Concepts in High Temperature Superconductivity

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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.**

Review chapter to appear in `The Physics of Conventional and Unconventional Superconductors' ed. by K. H. Bennemann and J. B. Ketterson (Springer-Verlag); 180 pages, including 49 figures

Cond-mat/0206217

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500 references

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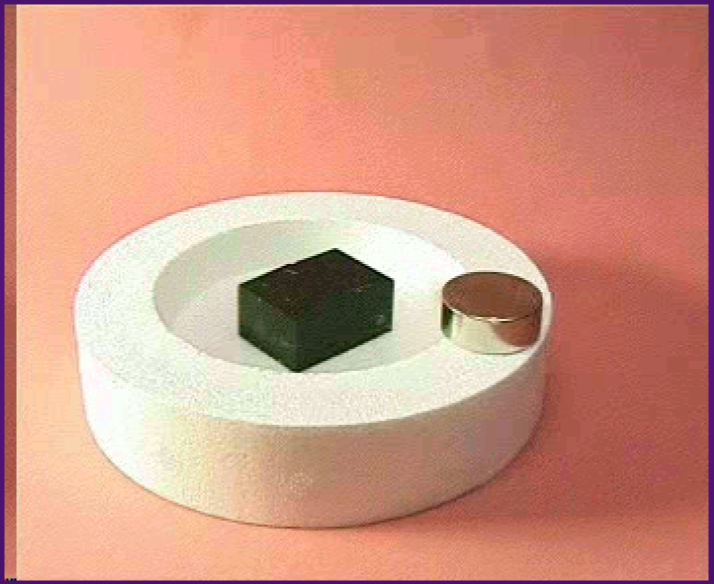
⋮

Superconductivity

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



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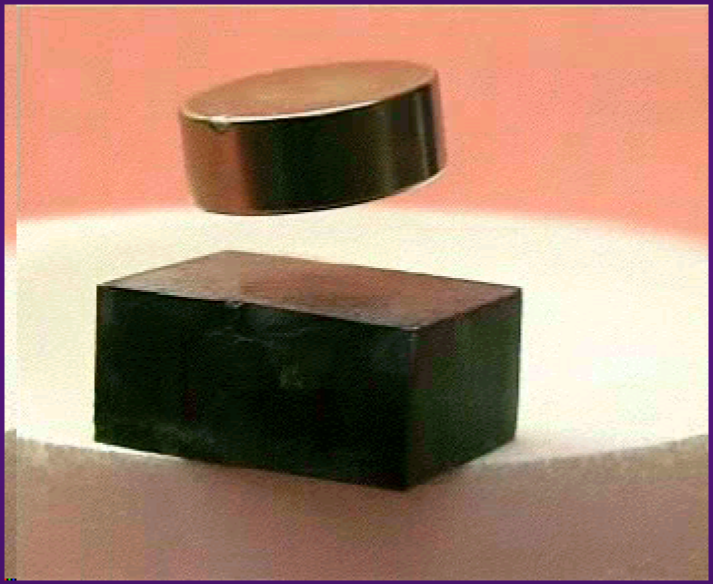
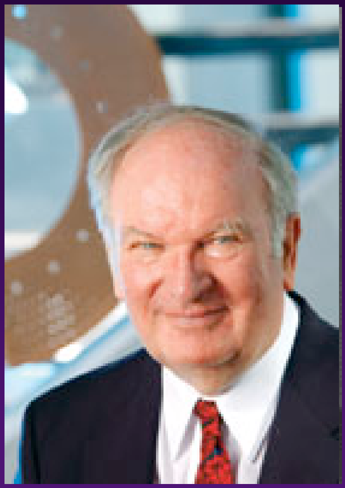


John Bardeen

Leon Cooper

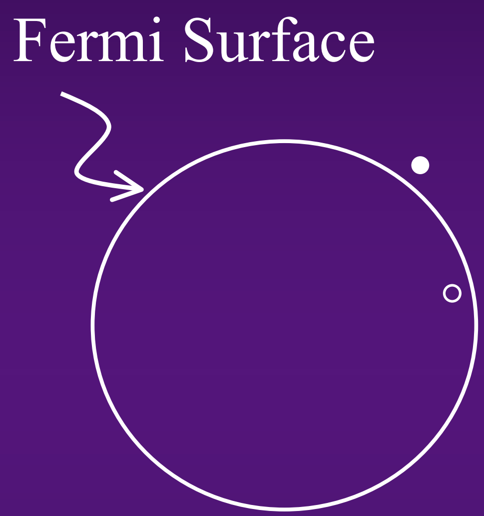


Bob Schrieffer

Conventional Superconductivity

- BCS Theory
- *Instability* of the metallic state

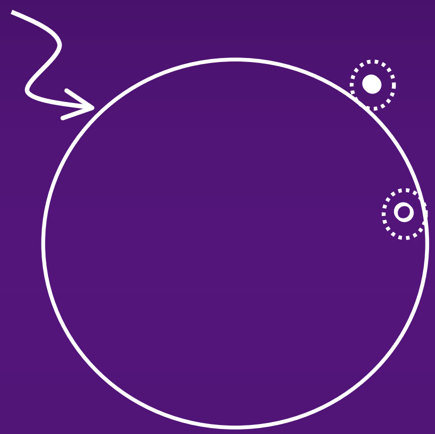
Simple Metals: The Fermi Gas



- Free Electrons E ~ 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



- 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

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

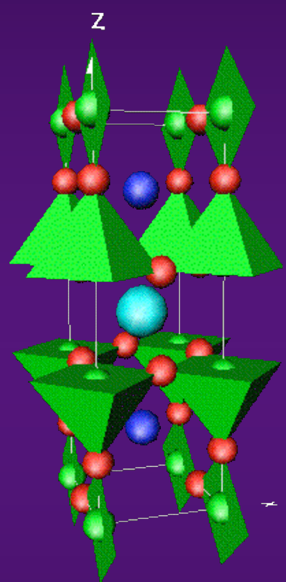
BCS Haiku:

Instability

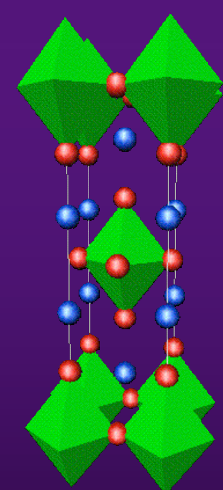
Of A Tranquil Fermi Sea—

Broken Symmetry

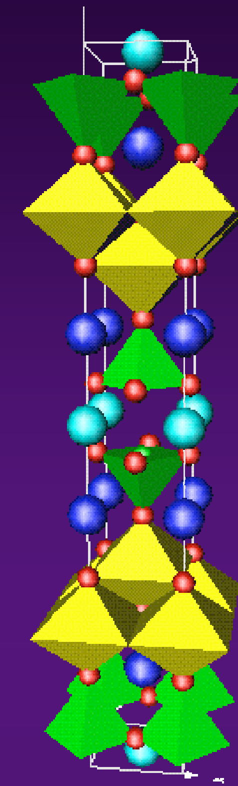
High Temperature Superconductors



$YBCO_7$

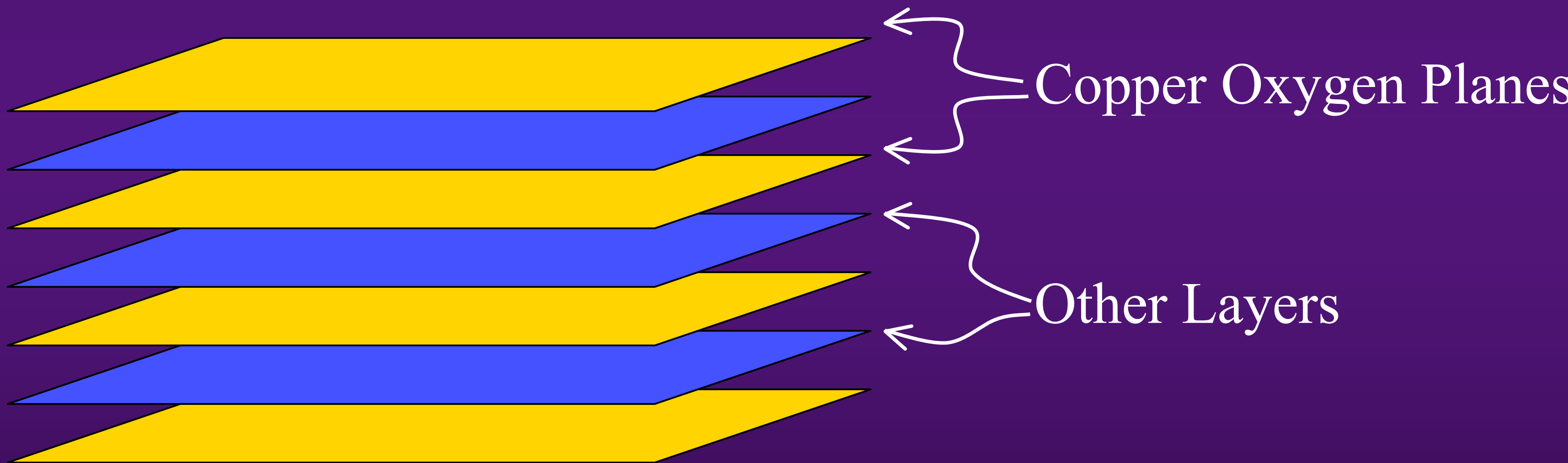


LSCO



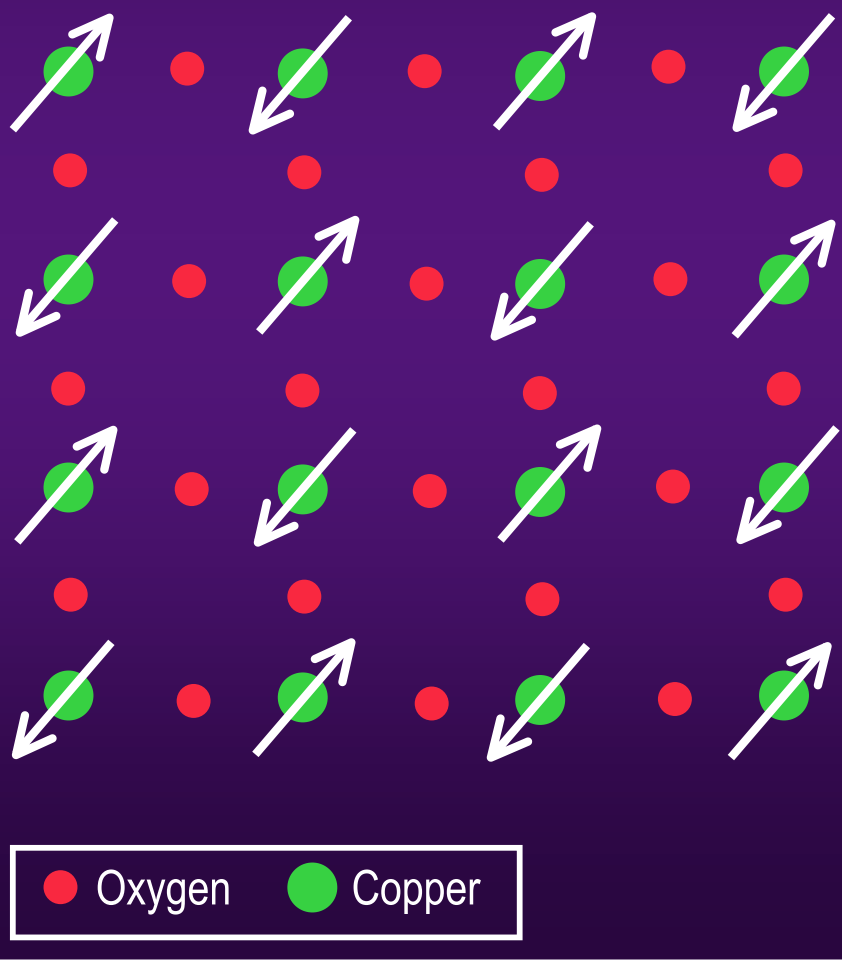
HgCuO

High Temperature Superconductors



Layered structure → quasi-2D system

High Temperature Superconductors



Copper-Oxygen Planes Important

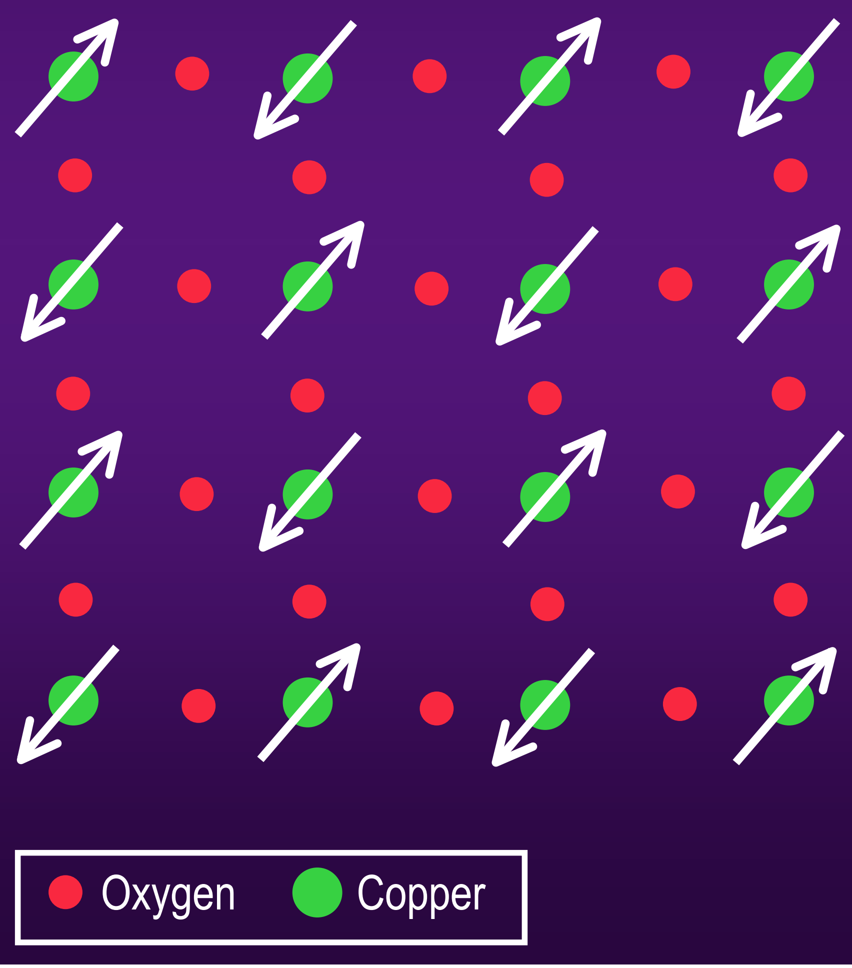
“Undoped” is half-filled

Antiferromagnet

Naive band theory fails

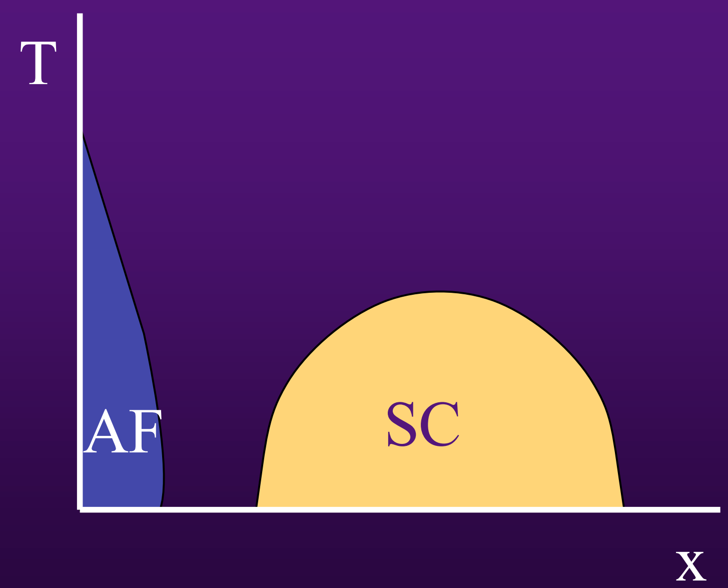
Strongly correlated

High Temperature Superconductors



Dope with holes

Superconducts at certain dopings



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

