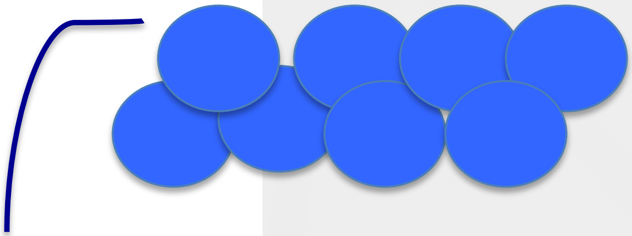
Superinsulators : a new state of matter with hadrons made of Cooper pairs

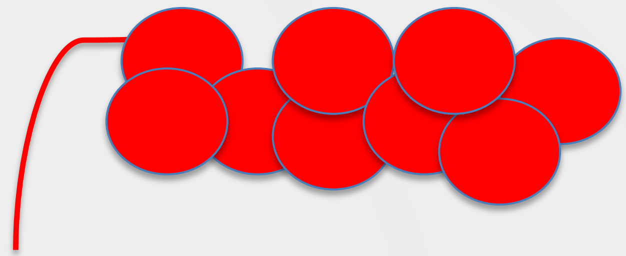
Carlo A. Trugenberger

Work with C. Diamantini, P. Sodano, V. Vinokur and L. Gammaitoni over 22 years

What is a superinsulator

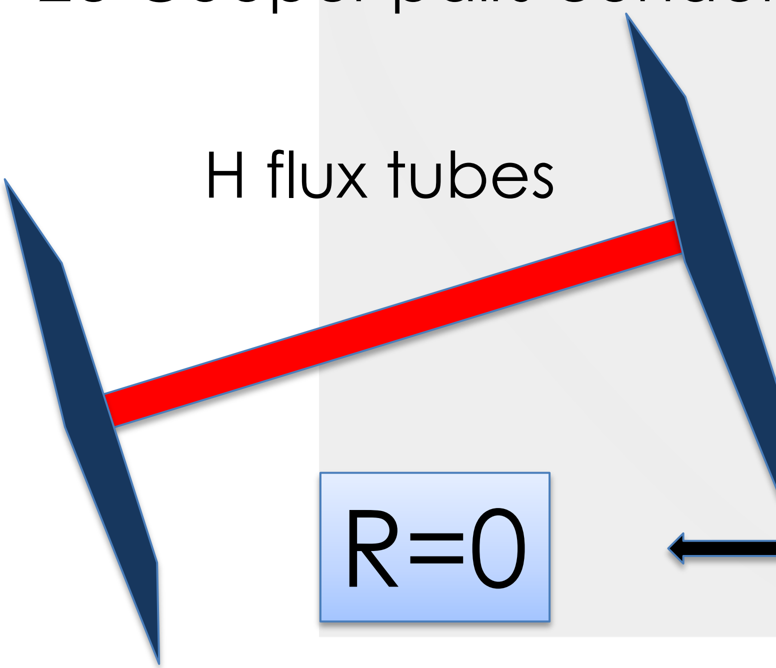
Superconductor	Superinsulator

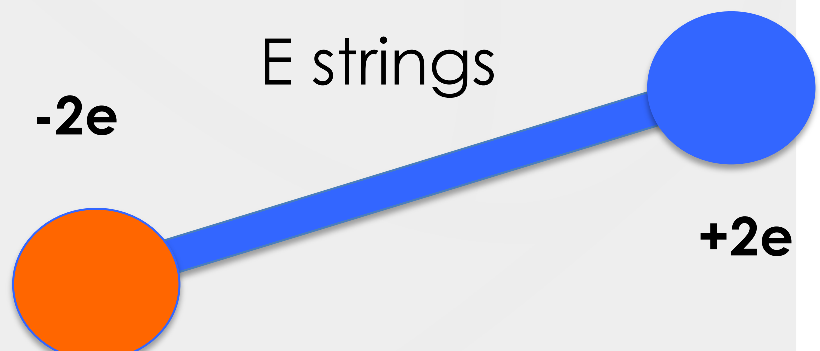




2e Cooper pairs condense

π/e magnetic monopoles condense





R=0 ⟷ R=∞

Dual

A bit of history

't Hooft 1978 (Nucl. Phys. B138 (1978) 1 on confinement)

"….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

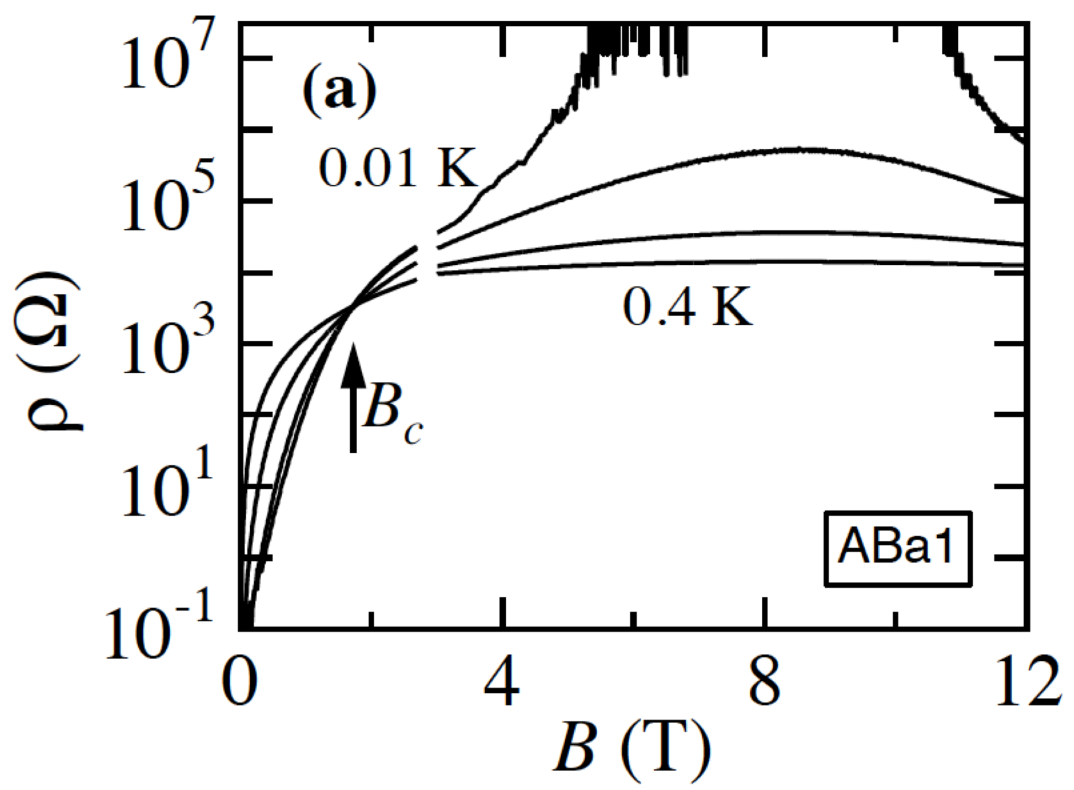
Predicted superinsulators in the 2D superconductor-insulator transition (SIT)

M. Krämer & S. Doniach 1998, Phys. Rev Lett. 81 (1998) 3523

Independent prediction of superinsulators in the SIT

A bit of history

Early evidence: D. Shahar et al.2005, Phys. Rev, Lett. 94, (2005) 017003, InO films



