Topological Superfluid Phase with Repulsive Fermionic Atoms

Gerardo Ortiz
Department of Physics - Indiana University

QPTn-9 – May 24th 2018

Is Landau theory the only possible framework for (Quantum or Thermal) Phase Transitions ?

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"There is life beyond the Landau paradigm"

– Anonymous

Landau versus Topological orders

Landau orders	Topological orders
(Local) Order parameter	String (non-local) Order / Topological Invariants
Broken (global) Symmetry	Robustness against local perturbations/ Bulk-boundary correspondence

The Nobel Prize in Physics 2016

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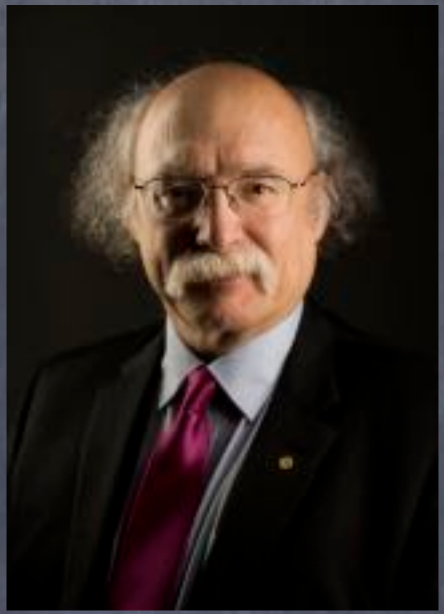
David J. Thouless
Prize share: 1/2



F. Duncan M. Haldane
Prize share: 1/4

J. Michael Kosterlitz
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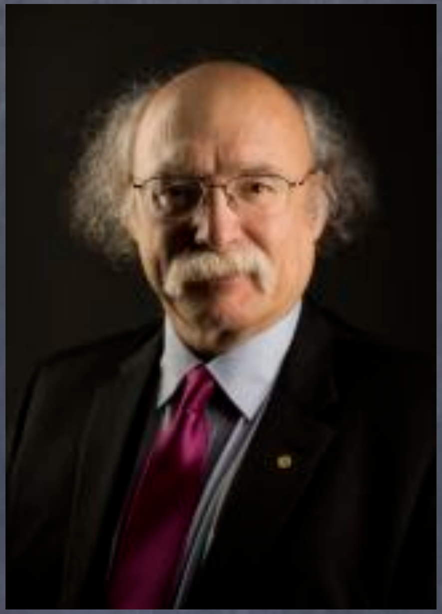

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"For theoretical discoveries of topological phase transitions and topological phases of matter"

- Most of the work on Topological Quantum Matter is based on the Mean-Field quasi-particle picture
  — Paired Superfluids are particle-number non-conserving
  — Zero-energy modes are Majorana fermions (MFs) by default
  — MFs are blueprints for topological quantum computation

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  — MFs are blueprints for topological quantum computation

- But real "closed systems" are interacting particle-number conserving (pnc) systems
  — What is a topological superfluid in a pnc system?
  — What is a Majorana fermion in a pnc system?
  — How one detects Majorana fermions?
  — Can one braid MFs in pnc systems?

Some Answers

PRL 113, 267002 (2014); Ann.Phys. 372, 357 (2016); PRB 95, 201114(RC) (2017)

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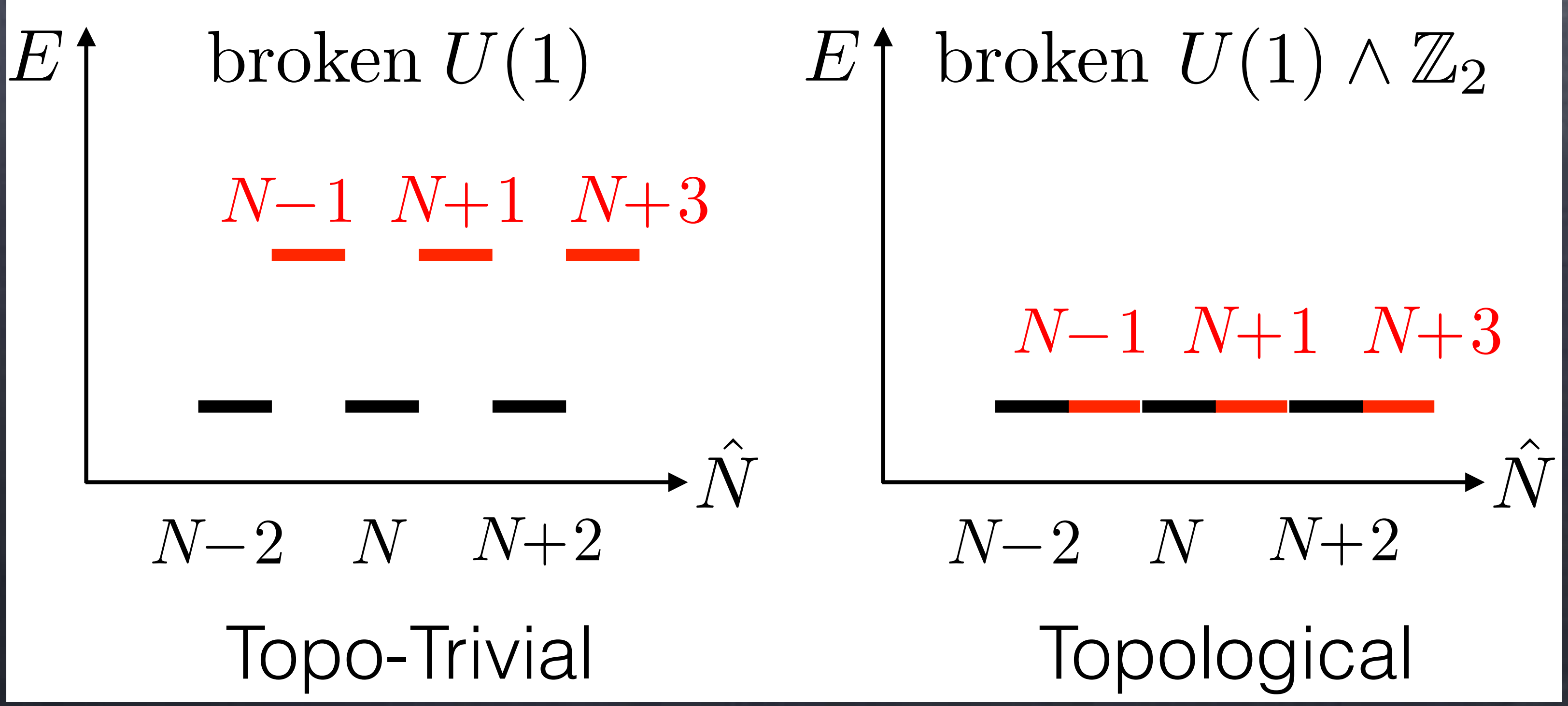
$$\lim_{N,V\to\infty} \frac{N}{V} = \rho = \text{constant}$$



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Can one prepare/manipulate/braid coherent superpositions of states with a different number of particles?

Majorana in the News

INTERVIEW 8 May 2013

Nothing to see: The man who made a Majorana particle

By Lisa Grossman

*Physicist **Leo Kouwenhoven** ended a 75-year hunt for the tricky Majorana fermion – a particle that is its own antiparticle – by creating one on a chip*

The New York Times | http://nyti.ms/1mfRwAV

TECHNOLOGY

Microsoft Makes Bet Quantum Computing Is Next Breakthrough

By JOHN MARKOFF JUNE 23, 2014

That may change soon. The company has been spending heavily and is contributing to 10 of the roughly 20 academic research groups exploring a long-hypothesized class of subatomic particles known as Majorana fermions. Beyond being a scientific advance, proving the existence of the Majorana would mean that it was likely they could be used to form qubits for this new form of quantum computing.

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News › Science

'Angel particle' which is both matter and anti-matter discovered in 'landmark' quantum physics breakthrough

Scientists say they have found the first evidence that 'Majorana fermions' exist, 80 years after they were first suggested

Ian Johnston Science Correspondent | @montaukian | Thursday 20 July 2017 18:41 BST | 98 comments

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The Independent Online

Two angels painted in Byzantium between 395 and 1453AD *Public domain image/St Catherine's Monastery, Mount Sinai*

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  - New physical mechanism for emergent superfluidity
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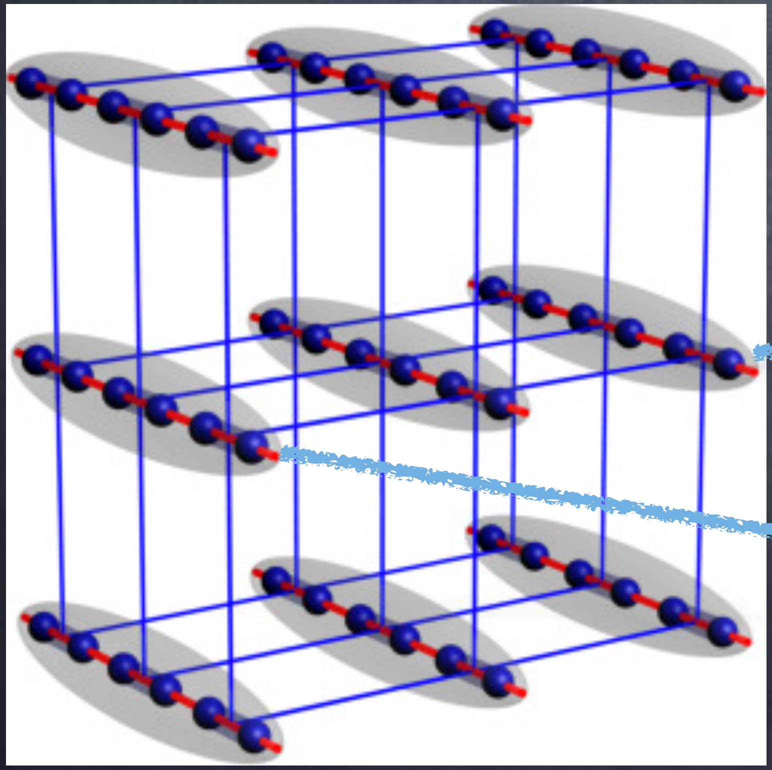

