研究計画B03：

冷却原子を用いた中性子過剰な低密度核物質の状態方程式

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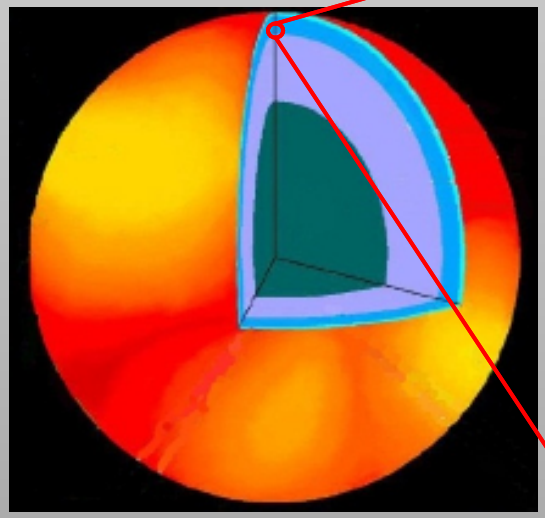
理化学研究所（理論）： 中務孝（分担）

Our mission

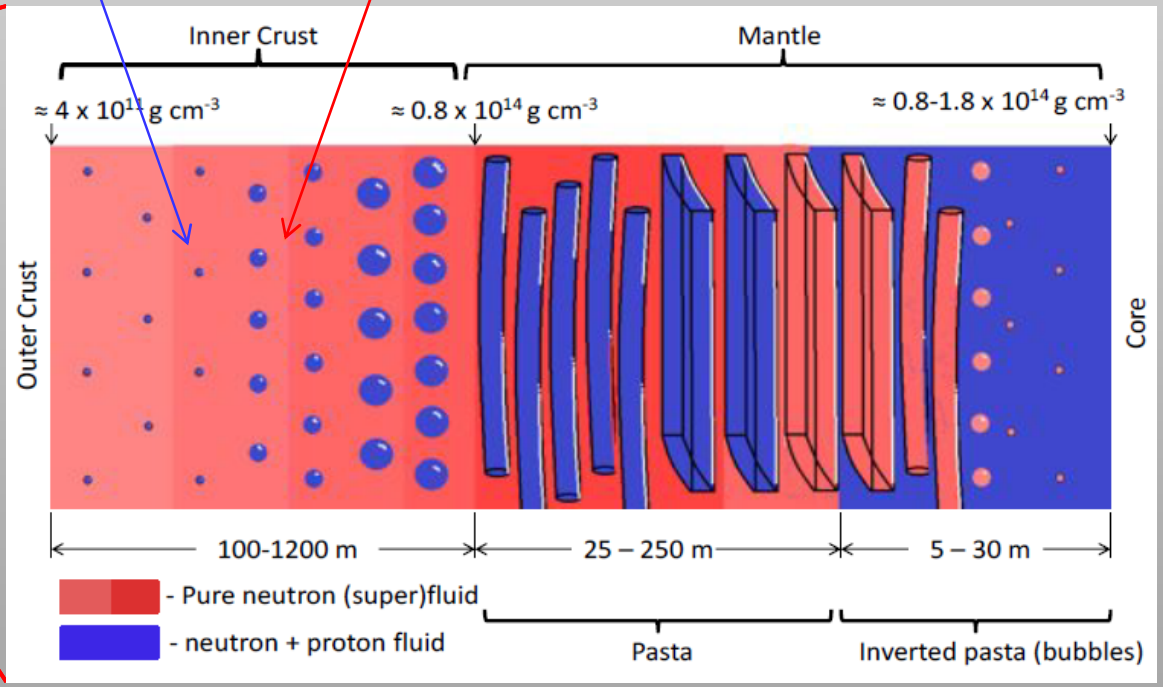
Simulation of neutron matter using cold Fermi gas

bcc crystal lattice of nuclei

Dripped neutrons from nuclei



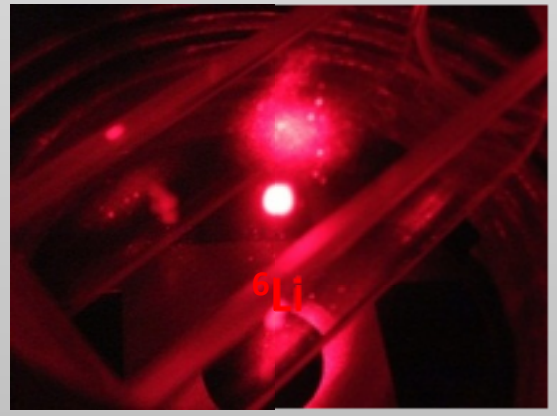
Neutron star



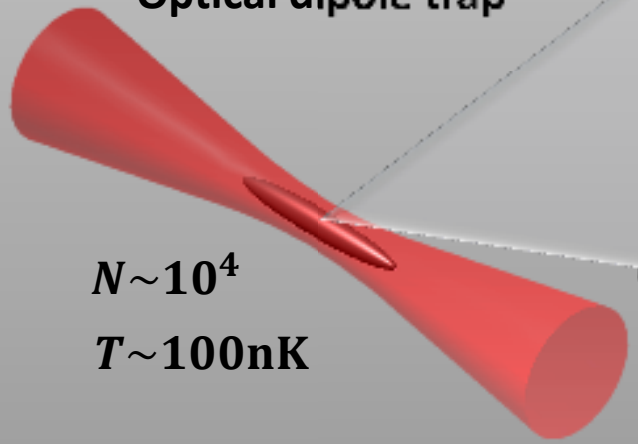
inner crust region [Newton, *et al.*, arXiv:1112.2018]

