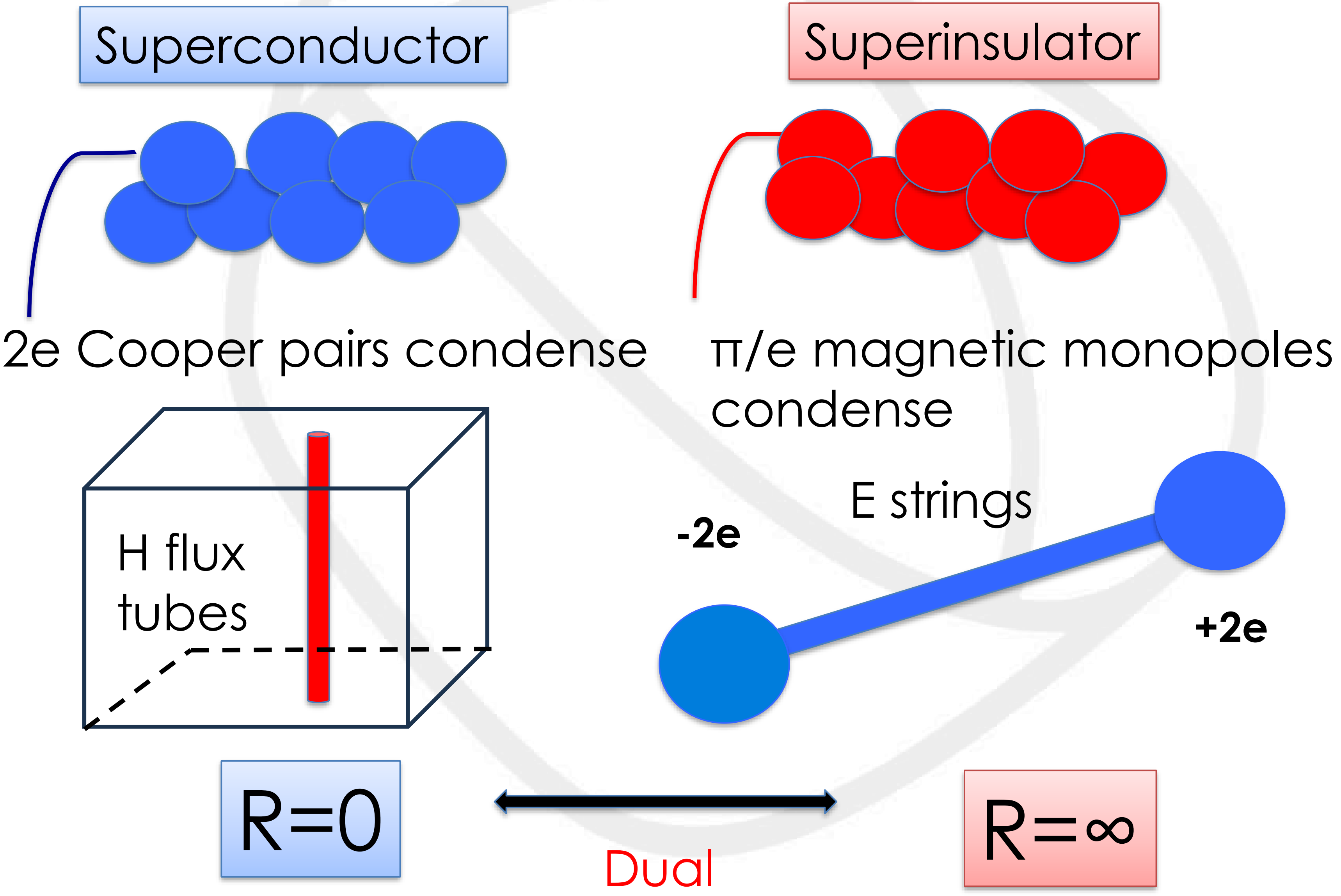
Superinsulation: magnetic monopoles and confinement in condensed matter

Carlo A. Trugenberger

Colloquium NYUAB,
February 2025

What is a superinsulator?



Superconductor

Superinsulator

2e Cooper pairs condense

π/e magnetic monopoles condense

H flux tubes

E strings

-2e

+2e

$R=0$

Dual

$R=\infty$

A bit of history

‘t Hooft 1978, Nucl. Phys. B138 (1978) 1

“….absolute confinement is realized in a phase which is in many respects similar to the superconducting phase. In a certain sense it is the extreme opposite ("superinsulator”)”

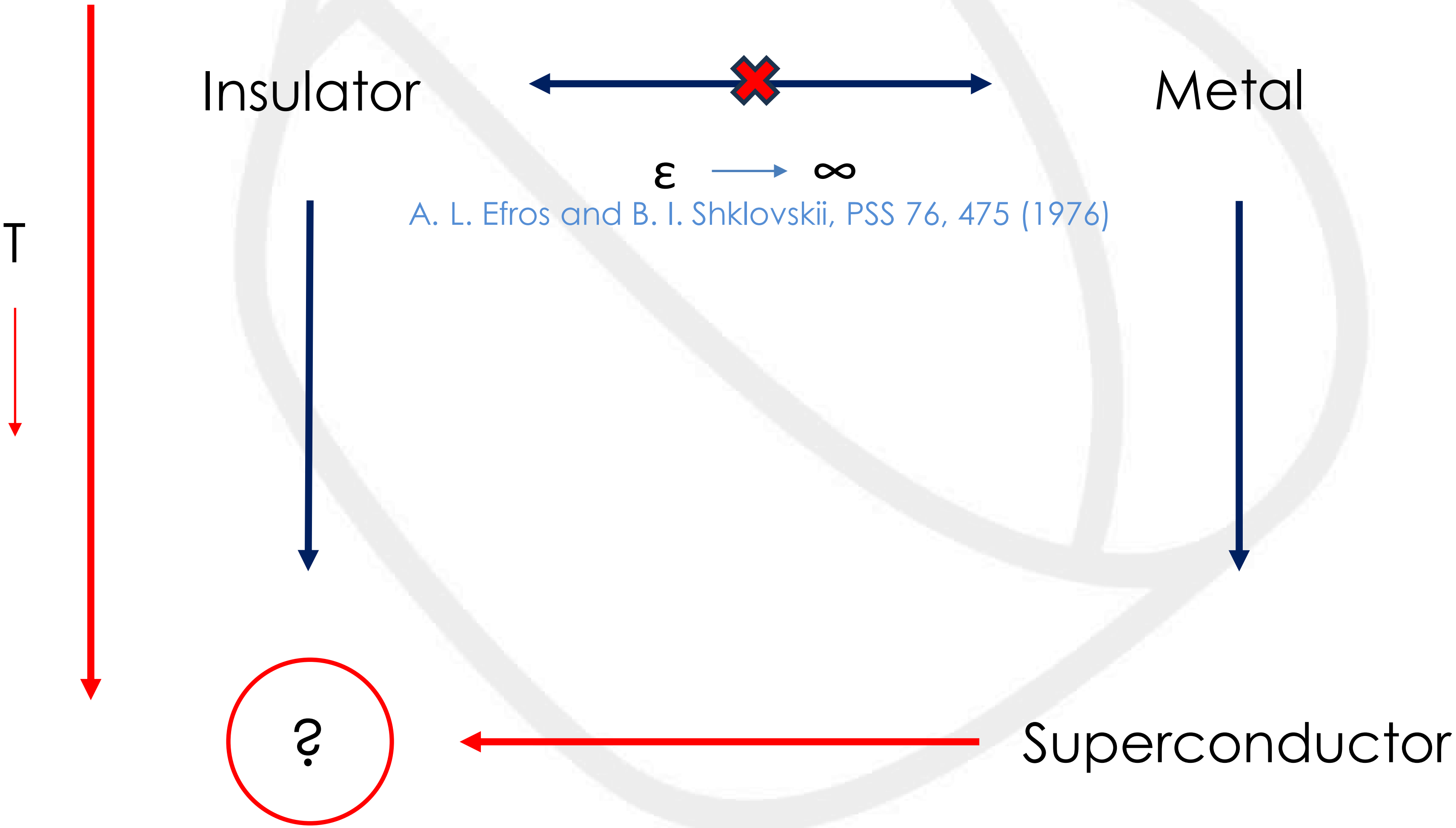
M. C. Diamantini, P. Sodano & C. A. T. 1996
Nucl. Phys. B474 (1996) 641

