Enhancing Tc in nano-structured materials

Mayoh, AGG, arXiv:1311.0295

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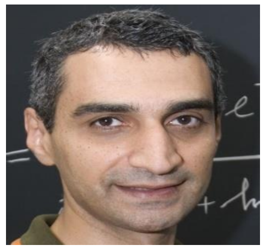


Yuzbashyan
Rutgers

Urbina
Regensburg

Richter
Regensburg

Bermudez
Cambridge

Way
Cambridge

Sangita Bose
Bombay

Altshuler
Columbia

Klaus Kern
Stuttgart

Mayoh
Cambridge

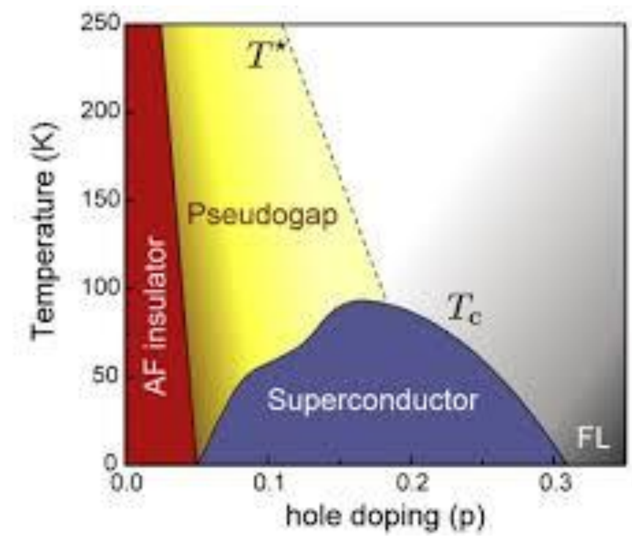
FCT
Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

MARIE CURIE ACTIONS

EPSRC
Engineering and Physical Sciences
Research Council

Superconductivity

Mavericks

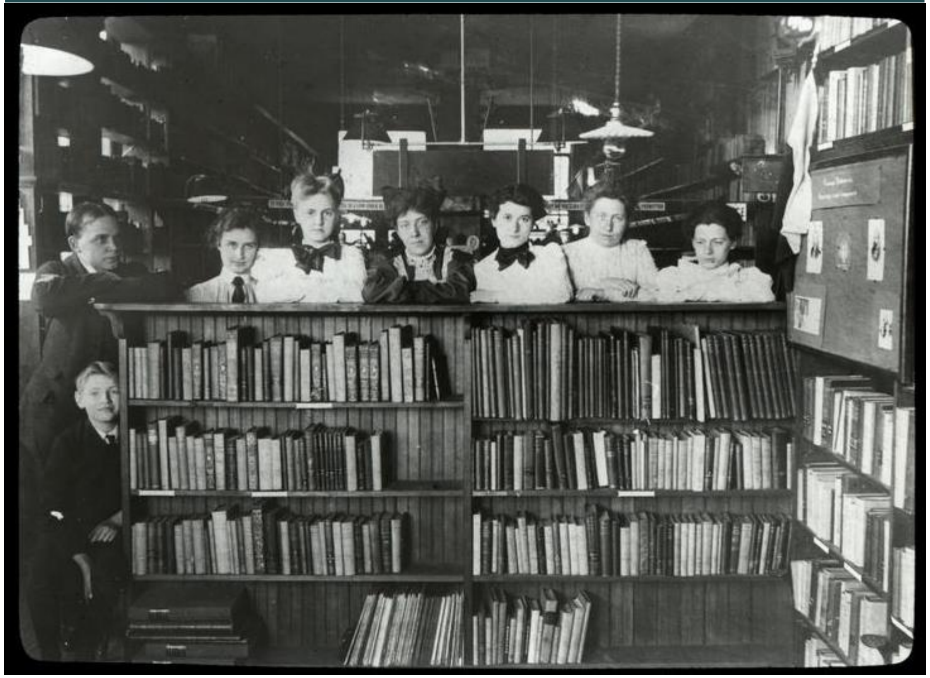


Quantum critical points ©

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 + ….

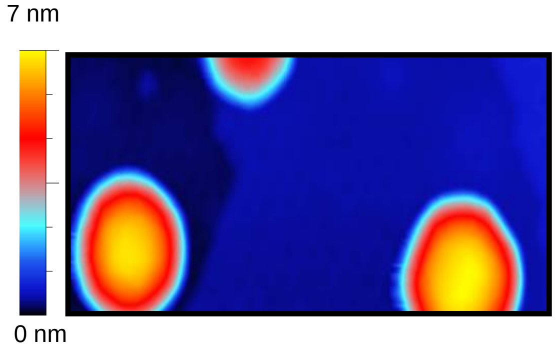
Abeles, Tinkham, Devoret, Goldman, Xue, Kern, Di Fazio, Schoen, Halperin, Leggett,Blatt….

Thin films

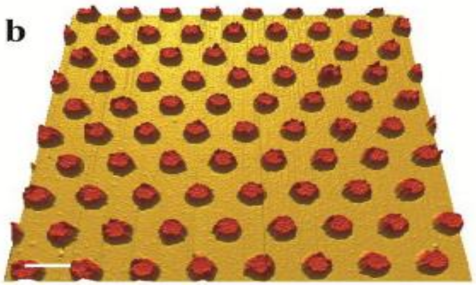
Josephson Junctions

Nanowires

Control



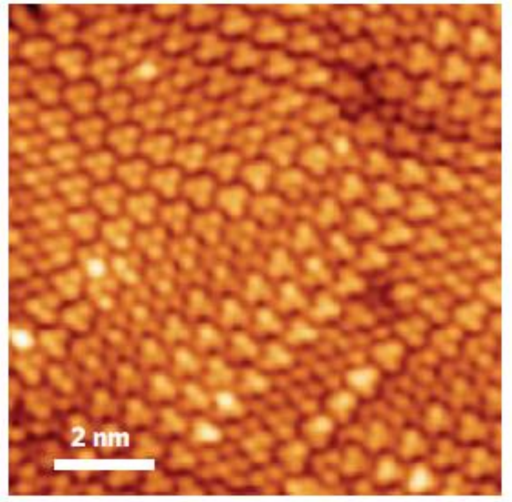
Grains



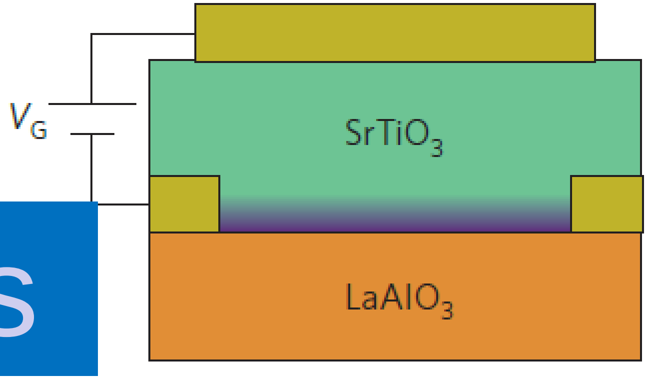
Far from equilibrium

Higher T_c?

