Fermion Mediated Interactions between Bosons in a Bose-Fermi mixture

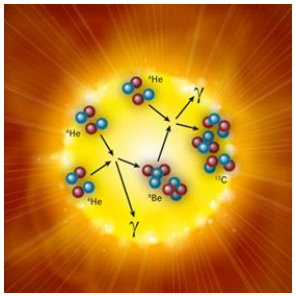
Chicago downtown

Cheng Chin

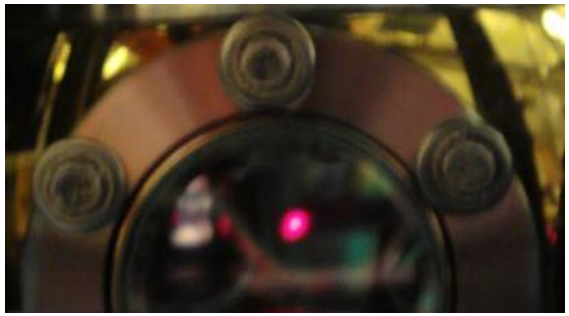
Horace B. Horton Professor
James Franck institute
Enrico Fermi institute
Department of Physics
University of Chicago

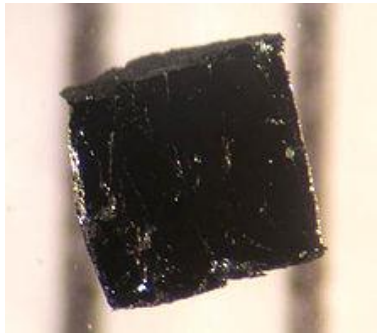
Quantum Simulation with Cold Atoms

THE UNIVERSITY OF CHICAGO

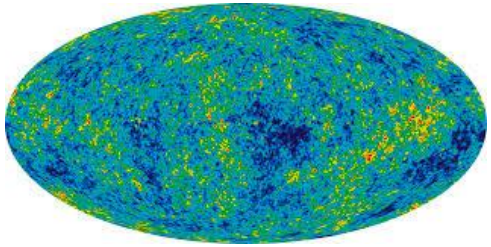


Nuclear Physics:
Feshbach resonance
Efimov physics

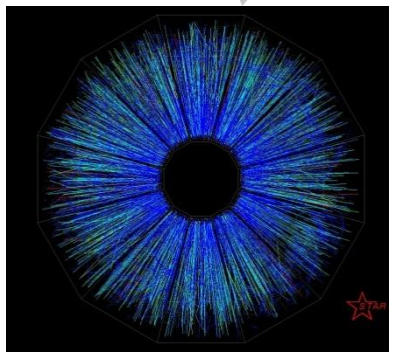




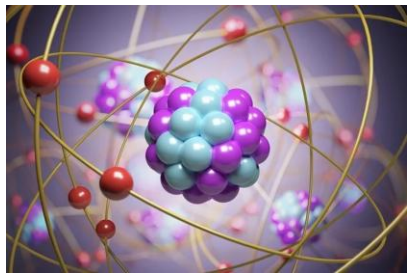
Condensed Matter:
RKKY interactions
Dynamical gauge field
Bilayer optical lattices



Cosmology and gravity
Kibble-Zurek mechanism
Inflation dynamics
Unruh radiation

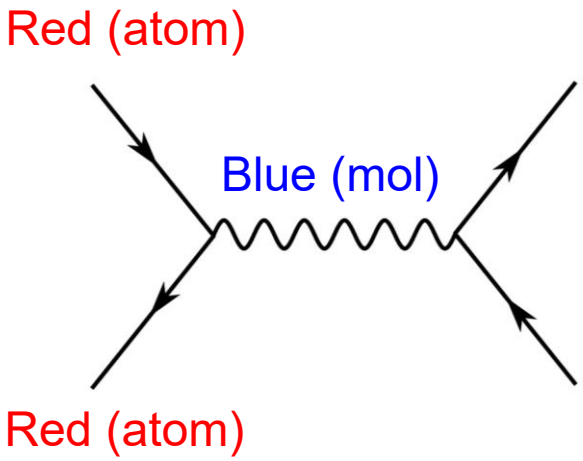


Jet Physics
Bose firework
HHG in BEC
Sub-jet structure
Pattern formation



Chemistry
Molecular BEC
Bose-enhance reaction
Phase doubling

Interactions generate entanglement



Feshbach resonance $m^{+}a_1 a_2 + H.c.$

Quantum optics $a_b^{+} a_r a_r + H.c.$

HEP $\bar{\psi}\gamma^{\mu}\psi A_{\mu} + H.c.$

…

Key features:

Cosmology
- Inflation
- Unruh radiaiton

Material
- Pairing
- Quasi-particles

Optics
- Entanglement
- Two-mode squeezing

Chemistry
- Collective Reactions

Normal vs Many-body Chemistry

Normal Chemistry

Example: $2H \rightarrow H_2$

Reaction rate

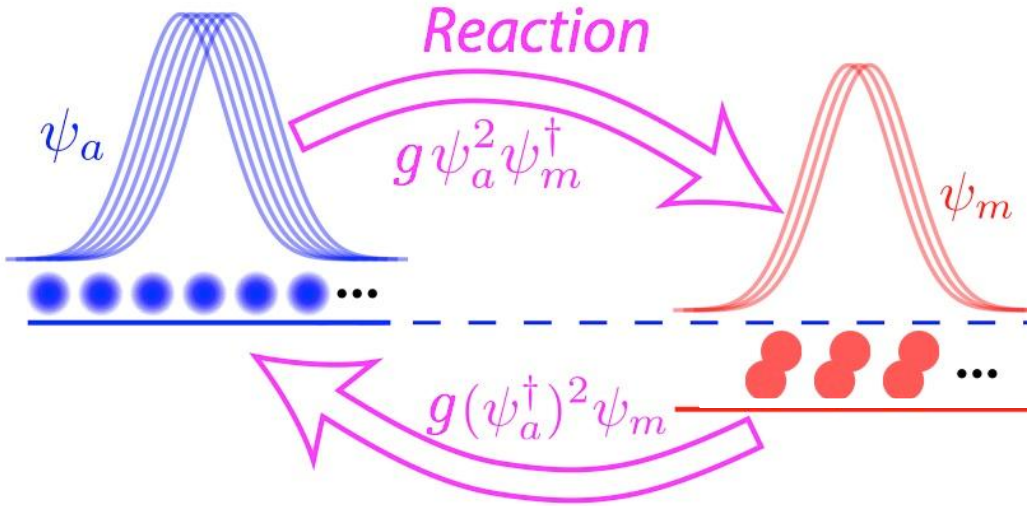
$\Gamma = \sigma_r v$ [H]

Many-body Chemistry

$$\hat{V}_{int} = g\hat{\psi}_m^+\hat{\psi}_a\hat{\psi}_a + g\hat{\psi}_m\hat{\psi}_a^+\hat{\psi}_a^+$$

$\hat{\psi}_m$: Molecular wave

$\hat{\psi}_a$: Atomic wave

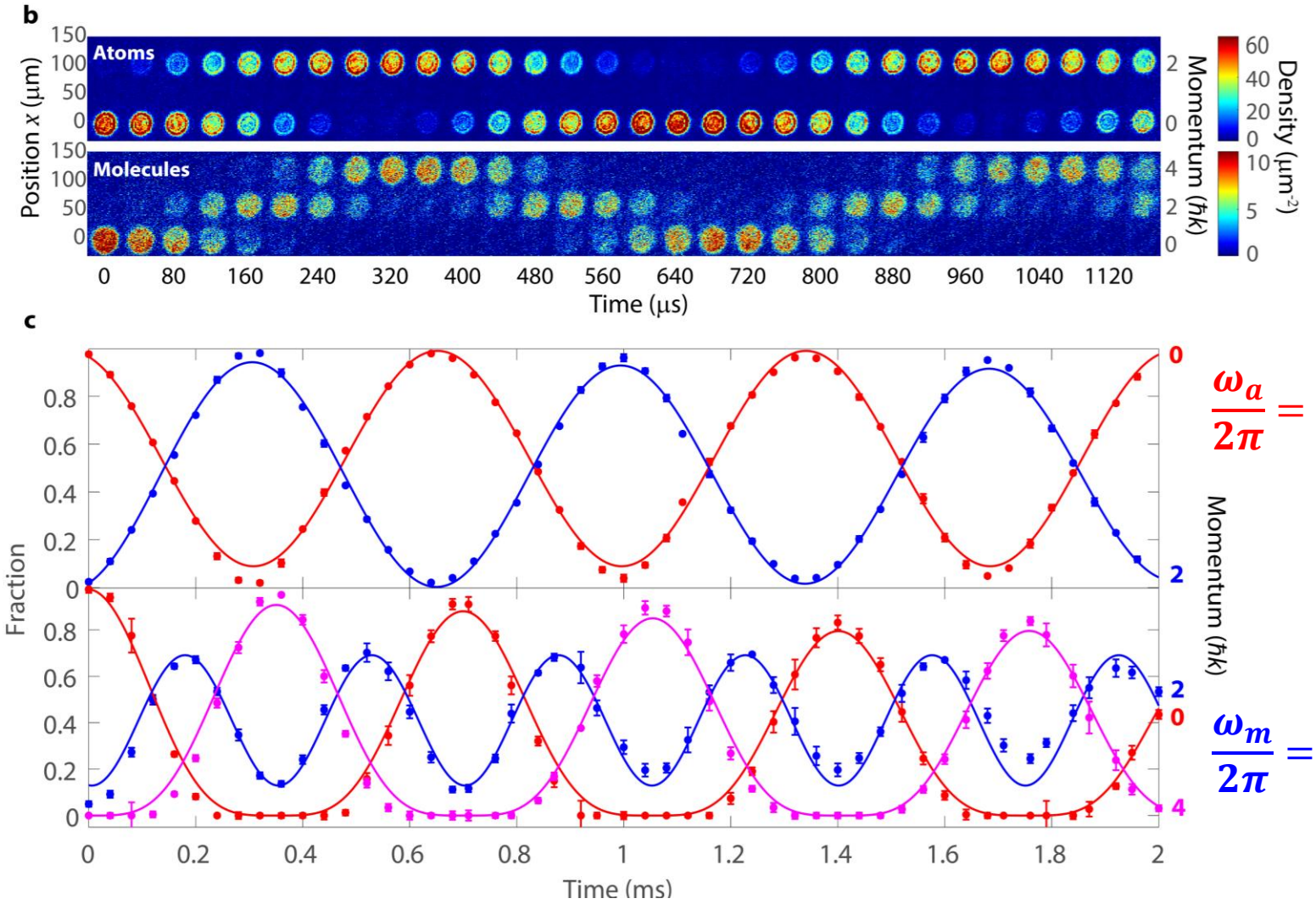


Features of Super-chemistry

- **A.-M. BEC coupling**
- **Bose enhanced reaction**
- **Phase matching**
- **Entanglement generation**

Superchemistry: Dynamics of Coupled Atomic and Molecular Bose-Einstein Condensates
D. Heinzen et al., PRL 84, 5029 (2000)