Predicted superinsulators in condensed matter: specifically at the 2D superconductor-insulator transition (SIT)

V. Vinokur et al. 2008, Nature 452 (2008) 613

Independent prediction of superinsulators in the SIT and experimental confirmation

The physics of large-ε



A. L. Efros and B. I. Shklovskii, PSS 76, 475 (1976)

Large-ε superconductors in the 2D limit

Coulomb interaction in the limit ε → ∞, thickness d → 0, d ε finite

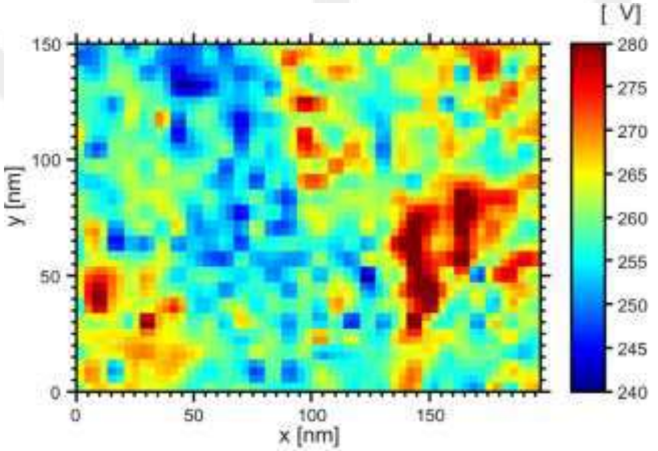
$(e^2/\lambda_e)\ \log|x/\lambda_e|$ screening length $\lambda_e = \varepsilon d$

For $\lambda_e > L$ = lateral dimension of system → **pure 2D electromagnetism**

Non-perturbative at large distances

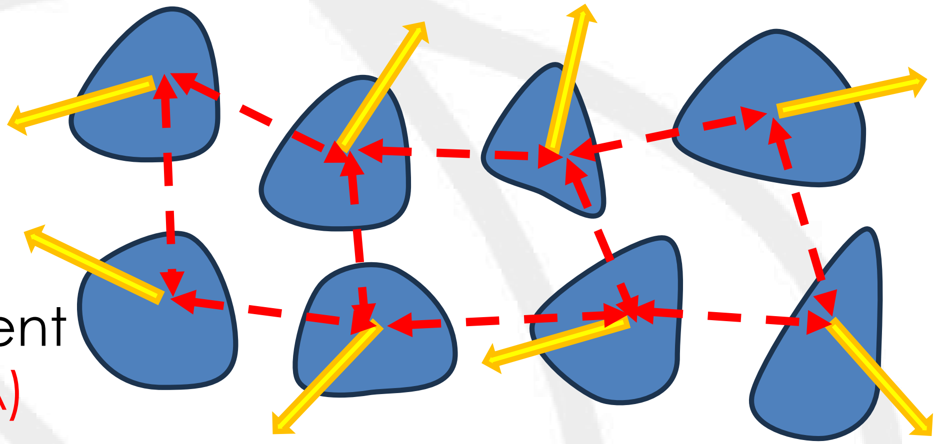
Condensate breaks up into a **granular structure**

Type-III superconductors



M. C. Diamantini et al., Adv. Science 1, 2206523 (2023)
M. C. Diamantini, C. A. T. and V. Vinokur, Phys. Rev. B110, 094506 (2024)

Emergent Josephson junction array and type-III vortices

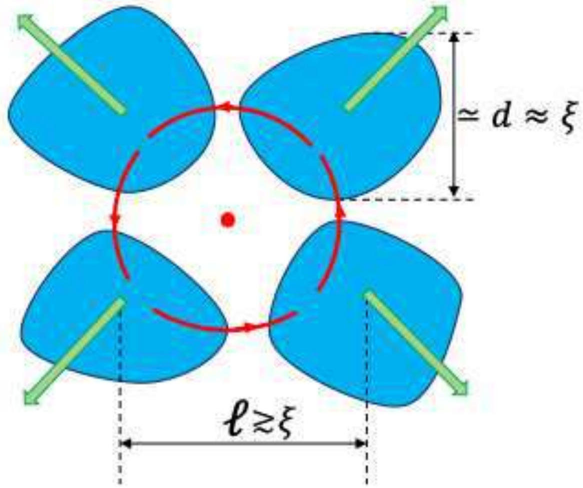


Josephson tunneling currents flow when phases aligned

Material becomes an emergent Josephson junction array (JJA)

Type-III vortices are not standard Abrikosov vortices: these do not even exist for small granules!

K. K. Likharev, Rev. Mod. Phys. 51, 101 (1979).



Pointlike XY vortices:

