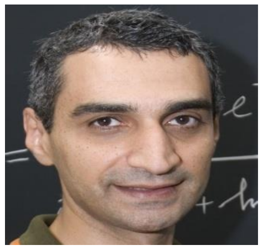
Smaller is different and more

Antonio M. García-García

Cavendish Laboratory, Cambridge University, Lisbon University

http://www.tcm.phy.cam.ac.uk/~amg73/

Pedro Ribeiro
Dresden



Yuzbashyan
Rutgers

Urbina
Regensburg

Richter
Regensburg

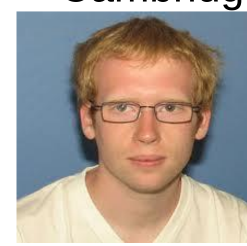
Bermudez
Cambridge

Way
Santa Barbara

Sangita Bose
Bombay

Altshuler
Columbia

Klaus Kern
Stuttgart



Mayoh
Cambridge

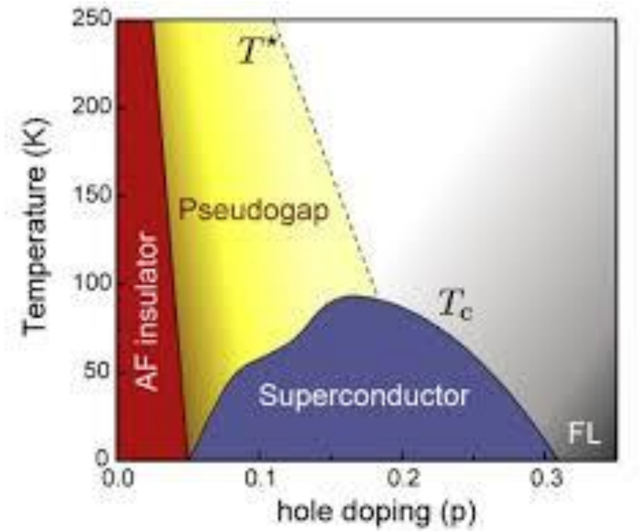
FCT
Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

MARIE CURIE ACTIONS

EPSRC
Engineering and Physical Sciences
Research Council

Superconductivity

Mavericks

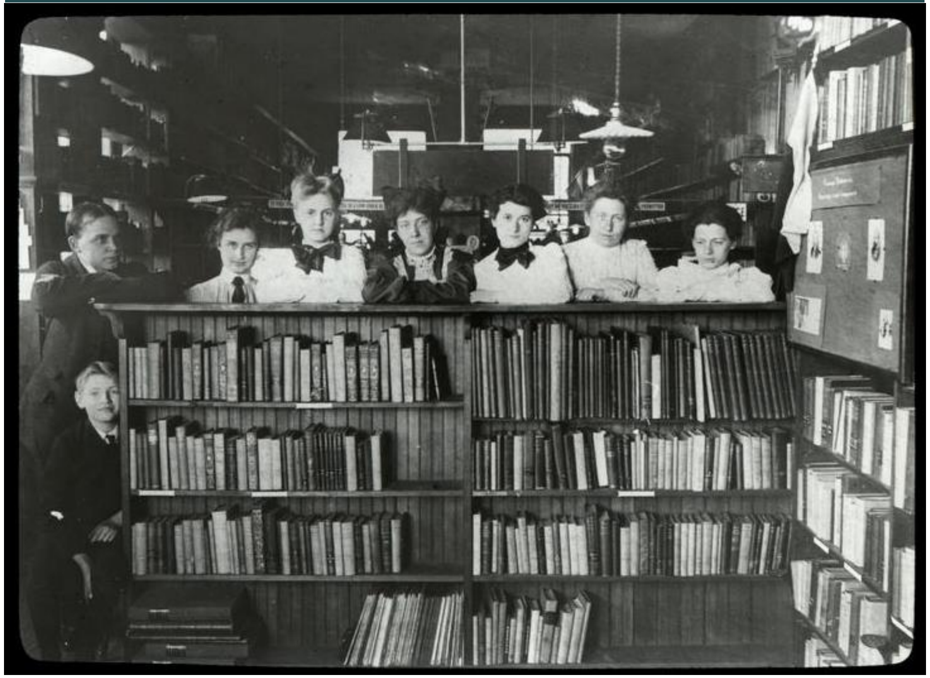


Quantum critical points ©

Cuprates	~100K	1986	Mueller & Bednorz
MgB_2	39K	2001	Akimitsu
FeSC	~50K	2006	Hotsono

Pb ~7K Al ~1K Sn ~3.7K Nb ~9.3K

Librarians



Thinner

Cleaner

Smaller

Granular

BCS + ….

Abeles, Tinkham, Devoret, Goldman, Xue, Kern, Di Fazio, Schoen, Halperin, Leggett,Blatt….

Thin films

Josephson Junctions

Nanowires

Control

No Control → Theory Drifts

Trial and error

How to enhance SC substantially?

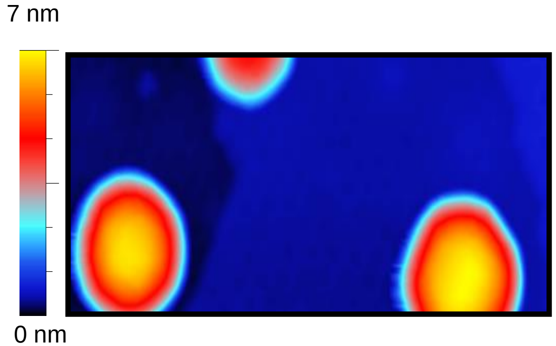
with **control**

Mechanism of SC in cuprates?

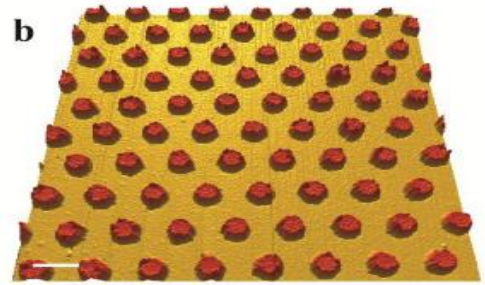
?

$\$10^6$ Question

\$10 Question



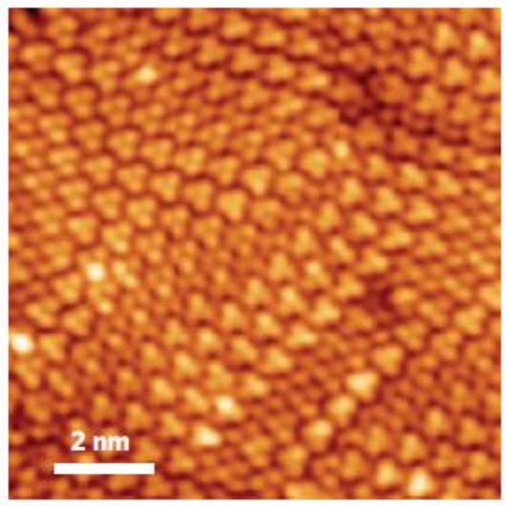
Smaller



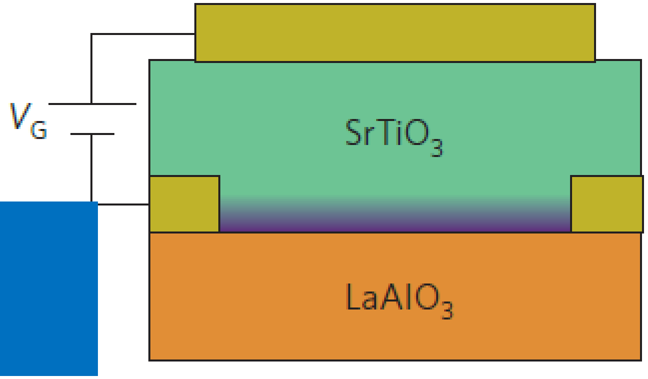
Far from equilibrium

Higher Tc?

Grainy

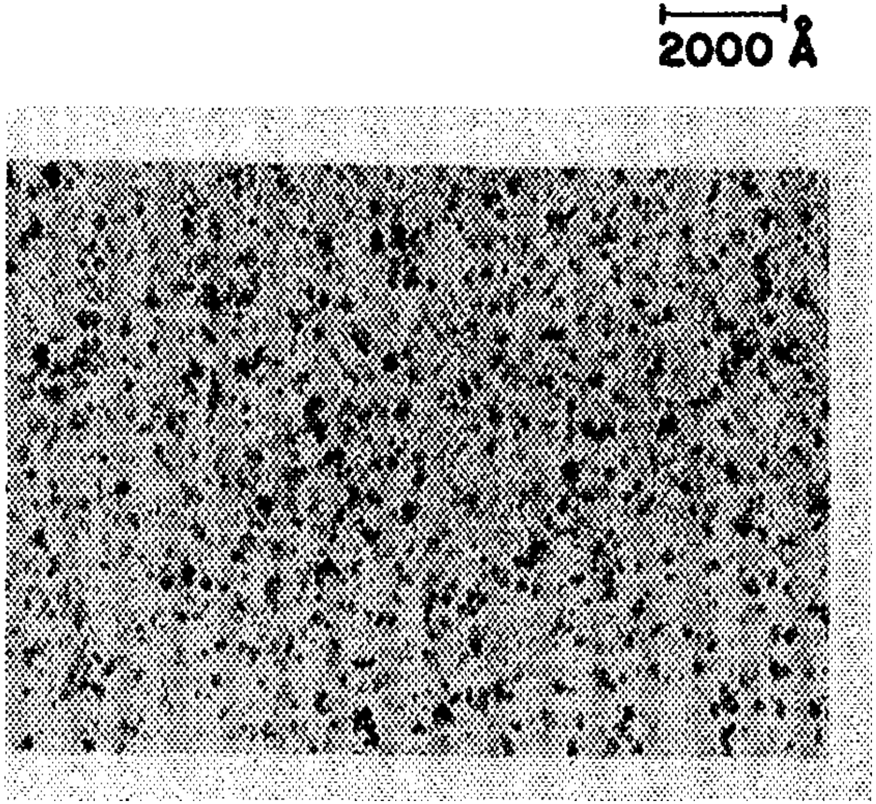


Packed



Thin Films?

Metal	T_c (°K)	T_c/T_{c0}	d (Å)	ρ_0
Al	3.0	2.6	40	0.19
Ga	7.2	6.5	···	0.20
Sn	4.1	1.1	110	0.31
In	3.7	1.1	110	0.36
Pb	7.2	1.0	···	0.53



Abeles, Cohen, Cullen, Phys. Rev. Lett., 17, 632 (1966)

Crow, Parks, Douglass, Jensen, Giaver, Zeller....

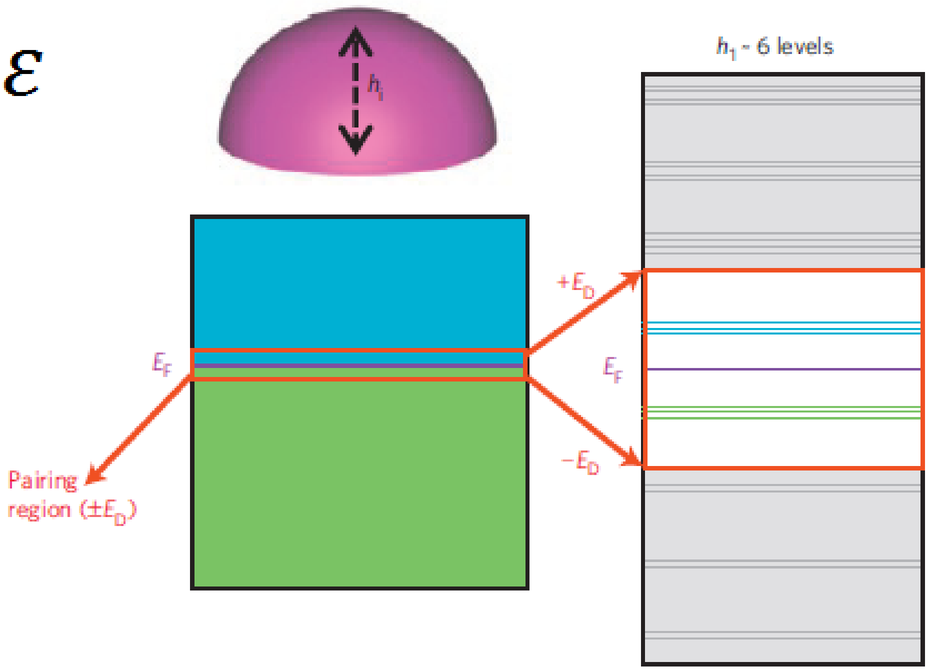
A.M. Goldman, Dynes, Tinkham…

BCS superconductivity

Finite size effects

$$\frac{2}{g} = \int_{-E_D}^{E_D} \frac{\nu(\varepsilon)}{\sqrt{\Delta^2 + \varepsilon^2}} d\varepsilon$$

$$\nu(\varepsilon) = \sum_i c_i \delta(\varepsilon - \varepsilon_i)$$



V → ∞
$\Delta \sim \varepsilon_D e^{-1/\lambda}$

V finite
Δ=?

Level Degeneracy

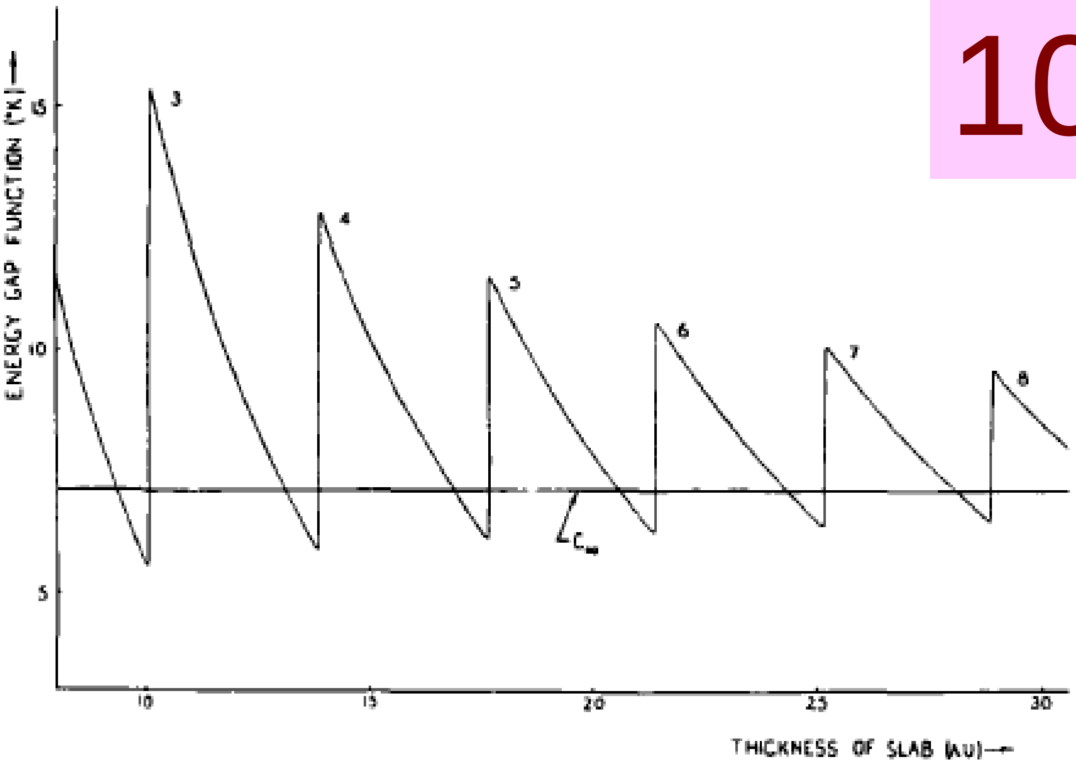
Shell Effects

Parmenter, Phys. Rev. 166, 392 (1967)

L ~ 5nm → $20T_c$!