Molecular Matterwave Phase Doubling

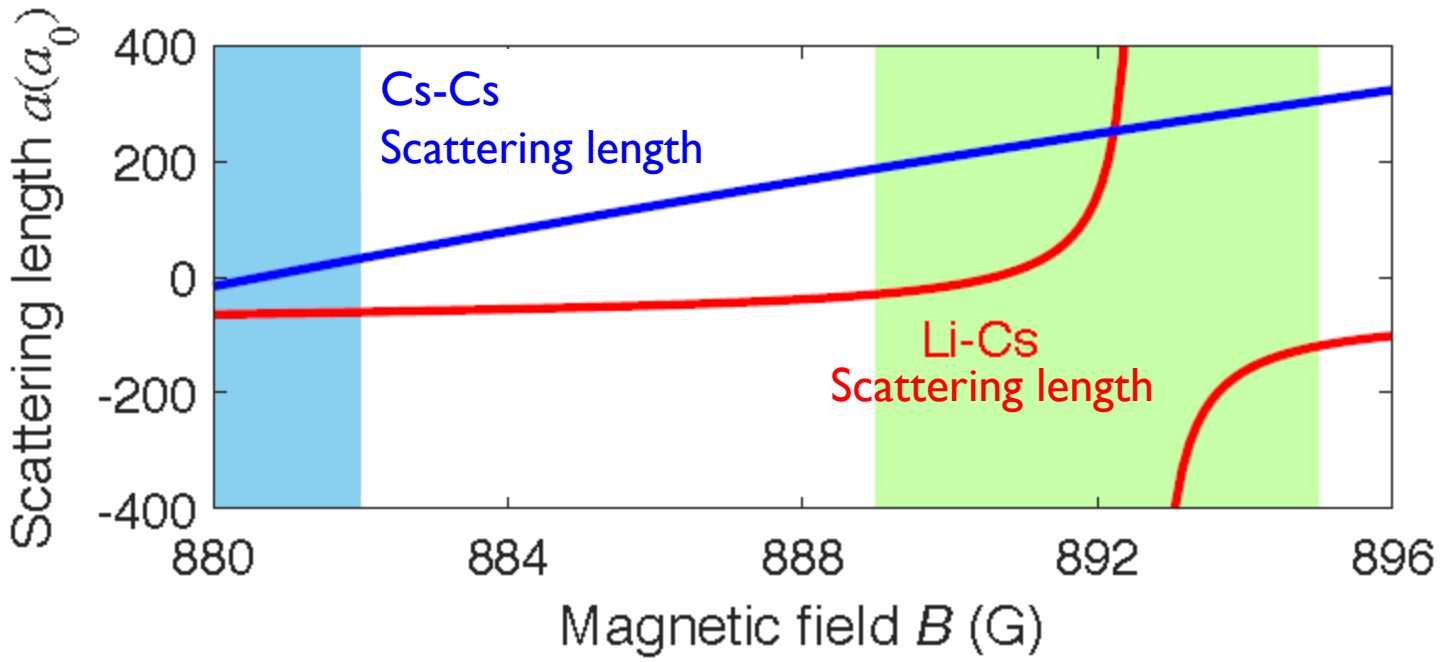


$\frac{\omega_a}{2\pi} = 0.7$ kHz

$\frac{\omega_m}{2\pi} = 1.4$ kHz

Shu Nagata, Tadej Mežnaršič, Chuixin Kong and Cheng Chin, Rep. Prog. Phys. 89 060501 (2026)

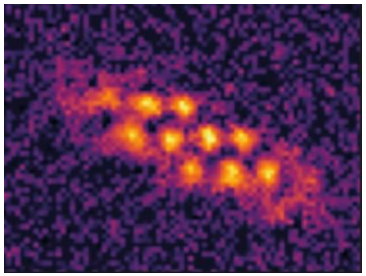
Lithium-Cesium Feshbach Resonance



Li-Cs Feshbach resonances (Chicago and Heidelberg): PRA '13,
Li-Cs_2 Efimov resonances: PRL '14 and '15 and Nature Physics 2017

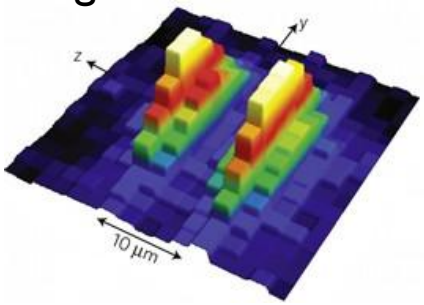
BEYOND CONTACT INTERACTIONS

Dipolar interactions



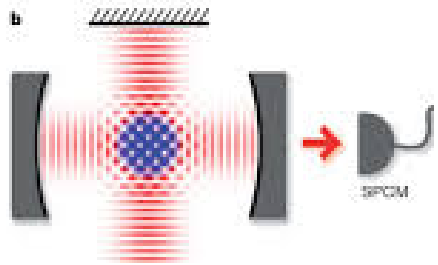
Cr (Stuggart 2008)
Supersolid (LENS, UIUC and Innsbruck, 2019)
Molecules (JILA 2008, Columbia 2024)

Rydberg state



Blockade (Institut d'Optique, Wisconsin 2009)
Photon-photon interactions (MIT/Harvard 2012)
Molecular interactions (Stuttgart 2012)

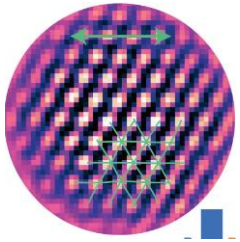
Cavity induced interacti



Collective cooling (MIT, MPQ 2003-
Dicke transition (ETH, 2010)

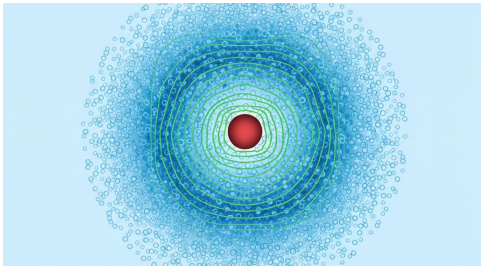
Our Experiments

Floquet Engineering



Lattice modulation (Chicago 2013-)
Interaction modulation (Chicago, Heidelberg, 2016-)