Cold atom system

Laser cooling



Optical dipole trap



$N \sim 10^4$

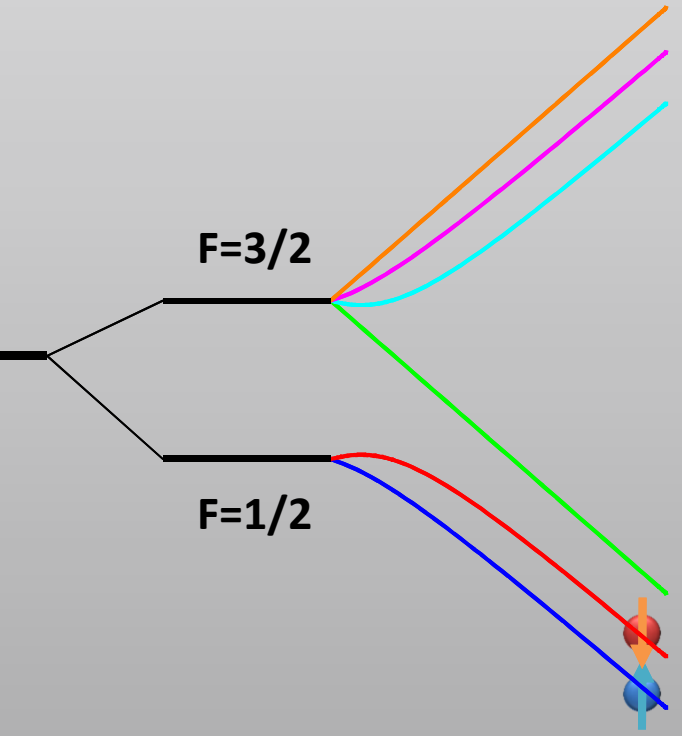
$T \sim 100\text{nK}$

^{6}Li

Electron spin : 1/2

Nuclear spin : 1

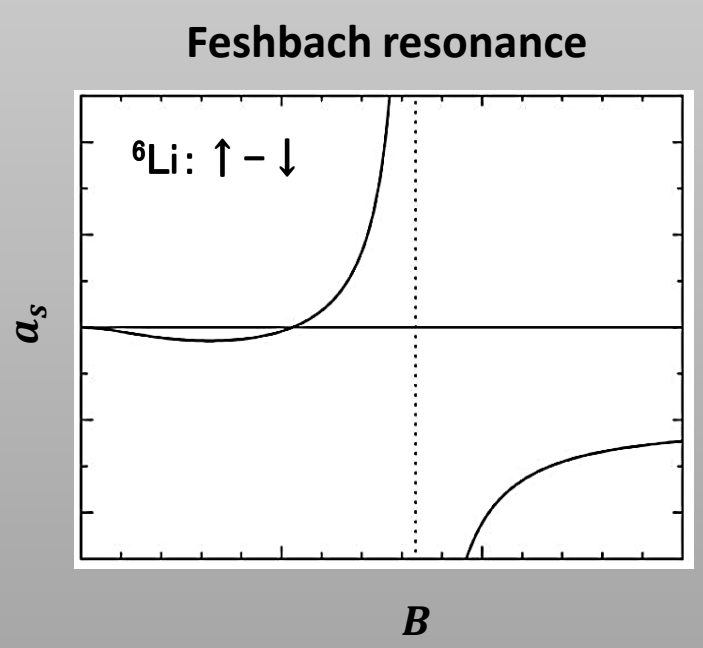
1,2,3-components Fermi system
using internal degree of freedom



Magnetic field

Cold atom system

- Tunable s-wave or p-wave interaction by Feshbach resonances
- Tunable temperature
- Pure system
- Precise measurement



Cold atom vs. Neutron matter

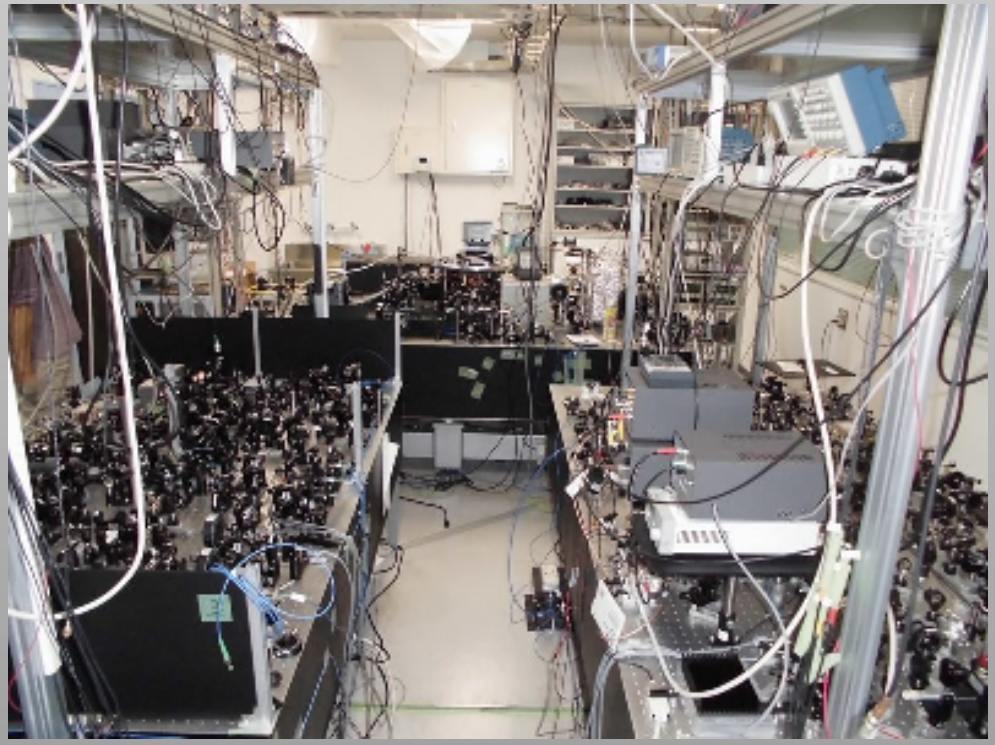
	Cold Fermi atom	Neutron matter
Interaction	s,p-wave	s,p-wave
Temperature : T	$\sim 10^{-7}$K	$\sim 10^{9}$K
Fermi temperature : T_{F}	$\sim 10^{-6}$K	$\sim 10^{10}$K
Interparticle distance : $\sim k_F^{-1}$	100nm	6~3fm
Scattering length : a	$-\infty \sim \infty$(Feshbach resonance)	-18.5 ± 0.3fm
Effective range : r_{e}	4.7nm	2.75 ± 0.11fm
↓	↓	↓
Temperature : T/T_F	$10 \sim 0.05$	$0.1 \sim 0$
Interaction : $-1/k_F a$	$-\infty$(BEC limit)$\sim +\infty$(BCS limit)	$0.28 \sim 0.04$
Effective range : $k_F r_e$	0.05	$0.53 \sim 3.3$
Phase transition : T_C/T_F	~ 0.2	~ 0.1
Superfluid gap : Δ/E_{F}	~ 0.6	~ 0.2
Lattice potential	Optical lattice, Ion crystal	Nuclei crystal

