Control and enhancement of superconductivity by finite size effects

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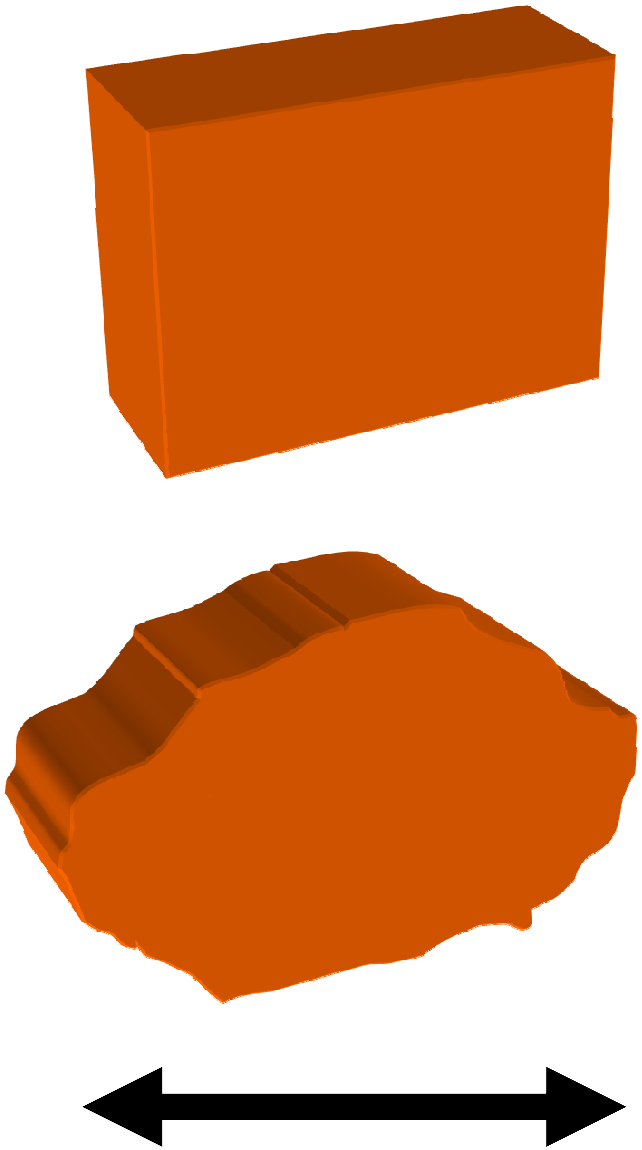
Phys. Rev. B 84,104525 (2011) Editor Suggestion

Phys. Rev. Lett. 108, 097004 (2012)

Nature Materials 9, 554, May 2010

Sangita Bose Bombay

Kern, Stuttgart Ugeda Brihuega,Michaelis



L ~ 10nm

1. Analytical description of a clean, finite-size superconductor?

2. Are these results applicable to realistic grains?

3. Is it possible to increase Tc?

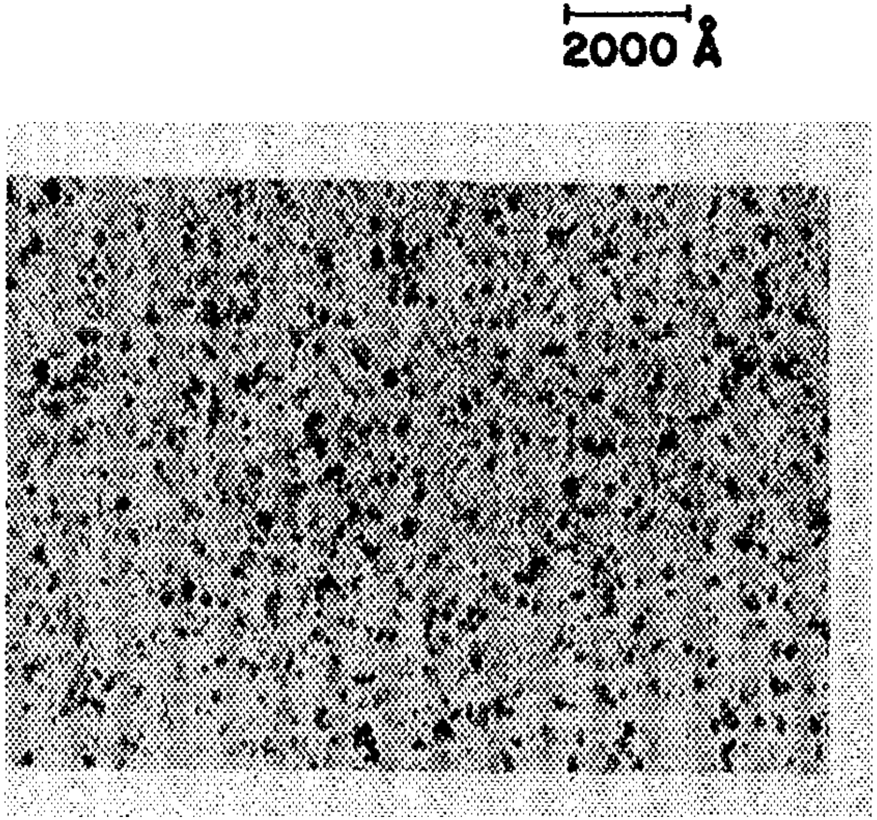
Experiments: A little history

Kammerer, Strongin, Phys. Lett. 17, 224 (1965)

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

Crow, Parks, Douglass, Jensen, Giaever, Zeller....

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

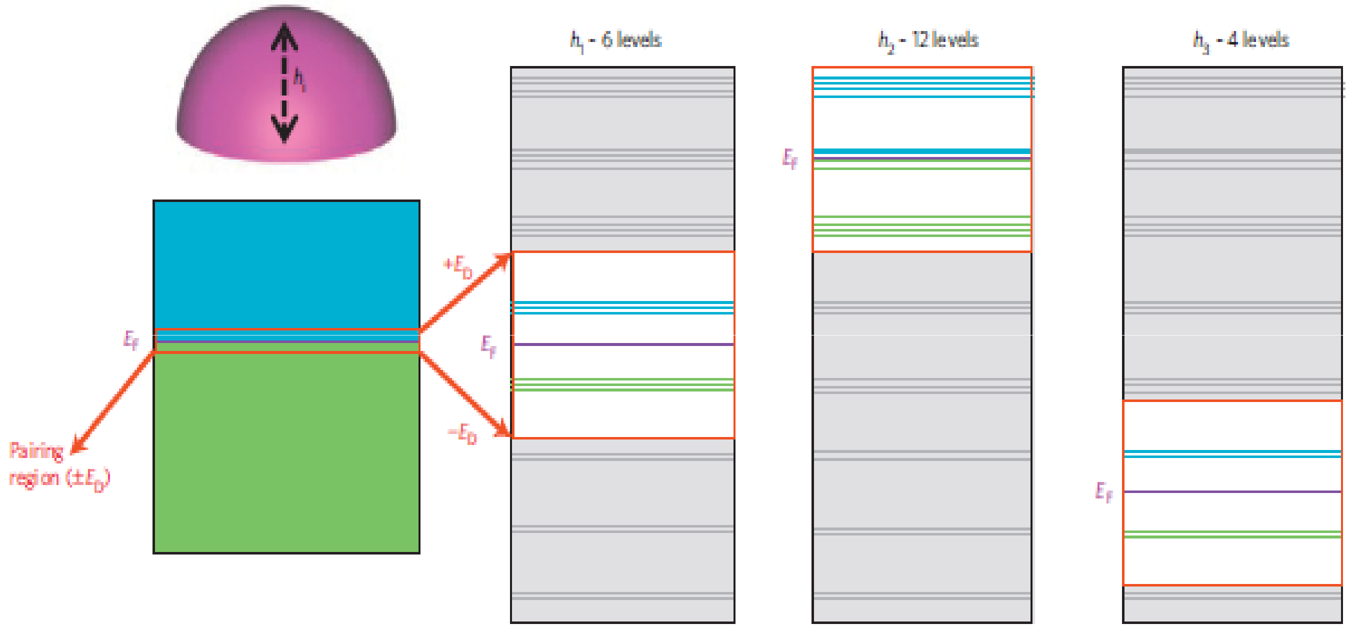


No exp control → **Theoretical drift**

Theory: A little history

Breaking of superconductivity for $\delta/\Delta_0 > 1$? Anderson (1959)

