Measurement of p-wave interaction energy in an ultracold spin-polarized Fermi gas of ^{6}Li

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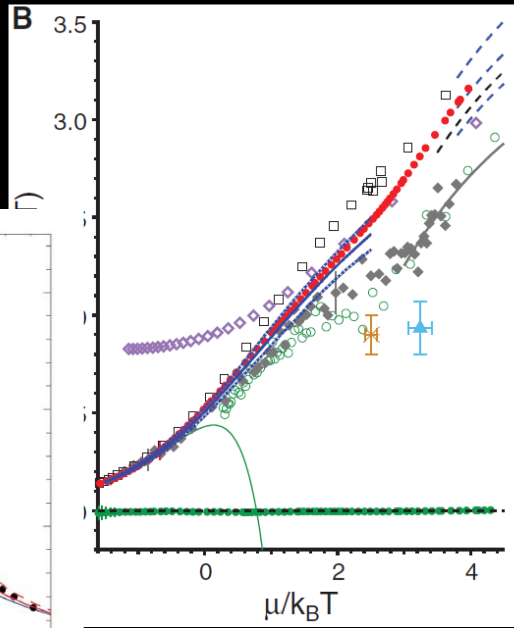
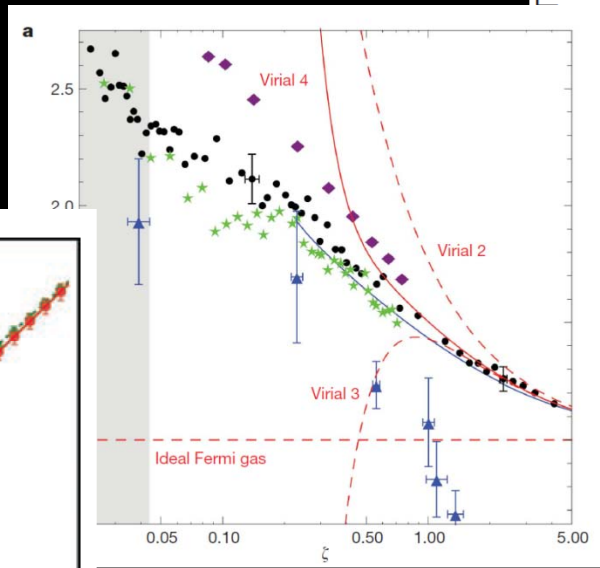
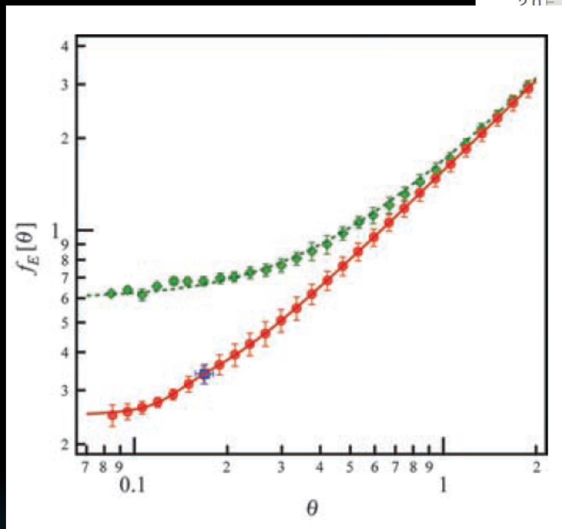
第3回中性子星核物質研究会　2014年9月25日熱川ハイツ

Experimental determination of Equation of State (EOS)

unitary Fermi gas (s-wave)







M. Ku, et al.
Science **335**, 563 (2012).

S. Nascimbene, et al.
Nature **463**, 1057 (2010).

M. Horikoshi, et al.
Science **327**, 442 (2010).

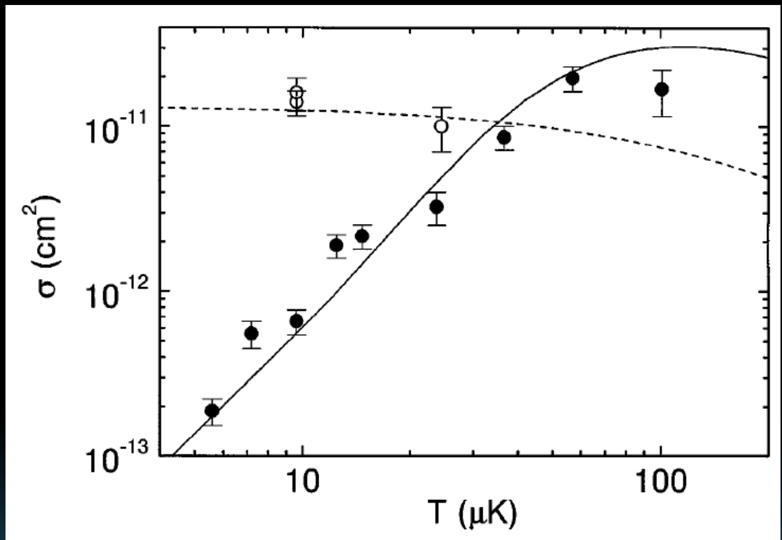
Our goal:
EOS for fermions with p-wave interactions

Scattering of identical particles

Bosons : *s*-wave (l=0), ~~*d*-wave (l=2), ...~~

Fermions : ~~*p*-wave~~ (l=1), ~~*f*-wave~~ (l=3), ~~...~~

Higher partial wave contribution decreases with temperature.



B. DeMarco et al.
Phys. Rev. Lett. **82**, 4208 (1999).

○ *s*-wave collision cross section between distinguishable fermions

● *p*-wave collision cross section between identical fermions

Threshold energy for ^{6}Li is on the order of mK.
(Typical temperature range ~ 1μK)

p-wave Feshbach resonance

- narrow Feshbach resonance

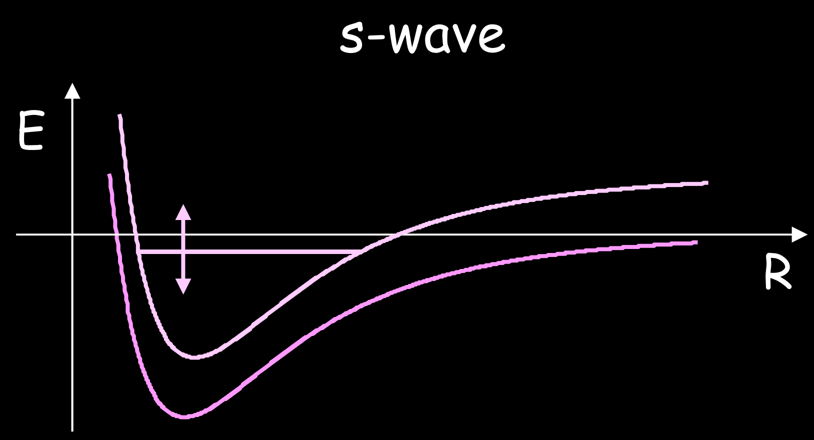
  Atoms need to tunnel through the barrier

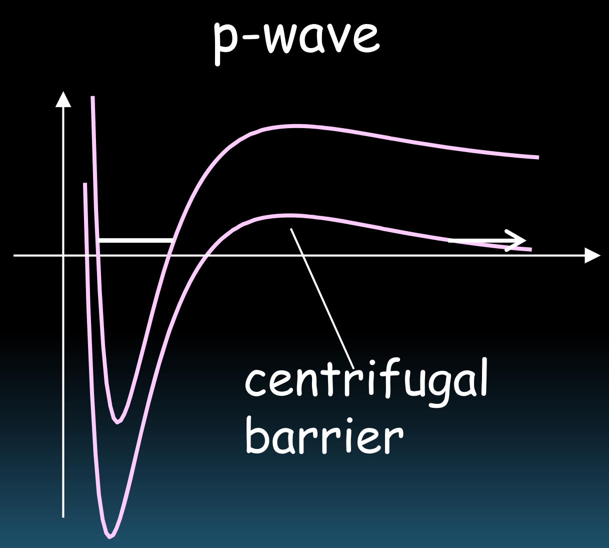
- quasi-bound state

  molecular state has finite lifetime even at higher energy than the dissociation limit

