Concepts in High Temperature Superconductivity

Concepts in High Temperature Superconductivity

E. W. Carlson, V. J. Emery, S. A. Kivelson,
D. Orgad

It is the purpose of this paper to explore the theory of high
temperature superconductivity. Much of the motivation for
this comes from the study of the cuprate high temperature
superconductors. However, **our primary focus is on the
core theoretical issues associated with the mechanism of
high temperature superconductivity more generally.** We
concentrate on physics at intermediate temperature scales
of order T_c (as well as the somewhat larger "pseudogap"
temperature) and energies of order the gap maximum, Δ_0
**Prominent themes throughout the article are the need
for a kinetic energy driven mechanism, and the role of
mesoscale structure in enhancing pairing from repulsive
interactions.**

Cond-mat/0206217

500 references

V. J. Emery, S. A. Kivelson,
E.Arrigoni, I.Bindloss,
E.Carlson, S.Chakravarty,
L.Chayes, K.Fabricius,
E.Fradkin, M.Granath, D-
H.Lee, H-Q. Lin, U.Low,
T.Lubensky, E.Manousakis,
Z.Nussinov, V.Oganesyan,
D.Orgad, L.Pryadko,
M.Salkola, Z-X.Shen,
J.Tranquada, O.Zachar
.
.
.

Superconductivity

- Fermions: Pauli exclusion principle
- Bosons can condense
- Stable phase of matter
- Macroscopic Quantum Behavior
- Pair wavefunction acts like "order parameter"
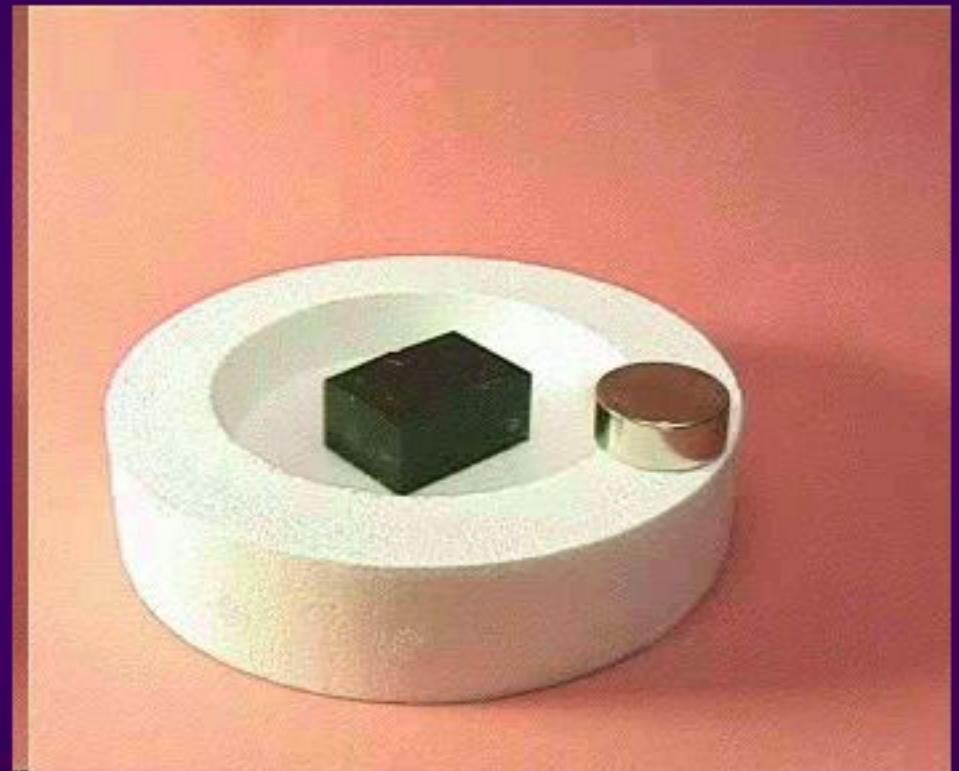
Superconductivity

- Fermions: Pauli exclusion principle

- Bosons can condense

- Stable phase of matter

- Macroscopic Quantum Behavior

- Pair wavefunction acts like "order parameter"
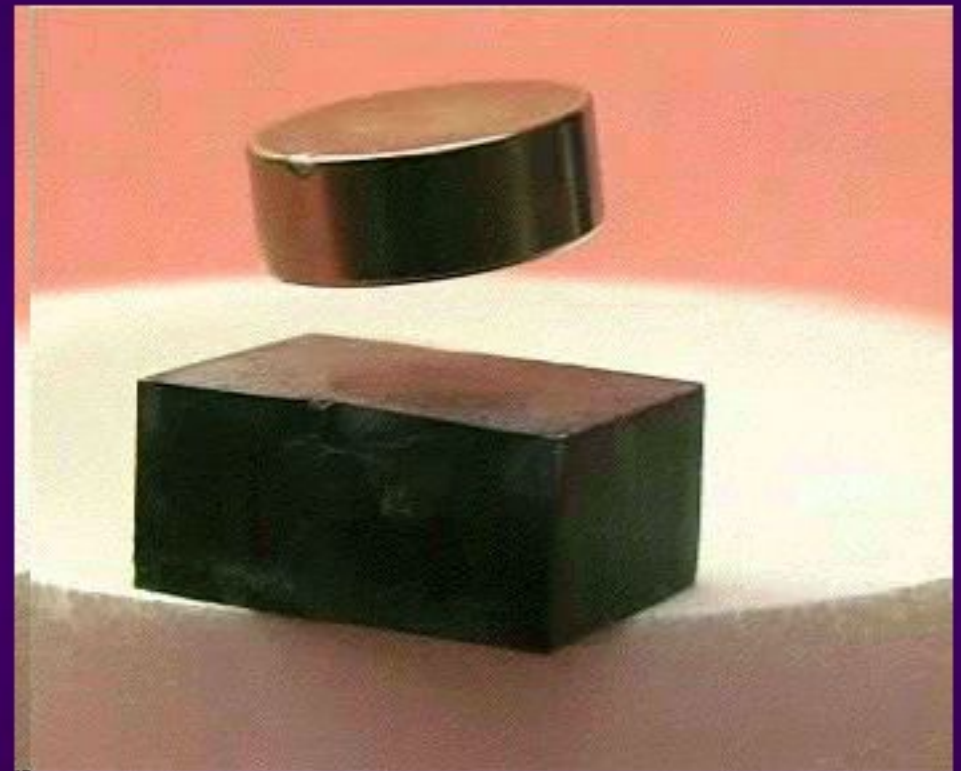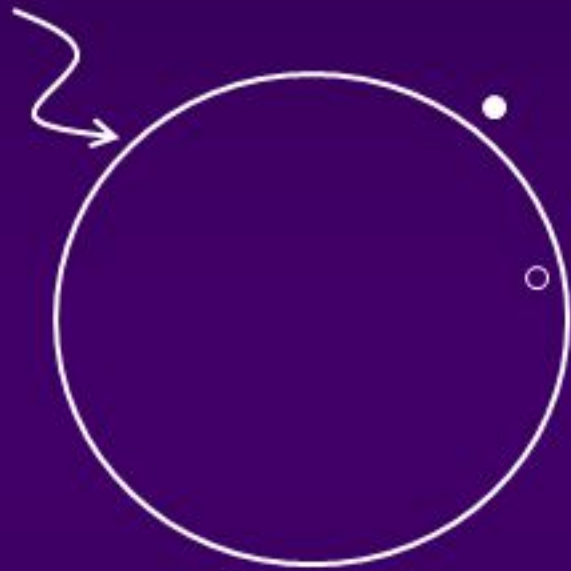
John Bardeen   Leon Cooper   Bob Schrieffer

Conventional Superconductivity

- BCS Theory
- *Instability* of the metallic state
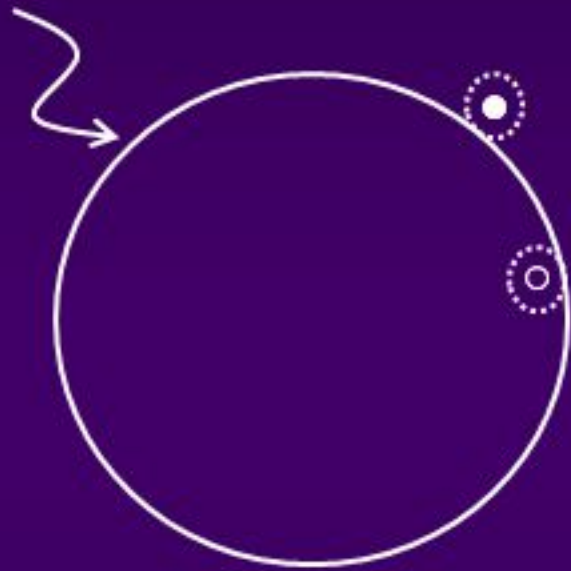
Simple Metals: The Fermi Gas

Fermi Surface

- Free Electrons $E \sim k^2$
- Pauli exclusion principle
- Fill to Fermi level

Adiabatically turn on temperature, most states unaffected
Very dilute gas of excitations: quasiparticles

Simple Metals: The Fermi Liquid

Fermi Surface

- Pauli exclusion principle
- Fill to Fermi level

Adiabatically turn on temperature, most states unaffected
Very dilute gas of excitations: quasiparticles

