# Superinsulators: the discovery of electric confinement in condensed matter systems

**M. Cristina Diamantini**

**Fourty years of Conformal Field Theory 2024**

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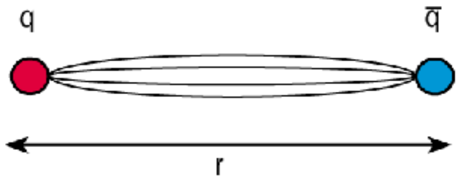
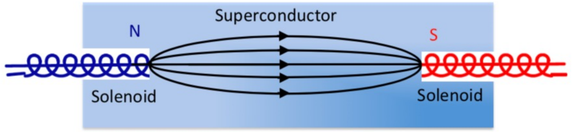
## quark confinement, dual superconductor



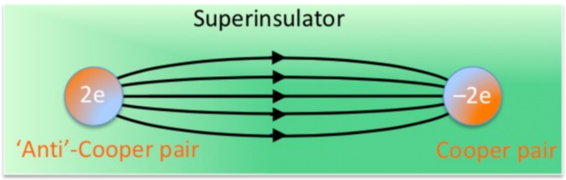




quarks bound by (chromo)-electric strings in a condensate of color magnetic monopoles (Mandelstam, ‘t Hooft, Polyakov)

mirror analogue to vortex formation in type II superconductors

### can we have “electric” mesons?

# superinsulators




### does a dual superconductor exist?

Polyakov's magnetic monopole condensation⟹ electric string
⟹ **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

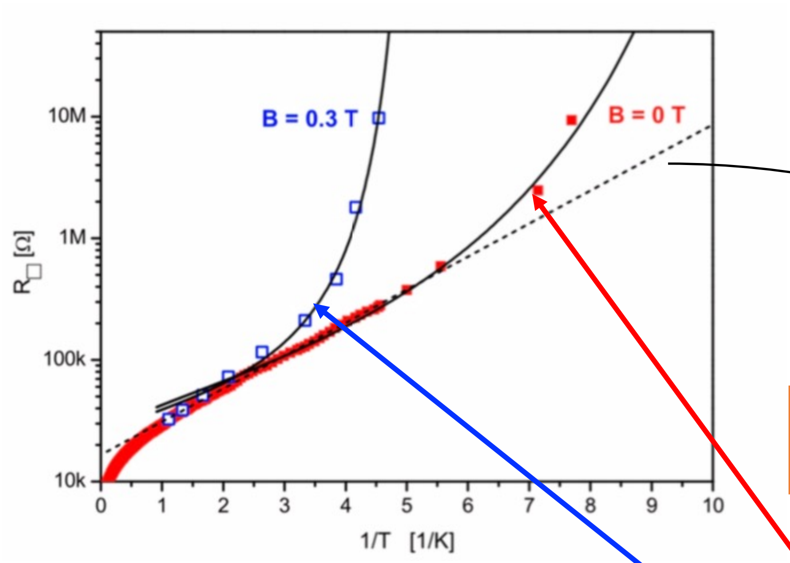
  $In_2O_3$ films (Sambandamurthy et al, Phys.Rev.Lett. 94(2005) 017003)

  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**



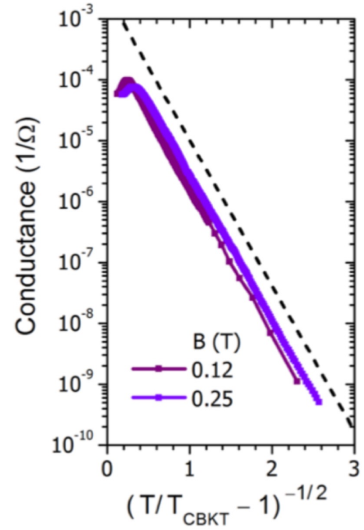

Arrhenius behaviour

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

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

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

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))