Thin Films

Shape Resonances



Blatt, Thompson, Phys. Lett. 5, 6 (1963)

$10T_c$!

Fluctuations?

Charge neutrality?

Substrate?

Yu, et al.,Rev. B 14, 996 (1976)

Bermudez, AGG, Phys. Rev. B 89, 064508 (2014) 89, 024510 (2014)

Thinner

Smoother

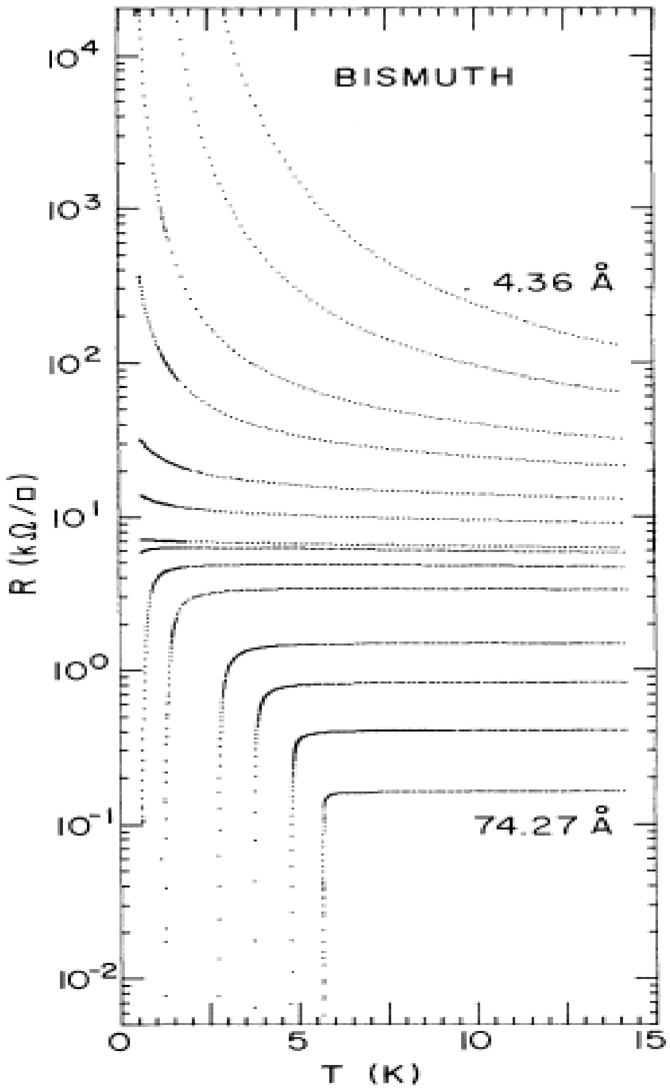
Disordered

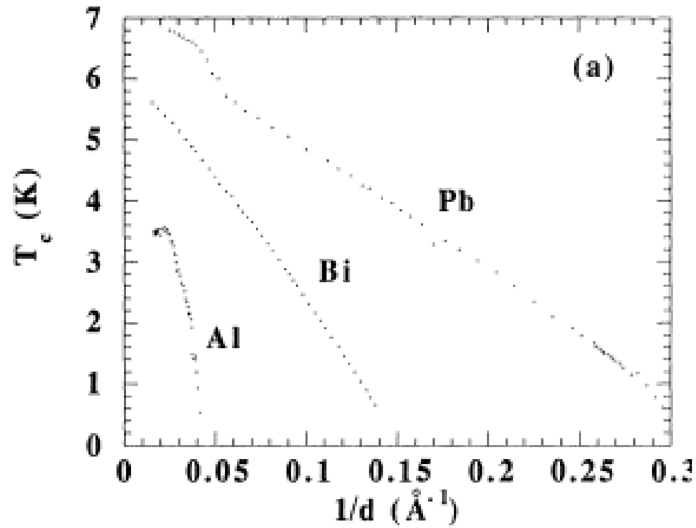
BKT

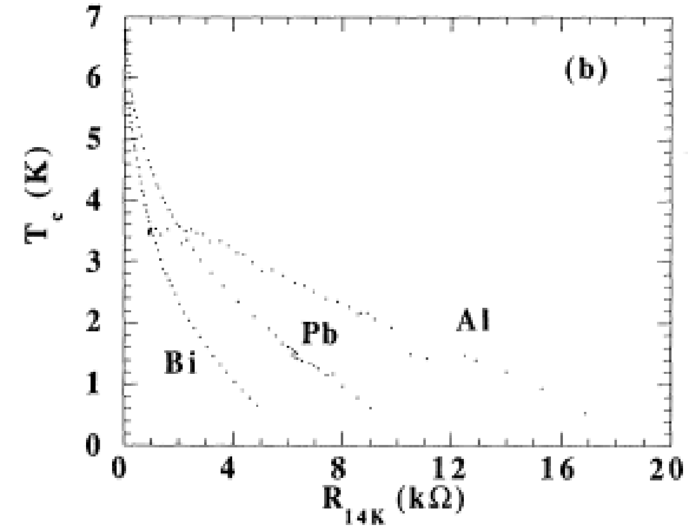
Transition

$R_N > R_q$

(anti)Vortex unbinding



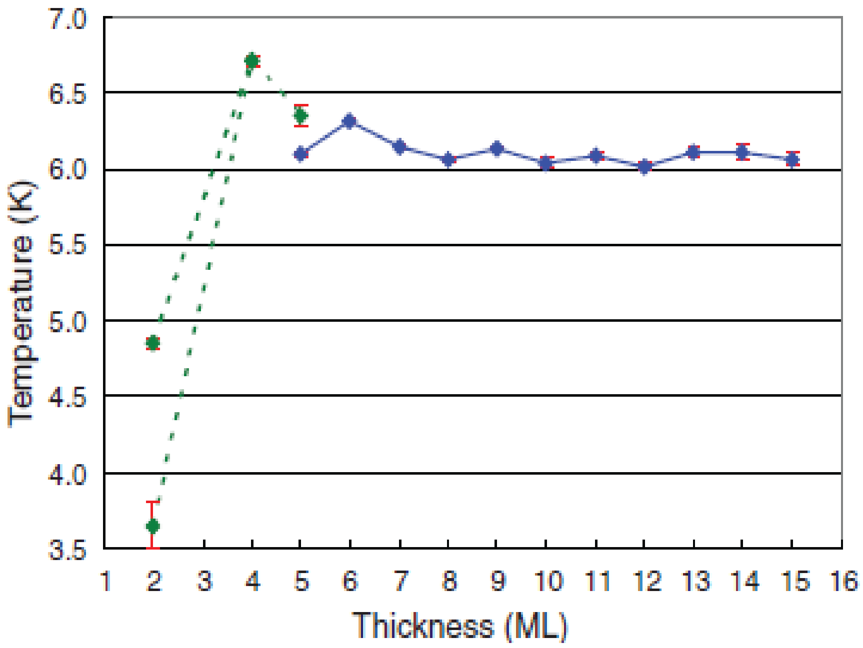




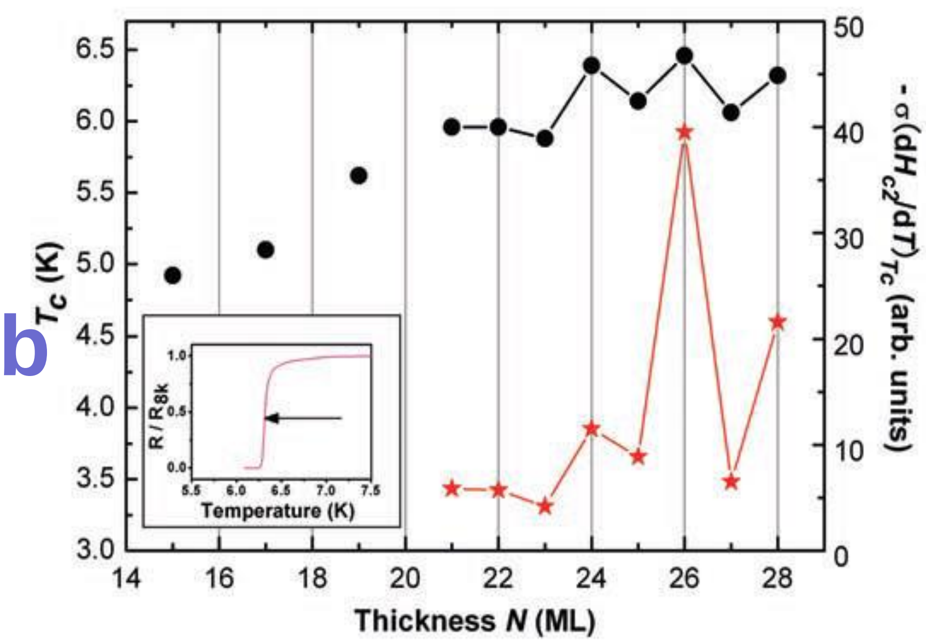
A.M. Goldman et al.

PRL 62 2180 (1989)
PRB 47 5931 (1993)

2000 Atomic scale **control**



Pb



Shih et al., Science 324, 1314 (2009)

Xue et al., Science 306, 1915 (2004)

Xue et al., Nat Phys, 6 (2010),104.

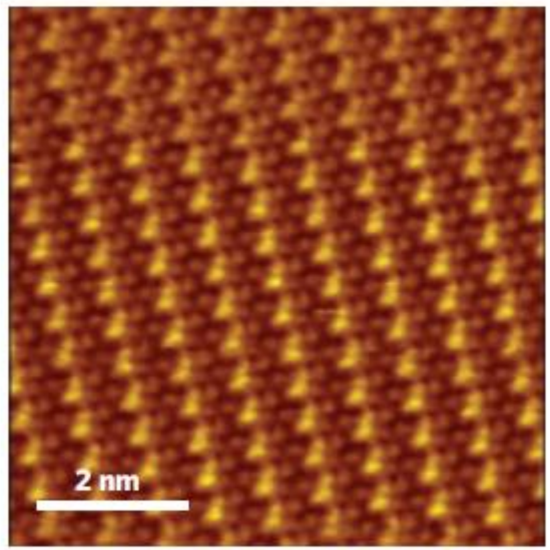
LETTERS
PUBLISHED ONLINE: 10 JANUARY 2010 | DOI: 10.1038/NPHYS1499
nature physics

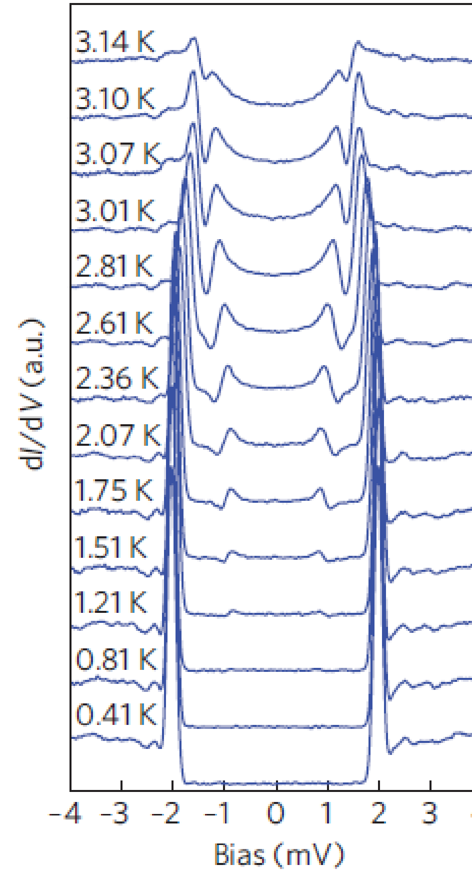
Superconductivity in one-atomic-layer metal films grown on Si(111)