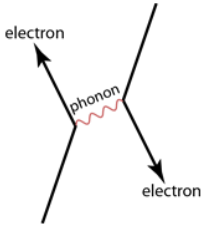
Fermion-mediated interactions



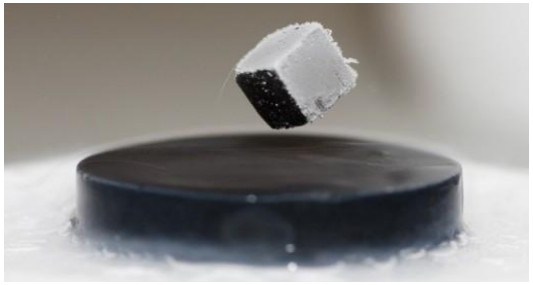
This talk

Mediated Interactions across Physics

BCS pairing



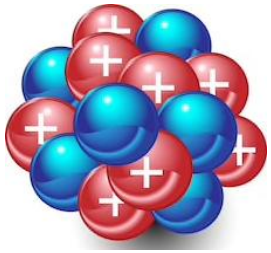
Phonon Mediated Interactions



Superconductivity

Yukawa Potential

Meson Mediated Interactions

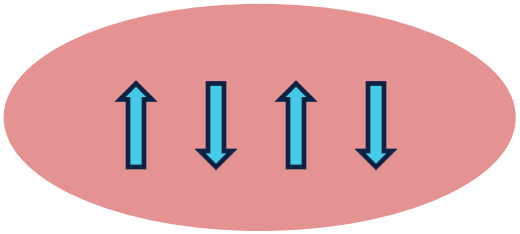


Atomic Nuclei

RKKY mechanism

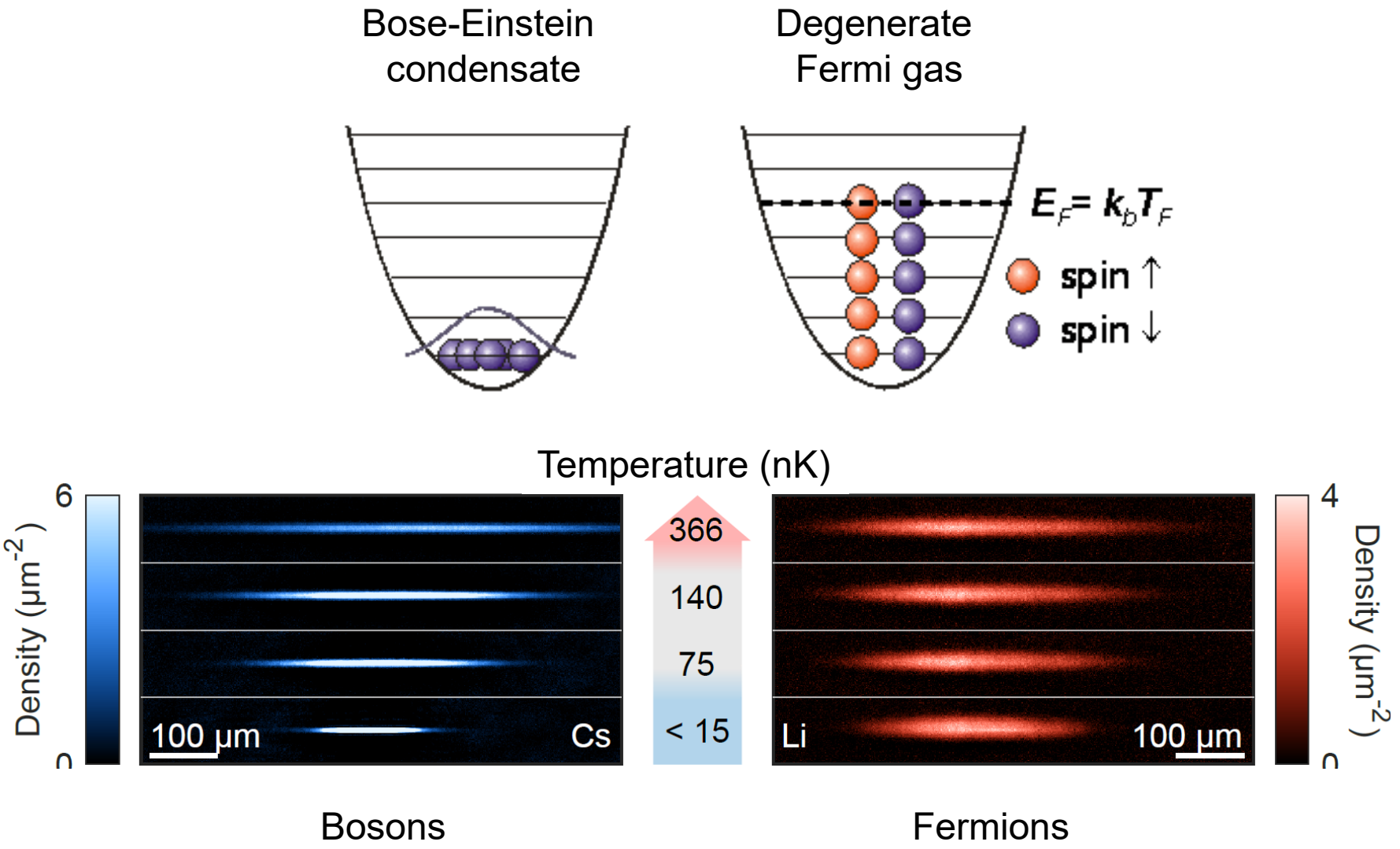
Ruderman-Kittel-Kasuya-Yosida

Fermion Mediated Interactions

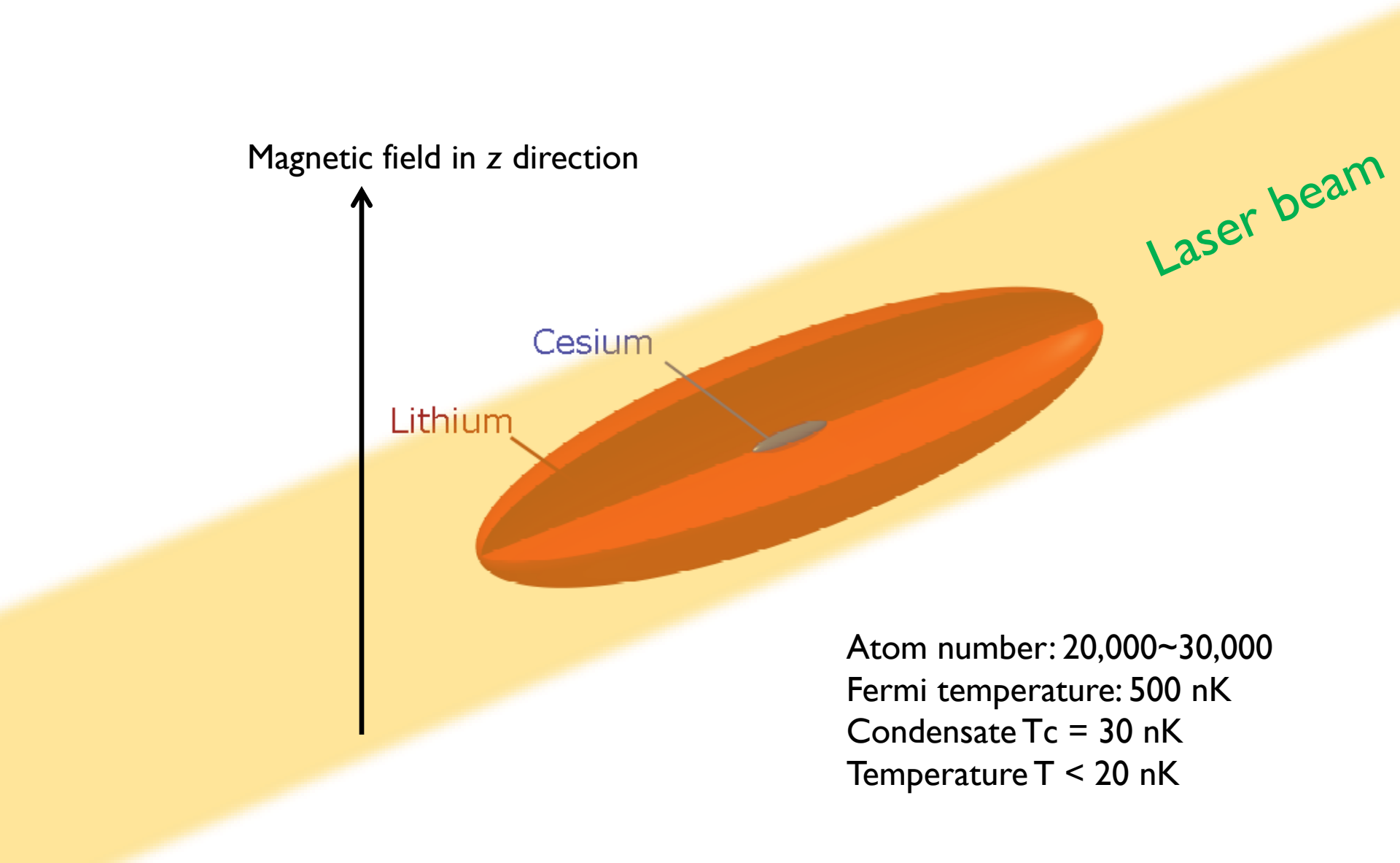


Magnetic Ordering

Atoms at low temperatures:
Bosons Einstein condensate and degenerate Fermi gas

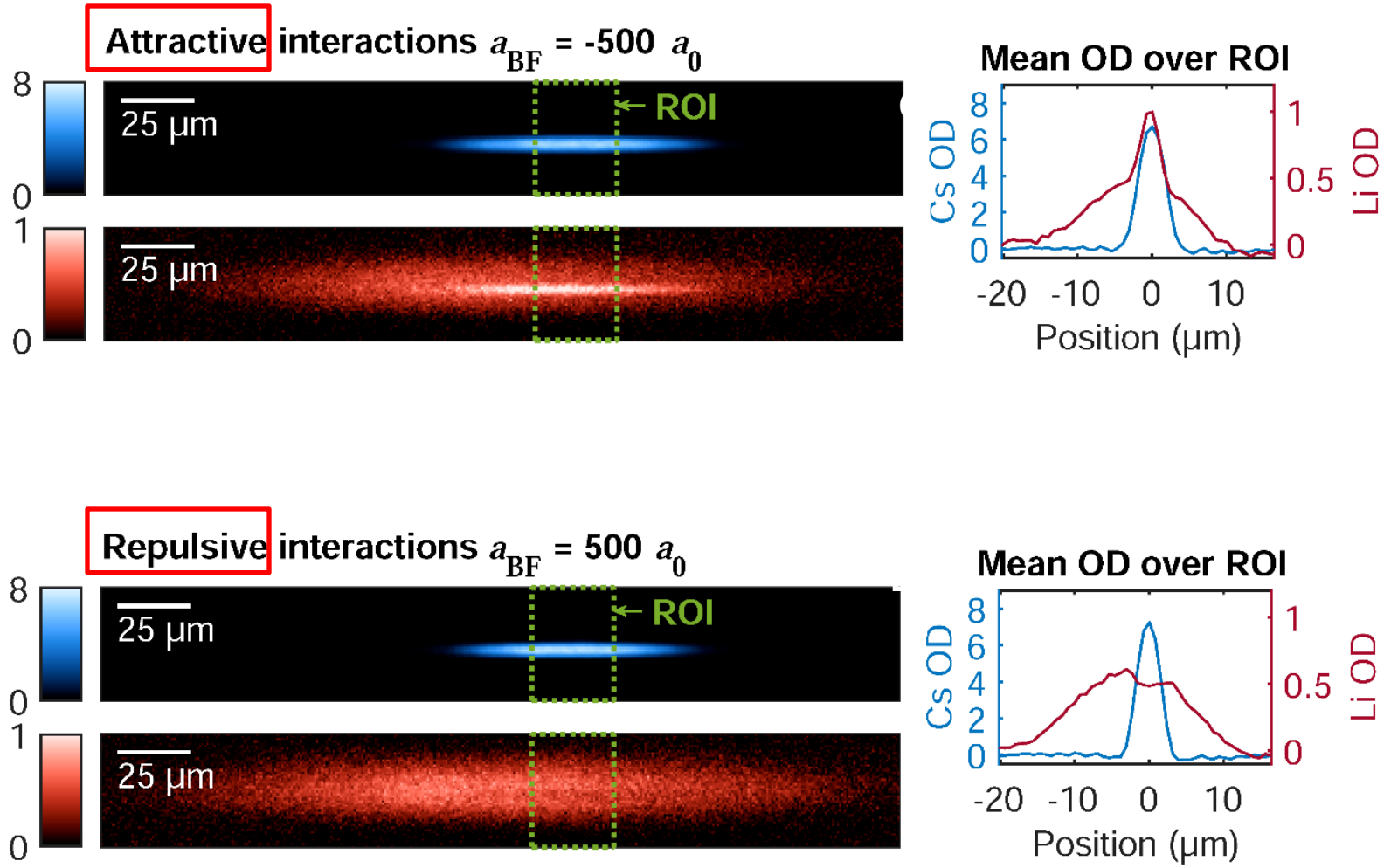


Degenerate quantum mixture of Cs133 and Li6



Atom number: 20,000~30,000
Fermi temperature: 500 nK
Condensate Tc = 30 nK
Temperature T < 20 nK

Simultaneous in situ imaging of Bose-Fermi mixture



Synopsis

RKKY – Efimov transition

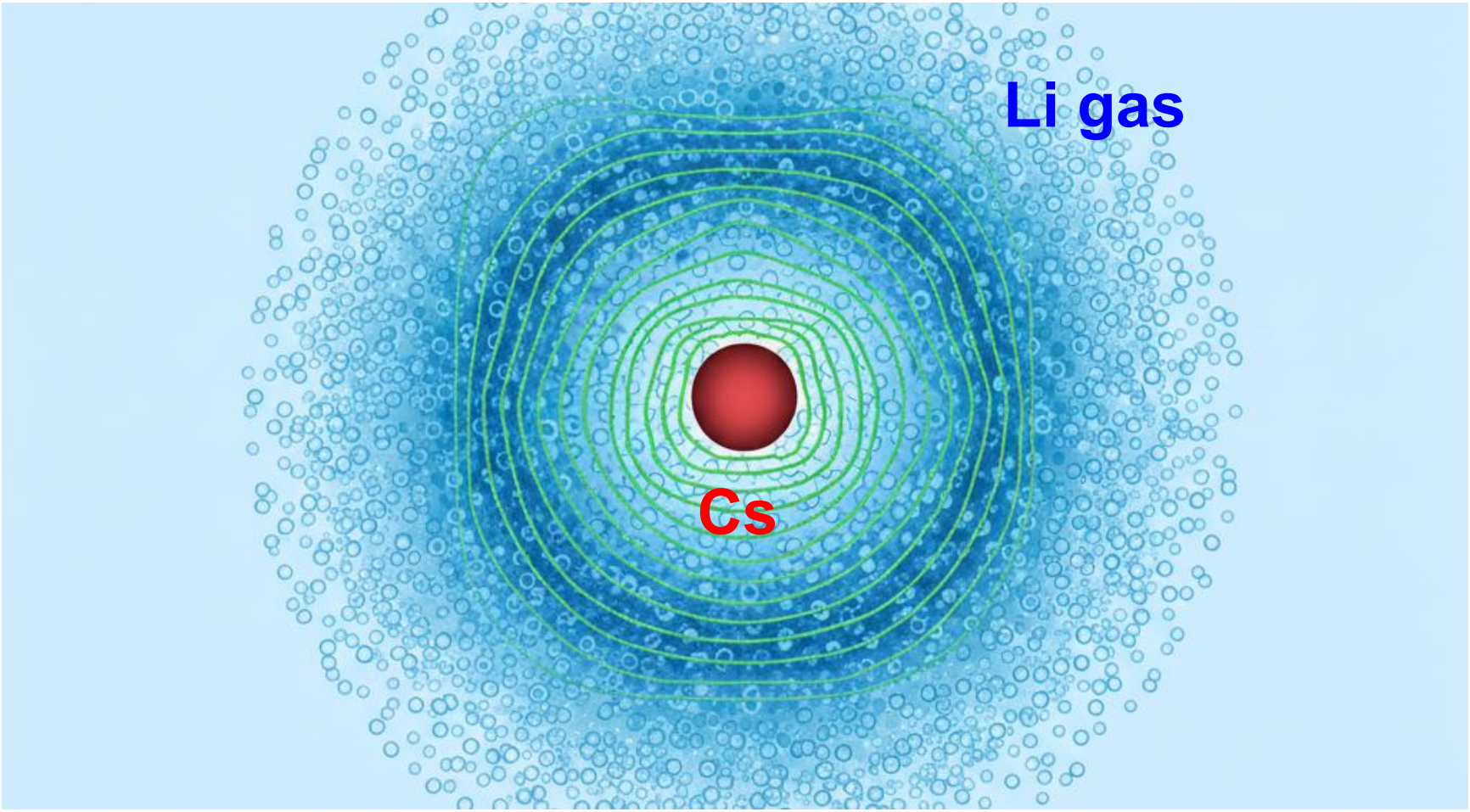
Heavy Boson-light Fermion mixture

Former experiments on Feshbach and Efimov resonances

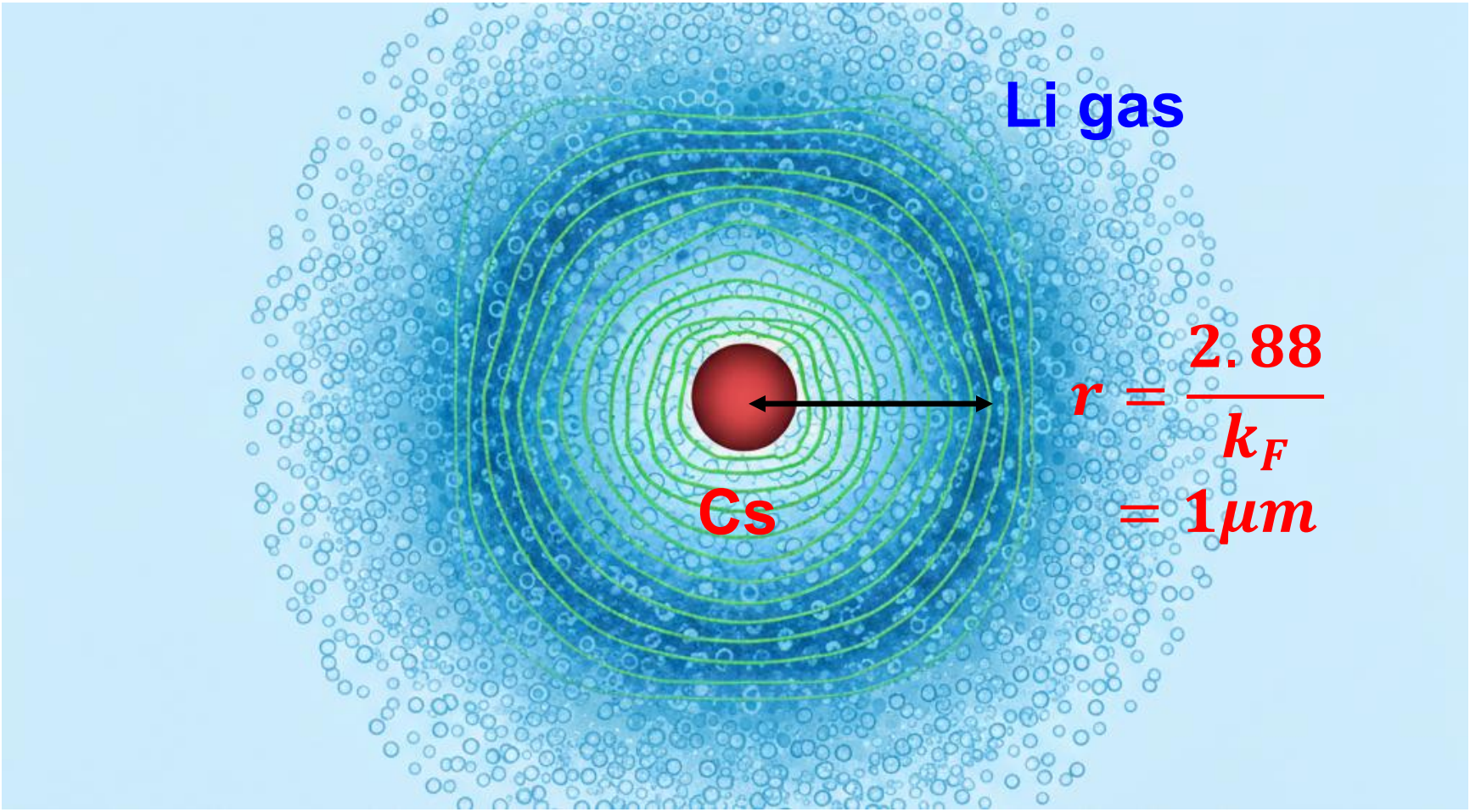
- *Equilibrium: Fermion mediated interactions*
- *Polaron to Polariton: Sound mode collapse and revival*
- *Strong coupling: Mediated scattering resonance*
- *Stability: Dispersion, heating and decay of BEC*

