From “Schmutzphysik” to “More is Different”:
a perspective on the modern condensed matter physics

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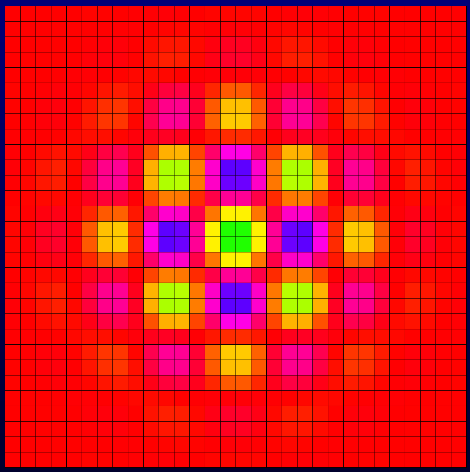


January 10, 2004

Wolfgang E. Pauli:
“Festkörpernphysik ist eine Schmutzphysik.”

“Condensed matter physics is physics of dirt.”

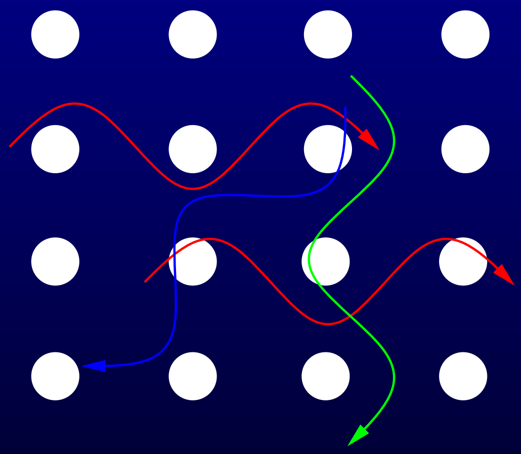
Philip W. Anderson:
“More is different!”

Collective phenomena in condensed matter systems.

Schmutzphysik “theory of everything”

$$H_{CM} = \sum_{i=1}^{N} \frac{\mathbf{p}_i^2}{2m_i} + \sum_{i<j} \frac{q_i q_j}{|\mathbf{r}_i - \mathbf{r}_j|}$$

Electrons + ions interacting via Coulomb forces.



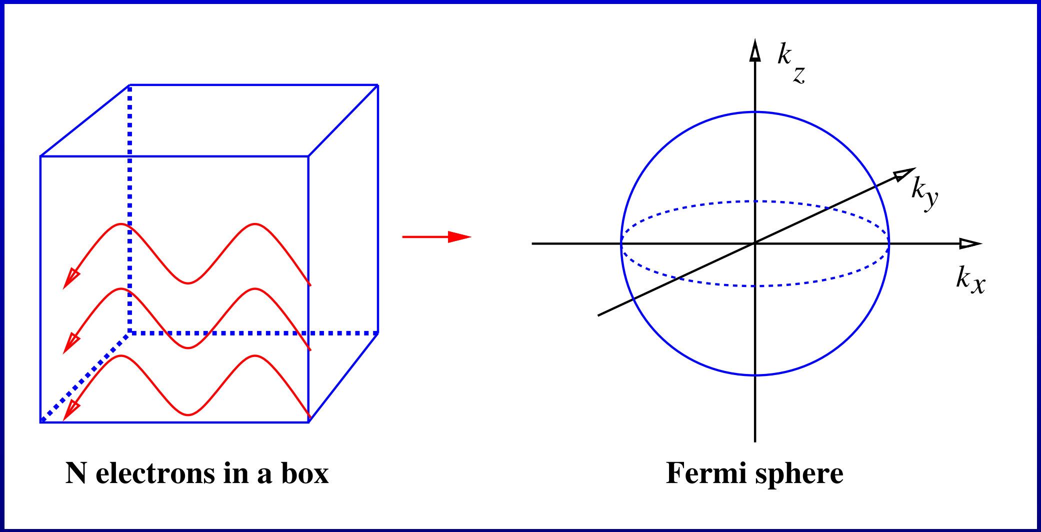
The problem is with $N \approx 10^{23}$ particles in every cm^3 of matter.

Landau's Fermi liquid paradigm

Lev Davidovich Landau:

"Electron states in solids are adiabatically connectible to the states of noninteracting electron gas"

Despite enormous Coulomb forces ($U_C \sim \frac{e^2}{a_0} \sim 1 - 10$eV) at low energies most metals behave like a free electron gas [Landau, 1957]



$$\epsilon(\mathbf{k}) = \frac{\hbar^2 \mathbf{k}^2}{2m^*}, \quad k_F = (3\pi^2 n)^{1/3}$$

Ground state ($T = 0$): all levels below Fermi momentum k_F are filled; levels above k_F empty.

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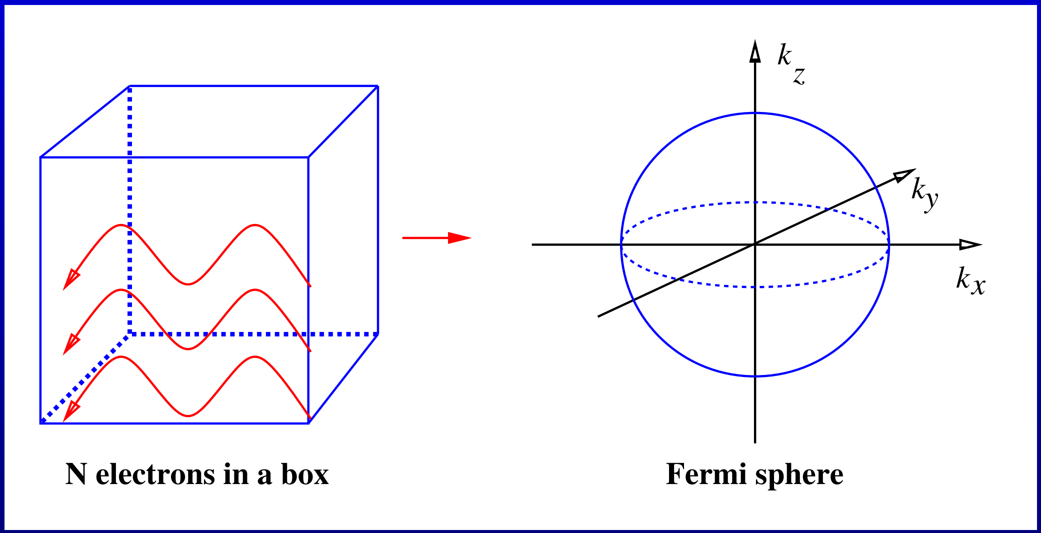

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Root cause: Pauli exclusion principle

$\rightarrow$ phase space for scattering near FS is severely limited.

Structure of electron propagator in FL

$$G(\mathbf{k},\omega) = \frac{1}{\omega - \epsilon_{\mathbf{k}} - \Sigma(\mathbf{k},\omega)} = \frac{z_{\mathbf{k}}}{\omega - E_{\mathbf{k}} + i\Gamma_{\mathbf{k}}} + G_{\text{incoh}}(\mathbf{k},\omega)$$

with

$z_{\mathbf{k}}^{-1} = [1 - \frac{\partial \mathrm{Re}\Sigma}{\partial \omega}]_{\omega = E_{\mathbf{k}}}$, “quasiparticle weight”

$\tau^{-1} \equiv \Gamma_{\mathbf{k}} \sim (E_{\mathbf{k}} - E_F)^2$, “quasiparticle lifetime”

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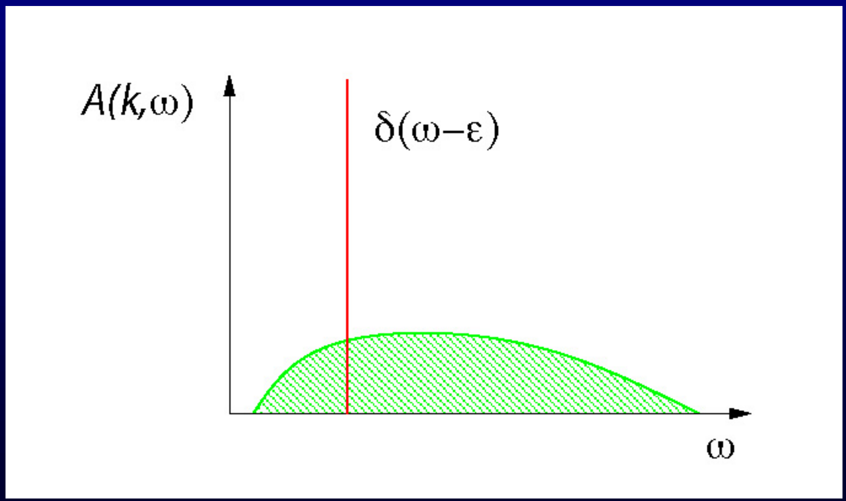
Spectral function:

$$\begin{aligned} A(\mathbf{k},\omega) &= -2\mathrm{Im}G(\mathbf{k},\omega) \\ &\simeq z_{\mathbf{k}}\delta(\omega - E_{\mathbf{k}}) + A_{\mathrm{incoh}}(\mathbf{k},\omega) \end{aligned}$$



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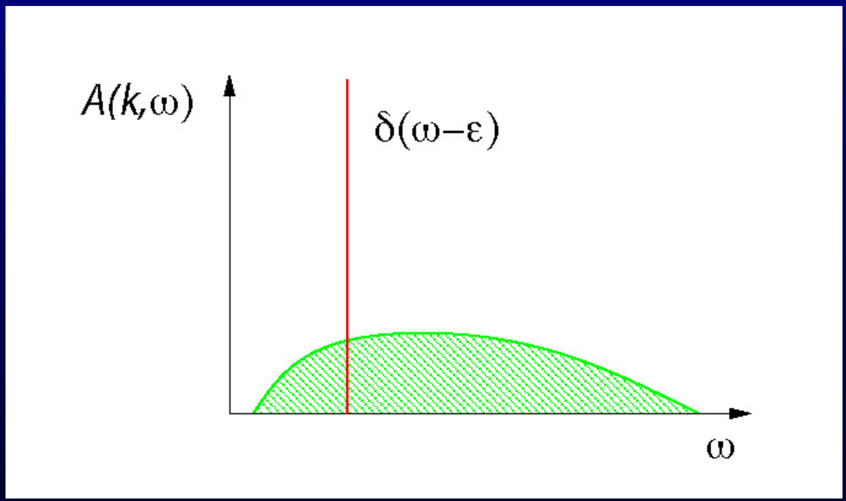

Electron remains a sharp excitation at FS.

