新学術「量子クラスターで読み解く物質の階層構造」キックオフシンポジウム
November 20 (2018) (TIT)

Pair formation and quantum many-body phenomena in strongly interacting ultracold atomic gases

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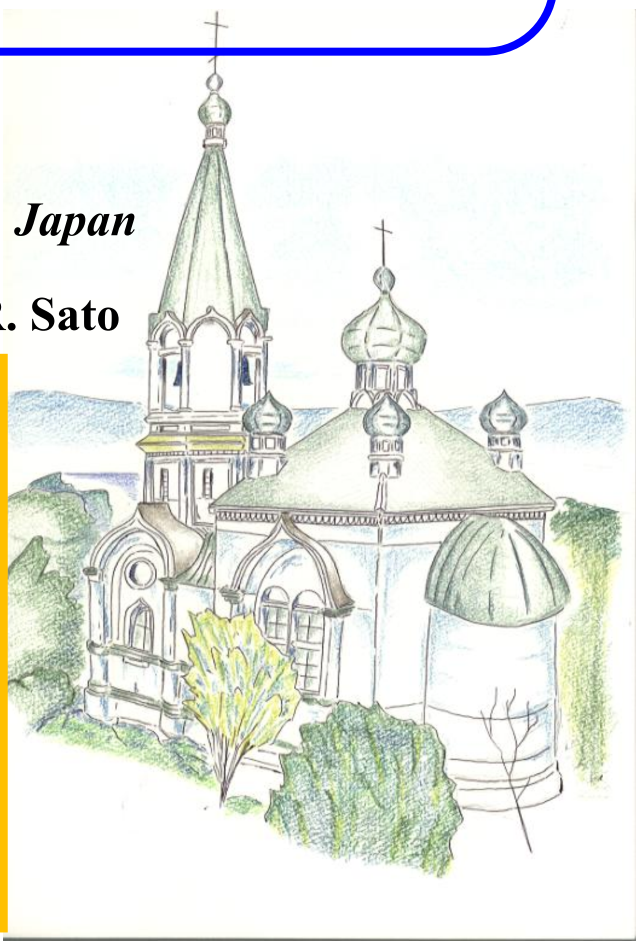
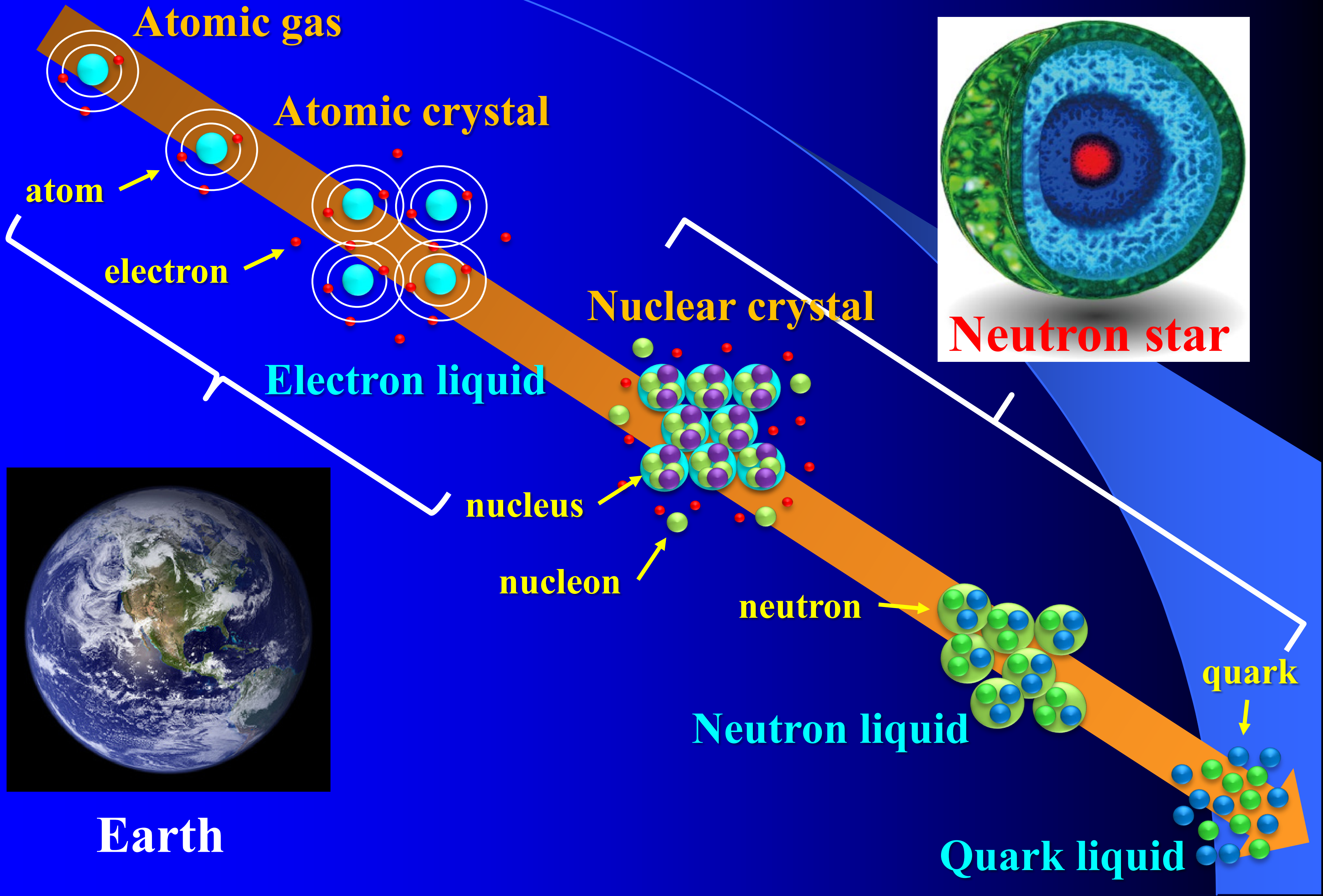
Collaborators: M. Soumita, D. Kagamihara, K. Manabe, R. Sato

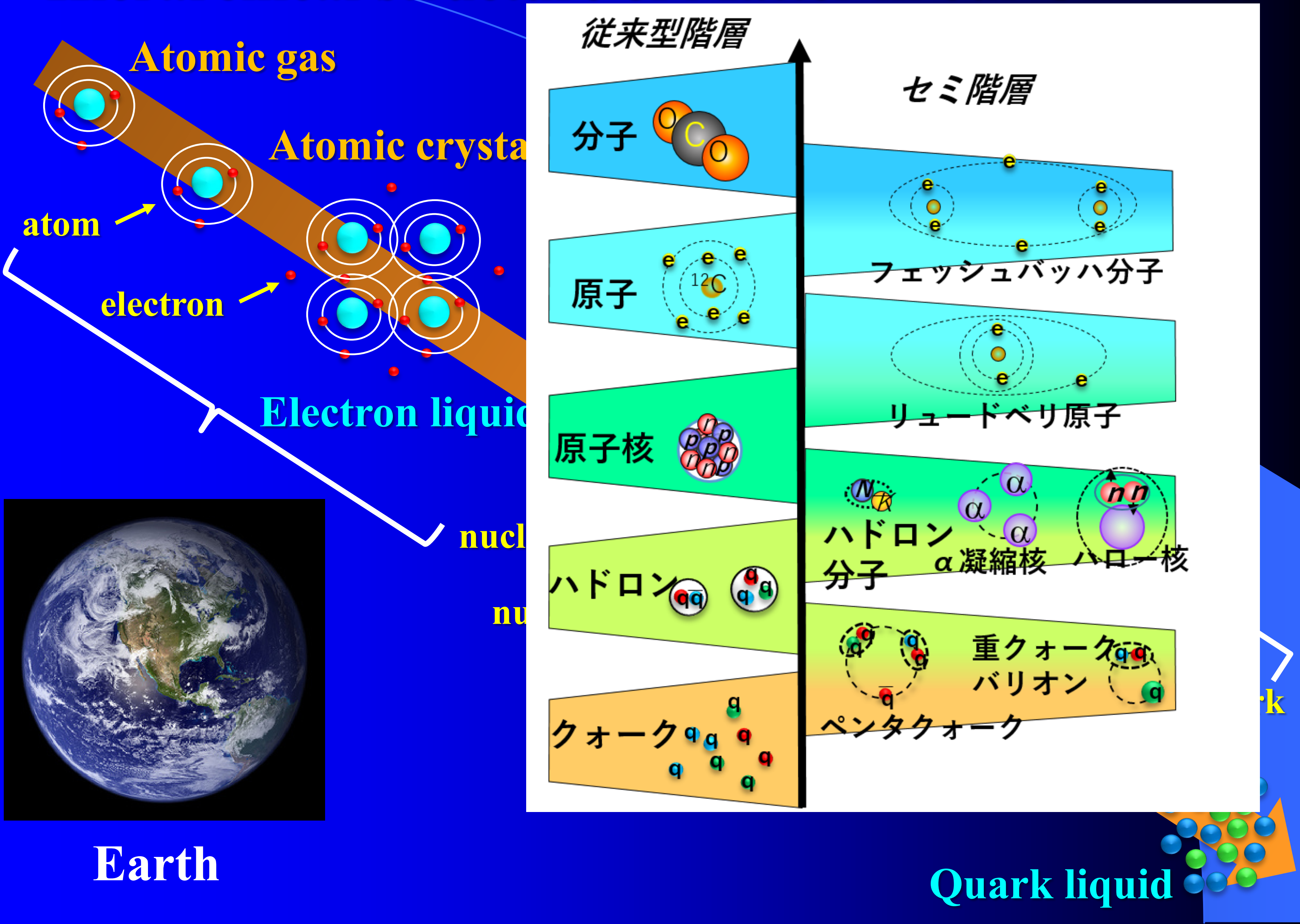


- **Introduction: Background and our strategy**
- **Four on-going topics**
  - **Compressibility: inter-cluster interaction**
  - **Shear viscosity: KSS conjecture**
  - **Bose-Fermi mixture: hetero-cluster**
  - **OFR: non-(^{6}Li, ^{40}K) superfluid Fermi atomic gas**
- **Summary**

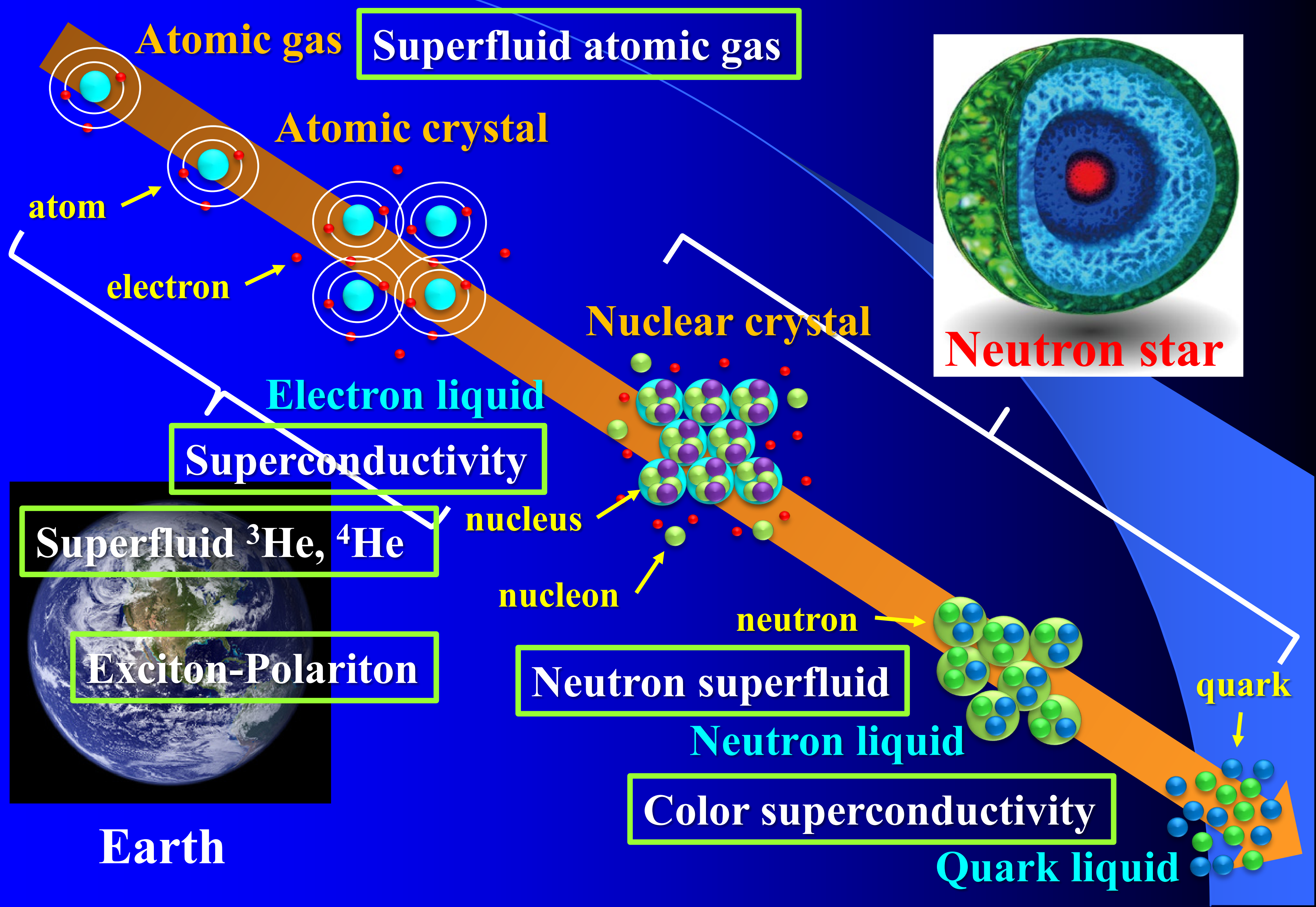
Hierarchical structure of Matter in our Universe



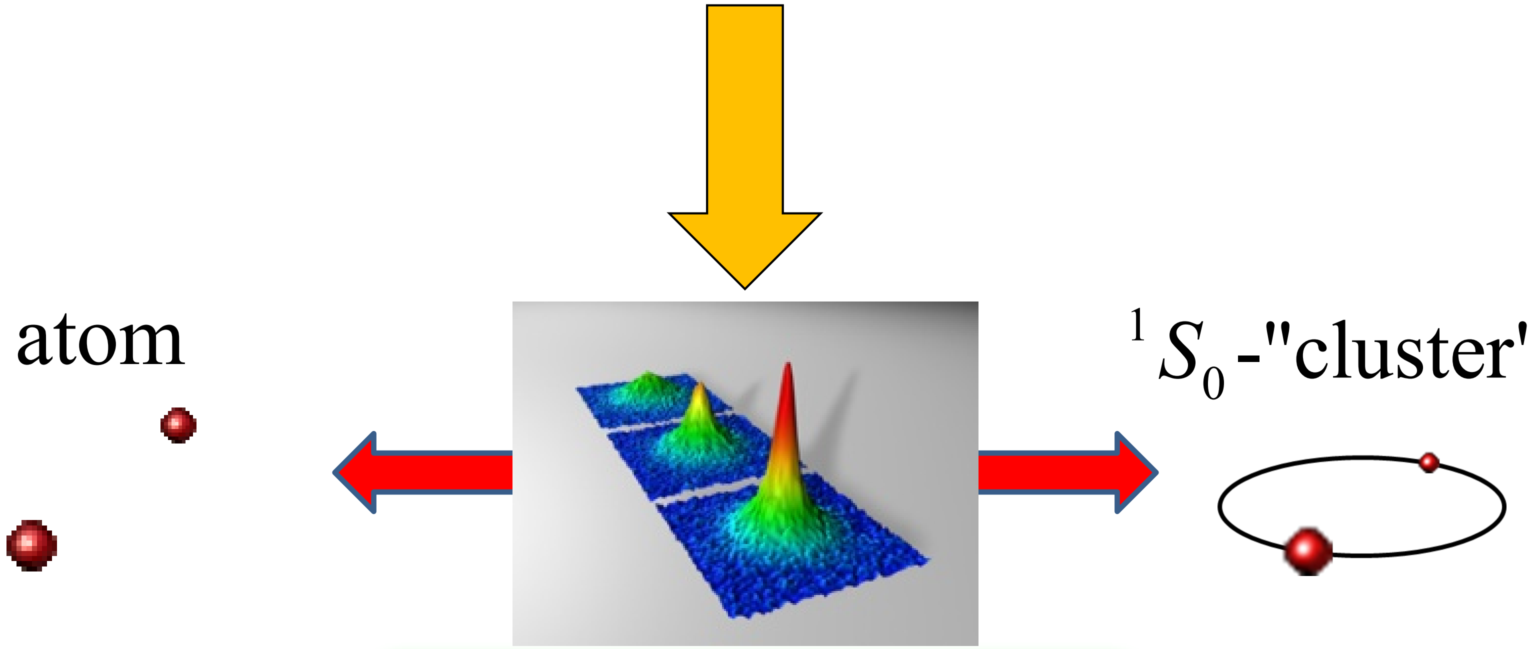
Hierarchical structure of Matter in our Universe



Superfluid: A possible approach to our Hierarchical world



Our Strategy to reach universality of our world, going beyond the hierarchy: Cold atom physics (C02)



Superfluid Fermi atom gas

- Tunable pairing interaction (Feshbach resonance)
- Various observable quantities
- Tunable statistics (Boson and Fermion)

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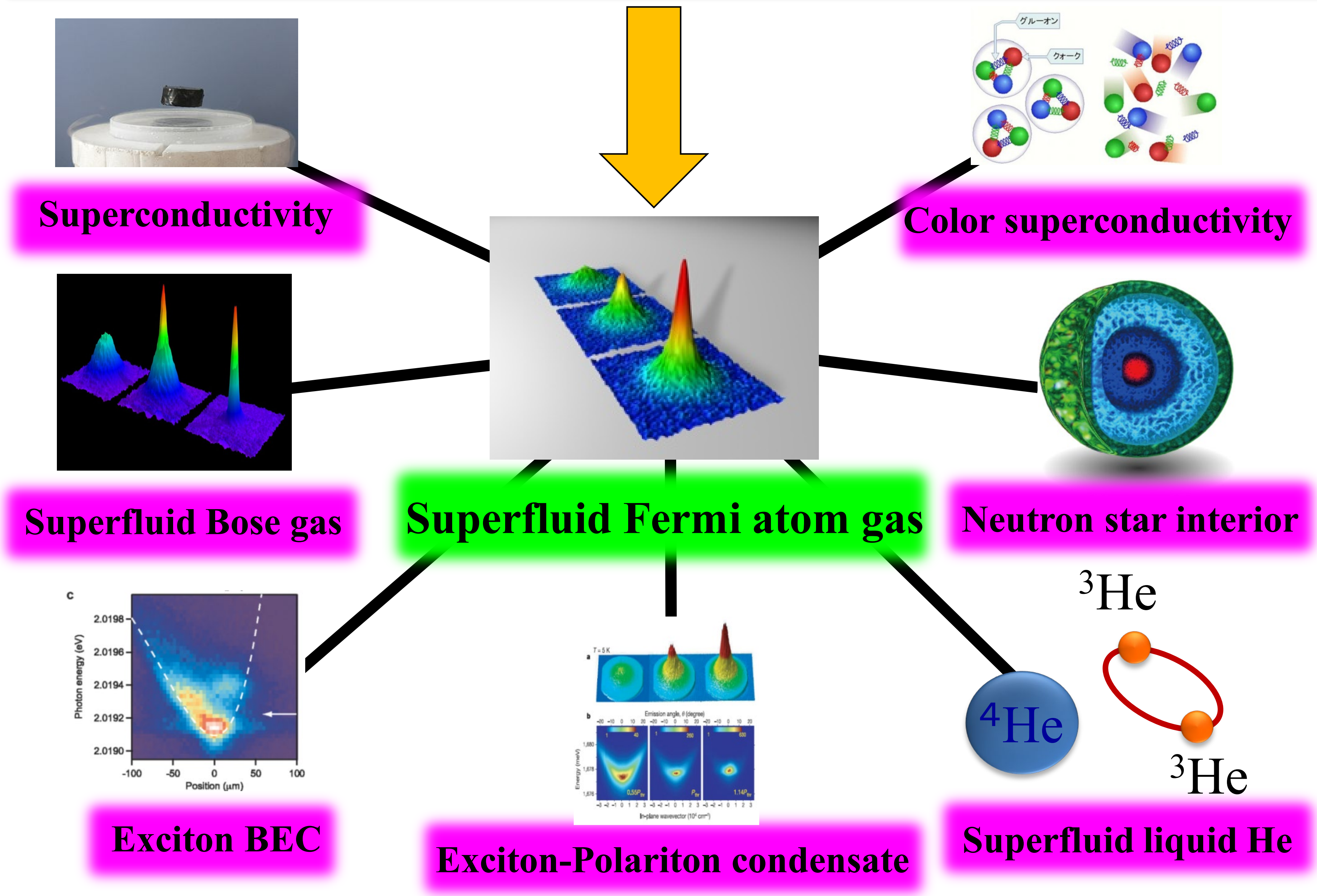