Physical picture

RKKY potential and Friedel oscillation

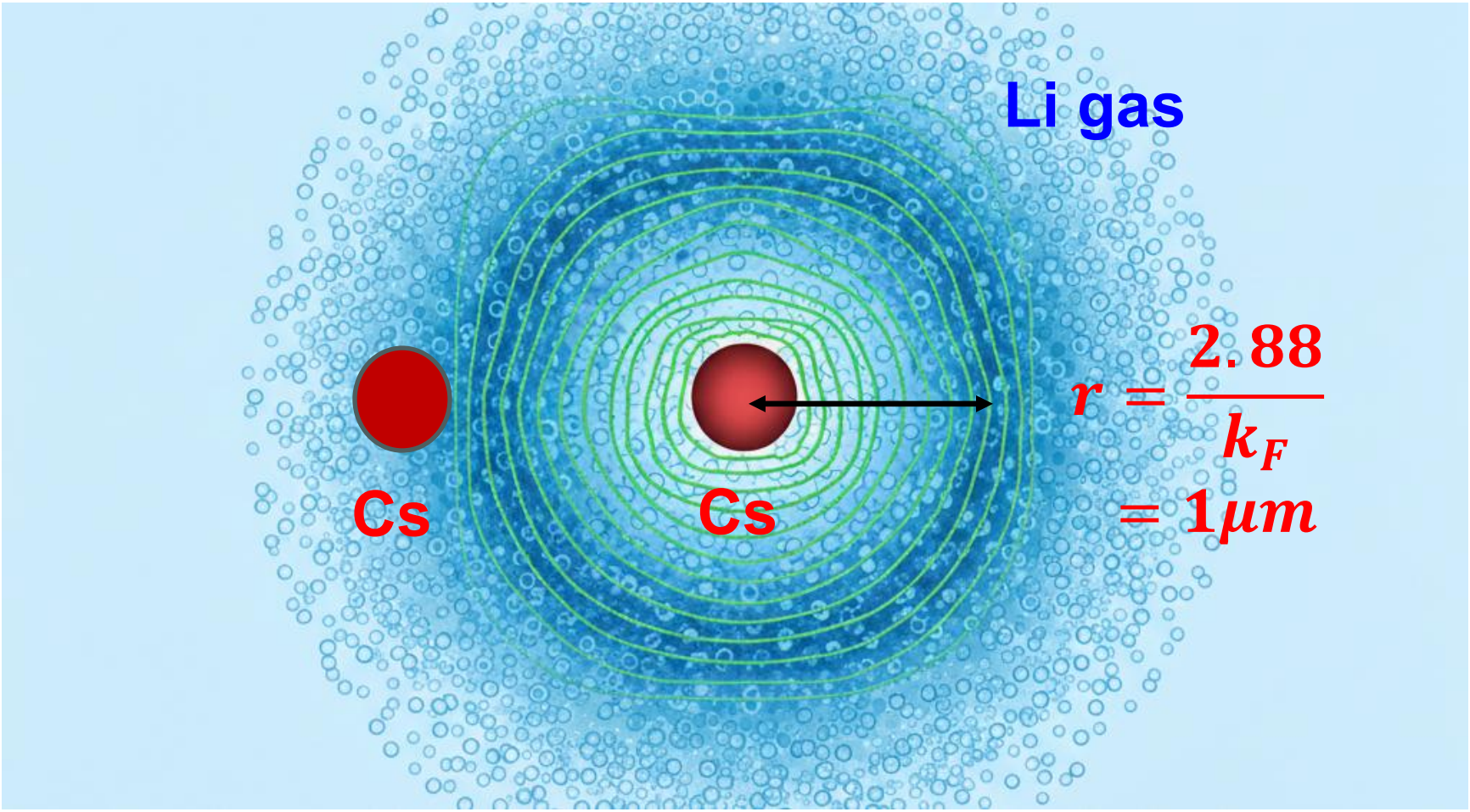


RKKY potential and Friedel oscillation



Nano Banana

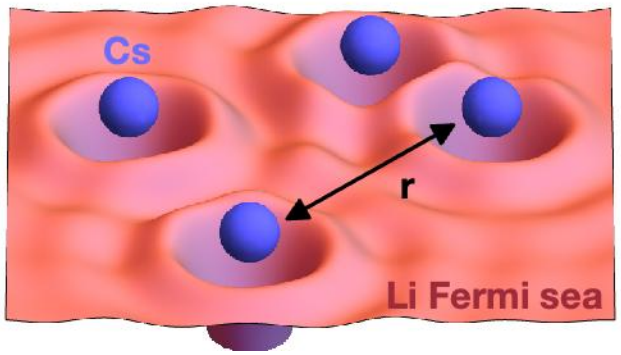
RKKY potential and Friedel oscillation



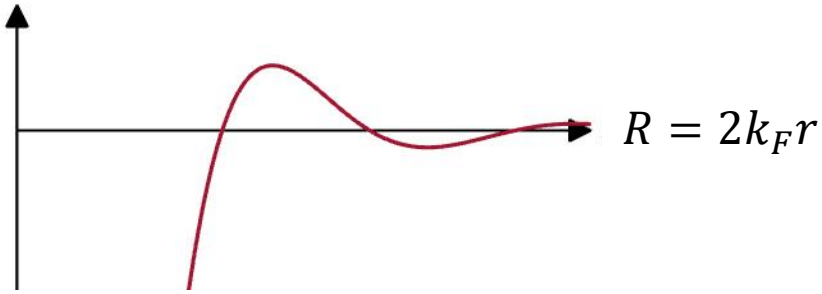
Nano Banana

Mediated interactions in different regimes

Ruderman-Kittle-Kasuya-Yosida regime $|k_F a_{BF}| \ll 1$



$$V_{RKKY}(r) = E_F \frac{8}{\pi}(k_F a_{BF})^2 \frac{R\cos R - \sin R}{R^4}$$



Mediated interactions in different regimes

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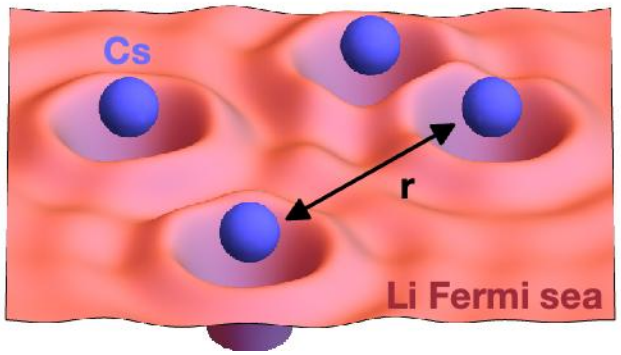

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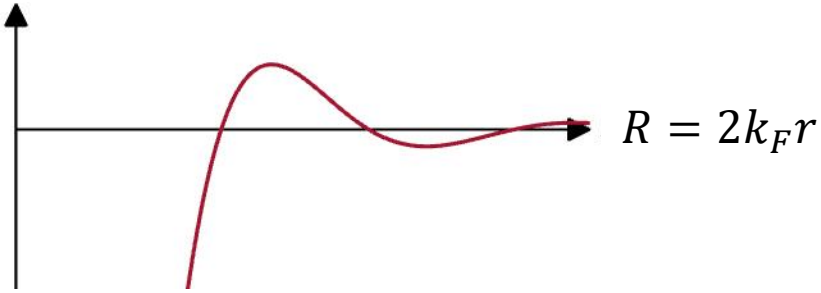
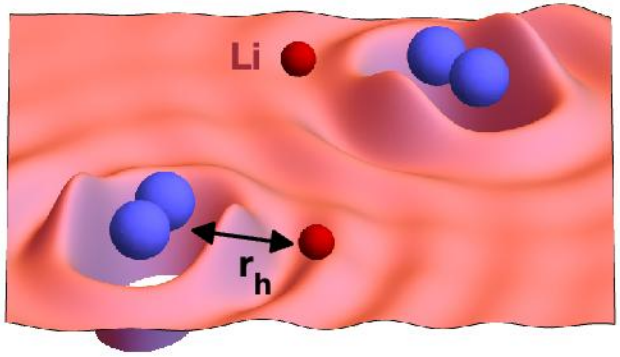
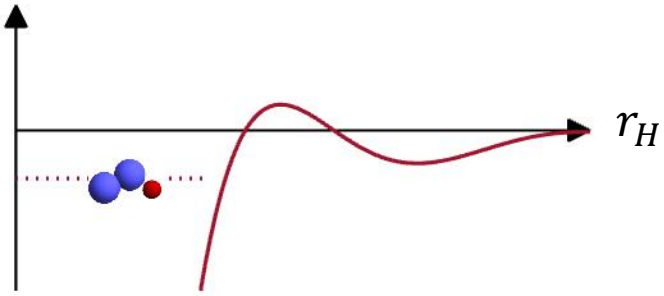


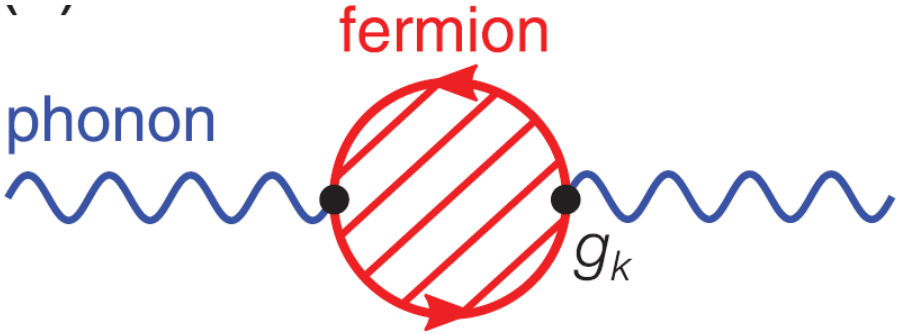
Efimov regime $|a_{BF}| \gg R_{vdW}$



$$V_{Efimov}(r) = -\frac{\hbar^2 \Theta(|a| - r)}{2m_r r^2}$$



From “Polaron” to “Polariton”



$$H = \sum_k \epsilon_k^F c_k^\dagger c_k + \sum_k \hbar\omega_k \alpha_k^\dagger \alpha_k + \sum_{k,q} g_k(\alpha_k + \alpha_{-k}^\dagger) c_q^\dagger c_{q-k}$$