Fermi Gas + Interactions → Fermi Liquid

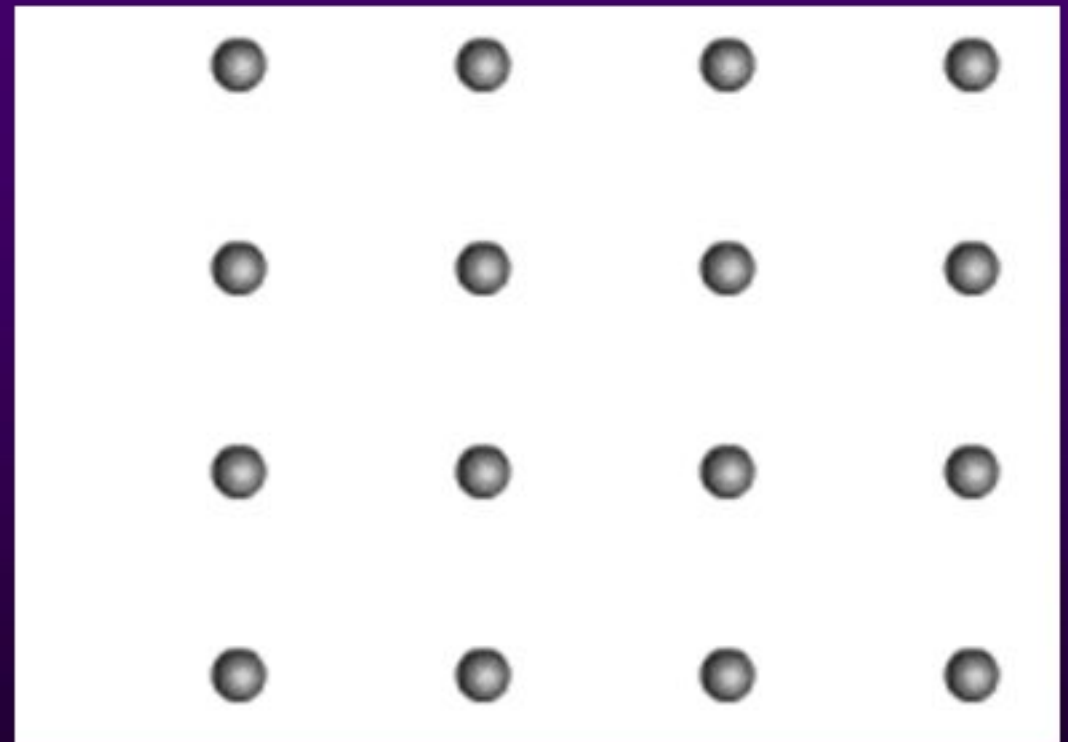Quasiparticles = Dressed Electrons

Kinetic Energy
Dominant

Cooper Pairing

- Fermi Liquid Unstable to Pairing
- Pair electrons near Fermi Surface
- Phonon mediated

Retardation is Essential
to overcome
Coulomb repulsion

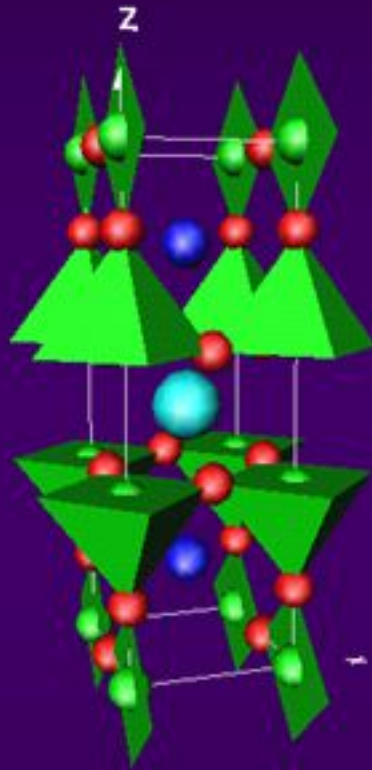$$\frac{E_F}{\omega_D} \approx 10^3$$

BCS Haiku:

Instability

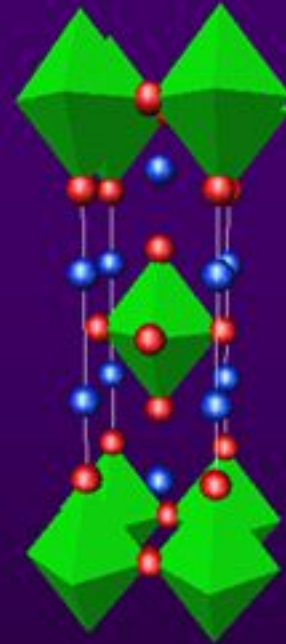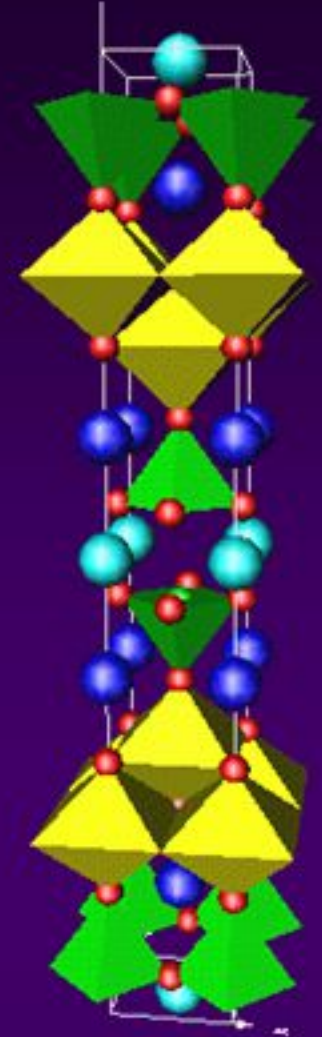*Of A Tranquil Fermi Sea—*

Broken Symmetry

High Temperature Superconductors

YBCO$_7$

LSCO

HgCuO

High Temperature Superconductors

Copper Oxygen Planes

Other Layers
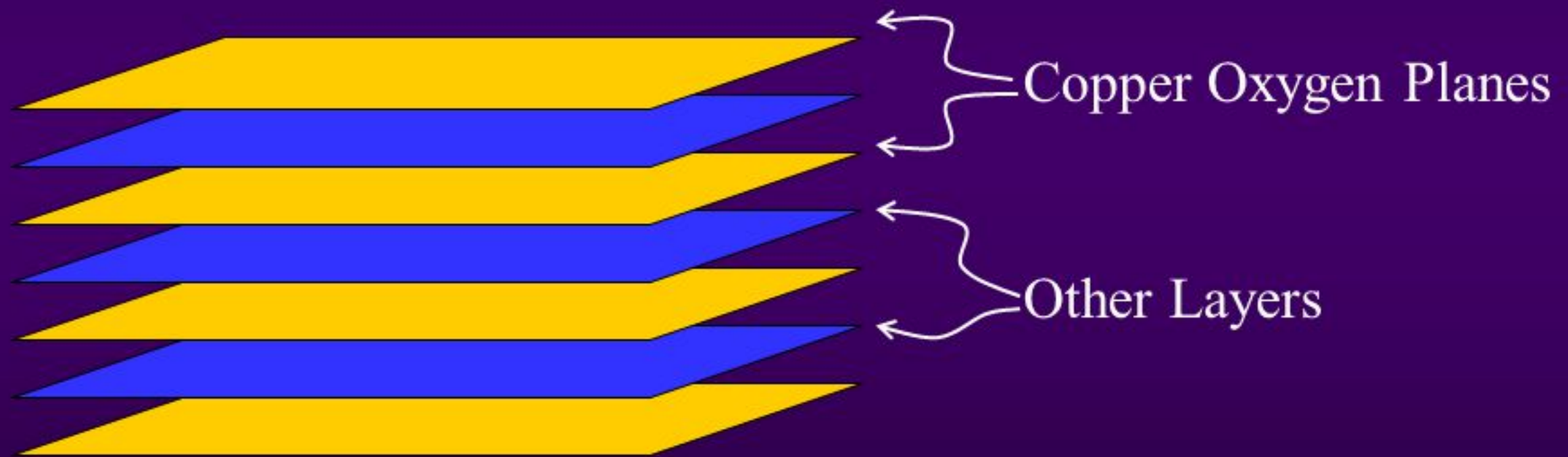
Layered structure → quasi-2D system

High Temperature Superconductors
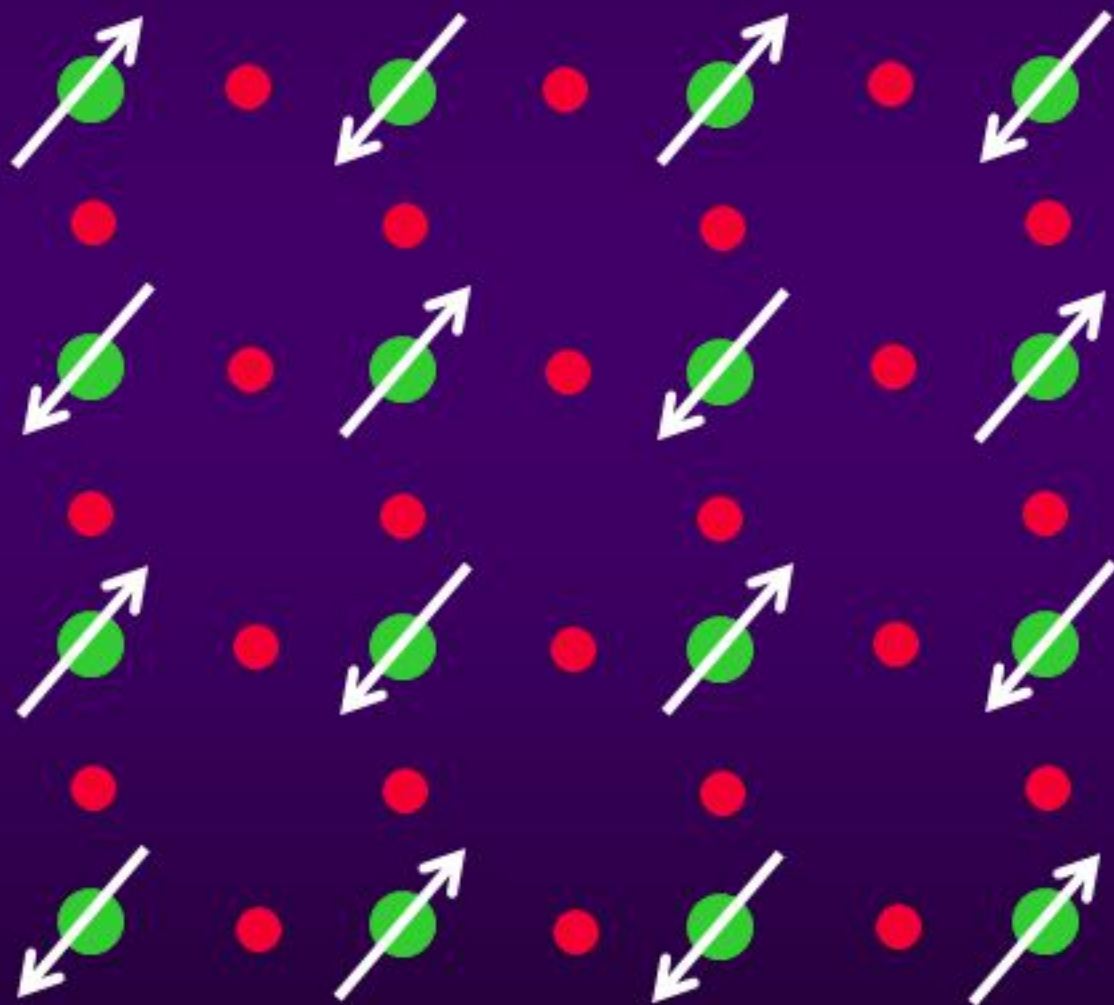
Copper-Oxygen Planes Important