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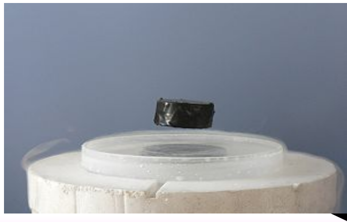
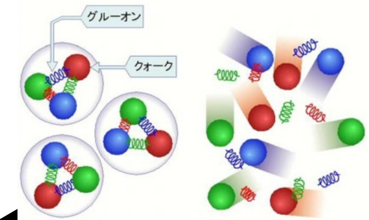
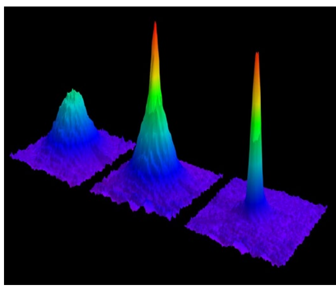


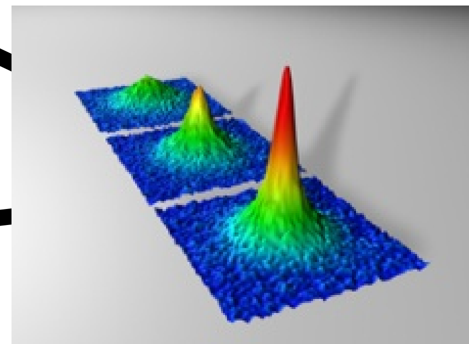
Superconductivity



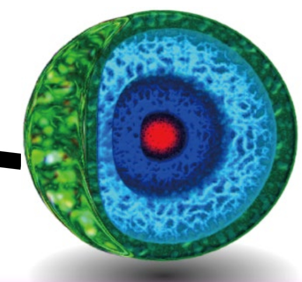
Color superconductivity



Superfluid Bose gas



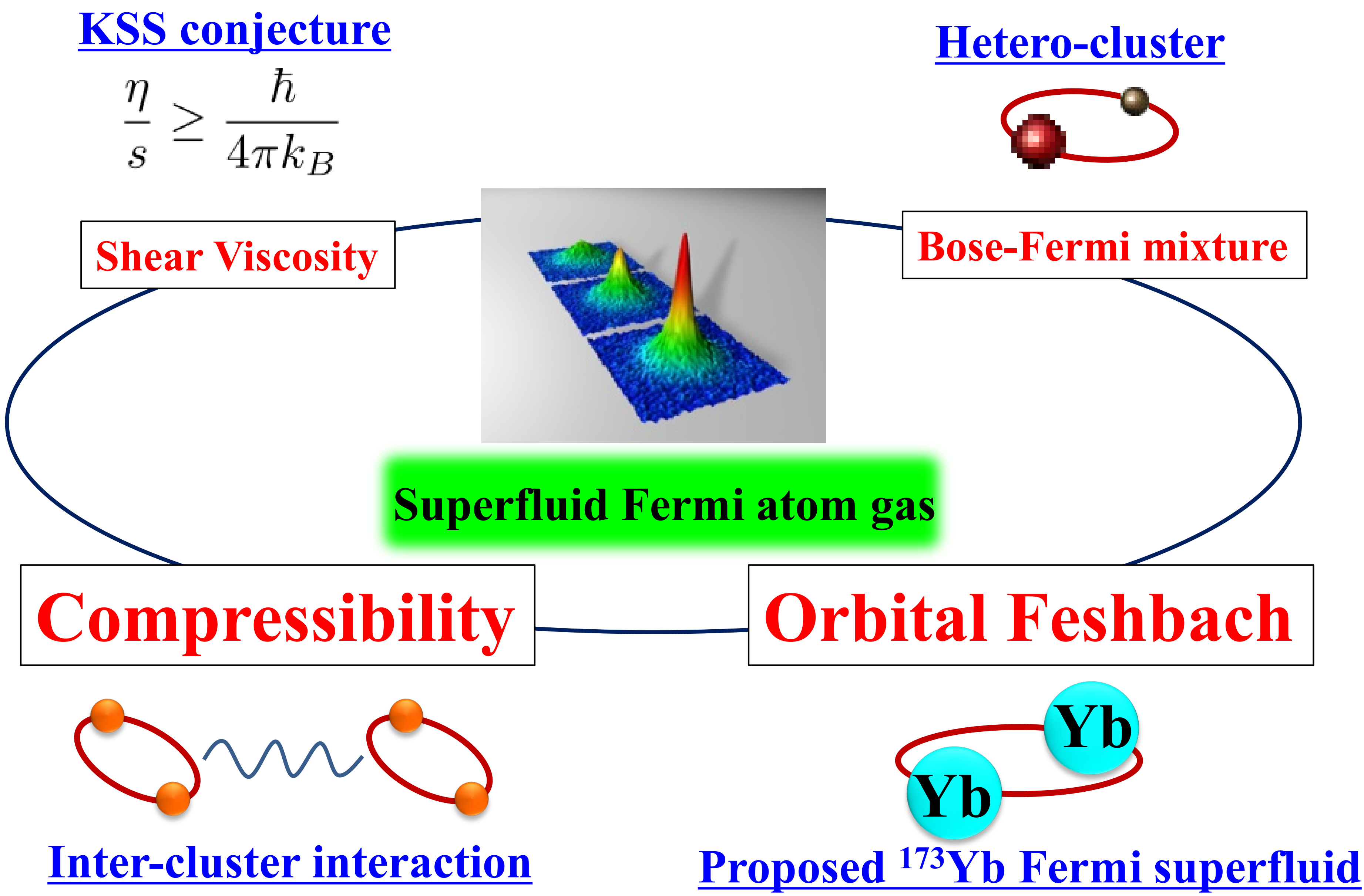
Superfluid Fermi atom gas



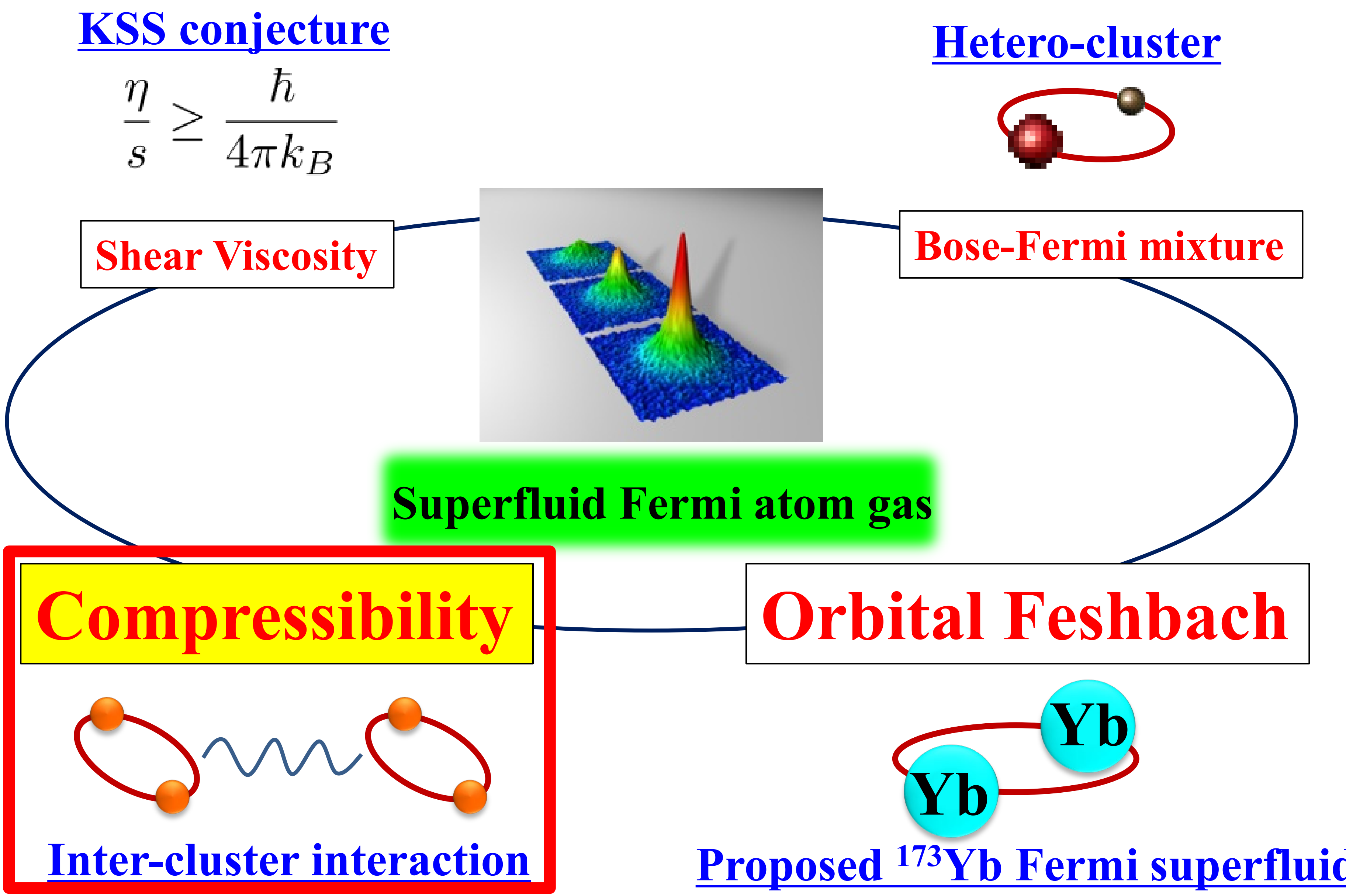
Neutron star interior

- Construction of quantitatively reliable many-body theories
- Understanding universal pairing (clustering) properties
  BCS-BEC crossover region
- Discussions with other “班” in this 新学術領域

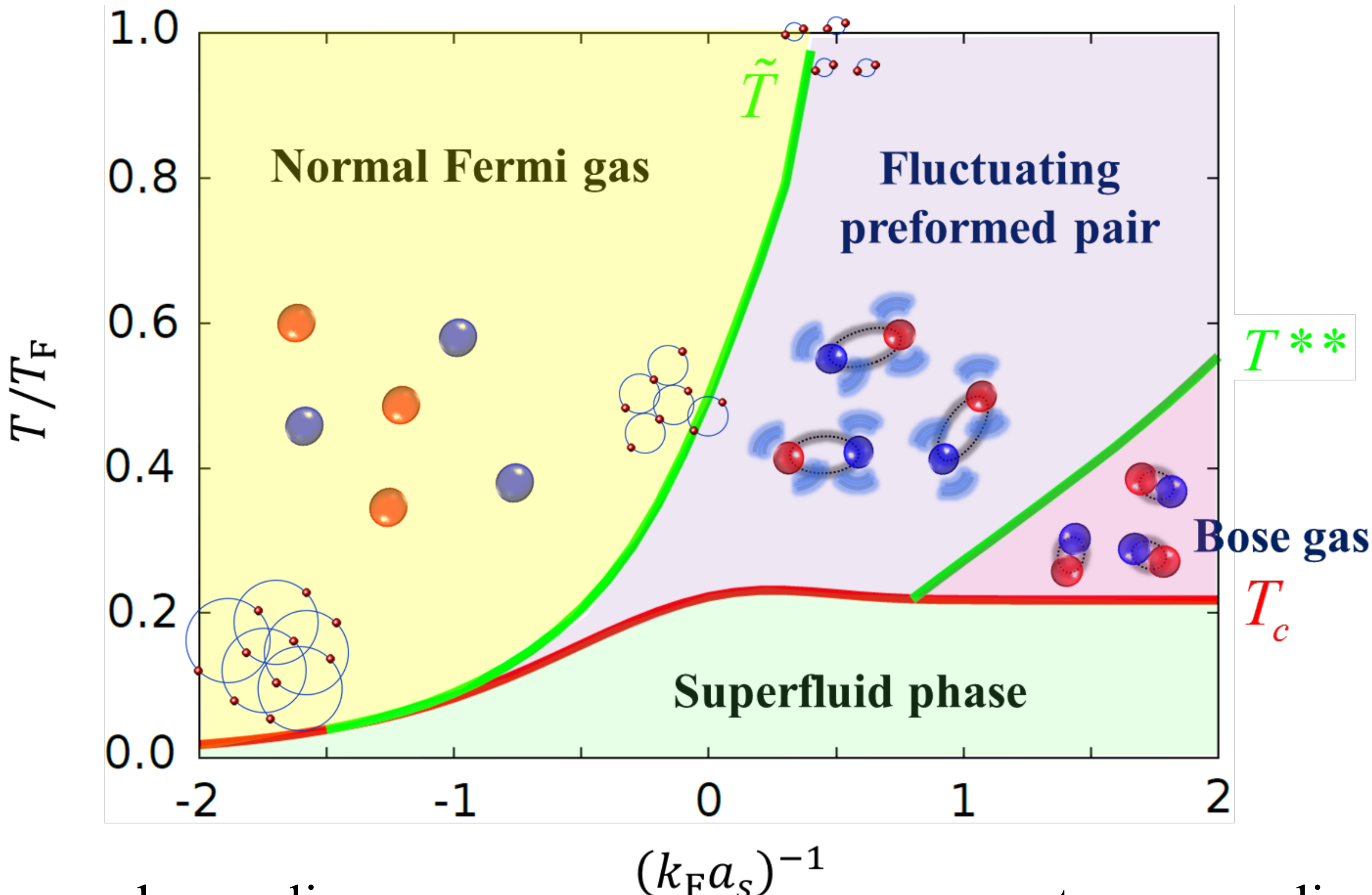
Our Strategy to reach universality of our world, going beyond the hierarchy: Cold atom physics (C02)



Our Strategy to reach universality of our world, going beyond the hierarchy: Cold atom physics (C02)



"BCS-BEC Crossover" Phase diagram

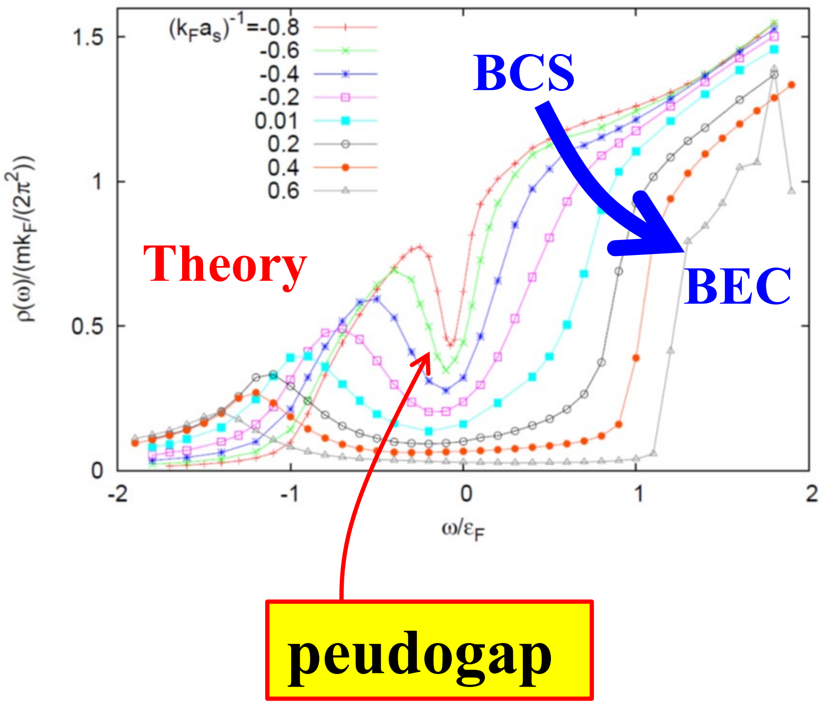


weak-coupling (BCS) → strong-coupling (BEC)

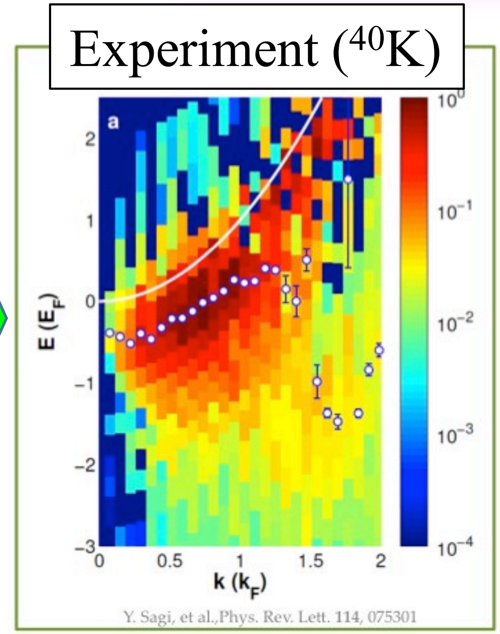
Pseudogap phenomenon in the BCS-BEC crossover region

Normal-state density of states

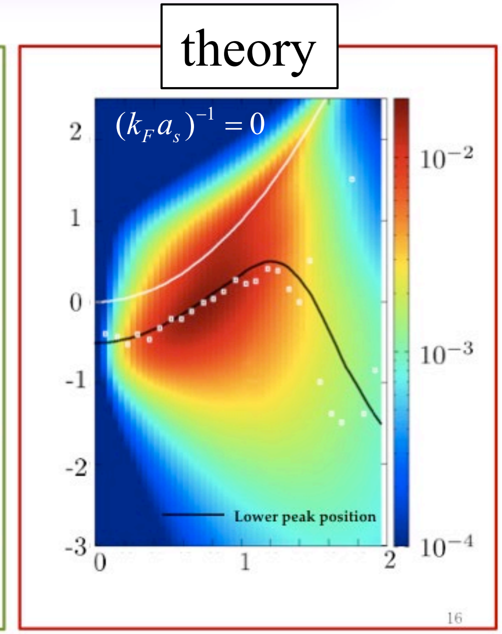
$T = T_c : \Delta = 0!$



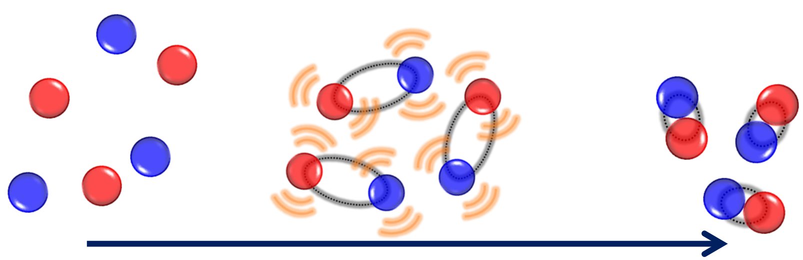
Photoemission spectrum



Y. Sagi, et al, PRL 114, 075301

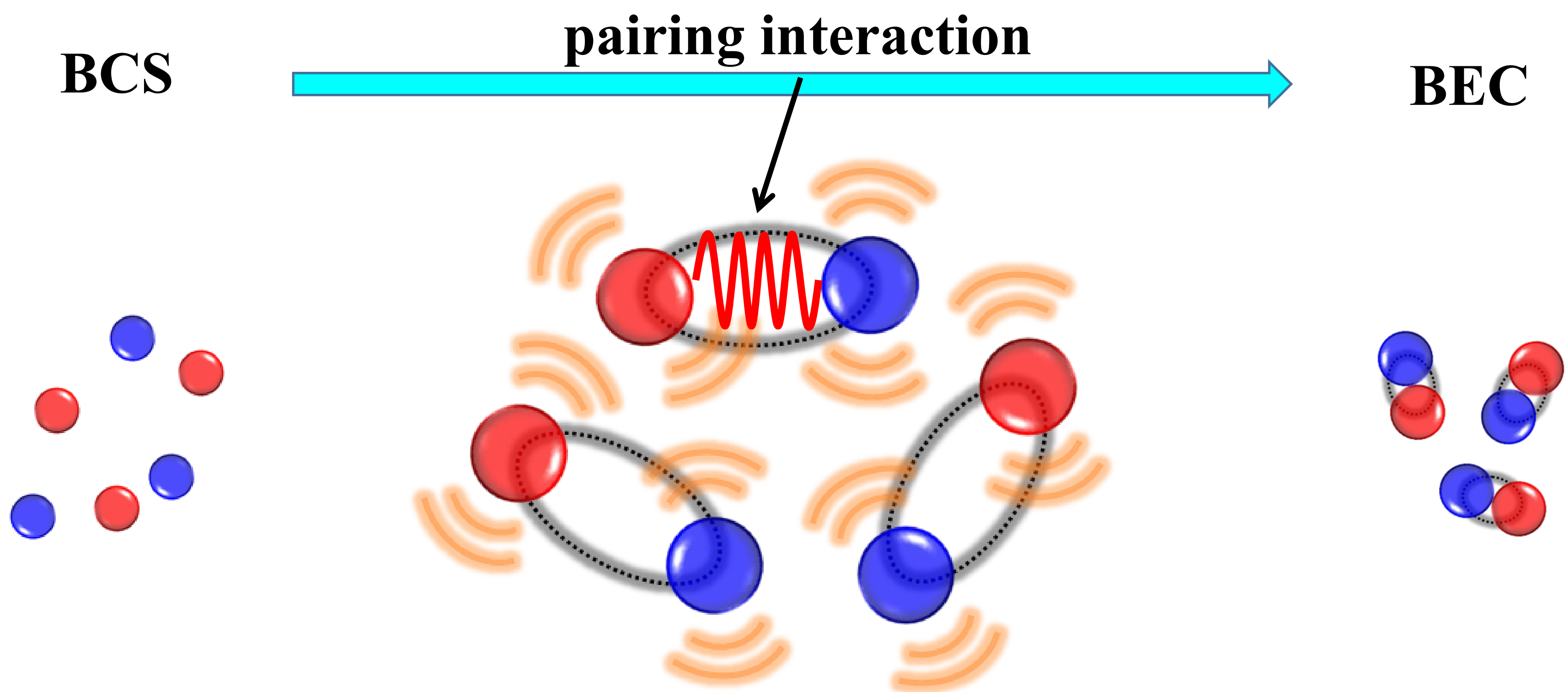


Ota, Ohashi et al, PRA (2016)