- **no dissipative core**
- **vortices can condense**

Interaction between vortices

$(1/e^2 \lambda_m) \log|x/\lambda_m| \quad \lambda_m = d/\lambda_L^2$

Competition between vortices and charges

Magnetic

$(1/ e^2 \lambda_m) \log|x|$

Electric

$(e^2/ \lambda_e) \log|x|$

$$g^2 = \lambda_e/e^4 \lambda_m$$

$g >> 1$

$g << 1$

Magnetic energy high
Electric energy low

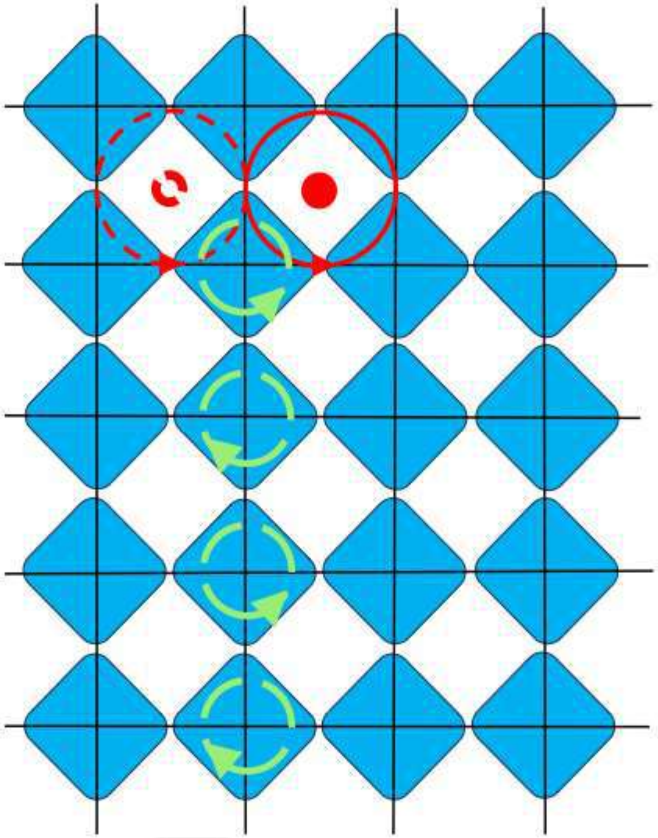
Electric energy high
Magnetic energy low

Charges “condense” (BKT)
$m_e (e, \lambda_e, \lambda_m) \rightarrow 0$

Vortices “condense”
$m_m (e, \lambda_e, \lambda_m) \rightarrow 0$

Quantum effects in granular quantum matter

2D quantum phase slips
→ **vortices highly mobile**
tunneling on dual lattice

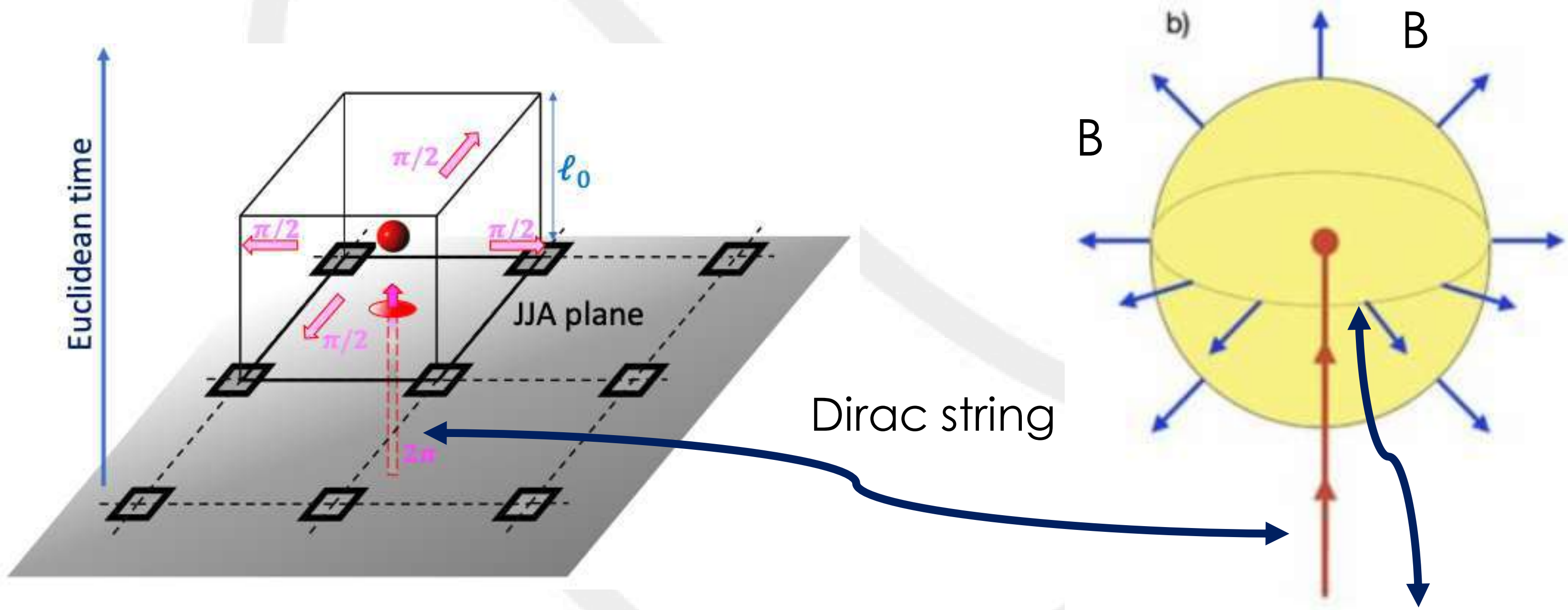


Effective field theory is
not XY model but rather
a **topological gauge theory**

Magnetic monopole instantons

Instantons = particles in Euclidean space-time
= tunnelling events in Minkowski space-time

$m_m\ (e, \lambda_e, \lambda_m) \rightarrow 0$ means tension → 0 in Euclidean space-time



Dirac string

Non-relativistic magnetic monopole

Only equator

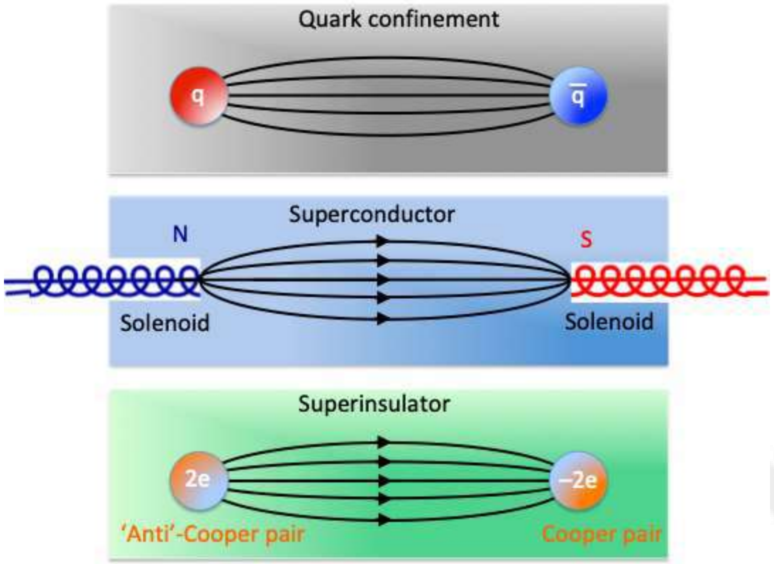
M. C. Diamantini, C. A. T. and V. M. Vinokur, Nat. Comm. Phys. 1, 77 (2018).