Arrays



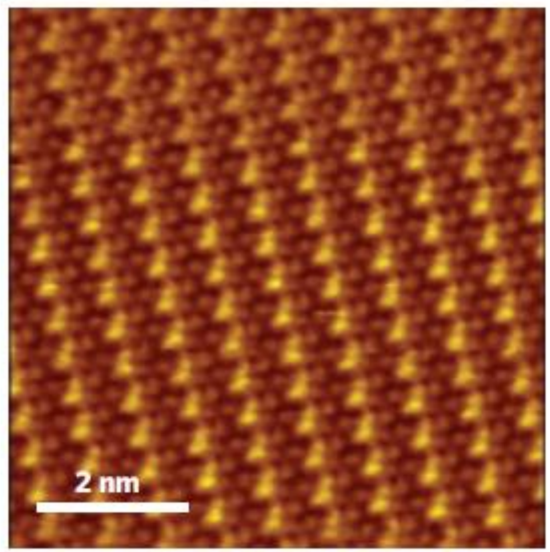
Interfaces

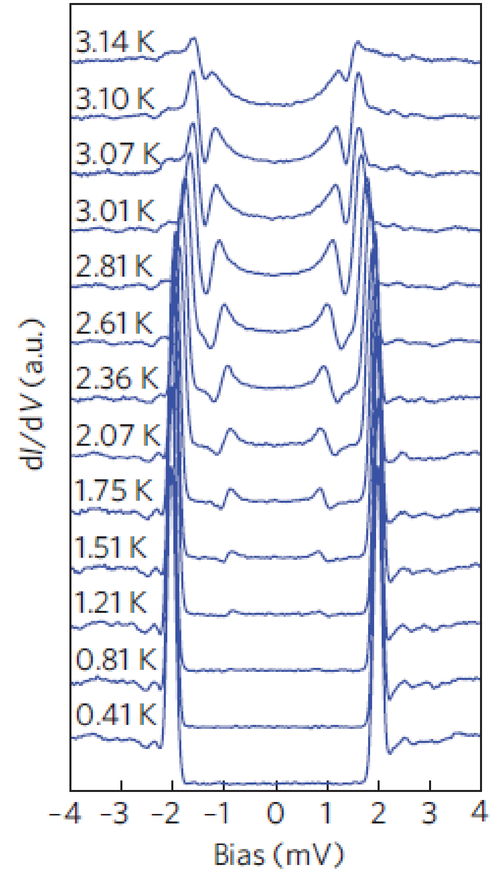


LETTERS
PUBLISHED ONLINE: 10 JANUARY 2010 | DOI: 10.1038/NPHYS1499
nature physics

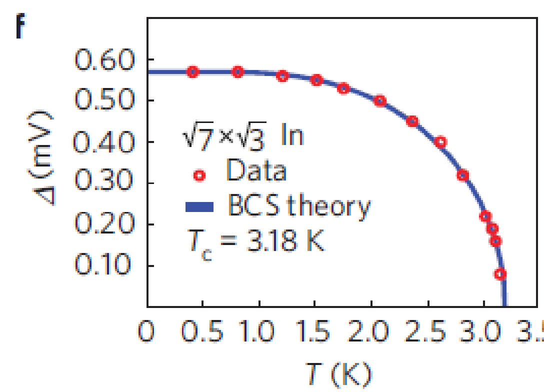
Superconductivity in one-atomic-layer metal films grown on Si(111)

Epitaxial growth



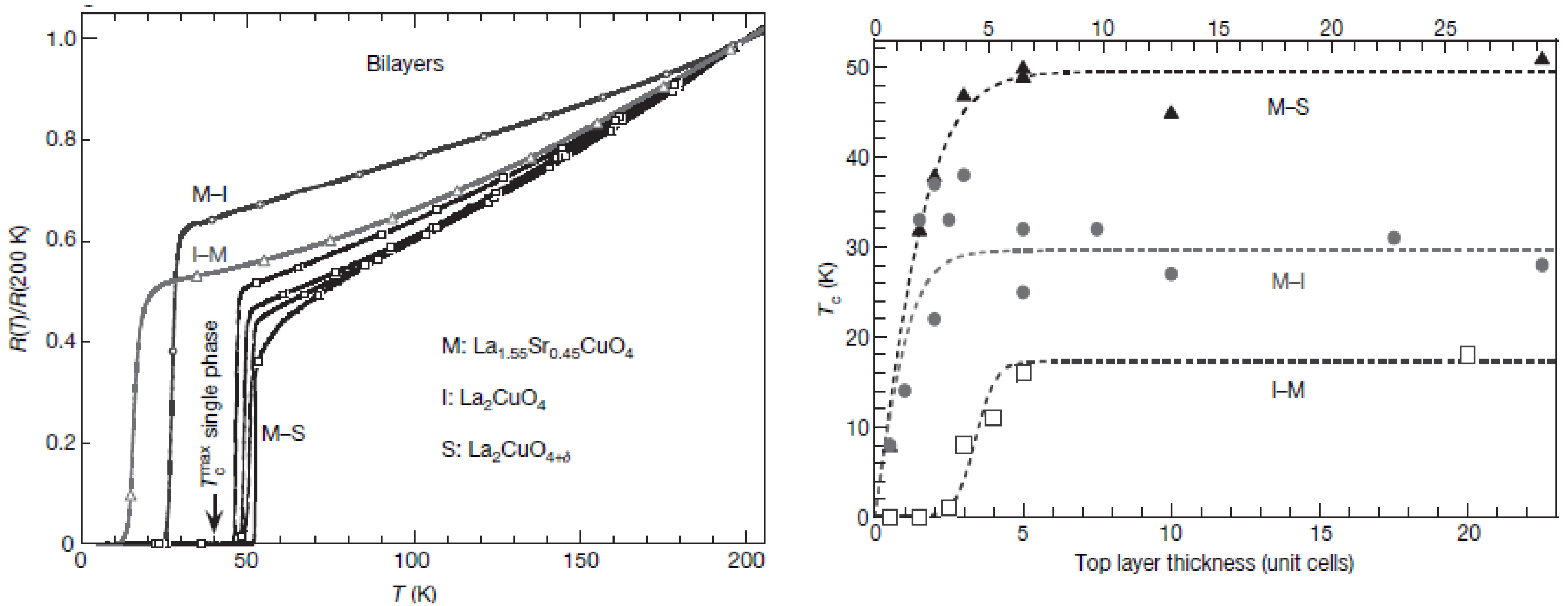


STM



No impurities

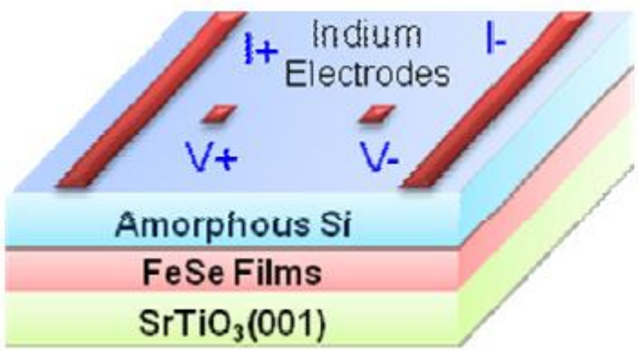
Cuprates high T_c Heterostructures

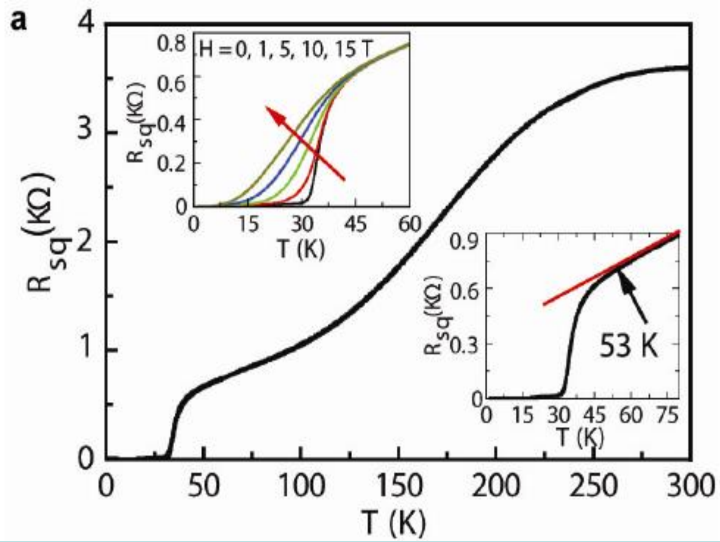


Bozovic et al., Nature 455, 782 (2008)

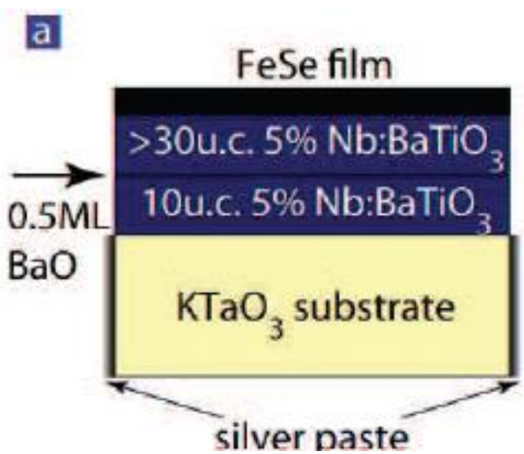
Higher T_c!!

