NiPS Laboratory
Noise in Physical Systems

Superinsulators: the discovery of electric confinement in condensed matter systems

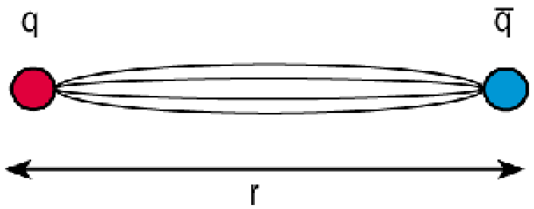
M. Cristina Diamantini

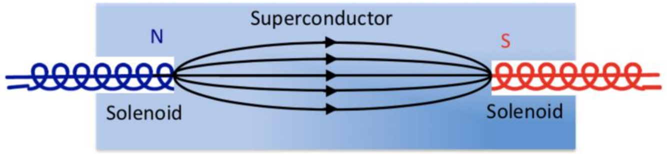
coll:

- **Carlo A. Trugenberger**, SwissScientific
- **Valerii Vinokur**, Terra Quantum AG
- **Luca Gammaitoni,** University of Perugia
- **Yavok Kopelevich,** Universidade Estadual de Campinas
- **Alexey Mironov, Svetlana Postolova,** Institute of Semiconductor Physics, Novosibirsk
- **Flavio Noguiera** Leibniz Institute Dresden
- **Nicola Poccia** Leibniz Institute Dresden
- **Christoph Strunk,** University of Regensburg

XVIth Quark Confinement and the Hadron Spectrum August 2024 Cairns, Australia

quark confinement, dual superconductor





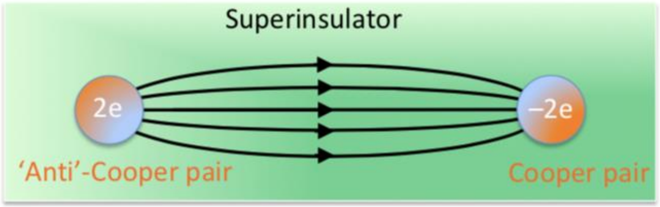
quarks bound by chromo-electric strings in a condensate of (color) magnetic monopoles (Mandelstam, ‘t Hooft, Polyakov)

mirror analogue to vortex formation in type II superconductors

can we have “electric” mesons?

does a dual superconductor exist?

superinsulators



Polyakov's magnetic monopole condensation$\Longrightarrow$ electric string
$\Longrightarrow$ **linear confinement** of Cooper pairs
one color QCD

Superconductor

R = 0

G= ∞

S duality

Mandelstam 'tHooft Polyakov

Superinsulator

R = ∞

G= 0

$$R_\square \propto e^{\frac{E_A}{T}}$$

Arrhenius behaviour, insulators

→

$$R_\square \propto e^{\sqrt{\frac{aT_{cr}}{T-T_{cr}}}}$$

superinsulator

- theoretically predicted in 1996

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

- experimentally observed in:

  In_2O_3 films (Sambandamurthy et al, Phys.Rev.Lett. 94(2005) 017003)

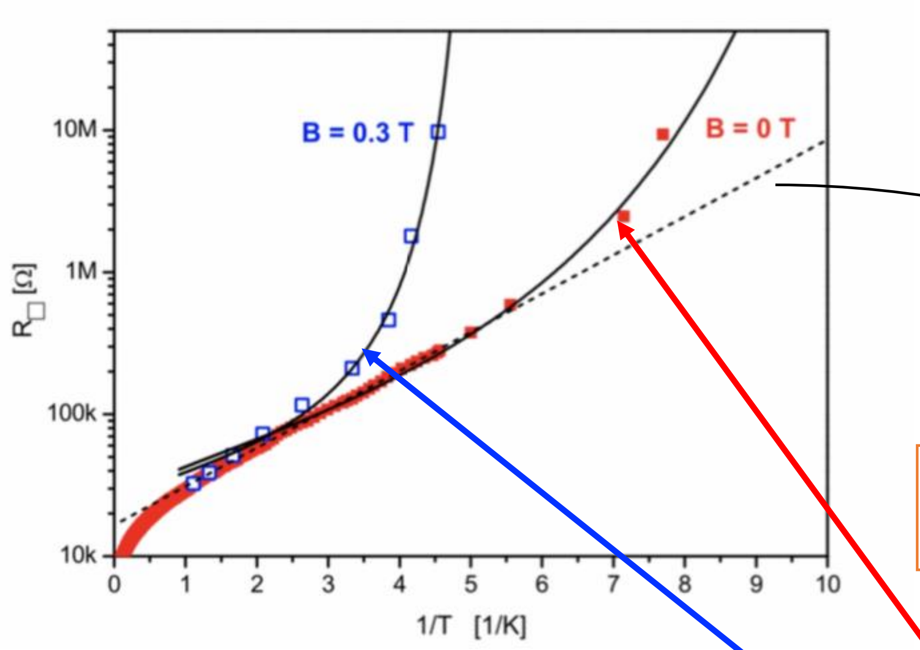
  TiN films (T. Baturina et al, Nature 452 (2008) 613)

- confirmed in NbTin films in 2017 (V. Vinokur et al, Scientific Reports 2018)

- final form of the model (C.A. Trugenberger, V. Vinokur, MCD,

  Nature Comm. Phys. 1:77 (2018))

(2+1)d:



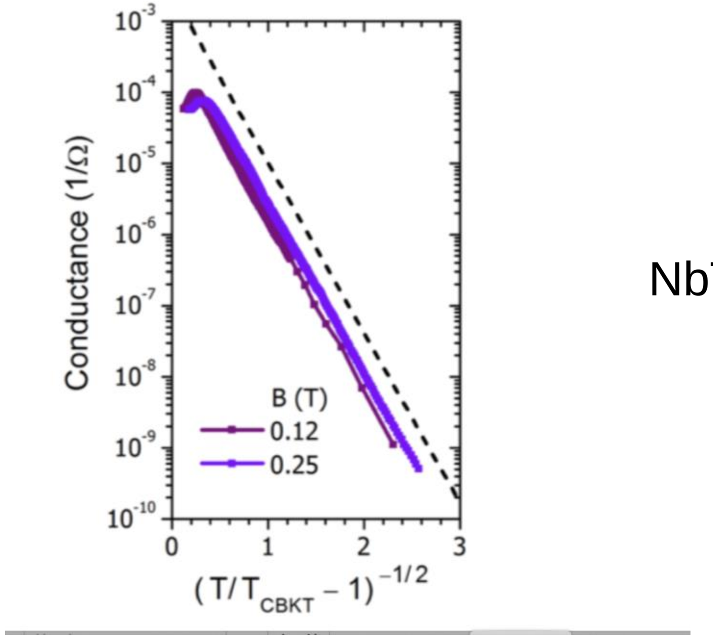
Arrhenius behaviour

$$R_\square \propto e^{\frac{E_A}{T}}$$

Sheet resistance as a function of inverse temperature for a TiN film.
(T. I. Baturina and V. M. Vinokur, Ann. Phys. 331, 236 – 257 (2013))

$T_{cr}(B = 0) = 0.062$ mK

$T_{cr}(B = 0.3T) = 0.175$ mK



NbTiN

hyperactivated behaviour characterizing superinsulators

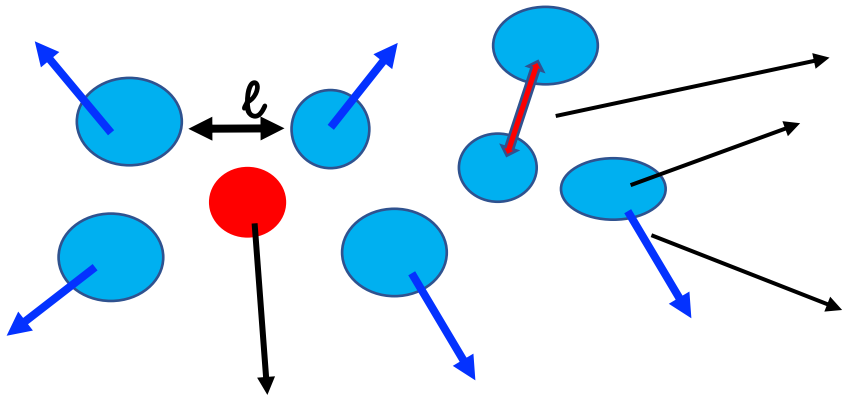
$$R_\square \propto e^{\sqrt{\frac{aT_{cr}}{T-T_{cr}}}}$$

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

Cooper pairs ⟷ Quarks

superconductor to insulator transition (SIT)

films: emergent granularity

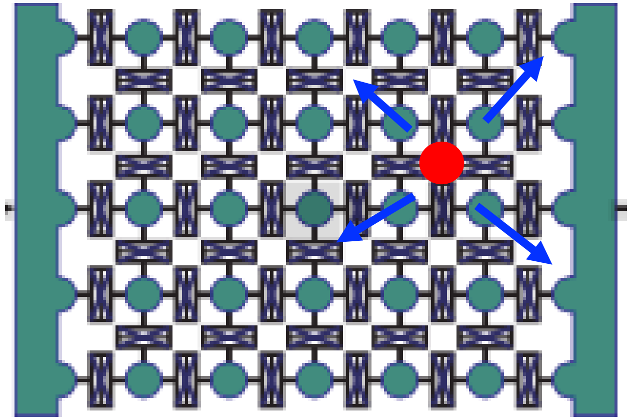


Cooper pair tunnelling

droplet of local SC

phase of the local order parameter

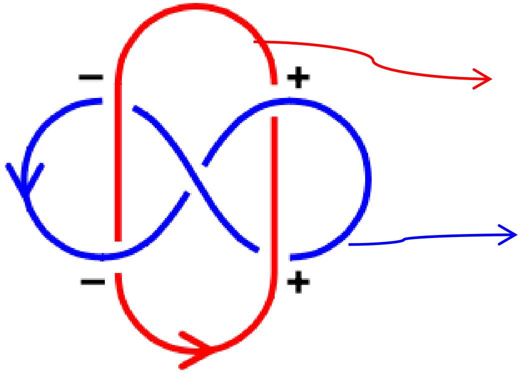
coreless ballistic **Josephson vortex**



Josephson junction arrays:

SIT:

- **Cooper pairs** and **vortices** are the relevant degrees of freedom (Fisher)
- SIT is driven by the competition between charge (Cooper pairs) and vortex **degrees of freedom**: **topological interactions**, Aharonov-Bohm-Casher; **gauge invariance**