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

<u>Amplitude</u>

Pairing
Gap

<u>Phase</u>

Phase Coherence
Superfluid Density

BCS is a mean field theory in which pairing precipitates order

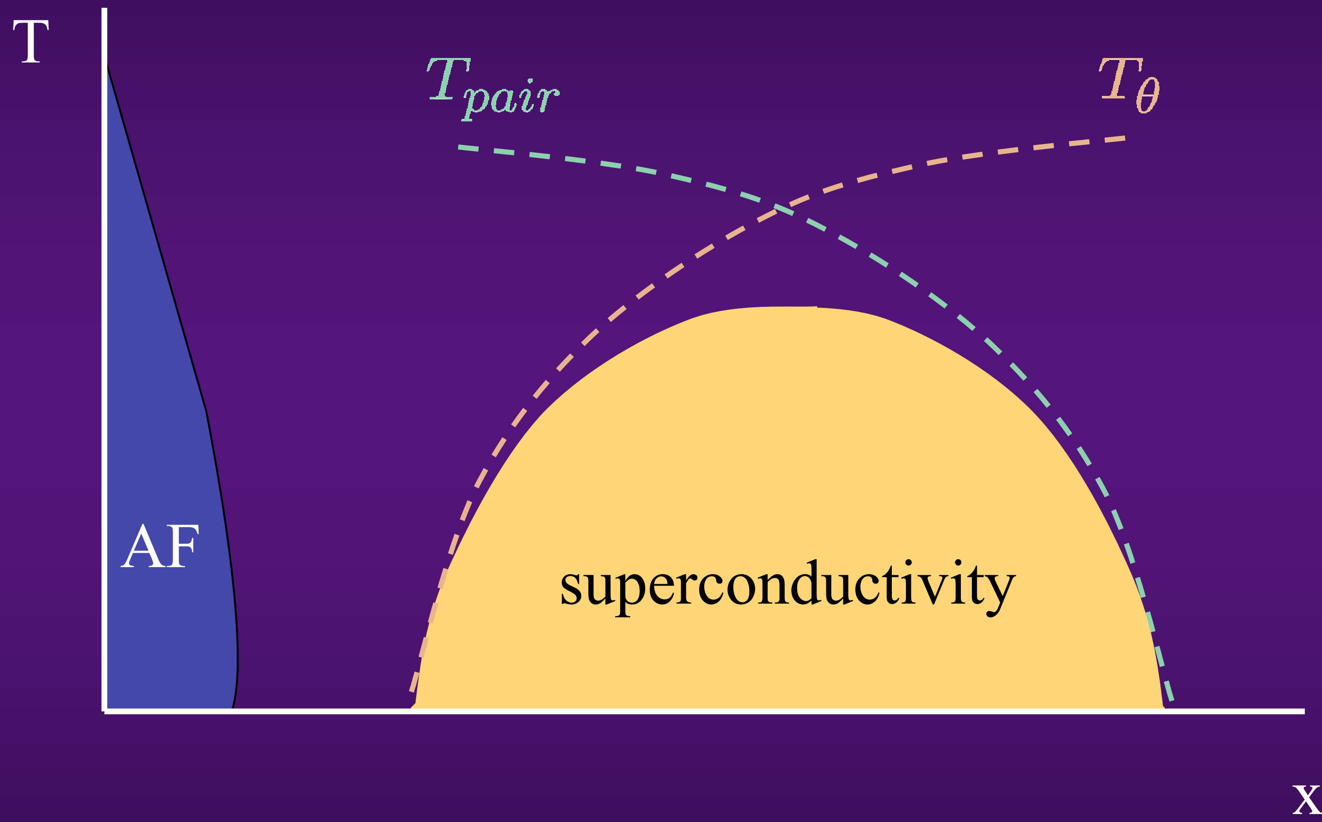
Material	$T_{pair}[K]$	$T_c[K]$	$T_\theta[K]$
Pb	7.9	7.2	$6X10^5$
Nb_3Sn	18.7	17.8	$2X10^4$
UBe_{13}	0.8	0.9	10^2
BaKBiO	17.4	26	$5X10^2$
K_3C_{60}	26	20	10^2
MgB_2	15	39	$1.4X10^3$

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

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  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: $\frac{E_F}{\omega_D} \approx 10^3$
- Cuprates: $\frac{E_F}{\omega_D} \approx 5$

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?

