DANILO LIARTE *
SEAN DEYO
JAMES MANISCALCO
MICHELLE KELLEY
NATHAN SITARAMAN
TOMAS ARIAS
MATTHIAS LIEPE
JAMES SETHNA

TOWARDS A FLOQUET THEORY OF PERIODICALLY DRIVEN SUPERCONDUCTORS

* Presenter

CORNELL UNIVERSITY FOUNDED A.D. 1865

The Center for BRIGHT BEAMS
A National Science Foundation Science & Technology Center

DANILO LIARTE *
SEAN DEYO
JAMES MANISCALCO
MICHELLE KELLEY
NATHAN SITARAMAN
TOMAS ARIAS
MATTHIAS LIEPE
JAMES SETHNA

TOWARDS A FLOQUET THEORY OF PERIODICALLY DRIVEN SUPERCONDUCTORS

* Presenter

CORNELL UNIVERSITY FOUNDED A.D. 1865

The Center for BRIGHT BEAMS
A National Science Foundation Science & Technology Center

SUPERCONDUCTIVITY UNDER EXTREME CONDITIONS

- High pressure (H-rich compounds).
- High-speed vortex (Abrikosov-Josephson).
- High magnetic field (magnets).
- High frequency vs. high field (Superconducting cavities).

SUPERCONDUCTIVITY UNDER EXTREME CONDITIONS

- High pressure (H-rich compounds).
- High-speed vortex (Abrikosov-Josephson).
- High magnetic field (magnets).
- High frequency vs. high field (Superconducting cavities).

SUPERCONDUCTIVITY UNDER EXTREME CONDITIONS

- High pressure (H-rich compounds).
- High-speed vortex (Abrikosov-Josephson).
- High magnetic field (magnets).
- High frequency vs. high field (Superconducting cavities).

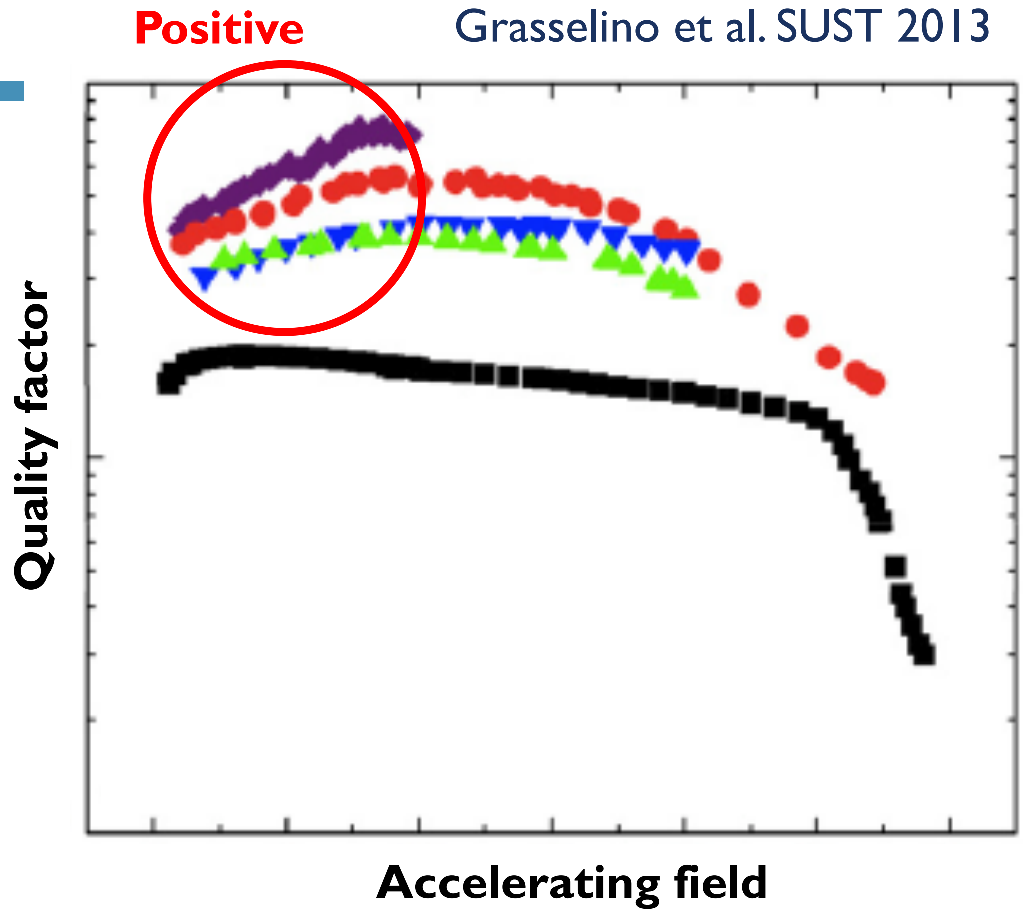
SUPERCONDUCTIVITY UNDER EXTREME CONDITIONS

- High pressure (H-rich compounds).
- High-speed vortex (Abrikosov-Josephson).
- High magnetic field (magnets).
- High frequency vs. high field (Superconducting cavities).