Q_μ

M_μ

$$S_{\text{linking}} = \int d^3x \; i \; 2\pi \; Q_\mu \epsilon_{\mu\alpha\nu} \frac{\partial_\alpha}{-\nabla^2} M_\nu$$

local formulation:
(Wilczek)

$$S^{CS} = \int d^3x \; i \, \frac{1}{2\pi} a_\mu \, \varepsilon_{\mu\nu\alpha} \, \partial_\nu b_\alpha + i \, a_\mu Q_\mu + i \, b_\mu M_\mu$$

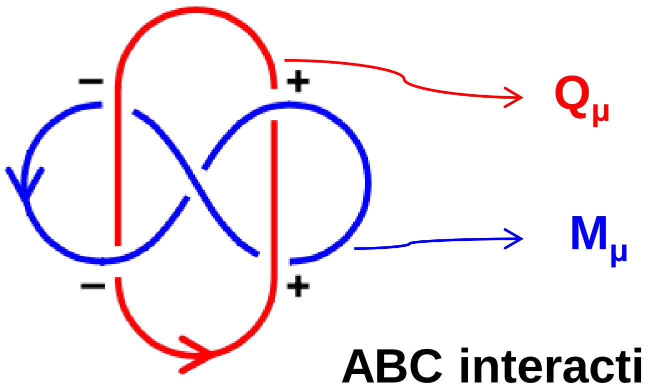
two emergent gauge fields a_μ (vector) and b_μ (pesudovector); emergent mixed Chern–Simons term**,** **U(1) x U(1) symmetry**

⚠ need regularization

(2+1)d **Sodano, Trugenberger, MCD (1996)**

$$S^{TM} = \int d^3x \, \frac{1}{2e_v^2} f_\mu f_\mu + \frac{1}{2eq^2} g_\mu g_\mu + i \frac{1}{2\pi} a_\mu \, \varepsilon_{\mu\nu\alpha} \, \partial_\nu b_\alpha + i \, a_\mu Q_\mu + i \, b_\mu M_\mu$$

$$f_\mu = \frac{1}{2} \varepsilon_{\mu\nu\alpha} f_{\nu\alpha} = \frac{1}{2} \varepsilon_{\mu\nu\alpha} \partial_\nu b_\alpha \qquad g_\mu = \frac{1}{2} \varepsilon_{\mu\nu\alpha} g_{\nu\alpha} = \frac{1}{2} \varepsilon_{\mu\nu\alpha} \partial_\nu a_\alpha$$



ABC interaction

a_μ and b_μ acquire a **topological mass**

$m = (e_v \, e_q) / 2\pi$

$[e_q^2] = m^{-d+3}$ $[e_v^2] = m^{d-1}$

$$e_q^2 = O\left(\frac{e^2}{2\pi d}\right),$$
electric energy scale of a droplets

$$e_v^2 = O\left(\frac{\pi}{e^2 \lambda_\perp}\right) = O\left(\frac{\pi d}{e^2 \lambda_L^2}\right)$$
magnetic energy scale of a droplets

$m = e_q \, e_v / 2\pi$

$g = e_v / e_q = O(d \, \ell / \alpha \lambda_L)$

relative strenght of magnetic and electric scales

$\alpha = e^2/4\pi$

3d:

$$S^{TM} = \int d^4x \, \frac{1}{2e_v^{\,2}} h_\mu h_\mu + \frac{1}{2e_q^{\,2}} g_\mu g_\mu + i \frac{k}{2\pi} a_\mu \, \varepsilon_{\mu\nu\alpha\beta} \, \partial_\nu b_{\alpha\beta} + i \, a_\mu Q_\mu + i \, b_{\mu\nu} M_{\mu\nu}$$

with $h_\mu = \frac{1}{2} \varepsilon_{\mu\nu\alpha\beta} \partial_\nu b_{\alpha\beta}$