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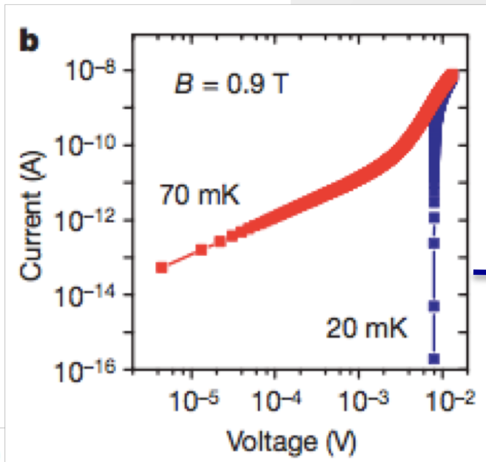
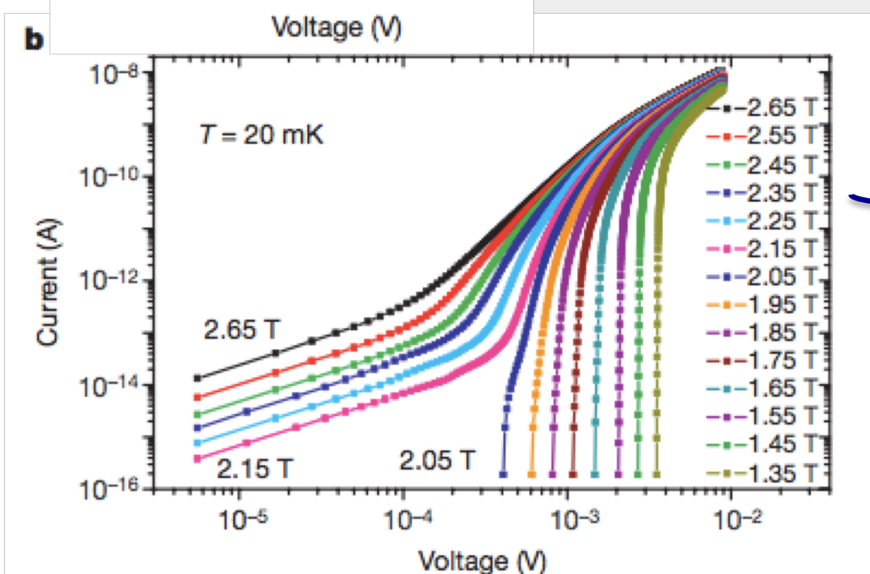
A bit of history

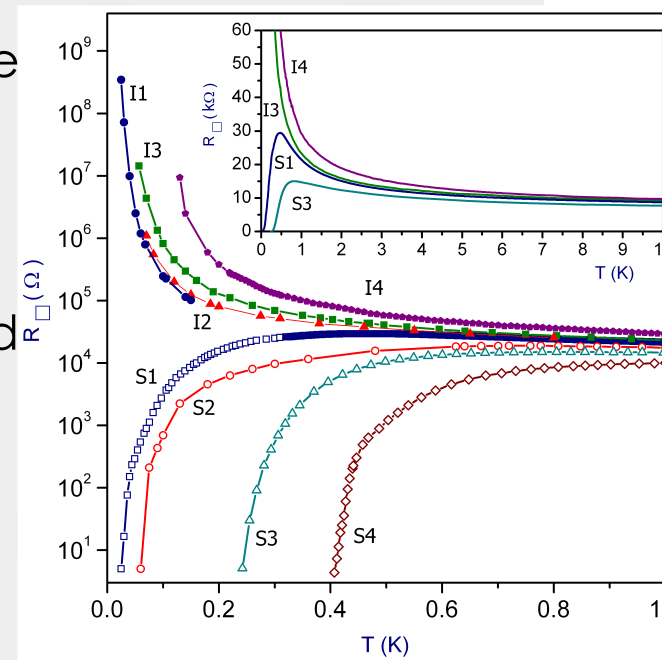
V. Vinokur et al.2008, Nature 452 (2008) 613, TiN films



Driven by temperature



Driven by magnetic field



SIT driven by disorder

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A bit of history

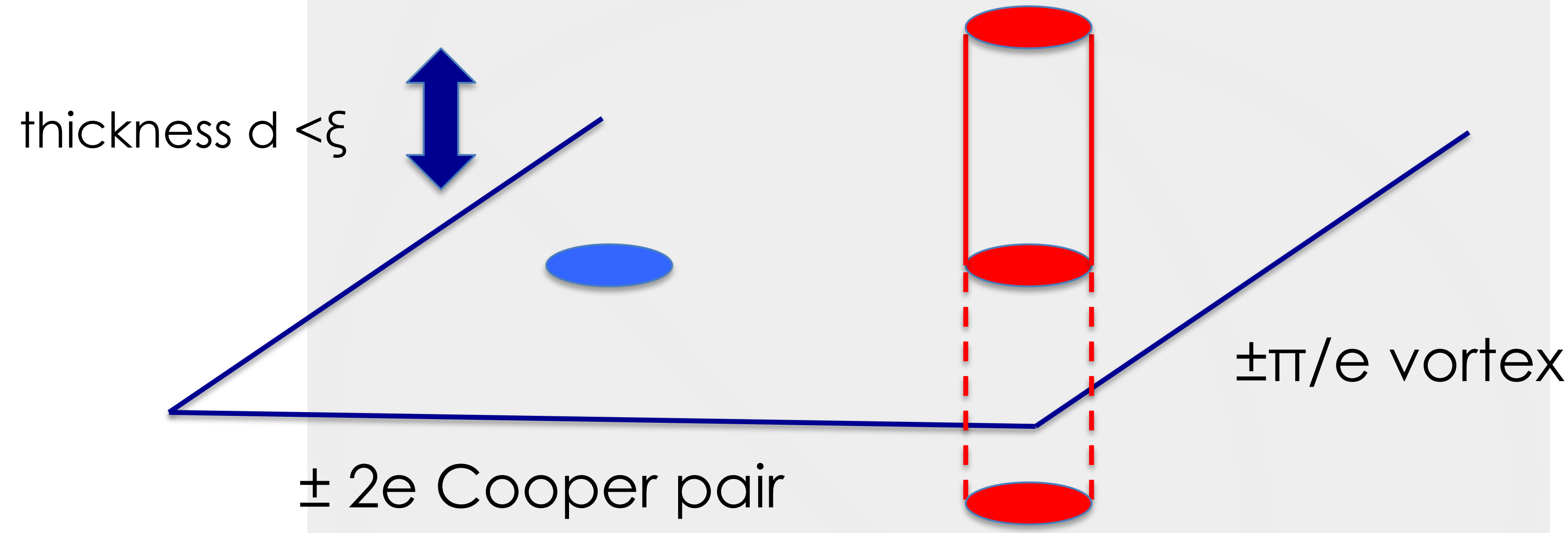
V. Vinokur et al. 2018, Scient. Rep. 8 (2018) 4082, NbTiN films

Charge Berezinskii-Kosterlitz-Thouless transition in superconducting NbTiN films

Alexey Yu. Mironov[1,2], Daniel M. Silevitch[4], Thomas Proslier[5], Svetlana V. Postolova[1,2], Maria V. Burdastyh[1,2], Anton K. Gutakovskii[1,2], Thomas F. Rosenbaum[4], Valerii V. Vinokur[6,7] & Tatyana I. Baturina[1,2,3,8]

Magnetic condensation in a BKT transition confirmed on NbTiN thin films

So why thin films (2D systems)



Thin film of superconducting material : BEC of charges ± 2e

Charges and vortices both "particles"
If charges condense why not vortices?