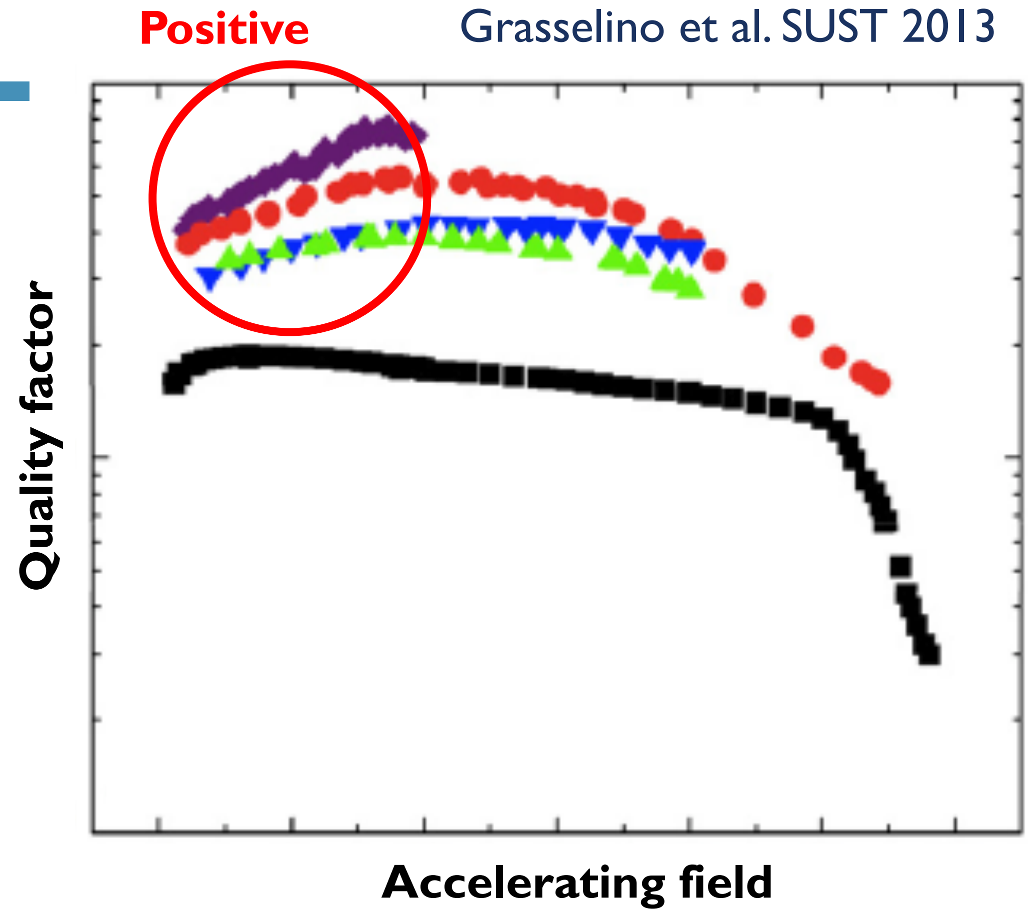
SUPERCONDUCTIVITY UNDER EXTREME CONDITIONS

- High pressure (H-rich compounds).
- High-speed vortex (Abrikosov-Josephson).
- High magnetic field (magnets).
- High frequency vs. high field (Superconducting cavities).

SUPERCONDUCTIVITY UNDER EXTREME CONDITIONS



Grasselino et al. SUST 2013



SUPERCONDUCTIVITY UNDER EXTREME CONDITIONS

HOW TO USE FLOQUET THEORY TO REDERIVE THE RESPONSE OF SUPERCONDUCTORS TO ELECTROMAGNETIC FIELDS, (AND HOPEFULLY DESCRIBE NEW PHYSICS…)

OUTLINE

- Cooper problem: Binding energy of two electrons in a filled Fermi sea
- Superconductor gap and ground-state energy using Floquet/BCS theory
- Dissipation: Paradigm shift?
- Final Considerations

OUTLINE

- Cooper problem: Binding energy of two electrons in a filled Fermi sea
- Superconductor gap and ground-state energy using Floquet/BCS theory
- Dissipation: Paradigm shift?
- Final Considerations

OUTLINE

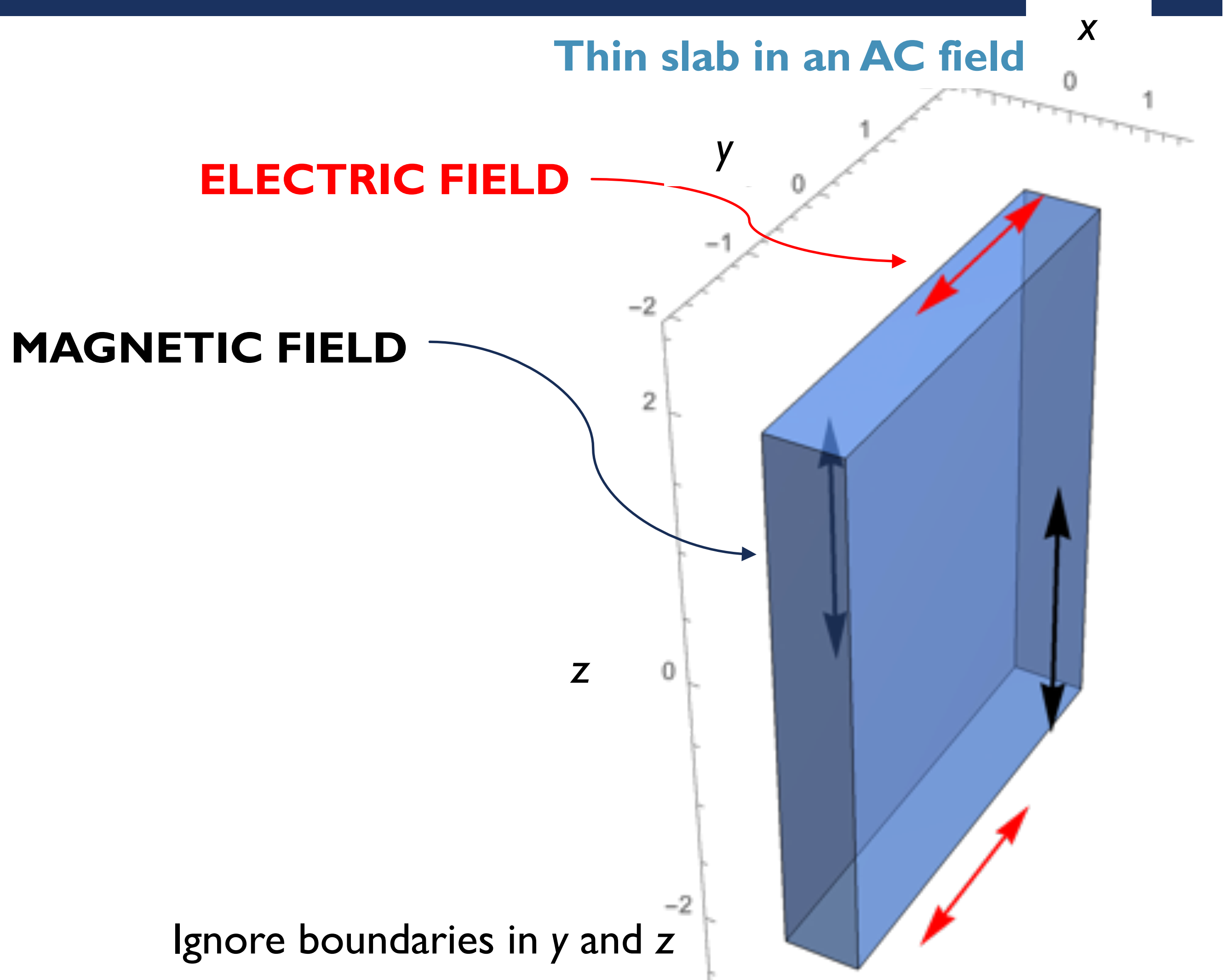
- Cooper problem: Binding energy of two electrons in a filled Fermi sea
- Superconductor gap and ground-state energy using Floquet/BCS theory
- Dissipation: Paradigm shift?
- Final Considerations

