Agenda

9:00 Wolfgang Ketterle: Introduction

9:10 Synthetic gauge fields and spin orbit coupling

Colin Kennedy: Synthetic Gauge Fields and Engineering New Lattice Models

Ian Spielman: Cold atoms and not just quantum simulators any more

9:50 Exotic new phenomena

Eugene Demler: Exotic phenomena with impurities

Ashwin Vishwanath: New topological phases with interacting bosons

10:30 COFFEE BREAK

11:00 New schemes for cooling and state prepratation

Dan Stamper-Kurn: Using magnons to measure and lower temperature

Andrew Daley: adiabatic state preparation and quantum magnetism

11:40 New systems and new probes

Jun Ye: Spectroscopic observation of SU(N)-symmetric interactions in Sr orbital magnetism".

Markus Greiner: Probing many-body entanglement

12:20 Martin Zwierlein: Summary and Outlook

New Phenomena with impurities

Mobile magnetic impurity in Fermi superfluids

Sarang Goplalakrishnan, Norm Yao, Misha Lukin, Eugene Demler (Harvard), Ivar Martin (Argonne), Colin Parker (Chicago)

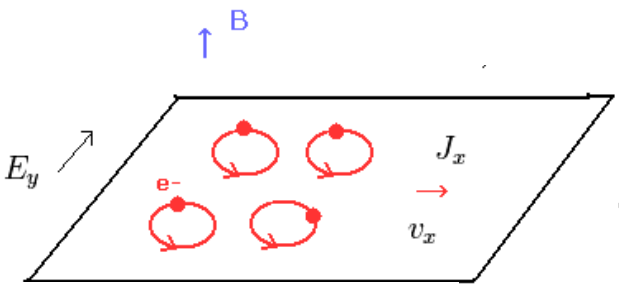
+ ongoing work with Gergely Zarand (TU Budapest)

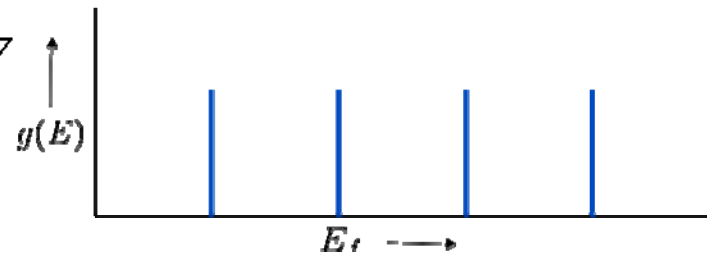
Mobile magnetic impurity in Fermi superfluids

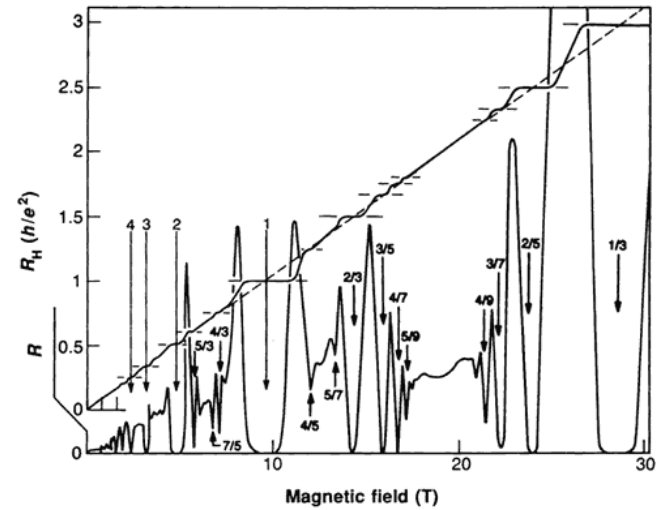
Sarang Goplalakrishnan, Colin Parker, Eugene Demler

