Kick-Off Meeting on
「Clustering as a window
on the hierarchical structure of quantum matters」

19 November 2018
Tokyo Institute of Technology

Ultracold atom study of exotic phenomena bridging different hierarchies

Kyoto University

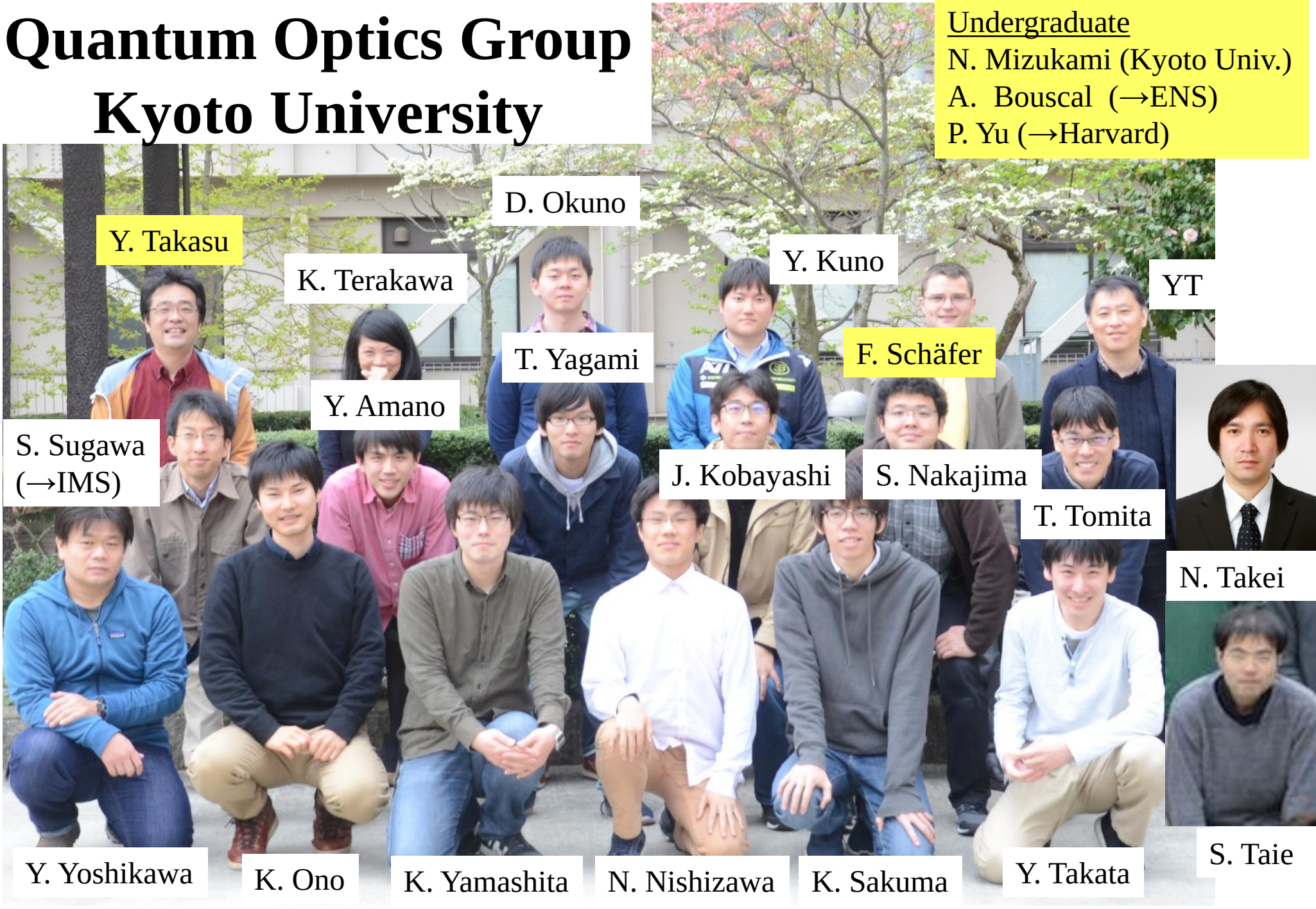
Y. Takahashi

C01: collaborators

Y. Takasu(Kyoto Univ.)

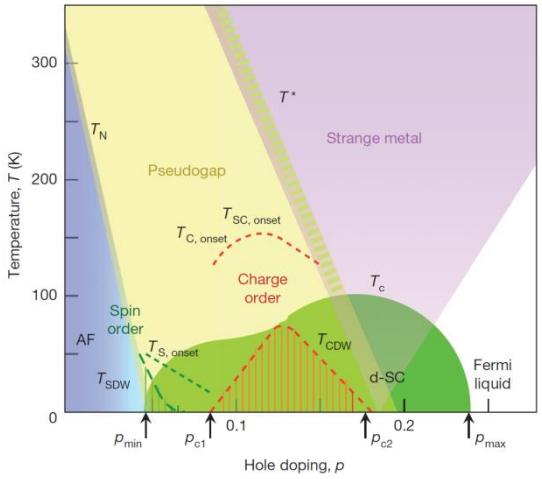
Y. Nishida(TIT)

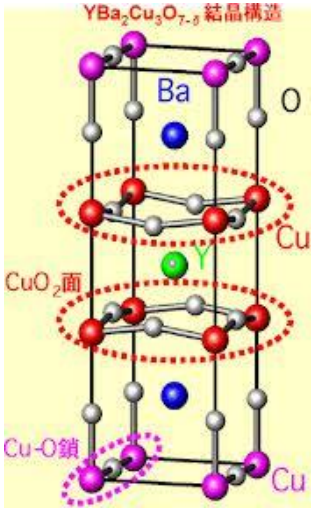
Quantum Optics Group
Kyoto University



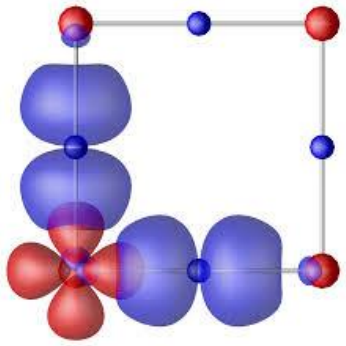
Quantum Simulation

condensed matter

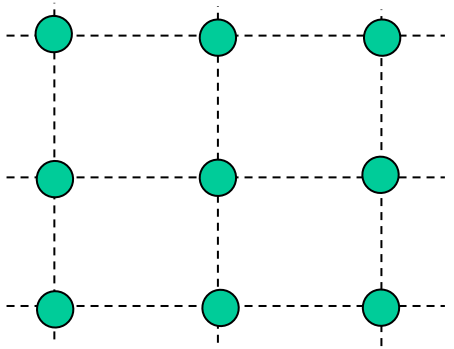




"CuO_2 plane (d-p model)"



"2D Square Lattice"



(Fermi) Hubbard Model

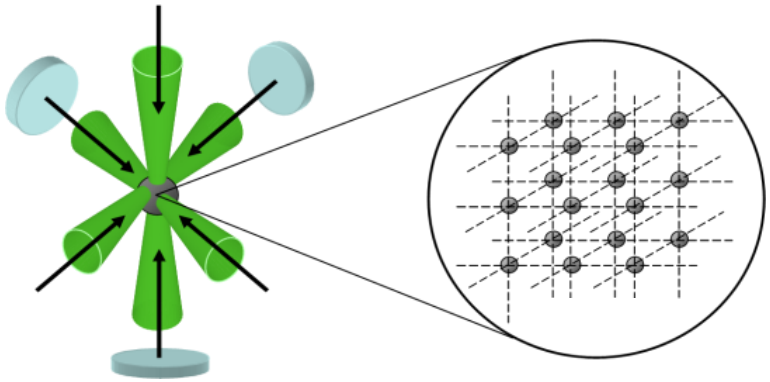
2D Square lattice

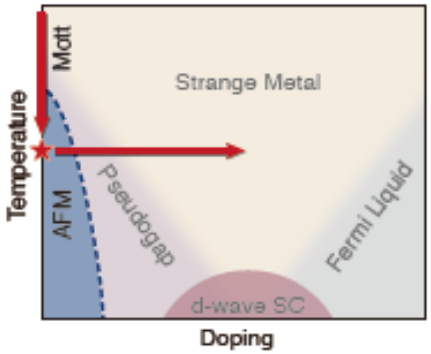
$$H = -t\sum_{<i,j>}(c_i^+ c_j + c_j^+ c_i) + U\sum_i n_{i,\uparrow} n_{i,\downarrow}$$

Numerical Simulation: QMC, DMFT, DMRG, ED,…

ultracold atoms in optical lattice

"highly Controllable"





