NiPS Laboratory
Noise in Physical Systems

UNIVERSITÀ DEGLI STUDI DI PERUGIA

INFN

Room-temperature superconductivity: is the next technological frontier in sight?

Maria Cristina Diamantini & Luca Gammaitoni

Coll:

- **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
- **Carlo A. Trugenberger,** SwissScientific
- **Valerii Vinokur,** Terra Quantum AG

Ambito 4: Fisica teorica delle Interazioni fondamentali

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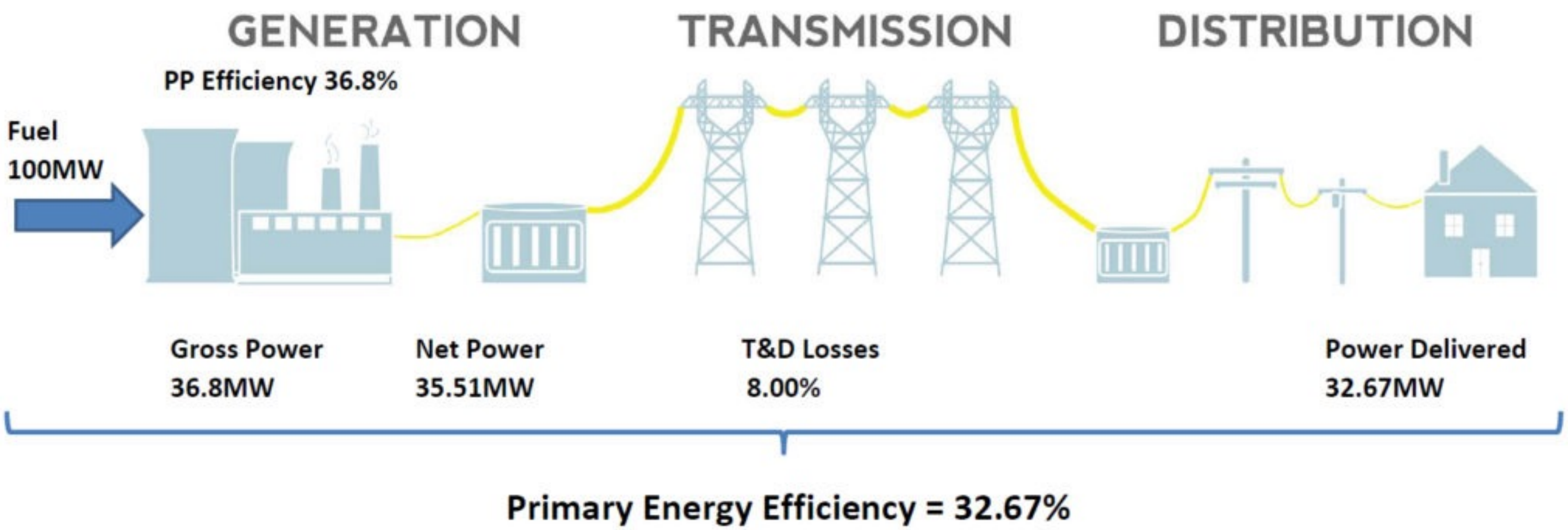
Energy loss in transport and storage



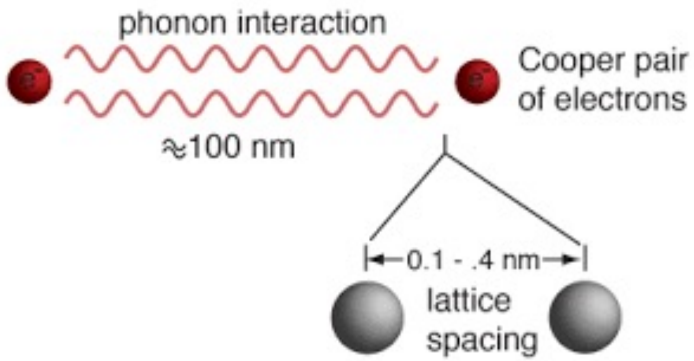
transport : ~ 5% energy waste by heat between plant and consumer over the transmission lines

heat is caused by electrons constantly bumping into each other when hurling down electric power lines

chaotic motion unavoidable in typical conducting materials can current flow dissipationlessly?