"Undoped" is half-filled

Antiferromagnet

Naive band theory fails

Strongly correlated
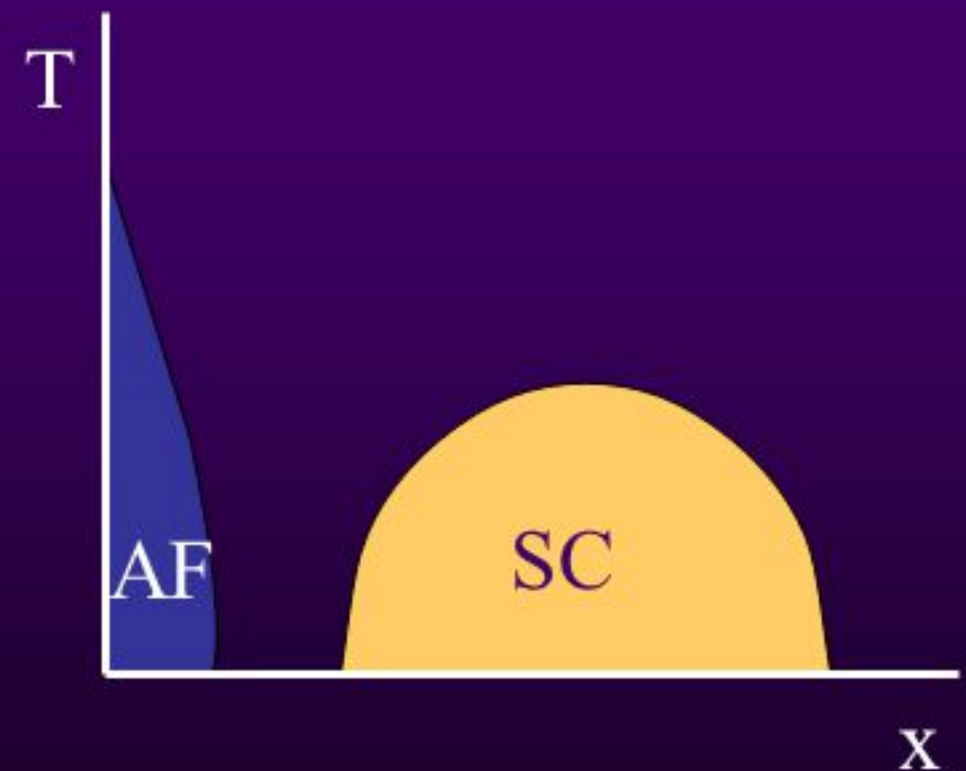
● Oxygen   ● Copper

High Temperature Superconductors

Dope with holes

Superconducts at certain dopings
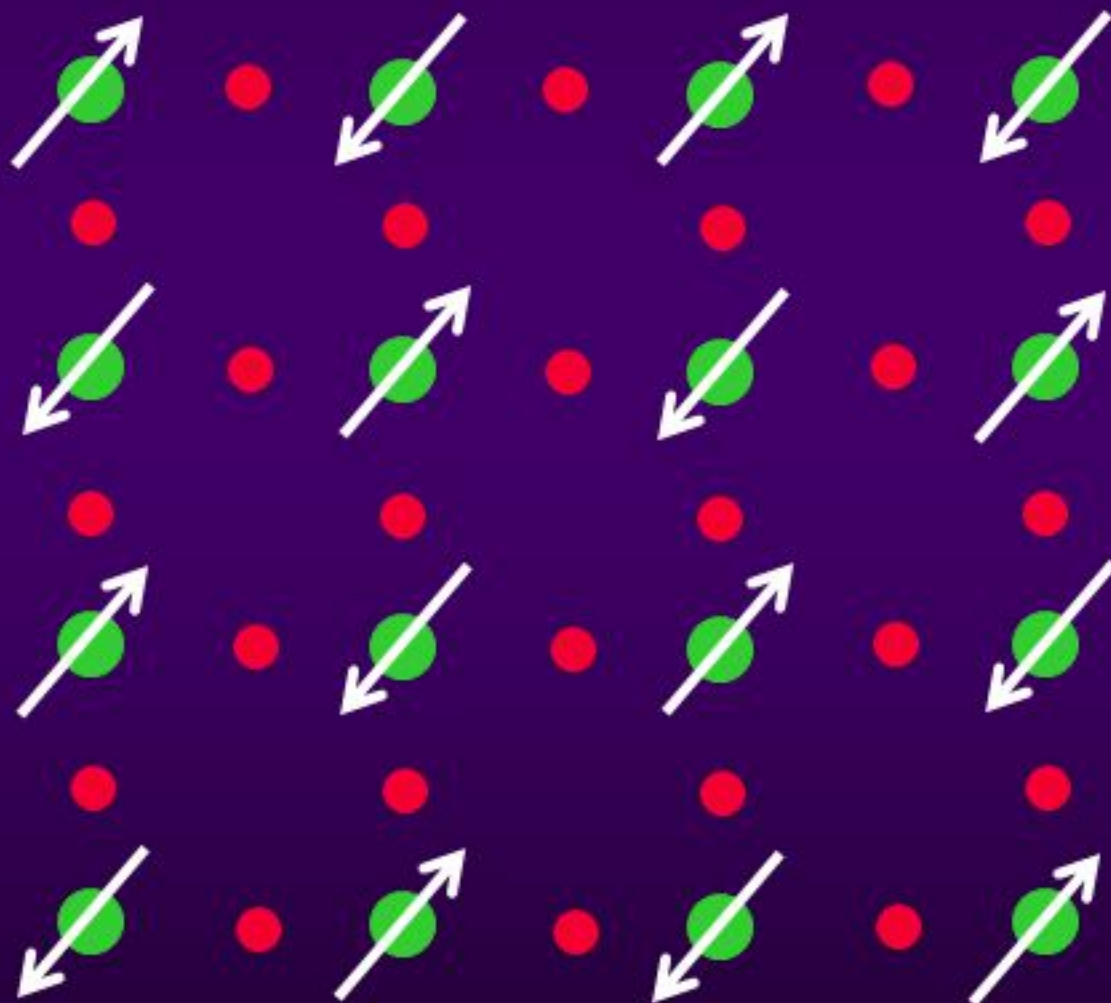
- Oxygen
- Copper

Mysteries of High Temperature Superconductivity

- Ceramic! (Brittle)
- "Non-Fermi liquid" normal state
- Magnetism nearby (antiferromagnetism)
- Make your own (robust)
  http://www.ornl.gov/reports/m/ornlm3063r1/pt7.html
- Pseudogap
- Phase ordering transition

Two Energy Scales in a Superconductor

Two component order parameter

$$\psi = \Delta e^{i\theta}$$

Amplitude

Phase

Pairing
Gap

Phase Coherence
Superfluid Density

BCS is a mean field theory in which pairing precipitates order

Material	$T_{pair}[K]$	$T_c[K]$	$T_\theta[K]$
Pb	7.9	7.2	6×10^5
Nb_3Sn	18.7	17.8	2×10^4
UBe_{13}	0.8	0.9	10^2
BaKBiO	17.4	26	5×10^2
K_3C_{60}	26	20	10^2
MgB_2	15	39	1.4×10^3

Phase Fluctuations Important in Cuprates

→

Material	$T_{pair}[K]$	$T_c[K]$	$T_\theta[K]$
LSCO (ud)	75	30	47
LSCO (op)	58	38	54
LSCO (od)		20	100
Hg-1201 (op)	192	96	180
Hg-1212 (op)	290	108	130
Hg-1223 (op)	435	133	130
Tl-2201 (op)	122	91	
Tl-2201 (od)		80	160
Tl-2201 (od)	26	25	
Bi-2212 (ud)	275	83	
Bi-2212 (op)	220	95	60
Bi-2212 (od)	104	62	
Y-123 (ud)		38	42
Y-123 (op)	116	90	140
Y-123 (od)	55	140	

Emery, Kivelson, Nature, **374**, 434 (1995)
EC, Kivelson, Emery, Manousakis, PRL **83**, 612 (1999)

