NiPS Laboratory
Noise in Physical Systems

Confinement and asymptotic freedom with Cooper pairs

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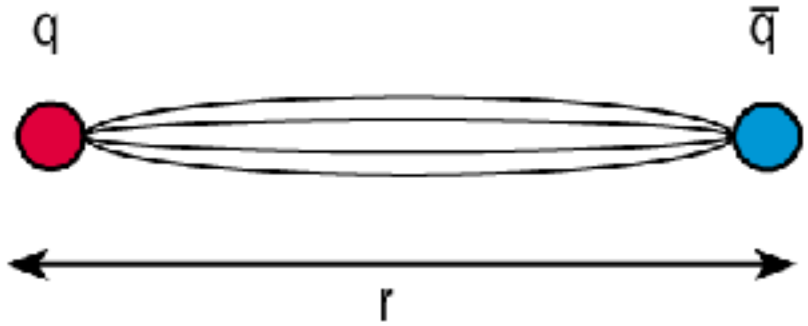
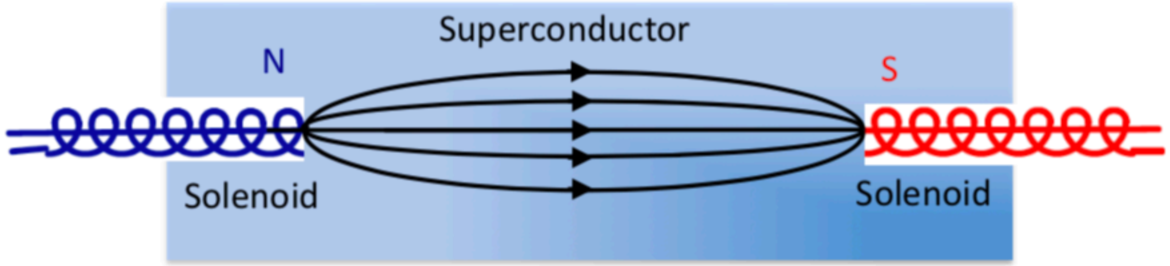
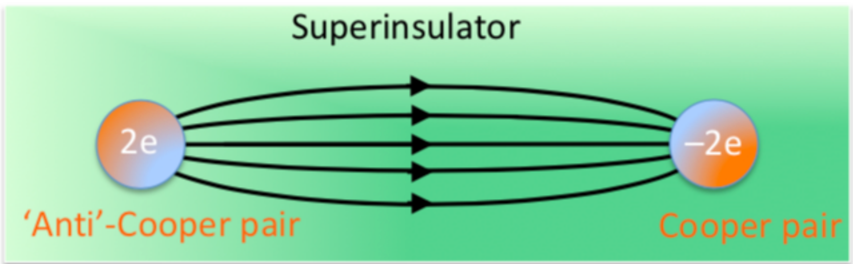
Model of quark confinement:



quarks bind by (chromo)-electric strings in a condensate of magnetic monopoles (Mandelstam, ‘t Hooft, Polyakov)

mirror analogue to vortex formation in type II superconductors





superinsulator ≡ dual superconductor
Polyakov's magnetic monopole condensation $\Longrightarrow$ electric string
$\Longrightarrow$ **linear confinement** of Cooper pairs