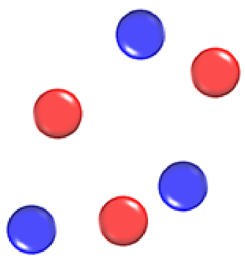
pairing interaction

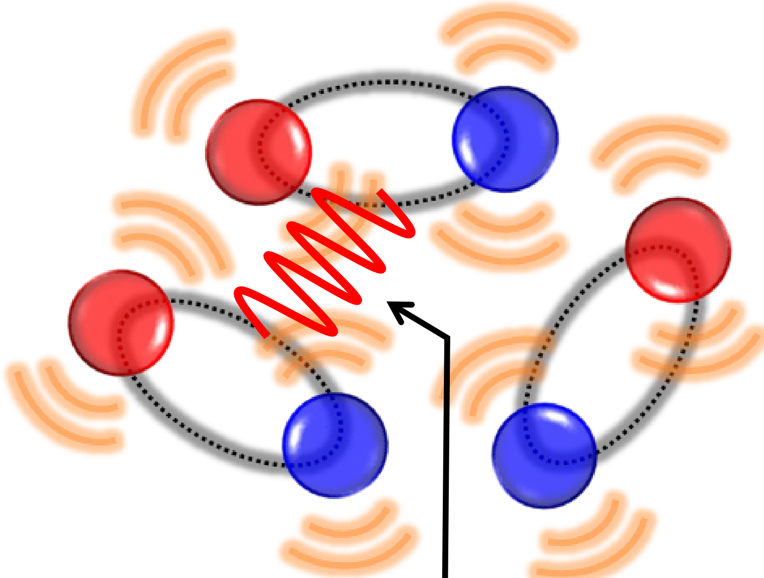
Next crucial topic in pairing physics: Inter-cluster interaction

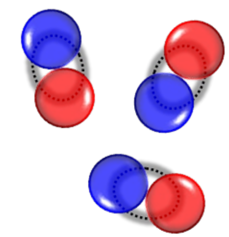


Next crucial topic in pairing physics: Inter-cluster interaction

BCS — **pairing interaction** → **BEC**







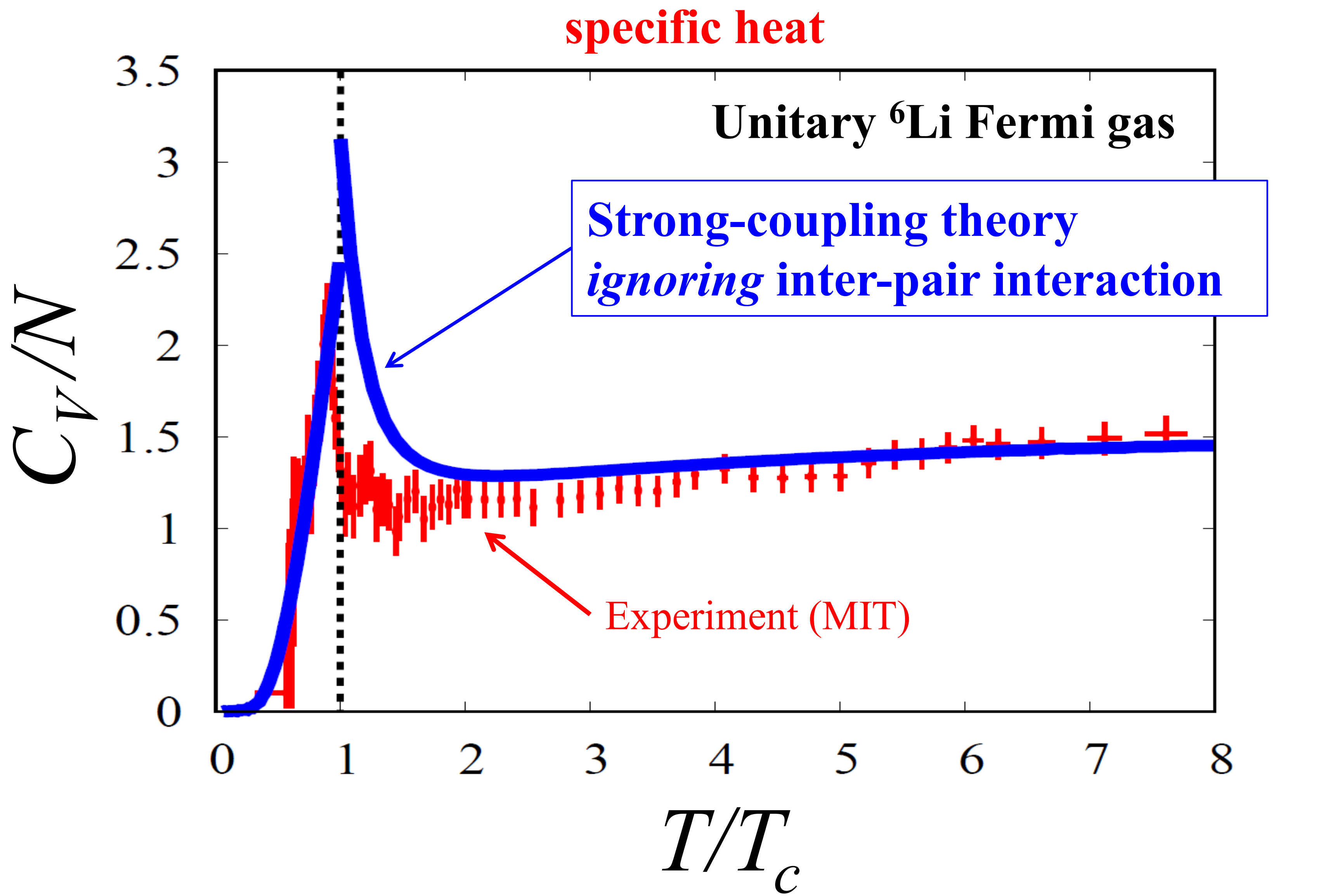
How does the interaction between pairs develop in the BCS-BEC crossover region?

$$V_M = \frac{4\pi a_M}{M_M} > 0$$

$$a_M = 0.6 a_s$$

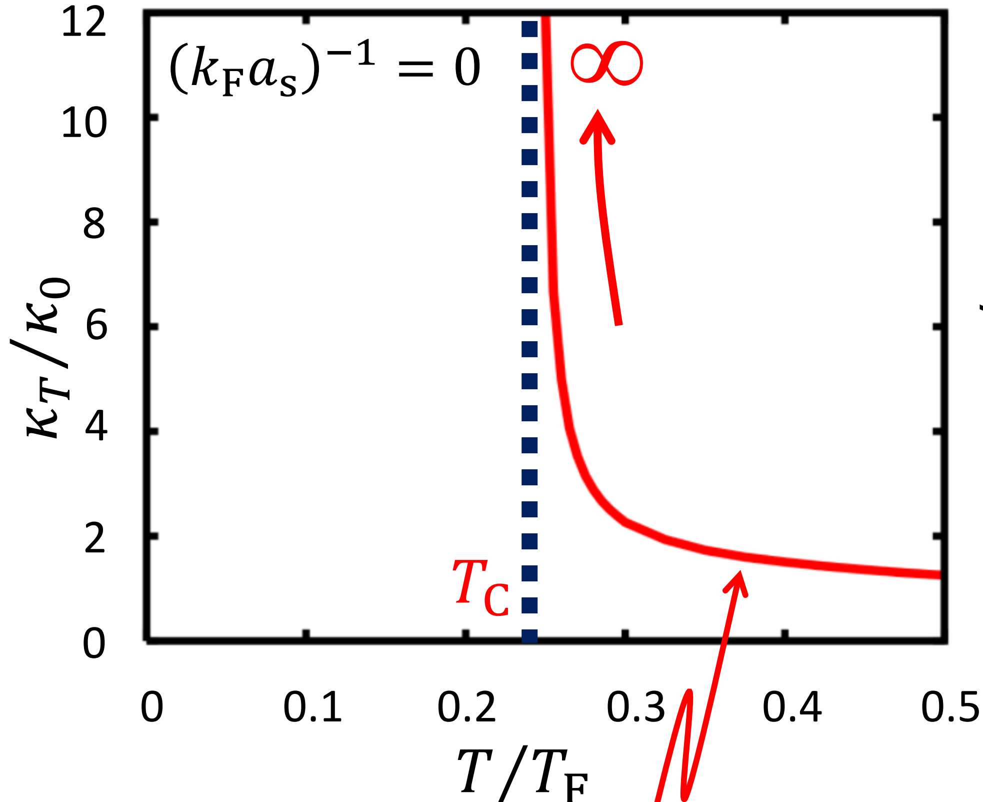
Petrov, PRL (2004)

Next crucial topic in pairing physics: Inter-cluster interaction

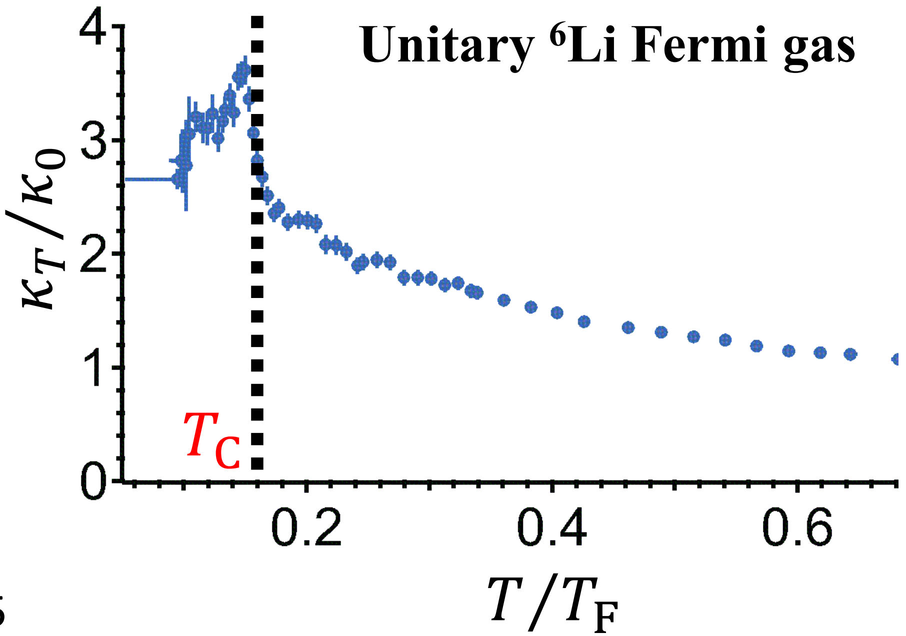


Next crucial topic in pairing physics: Inter-cluster interaction

Isothermal compressibility κ_T may be a promising quantity to clarify the inter-cluster (pair) interaction.



Strong-coupling theory *ignoring* inter-pair interaction

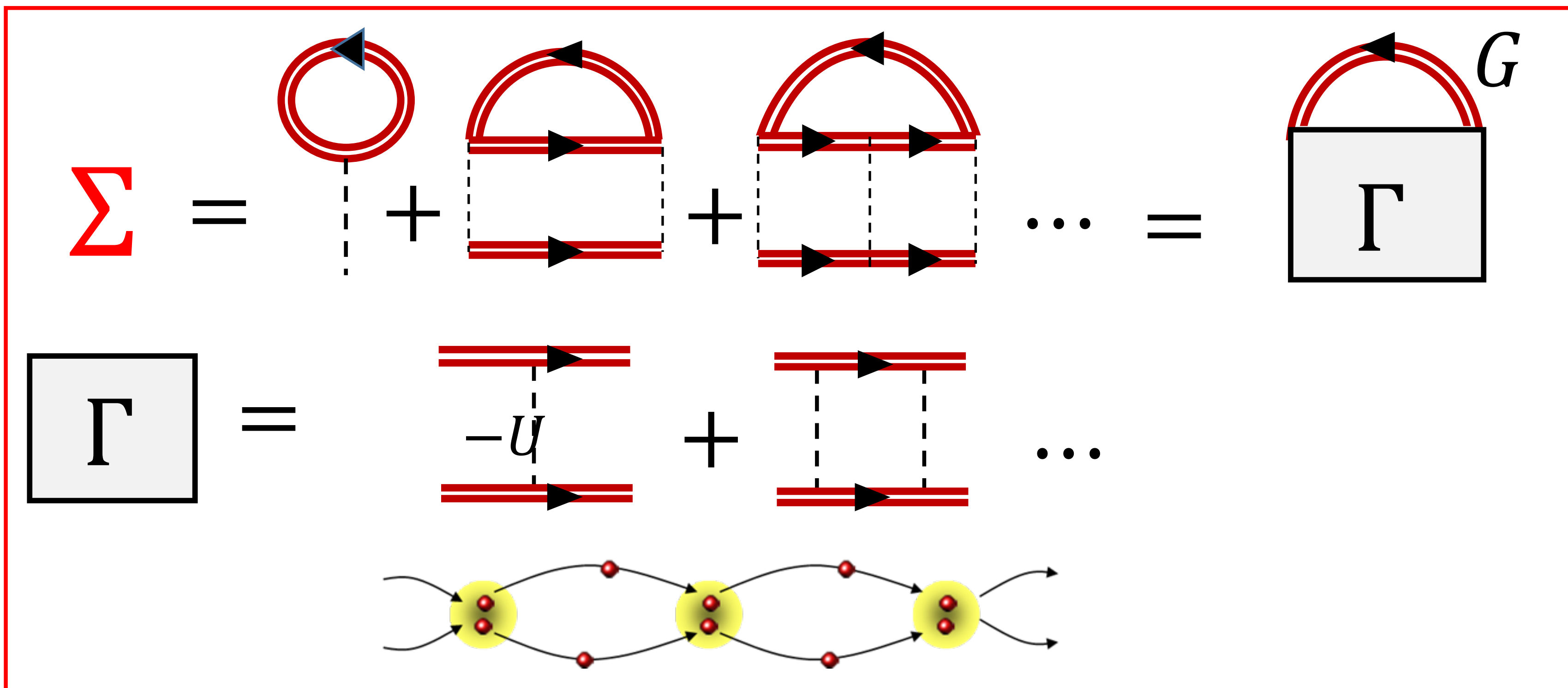


Ku *et al.*, Science **335**,563 (2012).

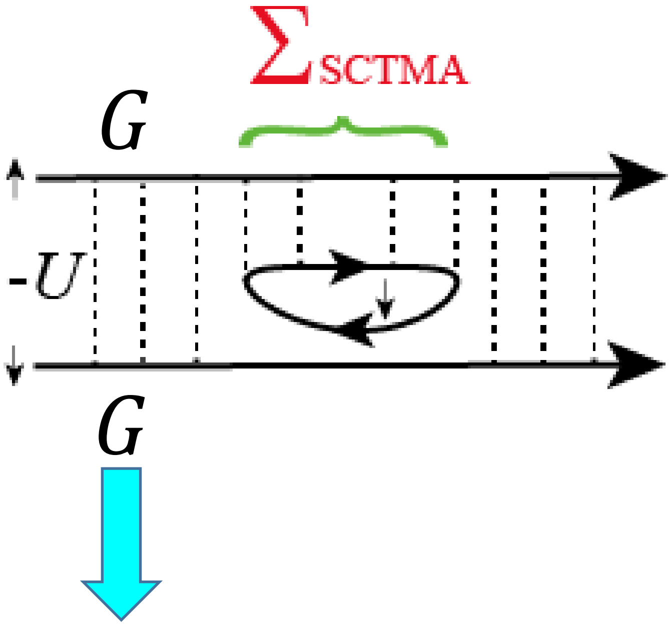
Strong-coupling theory involving inter-cluster interaction (SCTMA)

$$H=\sum_{p,\sigma}(\varepsilon_p-\mu)c^\dagger_{p\sigma}c_{p\sigma}-U\sum_{p,p',q}c^\dagger_{p+\frac{q}{2}\uparrow}c^\dagger_{-p+\frac{q}{2}\downarrow}c_{-p'+\frac{q}{2}\downarrow}c_{p'+\frac{q}{2}\uparrow}$$

$$G(\boldsymbol{p},i\omega_n)=\frac{1}{i\omega_n-\varepsilon_p+\mu-\Sigma(p,i\omega_n)}$$

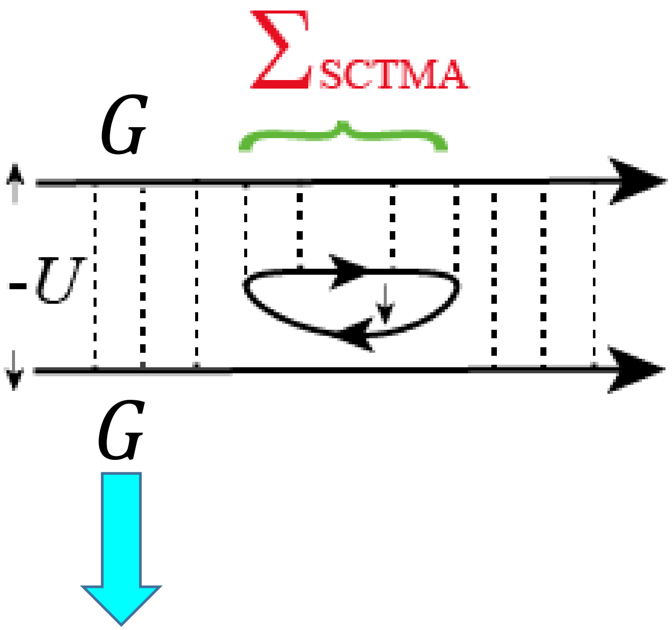


Strong-coupling theory involving inter-cluster interaction (SCTMA)



$$\frac{1}{i\omega_n - \varepsilon_p + \mu - \Sigma(p, i\omega_n)}$$

Strong-coupling theory involving inter-cluster interaction (SCTMA)



