Colliding Polaronic Clouds Immersed in a Fermi Sea

arXiv:1912.12832

Hiroyuki Tajima[A,B], Junichi Takahashi[C], Eiji Nakano[A,D], and Kei Iida[A]

[A]Kochi University, [B]RIKEN, [C]Waseda University, [D]Universität Frankfurt

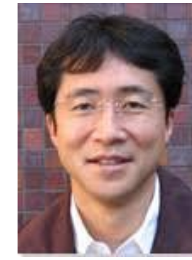
Outline

- Self-introduction
- Introduction
- Formulation
- Results
- Summary

Self-introduction -Hiroyuki Tajima-

Ph.D. (<u>March 2017</u>)
Thesis “*Thermodynamic properties of an ultracold Fermi gas in the BCS-BEC crossover region*”

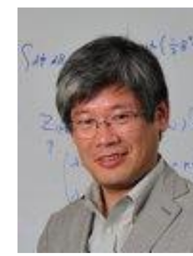
https://www.keio.ac.jp/ja/



Supervisor: Prof. Yoji Ohashi

<u>April 2017~September 2019</u>
Quantum Hadron Physics Laboratory,
RIKEN Nishina Center,
JSPS postdoctoral researcher (PD),

http://www.riken.jp/



Supervisor : Prof. Tetsuo Hatsuda

<u>October 2019~present</u>
I joined C02 group of “Clustering as a window on the hierarchical structure of quantum systems”, as a Specially Appointed Assistant Professor in Kochi University.

http://www.kochi-u.ac.jp/gakubu/rigaku/

Supervisor : Prof. Kei Iida

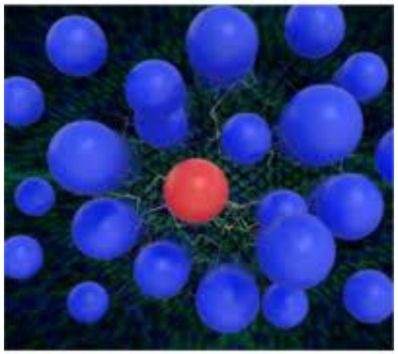
Outline

- Self-introduction
- Introduction
- Formulation
- Results
- Summary

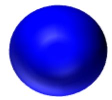
Polarons realized in ultracold atoms

One of the most fundamental quantum system due to its simplicity

Fermi (Bose) polaron: impurity immersed in Fermi (Bose) medium



https://images.app.goo.gl/Zghbzhzj3iK22ZDYA



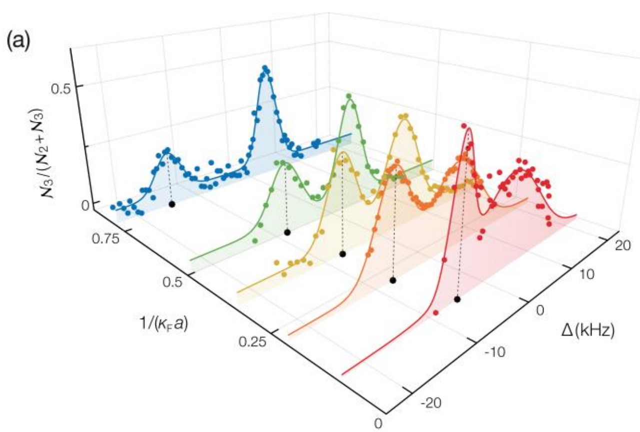
:Majority atom (medium)

:Minority atom (impurity)

Benchmark for many-body theories:

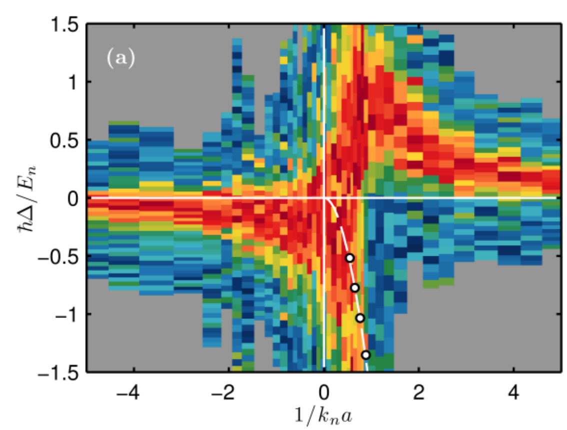
Variational method, *T*-matrix, Functional RG, QMC, etc..

Fermi polaron spectra



F. Scazza, *et al.*, Phys. Rev. Lett. **118**, 083602 (2017).

Bose polaron spectra

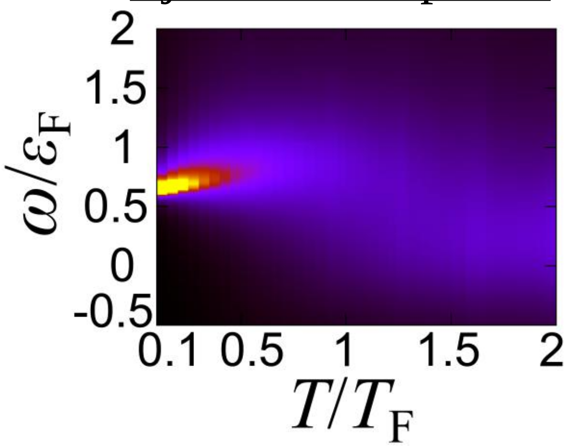


N. B. Jørgensen, *et al.*, Phys. Rev. Lett. **117**, 055302 (2016).

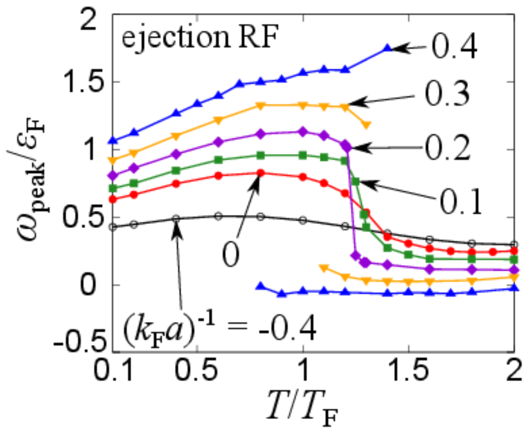
Thermal evolution of Fermi polarons

HT and S. Uchino Phys. Rev. A **99**, 063606 (2019).