Superconductor

$R = 0$

$G = \infty$

S duality

Mandelstam 'tHooft Polyakov

Superinsulator

$R = \infty$

$G = 0$

- theoretically predicted in 1996

  P. Sodano, C.A. Trugenberger, MCD, Nucl. Phys. B474 (1996) 641

- experimentally observed in TiN films in 2008

  Vinokur et al, Nature 452 (2008) 613

- confirmed in NbTin films in 2017

  Vinokour et al, Scientific report 2018

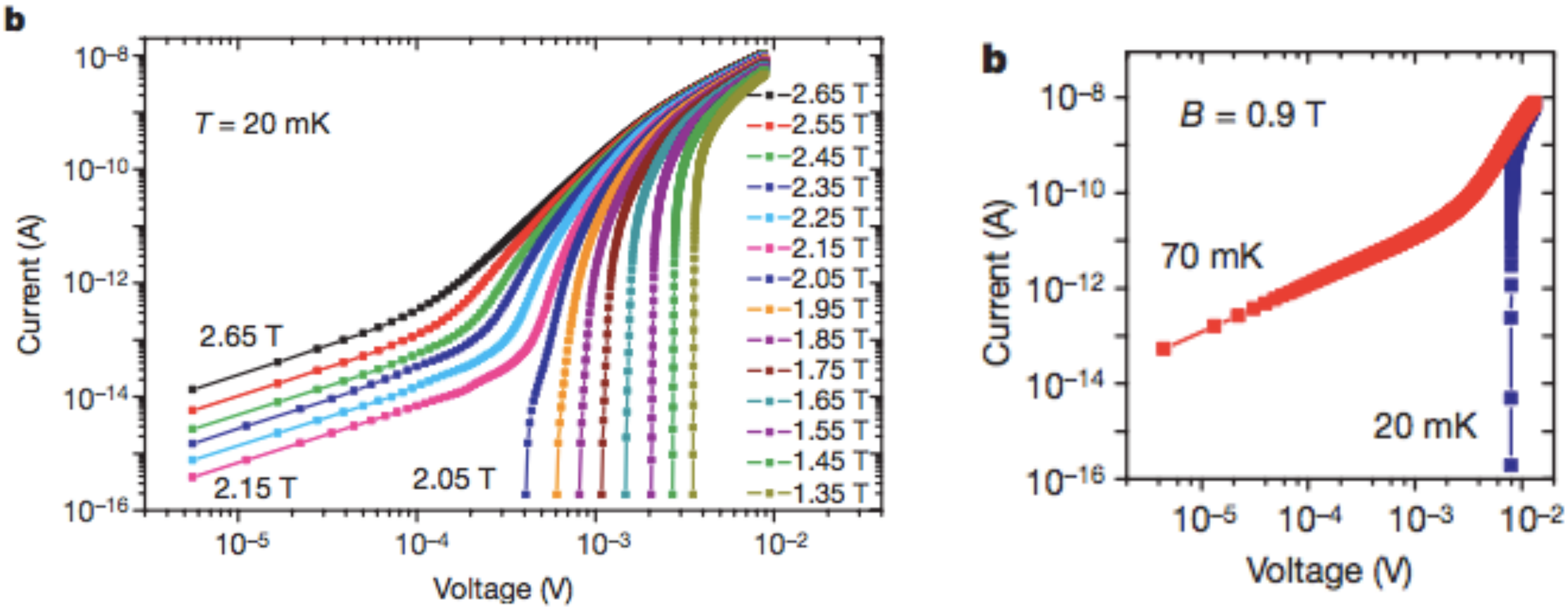
Superinsulation: realization and proof of confinement by monopole condensation and asymptotic freedom in solid state materials

Cooper pairs ⟷ Quarks

Results for homogeneously disordered TiN film (2D)

transition driven by:

- tuning disorder (thickness of the film)
- external magnetic field

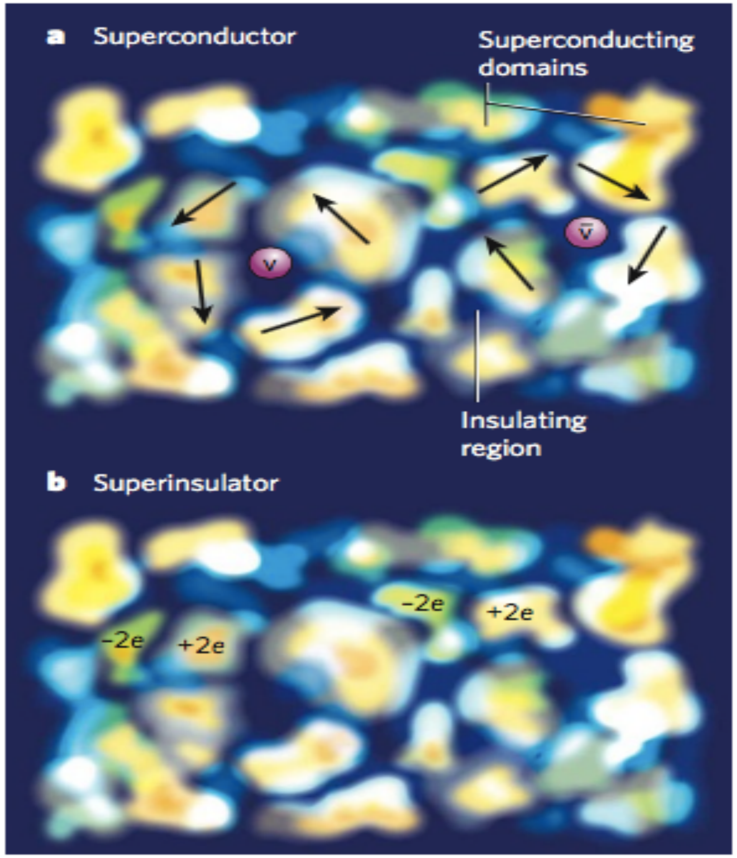


(Vinokur et al. Nature)

films modeled on Josephson junctions arrays

"*The film in a critical region of D-SIT can be viewed as* ***self-organized 2D JJ array!!!***" (Baturina)

- superinsulating state **dual** to the superconducting state
- experiments carried out on homogeneous disordered films → **emergent granularity**



(Fazio, Nature 452 (2008) 542)

V=0

Joule loss
P = IV = 0

I=0

SUPERCONDUCTIVITY – SUPERINSULATION DUALITY AND UNCERTAINTY PRINCIPLE

Meissner effect $\Longrightarrow$ phase coherence

The possibility of the existence of the superinsulating state
can be established from
the most fundamental quantum-mechanical standpoint:
uncertainty principle

Wave function of the condensate $\Psi = |\Psi| \exp(i\varphi)$

$$[N, \varphi] = i\hbar \quad \Longrightarrow \quad \Delta\varphi \Delta N \geqslant 1$$

Superconductor	**Superinsulator**
$\Delta\varphi = 0$	$\Delta N = 0$
φ well defined across the systems	Cooper pairs get pinned

PT BREAKING TOPOLOGICAL STATES OF MATTER

FQH states:

- gapped in the bulk; gapless edge excitations;
- low energy effective field theory, Chern-Simons:

  background independent;

  ground state degeneracy;

  quasiparticles have fractional charge and statistics;

- **Wen's idea**:

$$\boxed{j_\mu \propto \epsilon_{\mu\nu\alpha}\partial_\nu b_\alpha}$$

conserved matter current, b_μ U(1) pseudovector gauge field if j_μ is a charge current

- topological field theory at low energy (Euclidean):

$$\boxed{S = i\int d^3x \frac{k}{2\pi} b_\mu \epsilon_{\mu\nu\alpha}\partial_\nu b_\alpha} \longrightarrow$$

CS, P (T) breaking

PT INVARIANT TOPOLOGICAL STATES OF MATTER

can we have P and T symmetries?

2d

- two fluids model:

$\boxed{j_\mu \propto \epsilon_{\mu\nu\alpha}\partial_\nu b_\alpha}$ conserved charge current, b_μ is a pseudovector

$\boxed{\phi_\mu \propto \epsilon_{\mu\nu\alpha}\partial_\nu a_\alpha}$ conserved vortex current a_μ is a vector

$$\boxed{\mathrm{S} = i\int d^3x \frac{k}{2\pi} a_\mu \epsilon_{\mu\nu\alpha}\partial_\nu b_\alpha} \longrightarrow$$

mixed CS ≡ BF , P(T) invariant
U(1) x U(1)

- add kinetic term for the fictitious gauge fields

$$\boxed{\mathrm{S_{TM}} = \int d^3x \; \frac{1}{4e_f^2} f_{\mu\nu} f_{\mu\nu} + i\frac{k}{2\pi} a_\mu \epsilon_{\mu\nu\alpha}\partial_\nu b_\alpha + \frac{1}{4e_g^2} g_{\mu\nu} g_{\mu\nu}}$$

3d

$$j_\mu \propto \epsilon_{\mu\nu\alpha\beta}\partial_\nu b_{\alpha\beta}$$
$$\phi_{\mu\nu} \propto \epsilon_{\mu\nu\alpha\beta}\partial_\alpha a_\beta$$

→ charge current, $b_{\mu\nu}$ pseudotensor

→ vortex current, a_μ vector

$$S_{BF} = i\frac{k}{2\pi}\int d^4x \; b_{\mu\nu}\epsilon_{\mu\nu\alpha\beta}\partial_\alpha a_\beta$$