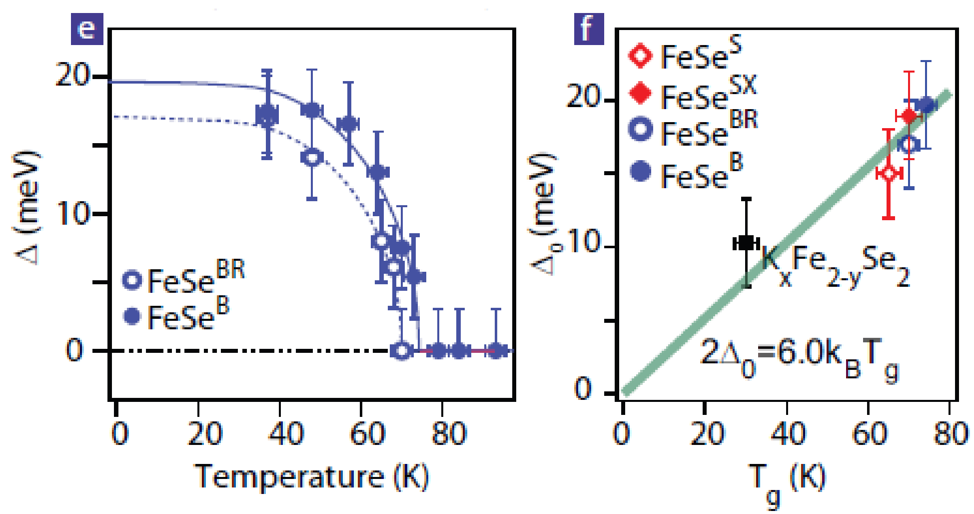
Iron Based Heterostructures





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





Feng, et. al, arXiv:1402.1357

Enhancement

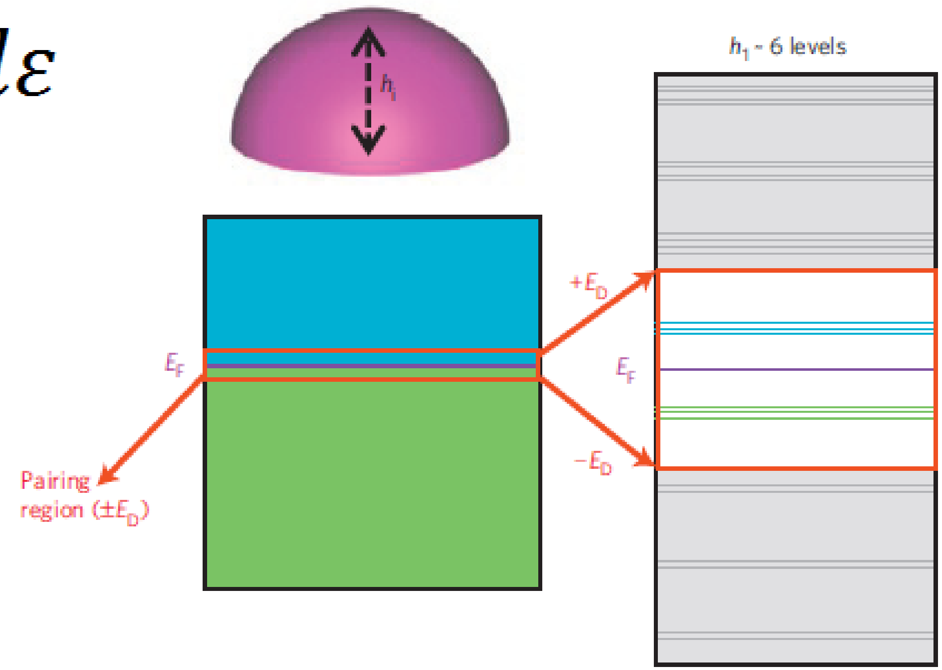
Single Grains

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

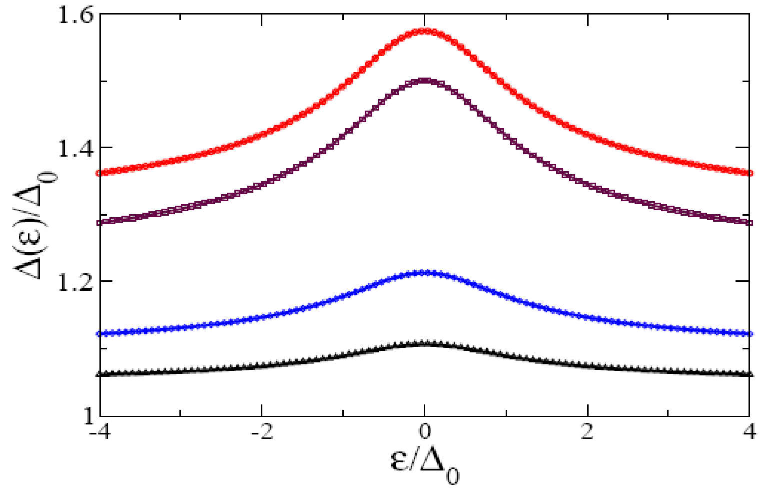
Parmenter, Phys. Rev. 166, 392 (1967)

L ~ 5nm → $20T_c$!

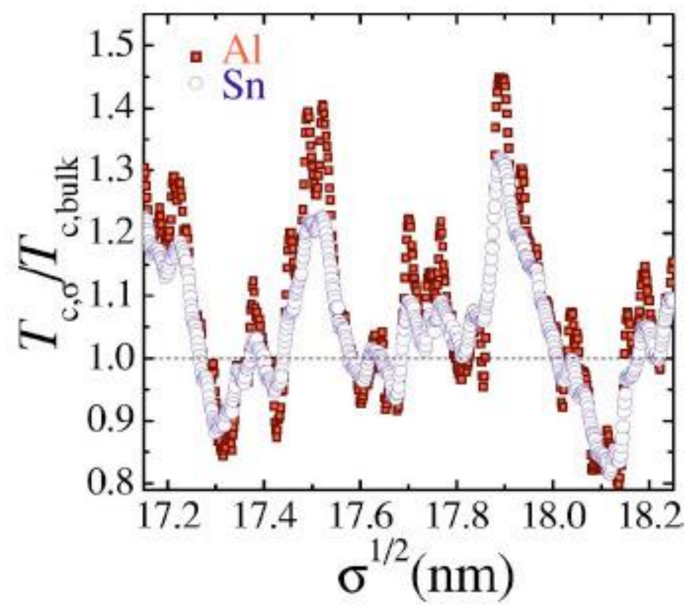
3d chaotic

$$\Delta \gg \delta$$

$$\frac{1}{k_F L} \ll 1$$



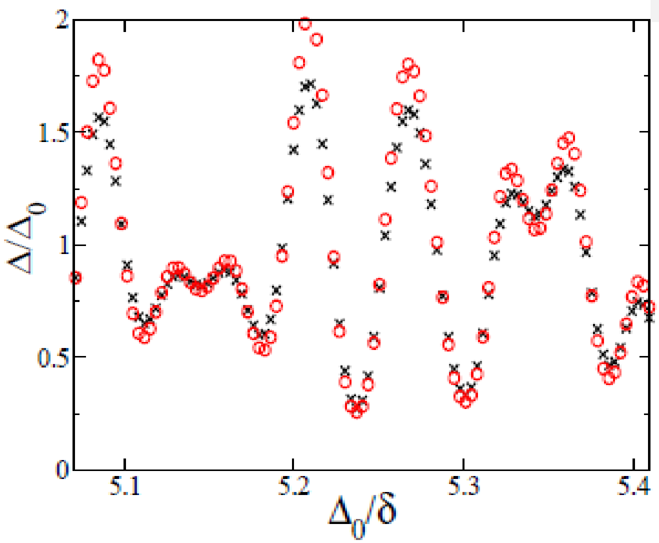
AGG, Altshuler, et al., PRL 100, 187001 (2008)
PRB 83, 014510 (2011)



3d integrable

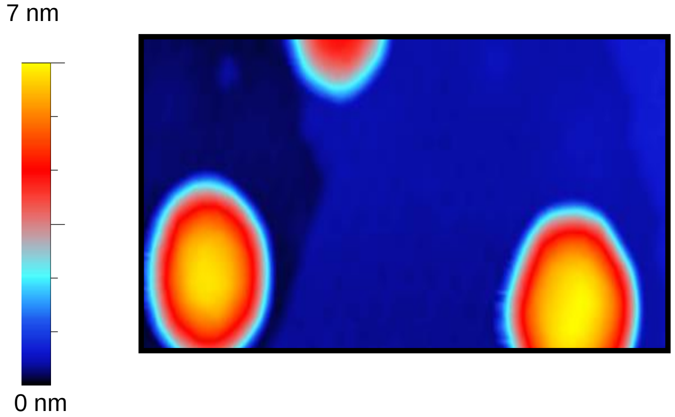
Kresin, Ovchinnikov, Boyaci (2007) Spheres

Heiselberg (2002): harmonic potentials.