- doublet structure

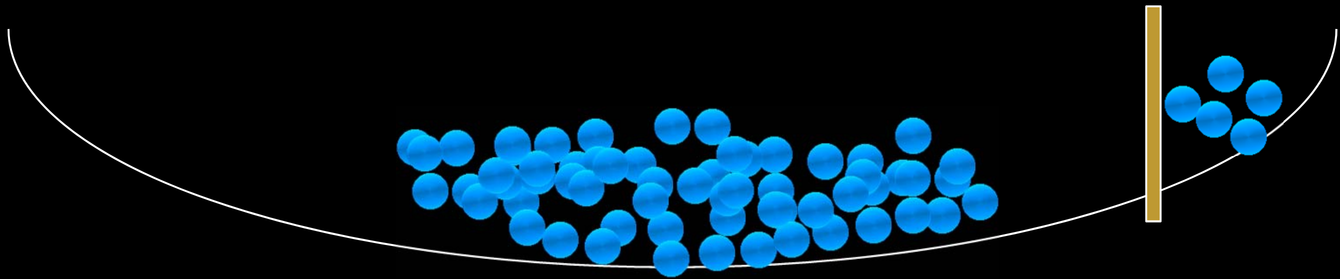
  spin-spin interaction



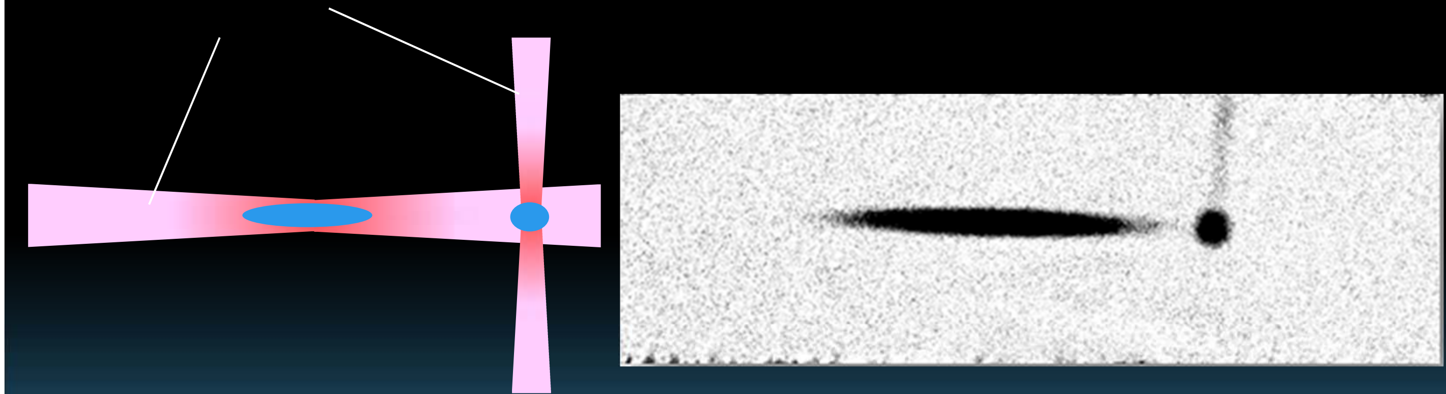


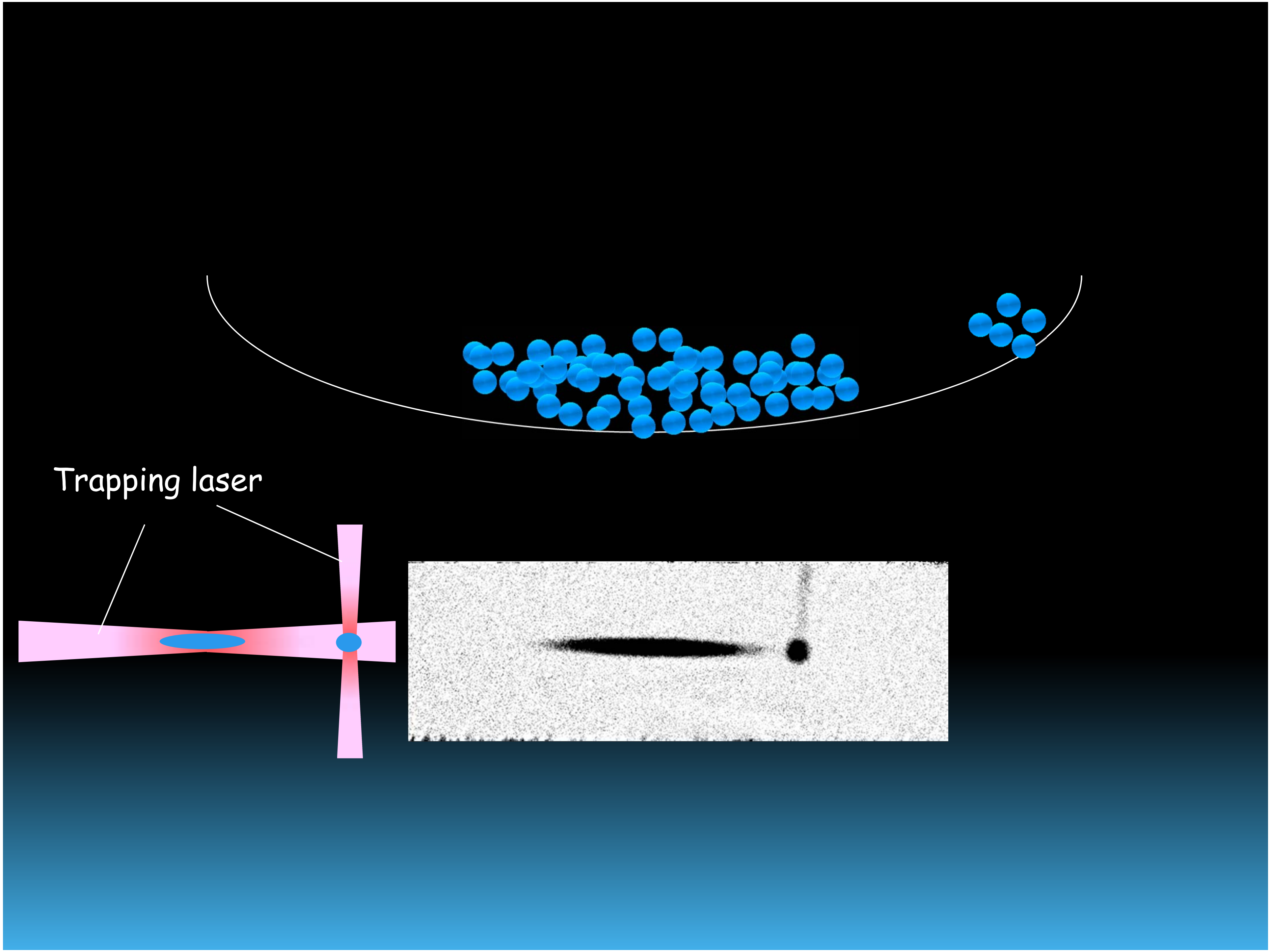
When the scattering length is tuned to nearly zero,

→ Atoms would not collide with each other

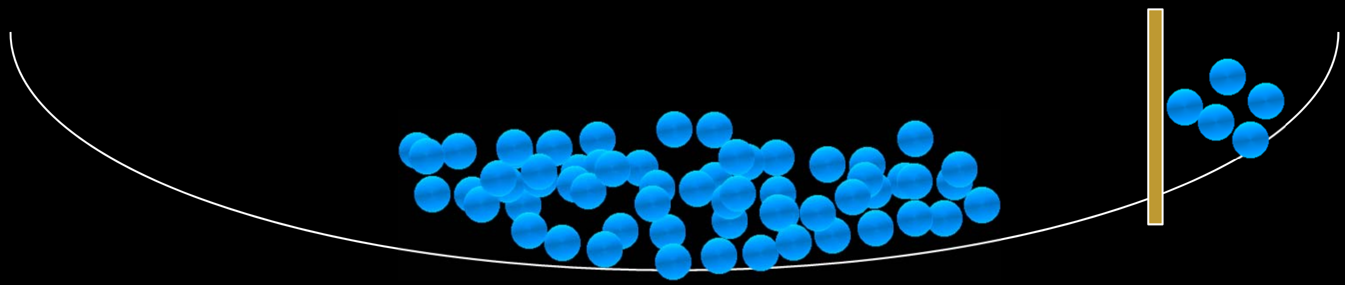


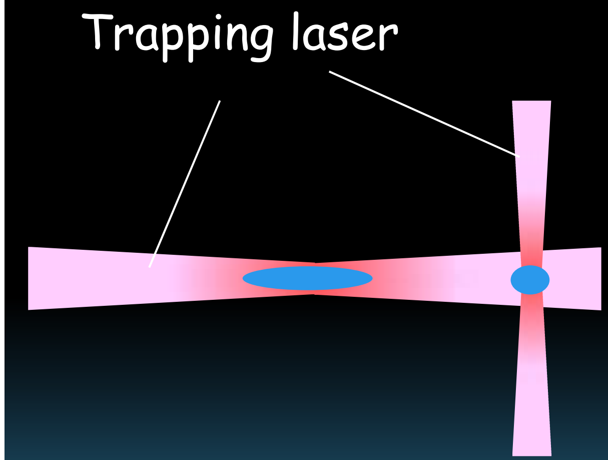
Trapping laser

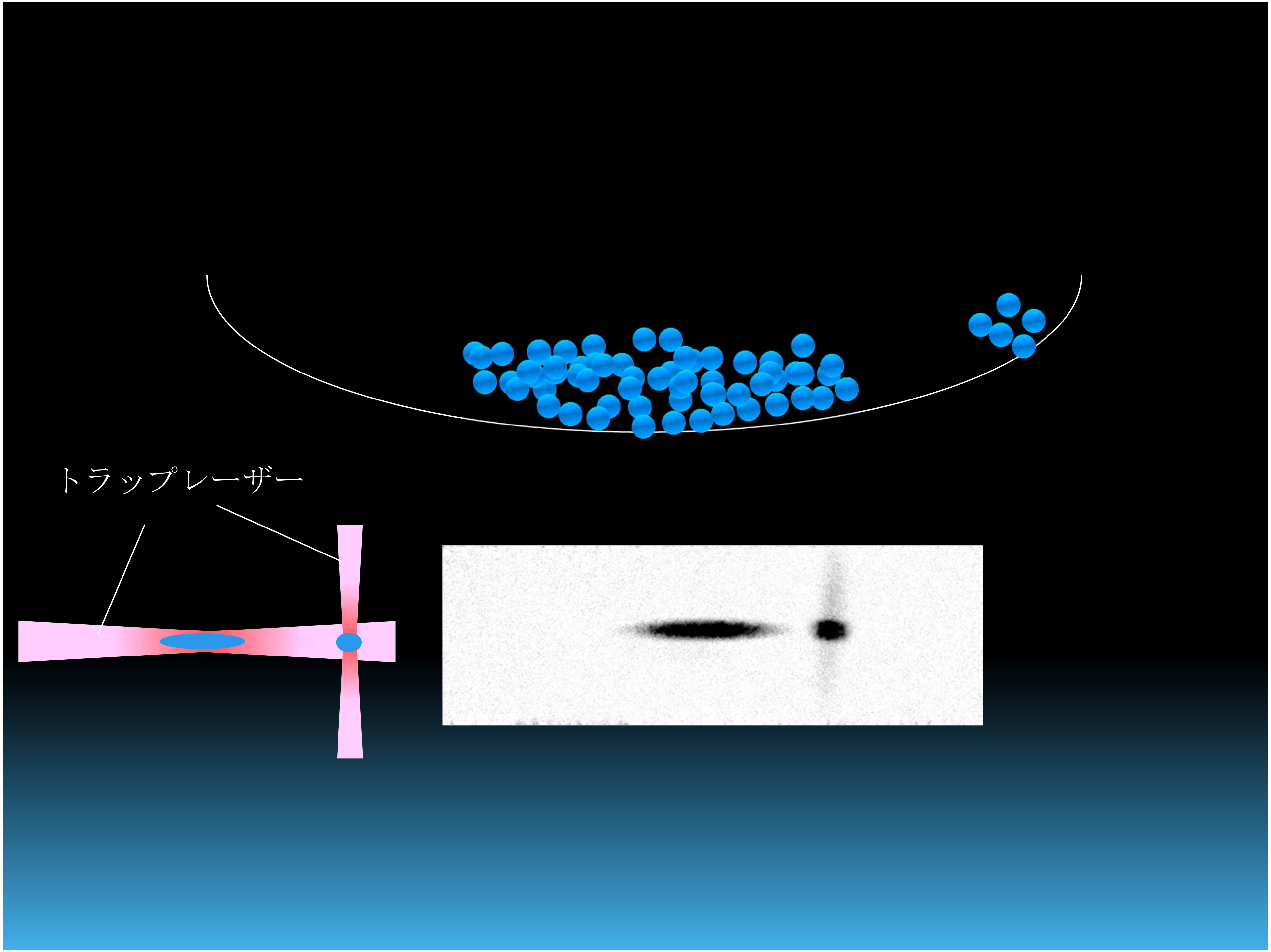


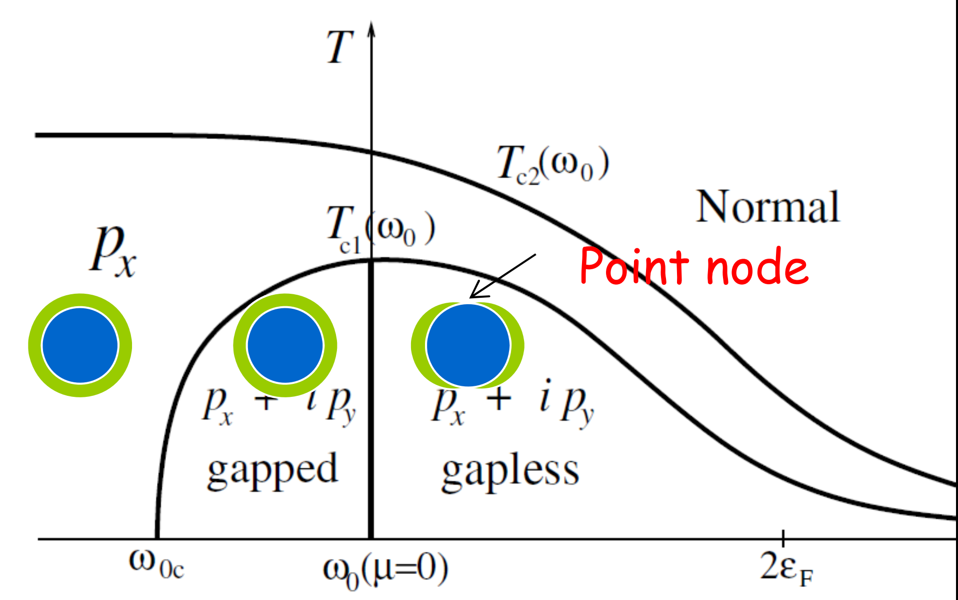

Trapping laser

At the unitarity limit,






トラップレーザー



Expected p-wave superfluid phase diagram :