Exceptions to FL paradigm

- 1D interacting systems (a.k.a. “Luttinger Liquids”)

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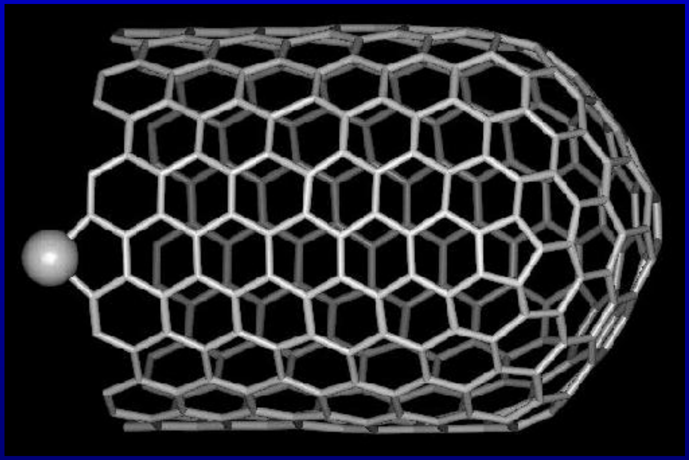
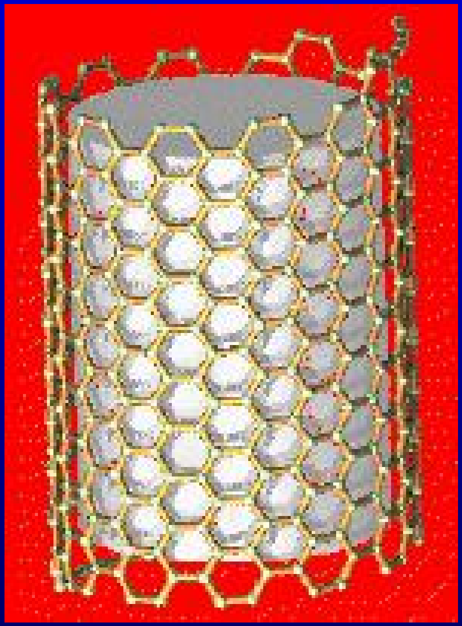
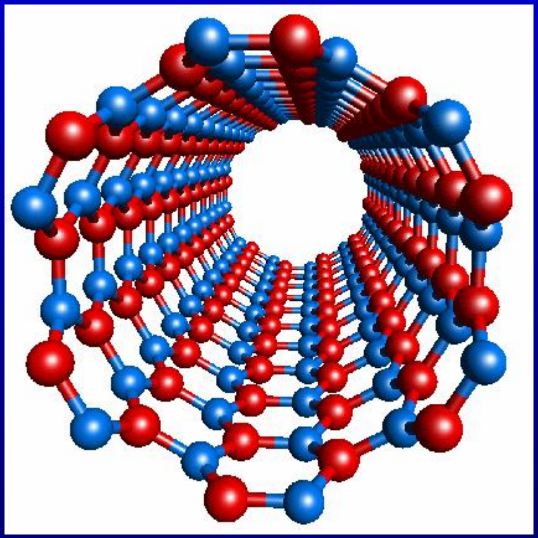
- Quantum Hall Fluids
- Systems near Quantum Criticality
- High-T_c Cuprate Superconductors (?)

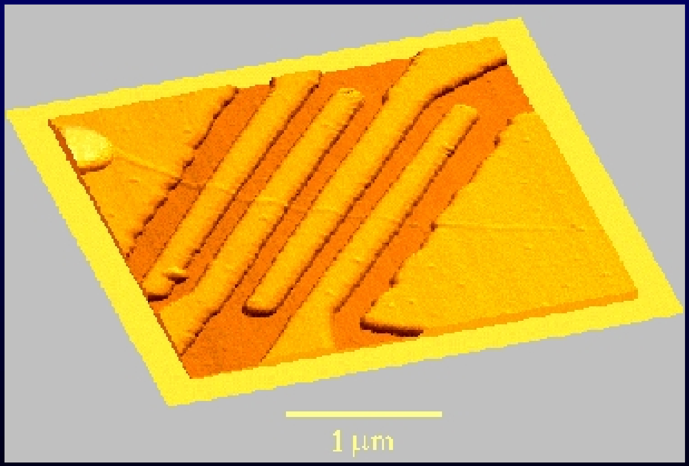
1D interacting systems

- carbon nanotubes, cleaved edge quantum wires





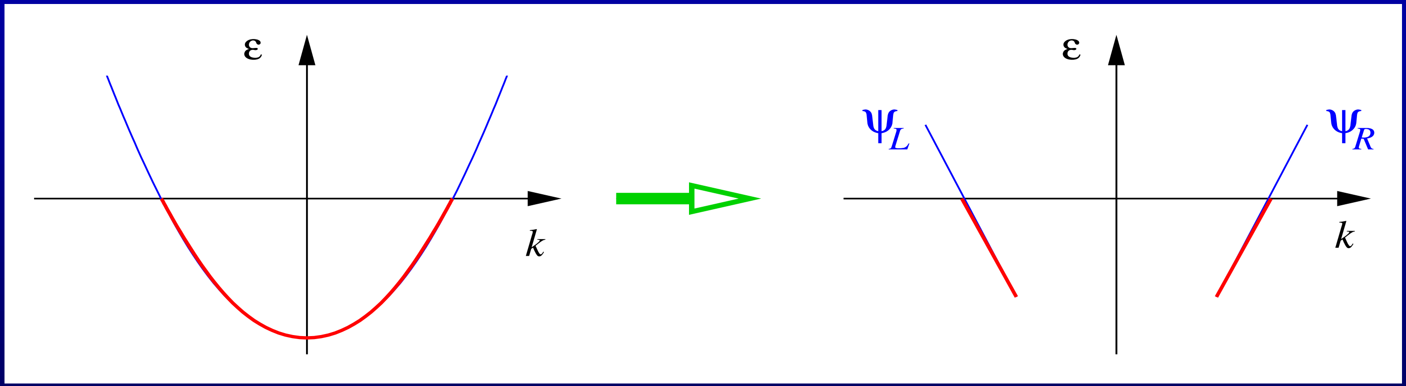




Description via "Bosonized" Hamiltonian:

$$H = v_F \left[\frac{g}{2} (\nabla \phi)^2 + \frac{1}{2g} (\nabla \theta)^2 \right], \quad \psi_{\mathrm{L/R}} \sim e^{i(\phi \pm \theta)}.$$

with g an interaction parameter; $g = 1$ for free electron gas while $g \neq 1$ when interactions present.



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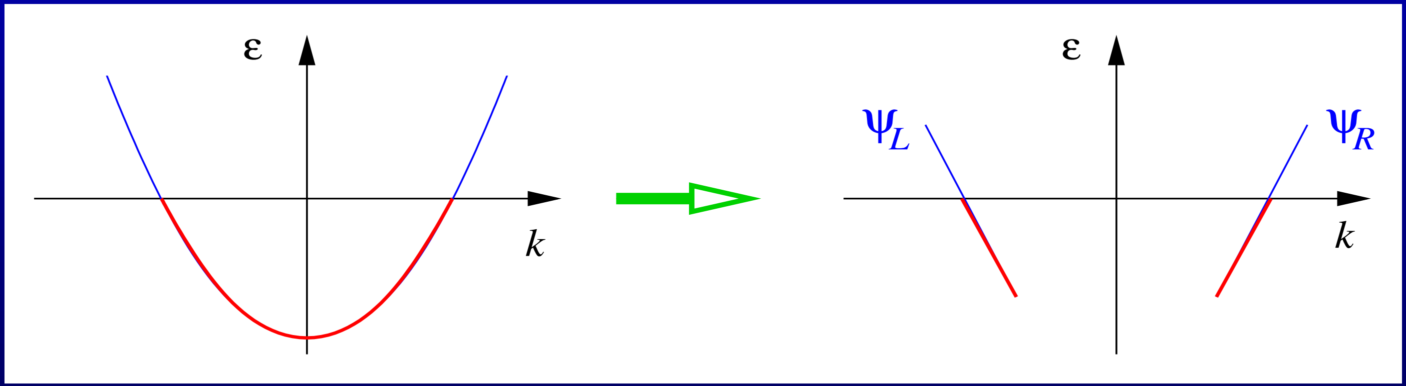


$\longrightarrow$ Luttinger liquid

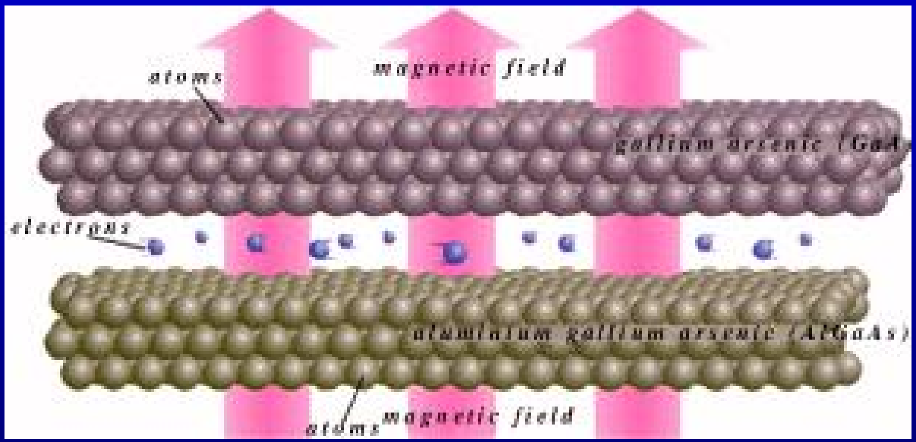
Electron correlations algebraic:

$$G(x,t) \approx (x - v_F t)^{-(g+g^{-1})/2}.$$

No sharp quasiparticles; $z_{\mathbf{k}} = 0$.

2D Quantum Hall Fluids

- 2D electron gas in strong magnetic field B.



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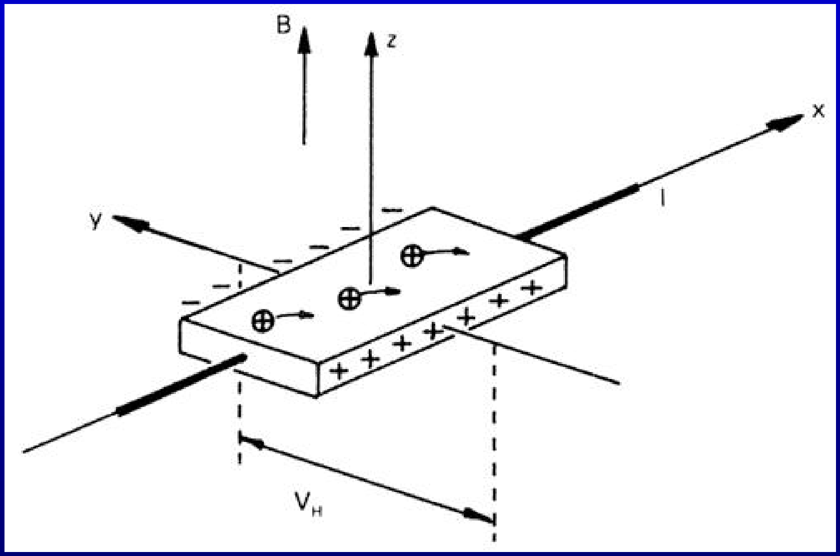

Experimental setup: “Hall effect geometry”

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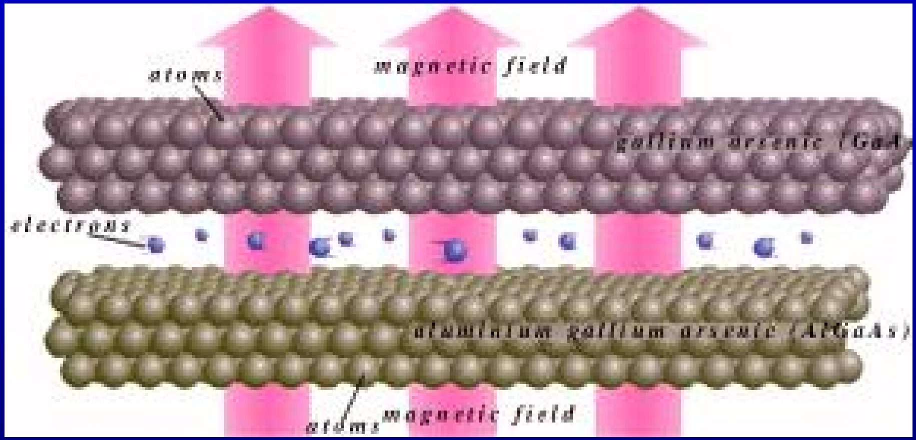