NbTiN

hyperactivated behaviour characterizing superinsulators

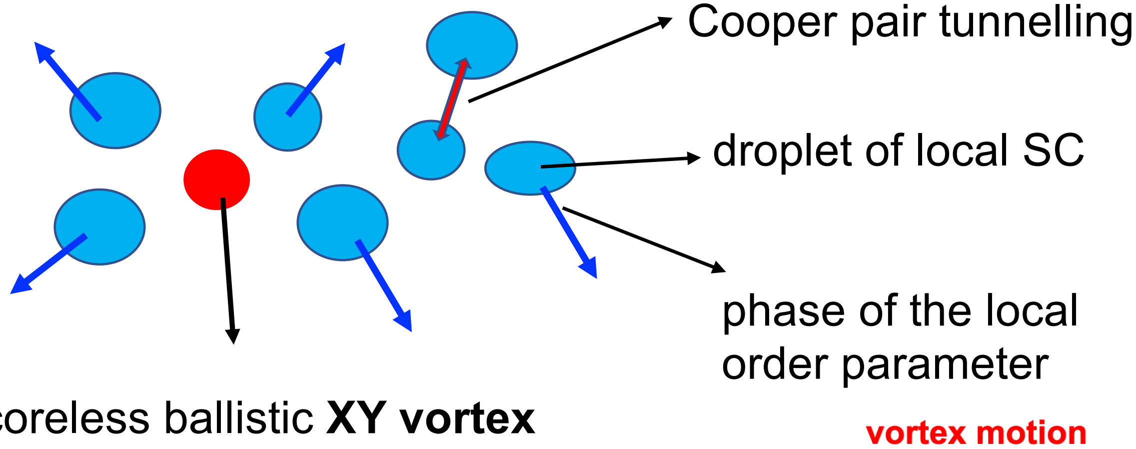
$$R_\square \propto e^{\sqrt{\frac{aT_{cr}}{T - T_{cr}}}}$$

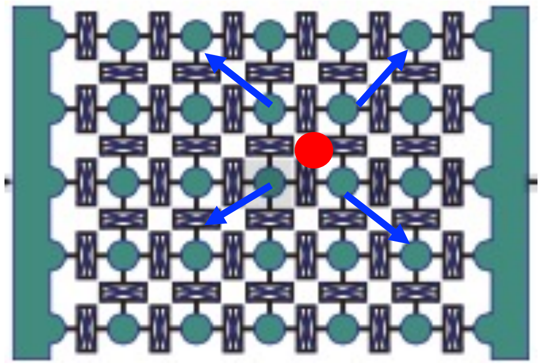
Superinsulation: realization and proof of confinement by monopole condensation in solid state materials

Cooper pairs ⟷ Quarks

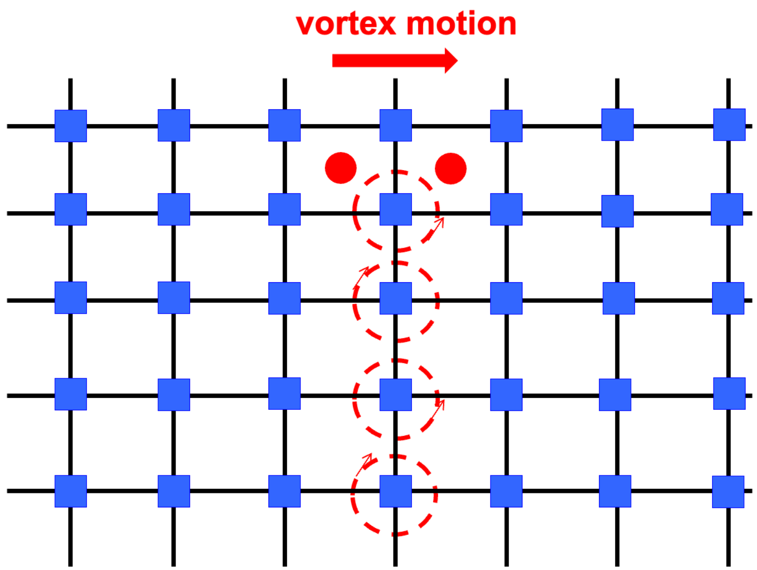
# superconductor to insulator transition (SIT)