Enhancing interaction by suppressing kinetic energy

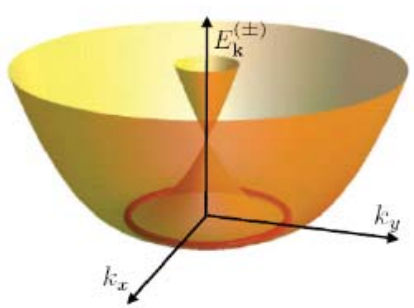
Example: fractional quantum Hall effect

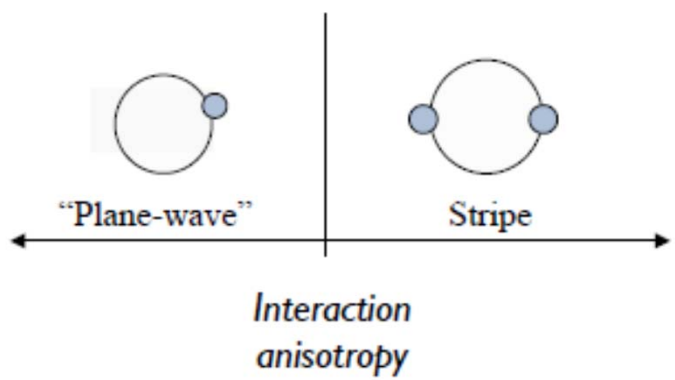






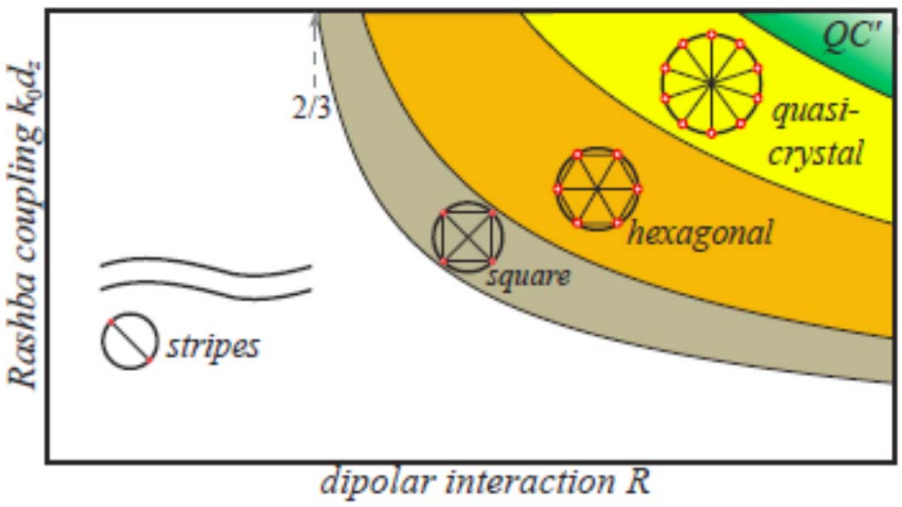
Example: spin orbit coupled BEC

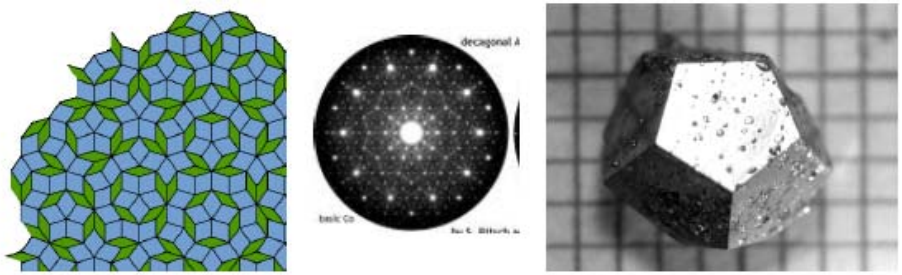




Quantum quasicrystals of spin-orbit coupled bosons

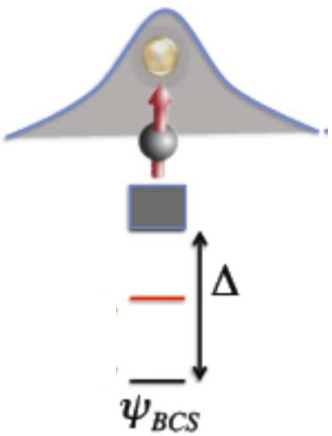
S. Gopalakrishnan et al., Phys. Rev. Lett. 111:185304 (2013)