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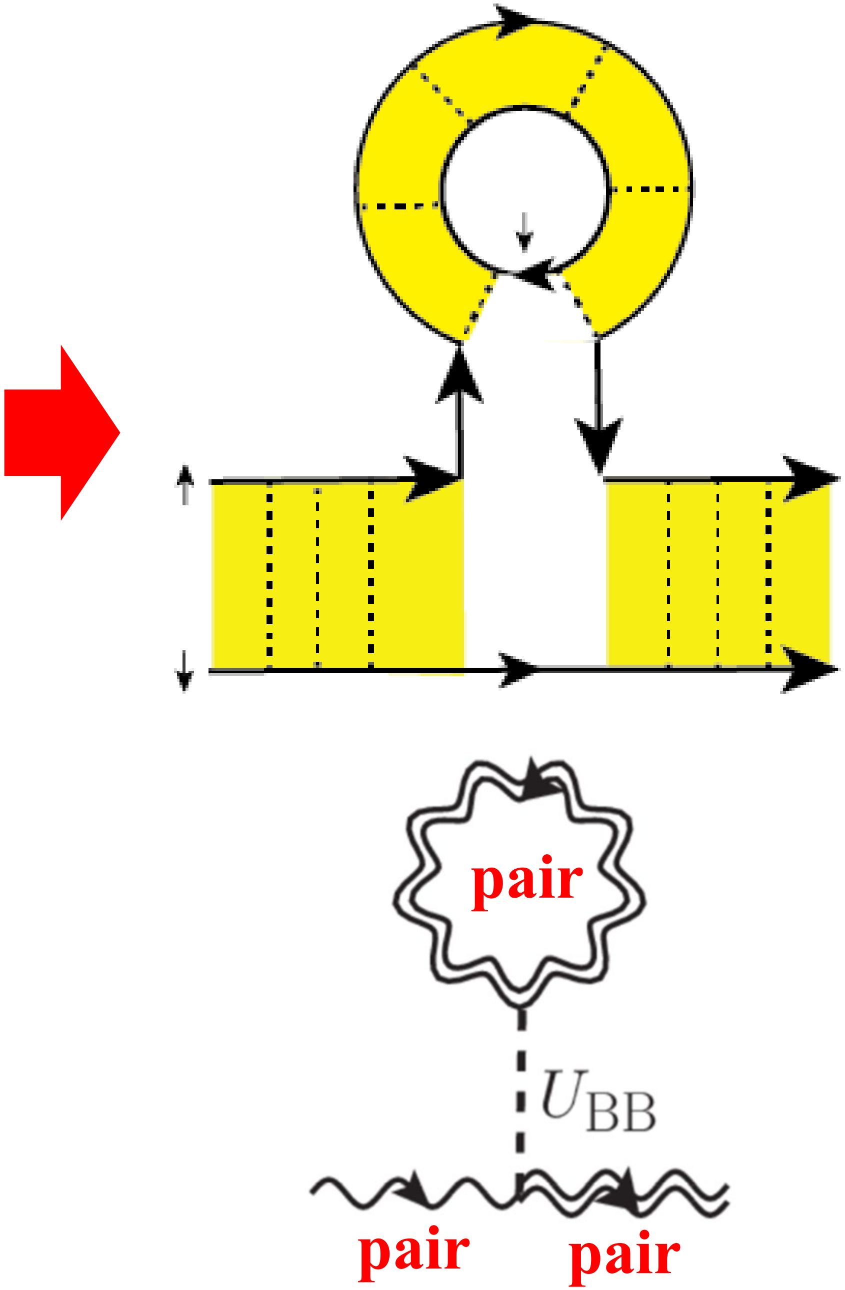
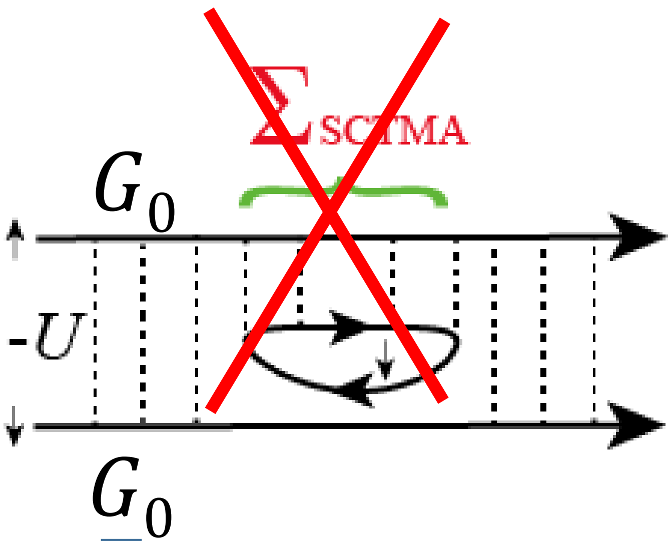
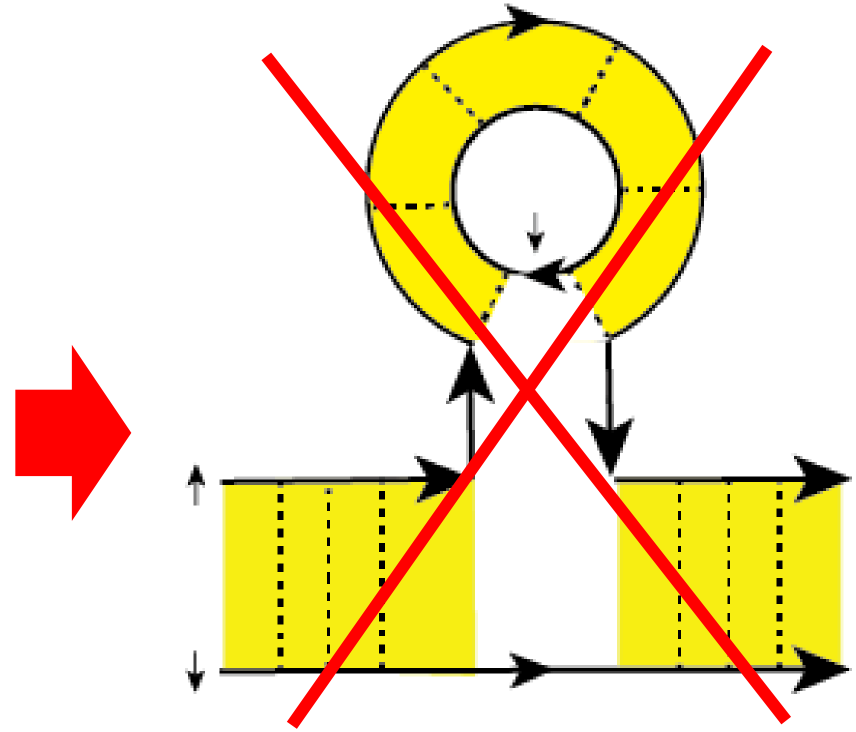


Strong-coupling theory involving inter-cluster interaction (SCTMA)



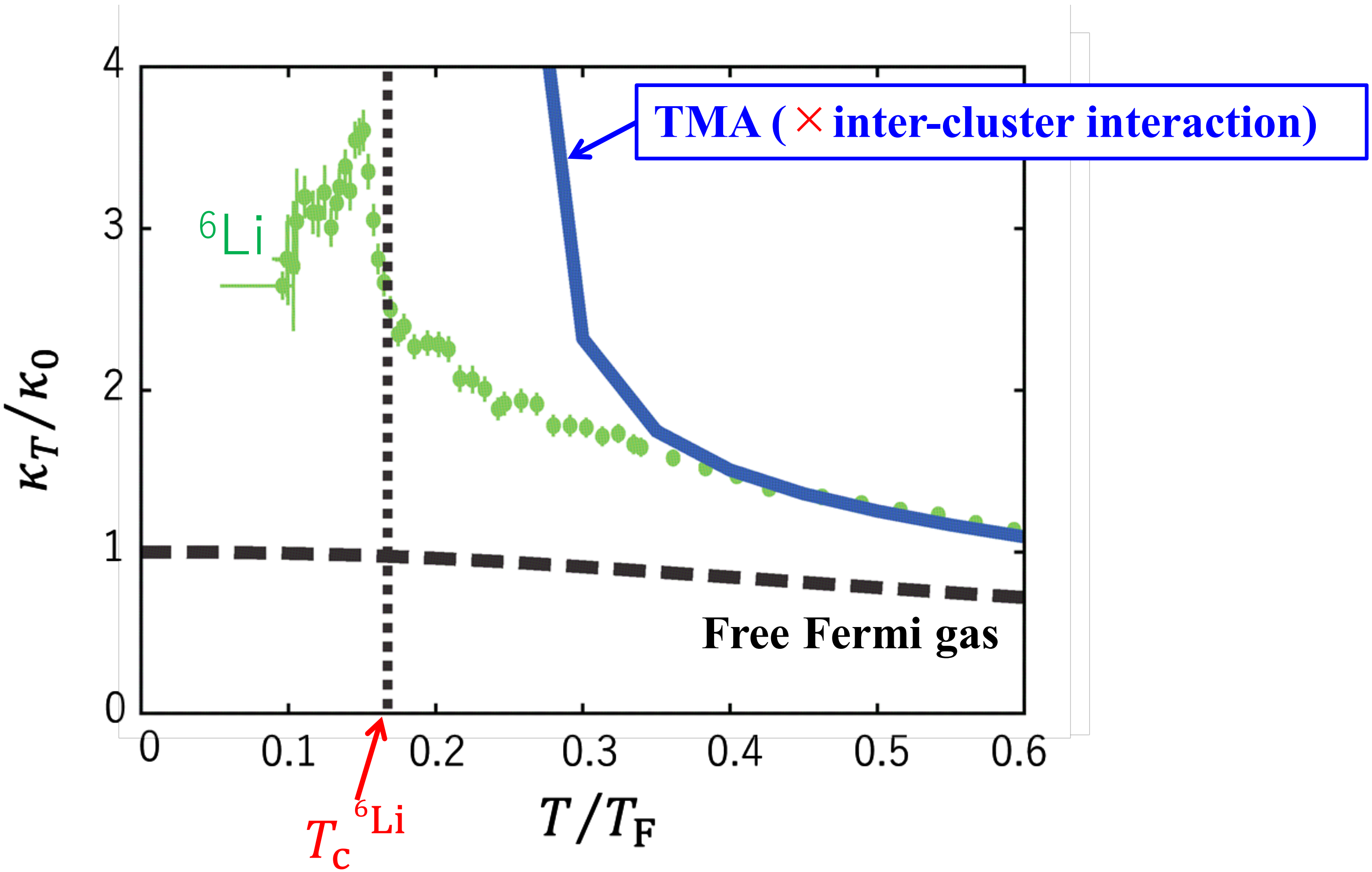


$$\frac{1}{i\omega_n - \varepsilon_p + \mu - \cancel{\Sigma(p, i\omega_n)}}$$

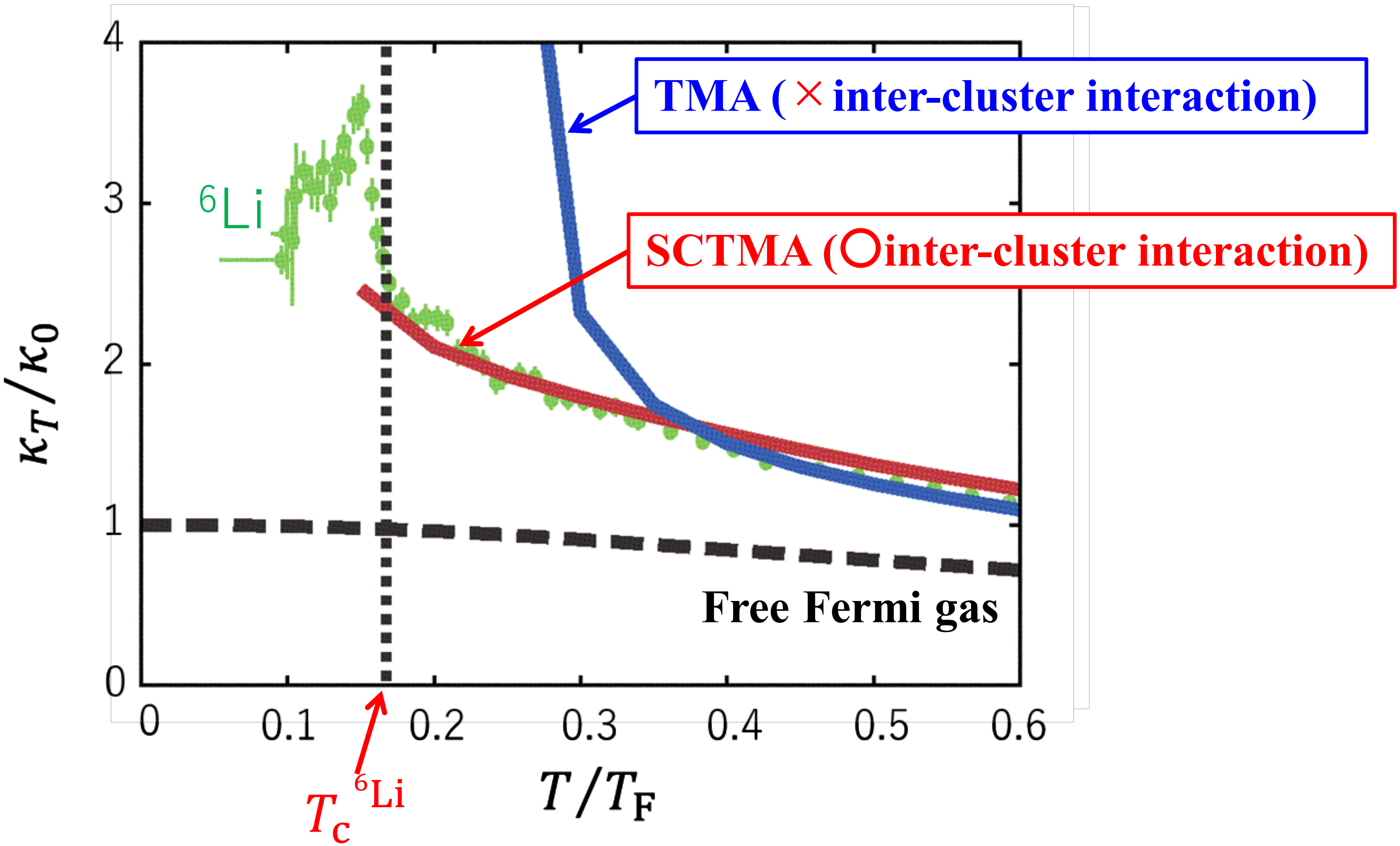
Non-interacting!!

This strong-coupling theory is sometimes referred to as TMA.

Quantitative comparison with experiment (unitarity limit)

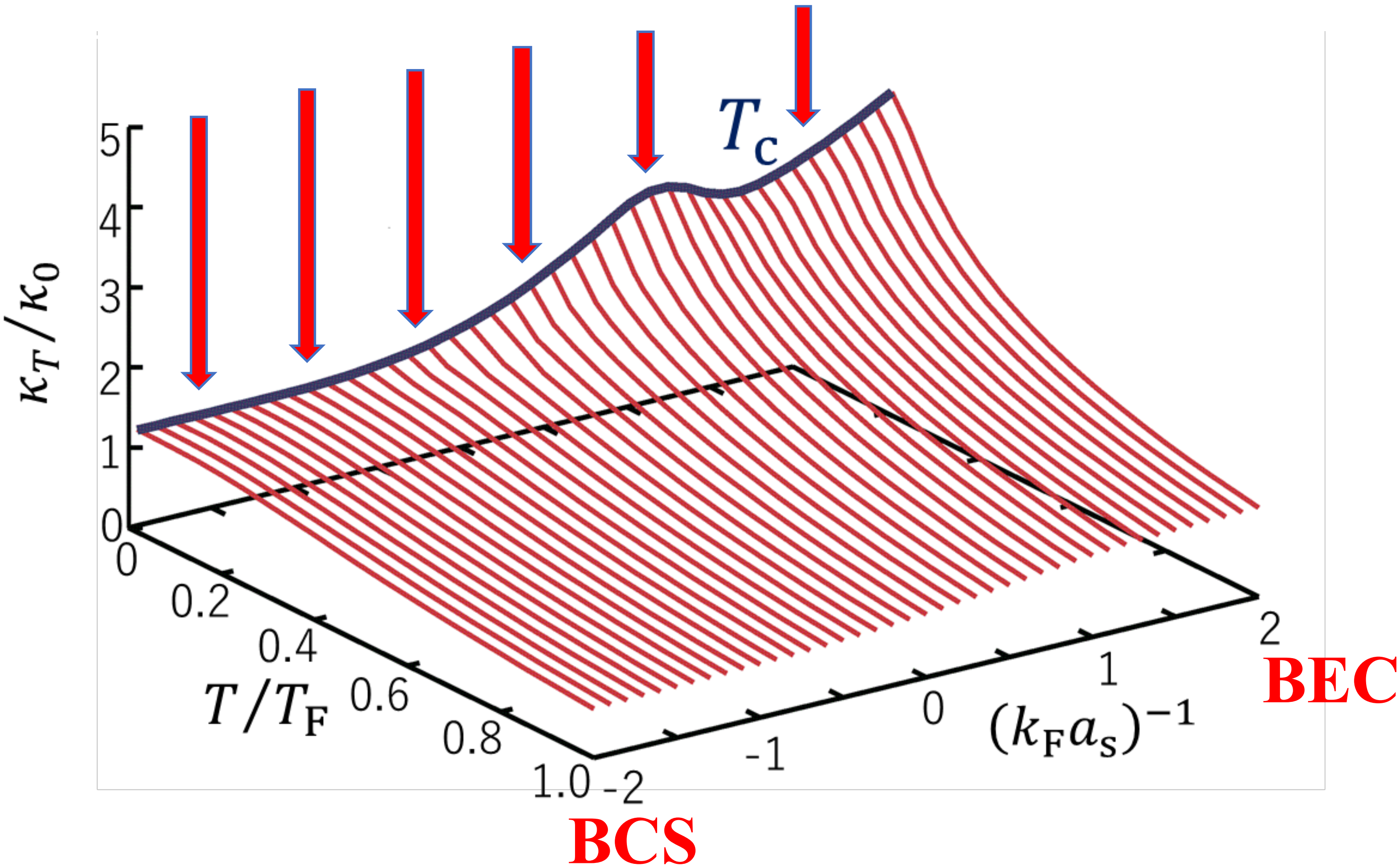


Quantitative comparison with experiment (unitarity limit)



SCTMA can quantitatively explain the compressibility observed in a unitary Fermi gas.

Calculated compressibility in the crossover region (SCTMA)



The inter-cluster interaction makes the compressibility converge in the whole BCS-BEC crossover region.

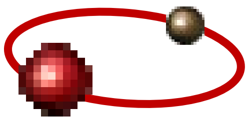
Our Strategy to reach universality of our world, going beyond the hierarchy: Cold atom physics (C02)

KSS conjecture

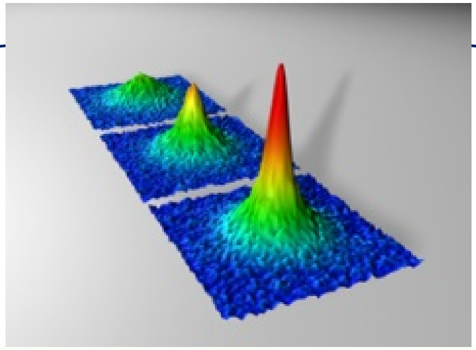
$$\frac{\eta}{s} \geq \frac{\hbar}{4\pi k_B}$$

Shear Viscosity

Hetero-cluster



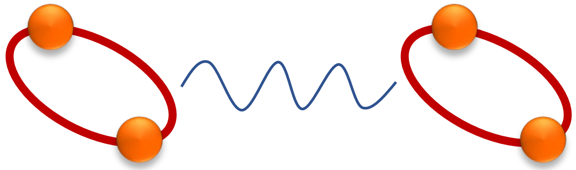
Bose-Fermi mixture



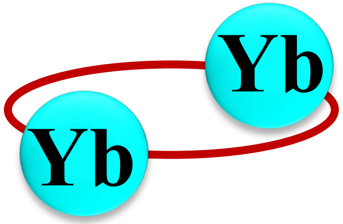
Superfluid Fermi atom gas

Compressibility

Orbital Feshbach



Inter-cluster interaction

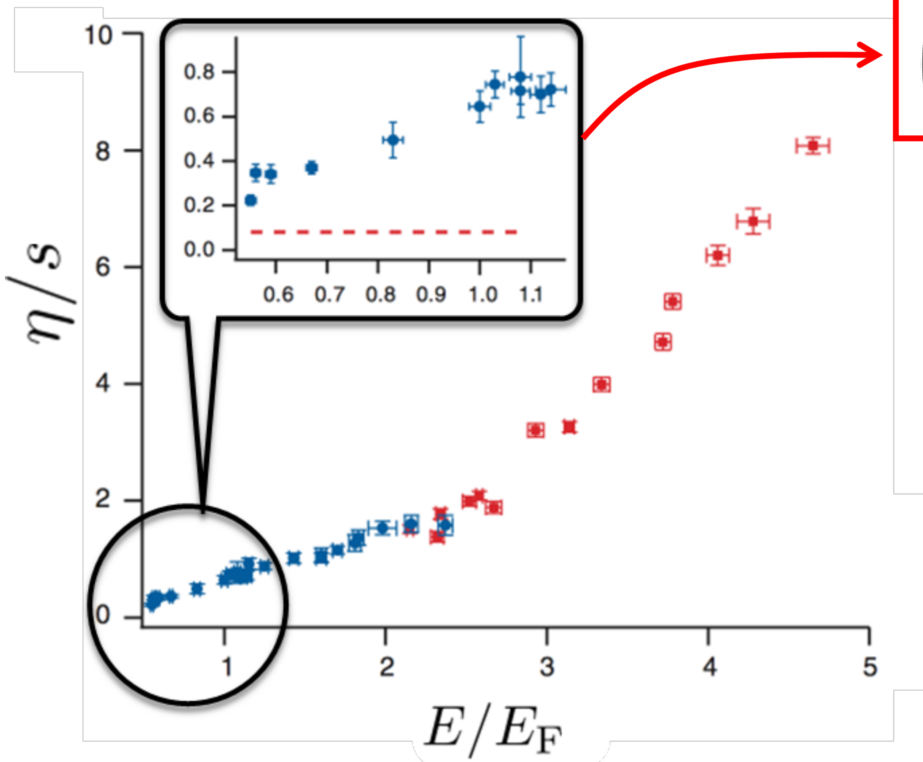


Proposed ^{173}Yb Fermi superfluid

Kovtan-Son-Starinets (KSS) conjecture (PRL 95 111601 (2005)

$$\frac{\text{shear viscosity}}{\text{entropy density}} = \frac{\eta}{s} \geq \frac{\hbar}{4\pi k_B}$$