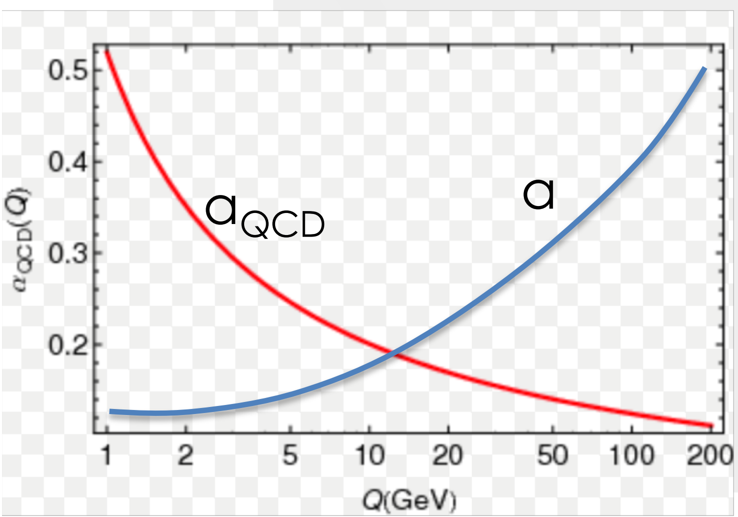
Everything depends on competition between magnetic energy scale $\mathbf{e_v^2 = (\pi / e)^2 (1/\lambda_P)}$ and Coulomb energy scale $\mathbf{e_q^2 = e^2/d}$ (λ_P = Pearl/London length)

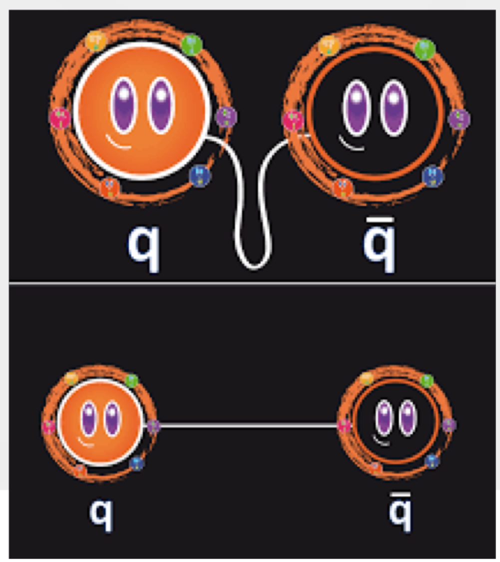
Gauge theories (GT)

Coulomb interaction
Abelian gauge theory
electromagnetism
- one coupling α
- one charge, electric

Strong interactions (hadrons)
non-Abelian SU(3) gauge th.
quantum chromodynamics
- one coupling α_{QCD}
- 3 types of charges, colour

Non-Abelian GT → Confinement + asymptotic freedom





MESONS + BARYONS

Compact QED
Single-color version of QCD

There are **two types of Abelian gauge theories** (Polyakov):

- **non compact** (gauge group R)
  - charge non-quantized, 1/r potential (3D)
- **compact** (gauge group U(1) i.e. a circle)
  - charge quantized
  - 2D : always confining like QCD
  - 3D : confining like QCD for $a > a_{cr}$
  - in confining phase: **linear potential → strings/mesons**

M. C. Diamantini, C. A. T. & V. Vinokur, Nature Comm. Phys., to appear : when Coulomb energy wins in 2D materials → always confining U(1) → el. strings → $R = \infty$

Superinsulator: Cooper pairs confined in neutral mesons by electric strings that prevent charge transport

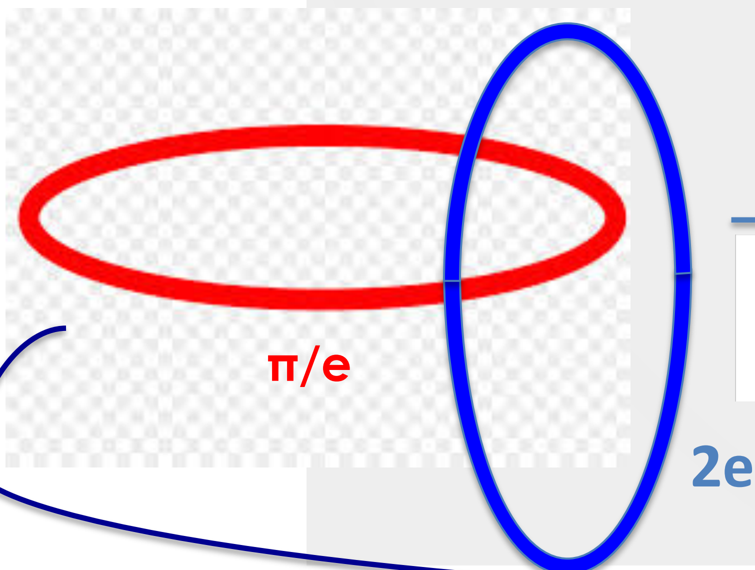
How do we find out when Coulomb energy wins over magnetic energy?

Sketch of the phase diagram derivation (**C. Diamantini, P. Sodano & C. A. T. 1996, Nucl. Phys. B474 (1996) 641**)

Charges + vortices → **topological Aharonov-Bohm-Casher interactions**

Local formulation requires Introduction of two emergent gauge fields a_μ and b_μ with Mixed Chern-Simons action

$$S^{CS} = \int d^3x \left[i \frac{n}{2\pi} a_\mu \epsilon_{\mu\alpha\nu} \partial_\alpha b_\nu + i\sqrt{n} a_\mu Q_\mu + i\sqrt{n} b_\mu M_\mu \right]$$



