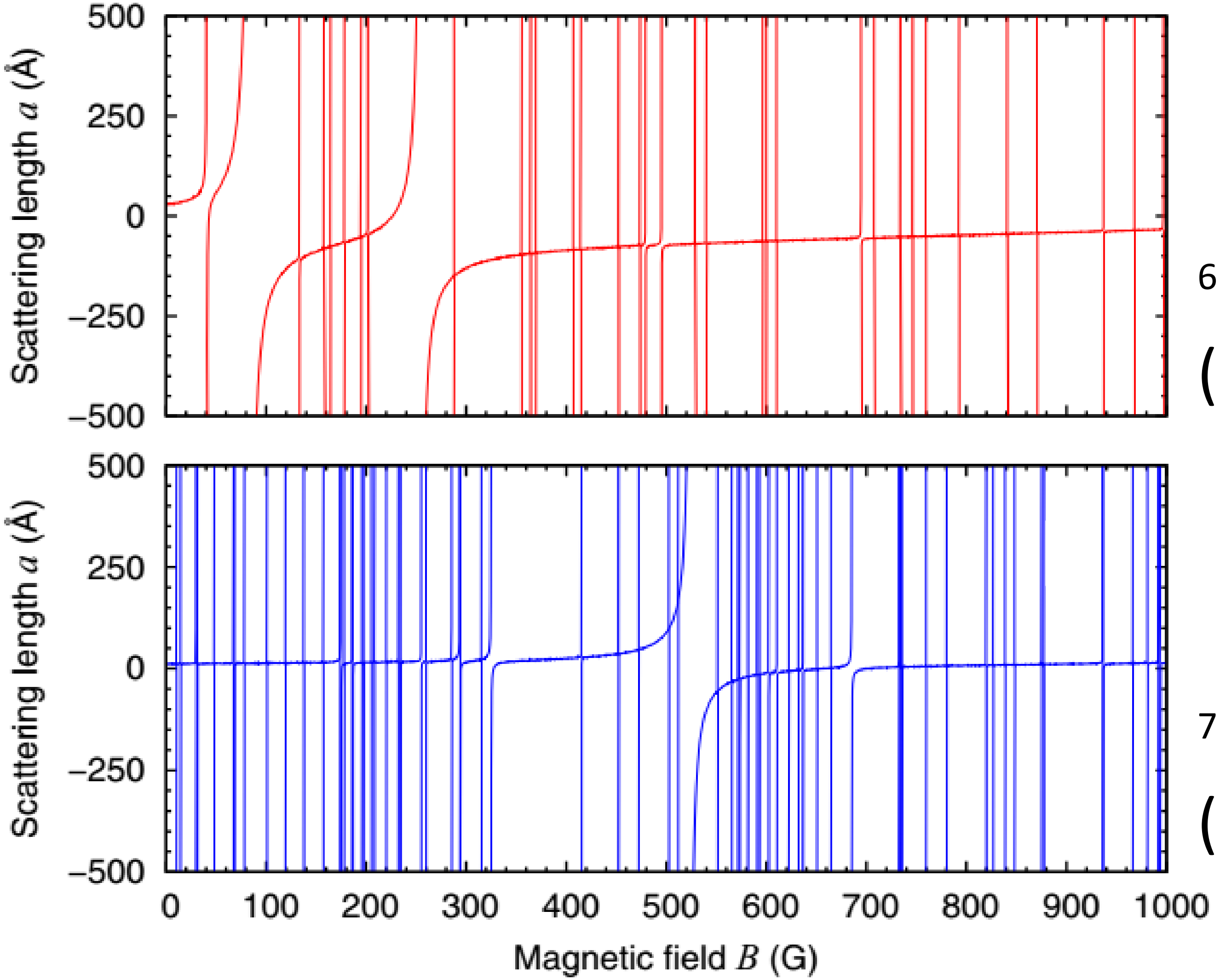
- Need mixed dimensional system with tunable interspecies interactions