Ejection RF spectra



Crossover to Transition

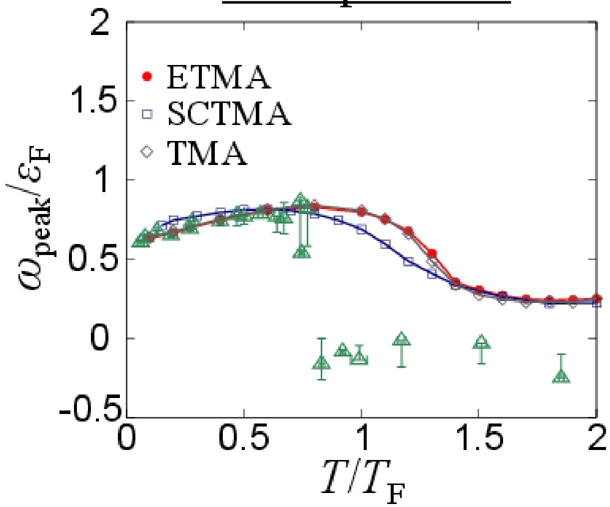


Collaborator

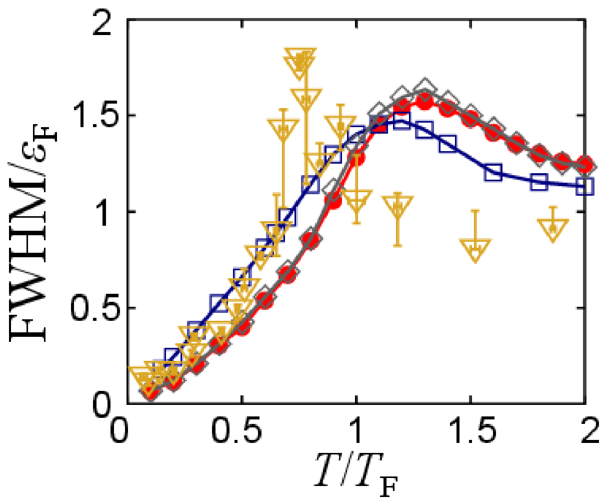
Shun Uchino (Waseda)

Comparison with experiments at unitarity [Yan, Phys. Rev. Lett. **122**, 093401 (2019).]

Peak position



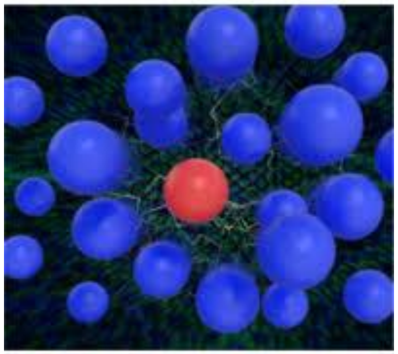
Full Width of Half Maximum



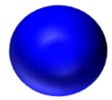
Polarons realized in ultracold atoms

One of the most fundamental quantum system due to its simplicity

Fermi (Bose) polaron: impurity immersed in Fermi (Bose) medium



https://images.app.goo.gl/Zghbzhzj3iK22ZDYA



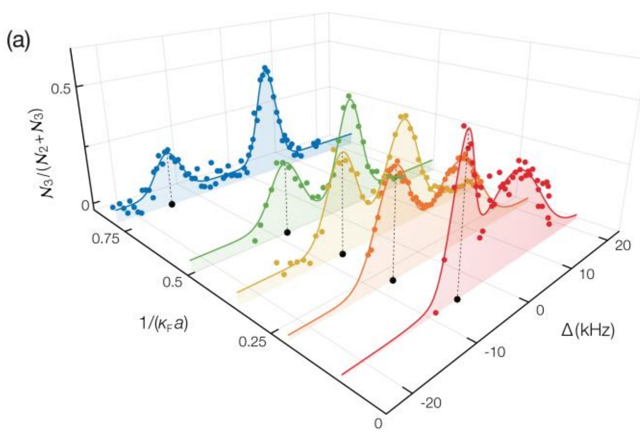
:Majority atom (medium)

:Minority atom (impurity)

Benchmark for many-body theories:

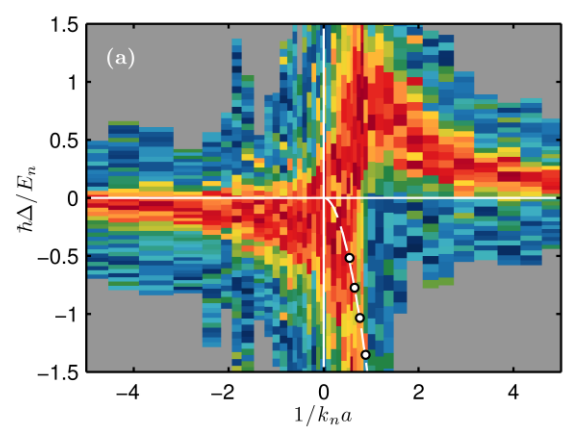
Variational method, *T*-matrix, Functional RG, QMC, etc..