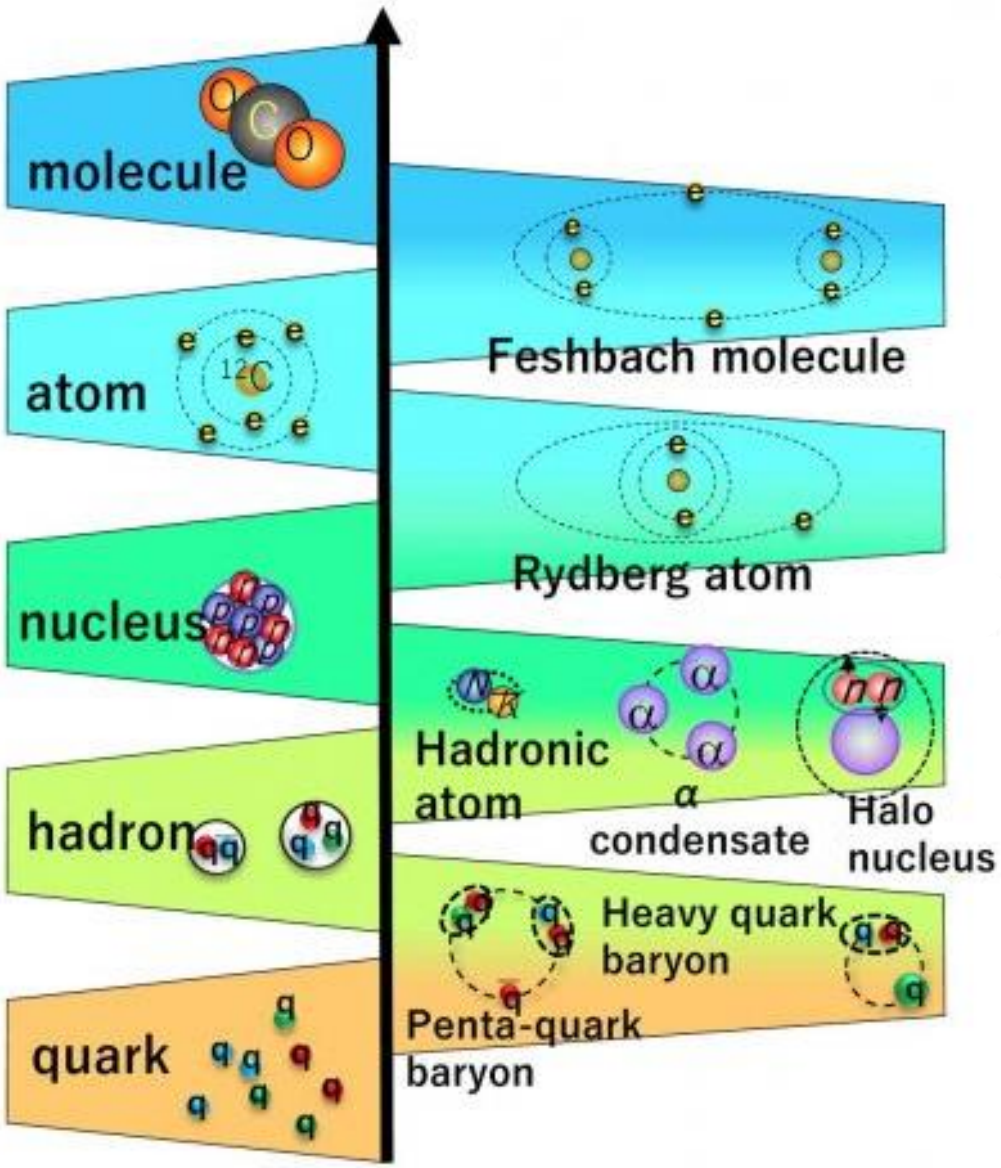
Quantum Simulation

quantum systems in various hierarchies and between them (quarks, hadron, nucleus, atom, molecules,…)

theoretical model

ultracold atoms

“highly controllable” (Feshbach resonance, mass ratio, dimensionality, quantum statistics,…)



Outline

1. Quantum Gas Mixture with Unequal Mass
   Novel features

2. Experimental system
   Yb-Li system: experiments
   Er-Li system: preparation

3. Other possibilities
   Rydberg state
   SU(4) singlet

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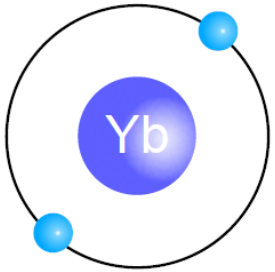
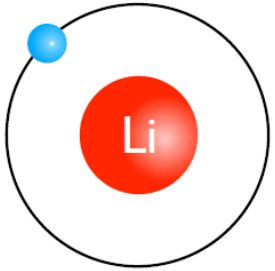
Quantum Gas Mixtures with Unequal Mass

Ytterbium (Yb) : heaviest



- Alkaline-earth-like atom (metastable ^3P states)
- Rich stable isotopes: 5 bosons (I = 0), 2 fermions (^{171}Yb, I = 1/2 ^{173}Yb, I=5/2)
- Atomic mass 173, 174 → heavy

Lithium (Li) : light

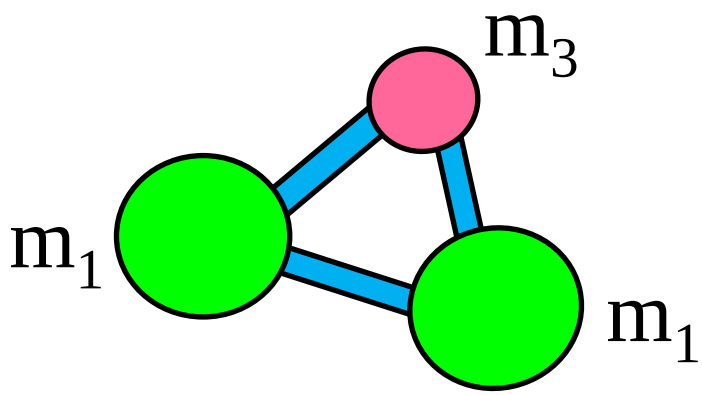


- Alkali atom
- Two stable isotopes: 1 boson (^{7}Li, I = 3/2), 1 fermion (^{6}Li, I = 1)
- Atomic mass 6 → light

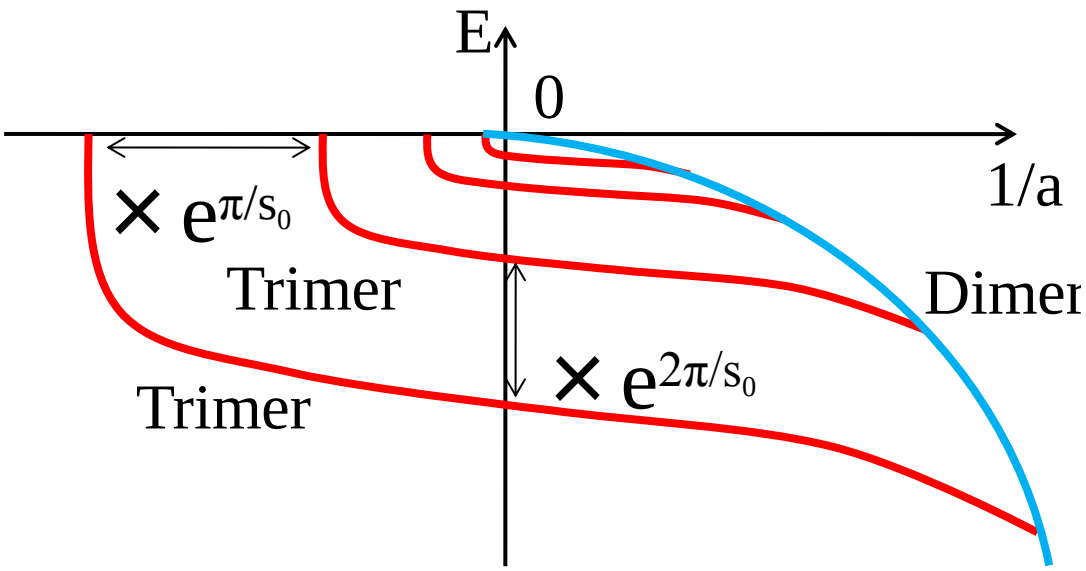
$$\frac{M_{Yb}}{M_{Li}} \simeq 29$$

→ Efimov Trimer
Bose/Fermi Polaron
Boson-mediated Superfluidity,
Anderson Orthogonality Catastrophe, …