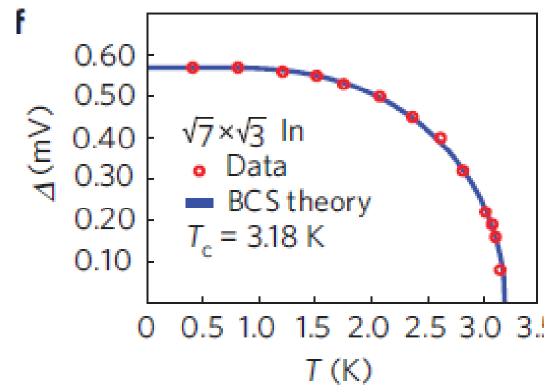
Epitaxial growth

STM

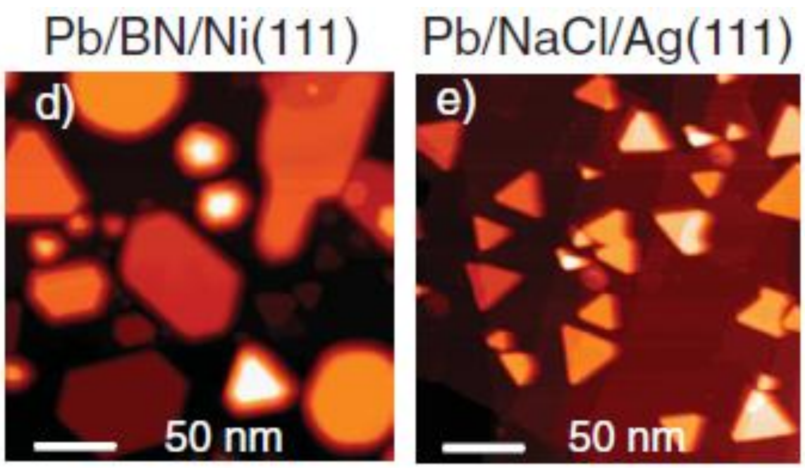
No impurities

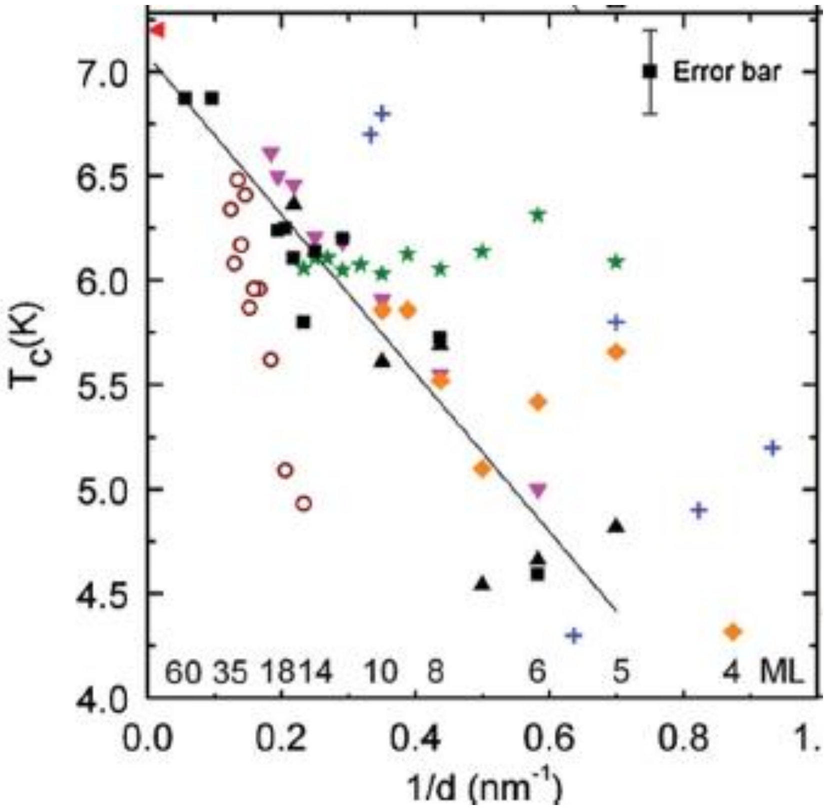


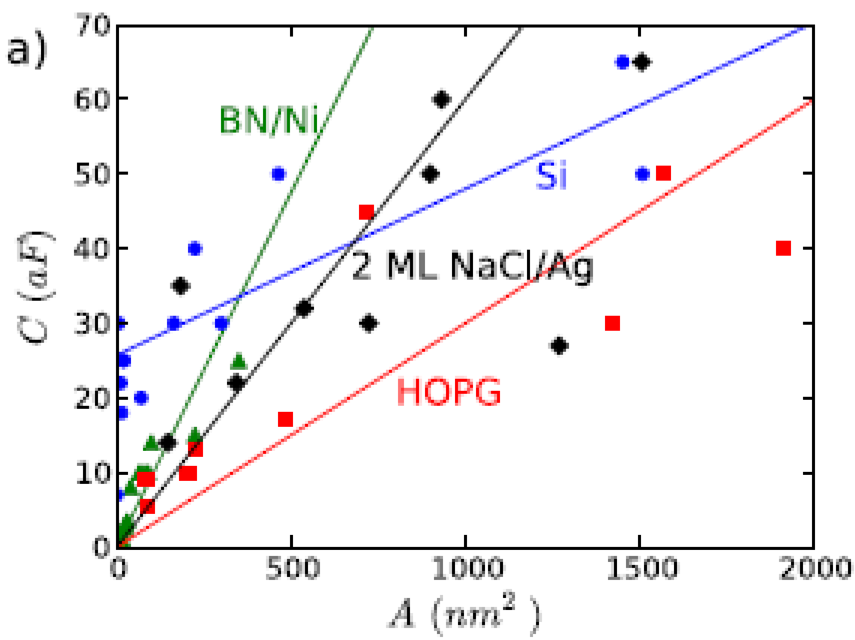




Islands







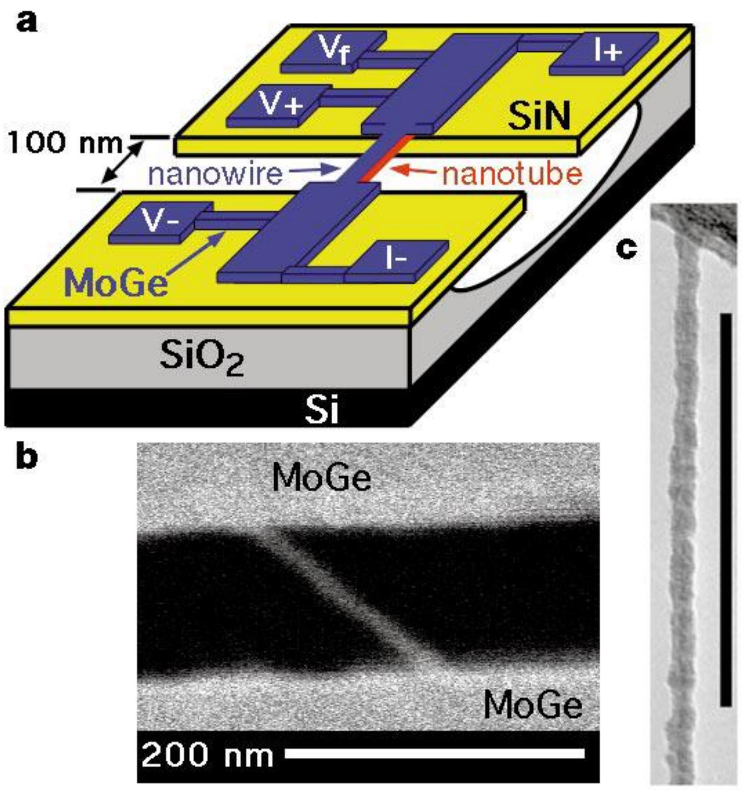
Schneider, et al.,
PRL 102, 207002 (2009)

PRL 108, 126802 (2012)

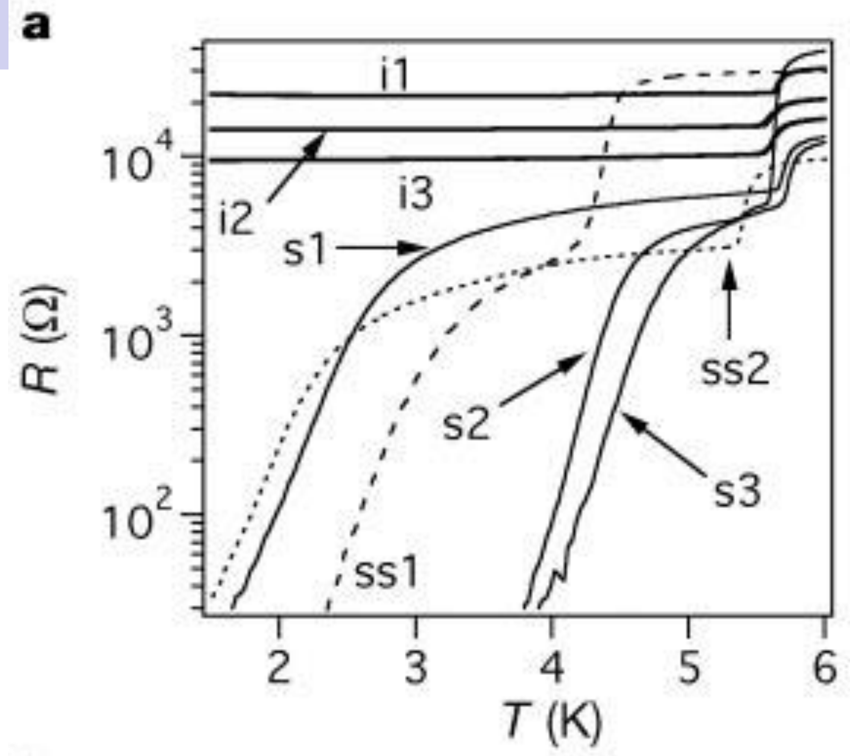
Hasegawa, et al.

Phys. Rev. Lett. 101, 167001 (2008)

Nanowires R <<ξ



Tinkham et al.
Nature 404, 971 (1990)



Superconductor
Insulator
transition

$$|\Delta(\mathrm{r},\mathrm{t})|e^{i\theta(r,t)}$$

Fluctuation

$$\Delta(r_0, t_0) \approx 0$$

Phase-slips

$$\theta \approx 0 \to 2\pi$$

Finite Resistence

$$R \propto e^{-S_{inst}}$$

Thermal

Langer & Ambegaokar, PR. 164, 498 (1967).

McCumber & Halperin PRB 1, 1054 (1970).

Instantons

Coulomb-Gas

BKT transition

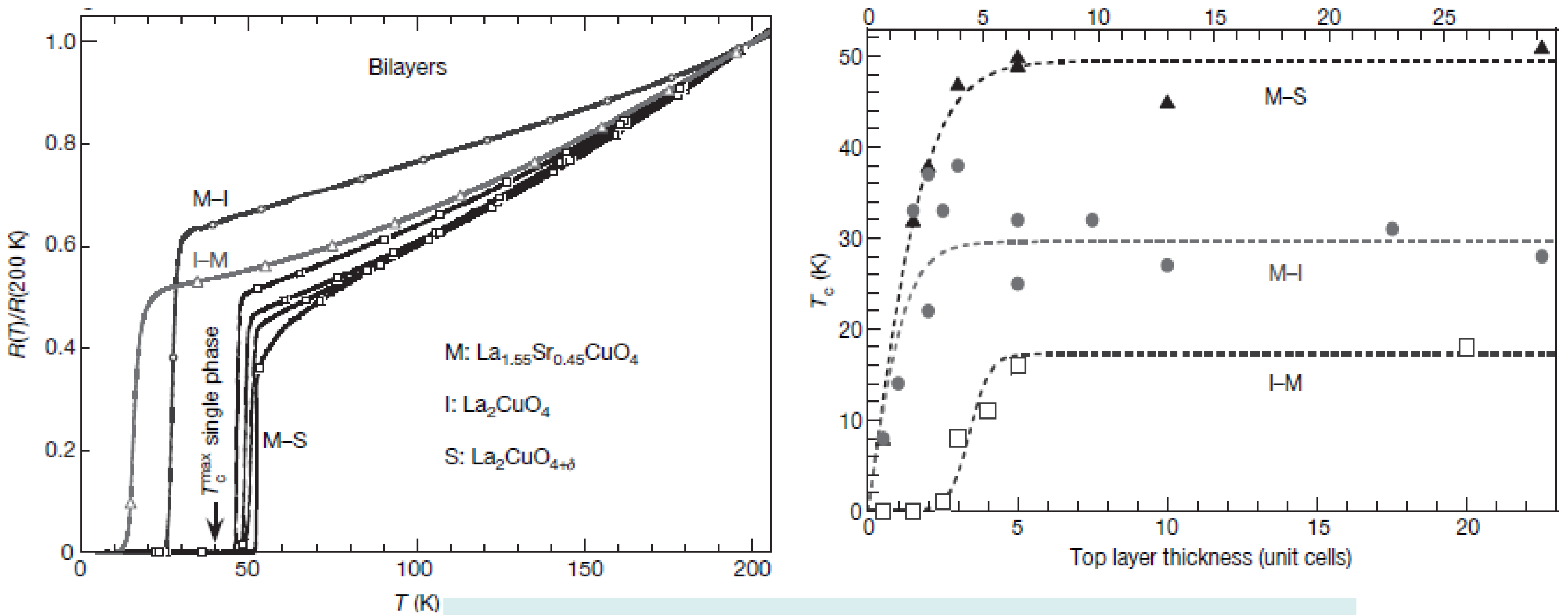
Quantum

Zaikin, A. D., Golubev, et al, PRL 78, 1552 (1997).

Quantitative?

Is enhancement of superconductivity possible?

Cuprates high T_c Heterostructures

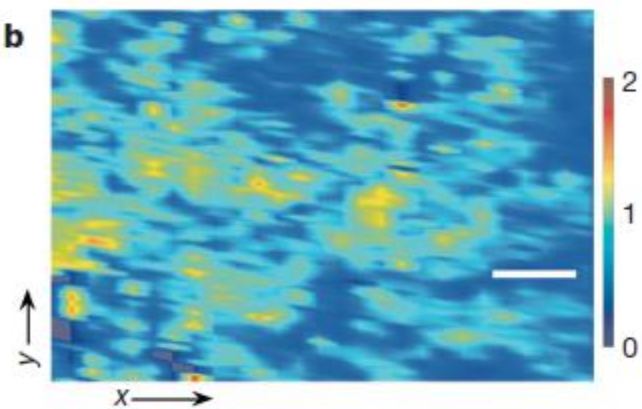


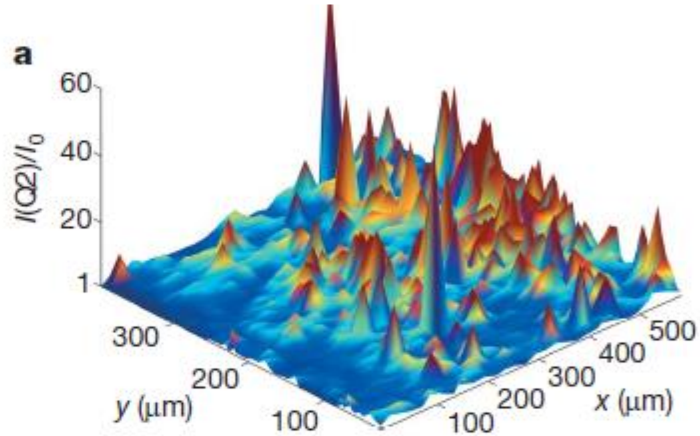
Bozovic et al., Nature 455, 782 (2008)

Higher T_c!!