Effective action for the SIT

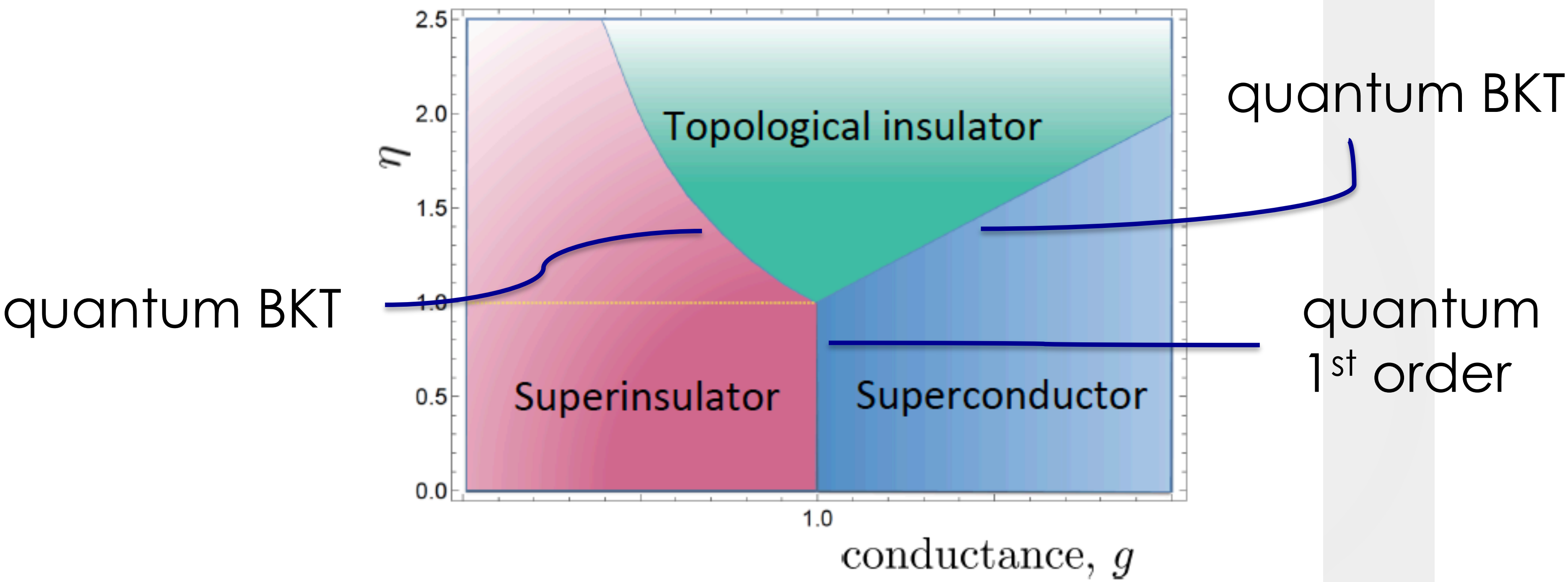
Gauge invariance completely dictates effective action

$$S_{2D} = \int d^3x\, i\frac{1}{\pi} a_\mu \epsilon_{\mu\alpha\nu} \partial_\alpha b_\nu + \frac{1}{2e_v^2 \mu_P} f_0^2 + \frac{\varepsilon_P}{2e_v^2} f_i^2 + \frac{1}{2e_q^2 \mu_P} g_0^2 + \frac{\varepsilon_P}{2e_q^2} g_i^2 + i\sqrt{2} a_\mu Q_\mu + i\sqrt{2} b_\mu M_\mu$$

$v_c = 1/\sqrt{\mu_P \varepsilon_P}$ is the velocity of light in the material

Integrate out gauge fields → effective action for charges and vortices alone → energy/entropy balance equations determine condensation conditions

Phase diagram for the SIT



$g = e_v/e_q$ ratio of magnetic/electric energies

$$\eta = \frac{1}{\alpha}\frac{(v_c/c)^2}{k}\frac{\pi^2}{\mu}G\left(\frac{(v_c/c)}{\alpha k}\right)$$