Superinsulation = electric confinement

Magnetic monopole instantons → linear confinement of electric charge

A. Polyakov, Phys. Lett. 59, 82 (1975).

Electric field squeezed into flux tube dual to Abrikosov vortices
Excitations: strings with ± 2e charges at their ends, **electric pions**



Characteristic scales:

- Photon mass: m (gap)
- String tension: σ
- Width of string: w = 1/m
- Length of string: $\ell_s = 1/\sqrt{\sigma}$

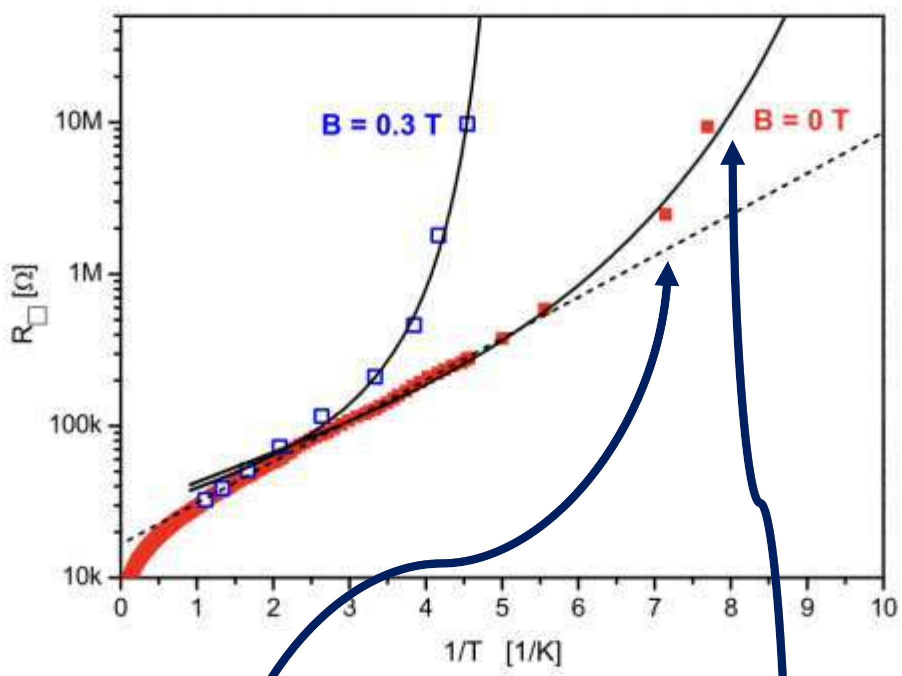
Consequences:

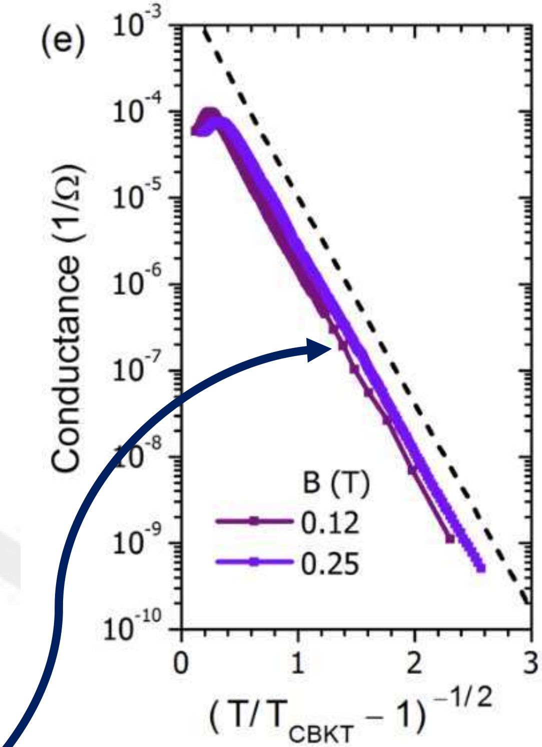
- **Infinite resistance** on scales > ℓ_s below T_{BKT} (point where tension=0)
- **BKT scaling of resistance**

Experiments

TiN

NbTiN





T. Baturina and V. M. Vinokur, Ann. Phys. 331, 236 (2013).

A. Yu. Mironov et al. Scient. Rep. 8, 4082 (2018)

$R \propto \exp(\Delta/T)$

$R \propto \exp(b/|T-T_{cbkt}|)^{1/2}$

Experiments

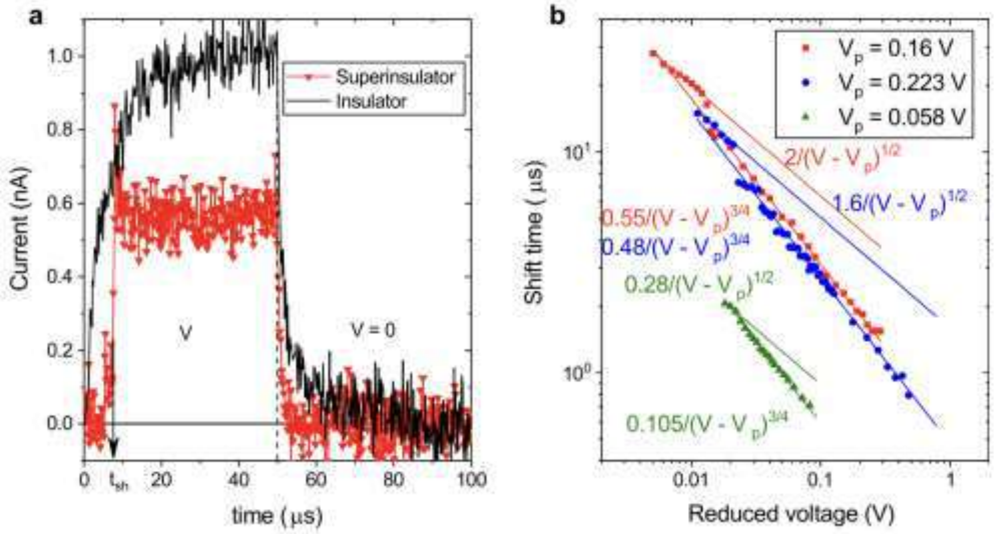
Pull two charges bound by linear potential by sudden voltage pulse

Constant attractive force $F_a = 2e\sigma = 2eV_{c1}/L.$

External repulsive force $F_r = 2eV/L.$

Newton, F=ma $r(t) = \frac{2e}{mL}(V - V_{c1})t^2 .$ r(t) = center of mass distance

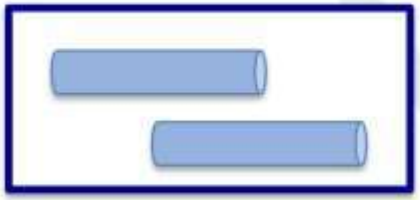
Curent passes when r(t) = L ➜ delay $t_{cr} = \sqrt{\frac{mL^2}{2e}}(V - V_{c1})^{\boxed{-1/2}}.$



A.Yu. Mironov et al. Scient. Rep. 12, 19918 (2022)