Enhancement of T_c by disorder

Fractal distributions of dopants enhances SC in cuprates



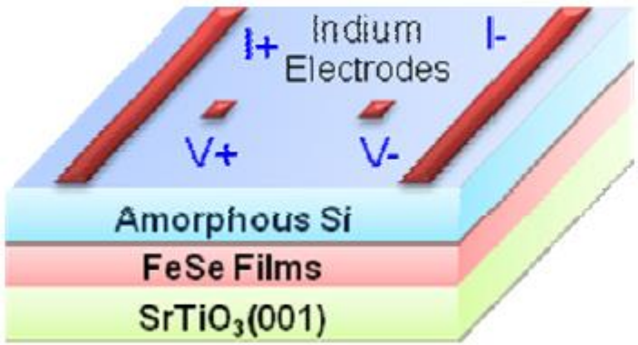


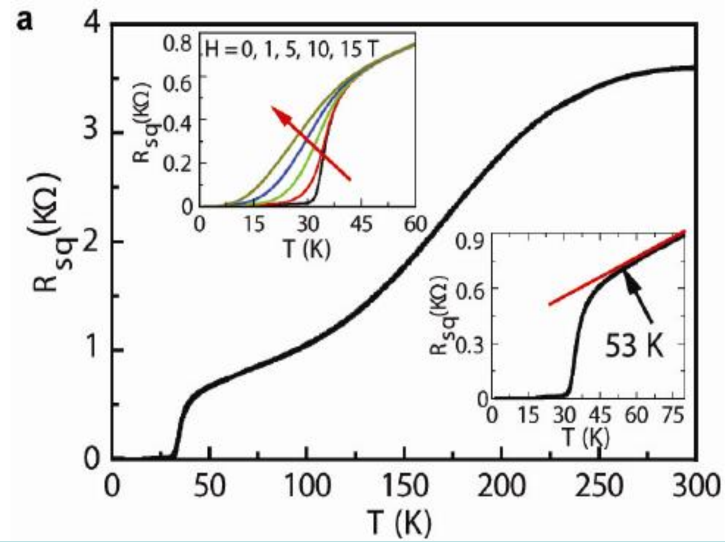
Bianconi, et al., Nature 466, 841 (2010)

Inhomogeneities ⟷ **Higher T_c**

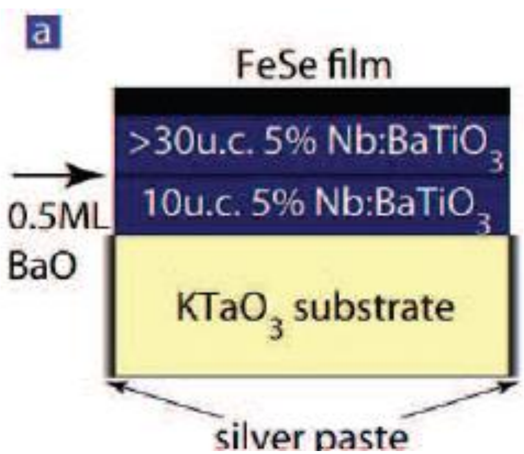
PRL 108, 017002 (2012)

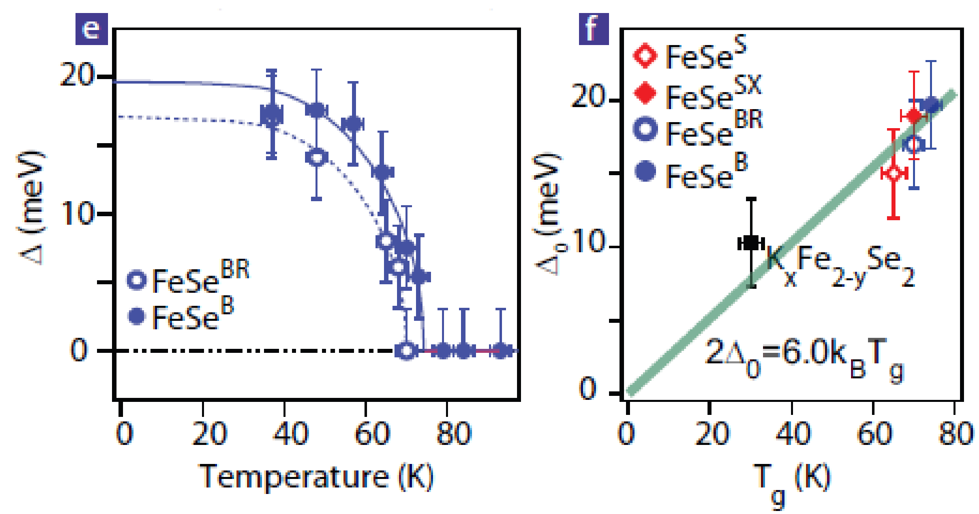
Iron Pnictides Heterostructures





Xue et al., Nature Communications 3, 931 (2013)





Feng, et. al, arXiv:1402.1357

Enhancement, yes

Origin?

Grains

$\Delta >> \delta$ Grains

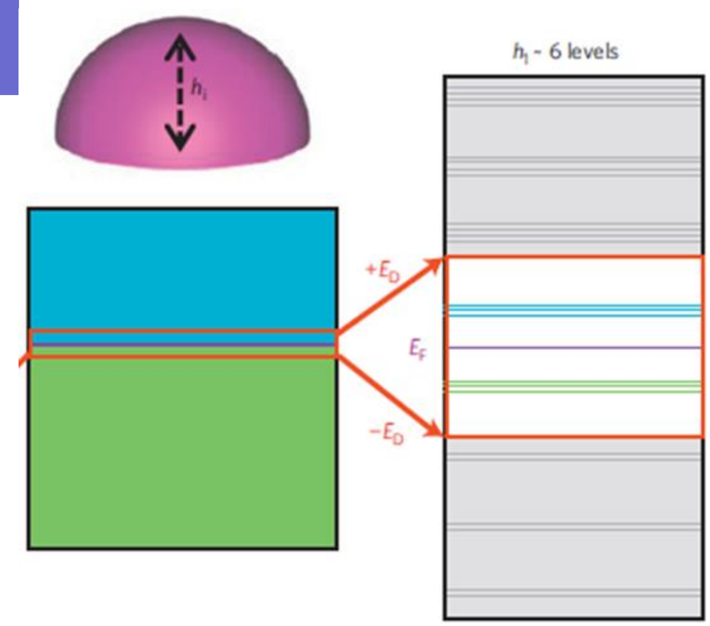
Heiselberg (2002): harmonic potentials, cold atom

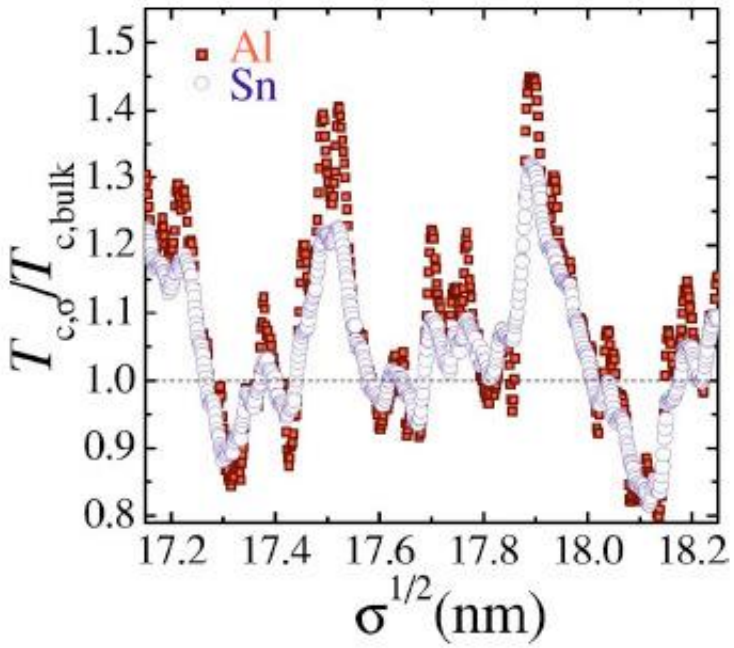
Kresin, Ovchinnikov, Boyaci (2007) : Spherical, too high T_c

Peeters, et al, (2005-): BCS, BdG in a wire, cylinder..

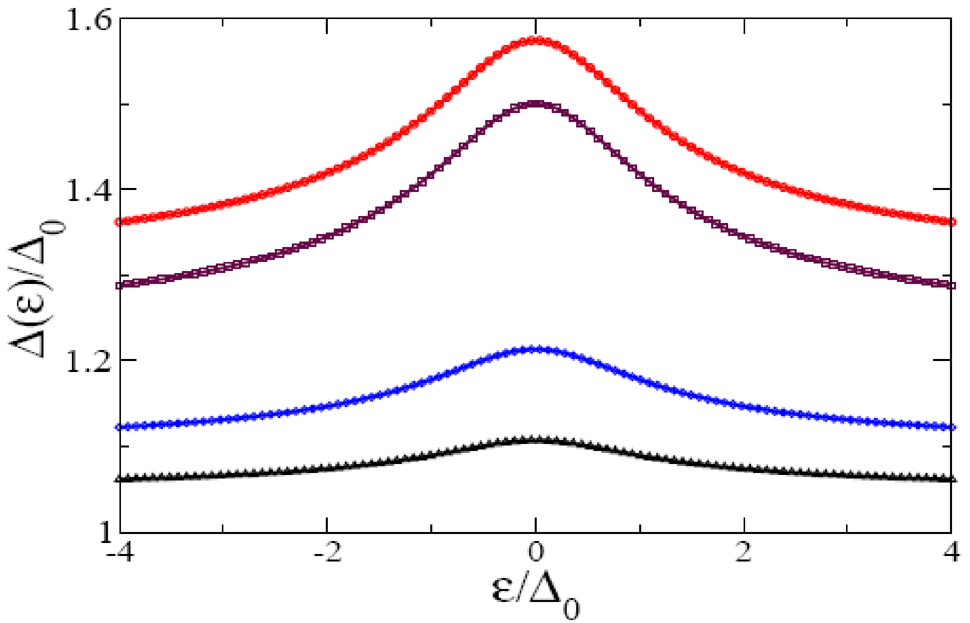
Devreese (2006): Richardson equations in a box

Olofsson (2008): Estimation of fluctuations in BCS





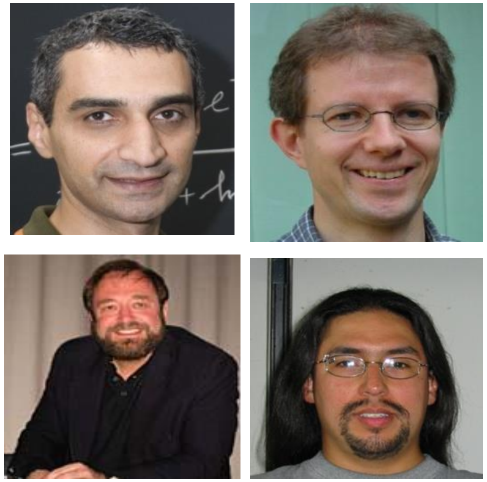
3d chaotic



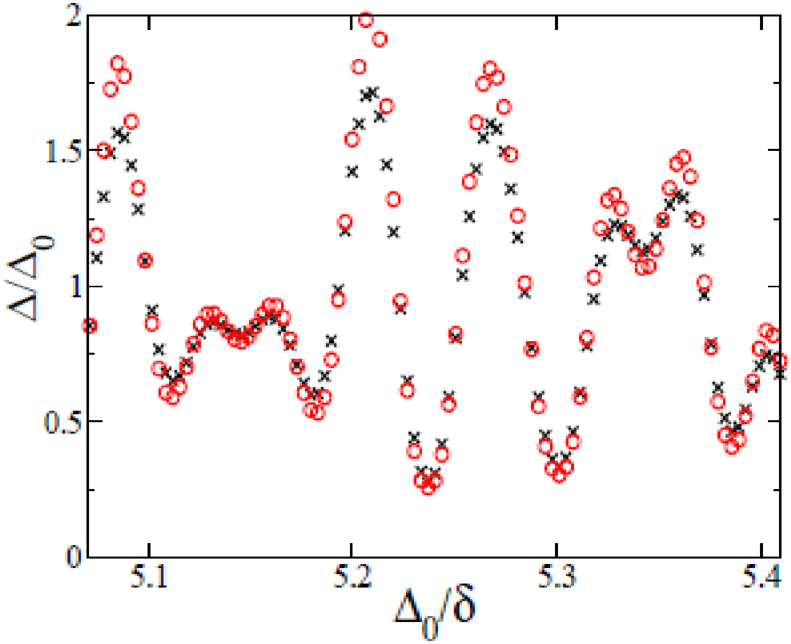
Al grain

$k_F = 17.5\ nm^{-1}$

$\Delta_0 = 0.24mV$



3d integrable



PRL 100, 187001 (2008)   PRB 83, 014510 (2011)