→ **BF , P(T) invariant**

U(1) x U(1)

+ kinetic for a_μ and $b_{\mu\nu}$

$$S_{TM} = \int d^4x \frac{1}{12e_g^2} h_{\mu\nu\rho}h_{\mu\nu\rho} - \frac{i\kappa}{8\pi} b_{\mu\nu}\epsilon_{\mu\nu\lambda\rho}f_{\lambda\rho} + \frac{1}{4e_f^2} f_{\mu\nu}f_{\mu\nu}$$

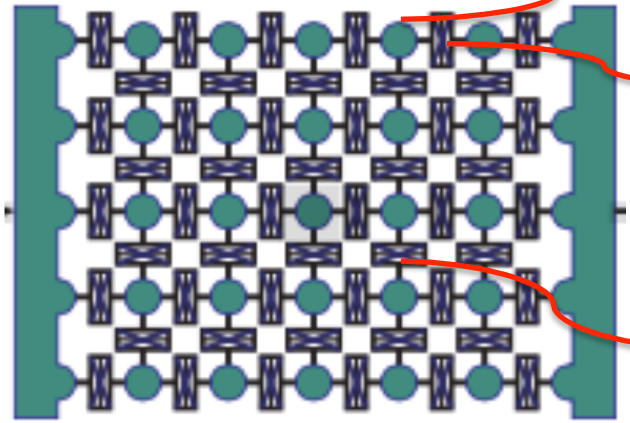
S_{TM} was first proposed in 2 and 3d as a field theory description of topological phases of condensed matter systems in 1996 (Sodano, Trugenberger, MCD)

- a_μ and b_μ ($b_{\mu\nu}$) acquires a topological mass $m = (k\, e_f\, e_g)/2\pi$
- k is a dimensionless parameter, it determines the ground state degeneracy on manifold with non trivial topology and the statitistics
- $[e_f^2] = m^{-d+3}$ $[e_g^2] = m^{d-1}$ naively irrelevant (first one marginal in 3d) but necessary to correctly define the limit $m \to \infty$ (pure CS limit)

  (Dunne, Jackiw, Trugenberger, 1990)
- they enter in the phase structure of the theory

JOSEPHSON JUNCTION ARRAYS

Planar arrays of spacing l



V_x, φ_x

superconducting island
C_0 = ground capacitance

Josephson coupling E_J ; C nearest neighbours capacitance, $E_C = e^2/2C$ charging energy

$$H = \sum_{\mathbf{x}} \frac{C_0}{2} V_{\mathbf{x}} + \sum_{<\mathbf{xy}>} \frac{C}{2} (V_{\mathbf{y}} - V_{\mathbf{x}})^2 + E_J (1 - \cos 2 (\Phi_{\mathbf{y}} - \Phi_{\mathbf{x}}))$$

V= electric potential of the island; φ = phase of its order parameter ;
$C \gg C_0$ (C_0=0) ⟹ two relevant parameter: $(8\, E_J\, E_C)^{1/2}$ Josephson plasma frequency; E_J / E_C

Action:

- two Coulomb gases for charges and vortices + kinetic term for the charges +Aharonov-Bohm topological interaction between charges and vortices (Fazio, Schön; Phys.Rev.B 43 (1991) 5307)
- add kinetic term for vortices $\Longrightarrow$ **perfect duality between charges and vortices** (Sodano Trugenberger MCD)

T=0 exact mapping (Sodano Trugenberger MCD) between the action of JJA and (Euclidean lattice, with lattice spacing l)

$$\boxed{Z = \sum_{\{M_\mu, Q_\mu\}} \int \mathcal{D}a_\mu \mathcal{D}b_\mu \exp -S}$$

$$e_f^2 = 2\pi^2 E_j$$

$$S = \sum_x \frac{\ell^3}{4e_f^2} f_{\mu\nu} f_{\mu\nu} + i\frac{\ell^3}{\pi} a_\mu \epsilon_{\mu\nu\alpha} d_\nu b_\alpha + \frac{\ell^3}{4e_g^2} g_{\mu\nu} g_{\mu\nu} +$$