NbTiN

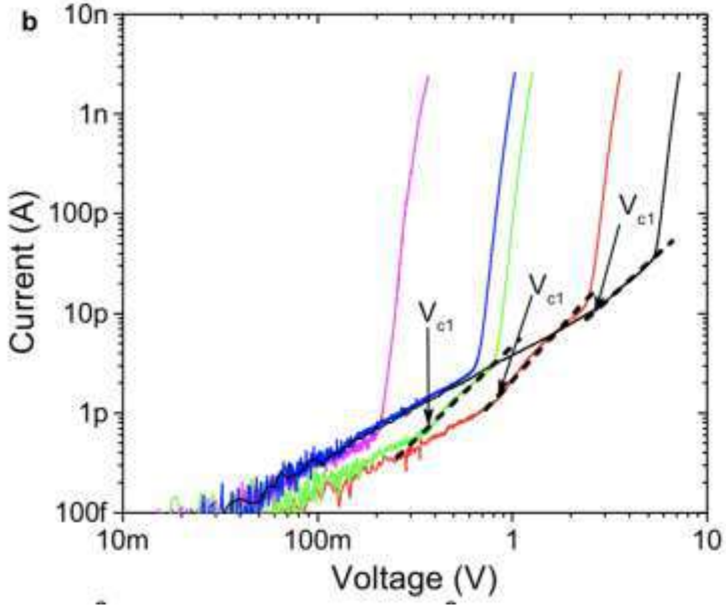
Electric Meissner and mixed states



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

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

$V > V_{c2}$
superinsulation
destroyed

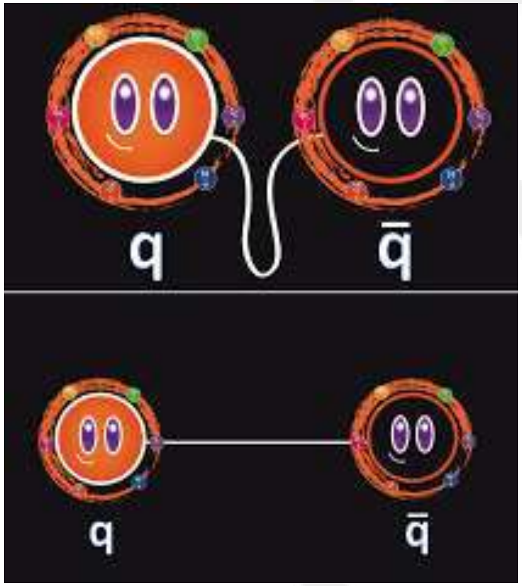


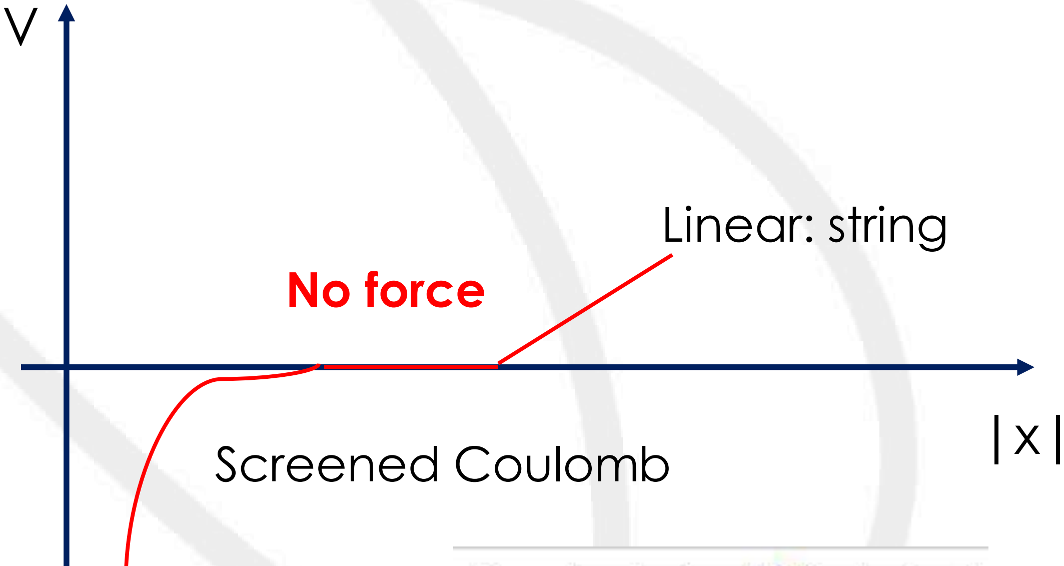
NbTiN

Two kinks in IV curves

A.Yu. Mironov et al. Nat. Comm. Phys. 4, 142 (2020)

Asymptotic freedom



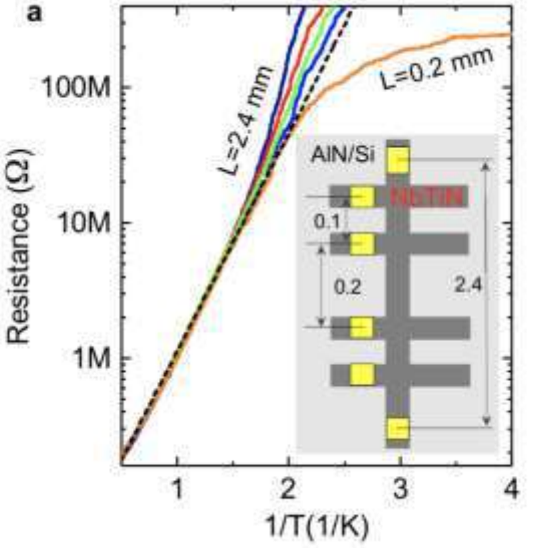

V

Linear: string

No force

Screened Coulomb

|x|



Make sample smaller -> interior of a pion

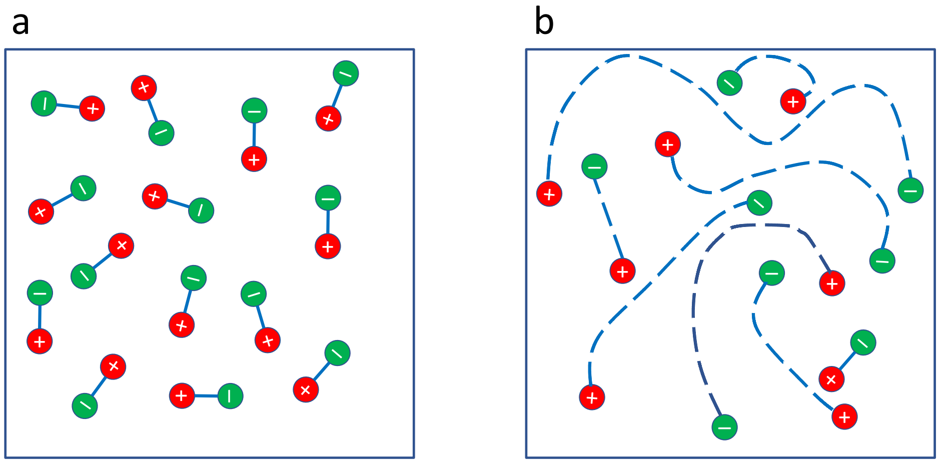
No force -> **metallic saturation**

3D superinsulators

Granular superconductors exist in 3D C. Parra et al., PNAS 118, e2017810118 (2021)