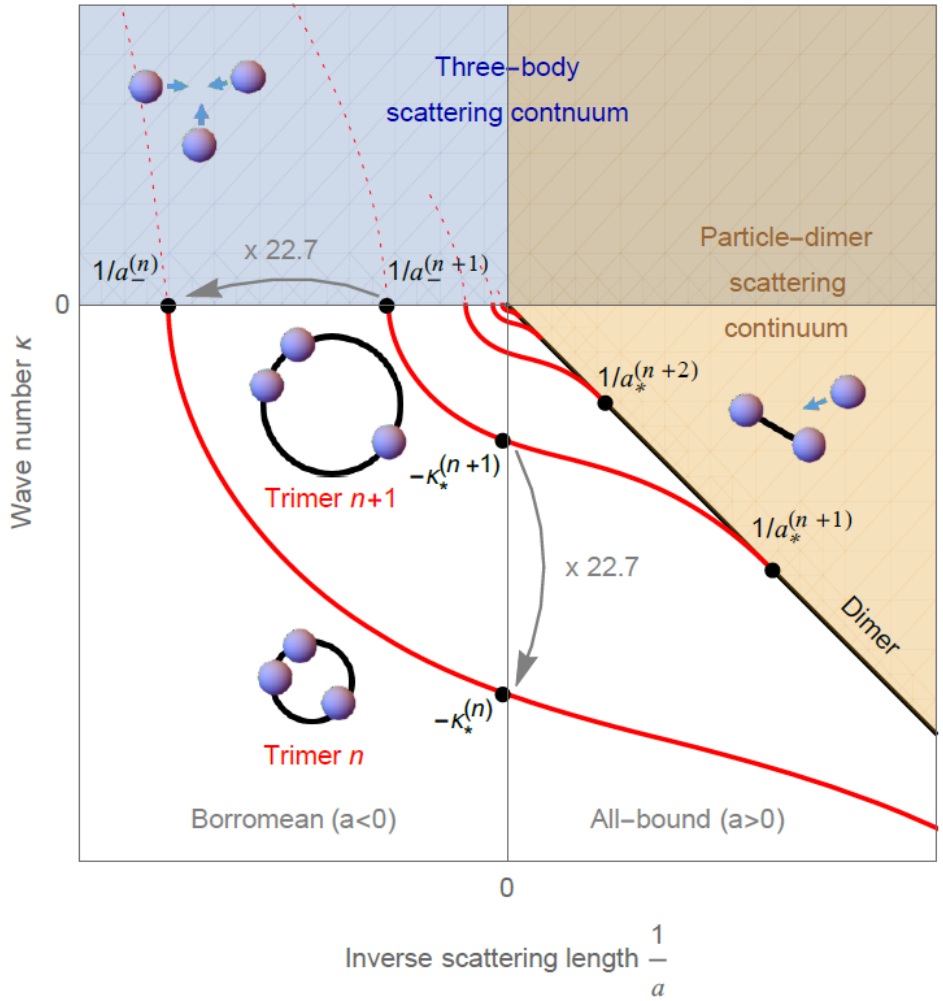
Efimov Trimer



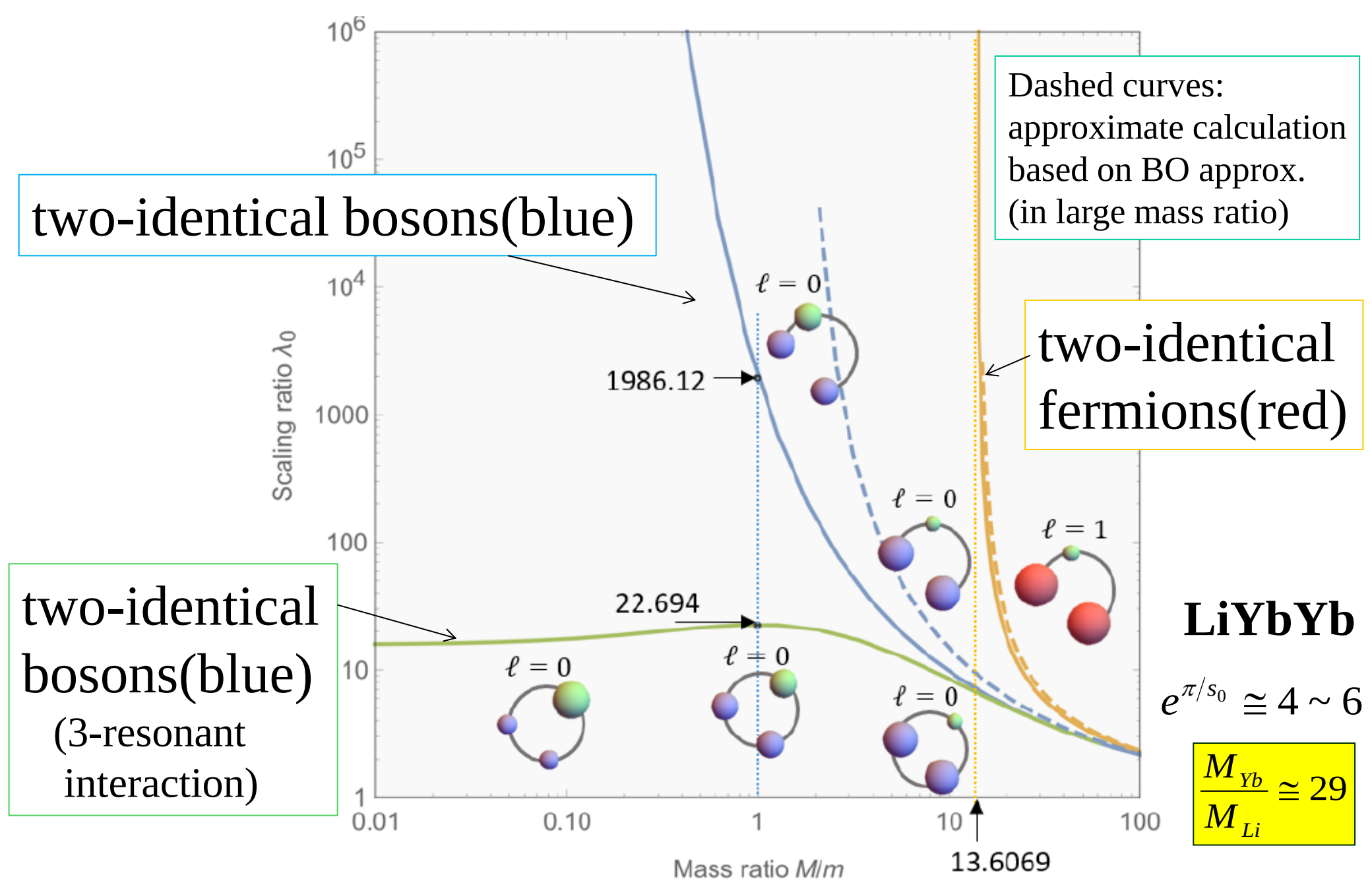
[Amado and Noble, Efimov, Ovchinnikov and Sigal]



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



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

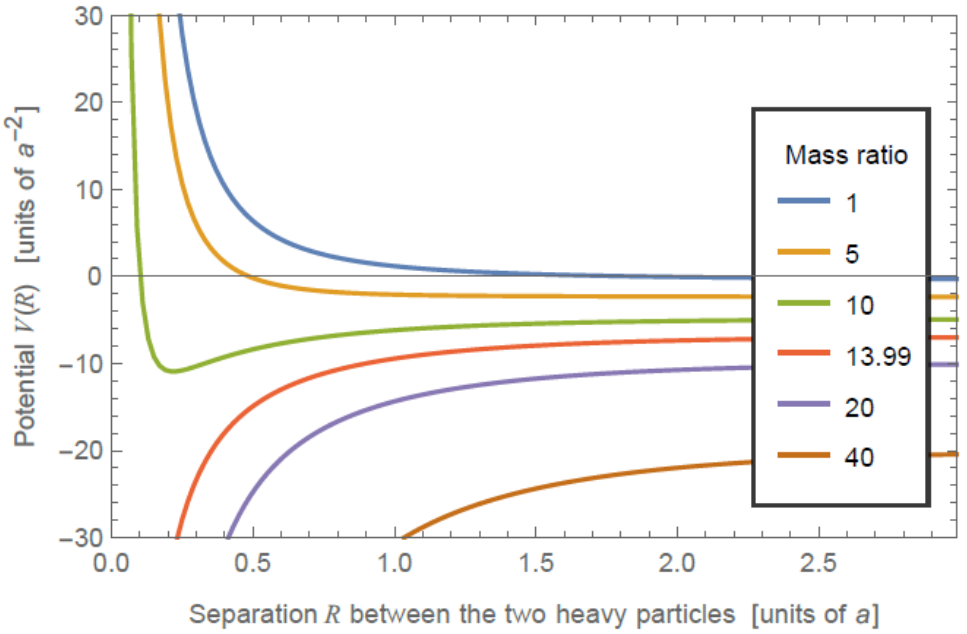


[P. Naidon and S. Endo, Rep. Prog. Phys. 80, 056001(2017)]

Large mass ratio

2 heavy identical fermions
and
1 light particle

effective potential between 2 identical fermions



- (Mixed) dimensionality
  mass ratio, quantum statistics
- More than three particles
  mass-imbalanced Fermi mixtures
- Effect of many-body background (BEC, Fermi sea)

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

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”

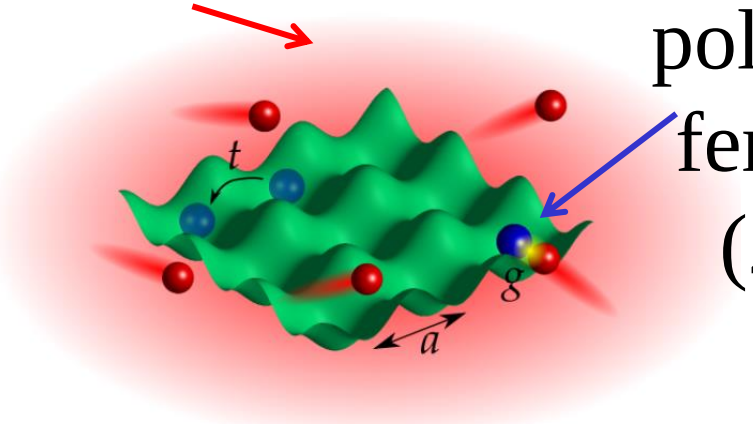
$$V_{\rm ind}(i,j) = -g^2 \frac{n_0 m_B}{\pi} \frac{e^{-\sqrt{2}|\mathbf{r}_i - \mathbf{r}_j|/\xi_{\rm B}}}{|\mathbf{r}_i - \mathbf{r}_j|}$$

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

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

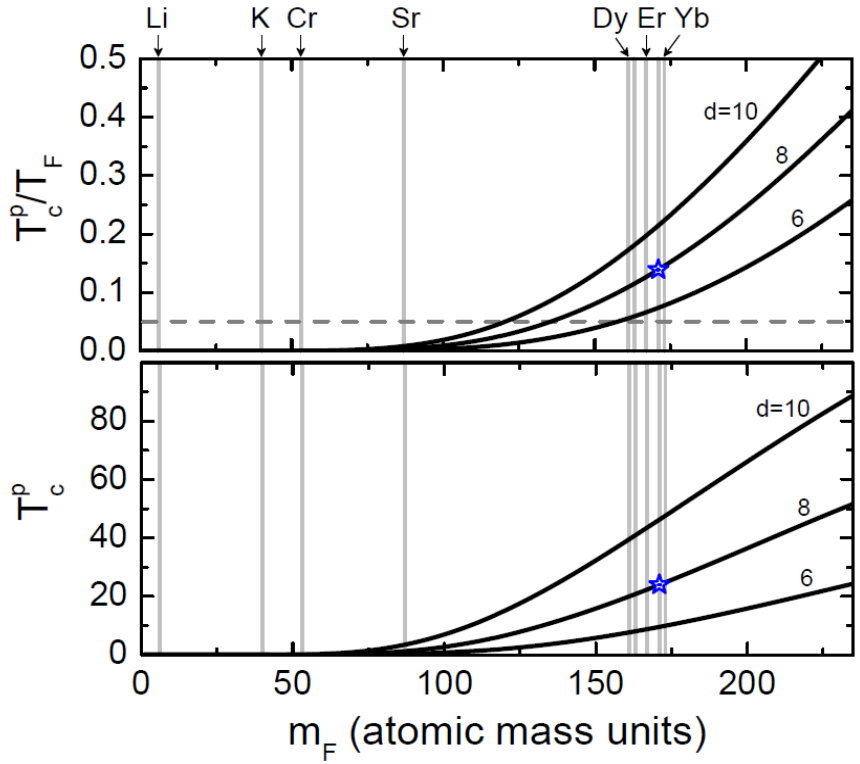
^{7}Li

boson (3D)



polarized fermion (2D)