OUTLINE

- Cooper problem: Binding energy of two electrons in a filled Fermi sea
- Superconductor gap and ground-state energy using Floquet/BCS theory
- Dissipation: Paradigm shift?
- Final Considerations

COOPER PROBLEM: BINDING ENERGY OF TWO ELECTRONS IN A FILLED FERMI SEA

Thin slab in an AC field



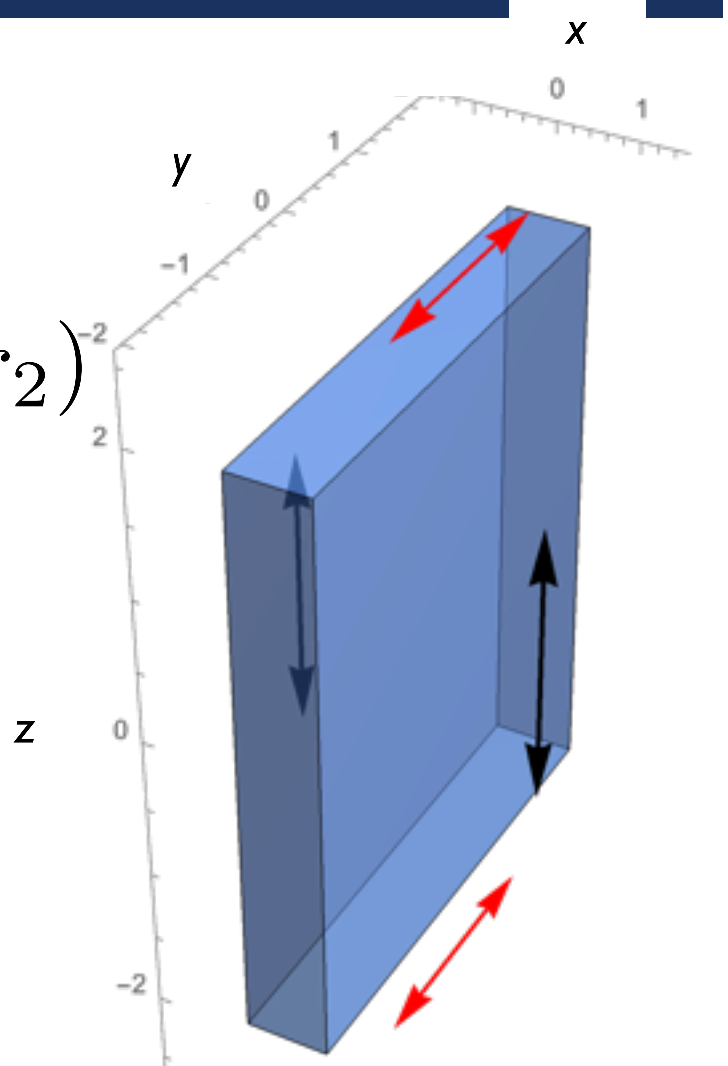
Ignore boundaries in *y* and *z*

COOPER PROBLEM: BINDING ENERGY OF TWO ELECTRONS IN A FILLED FERMI SEA

$$H = \frac{1}{2m}\left(p_1 - eA_1\right)^2 + \frac{1}{2m}\left(p_2 - eA_2\right)^2 - eA_0(r_1) - eA_0(r_2) + V(r_1 - r_2)$$