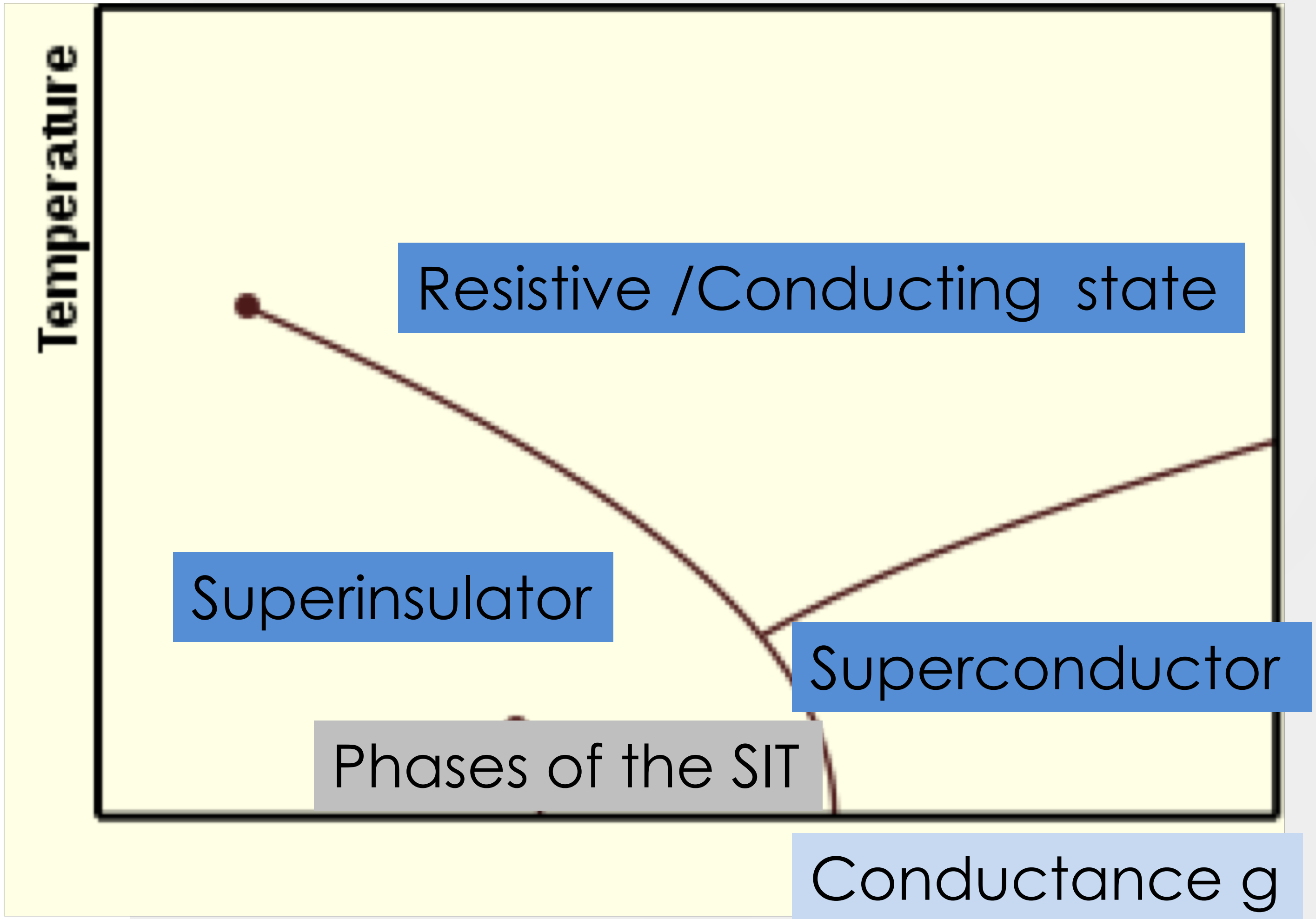
Strength of quantum fluct. 1/a

Material parameters v_c and

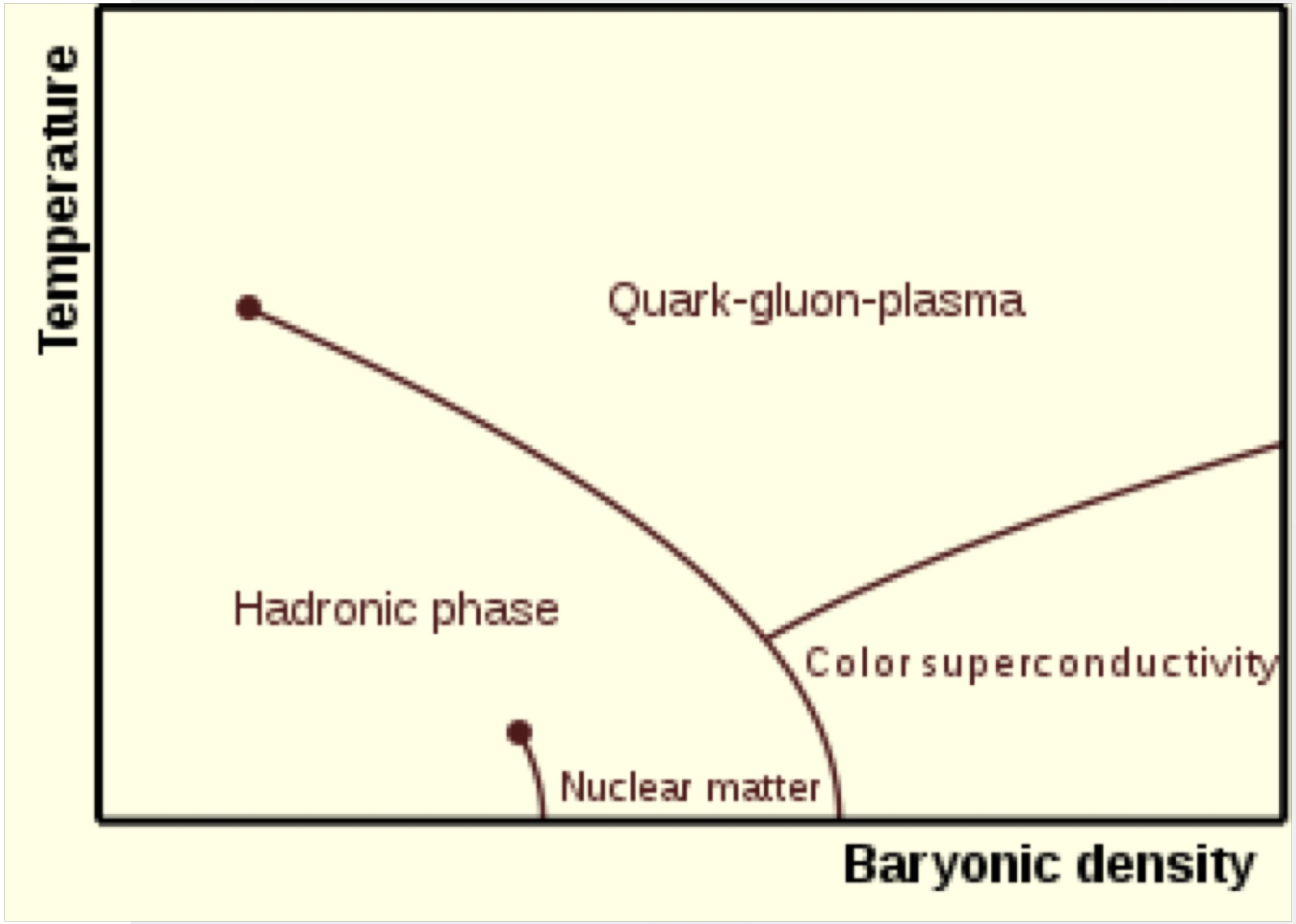
$$k = \lambda_\perp/\xi$$

Landau parameter

Temperature phase diagram of the SIT



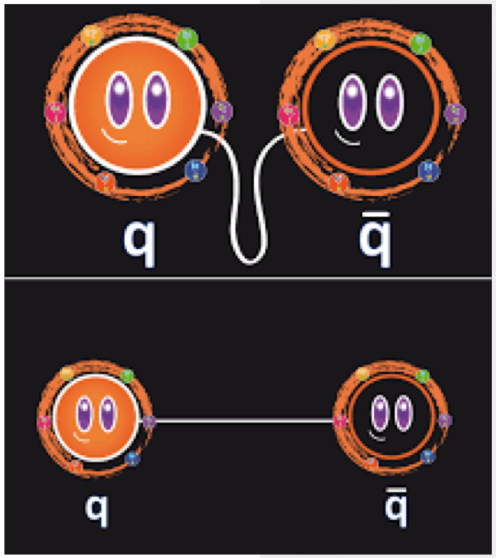
Phase diagram of QCD



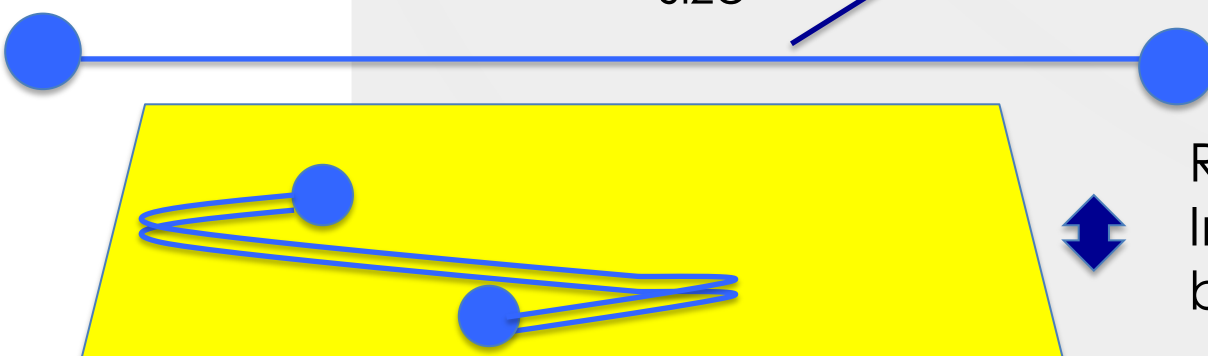
Asymptotic freedom

In nature it is impossible to look directly inside a hadron

Here we could make sample smaller than meson size….



From this range linear potential is felt / meson size



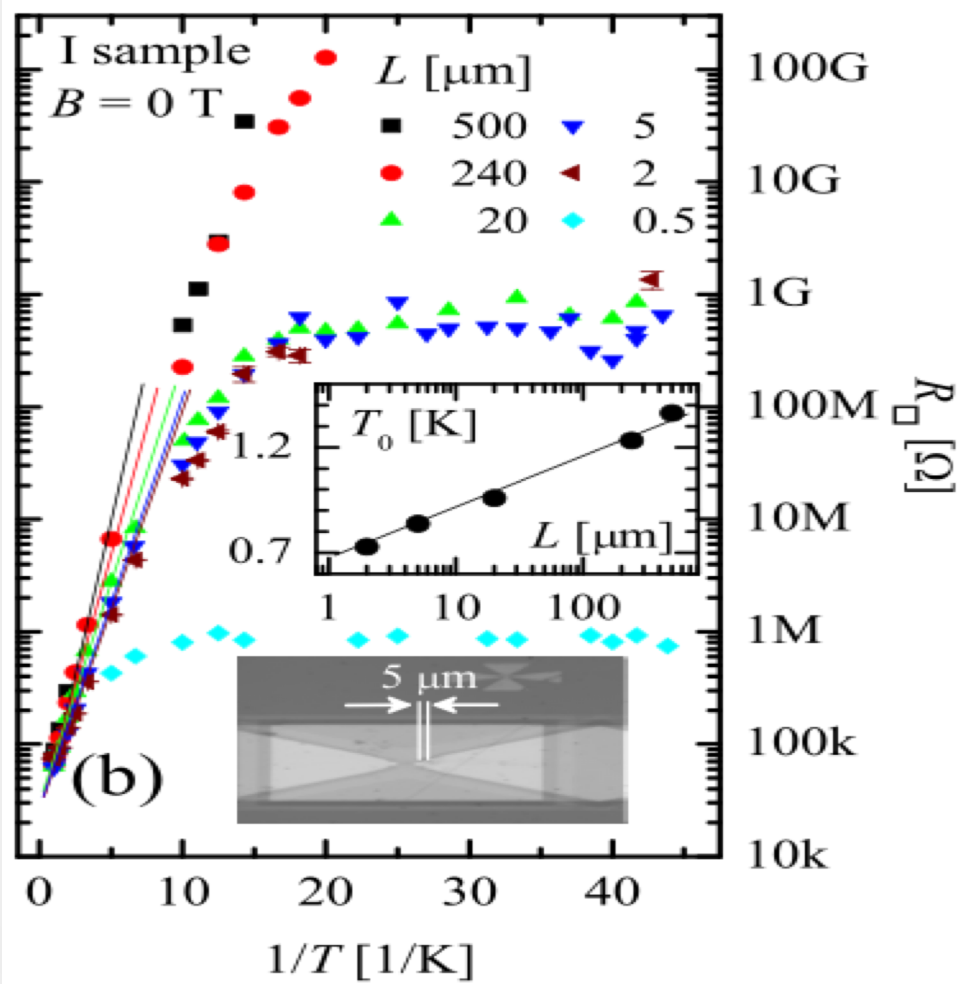
Range of Coulomb Interaction screened by photon mass