Parmenter, Blatt, Thompson (60's) : BCS in a rectangular grain



Heiselberg (2002): BCS in harmonic potentials, cold atom appl

Shanenko, Croitoru, Peeters (2005-): BCS in a wire, cylinder

Devreese (2006): Richardson equations in a box

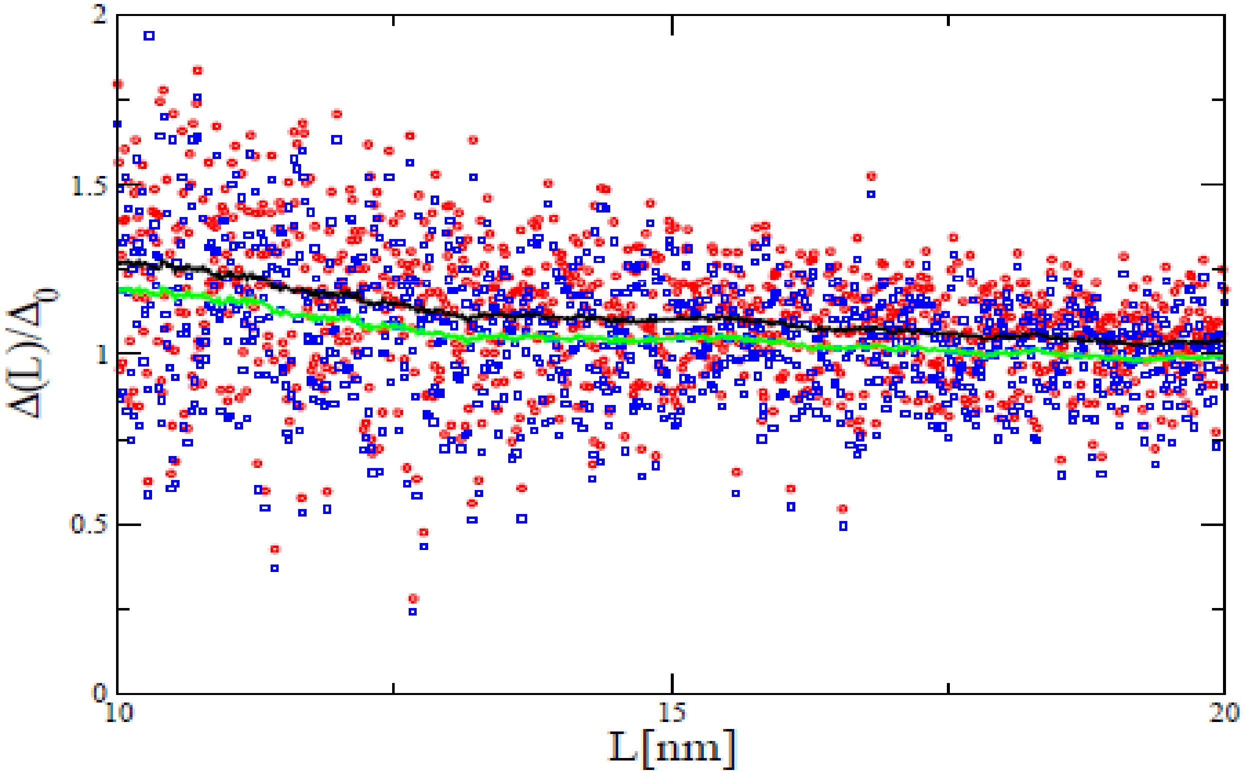
Kresin, Boyaci, Ovchinnikov (2007) : Spherical grain, high T_c

Olofsson (2008): Estimation of fluctuations within BCS

Fluctuations
ξ > L

Symmetries

No fluctuations
ξ < L



$\Delta_0 \sim \delta$

No long range order

2008

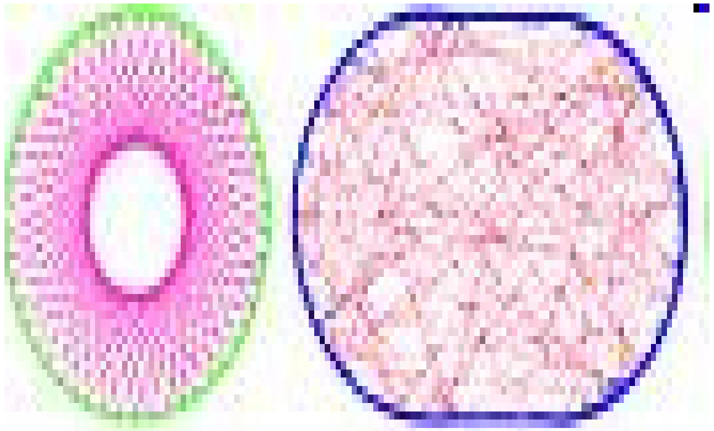
Chaotic grains?

$$\frac{2}{g} = \sum_{|\varepsilon_i|<E_D} \frac{c_i}{\sqrt{\Delta^2 + \varepsilon_i^2}}$$

ε_i = eigenvalues 1-body problem

Analytical? **$1/k_F L \ll 1$**

Semiclassical techniques



Quantum observables in terms of classical quantities
Berry, Gutzwiller, Balian, Bloch

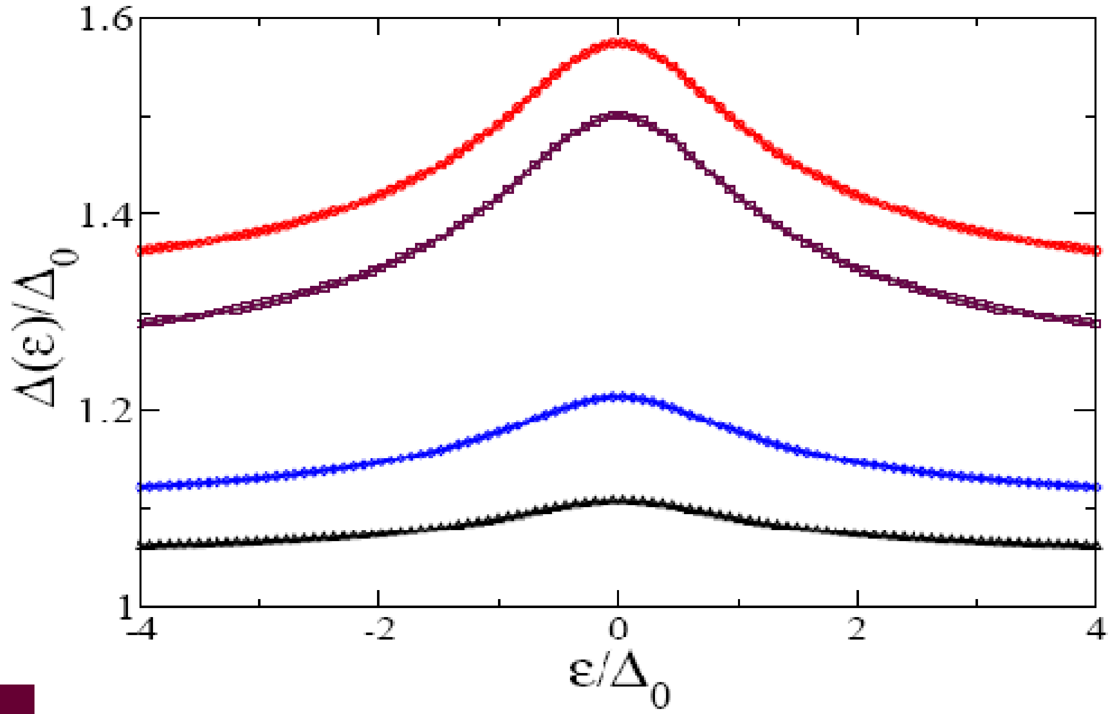
$$\nu(\varepsilon) \Leftrightarrow L_p$$

3d chaotic

Al grain

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

$\Delta_0 = 0.24mV$



For L< 9nm leading correction comes from matrix elements

Phys. Rev. Lett. 100, 187001 (2008)