candidate of fermions



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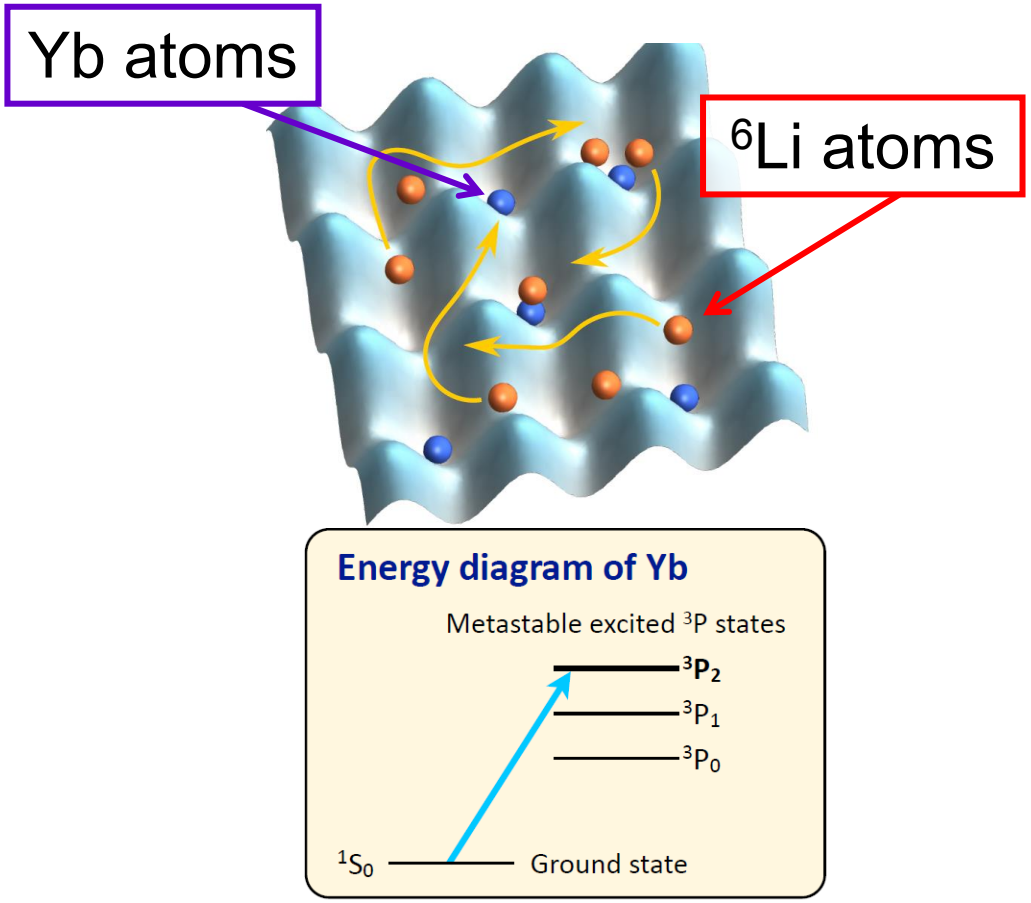
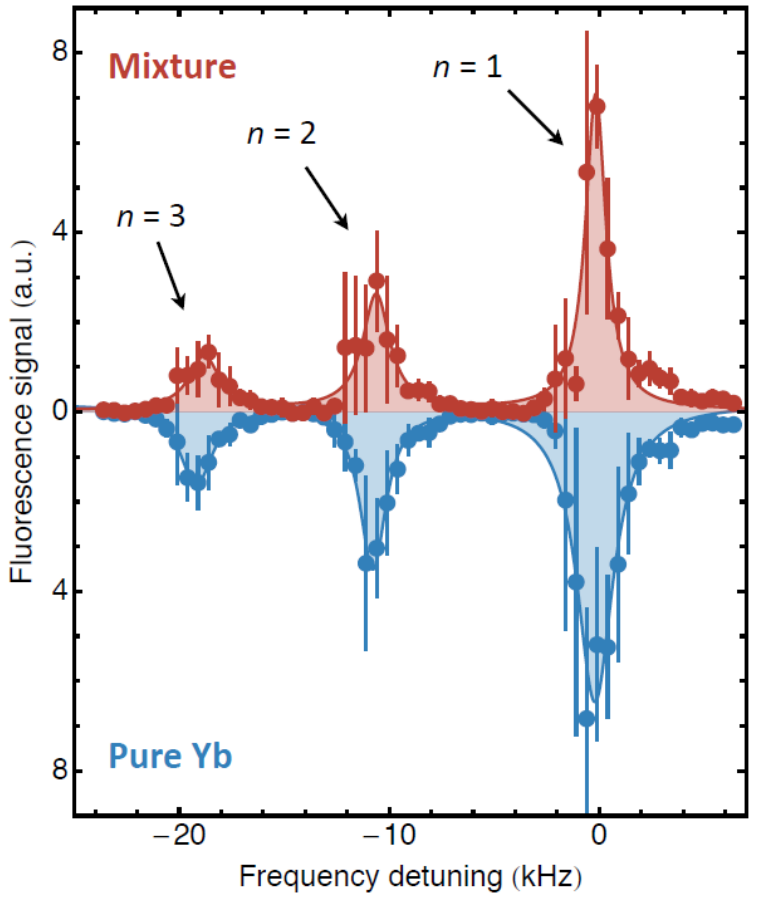
Successful Creation of Quantum Gas Mixture of Yb atoms immersed in a Fermi sea of ^{6}Li





[H. Hara *et al.* ,PRL **106**, 205304, (2011)]

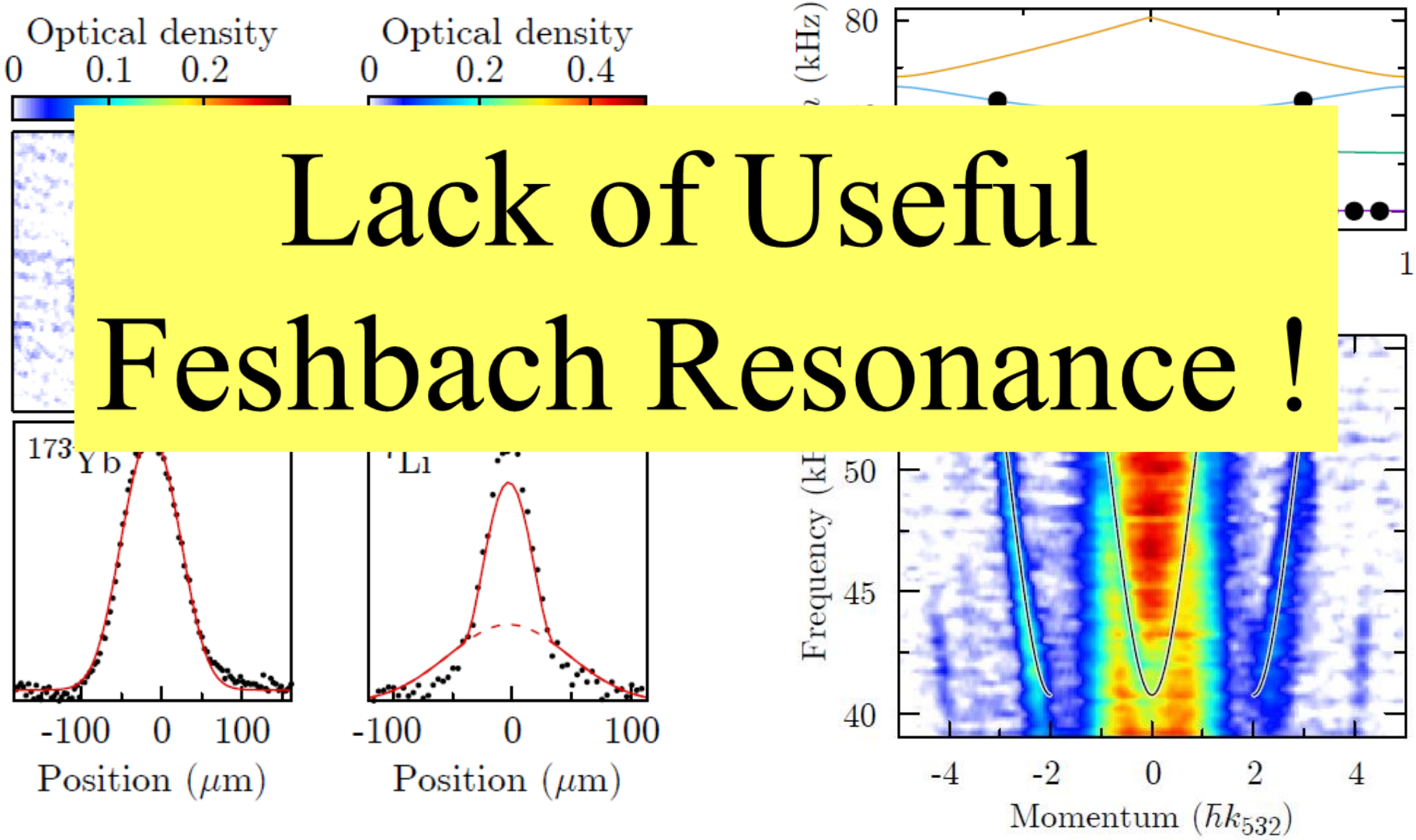
[H. Konishi *et al*, *New J. Phys*. **19** 103039 (2017)]

[F. Schäfer *et al*, *New J. Phys*. **19** 103039 (2017), **Highlights 2017**]

[F. Schäfer et al, Phys. Rev. A **96**, 032711 (2017)]

Experimental realization of ultracold Yb-^{7}Li mixtures in mixed dimensions

[F. Schäfer et al, Phys. Rev. A, Rapid Communication (2018) in press, **Editors' Suggestion**]

