NTHU, Taiwan, Feb. 7, 2025

Measurement of the Variation of Electron-to-Proton Mass Ratio Using Ultracold Molecules Produced from Laser-Cooled Atoms

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Univeristy

Osaka
Metropolitan
University

Outline

- Introduction
- Feshbach resonance
- Ultracold molecules
- Efimov state
- Outlook

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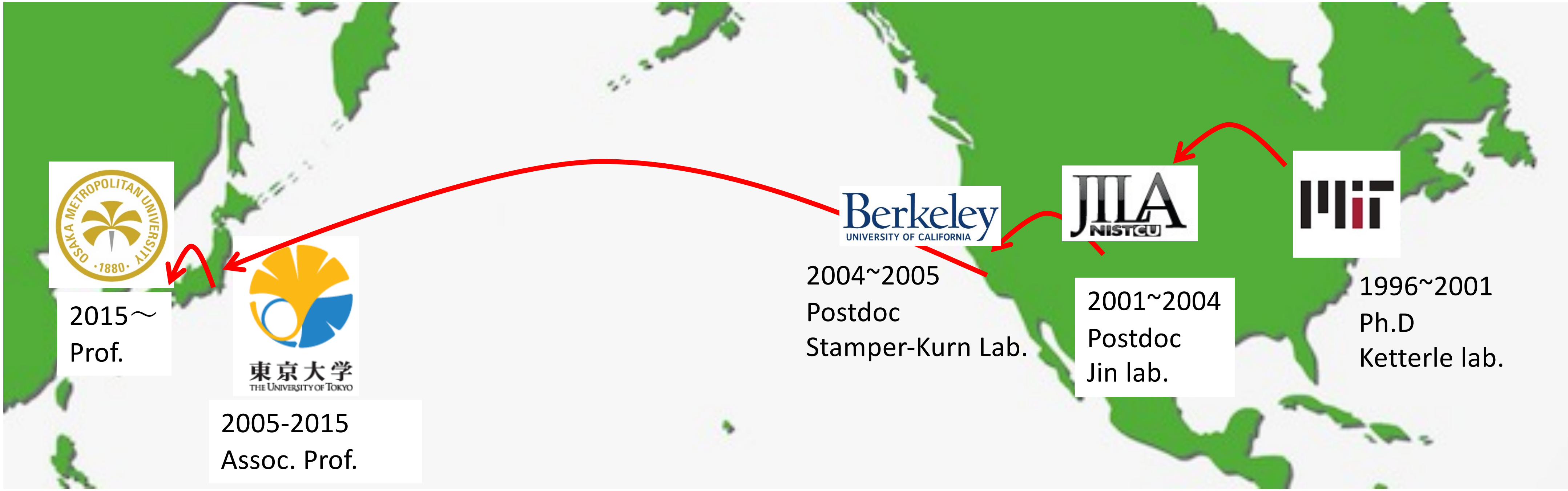
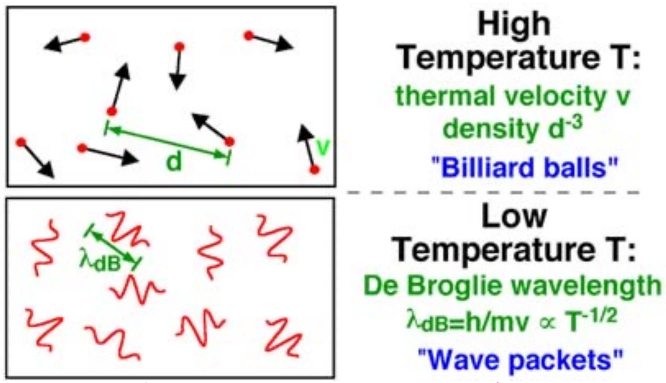
My "move"

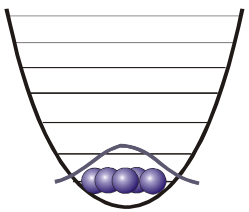

2015～
Prof.
2005-2015
Assoc. Prof.
2004~2005
Postdoc
Stamper-Kurn Lab.
2001~2004
Postdoc
Jin lab.
1996~2001
Ph.D
Ketterle lab.

What is ultracold quantum gas?



Further lower temperature

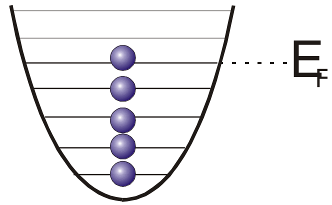
Bosons



BEC

phase transition at T_C

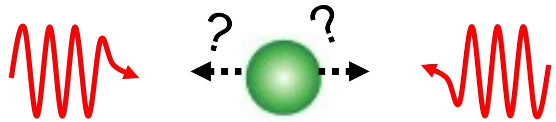
Fermions

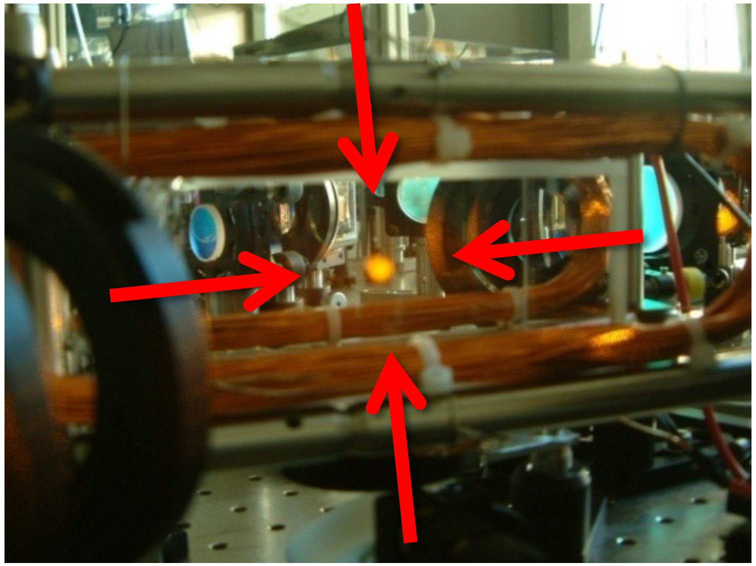


Fermi sea of atoms

gradually emerges for $T<T_F$

Laser cooling !



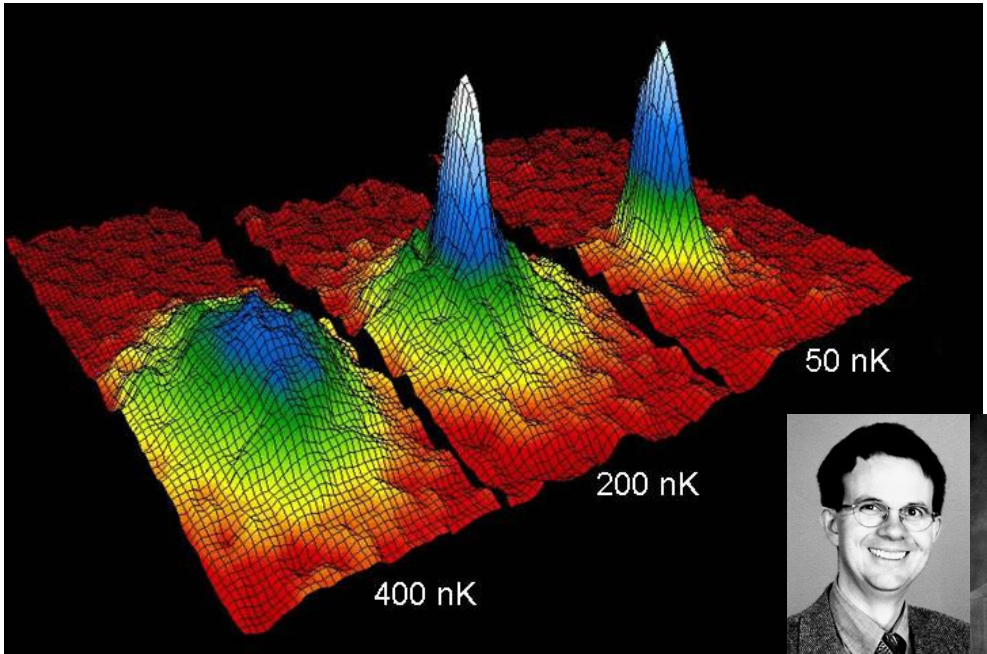


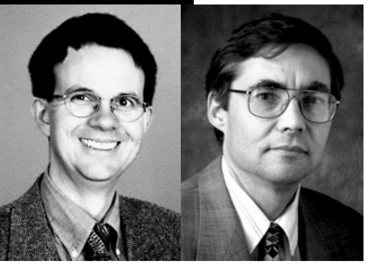
10^{-6}

300 K → 300 μK

Further bringing down the temperature
by another factor of 10^{-3}...

Bose-Einstein Condensate!





$$i\hbar \frac{\partial \Psi(\vec{r},t)}{\partial t} = \left[-\frac{\hbar^2}{2m}\nabla^2 + V_{ext}(\vec{r}) + \frac{4\pi\hbar^2 \boldsymbol{a}}{m} |\Psi(\vec{r},t)|^2 \right] \Psi(\vec{r},t)$$

Anderson et al.,
Science,
269 198 (1995)

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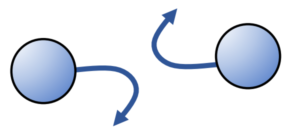
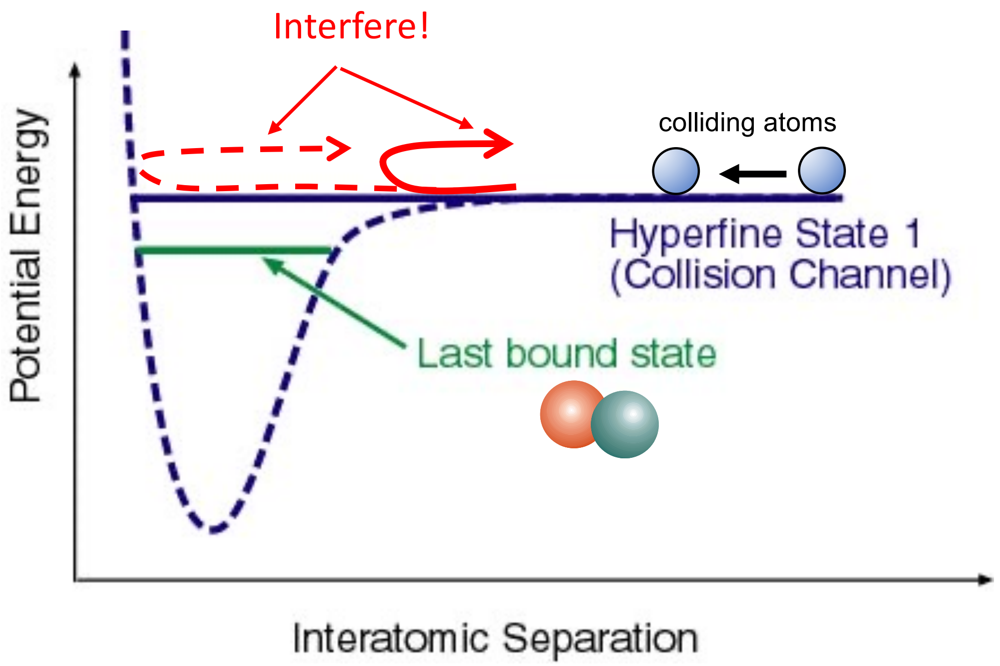
What is the scattering length a ?