2D XY vortices become 1D extended objects, still no dissipative core

Vortices have tension: dipoles



Tension ➜ 0: monopoles which can condense

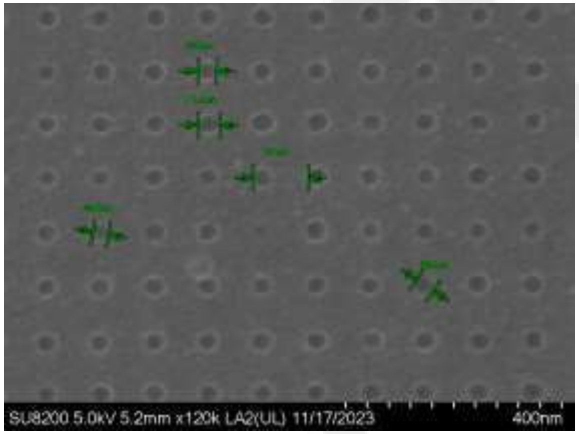
Main difference: resistance scaling BKT -> VFT due to behaviour of strings

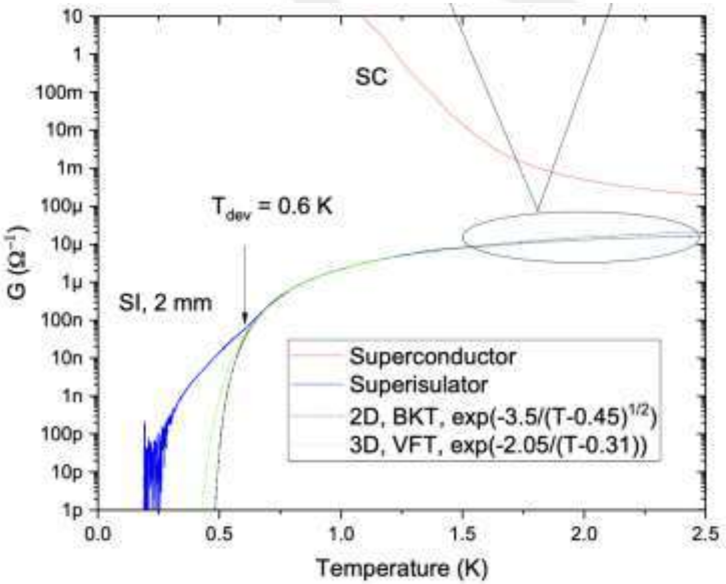
$$R(T) \propto \mathrm{e}^{\frac{b_2}{\sqrt{|T-T_{\mathrm{BKT}}|}}} . \quad \Longrightarrow \quad \boxed{R(T) \propto \mathrm{e}^{\frac{b_3}{|T-T_{\mathrm{VFT}}|}} .}$$

M. C. Diamantini et al., Sci. Rep. 8, 15718 (2018)

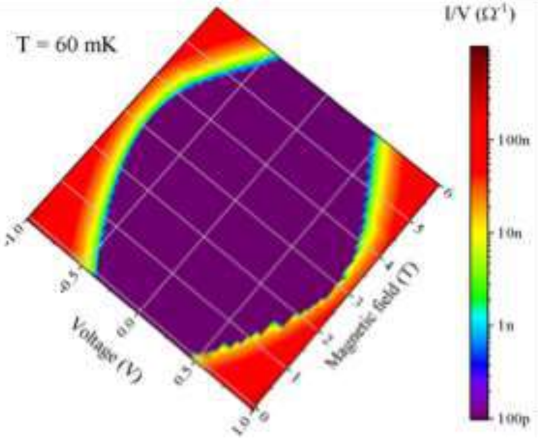
Nanopatterned materials

Effective JJA as nanopatterned NbTiN film: **O(10^7) granules**





A. Mironov et al, Nature Comm. in review



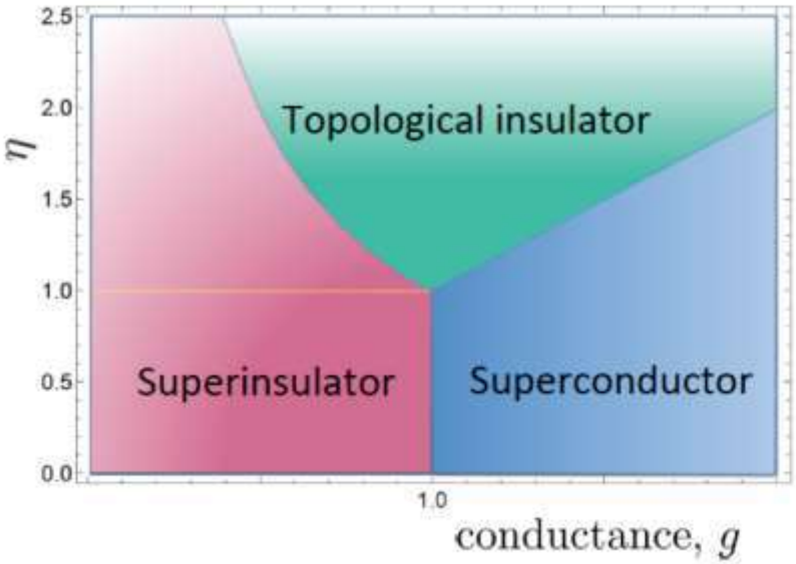
Bose metal a.k.a bosonic topological insulator

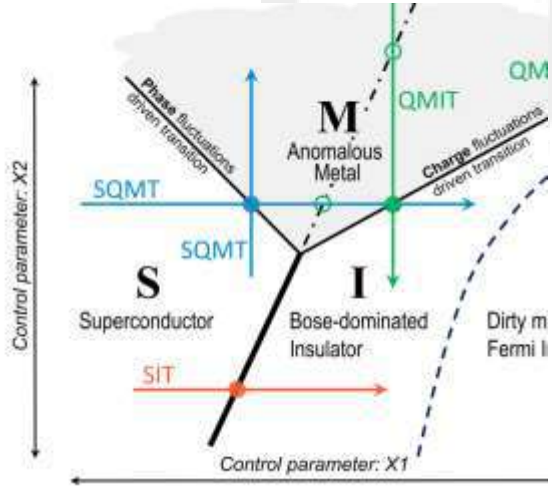
M. C. Diamantini, P. Sodano and C. A. T. Nucl. Phys. A474, 641 (1996).

Charge or vortex condensates are only possibilities?