T_c and the Energy Scales
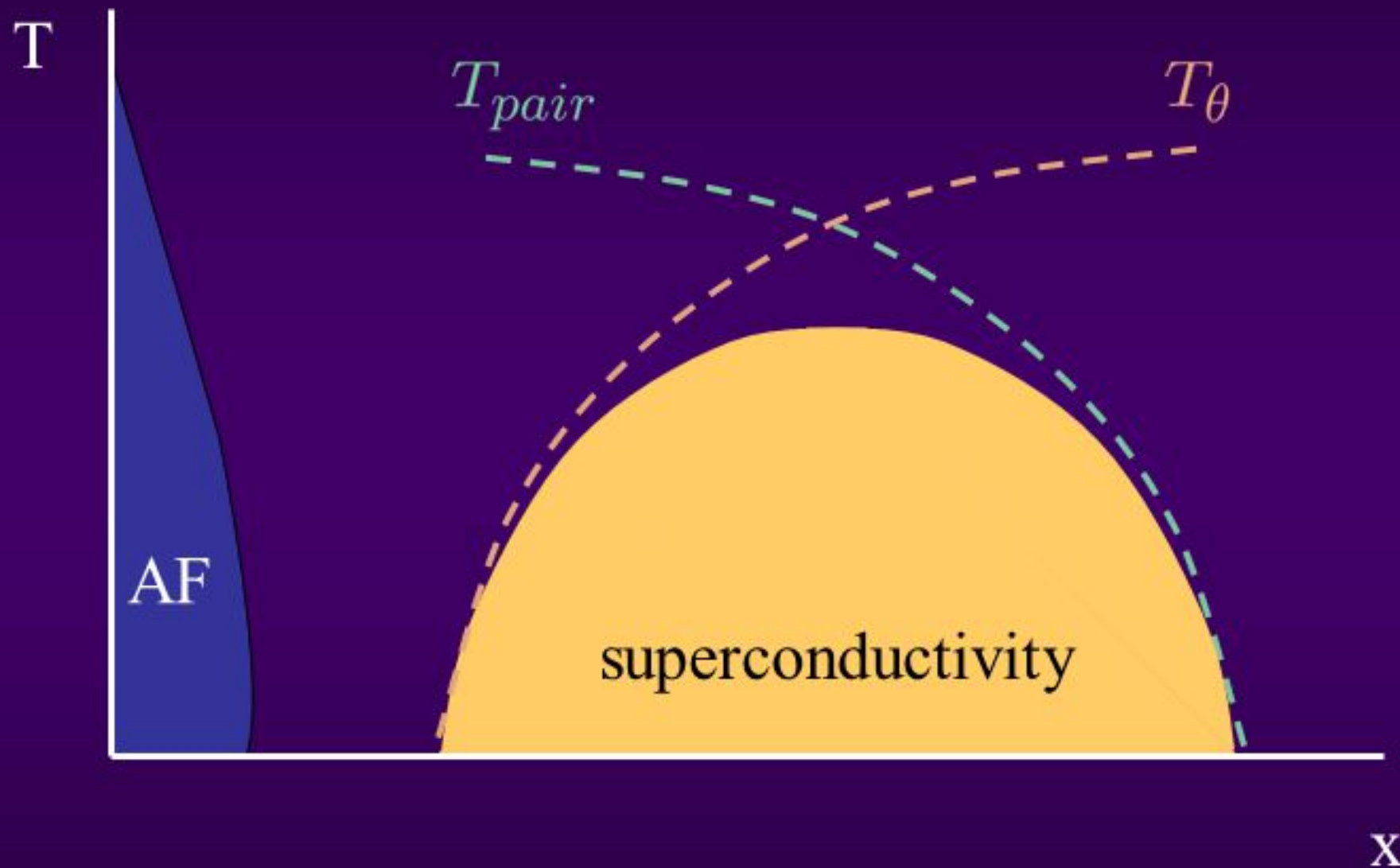
BCS: $T_\theta \sim 1000\ T_c$

HTSC: $T_\theta \sim T_c$ underdoped

Mysteries of High Temperature Superconductivity

- Ceramic! (Brittle)

- "Non-Fermi liquid" normal state

- Magnetism nearby (antiferromagnetism)

- Make your own   (robust)
  http://www.ornl.gov/reports/m/ornlm3063r1/pt7.html

- Pseudogap

- Phase ordering transition

BCS to the rescue?

There is no room for retardation in the cuprates

- BCS: $\quad \dfrac{E_F}{\omega_D} \approx 10^3$
- Cuprates: $\quad \dfrac{E_F}{\omega_D} \approx 5$

How do we get a high pairing scale despite the strong Coulomb repulsion?

A Fermi Surface Instability Requires a Fermi Surface!

How do we get superconductivity
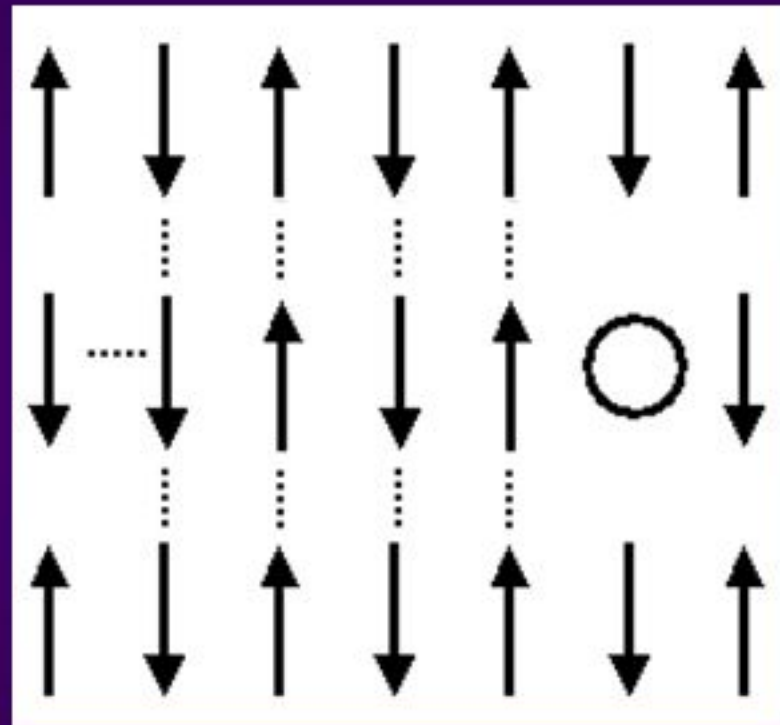from a non-Fermi liquid?

Fermi Liquid

- k-space structure
- Kinetic energy
  is minimized
- Pairing is potential energy
  driven

Strong Correlation

- Real space structure
- Kinetic energy
  is highly frustrated
- System works to relieve KE
  frustration

Doped Antiferromagnets

Hole Motion is Frustrated

Doped Antiferromagnets

- <u>Compromise # 1</u>: Phase Separation
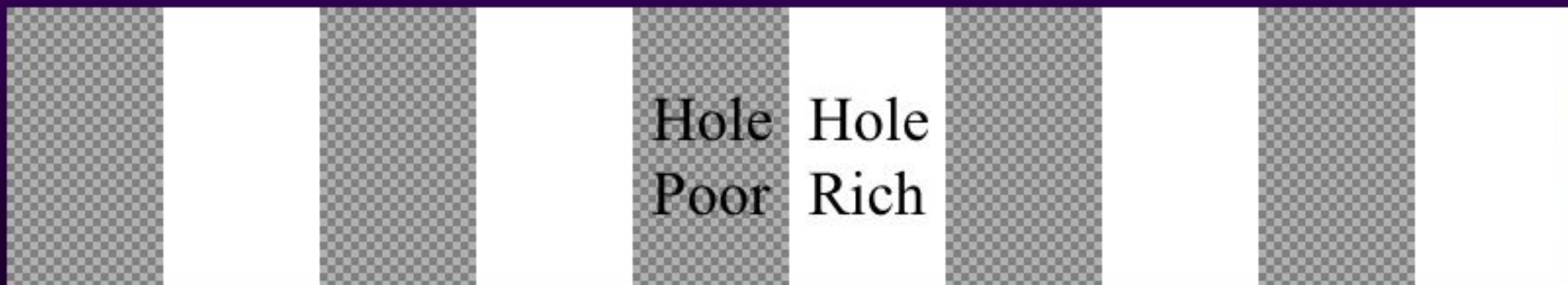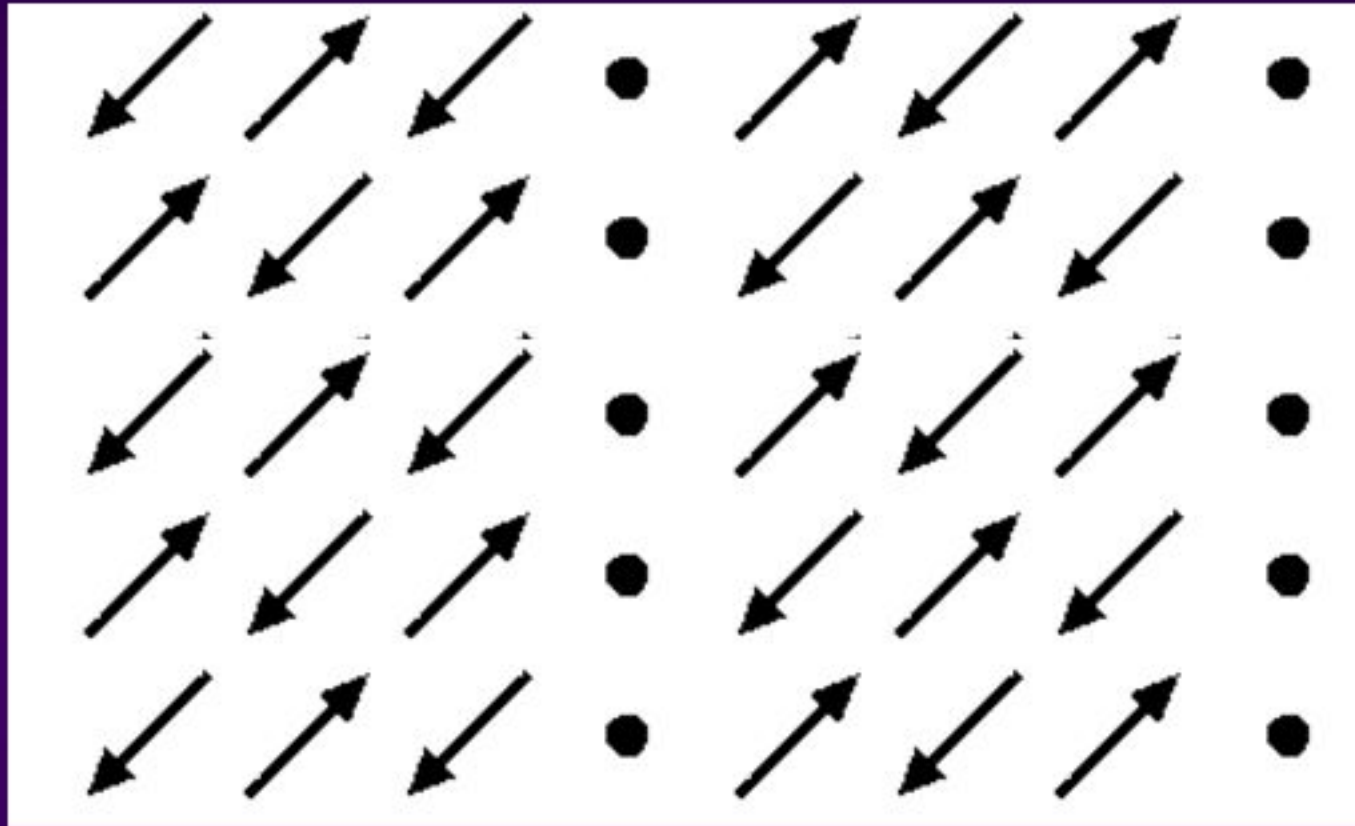- Relieves some KE frustration

Pure AF   **Hole Rich**

Like Salt Crystallizing
From Salt Water,
The Precipitate (AF) is Pure

Coulomb Frustrated Phase Separation

- Long range homogeneity
- Short range phase separation
- <u>Compromise # 2</u>: *mesoscale structure*
- Patches interleave
- quasi-1D structure – stripes ?