Fermi polaron spectra



F. Scazza, *et al*., Phys. Rev. Lett. **118**, 083602 (2017).

Bose polaron spectra

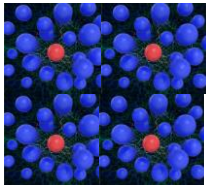


N. B. Jørgensen, *et al*., Phys. Rev. Lett. **117**, 055302 (2016).

Hierarchical Physics of Quantum Impurities

Higher hierarchy

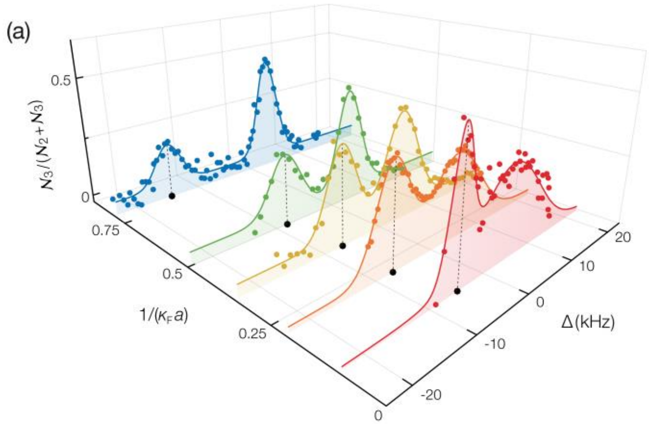
How do many polarons behave?



Lower hierarchy

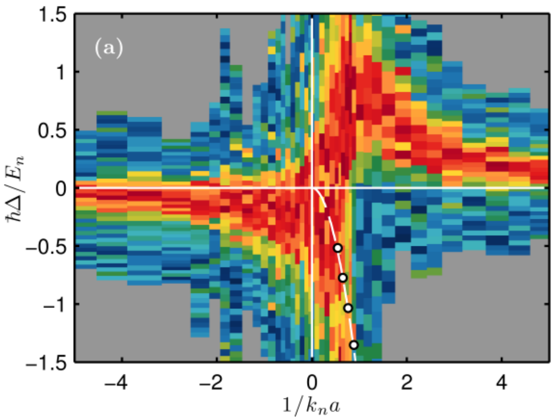
How is a polaron formed in Fermi sea or BEC?

Fermi polaron spectra



F. Scazza, *et al.*, Phys. Rev. Lett. **118**, 083602 (2017).

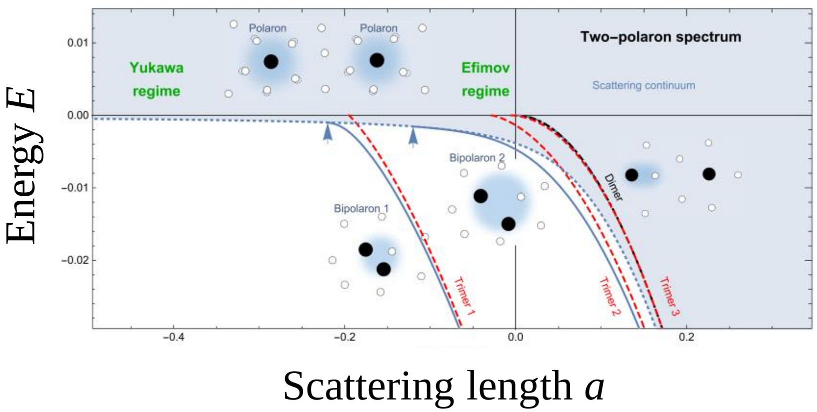
Bose polaron spectra



N. B. Jørgensen, *et al.*, Phys. Rev. Lett. **117**, 055302 (2016).

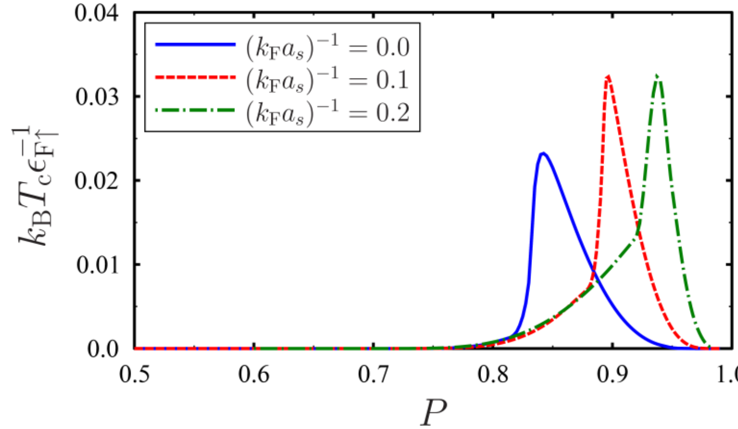
“Many-body Physics of Polarons”

<u>Bipolaron and Efimov effects in BEC</u>



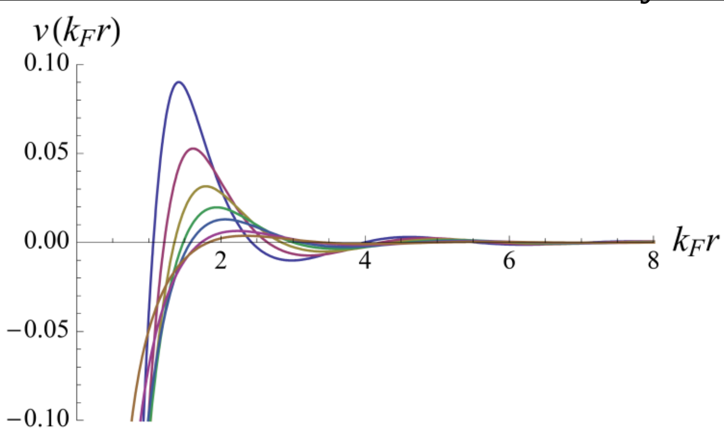
P. Naidon, J. Phys. Soc. Jpn. **87**, 043002 (2018)