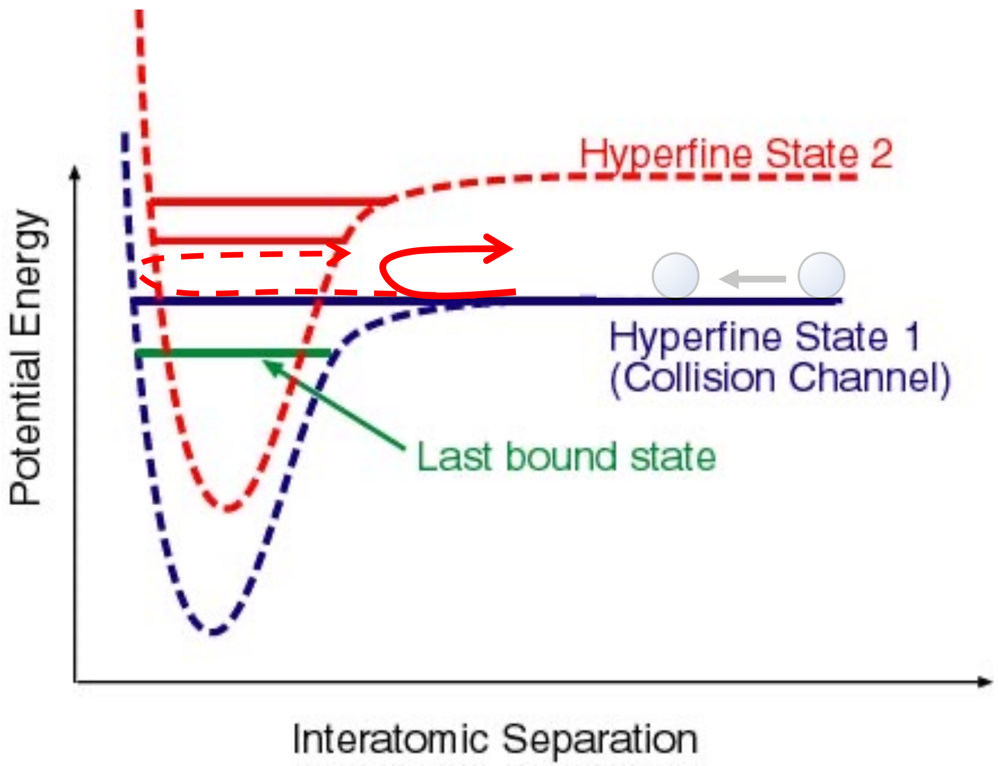


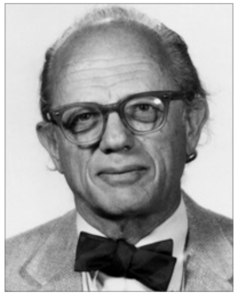
The "a" characterises the two-body collision.

$$\left(-\frac{\hbar^2}{2\mu}\left(\frac{\partial^2}{\partial r^2}+\frac{2}{r}\frac{\partial}{\partial r}\right)+\frac{\hat{L}^2}{2\mu r^2}+U(r)\right)\psi(\vec{r})=E\psi(\vec{r}) \qquad \psi(\vec{r})=\exp(ikz)+\frac{f(\theta)}{r}\exp(ikr) \qquad f(\theta)\rightarrow -a$$



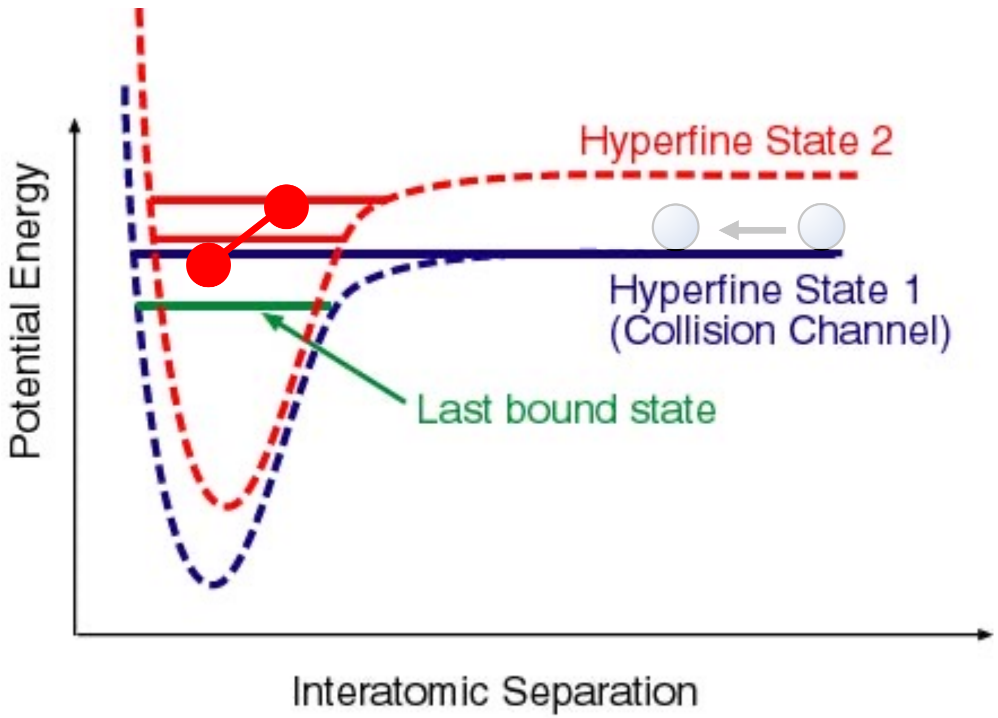
What will happen if there are other internal states?

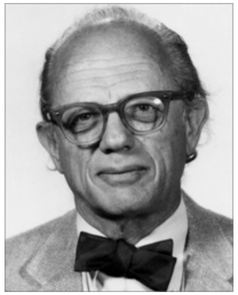




H. Feshbach

What will happen if there are other internal states?

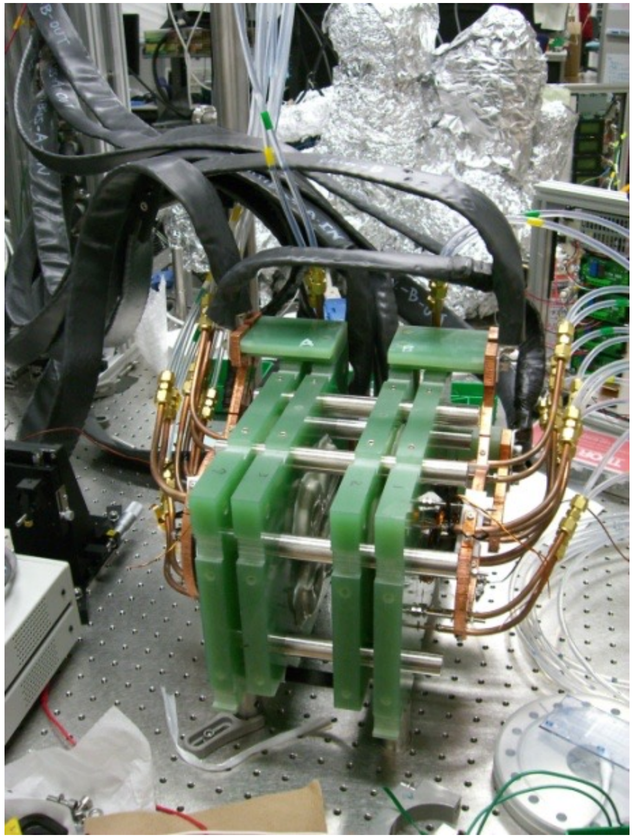




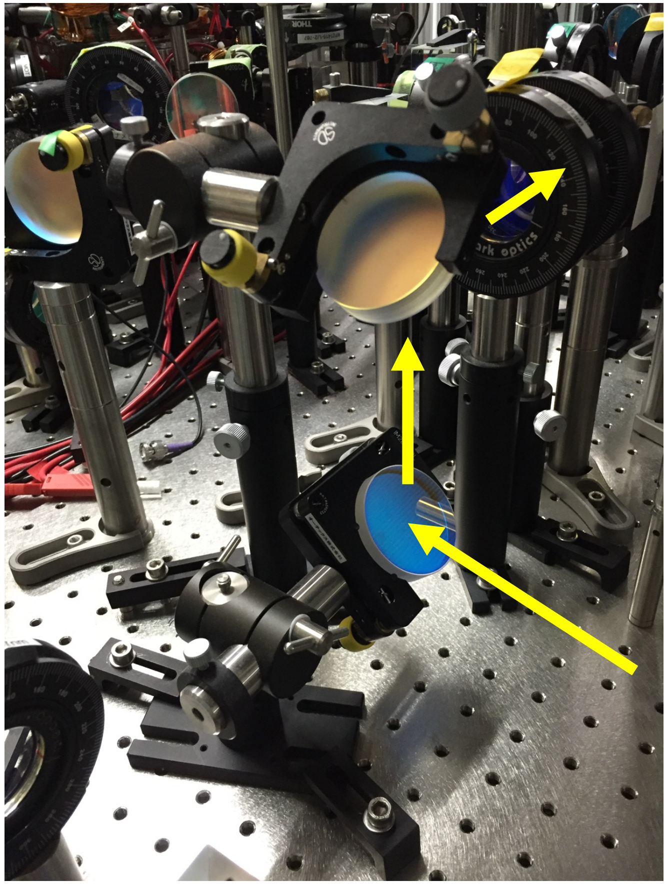
H. Feshbach

→ We can use the bias magnetic field to shift the hyperfine state 2!