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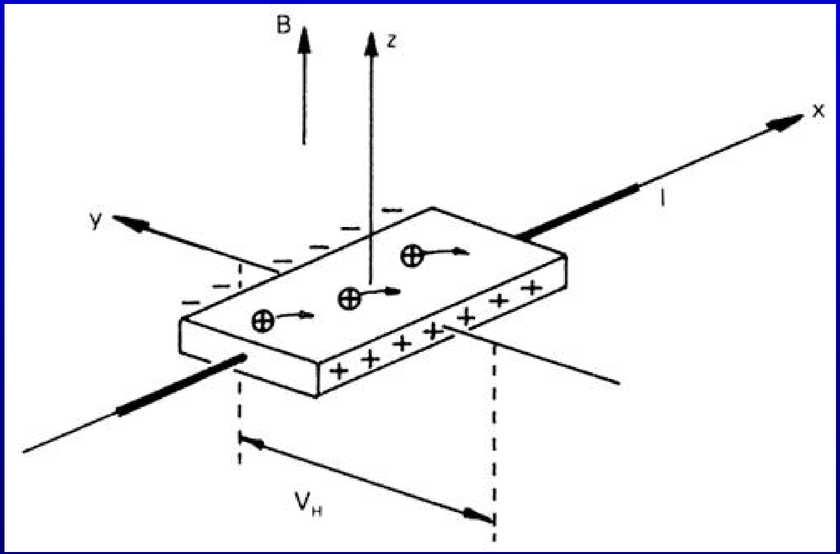
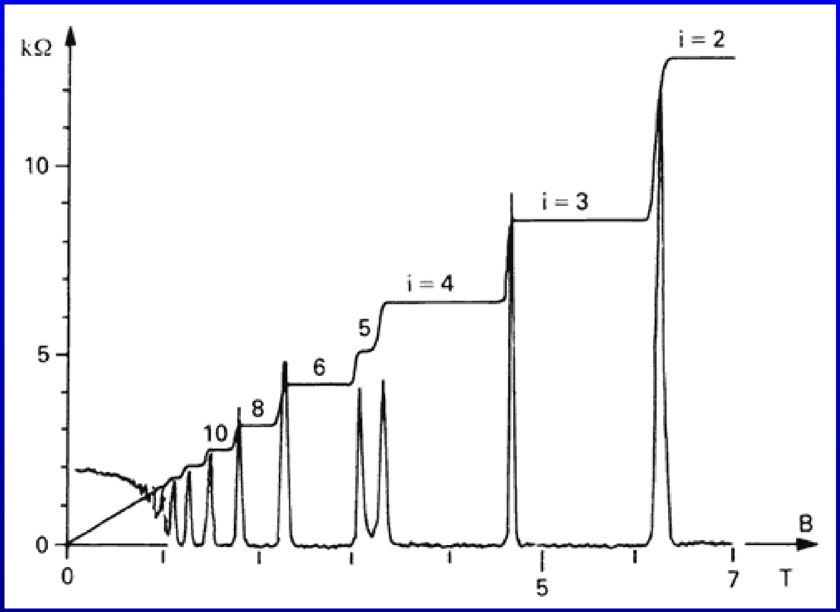
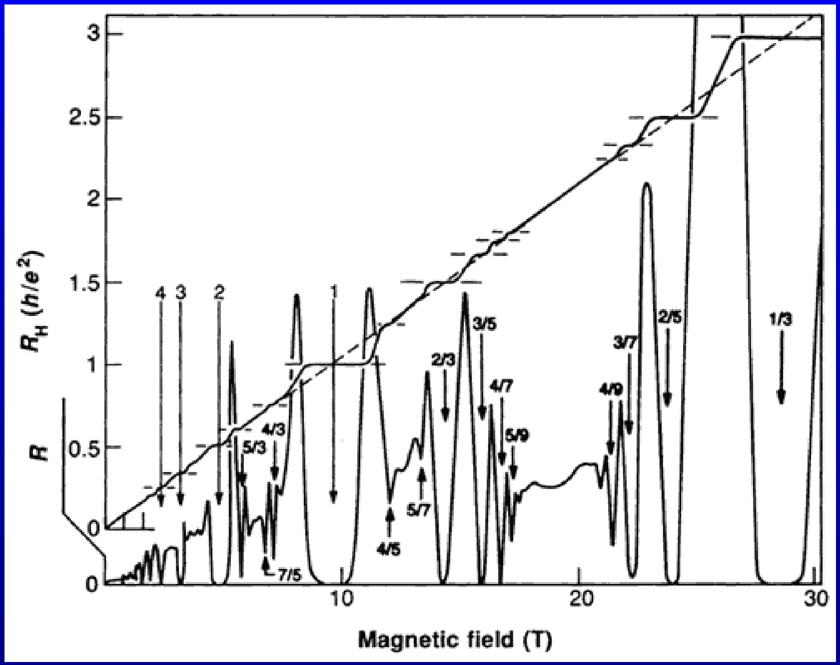


Experimental setup: “Hall effect geometry”

Classically, the magnetoresistance ρ_{xx} should be field independent while the Hall resistance ρ_{xy} proportional to B.



“integer” [von Klitzing, 1980]



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The Hall resistance is quantized,

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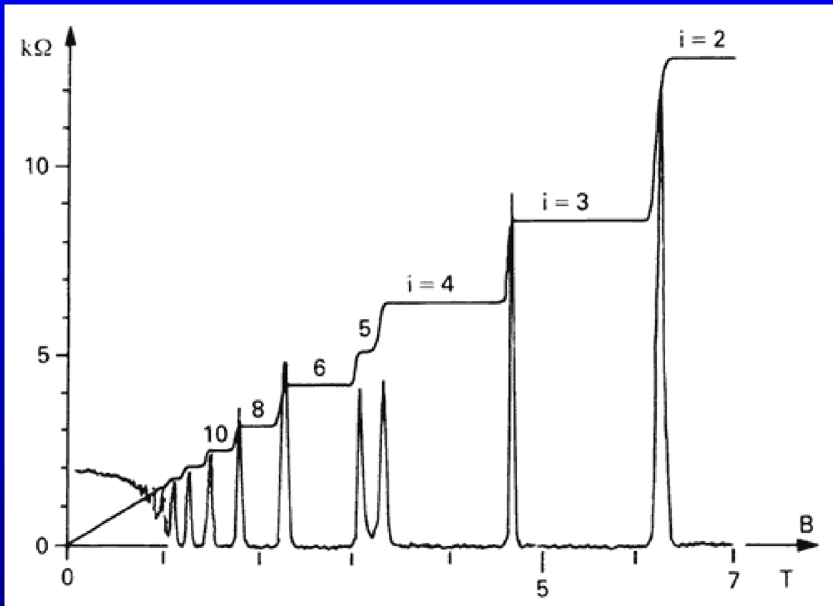

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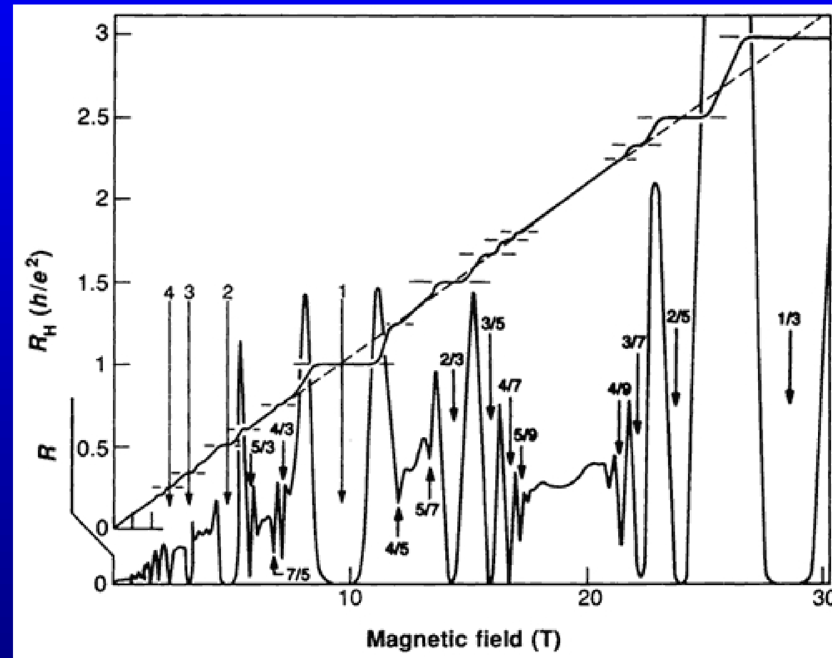

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In fractional QHE experiment indicates that elementary excitations carry *fractional charges*.

Laughlin's wavefunction ($z = x - iy$):

$$\psi_m(\{z\}) = \prod_{j<k}^{N} (z_j - z_k)^m \prod_{j=1}^{N} e^{-|z_j|^2/4\ell_0^2}$$


Bob Laughlin

Incompressible quantum fluid with fractionally charged elementary excitations ($q = e/m$, m being an inverse "filling fraction").

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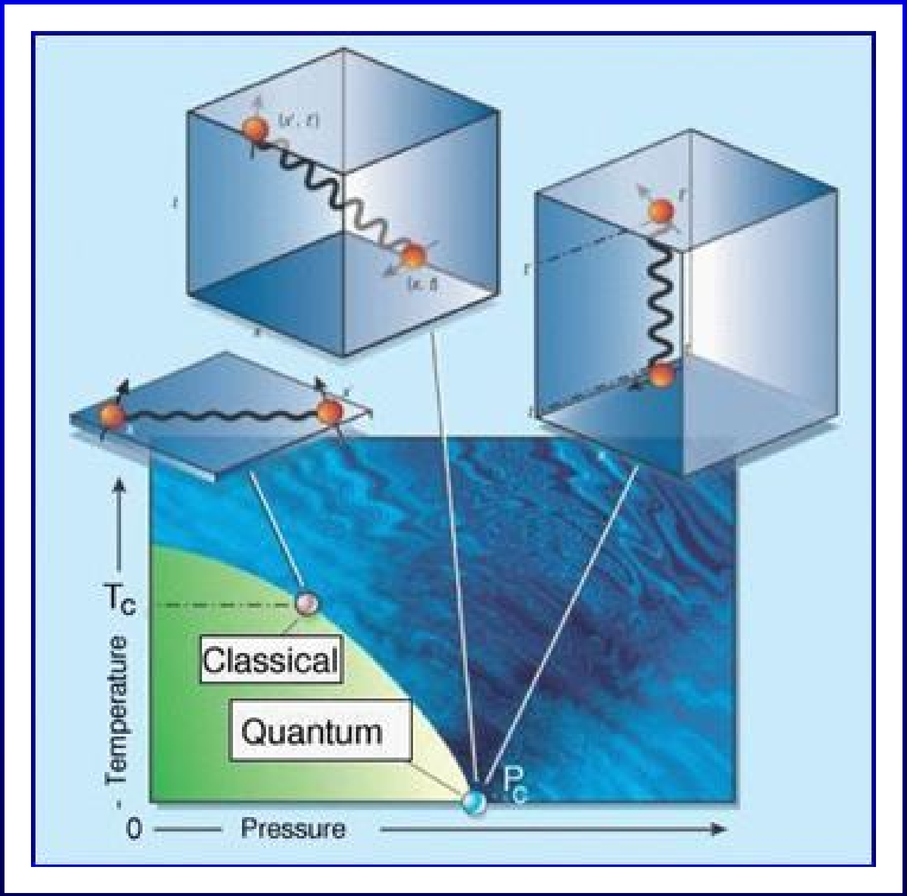
This state of matter in not adiabatically deformable into a Fermi liquid.

Quantum criticality

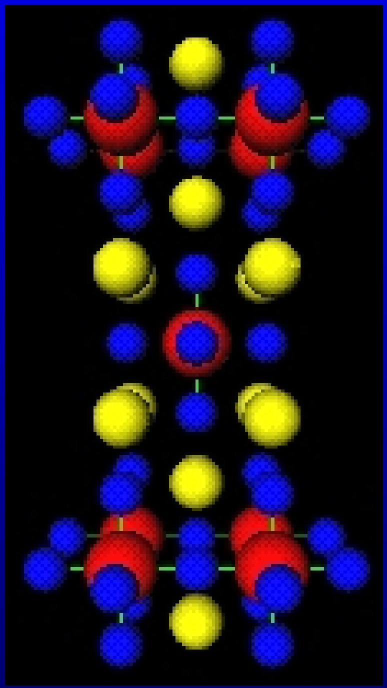


In the "quantum critical" region near a quantum phase transition electrons coupled to critical collective modes may exhibit non-FL behavior with algebraic long-distance correlations.