**films: emergent granularity**



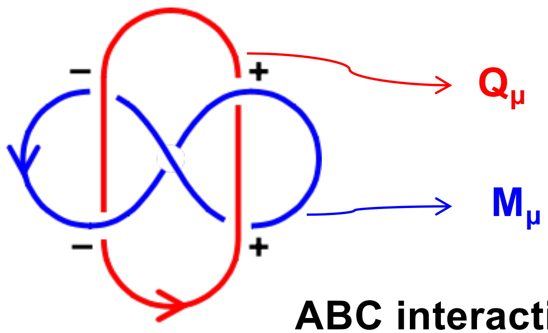
**Josephson junction arrays:**



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

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

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




**ABC interaction**

$a_\mu$ and $b_\mu$ acquire a topological mass

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

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

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

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

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

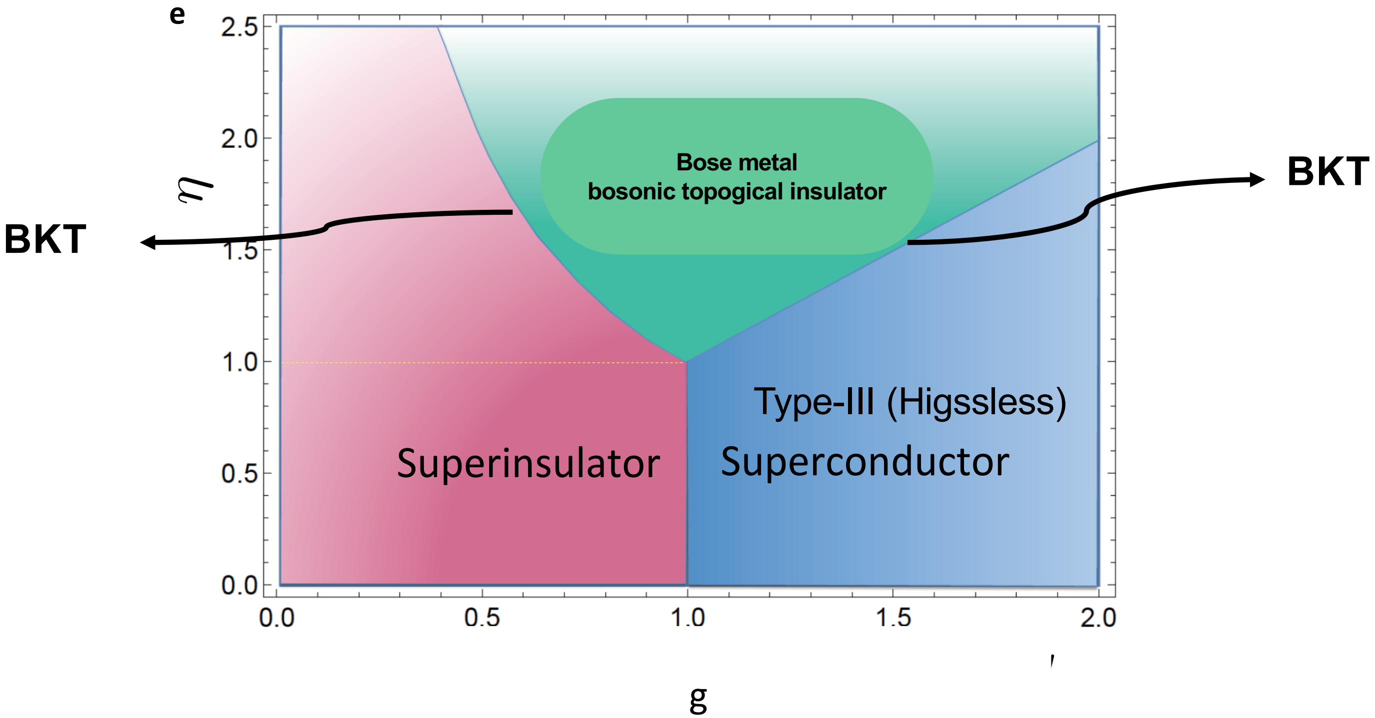
**$g = e_v / e_q = O(d \, \ell / \alpha \lambda_L)$**

relative strenght of magnetic and electric scales

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

**T=0**

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



# Superinsulating phase

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

***induced effective action $S^{eff}(A_\mu)$ for the electromagnetic gauge potential $A_\mu$*** $Q_i = 0$

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

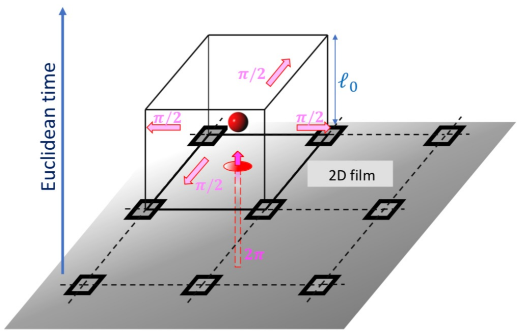
**non-relativistic compact QED** in 3d euclidean (Polyakov)