^{6}Li unitary Fermi gas



C. Cao, *et al.*, Science **331** 58 (2011)

$$(\eta/s)_{\min} \sim 2.7\hbar/4\pi k_B$$

- Quark Gluon Plasma

$$(\eta/s)_{\min} \sim 2\hbar/4\pi k_B$$

- Superfluid ^{4}He

$$(\eta/s)_{\min} \sim 5\hbar/4\pi k_B$$

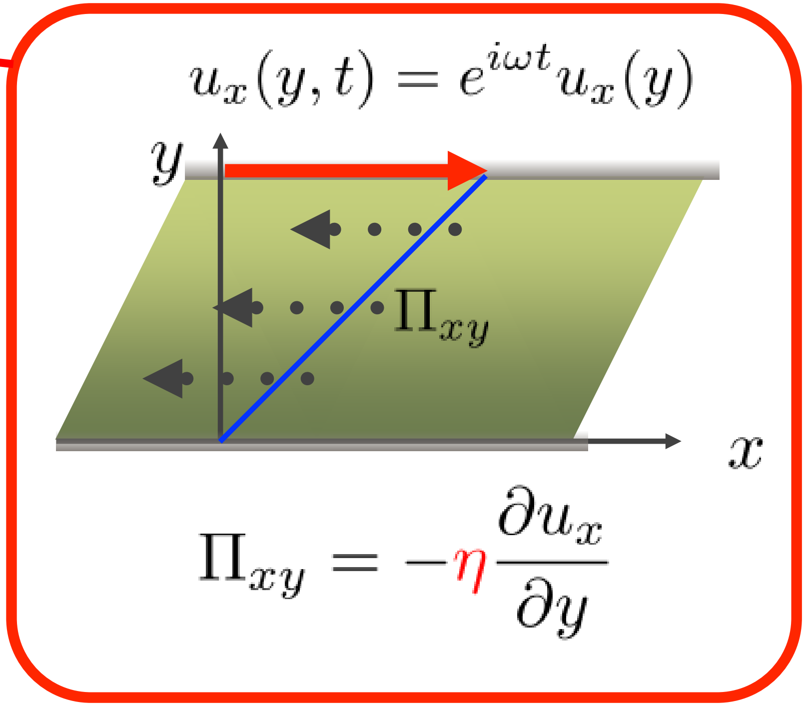
- N_2 (room temp., 1atm)

$$(\eta/s) \sim 3.3 \times 10^3 \hbar/4\pi k_B$$

Shear viscosity in the BCS-BEC crossover region

- perturbation

$$H' = \frac{1}{i\omega}\frac{\partial u_x}{\partial y}\int d^3\boldsymbol{r}\,\Pi_{xy}$$



- Stress-tensor operator

$$\hat{\Pi}_{xy} = \sum_{\boldsymbol{p},\sigma}\frac{p_x p_y}{m}c^\dagger_{\boldsymbol{p},\sigma}c_{\boldsymbol{p},\sigma}$$

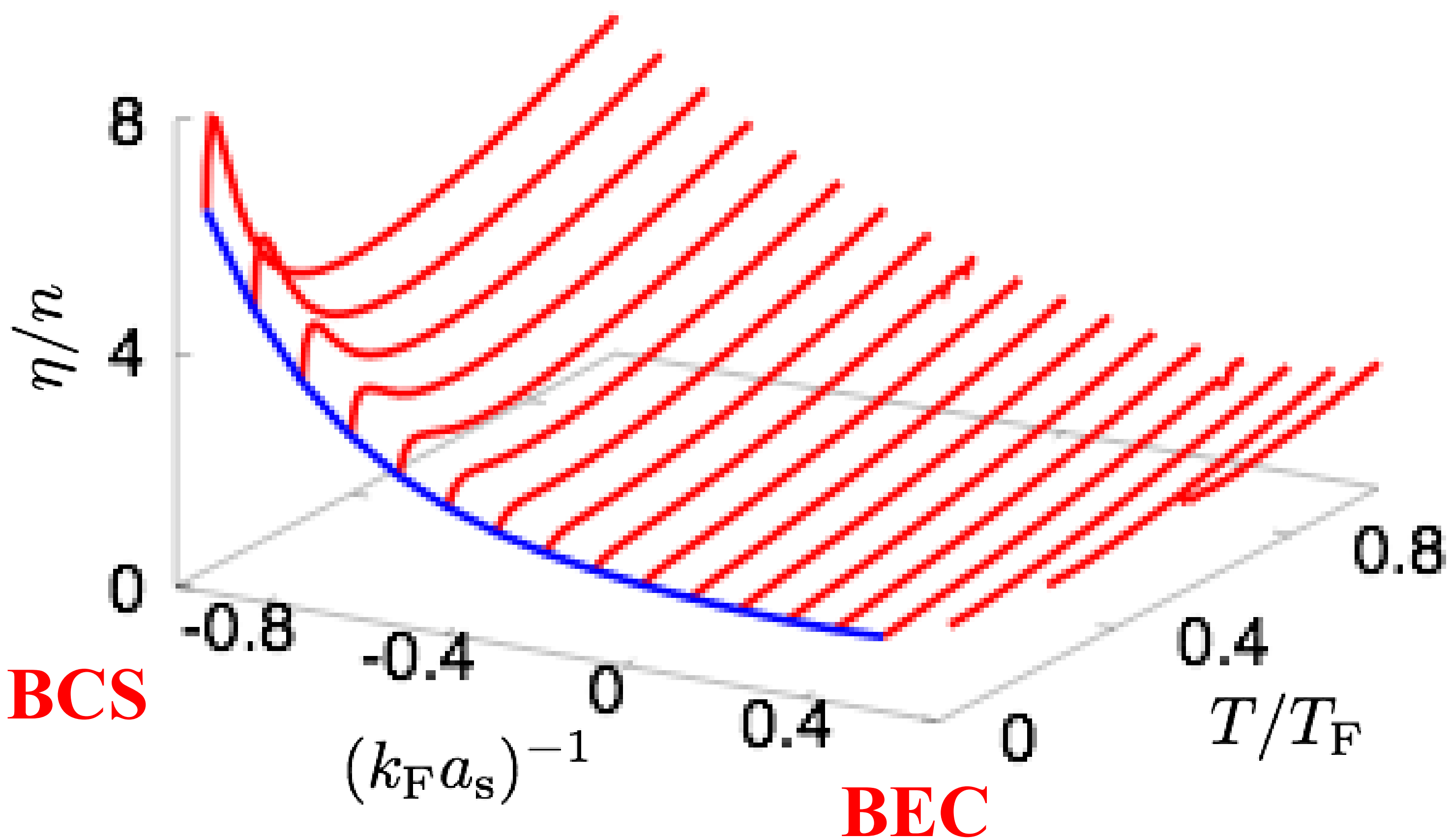
- shear viscosity

$$\eta = -\lim_{\omega\to 0}\frac{\mathrm{Im}\Xi(\omega)}{\omega}$$

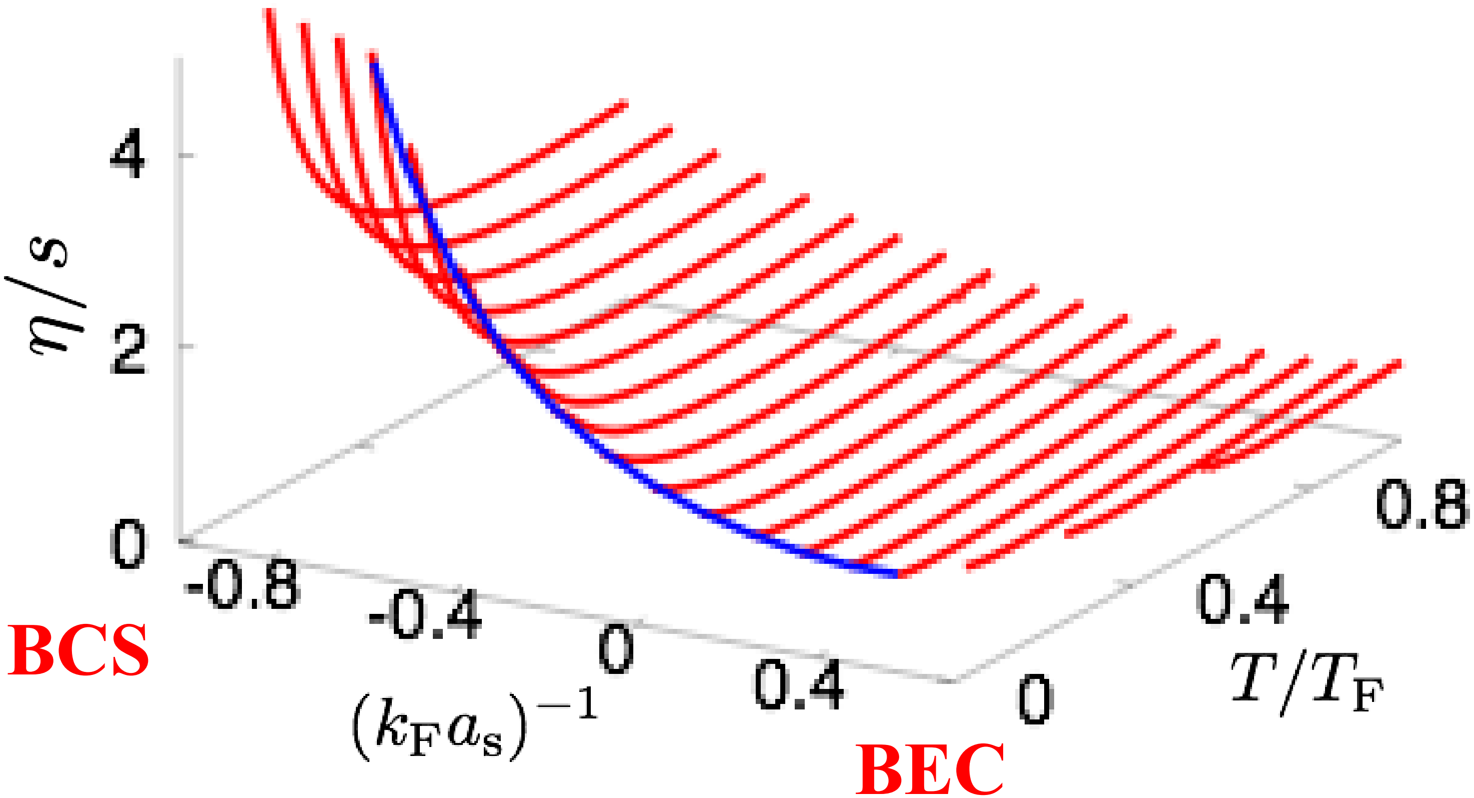
$$\Xi(\omega) = -i\int d\boldsymbol{r}dte^{\imath\omega t}\theta(t)\left\langle[\hat{\Pi}^{xy}(\boldsymbol{r},t),\hat{\Pi}^{xy}(\boldsymbol{0},0)]\right\rangle$$

We evaluate the shear viscosity including the self-energy and vertex corrections in a consistent manner, within the framework of SCTMA.

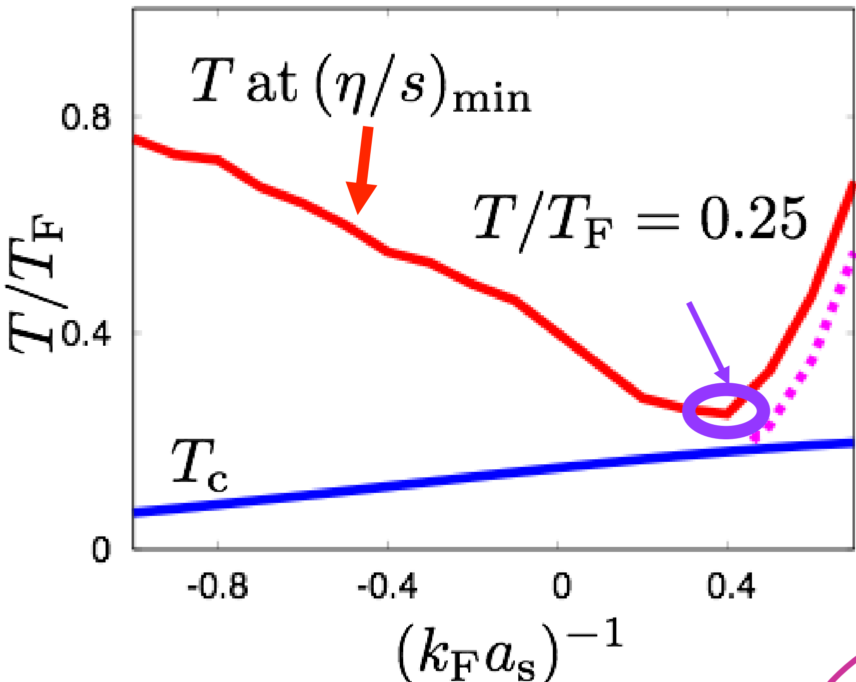
Shear viscosity in the BCS-BEC crossover region

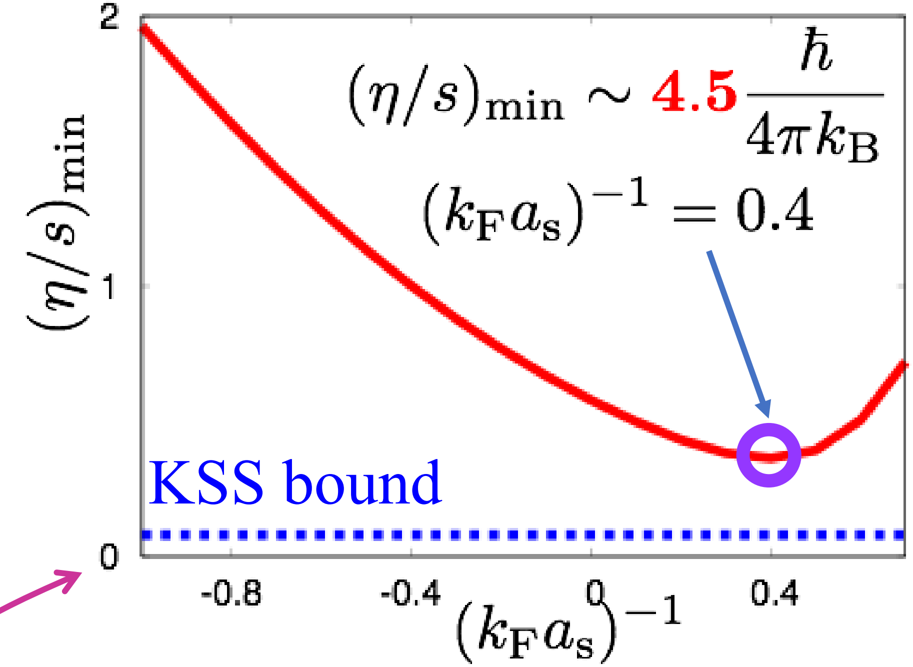


Calculated η/s in the BCS-BEC crossover region

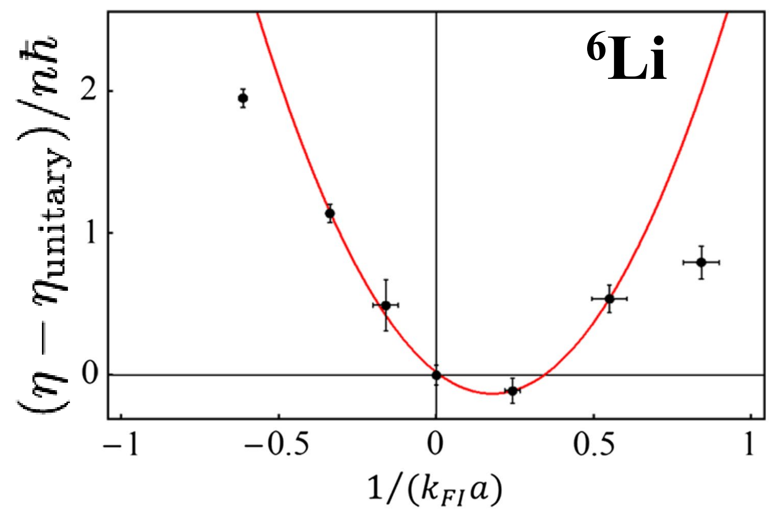


Where is minimum η/s ?



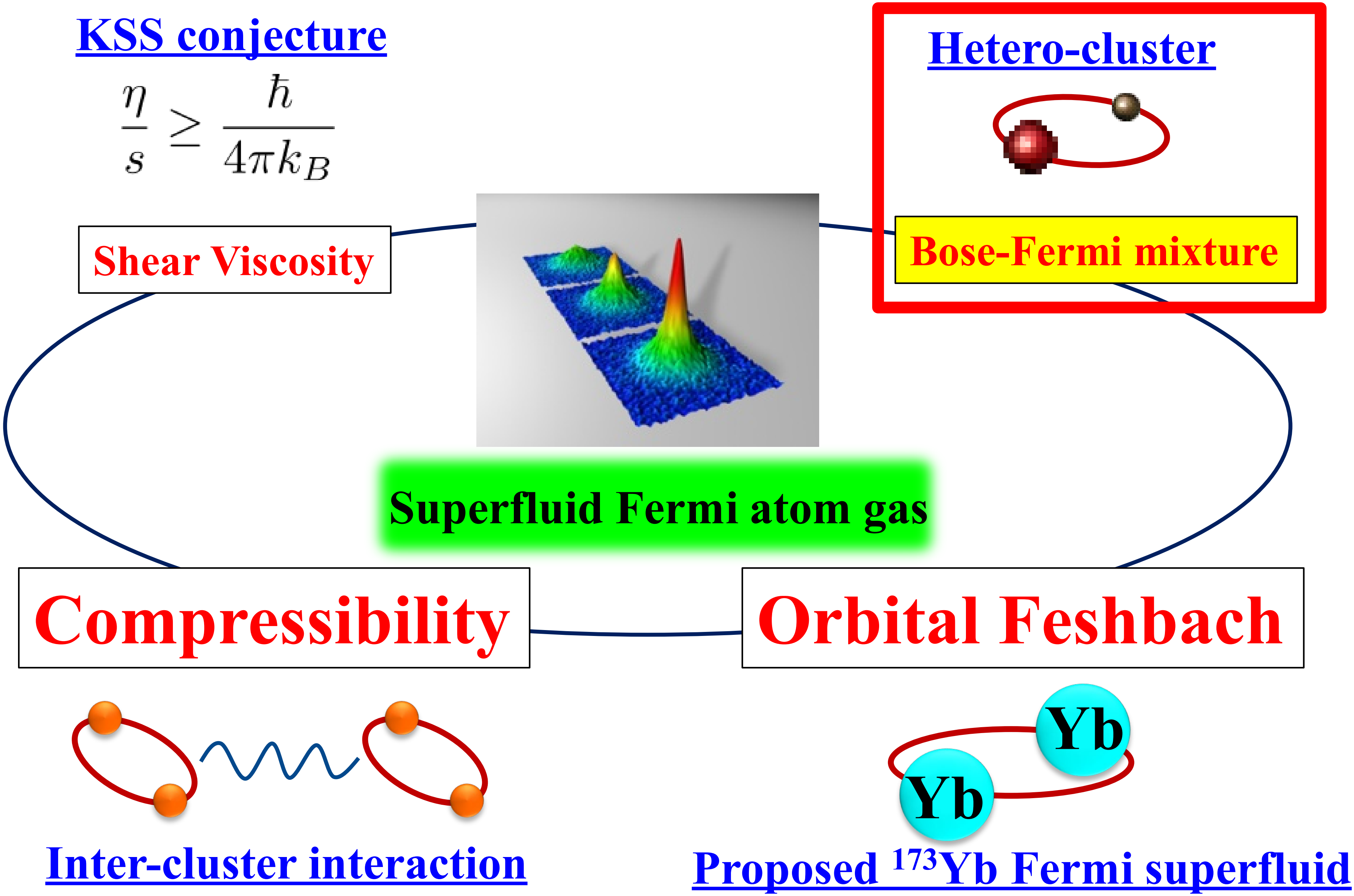


The minimal value of η/s is realized slightly away from the unitarity (?).