Quest for non-FL behavior in high-T_c cuprates

Experimental hints:

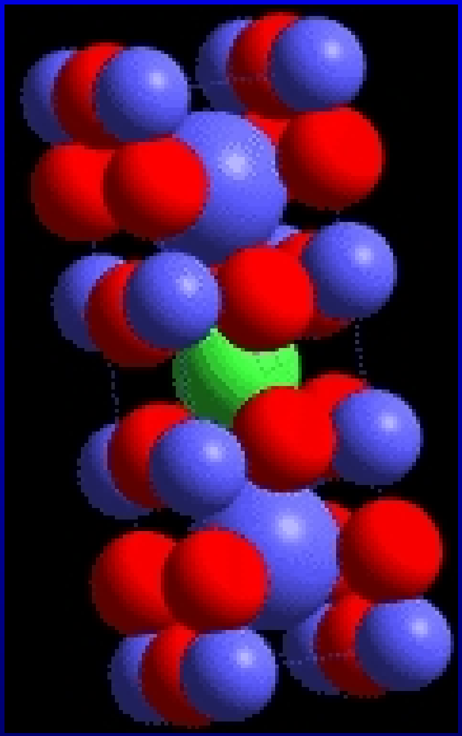
- DC resistivity in ab-plane: $\rho_{ab} \sim T$
- DC resistivity along c-axis: $\rho_c \sim 1/T$
- absence of sharp quasiparticles peaks seen by ARPES as STS
- and many other apparent deviations from FL orthodoxy



$La_{2-x}Sr_xCuO_4$

Candidate theoretical scenarios:

- Anderson's RVB theory
- various gauge field theories with spin-charge separation
- 1D stripe phases with Luttinger liquid physics
- anyon superconductivity
- competing orders
- order parameter phase fluctuations



$YBa_2Cu_3O_{7-x}$

Phase fluctuations in cuprates: QED$_3$ theory of the pseudogap state

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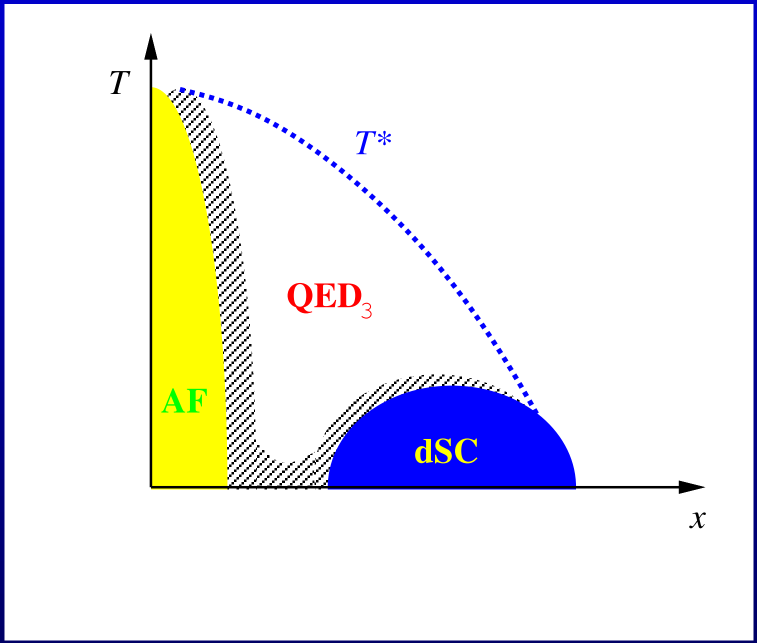
M. Franz, Z. Tesanovic, and O. Vafek

Phys. Rev. Lett. 87, 257003 (2001),

Phys. Rev. B 66, 054535 (2002)

Two ways of destroying the SC order

SC order parameter is a complex scalar field: $\Delta(\mathbf{r}) = |\Delta(\mathbf{r})|e^{i\theta(\mathbf{r})}$.



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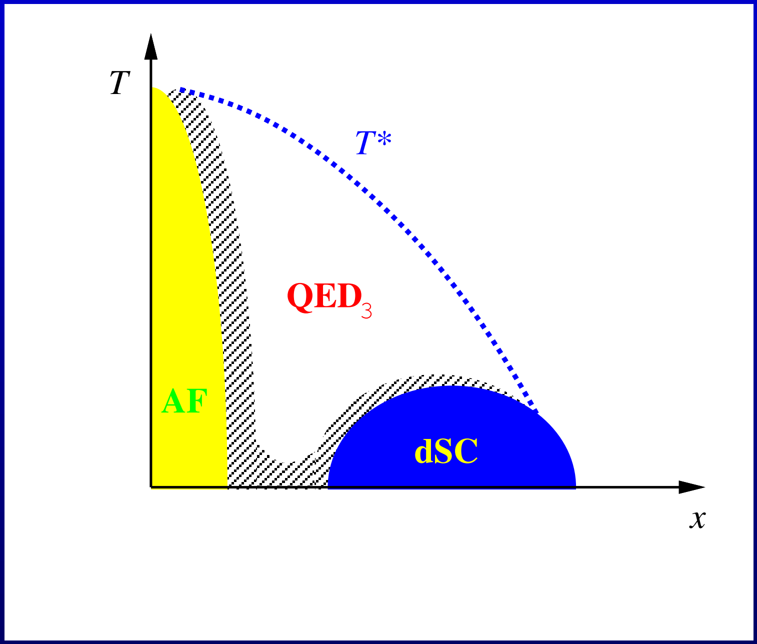

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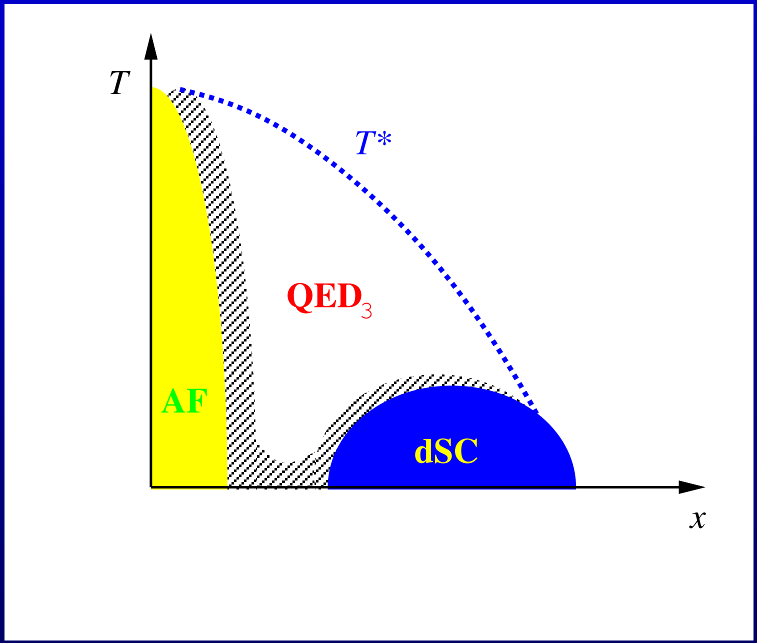

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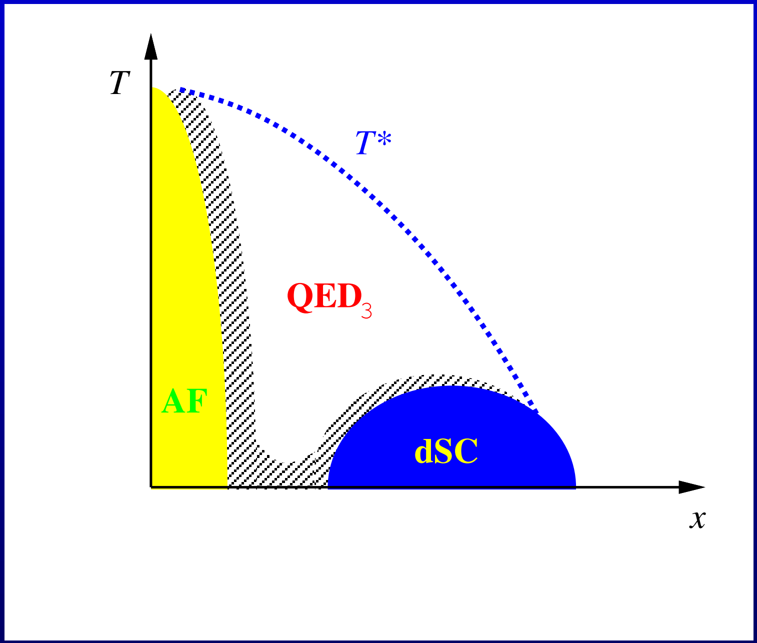

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Kosterlitz-Thouless "vortex-antivortex" unbinding transition with $T_c \sim \rho_s$, the superfluid density.

What is Vortex?

Vortices: from mundane to profound...

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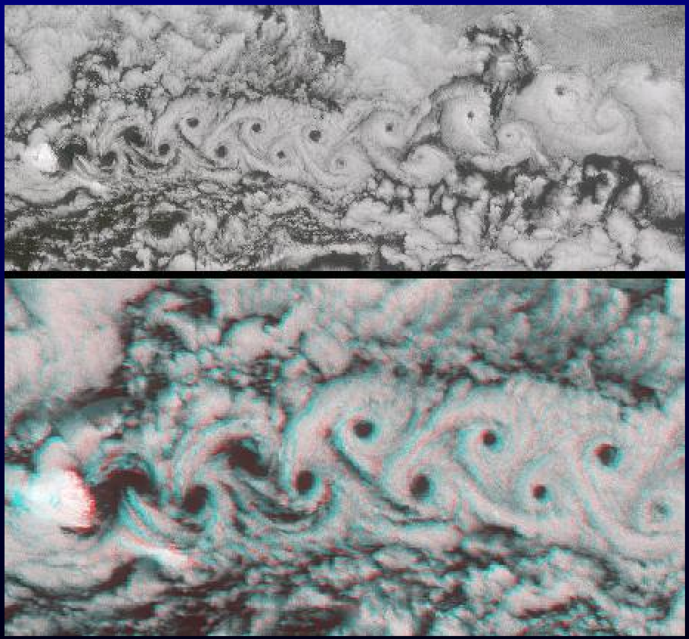

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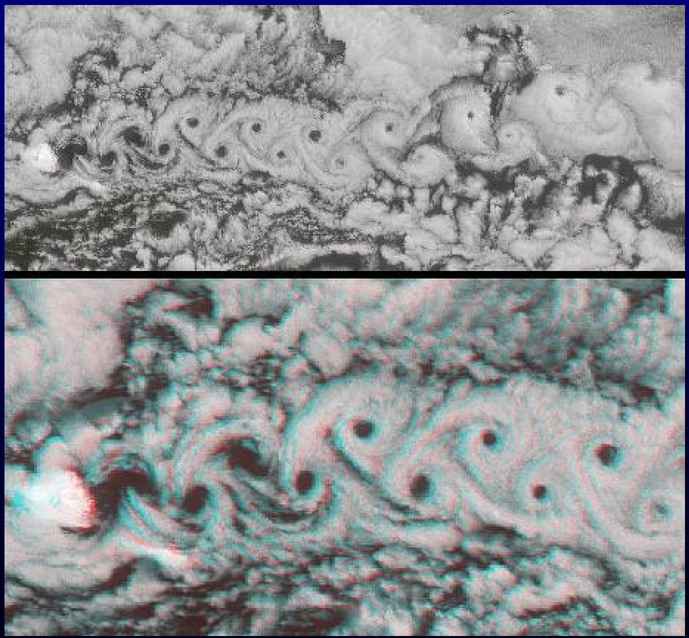


STAR TREK
DEEP SPACE NINE
VORTEX
EPISODE 12

Vortices in superconductors

Vortex is a *topological defect* in the SC order parameter, $\Delta(\mathbf{r}) = |\Delta(\mathbf{r})|e^{i\theta(\mathbf{r})}$.

The phase θ winds by 2π on encircling a vortex while the amplitude goes to zero at the vortex center, $|\Delta(r)| \rightarrow 0$.