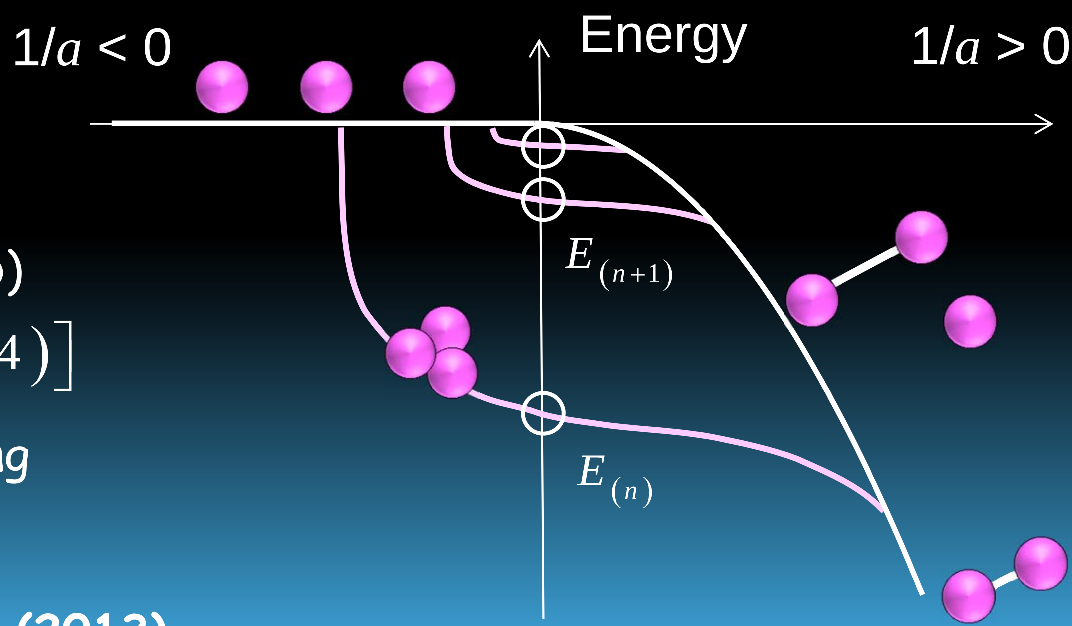
V. Gurarie et al.
PRL **94**, 230403 (2005)

"Super" Efimov effect

p-wave resonance
in identical fermions (2D)

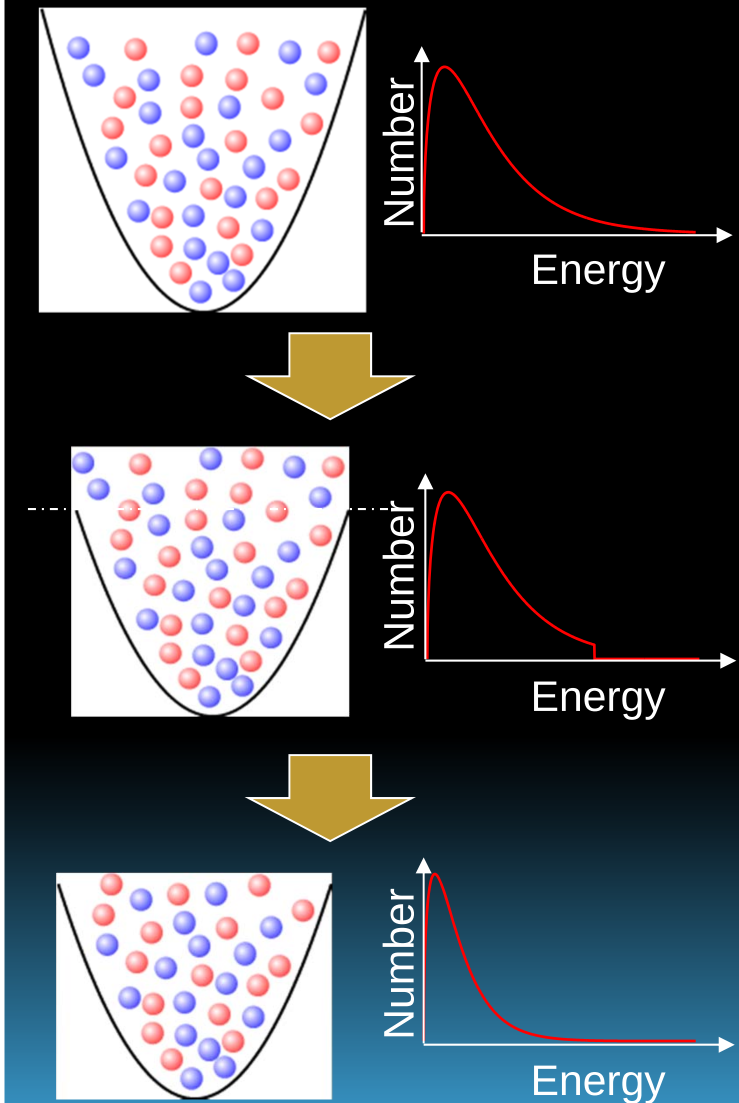
$$E_{(n)} \propto \exp\left[-A\exp\left(3\pi n/4\right)\right]$$

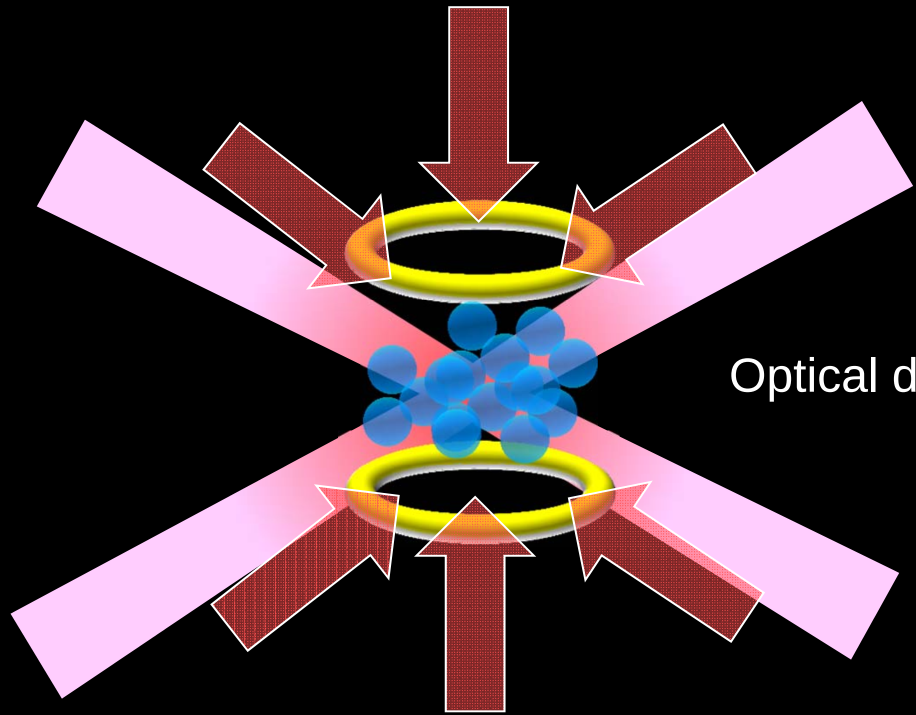
doubly-exponential scaling

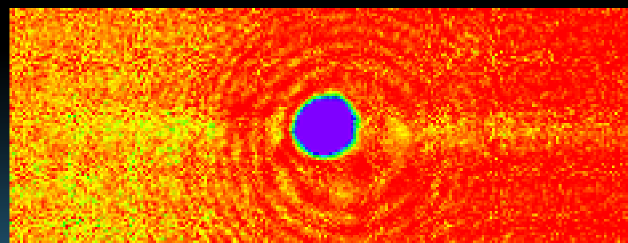


Y. Nishida et al.,
Phys. Rev. Lett. 110, 235301 (2013)

Evaporative cooling in an optical dipole trap

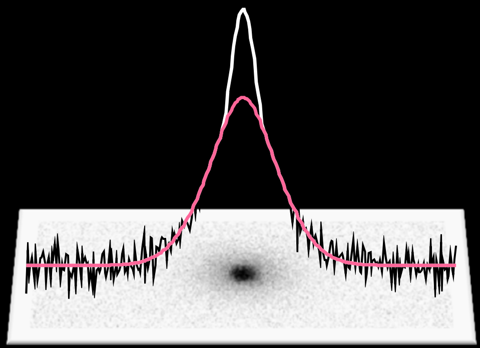






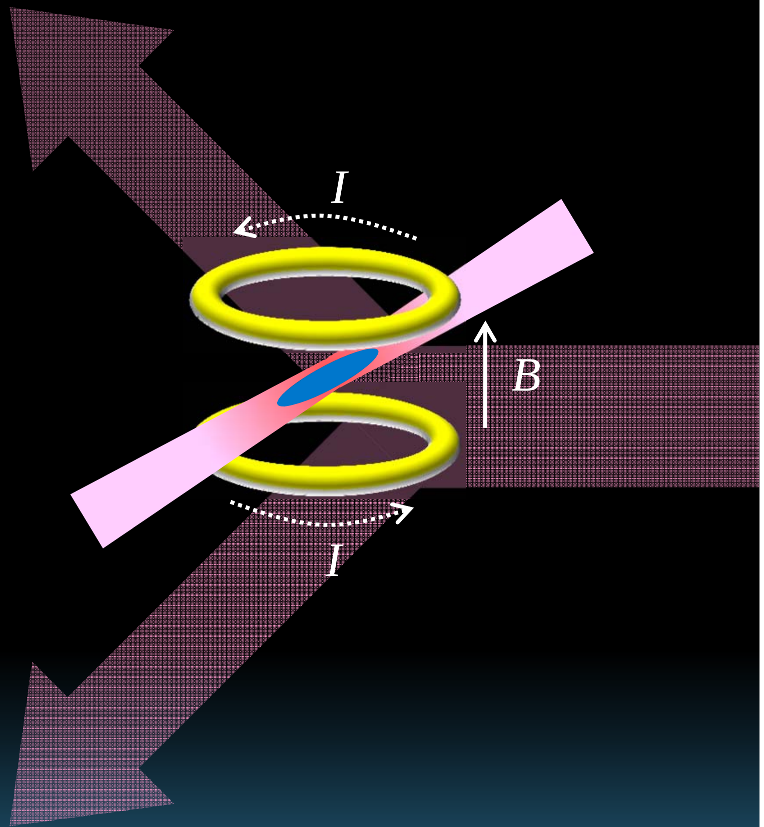
Size ~ 10-100μm
Aspect ratio ~ 5:4:1
Number of atoms ~10^5-10^6
Temperature ~ 1μK