$$e_g^2 = 4E_c$$

$$+ i\ell\sqrt{2} a_\mu Q_\mu + i\ell\sqrt{2} b_\mu M_\mu$$

$$f^\mu = \frac{1}{2}\epsilon^{\mu\nu\alpha} f_{\nu\alpha} = \epsilon^{\mu\nu\alpha}\partial_\nu b_\alpha \qquad j^\mu = \frac{\sqrt{2}}{2\pi} f^\mu$$

conserved charge current

$$g^\mu = \frac{1}{2}\epsilon^{\mu\nu\alpha} g_{\nu\alpha} = \epsilon^{\mu\nu\alpha}\partial_\nu a_\alpha \qquad \phi^\mu = \frac{\sqrt{2}}{2\pi} g^\mu$$

conserved vortex current

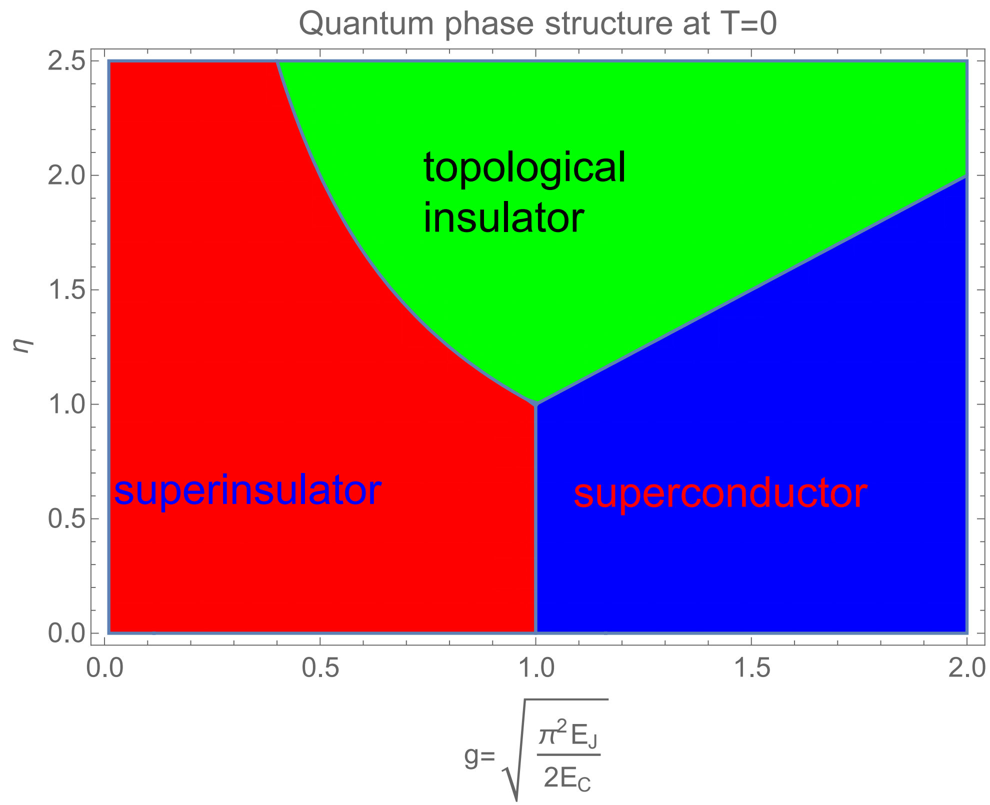
mixed Chern-Simons term is **periodic ⟹ presence of topological defects**