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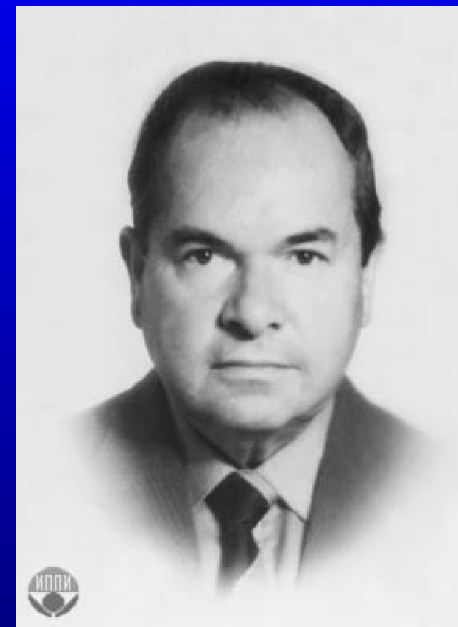

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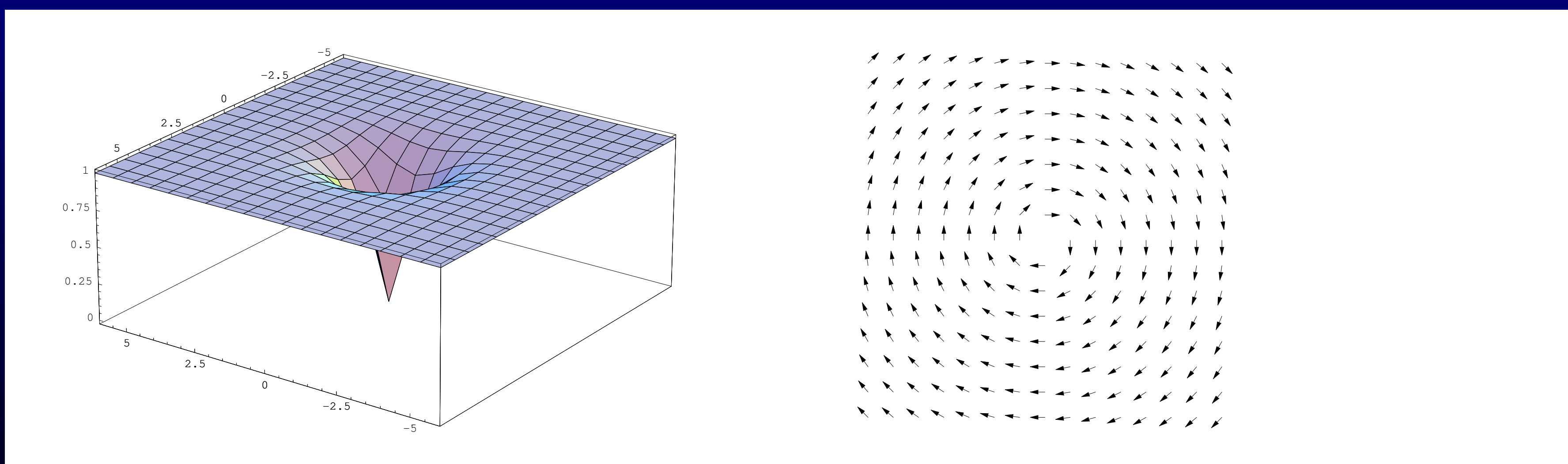
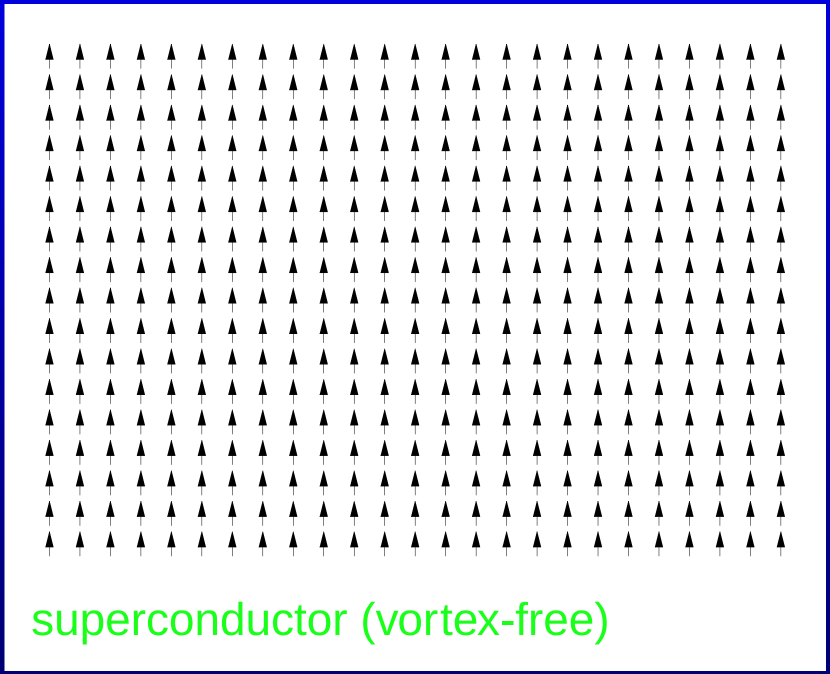


Vortex Pairs and Kosterlitz-Thouless transition



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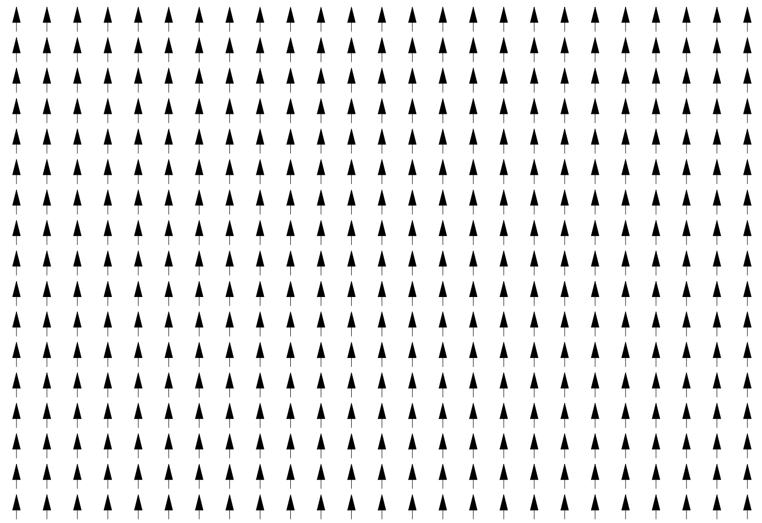
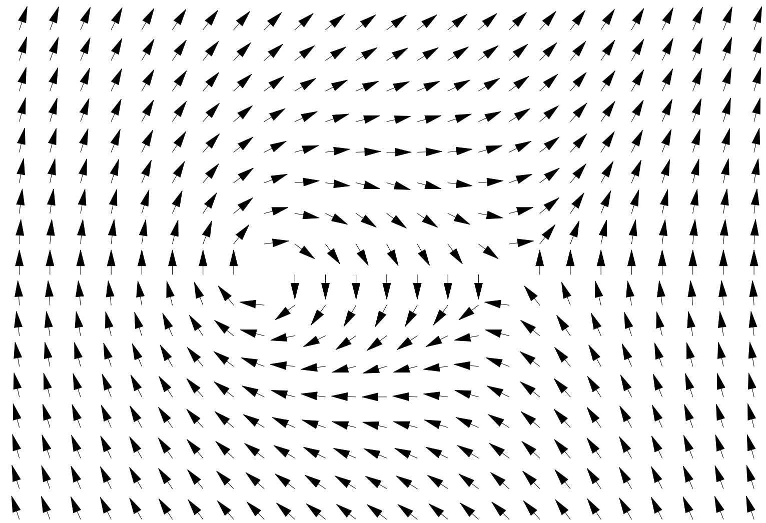


superconductor (vortex-free)



vortex-antivortex pair

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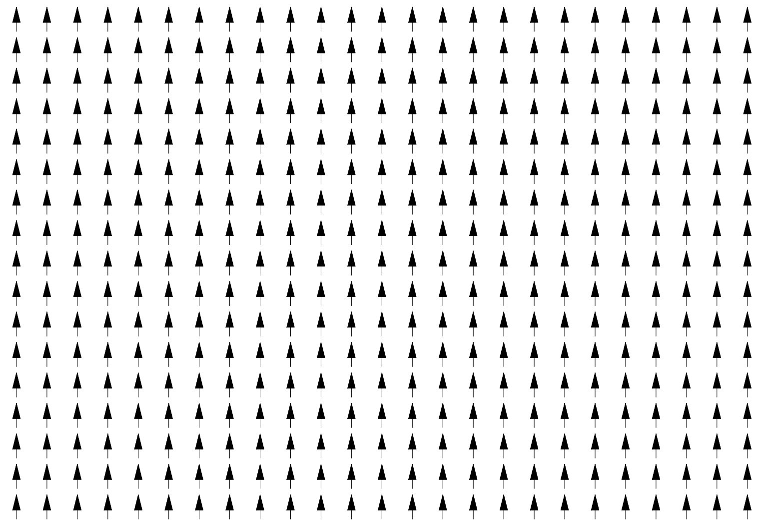

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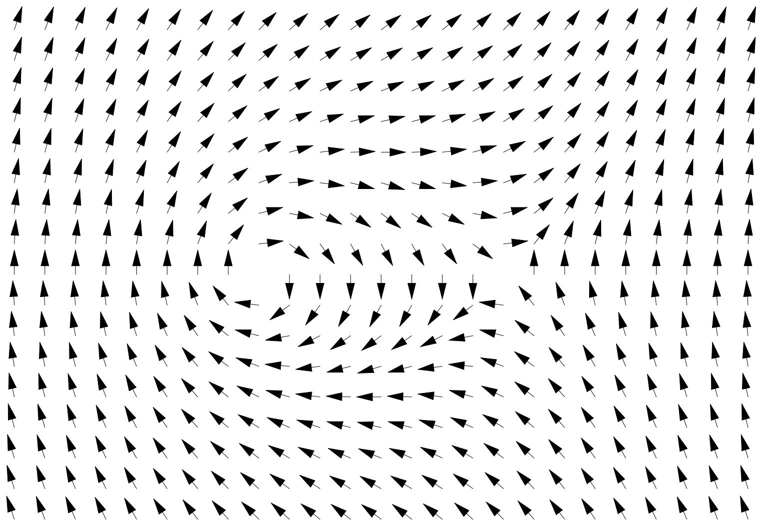

vortex-antivortex pair

When vortex-antivortex pairs unbind the phase coherence is lost and superconductor goes normal.

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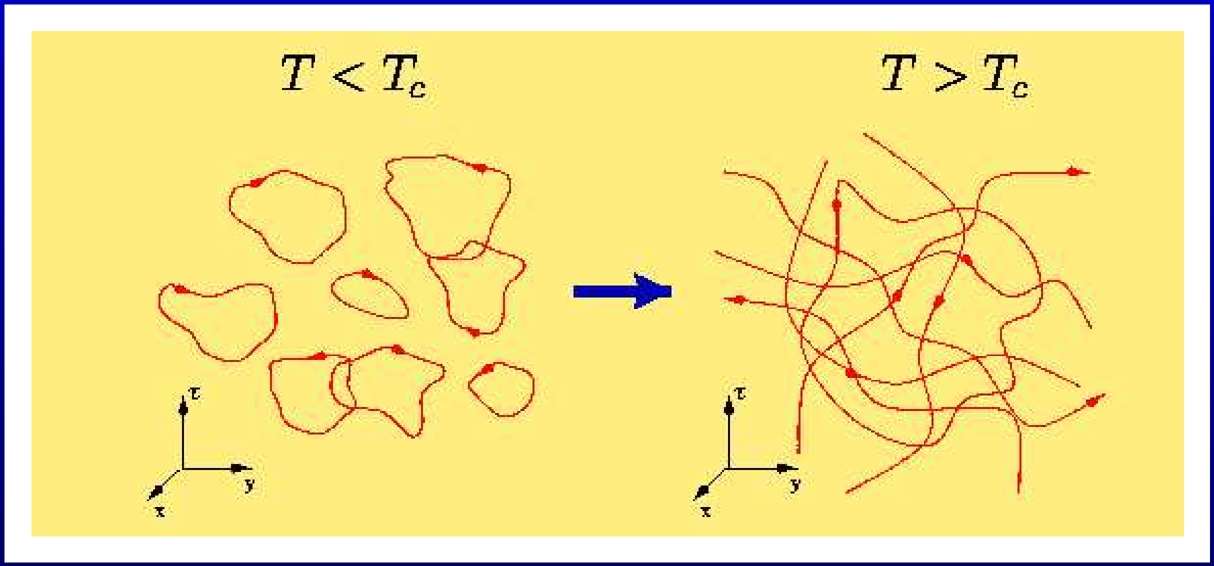
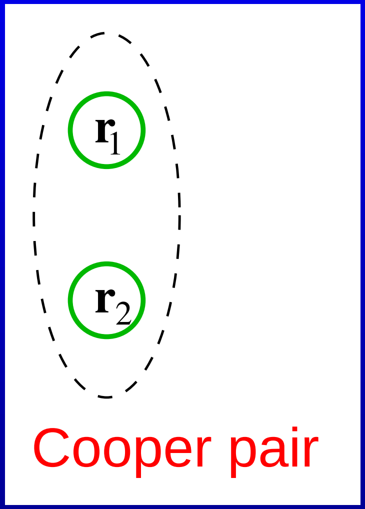


This transition is in the “3D XY” universality class.

d-wave superconductivity in cuprates



Superconducting order parameter is an anomalous average

$$\Delta(\mathbf{r}_1, \mathbf{r}_2) = \langle c_\uparrow(\mathbf{r}_1) c_\downarrow(\mathbf{r}_2) \rangle,$$

where $c^\dagger_\sigma(\mathbf{r})$ creates electron with spin σ at point $\mathbf{r}$.

