第8回クラスター階層領域研究会

(C02 group)

Experimental evaluation of the Virial coefficients for Unitary Fermi gases

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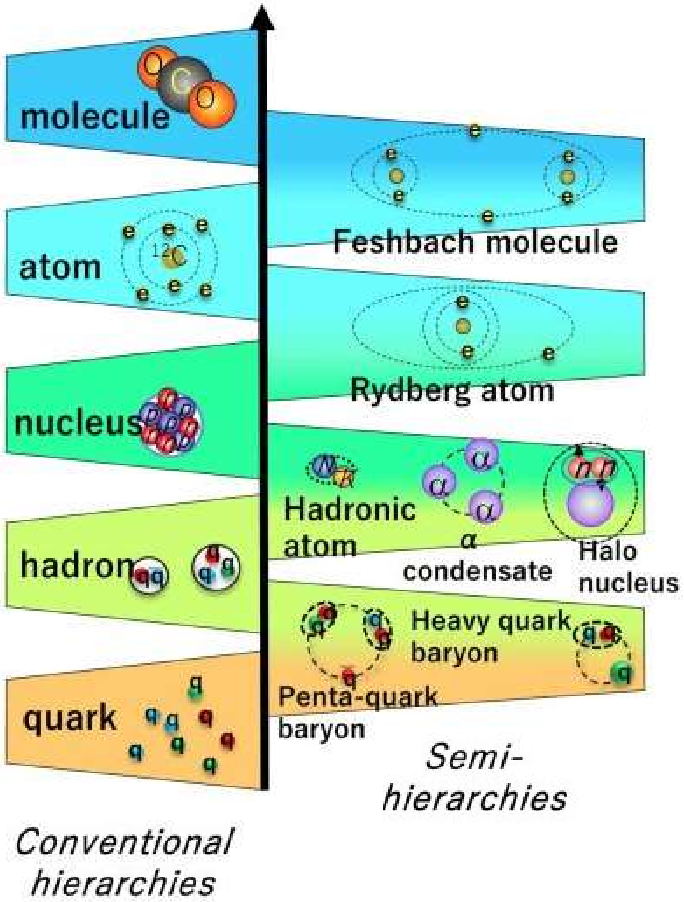
NITEP

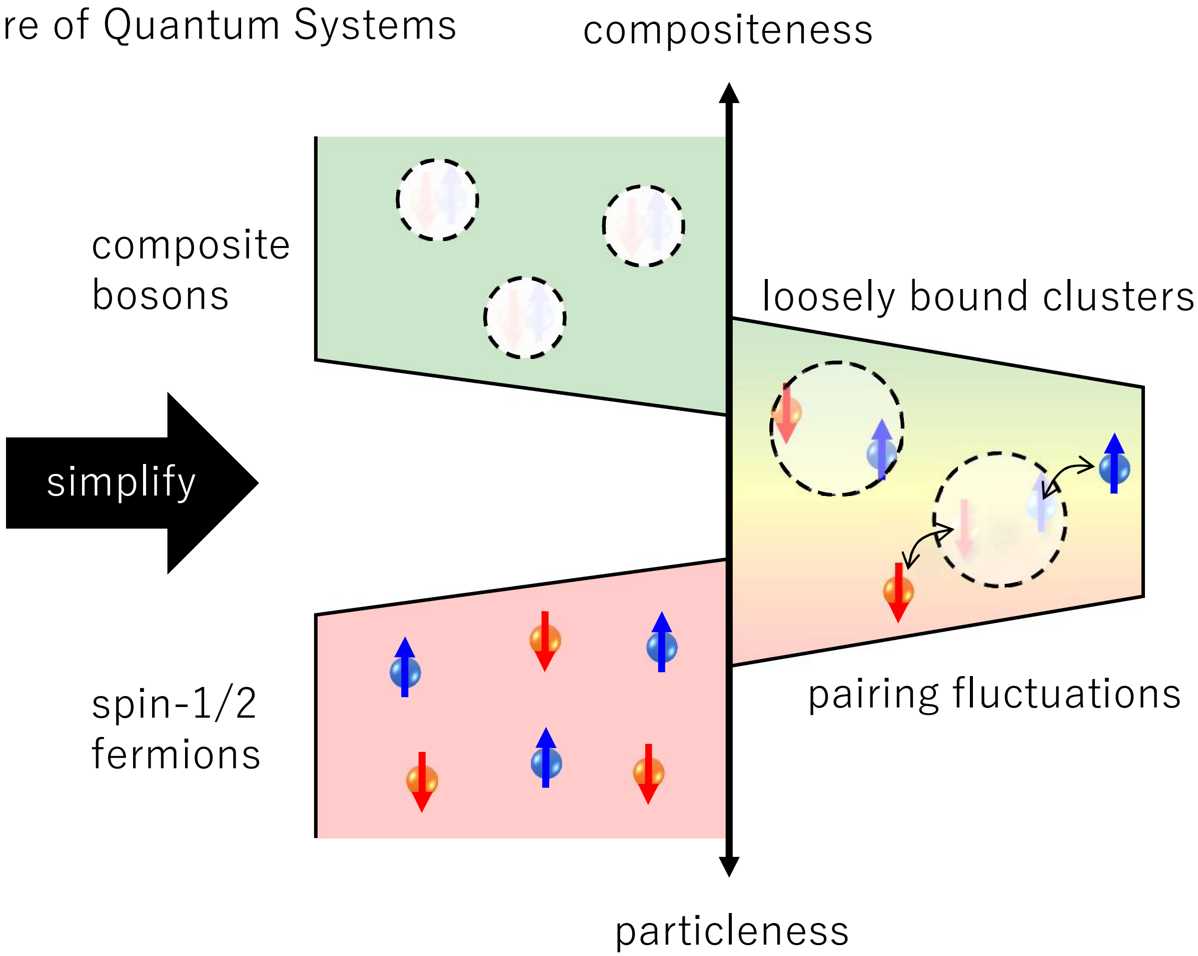
Clusters & Hierarchies

2023年2月9日-11日　大阪大学&オンライン

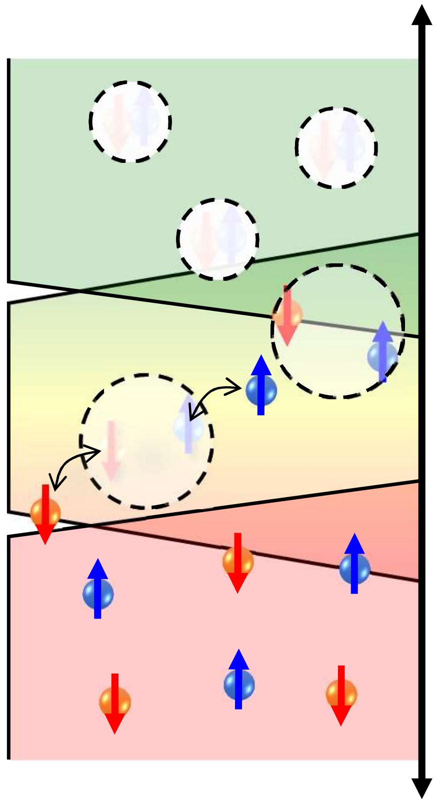
Introduction

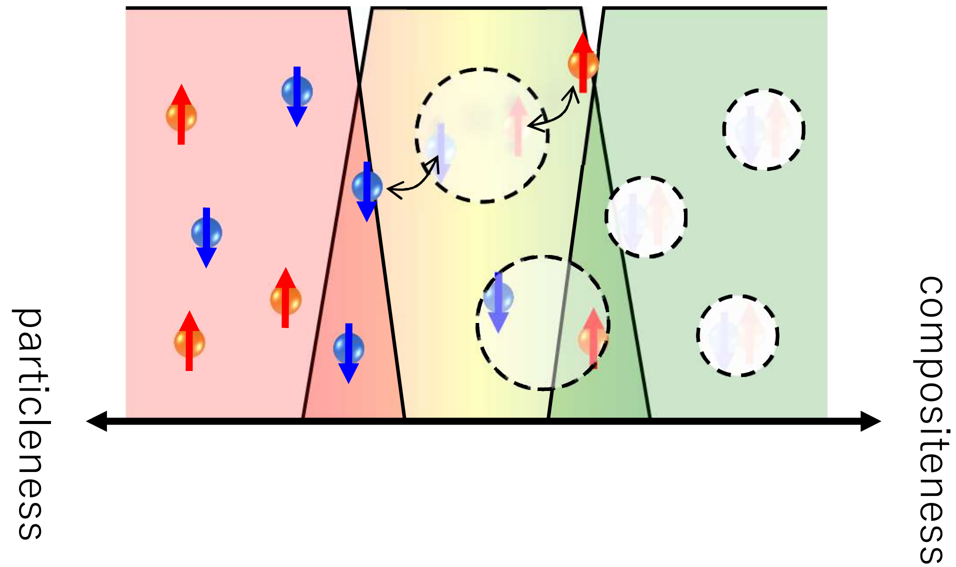
Simplify the Hierarchical Structure of Quantum Systems