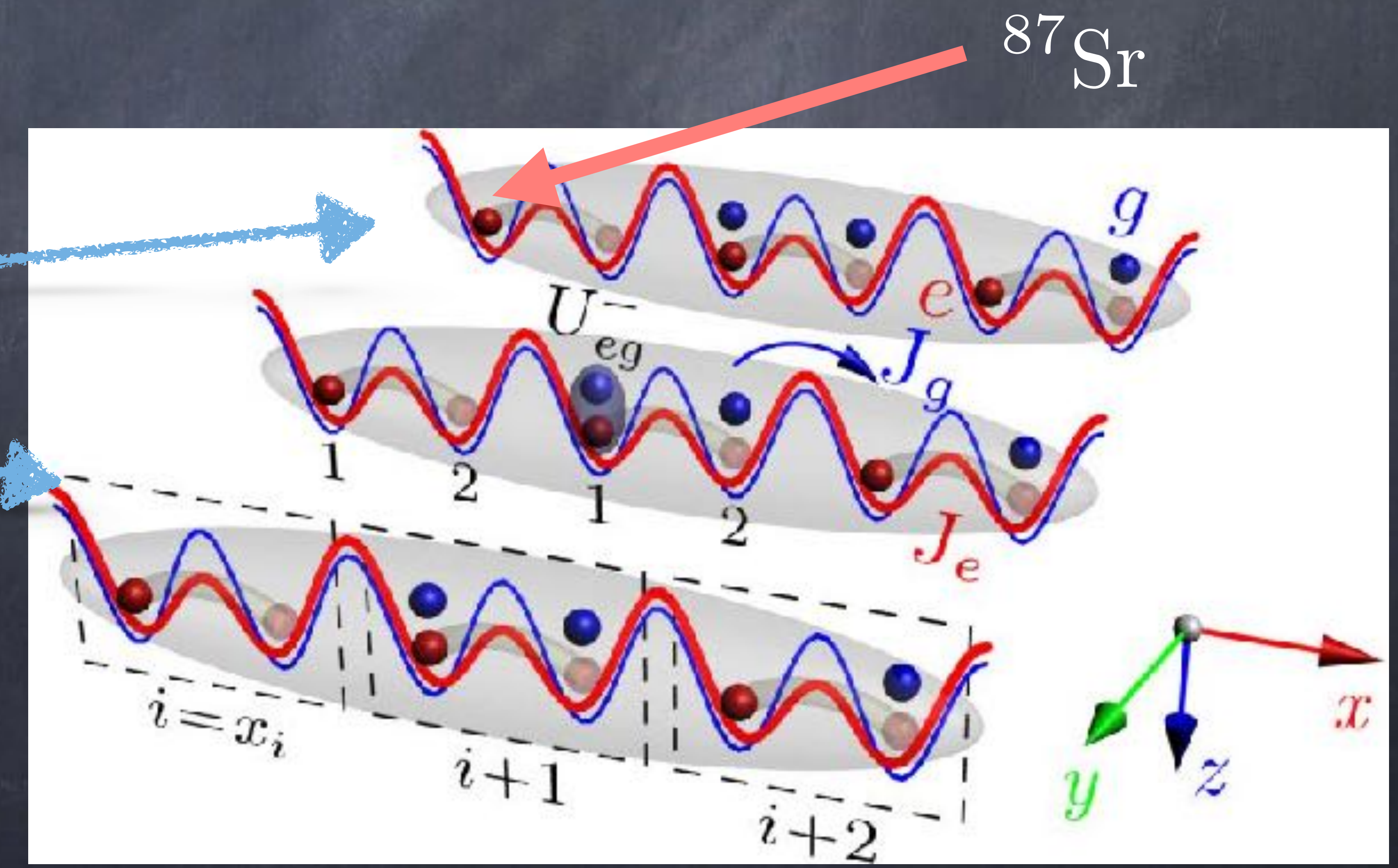

Collaborators:

Leonid Isaev: JILA, University of Colorado - Boulder

Ana Maria Rey: JILA, University of Colorado - Boulder

Adam Kaufman: JILA, University of Colorado - Boulder

Mostly: PRL 113, 267002 (2014) Ann.Phys. 372, 357 (2016)
and arXiv:1710.02768

Outline

- Motivation
  - What and Why Topological Superfluidity?
- Repulsive Superfluidity in Optical Lattices
  - Fermion Pairing from Repulsion
  - Attraction from Local Fluctuations: New Mechanism
  - Topological Superfluid State in a quasi-1D Lattice
  - Topological Superfluidity in 2-D
- Developing Probes in AMO Experiments
  - Probing Topological Superfluidity

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(Clock-State-Dependent Optical Superlattice)

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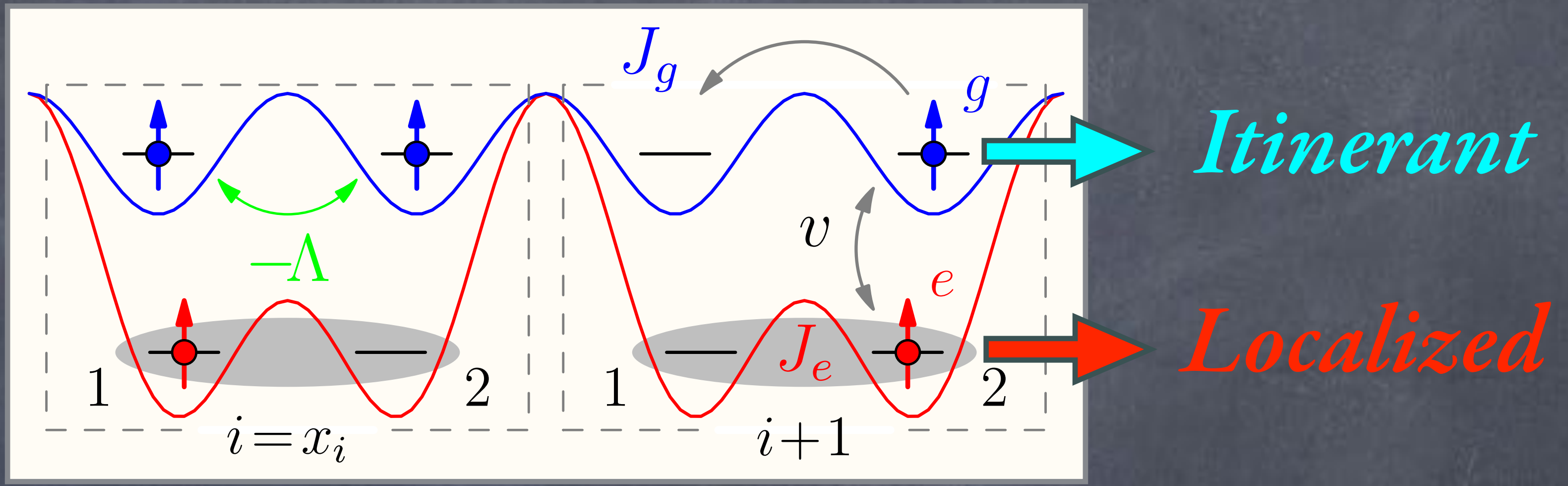
- Main ingredients
  - Optical superlattice
  - Spin-orbit coupling



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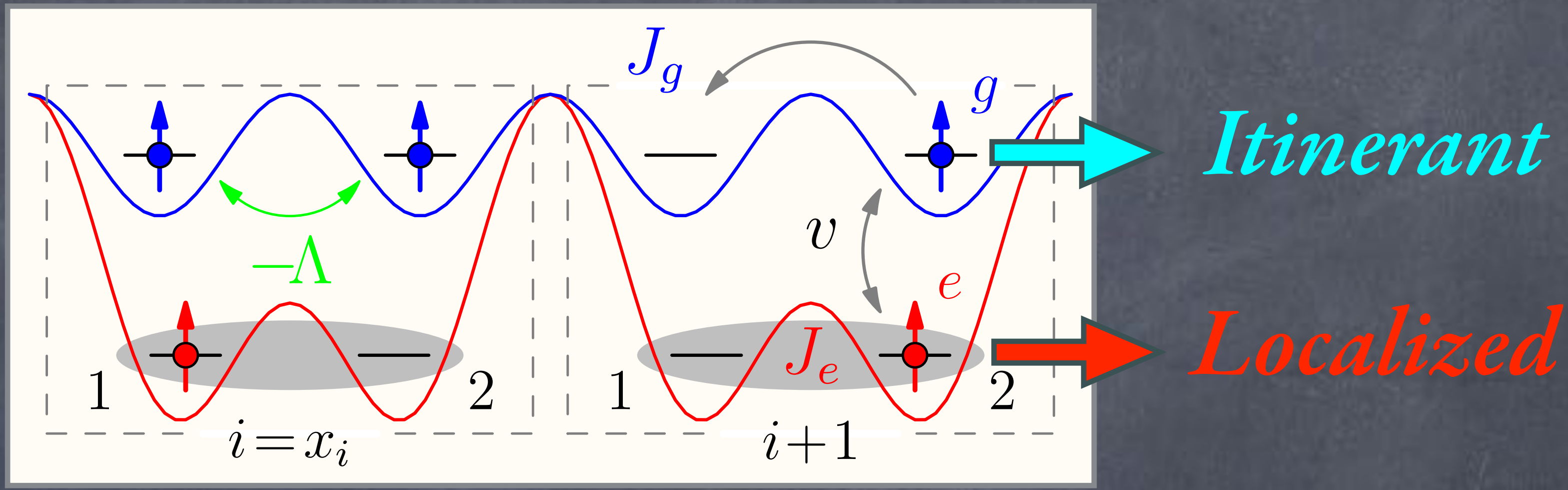
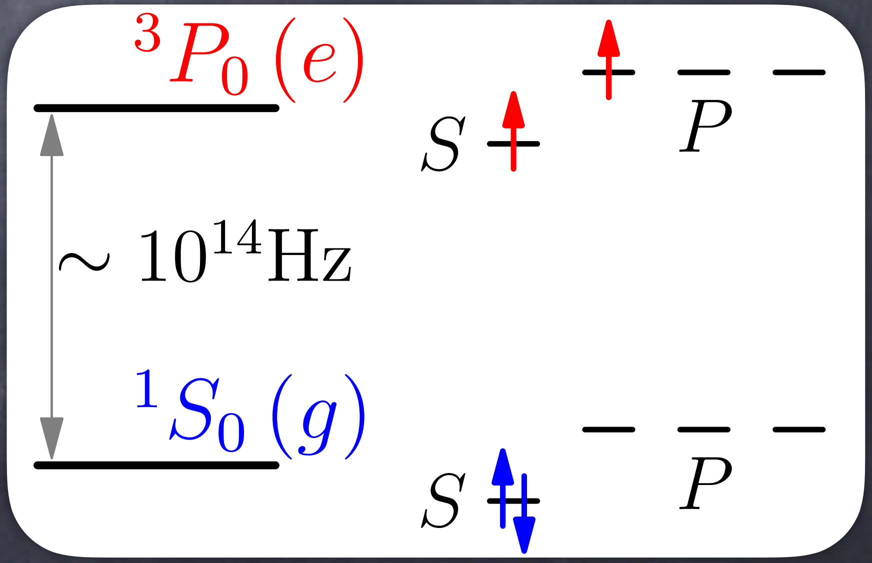


- Alcaline-earth atoms $^{171}\mathrm{Yb}$, $^{173}\mathrm{Yb}$, $^{87}\mathrm{Sr}$
  - Electronic states: $^1S_0$, $^3P_0$ with $J = 0$
  - Many nuclear spin states
  - Nuclear spins decoupled from electrons