Devreese (2006): Richardson equations in a box

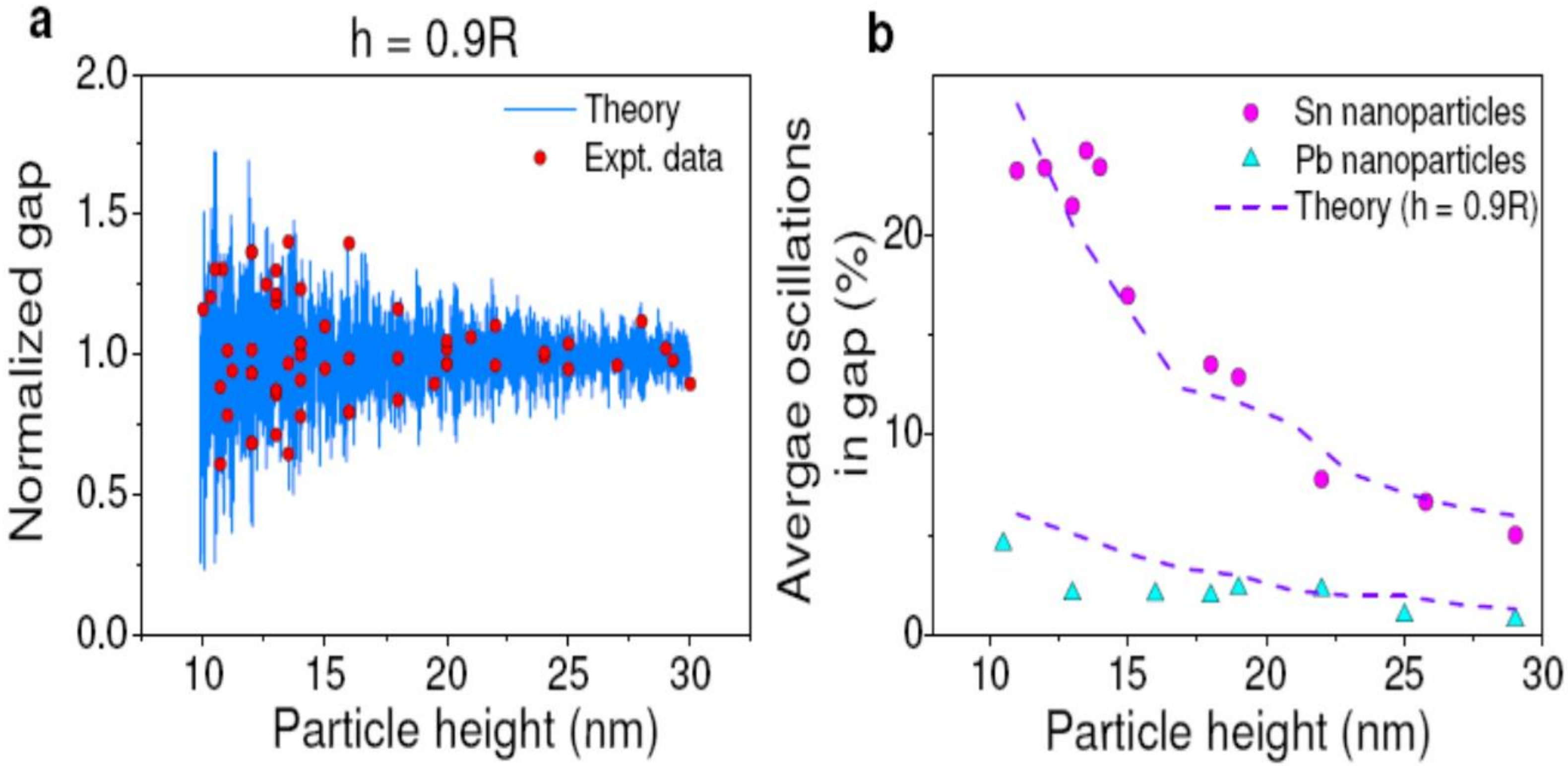
Peeters, et al, (2005-): BCS, BdG in a wire, cylinder