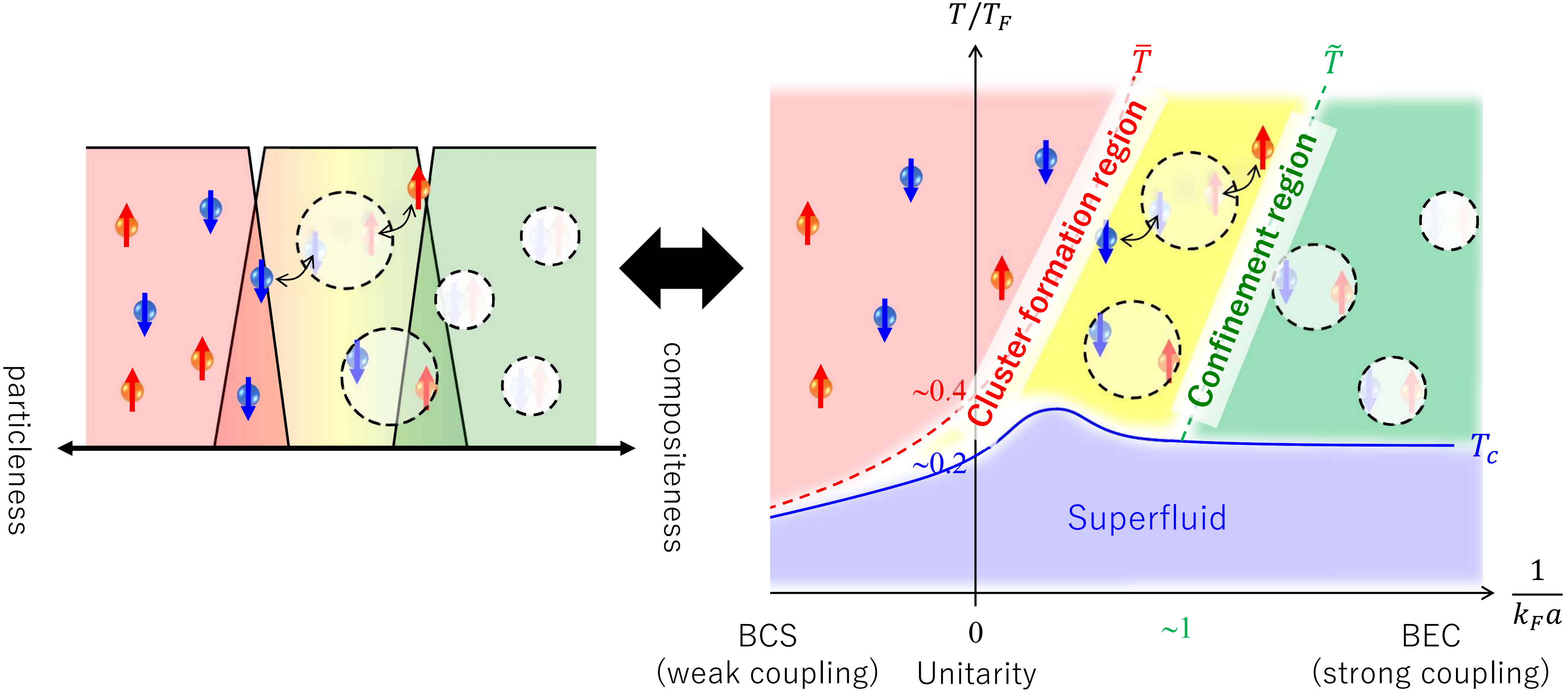


Introduction




particleness
compositeness

The phase diagram of spin-1/2 fermions with s-wave interactions



Today's talk is about Virial coefficients

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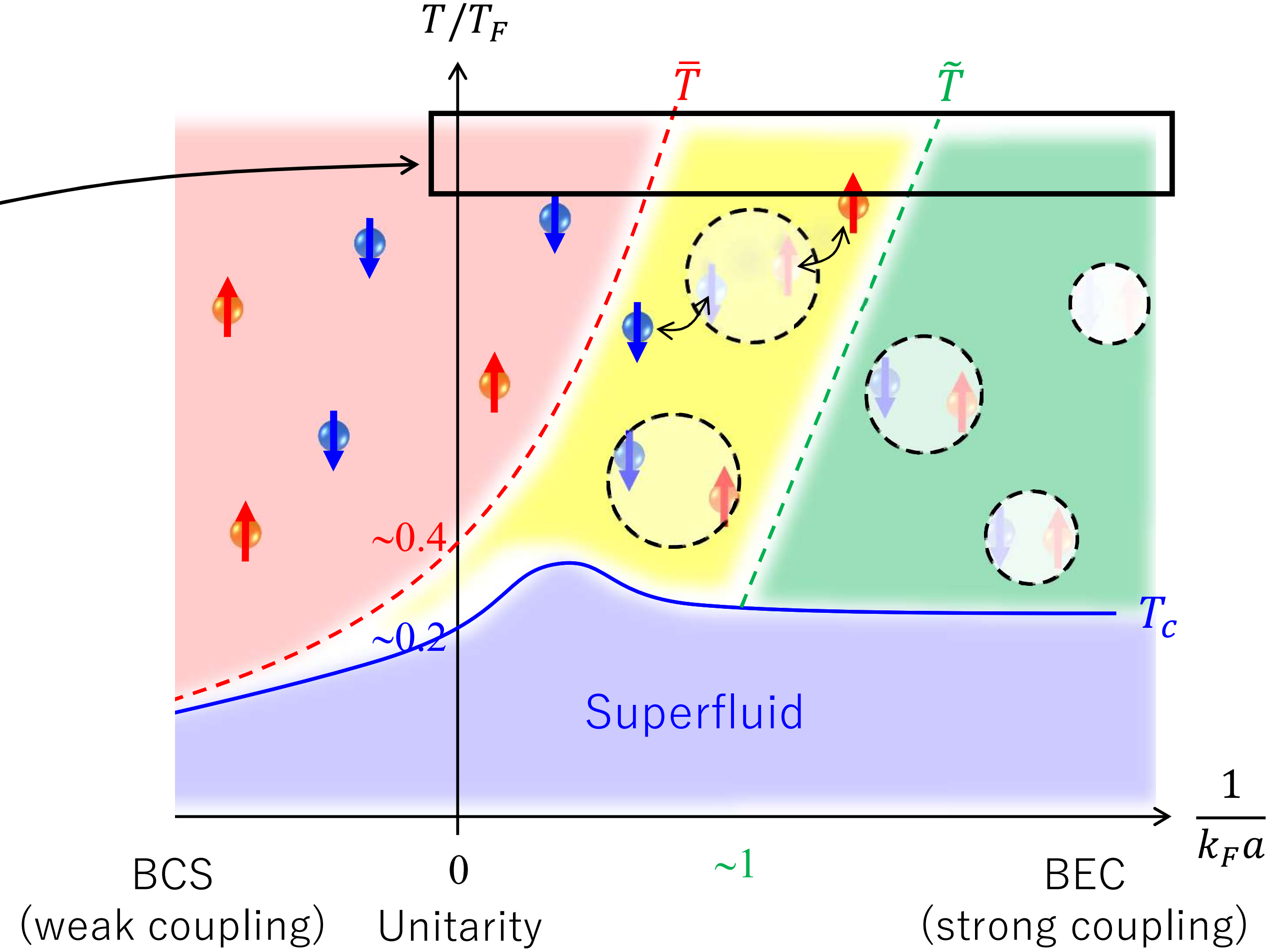
EOS at high temperature



Virial EOS and few-body physics

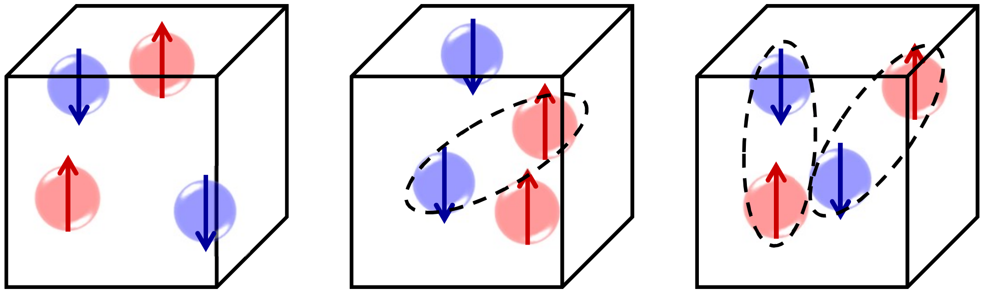
EOS = ideal Fermi gas + interaction effects

Fugacity : $z_{\alpha=\uparrow,\downarrow} \equiv \exp\left(\frac{\mu_\alpha}{k_B T}\right)$

Ideal Fermi gas : $f_P^{(0)}(z_\alpha) = -\mathrm{PolyLog}_{5/2}(-z_\alpha)$

$$P\frac{\lambda_T^3(T)}{k_B T} = f_P^{(0)}(z_\uparrow) + f_P^{(0)}(z_\downarrow) + \left\{\Delta b_{1,1}\left(\frac{\lambda_T(T)}{a_s}\right) z_\uparrow z_\downarrow + \Delta b_{2,1}\left(\frac{\lambda_T(T)}{a_s}\right)(z_\uparrow^2 z_\downarrow + z_\uparrow z_\downarrow^2) + \left(\Delta b_{3,1}\left(\frac{\lambda_T(T)}{a_s}\right)(z_\uparrow^3 z_\downarrow + z_\uparrow z_\downarrow^3) + \Delta b_{2,2}\left(\frac{\lambda_T(T)}{a_s}\right) z_\uparrow^2 z_\downarrow^2\right) + \cdots\right\}$$

2nd order | 3rd order | 4th order | 4th order



partition function of 4 fermions with ↑↑↓↓

$$Q_{\uparrow\uparrow\downarrow\downarrow} = \sum_{i=0}^{\infty} \exp\left(-\frac{E_{\uparrow\uparrow\downarrow\downarrow i}}{k_B T}\right)$$

$$Q_1 \equiv Q_\uparrow = Q_\downarrow$$

$$Q_2 \equiv Q_{\uparrow\uparrow} = Q_{\downarrow\downarrow}$$

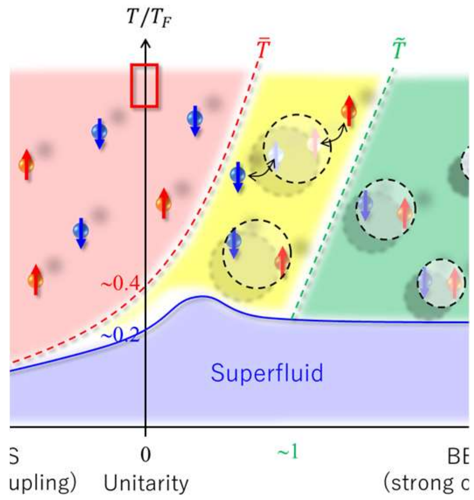
$$Q_3 \equiv Q_{\uparrow\uparrow\uparrow} = Q_{\downarrow\downarrow}$$

$$\left(Q_{\uparrow\uparrow\downarrow\downarrow} - \frac{Q_{\uparrow\downarrow}^2}{2} - 2Q_1 Q_{\uparrow\downarrow\downarrow} + 2Q_1^2 Q_{\uparrow\downarrow} - \frac{3Q_1^4}{2} + 2Q_1^2 Q_2 - Q_2^2\right)/Q_1$$

Virial coefficients at unitary limit

	Δb_2	Ref
Exp	$\frac{1}{\sqrt{2}}$	E. Beth and G. E. Uhlenbeck, Physica 4, **915** (1937)

	$\Delta b_3 = \frac{1}{2}\Delta b_{1,1}$	Ref
Theo	-0.3551030264521	Endo, PRA **92** 053624(2015) and Castin, Sci. **Post 3** 049 (2020)
Theo	-0.35510298	Liu, Hu, Drummond, PRA **82**, 023619 (2010)
Exp	**-0.35(2) @ENS**	S. Nascimbène, Nature **463**.7284, 1057-1060 (2010)



	$\Delta b_4 = \Delta b_{3,1} + \frac{1}{2}\Delta b_{2,2}$	$\Delta b_{3,1}$	$\Delta b_{2,2}$	Ref
Theo	0.062(1)	0.1838(4)	-0.244(2)	Endo, Castin, J. Phys. A **49**, 265301 (2016)
Theo	0.078(18)	0.170(12)	-0.184(26)	Yan, Blume, PRL **116**, 230401 (2016)
Exp	**0.096(15) @ENS**	-	-	S. Nascimbène, Nature **463**.7284, 1057-1060 (2010)
Exp	**0.096(10) @MIT**	-	-	Mark J. H. Ku, Science **335**.6068, 563-567 (2012)