Laboratory

東京大学
（光量子科学研究センター）

***S*-wave interacting Fermi gas**

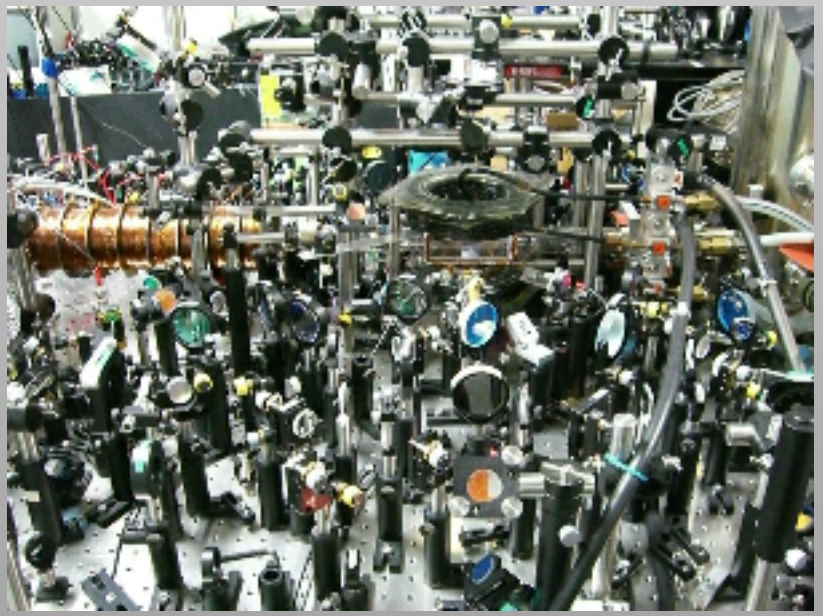
^{6}Li-^{7}Li mixed system



電気通信大学
（レーザー新世代研究センター）

***p*-wave interacting Fermi gas**

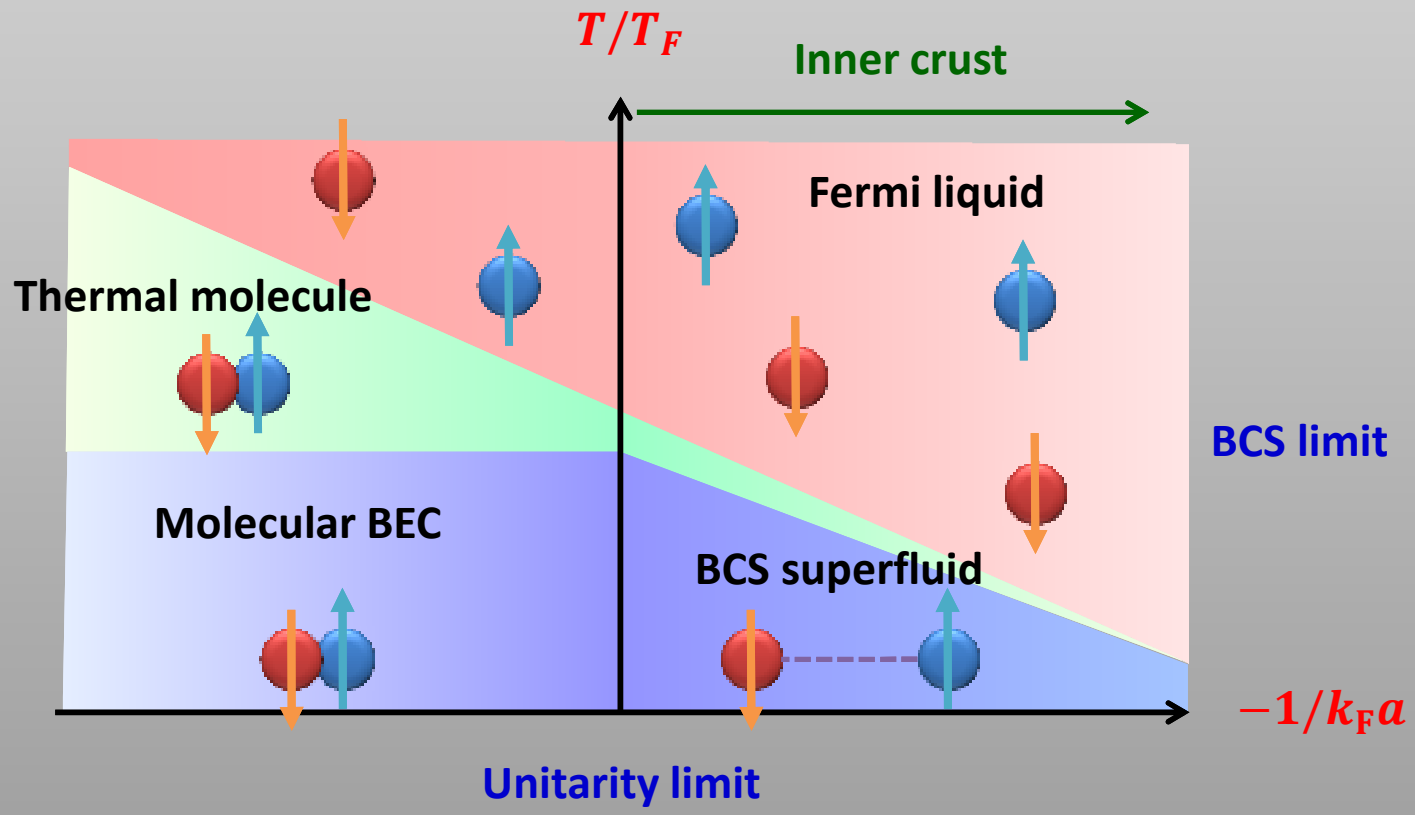
^{6}Li system



Project 1 : EOS of interacting two-component Fermi gas