Cooper pairs essentially free: metallic behaviour expected

Asymptotic freedom

Estimate:
meson size in TiN films <~ 60μm

Dependence of resistance on sample size for TiN films



What about 3D?

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

M. C. Diamantini, C. A. T. & V. Vinokur, Nature Comm. Phys., to appear

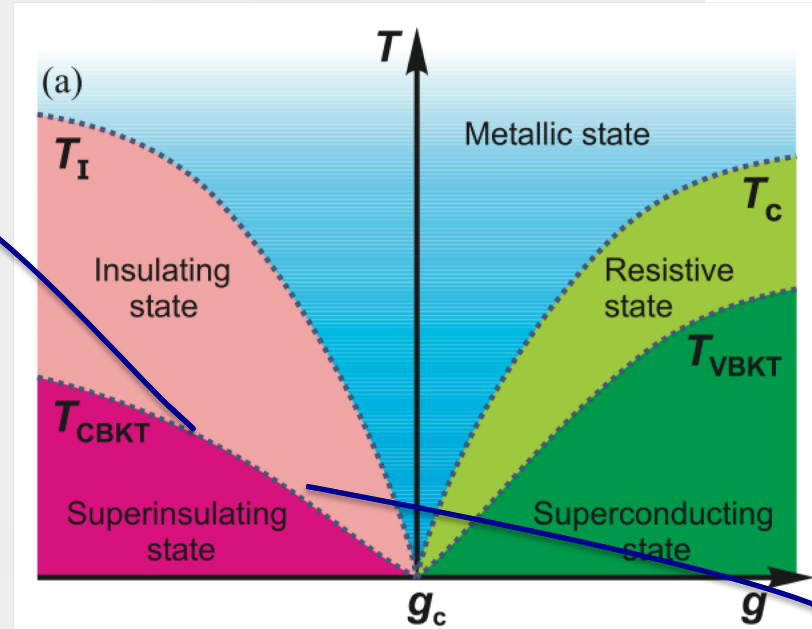
Superinsulators exist also in 3D → new state of matter

In 3D vortices are one-dim. objects (loops) → new type of condensate → spaghetti phase

Observable consequences? Yes, finite T scaling of R!

2D → Berezinski-Kosterlitz-Thouless (BKT) transition

$$R \propto \exp\left(c/\sqrt{|T-T_c|}\right)$$



M. C. Diamantini, L. Gammaitoni, C. A. T. & V. Vinokur, Scient. Rep. 8 (2018) 15718

3D → Vogel-Fulcher-Tamman criticality

$$R \propto \exp\left(c/|T-T_c|\right)$$

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VFT critical behaviour

2D XY model ➜ BKT critical behaviour (2016 Nobel prize)

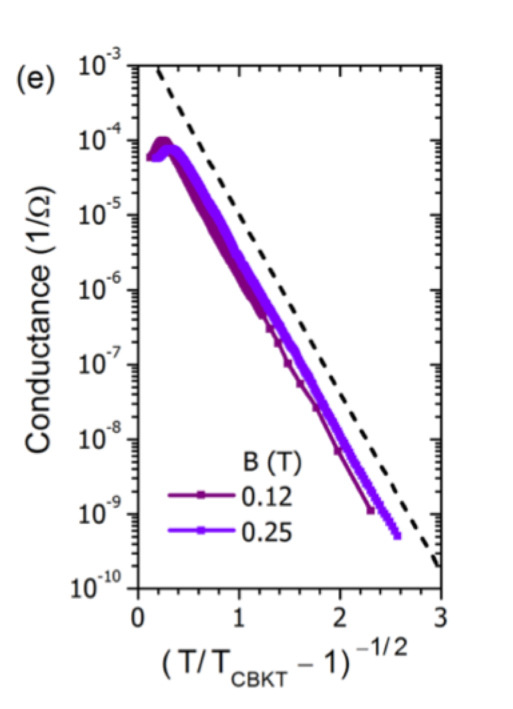
M. Vasin, V. Ryzhov & V. Vinokur, arXiv:1712.00757

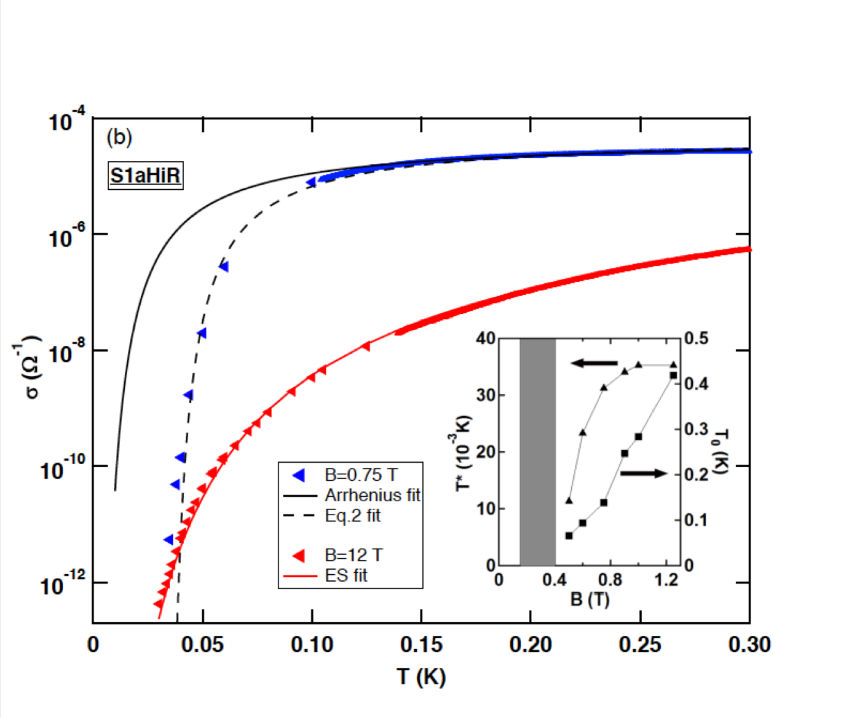
3D XY model with quenched disorder ➜ VFT critical behaviour and spin glass in the low T phase

It appears that 3D superinsulators form a disordered glass phase with spontaneous disorder

First system with a condensate of extended excitations (loops). Generalization to any "brane"?