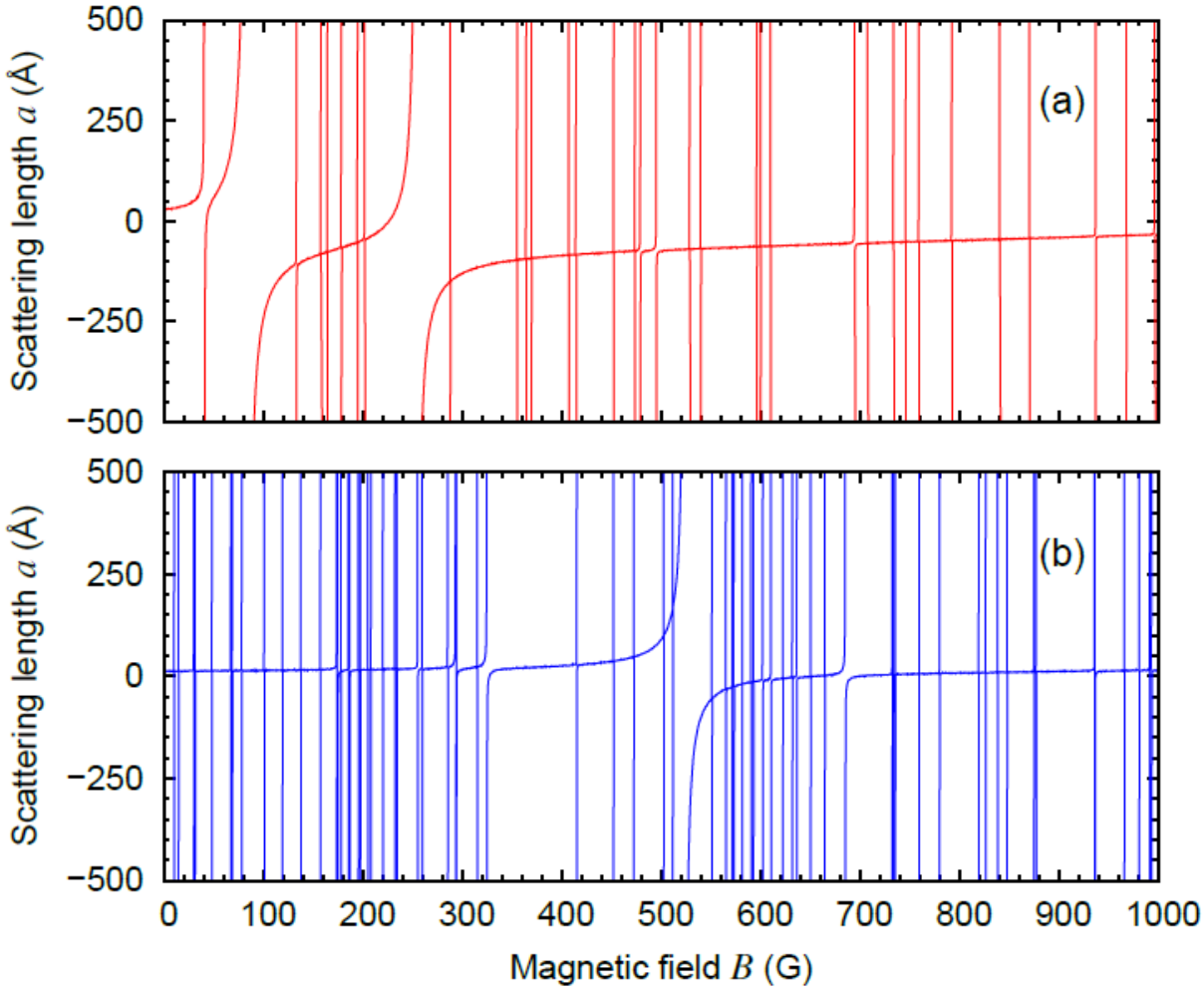


Magnetically tunable Feshbach resonances in **Li+Er**

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

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

^{166}Er(b) +^{7}Li(b)



K. Aikawa (Er cooling experiment)

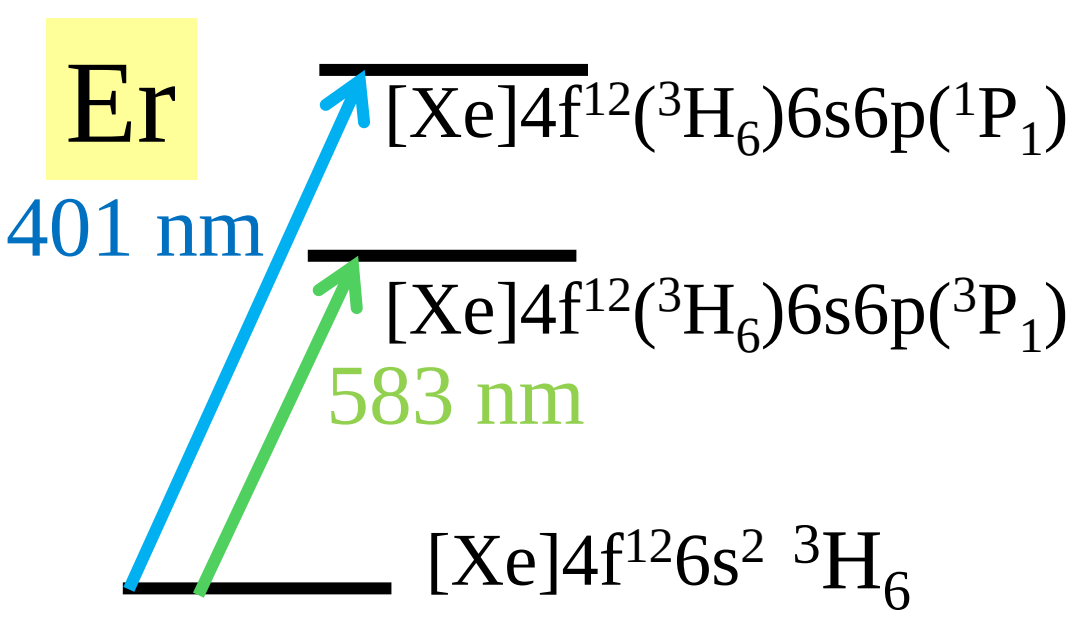
J. Hutson (Er Feshbach resonance calculation)

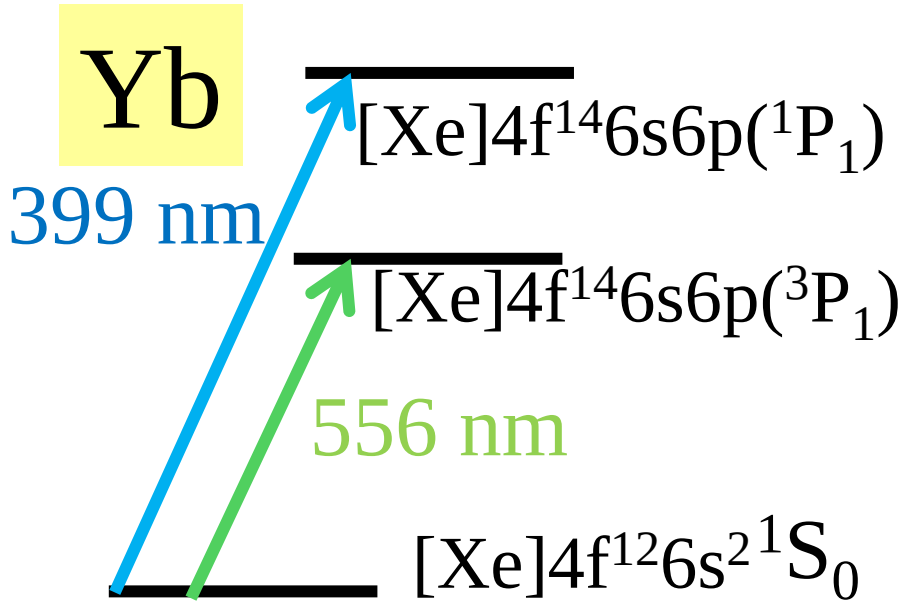
Er: $[Xe]4f^{12}6s^2$ (Yb: $[Xe]4f^{14}6s^2$)

mass m [amu]	abundance [%]	nuclear spin I	statistic
162	0.1	0	boson
164	1.6	0	boson
166	33.5	0	boson
167	22.9	7/2	fermion
168	27.0	0	boson
170	14.9	0	boson