R ~ 4-30nm, Pb, Sn

A gap is still observed

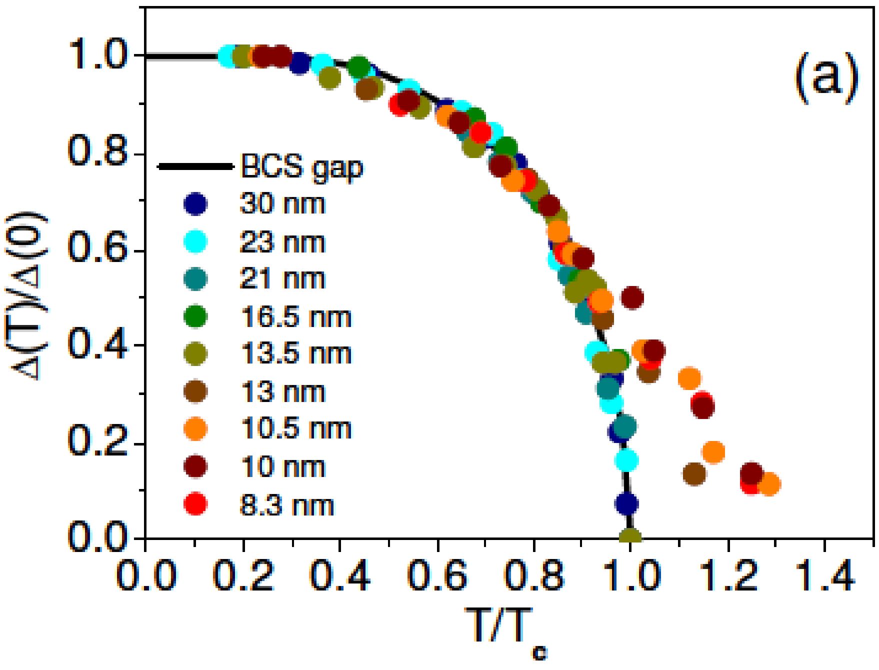
Almost hemispherical

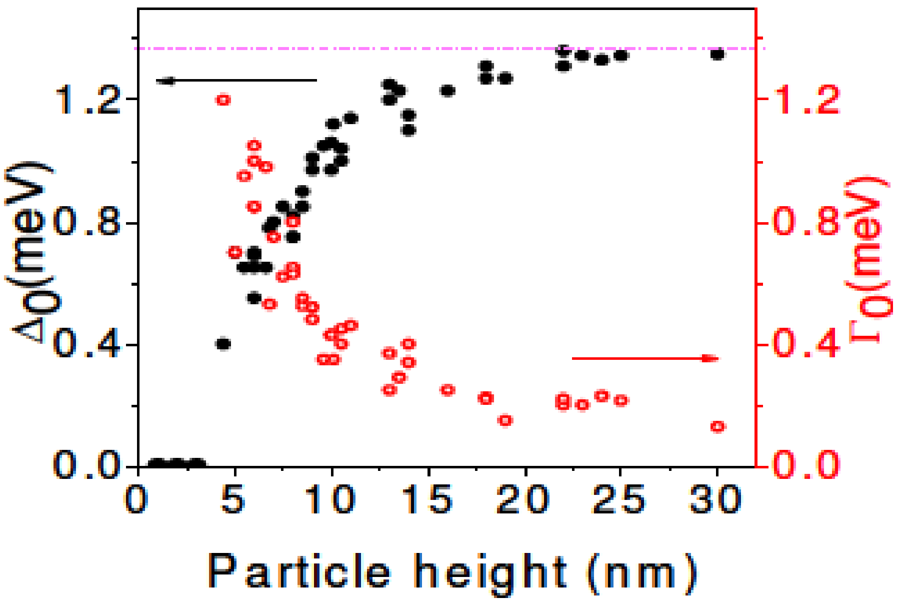


Bose, AGG, Kern, et al., Nature Materials 2010

Beyond mean field

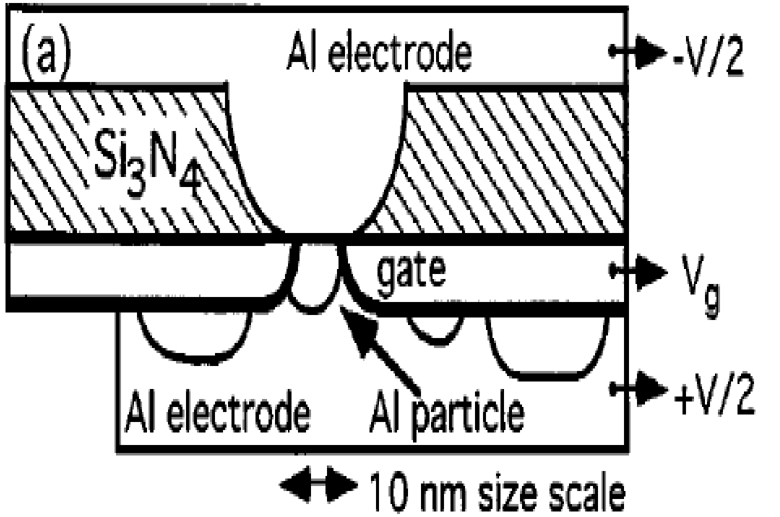
$\Delta \sim \delta$





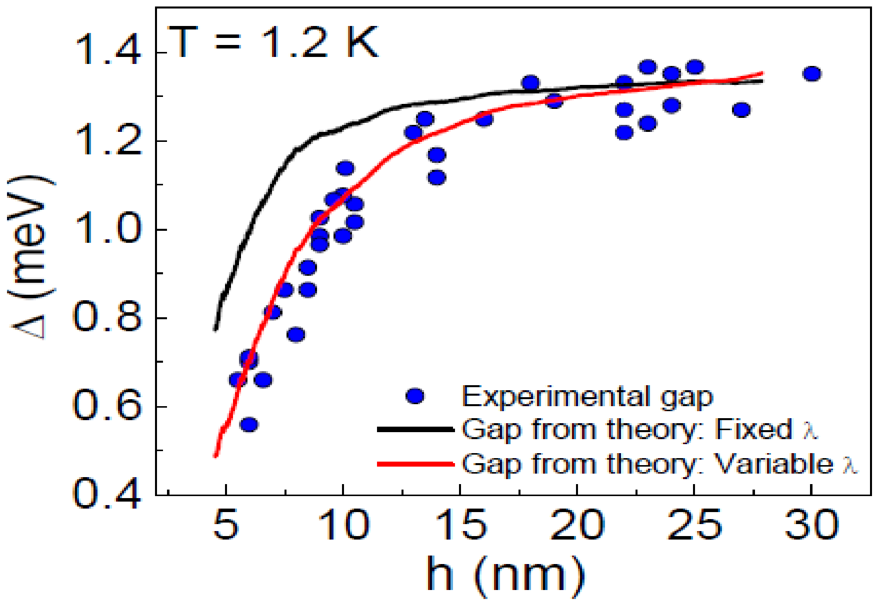
Supercon ductivity?

1959

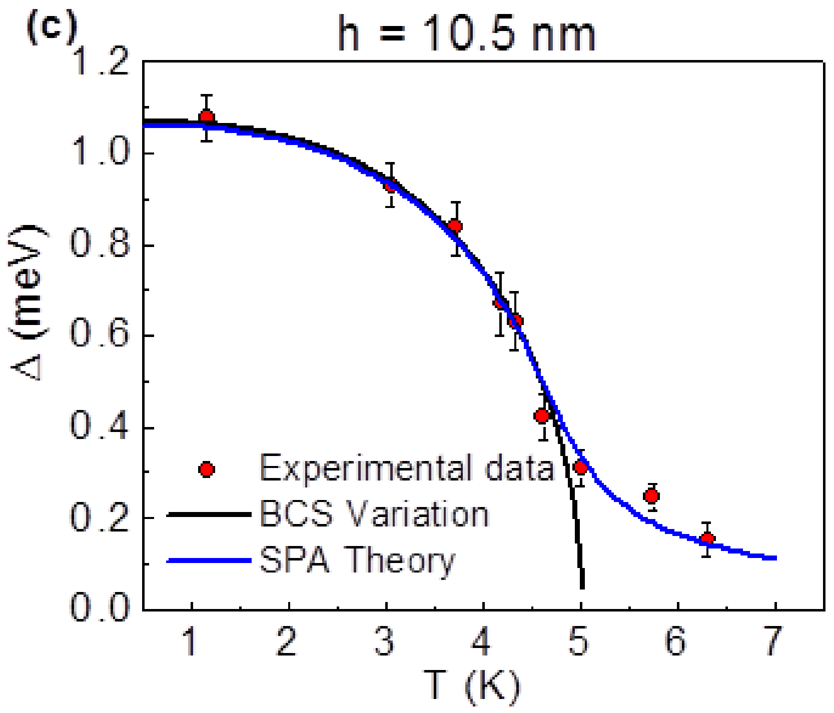


Tinkham 95

Quantum Fluctuations
Richardson's equations



and



Thermal Fluctuations
Static Path Approach

Brihuega, AGG, Ribeiro, Bose, Kern
PRB 84,104525 (2011)
Editor's Suggestion

Quantum + Thermal?