^{6}Li in quantum degenerate regime



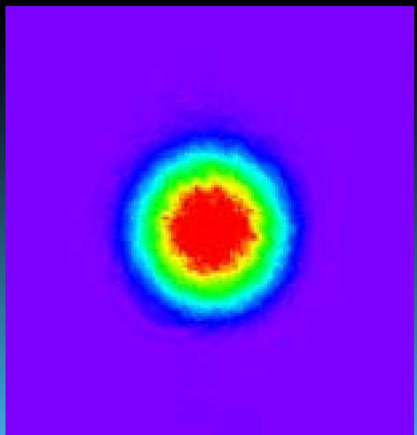
molecular BEC

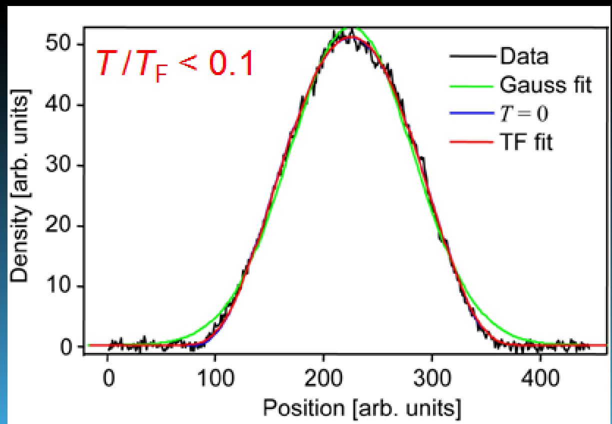
B = 650 ~ 800 G



degenerate Fermi gas

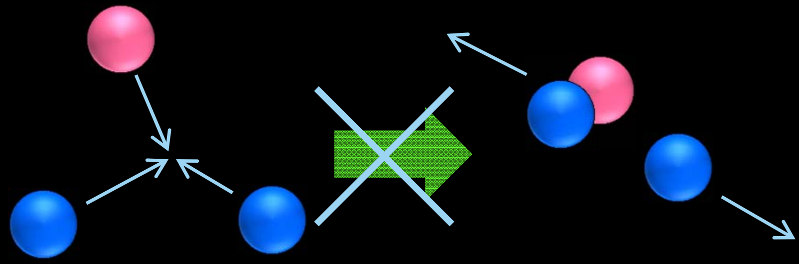
B = 0 ~ 500, 800 ~ G





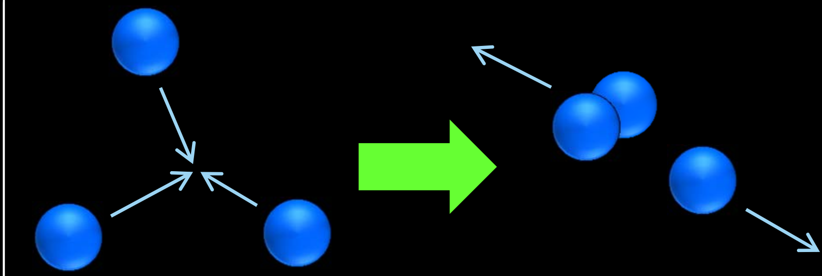
Interaction and loss are the opposite sides of the same coin…

s-wave case



two-component fermions with
s-wave interaction
-> stable against 3-body loss

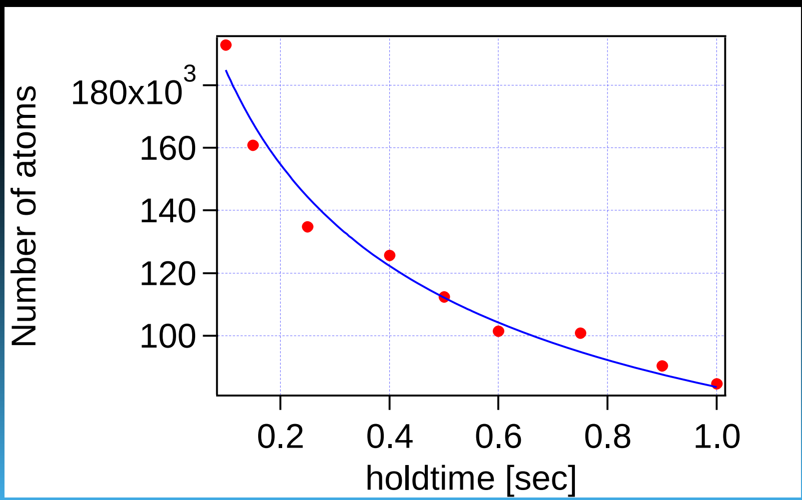
p-wave case

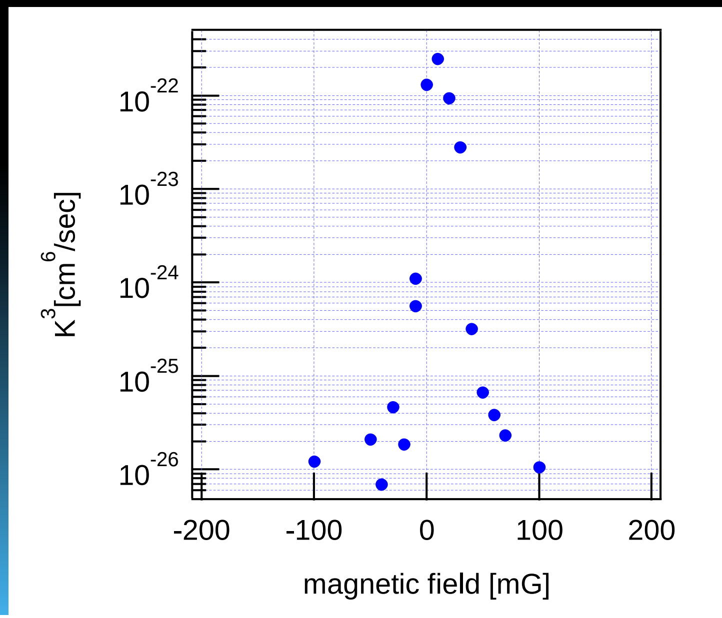


3-body loss is crucial

$$\dot{n} = -K_3 n^3$$

decay plot





Work done so far with p-wave Feshbach resonances

^{40}K

✓ p-wave Feshbach resonance [1]

✓ splitting between $m_l = 0$ and $|m_l| = 1$ resonances[2]

✓ p-wave molecule creation [3]

[1] C. A. Regal et. al. PRL **90**, 053201 (2003)
[2] C. Ticknor et. al. PRA **69**, 042712 (2004)
[3] J. P. Gaebler et. al. PRL **98**, 200403 (2007)

^{6}Li

✓ observation of p-wave Feshbach resonances[4-6]

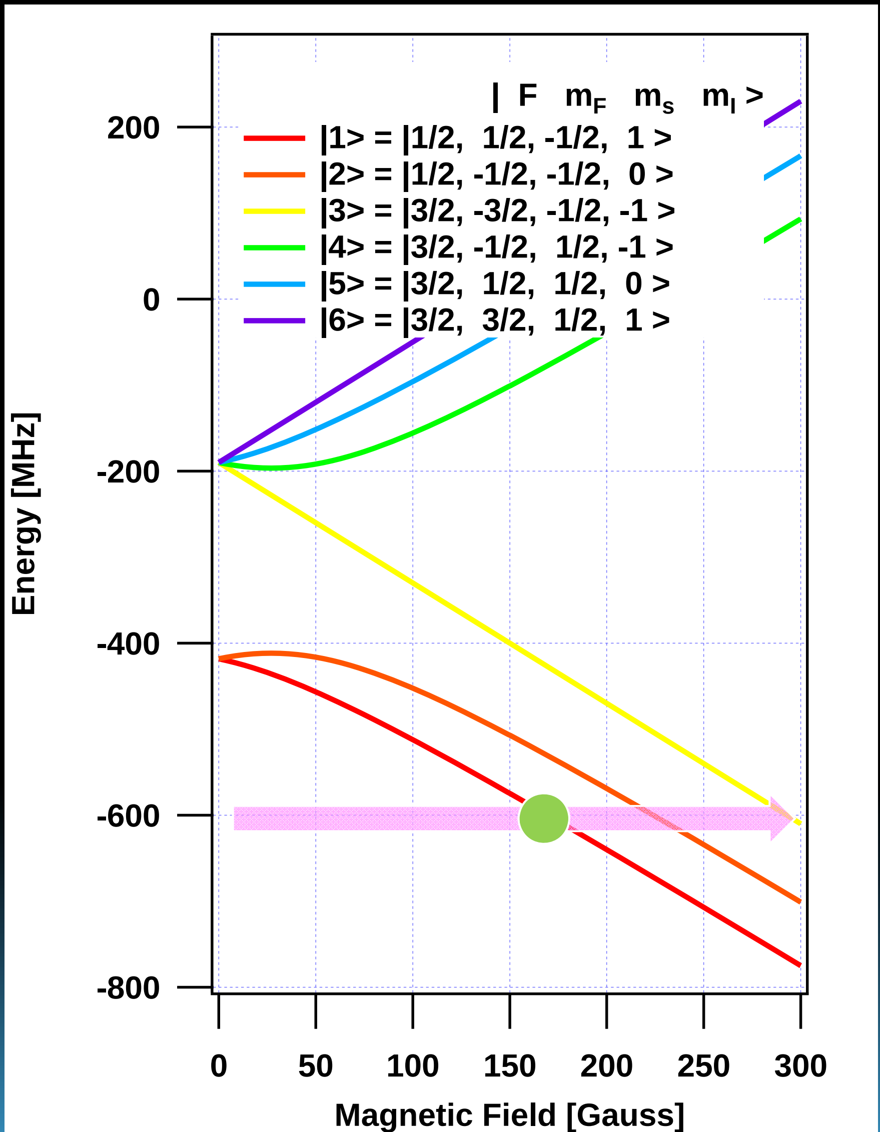
✓ "loss" and "recovery" of atoms near the p-wave Feshbach resonance[4]