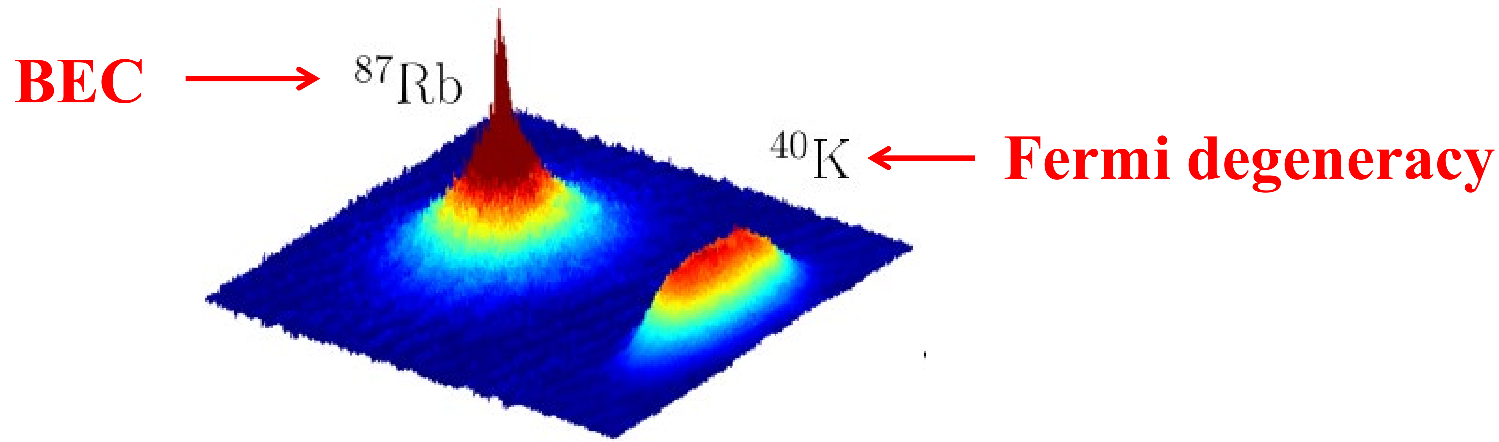
E. Elliott et al. Phys. Rev. Lett. **113** 020406 (2014)

Our Strategy to reach universality of our world, going beyond the hierarchy: Cold atom physics (C02)

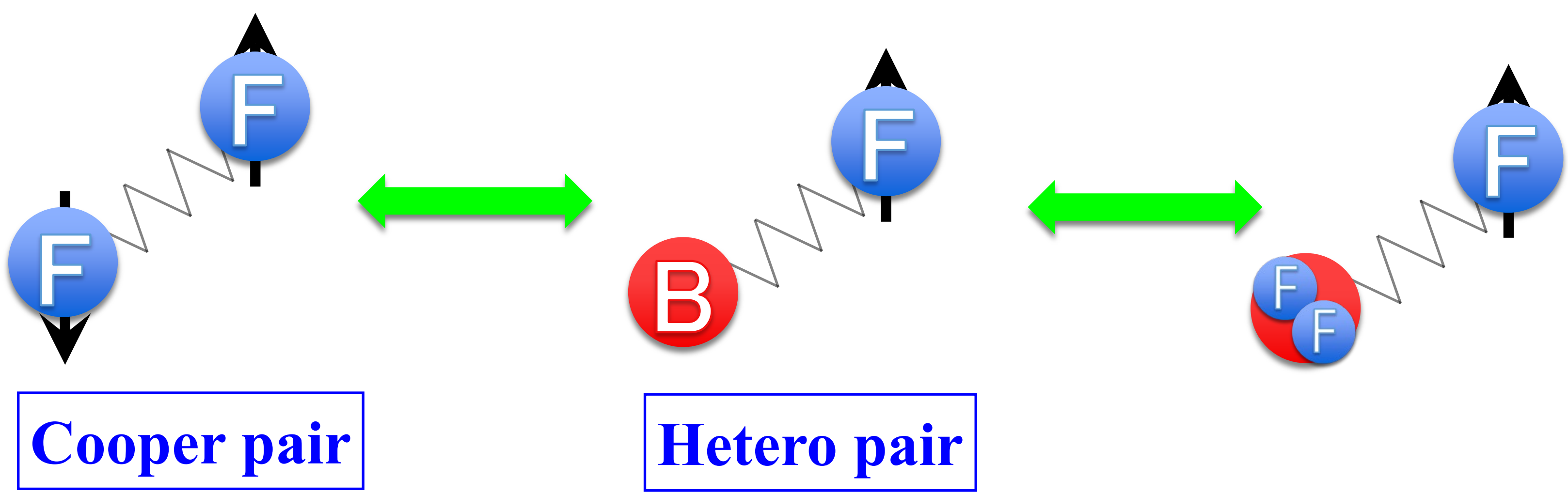


Bose-Fermi mixture with a Feshbach resonance

Tuning a pairing interaction is also possible in a Bose-Fermi mixture.



C. Ospelkaus PRL **96**, 020401 (2006)



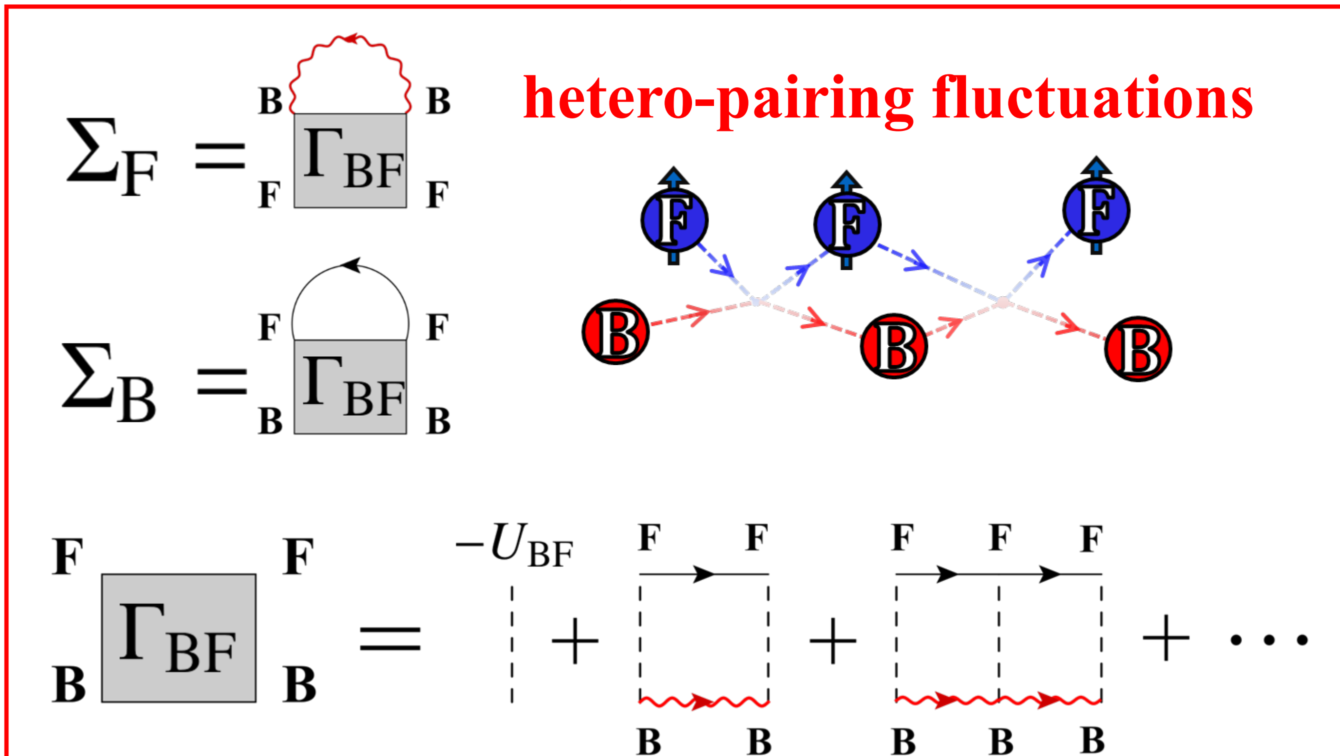
Variation of Bose-Fermi mixture

Fermi–Bose mixture	T/T_F	N_f	N_b	ω_f/ω_b	Reference	Year	Institution
$^6Li-^7Li$	0.25	1.4×10^5	2.2×10^4	1.08	[21]	2001	Rice University
$^6Li-^7Li$	0.2 ± 0.1	4×10^3	10^4	1.08	[22]	2001	ENS, Paris
$^{40}K-^{87}Rb$	0.30	10^4	2×10^4	1.47	[26]	2002	LENS, Florence
$^6Li-^{23}Na$	$0.05^{+0.03}_{-0.02}$	3×10^7	6×10^6	1.94	[90]	2003	MIT
$^{40}K-^{87}Rb$	0.20	10^4	2.5×10^5	1.47	[92]	2004	JILA, Boulder
$^{40}K-^{87}Rb$	0.32	6×10^5	4×10^5	1.47	[95]	2005	ETH, Zurich
$^3He-^4He$	0.45	10^6	10^6	1.15	[108]	2006	Free University of Amsterdam
$^{40}K-^{87}Rb$	0.1	9×10^5	BDL	1.47	[93]	2006	Institüt für Laserphysik, Hamburg
$^{40}K-^{87}Rb$	0.9	2×10^4	BDL	1.47	[96]	2007	University of Toronto
$^6Li-^{87}Rb$	0.90	1.4×10^5	4×10^6	2.5	[102]	2008	University of Tübingen
$^{173}Yb-^{174}Yb$	0.3	10^4	3×10^4	1.00	[115]	2009	Kyoto University
$^6Li-^{174}Yb$	0.08 ± 0.01	2.5×10^4	1.5×10^4	3.90	[118]	2011	Kyoto University
$^6Li-^{174}Yb$	0.3	1.2×10^4	2.3×10^4	8.20	[119]	2011	University of Washington, Seattle
$^{40}K-^{87}Rb$	0.3	2.0×10^6	10^5	1.47	[98]	2011	Shanxi University
$^{23}Na-^{40}K$	0.35	3.0×10^5	10^6	—	[124]	2012	MIT
$^{84}Sr-^{87}Sr$	0.30 ± 0.05	2.0×10^4	10^5	0.98	[117]	2012	Universität Innsbruck
$^6Li-^7Li$	0.03	2.5×10^5	2.5×10^4	1.08	[88]	2015	ENS, Paris
$^{87}Rb-^{171}Yb$	0.16 ± 0.02	2.4×10^5	3.5×10^5	2.00	[123]	2015	University of Maryland–NIST
$^6Li-^{41}K$	0.07	1.5×10^6	1.8×10^5	2.23	[125]	2016	USTC Hefei and Shanghai

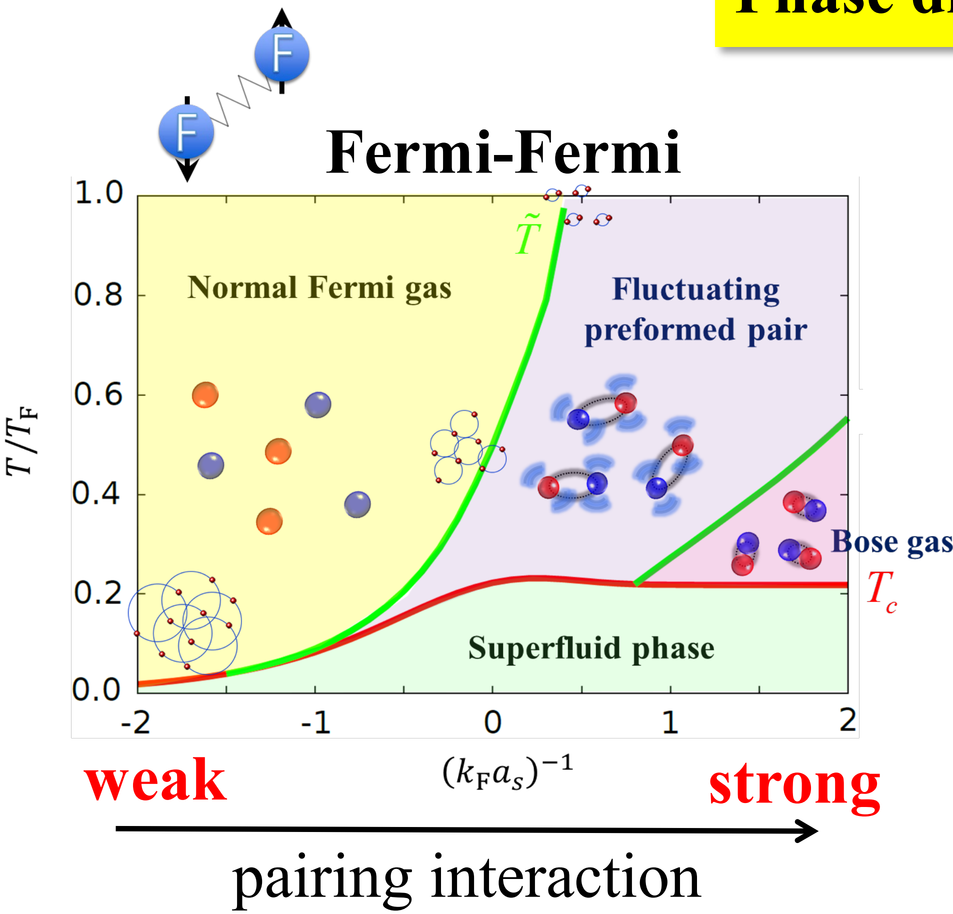
Strong-coupling theory involving hetero-pairing fluctuations

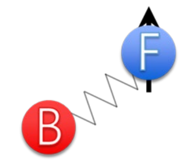
$$H_{\rm BF} = \sum_{\boldsymbol{p}} \xi^{\rm B}_{\boldsymbol{p}} b^\dagger_{\boldsymbol{p}} b_{\boldsymbol{p}} + \sum_{\boldsymbol{p}} \xi^{\rm F}_{\boldsymbol{p}} f^\dagger_{\boldsymbol{p}} f_{\boldsymbol{p}} - U_{\rm BF} \sum_{\boldsymbol{p},\boldsymbol{p}',\boldsymbol{q}} b^\dagger_{\boldsymbol{p}+\boldsymbol{q}/2} f^\dagger_{-\boldsymbol{p}+\boldsymbol{q}/2} f_{\boldsymbol{p}'+\boldsymbol{q}/2} b_{-\boldsymbol{p}'+\boldsymbol{q}/2}$$

$$G_{B,F}(\boldsymbol{p}, i\omega_n) = \frac{1}{i\omega_n - \varepsilon_p + \mu - \Sigma_{B,F}(p, i\omega_n)}$$