Single, Isolated Sn and Pb grains

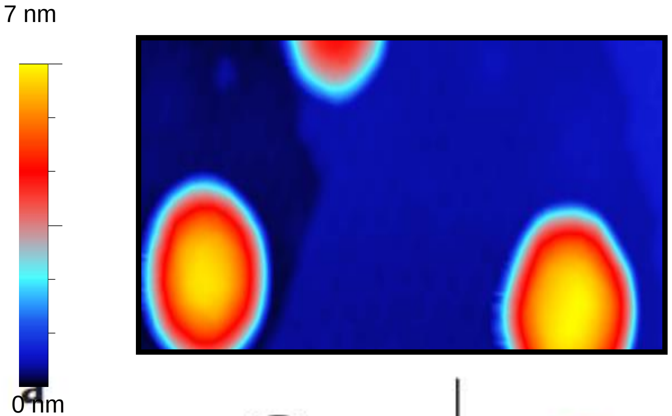

Kern

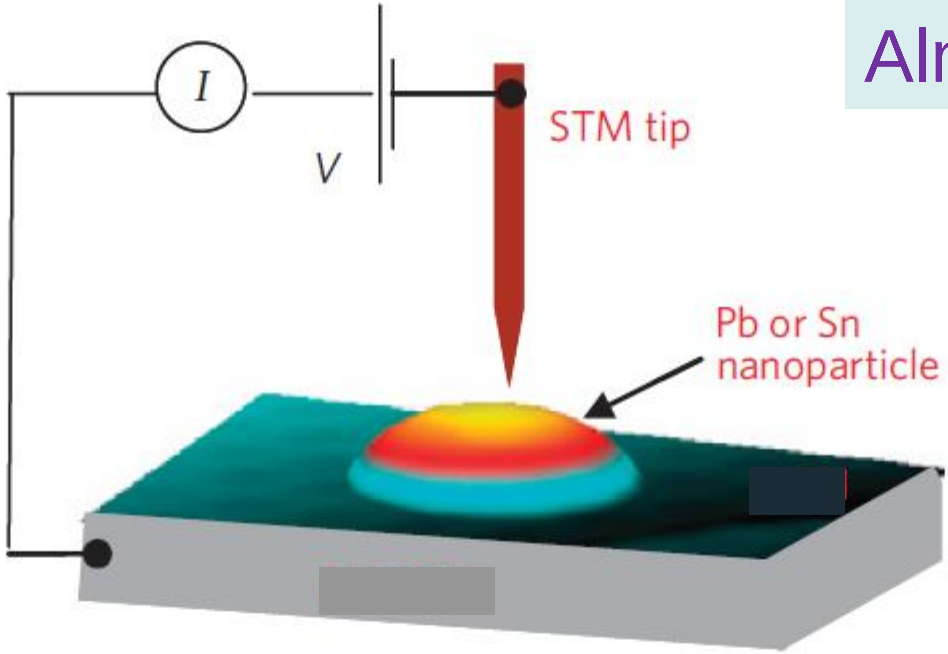

Bose

R ~ 4-30nm

B closes gap

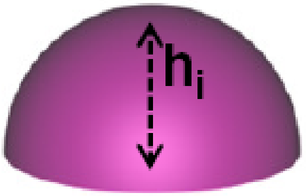
Almost hemispherical





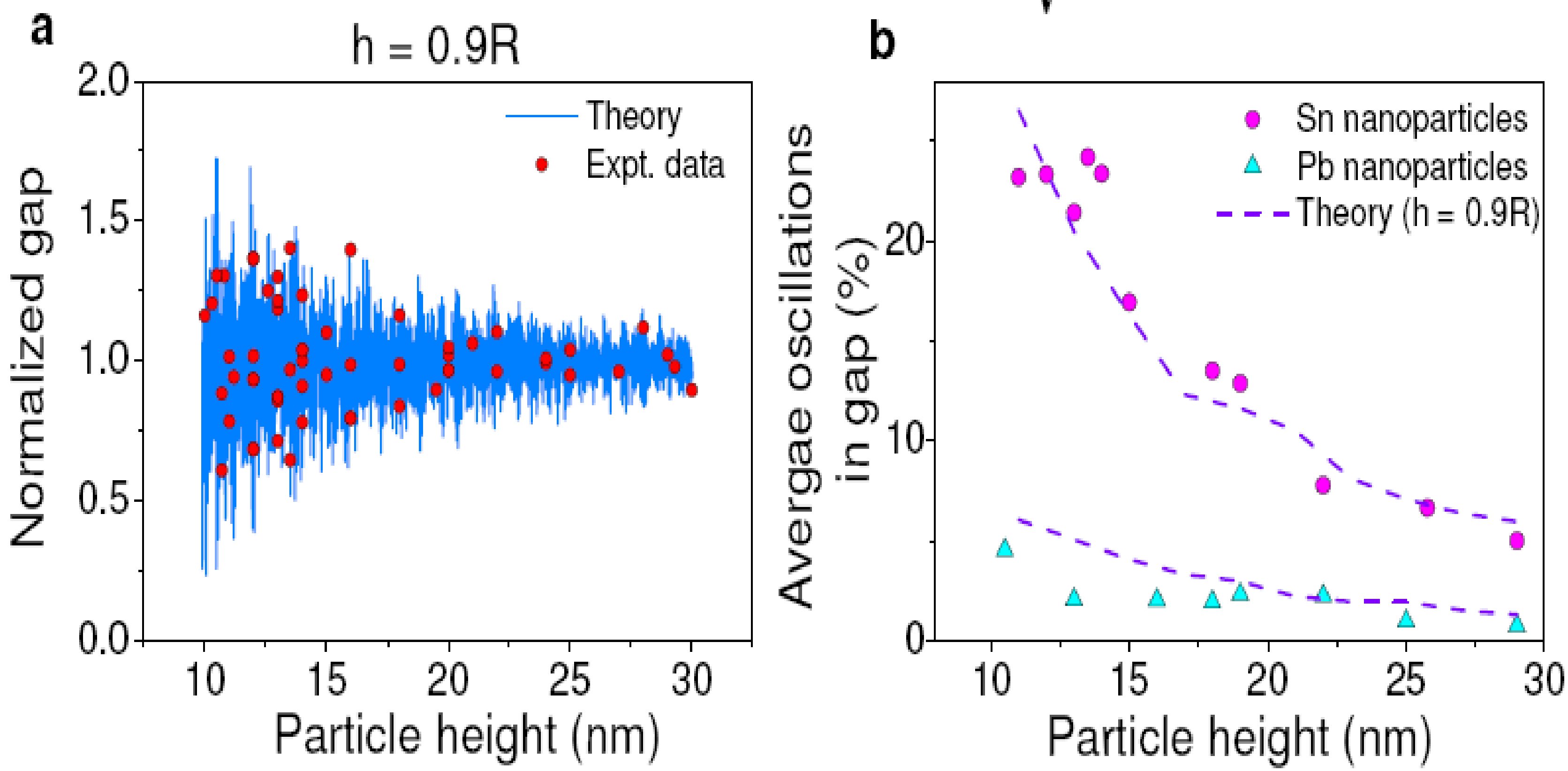
STM

Tunneling conductance



+

$$\Delta(\epsilon) = \frac{1}{2}\int_{-\epsilon_D}^{\epsilon_D} \frac{\Delta(\epsilon')I(\epsilon,\epsilon')}{\sqrt{\epsilon'^2+\Delta^2(\epsilon')}}\nu(\epsilon')d\epsilon'$$



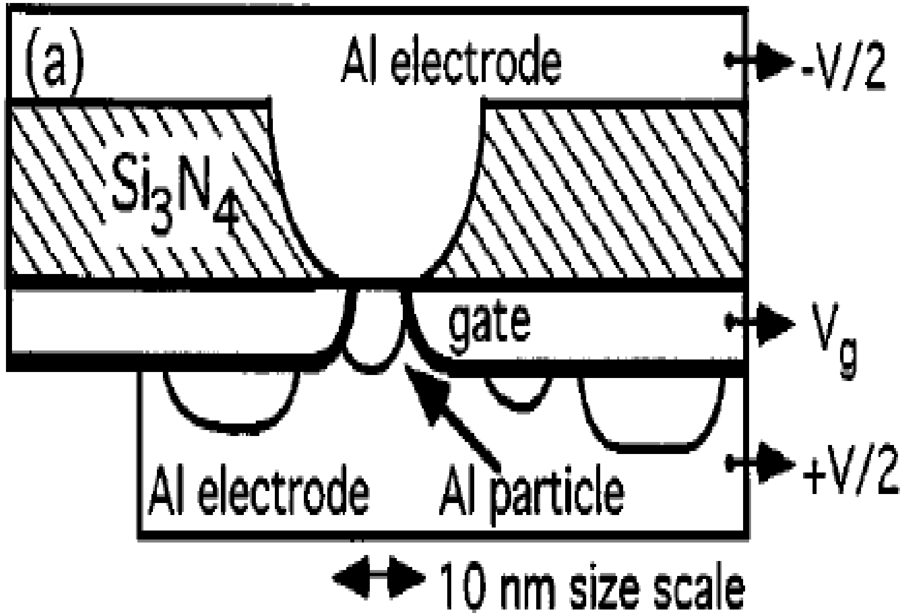
Bose, AGG, Nature Materials 2010

$\Delta \sim \delta$

Ralph, Black, Tinkham,
Superconductivity in
Single Metal Particles
***PRL* 74, 3241-3244 (1995).**

Supercon ductivity?

1959



Yes, superconductivity

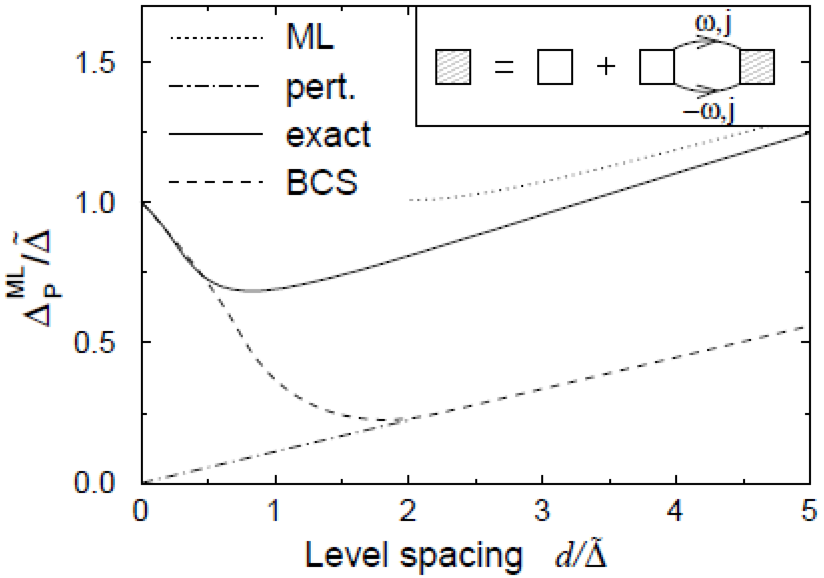
B closes gap

Odd-even effects

Isolated grain?

T = 0
Ultrasmall grains
$\delta / \Delta_0 > 1$

von Delft, Braun, Larkin, Sierra, Dukelsky, Yuzbashyan, Matveev, Smith, Ambegaokar



Exact diagonalization, RPA, Path Integral, Montecarlo......

Richardson

It’s exact. I did it 20 years ago

BCS fine until $\delta / \Delta_0 \sim 1/2$

BCS sharp transition

Richardson no transition

J. von Delft et al., Phys. Rep., 345, 61 (2001)

T=0 deviations from mean field

Richardson's equations

Von Delft, Braun, Dukelsky, Marsiglio, Sierra, Smith, Ambegaokar

$$-\frac{1}{\lambda d}+\sum_{j=1}^{m}{}'\frac{1}{E_i-E_j}=\frac{1}{2}\sum_{k=1}^{n}\frac{1}{E_i-\epsilon_k}\qquad i=1,\ldots,m$$

Ground state energy

$$E=2\sum_{i=1}^{m}E_i+\sum_{B}\epsilon_B$$

Expansion in δ/Δ_0

$$\Delta^b=2\Delta_0-d\sqrt{1+\frac{\Delta_0^2}{D^2}}+\frac{d\Delta_0}{D}[1+\phi(\lambda)]$$

$D \equiv E_D$

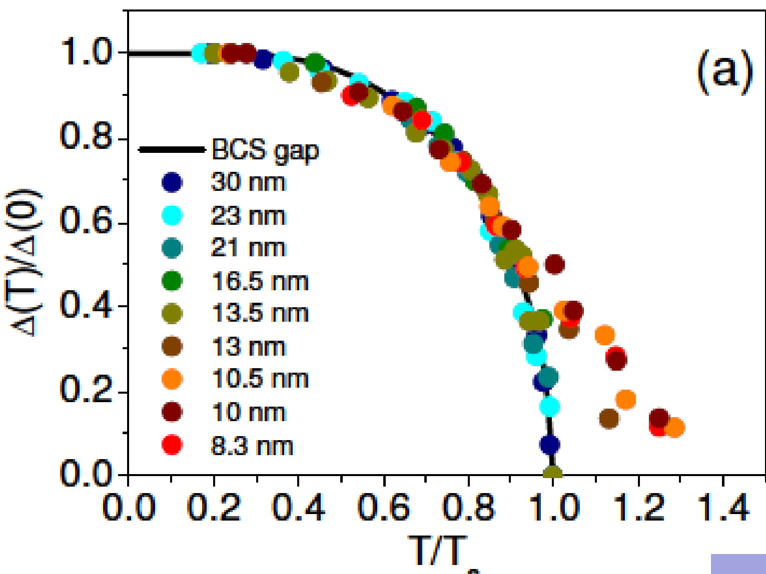
$d \equiv \delta$

Richardson ~ 1968,
Yuzbashyan, Altshuler ~ 2005

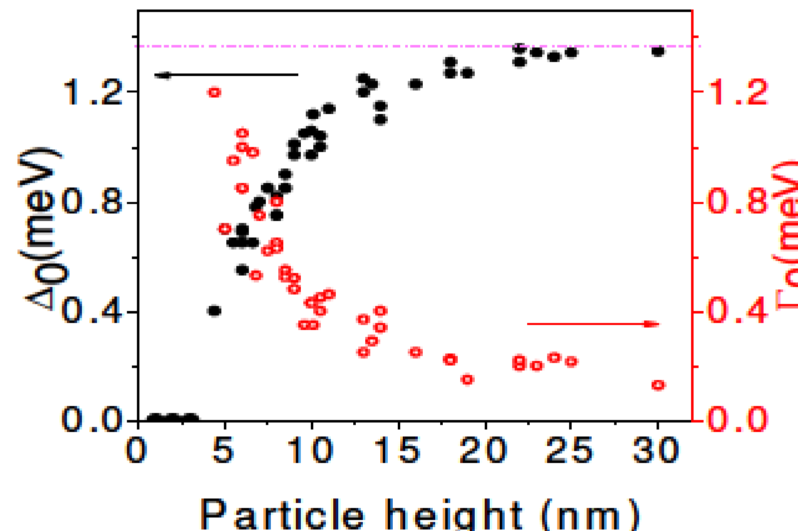
More fun?

Why not

Ribeiro,
Dresden



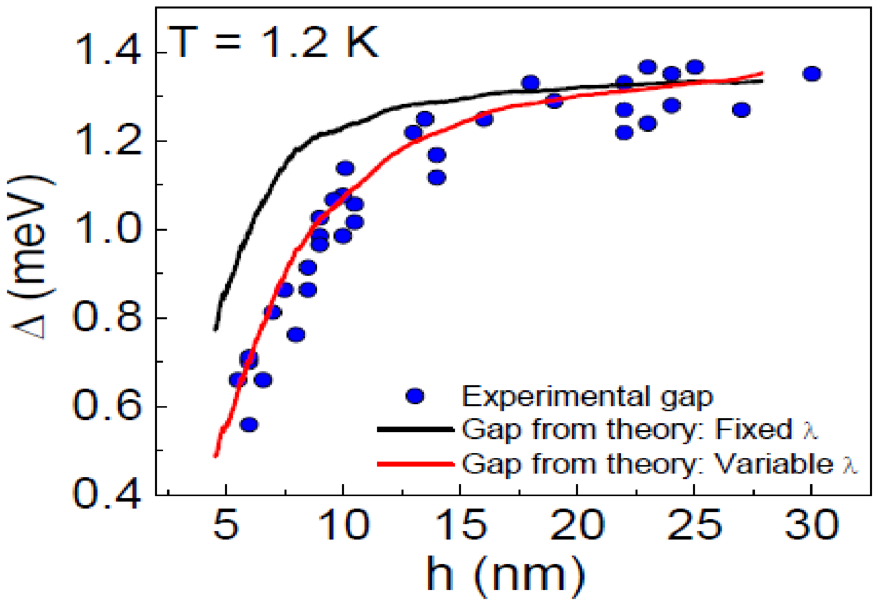
Pb

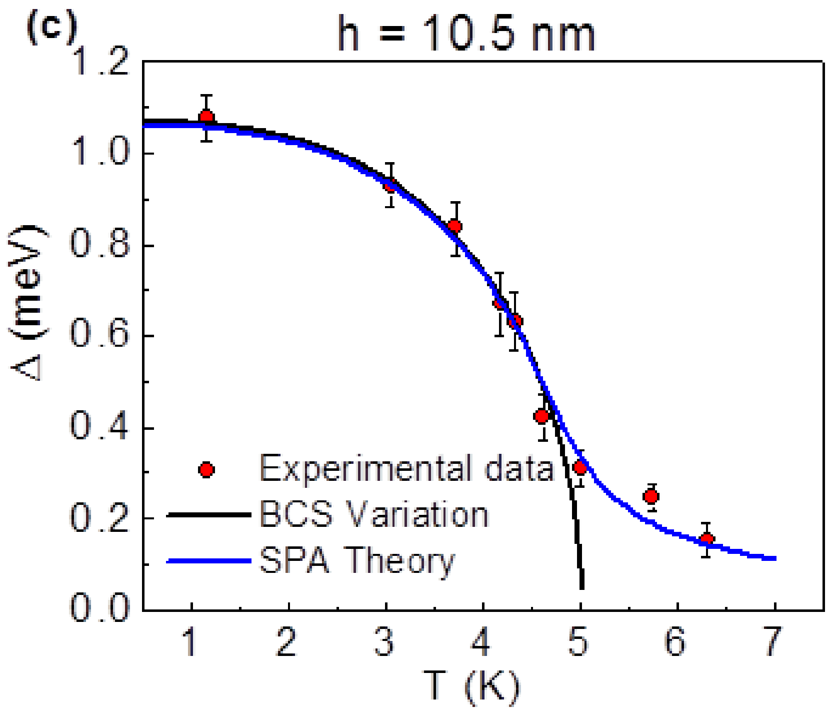


Beyond
mean field

Quantum Fluctuations
Richardson's equations

and





Thermal Fluctuations
Static Path Approach

Scalapino, et al.