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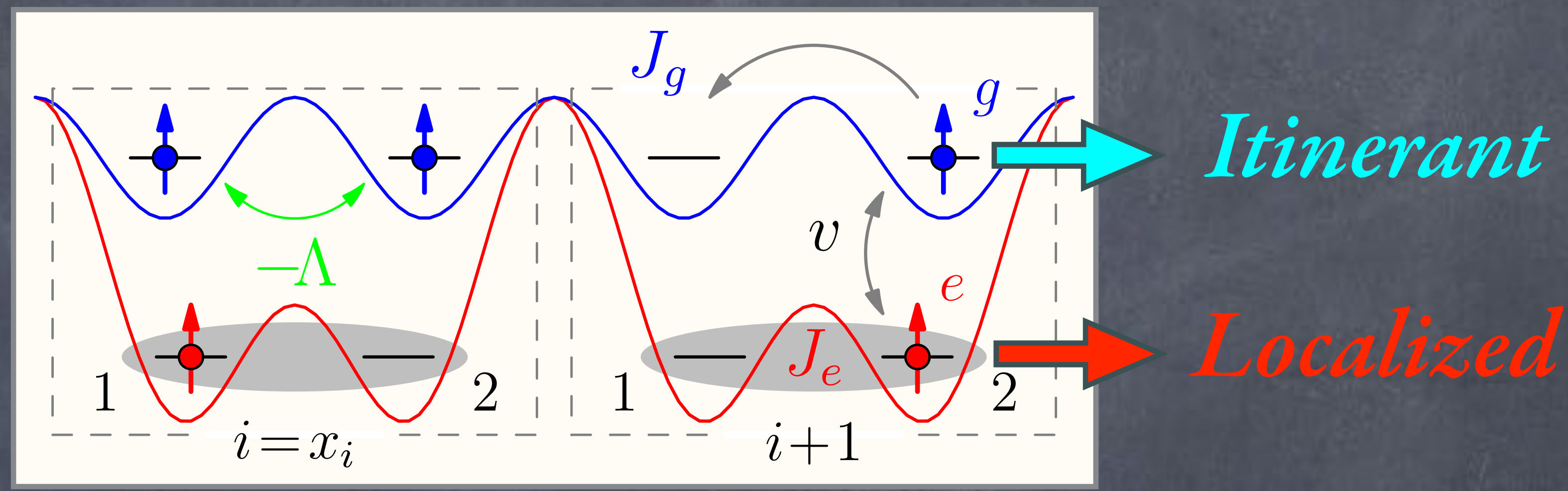

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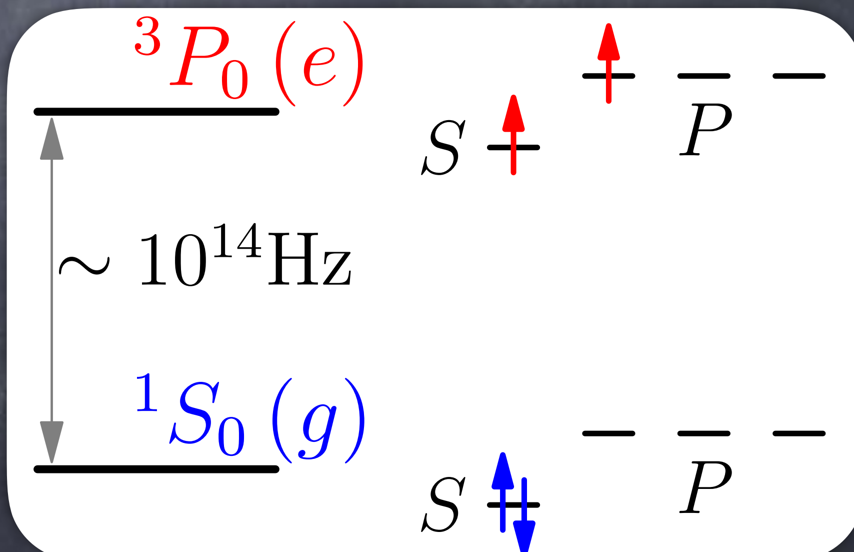

- **New Mechanism of Pairing: Engineer Subsystem Mediator**
  - Interplay between atomic repulsion and kinetic energy

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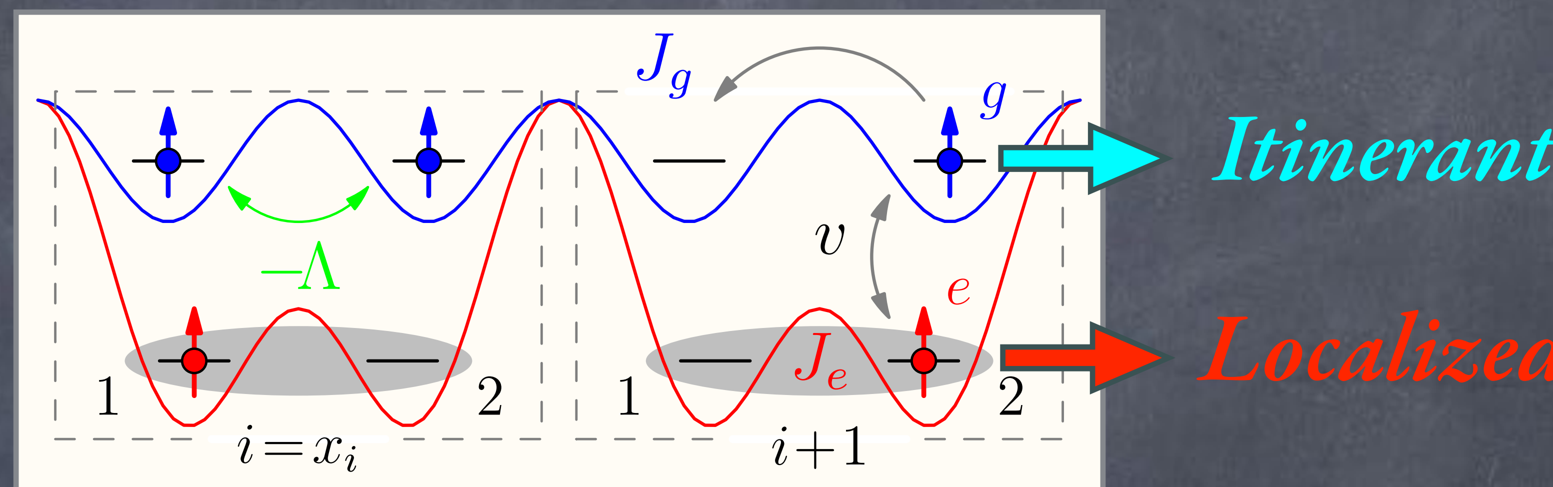

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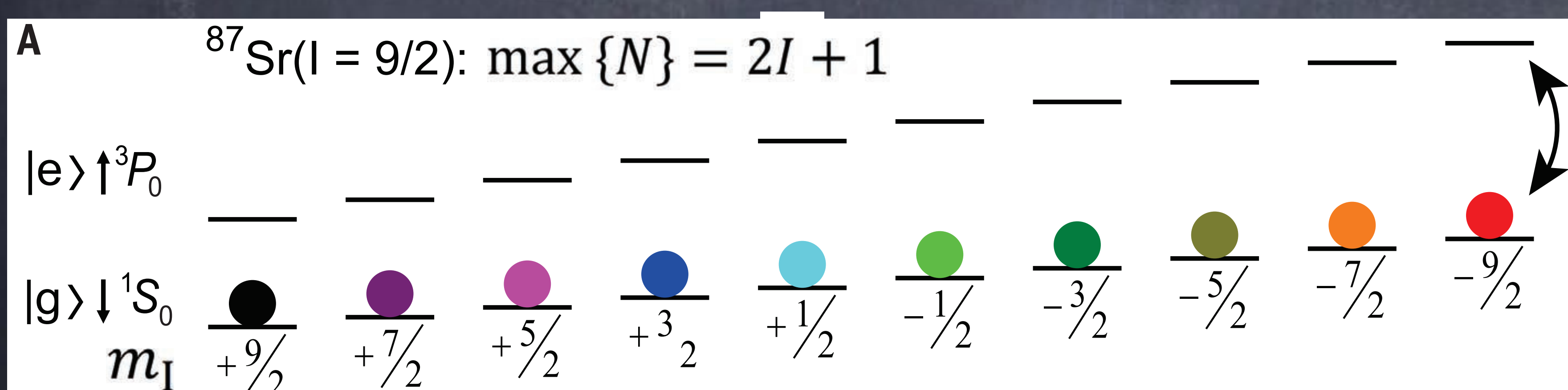

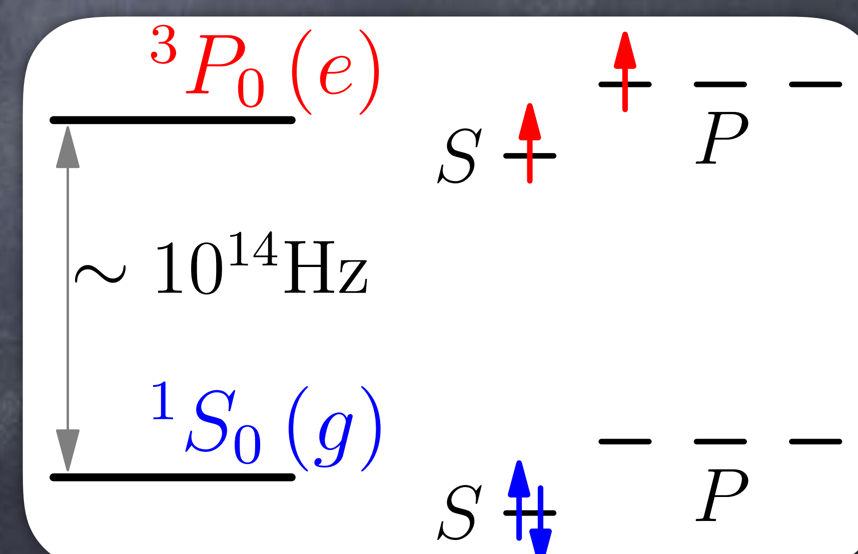

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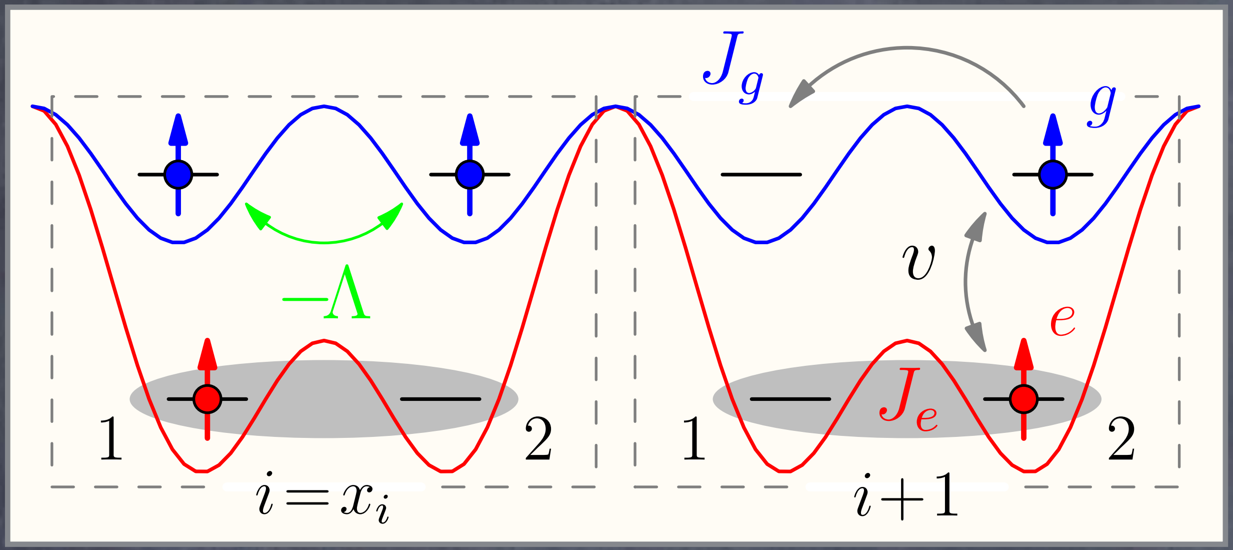
Superfluid State in a quasi-1D Lattice