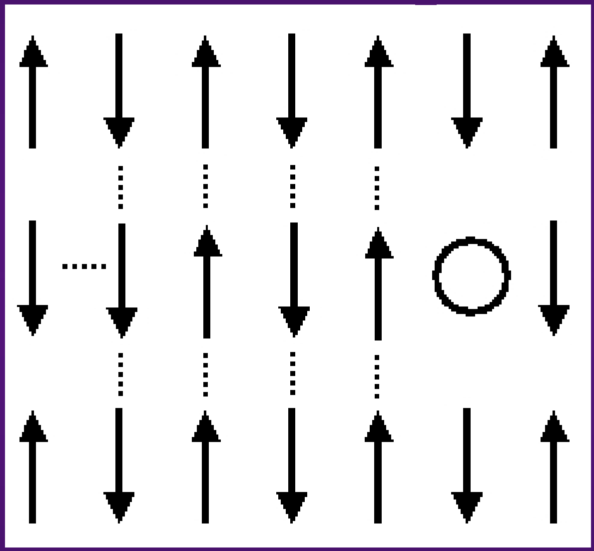
Fermi Liquid

- 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

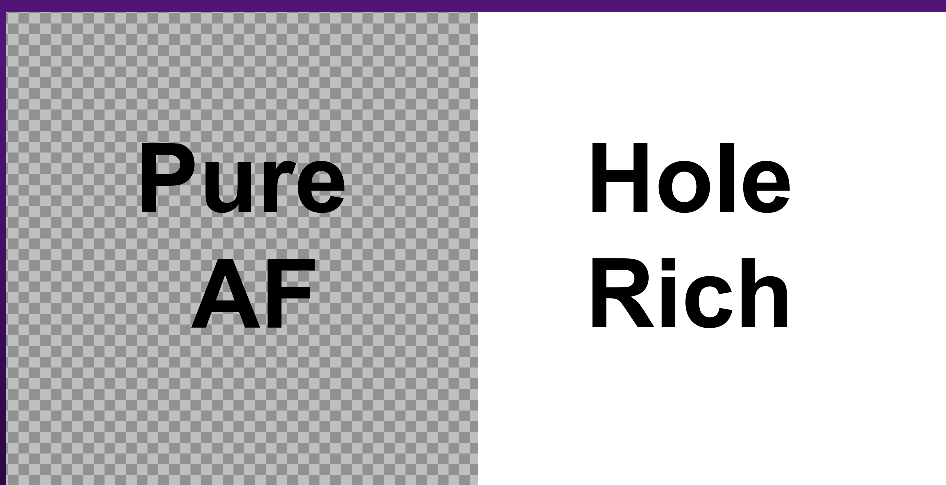
Doped Antiferromagnets



Hole Motion is Frustrated

Doped Antiferromagnets

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

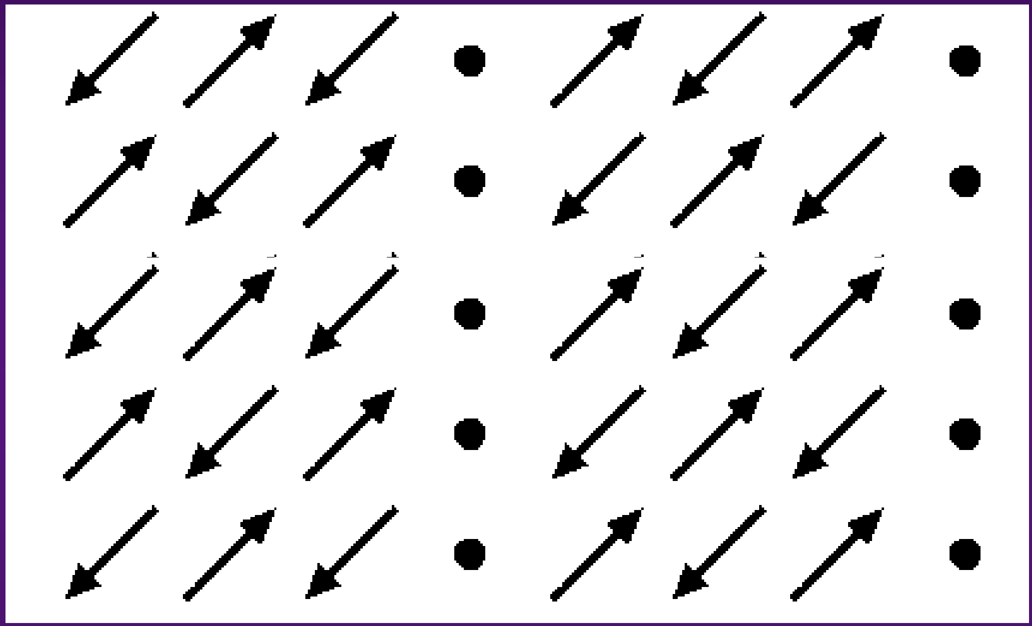


Like Salt Crystallizing
From Salt Water,
The Precipitate (AF) is Pure

Coulomb Frustrated Phase Separation

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

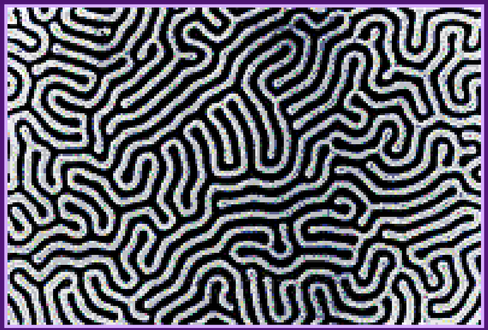
Stripes



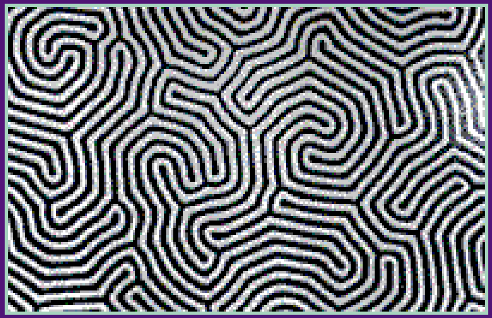
Rivers of charge between antiferromagnetic strips