Hole Poor   Hole Rich

Stripes

Rivers of charge between antiferromagnetic strips
Electronic structure becomes effectively 1D

Competition often produces stripes

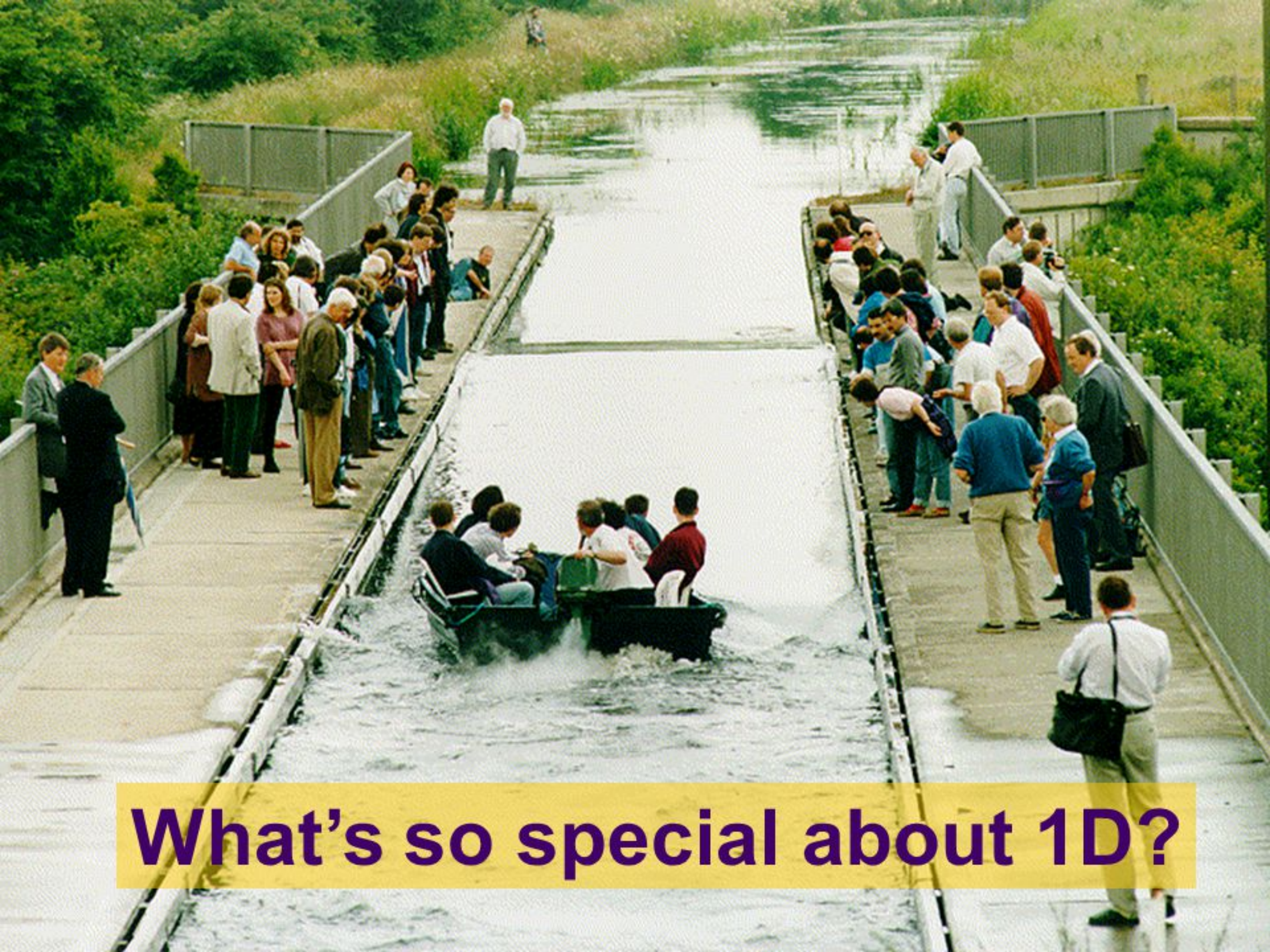Ferrofluid confined between two glass plates
Period ~ 1cm

Ferromagnetic garnet film
Faraday effect
Period ~ 10^{-5} m

Ferromagnetic garnet film
Period ~ 10^{-5} m

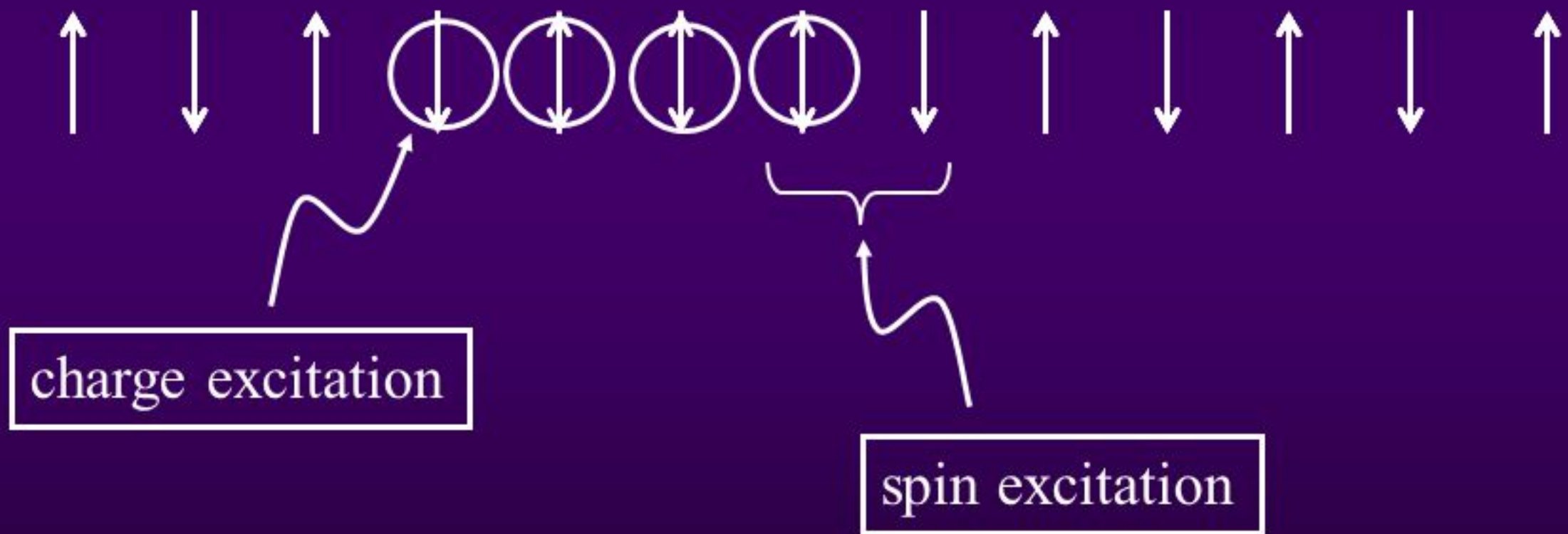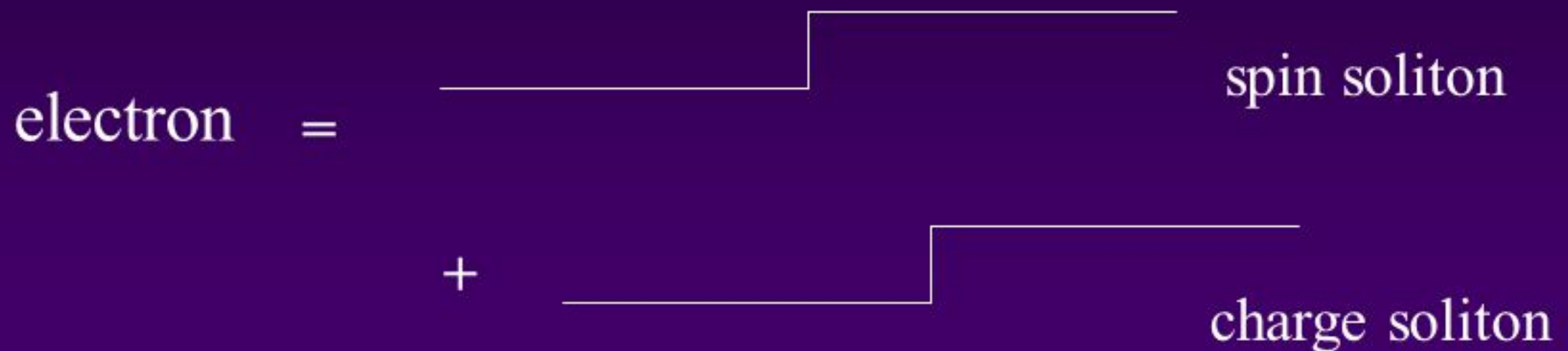Block copolymers
Period ~ 4×10^{-8} m

What's so special about 1D?