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

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



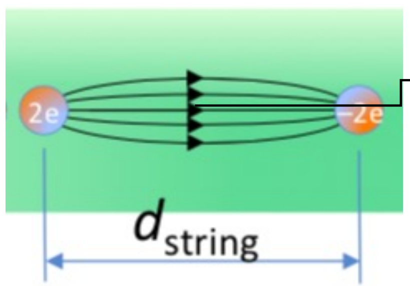

$$S_{TOP} = \frac{2\pi^2}{e_{\rm eff}^2} \sum_x m \frac{1}{-\nabla_2^2} m$$

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

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

Wilson loop:

$V(x) = \sigma x$ $\sigma$ = string tension

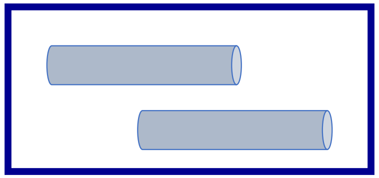



$W_{string} = 1/m_\gamma$ (Caselle et al)

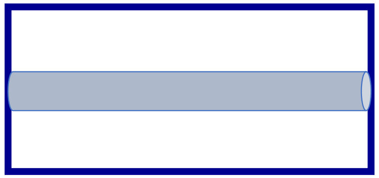
instantons disorder the system $\Longrightarrow$ ***photon acquires a dynamical mass*** $m_\gamma$

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

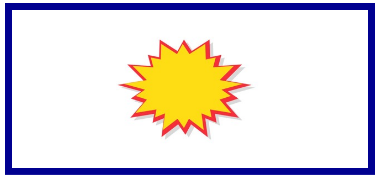
**Electric pions**: no U(1) charge observable for $d > d_s = 1/\sqrt{\sigma}$
→ **infinite resistance** in large enough samples (finite T)



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



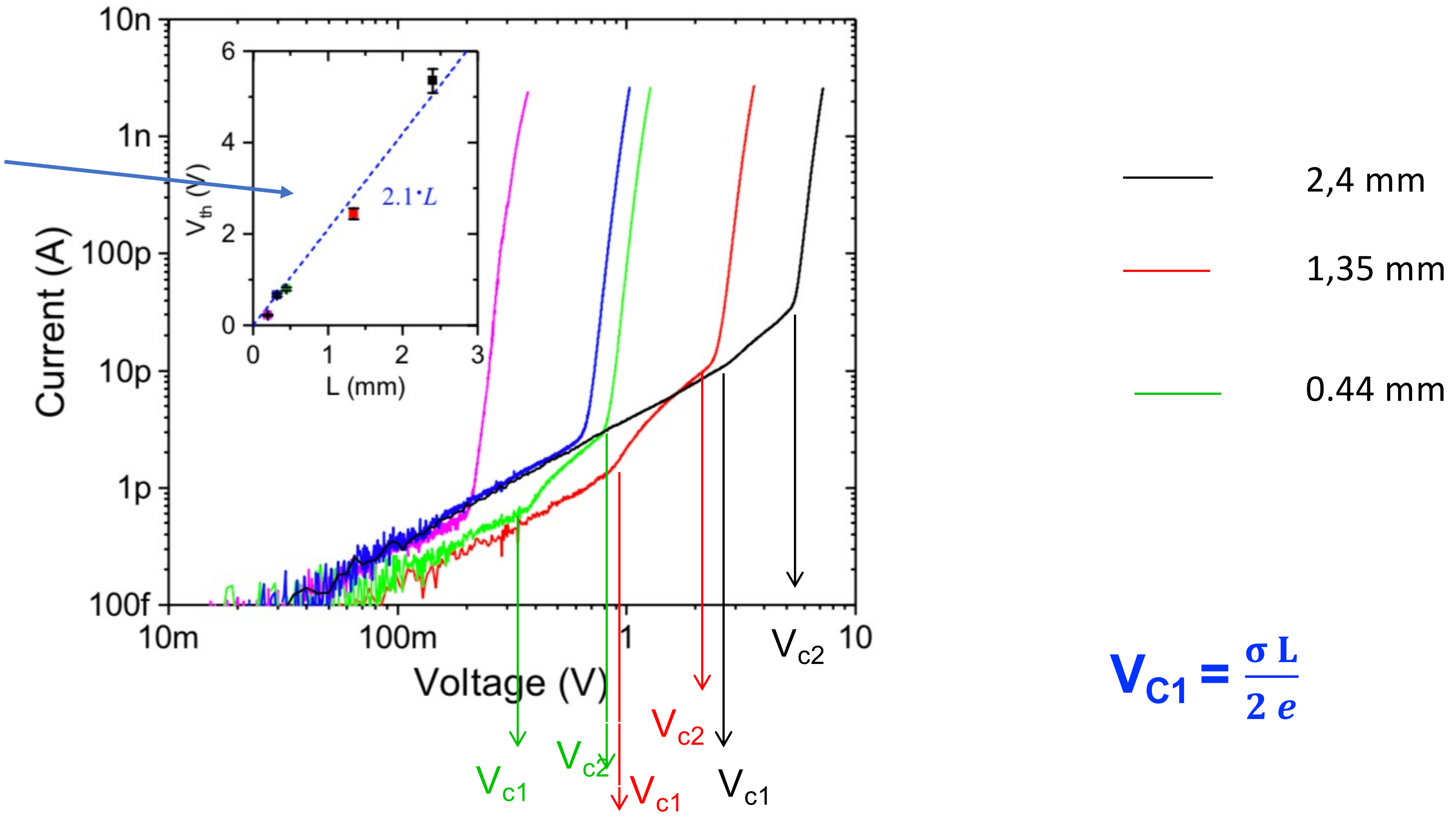
$V_{c1} < V < V_{c2}$
flux penetration
current passes