<u>*P*-wave superfluid of Fermi polarons</u>



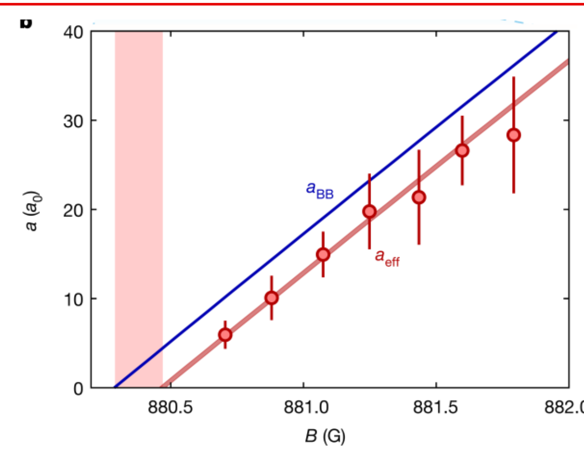
K. R. Patton, *et al.*, Phys. Rev. A **83**, 051607(R) (2011).

<u>RKKY interaction between two heavy fermions</u>



Y. Nishida, Phys. Rev. A **79**, 013629 (2009).

<u>Fermion-mediated interaction in Cs-Li mixture</u>

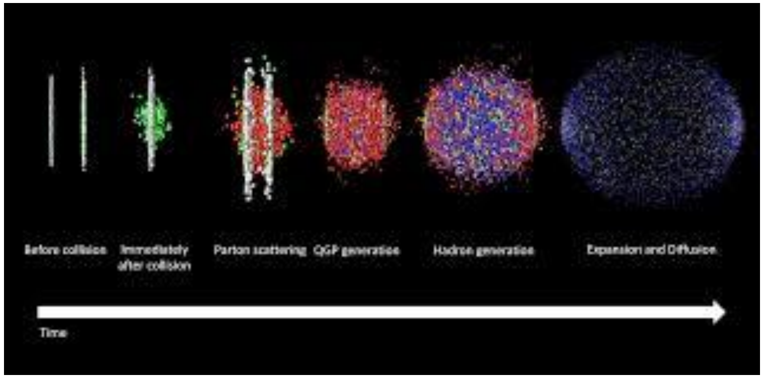


B. J. DeSalvo, *et al.*, Nature **568**, 61 (2019).

What happens if two polaronic clouds collide?

In nuclear physics…

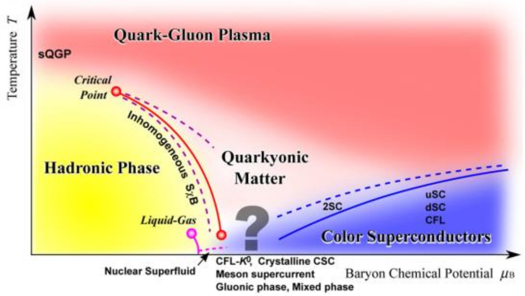
http://alice-j.org/



Hydrodynamic behavior
Information of lower hierarchy

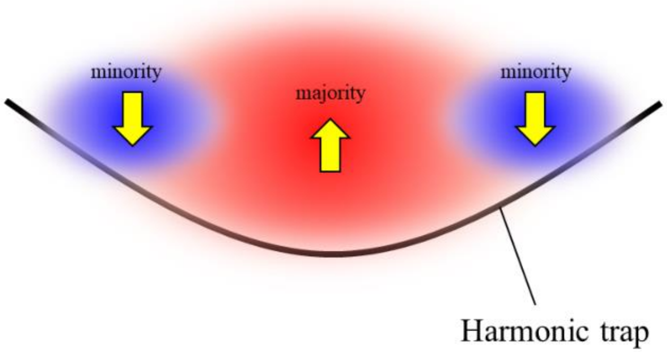
Lower hierarchy

It is difficult to obtain precise prediction



Rept. Prog. Phys. **74**, 014001 (2011).