Fermi energy Phonon energy Coupling

T. Enss and W. Zwerger, Eur. Phys. J. B 68, 383 (2009)

Compared with photons in solid

Conductor: $g_k \to const.$

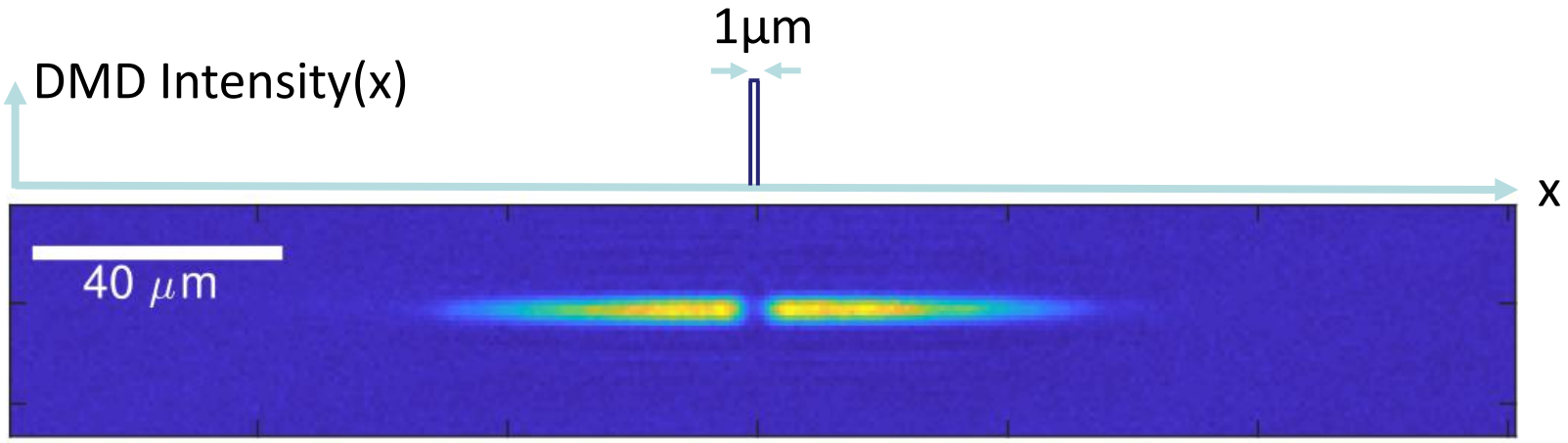
Insulator: $g_k \propto k$

BEC phonons in Fermi gas

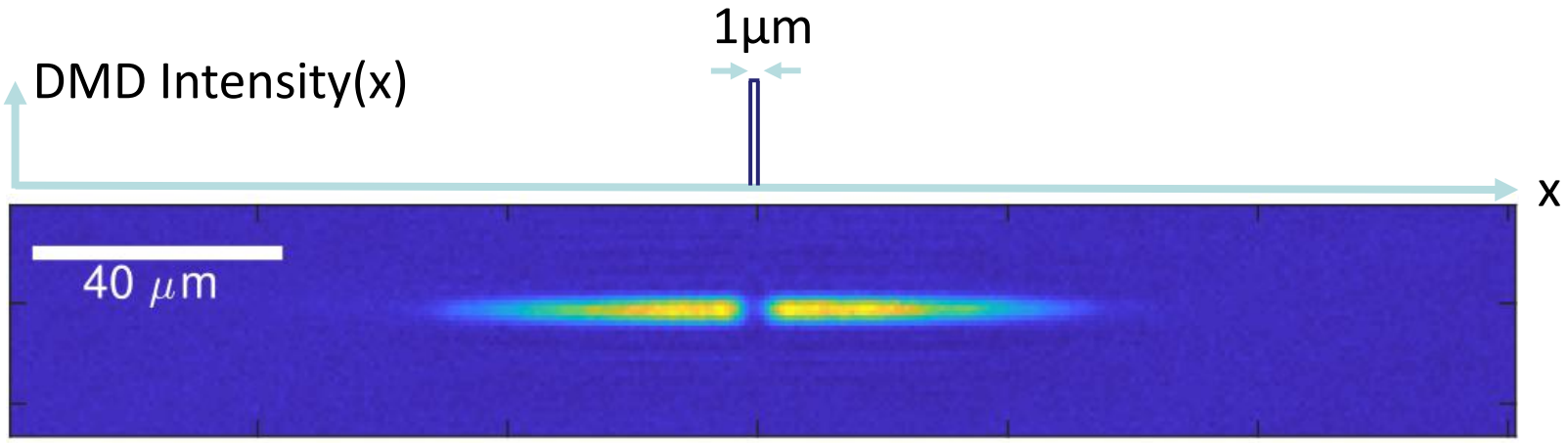
Gapless Fermi gas $g_k \propto k$

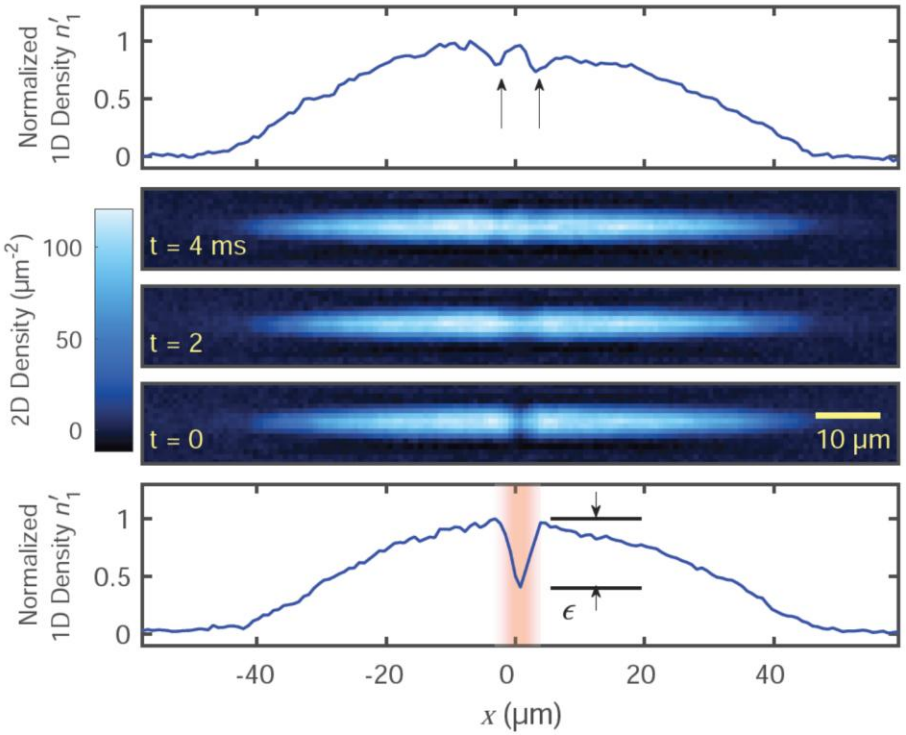
Gapped Fermi gas $g_k = o(k)$

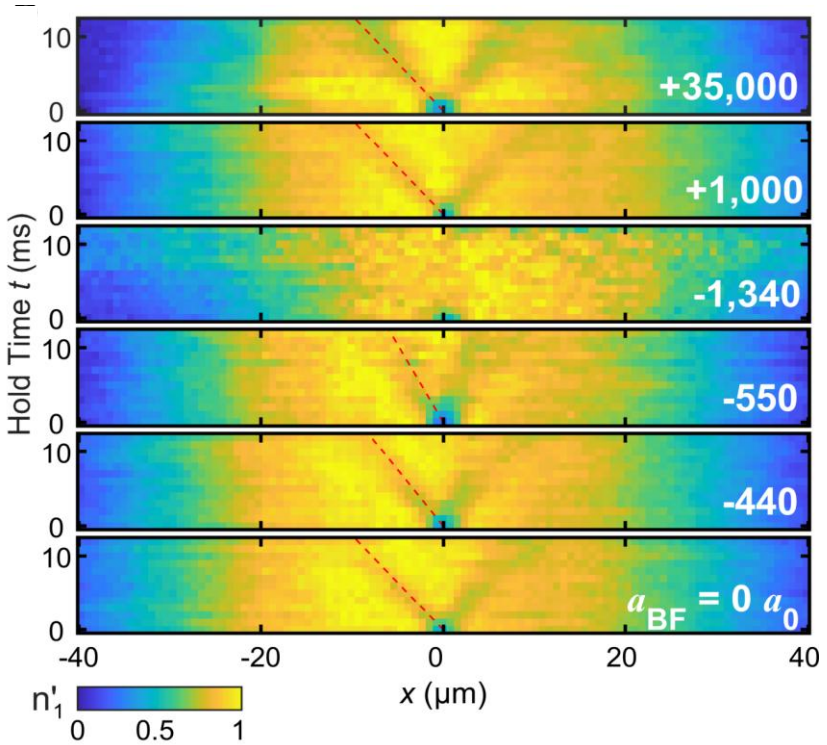
Sound propagation in Cs BEC



Sound propagation in Cs-Li mixture



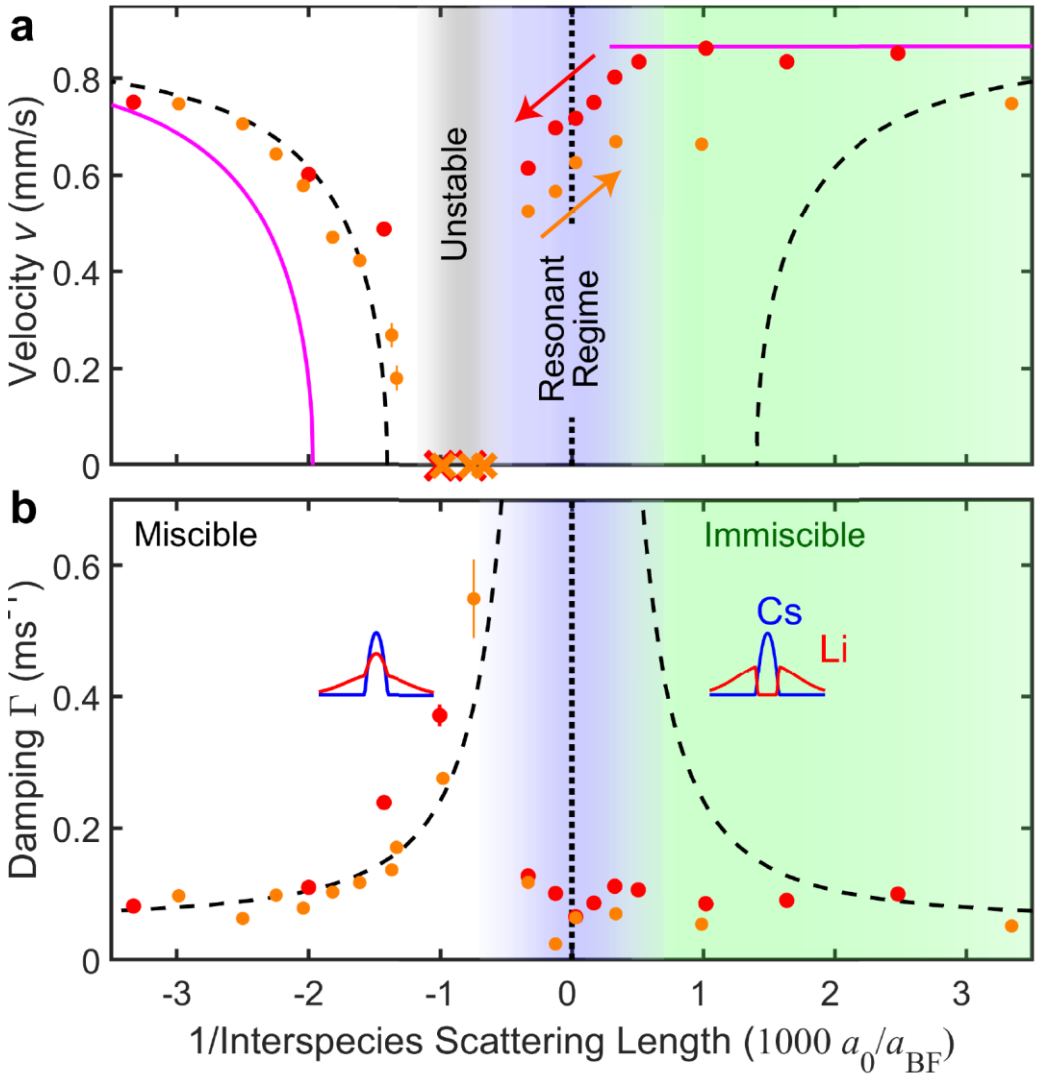




Quench and revival of sound across propagation across the Feshbach resonance

Sound speed

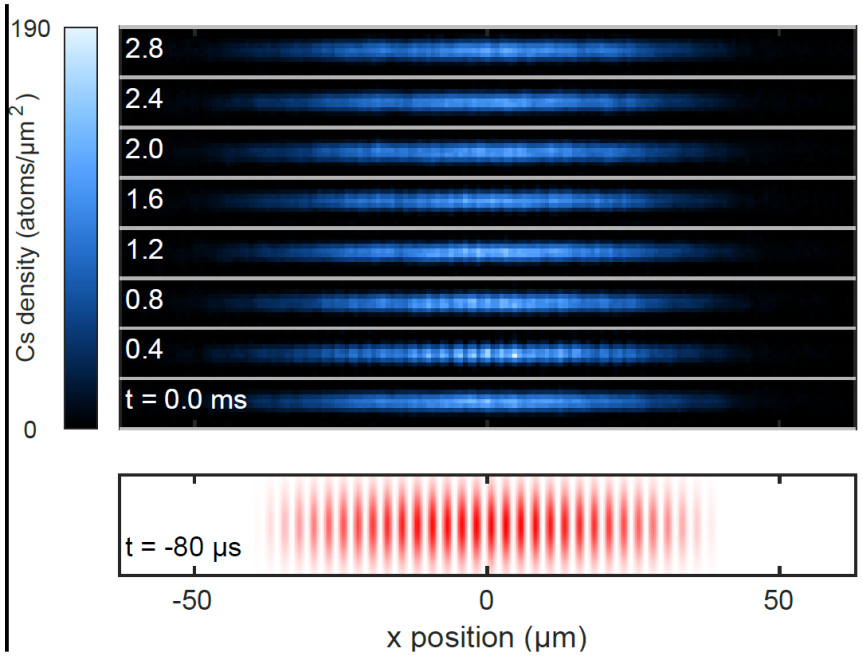
damping



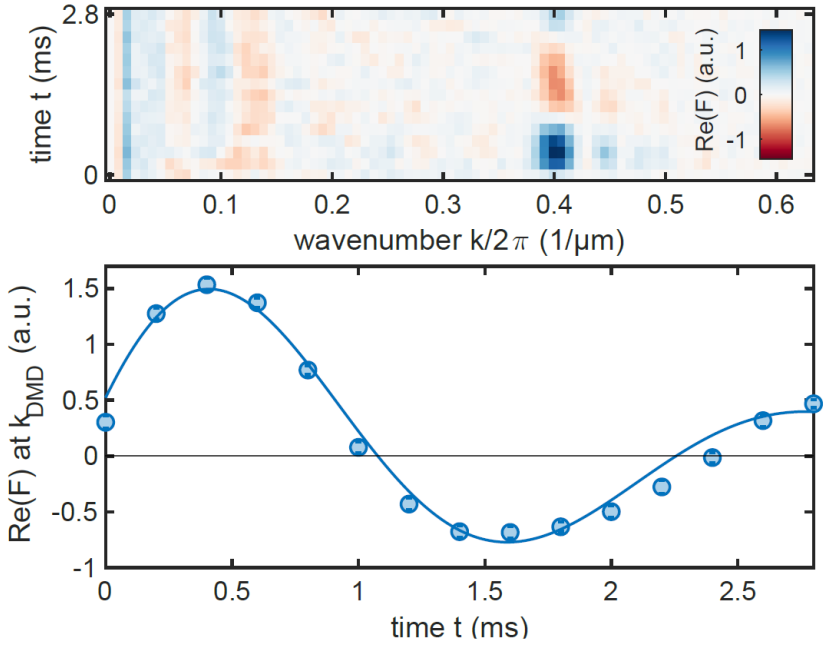