$V > V_{c2}$
superinsulation
destroyed

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

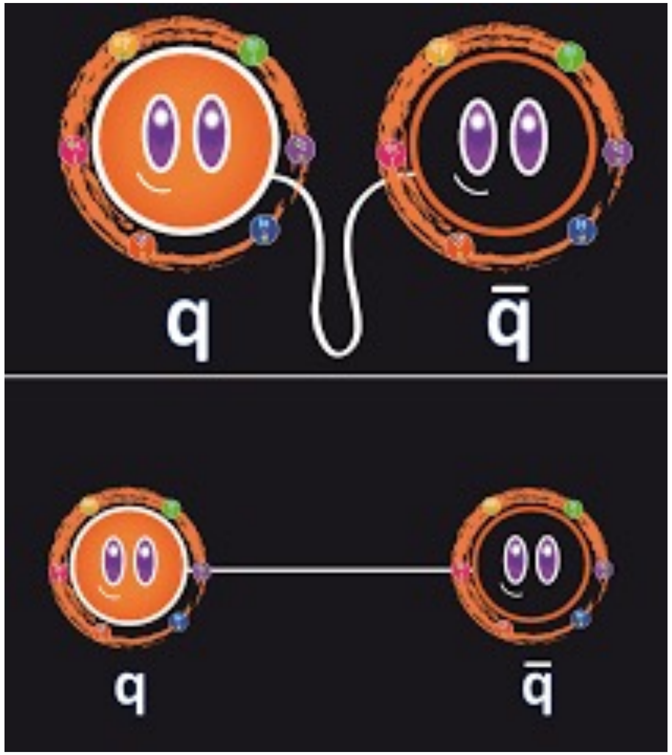
$V_{C2} \propto L$




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

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

# look inside an electric pion



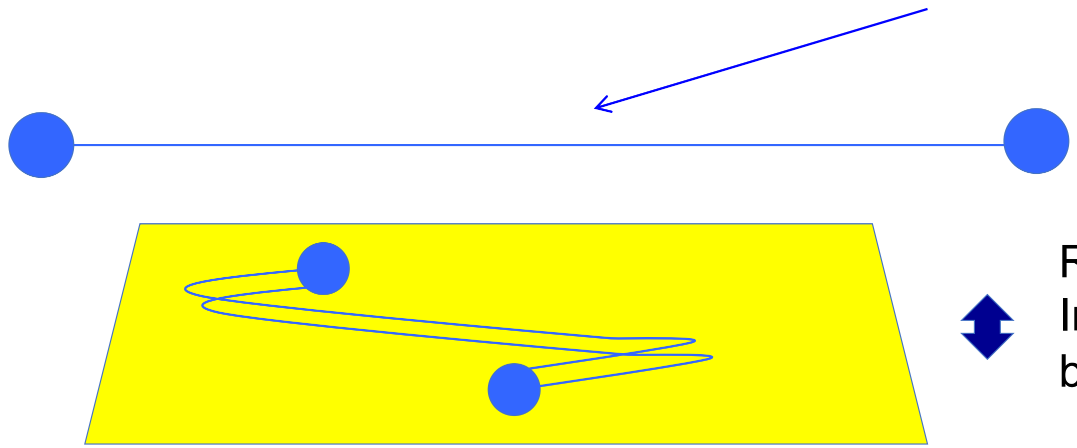

at smaller scales tension vanishes while Coulomb interaction remains screened

⬇

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 ≡ $T_{CBKT}$

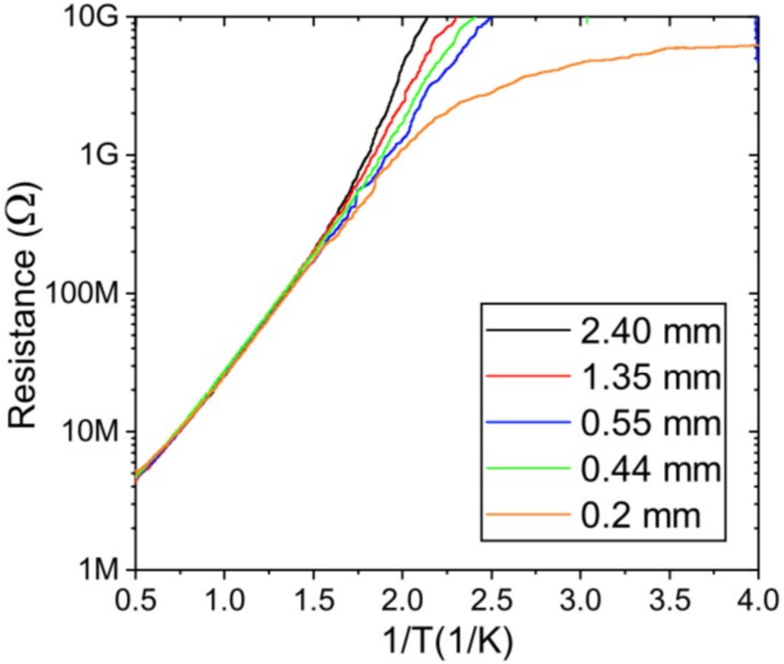
# NbTiN films:

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

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