T, $\delta/\Delta_0 << 1$

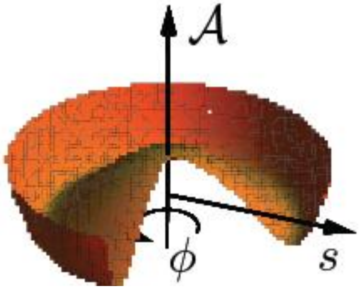
Divergences at intermediate T

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

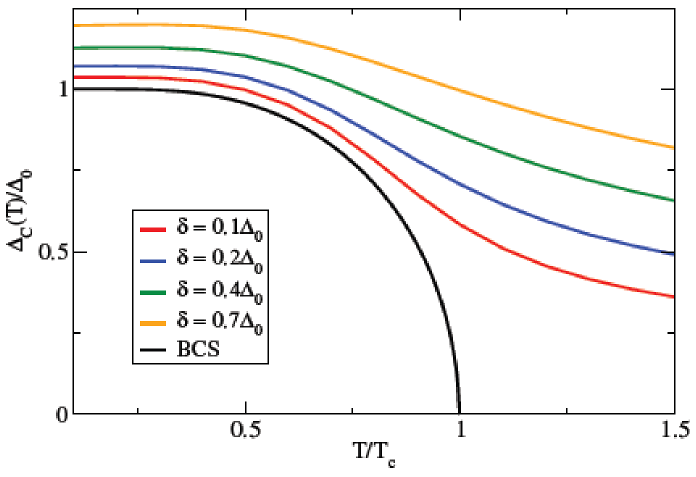
Harmful Zero Modes

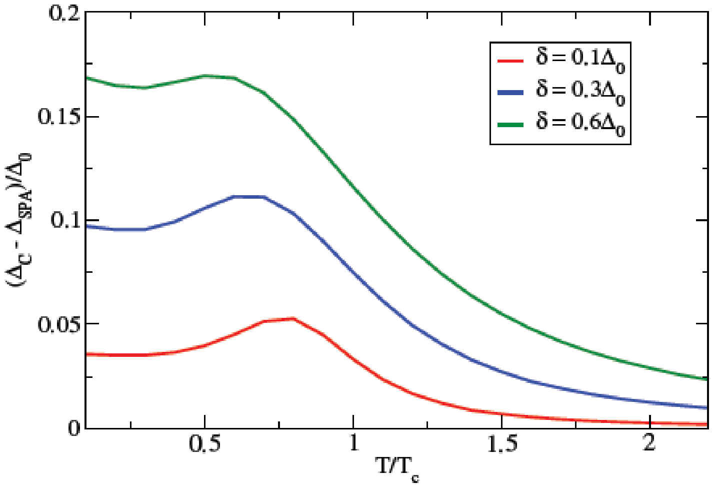
Polar coordinates

Quantum fluctuations ~ Charging effects



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





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

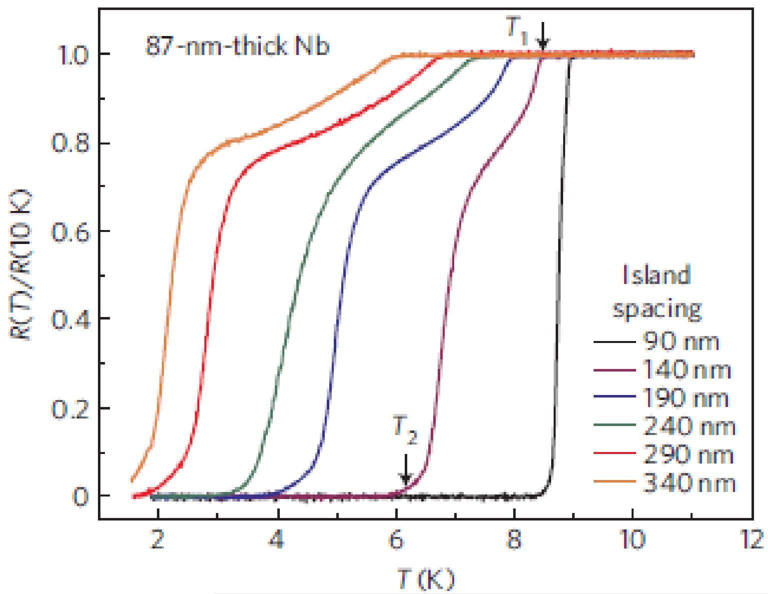
True phase coherence in single nanograins?

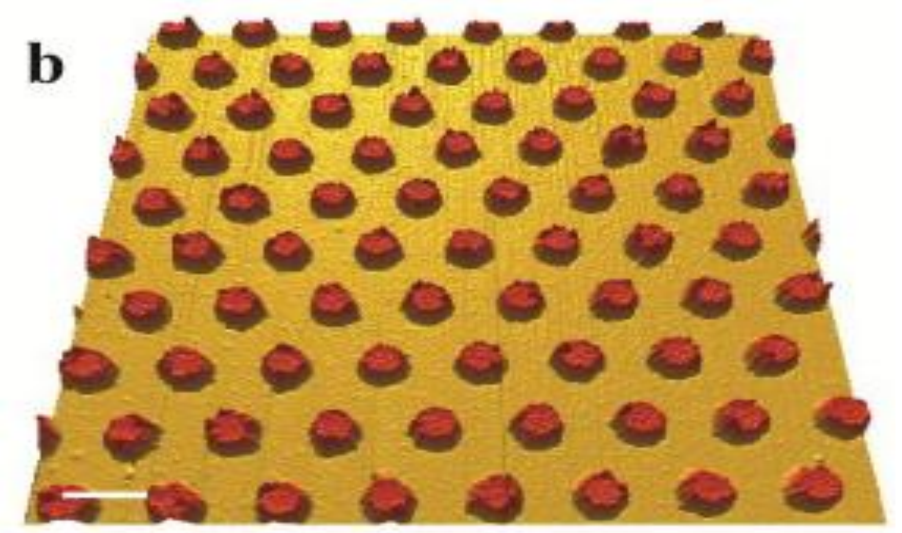
No

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

Josephson array?

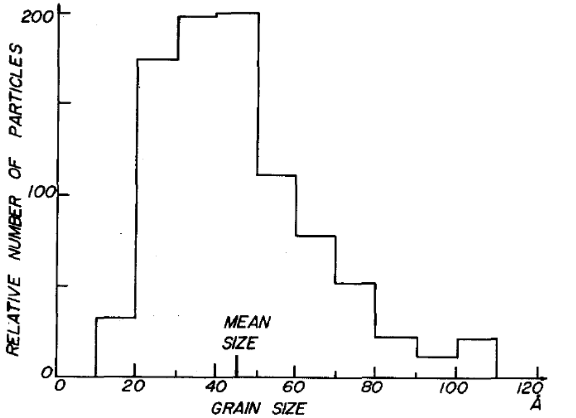
Maybe

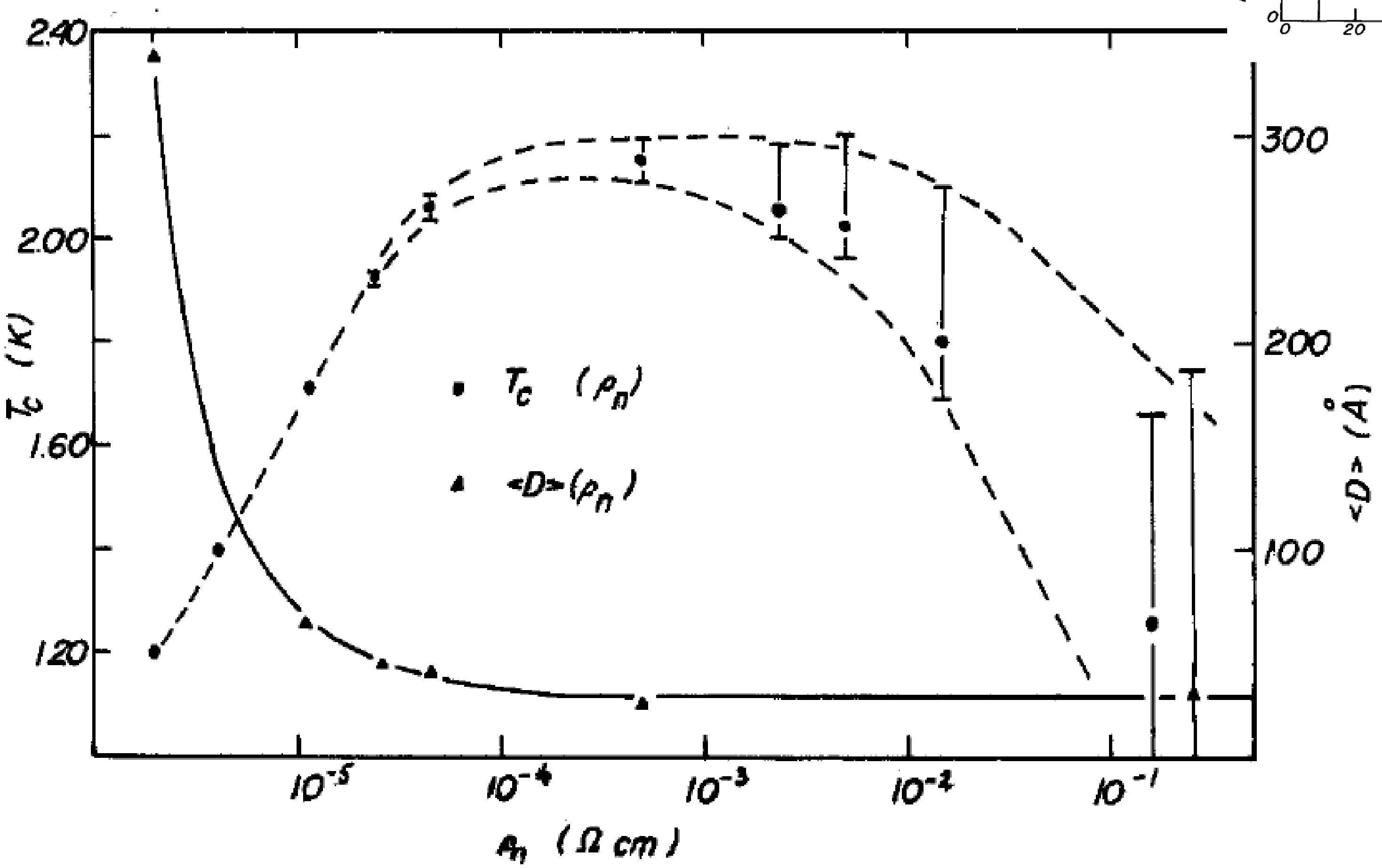




Mason, et al, Nature Physics 8 59 (2012)