produce energy by turbines in the windy North Sea or by solar panels in the sunny Sahara and deliver it without losses in New York, Paris or Shanghai

superconductors: under certain conditions, electrons are forced into a unique quantum state → Bose condensate where they cannot scatter anymore



BCS energy of Cooper pairs very low (10^{-3} ev) ⟹ very low $\mathbf{T_C}$ **0-10 K**

Li 4×10^{-4} K
Al 1.20 K
Hg 4.15 K
Pb 7.19 K
Nb 9.26 K

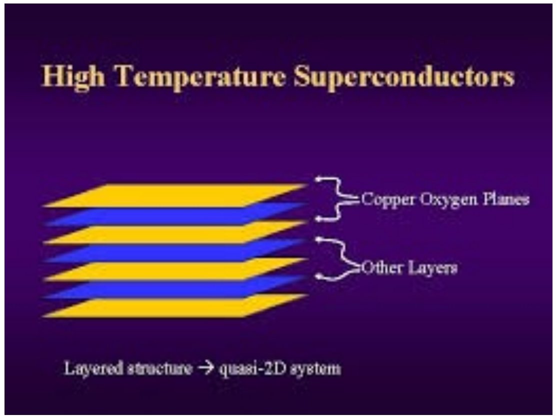
1986: Bednorz and Müller induced superconductivity in lanthanum barium copper oxide (LBCO) 35 K, followed by BSCCO (T_c 107K) and YBCO (T_c 92K) $\Longrightarrow$ high-temperature superconductors (HTS)
Nobel prize in 1987 "for their important breakthrough in the discovery of superconductivity in ceramic materials"

2020: carbonaceous sulfur hydride CH_8S, hydrogen based material, was announced as **room temperature superconductor**: **T_C 15 °C** at a pressure of 267 GPa pressure equivalent to three quarters of the pressure at the center of the Earth

BCS fails to describe HTS:

- Cooper pairs are localized
- need of strong coupling

HTS layered materials



for cuprates films T_c does not depend on the thickness, same as bulk, 3d effect

Dirac monopoles

Maxwell equations

vacuum **matter**

$\nabla E = 0;\ \nabla \wedge B - (\partial/\partial t)\, E = 0$ $\nabla E = \rho;\ \nabla \wedge B - (\partial/\partial t)\, E = j$

$\nabla B = 0;\ \nabla \wedge E + (\partial/\partial t) B = 0$ $\nabla B = 0;\ \nabla \wedge E + (\partial/\partial t) B = 0$

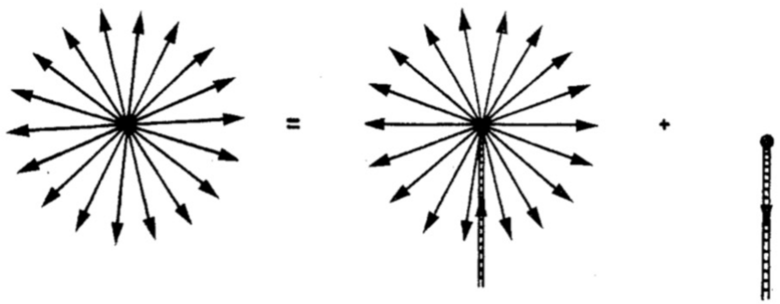
electric magnetic duality broken in presence of matter

$\nabla B = g$?