Observation of sound propagation in a strongly interacting Bose-Fermi mixture
Krutik Patel, Geyue Cai, Henry Ando, Cheng Chin, Phys. Rev. Lett. 131, 083003 (2023)

Dispersion Measurement

Phase imprinting with a short pulse



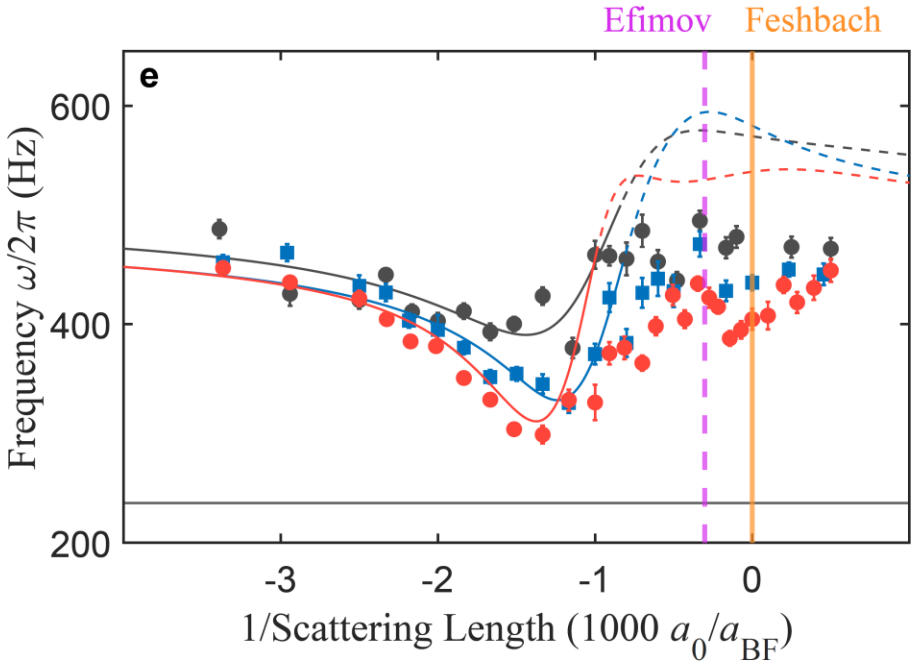
Density structure factor S(k.t)

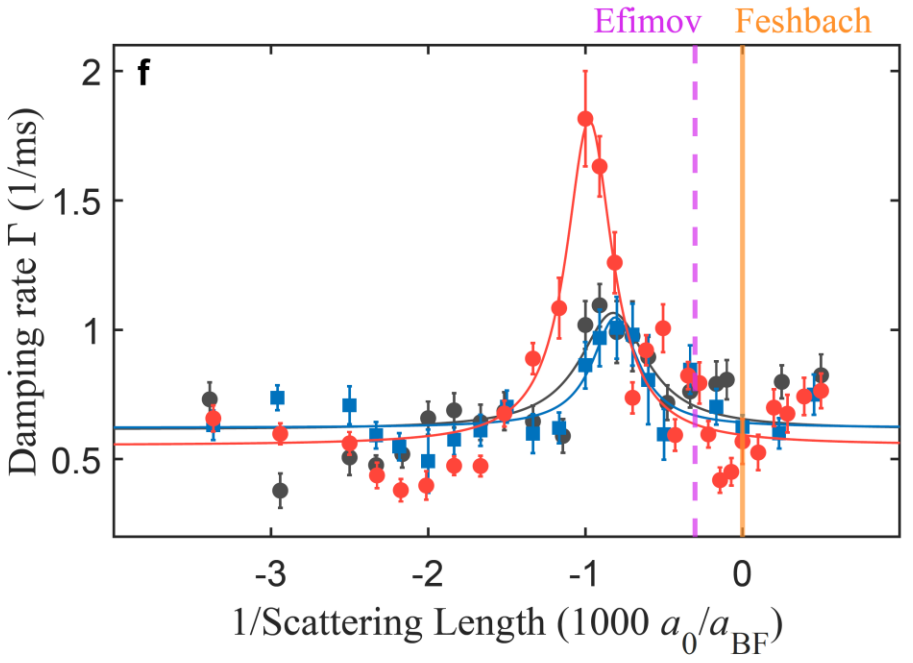


Extract frequency ω and damping Γ

Dispersion of Mediated Interactions

New mediated resonance!

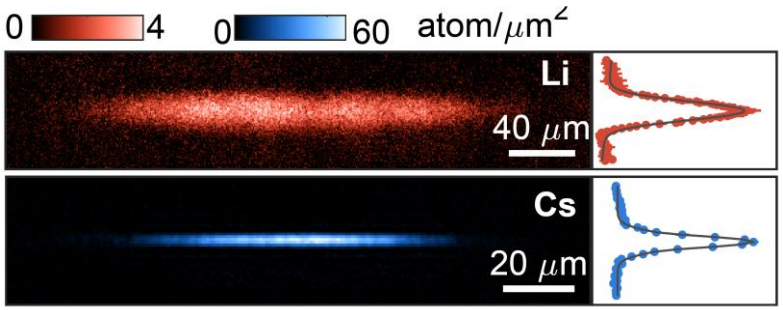


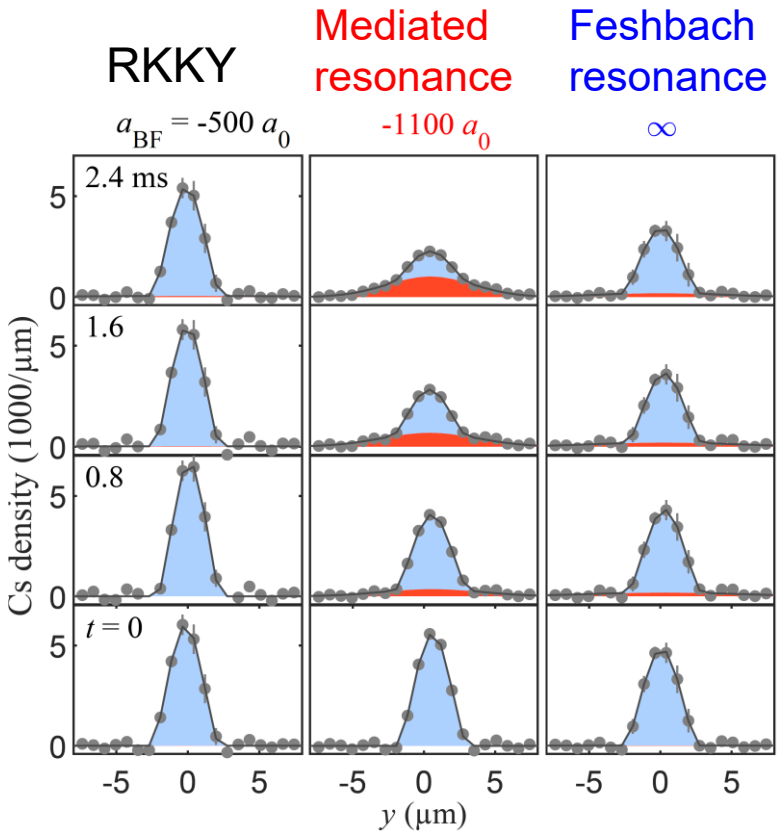


Fermion mediated pairing in the RKKY-Efimov transition regime
G. Cai, H. Ando, S. McCusker, C. C, PRL (2026)

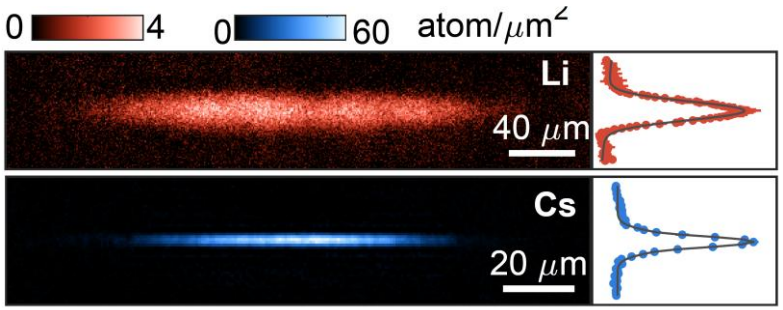
Red: 100% Fermions
Blue: 50% Fermions
Black: 25% Fermions