Q_μ electric topological defects

M_μ magnetic topological defects

⟹

phase structure determined by the condensation (lack of) of topological defects



$g = \sqrt{(2E_C/\pi^2 E_J)}$

$$\eta = \frac{\pi m \ell G(m\ell)}{\mu}$$

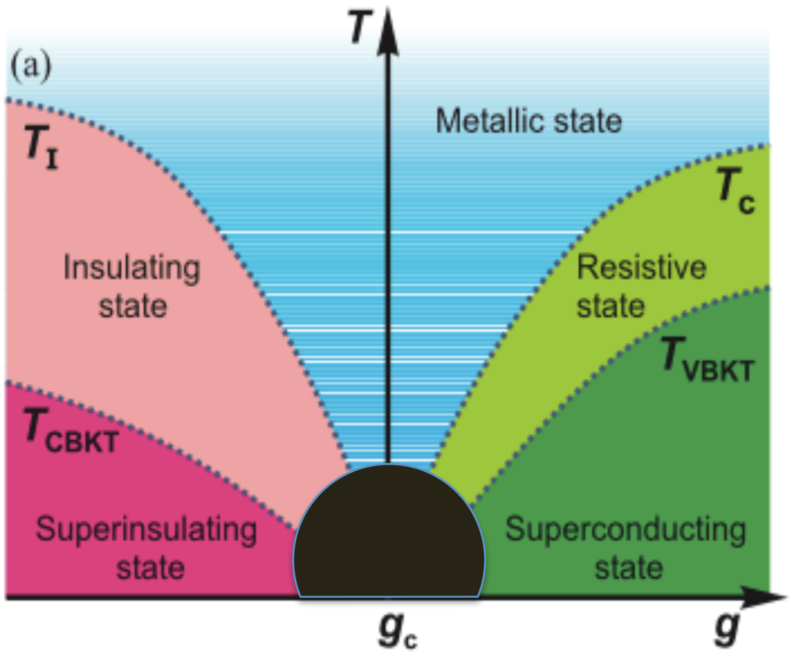
with G(ml) diagonal part of the lattice kernel:

$$\ell^2(m^2 - \nabla^2) G(x-y) = \delta(x-y)$$

μ: numerical factor

$\eta < 1$: $\eta <$ g $< 1/\eta$ coexistence region for electric and magnetic charges ⇒ first-order direct transition

(Baturina and Vinokour 2013)



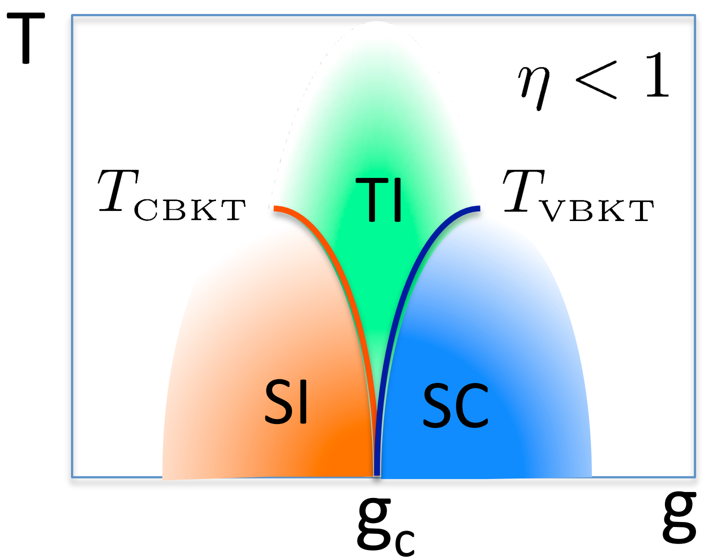
T_{VBKT} : Kosterlitz –Thouless transition for vortex/antivortex pairs

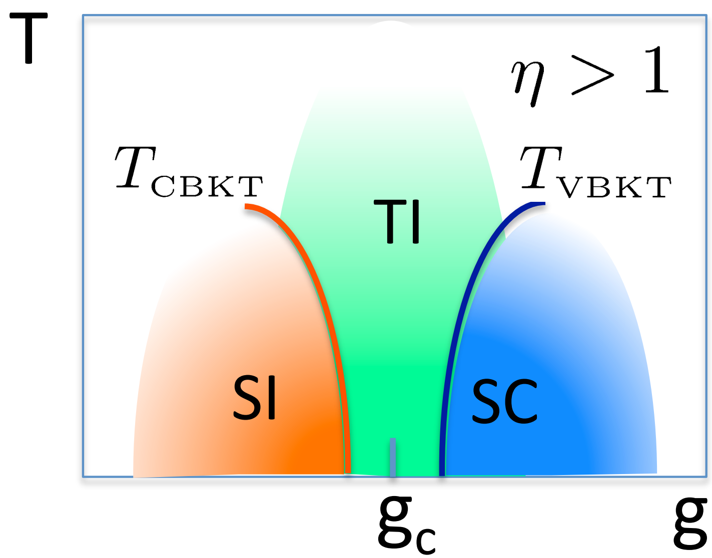
T_{CBKT} : Kosterlitz –Thouless transition for Cooper pairs/anti-Cooper pairs dipole