Predicted Lithium-Erbium Feshbach spectrum

- Detailed calculations by González-Martínez and Żuchowski

PRA 92, 022708 (2015)



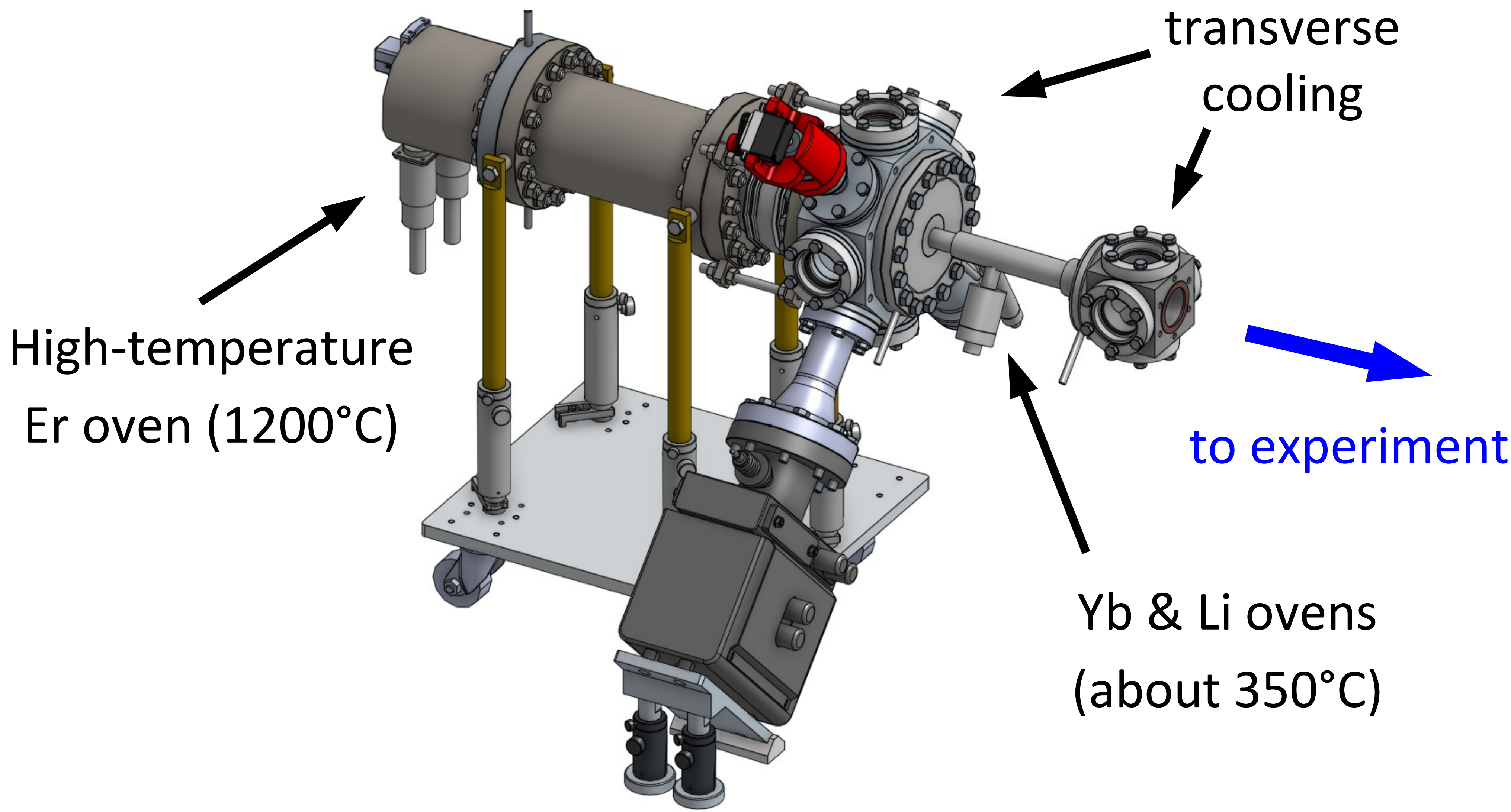
^{6}Li-^{166}Er (Fermi-Bose)