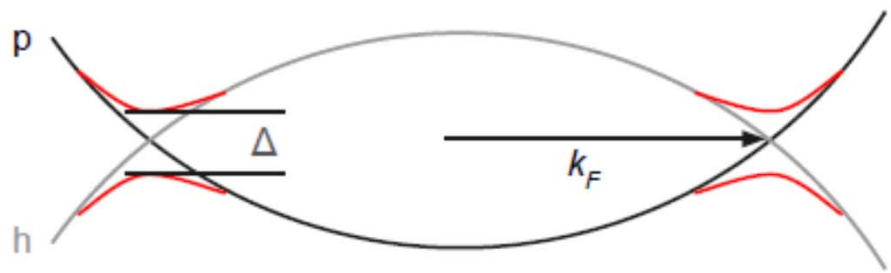


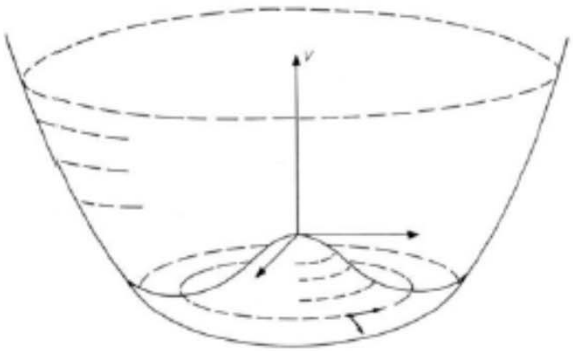
Using mobile magnetic impurities in Fermi superfluids to realize exotic states

Bound states on magnetic impurities in superconductors



BCS pairing → Mexican hat





DOS singularity ($1/\sqrt{E}$, "1D-like") at bottom of quasiparticle band, weak-coupling bound state with polynomial energy

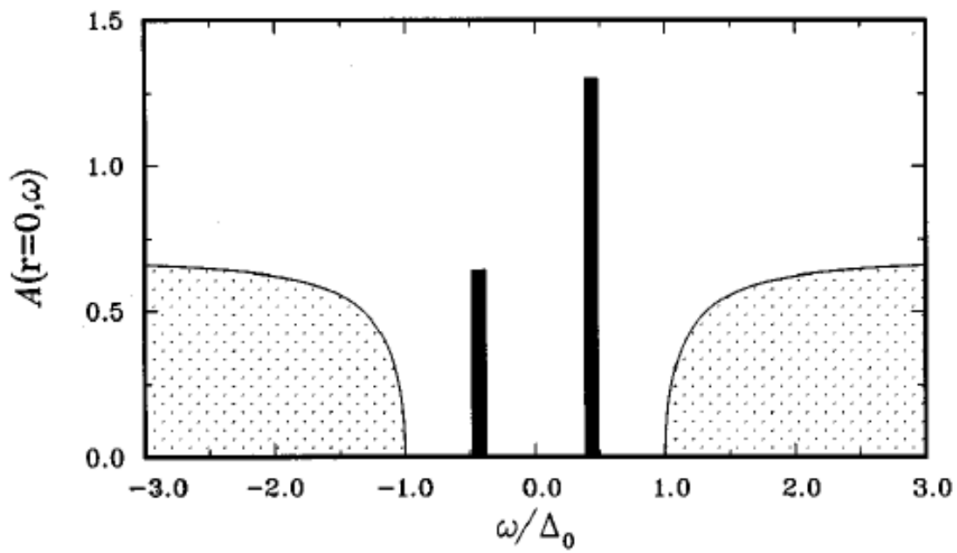
$$E \sim \Delta \frac{1-(\pi N(E_F)J)^2}{1+(\pi N(E_F)J)^2}$$

interspecies coupling

Impurity must be magnetic, otherwise quasiparticles decouple from it at low energies

Bound states on magnetic impurities in superconductors

Yu, Acta Phys. Sin. 21, 75 (1965)
Shiba, Prof. Theor. Phys. 40, 435 (1968).
Rusinov, Sov. Phys. JETP Lett. 9, 85 (1969)