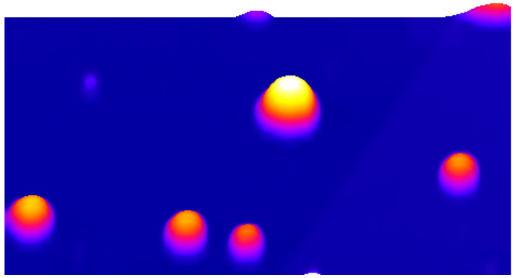
L = 6nm, Dirichlet, δ/Δ_0=0.67

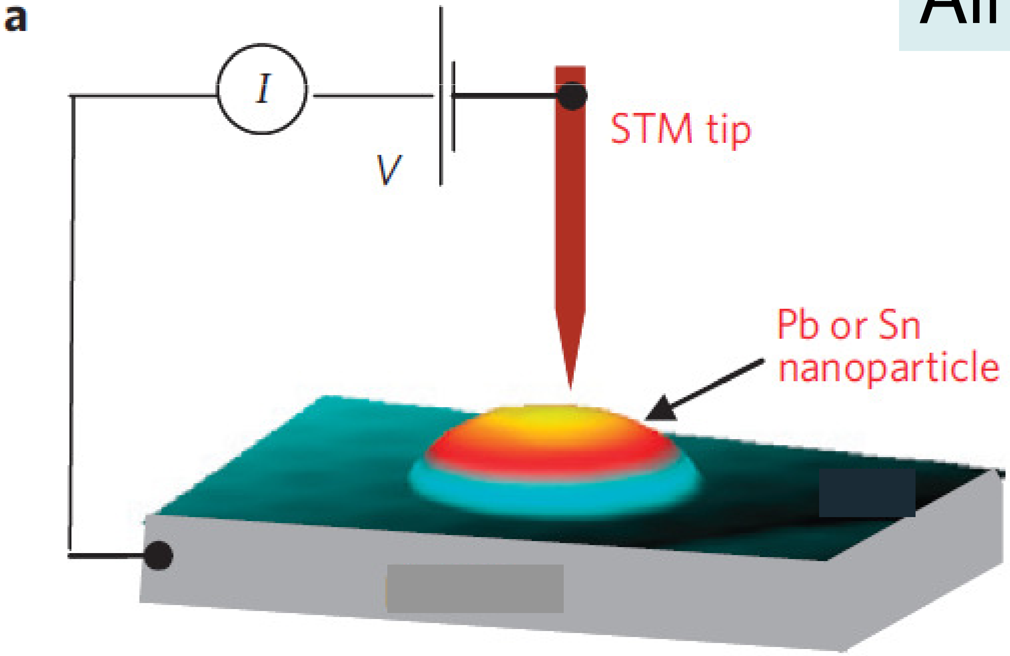
L= 6nm, Neumann, $\delta/\Delta_{0,}$=0.67