Electronic structure becomes effectively 1D

Competition often produces stripes

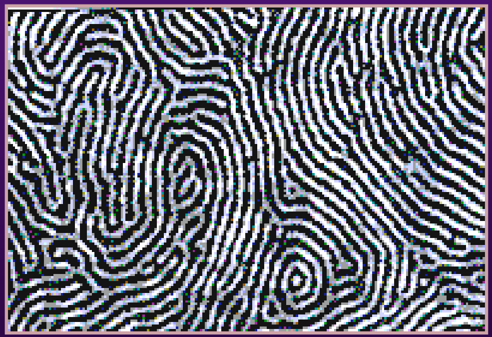


Ferrofluid
confined between
two glass plates
Period ~ 1cm

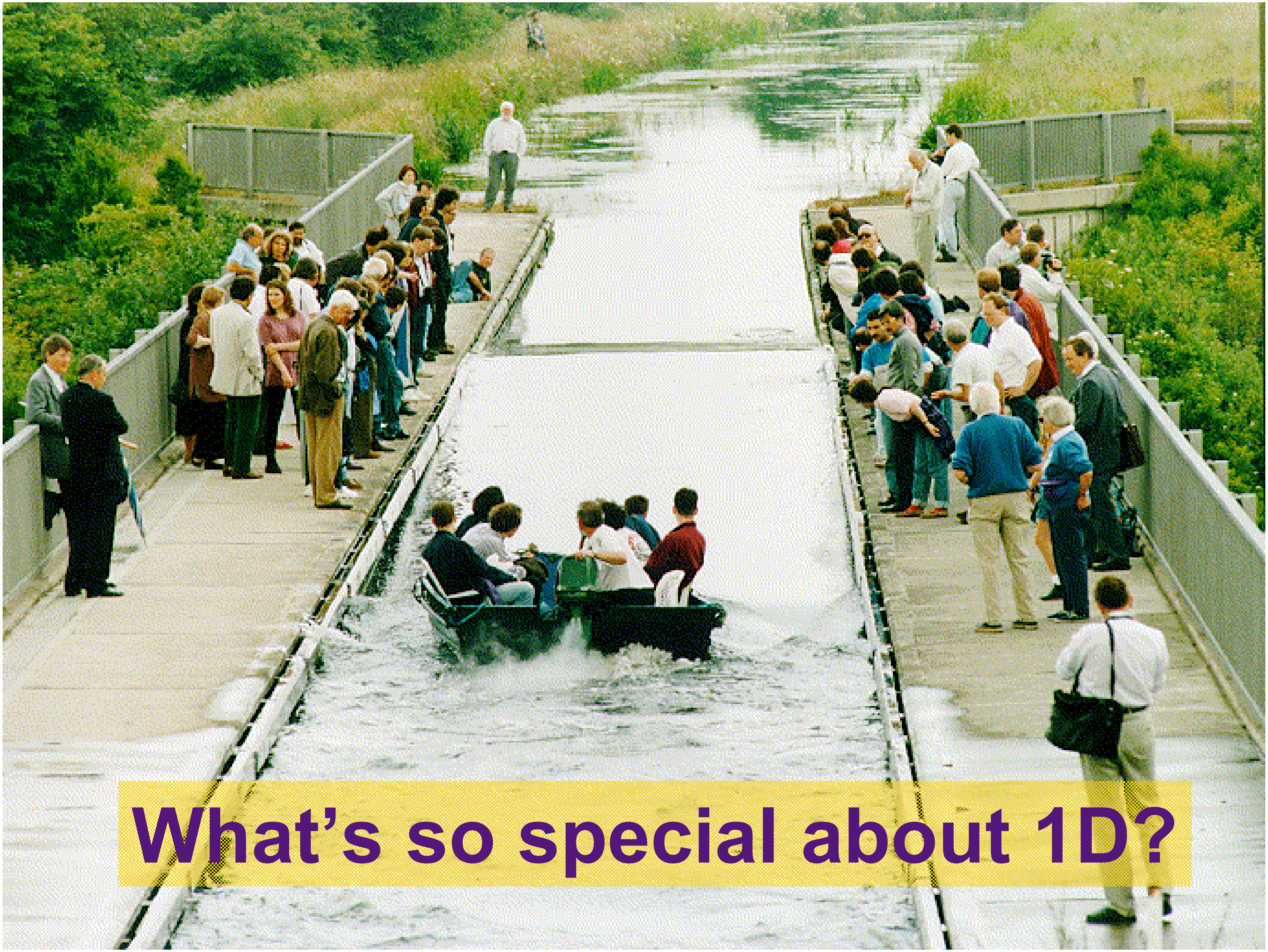


Ferromagnetic
garnet film
Faraday effect
Period ~ 10^{-5} m

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

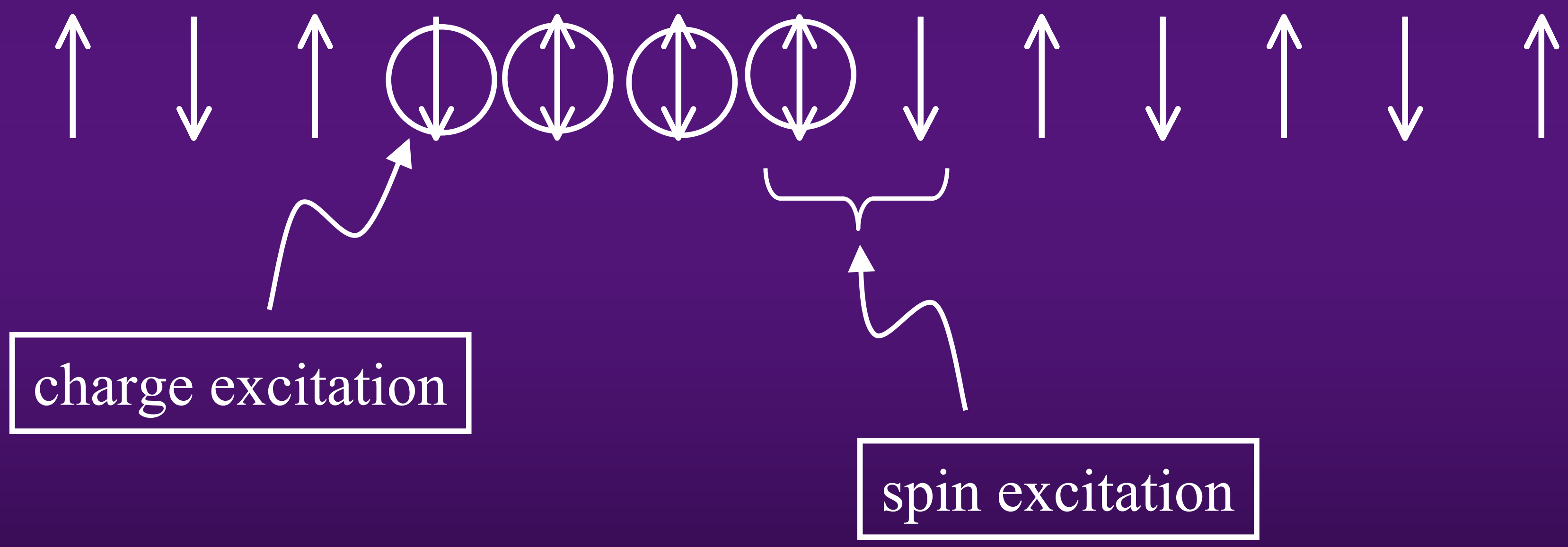


Block copolymers
Period ~ $4X10^{-8}$ m



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

Hamiltonian of interacting fermions

becomes Hamiltonian of non-interacting bosons

Spin Charge Separation
Electron No Longer Exists!

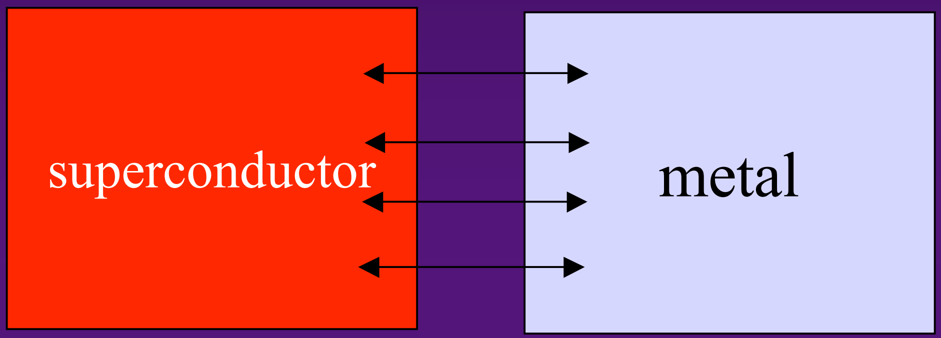
Non-Fermi Liquid
(Luttinger Liquid)

Advantages of a quasi-1D Superconductor

- non-Fermi liquid
- strongly correlated
- controlled calculations

Kinetic Energy Driven Pairing?

→ Proximity Effect



Individually, free energies minimized

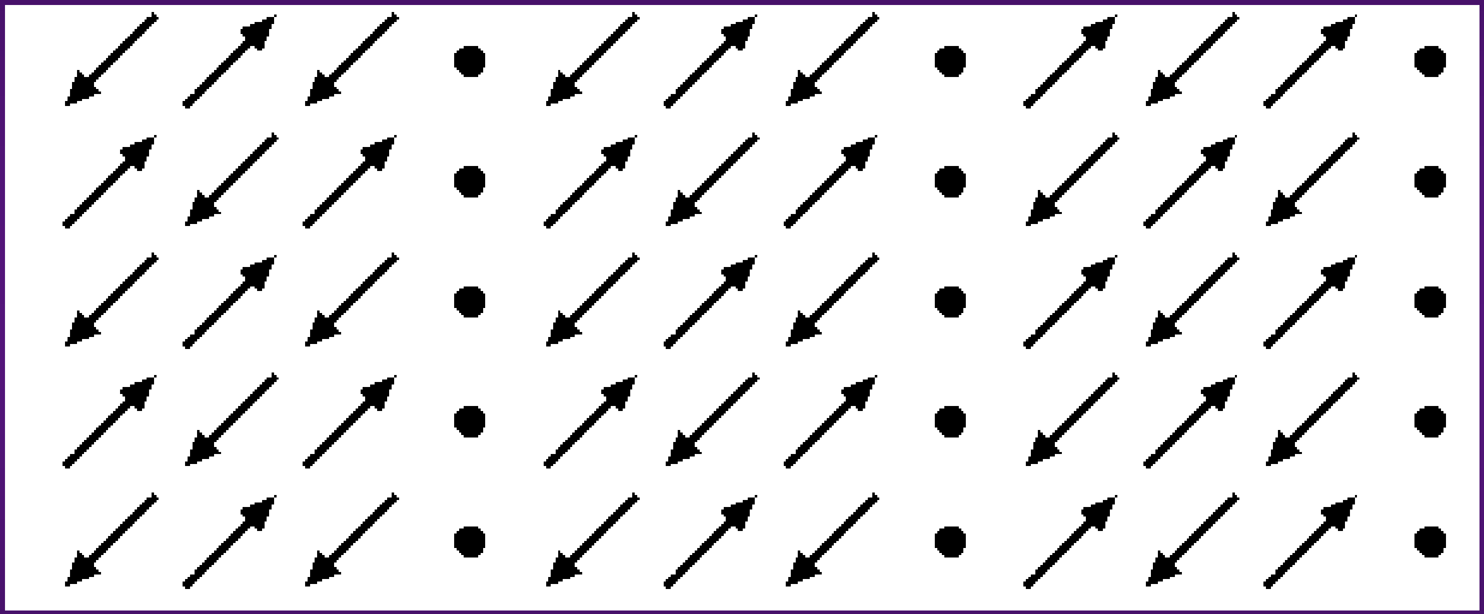
Metal pairs (at a cost!) to minimize kinetic energy across the barrier

Spin Charge Separation

- 1D spin-charge separation
- Pair spins only
- Avoid Coulomb Repulsion!