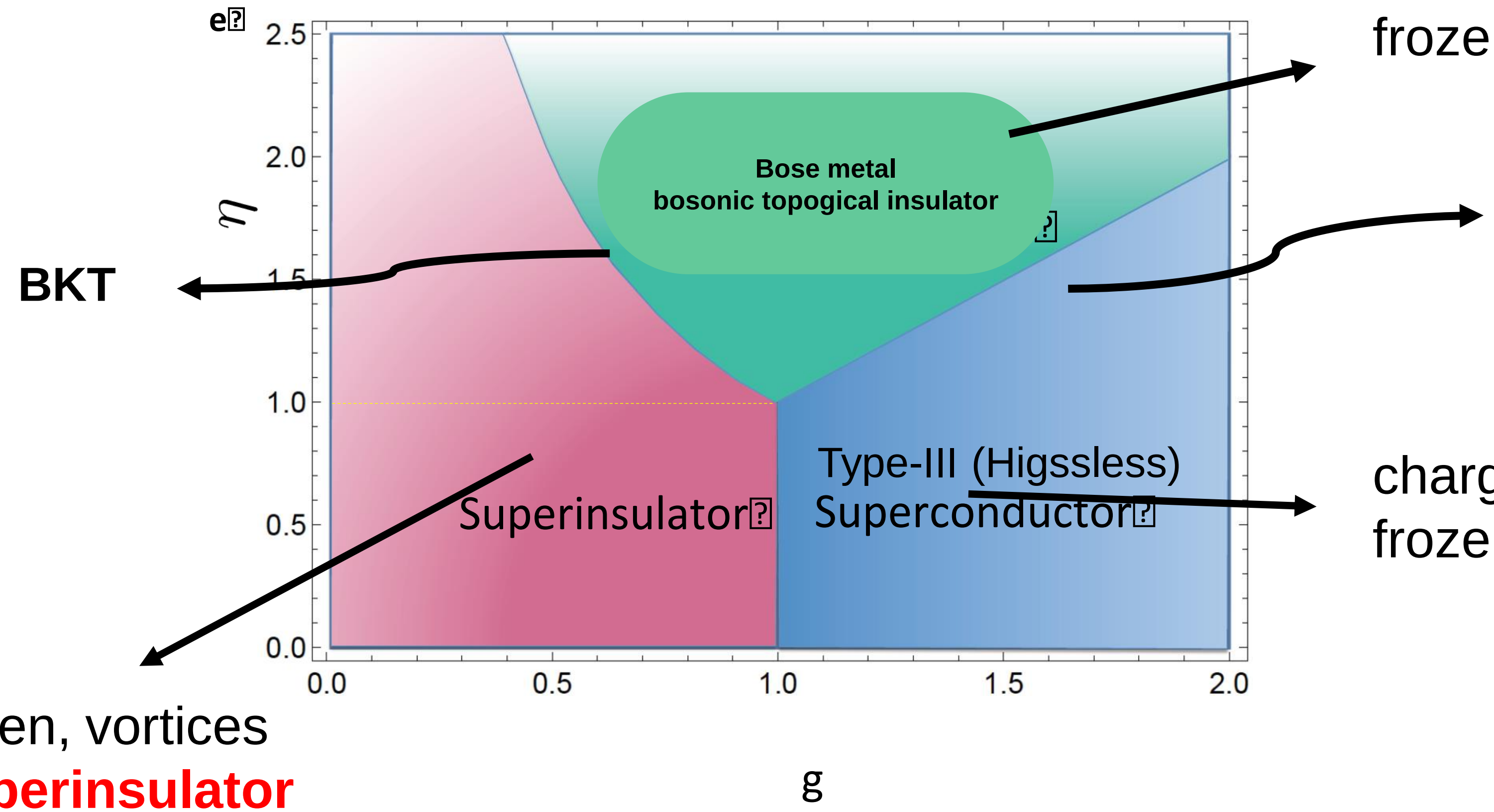
S^{TM} : generalization of CS mass to BF theory, **topological mass generation**

- a_μ and b_μ ($b_{\mu\nu}$) acquire a topological mass $m = (k \, e_q \, e_v)/2\pi$
- k is a dimensionless parameter, it determines the ground state degeneracy on manifold with non trivial topology and the statistics (k=1)
- $[e_q^2] = m^{-d+3}$ $[e_v^2] = m^{d-1}$ naively irrelevant 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

T=0

phase structure: couple with e.m. field ⟶ $S_{eff}\,(A_\mu\,,\,Q_\mu,\,M_\mu\,)$



both charges and vortices frozen➔ **Bose metal**

charges mobile, vortices frozen➔ **superconductor**

charges frozen, vortices mobile➔ **superinsulator**

these phases have been observed in superconducting films

Superinsulating phase

first predicted in: P. Sodano, C. A. Trugenberger and MCD, Nucl. Phys, B474, 641 (1996)

induced effective action S^{eff} (A_μ) for the electromagnetic gauge potential A_μ $Q_i = 0$

$$S \to S + i \sum_x A_\mu j_\mu = S + i \sum_x A_\mu \epsilon_{\mu\alpha\nu} \Delta_\alpha b_\nu$$

non-relativistic compact QED in 3d euclidean (Polyakov)

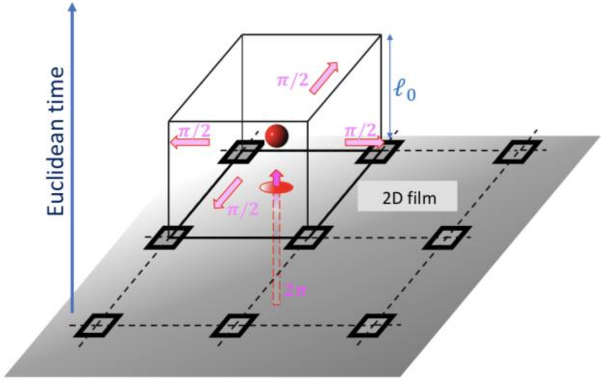
$$S_{\rm top}\left(M_\mu, A_\mu\right) = \sum_{x,i} \frac{1}{2e^2_{\rm eff}} \left(\mathcal{F}_i + 2\pi M_i\right)^2$$

$e^2_{eff} \propto 1 / g \approx e^2 \, O(\lambda_L /d)$ (F_i = (dual) electromagnetic fields)