^{7}Li-^{166}Er (Bose-Bose)

► Expect that also Bose-Fermi system has Feshbach resonances

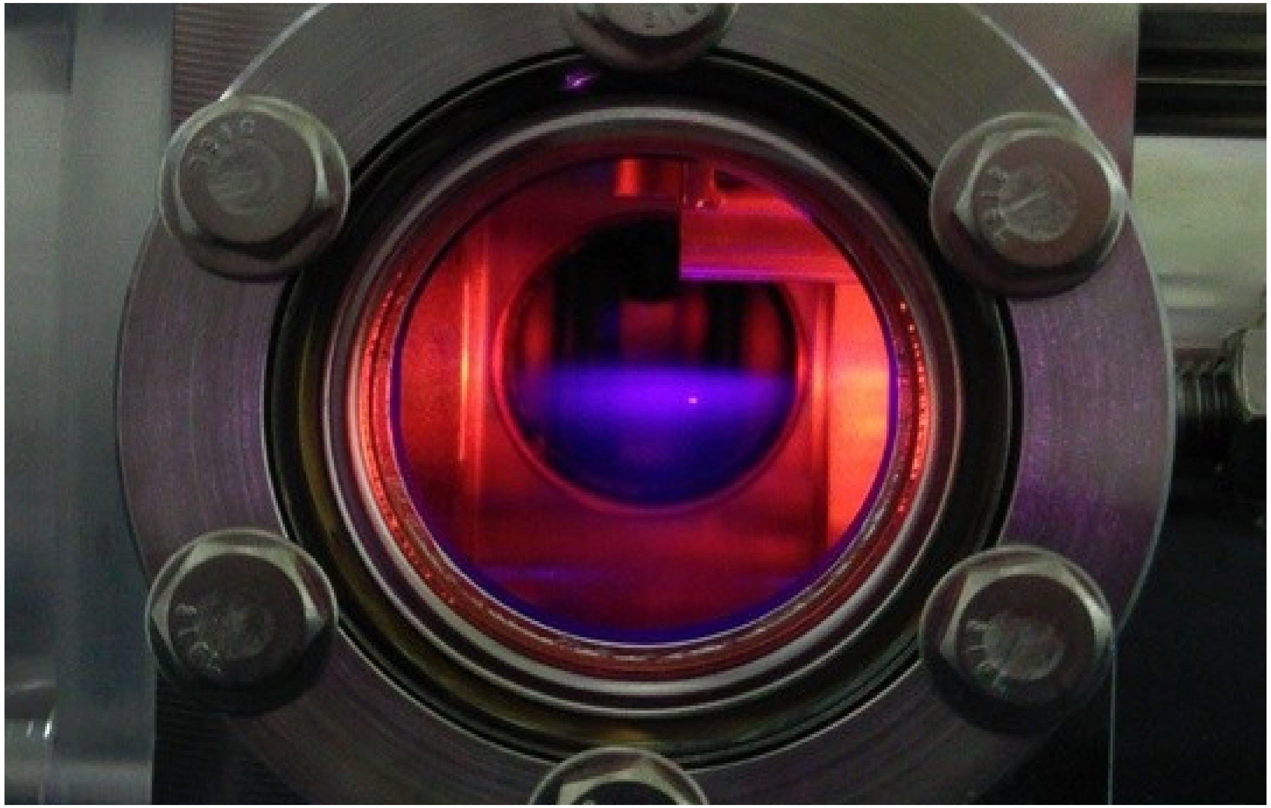
The Kyoto Erbium-Ytterbium-Lithium experiment

- We still have plans for Li-Yb
  $\rightarrow$ add Er to create a three-species experiment