L = 8nm, Dirichlet, δ/Δ_0=0.32

L = 10nm, Dirichlet, $\delta/\Delta_{0,}$= 0.08

2010





Single, Isolated

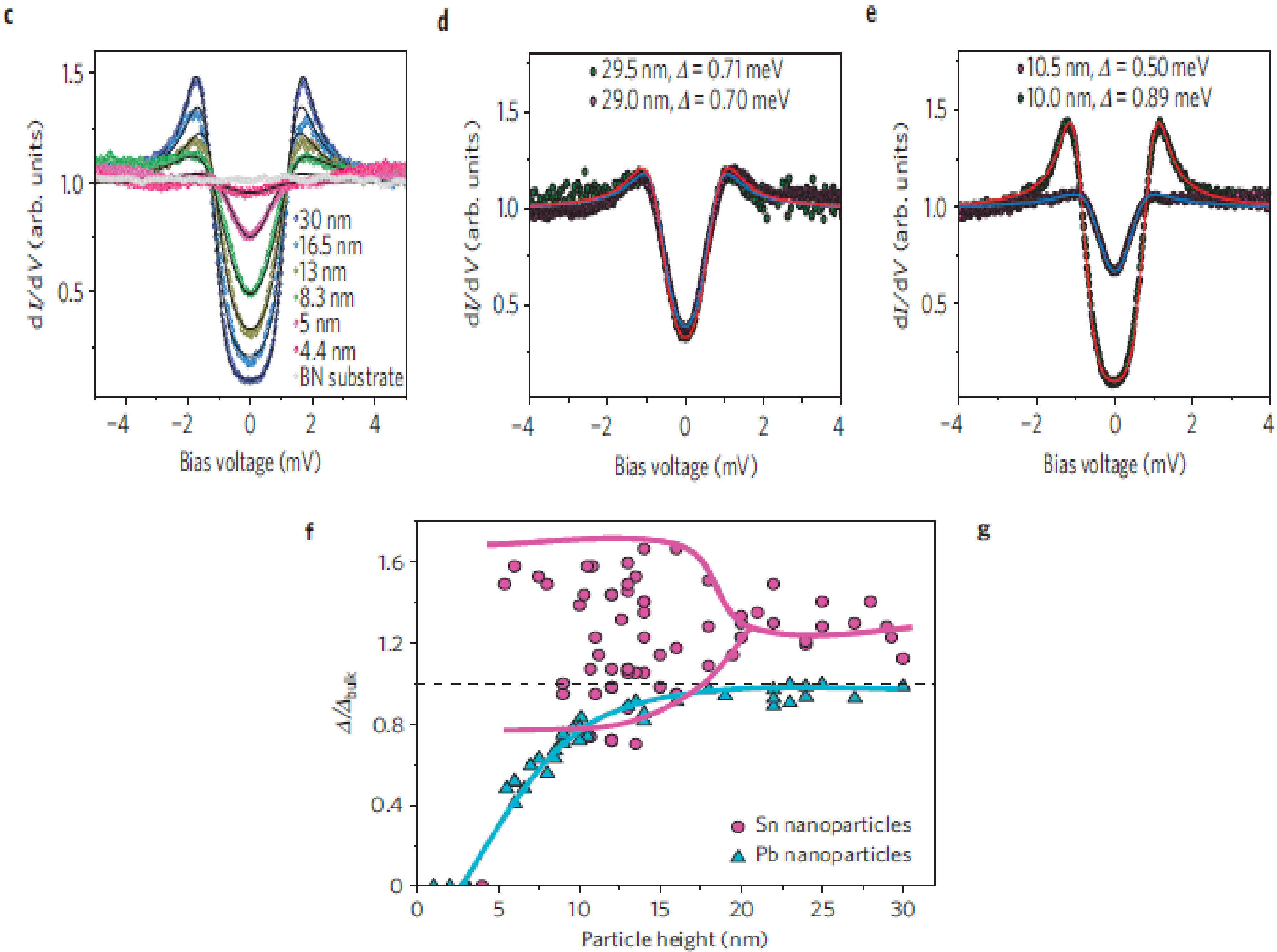
R ~ 4-30nm

B closes gap

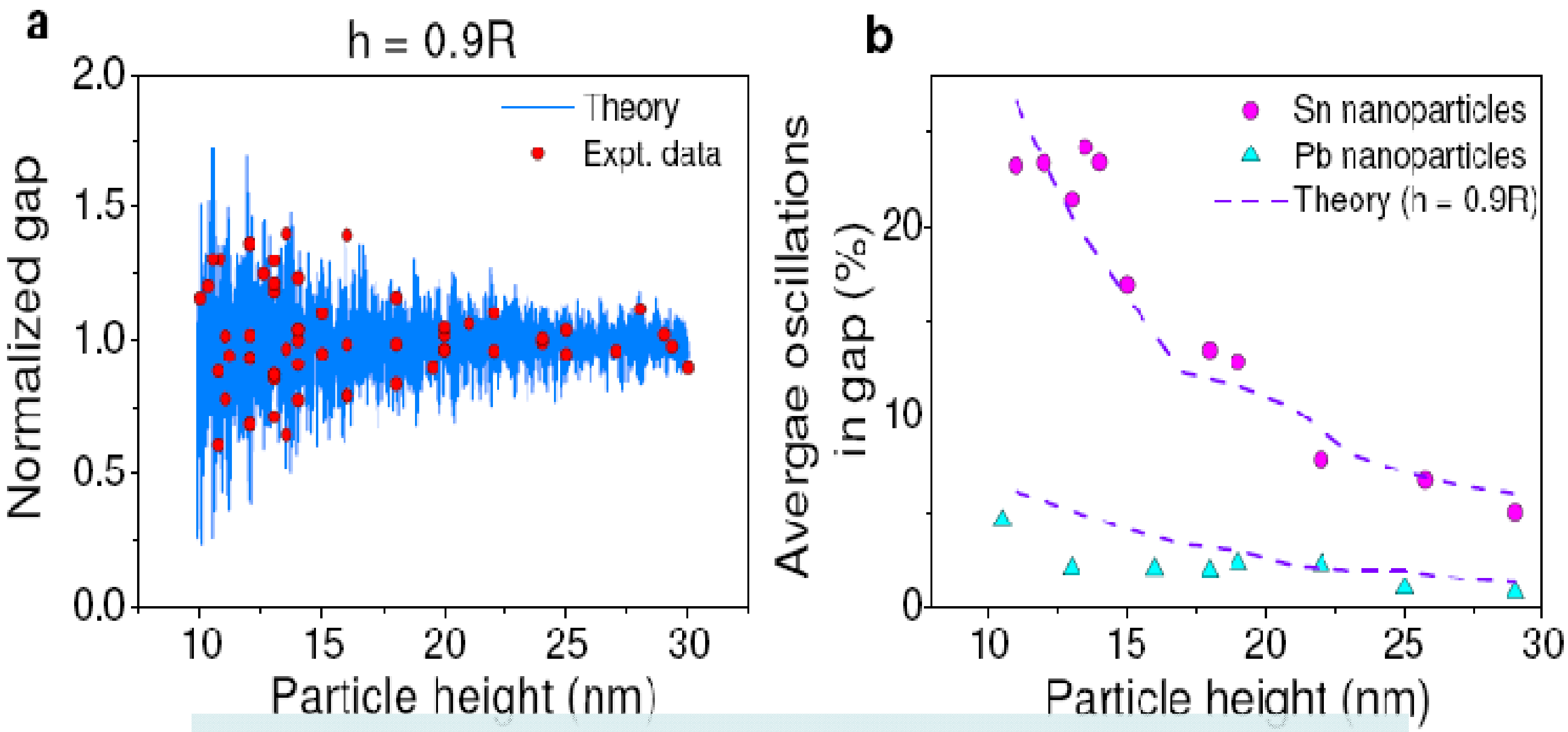
Almost hemispherical

Experimental output

Tunneling conductance

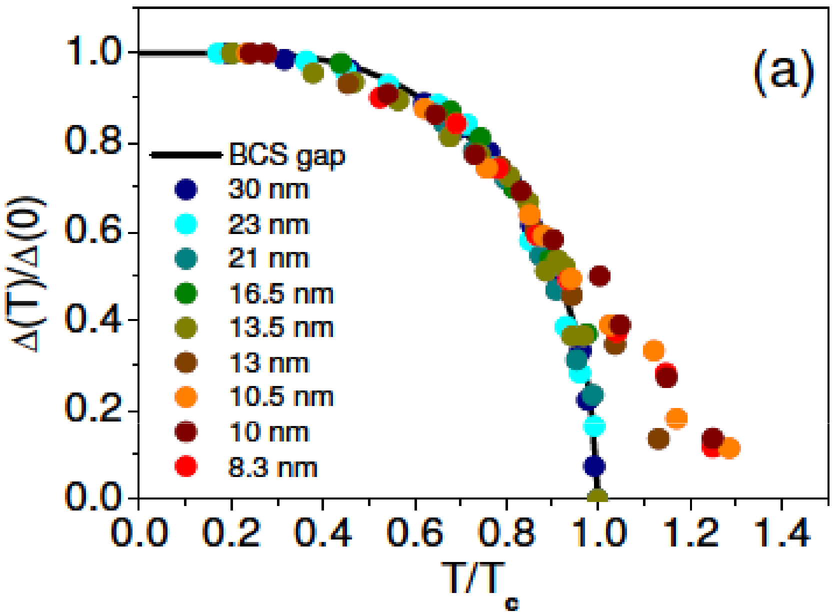


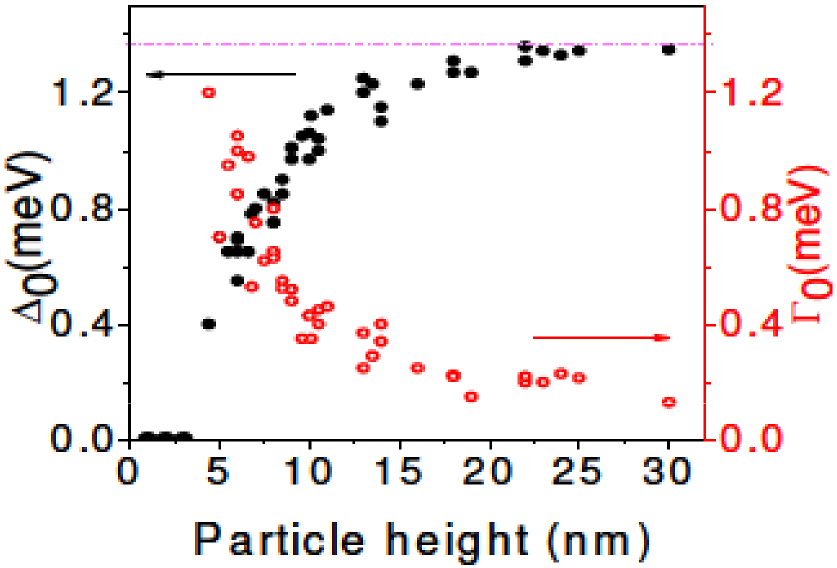
c
d
e
1.5
1.0
0.5
dI/dV (arb. units)
30 nm
16.5 nm
13 nm
8.3 nm
5 nm
4.4 nm
BN substrate
-4
-2
0
2
4
Bias voltage (mV)
29.5 nm, Δ = 0.71 meV
29.0 nm, Δ = 0.70 meV
10.5 nm, Δ = 0.50 meV
10.0 nm, Δ = 0.89 meV
f
g
1.6
1.2
0.8
0.4
0
Δ/Δbulk
Sn nanoparticles
Pb nanoparticles
0
5
10
15
20
25
30
Particle height (nm)



Nature Materials 9, 554, (2010)

Superconductivity **in single isolated** Pb nanograins





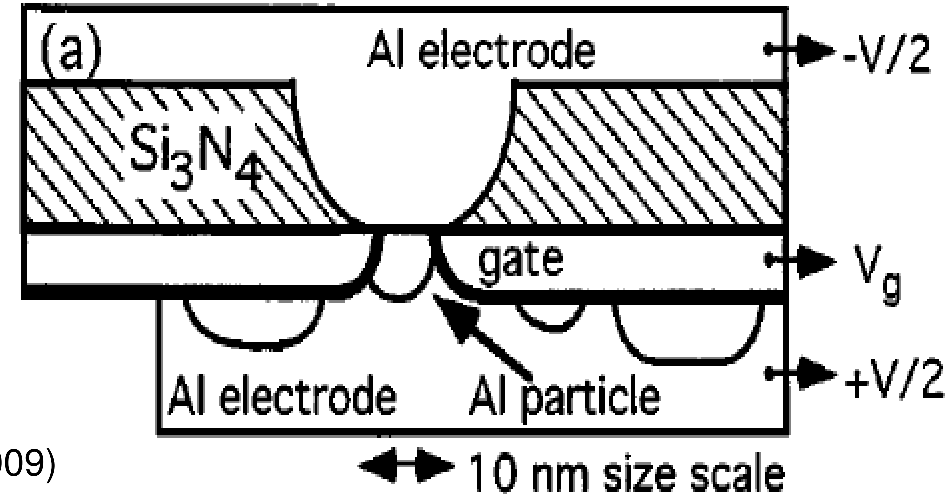
Phys. Rev. B 84,104525 (2011)
Editor Suggestion

$\Delta(T) > 0$ for $T > T_c$

$\Delta(0)$ ↓↓ for $L < 10$nm

Physics beyond mean-field

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



Nature 404, 971974 (2000), Science 324, 1314 (2009)

Even for $\delta/\Delta_0 \leq 1$ there is superconductivity

Odd-even effects

No isolated, size/shape unknown

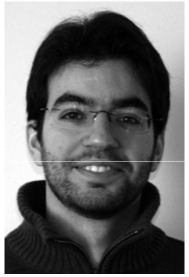
Theory beyond mean field

$\delta/\Delta_0 \ll 1$
Any T

T = 0
RPA

$T \sim T_c$
Static Path Approach

RPA+SPA
Ribeiro and AGG,
Phys. Rev. Lett. 108, 097004 (2012)



Any δ/Δ_0
T=0

Richardson
exact solution
Von Delft, Braun, Dukelsky, Sierra

Exact low energy excitations

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

Coulomb, phonons?