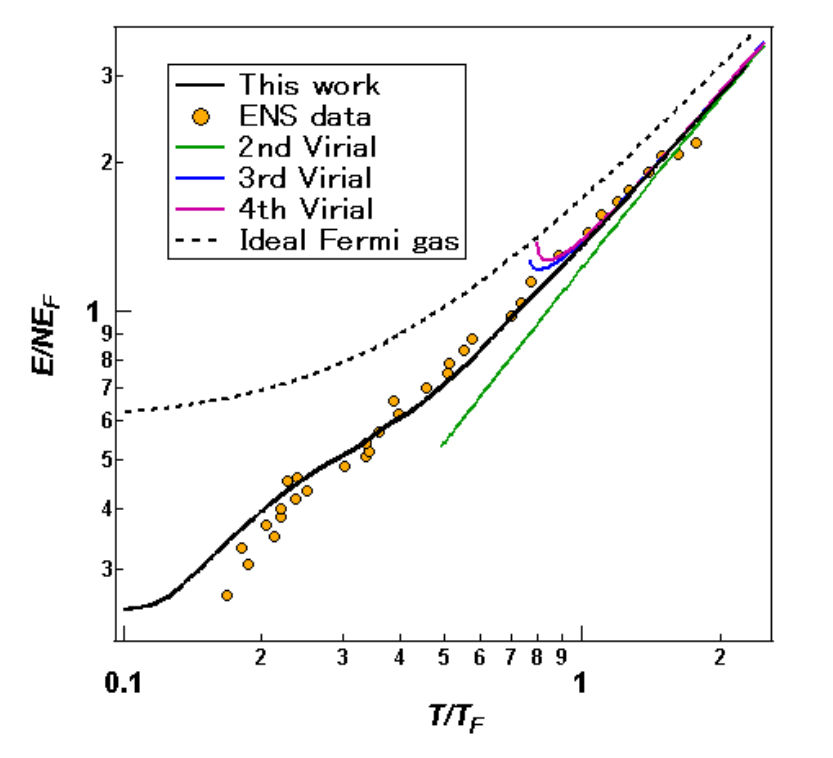
Grand potential (EOS) : $\Omega = P\left(T, \mu, a^{-1}\right)V$

s-wave interactions under dilute limit : $k_{\mathrm{F}} r_{\mathrm{e}} = 0$



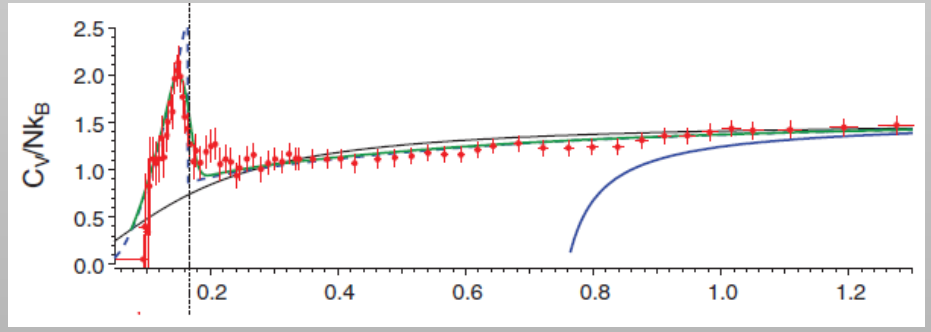
Project 1 : EOS of interacting two-component Fermi gas