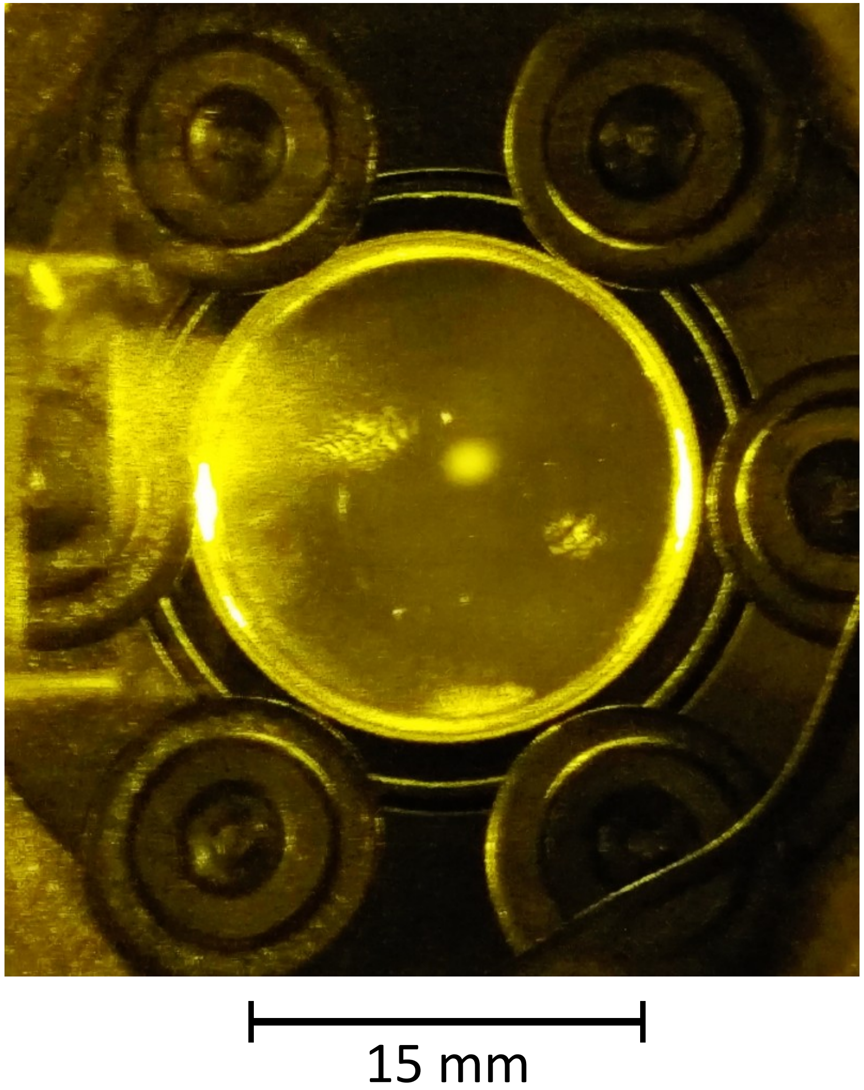


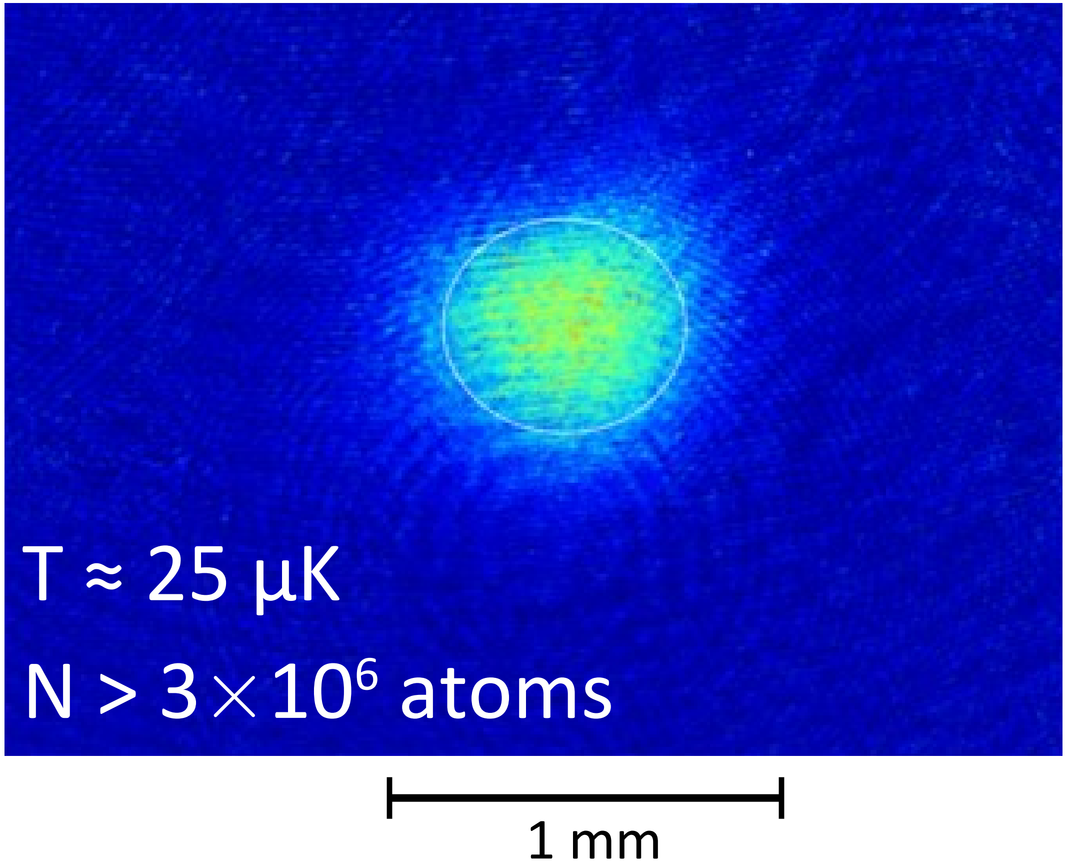
Status of the experiment upgrade

- Installation of new triple-species oven completed
- ^{7}Li-^{174}Yb and ^{6}Li-^{174}Yb quantum degenerate mixtures recovered
- Preparation of laser systems (401 nm, 583 nm) for Er completed
- Currently optimizing trapping and cooling of the ^{168}Er atoms