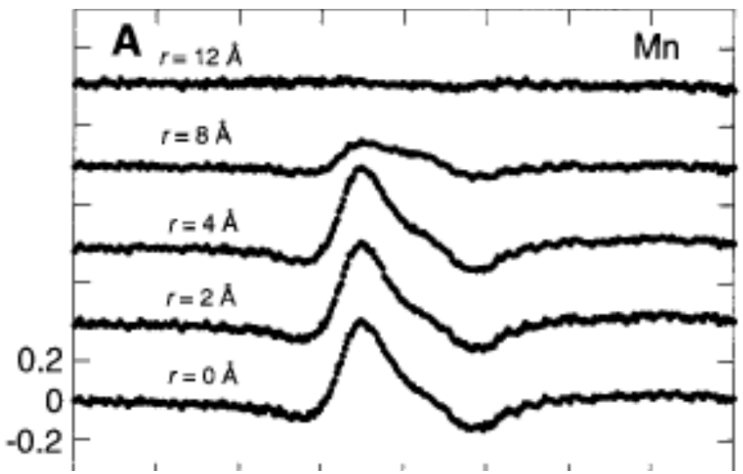
Salkola, Balatsky, Schrieffer, PRB 55:12648 (1997)

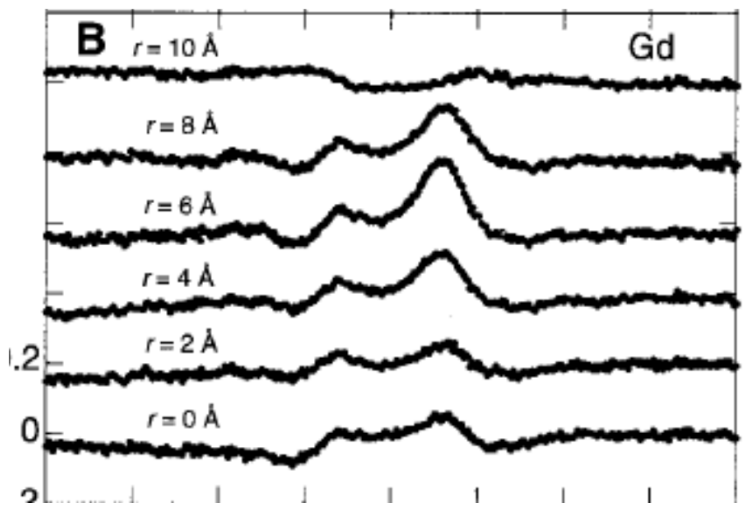
Probing the Local Effects of Magnetic Impurities on Superconductivity

Ali Yazdani,* B. A. Jones, C. P. Lutz, M. F. Crommie,†
D. M. Eigler

Science 275:1767 (1997)