Experimental setup

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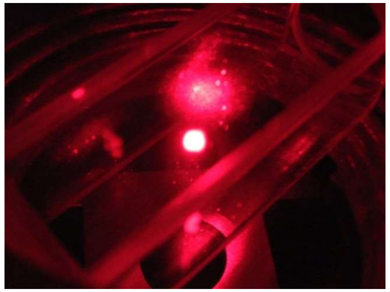
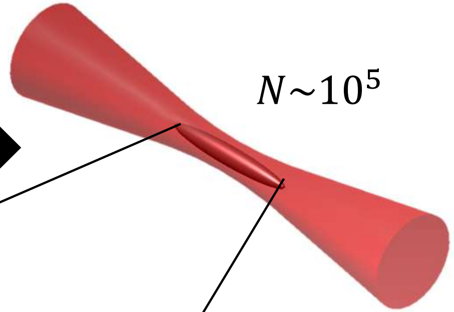
600K



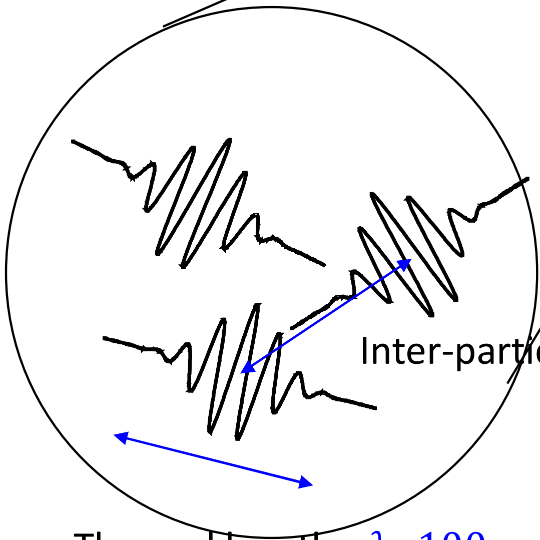
Laser cooling
$T\sim1\mathrm{mK}$

Optical trap



$N\sim10^5$

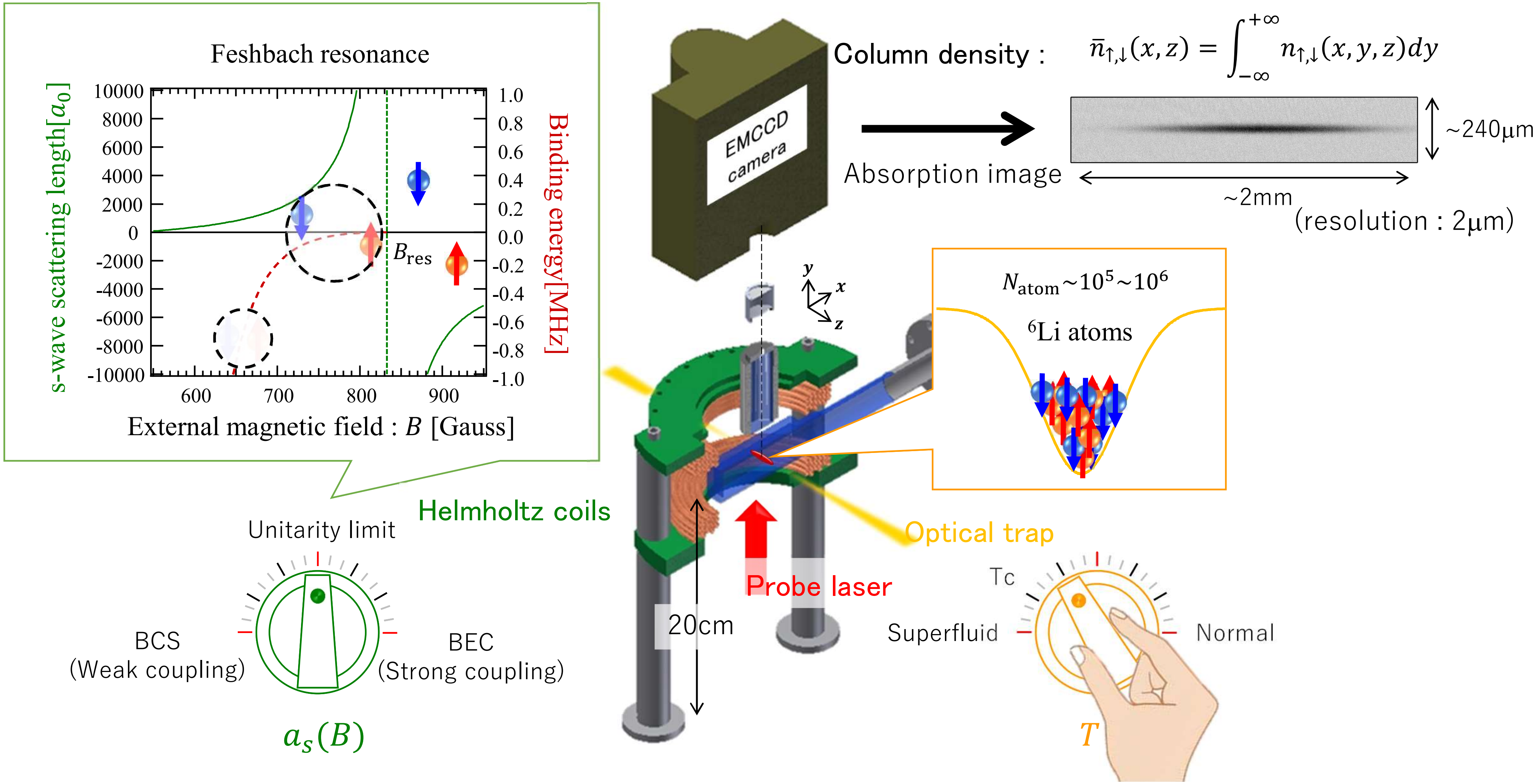
$T\sim100\mathrm{nK}$
(-273.1500001°C)



Inter-particle distance : $d\sim100\mathrm{nm}$

Thermal length : $\lambda\sim100\mathrm{nm}$

Experimental setup



EOS construction at unitary limit

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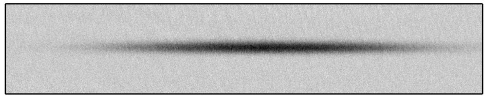
Column density



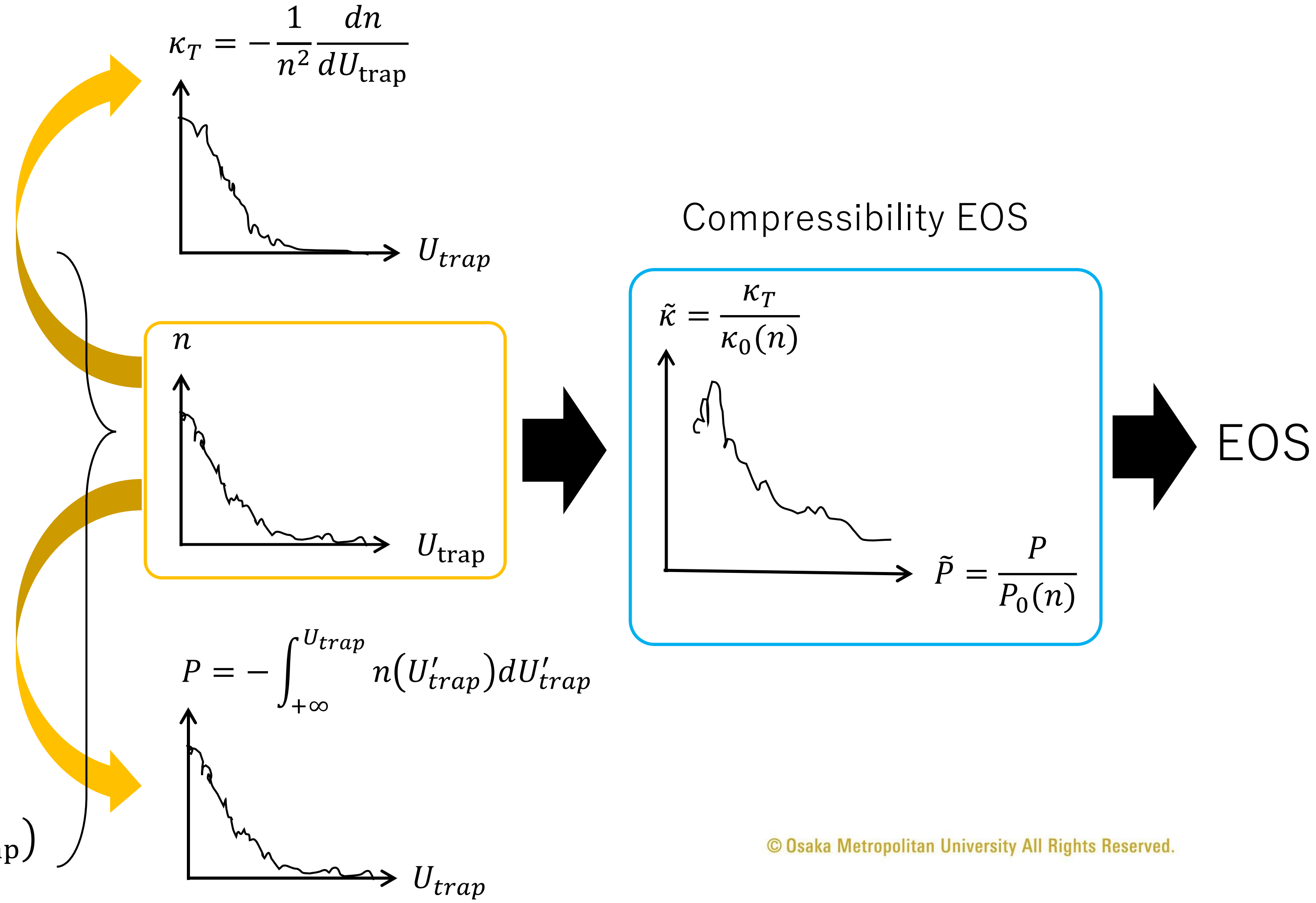
Inverse Abel

- Local density : $n(r, z)$

- Trapping potential : $U_{\mathrm{trap}}(r, z)$

- Local density approximation :

$$n(\boldsymbol{r}) = n(T, \mu(\boldsymbol{r}))$$
$$\simeq n\left(T, \mu_0 - U_{\mathrm{trap}}(\boldsymbol{r})\right) = n(U_{\mathrm{trap}})$$