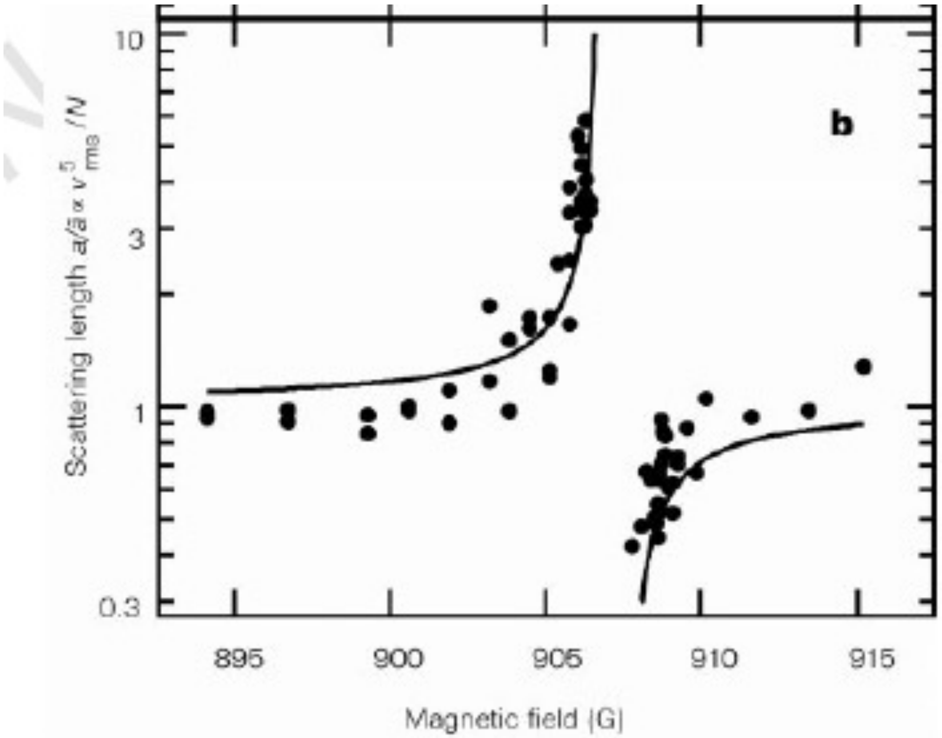
Technical problem: magnetic field was used for confinement



Optical trap was developed to make magnetic field "free"

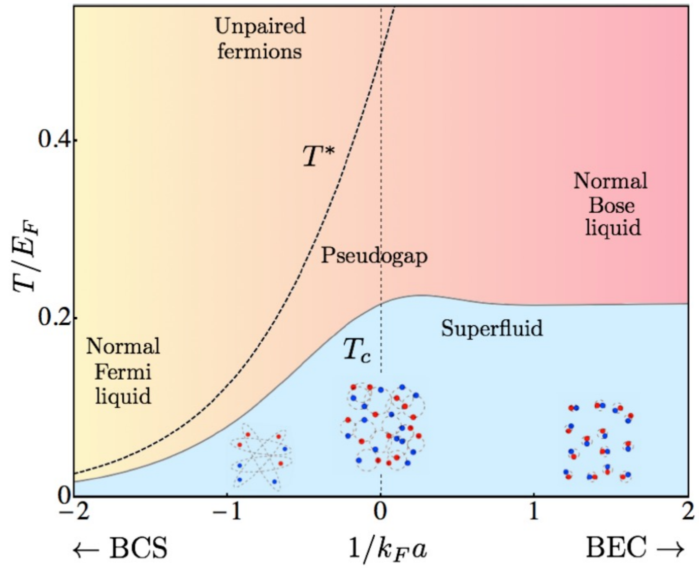


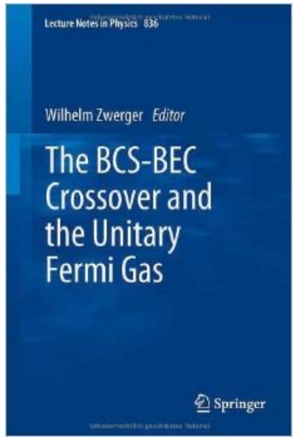
First observation of Feshbach resonance



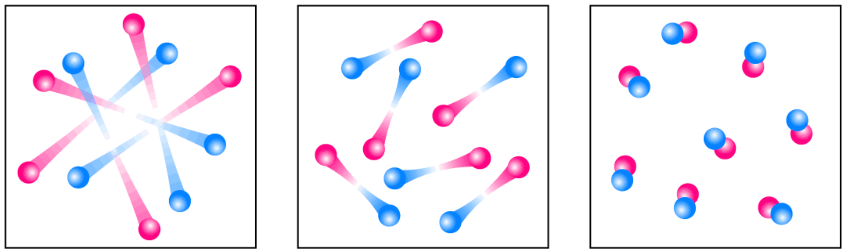
"Observation of Feshbach resonances in a Bose-Einstein condensate."
SI *et al.*, Nature **392**, 151 (1998).

BCS-BEC crossover was realized using Fermionic atoms!





W. Zwerger (Editor)



BCS ←

→ BEC

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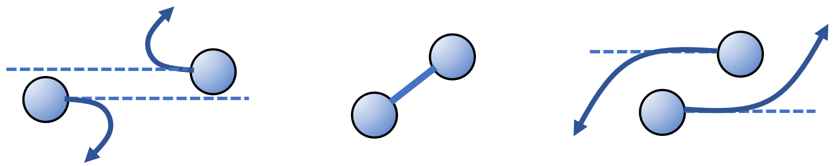
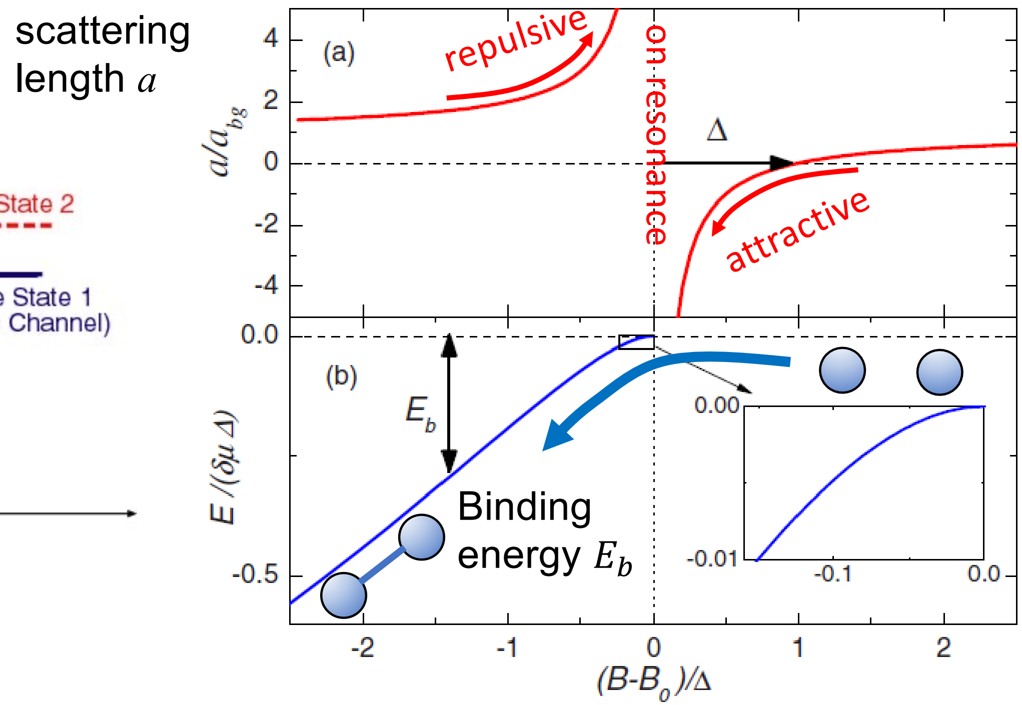
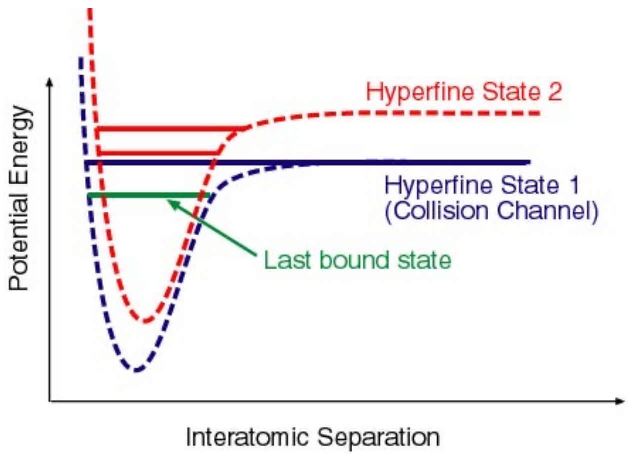
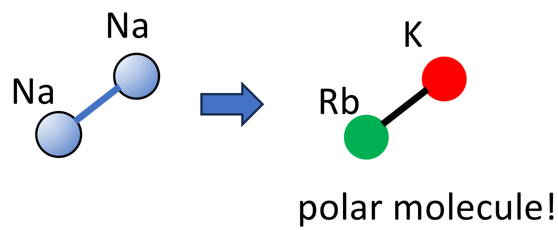
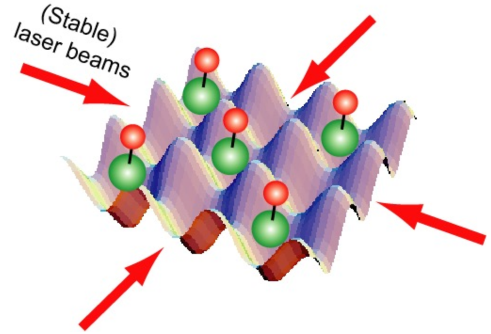
Feshbach resonance and molecules





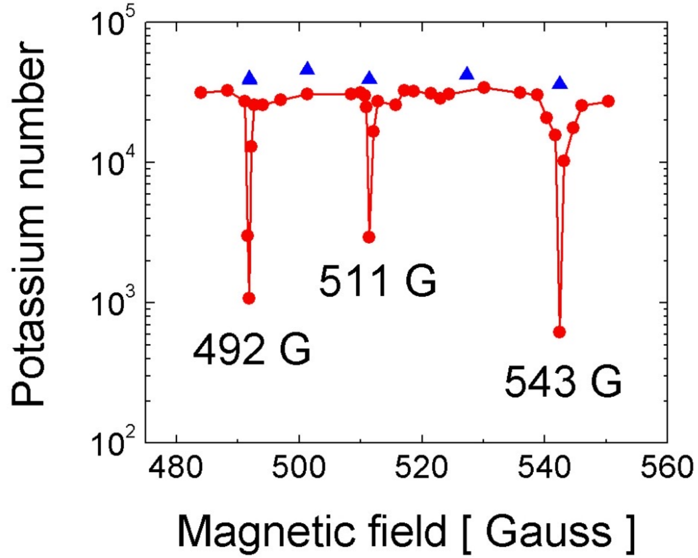


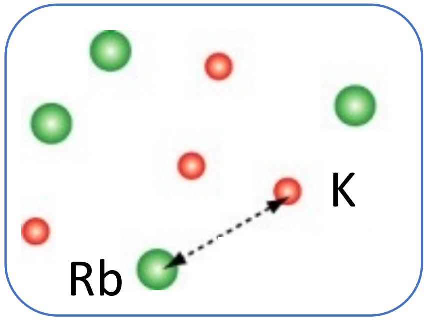




Review of Modern
Physics, 82, 1225 (2010)