Al evaporated on a glass substrate

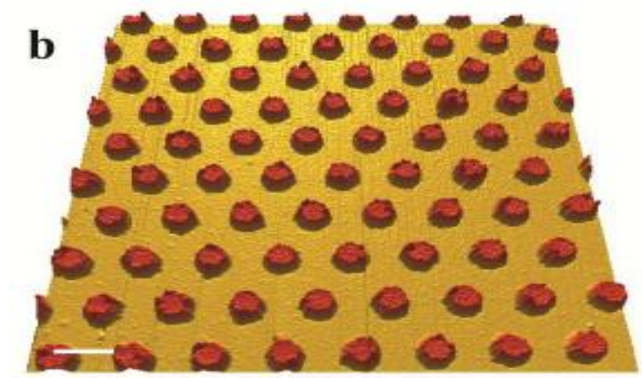




Deutscher 73’

Engineering granular materials

Optimal but realistic

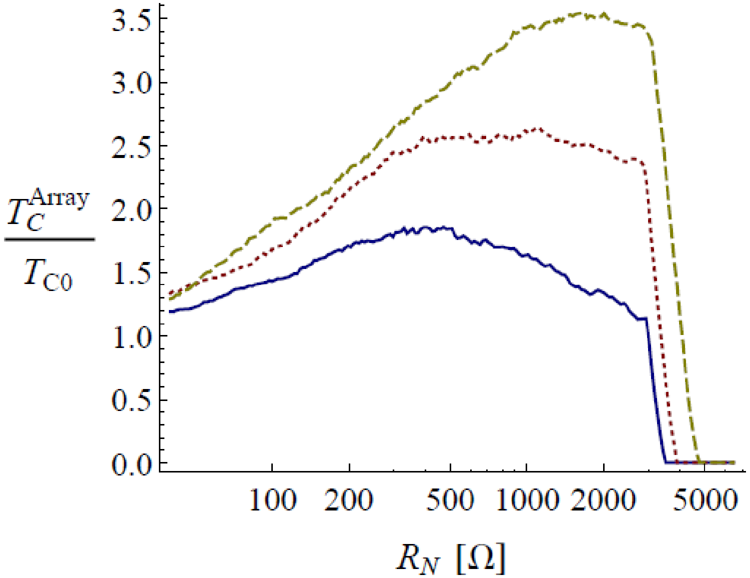


Size

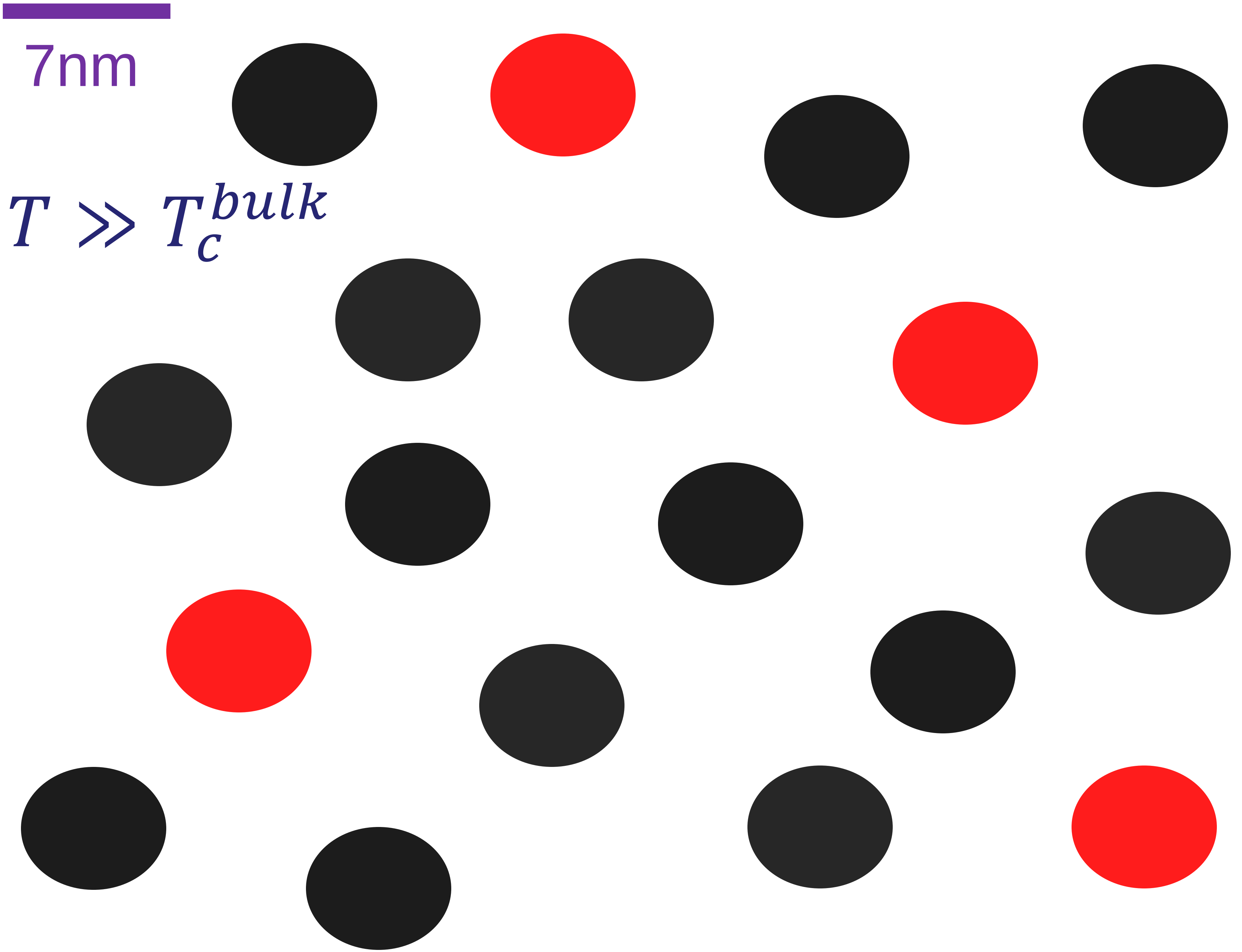
Variance

Packing

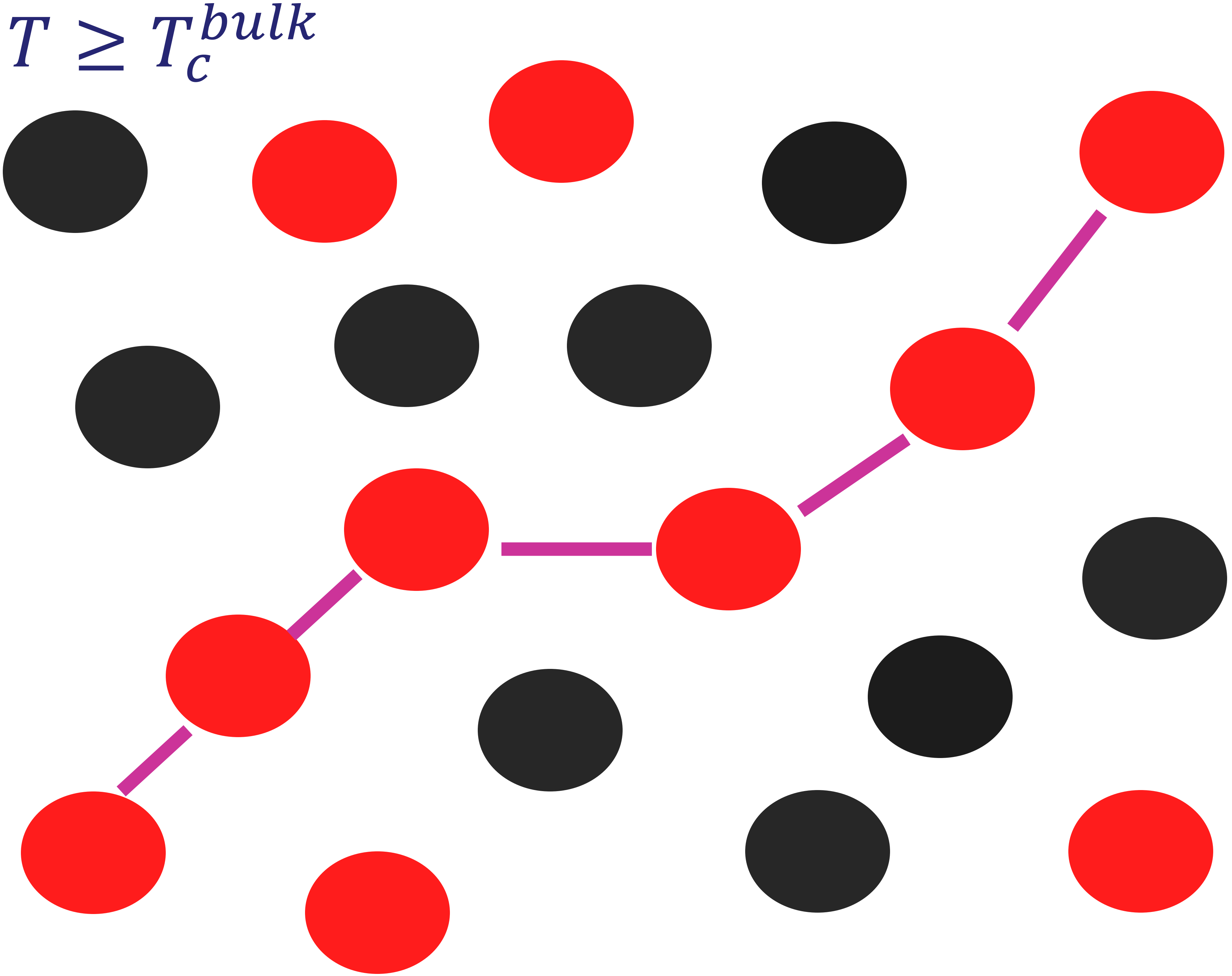
Tc=1.3Tc^bulk
Tc=1.5Tc^bulk
Tc=3.0Tc^bulk!!!

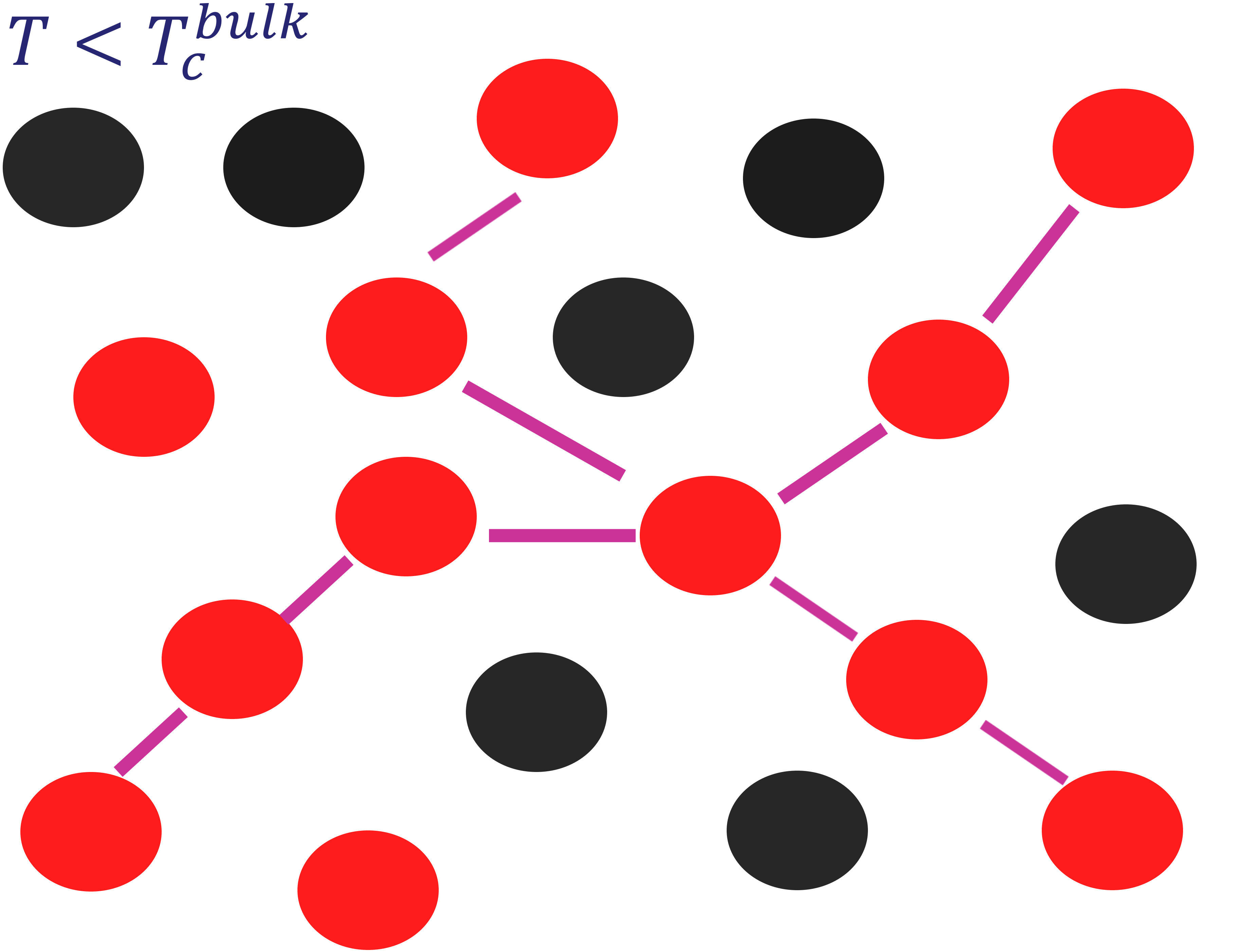


Mayoh, AGG, arXiv:1311.0295