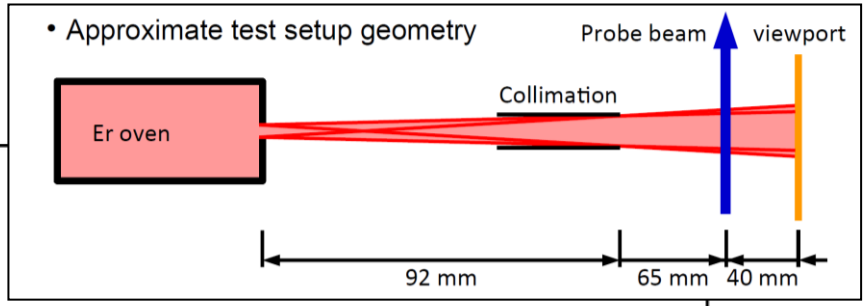
from
J. Schindler

M(Er)/m(Li)= 23.14 ~ 28.3





Fluorescence spectroscopy results

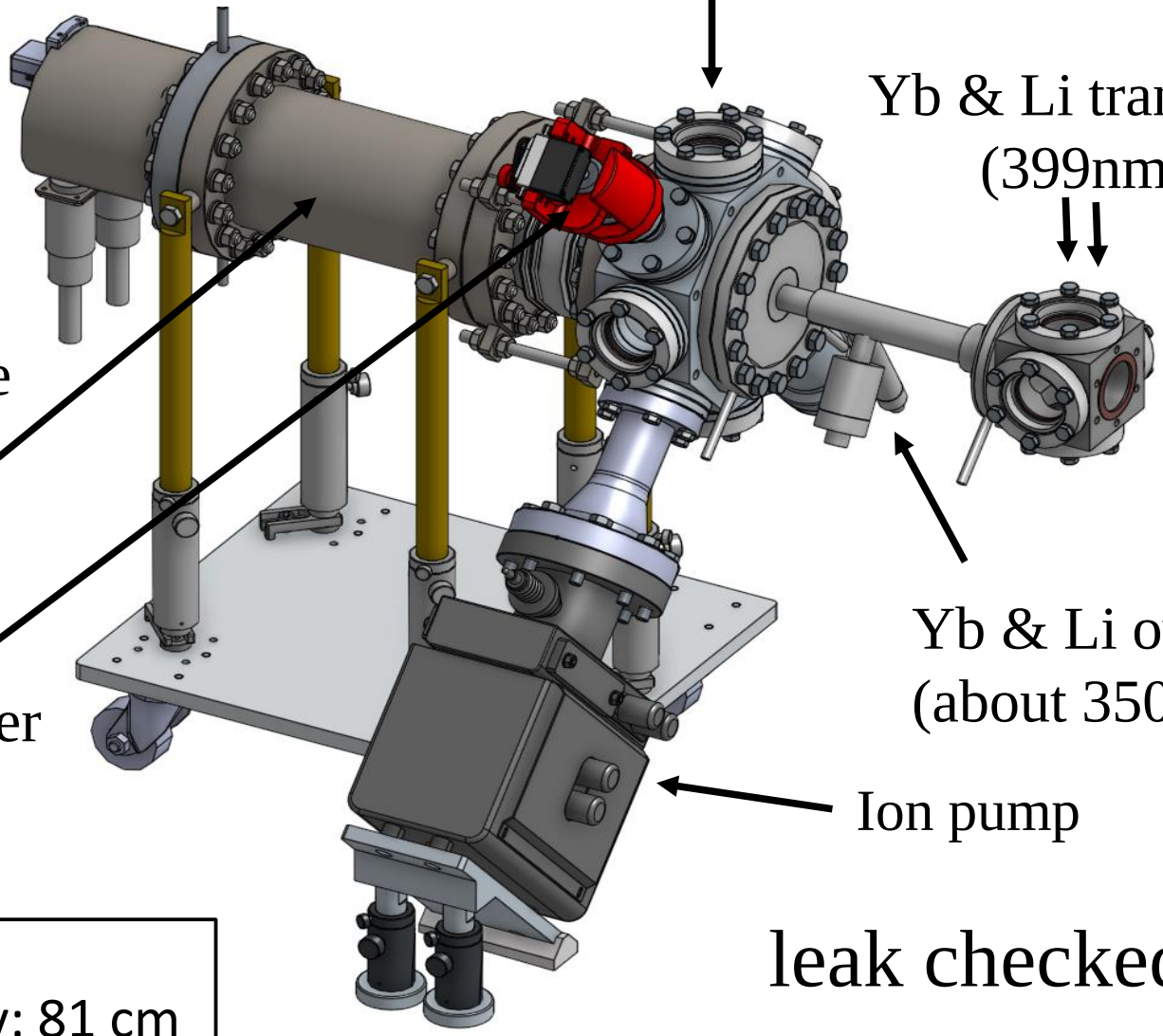


Innsbruck
1144°C
1106°C
1073°C

^{166}Er
^{168}Er
^{170}Er
fermion:
^{167}Er
^{164}Er

Intensity (arb.u.)
0.0
0.5
1.0
1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
Frequency (GHz)

Er-Li-Yb Oven



Er transverse cooling (401nm)

Yb & Li transverse cooling
(399nm & 671nm)

High-temperature
Ta crucible oven
(about 1100°C)

to experiment

Yb & Li oven
(about 350 °C)