1D: Spin-Charge Separation

1D: "Bosonization transformation"

Expresses fermions as kinks in boson fields:

electron =

spin soliton

+

charge soliton

becomes

Hamiltonian of interacting fermions
Hamiltonian of non-interacting bosons

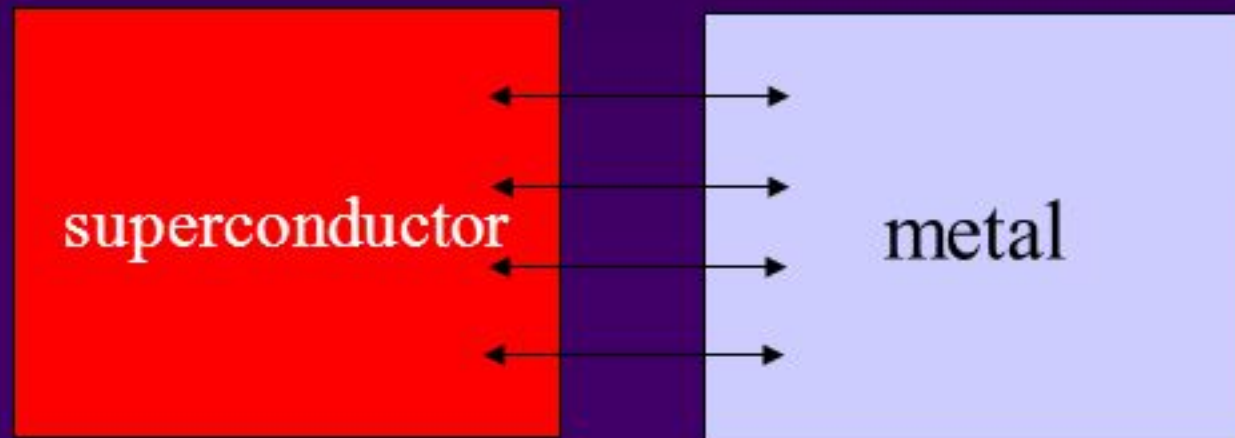Spin Charge Separation
Electron No Longer Exists!

Non-Fermi Liquid
(Luttinger Liquid)

Advantages of a quasi-1D Superconductor

- non-Fermi liquid
- strongly correlated
- controlled calculations

Kinetic Energy Driven Pairing?

→ Proximity Effect
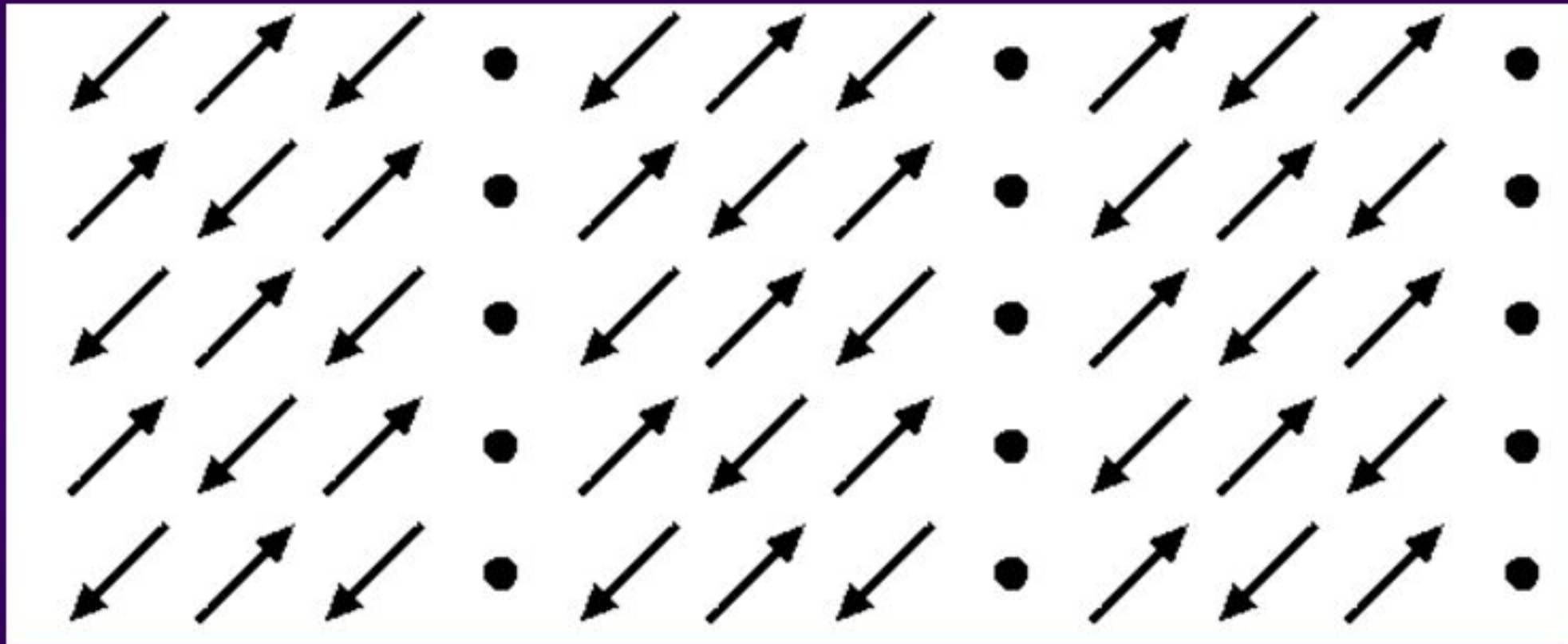

Individually, free energies minimized

Metal pairs (at a cost!) to minimize kinetic energy across the barrier

Spin Charge Separation

- 1D spin-charge separation
- Pair spins only
- Avoid Coulomb Repulsion!
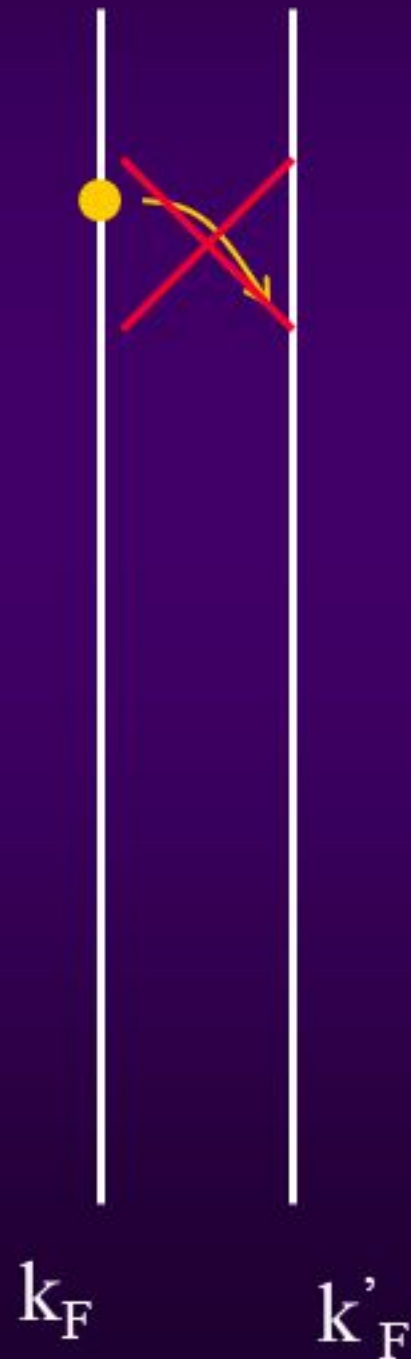
Spin Gap Proximity Effect

Kinetic energy driven pairing in a quasi-1D superconductor

Metallic charge stripe acquires spin gap through
communication with gapped environment

Spin Gap Proximity Effect

Kinetic energy driven pairing in a quasi-1D superconductor

$$k_F \neq k'_F$$

Conserve momentum and energy
Single particle tunneling is irrelevant

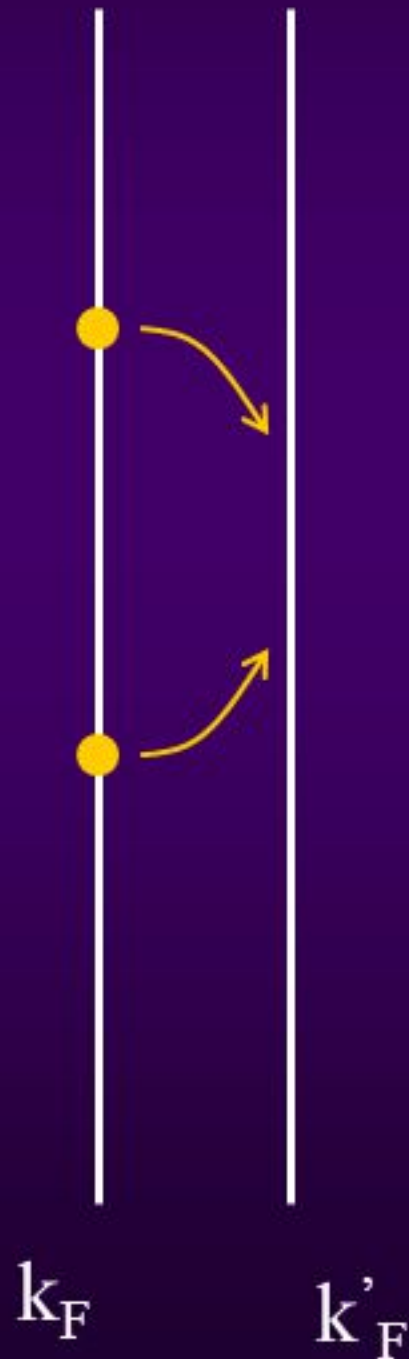k_F k'_F

Spin Gap Proximity Effect

Kinetic energy driven pairing in a quasi-1D superconductor

$$k_F \neq k'_F$$

Conserve momentum and energy
Single particle tunneling is irrelevant

But pairs of zero total momentum
can tunnel at low energy
→ pairs form to reduce kinetic energy