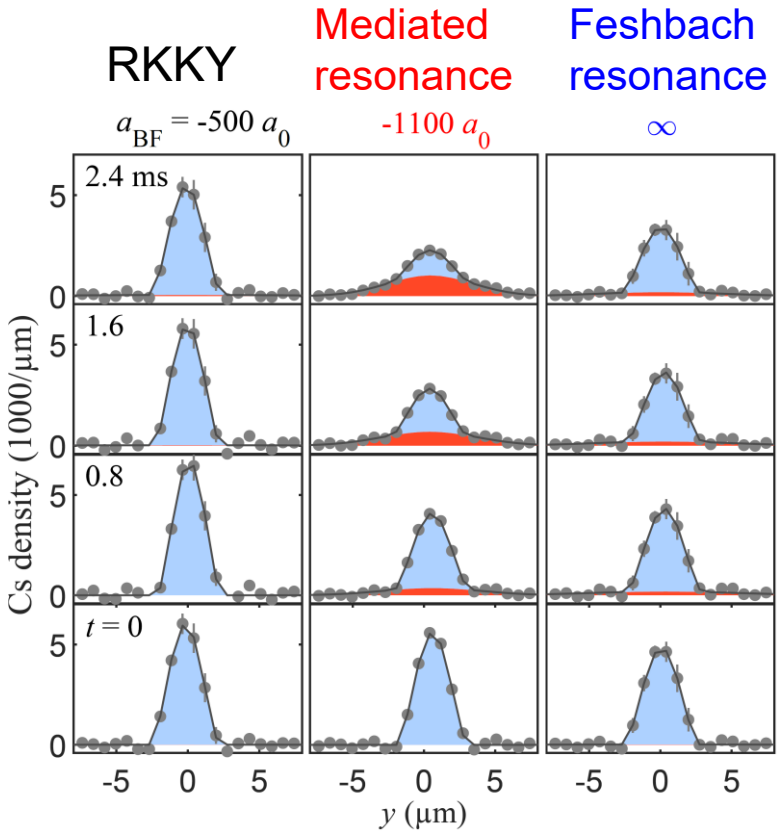
Damping and heating at mediated resonance

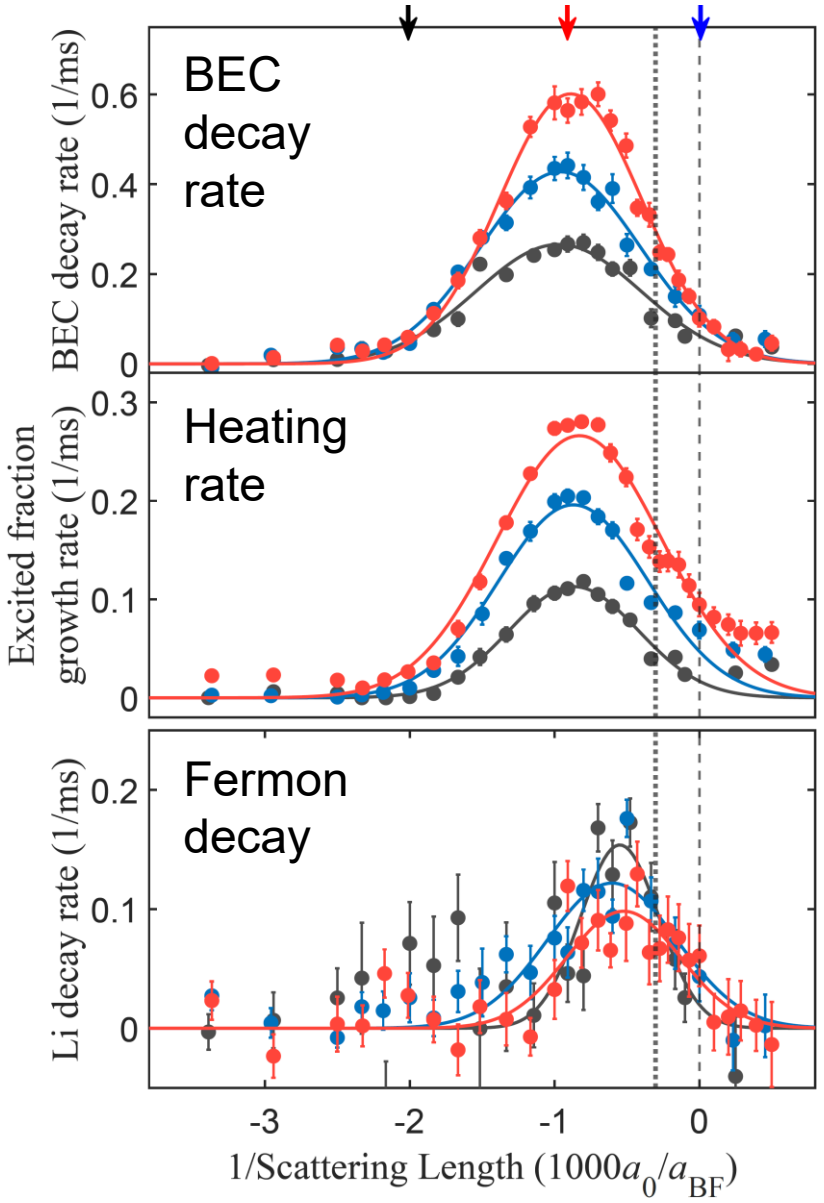




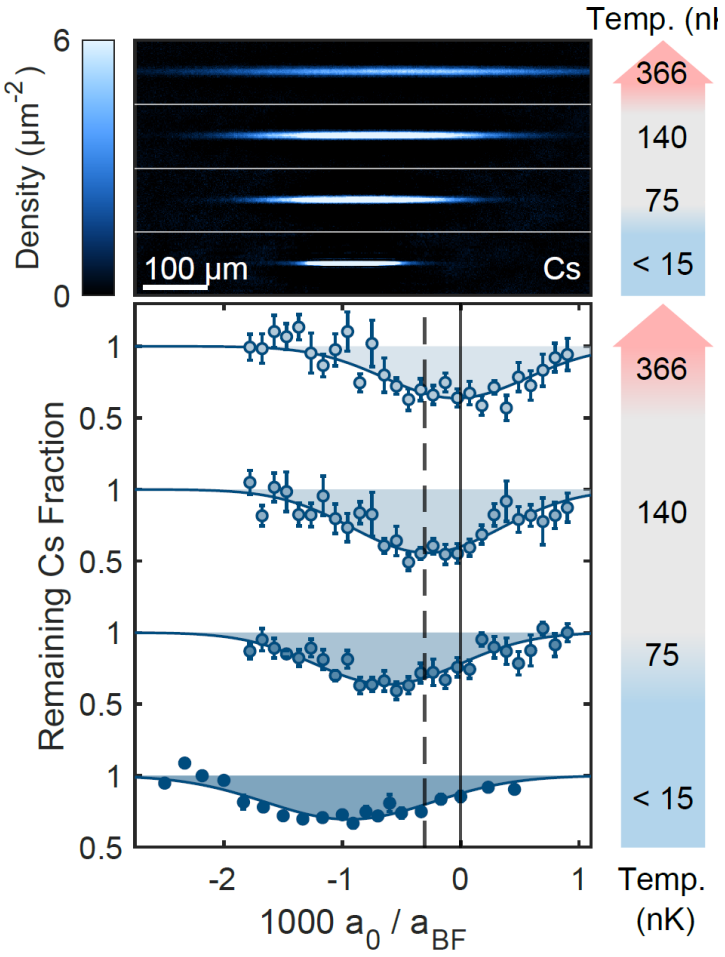
Damping and heating at mediated resonance







From thermal to quantum gas



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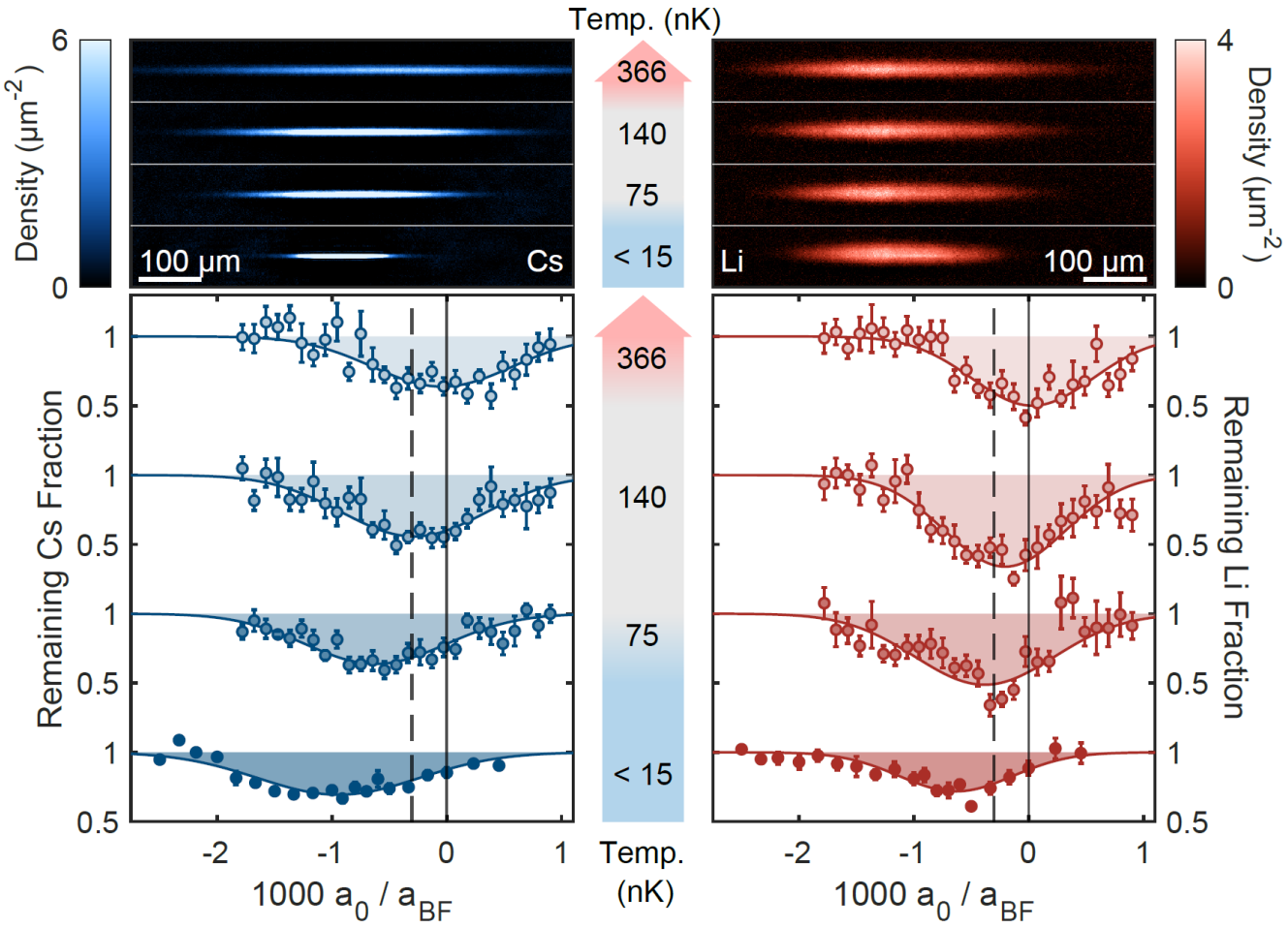
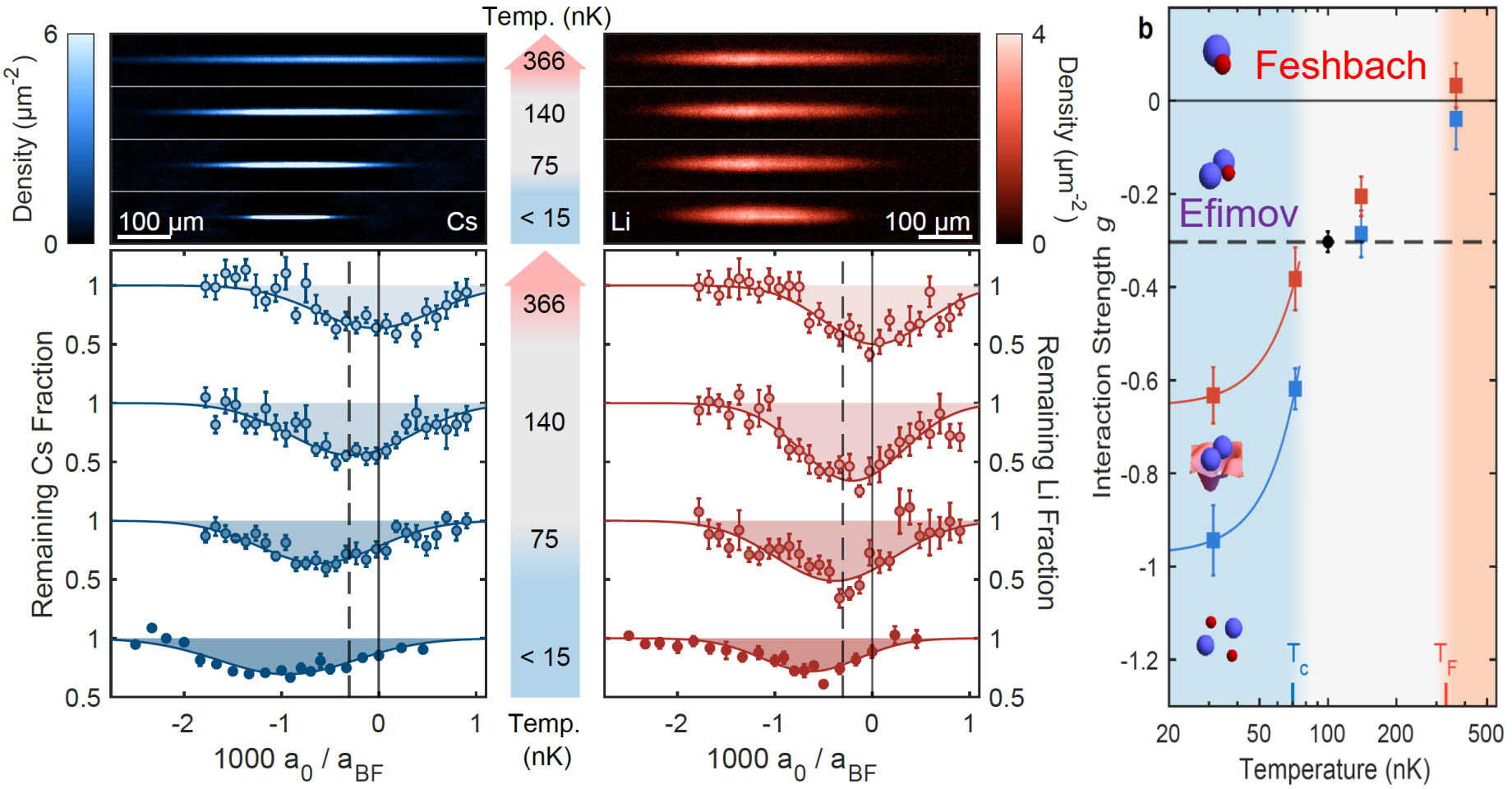
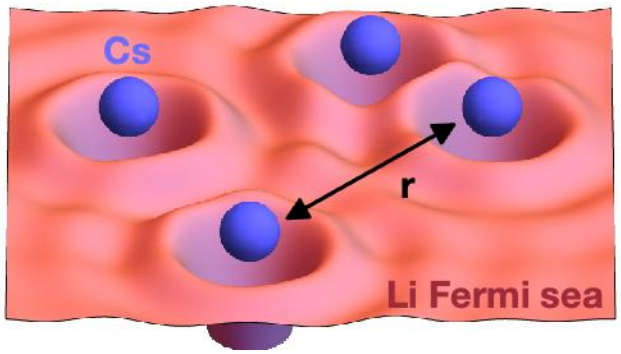
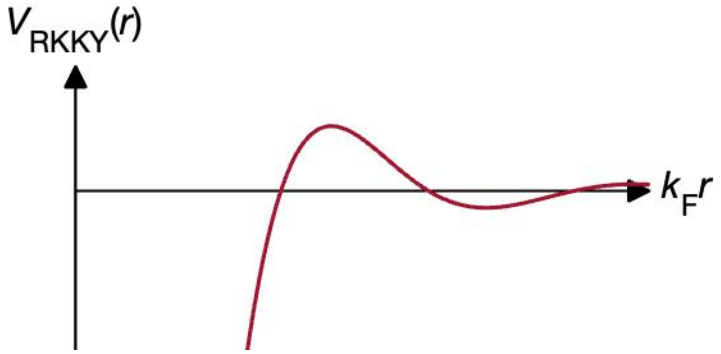