TWO INTERACTING ELECTRONS

The other electrons prevent occupation below the Fermi level



COOPER PROBLEM: BINDING ENERGY OF TWO ELECTRONS IN A FILLED FERMI SEA

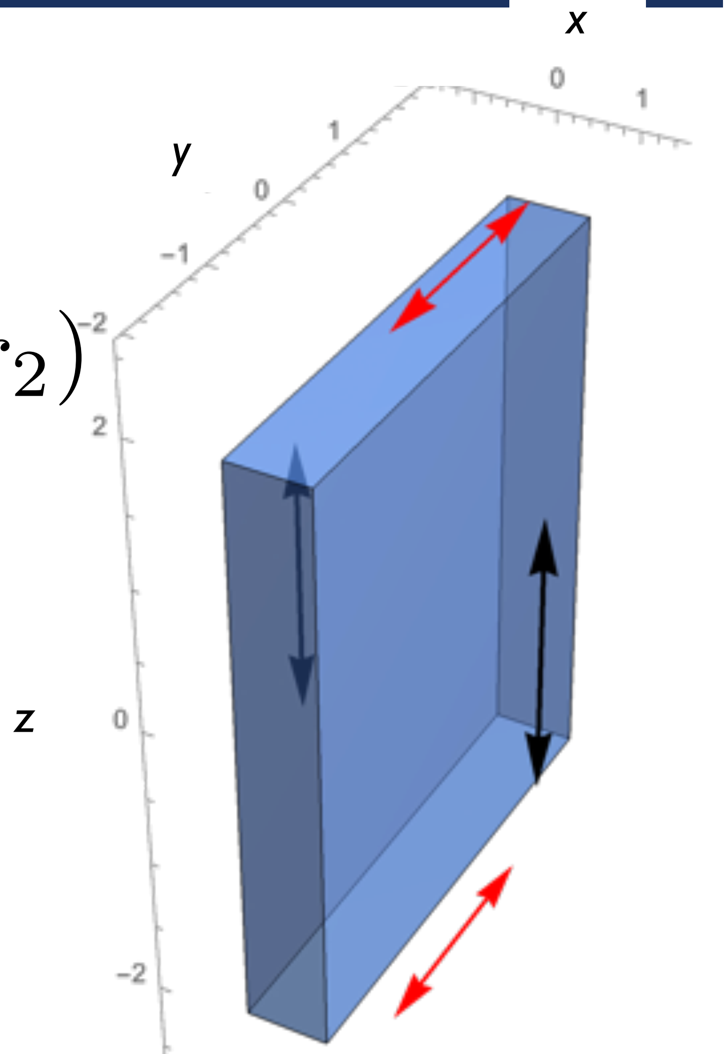
$$H = \frac{1}{2m}(p_1 - eA_1)^2 + \frac{1}{2m}(p_2 - eA_2)^2 - eA_0(r_1) - eA_0(r_2) + V(r_1 - r_2)$$

$$A_{0i} = 0$$

$$A_i = \{0, B(t)x, 0\}$$

'WEYL-LANDAU' GAUGE

$$B(t) = B_0 \sin(\omega t)$$



COOPER PROBLEM: BINDING ENERGY OF TWO ELECTRONS IN A FILLED FERMI SEA

$$H = \frac{1}{2m}\left(p_1 - eA_1\right)^2 + \frac{1}{2m}\left(p_2 - eA_2\right)^2 - eA_0(r_1) - eA_0(r_2) + V(r_1 - r_2)$$

COOPER PROBLEM: BINDING ENERGY OF TWO ELECTRONS IN A FILLED FERMI SEA

$$H = \frac{1}{2m}\left(p_1 - eA_1\right)^2 + \frac{1}{2m}\left(p_2 - eA_2\right)^2$$
$$- eA_0(r_1) - eA_0(r_2) + V(r_1 -$$

FLOQUET THEORY

$$U(t, t+T) = e^{iH_F T/\hbar}$$

COOPER PROBLEM: BINDING ENERGY OF TWO ELECTRONS IN A FILLED FERMI SEA

$$H = \frac{1}{2m}(p_1 - eA_1)^2 + \frac{1}{2m}(p_2 - eA_2)^2$$
$$- eA_0(r_1) - eA_0(r_2) + V(r_1$$

FLOQUET THEORY

$$U(t, t+T) = e^{iH_F T/\hbar}$$

- High frequency limit
- Magnus expansion, BCH, …
- Effective Hamiltonian

COOPER PROBLEM: BINDING ENERGY OF TWO ELECTRONS IN A FILLED FERMI SEA

$$H = \frac{1}{2m}\left(p_1 - eA_1\right)^2 + \frac{1}{2m}\left(p_2 - eA_2\right)^2$$
$$- eA_0(r_1) - eA_0(r_2) + V(r_1 -$$

FLOQUET THEORY

$$U(t, t+T) = e^{iH_F T/\hbar}$$

- High frequency limit
- Magnus expansion, BCH, …
- Effective Hamiltonian

Eckardt & Anisimovas, *New J. Phys.* (2015)

COOPER PROBLEM: BINDING ENERGY OF TWO ELECTRONS IN A FILLED FERMI SEA

$$H = \frac{1}{2m}(p_1 - eA_1)^2 + \frac{1}{2m}(p_2 - eA_2)^2$$
$$- eA_0(r_1) - eA_0(r_2) + V(r_1 -$$

FLOQUET THEORY

$$U(t, t+T) = e^{iH_F T/\hbar}$$

- High frequency limit
- Magnus expansion, BCH, …
- Effective Hamiltonian

COOPER PROBLEM: BINDING ENERGY OF TWO ELECTRONS IN A FILLED FERMI SEA

$$H = \frac{1}{2m}(p_1 - eA_1)^2 + \frac{1}{2m}(p_2 - eA_2)^2$$
$$- eA_0(r_1) - eA_0(r_2) + V(r_1 - r_2)$$

$$H_F = \sum_{i=1}^{2} \left\{ \frac{{p_{i,x}}^2}{2m} + \frac{{p_{i,y}}^2}{2m'} + \frac{{p_{i,z}}^2}{2m} \right\} + V(r_1 - r_2)$$

COOPER PROBLEM: BINDING ENERGY OF TWO ELECTRONS IN A FILLED FERMI SEA

$$H = \frac{1}{2m}(p_1 - eA_1)^2 + \frac{1}{2m}(p_2 - eA_2)^2 - eA_0(r_1) - eA_0(r_2) + V(r_1 - r_2)$$

Cyclotron frequency at maximum field

$$m' = m\left[1 - \frac{1}{2}\left(\frac{\omega_c}{\omega}\right)^2\right]$$

EFFECTIVE MASS

$$H_F = \sum_{i=1}^{2}\left\{\frac{{p_{i,x}}^2}{2m} + \frac{{p_{i,y}}^2}{2m'} + \frac{{p_{i,z}}^2}{2m}\right\} + V(r_1 - r_2)$$