No! Charges and vortices can be both out of condensate

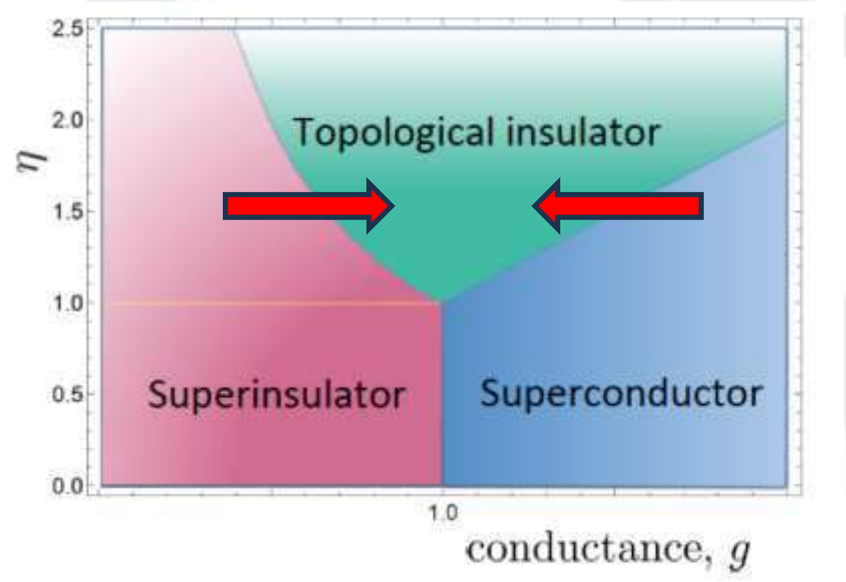
Then they are frozen into a topological state by mutual statistics frustration → conduction on the edges → metallic saturation of the resistance around R_Q → Bose metal





X. Zhang et al., PNAS 119, e2202496119 (2022)

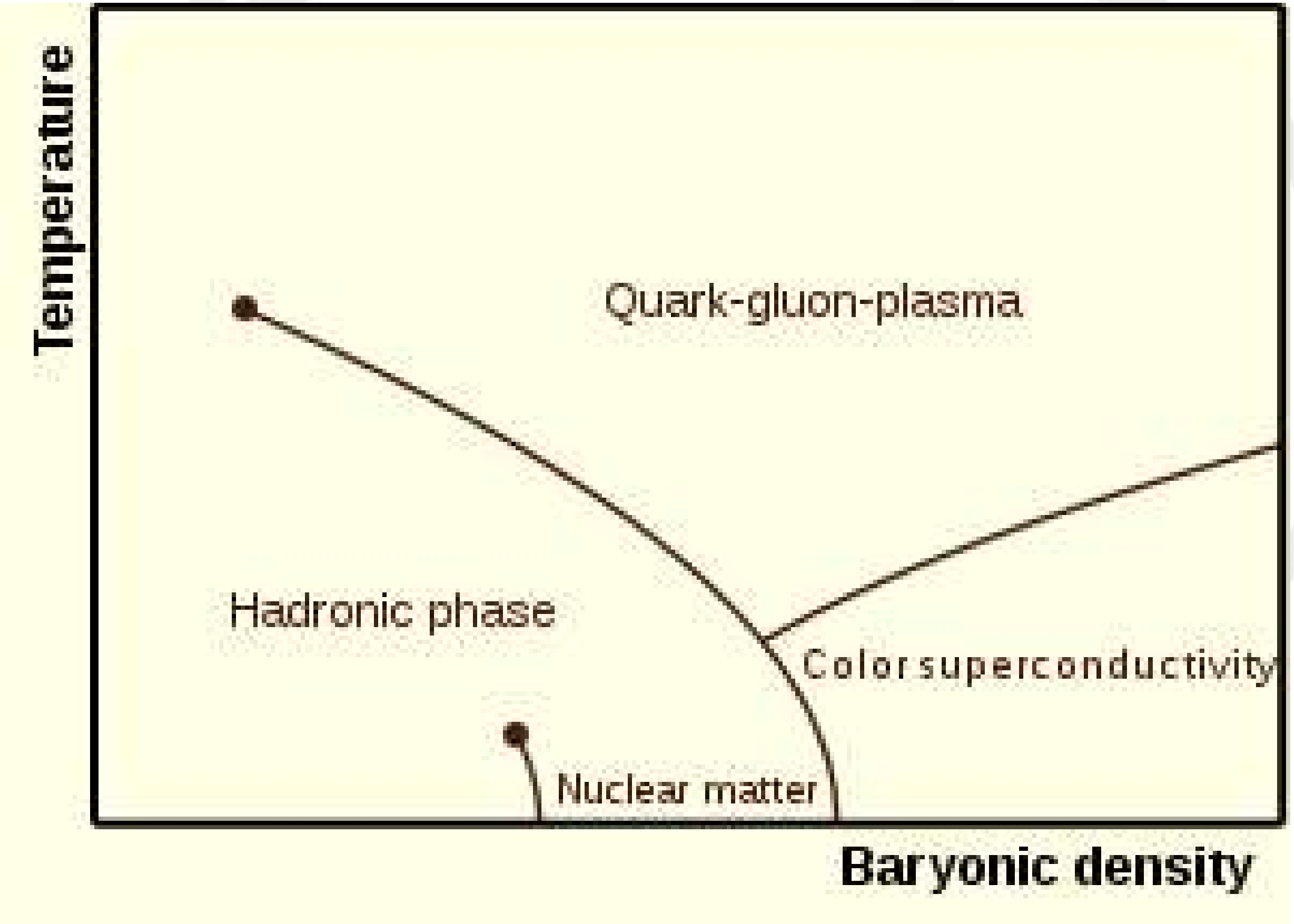
Quantum BKT transitions in 2D



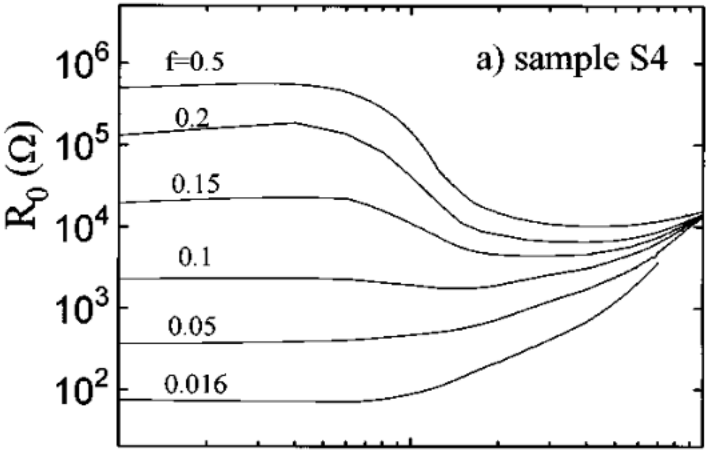
Quantum transition in 2D governed by field theory in (2+1)D

Quantum BKT transition in 2D possible because ε ➜ ∞ effectively lowers by 1 the dimensions