Calibration of the trapping potential

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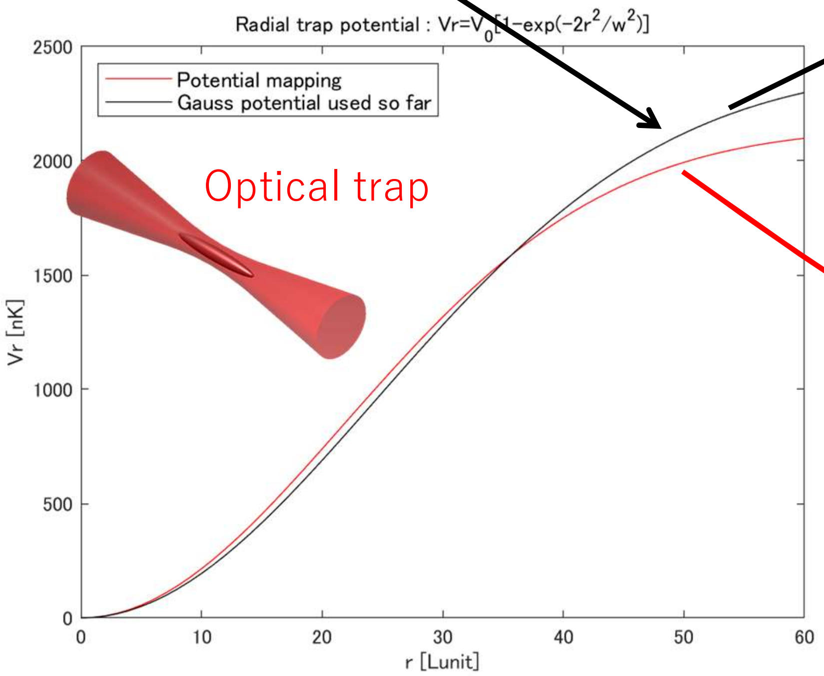
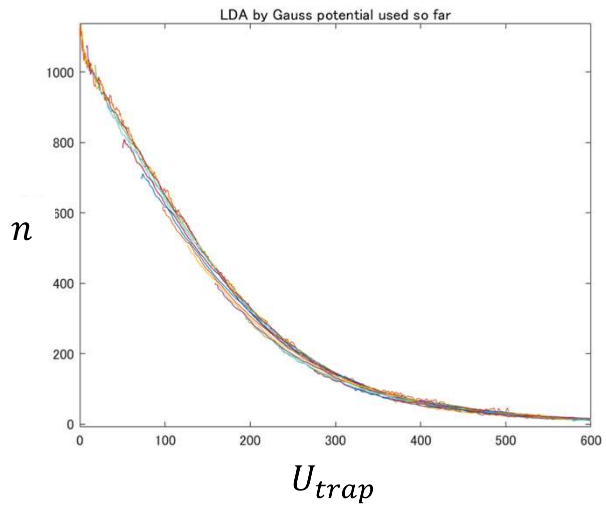
The shape of an optical trap potential is normally determined by

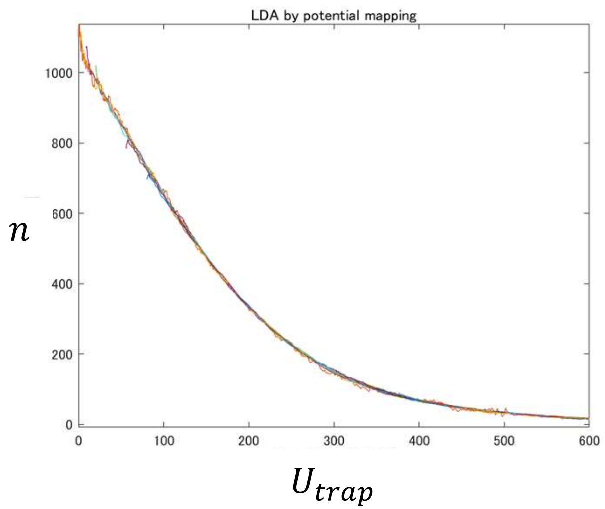
- laser power
- trapping frequency

They have uncertainties



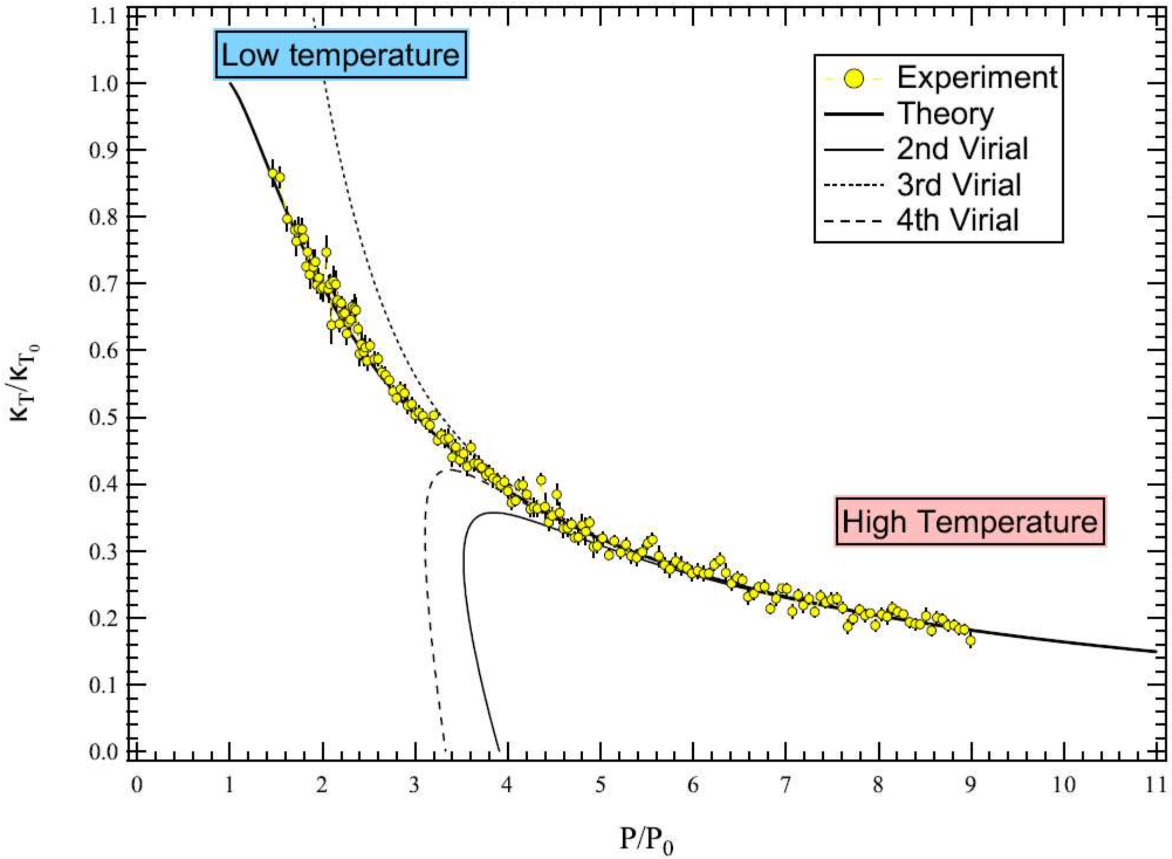
calibration





Benchmark : Ideal Fermi gas

Compressibility EOS



Unitary Fermi gas : $a^{-1} = 0$

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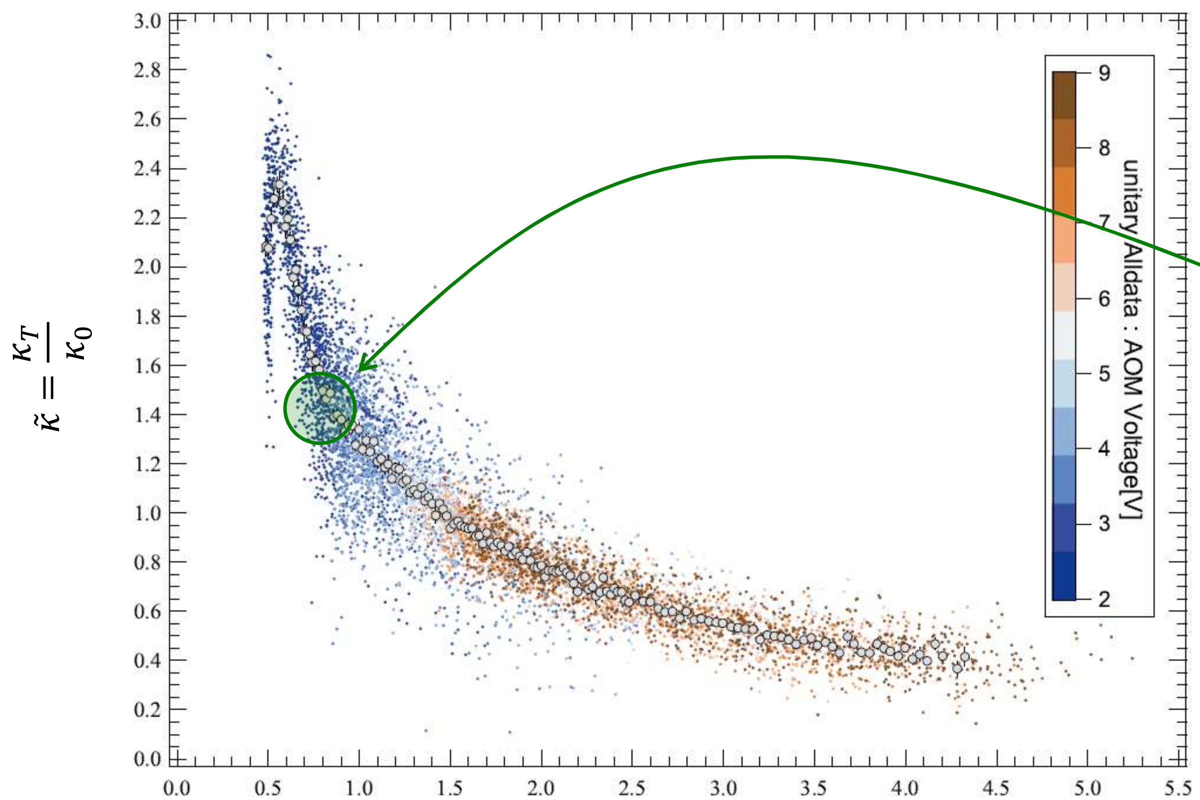
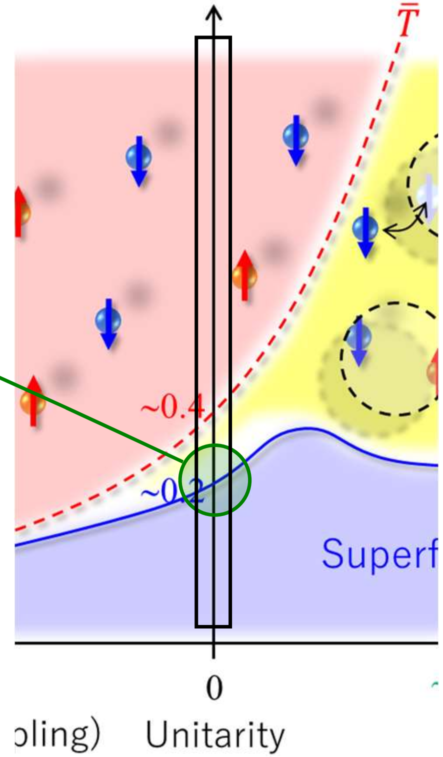
Compressibility EOS