COOPER PROBLEM: BINDING ENERGY OF TWO ELECTRONS IN A FILLED FERMI SEA

THE COOPER PROBLEM

- Change of coordinates and Fourier expansion
- Bethe-Goldstone equation for two interacting electrons
- The Cooper model
- Perturbation theory and binding energy

$$H_F = \sum_{i=1}^{2} \left\{ \frac{{p_{i,x}}^2}{2m} + \frac{{p_{i,y}}^2}{2m'} + \frac{{p_{i,z}}^2}{2m} \right\} + V(r_1 - r_2)$$

COOPER PROBLEM: BINDING ENERGY OF TWO ELECTRONS IN A FILLED FERMI SEA

THE COOPER PROBLEM

- Change of coordinates and Fourier expansion
- Bethe-Goldstone equation for two interacting electrons
- The Cooper model
- Perturbation theory and binding energy

$$H_F = \sum_{i=1}^{2} \left\{ \frac{{p_{i,x}}^2}{2m} + \frac{{p_{i,y}}^2}{2m'} + \frac{{p_{i,z}}^2}{2m} \right\} + V(r_1 - r_2)$$

COOPER PROBLEM: BINDING ENERGY OF TWO ELECTRONS IN A FILLED FERMI SEA

THE COOPER PROBLEM

- Change of coordinates and Fourier expansion
- Bethe-Goldstone equation for two interacting electrons
- The Cooper model
- Perturbation theory and binding energy

$$H_F = \sum_{i=1}^{2} \left\{ \frac{{p_{i,x}}^2}{2m} + \frac{{p_{i,y}}^2}{2m'} + \frac{{p_{i,z}}^2}{2m} \right\} + V(r_1 - r_2)$$

COOPER PROBLEM: BINDING ENERGY OF TWO ELECTRONS IN A FILLED FERMI SEA

THE COOPER PROBLEM

- Change of coordinates and Fourier expansion
- Bethe-Goldstone equation for two interacting electrons
- The Cooper model
- Perturbation theory and binding energy

$$V_{k,k'} = \begin{cases} -\frac{V}{L^2 D}, & \text{if } |\frac{\hbar^2 k^2}{2m} - \epsilon_F| \text{ and } |\frac{\hbar^2 k'^2}{2m} - \epsilon_F| < \hbar\omega_D \\ 0, & \text{otherwise.} \end{cases}$$

COOPER PROBLEM: BINDING ENERGY OF TWO ELECTRONS IN A FILLED FERMI SEA

THE COOPER PROBLEM

- Change of coordinates and Fourier expansion
- Bethe-Goldstone equation for two interacting electrons
- The Cooper model
- Perturbation theory and binding energy

$$-\epsilon \approx 2\hbar\omega_D e^{-\frac{2}{V\mathcal{N}(0)}} \left[1 - \frac{1}{6}\left(\frac{2}{V\mathcal{N}(0)} + \frac{\epsilon_F}{\epsilon_D} e^{\frac{2}{V\mathcal{N}(0)}}\right)\left(\frac{\omega_c}{\omega}\right)^2\right]$$

COOPER PROBLEM: BINDING ENERGY OF TWO ELECTRONS IN A FILLED FERMI SEA

THE COOPER PROBLEM

- Change of coordinates and Fourier expansion
- Bethe-Goldstone equation for two interacting electrons
- The Cooper model
- Perturbation theory and binding energy

$$-\epsilon \approx 2\hbar\omega_D e^{-\frac{2}{V\mathcal{N}(0)}} \left[1 - \frac{1}{6}\left(\frac{2}{V\mathcal{N}(0)} + \frac{\epsilon_F}{\epsilon_D} e^{\frac{2}{V\mathcal{N}(0)}}\right)\left(\frac{\omega_c}{\omega}\right)^2\right]$$

SUPERCONDUCTOR GAP AND GROUND-STATE ENERGY USING FLOQUET/BCS THEORY

SUPERCONDUCTOR GAP AND GROUND-STATE ENERGY USING FLOQUET/BCS THEORY

SUPERCONDUCTOR GAP

$$\frac{\Delta}{\hbar\omega_D} = \left[\sinh\left(\frac{1}{V\mathcal{N}(0)\left(1 - \frac{1}{6}\left(\frac{\omega_c}{\omega}\right)^2\right)}\right)\right]^{-1}$$

SUPERCONDUCTOR GAP AND GROUND-STATE ENERGY USING FLOQUET/BCS THEORY

SUPERCONDUCTOR GAP

$$\frac{\Delta}{\hbar\omega_D} = \left[\sinh\left(\frac{1}{V\mathcal{N}(0)\left(1-\frac{1}{6}\left(\frac{\omega_c}{\omega}\right)^2\right)}\right)\right]^{-1}$$

SUPERCONDUCTOR GAP AND GROUND-STATE ENERGY USING FLOQUET/BCS THEORY

SUPERCONDUCTOR GAP

$$\frac{\Delta}{\hbar\omega_D} = \left[\sinh\left(\frac{1}{V\mathcal{N}(0)\left(1-\frac{1}{6}\left(\frac{\omega_c}{\omega}\right)^2\right)}\right)\right]^{-1}$$