- Mobile g-atoms
- e-atoms: 1 atom/dimer
- $i = 1 \ldots N_d$, $v \sim a_{eg}^-$
- m, n = Nuclear spins

$$H = -J_e \sum_{in} (e^\dagger_{i,1n} e_{i,2n} + \text{h.c.}) + U_{gg} \sum_{ia} n^g_{ia}(n^g_{ia} - 1) -$$

$$-J_g \sum_{in} (g^\dagger_{i,1n} g_{i,2n} + g^\dagger_{i+1,1n} g_{i,2n} + \text{h.c.}) +$$

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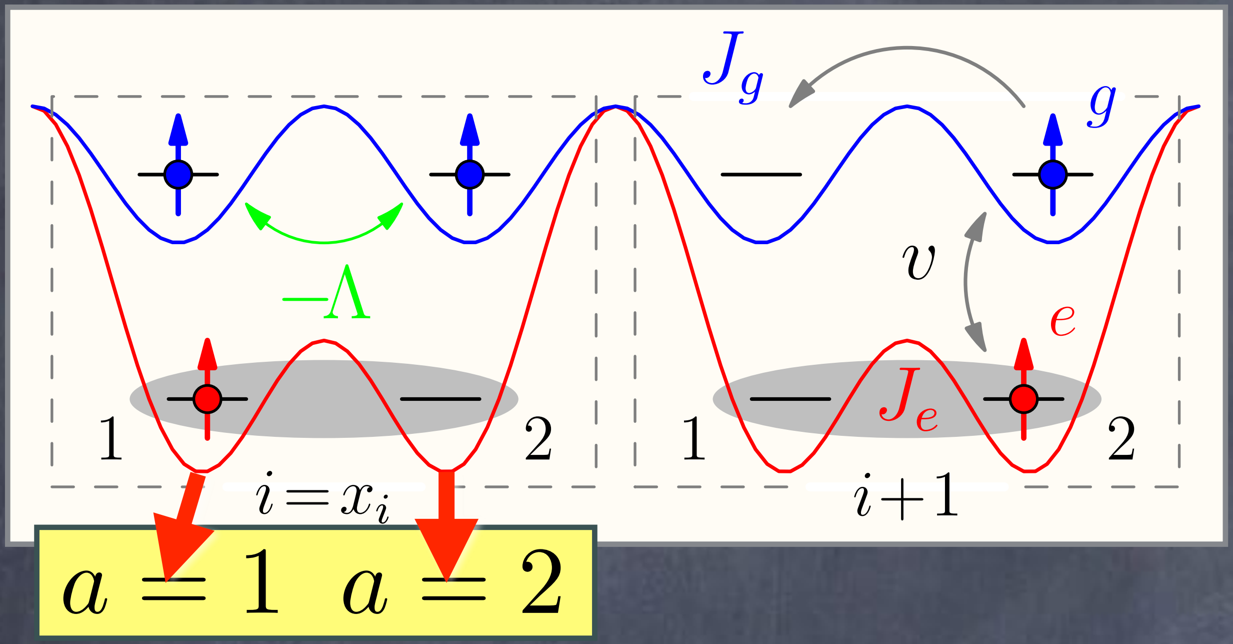

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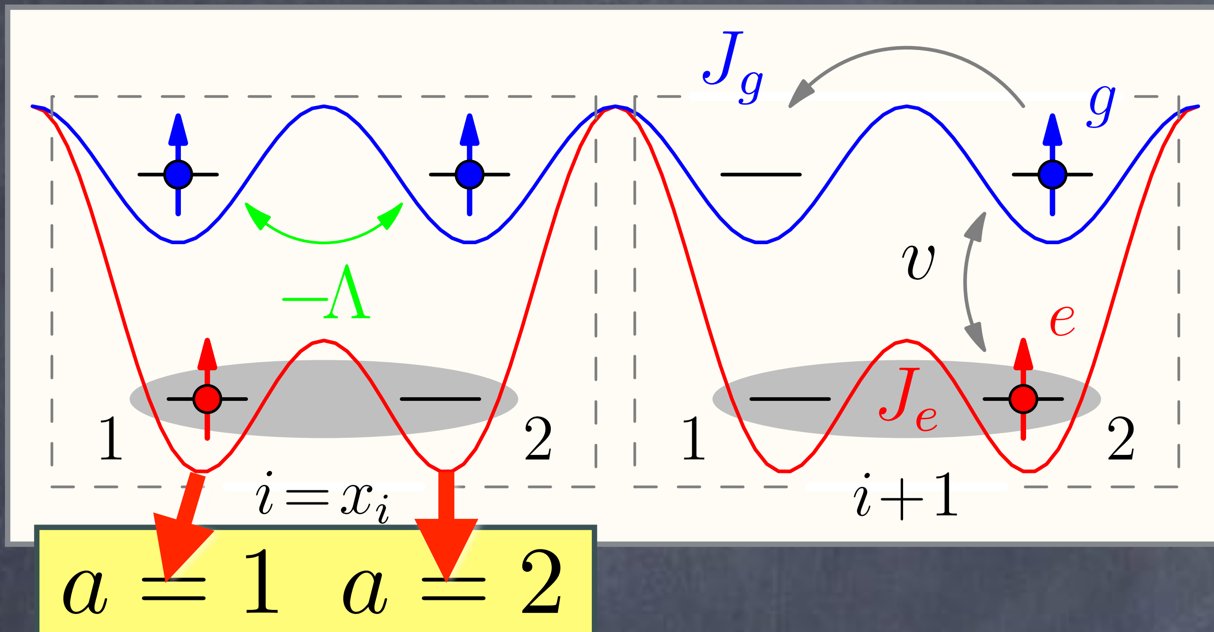

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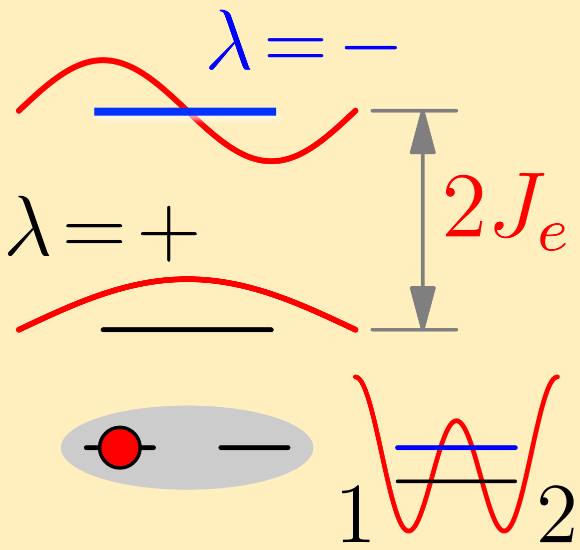
$$\underbrace{(U_{eg}+V_{\text{ex}})}_{v} \sum_i n^e_{ia\uparrow} n^g_{ia\uparrow}$$

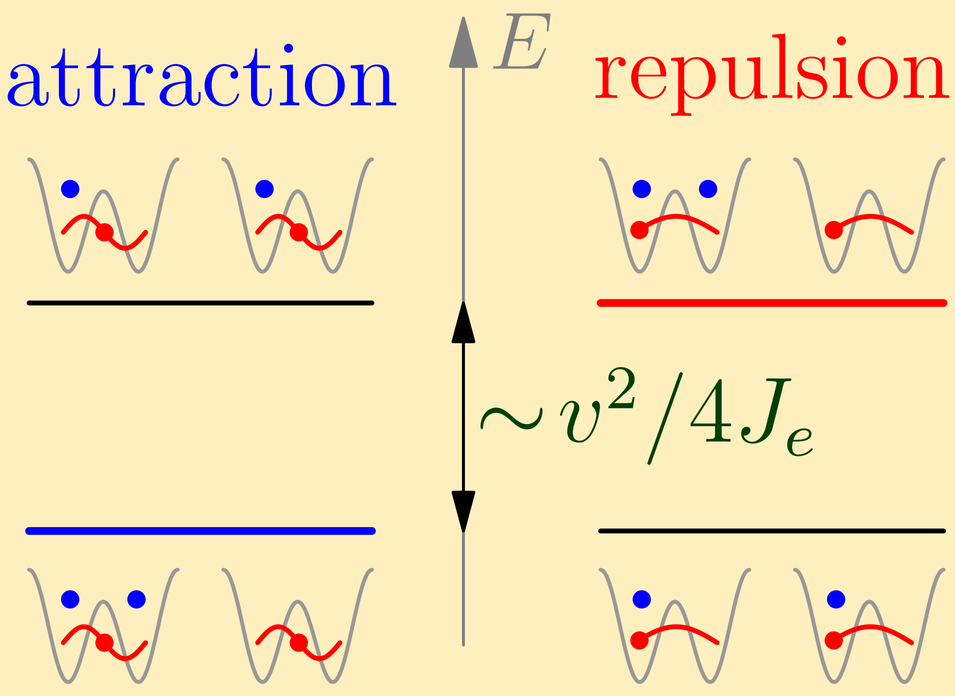
→ **Nuclear spin-polarized**

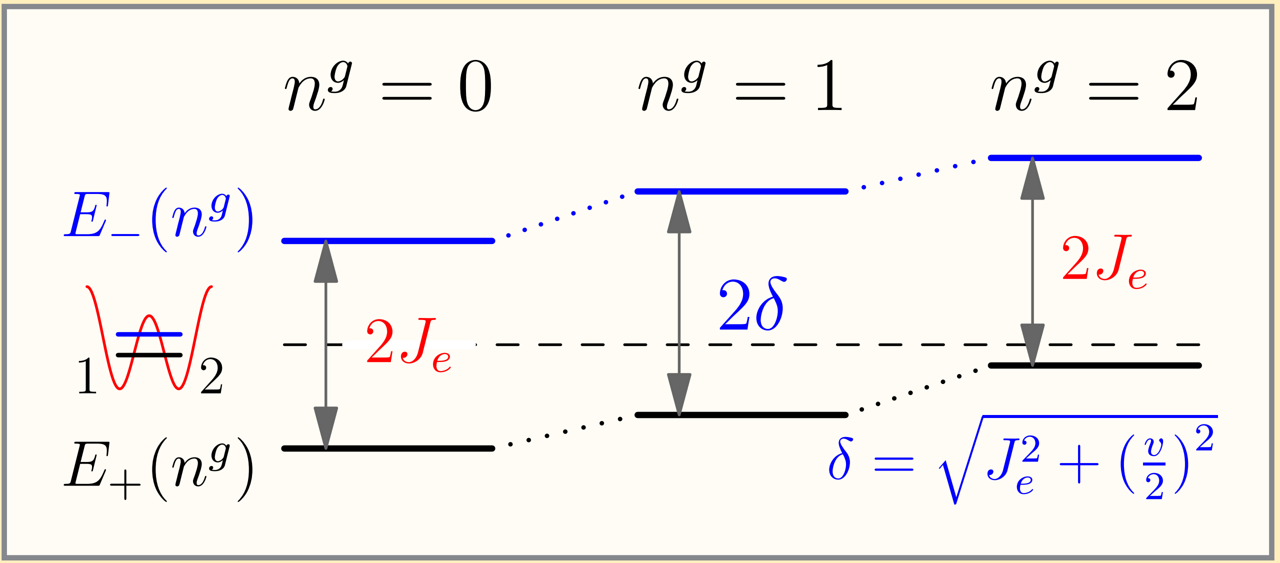
Emergent Fermion pairing



- e-atom quantum fluctuations
  - Consider $J_e \gg J_g, v$
  - Preparing e-atoms in a given motional state