PRB 84,104525 (2011)
Editor's Suggestion

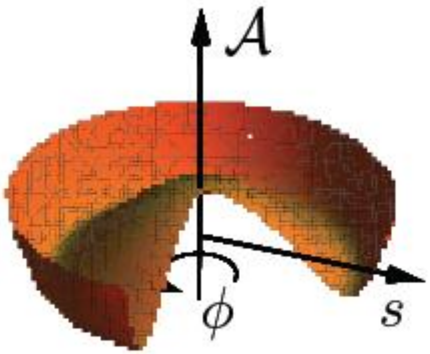
Quantum + Thermal? $T, \delta/\Delta_0 << 1$

Divergences at intermediate T

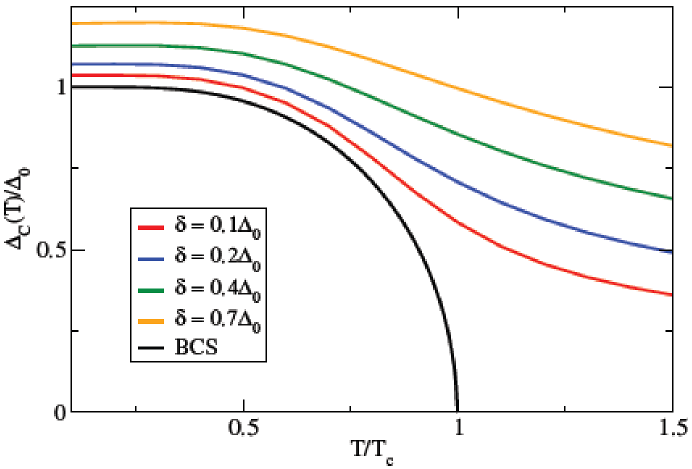
Rossignoli and Canosa
Ann. of Phys. 275, 1, (1999)

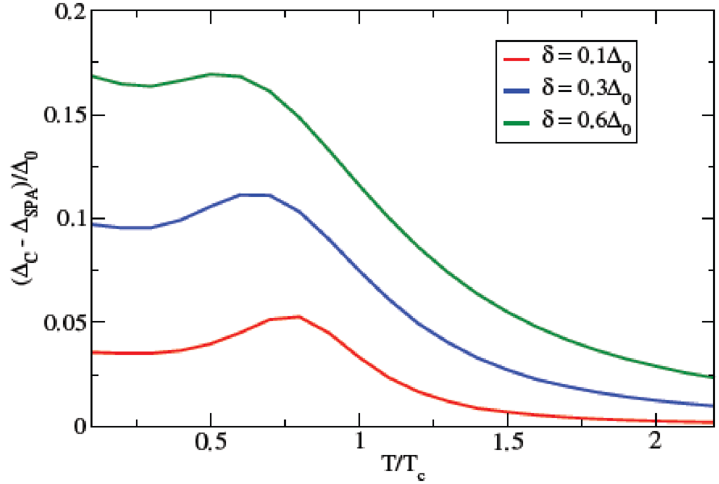
Harmful Zero Modes

Polar coordinates



$$\Delta(\tau) = s(\tau)e^{i\phi(\tau)}$$

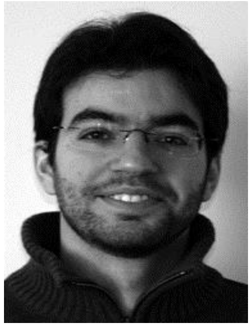




Ribeiro and AGG, **Phys. Rev. Lett. 108, 097004 (2012)**

Charging effects?

The same



Perturbative

$$\Xi_m^{\phi\phi} = \sum_k r_k \frac{2\beta s_0^2 \Omega_m^2}{\Omega_m^2 + (2\xi_{0k})^2} \sim \frac{\beta}{\delta}\Omega_m^2$$

Charging effects

$$\longrightarrow \quad \delta^{-1}\int_0^\beta d\tau\,(\partial_\tau \delta\phi)^2$$

Non perturbative

$$\phi(\tau) = \phi_0 + 2\pi M\tau/\beta + \delta\phi(\tau)$$

Odd-Even at T=0

Charging
=
fluctuations

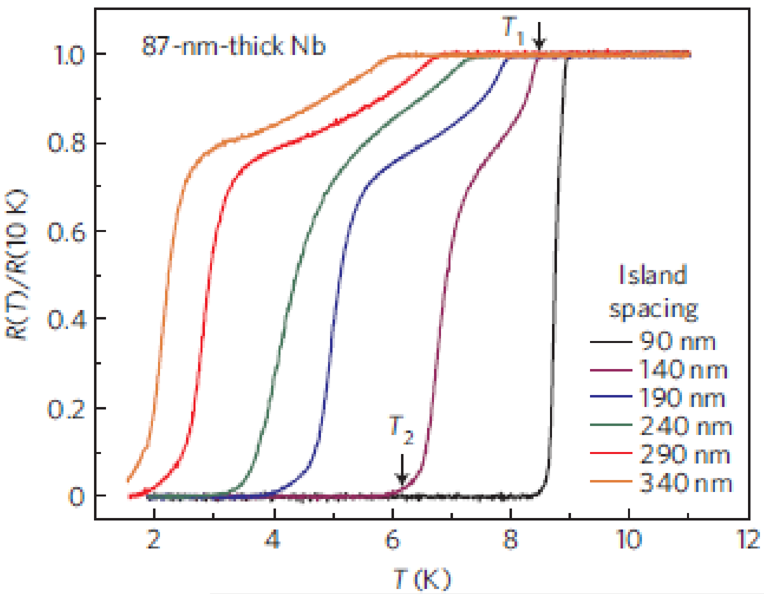
True phase coherence in single nanograins?

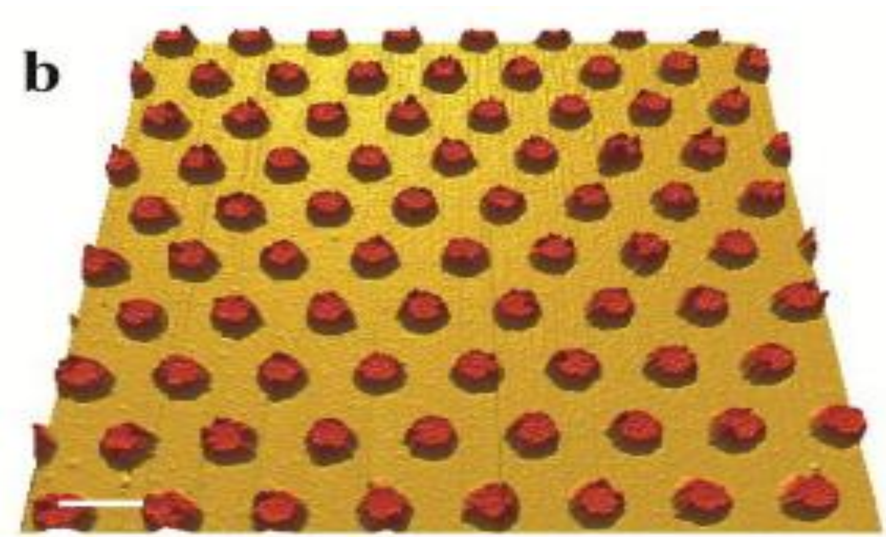
No

$\Delta N \Delta \phi \geq \hbar$

Josephson array?

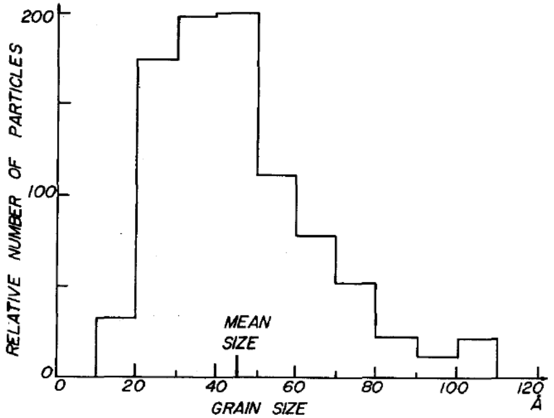
Maybe

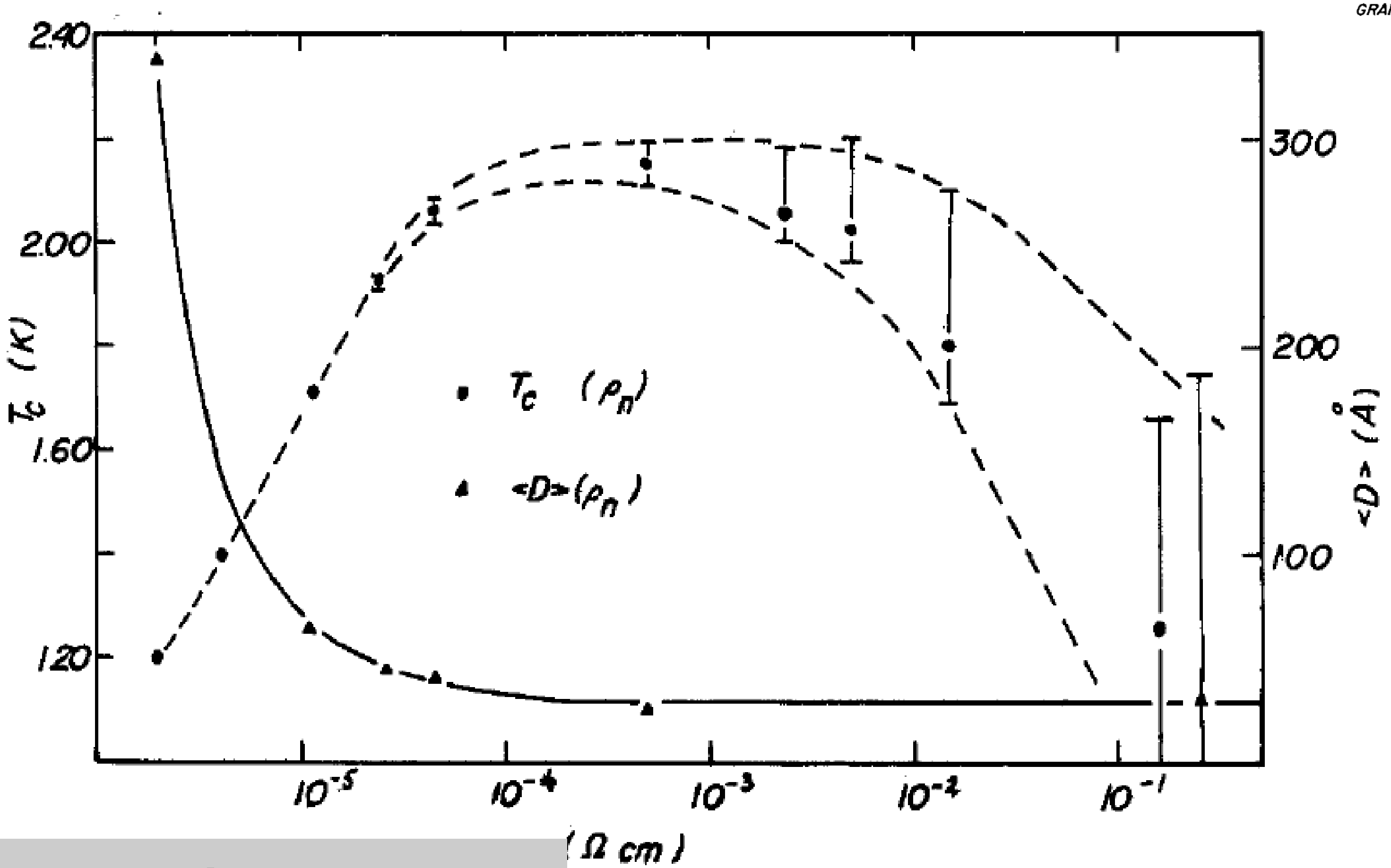




Mason, et al, Nature Physics 8 59 (2012)

Al evaporated on a glass substrate

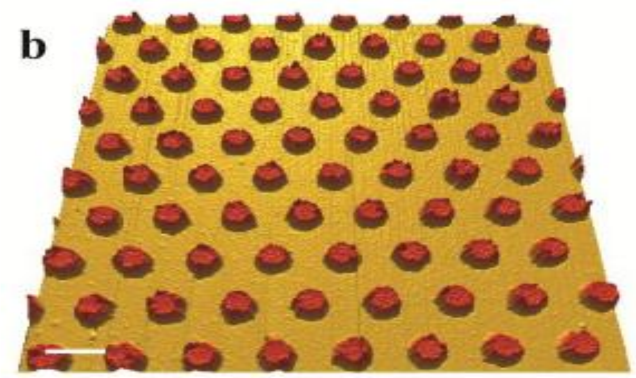




Deutscher 73’

Engineering granular materials

Optimal but realistic



Size

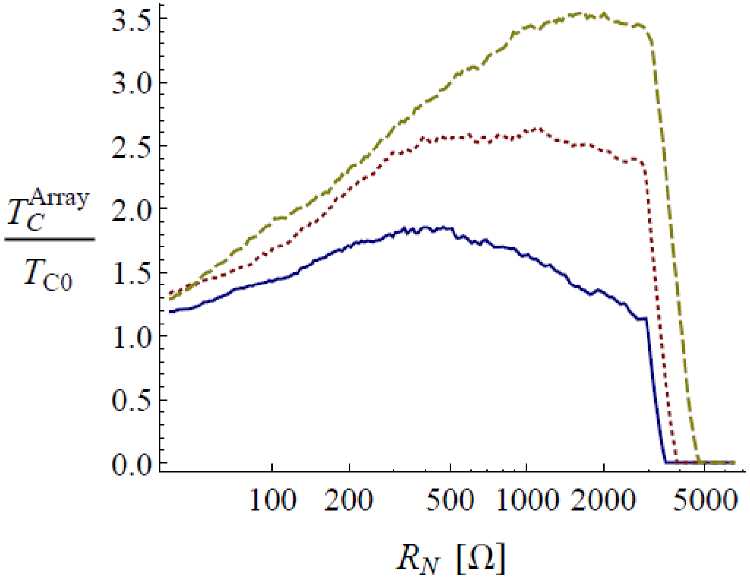
Variance

Packing

$Tc=1.3Tc^{bulk}$

$Tc=1.5Tc^{bulk}$

$Tc=3.0Tc^{bulk}$!!!