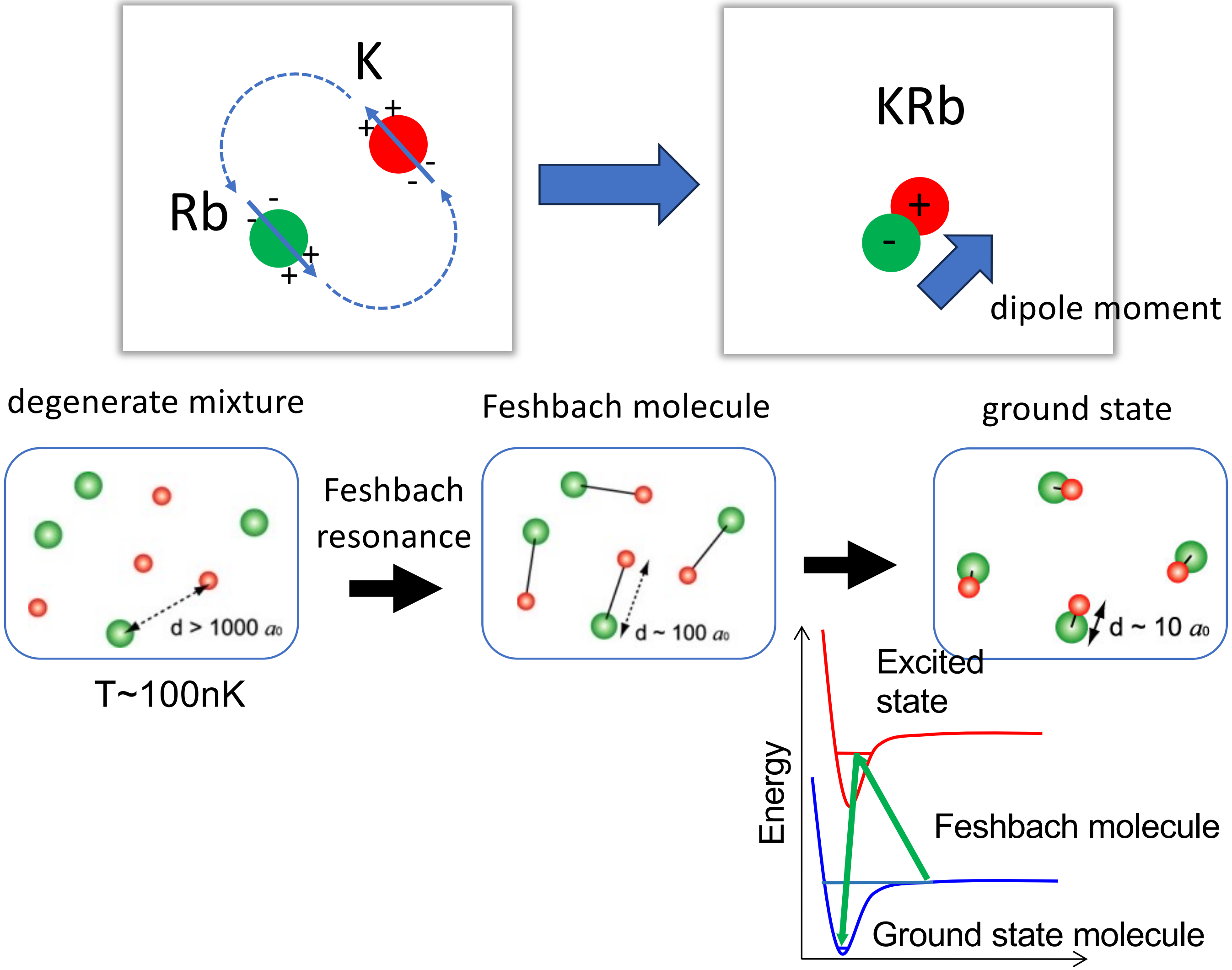
First observation of heteronuclear Feshbach reosnance





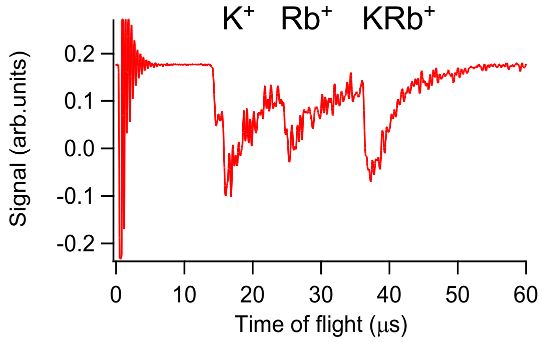
SI *et al*., Phys. Rev. Lett. **93**, 183201 (2004)

Feshbach molecule vs "real" molecule

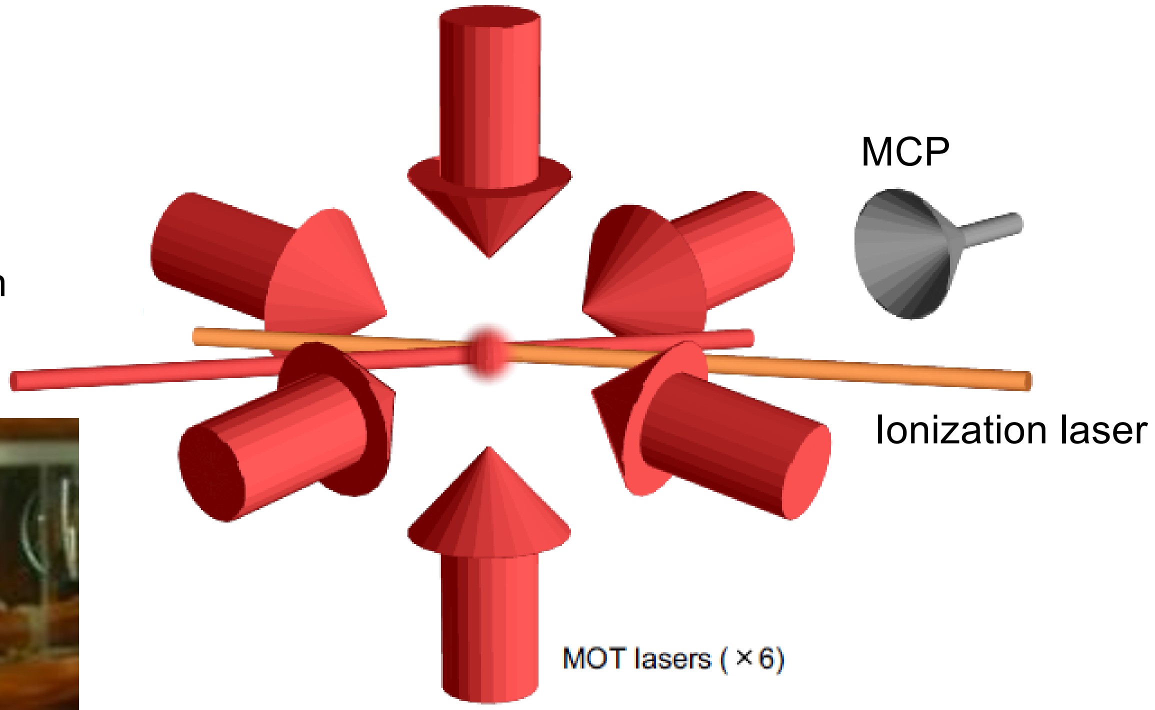


"Stimulated
Raman
Adiabatic
Passage"
="STIRAP"

Our setup for molecular spectroscopy

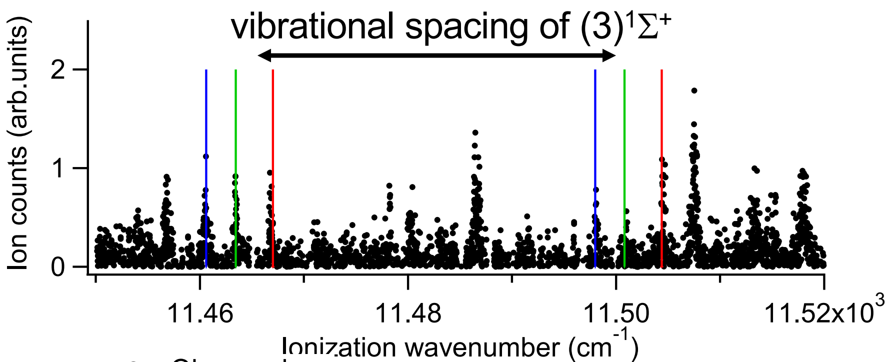


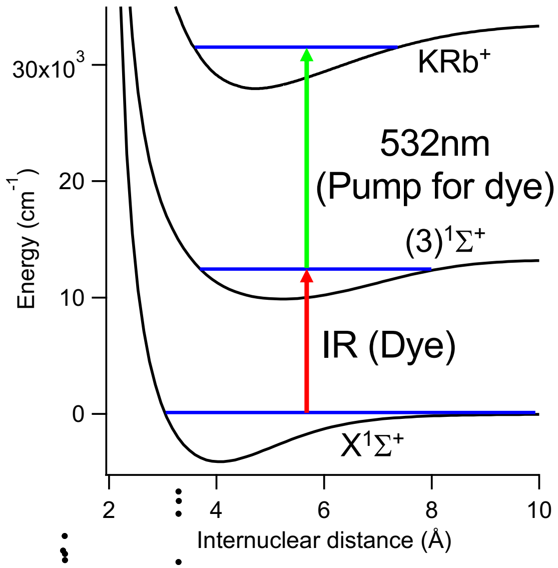
- Dual species MOT (K, Rb)
- Photoassociation
- Spectroscopy
- Detect molecules with REMPI (Resonant-Enhanced MultiPhoton Ionization)