- Local Pairing: $\Delta_\pm \approx \pm v^2/4J_e = \pm\Lambda$
  - sym $\longrightarrow$ repulsion of g-atoms
    antisym $\longrightarrow$ attraction of g-atoms
  - e-g interaction: $H_{eg} = v(n_1^e n_1^g + n_2^e n_2^g)$





- $\Delta_+ = E_+(2) + E_+(0) - 2E_+(1) \approx v^2/4J_e$
- $\Delta_- = E_-(2) + E_-(0) - 2E_-(1) \approx -v^2/4J_e$

Effective Model (Schrieffer-Wolff Transformation)

$$H_{\rm ef} = -J_g \sum_k (g_{k1}^\dagger \; g_{k2}^\dagger) \underbrace{\begin{pmatrix} 0 & 1+e^{-\mathrm{i}k} \\ 1+e^{\mathrm{i}k} & 0 \end{pmatrix}} \begin{pmatrix} g_{k1} \\ g_{k2} \end{pmatrix} - \frac{v^2}{4J_e} \sum_i n_{i,1}^g n_{i,2}^g$$

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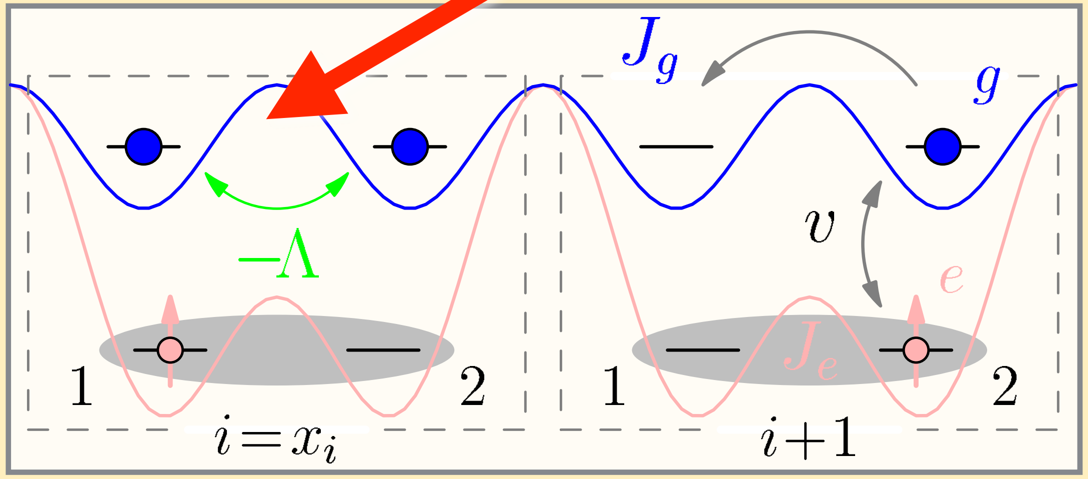
- Attraction is intra-dimer



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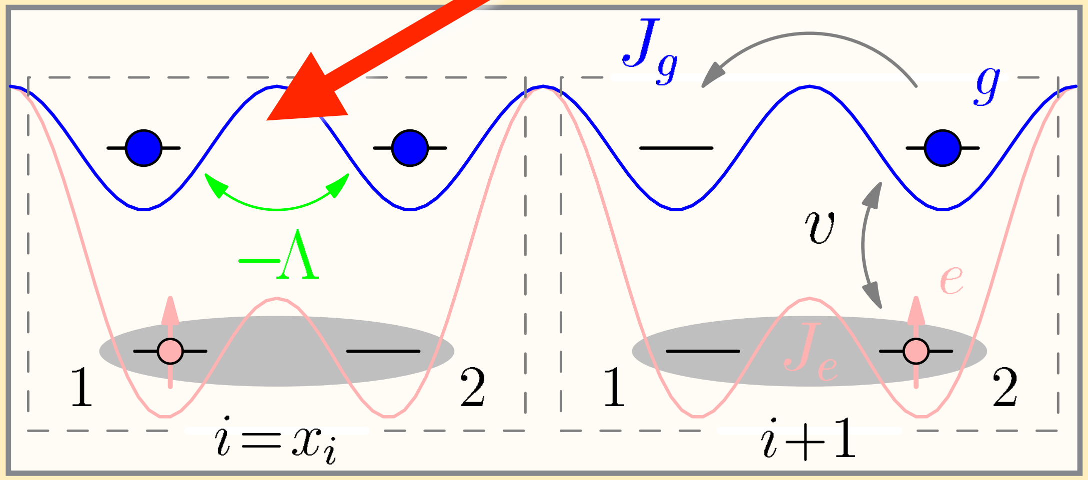
- Attraction is intra-dimer
- Effective spin-orbit interaction

due to doubling of unit cell



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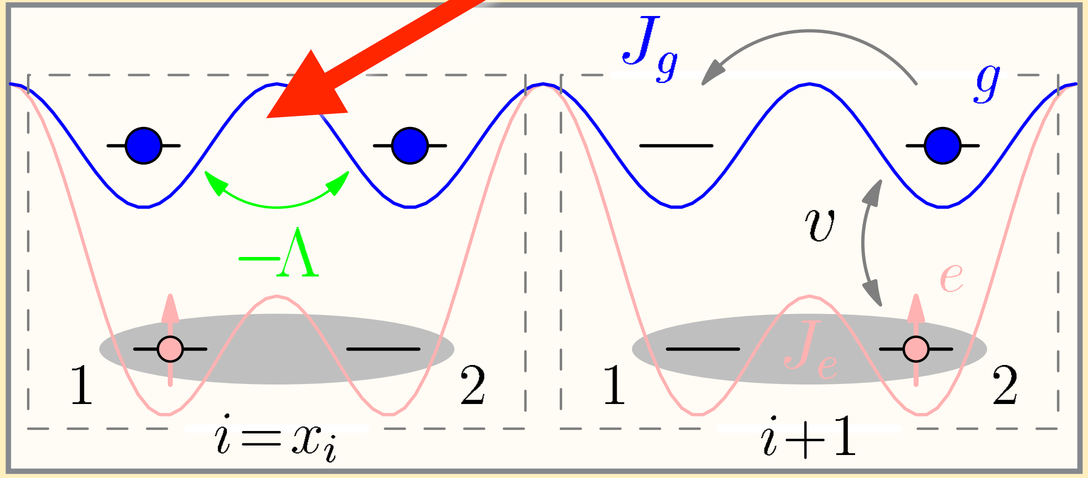
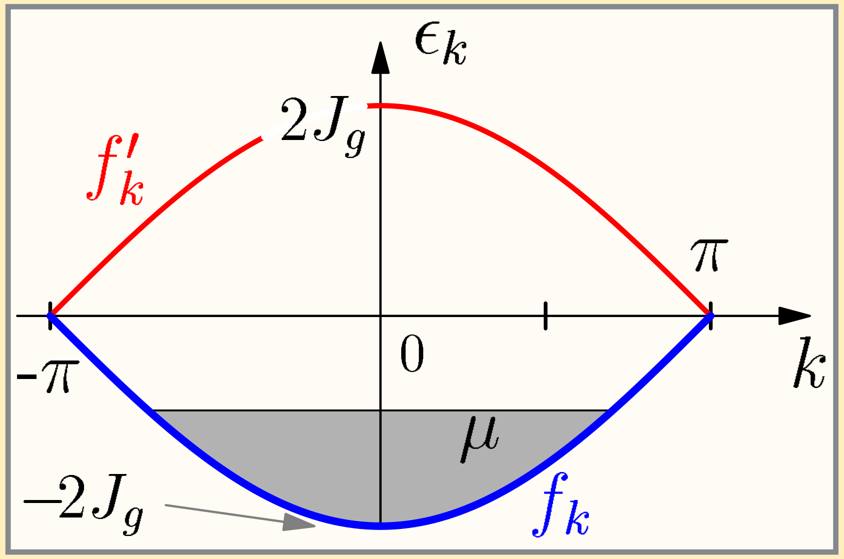




p-wave symmetry

Non-interacting band-structure

- Quasiparticle states

$$\begin{pmatrix} g_{k1} \\ g_{k2} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} f_k + f'_k \\ \frac{1+e^{\mathrm{i}k}}{\sqrt{2(1+\cos k)}} [f_k - f'_k] \end{pmatrix}$$

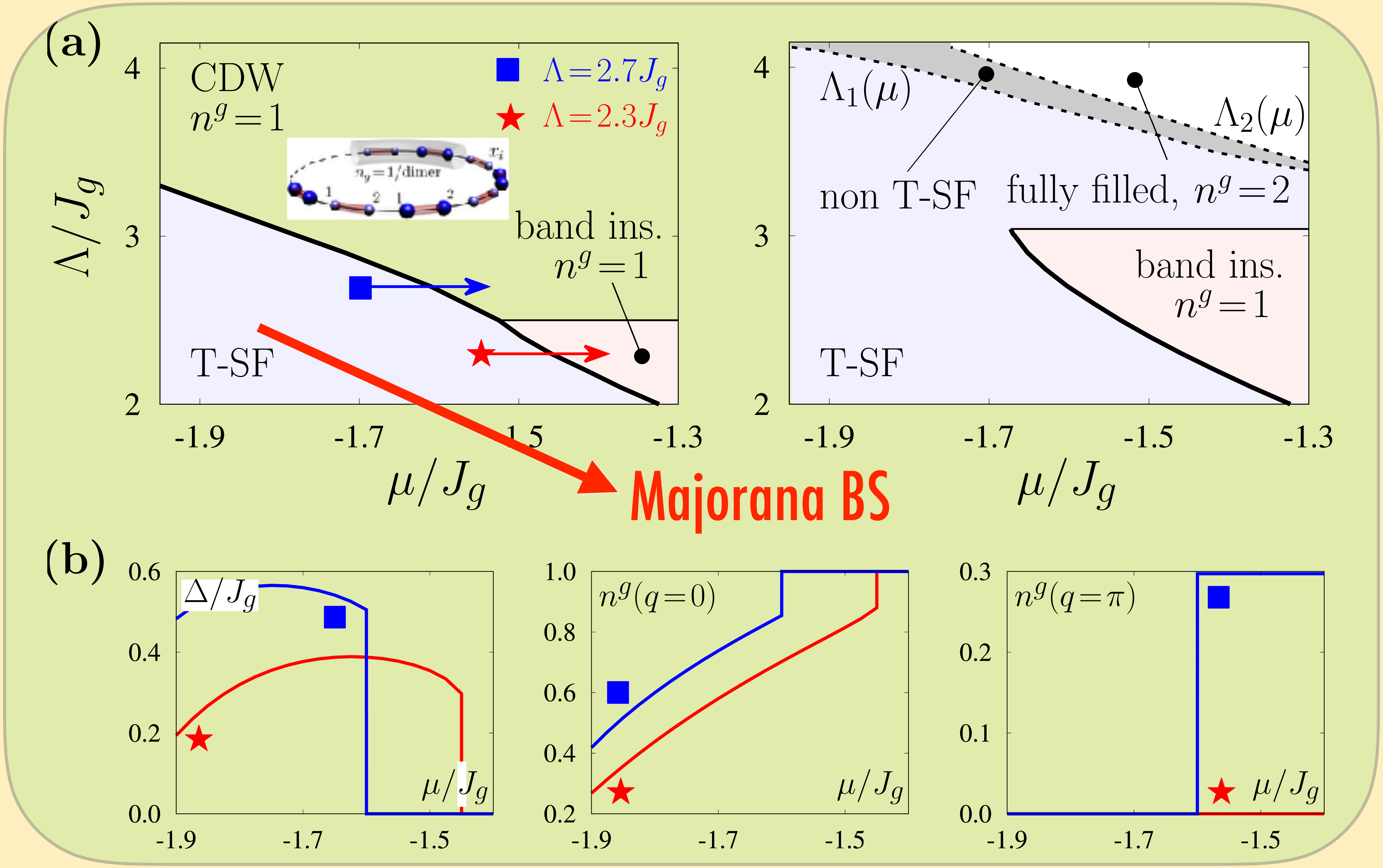
- Energies:

$$E_k = \pm J_g \sqrt{2(1+\cos k)}$$

Phase Diagram in quasi-1D

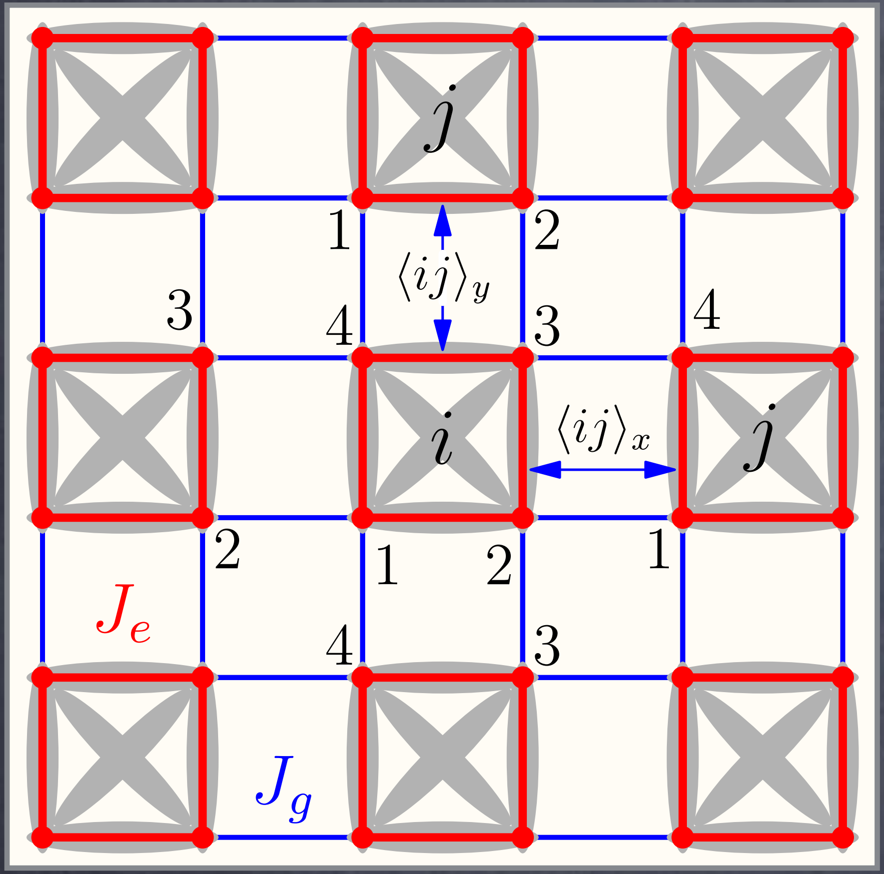
Unconstrained

Single-site unit cell



Topological Superfluidity in two-dimensions

$(p_x + ip_y)$-wave symmetry



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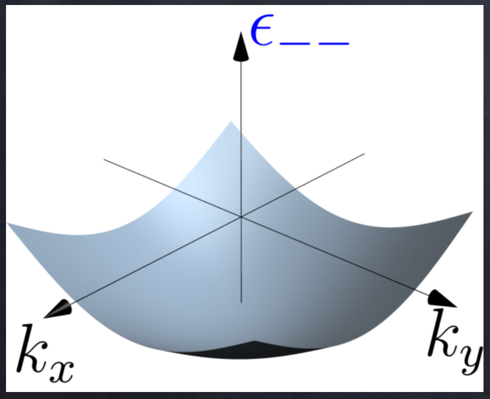
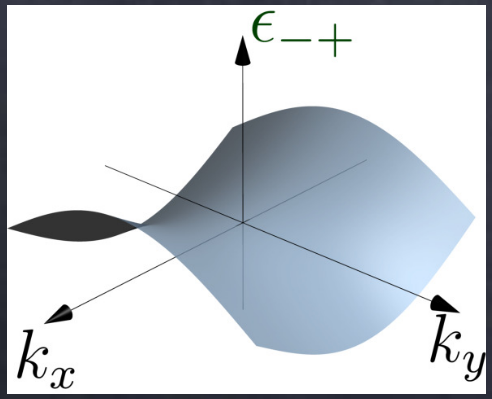
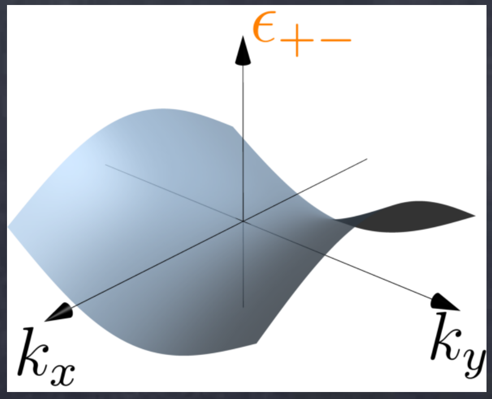
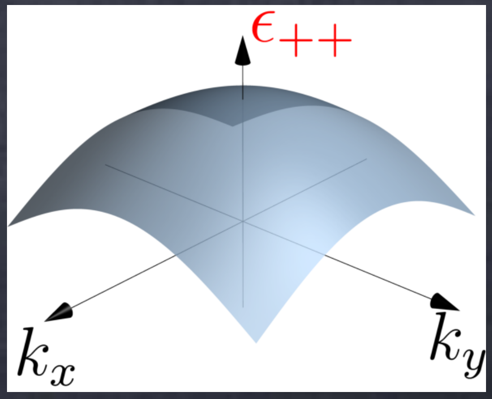
$$- J_g \sum_{i,\square_{ab}} (g^\dagger_{ia} g_{ib} + \text{h.c.}) -$$
$$- J_g \sum_{\langle ij\rangle_x} (g^\dagger_{i,2} g_{j,1} + g^\dagger_{i,3} g_{j,4} + \text{h.c.}) -$$
$$- J_g \sum_{\langle ij\rangle_y} (g^\dagger_{i,4} g_{j,1} + g^\dagger_{i,3} g_{j,2} + \text{h.c.})$$

- *g*-atom dispersion: $\epsilon_{n_x n_y} = 2J_g\left(n_x \cos\frac{k_x}{2} + n_y \cos\frac{k_y}{2}\right),\ n_{x,y} = \pm 1$









Outline

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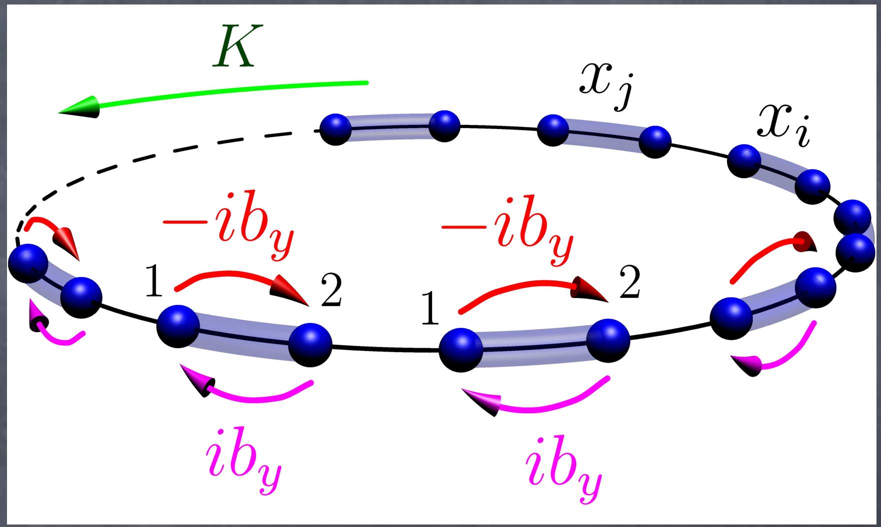
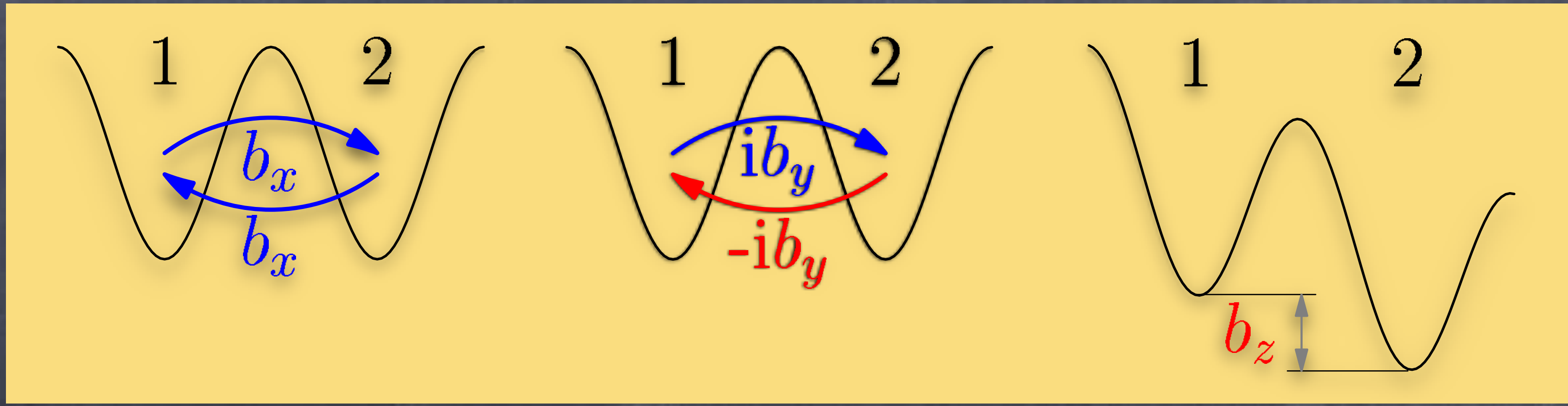
Synthetic Magneto-Electric Effect (Spin-Galvanic Effect)