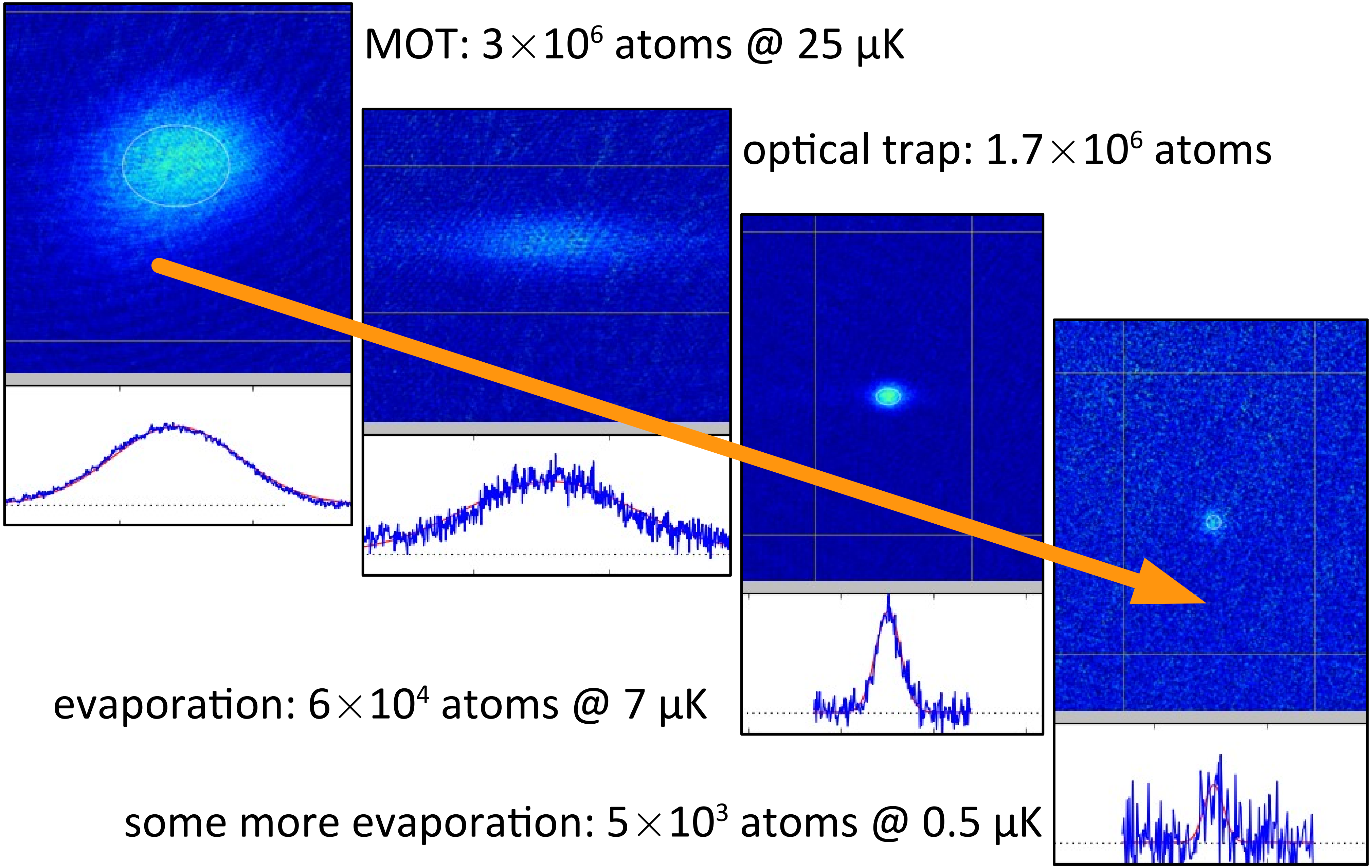
MOT of ^{168}Er atoms





► Successful trapping of Er atoms in MOT (magneto-optical trap)

Towards ultracold ^{168}Er atoms



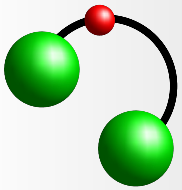
MOT: 3×10^6 atoms @ 25 µK

optical trap: 1.7×10^6 atoms

evaporation: 6×10^4 atoms @ 7 µK

some more evaporation: 5×10^3 atoms @ 0.5 µK

Summary



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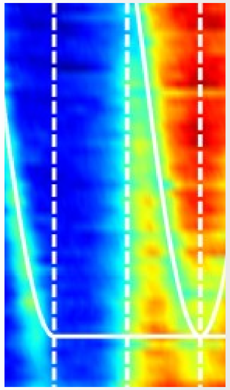

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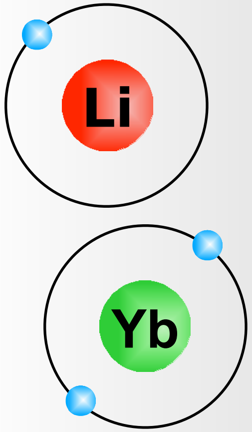

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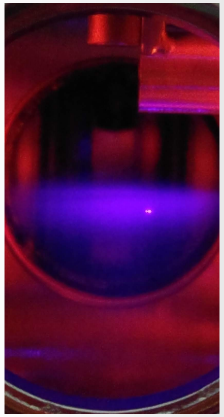

Work towards a new mixture in mixed dimensions with tunable interactions

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