What?

Nano spheres

3D

Tight binding

R: σ~ $1nm$

$\bar{R} \geq 4nm$

Quasi particle tunnelling

Capacitance

$$P(R) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(R-\bar{R})^2}{2\sigma^2}}$$

Clean

How?

Open grain

JJ Array

BCS

Semiclassical

Mean field

Percolation

Single grain

Tunneling

Smooth DOS

$$\delta g(\epsilon) = \frac{3}{2}\sqrt{\frac{\pi}{kR}}\sum_{w=1}^{\infty}\sum_{v=2w}^{\infty}(-1)^w \sin(2\theta_{v,w})\sqrt{\frac{\sin\theta_{vw}}{v}}\sin\Theta_{vw}\omega(R_N, L_P^{v,w}) - \frac{3}{4}\frac{1}{kR}\sum_{w=1}^{\infty}\frac{1}{w}\sin(L_P^w k)\omega(R_N, L_P^w)$$

$$\omega(R_N, L_P) = e^{-\frac{4zL_P R_Q}{R_N \nu(0) v_F h}}$$

$$1 = \frac{\lambda}{2}\int_{-\epsilon_D}^{\epsilon_D}\frac{1}{\sqrt{\epsilon'^2+\Delta^2}}\frac{\nu(\epsilon')}{\nu_{TF}(0)}\tanh\left(\frac{\beta\sqrt{\epsilon'^2+\Delta^2}}{2}\right)d\epsilon'$$

Open grain

Weaker size effects

3D Array

INHOMOGENEOUS

$$S = \frac{1}{2}\int_0^\beta d\tau \sum_i \frac{\dot{\phi}_i^2}{E_Q} - \frac{1}{2}\sum_{\langle ij\rangle}\int_0^\beta d\tau J_{ij}\cos(2(\phi_i(\tau)-\phi_j(\tau))) +$$

$$2\sum_{\langle ij\rangle}\int_0^\beta d\tau \int_0^\beta d\tau' G_{ij}(\tau-\tau')\sin^2(\frac{1}{4}(\delta\phi_{ij}(\tau)-\delta\phi_{ij}(\tau')))$$

Schoen, Zaikin,Fazio..

$$J_{ij} = \frac{\Delta_i\Delta_j}{\beta}\frac{R_Q}{R_N}\sum_{l=-\infty}^{\infty}\frac{1}{\sqrt{((\frac{\pi(2l+1)}{\beta})^2+\Delta_i^2)((\frac{\pi(2l+1)}{\beta})^2+\Delta_j^2)}}$$

HOMOGENEOUS

$D_p \sim 2.55$

T

#SCG

$$\bar{z} = zp$$

$$1 = \frac{\tilde{E}_Q}{\bar{z}J} + e^{-\beta\tilde{E}_Q/2}$$

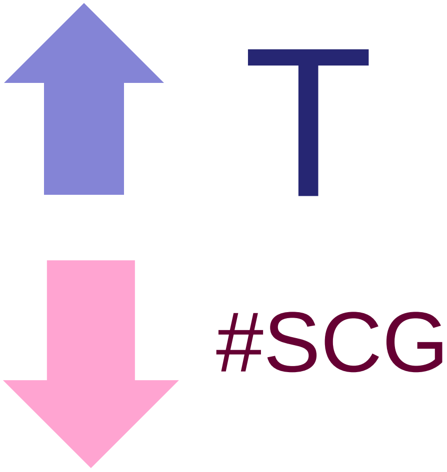
T_c ?

$$\tilde{E}_Q = (\frac{1}{E_Q} + \frac{\eta}{E_Q^*})^{-1} \quad J = \frac{\bar{\Delta}R_Q}{2R_N}\tanh(\frac{\beta\bar{\Delta}}{2}) \quad E_Q^* = \frac{124e^2\bar{\Delta}R_N}{3\pi\hbar}$$

Wait!

Percolation?

T_c

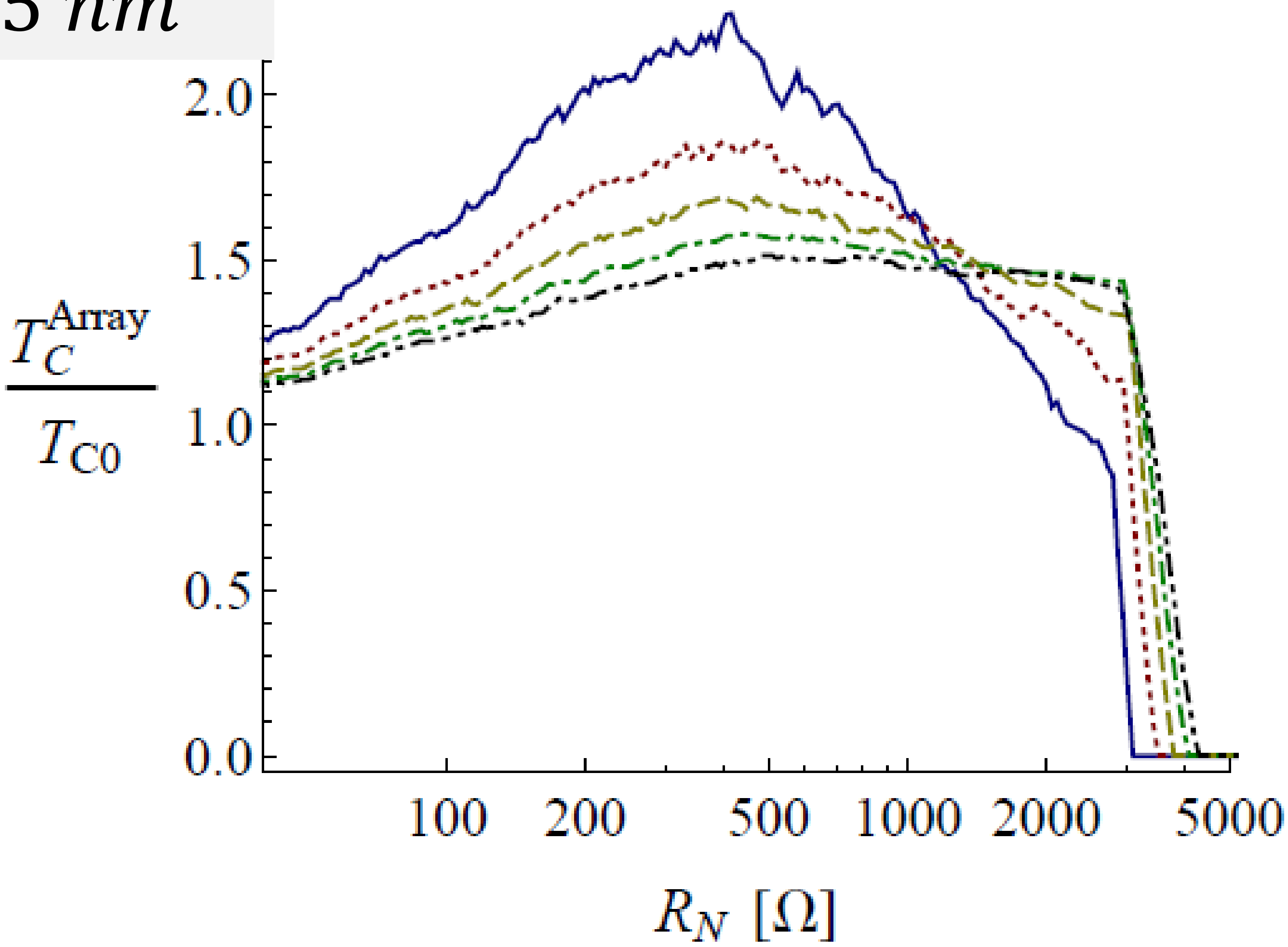


Mean field?

$\lambda = 0.2, 0.25, 0.3, 0.35\ nm$

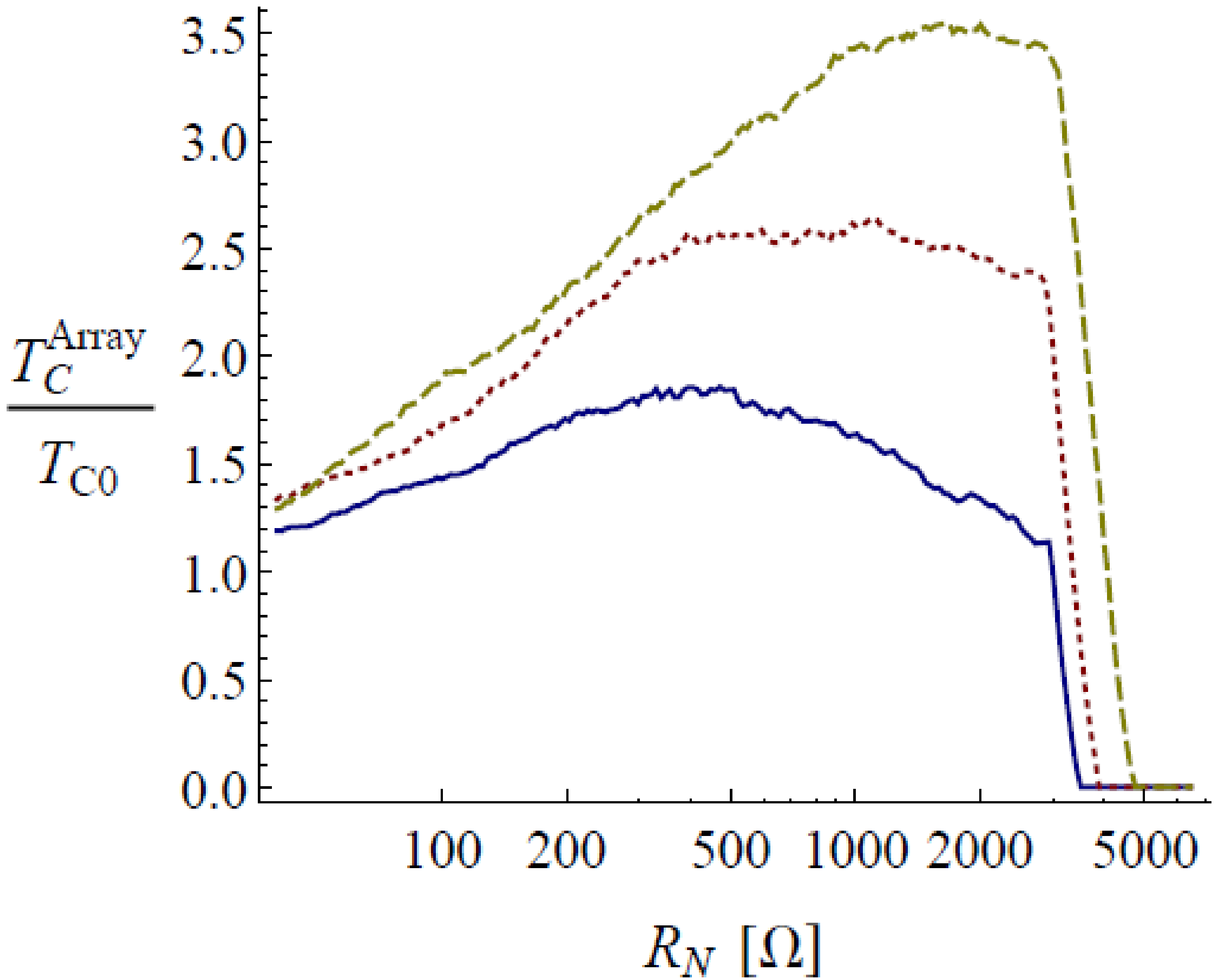
$\sigma = 1\ nm$

$\bar{R} = 5\ nm$



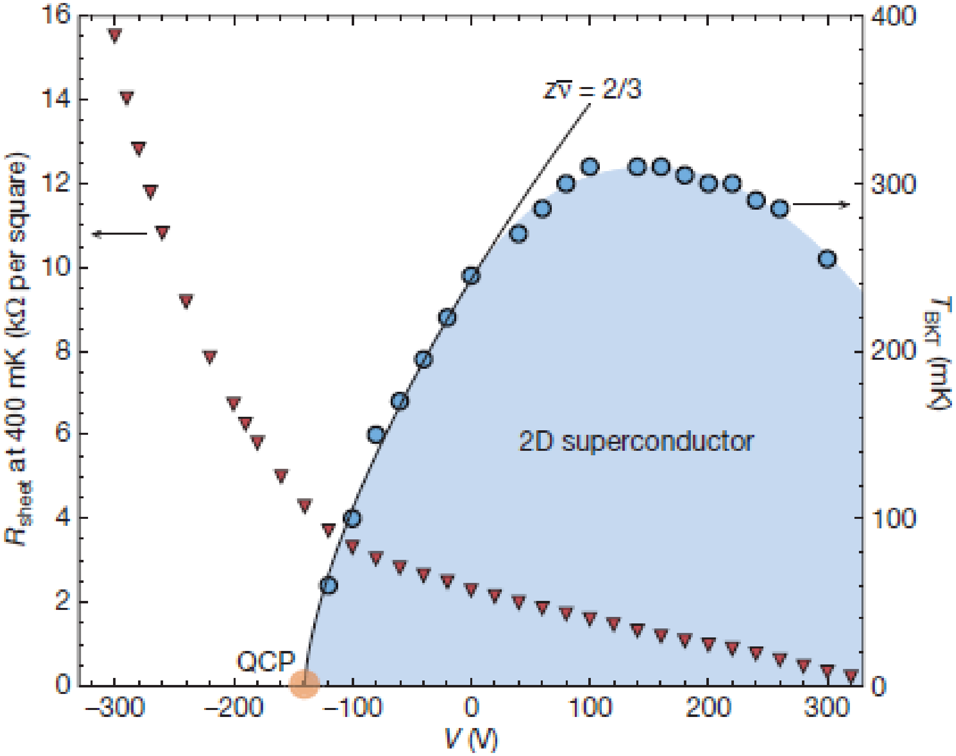
$Packing = Cubic, BCC, FCC$

$\sigma = 1\ nm$
$\bar{R} = 5\ nm$
$\lambda = 0.25$



Recent Developments

$LaAlO_3$ /$SrTiO_3$ Heterostructures



Triscone, Nature 456 624 (2008)

Lesueur, arXiv:1112.2633

PRL 104, 126803 (2010)
PRB 85, 020457 (2012)