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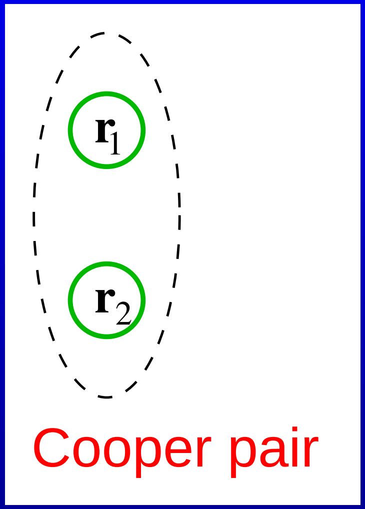

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One may classify various order parameters according to the spin and the internal angular momentum of the pair. For spin singlet state the spatial part of the wavefunction has to be symmetric, implying (for 2D system)

$$l_z = 0, \pm 2, \pm 4, \ldots$$

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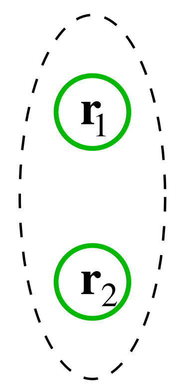

Cooper pair

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Most conventional superconductors have $l_z = 0$ (s-wave). There exist "unconventional" superconductors which exhibit *spin triplet* pairing or spin singlet with higher angular momentum.

Superconducting order parameter in cuprates exhibits d-wave symmetry

$$\Delta_{\mathbf{k}} = \Delta_0(\cos k_x - \cos k_y),$$

i.e. changes sign upon 90^o rotation.

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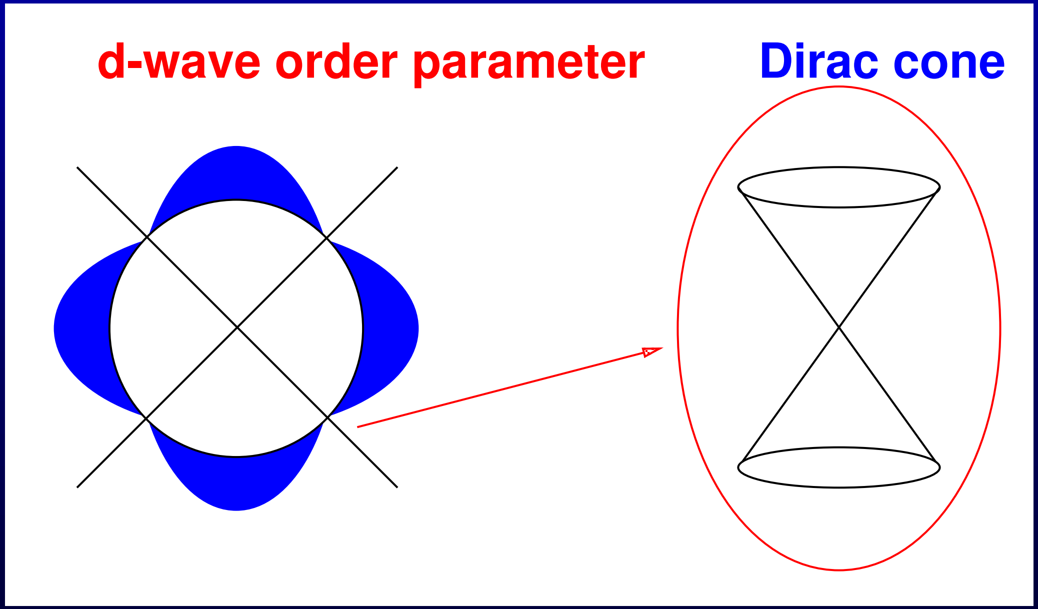
Low-energy excitations, $E_{\mathbf{k}} = \sqrt{\epsilon_{\mathbf{k}}^2 + \Delta_{\mathbf{k}}^2}$, occur near 4 nodal points:



"Dirac Fermions"

Superconducting order parameter in cuprates exhibits d-wave symmetry

$$\Delta_{\mathbf{k}} = \Delta_0(\cos k_x - \cos k_y),$$

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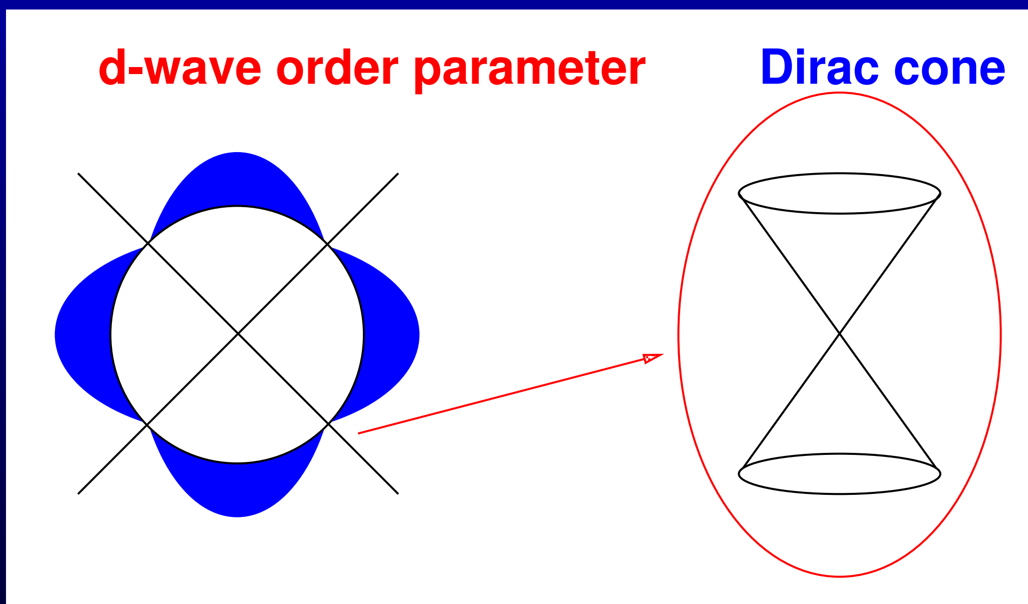

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d-wave superconductivity + (quantum) unbound vortices

- Interesting fundamental theoretical problem.

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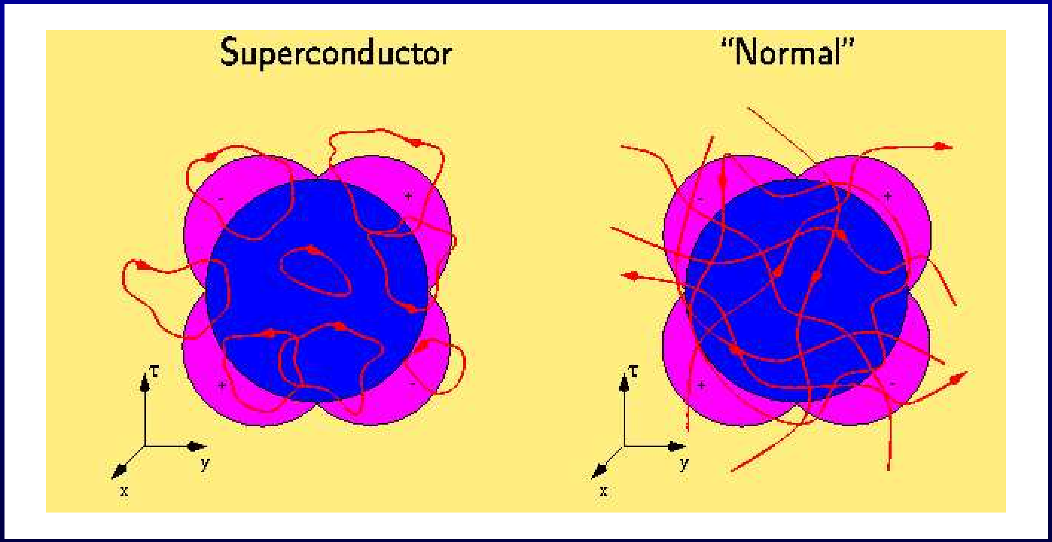
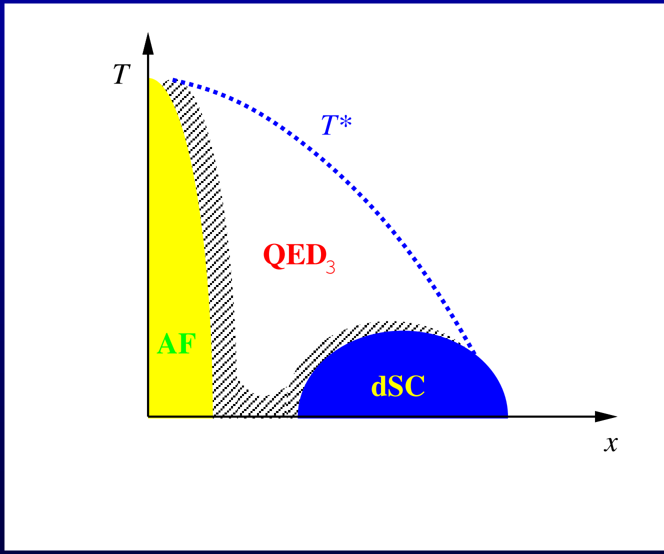
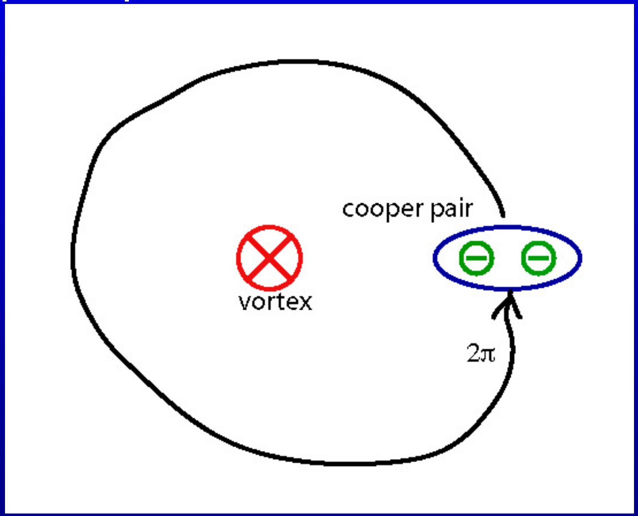




Electron-vortex interaction: tricky business

On encircling a vortex, a Cooper pair acquires phase 2π.