M_i^T can be reabsorbed into F_i

$$M_i^L = \frac{\Delta_i}{\nabla^2} m \;, m \in \mathbb{Z}$$

m are **magnetic monopoles**: **tunneling events** between vortex sectors



$$S_{TOP} = \frac{2\pi^2}{e^2_{\rm eff}} \sum_x m \frac{1}{-\nabla^2_2} m$$

near SIT $(e^2_{\rm eff}/2\pi)\ln|\mathbf{x}|$, $\Rightarrow$ **BKT transition**

$g < g_{crit}$ deconfined instantons $\Rightarrow$ **charge confinement**

Wilson Loop

Wilson loop: its expectation value measures the potential between static external test charges q (2e) and anti-charges:

$$W(C) \equiv \exp\ i\ I\ q \sum_x q_\mu A_\mu$$

rectangular loop, for $T \rightarrow \infty$

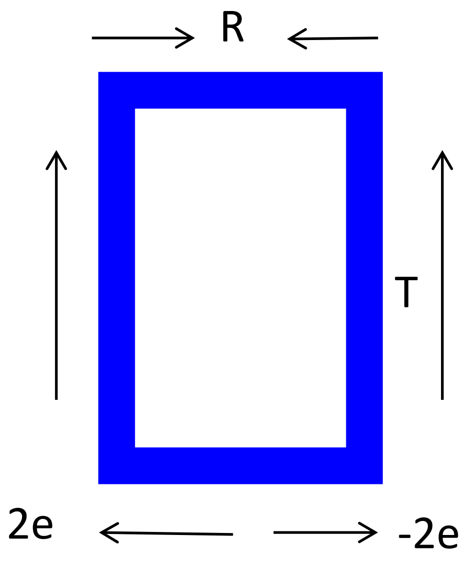
$$\langle W(C) \rangle \propto_{T\rightarrow\infty} \exp -V(R)\, T$$

$$\langle W(C) \rangle \propto \exp -\sigma A \Rightarrow V(R) = \sigma R$$

A = area enclosed by the loop C

σ emergent scale, **string tension**

$$\langle W(C) \rangle = \exp - S_{CS}(\sigma_{\mu\nu})$$



$S_{CS}(\sigma_{\mu\nu})$: confining string action (Quevedo and Trugenberger; Polyakov)

true also in 3d ⇒ superinsulation can exist also in 3d

$$\sigma = \frac{\sqrt{8}}{\ell_0 \ell} \frac{e_{\text{eff}}}{\pi} e^{-\frac{\pi^2}{e_{\text{eff}}^2} G_2(0)}$$

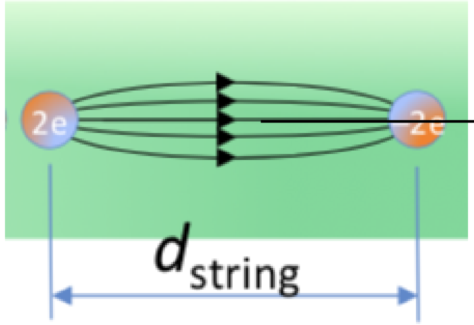
$G_2(0)$ is the value of the 2D lattice Coulomb kernel at coinciding points

instantons disorder the system ⟹ **photon acquires a dynamical mass m_γ**

$$m_\gamma^2 = \frac{8\pi^2}{e_{\text{eff}}^2 l^2} \exp \frac{-2\pi^2 G(0)}{e_{\text{eff}}^2}$$

$\lambda_{el} = 1/m_\gamma$ **screening of Coulomb interaction**

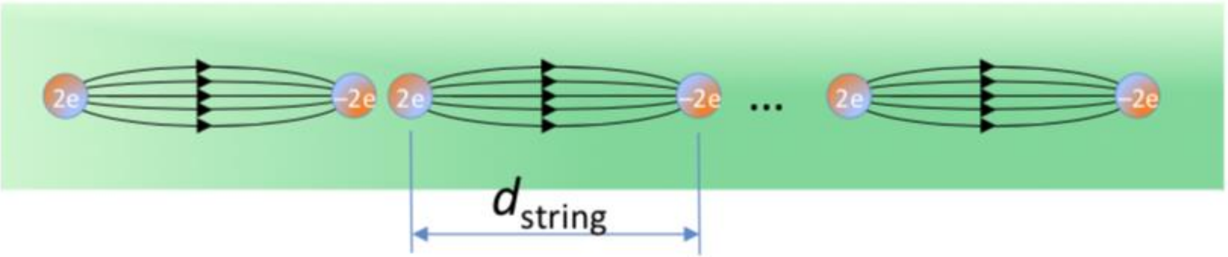
linear confinement of Cooper pairs into neutral "U(1) mesons"

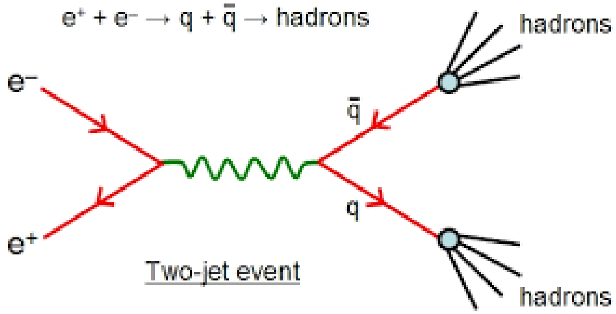


$w_{string} = 1/m_\gamma$ (Caselle et al)

$d_{string} \simeq (\hbar v_c)/\sigma)^{1/2}$

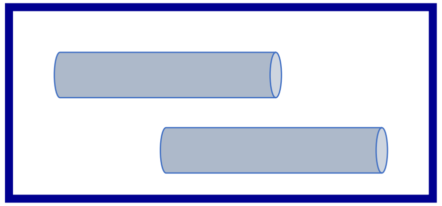
near SIT : **$d_{string} >> l$**



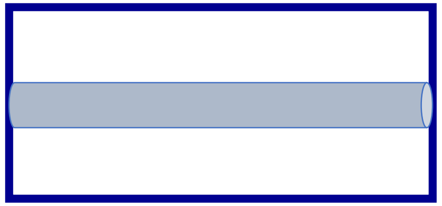


long strings unstable, string fragmentation via creation of charge-anticharge pairs like formation of hadron jets at LHC ⟹ creation of neutral mesons ($V \approx 2m_{CP}$,V applied voltage)