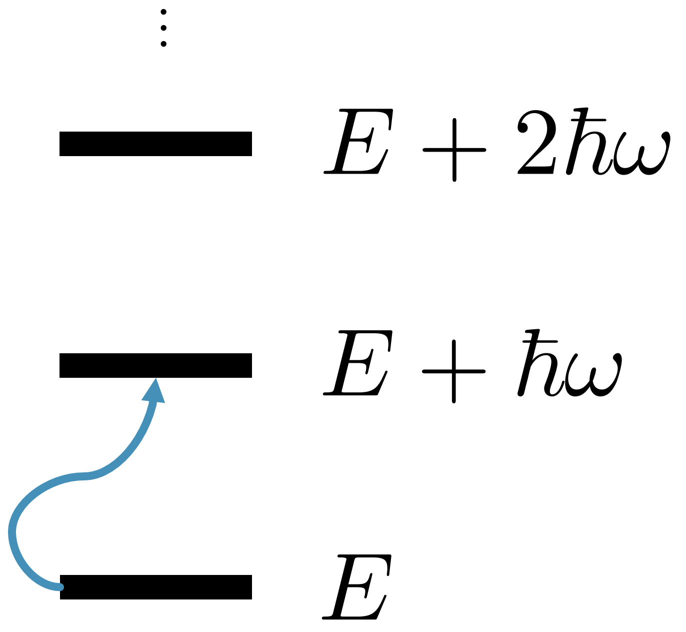
GROUND-STATE ENERGY

$$\langle\psi_{BCS}|\, H'_R \,|\psi_{BCS}\rangle - E_0 = -\frac{1}{2}\mathcal{N}(0)\Delta^2\left[1-\frac{1}{2}\left(\frac{\omega_c}{\omega}\right)^2\right]$$

DISSIPATION

DISSIPATION

THE BCS PICTURE

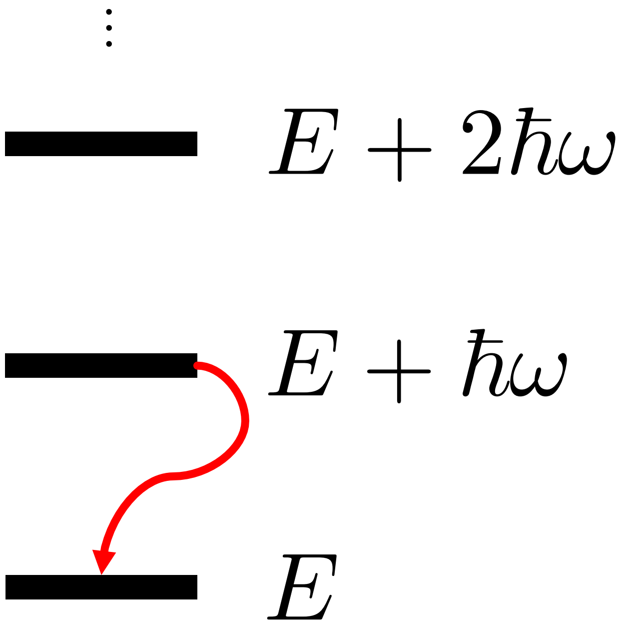


- Absorb a photon: transition to state with energy E + h ω
- Emit a photon: transition to state with energy E
- Conductivity proportional to net transition rate

Semiconductor model: Tinkham, *Introduction to Superconductivity*

DISSIPATION

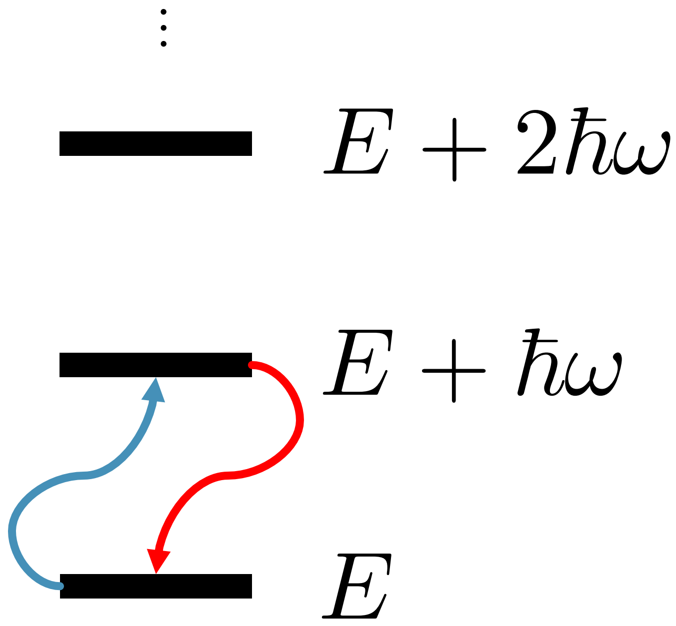
THE BCS PICTURE



- Absorb a photon: transition to state with energy E + h ω
- Emit a photon: transition to state with energy E
- Conductivity proportional to net transition rate

DISSIPATION

THE BCS PICTURE

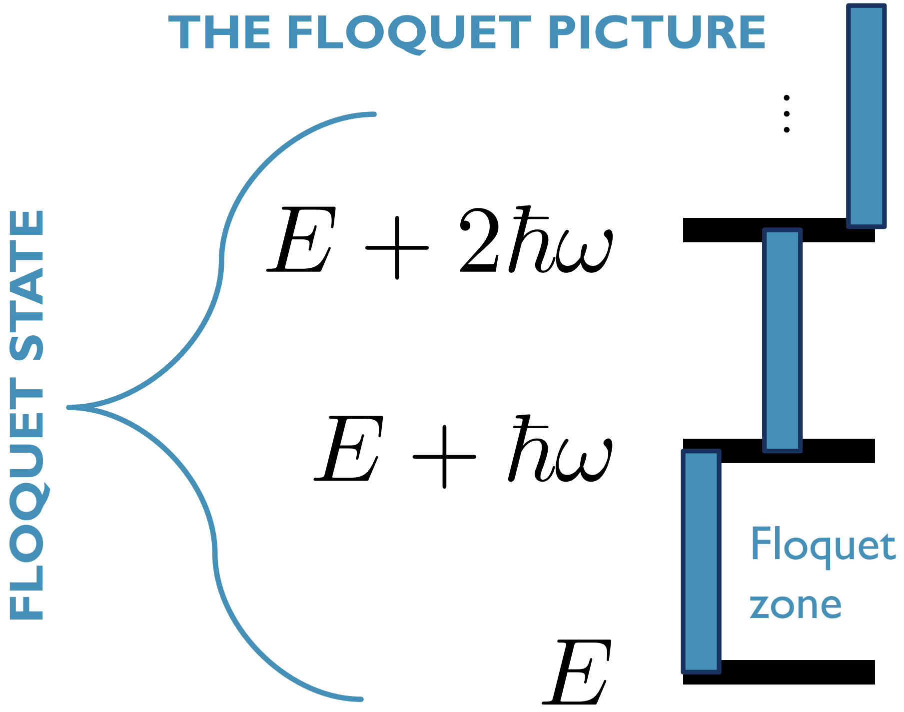


- Absorb a photon: transition to state with energy E + h ω
- Emit a photon: transition to state with energy E
- Conductivity proportional to net transition rate