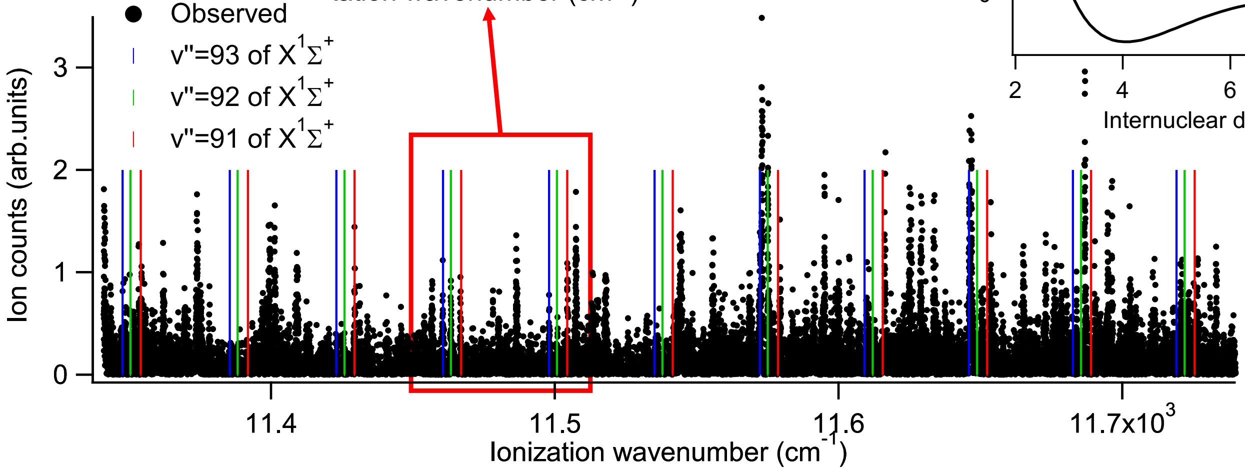


Ionization spectroscopy of the $(3)^1\Sigma^+$ state

- Ionize by two pulses: IR(~870nm)+532nm

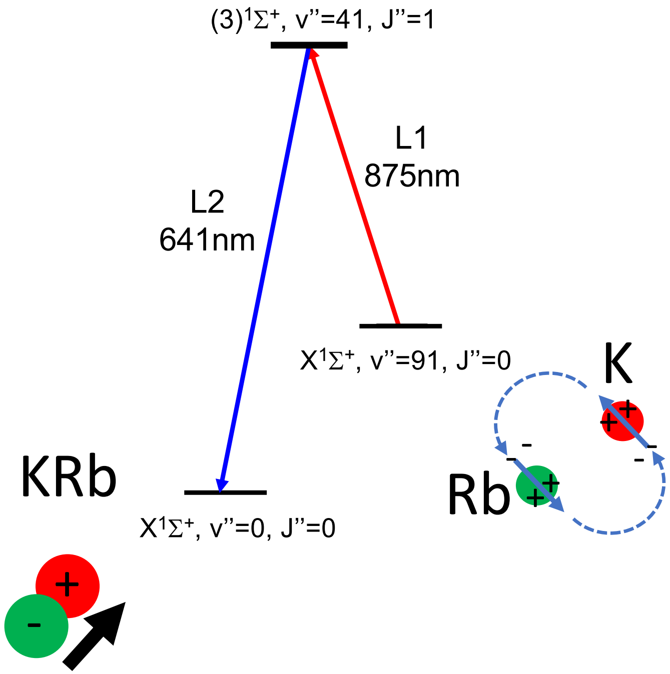


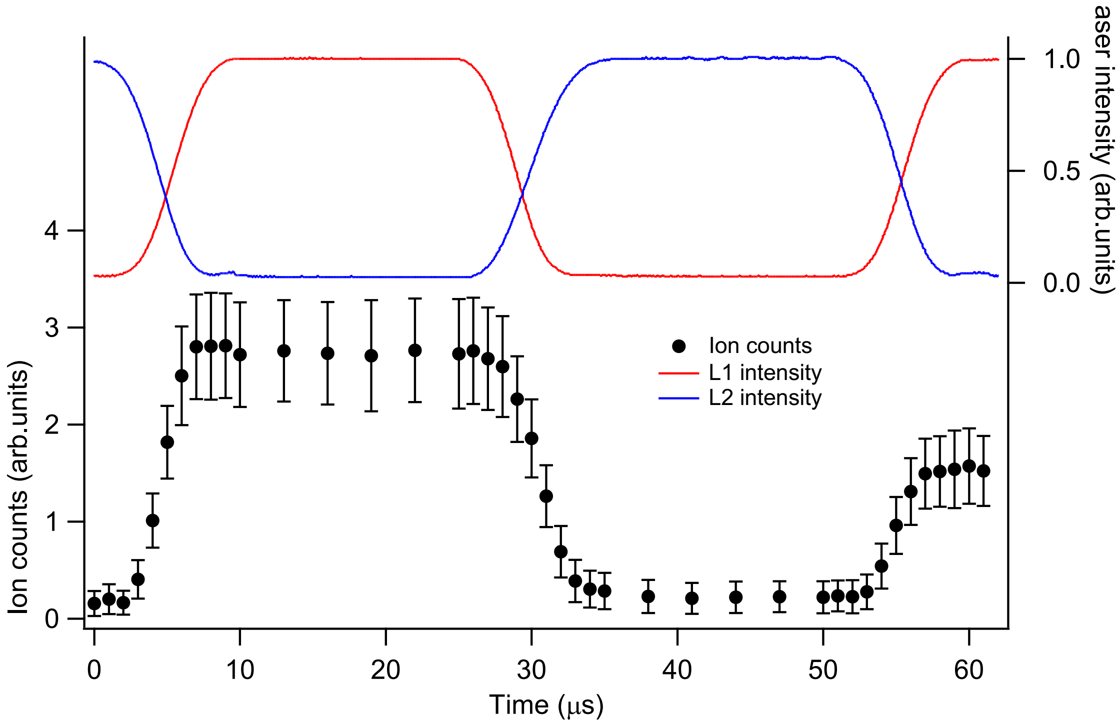




- No information on rotational levels

Production of ultracold ro-vibrational ground sate molecules via STIRAP

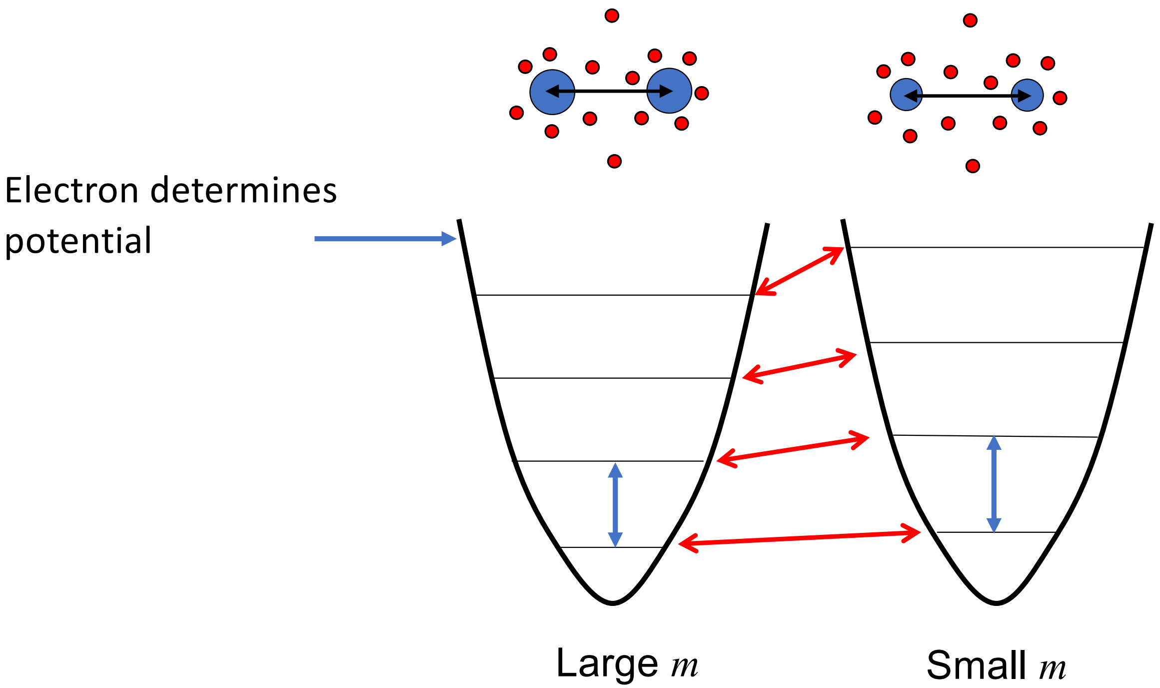




K. Aikawa, ... and SI, PRL **105**, 203001 (2010)

Why molecule spectroscopy for electron-to-proton mass ratio $\mu = \frac{m_e}{M_p}$?

Suppose $m_e = const$, while M_p is changing.



$$\frac{\delta\omega}{\omega} = \frac{1}{2}\frac{\delta\mu}{\mu}$$

Enhanced sensitivity for alkali-alkali molecule?

Prof. DeMille's proposal

PRL **100,** 043202 (2008) PHYSICAL REVIEW LETTERS week ending 1 FEBRUARY 2008

Enhanced Sensitivity to Variation of m_e/m_p in Molecular Spectra

D. DeMille,[1] S. Sainis,[1] J. Sage,[1] T. Bergeman,[2] S. Kotochigova,[3] and E. Tiesinga[4]
[1]Department of Physics, Yale University, New Haven, Connecticut 06520, USA
[2]Department of Physics and Astronomy, SUNY, Stony Brook, New York 11794, USA
[3]Physics Department, Temple University, Philadelphia, Pennsylvania 19122, USA
[4]Joint Quantum Institute and Atomic Physics Division, National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA

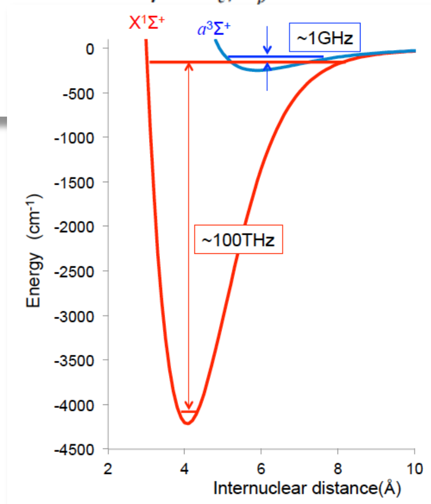
(Received 6 September 2007; published 29 January 2008)

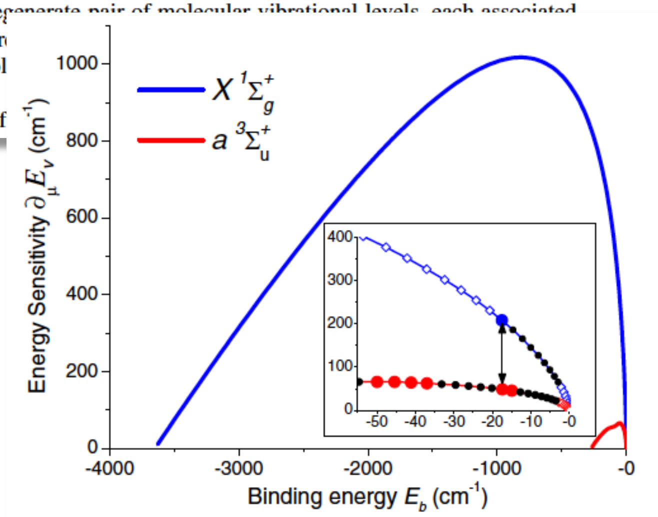
We propose new experiments with high sensitivity to a possible variation of the electron-to-proton mass ratio $\mu \equiv m_e/m_p$. We consider a nearly deg... . With r... an absol... in Cs_2, ... ing for f...

singlet potential = deep
→sensitive to

triplet potential = shallow
→insensitive

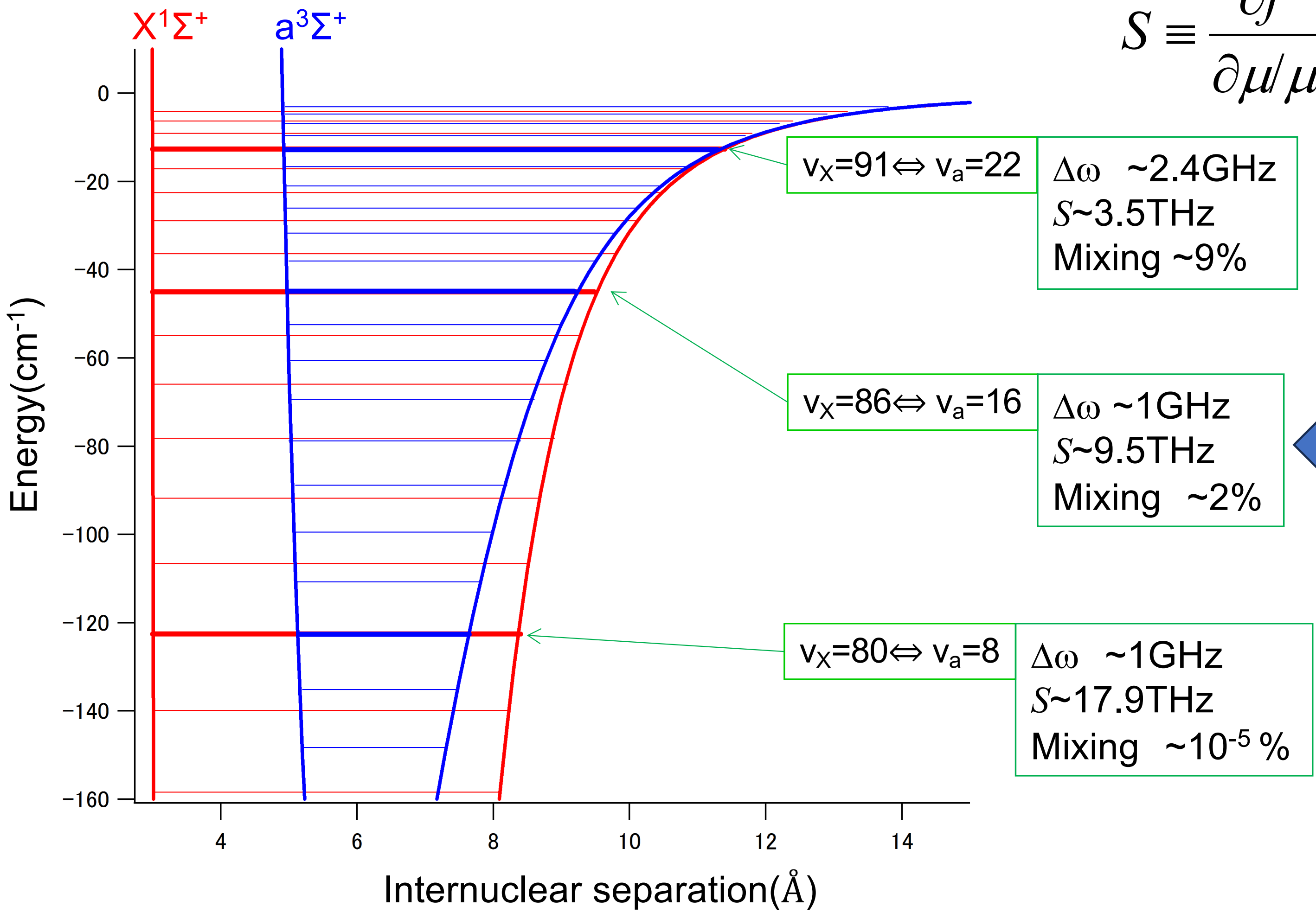
Measure microwave transition between singlet and triplet bound state!