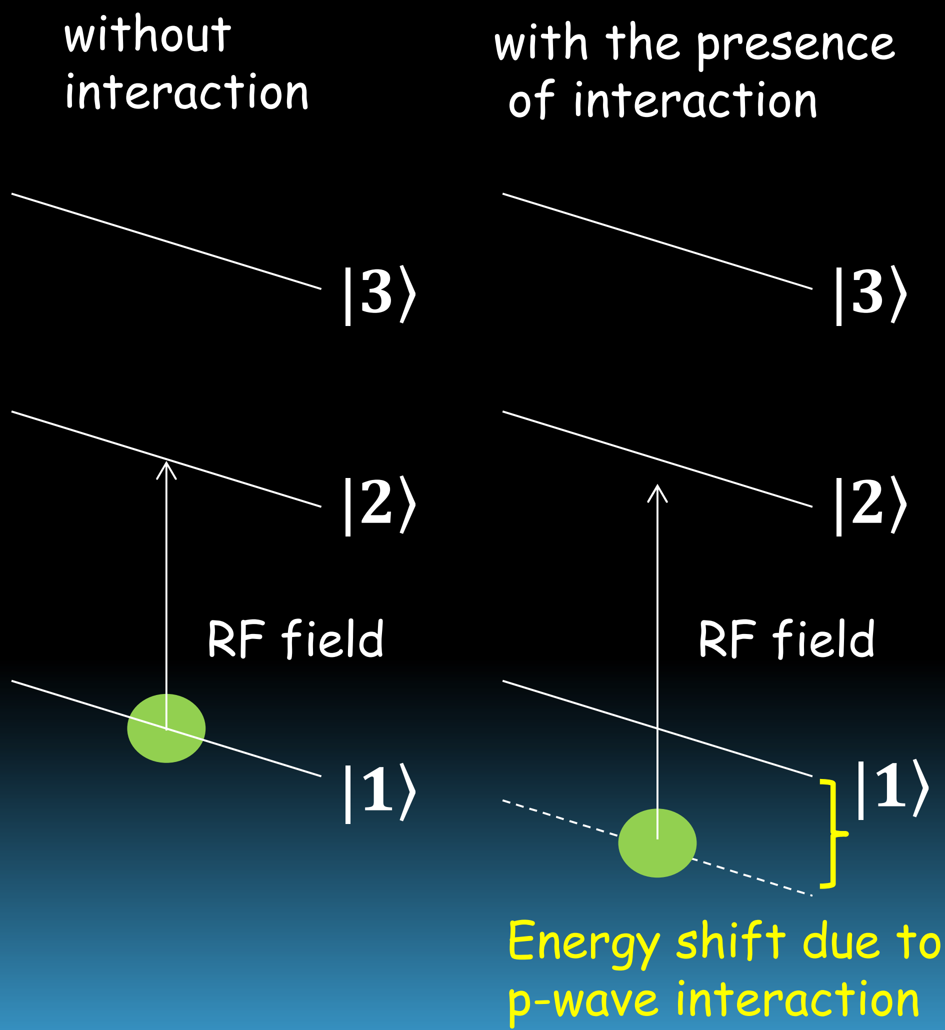
✓ determination of the magnetic moment of p-wave molecular state[6]

✓ p-wave molecule creation [7,8]

[4] J. Zhang et al. PRA **70**, 030702(R) (2004)
[5] C. H. Schunck et al. PRA **71**, 045601 (2005)
[6] J. Fuchs et al. PRA **77**, 053616 (2008)
[7] Y. Inada et al. PRL **101**, 100401 (2008)
[8] R. A. W. Maier et al. PRA **81**, 064701 (2010)

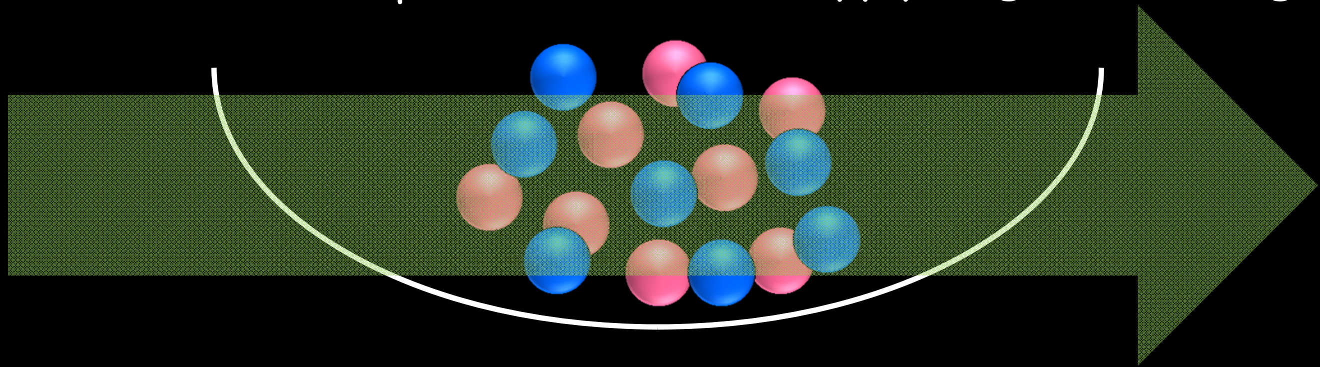
The way to probe interaction - RF spectroscopy



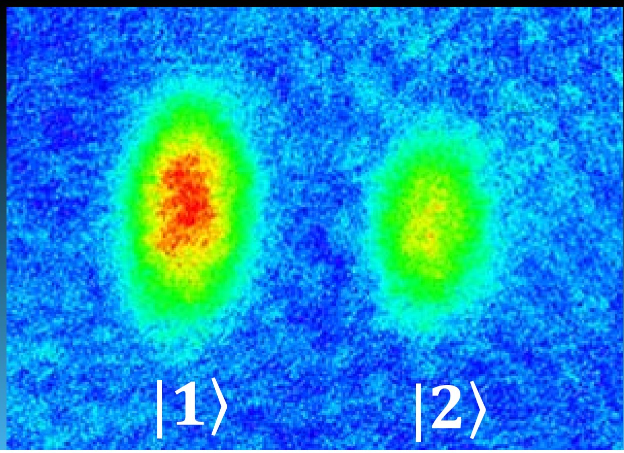


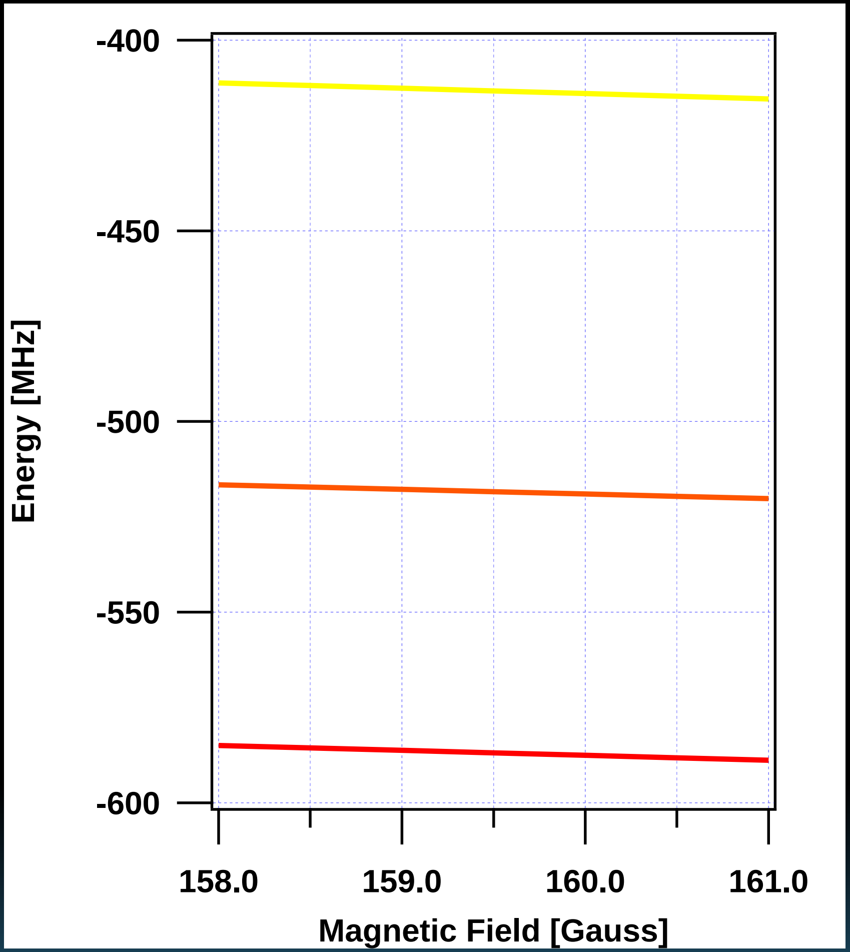
Stern-Gerlach measurement

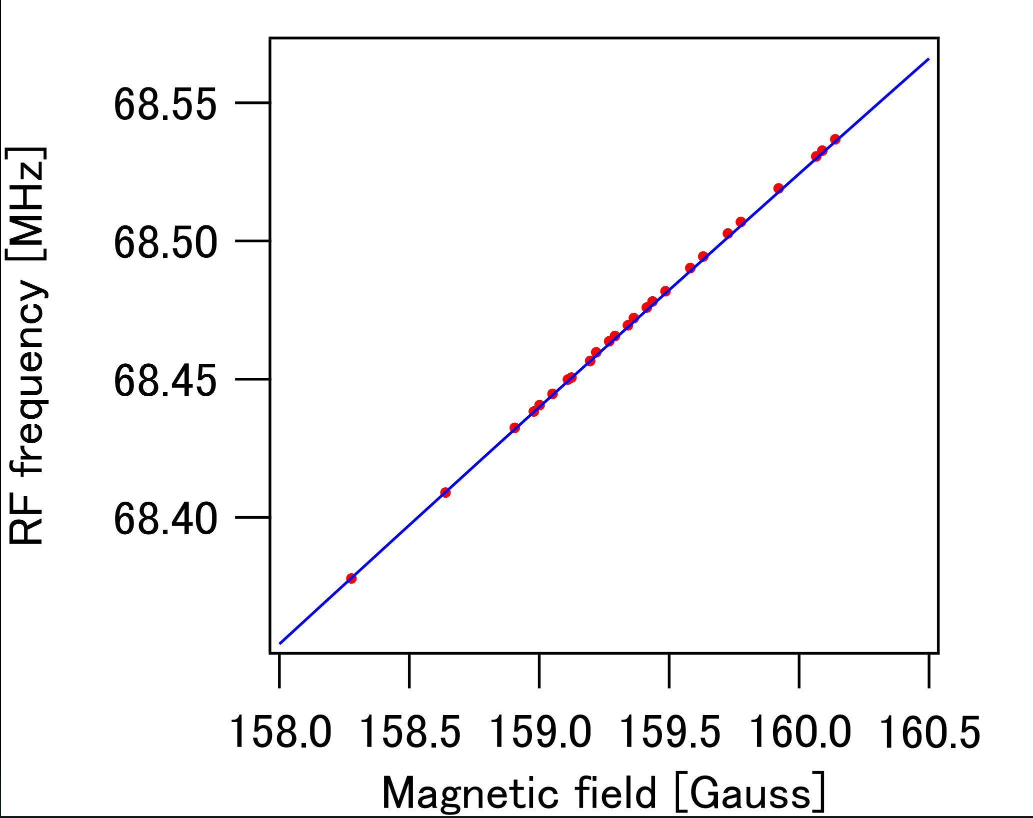
Turn off the trap ⟶ Apply magnetic field gradient