$$g = \int_S \boldsymbol{B} . \mathrm{d}\boldsymbol{S}$$

$$\boldsymbol{B} = \frac{g}{4\pi r^3} \boldsymbol{r}.$$

$$\frac{qg}{4\pi \hbar} = \tfrac{1}{2} n$$

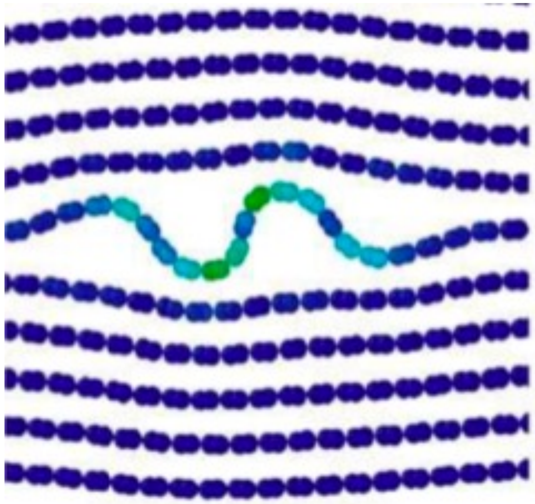


Psudo-magnetic monopoles

defects in condensed matter systems can be described by effective gauge fields
(H. Kleinert)

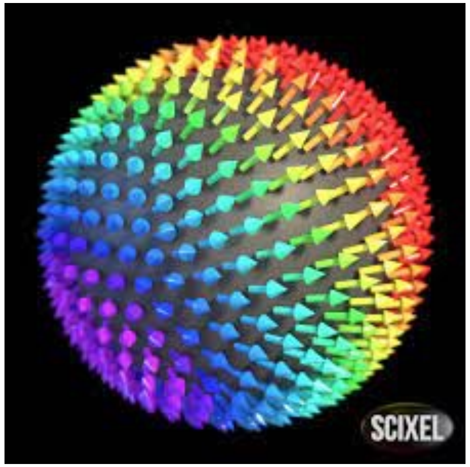
graphene sheets: strains, dislocations and curved protuberances ≡ effective gauge field coupled to low-lying electronic degrees of freedom
(Kane, Mele, Guinea, Vozmediano)

curvature of graphene nanobubbles is equivalent to a pseudo-magnetic monopole at the center of the bubble (Vozmediano)

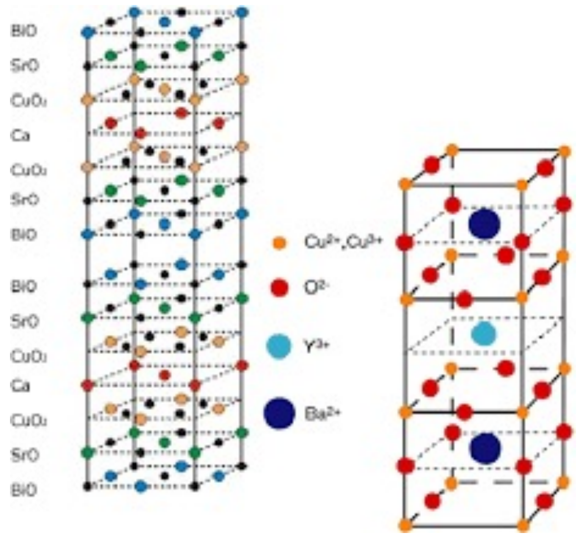


two planes, each one carrying matching half-spheres
$\Longrightarrow$ local curvature "bubbles" corresponding
to pseudo-magnetic monopoles in an overall
flat material, e.g. riplocations in graphite

CuO planes of cuprates, magnetically ordered Mott insulators: non-collinear magnetic structure (defect) can be represented as an effective compact U(1) gauge field
⟹ quantized topological defects forming spin hedgehogs correspond then to pseudo-magnetic monopoles