Any δ/Δ_0
Any T

Not Yet

Pb
$L < 10\text{-}15$nm

Physical effect	Theory
Strong coupling	Eliashberg theory Scattering, recombination, phonon spec.,Coulomb
Thermal fluctuations δ/T_c	Path integral SPA, Scalapino
Quantum fluctuations δ/Δ, E_D	Richardson equations, RPA Von Delft, Sierra, Braun,Dukelsky
BCS Finite-size corrections	Semiclassical AGG, et al., Phys. Rev. Lett. 100, 187001 (2008)

Finite T ~ T_c

Thermal fluctuations

Static Path Approach

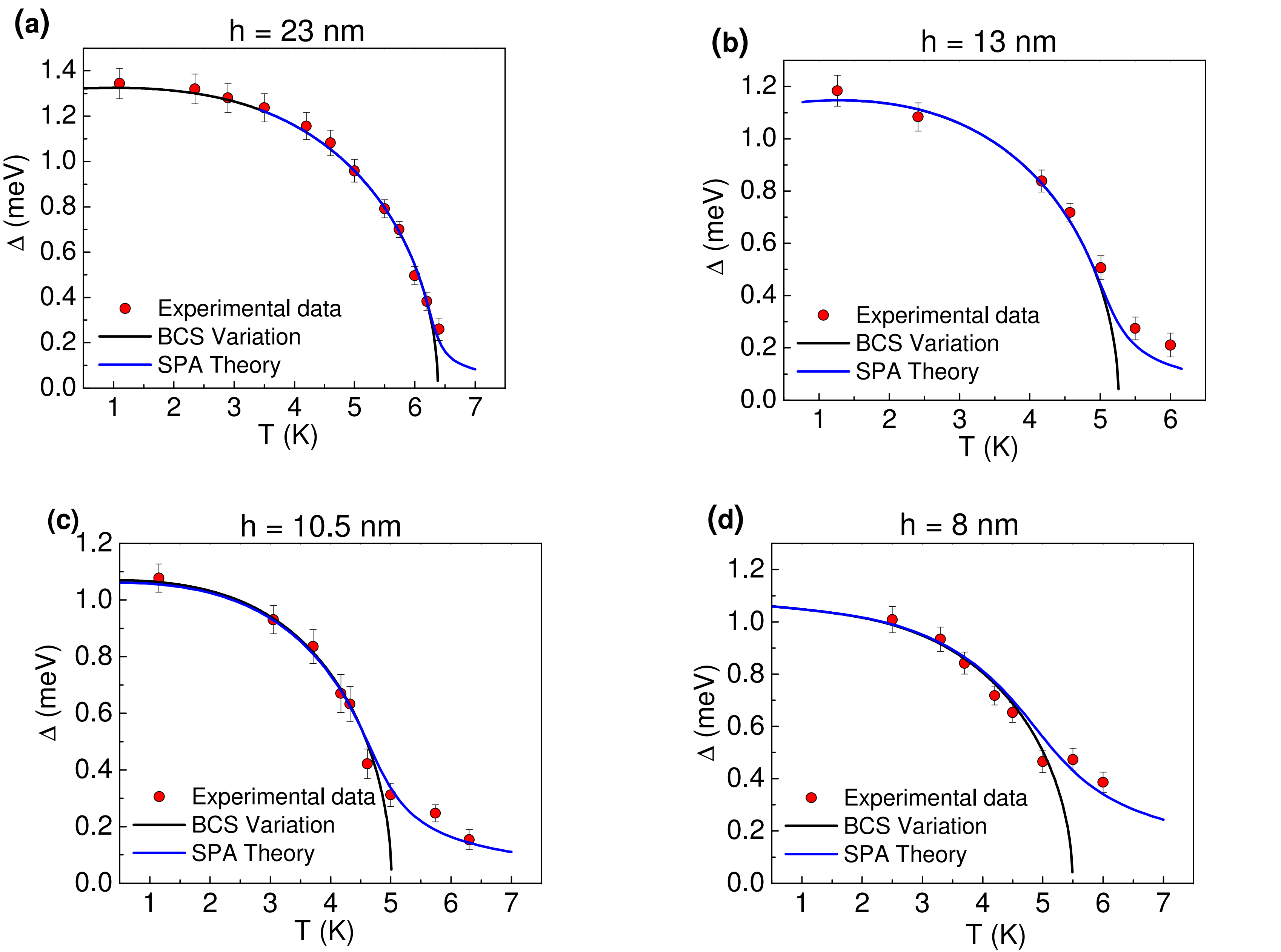
BCS finite size effects

Parmentier, Blatt, 60's
Leboeuf, Peeters, Shanenko, 00's
AGG, et al., PRL 100, 187001 (2008)

Blocking

Richardson formalism

$\lambda(T)$ simple
interpolation



(a)
h = 23 nm
Δ (meV)
T (K)
Experimental data
BCS Variation
SPA Theory
(b)
h = 13 nm
Δ (meV)
T (K)
Experimental data
BCS Variation
SPA Theory
(c)
h = 10.5 nm
Δ (meV)
T (K)
Experimental data
BCS Variation
SPA Theory
(d)
h = 8 nm
Δ (meV)
T (K)
Experimental data
BCS Variation
SPA Theory