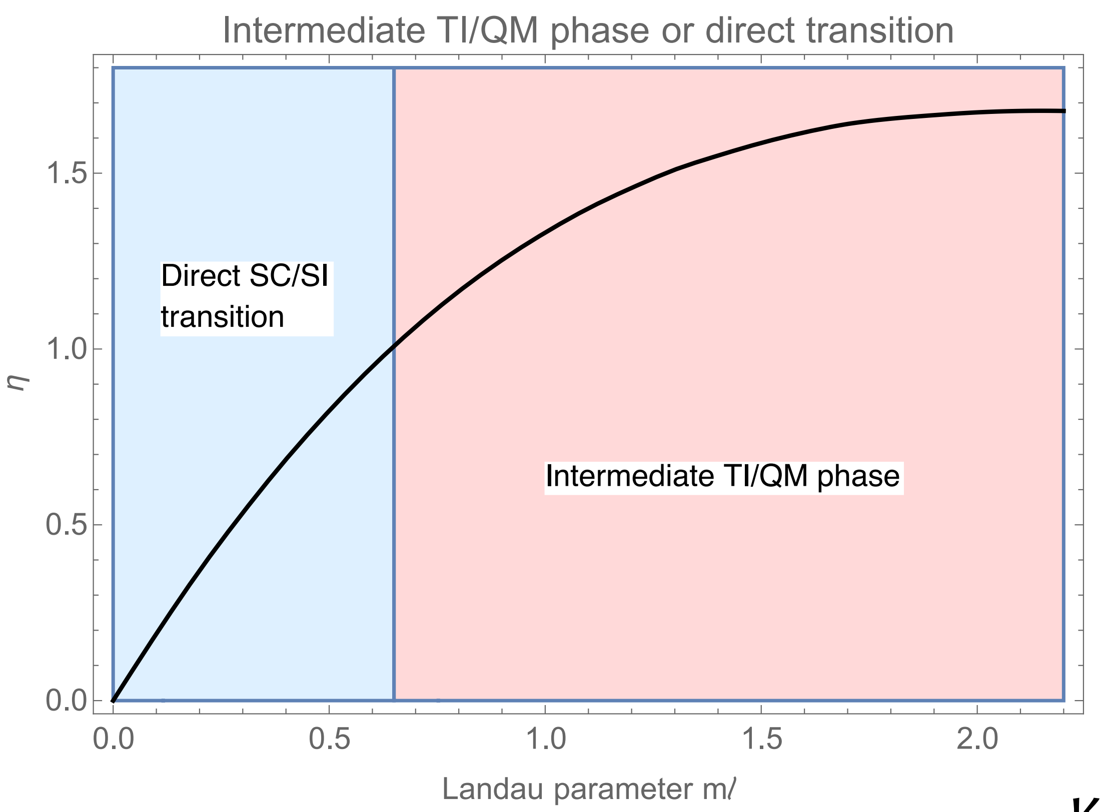
in the region $T_{CBKT} < T < T_I$ and $T_{VBKT} < T < T_C$ Cooper pairs are present

insulating and resistive states are topological insulating states

charge BKT experimentally observed in 2017 (Baturina,Vinokour et al)







$E_C = 4e^2/a$

$E_J \simeq 1/(16\pi e^2 \lambda)$

$a = \begin{cases} r\,\xi \text{ in 3d} \\ d \text{ in 2d} \end{cases}$

$\lambda = \begin{cases} \lambda_L \text{ in 3d} \\ \lambda_\perp \text{ in 2d} \end{cases}$

$\kappa = \lambda_\perp / l$ Landau parameter

$\alpha = e^2/(\hbar c)$

d = film thickness

$l \approx \xi$ coherence length

λ_L = London penetration depth

$\lambda_\perp = \lambda_L^2/d$ Pearl length 2d

$ml \propto (1/8\alpha)\ (1/\kappa)$

quantum behavior

characteristic of the material

SUPERINSULATING PHASE

induced effective action $S^{eff}(A_\mu)$ for the electromagnetic gauge potential A_μ