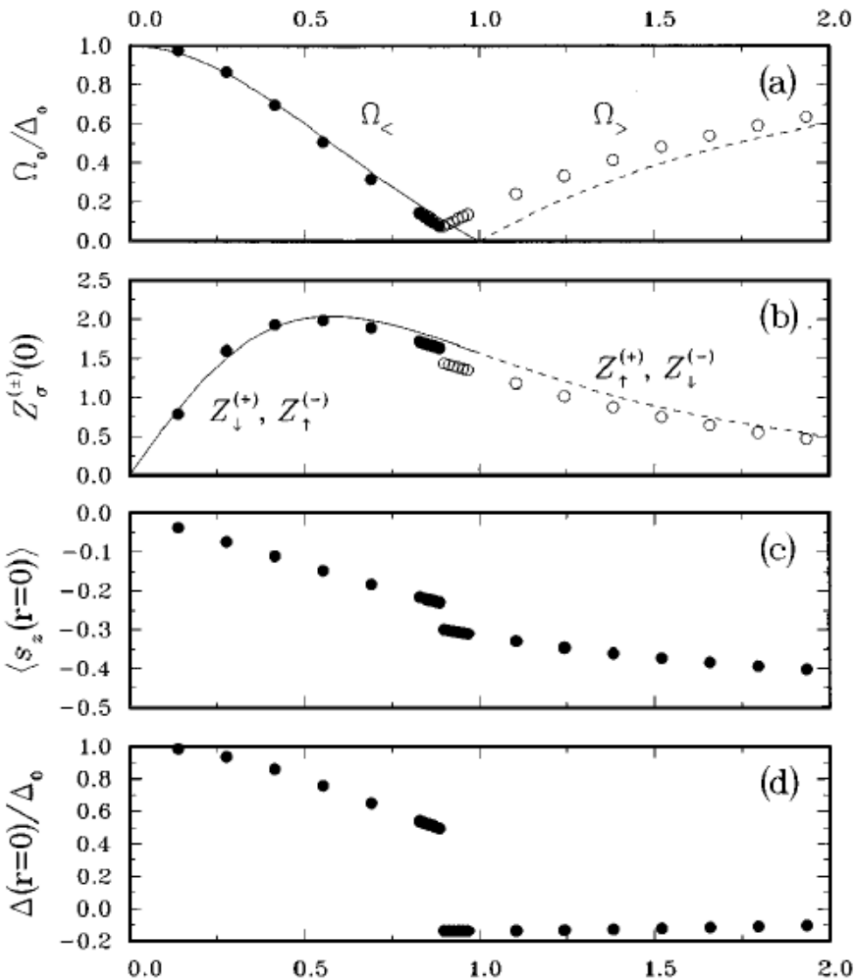
Local density of states near





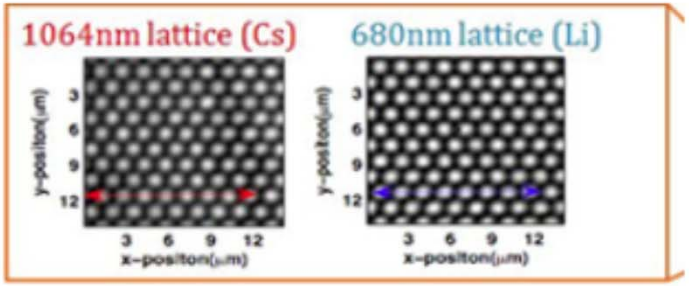
Parity changing transition

Salkola, Balatsky, Schrieffer, PRB 55:12648 (1997)



Analogous to Kondo singlet formation

Possible realization: Cs impurities in Li fermionic condensate



e.g. Cheng Chin's group

other possible mixtures
in experiments by
W. Ketterle, M. Zwierlein

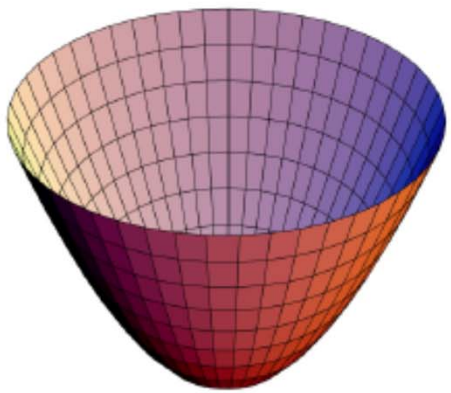
- Heavy Cs impurities in light Li fermionic condensate
- Interactions between Cs and the two hyperfine states of Li can be tuned independently via heteronuclear Feshbach resonance: impurities are "magnetic"
- Infinite-mass limit: Shiba states bound to each Cs atom
  - Our question: **fate of a mobile Shiba state**

Bound state of Bogoliubov quasiparticle and impurity atom

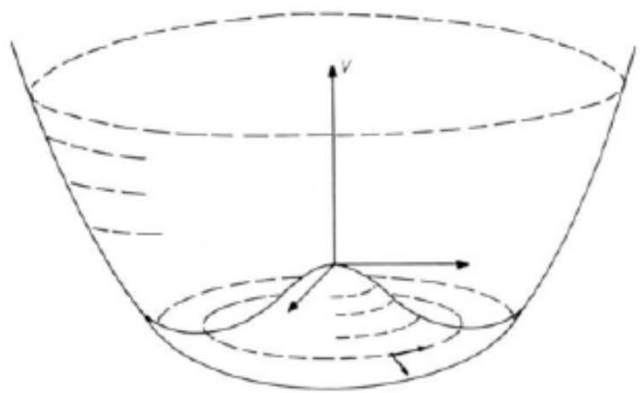
Overall Hamiltonian $$H_0 = \sum_{k\sigma} \xi_k \gamma^\dagger_{k\sigma} \gamma_{k\sigma} + p^2/2M$$

$$H_1 = J \sum_{kq\sigma} e^{iqr} (\gamma^\dagger_{k+q,\sigma} \gamma_{k,\sigma} + \cancel{\gamma^\dagger \gamma^\dagger + \text{h.c.}})$$