Energy vs. Temperature at the unitarity limit



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

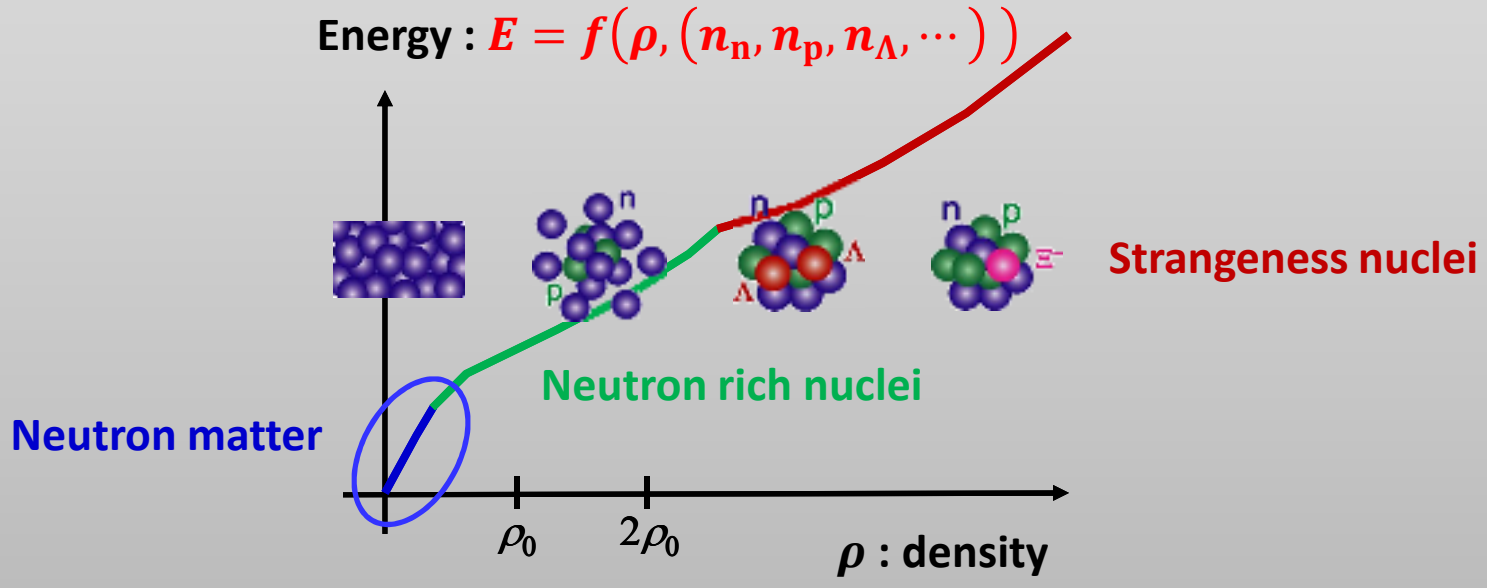
Heat capacity



T/T_{F}

[Mark J. H. Ku, *et al.*, 335, 563 (2012)]

Project 1 : EOS of interacting two-component Fermi gas



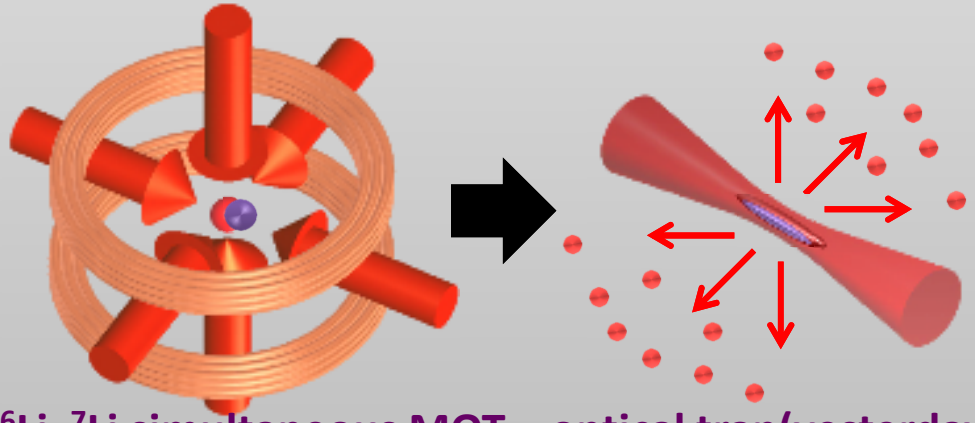
Cold Fermi atoms : $\frac{E}{E_F}\left(\frac{T}{T_F}, -\frac{1}{k_F a}\right)$ → **Correction** → Neutron matter : $\frac{E}{E_F}\left(\frac{T}{T_F}, -\frac{1}{k_F a}, k_F r_e\right)$ → **Neutron stars :** $E = f(\rho, (n_n))$

$$\frac{\partial E}{\partial (k_F r_e)} = \zeta \quad (\zeta = 0.127(4) \text{ @ } |\infty| = 0, T = 0)$$

[Forbes, *et al.*, arXiv:1205.4815]
[Werner and Castin, Phys. Rev. A 86, 013626 (2012)]