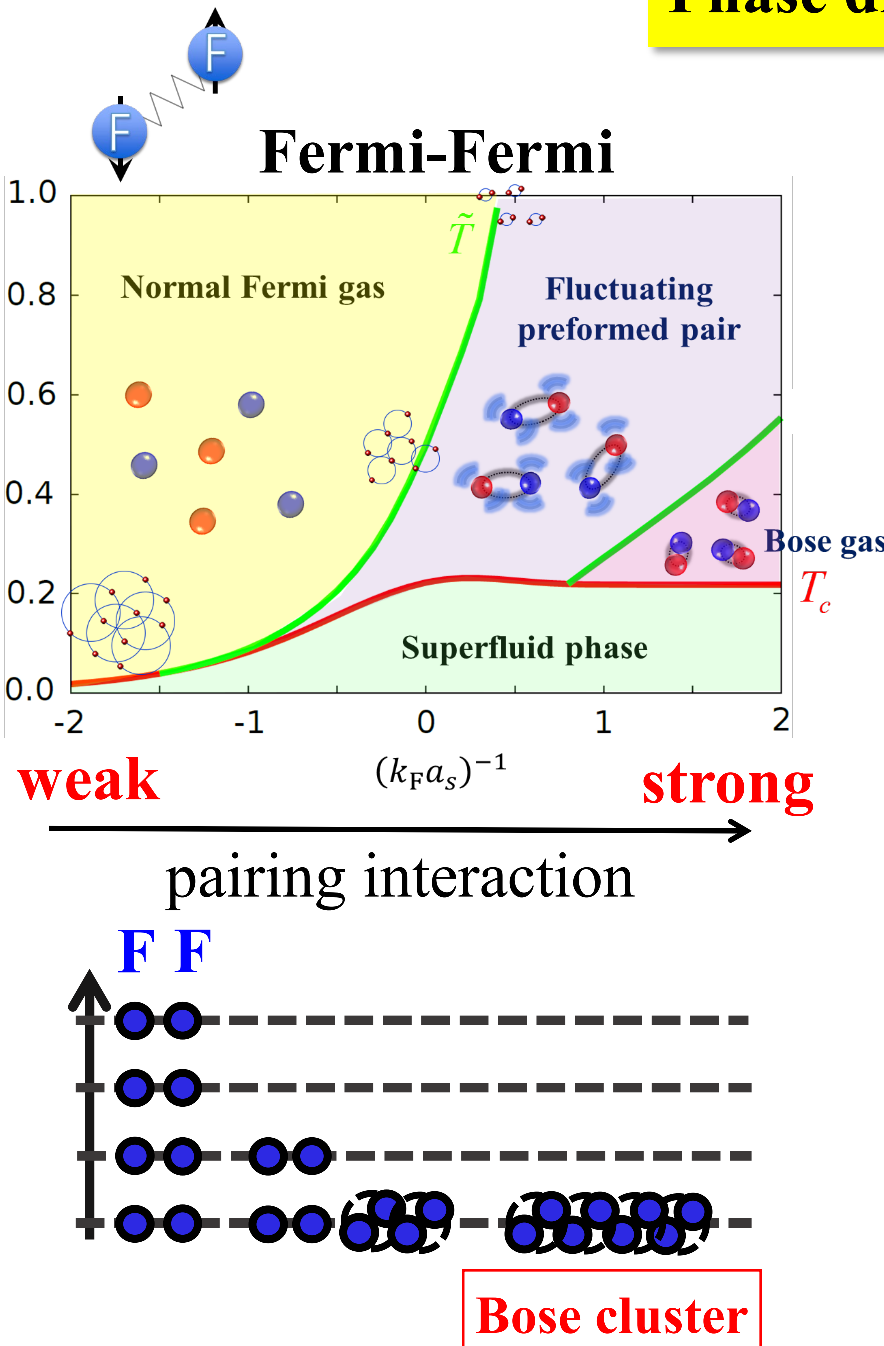


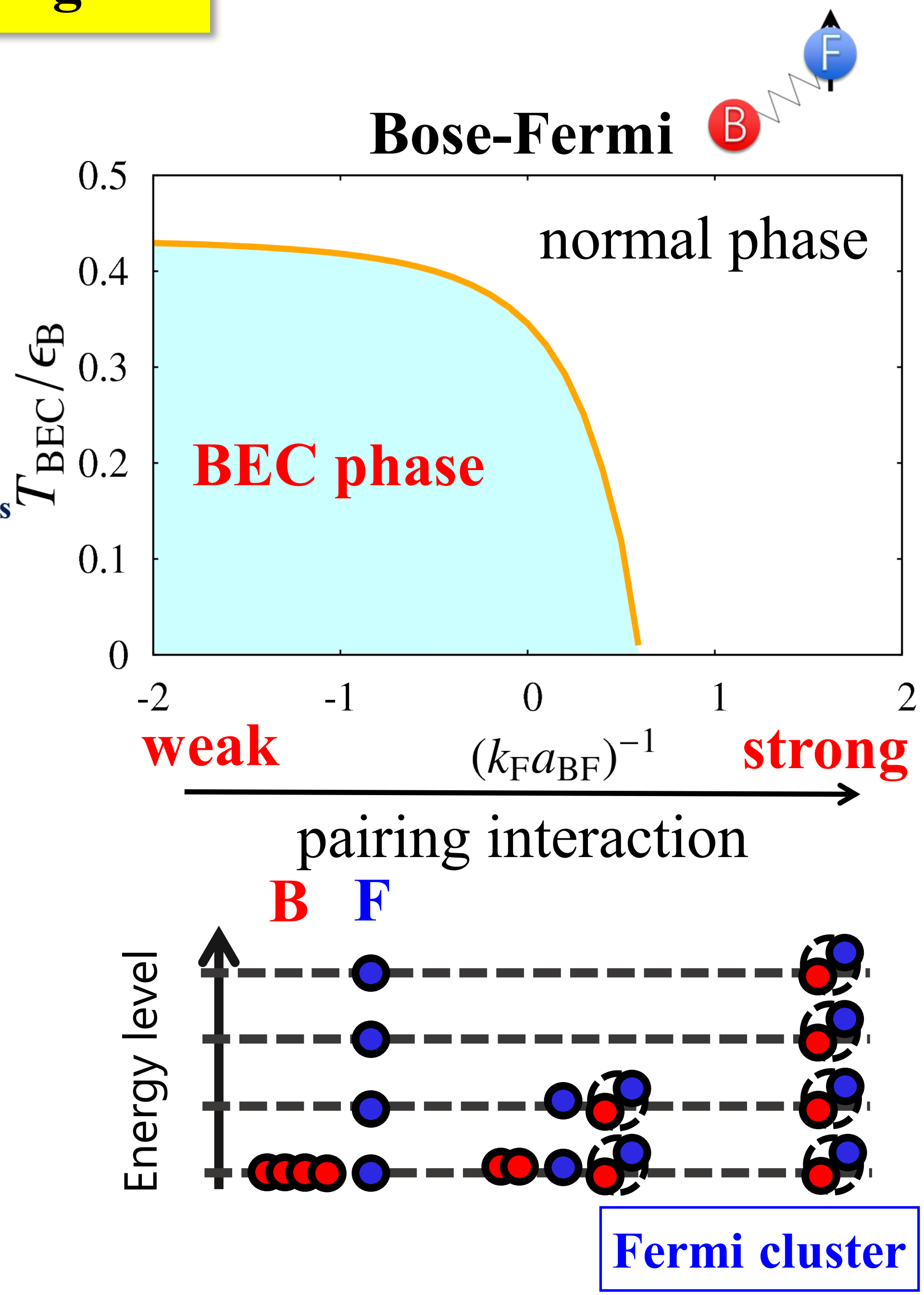
Phase diagram



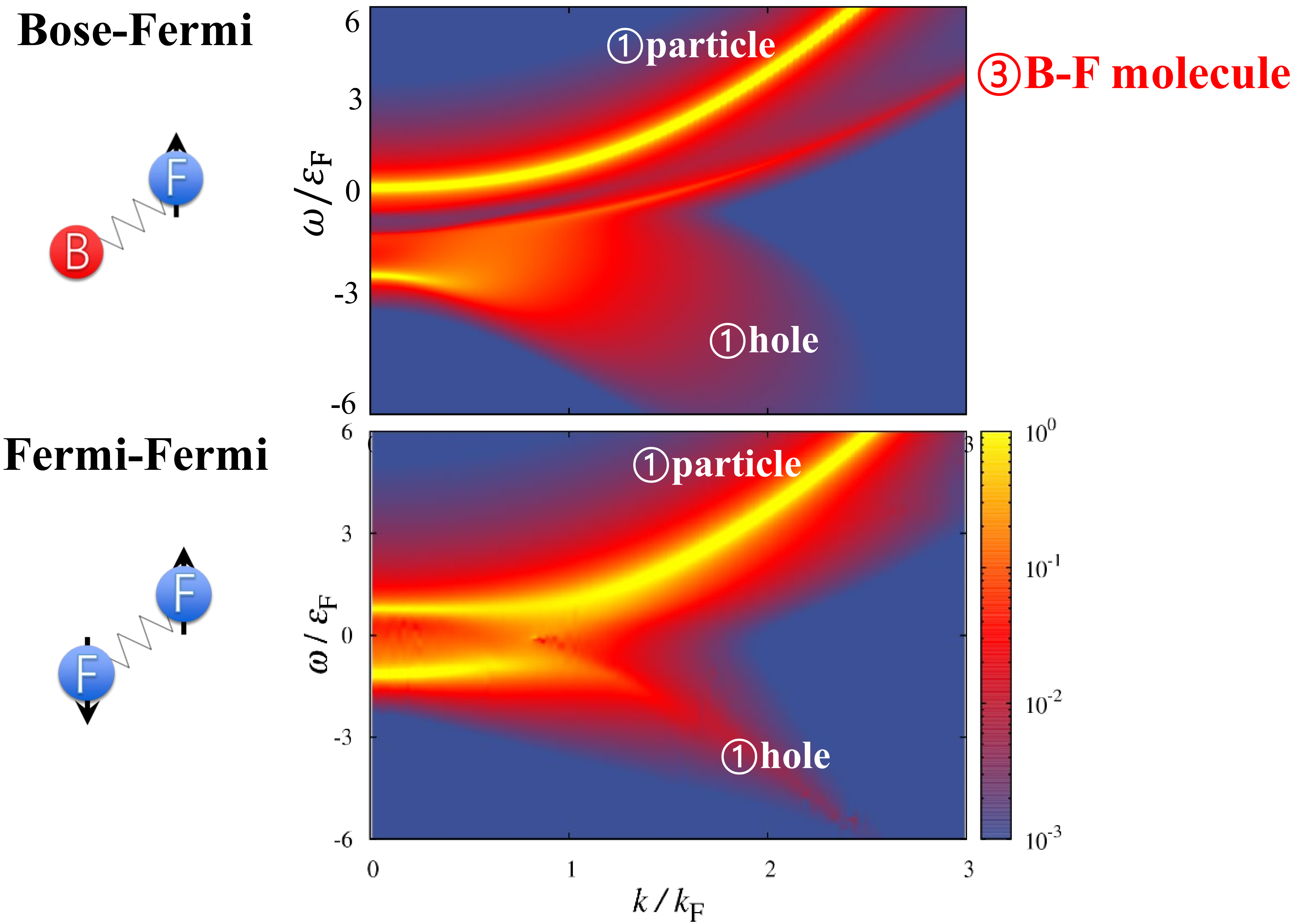


Phase diagram

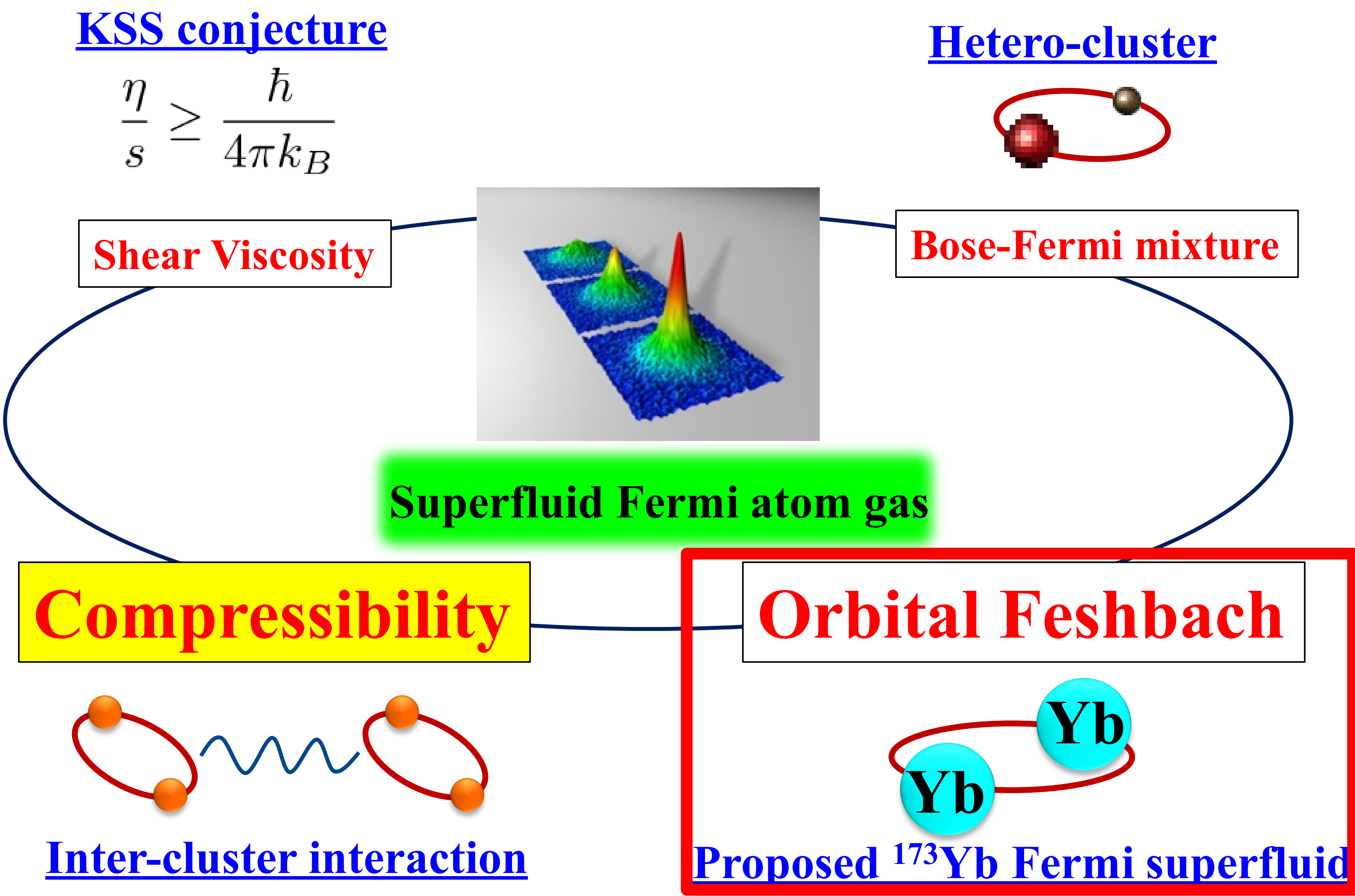




Fermi single-particle excitations (T>Tc)



Our Strategy to reach universality of our world, going beyond the hierarchy: Cold atom physics (C02)



Superconductivity of single-metal elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 **H** 1.0079																	2 **He** 4.0026
3 **Li** 6.941	4 **Be** 9.0122											5 **B** 10.811	6 **C** 12.011	7 **N** 14.007	8 **O** 15.999	9 **F** 18.998	10 **Ne** 20.180
11 **Na** 22.990	12 **Mg** 24.305											13 **Al** 26.982	14 **Si** 28.086	15 **P** 30.974	16 **S** 32.065	17 **Cl** 35.453	18 **Ar** 39.948
19 **K** 39.098	20 **Ca** 40.078	21 **Sc** 44.956	22 **Ti** 47.867	23 **V** 50.942	24 **Cr** 51.996	25 **Mn** 54.938	26 **Fe** 55.845	27 **Co** 58.933	28 **Ni** 58.693	29 **Cu** 63.546	30 **Zn** 65.409	31 **Ga** 69.723	32 **Ge** 72.64	33 **As** 74.922	34 **Se** 78.96	35 **Br** 79.904	36 **Kr** 83.798
37 **Rb** 85.468	38 **Sr** 87.62	39 **Y** 88.906	40 **Zr** 91.224	41 **Nb** 92.906	42 **Mo** 95.94	43 **Tc** (98)	44 **Ru** 101.07	45 **Rh** 102.91	46 **Pd** 106.42	47 **Ag** 107.87	48 **Cd** 112.41	49 **In** 114.82	50 **Sn** 118.71	51 **Sb** 121.76	52 **Te** 127.60	53 **I** 126.90	54 **Xe** 131.29
55 **Cs** 132.91	56 **Ba** 137.33	57-71 *	72 **Hf** 178.49	73 **Ta** 180.95	74 **W** 183.84	75 **Re** 186.21	76 **Os** 190.23	77 **Ir** 192.22	78 **Pt** 195.08	79 **Au** 196.97	80 **Hg** 200.59	81 **Tl** 204.38	82 **Pb** 207.2	83 **Bi** 208.98	84 **Po** (209)	85 **At** (210)	86 **Rn** (222)
87 **Fr** (223)	88 **Ra** (226)	89-103 #	104 **Rf** (261)	105 **Db** (262)	106 **Sg** (266)	107 **Bh** (264)	108 **Hs** (277)	109 **Mt** (268)	110 **Ds** (281)	111 **Rg** (272)	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	Ts	118 Og

* Lanthanide series	57 **La** 138.91	58 **Ce** 140.12	59 **Pr** 140.91	60 **Nd** 144.24	61 **Pm** (145)	62 **Sm** 150.36	63 **Eu** 151.96	64 **Gd** 157.25	65 **Tb** 158.93	66 **Dy** 162.50	67 **Ho** 164.93	68 **Er** 167.26	69 **Tm** 168.93	70 **Yb** 173.04	71 **Lu** 174.97
# Actinide series	89 **Ac** (227)	90 **Th** 232.04	91 **Pa** 231.04	92 **U** 238.03	93 **Np** (237)	94 **Pu** (244)	95 **Am** (243)	96 **Cm** (247)	97 **Bk** (247)	98 **Cf** (251)	99 **Es** (252)	100 **Fm** (257)	101 **Md** (258)	102 **No** (259)	103 **Lr** (262)

atomosphere

Under pressure

Fermi gas superfluids

Only two kinds of Fermi atomic gases exhibit the superfluid transition.

Magnetic Feshbach resonance

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 **H** 1.0079																	2 **He** 4.0026
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19 **K** 39.098	20 **Ca** 40.078	21 **Sc** 44.956	22 **Ti** 47.867	23 **V** 50.942	24 **Cr** 51.996	25 **Mn** 54.938	26 **Fe** 55.845	27 **Co** 58.933	28 **Ni** 58.693	29 **Cu** 63.546	30 **Zn** 65.409	31 **Ga** 69.723	32 **Ge** 72.64	33 **As** 74.922	34 **Se** 78.96	35 **Br** 79.904	36 **Kr** 83.798
37 **Rb** 85.468	38 **Sr** 87.62	39 **Y** 88.906	40 **Zr** 91.224	41 **Nb** 92.906	42 **Mo** 95.94	43 **Tc** (98)	44 **Ru** 101.07	45 **Rh** 102.91	46 **Pd** 106.42	47 **Ag** 107.87	48 **Cd** 112.41	49 **In** 114.82	50 **Sn** 118.71	51 **Sb** 121.76	52 **Te** 127.60	53 **I** 126.90	54 **Xe** 131.29
55 **Cs** 132.91	56 **Ba** 137.33	57-71 *	72 **Hf** 178.49	73 **Ta** 180.95	74 **W** 183.84	75 **Re** 186.21	76 **Os** 190.23	77 **Ir** 192.22	78 **Pt** 195.08	79 **Au** 196.97	80 **Hg** 200.59	81 **Tl** 204.38	82 **Pb** 207.2	83 **Bi** 208.98	84 **Po** (209)	85 **At** (210)	86 **Rn** (222)
87 **Fr** (223)	88 **Ra** (226)	89-103 #	104 **Rf** (261)	105 **Db** (262)	106 **Sg** (266)	107 **Bh** (264)	108 **Hs** (277)	109 **Mt** (268)	110 **Ds** (281)	111 **Rg** (272)	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	Ts	118 Og

* Lanthanide series	57 **La** 138.91	58 **Ce** 140.12	59 **Pr** 140.91	60 **Nd** 144.24	61 **Pm** (145)	62 **Sm** 150.36	63 **Eu** 151.96	64 **Gd** 157.25	65 **Tb** 158.93	66 **Dy** 162.50	67 **Ho** 164.93	68 **Er** 167.26	69 **Tm** 168.93	70 **Yb** 173.04	71 **Lu** 174.97
# Actinide series	89 **Ac** (227)	90 **Th** 232.04	91 **Pa** 231.04	92 **U** 238.03	93 **Np** (237)	94 **Pu** (244)	95 **Am** (243)	96 **Cm** (247)	97 **Bk** (247)	98 **Cf** (251)	99 **Es** (252)	100 **Fm** (257)	101 **Md** (258)	102 **No** (259)	103 **Lr** (262)

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55 **Cs** 132.91	56 **Ba** 137.33	57-71 *	72 **Hf** 178.49	73 **Ta** 180.95	74 **W** 183.84	75 **Re** 186.21	76 **Os** 190.23	77 **Ir** 192.22	78 **Pt** 195.08	79 **Au** 196.97	80 **Hg** 200.59	81 **Tl** 204.38	82 **Pb** 207.2	83 **Bi** 208.98	84 **Po** (209)	85 **At** (210)	86 **Rn** (222)
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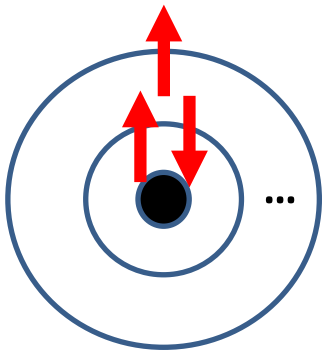
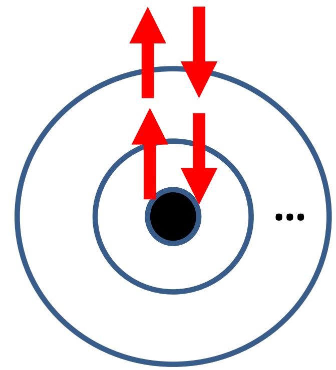
***Orbital* Feshbach resonance**

Limitation of broad *Magnetic* Feshbach resonance pairing mehanism

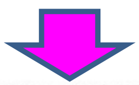
Active electron spin is essentially needed in this pairing mechanism.

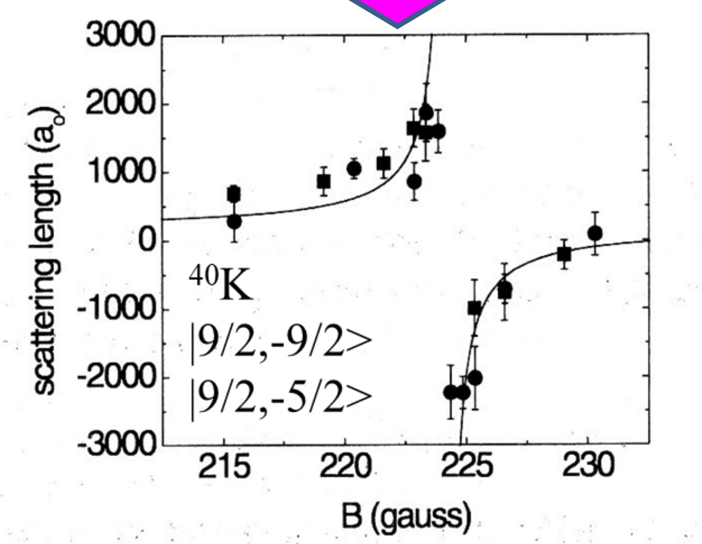




alkaline atom

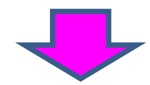
^{40}K, ^{6}Li

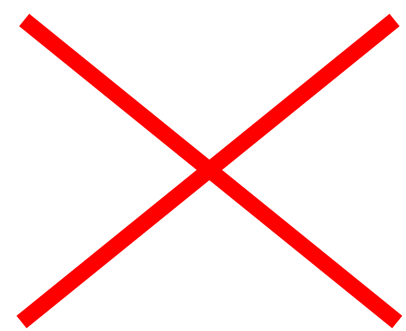




rare earth atom

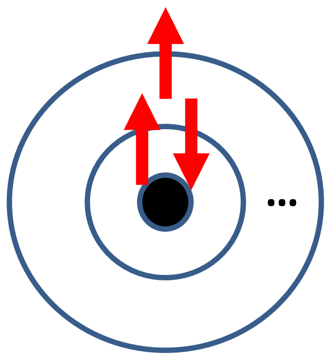
^{173}Yb





New resonance in ^{173}Yb Fermi gas: Orbital Feshbach resonance

Active electron spin is essentially needed in this pairing mechanism.