Odd sector: two-body problem with different dispersions:



impurity



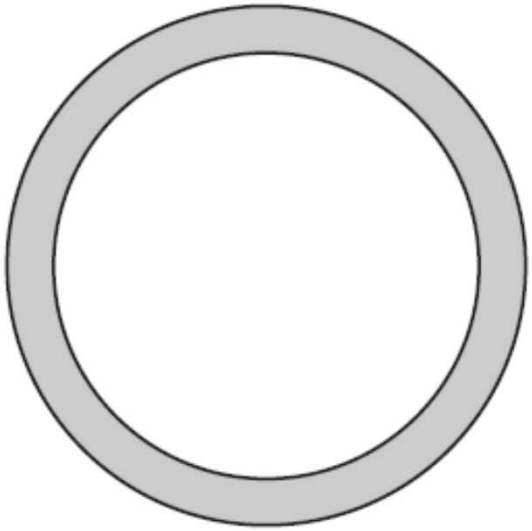
Bogoliubov qp

Sketch of the wavefunction

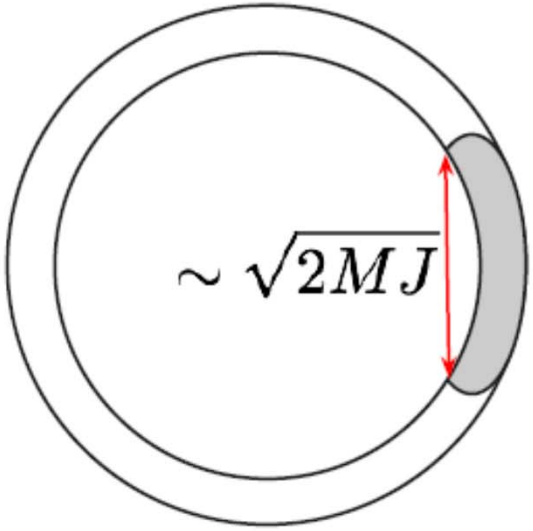
Total momentum conserved, ~ k_F

Scattering across Mexican hat costs impurity recoil

$$\mathcal{E} \simeq k_F^2/2M \gg J$$

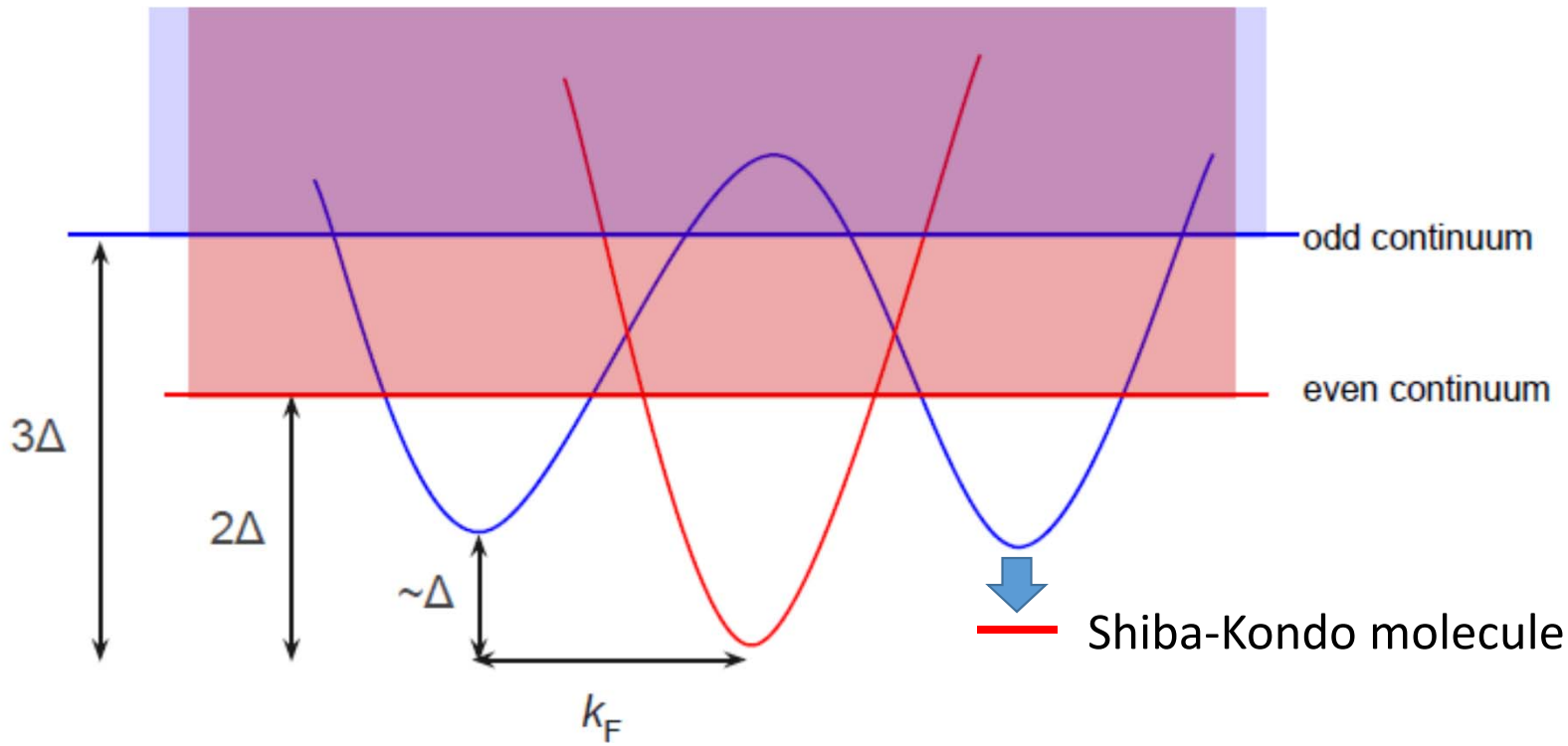


fixed case



mobile case

Strong interaction: global minimum