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

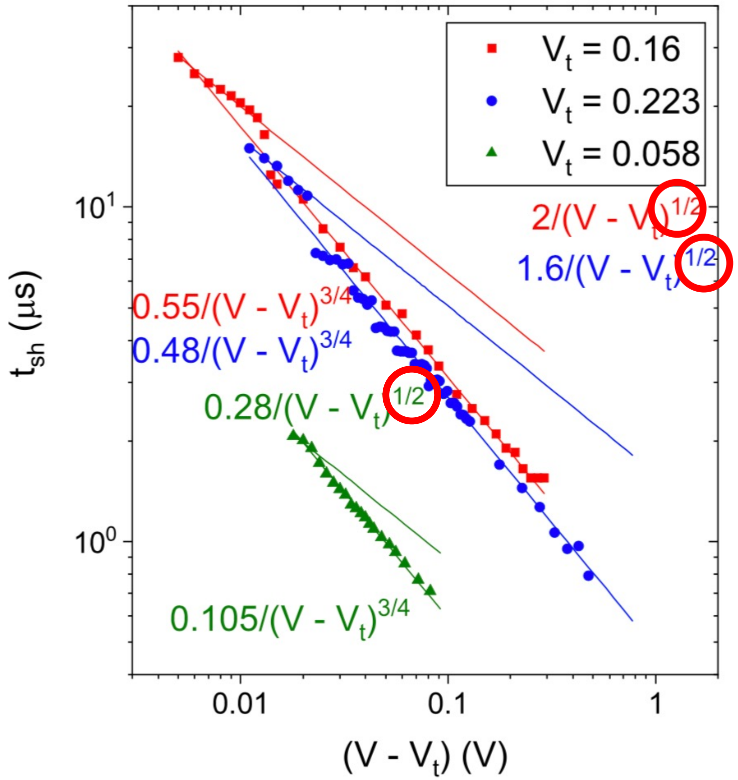
$\boxed{d_{string} \leq 0.13\ mm}$



**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: $\boldsymbol{t_{sh} \propto (V - V_p)^{-\mu}}$ ; $V_p$ effective threshold voltage

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




measurements are taken on the superinsulating NbTiN

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

$$F_r = 2eV/L.$$

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

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

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

# THANK YOU

# BUON COMPLEANNO ANDREA