Low T $\tilde{P} = \frac{P}{P_0}$ High T

Unitary Fermi gas : $a^{-1} = 0$

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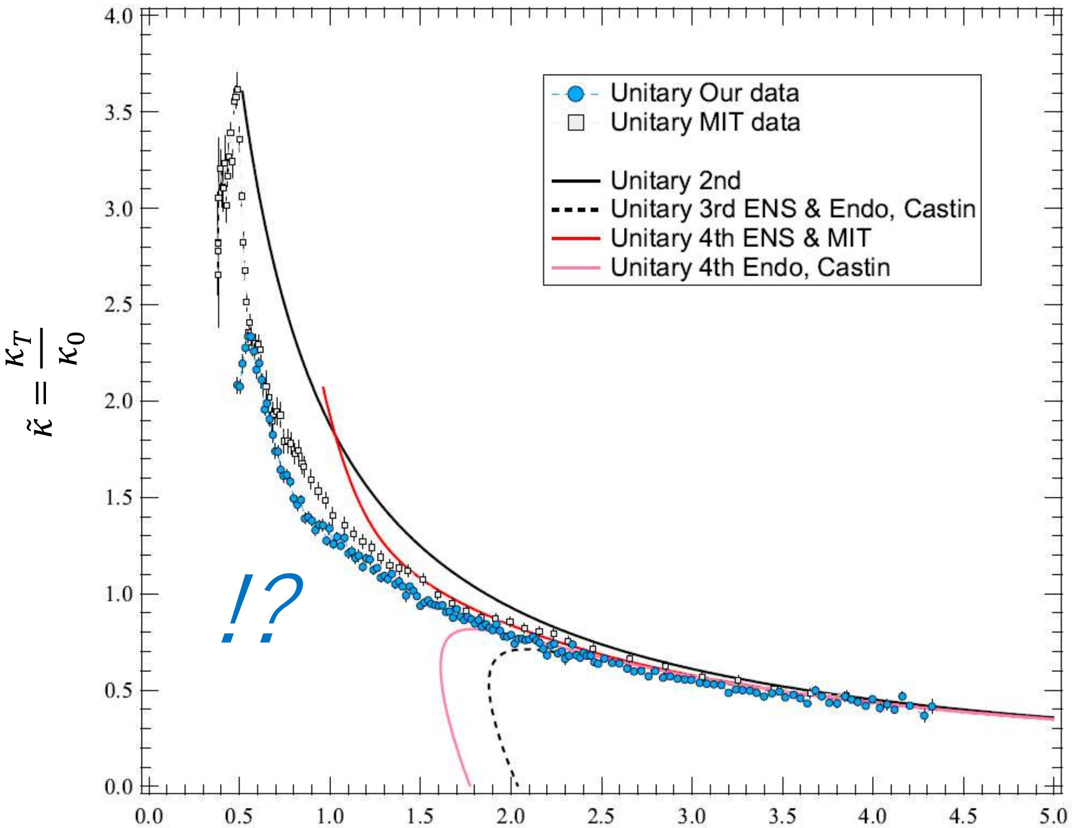
Compressibility EOS



$\tilde{P} = \frac{P}{P_0}$

Low T

High T

Radial confinement dependence

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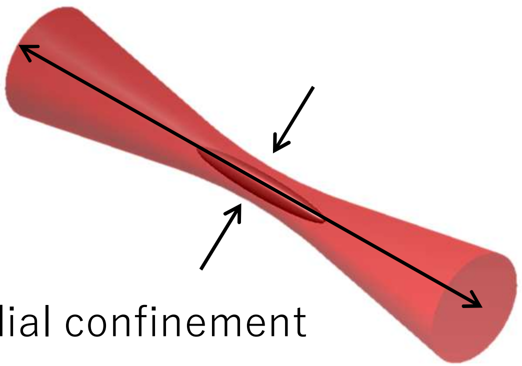
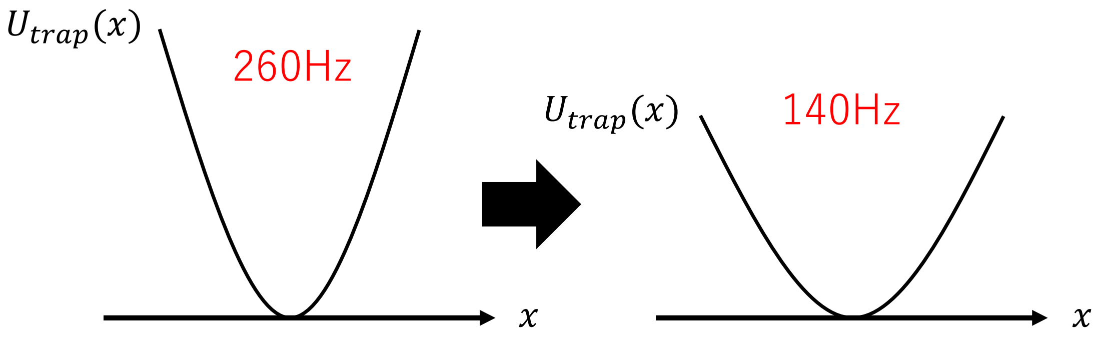
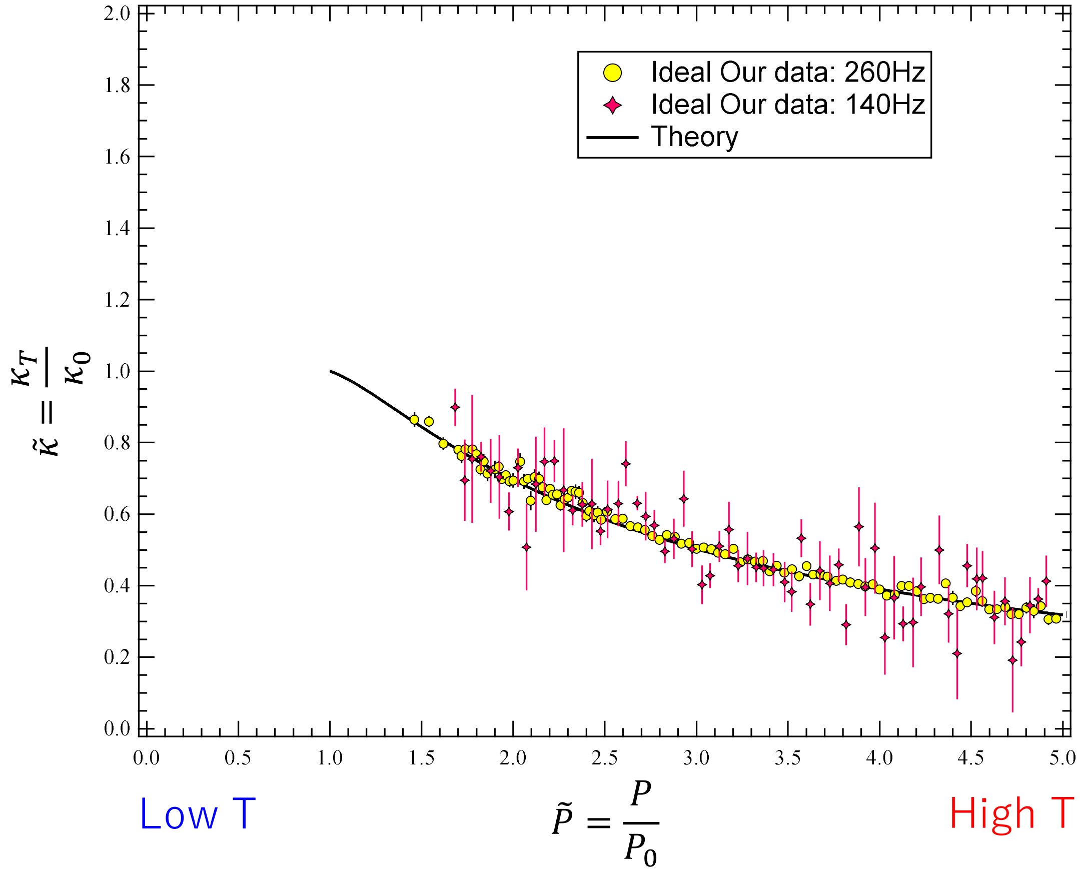
Fixed axial confinement : ~7Hz