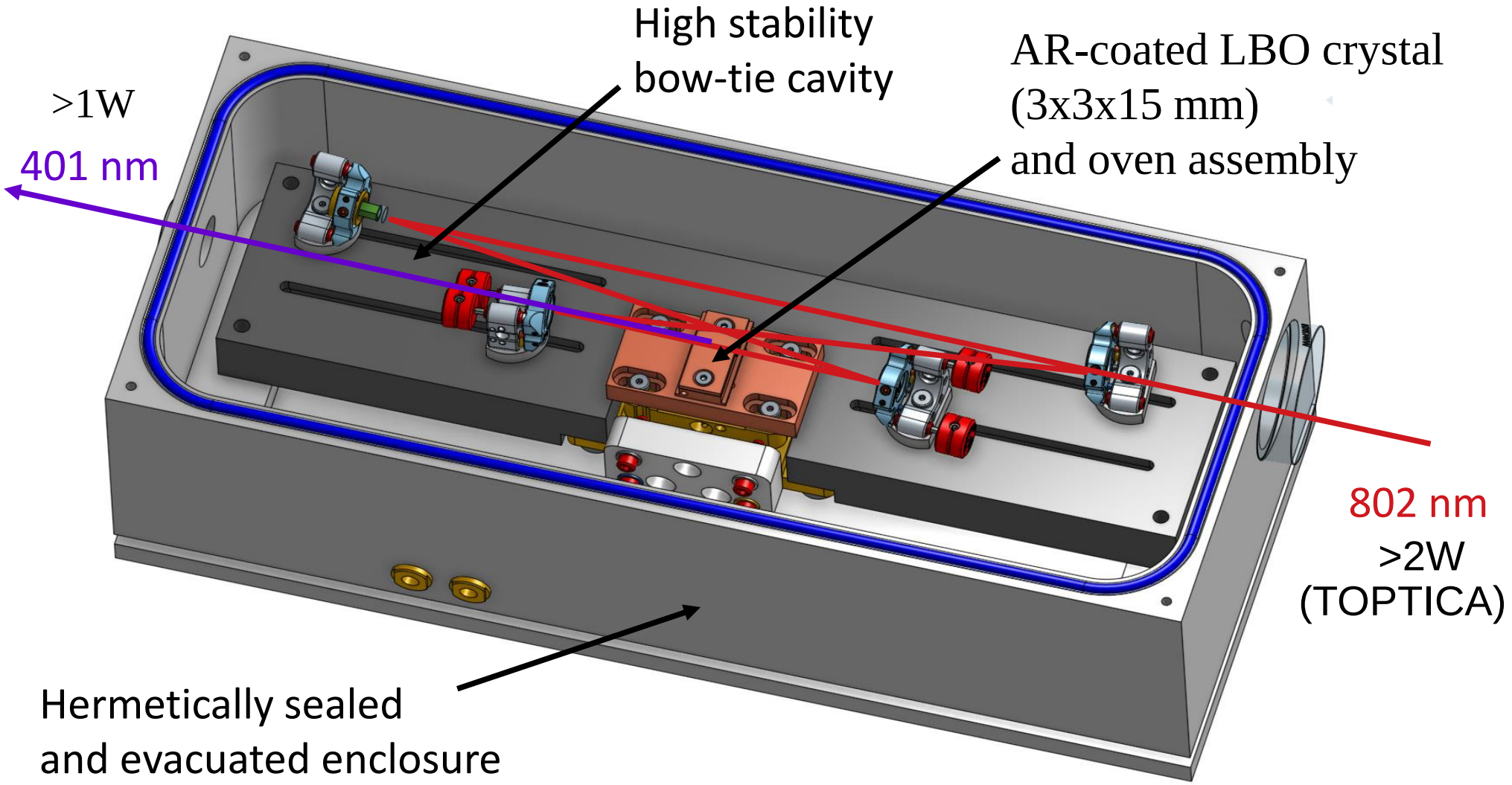
Linear shift shutter
for Er beam

Ion pump

total length of
oven assembly: 81 cm

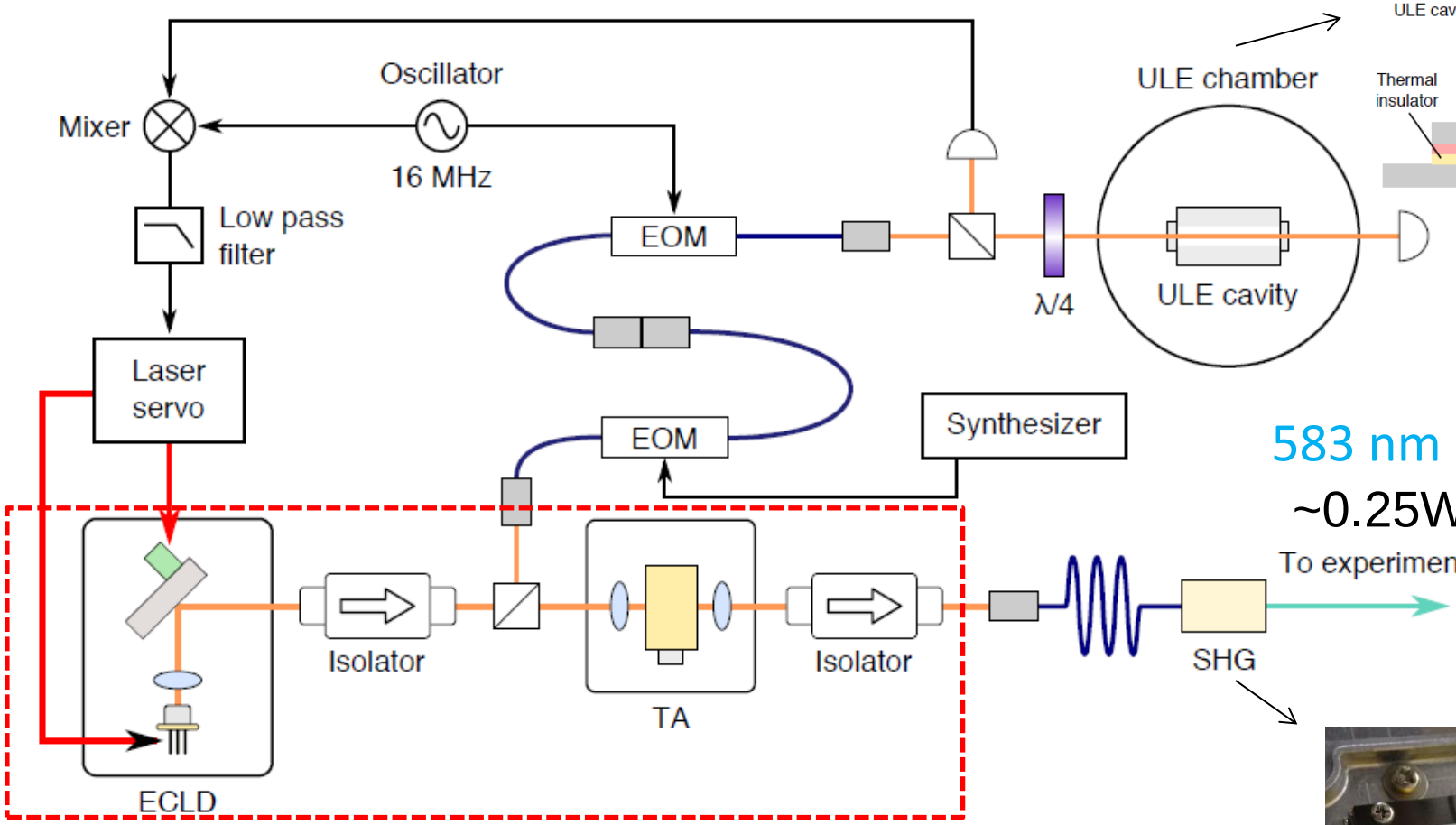
leak checked
temperature checked

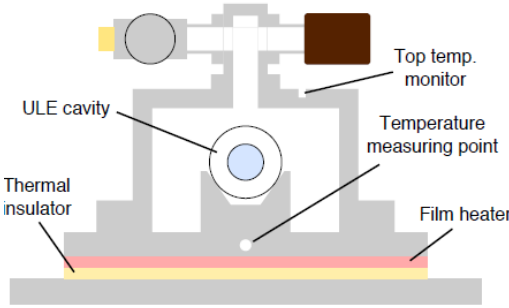
401 nm Light for Er cooling



Ref. Pizzocaro *et al.*, Appl. Opt. 53, 3388 (2014)

583 nm Light for Er cooling





$\Delta f < 100\ kHz$

Waveguide PPLN (NEL)

Conversion >100 %/W

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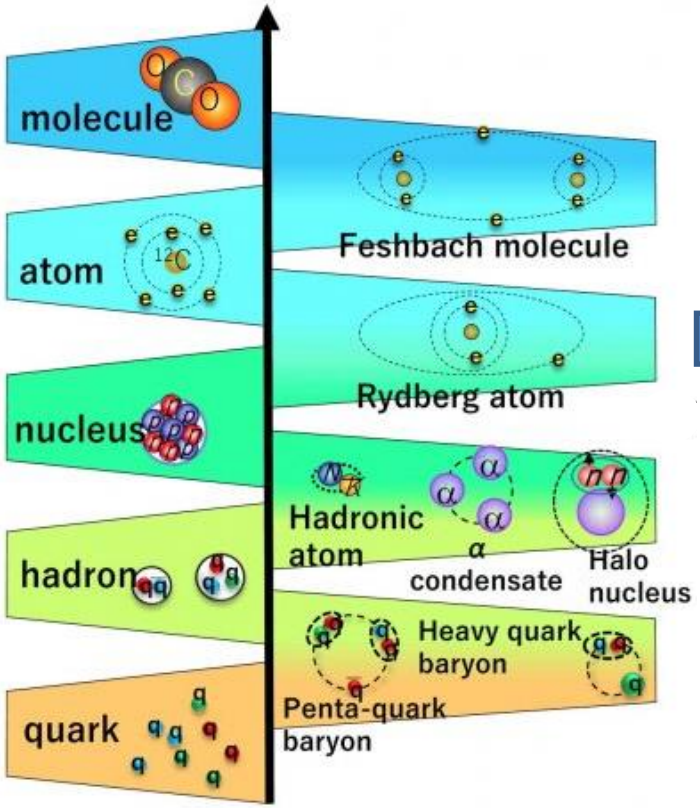
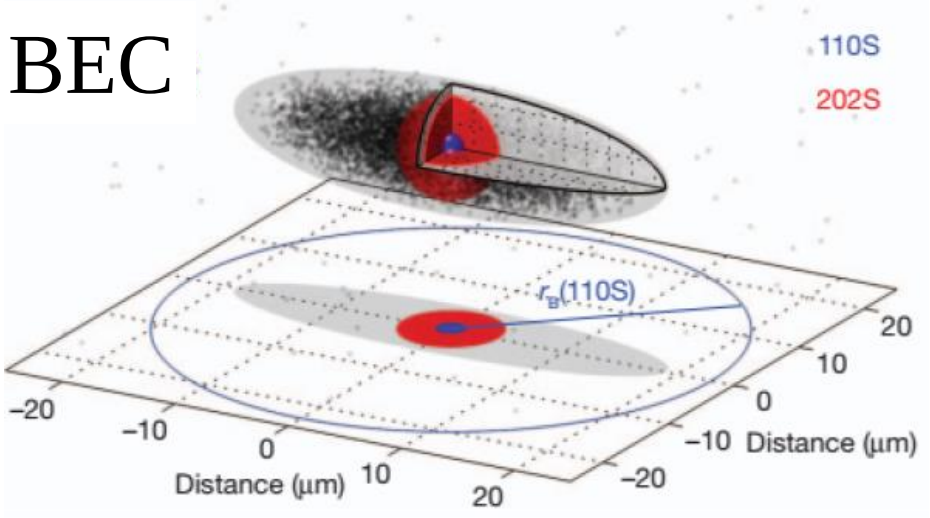
Yb(-Li) Rydberg Excitation