$^{41}K^{87}Rb$

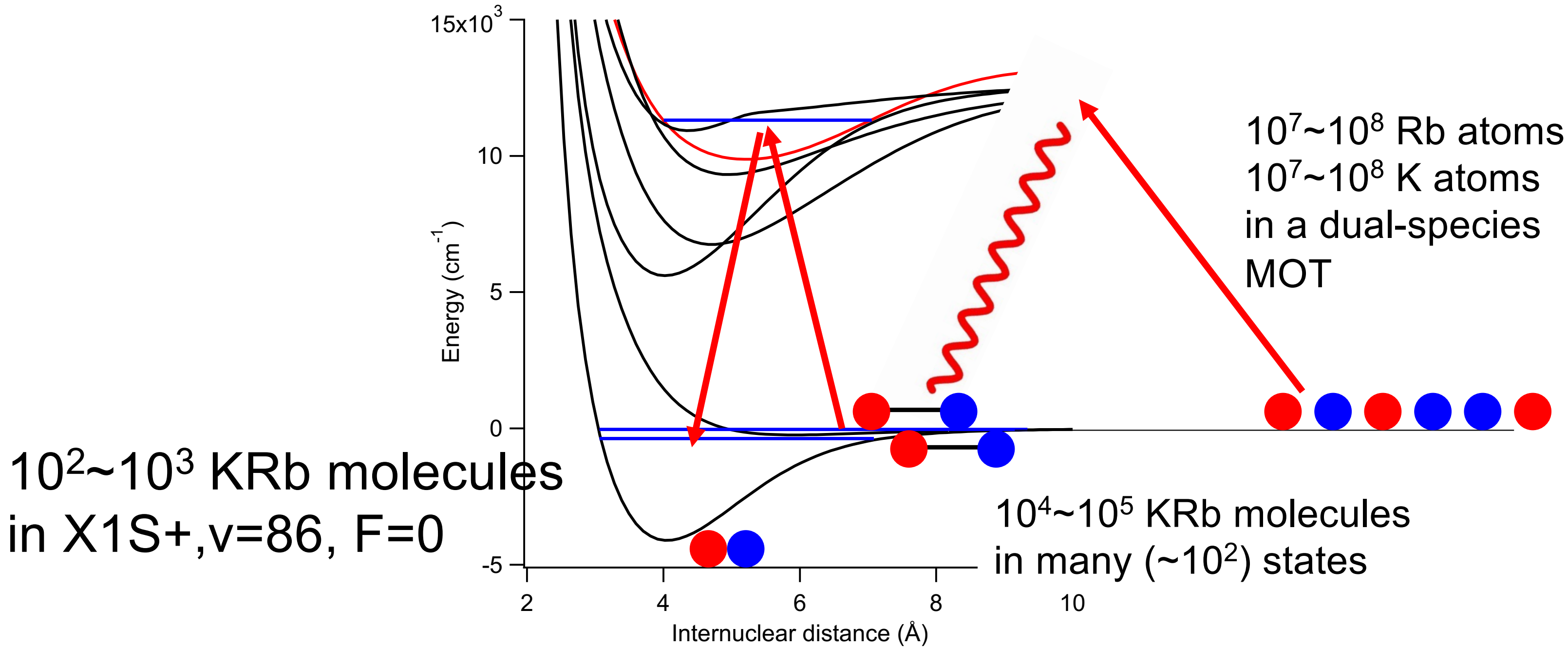
$$S \equiv \frac{\partial f}{\partial \mu / \mu}$$



Large sensitivity with reasonable transition moment

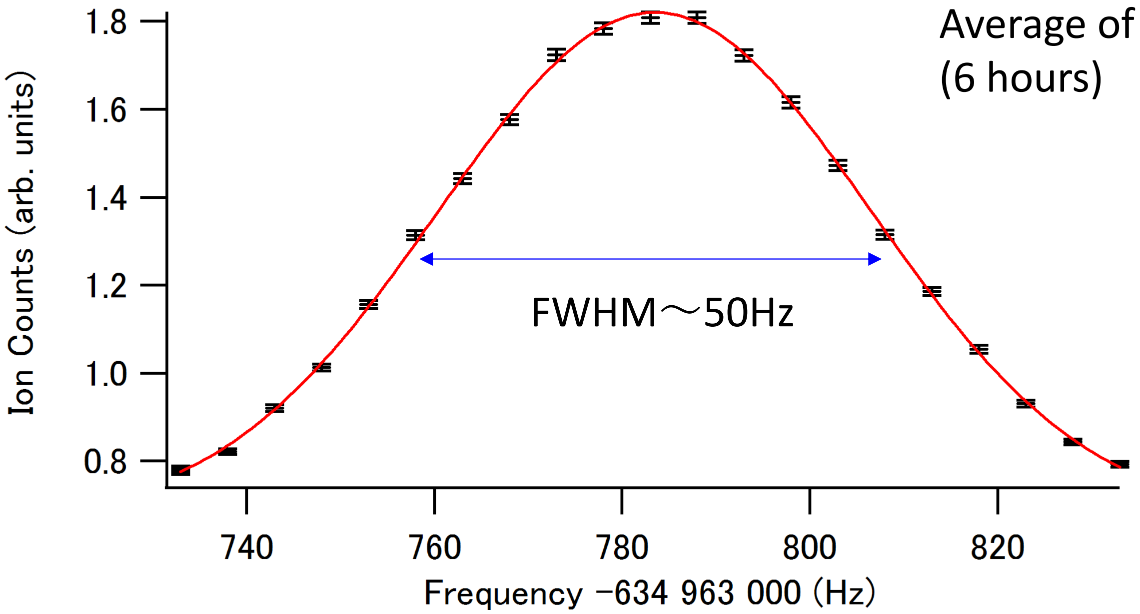
→use this!

STIRAP transfer to the target state



temperature ~ 100μK,
repetition rate ~ 10Hz

Obtained signal for $m_F = 0$



Average of 5000 sweeps (6 hours)

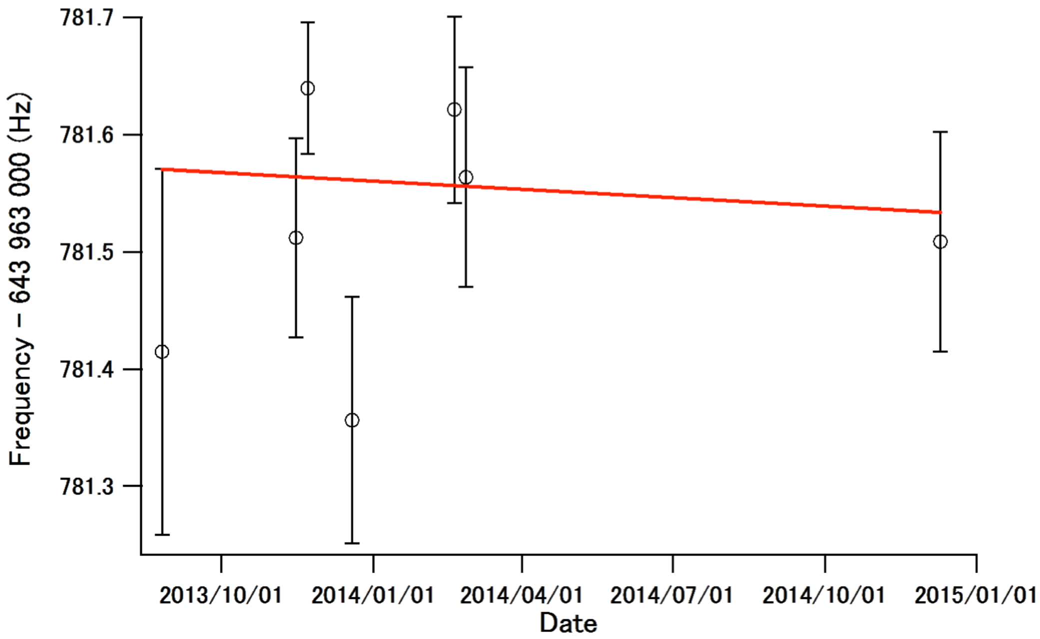
634 963 783.458 ± 0.093 Hz

634 963 781.564 ± 0.094 Hz

Zeeman shift compensation

S/N ~ 500 (c.f. Number of molecules used ~ 10^6)

Good News: we broke the world record set by SF_6!



$$\frac{1}{\mu}\frac{\partial \mu}{\partial t} = \left(0.30 \pm 1.00_{\text{Stat}} \pm 0.16_{\text{Sys}}\right) \times 10^{-14} \text{ / year}$$

J. Kobayashi, A. Ogino, and SI, Nature Comm. 10, 3771 (2019)

1.0/5.6

$$\frac{1}{\mu}\frac{\partial \mu}{\partial t} = \left(3.8 \pm 5.6\right) \times 10^{-14} \text{ / year}$$

A. Shelkovnikov et al., PRL 100, 150801(2008)

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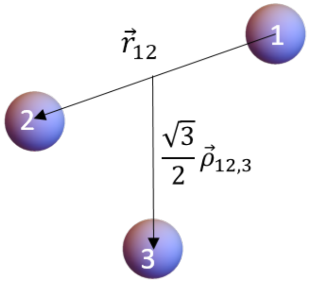
Efimov trimers