NbTiN vs. InO





NbTiN, d <ξ→ 2D

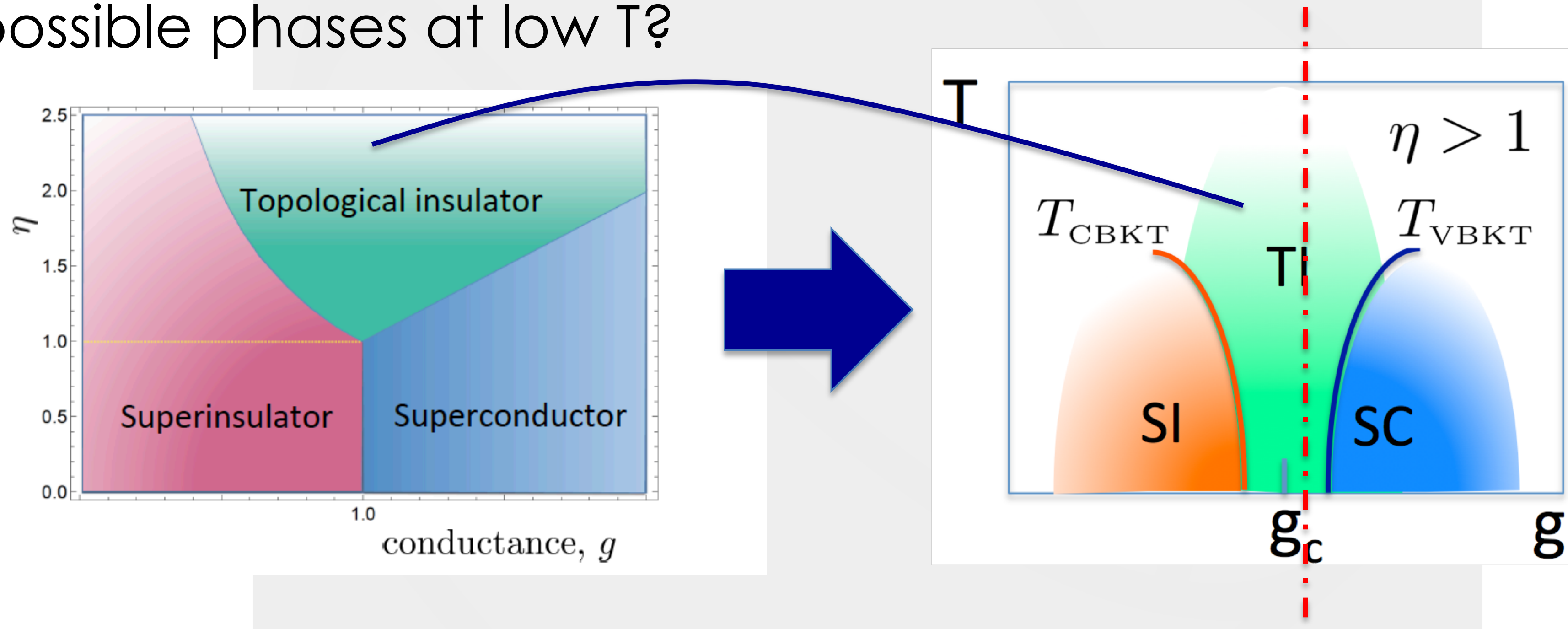
InO, ξ<< d → 3D ?

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

M. Ovadia et al. Scient. Rep. 5 (2015) 13503

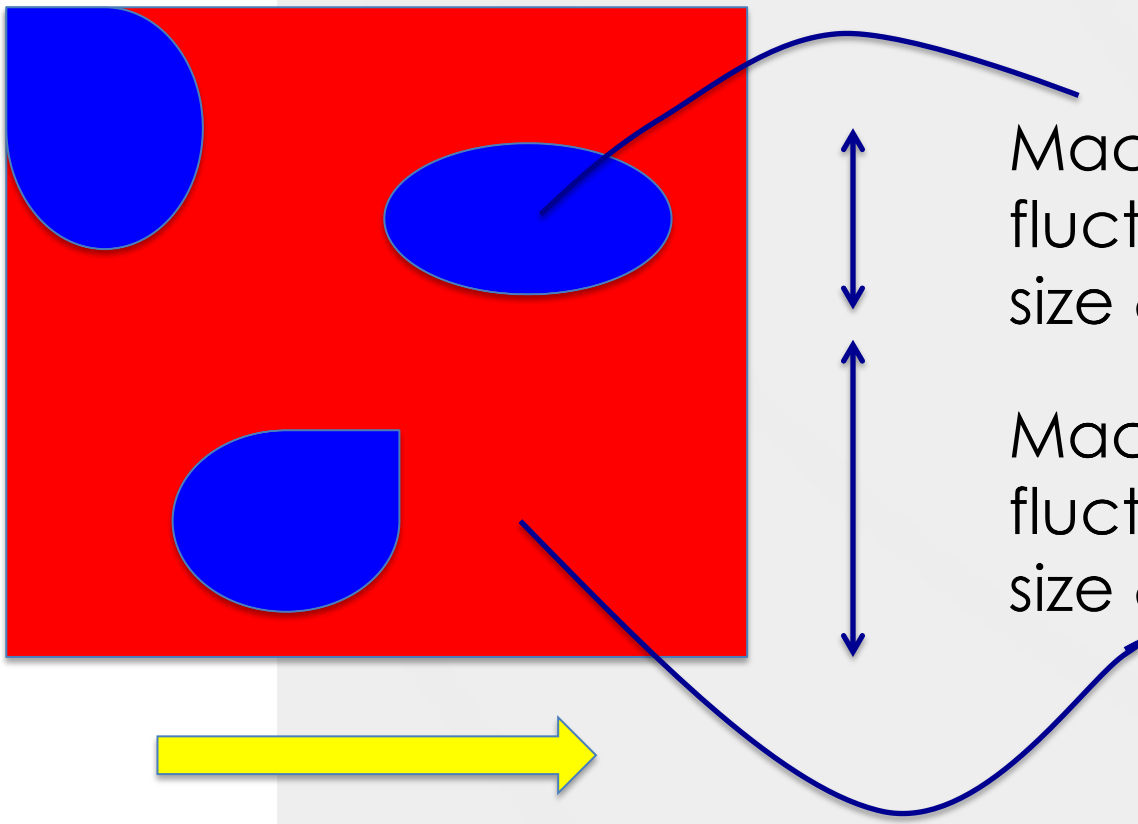
Failed superconductivity

Are superconductor and superinsulator the only two possible phases at low T?