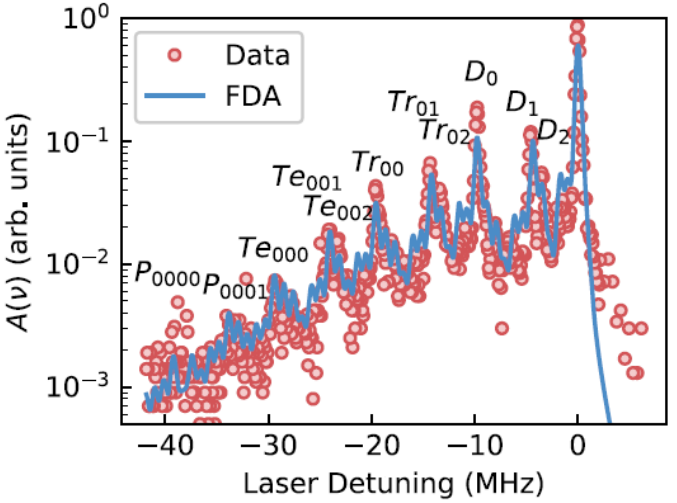


Rb BEC



J. Balewski *et al.*, Nature 502, 664 (2013)

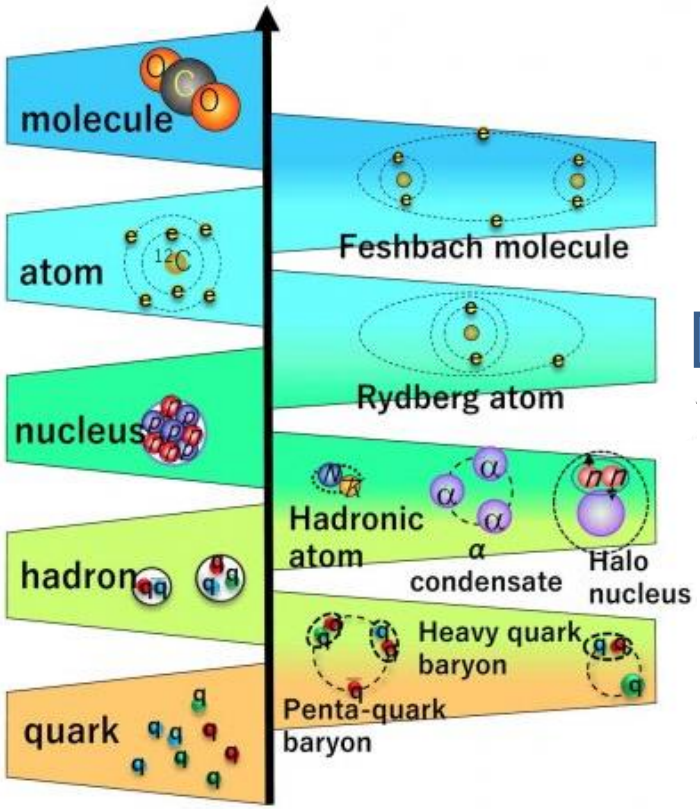
Sr BEC:
Rydberg Polaron
& molecules



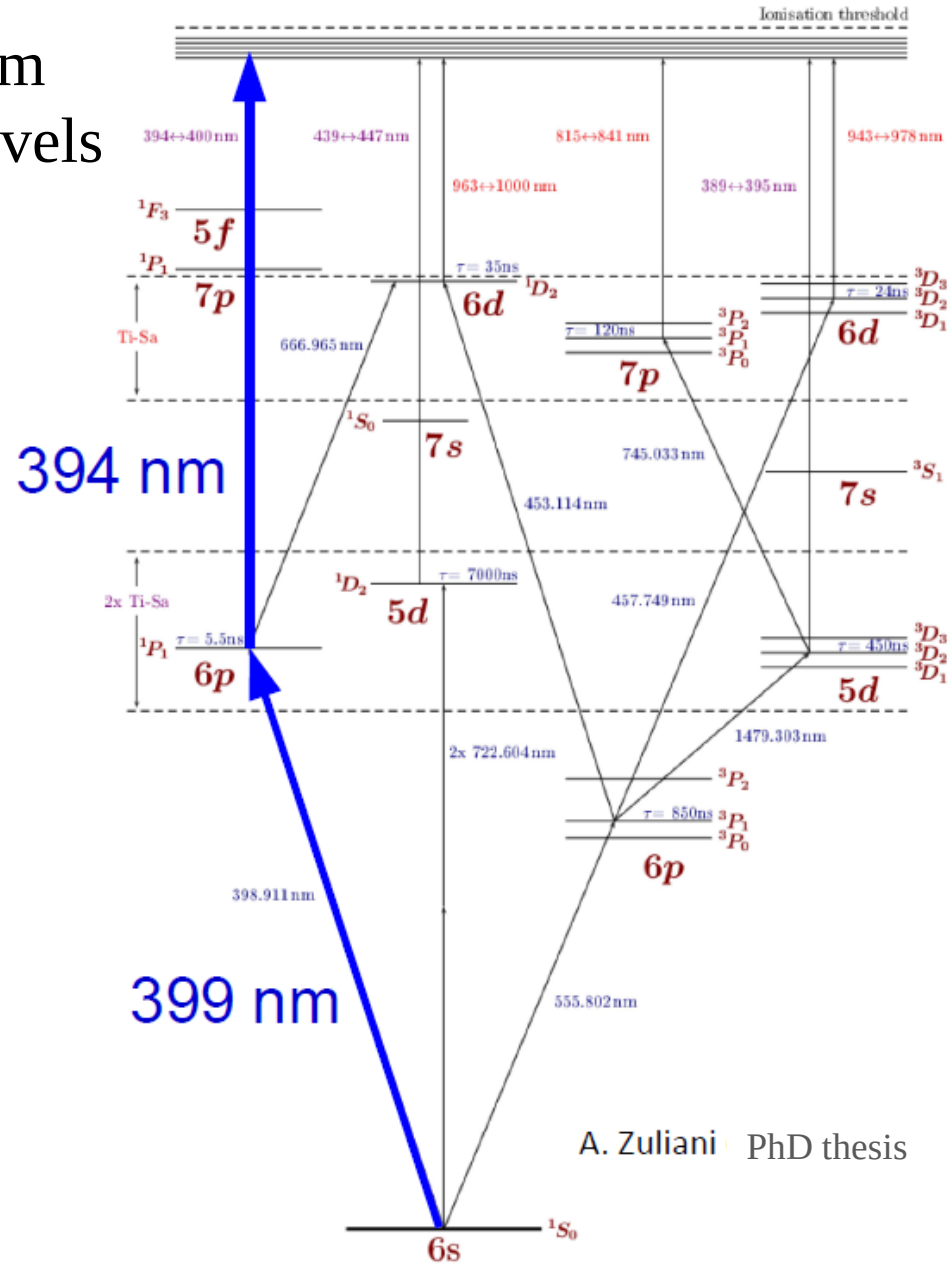
[F. Camargo *et al*, PRL(2018)]

Yb-Li system: H. Sadeghpour (Harvard)

Yb(-Li) Rydberg Excitation

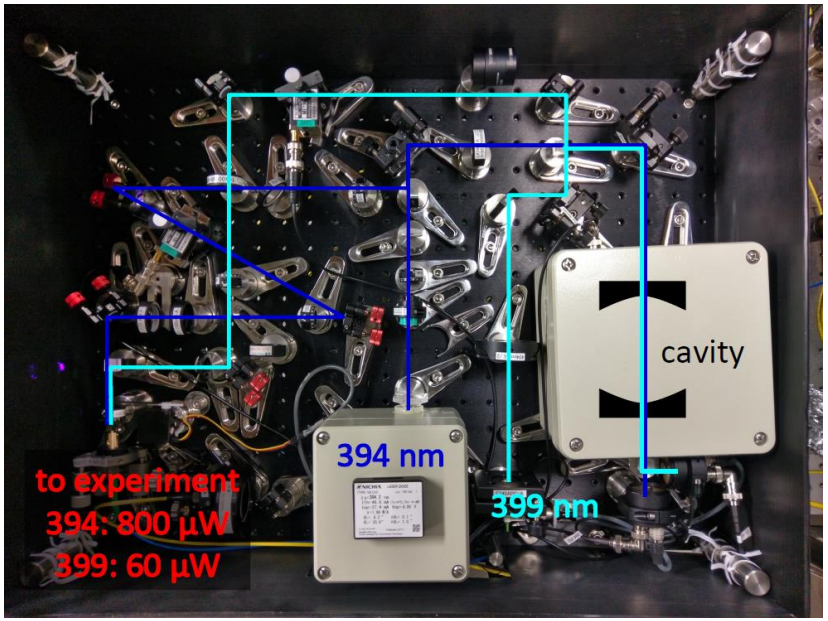


Yb atom
energy levels

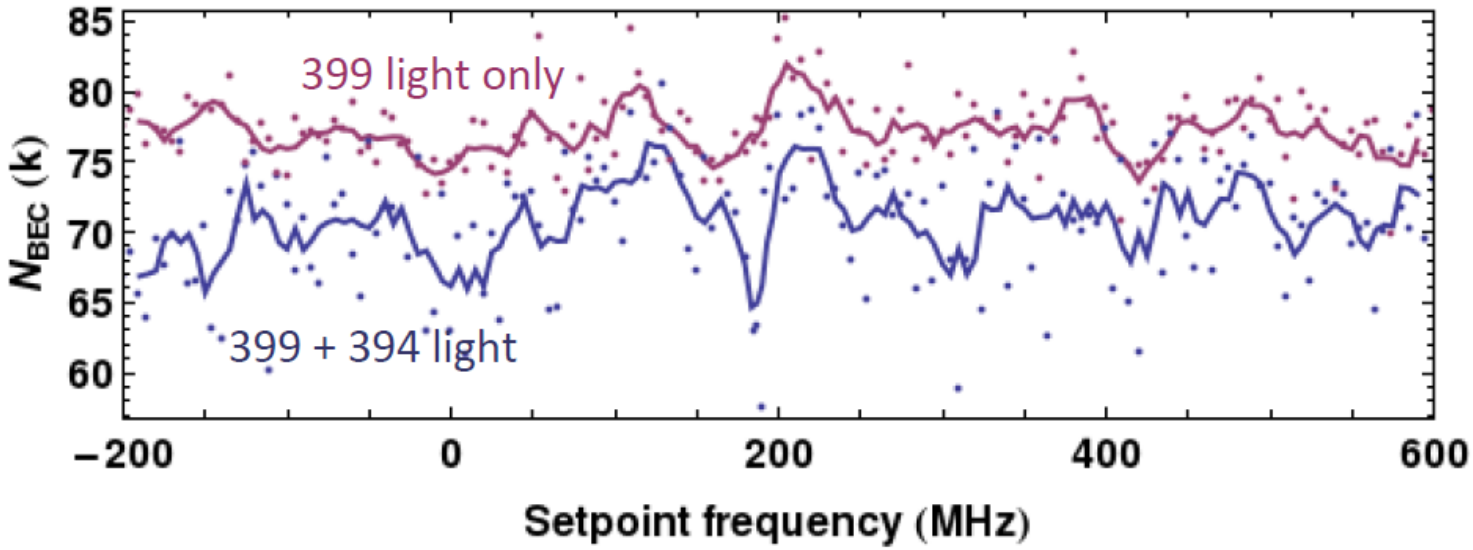


Yb(-Li) Rydberg Excitation

laser systems
(399 nm & 394 nm)

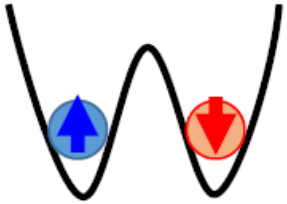


measurement
result



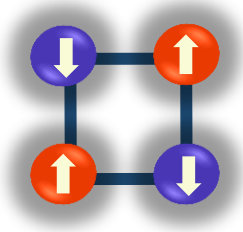
SU(4) singlet: 4-body entangled state

SU(2) in dimer

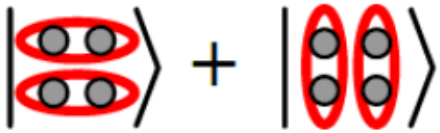


$$|S_{SU(2)}(\sigma_1\sigma_2)\rangle = |\sigma_1,\sigma_2\rangle - |\sigma_2,\sigma_1\rangle$$

SU(2) in plaquette

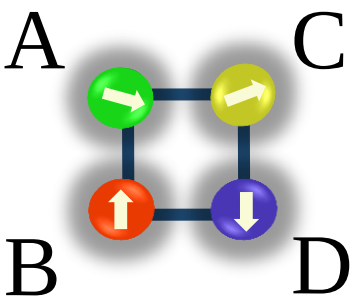


$$|s-\mathrm{RVB}\rangle =$$



SU(4) in plaquette

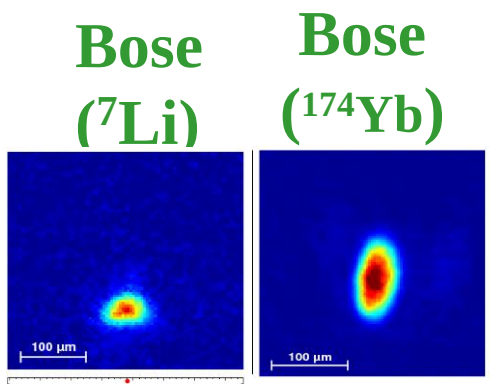
$$|S_{\mathrm{SU}(4)}\rangle = \frac{1}{\sqrt{6}} \sum_{\{\sigma,\tau\}} |S^{AB}_{\mathrm{SU2}}(\sigma\tau), S^{CD}_{\mathrm{SU2}}(\overline{\sigma\tau})\rangle$$



Summary

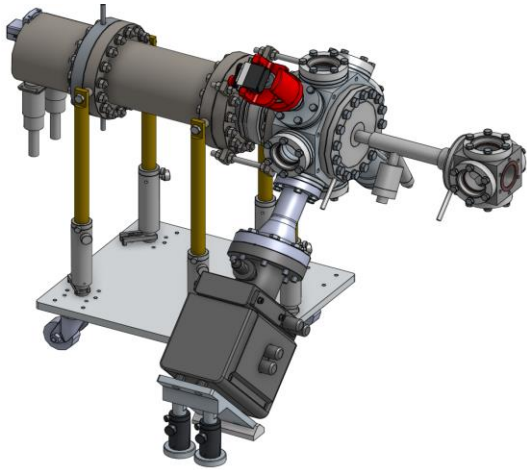
1. Quantum Gas Mixture with Unequal Mass

   various YbLi quantum gas mixtures
   (b-b, f-f, b-f, f-b) in mixed dimensions



2. Prospects for Er-Li Quantum Gas Mixture

   construction of Er-Li(-Yb) oven
   design of light sources



3. Other possibilities

   Yb(-Li) Rydberg excitation
   realization of SU(4) singlet