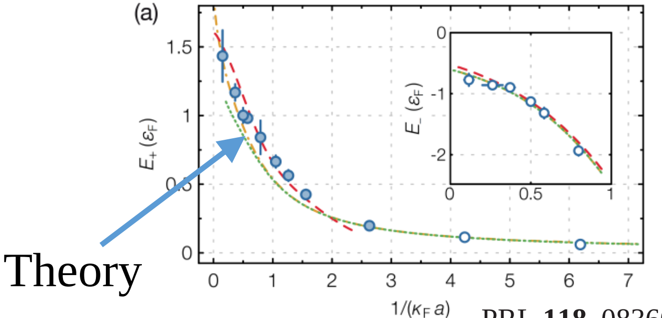
In polaron physics…



Today's talk

Lower hierarchy

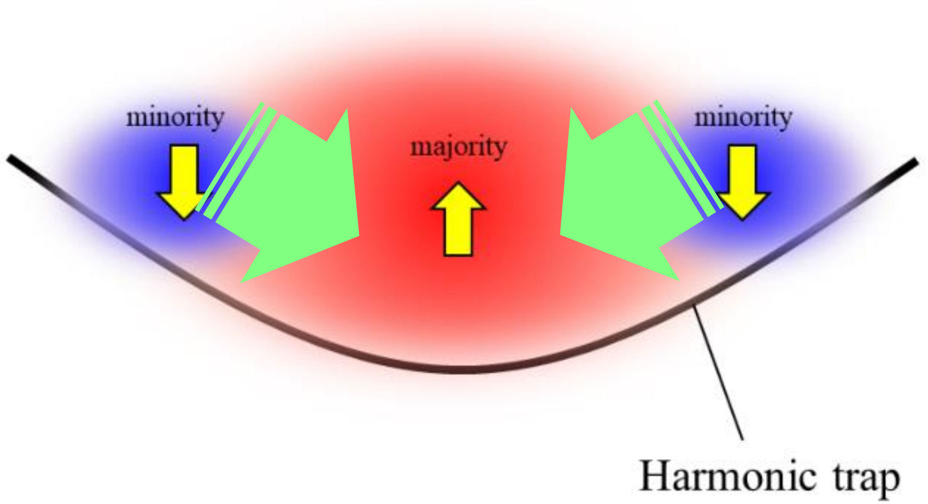
Experimental results agree with theories



PRL **118**, 083602 (2017).

Today’s talk

- We theoretically investigate collisional dynamics of polaronic clouds immersed in a Fermi sea at unitarity by solving the non-linear hydrodynamic equation.
- We discuss how polaron properties appear during the collision.



Outline

- Self-introduction
- Introduction
- Formulation
- Results
- Summary

Hydrodynamic equations for Fermi polarons

Euler equation

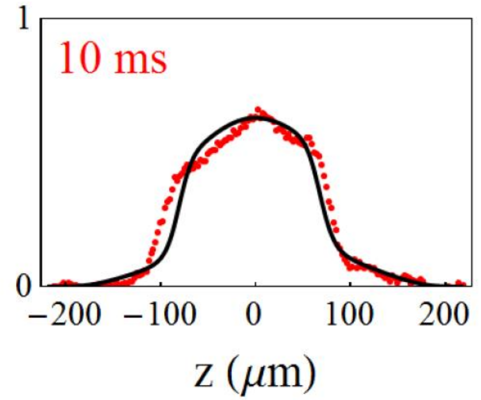
$$\frac{\partial \boldsymbol{v}_\sigma}{\partial t} + \frac{\nabla v_\sigma^2}{2} = -\frac{\nabla}{m_\sigma^*}\left(\frac{\partial E}{\partial n_\sigma} + V_{\mathrm{trap},\sigma}\right) - \gamma_\sigma \boldsymbol{v}_\sigma$$

Continuity equation

$$\frac{\partial n_\sigma}{\partial t} + \nabla \cdot (n_\sigma \boldsymbol{v}_\sigma) = 0$$

Hydrodynamics of unitary Fermi gases

Euler equation works well



J. A. Joseph, *et al*., Phys. Rev. Lett. **106**, 150401 (2011).

σ: pseudospin (↑:majority, ↓: minority)

n_σ: number density

v_σ: velocity field

E: energy density

γ_σ: spin relaxation rate

$V_{\mathrm{trap},\sigma} = m_\sigma(\omega_\perp^2 r_\perp^2 + \omega_z^2 r_z^2)/2$: harmonic trap

m_σ: atomic mass

Bulk viscosity: $\zeta = 0$ at the unitarity limit due to the conformal symmetry

Shear viscosity: $\eta \simeq 0$ at unitarity limit of unpolarized case (which we neglect for simplicity).

Energy density of unitary Fermi polarons

$$E = \Xi_{\mathrm{P}} + \Xi_{\mathrm{A}} + \Xi_{\mathrm{F}} + \Xi_{\mathrm{G}} + O(n_\downarrow^4)$$

Ξ_{P}: Fermi pressure term

Ξ_{A}: attractive polaron binding energy

Ξ_{F}: polaron-polaron interaction

Ξ_{G}: three-polaron interaction

Driving forces for polarons

Impurity Fermi pressure

$$\nabla\left(\frac{\partial \Xi_{\mathrm{P}}}{\partial n_\downarrow}\right) = \frac{(6\pi^2)^{\frac{2}{3}}}{3m_\downarrow^*}\frac{\nabla n_\downarrow}{n_\downarrow^{\frac{1}{3}}}$$

One-body potential

$$\nabla\left(\frac{\partial \Xi_{\mathrm{A}}}{\partial n_\downarrow}\right) = -\frac{(6\pi^2)^{\frac{2}{3}}\chi}{3m_\uparrow}\frac{\nabla n_\uparrow}{n_\uparrow^{\frac{1}{3}}}$$

Induced multi-body force

$$\nabla\left(\frac{\partial \Xi_{\mathrm{F}}}{\partial n_\downarrow}\right) = \frac{(6\pi^2)^{\frac{2}{3}}\kappa}{5m_\uparrow n_\uparrow^{\frac{1}{3}}}\left[3\nabla n_\downarrow - \frac{n_\downarrow}{n_\uparrow}\nabla n_\uparrow\right]$$

$$\nabla\left(\frac{\partial \Xi_{\mathrm{G}}}{\partial n_\downarrow}\right) = \frac{(6\pi^2)^{\frac{2}{3}}\lambda}{5m_\uparrow n_\downarrow^{\frac{1}{3}}}\left[9\frac{n_\downarrow}{n_\uparrow}\nabla n_\downarrow - 2\left(\frac{n_\downarrow}{n_\uparrow}\right)^2\nabla n_\uparrow\right]$$