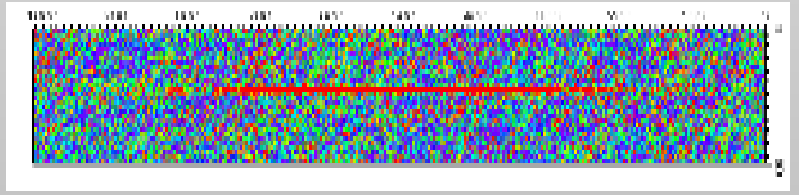
Project 1 : present status

Kickoff simposium@2012/10/26,27

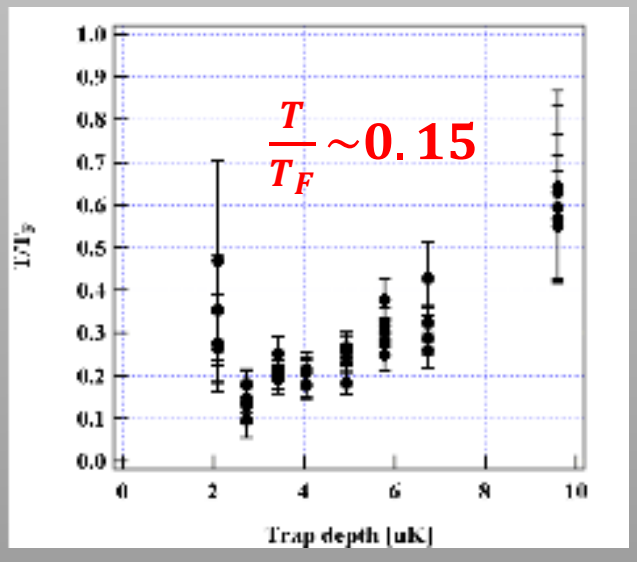


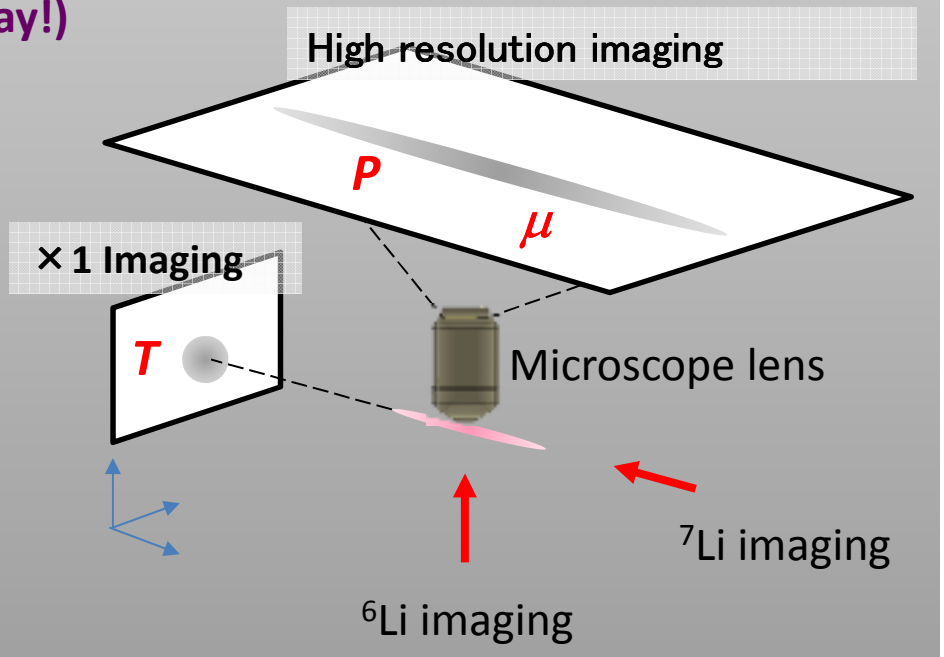
^{6}Li- ^{7}Li simultaneous MOT ,optical trap(yesterday!)

Construction of imaging systems



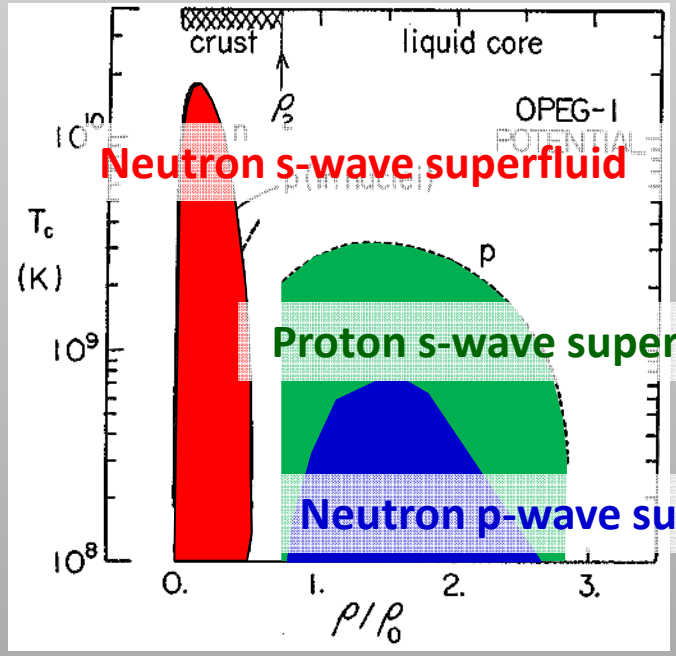
^{6}Li only with a small scattering length