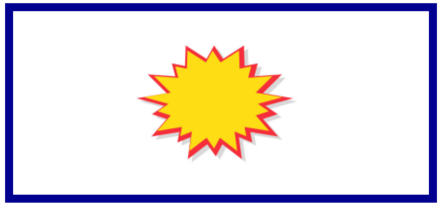
Electric pions: no U(1) charge observable for $d > d_s = 1/\sqrt{\sigma}$
→ **infinite resistance** in large enough samples (finite T)



$V < V_{c1}$
only neutral pions
no current



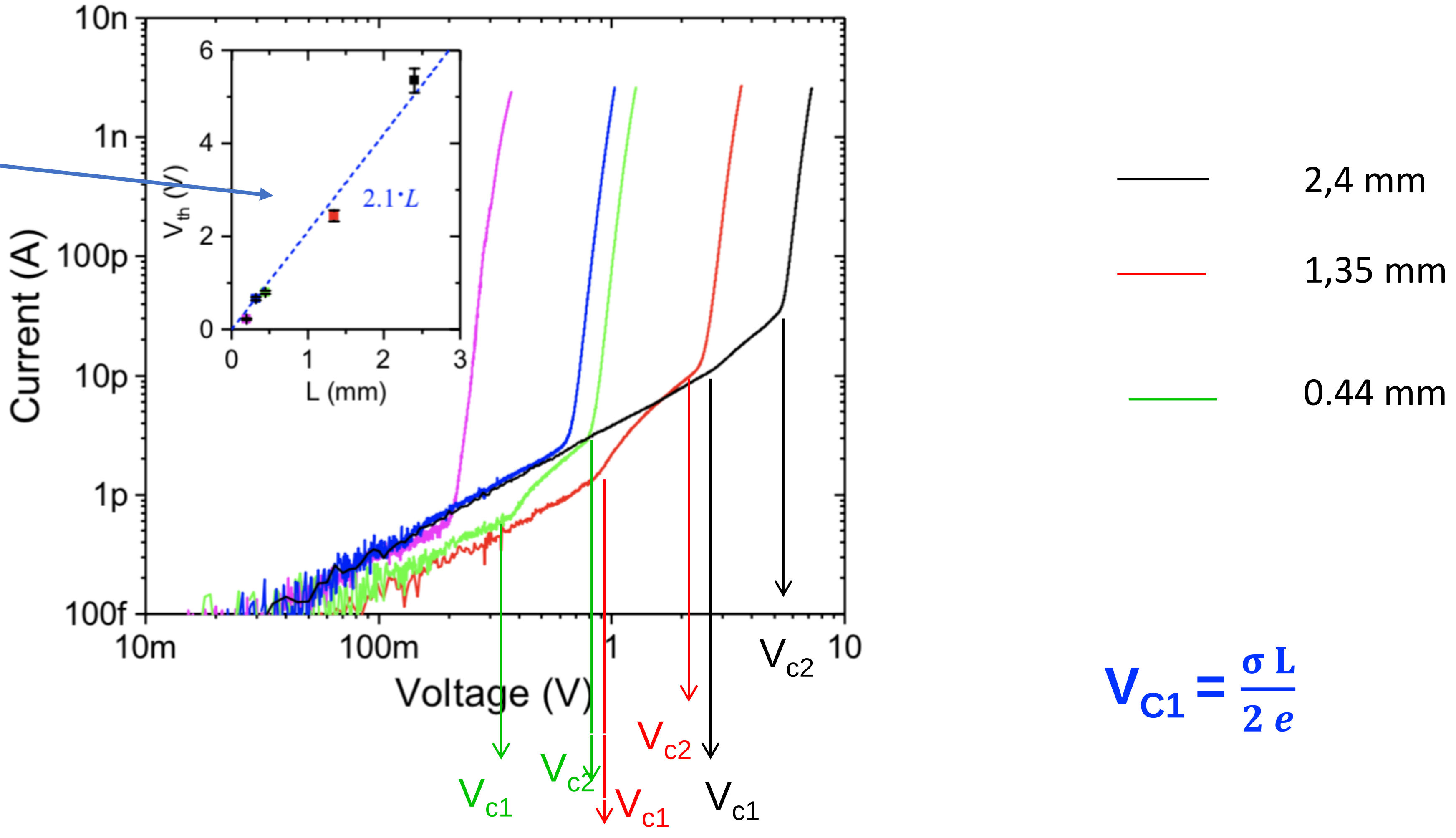
$V_{c1} < V < V_{c2}$
flux penetration
current passes