Ansatz for Majority cloud (Thomas-Fermi)

$$n_\uparrow = \frac{(2m_\uparrow)^{3/2}}{6\pi^2}\left[E_{F,0} - V_{\mathrm{trap},\sigma}(r_\perp, z)\right]^{3/2}$$

Parameters for unitary Fermi polarons

Single-polaron properties

Polaron energy: $E_P = -\chi\varepsilon_{F,\uparrow} = -0.6\varepsilon_{F,\uparrow}$

Polaron effective mass: $m_\downarrow^* = 1.17 m_\downarrow$

Consistent with experiments and theories

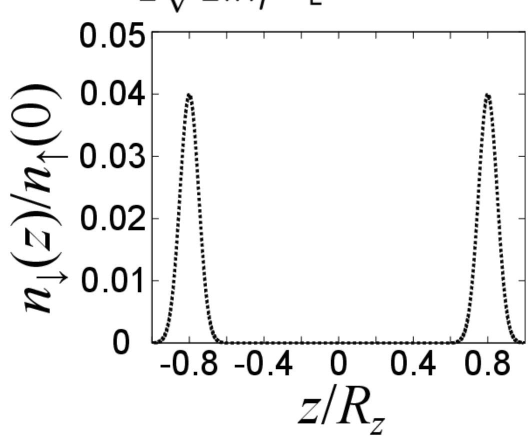
Majority number and trap potential

$$N_\uparrow = 1.5 \times 10^5 \quad \omega_z/\omega_\perp = 20/233$$

Following experiment PRL **118**, 083602 (2017).

Initial minority density profile

$$n_\downarrow(z, t=0) = \frac{Y n_\uparrow(0)}{2\sqrt{2\pi\eta^2}} \left[e^{-\frac{(z+z_I)^2}{2\eta^2}} + e^{-\frac{(z-z_I)^2}{2\eta^2}} \right]$$

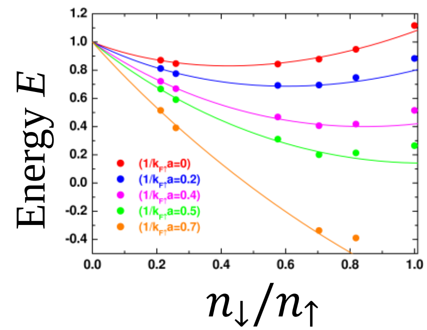


Multi-polaron properties

$$\Xi_F = \frac{3}{5}\kappa \frac{\varepsilon_{F,\uparrow}}{n_\uparrow} n_\downarrow^2$$

$$(\kappa = 0.2)$$

$$\Xi_G = 0$$



Weak two-body repulsion from FN-DMC

S. Pilati *et al.*, PRL **100**, 030401 (2008).

To simplify the problem, we restrict ourselves in the axial (z-axis) mode.

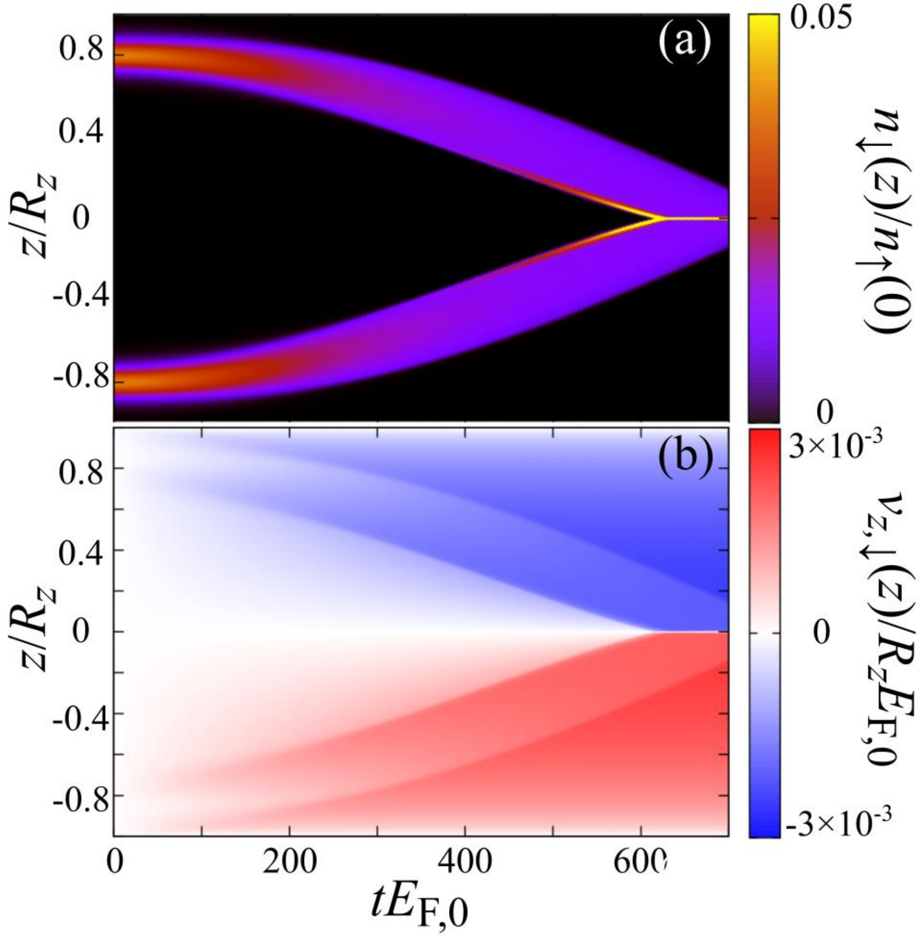
$$\frac{\partial v_{z,\sigma}}{\partial t} = -\frac{1}{m_\sigma^*}\frac{\partial}{\partial z}\left(\frac{\partial E}{\partial n_\sigma}\right) - \gamma_\sigma v_{z,\sigma} - v_{z,\sigma}\frac{\partial v_{z,\sigma}}{\partial z} - \frac{m_\sigma}{m_\sigma^*}\omega_z^2 z,$$

$$\frac{\partial n_\sigma}{\partial t} = -v_{z,\sigma}\frac{\partial n_\sigma}{\partial z} - n_\sigma \frac{\partial v_{z,\sigma}}{\partial z},$$