Ideal Fermi gas



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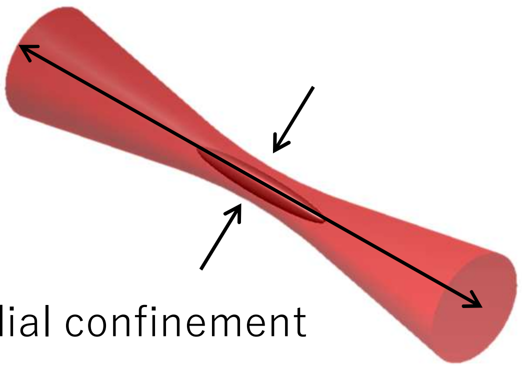
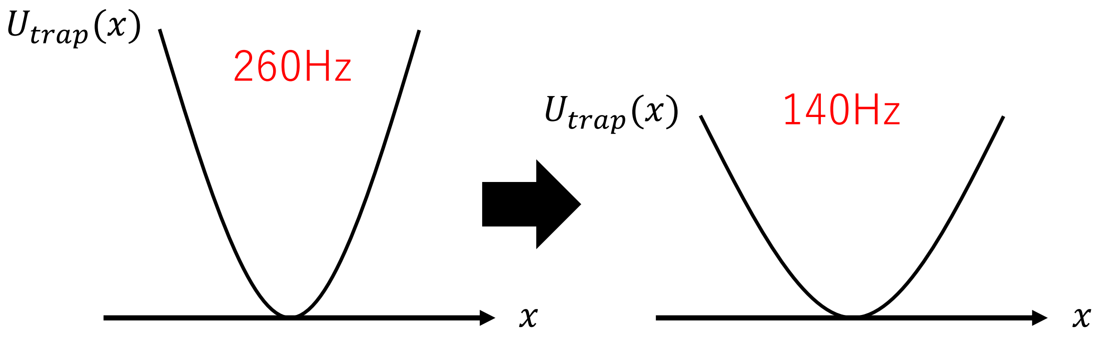
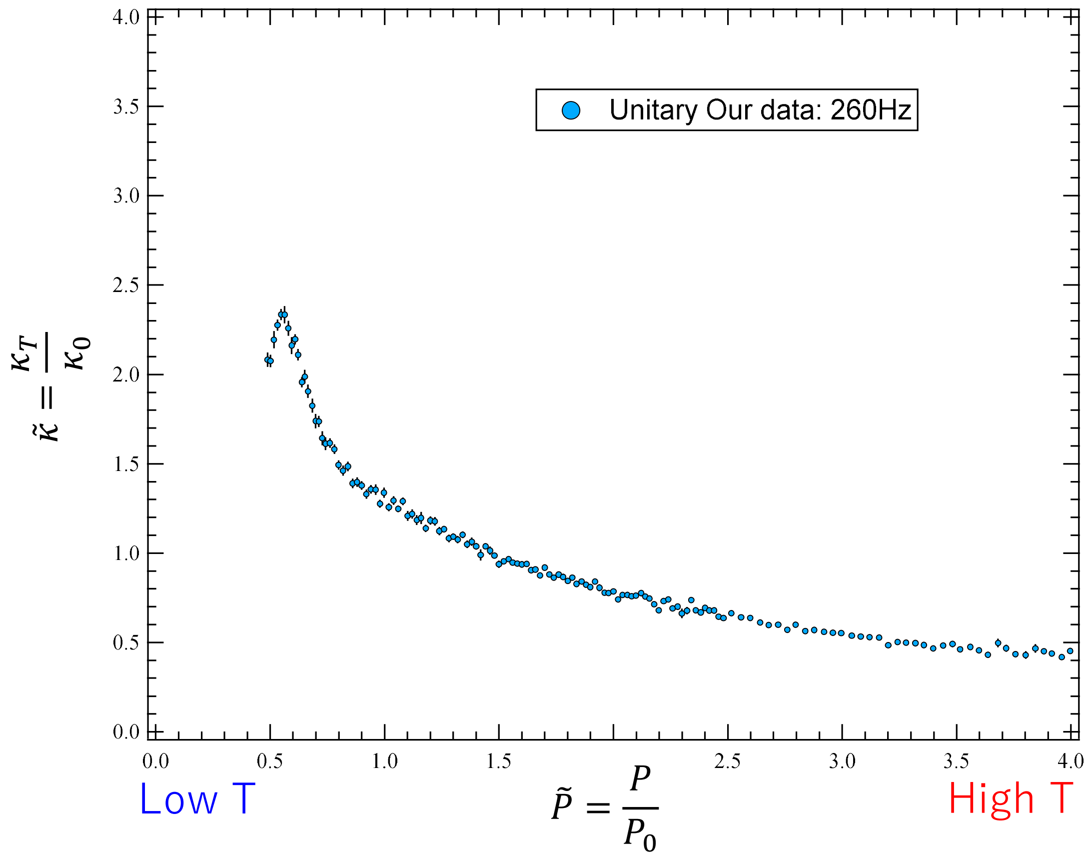




Unitary Fermi gas



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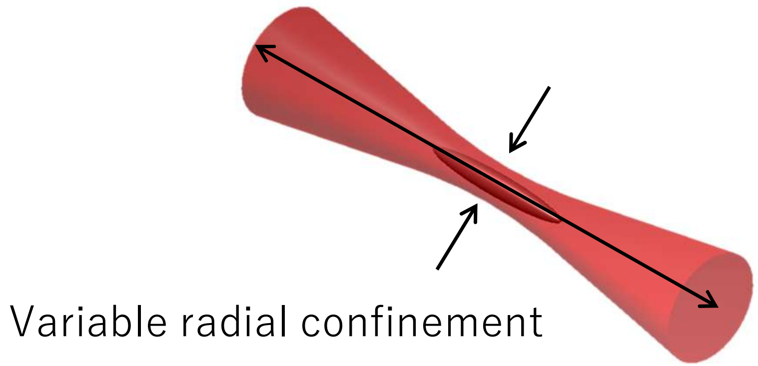

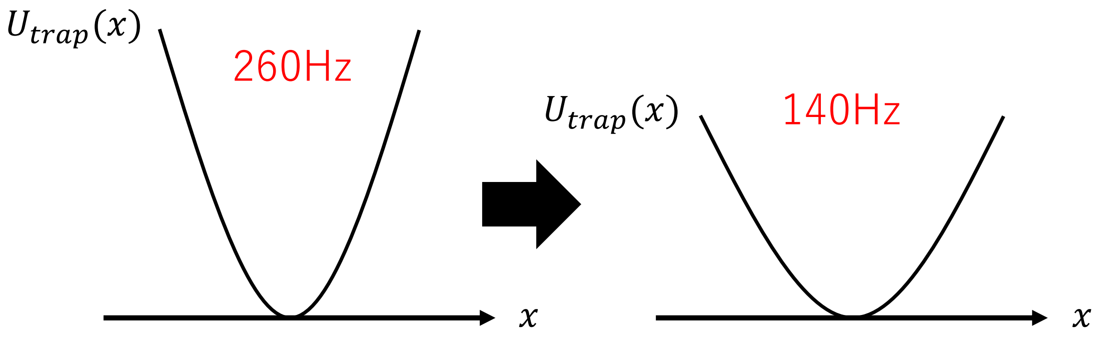

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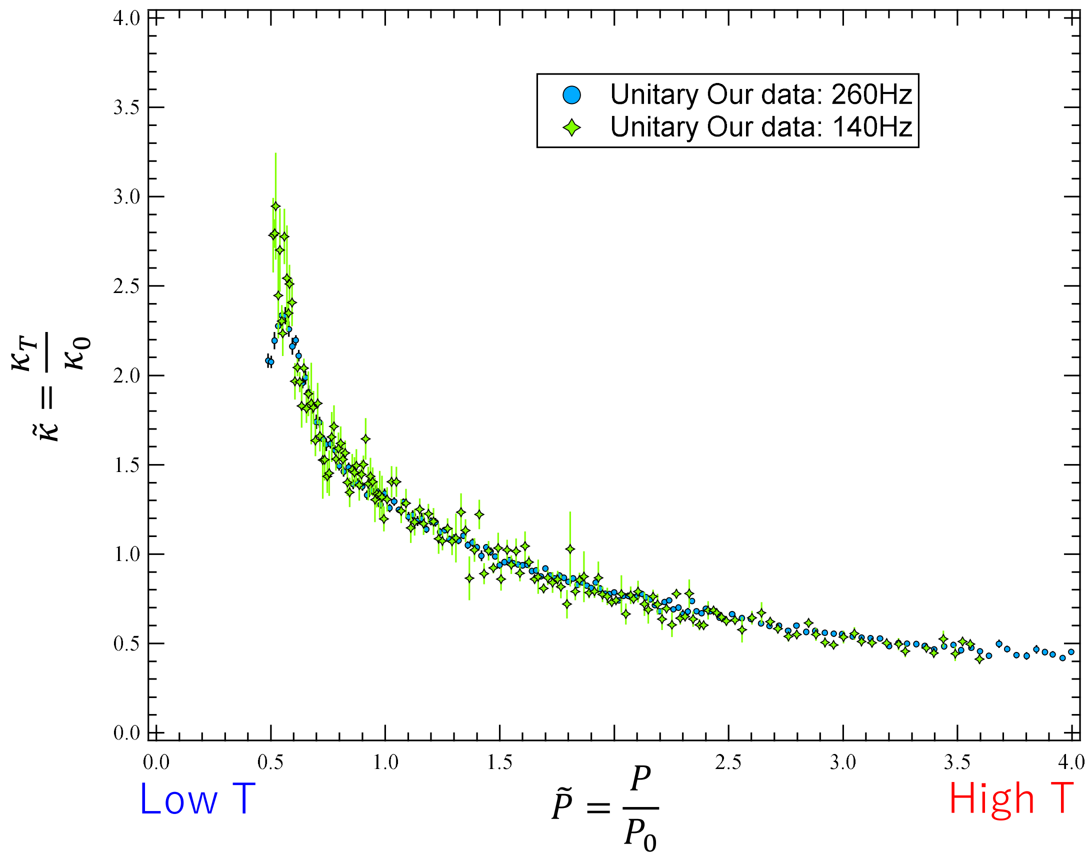
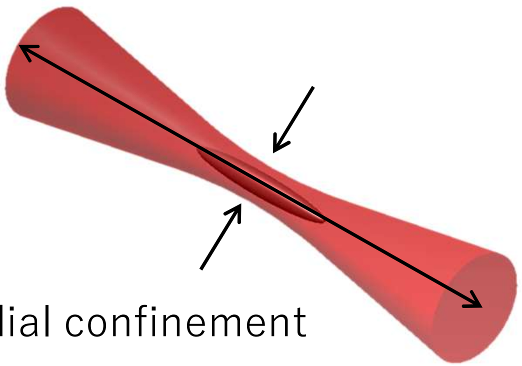
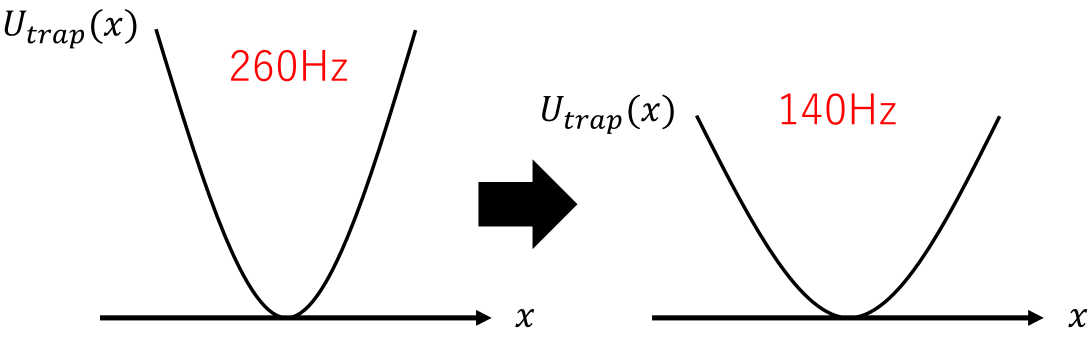