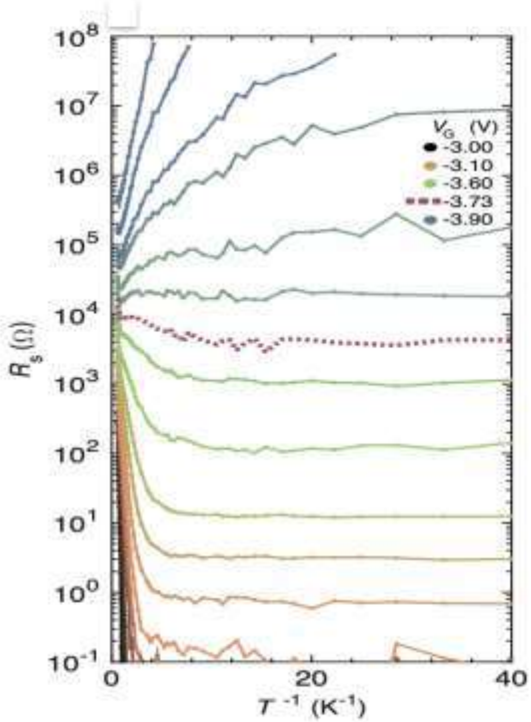
Phase diagram of baryonic matter



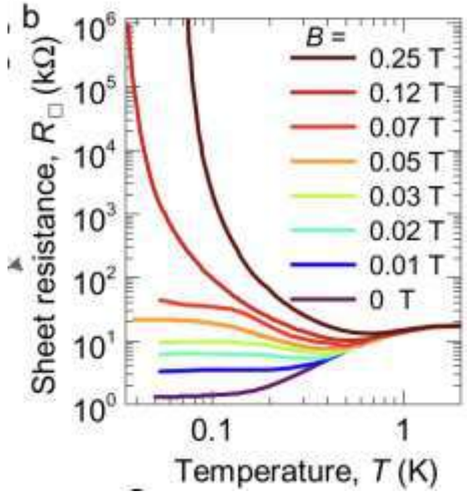
Bose metals in materials / JJA



Van der Zant et al. Phys. Rev. B54, 10081 (1996).



Bottcher et al. Nat. Phys. 14, 1138 (2018).



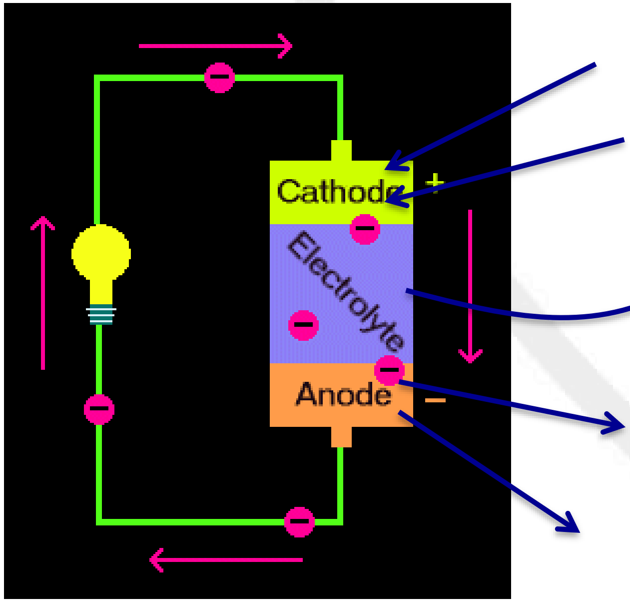
NbTiN

M. C. Diamantini et al., Phys. Lett. A384, 126570 (2020).

Possible technological applications of superinsulators: perfect batteries

Superconductors perfectly store currents
Superinsulators perfectly store charge

Superinsulators enable “perfect batteries”

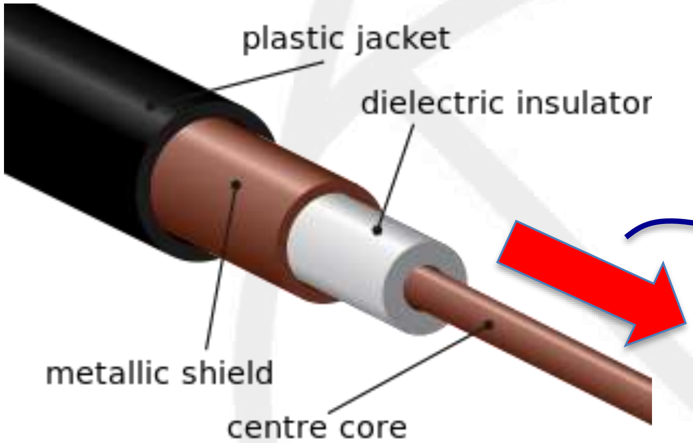


Losses due to self-discharge

This cannot happen if cathode and anode coated with superinsulator

electrons

Cutting losses to AC power lines



Power flows as an EM wave down the **interior** of the cable

Poynting vector

Two major sources of losses:

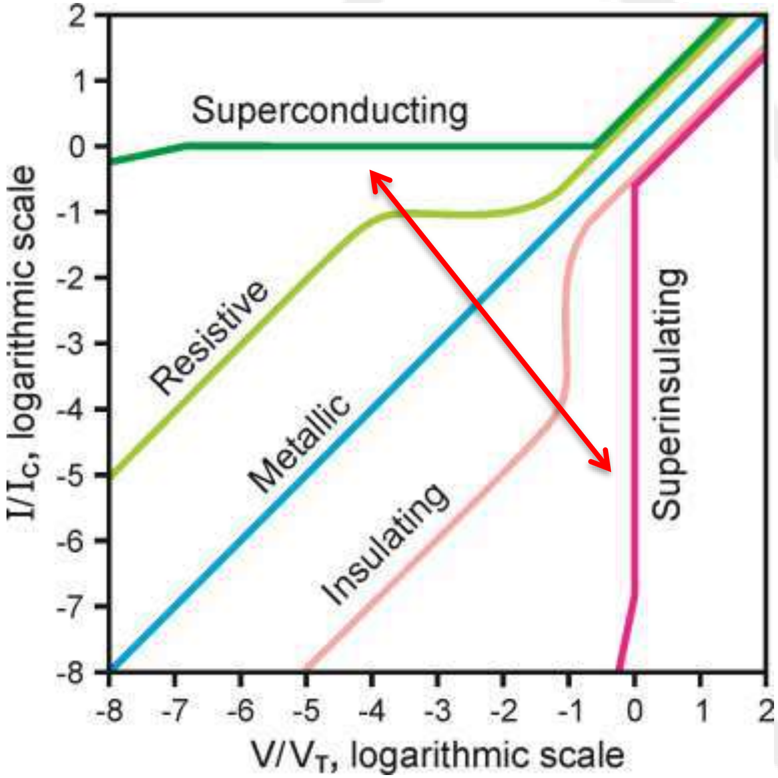
- **Conductor losses** (CL): finite R of the conductor
- **Dielectric losses** (DL): electric fields in the dielectric insulator cause currents and heat

CL can be eliminated by **superconducting cables**
DL can be eliminated by **superinsulating shields**

Towards AC power lines with no losses….

Ultrafast switches with no energy loss

Dual current - voltage characteristics



Superfast/efficient switch :

- upon local heating current jumps 6 order of magnitude
- no loss of energy apart when switching

Take away

- **Magnetic monopoles** appear naturally in granular, type-III superconductors
- They lead to **electric confinement in materials** via the old ‘t Hooft / Polyakov mechanism
- The ensuing state of matter is dual to superconductors and has R = ∞ (even at finite temperatures) : **superinsulators**
- For the moment T_c and V_c still very low for any real application