From thermal to quantum gas



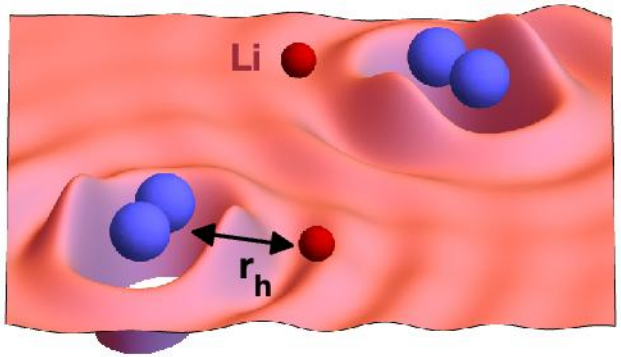
Ruderman-Kittle-Kasuya-Yosida potential $|a_{BF}| \ll k_F^{-1}$

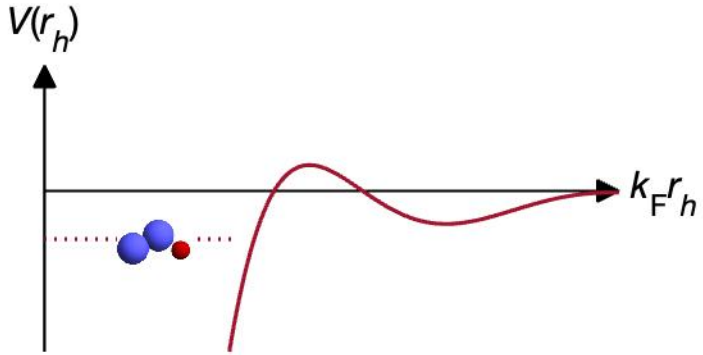




Efimov potential

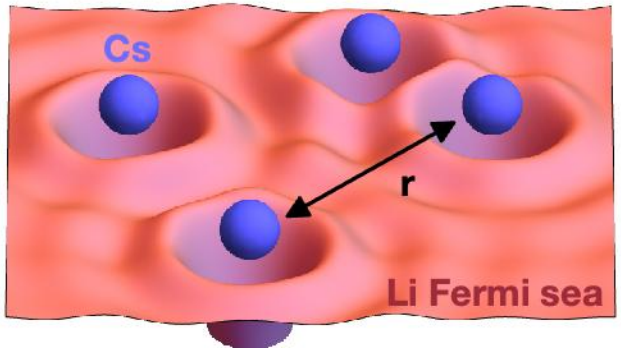
$|a_{BF}| \gg R_{vdW}$

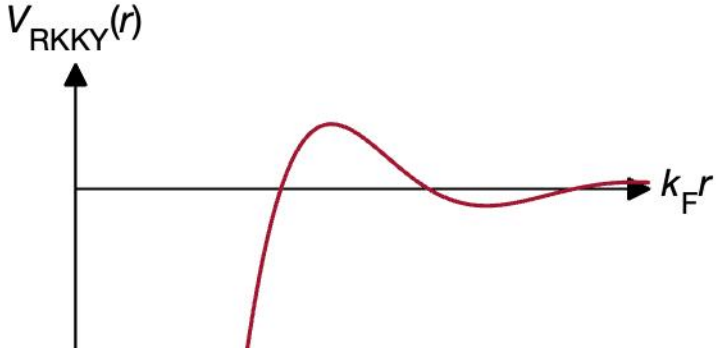




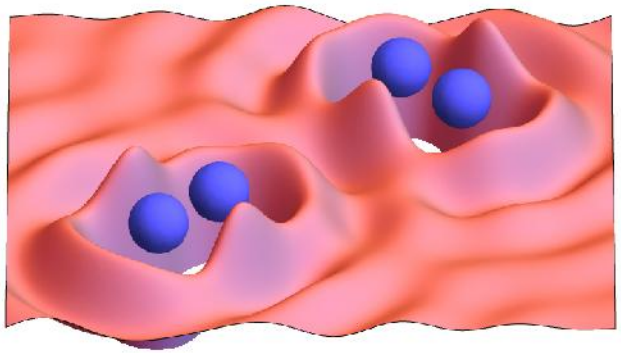
Ruderman-Kittle-Kasuya-Yosida potential $|a_{BF}| \ll k_F^{-1}$

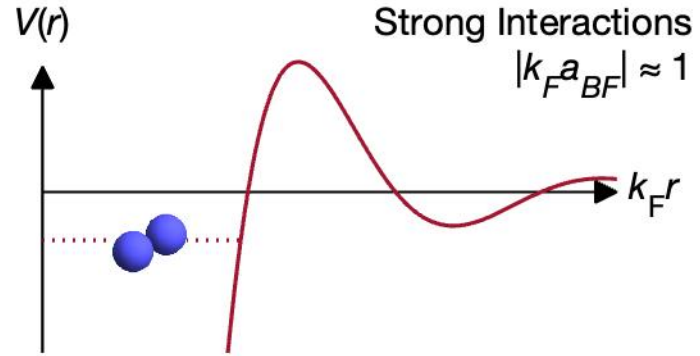
Attraction



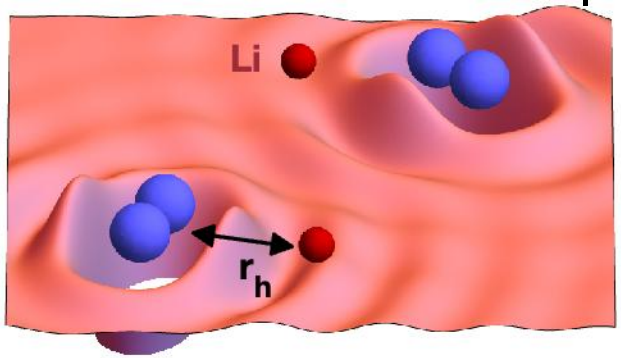


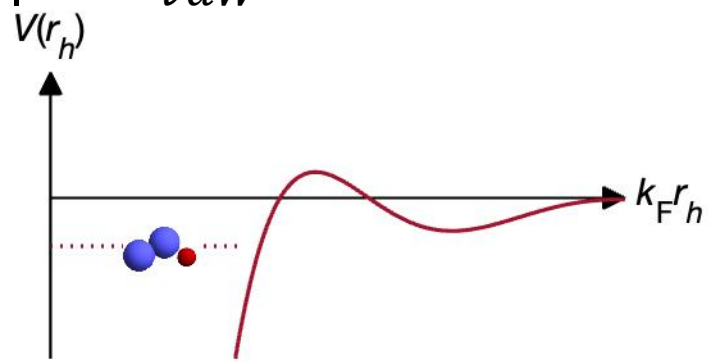
Fermion gas mediated pairing $|a_{BF}| \approx k_F^{-1}$





Efimov Cs2Li trimer $|a_{BF}| \gg R_{vdW}$





Conclusion

RKKY potential

- Fermion mediated interactions
- Quench of sound propagation

Fermion-mediated resonance

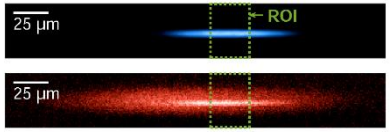
- Resonance in dispersion, damping, BEC decay at
  Exp: $k_F a_{BF} = -0.51$

  Theory: $\mathrm{k_F} \approx -\sqrt{\frac{m_F}{m_B}(2.5 + 3.1 k_F a_{BB})}$

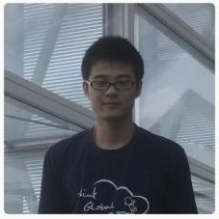
Efimov states

- LiCs2 three-body bound states

Acknowledgement



LiCs Team


Geyue Cai

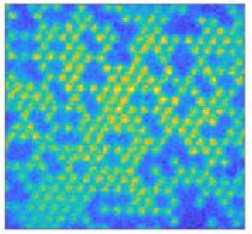

Sarah McCusker


Henry Ando

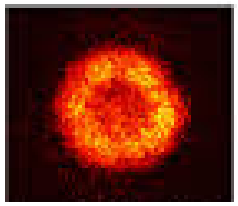
Theory


Tilman Enss (Heidelberg)


Michael Rautenberg (Heidelberg)



Cs BEC




Shu Nagata


Dr. Tadej Meznarsic


Lambert Kong

Quantum Matter Synthesizer


Jiamei Zhang


Lauren Weiss


Evan Yamaguchi