Project 2 : p-wave superfluidity

Superfluid phase diagram in neutron stars

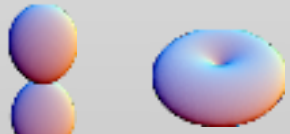


Proton s-wave superconducting

Neutron p-wave superfluid

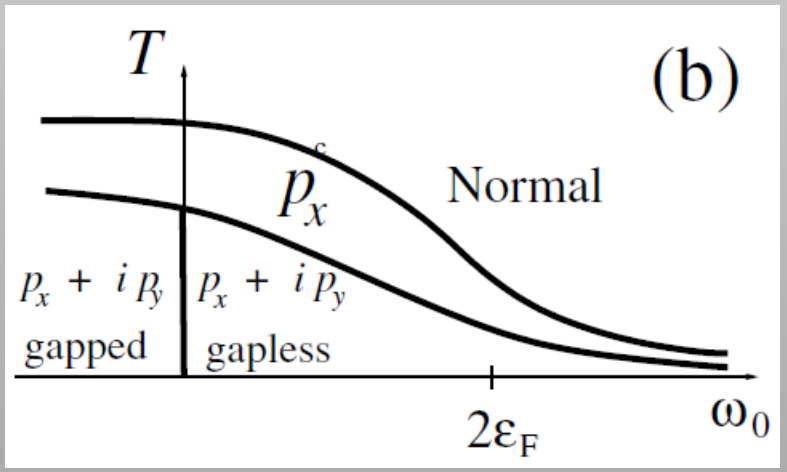
[T. Takatsuka and R. Tamagaki, Progress of Theoretical Physics Supplement 112, 27 (1993)]

***p*-wave ($l = 1$)**



m_l=0 $|m_l|$=1

Interaction vs. temperature



[V. Gurarie, *et. al.*, Phys. Rev. Lett. 94, 230403 (2005)]

Project 2 : present status

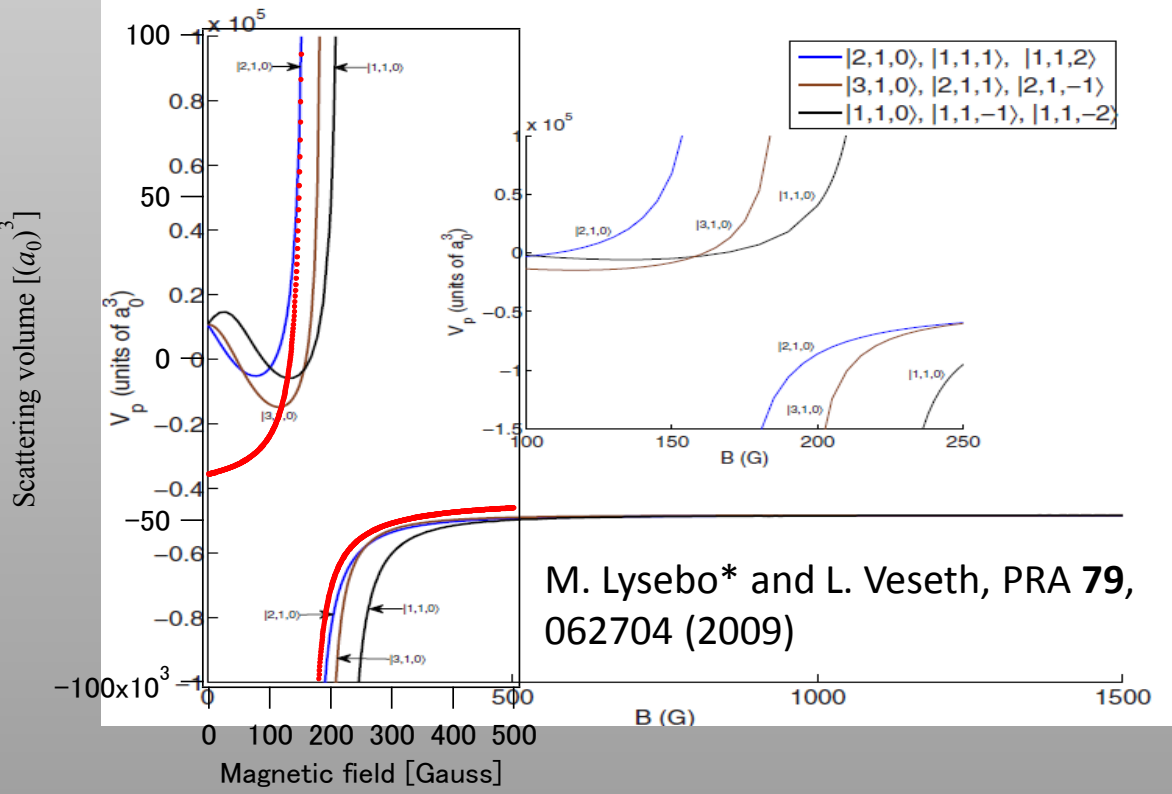
PHYSICAL REVIEW A **88**, 012710 (2013)

Experimental determination of *p*-wave scattering parameters in ultracold ^{6}Li atoms

Takuya Nakasuji,[1] Jun Yoshida,[1] and Takashi Mukaiyama[1,2]