Spin Gap Proximity Effect

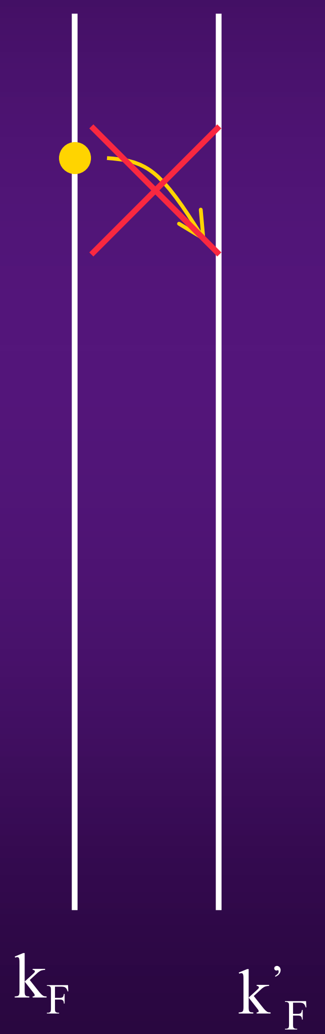
Kinetic energy driven pairing in a quasi-1D superconductor



Metallic charge stripe acquires spin gap through communication with gapped environment

Spin Gap Proximity Effect

Kinetic energy driven pairing in a quasi-1D superconductor

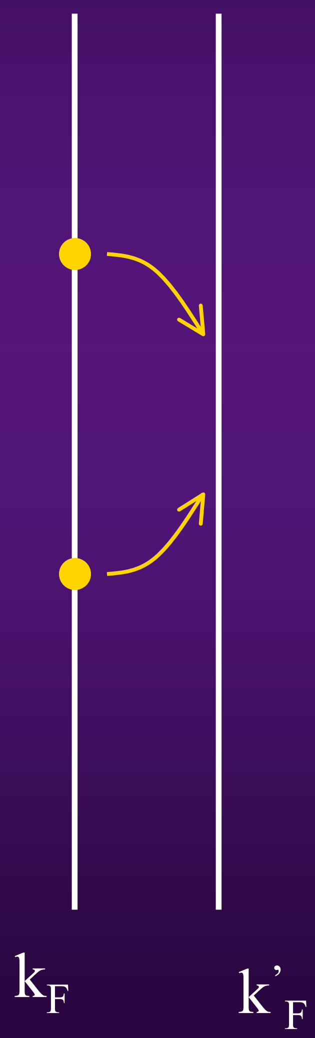


$k_F \neq k'_F$

Conserve momentum and energy
Single particle tunneling is irrelevant

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

1D is Special

Spin Gap = CDW Gap = Superconducting Gap

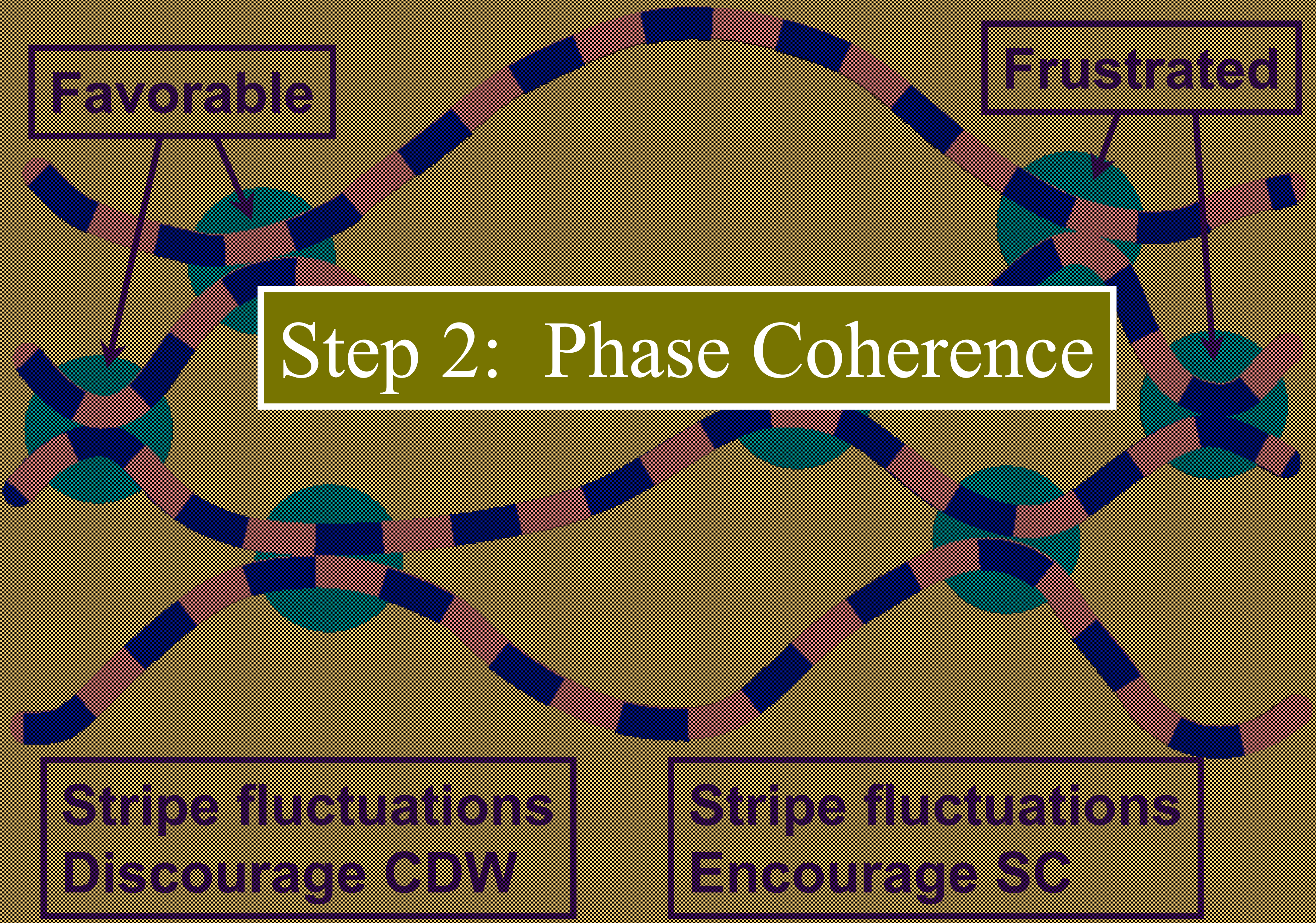
$$\chi_{CDW} \approx \Delta_S T^{(K_c - 2)} \qquad \chi_{SS} \approx \Delta_S T^{(1/K_c - 2)}$$

Which will win?