Outline

- Self-introduction
- Introduction
- Formulation
- **Results**
- Summary

Impurity density profile and velocity field



Collision time

1/4-period of dipole mode

$$t_c \simeq \frac{1}{4}\frac{2\pi}{\omega_z^*} = 666E_{F,0}^{-1}$$

$$\omega_z^* = \omega_z\sqrt{\frac{m_\downarrow}{m_\downarrow^*}(1+\chi)}$$

Frequency is renormalized due to polaron energy and effective mass

Impurity clouds are broadened due to Fermi pressure as well as polaron-polaron repulsion

Polaron-polaron interaction in the absence of impurity Fermi pressure

Two clouds collapse at the collision

Impurity clouds form central core as well as remnants

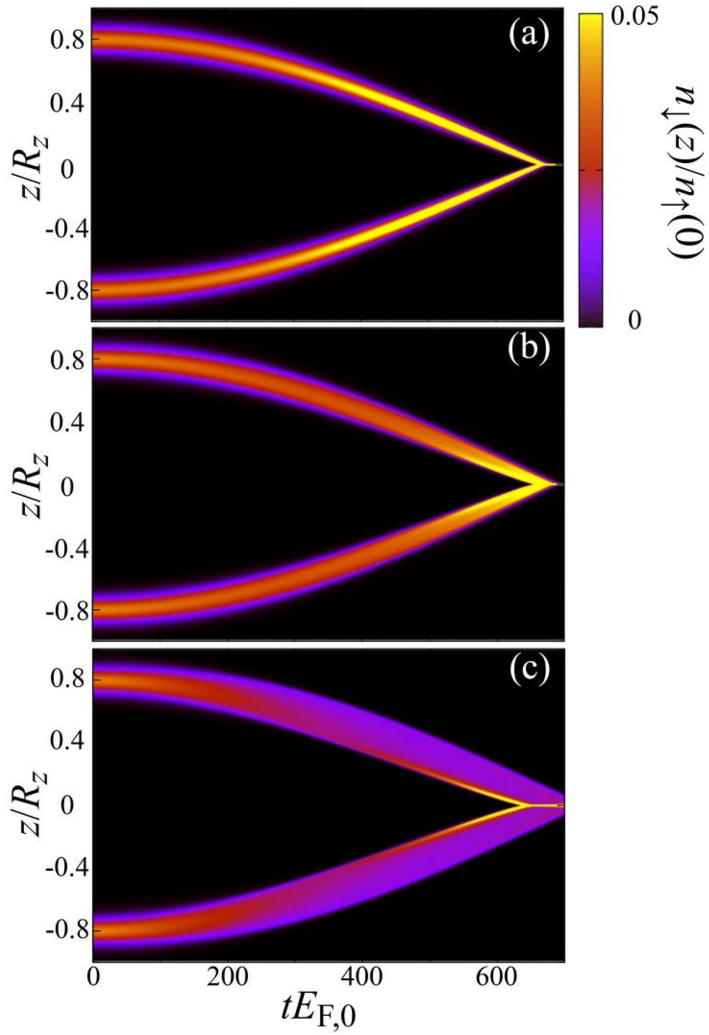
Weak repulsion

Strong repulsion

$\kappa = 0$

$\kappa = 0.2$

$\kappa = 1$



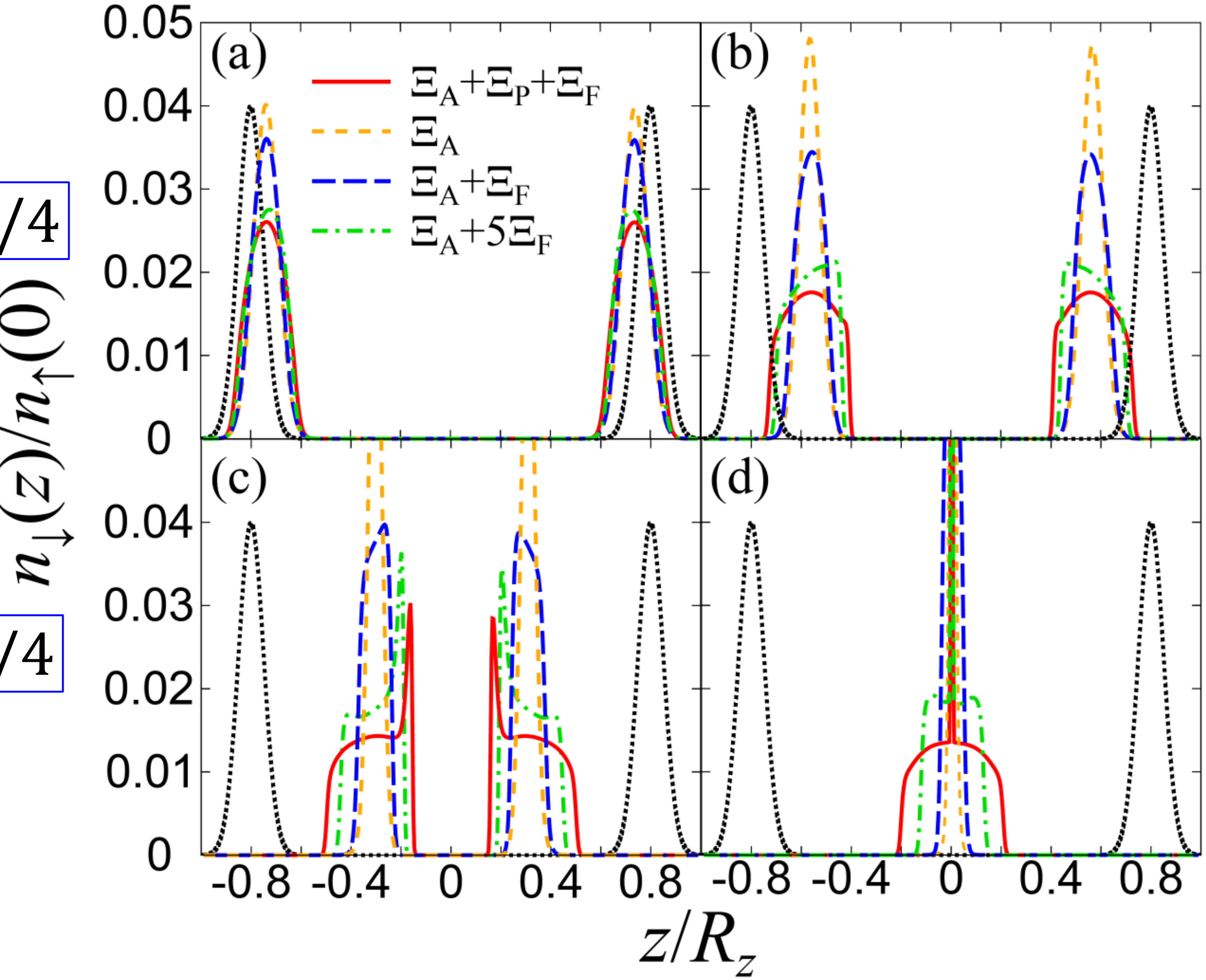