Step 1: Pairing

k_F k'_F

1D is Special

Spin Gap = CDW Gap = Superconducting Gap
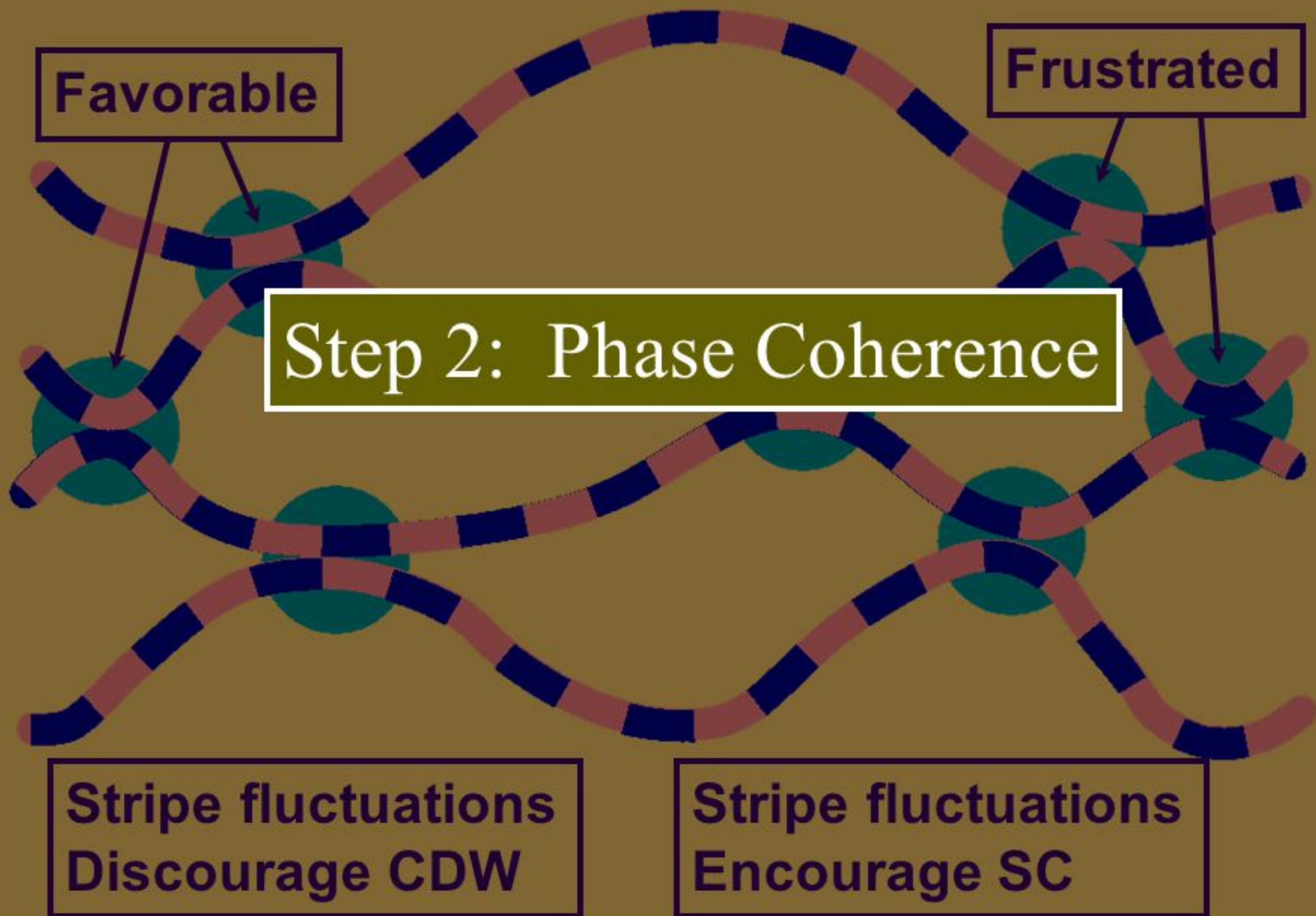
$$\chi_{CDW} \approx \Delta_S T^{(K_c - 2)} \qquad \chi_{SS} \approx \Delta_S T^{(1/K_c - 2)}$$

Which will win?

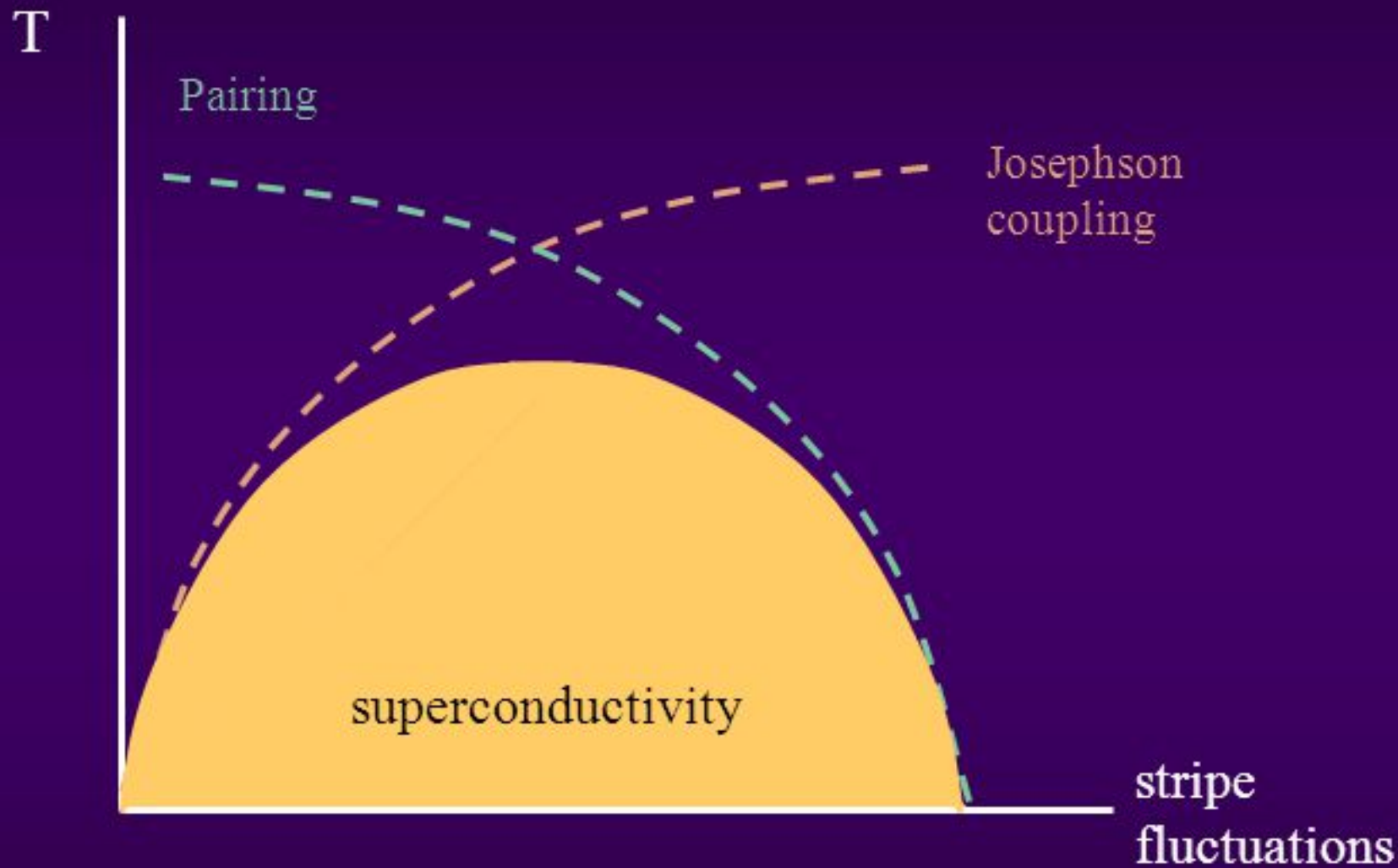CDW stronger for repulsive interactions ($K_c < 1$)

Don't Make a High Temperature Insulator!

Stripe Fluctuations

Favorable

Frustrated

Step 2: Phase Coherence

Stripe fluctuations Discourage CDW

Stripe fluctuations Encourage SC

Inherent Competition

$\triangle_{SC} >> \hbar\omega_{stripe}$

→ think local stripe order

$\triangle_{SC} << \hbar\omega_{stripe}$

→ think "stripe phonon"