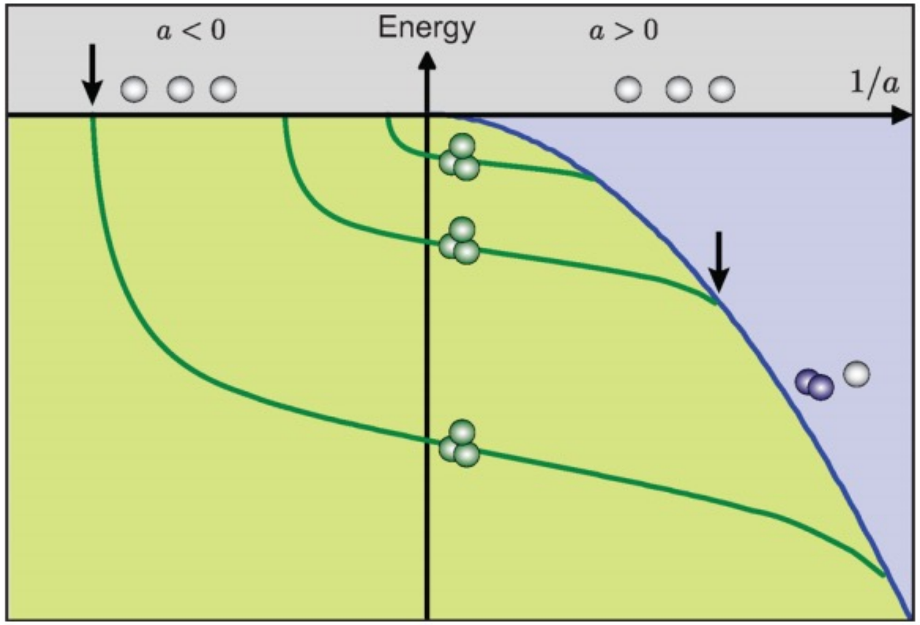


$$H = \sum_{i=1,2,3} \frac{\vec{p}_i^{\,2}}{2m} + \sum_{i<j} V\left(\left|\vec{x}_i - \vec{x}_j\right|\right)$$

$a \to \infty$

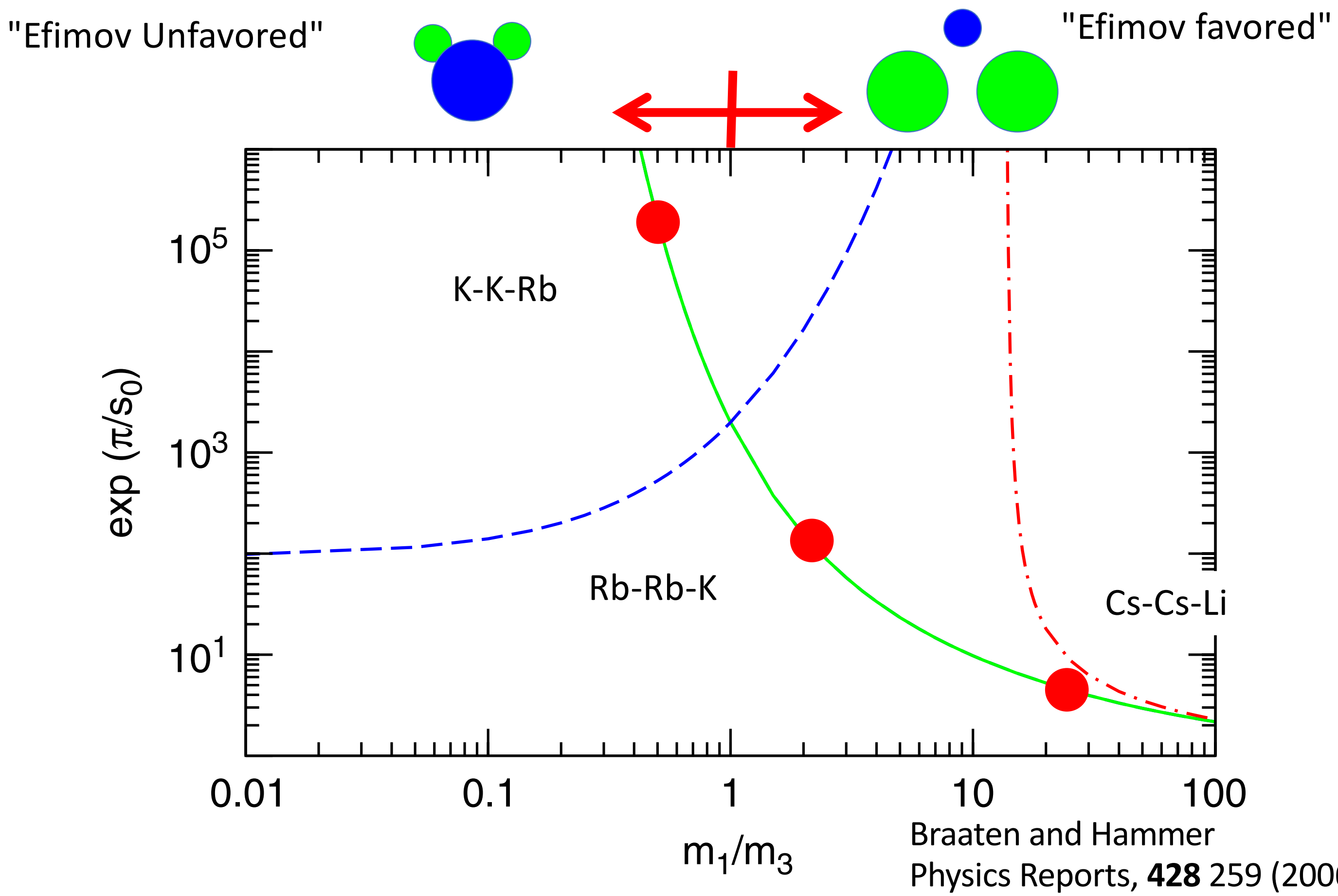
$$H' = \frac{p_R^2}{2\mu} - \frac{\left(s_0^2 + 1/4\right)\hbar^2}{2\mu R^2} + V\left(R\right)$$

$$\frac{E_{n+1}}{E_n} = \exp\left(-\frac{2\pi}{s_0}\right) \sim \left(\frac{1}{22.7}\right)^2 \sim \frac{1}{515}$$



Francesca Ferlaino and Rudolf Grimm, *Physics* **3**, 9 (2010).

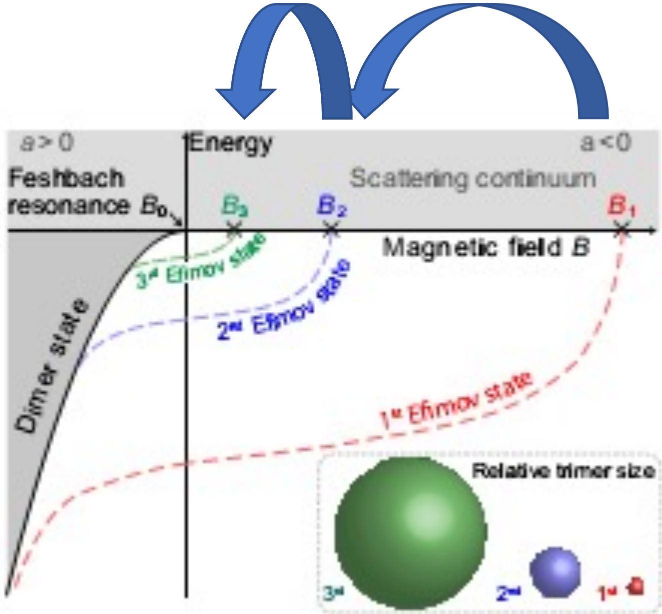
Efimov trimers for hetero-nuclear systems

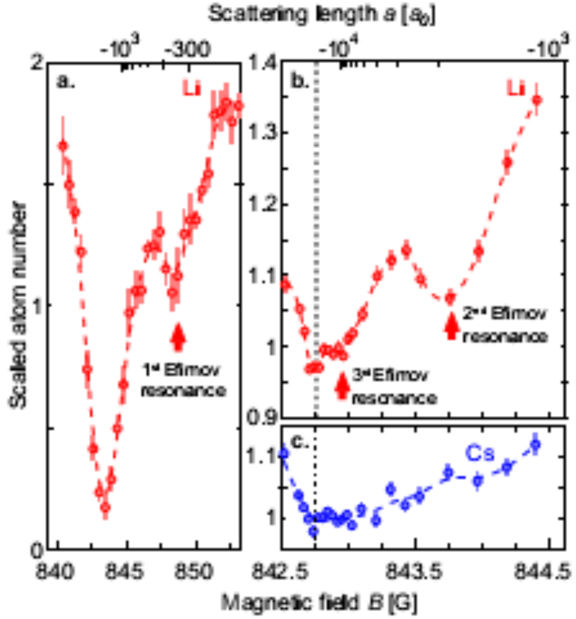


Braaten and Hammer
Physics Reports, **428** 259 (2006)

Li-Cs system is one of the best system

$$e^{\pi / s_0} \approx 4.9$$

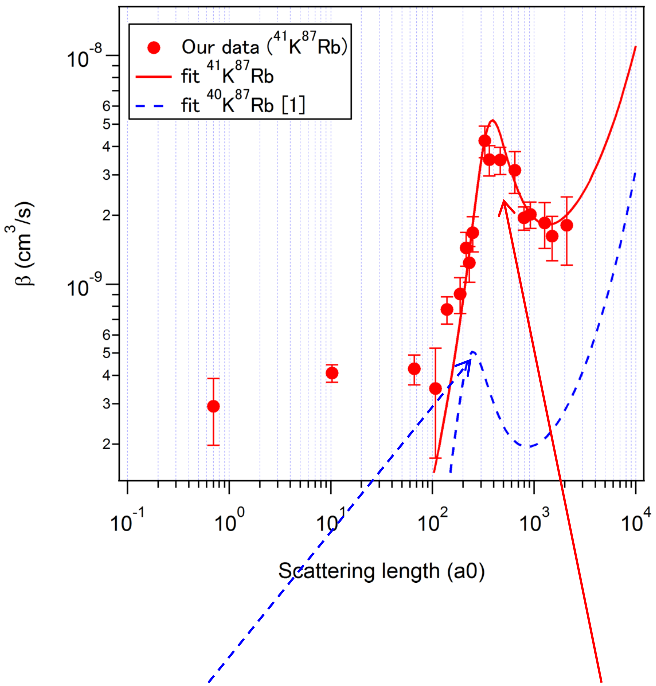




Shih-Kuang Tung *et al.*, Phys. Rev. Lett. 113, 240402 (2014)