T=0

BCS finite size effects

Shell effects are suppressed

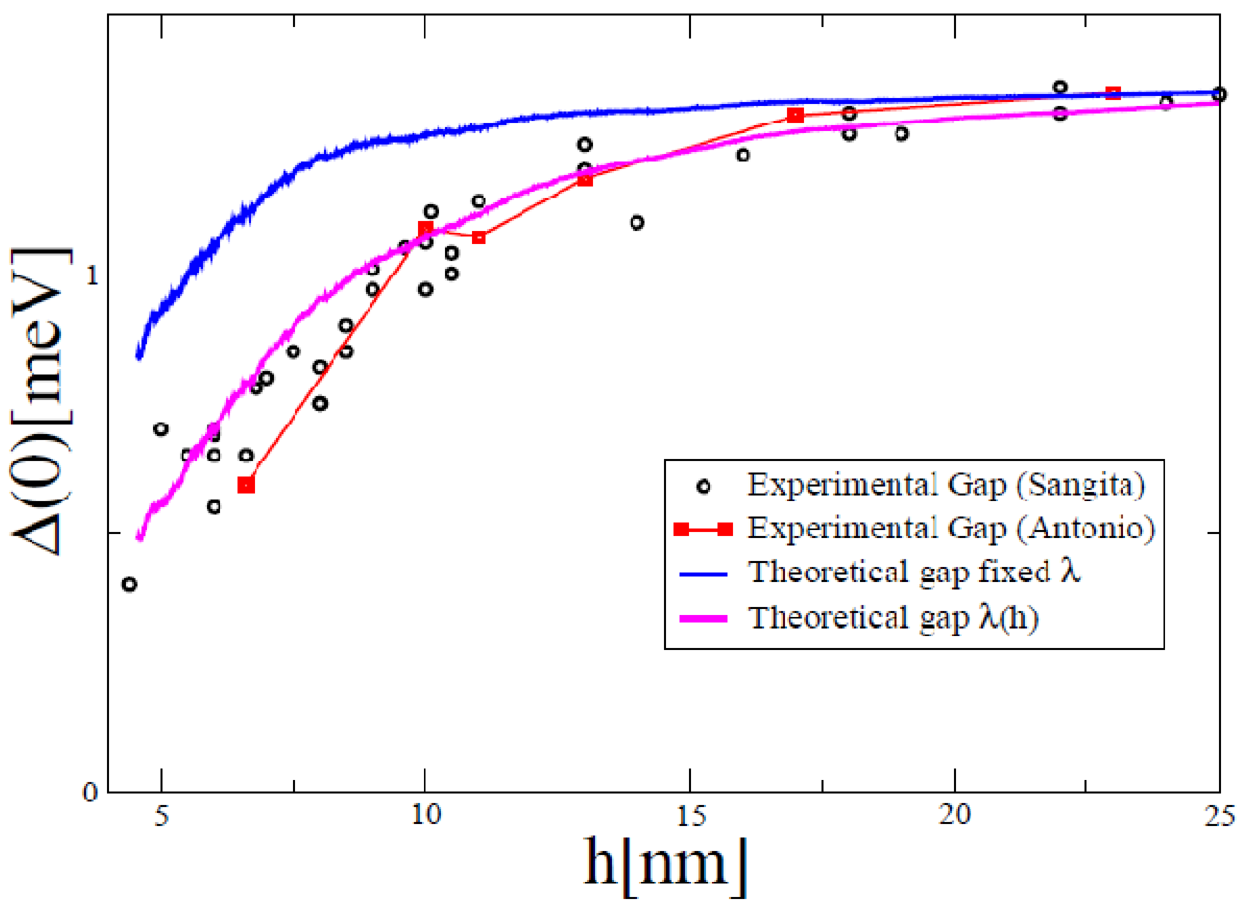
Deviations from BCS

Blocking effect only

No fluctuations!

Not important R > 5nm

$\lambda = \lambda(h)$



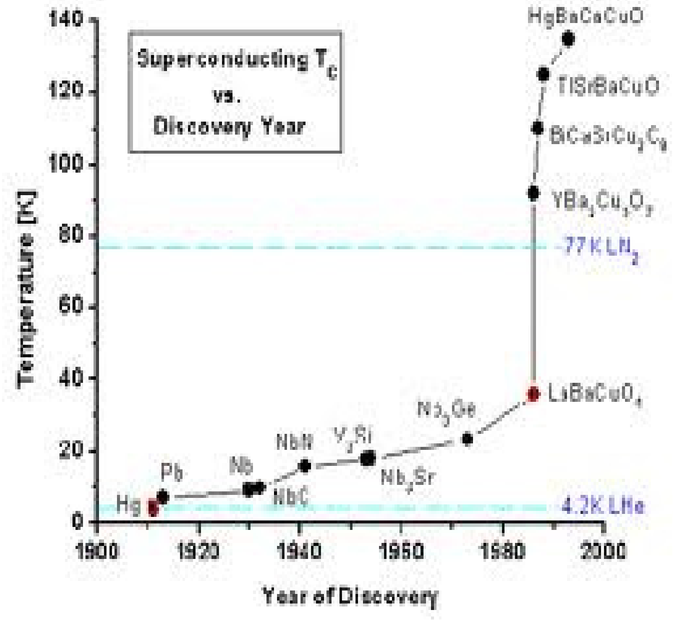
Phys. Rev. B **84**, 104525 (2011)
Editor Suggestions

Enhancement of superconductivity in iron pnictides by finite size effects

Phys. Rev. B 84, 172502 (2011)

Pedro Sacramento, Lisbon
Miguel Araujo, Lisbon

Iron Pnictides ?



Phys. Rev. B 84, 172502 (2011)

Wishes	Fears
Robustness	No Fermi liquid
Experiments	No decent model
	$\xi \sim 2$ nm

Mean field is OK in iron pnictides

We have got the code

Is technically feasible?

Any reasonable model?

2 band model

Bang, Choi, Raghu, Scalapino

$$\epsilon_h(k) = t_1^h(\cos k_x + \cos k_y) + t_2^h \cos k_x \cos k_y + \epsilon^h$$

$$\epsilon_e(k) = t_1^e(\cos k_x + \cos k_y) + t_2^e \cos \frac{k_x}{2} \cos \frac{k_y}{2} + \epsilon^e$$

Gap equation

$$\Delta_h = -\sum_{k'} V_{hh}\Delta_h \frac{\tanh(\frac{E_h(k')}{2T})}{2E_h(k')} + V_{he}\Delta_e \frac{\tanh(\frac{E_e(k')}{2T})}{2E_e(k')}$$

$$\Delta_e = -\sum_{k'} V_{eh}\Delta_h \frac{\tanh(\frac{E_h(k')}{2T})}{2E_h(k')} + V_{ee}\Delta_e \frac{\tanh(\frac{E_e(k')}{2T})}{2E_e(k')}$$

Critical Temp

$$T_c(L) \approx 1.136\omega_{\mathrm{AFM}} \exp(-1/\lambda_{\mathrm{eff}})$$

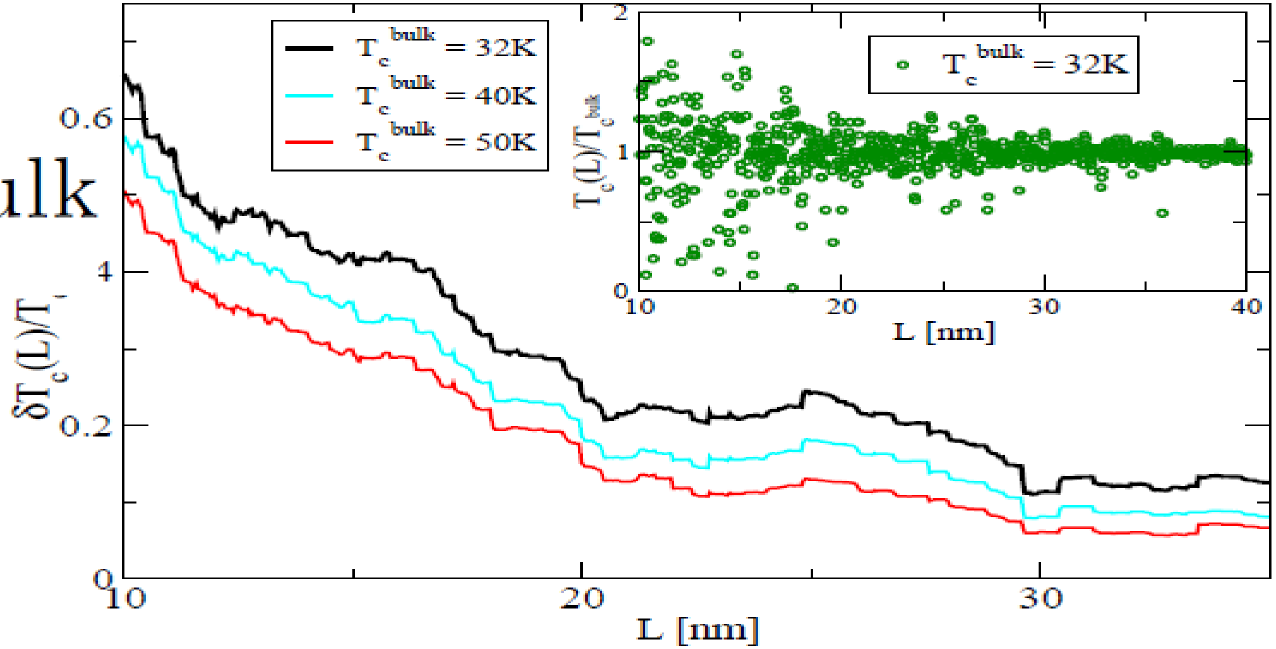
$$\lambda_{\mathrm{eff}} = \lambda_{\mathrm{bulk}} \sqrt{\frac{N^e_{\xi_e}(0) N^h_{\xi_h}(0)}{N^e(0) N^h(0)}}$$