Control &Tunability

Spin-Orbit

Disorder

Magnetism

E Field effect

Relevance

Localization

Exotic Quantum Matter

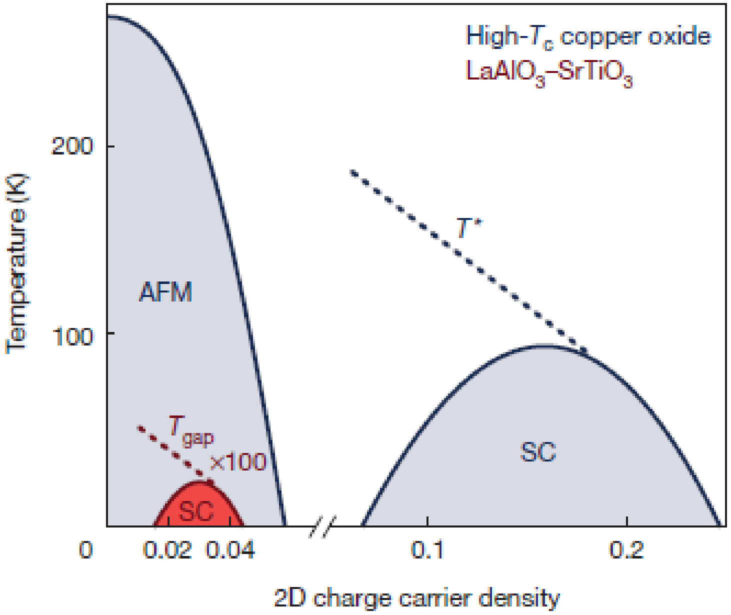
Topology

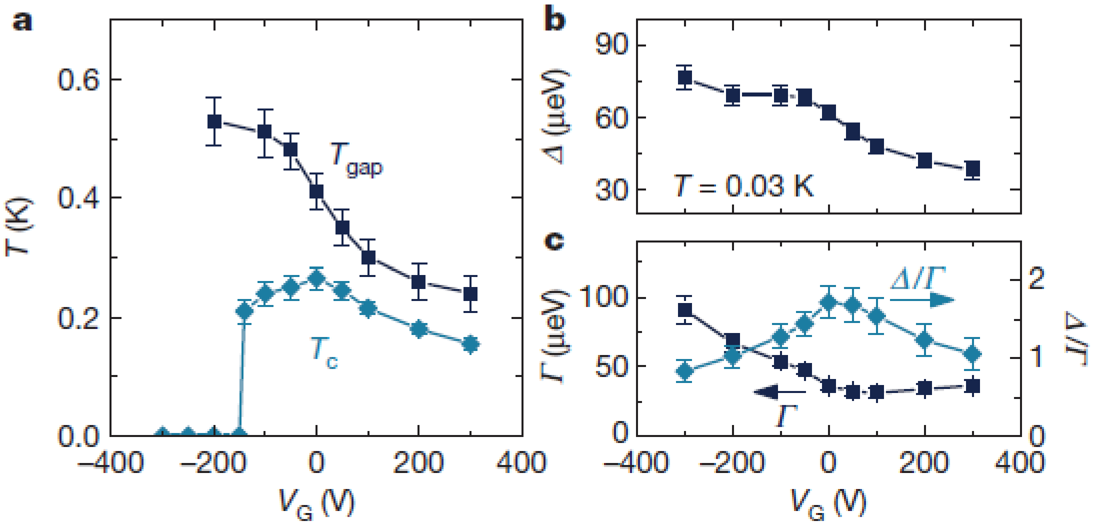
Mocking Cuprates

Electric Field Effect

+

2D LTO/STO





No chemical doping

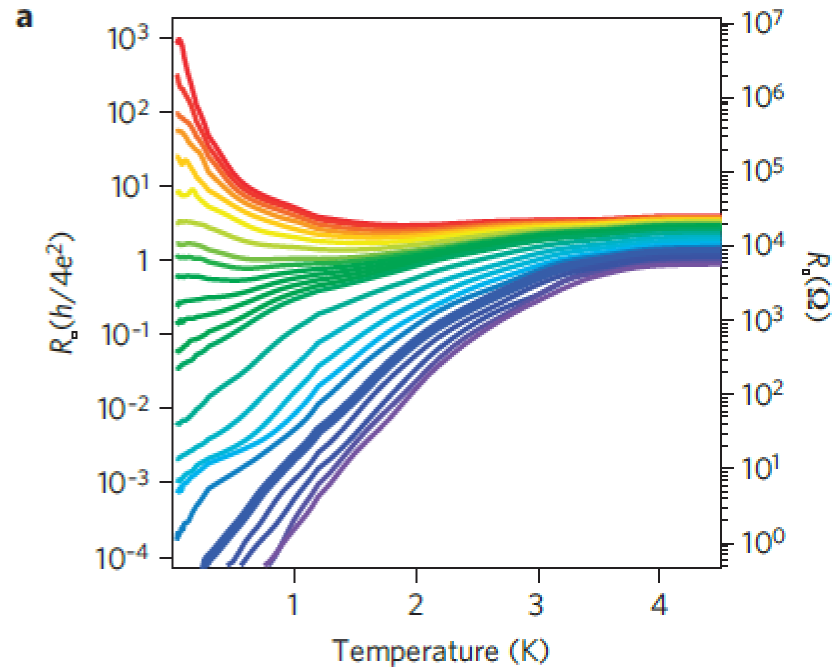
Pseudogap

Mannhart et al., Nature 502, 528 (2013)

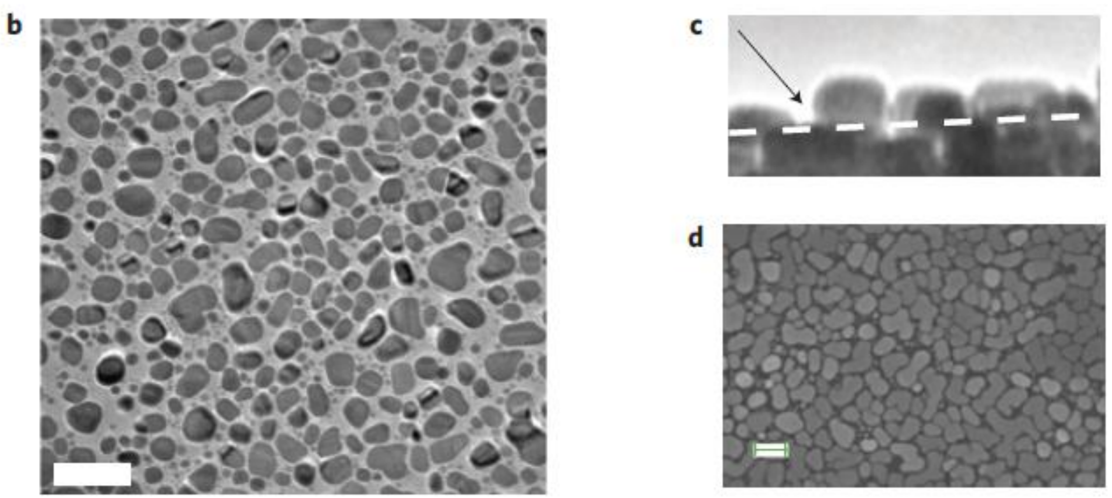
Graphene

+

Granular Sn



Sn



Stabilization of SC fluctuations?

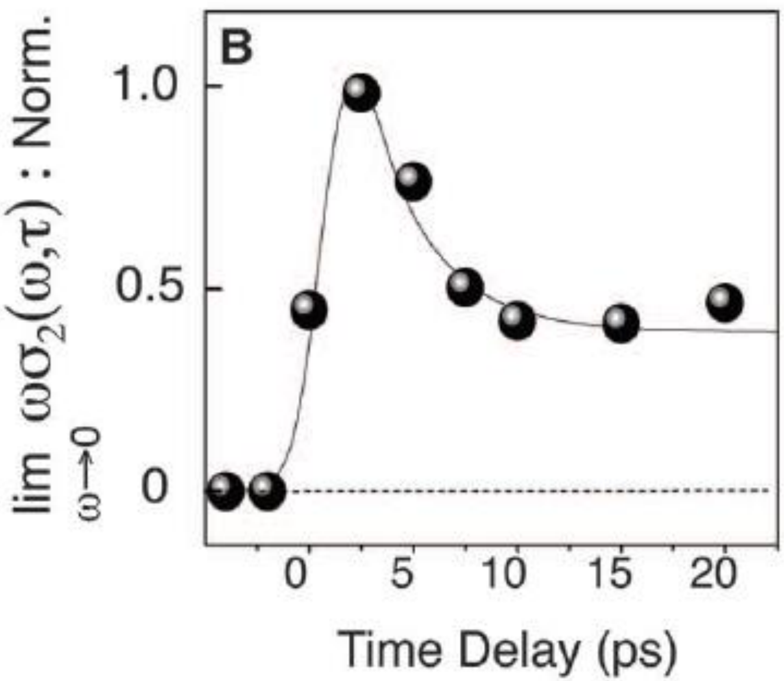
Allain, Bouchiat, et al., Nat. Mat. 11, 590 (2012)

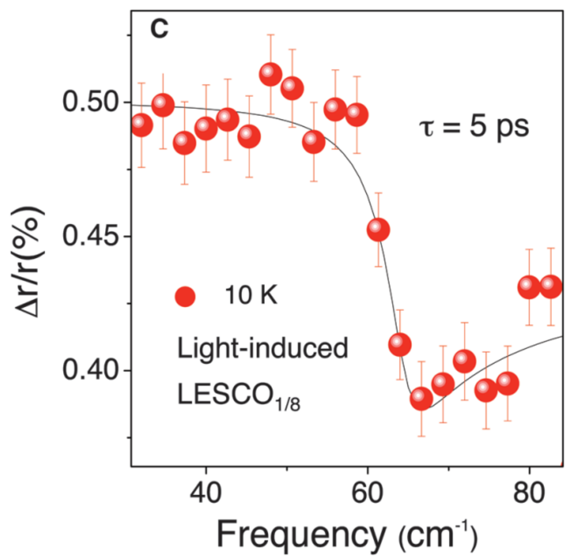
Transient Superconductivity

Pump & Probe

Femtosecond Pulses

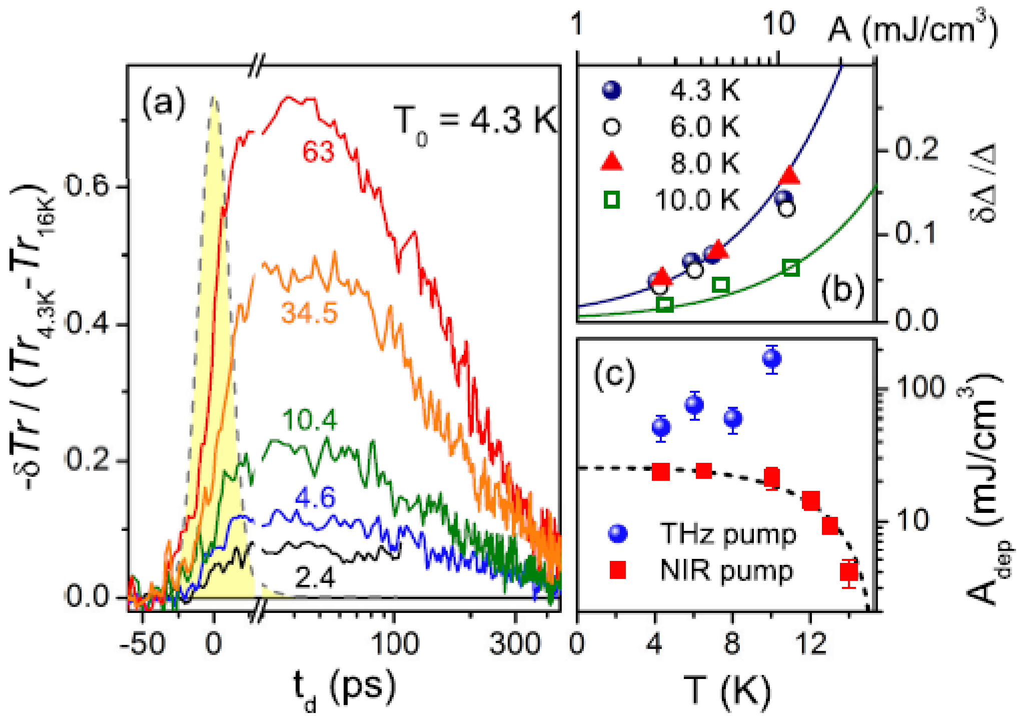
ARPES





Light-Induced Superconductivity in a Stripe-Ordered Cuprate
D. Fausti *et al.*
Science **331**, 189 (2011);
DOI: 10.1126/science.1197294

Transient Increase of the Energy Gap of Superconducting NbN Thin Films Excited by Resonant Narrow-Band Terahertz Pulses

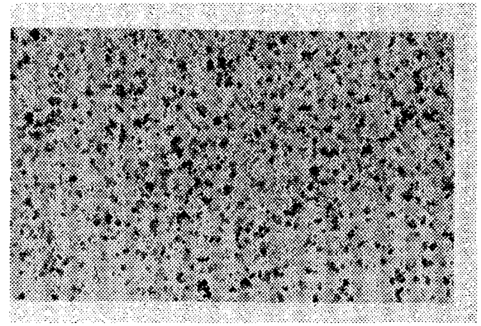


Nano-engineered material?

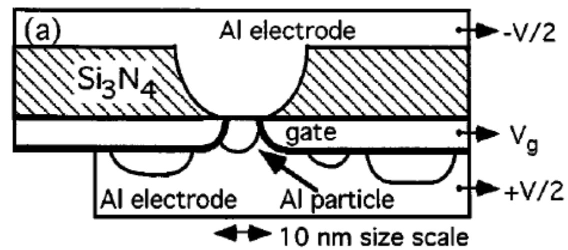
Permanent?

+Experimental control

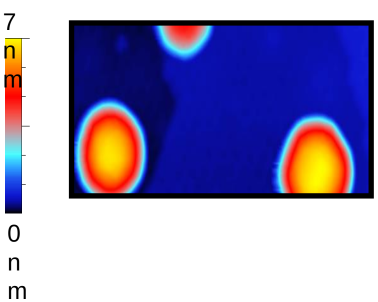
+Predictive power

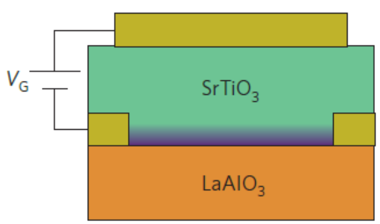


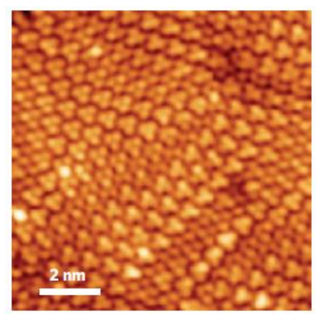
1966

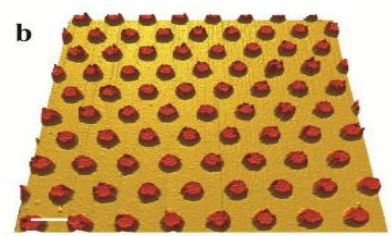


1995









Now

Engineering of ~~(very)~~ high T_c materials

?

ευχαριστίες