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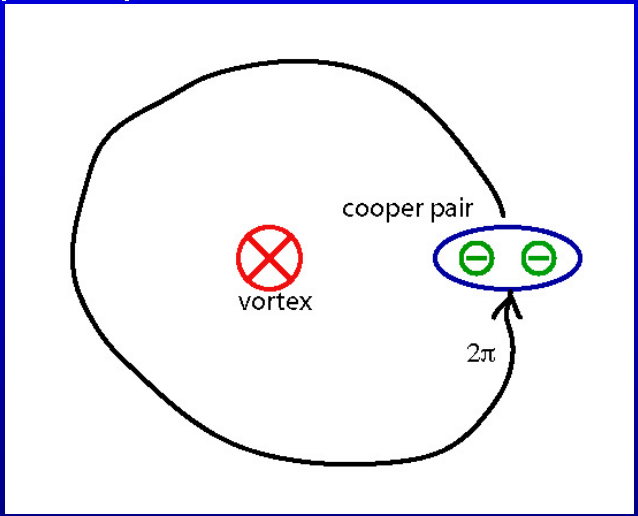

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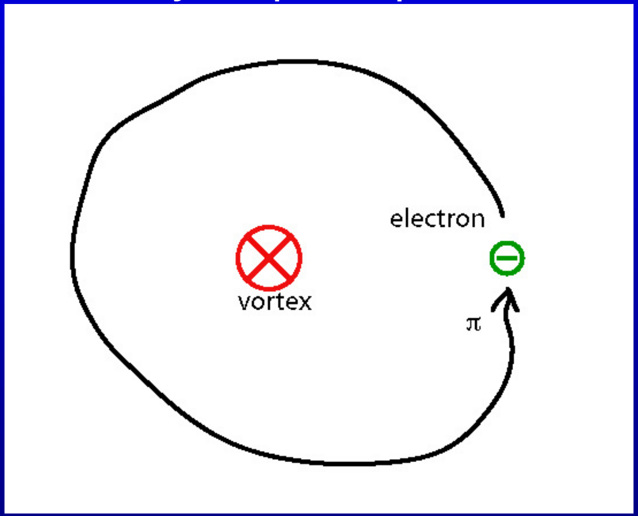

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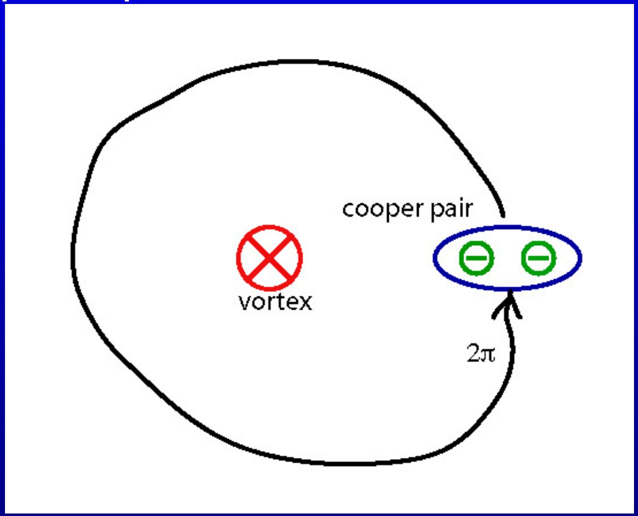

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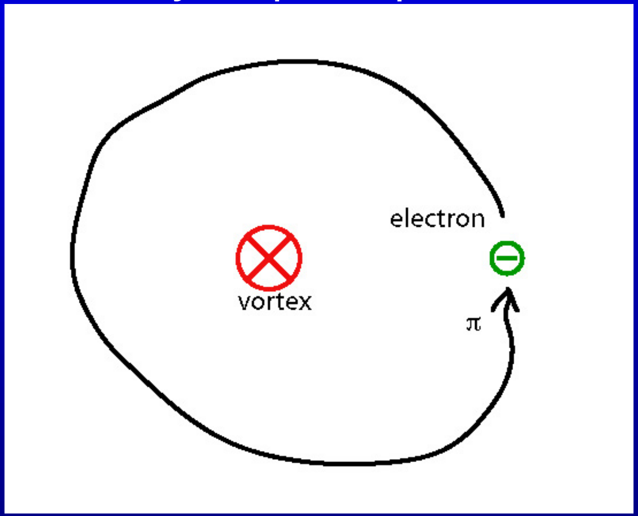
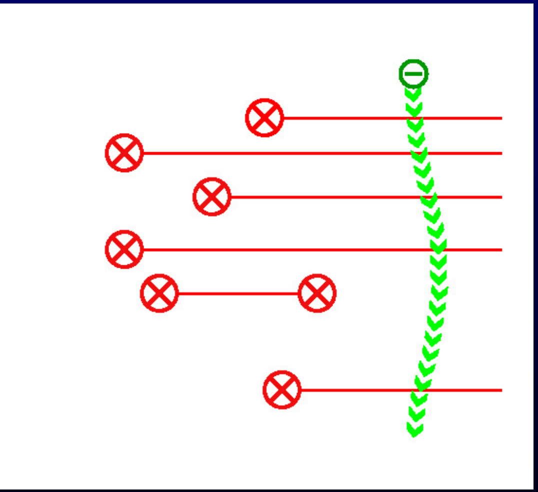


This results in branch cuts in electron wavefunction emanating from each vortex:



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Solved by a singular gauge transformation,

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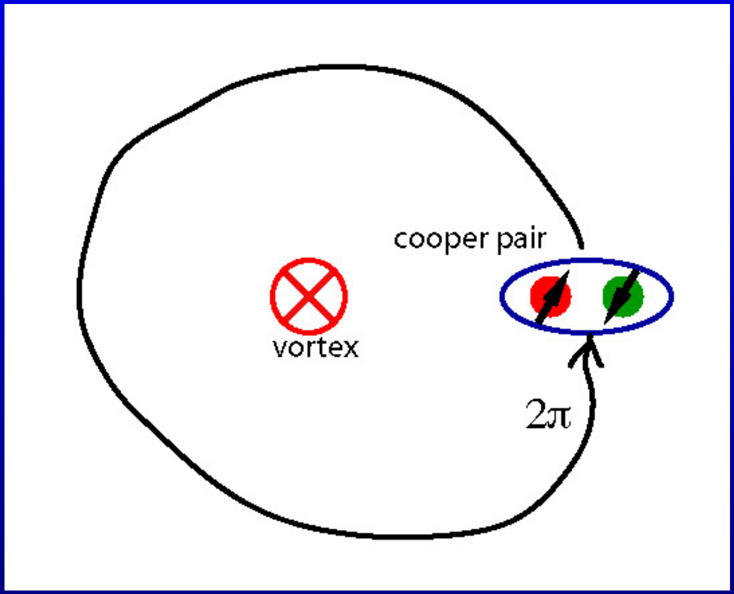
Sometimes referred to as "FT transformation". Introduces a gauge field that describes the physics of the vortex branch cuts.

Physical essence of the FT transformation



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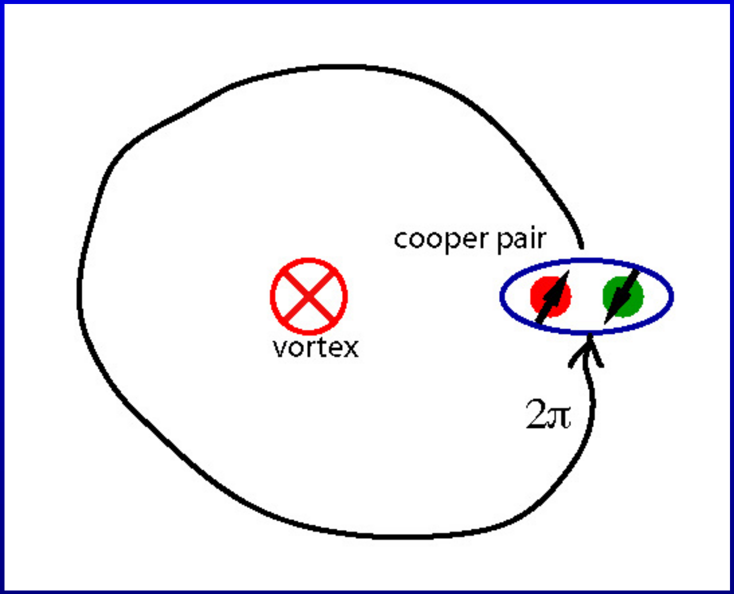

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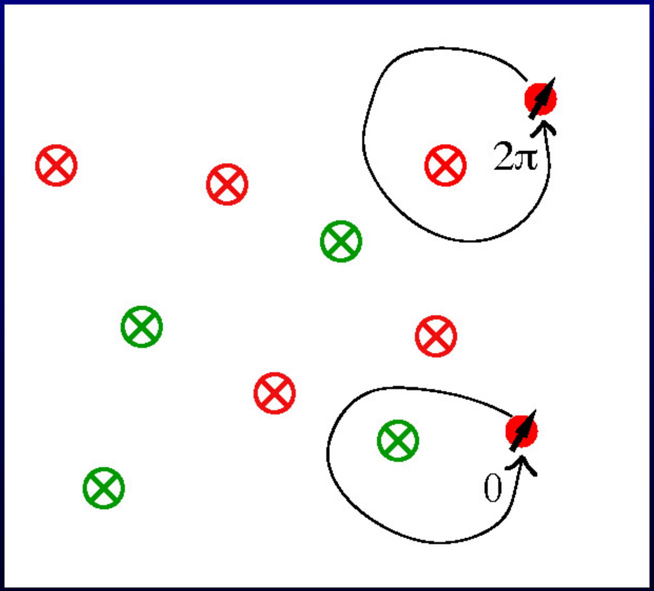

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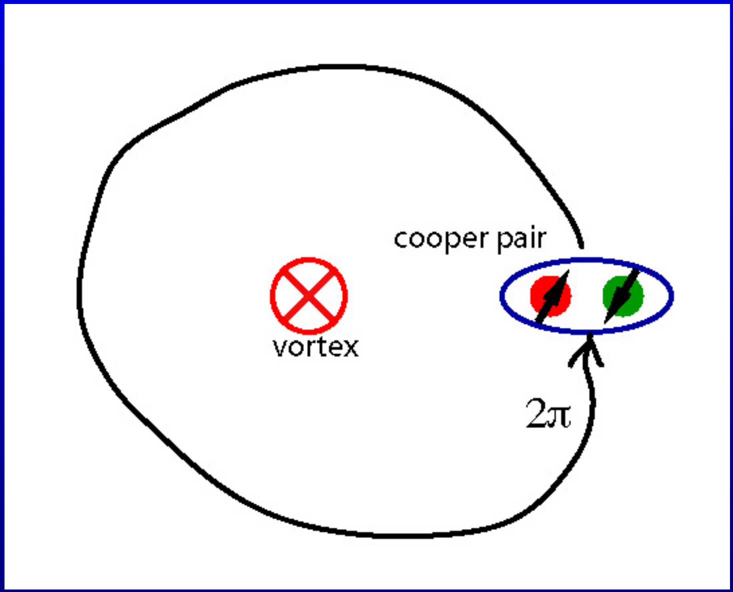

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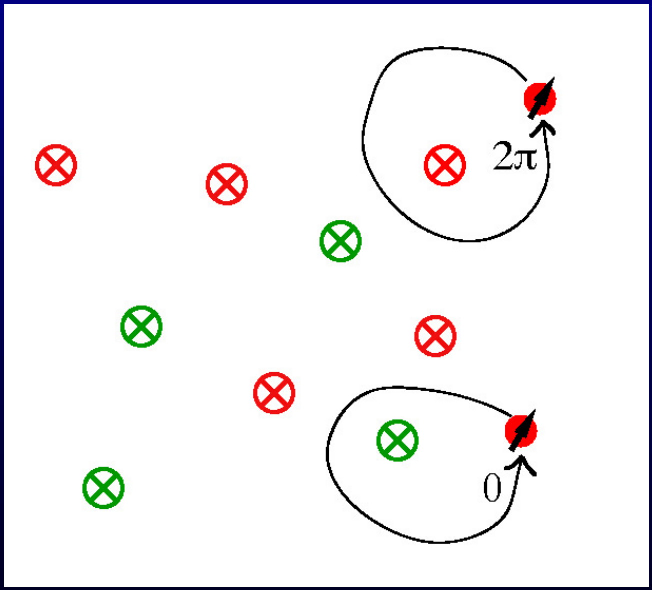

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- O. Vafek, A. Melikyan, M.Franz and Z. Tešanović Phys. Rev. B **63**, 134509 (2001).
- D. Knapp, C. Kallin and A.J. Berlinsky, Phys. Rev. B **64**, 014502 (2001).
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QED$_3$: Quantum Electrodynamics in 2+1 Dimensions

At low energies and long lengthscales the d-wave quasiparticles coupled to fluctuating vortices are described by the effective Lagrangian

$$\mathcal{L} = \sum_{n=1}^{N} \bar{\Psi}_n \gamma_\mu (\partial_\mu - i a_\mu) \Psi_n + \mathcal{L}_v[a_\mu]$$

where $\Psi_n(x)$ is a 4-component spinor describing the n-th pair of nodes, a_μ is an emergent $U(1)$ gauge field that encodes the physics of the branch cuts residing on the fluctuating vortices.