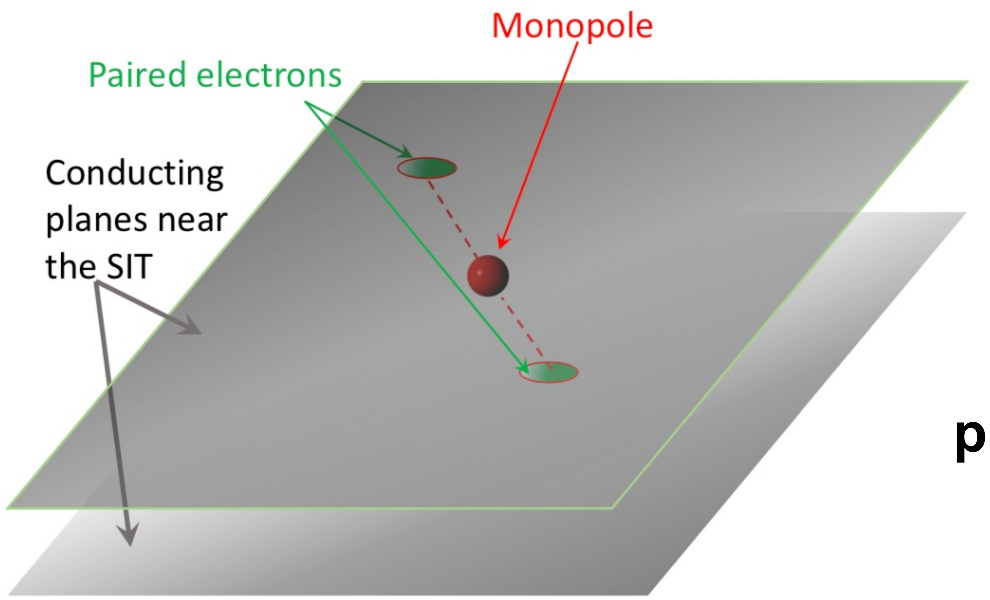
the presence of pseudo-magnetic monopoles also requires at least two planes



BSSCO

Monopole binding model

idea: heavy monopoles bind electrons and anchor pairs forming nucleation points for a superconducting granular array that emerges upon cooling the system down from the temperature of pair formation, T_{pair} to T_C



patent pending

3 bodies problem

- strength of the interaction determined by the monopole charge g
- quantization condition:

  $eg/2\pi = n$ $n \in Z$; e = electron charge

  the product of the electric and the magnetic charge is **O(1)** $\Longrightarrow$ **strong-coupling pairing mechanism**
- total spin S = 0, spin of each electrons has a hedgehog configuration || or anti || to the monopole magnetic field
- monopoles induce a magnetic moment that cancels the centrifugal barrier or turn it negative for all value of momentum **l**

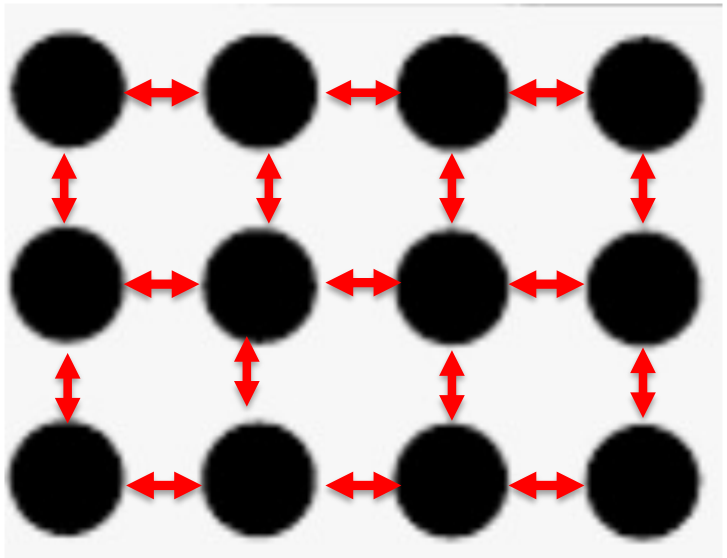
  $$2l \leq |eg/2\pi|$$

  $\Longrightarrow$ different monopoles charges can accommodate s , p, d waves pairing optimal l values:

- bigger l values make magnetic moment attraction stronger
- bigger l values make monopoles heavier ⟹ more difficult to nucleate

localized pairs are the nucleation centres for superconducting droplets
global superconductivity: sufficient monopoles have formed ⟹ droplets linked by tunnelling junctions form an infinite cluster

T_C : s wave pairing for granular size and interplane distance of O(1) nm we get **T_C (10^2)**



graphite: local superconductivity concentrated around defects has indeed been detected with critical temperatures of up to **300 K**, and forms a Josephson-junction-array-like structures that could lead to global superconductivity once their typical spacing is small enough to allow tunneling to set in
(Kopelevich et al.)