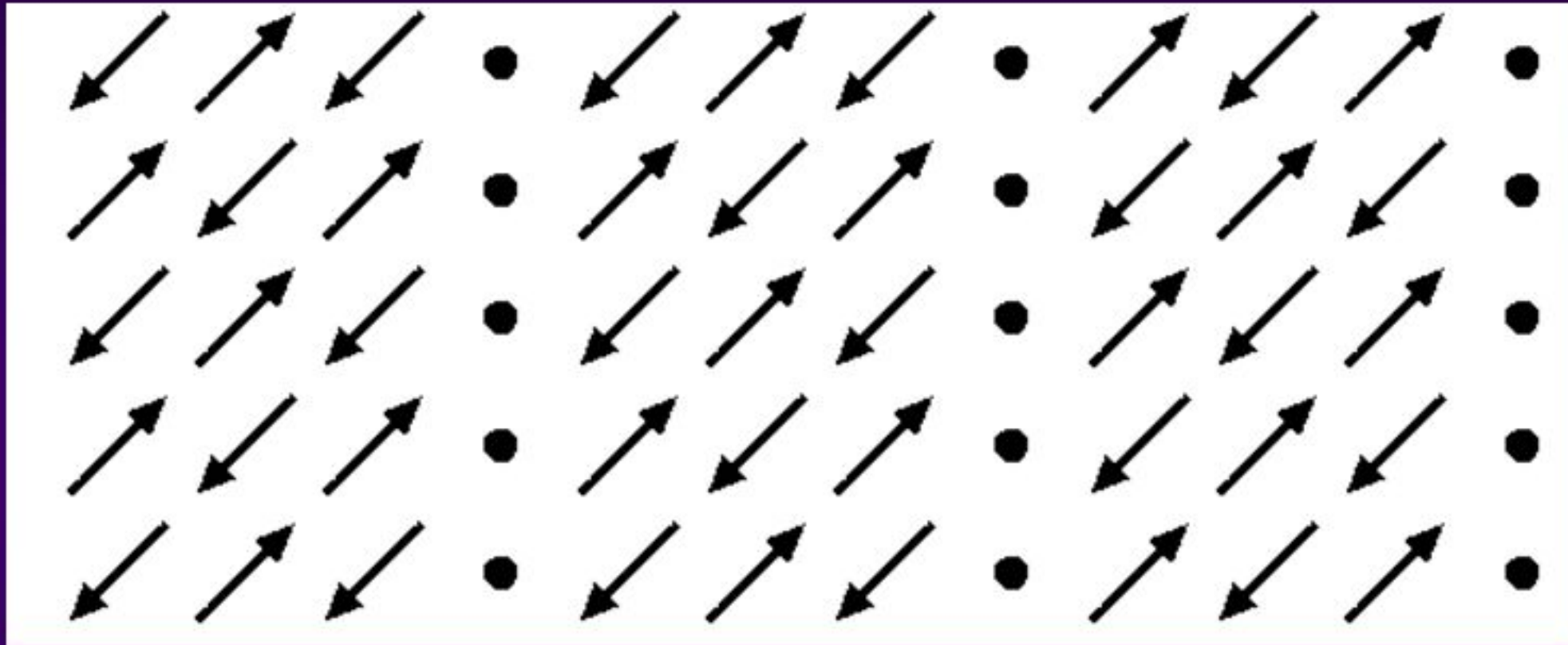Static Stripes
  Good pairing
  Bad phase coherence

Fluctuating Stripes
  Bad pairing
  Good phase coherence

Behavior of a Quasi-1D Superconductor

Treat rivers of charge as 1D objects

Behavior of a Quasi-1D Superconductor

High Temperature   *Effective Dimension = 1*

     Spin charge separation on the Rivers of Charge

     Electron dissolves

     Non-Fermi Liquid (Luttinger Liquid)

## Intermediate Temperature   *Effective Dimension = 1*

     Rivers of charge acquire spin gap from local environment

     Pseudogap

     Non-Fermi Liquid (Luther-Emery Liquid)

Low Temperature   *Effective Dimension = 3*

     1D system cannot order → Dimensional Crossover

     Pair tunneling between rivers produces phase coherence

     Electron recombines

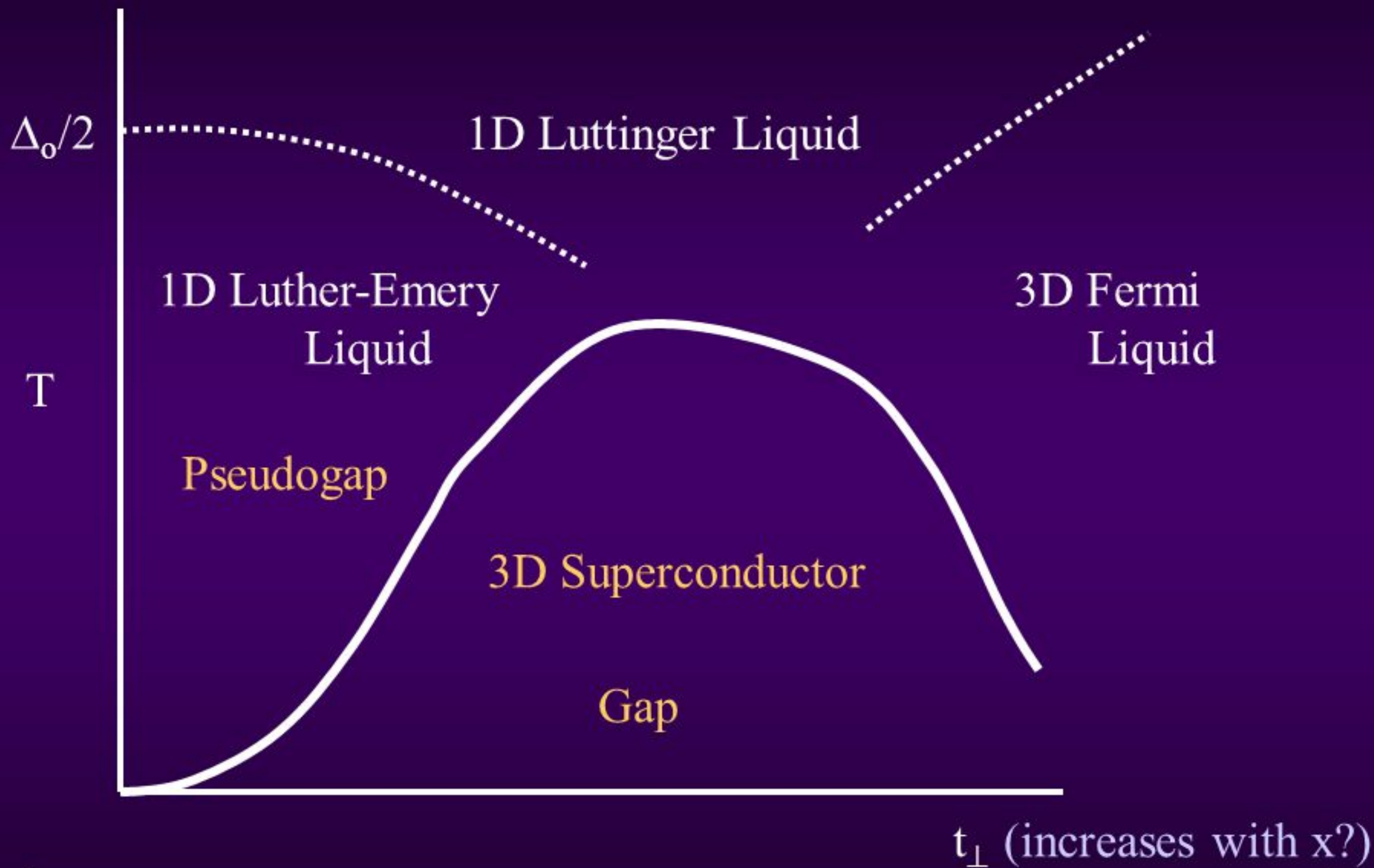# Dimensional Crossover and the Quasiparticle

confinement
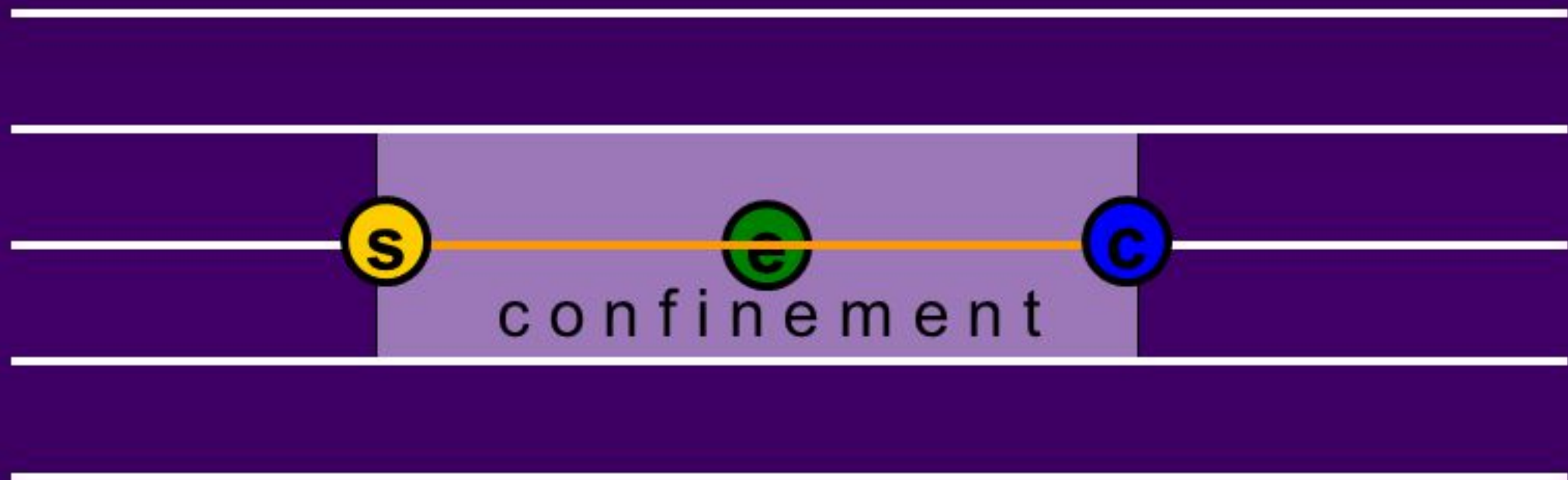
Superconducting order parameter switches sign across each soliton

Chains coupled in superconducting state

Dimensional Crossover and the Quasiparticle

Bound state of spin and charge
→ Electron is stable in superconducting state

Crossover Diagram of a Quasi-1D Superconductor

Is mesoscale structure necessary for high T_c superconductivity?

- Mesoscale structure can enhance pairing (spin-gap)
- May be necessary to get pairing from repulsion
- Always bad for phase ordering

Conclusions

Strongly correlated → Kinetic Energy driven order

     Formation of mesoscale structure

     Formation of pairs by proximity effect

     Phase coherence by pair tunneling between stripes

Quasi-1D Superconductor

     (Controlled calculations)

     Non-Fermi liquid normal state

     Pseudogap state

     Strong pairing from repulsive interactions

     Inherent competition between stripes and superconductivity

     Dimensional crossover to superconducting state