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Pseudogap phase is described by QED$_3$ theory of $N = 2$ flavors of massless Dirac fermions minimally coupled to non-compact $U(1)$ massless gauge field.

Properties of QED$_3$

- Non-Fermi liquid “symmetric phase”

Electron propagator exhibits anomalous dimension $\nu = 8/3\pi^2 N$,

$$G(\omega, \mathbf{k}) = \frac{\omega + \tau_3 \epsilon_{\mathbf{k}}}{[\epsilon_{\mathbf{k}}^2 + \Delta_{\mathbf{k}}^2 - \omega^2]^{1-\nu/2}}.$$

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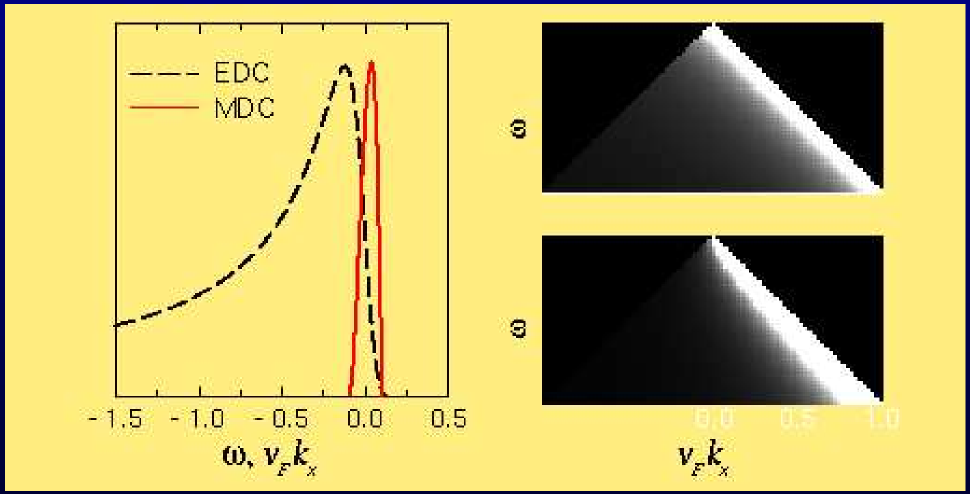
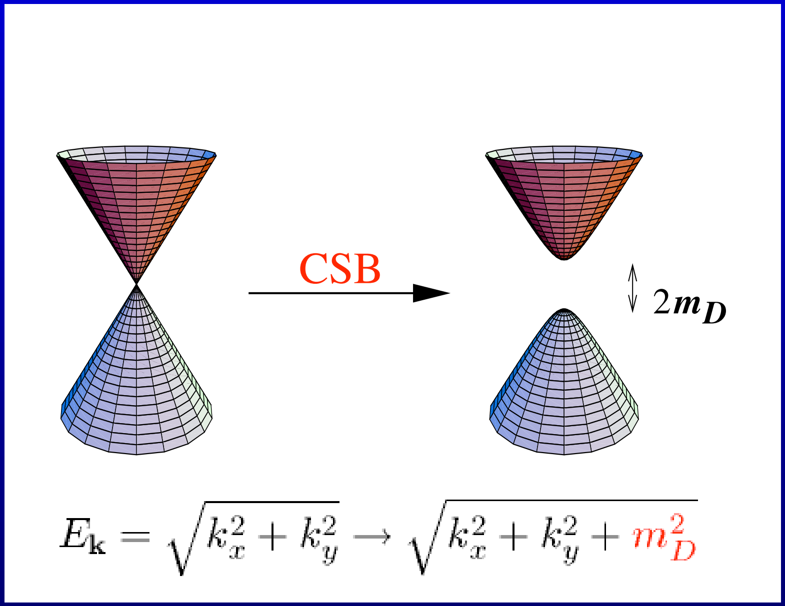
$\longrightarrow$ non-FL spectral function $A(\omega, \mathbf{k})$ with no poles:



- Phase in which chiral symmetry of QED$_3$ is spontaneously broken, giving rise to *dynamical mass generation*:



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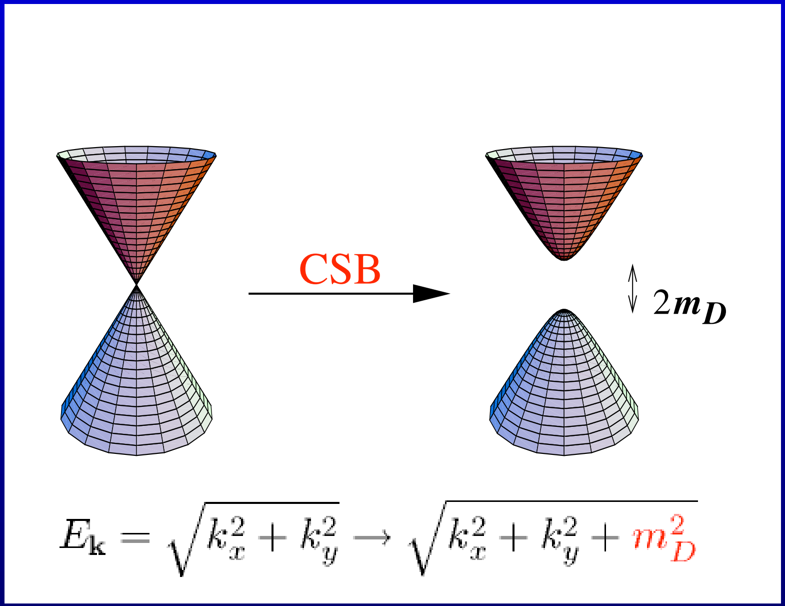

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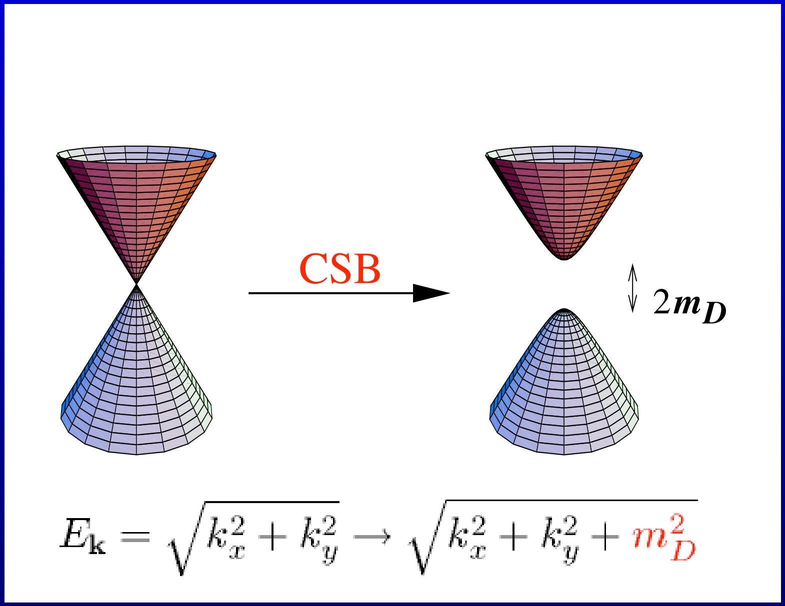

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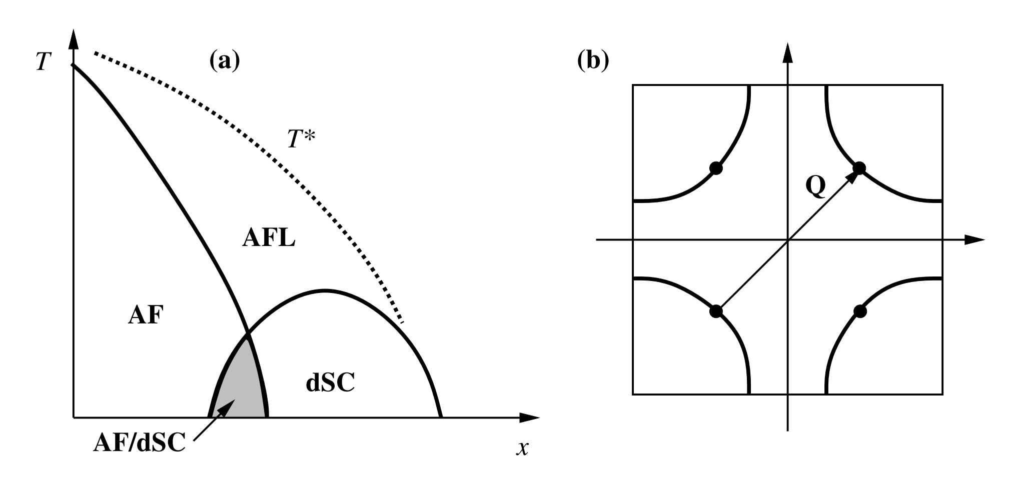

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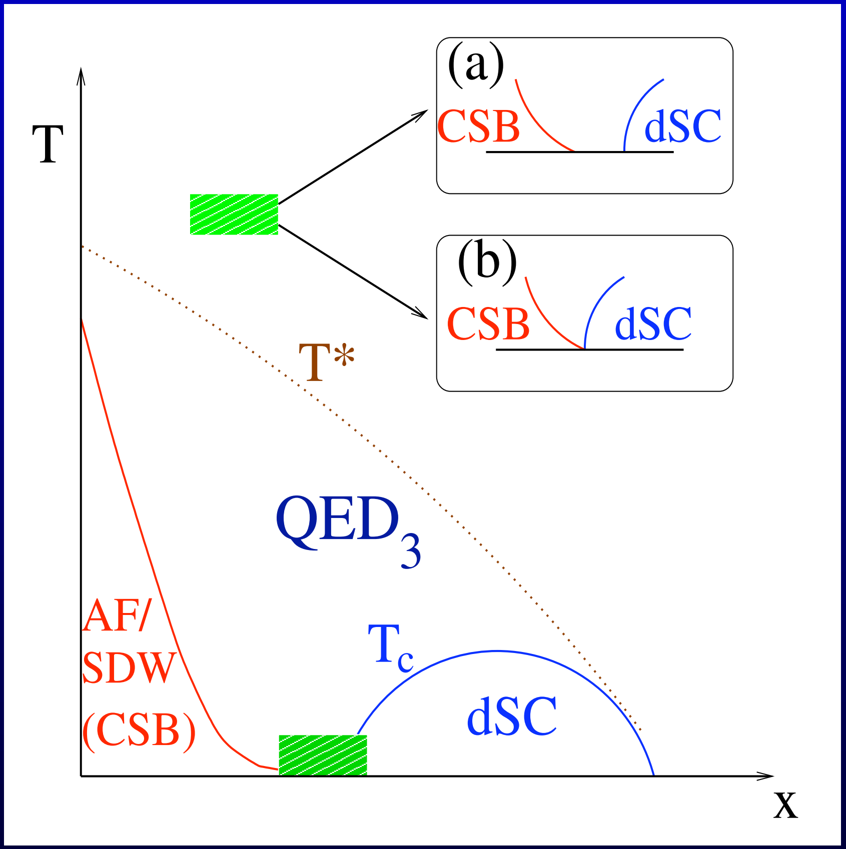
Whether right or wrong - and only time will tell - the QED_3 theory of cuprates offers exciting possibilities for

- Non-Fermi liquid state of electronic matter in 2D (the "QED_3 symmetric phase")
- A controlled way to reach AF insulator by phase-disordering a d-wave superconductor.



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