Radial confinement dependence

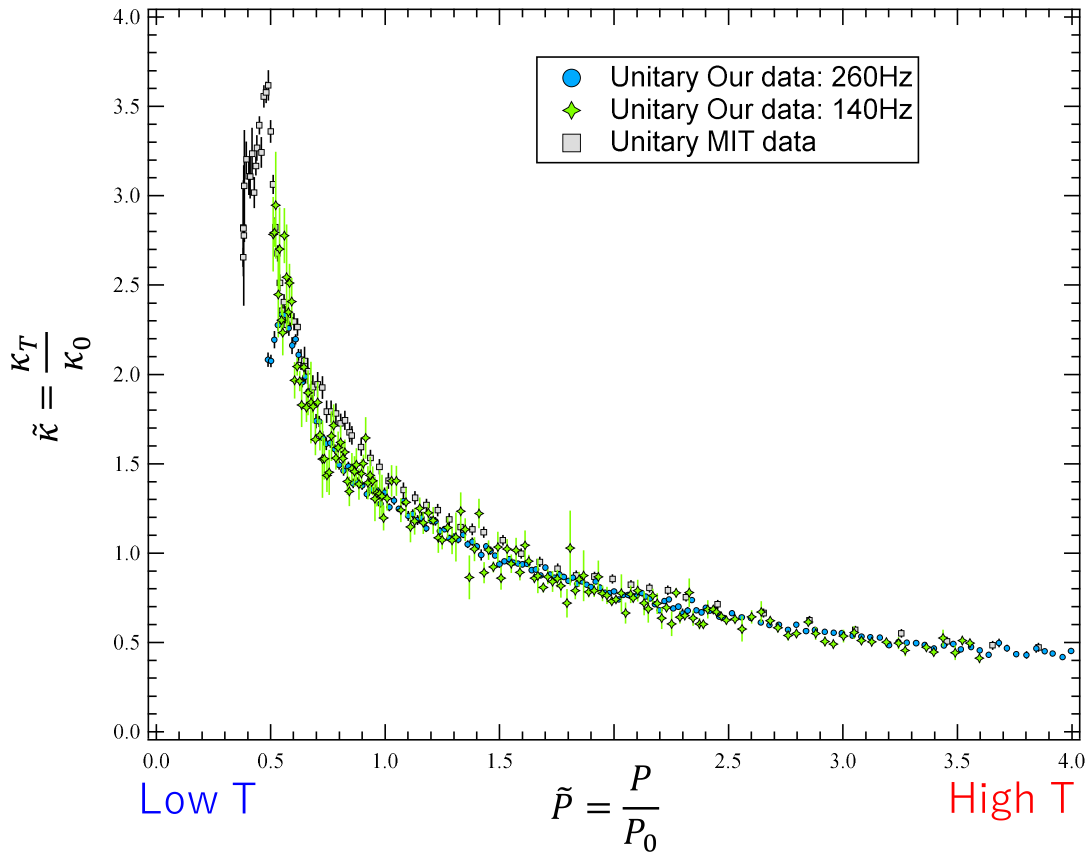
Fixed axial confinement : ~7Hz



Variable radial confinement



Unitary Fermi gas



Discussion : What changes the EOS?

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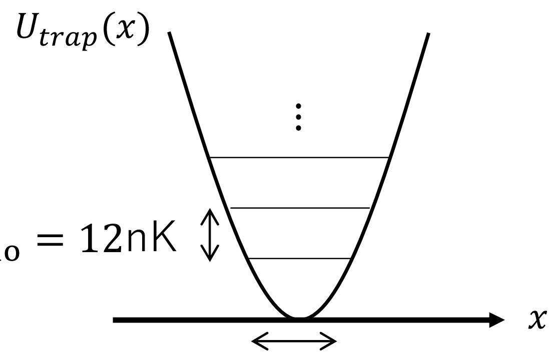
- Semiclassical condition : $E_F \gg \Delta E_{\mathrm{ho}}$
- LDA available condition : $k_F l_{ho} \gg 1$

Typical Fermi energy : $E_{\mathrm{F}} = 200\mathrm{nK}$
Pairing Gap : $\Delta_{\mathrm{pair}} \sim 0.5 E_F$

260Hz



$\Delta E_{\mathrm{ho}} = 12\mathrm{nK}$

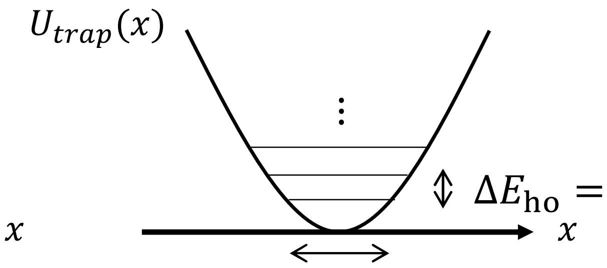
$\frac{E_{\mathrm{F}}}{\Delta E_{\mathrm{ho}}} = 17 \gg 1$

$\frac{\Delta_{\mathrm{pair}}}{\Delta E_{\mathrm{ho}}} = 8 > 1$

$l_{\mathrm{ho}} = 16\mu\mathrm{m}$

$k_F l_{ho} = 40 \gg 1$

140Hz



$\Delta E_{\mathrm{ho}} = 6.7\mathrm{nK}$

$\frac{E_{\mathrm{F}}}{\Delta E_{\mathrm{ho}}} = 30 \gg 1$

$\frac{\Delta_{\mathrm{pair}}}{\Delta E_{\mathrm{ho}}} = 15 > 1$

$l_{\mathrm{ho}} = 22\mu\mathrm{m}$

$k_F l_{ho} = 50 \gg 1$

Radial confinement dependence

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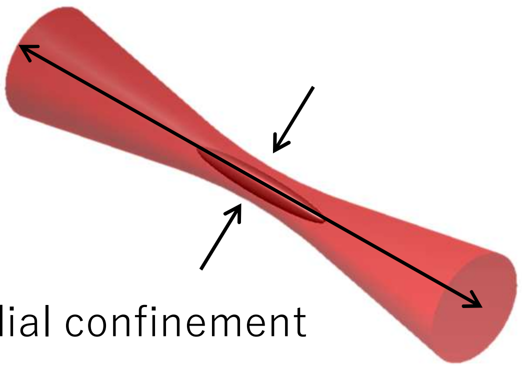
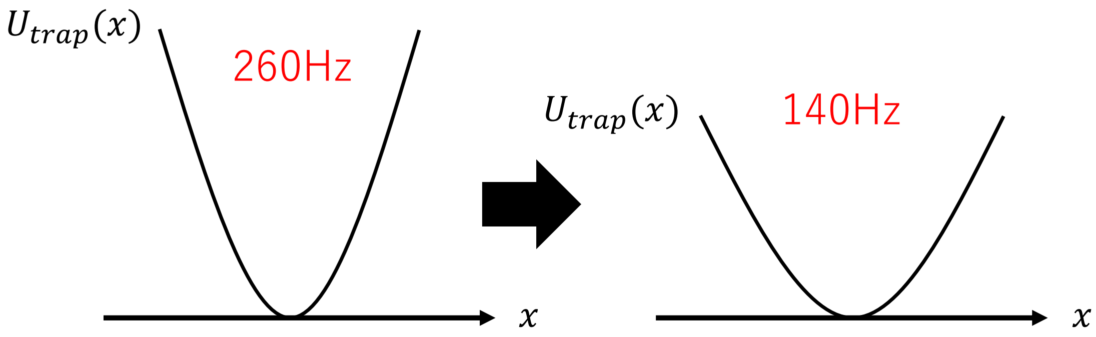
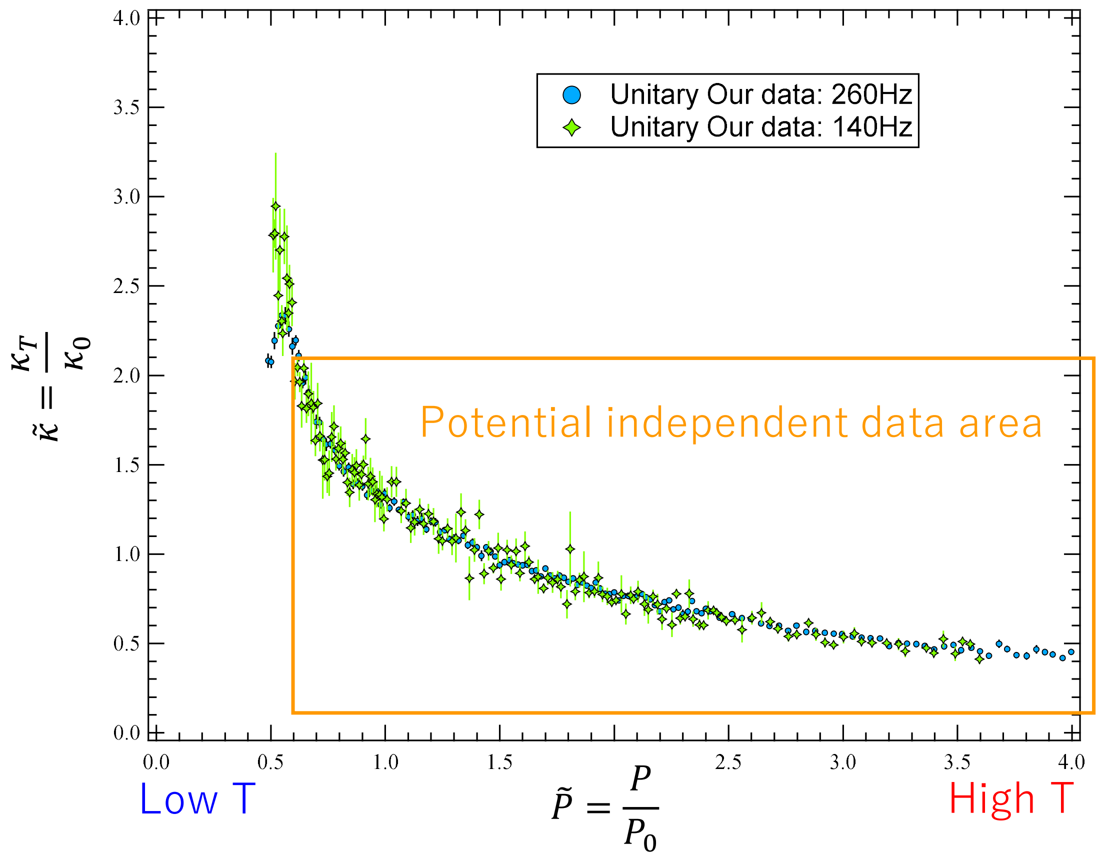
Fixed axial confinement : ~7Hz