Expected scaling (4.9) was observed

We observed Efimov resonance between ^{87}Rb and ^{41}K^{87}Rb

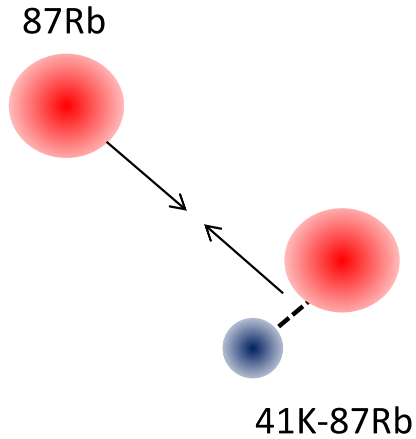


40K87Rb (JILA)

$$a^* = 230(10)\ a_0$$

41K87Rb (Tokyo)

$$a^* = 360(19)\ a_0$$



K. Kato, and SI, PRL. 118, 163401 (2017).

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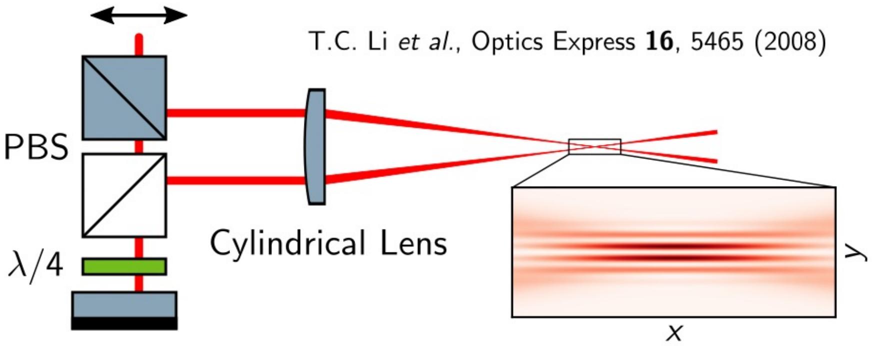
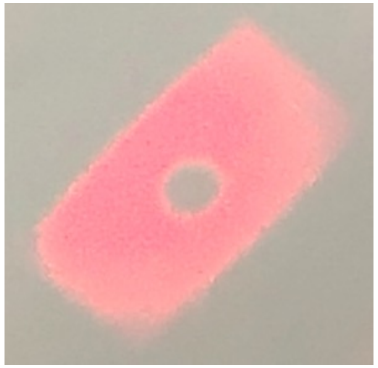
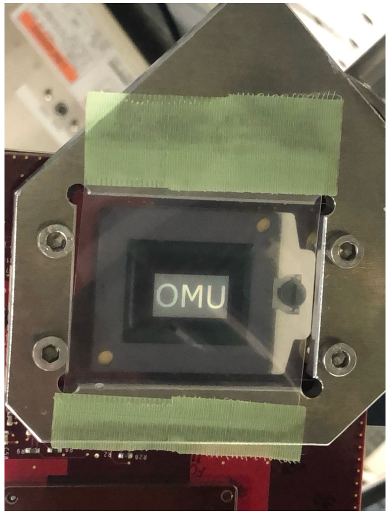
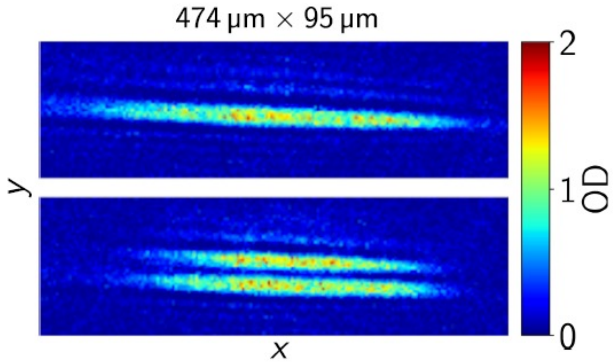
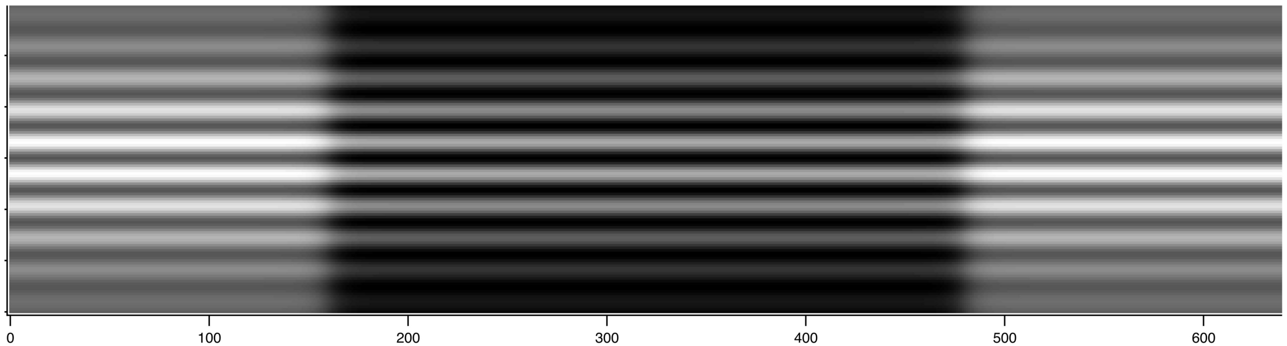
Current interest:
mixture in a box trap



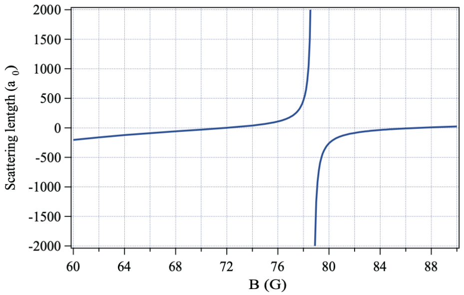


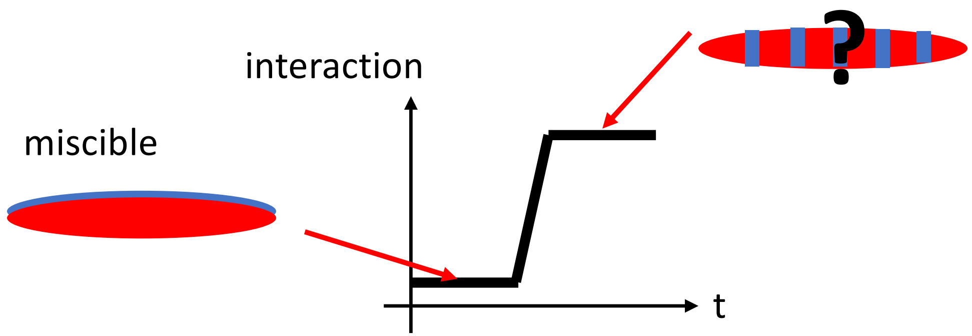


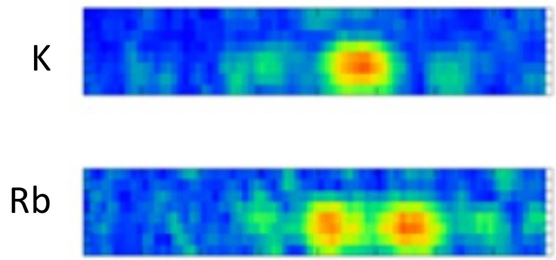




Quench dynamics of dual BEC

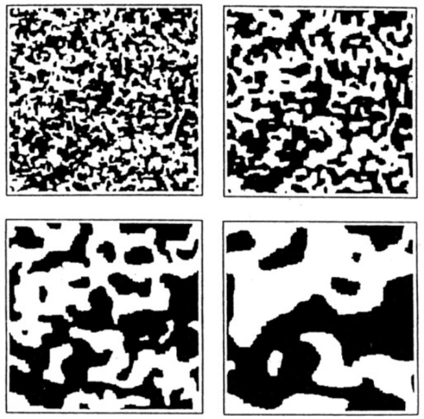






21µm × 206µm

Dynamical scaling?



A. J. Bray, Adv. Phys. 43, 357 (1994).

collaboration with
Prof. H. Takeuchi(OMU)

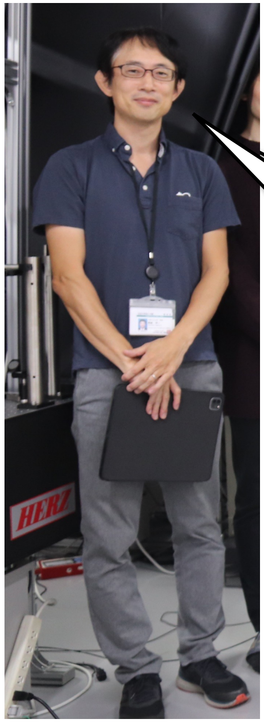
ERATO

Quantum simulation of nucleus

大阪公立大学 Osaka Metropolitan University

C班：冷却原子実験　　GL : 堀越宗一(大阪公立大学)
井上慎(大阪公大), 板垣直之(大阪公大), 堀内渉(大阪公大), 加藤宏平(大阪公大)

Team leader ： Munekazu Horikoshi



- Quantum simulation of nuclear physics
- Precision measurement

We need to **simulate nucleus!**

Injecting Dy atoms in an optical trap
= protons and neutrons in a shell potential

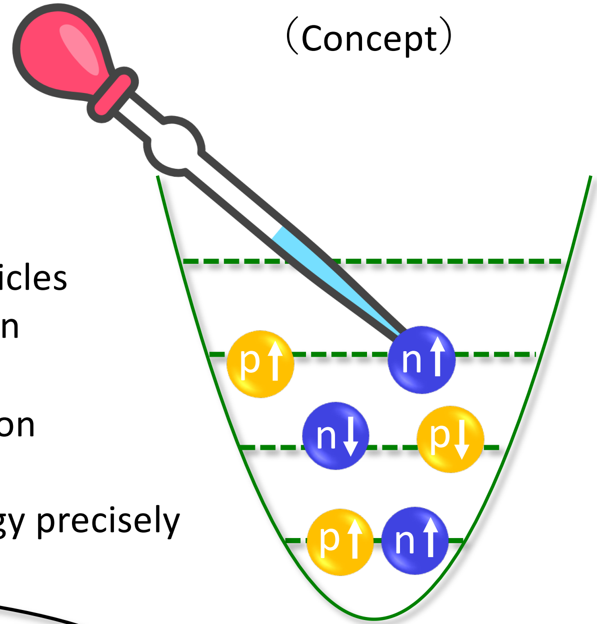
We control

- Number of particles
- spin composition
- interaction
- energy separation

and measure energy precisely

Nucleons have large magnetic moment
→ **Let's use Dy atoms!**

（Concept）



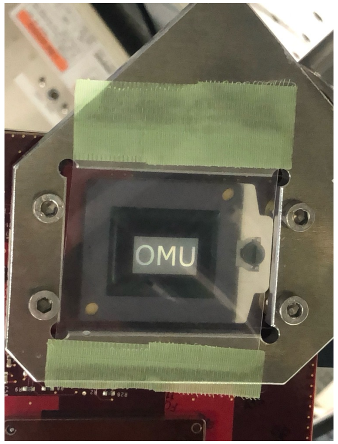
shell potential

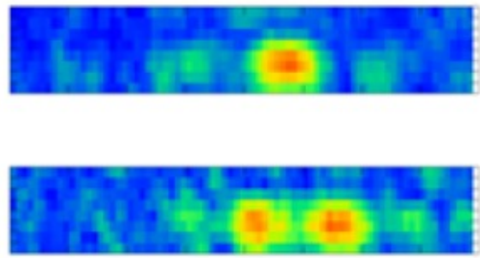
Conclusion and Outlook

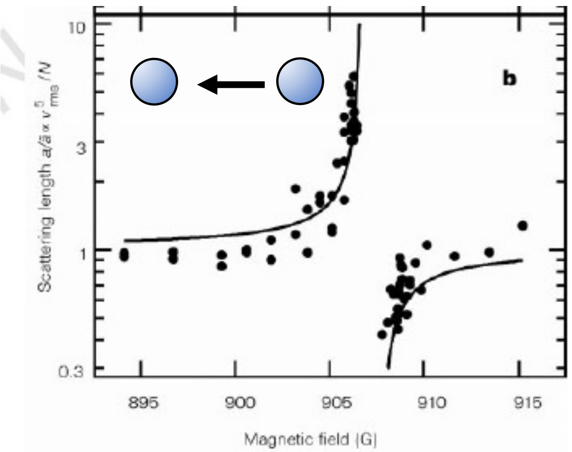
We have been exploring fundamental physics using ultracold atoms and molecules.

- Feshbach resonances
- production of rovibrational ground state polar molecules
- heteronuclear efimov state
- stability of me/Mp

- (degenerate mixtures in a box potential?)







KRb