Rectangle

$$\delta T_c(L)/T_c^{\rm bulk}$$

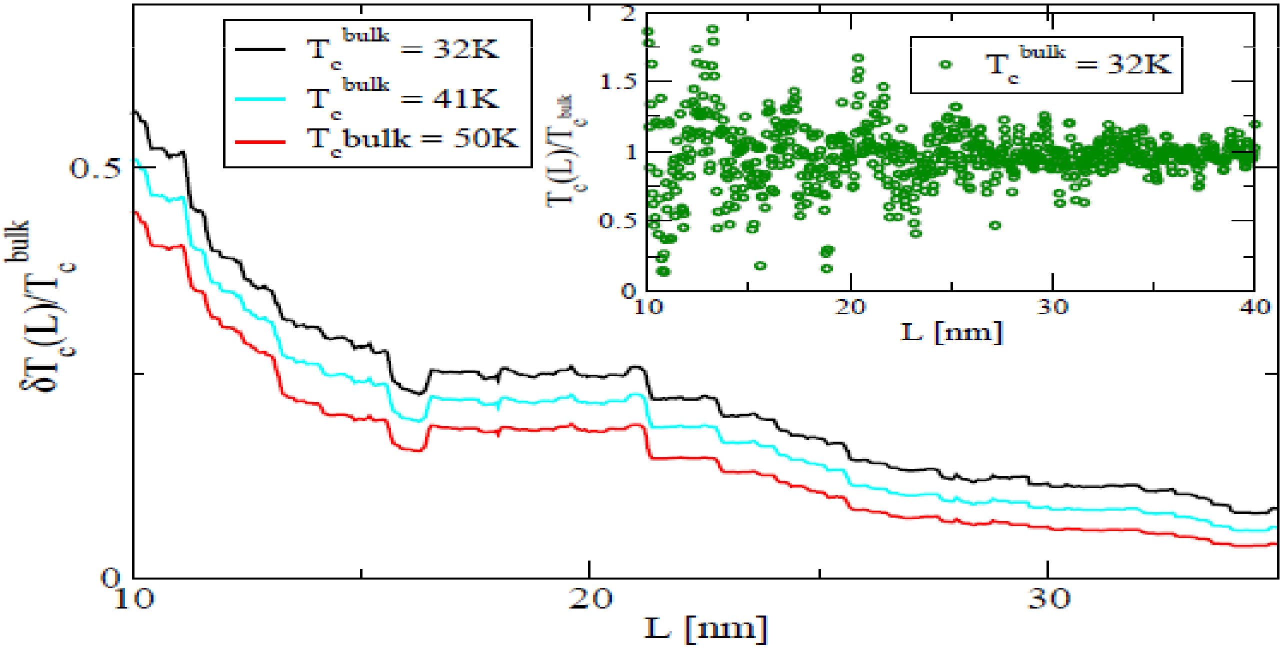
2 Band

Raghu, et al.