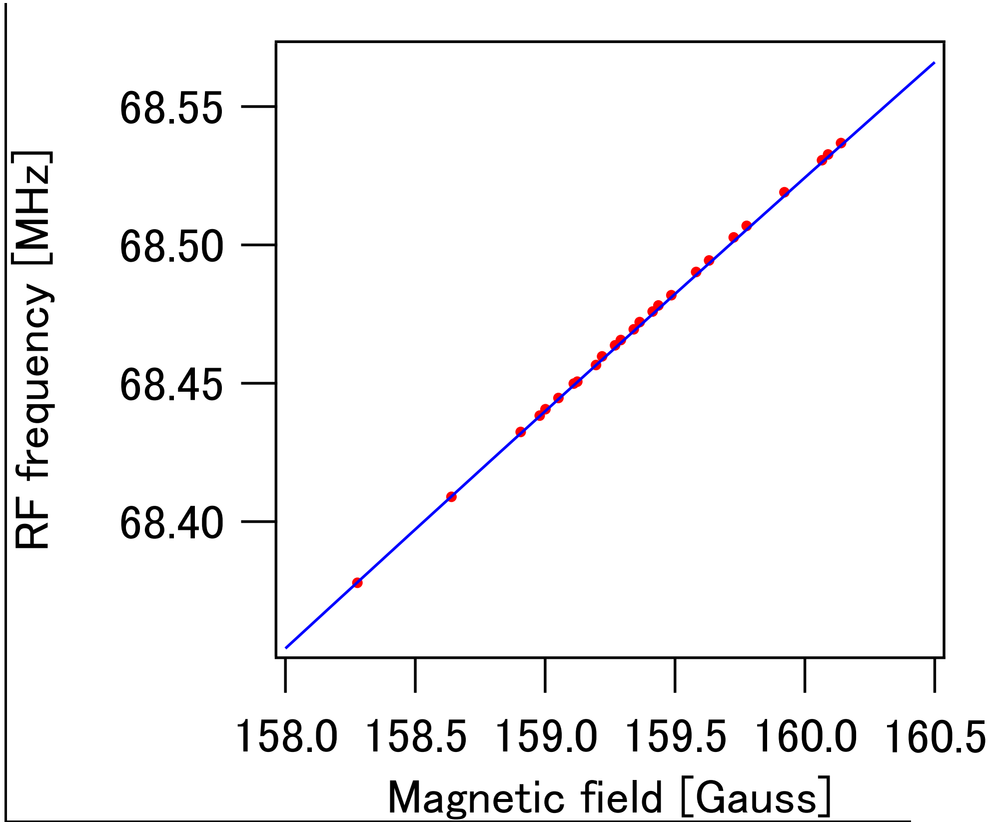


$|1\rangle$ $|2\rangle$




-400
-450
-500
-550
-600
Energy [MHz]
158.0
159.0
160.0
161.0
Magnetic Field [Gauss]

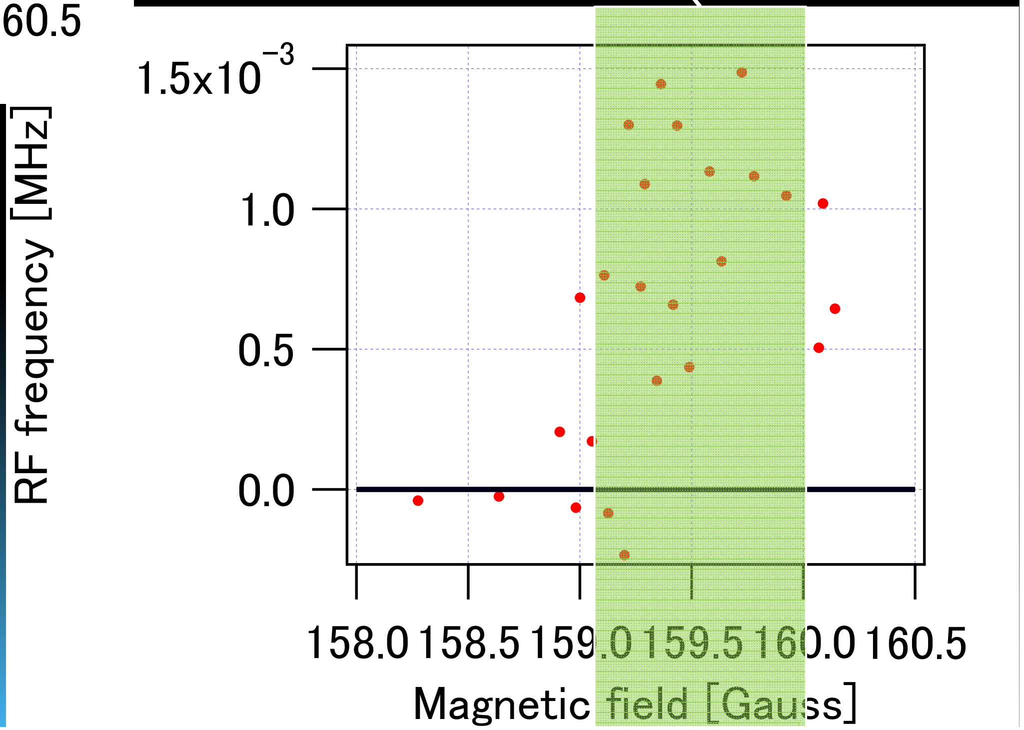

68.55
68.50
68.45
68.40
RF frequency [MHz]
158.0
158.5
159.0
159.5
160.0
160.5
Magnetic field [Gauss]



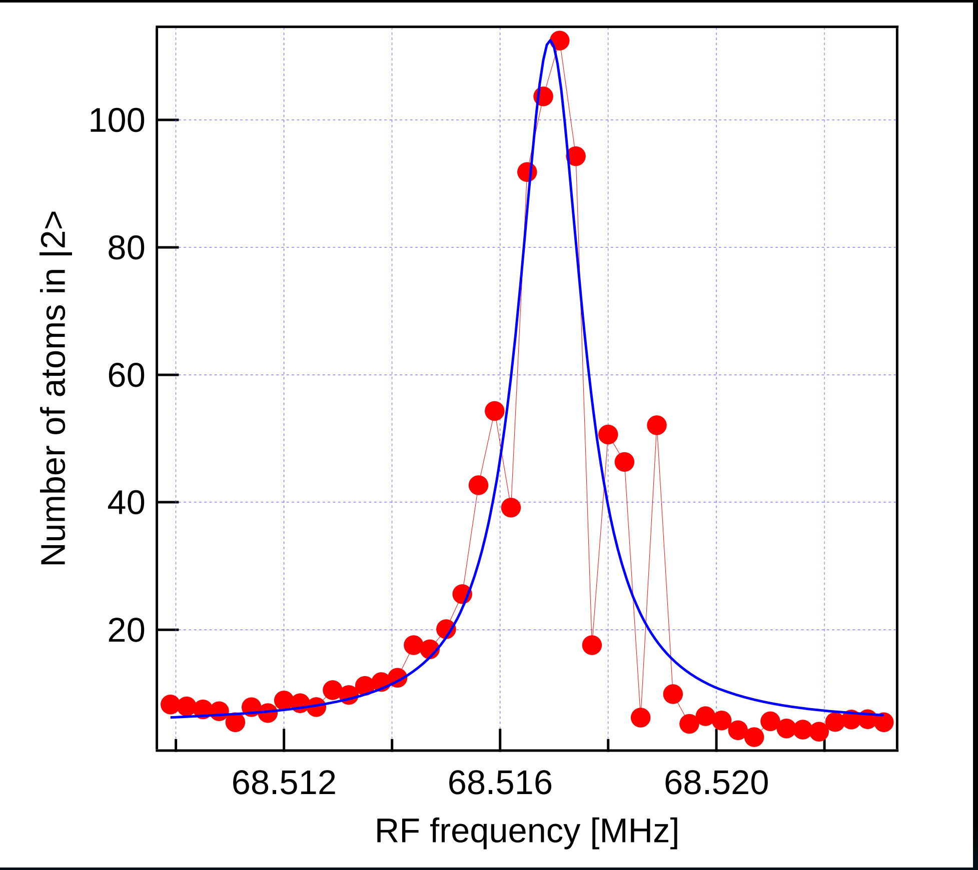
Preliminary!

Region where atomic loss is prominent

Subtract obvious energy shift from data

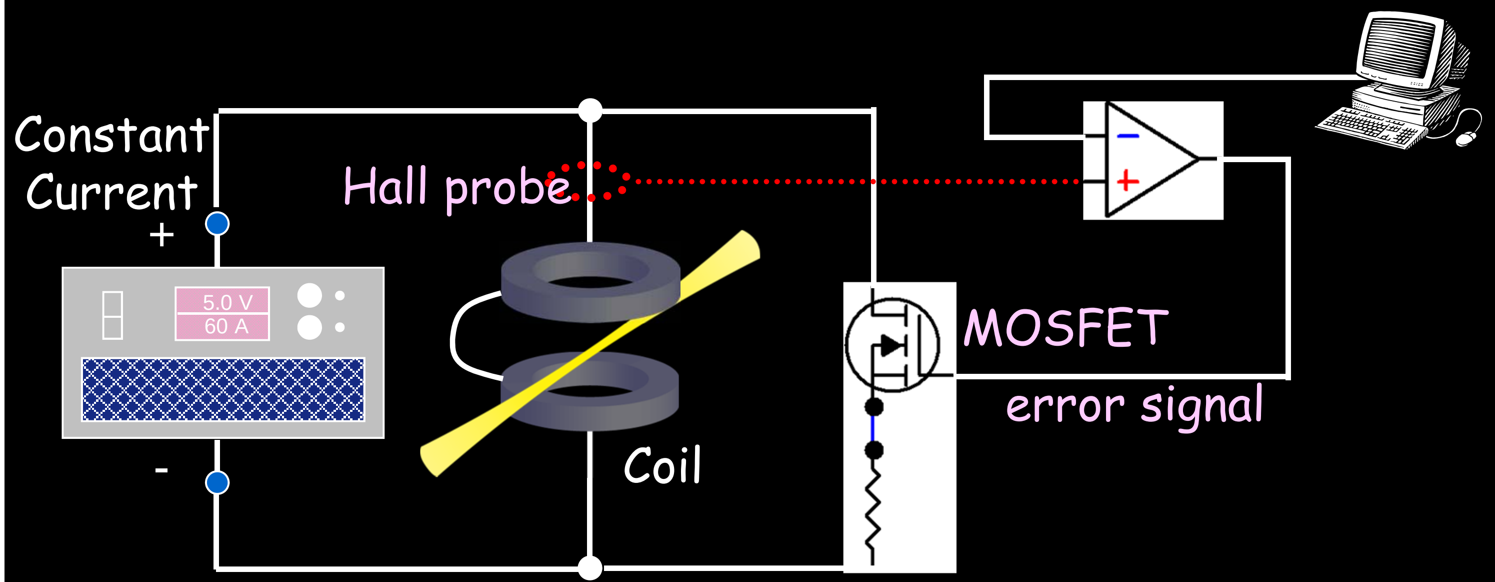


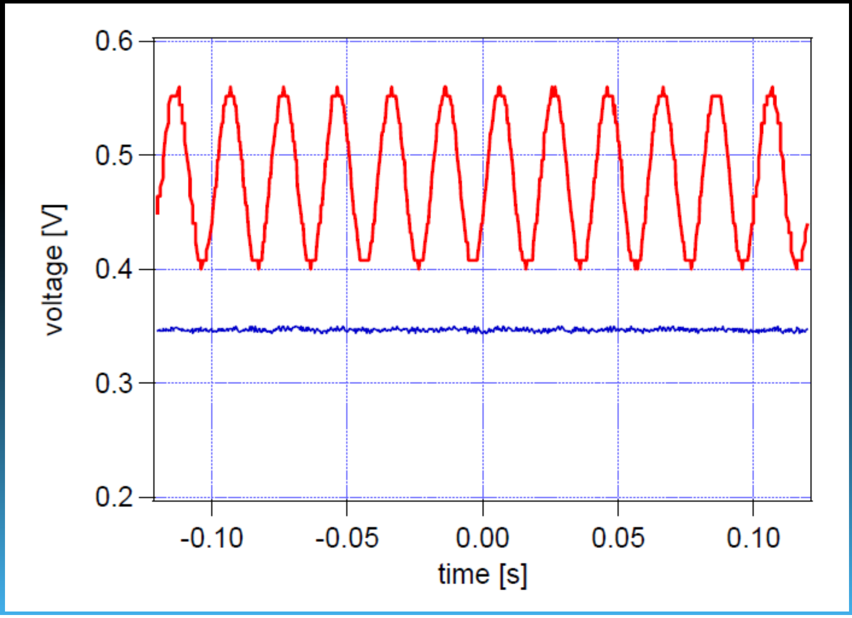
Typical RF spectrum



- 12 mG drift corresponds to 1 kHz (half div) shift of the resonance
- Slight asymmetry observed