DISSIPATION

THE BCS PICTURE

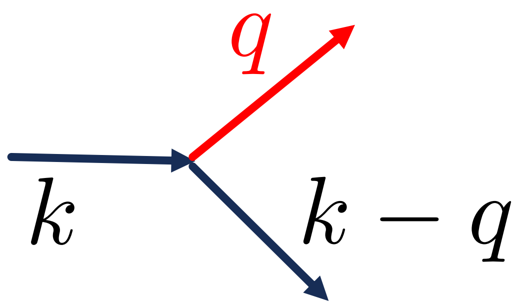
THE FLOQUET PICTURE



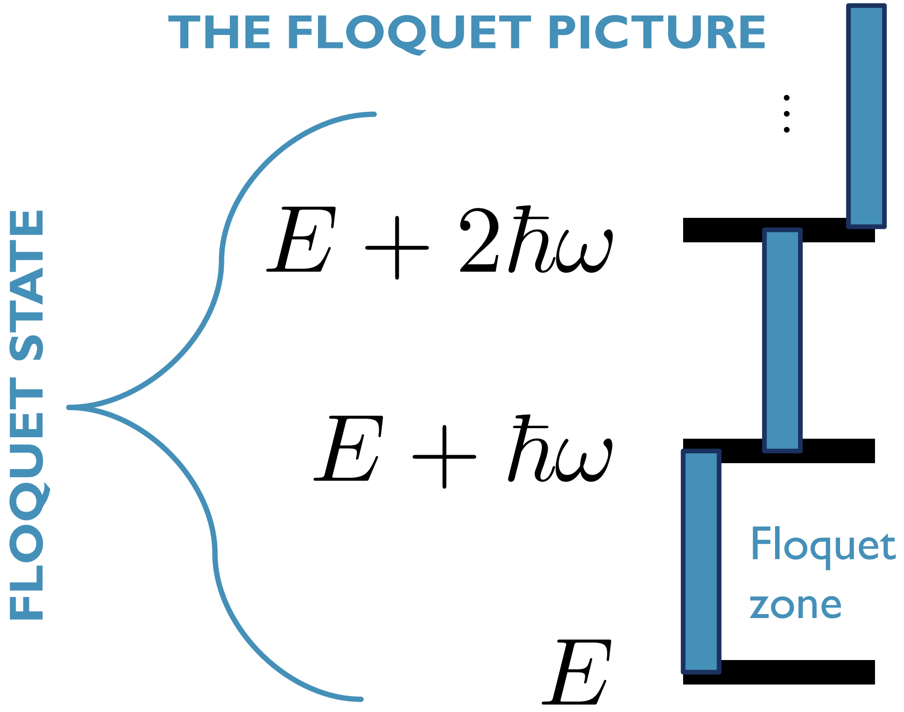
NO PHOTON EMISSION OR ABSORPTION: COHERENT SUPERPOSITION OF STATES WITH ENERGY SEPARATED BY h ω

DISSIPATION: CHANGE OF PARADIGM?