p-wave Feshbach resonance

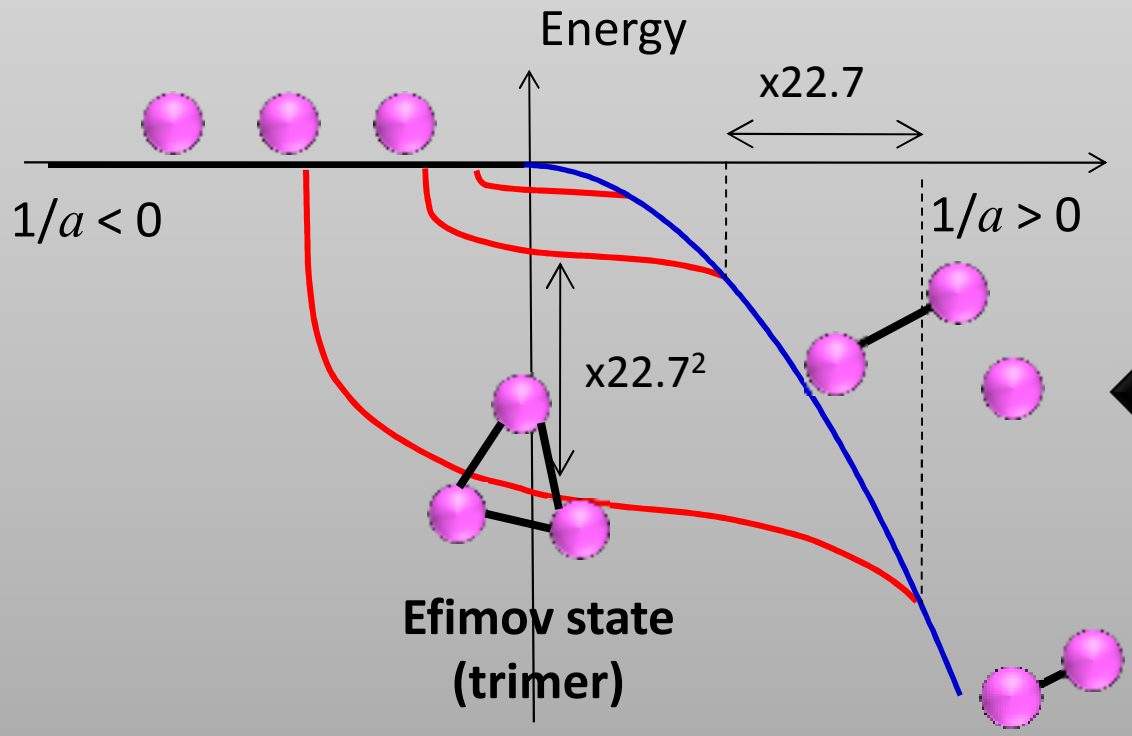
$$V_p(B) = V_{bg}\left(1 - \frac{\Delta B}{B - B_{res}}\right)$$



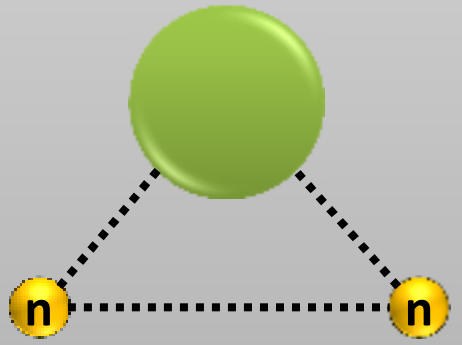
M. Lysebo* and L. Veseth, PRA **79**, 062704 (2009)

Project 3 : Three-body university - Efimov physics

Equal mass with s-wave interactions



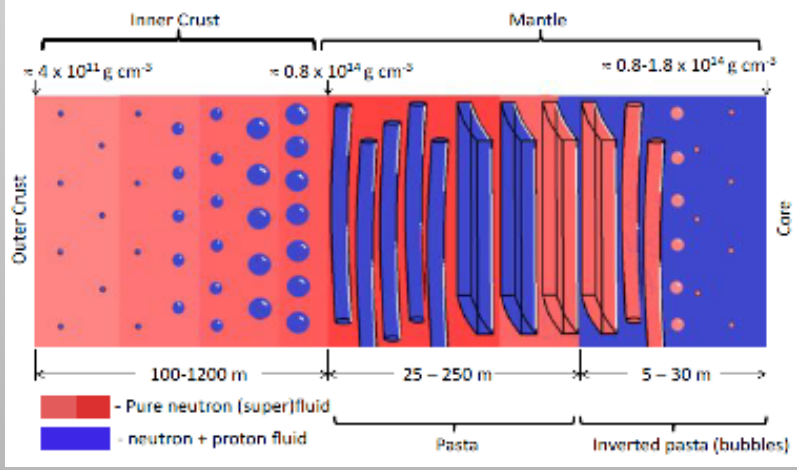
Halo sate
(^{6}He, ^{11}Li, ^{17}B, ^{19}B, ^{22}C)

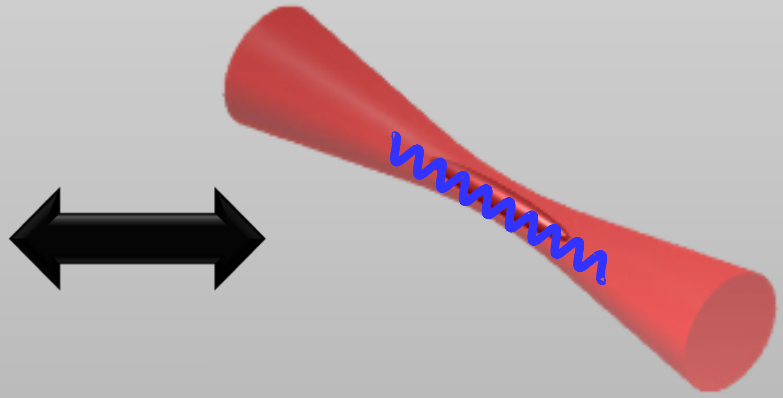


- **Mass imbalanced Efimov state using ^{6}Li-^{7}Li system**
- **Efimov state with p-wave scattering length**

Other projects

- **Fermi superfluid in a periodic potential**





[G. Watanabe, *et a*l., Phys. Rev. Lett. **107**, 270404 (2011)]

Summary

研究計画B03：

冷却原子を用いた中性子過剰な低密度核物質の状態方程式

- 相互作用しているフェルミ粒子系の状態方程式
- 新規の3体束縛状態の探査
- p波超流動の実現