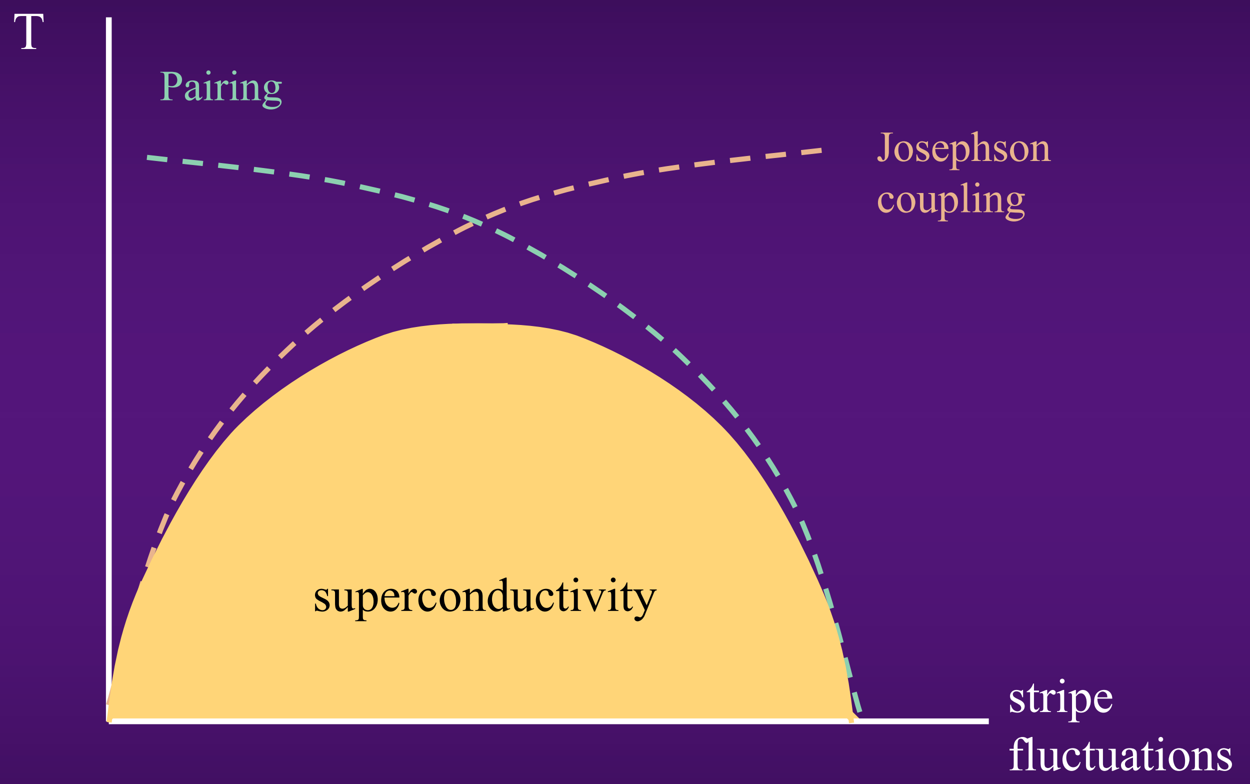
CDW stronger for repulsive interactions (K_c<1)

Don't Make a High Temperature Insulator!