current stabilization





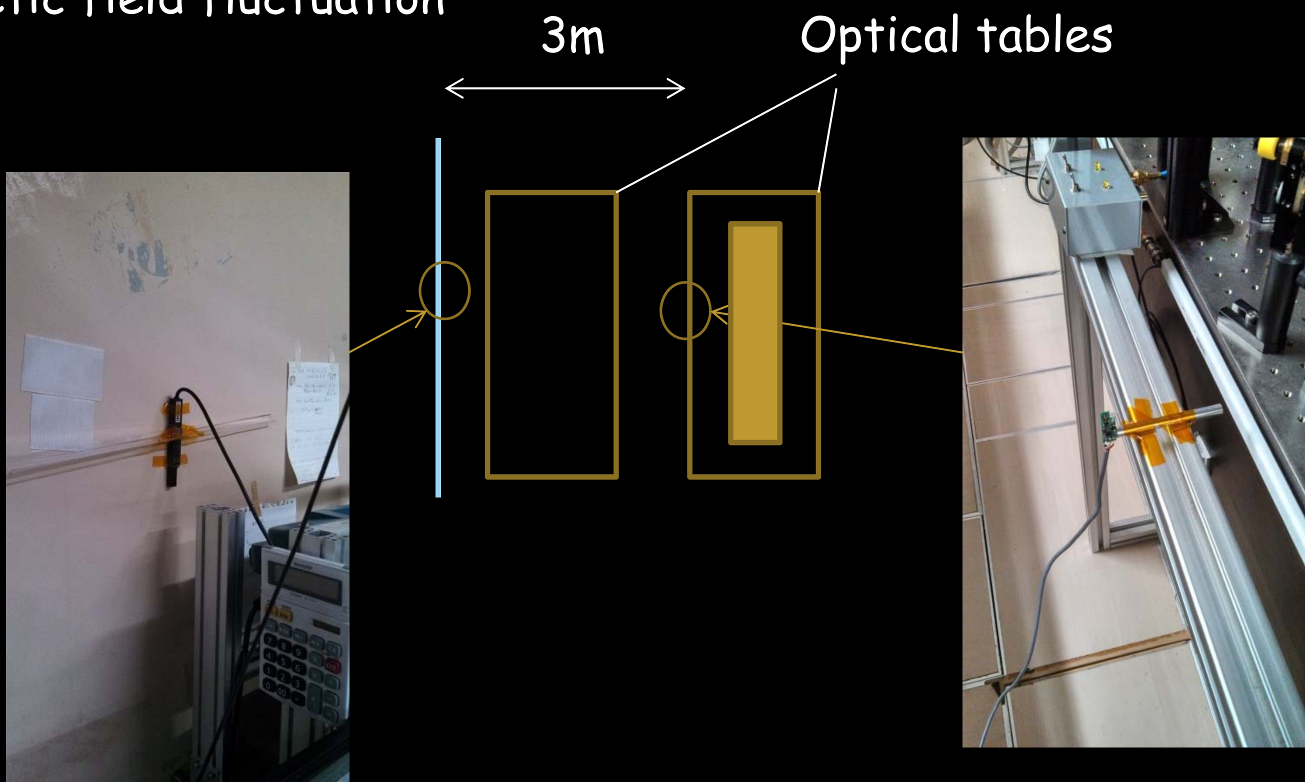
Without stabilization

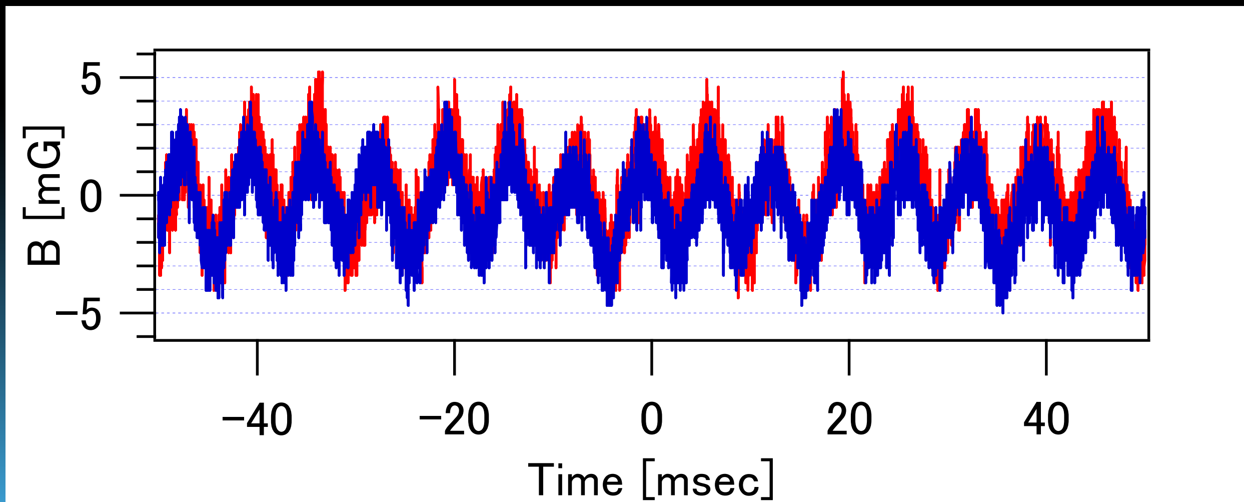
B fluctuation ~ 300 mG

With stabilization

B fluctuation ~ 4 mG@160G

Magnetic field fluctuation





red: near the wall
blue: on the machine table

High-temperature expansion of a grand partition function

$$\Xi = \mathrm{Tr} e^{-(H-\mu N)/k_{\mathrm{B}}T} = \Xi^{(0)} + 2\sqrt{2}\left(\frac{Vz^2}{\lambda^3}\right) b_2 + O\left(z^3\right)$$

$$z = e^{\mu/k_{\mathrm{B}}T} << 1$$

$$b_2 = \sum_{\substack{\text{bound}\\\text{states}}} e^{|E_{\mathrm{b}}|/k_{\mathrm{B}}T} + \sum_{l=0}^{\infty}(2l+1)\int_0^{\infty}\frac{\mathrm{d}k}{\pi}\frac{\mathrm{d}\delta_l(k)}{\mathrm{d}k}e^{-\lambda^2 k^2/2\pi}$$

$$\lambda \equiv h\Big/\sqrt{2\pi m k_{\mathrm{B}}T}$$

"Statistical Mechanics"
Kerson Huang

Interaction energy

$$\varepsilon_{\mathrm{int}} = \frac{3nk_{\mathrm{B}}T}{2}\left(n\lambda^3\right)\left[-\frac{b_2}{\sqrt{2}} + \frac{\sqrt{2}}{3}T\frac{\partial b_2}{\partial T}\right]$$

T. -L. Ho and E. J. Muller, Phys. Rev. Lett. 92, 160404 (2004)

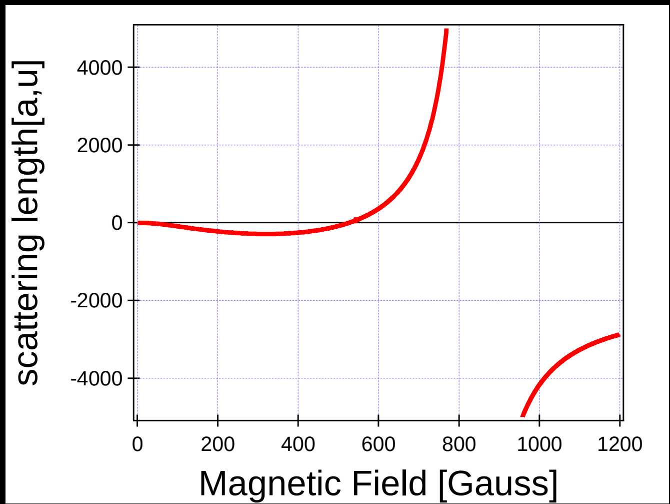
p-wave scattering phase shift

$$\cot\delta_p(k) = \frac{1}{k^3}\left(-\frac{1}{V} + k_{\mathrm{e}}k^2\right)$$

V and ke have to be determined from a separate experiment.