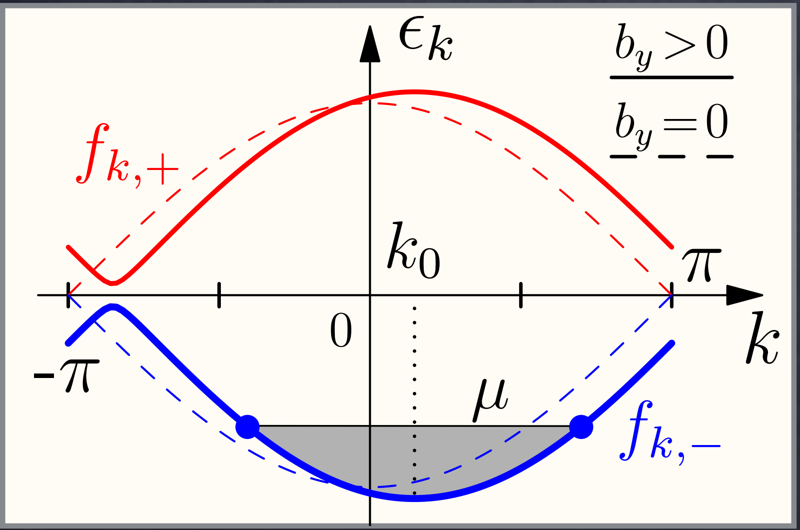
- Laser-induced Magnetic Field

$$\delta H_M = -\sum_{i,a,b} (\boldsymbol{b}\cdot\boldsymbol{\sigma}_{ab}) g^\dagger_{ia} g_{ib}$$

  - $b_x/b_y \leftrightarrow$ intra-dimer real/complex hopping
  - $b_z =$ relative energy shift of dimer sites

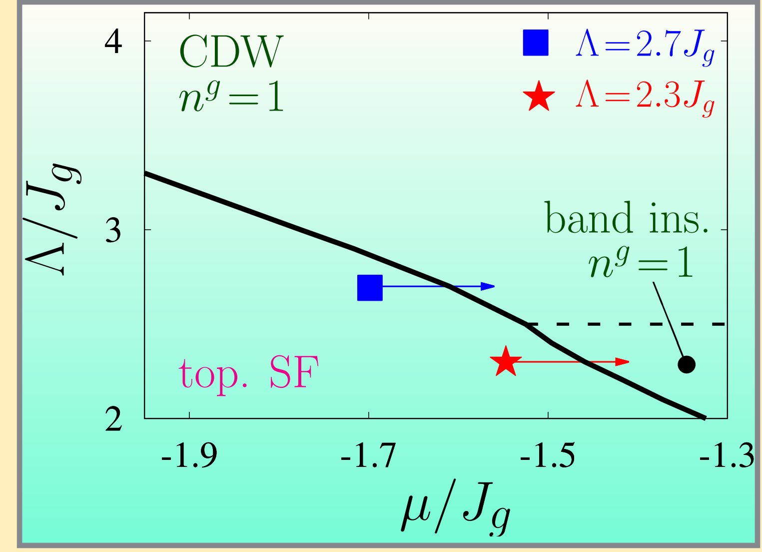




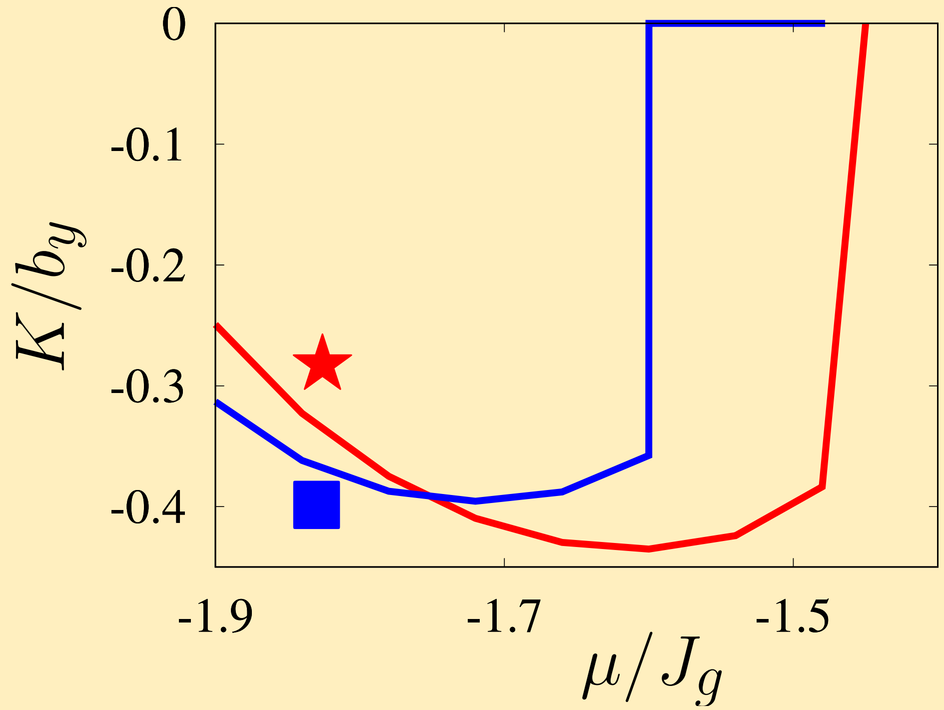


- Time-reversal Symmetry $\mathcal{T}$
  - $g_{k,a} \to g_{-k,a}$ and a c-number $c \to c^*$
  - Only b_y breaks $\mathcal{T}$
  - We consider $\boldsymbol{b} = (0,\ b_y,\ 0)$

Unveiling the Superfluid State

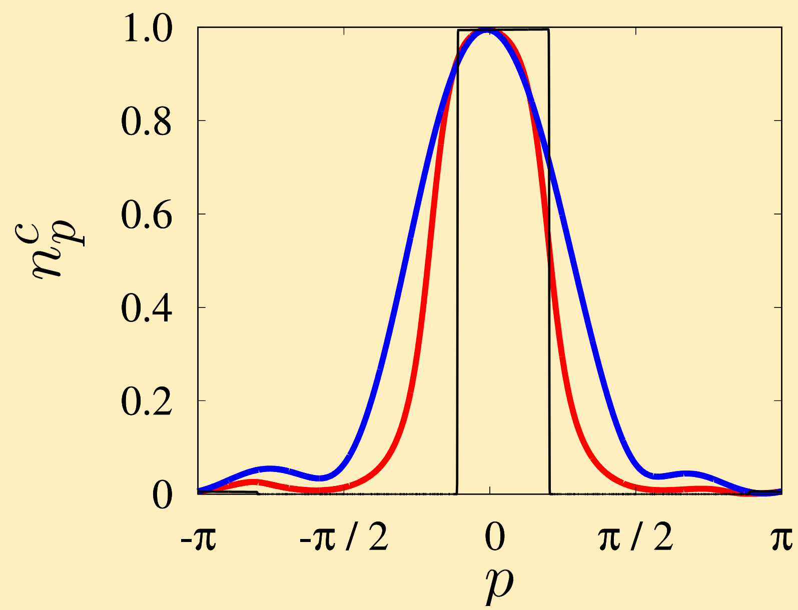


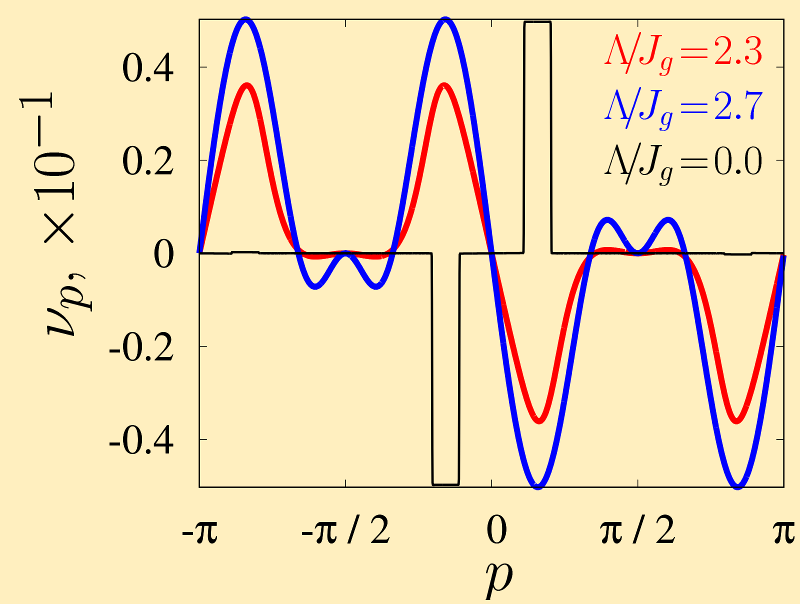
Linear Mass Current Response



- $b_y \ll |\Delta|$ to avoid FFLO states
- Supercurrent K is a fingerprint of a SF

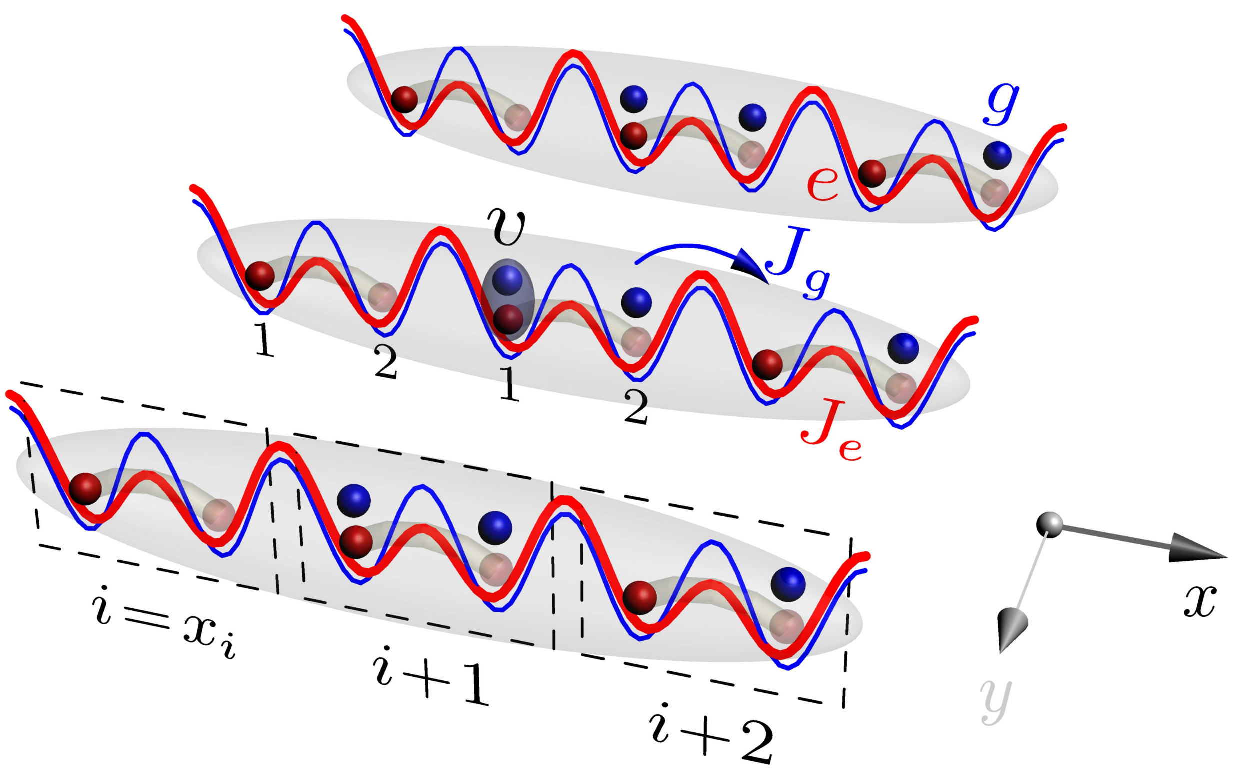
Momentum Distribution Asymmetry $[\nu_p = J_g(n^c_p - n^c_{-p})/b_y]$