As J increases, odd branch comes down in energy, eventually becomes global ground state (can be captured via T-matrix approach)

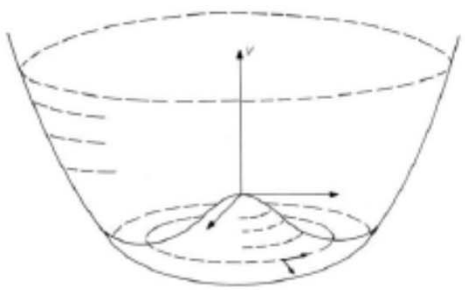
“Exotic” molecule

Mass of the relative coordinate

$$\frac{1}{\mu^{\parallel}} = \frac{1}{M} + \frac{1}{\infty}; \quad \frac{1}{\mu^{\perp}} = \frac{1}{M} + v_F^2 \Delta$$

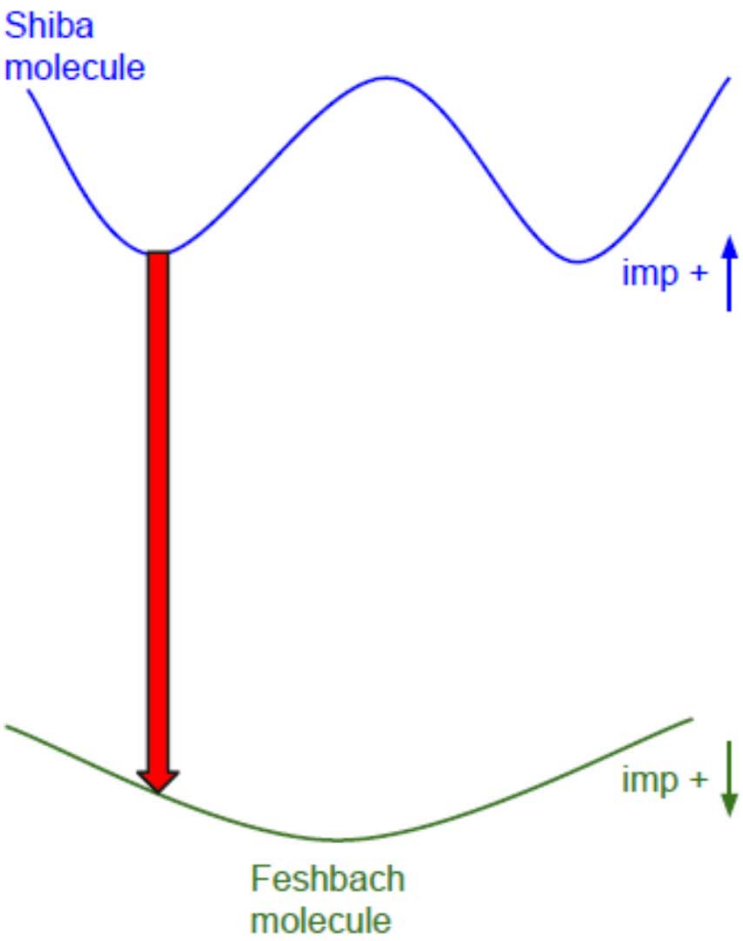
What about the center-of-mass coordinate?