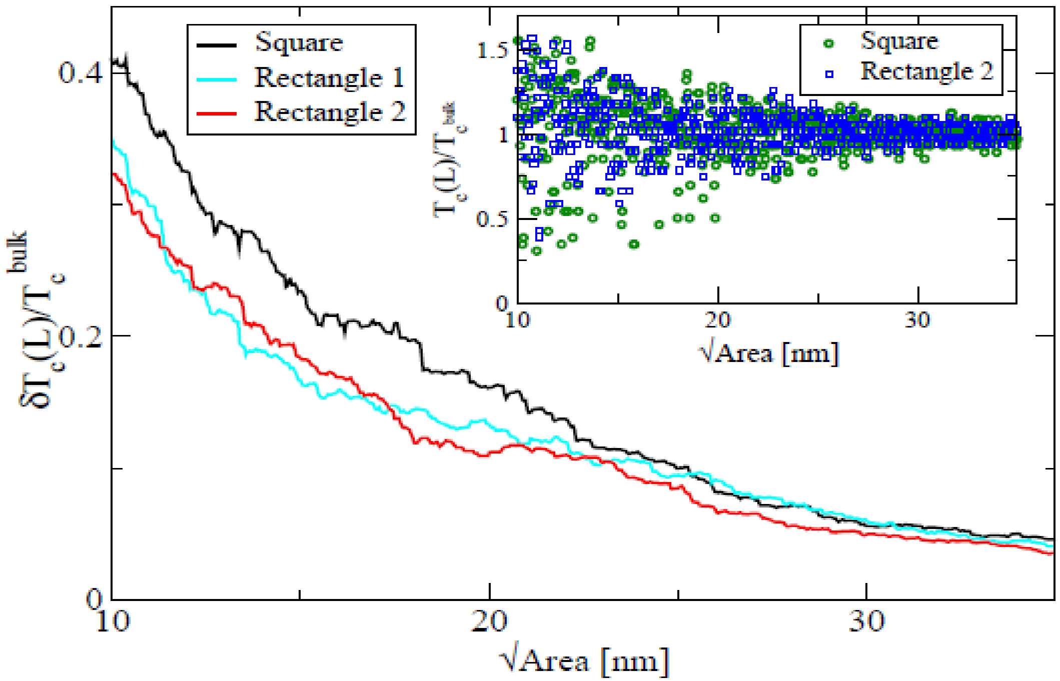
5 Band

Graser,
Scalapino

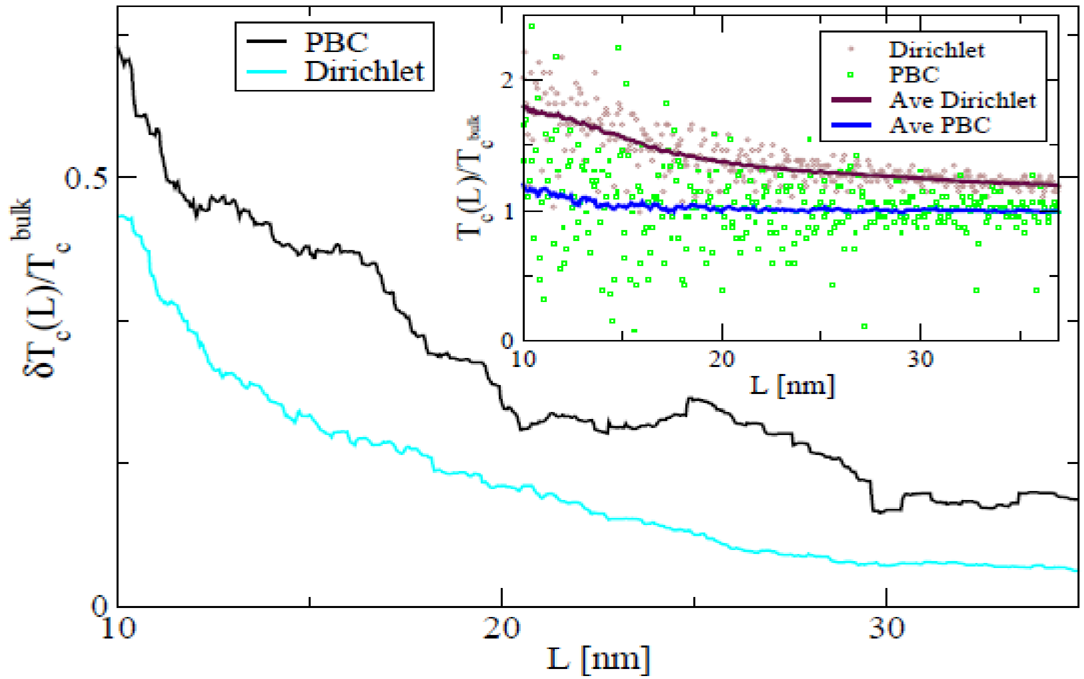


Robustness

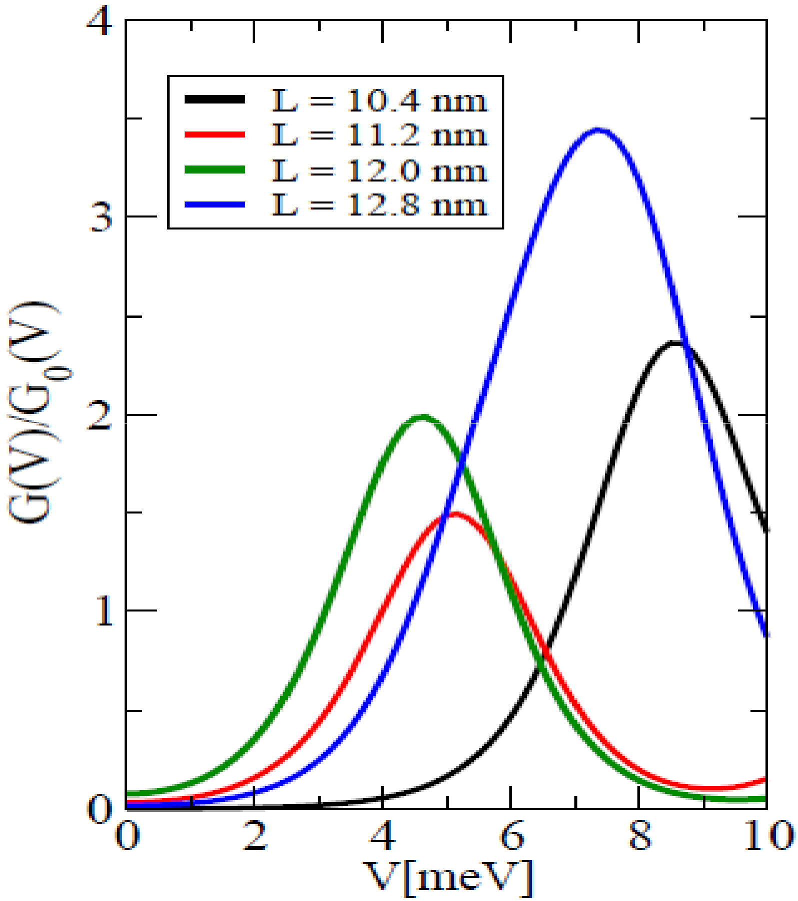
Geometry

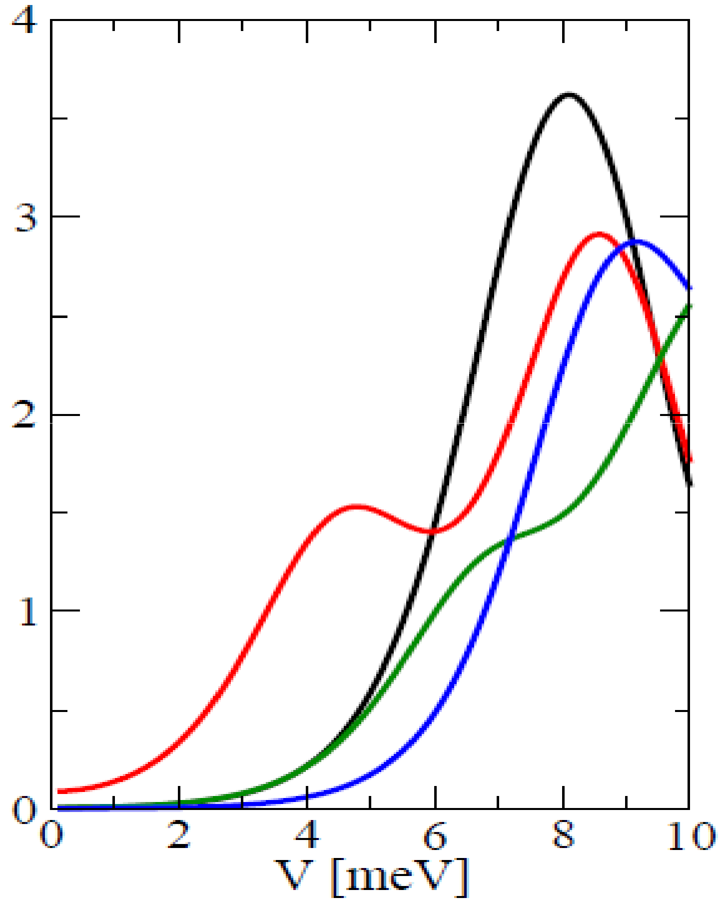


Boundary conditions



Experiments → **STM**



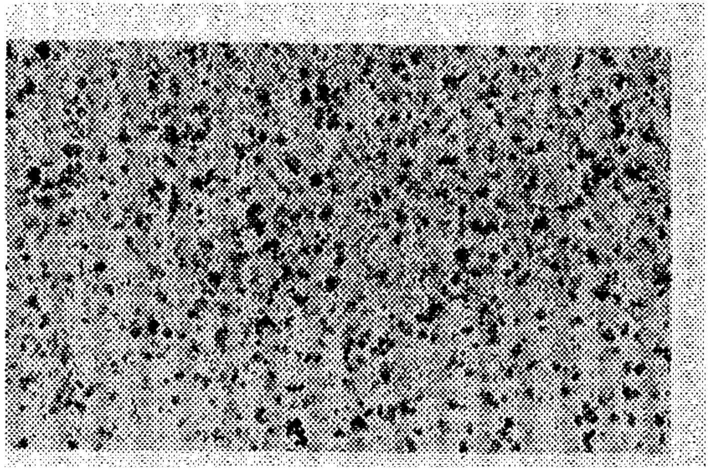


Differential conductance

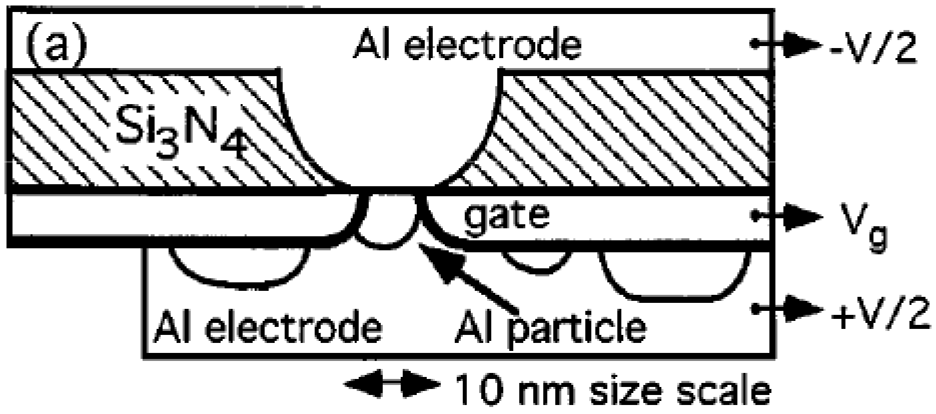
$$G(V) = \frac{1}{4Tk_B} \int_{-\infty}^{\infty} d\omega \, N_s(\omega) \left[\frac{1}{\cosh^2\left(\frac{\omega+V}{2k_BT}\right)} \right]$$

+Experimental control

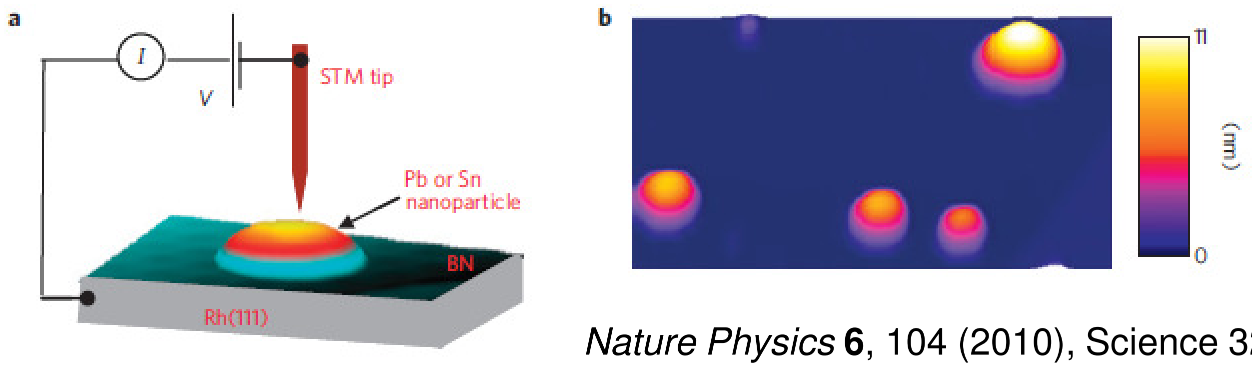
+Predictive power



1966



1995



2010

Nature Physics **6**, 104 (2010), Science 324, 1314 (2009).

2020

CONTROL

↓

PREDICTIVE POWER

↓

Enhancement of superconductivity

THANKS!