2d : M_μ condense, Q_μ diluted

M_μ can be open ending in magnetic monopole

$$\exp(-S^{eff}) = \sum_{M_\mu} \exp \sum_x \left[-\gamma \left(M_\mu - e\, l^2 F_\mu \backslash \pi\right)^2 \right]$$

$\gamma = g\mu\eta$

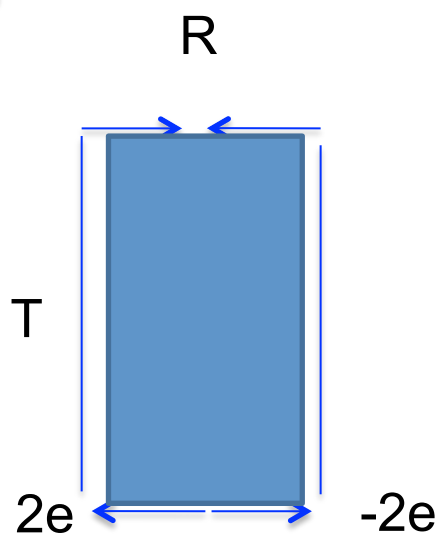
Villain approximation compact QED in 2d

$$S_{QED} = \gamma/2\pi^2 \sum_x \left[1 - \cos(2e\, l^2 F_\mu) \right]$$

(Polyakov)

area law:

$$W(C) \propto_{T \to \infty} \exp -V(R)\, T$$
$$W(C) \propto \exp -\sigma A \Rightarrow V(R) = \sigma R$$



*dual Meissner effect, charge confinement in a monopole condensate, **true also in 3d ⇒ superinsulation can exist also in 3d***

string tension (Polyakov; Kogan and Kovner; Quevedo, Trugenberger, and MCD)

2d:

$$\boxed{\sigma = \frac{\pi^{3/2}}{l^2} \exp\left(-\frac{\mu\eta}{16\pi e^2}\sqrt{\frac{\pi^2 E_J}{2E_C}}\right)}$$

3d:

$$\boxed{\sigma = \frac{1}{64\pi l^2} K_0(\gamma/2)}$$

QCD confining string like picture :

linear confinement of Cooper pairs into neutral "U(1) mesons"

typical size $\boxed{L \simeq (1/\sigma)^{1/2}}$

$L \geq O(l)$ near the direct superconductor to superinsulator transition for $\eta < 1$ (but not too small) ⇒ new spatial scale spontaneously emerging near these transitions, describing U(1) mesons extending over several lengths of the UV cutoff

HINT OF ASYMPTOTIC FREEDOM

reverse of the confinement on scales smaller than the typical string size

SIT: string scale can be inferred from experimental data

$d_{string} = \hbar\ vc\ /\ KT_{CBKT}$

KT_{CBKT} energy required to break up the string

d_{string} scale associated with this energy

TiN films: $T_{CBKT} = 60\ mK^{O}$

vc = c/4.10^5 (Baturina and Vinokour)

$d_{string} \approx 60\ \mu m$

study of formation of superinsulators in TiN films of different sizes (Kalok et al): samples of size ≤ 20μm 2d thermally activated behavior **saturates to the metallic**

Thank you!!!!

DECONFINEMENT CRITICALITY

TiN and NbTiN films:

2 d: superinsulating critical temperature ≡ T_{CBKT} of the charge BKT transition

logarithmic and linear confinement (Yaffe and Svetiski) $\Longrightarrow$ **Berezinski-Kosterlitz-Thouless critical scaling**

$$\boxed{R_{\square} \propto \exp[-\mathrm{const}(\sqrt{\mathrm{T_{BKT}} - \mathrm{T}}]}$$

strong support for superinsulation as Mandelstam-'t Hooft-Polyakov confinement mechanism

InO films: "more" 3d than TiN and NbTiN films($\xi >> d$) (Shahar et al)

$$\boxed{R_{\square} \propto \exp[-\mathrm{const}/(\mathrm{T_0} - \mathrm{T})]}$$

Vogel-Fulcher-Tamman criticality ≡ behaviour of one-dimensional confining strings in 3d (Diamantini, Gammaitoni, Trugenberger and Vinokour)

gauge theory of the BKT transition in the disordered XY-model (Vasin, Ryhzov and Vinokour): BKT criticality $\Longrightarrow$ VFT behavior in 3D