THE BCS PICTURE



THE FLOQUET PICTURE

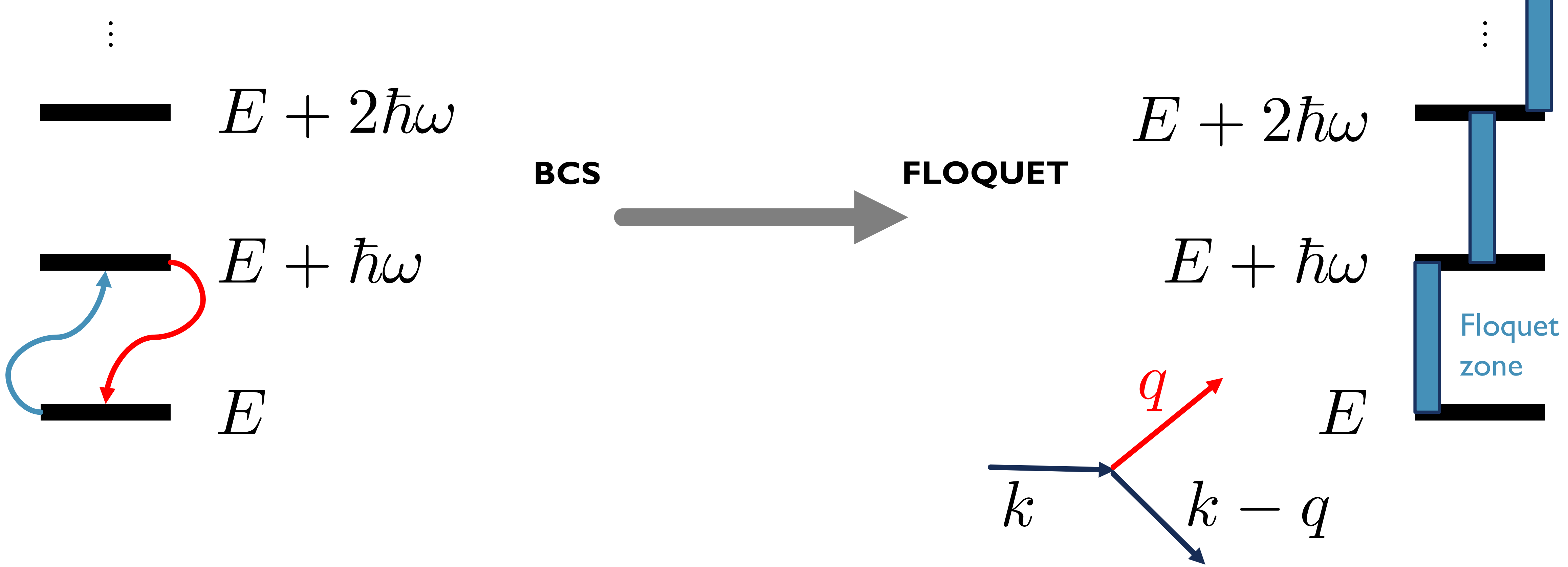


DISSIPATION CAN ONLY HAPPEN WHEN THE COHERENT SUM OVER FLOQUET STATES IS BROKEN BY COLLISIONS

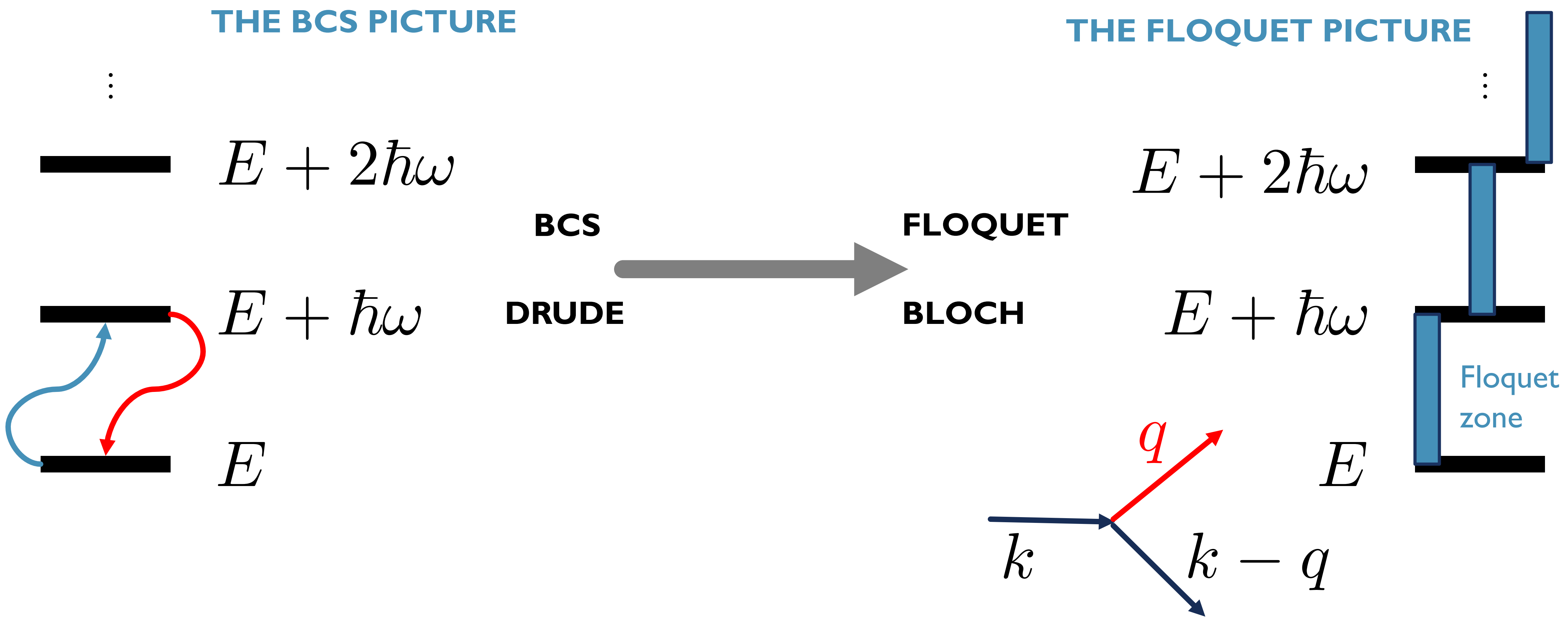
DISSIPATION: CHANGE OF PARADIGM?

THE BCS PICTURE

THE FLOQUET PICTURE



DISSIPATION: CHANGE OF PARADIGM?



FINAL CONSIDERATIONS

In progress…

- Towards a Floquet theory of periodically-driven superconductors.
- Cooper problem in the high-frequency limit.
- Preliminary results of a BCS theory using Floquet states.
- Paradigm shift? Dissipation and the breaking of the coherent sum over Floquet states.

FINAL CONSIDERATIONS

In progress…

- Towards a Floquet theory of periodically-driven superconductors.
- Cooper problem in the high-frequency limit.
- Preliminary results of a BCS theory using Floquet states.
- Paradigm shift? Dissipation and the breaking of the coherent sum over Floquet states.

FINAL CONSIDERATIONS

In progress…

- Towards a Floquet theory of periodically-driven superconductors.
- Cooper problem in the high-frequency limit.
- Preliminary results of a BCS theory using Floquet states.
- Paradigm shift? Dissipation and the breaking of the coherent sum over Floquet states.

FINAL CONSIDERATIONS

In progress…

- Towards a Floquet theory of periodically-driven superconductors.
- Cooper problem in the high-frequency limit.
- Preliminary results of a BCS theory using Floquet states.
- Paradigm shift? Dissipation and the breaking of the coherent sum over Floquet states.

THANK YOU

APS physics MARCH MEETING 2020
MARCH 2-6 DENVER, CO

CORNELL UNIVERSITY
FOUNDED A.D. 1865

The Center for BRIGHT BEAMS
A National Science Foundation Science & Technology Center