$V > V_{c2}$
superinsulation
destroyed

NbTiN at 50 mK $R_{\square}(T = 2K) = 2M\Omega$

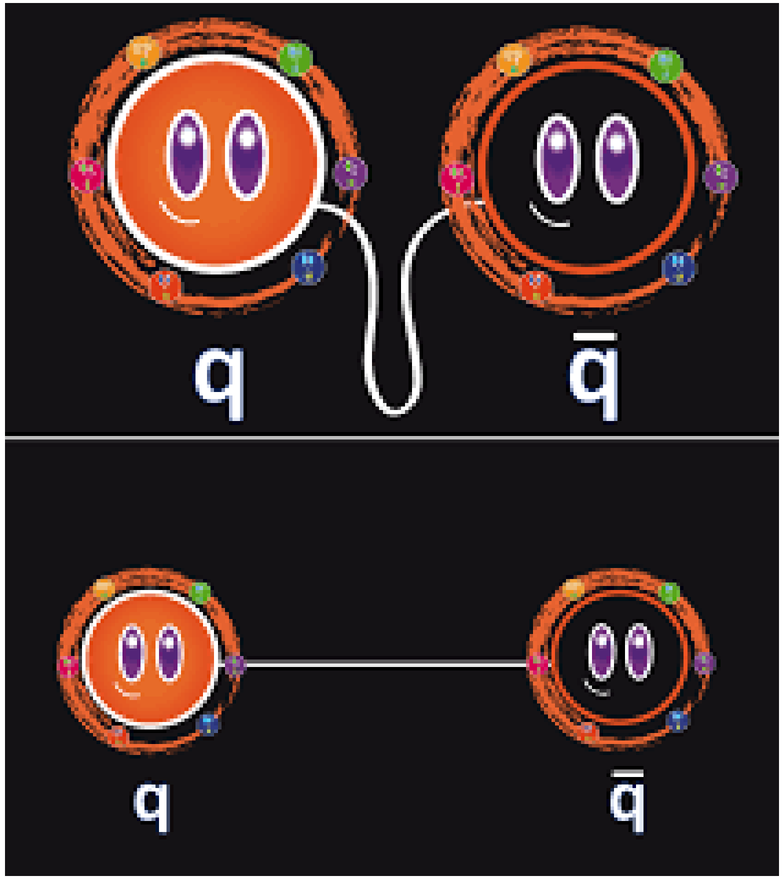
$V_{C2} \propto L$



$$V_{C1} = \frac{\sigma L}{2e}$$

(Postolova, Mironov, Gammaitoni, Strunk, Trugenberger, Vinokour, MCD, Nature Comm. Phys. 3:142 (2020))

look inside an electric pion



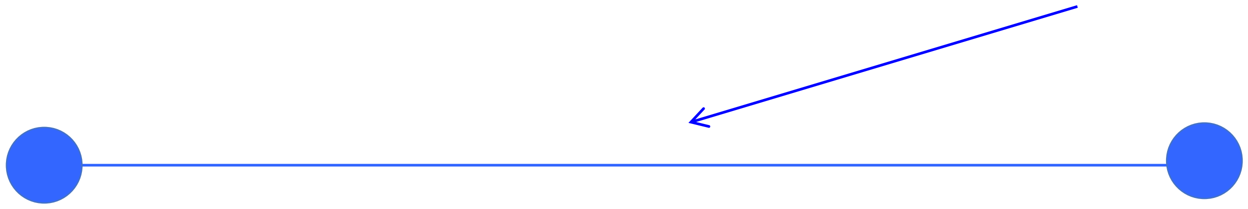
at smaller scales tension vanishes while Coulomb interaction remains screened

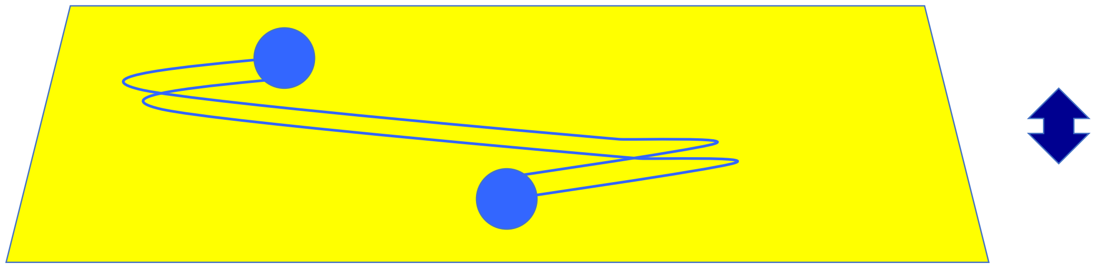
⬇

sample < electric pion size: transition from hyperactivated to metallic behaviour