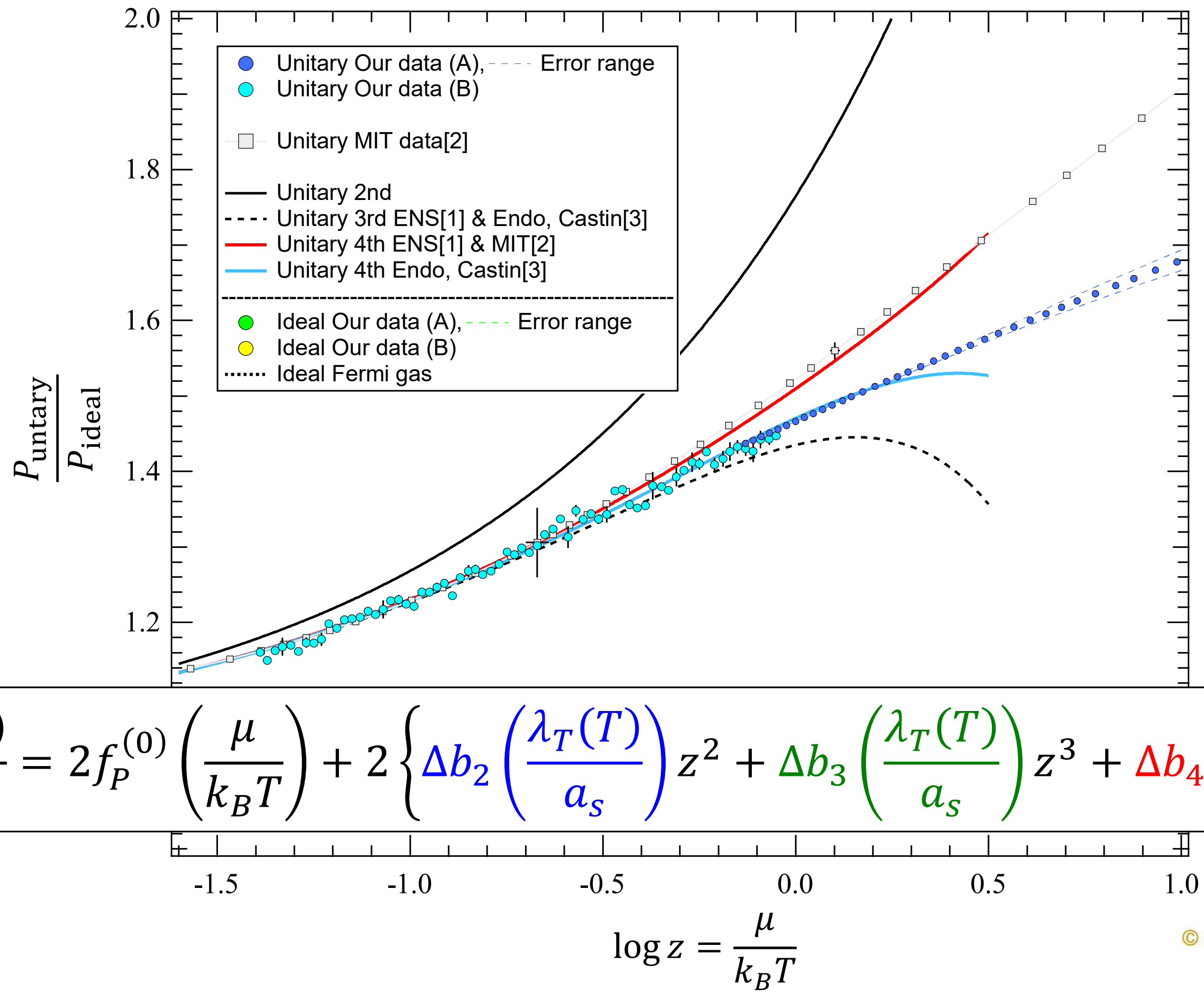
Variable radial confinement



Unitary Fermi gas



Evaluation of the Virial coefficients



$$P\frac{\lambda_T^3(T)}{k_B T} = 2 f_P^{(0)}\left(\frac{\mu}{k_B T}\right) + 2\left\{\Delta b_2\left(\frac{\lambda_T(T)}{a_s}\right) z^2 + \Delta b_3\left(\frac{\lambda_T(T)}{a_s}\right) z^3 + \Delta b_4\left(\frac{\lambda_T(T)}{a_s}\right) z^4 + \cdots\right\}$$

Evaluation of the Virial coefficients

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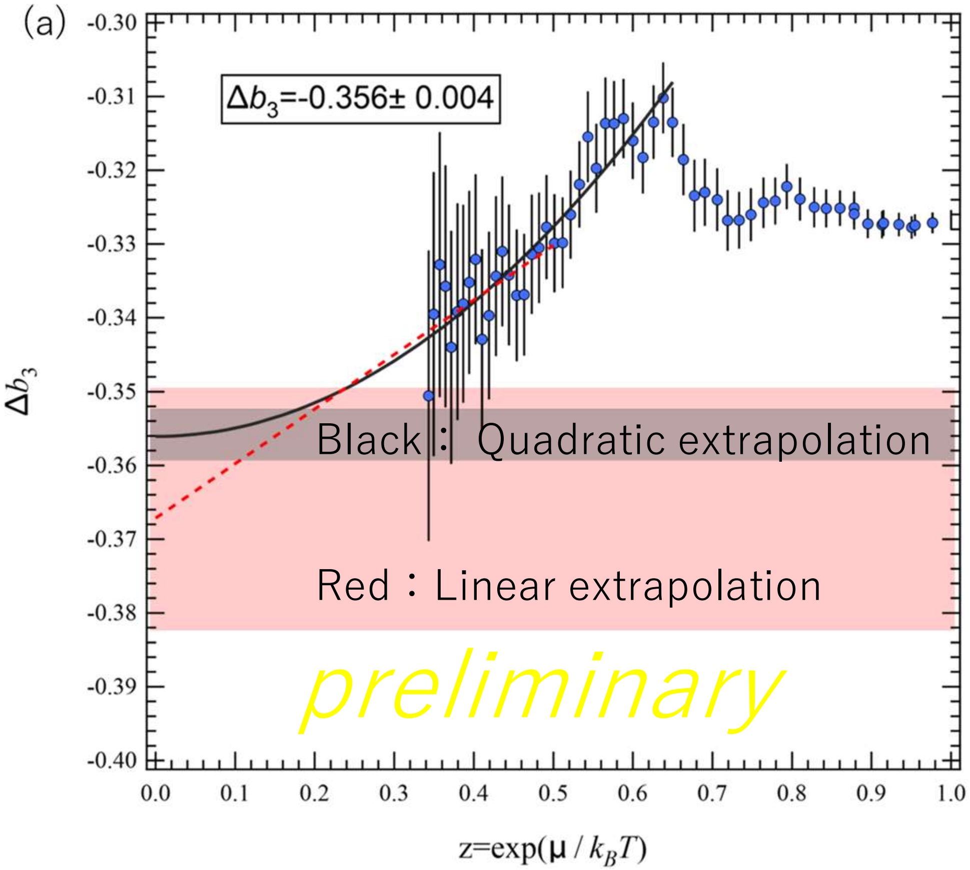

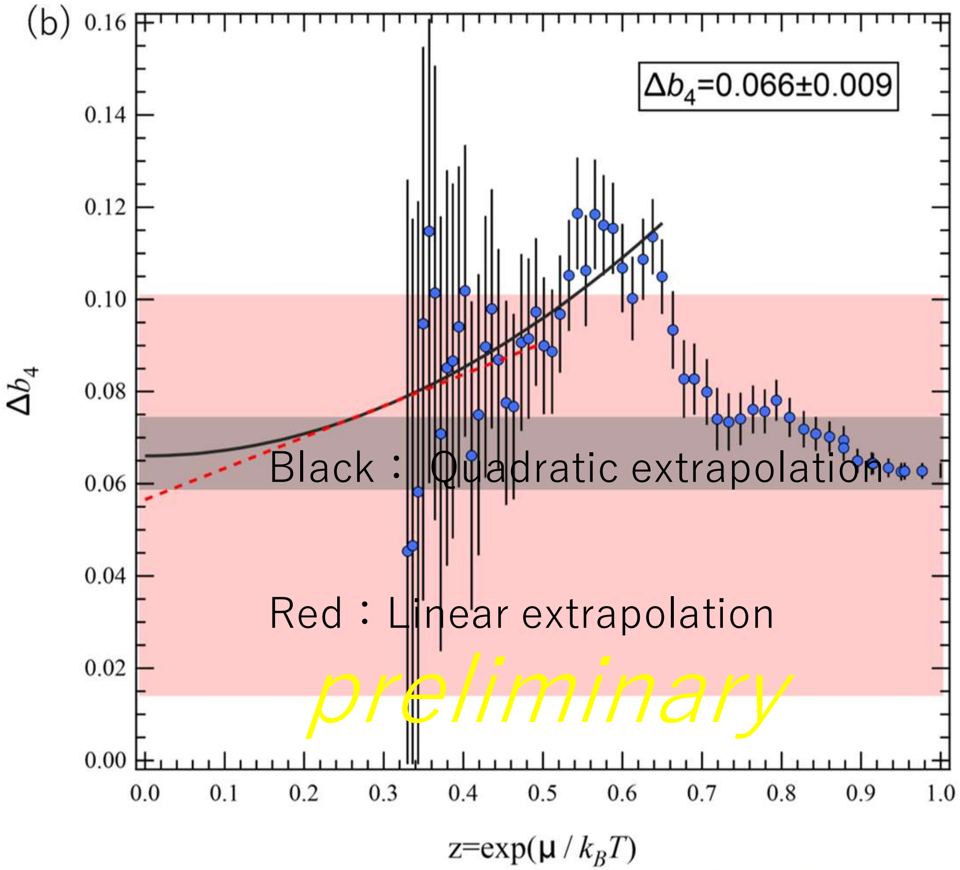

Evaluation of the Virial coefficients

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	$\Delta b_3 = \frac{1}{2}\Delta b_{1,1}$	Ref
Theo Theo Exp This work	-0.3551030264521 -0.35510298 **-0.35(2) @ENS** **-0.356(4)**	Endo, PRA **92** 053624(2015) and Castin, Sci. **Post 3** 049 (2020) Liu, Hu, Drummond, PRA **82**, 023619 (2010) S. Nascimbène, Nature **463**.7284, 1057-1060 (2010)

	$\Delta b_4 = \Delta b_{3,1} + \frac{1}{2}\Delta b_{2,2}$	$\Delta b_{3,1}$	$\Delta b_{2,2}$	Ref
Theo Theo Exp Exp This work	0.062(1) 0.078(18) **0.096(15) @ENS** **0.096(10) @MIT** **0.066(9)**	0.1838(4) 0.170(12) - -	-0.244(2) -0.184(26) - -	Endo, Castin, J. Phys. A **49**, 265301 (2016) Yan, Blume, PRL **116**, 230401 (2016) S. Nascimbène, Nature **463**.7284, 1057-1060 (2010) Mark J. H. Ku, Science **335**.6068, 563-567 (2012)

Summary

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