$$\mathbb{M}^{\parallel} = \infty; \mathbb{M}^{\perp} = M + \Delta / v_F^2$$



Molecule itself has Mexican-hat dispersion: impurity momentum ~ 0, quasiparticle momentum ~ k_F in any direction

Detection via RF



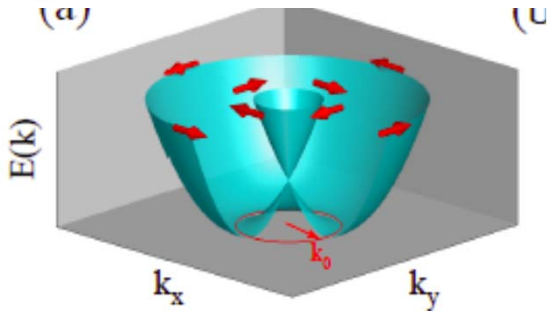
Tune to Cs-Li scattering length attractive for “up spins”, repulsive for “down spins”

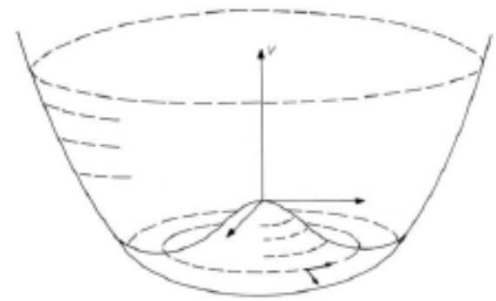
Implies existence of Feshbach molecule between impurity and down spins

Exotic many-body phases?

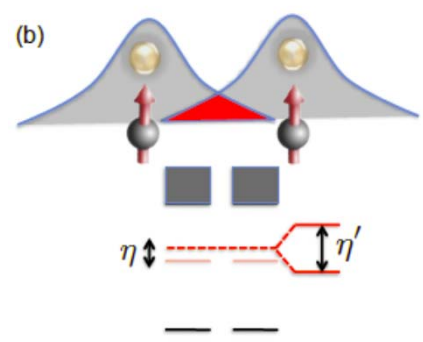
Reminiscent of electrons with spin-orbit coupling

$$H = \sum_j \left\{ \frac{1}{2m} \left[-\nabla_j^2 - \frac{2k_0}{i} (\nabla_j \times \hat{z}) \cdot \vec{\sigma}_j \right] + E_0 \right\}$$





Interaction between two Shiba states: Yao et al., 13092633



$$\eta_{\uparrow\uparrow} = -\frac{\Delta}{2} \frac{\cos(k_f r)}{(k_f r)^2} e^{-\frac{2r}{\xi}}$$

in 2D and contact interaction, ground state: breaks rotational symmetry. Wigner crystal or nematic.
Berg, Rudner, Kivelson (2012)

For contact interaction Wigner crystal with aspect ratio $\eta^\star \sim \left(n/k_0^2\right)^{-\frac{1}{3}}$ has energy per particle parametrically better than uniform phase

$$\varepsilon^\star\left(\eta^\star\right) \sim |E_0| \left(n/k_0^2\right)^{\frac{4}{3}}$$