Stripe Fluctuations



Inherent Competition



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

→ think local stripe order

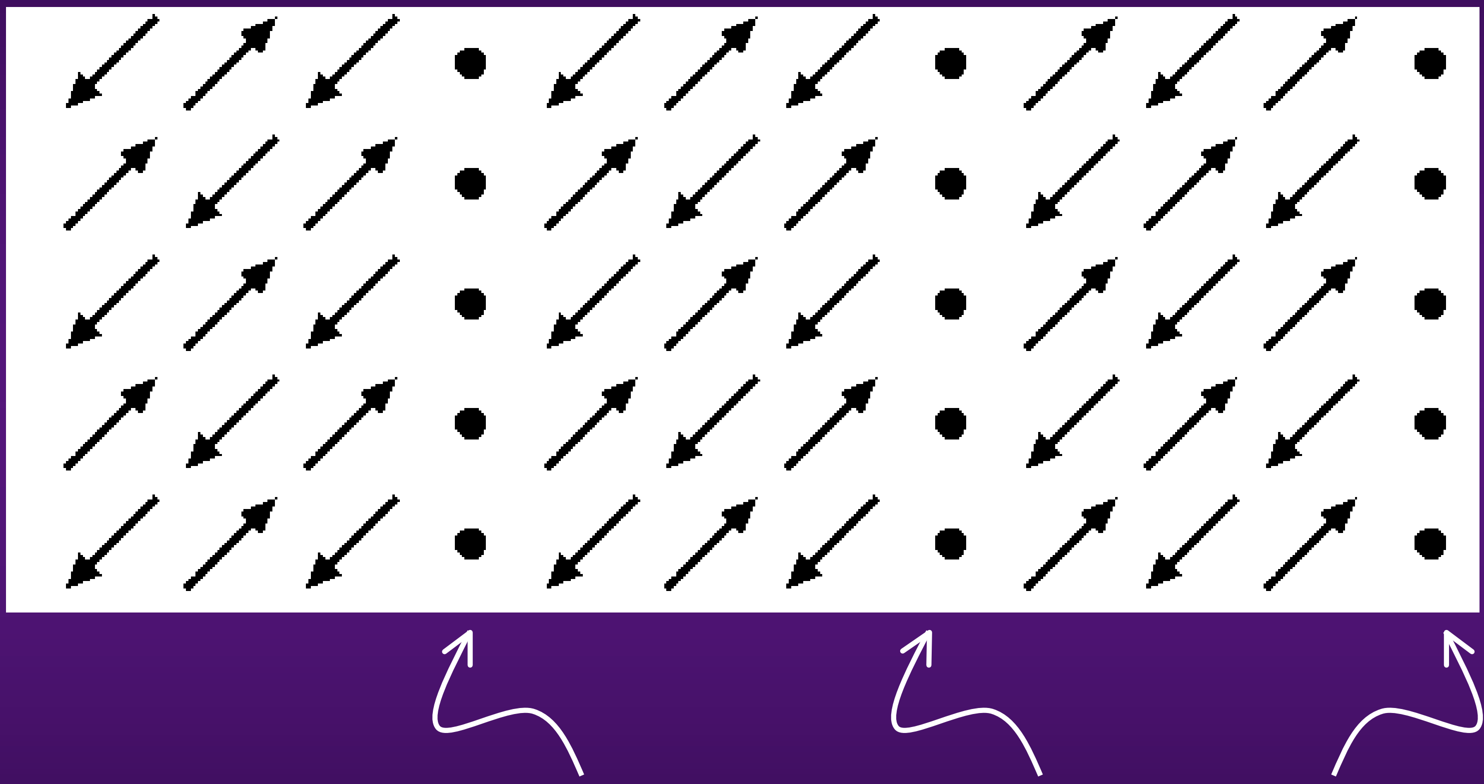
$\Delta_{SC} << \hbar\omega_{stripe}$

→ 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

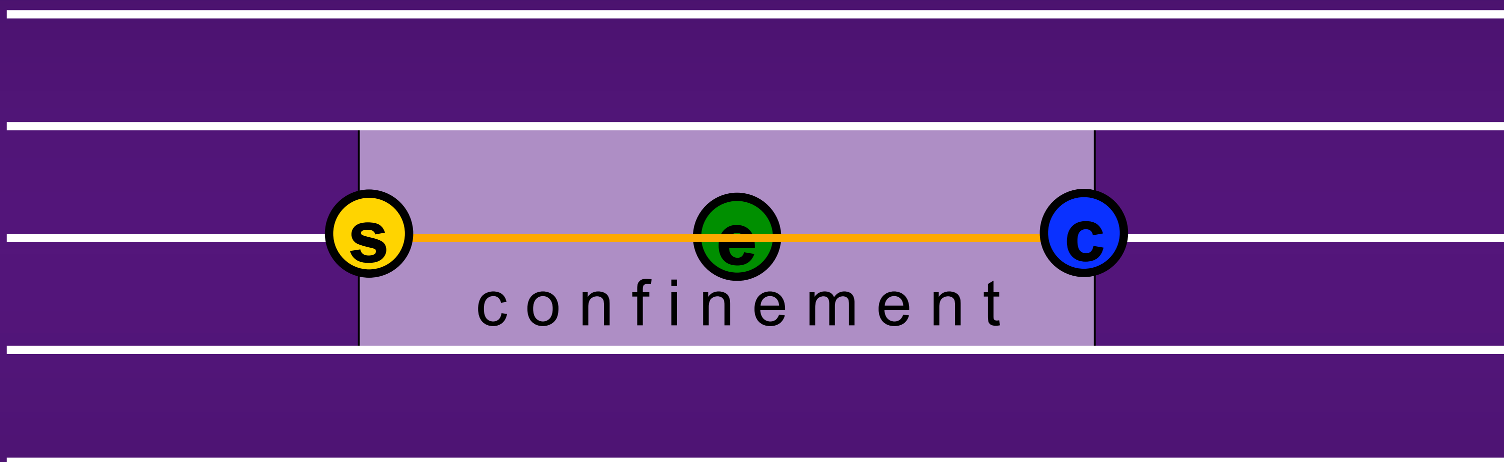
Effective Dimension = 3

1D system cannot order → Dimensional Crossover

Pair tunneling between rivers produces phase coherence

Electron recombines

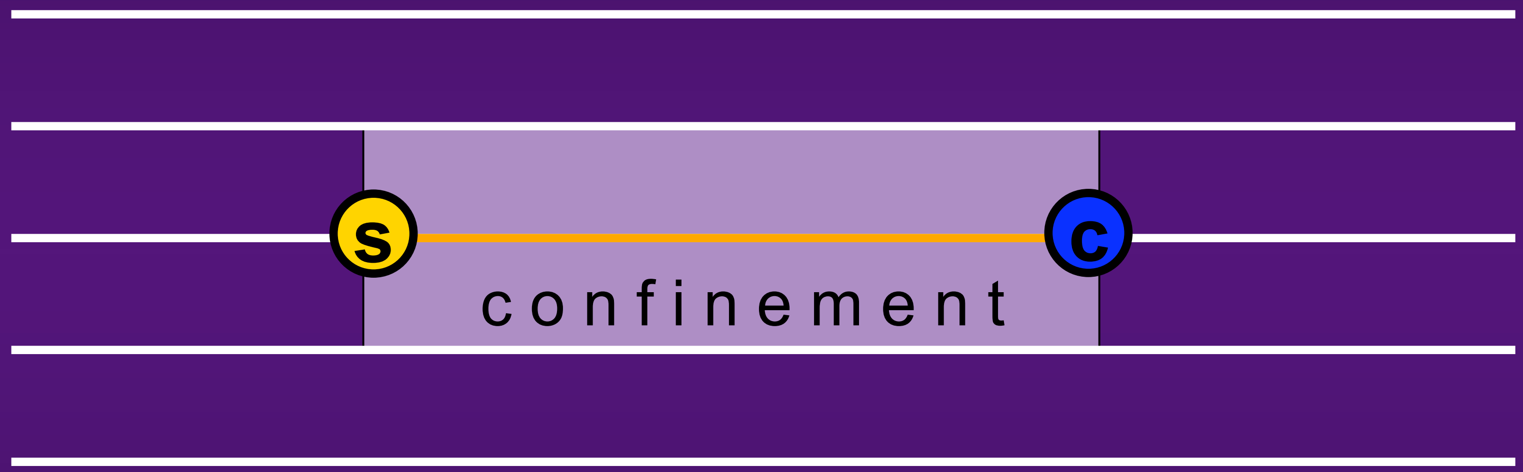
Dimensional Crossover and the Quasiparticle



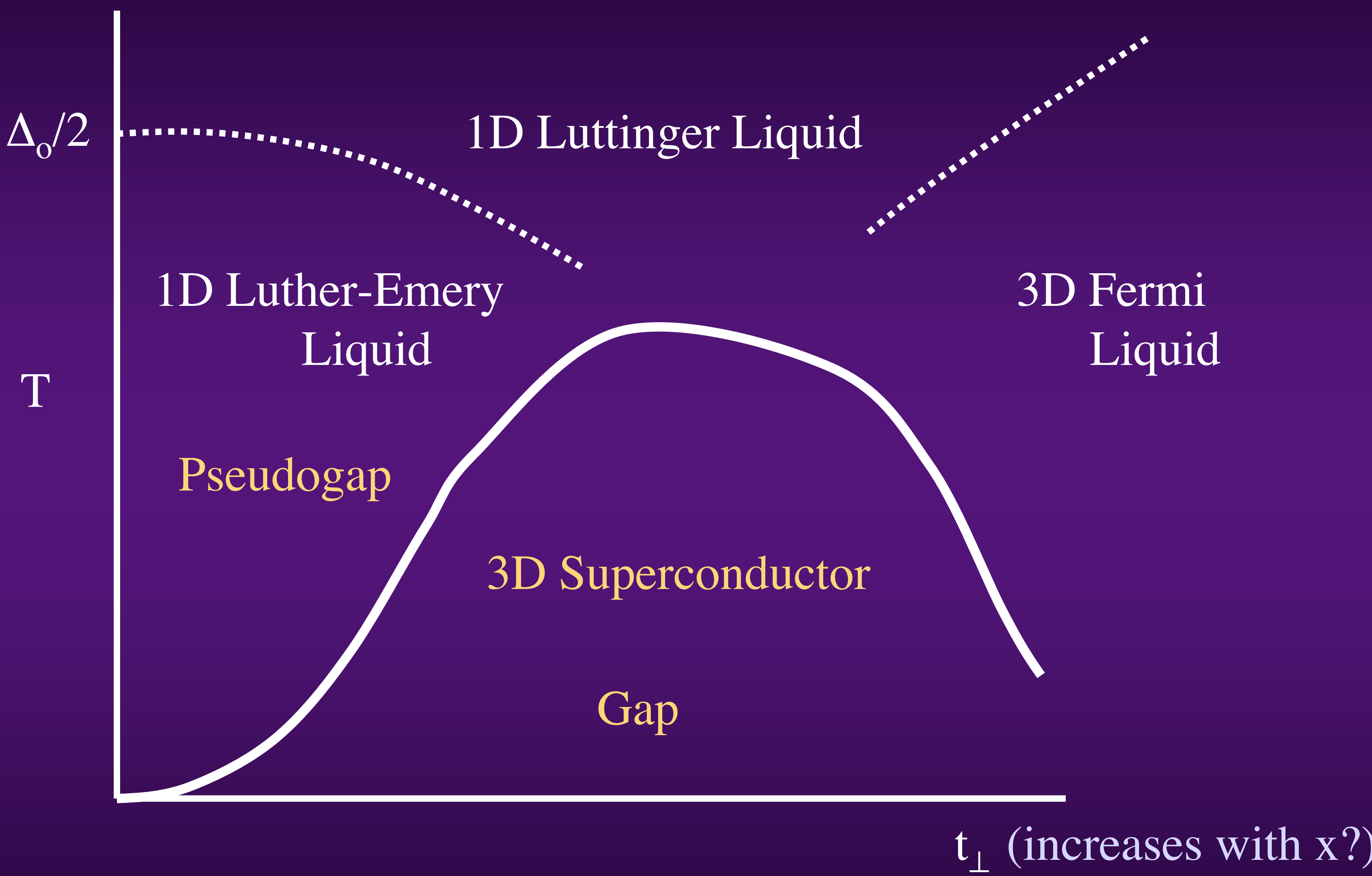
Superconducting order parameter switches sign across each soliton

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