thecnological challenge: how to create enough defects

Storage

Superconductor

R = 0

G= ∞

S duality

Mandelstam 'tHooft
Polyakov

Superinsulator

R = ∞

G= 0

- theoretically predicted in 1996

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

- experimentally observed in

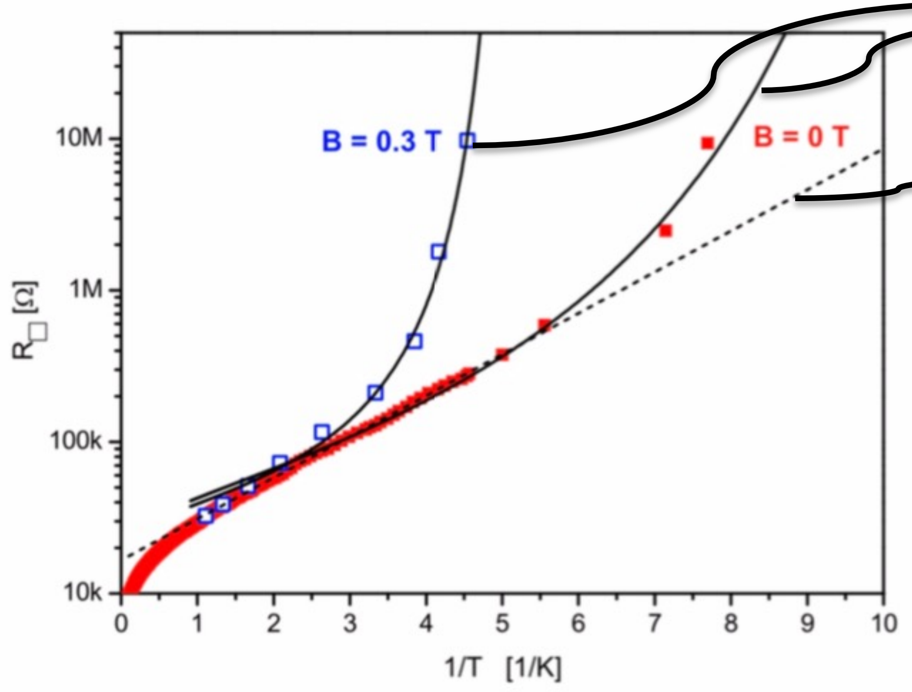
  In_2O_3 films (Sambandamurthy et al, Phys.Rev.Lett. 94(2005) 017003)

  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))



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

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

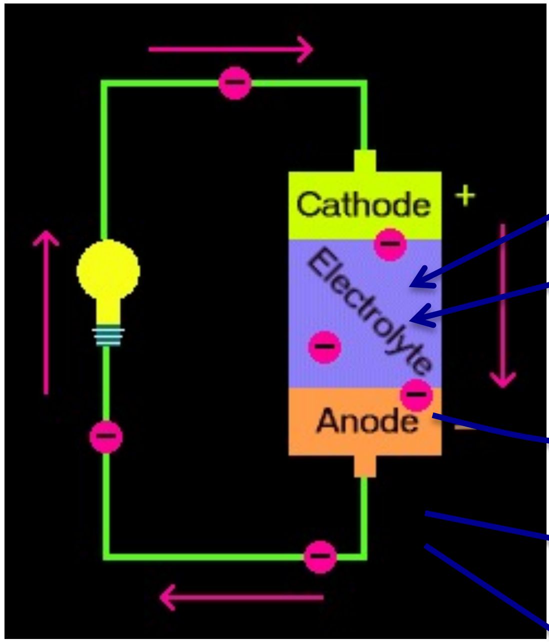
Sheet resistance as a function of inverse temperature for a TiN film.
T_{cr}(B = 0) = 0.062 mK
T_{cr}(B = 0.3T) = 0.175 mK .
(T. I. Baturina and V. M. Vinokur, Ann. Phys. 331, 236 – 257 (2013))

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

Cooper pairs ⟷ Quarks

Superconductors perfectly store currents
Superinsulators perfectly store charge

Superinsulators are "perfect batteries"



Losses due to self-discharge

electrons

This cannot happen if cathode and anode coated with superinsulator

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THANK YOU!!!!