Scattering parameters

s-wave, ^{6}Li, $|1\rangle-|2\rangle$



$$f_s(k) = \frac{1}{-1/a(B) + r_s k^2/2 - ik}$$

$$a(B) = a_{bg}\left(1 + \frac{\Delta B}{B - B_{res}}\right)$$

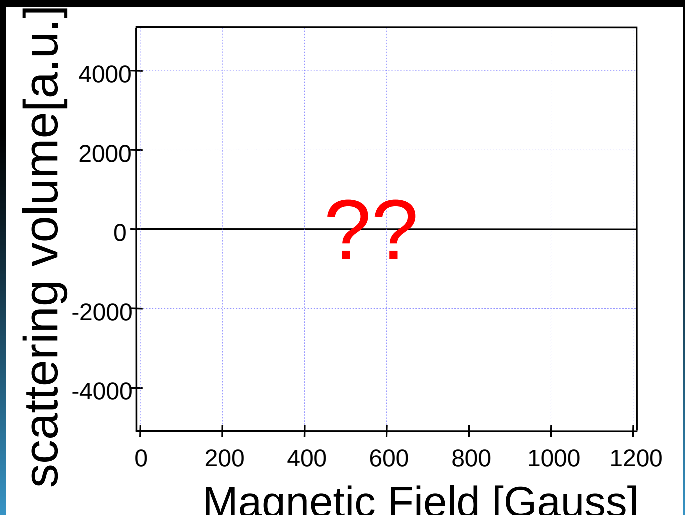
$a_{bg} = 1582\, a_0$

$\Delta B = -262.3\,[\mathrm{G}]$

$B_{res} = 832.18\,[\mathrm{G}]$

G. Zurn et al.
Phys. Rev. Lett.
110, 135301 (2013)

p-wave, ^{6}Li, $|1\rangle-|1\rangle$

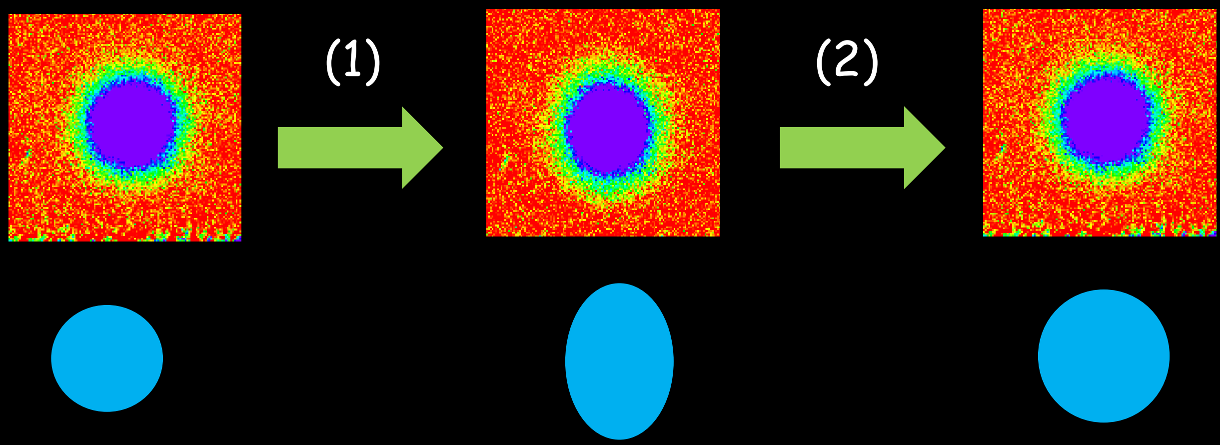


$$f_p(k) = \frac{k^2}{-1/V(B) + k_e k^2/2 - ik^3}$$

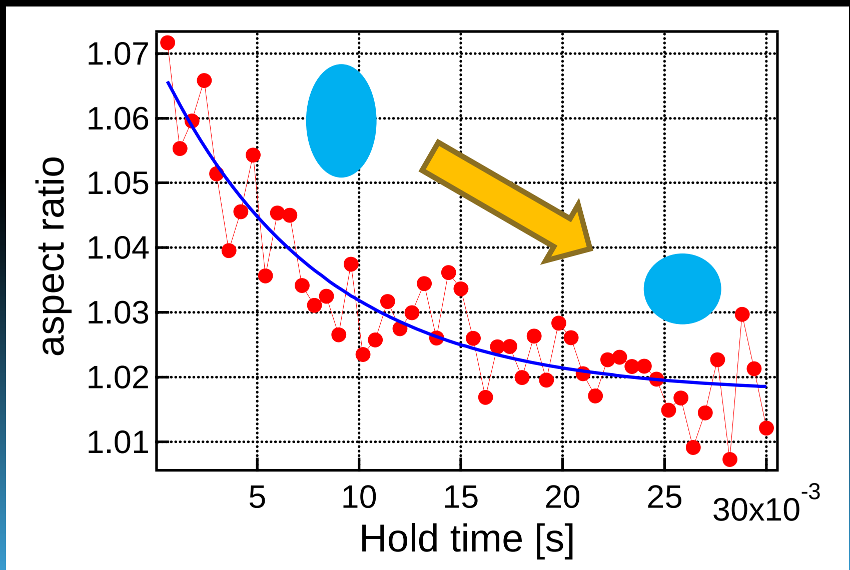
$$V(B) = \boxed{a_{bg}^3}\left(1 + \frac{\boxed{\Delta B}}{B - \boxed{B_{res}}}\right)$$

$\square$ ... unknown parameters

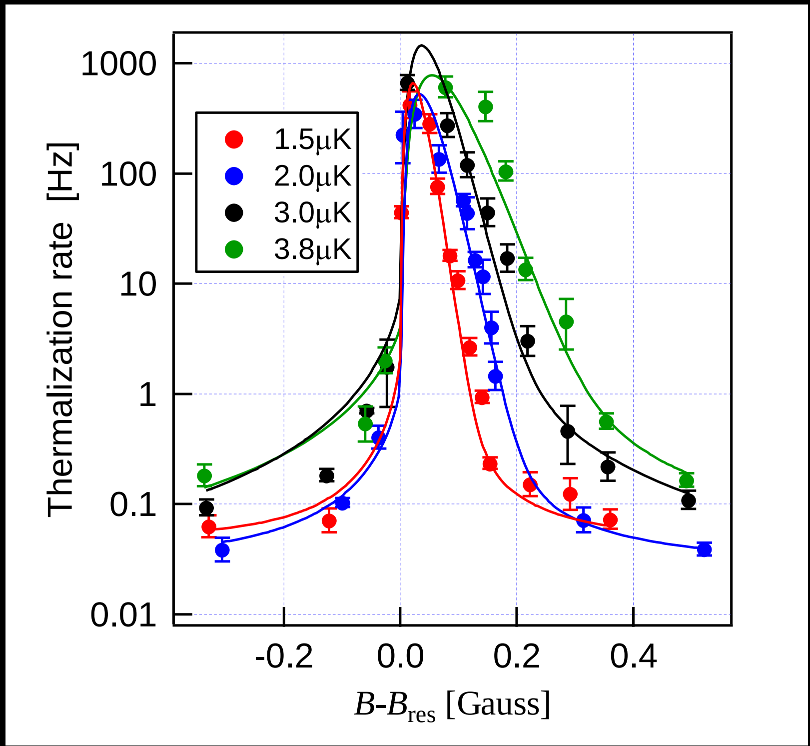
Images taken after ballistic expansion



(1) modulate trap laser intensity at 3.4 kHz to add energy in one direction
(2) cross-dimensional thermalization due to elastic collisions



Elastic collision cross-section can be derived from the timescale of the thermalization.



T. Nakasuji, J. Yoshida, and T. Mukaiyama, Physical Review A **88**, 012710 (2013).

$$V_{bg} \times \Delta B = 2.8 \times 10^{6} a_0^3 \; [\mathrm{Gauss}]$$

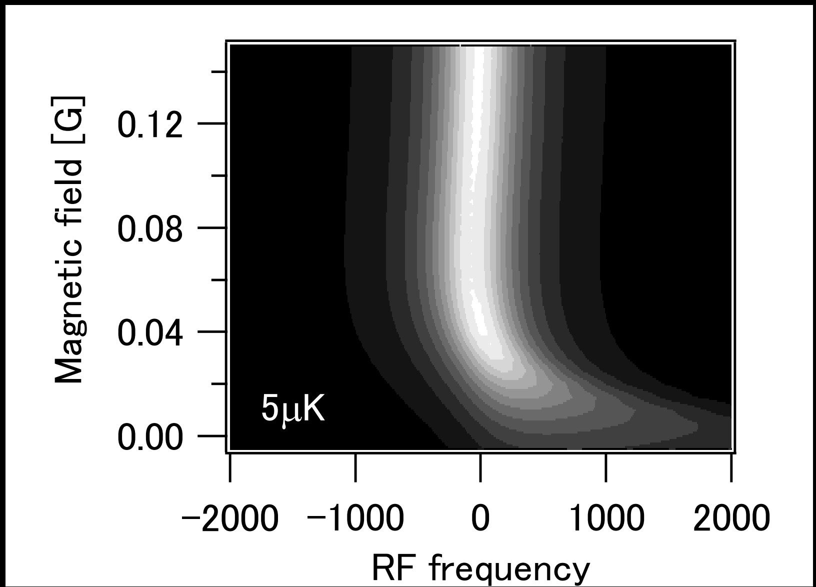
$$k_e = -0.058 a_0^{-1}$$

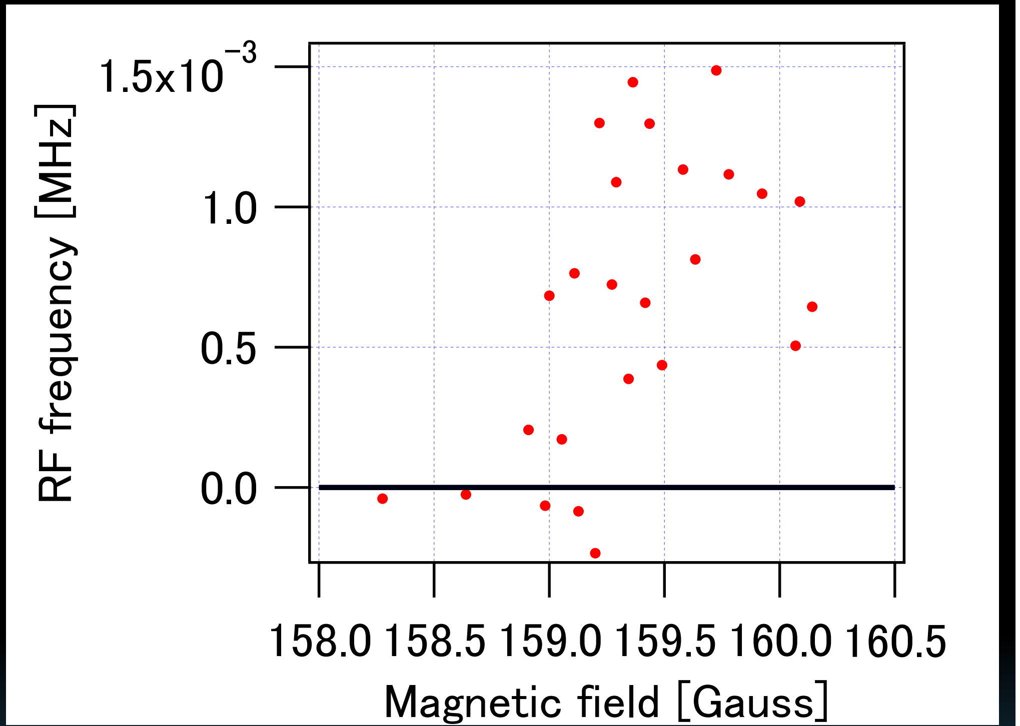
$$\langle n^2 \rangle \times \sqrt{\frac{2}{m\pi}} (k_B T)^{-5/2} \bullet 4\pi(2l+1) \left| f_l(E) \right| E^2 \exp(-E/k_B T)\, dE$$

$$f_{l=1}(k,B) = \frac{k^2}{-\frac{1}{V(B)} + k_e k^2 - i k^3} \qquad \frac{1}{V(B)} = V_{bg}^{-1} \left[1 + \frac{\Delta B}{B - B_{res}} \right]^{-1}$$

Calculation result

T=5μK $n\lambda^3 = 0.03$





Order of energy shift ~ 1 kHz
Magnetic field range ~ 40 mG

Order of energy shift ~ 1 kHz
Magnetic field range ~ 1 G

Summary

RF spectroscopy to probe p-wave interaction in a spin-polarized Fermi gas

- Systematic study on temperature dependence
- Reduction of magnetic field fluctuation
- Further integration to improve S/N ratio

are needed to claim the first measurement of p-wave interaction energy.

研究室メンバー

土師	慎祐	特任助教
齋藤	了一	M2
藤永	宗和	M2
吉田	純	M2
松田	優衣	M1
張	志琪	M1
興野	一樹	B4
服部	敬太	B4
向山	敬	PI