$\lambda_{\rm el} < L < d_s.$

From this range linear potential is felt / meson size





Range of Coulomb Interaction screened by photon mass

Cooper pairs essentially free: metallic behaviour expected

SIT: string scale can be inferred from experimental data

$d_{string} = \hbar\, v_c \,/\, KT_C$

KT_C energy required to break up the string

d_{string} scale associated with this energy

v_c = speed of light in the material

T_C = superinsulation critical temperature ≡ T_{CBKT}

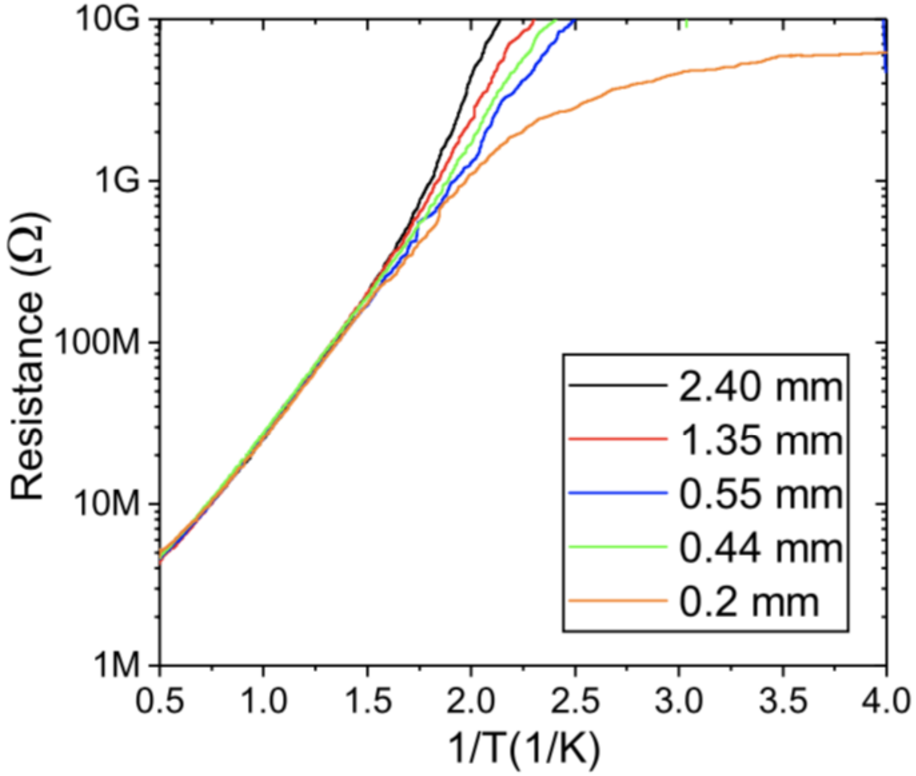
NbTiN films:

(Postolova, Mironov, Gammaitoni, Strunk, Trugenberger, Vinokour, MCD, Nature Comm. Phys. 3:142 (2020))

$R_{\square}(T = 2K) = 0.2M\Omega$

$T_{CBKT} = 400$ mK^{O}
$v_c = 10^6$ ms^{-1}
$\varepsilon \approx 800$

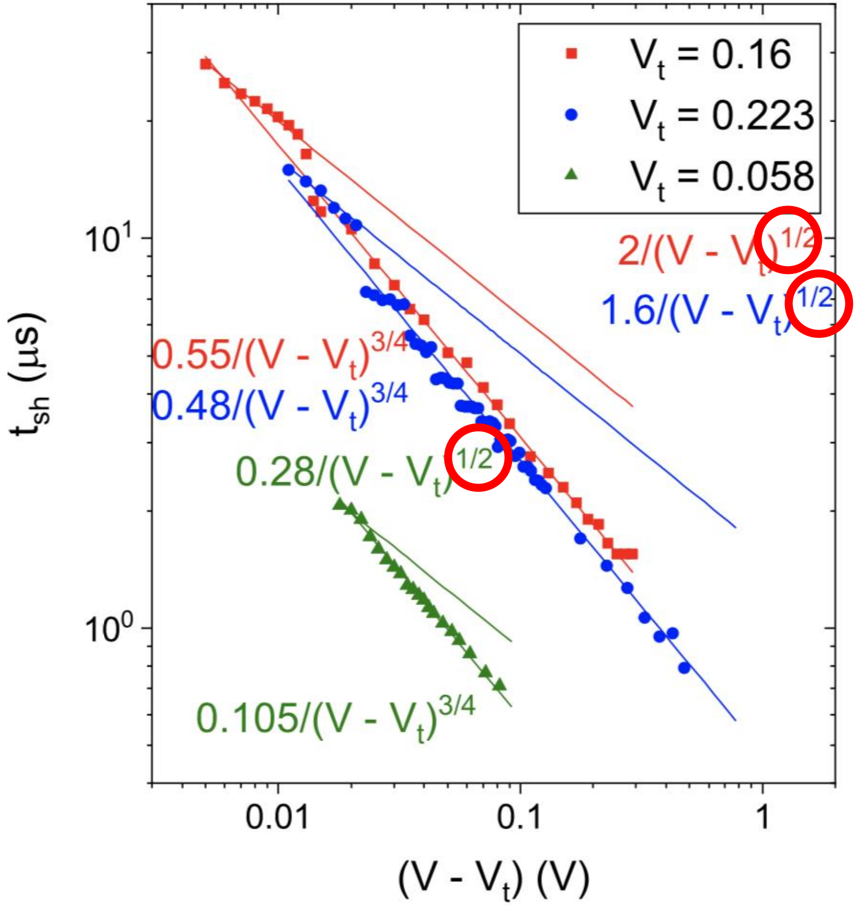
$d_{string} \leq 0.13$ mm



Non-equilibrium relaxation of the electric pions in superinsulating films:

t_{sh} time delay of the current passage in the superinsulator related to applied voltage V via the power law: $t_{sh} \propto (V - V_p)^{-\mu}$; V_p effective threshold voltage

μ = 1/2 direct experimental evidence for the electric strings' linear potential confining charges



$$F_a = 2e\sigma = 2eV_{cr}/L.$$

$$F_r = 2eV/L.$$

$$a = (2/m)F_{tot} = (4e/mL)(V - V_{cr}).$$

$$r(t) = \frac{2e}{mL}(V - V_{cr})\,t^2$$

$$t_{cr} = \sqrt{\frac{mL^2}{2e}}\,(V - V_{cr})^{-1/2}$$

measurements are taken on the superinsulating NbTiN

THANK YOU