Here Bose condensation of charges favoured by thermal considerations but prevented by strong quantum fluctuations → a **bosonic topological insulator** forms (often called **Bose metal** in the literature)

Bosonic topological insulator
Bose metal



Macroscopic vortex fluctuations
size ξ_{BKT} (g)

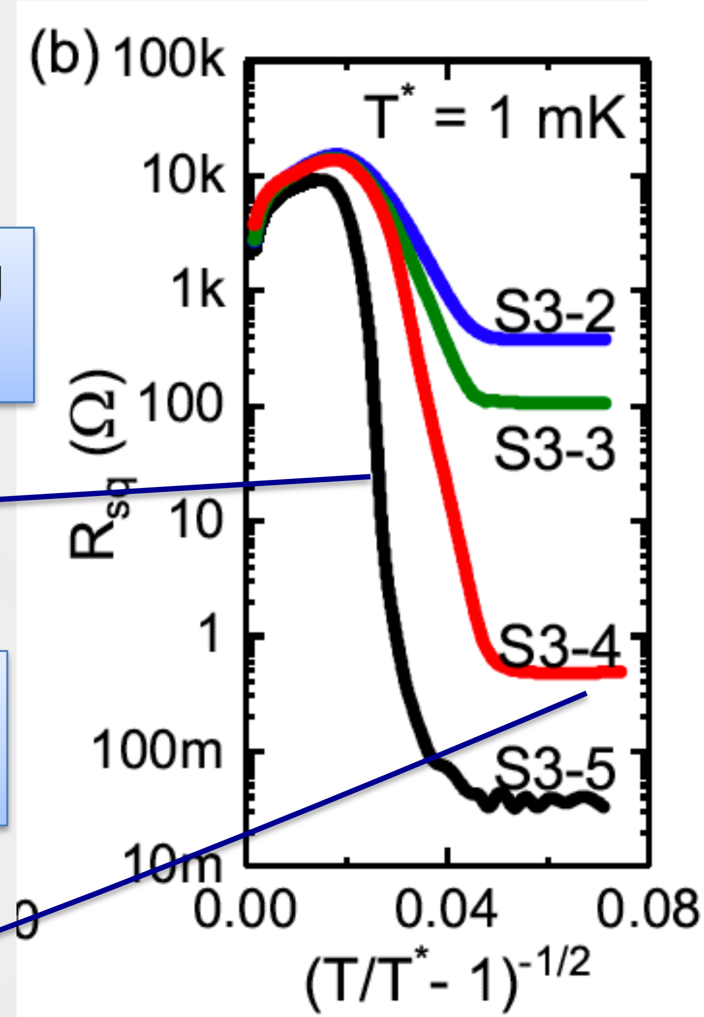
Macroscopic charge fluctuations
size ξ_{BKT} (1/g)

Bulk frozen, ballistic charge conduction along the edges → metallic behaviour but no Hall effect

Bose metal in NbTiN

On its way to a superconducting BKT transition

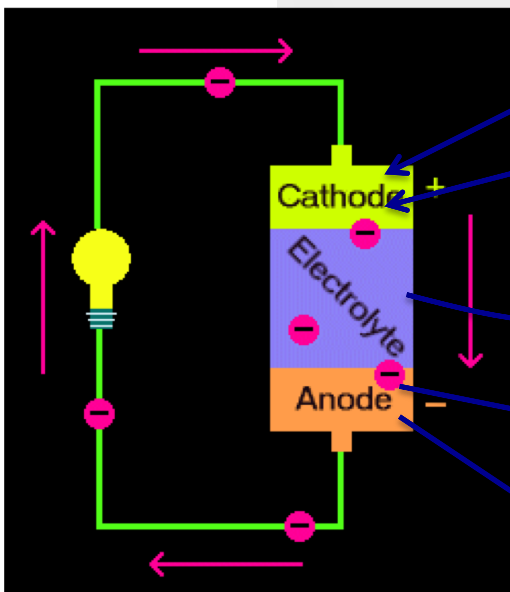
Saturation when the Bose metal phase is hit upon



Possible technological applications of superinsulators: perfect batteries

Superconductors perfectly store currents
Superinsulators perfectly store charge

Superinsulators are "perfect batteries"

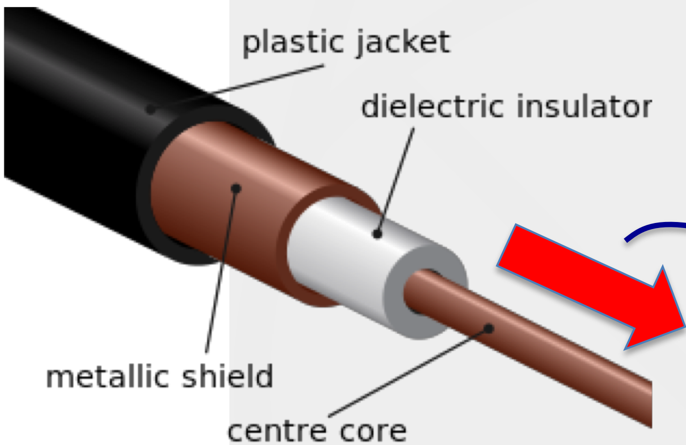


Losses due to self-discharge

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:

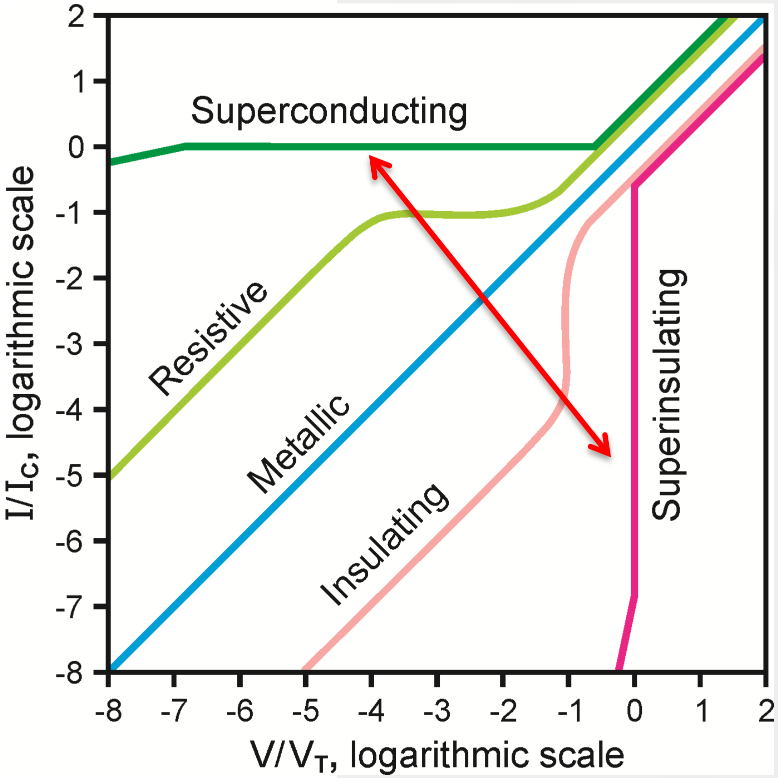
- **Conductor losses** (CL): finite R of the conductor
- **Dielectric losses** (DL): electric fields in the dielectric insulator cause currents and heat

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

Towards AC power lines with no (small) 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

In general SIs are a much better support for electronic devices than SCs: SCs still consume energy from current leakages, SIs absolutely no energy loss

Conclusion and outlook

Superinsulators have twofold relevance

- **Pure science**: easily accessible laboratory to study confinement and asymptotic freedom ideas
- **Applied science**: new engineering materials with many potential practical applications

The search for high-T_C superinsulators is on…..

Thank you