alkaline atom

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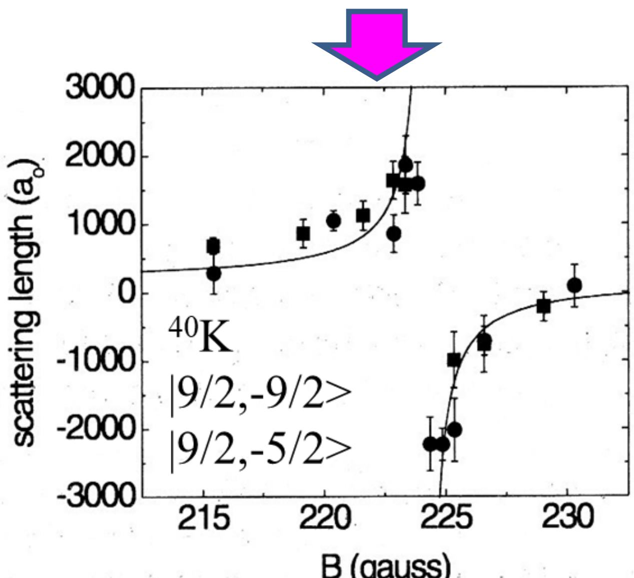
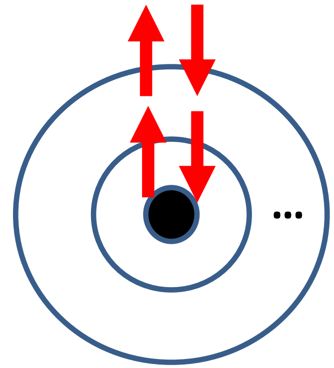
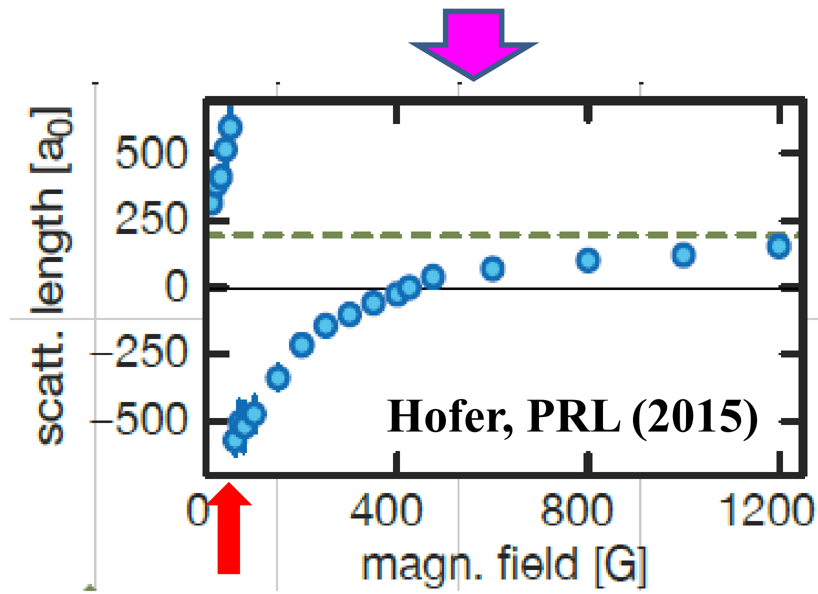




rare earth atom

^{173}Yb



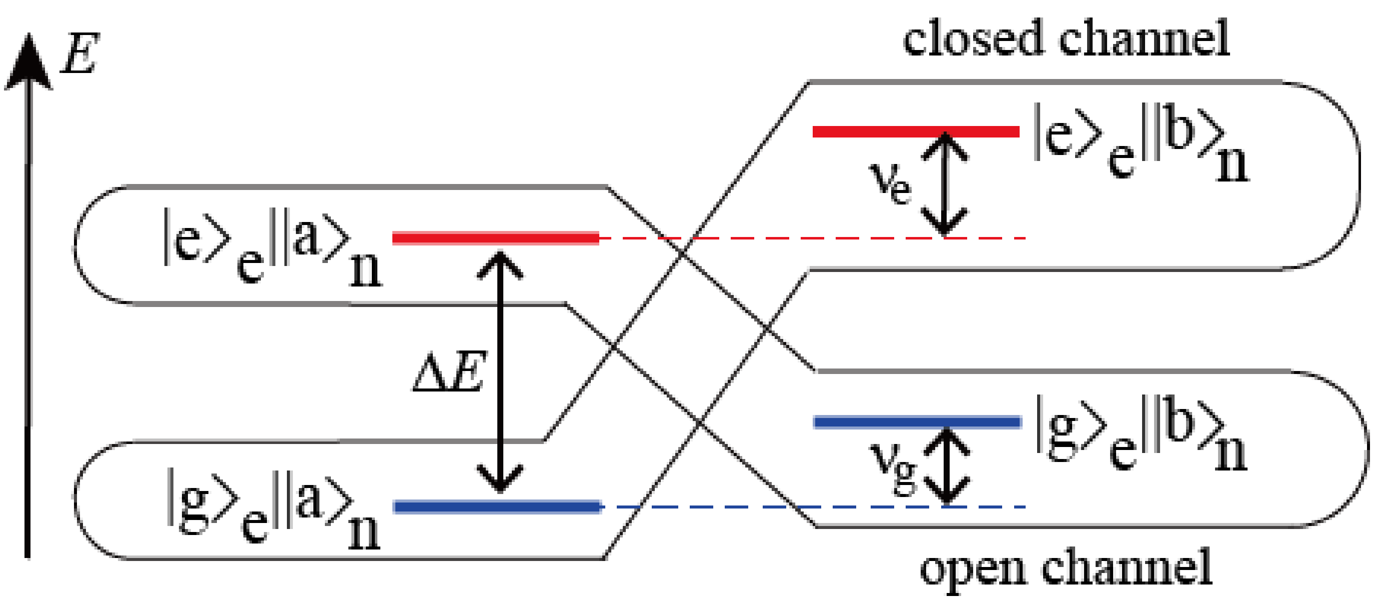
New resonance in ^{173}Yb Fermi gas: Orbital Feshbach resonance

two orbital states **two nulear-spin states (I=5/2)**

^{173}Yb

ground state $^1S_0$ $|g\rangle_e$ $\otimes$ $\|a\rangle_n$

excited state $^3P_0$ $|e\rangle_e$ $\|b\rangle_n$



An external magnetic field B induces ν_e and ν_g.

New resonance in ^{173}Yb Fermi gas: Orbital Feshbach resonance

two orbital states | **two nulear-spin states (I=5/2)**

^{173}Yb

ground state $^1S_0$ $|g\rangle_e$

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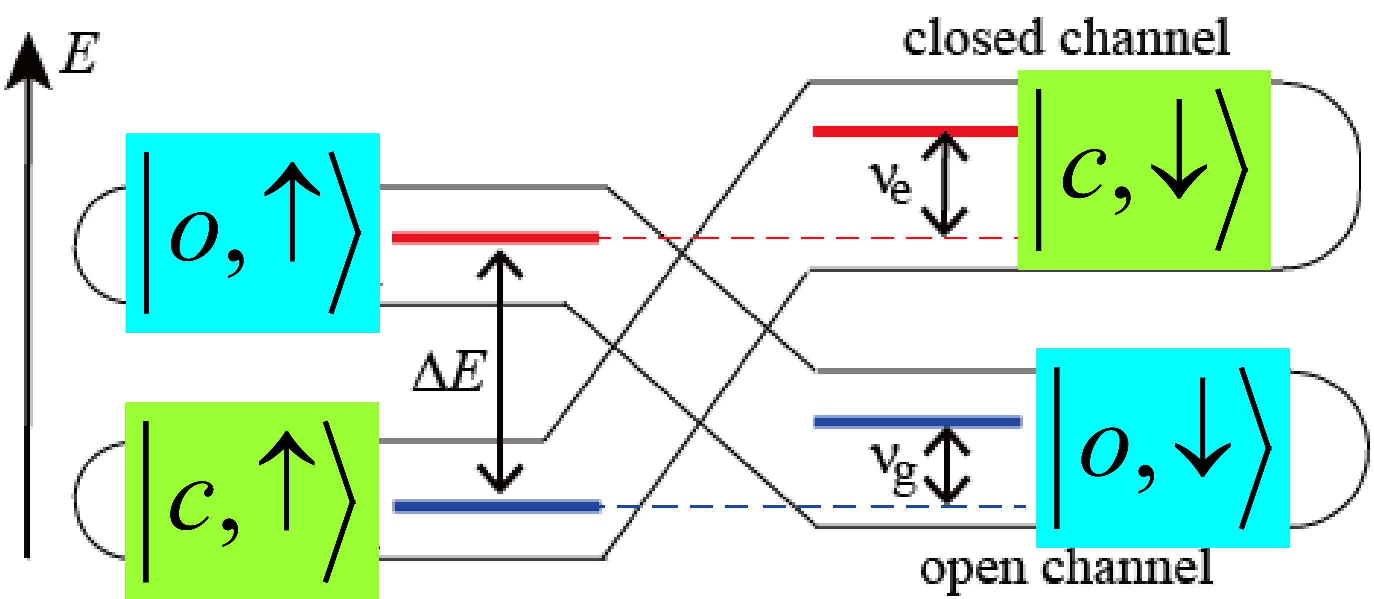
$\otimes$

$\|a\rangle_n$

$\|b\rangle_n$



An external magnetic field B induces ν_e and ν_g.

^{173}Yb Fermi gas with OFR = "two-band" Fermi system

$$H = \sum_{\mathbf{p},\sigma=\uparrow\downarrow} \left[\varepsilon_{\mathbf{p}} - \mu\right] c^{\dagger}_{o,\sigma,\mathbf{p}} c_{o,\sigma,\mathbf{p}} \quad \text{(open channel)}$$

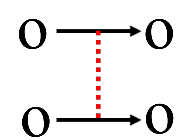
$$+ \sum_{\mathbf{p},\sigma=\uparrow\downarrow} \left[\varepsilon_{\mathbf{p}} + \nu/2 - \mu\right] c^{\dagger}_{c,\sigma,\mathbf{p}} c_{c,\sigma,\mathbf{p}} \quad \text{(closed channel)}$$

two-band system!

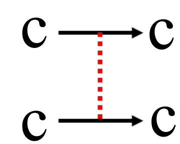
Feshbach molecular channel

$$\nu/2 = \nu_e - \nu_g \propto B$$

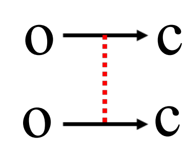
$$+ \frac{U_{\text{intra}}}{2} \sum_{\mathbf{p},\mathbf{p}',\mathbf{q}} \left[c^{\dagger}_{o,\uparrow,\mathbf{p}+\mathbf{q}/2} c^{\dagger}_{o,\downarrow,-\mathbf{p}+\mathbf{q}/2} c_{o,\downarrow,-\mathbf{p}'+\mathbf{q}/2} c_{o,\uparrow,\mathbf{p}'+\mathbf{q}/2} \right]$$



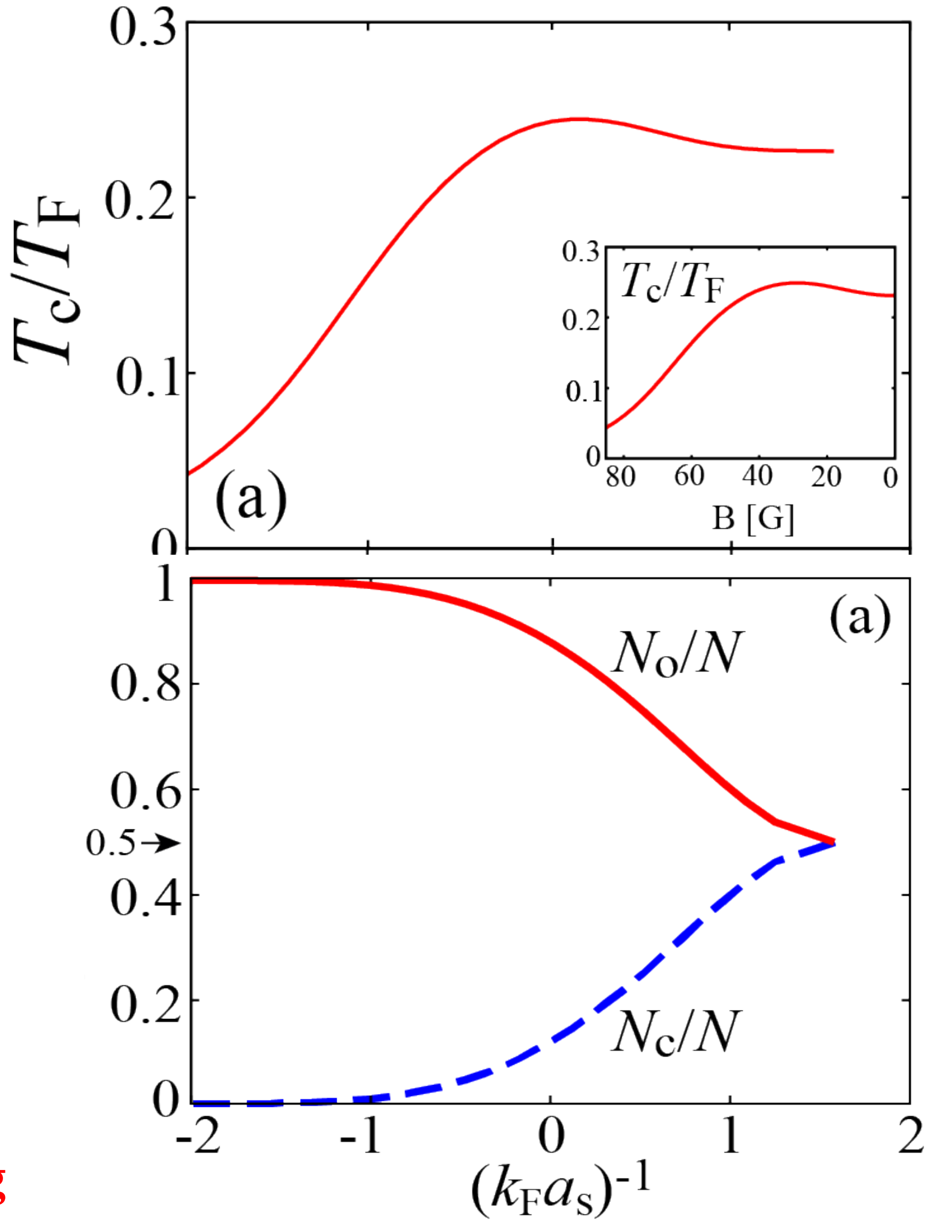
$$+ \frac{U_{\text{intra}}}{2} \sum_{\mathbf{p},\mathbf{p}',\mathbf{q}} \left[c^{\dagger}_{c,\uparrow,\mathbf{p}+\mathbf{q}/2} c^{\dagger}_{c,\downarrow,-\mathbf{p}+\mathbf{q}/2} c_{c,\downarrow,-\mathbf{p}'+\mathbf{q}/2} c_{c,\uparrow,\mathbf{p}'+\mathbf{q}/2} \right]$$



$$+ \frac{U_{\text{inter}}}{2} \sum_{\mathbf{p},\mathbf{p}',\mathbf{q}} \left[c^{\dagger}_{o,\uparrow,\mathbf{p}+\mathbf{q}/2} c^{\dagger}_{o,\downarrow,-\mathbf{p}+\mathbf{q}/2} c_{c,\downarrow,-\mathbf{p}'+\mathbf{q}/2} c_{c,\uparrow,\mathbf{p}'+\mathbf{q}/2} + \text{h.c.} \right]$$



Calculated Tc and particle fraction in the closed channel

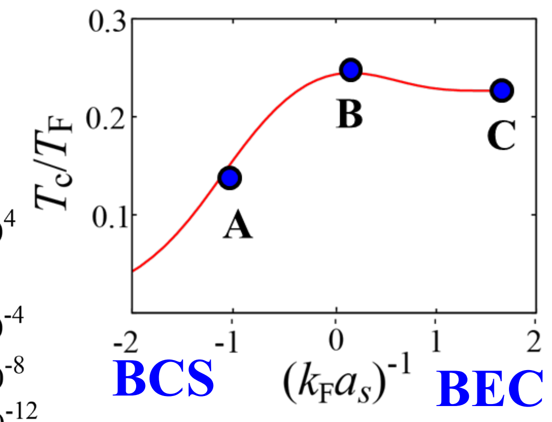


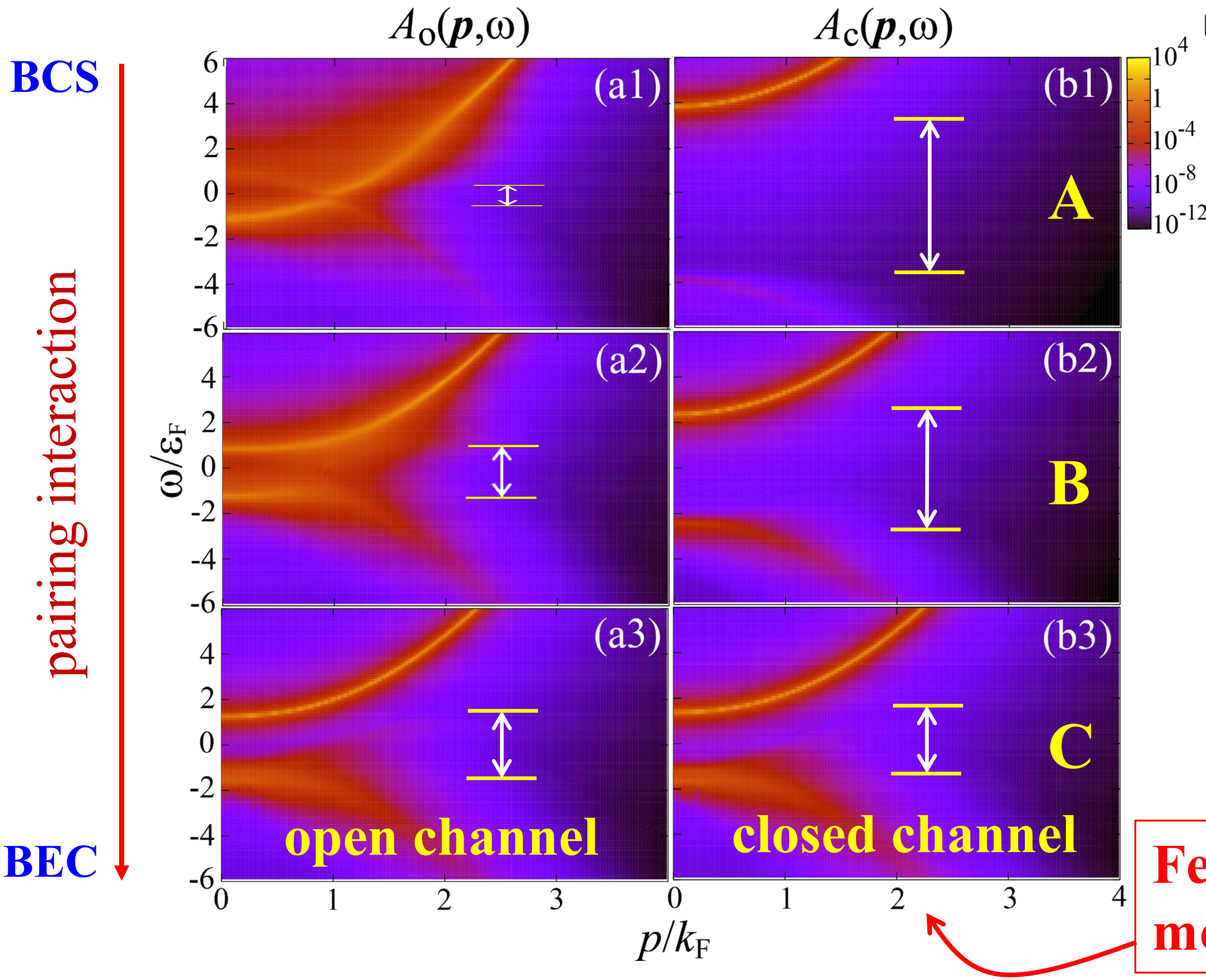
weak-coupling
BCS

strong-coupling
BEC

Single-particle excitations at Tc in the crossover region

$$A_\alpha(\mathbf{p},\omega) = -\frac{1}{\pi}\mathrm{Im}\left[G_\alpha(\mathbf{p}, i\omega_n \to \omega + i\delta)\right]$$



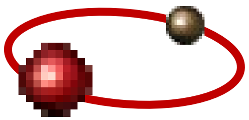


Summary (C02)

KSS conjecture

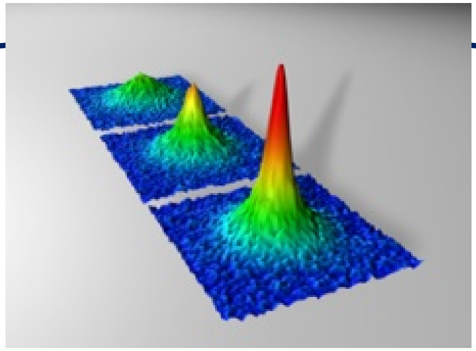
$$\frac{\eta}{s} \geq \frac{\hbar}{4\pi k_B}$$

Hetero-cluster



Shear Viscosity

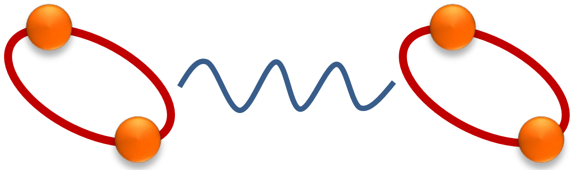
Bose-Fermi mixture



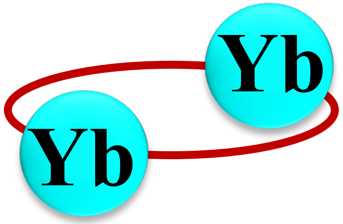
Superfluid Fermi atom gas

Compressibility

Orbital Feshbach



Inter-cluster interaction



Proposed ^{173}Yb Fermi superfluid

Summary (C02)

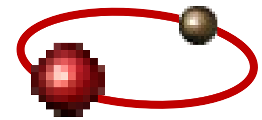
KSS conjecture

$$\frac{\eta}{s} \geq \frac{\hbar}{4\pi k_B}$$

Shear Viscosity

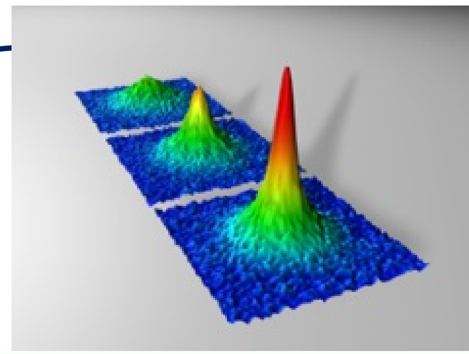
Non-equilibrium pairing phenomenon

Hetero-cluster



Bose-Fermi mixture

Neutron-star cooling (PBF)

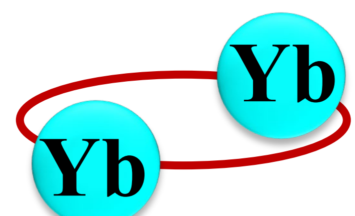


Superfluid Fermi atom gas

Compressibility

Orbital Feshbach

Inter-cluster interaction



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