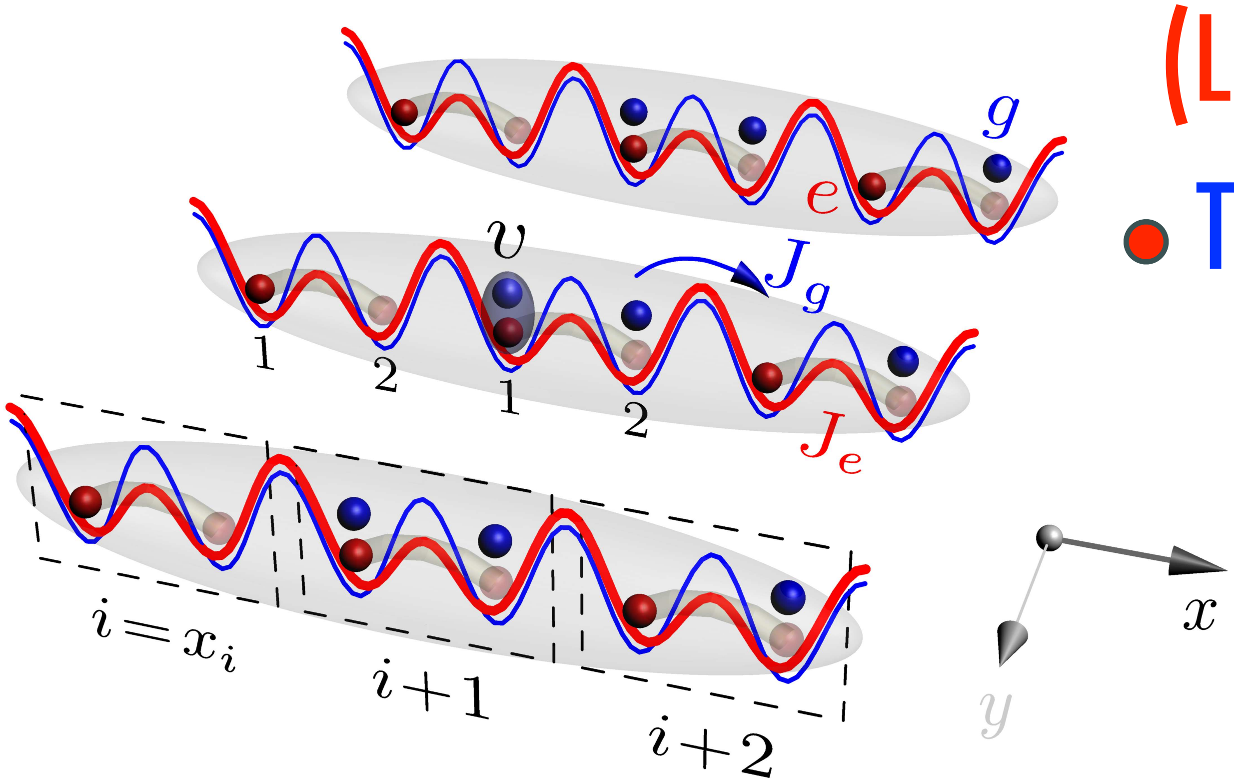


- Time-of-flight measurement
- Fingerprint of a SF

Conclusions



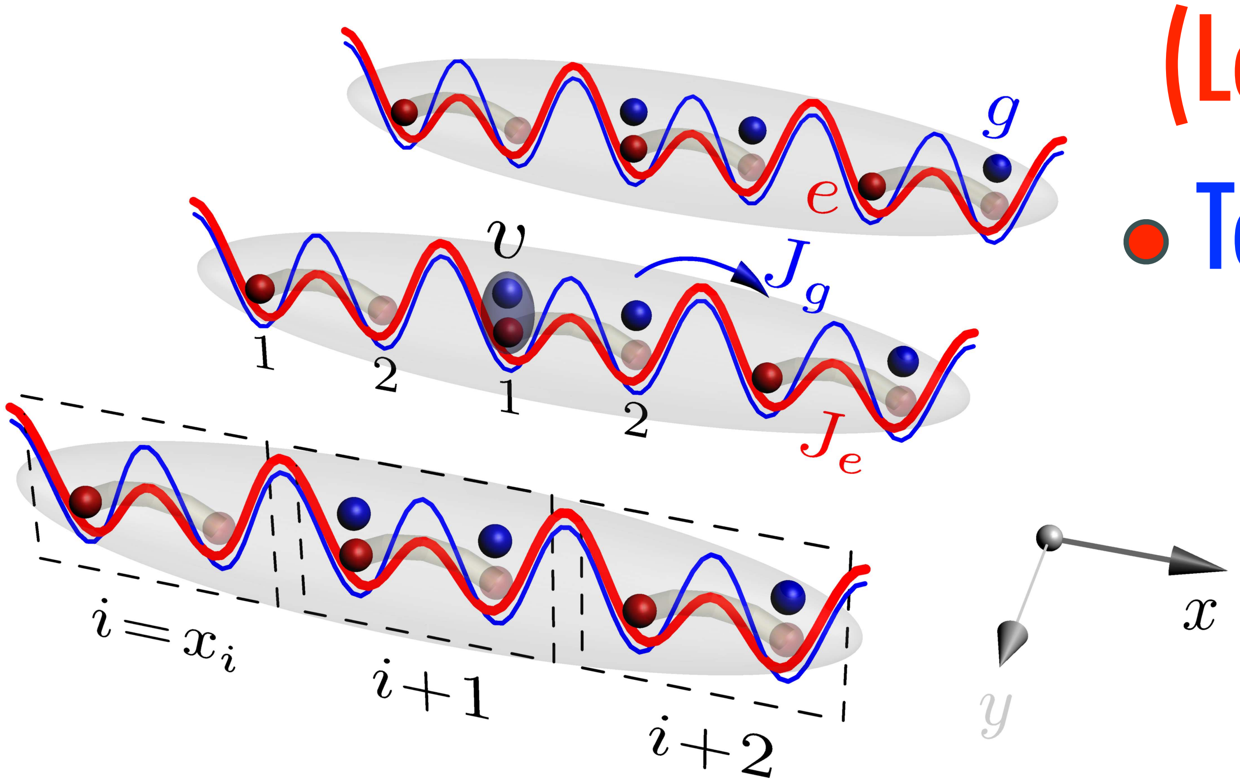
Conclusions



- New Mechanism for Repulsive Fermionic SF
  (Local kinetic-energy Fluctuations)
- Topological p-wave Superfluidity
  (Due to Emergent SOC)
- New Magneto-Electric Effect

  and Experimental Probes

Conclusions



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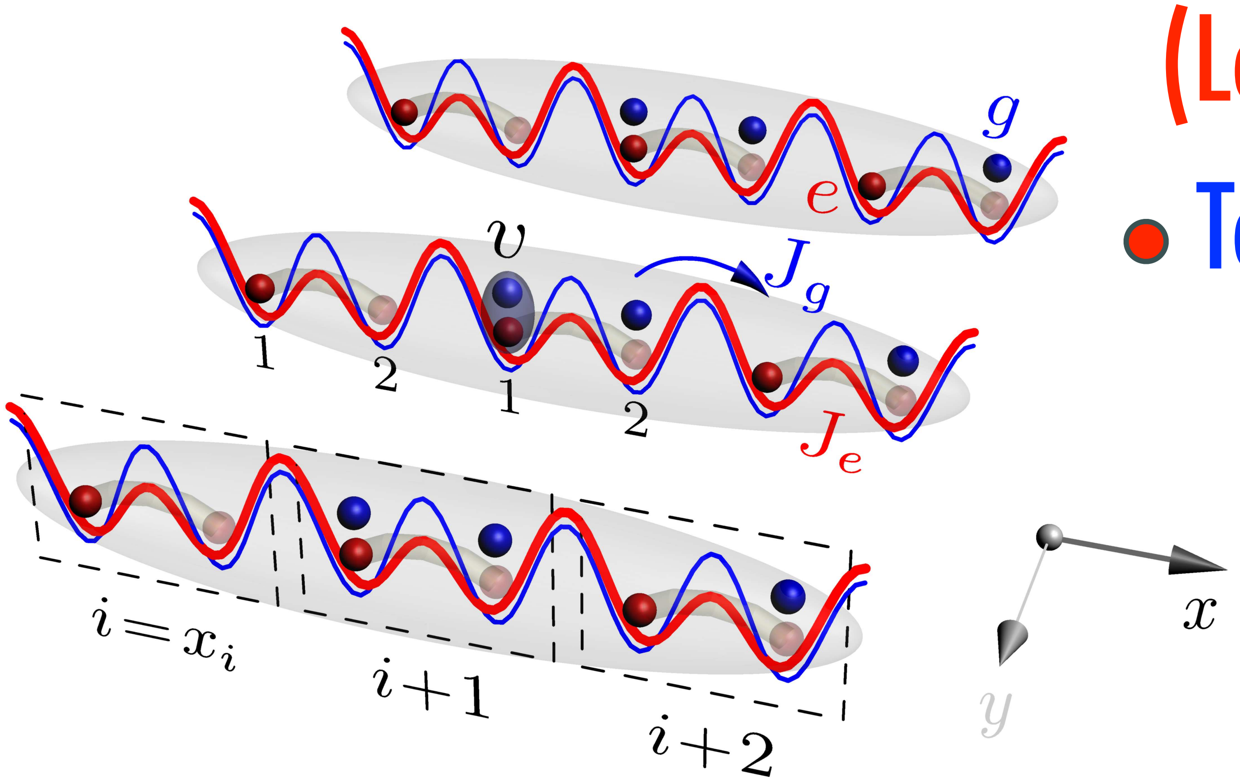

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Conclusions

Chi l'ha visto ?

Ettore Majorana, ordinario di fisica teorica all' Università di Napoli, è misteriosamente scomparso dagli ultimi di marzo. Di anni 31, alto metri 1,70, snello, con capelli neri, occhi scuri, una lunga cicatrice sul dorso di una mano. Chi ne sapesse qualcosa è pregato di scrivere al R. P. E. Marianecci, Viale Regina Margherita 66 - Roma.

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Majorana: The Mystery Must Be Solved

- Use of realistic able interactions (no heating)
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- Open Question: Can we detect/manipulate Majorana modes?