2D plot of impurity density profiles

$t = t_c/4$

$t = t_c/2$

$t = 3t_c/4$

$t = t_c$



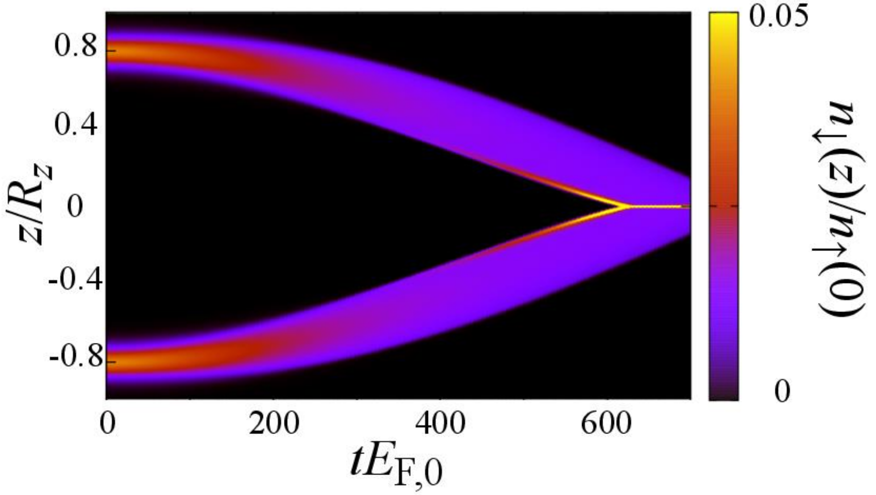
Outline

- Self-introduction
- Introduction
- Formulation
- Results
- Summary

Summary

arXiv:1912.12832

- We propose a new protocol to investigate hierarchical physics of quantum impurities, namely polarons realized in ultracold atoms.
- Based on the hydrodynamic equations, we demonstrate how polaron properties appear in the collisional dynamics of unitary Fermi polaronic clouds.



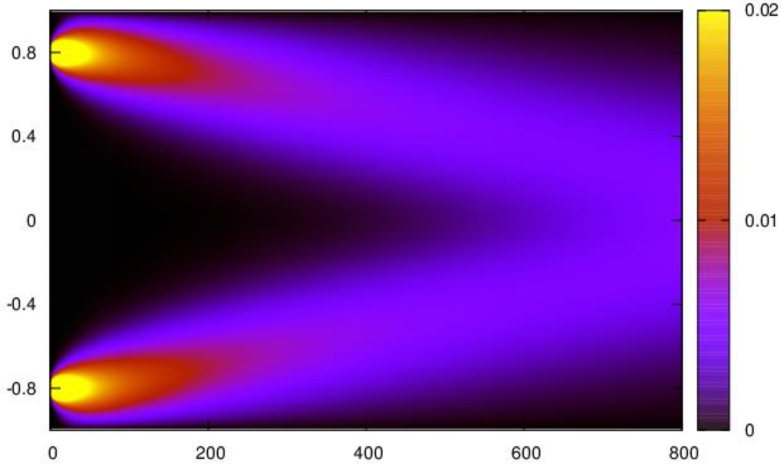
<u>Future work</u>

- Three-dimensional dynamics
- Viscosity coefficients
- Induced long-range interaction
- Bose polarons
- Collisionless to hydrodynamic

etc…

Spin-relaxation effects

Critical damping



Over-damping