7nm
$T \gg T_c^{bulk}$


$T \geq T_c^{bulk}$


$T < T_c^{bulk}$

Designing JJ arrays:

Realistic, doable, optimal

3D

Nano spheres

Clean

Quasi particle tunnelling

NO BKT

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

YES BCS

$$\bar{R} \geq 4nm$$
$$\sigma \sim 1nm$$

Charging

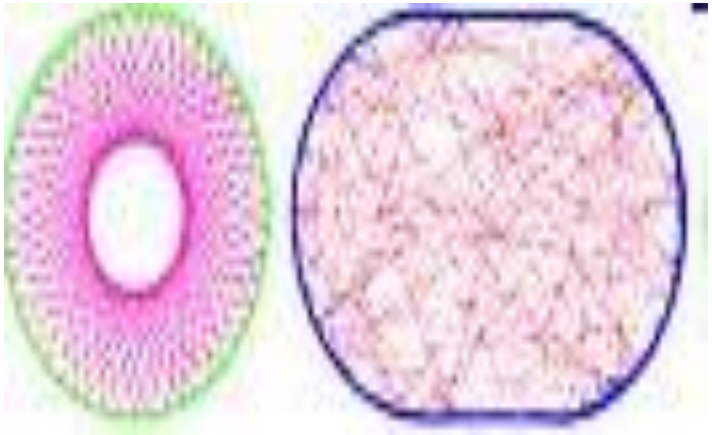
Packing

How?

Single grain

$$\Delta \gg \delta$$

BCS



$$\frac{1}{k_F L} \ll 1$$

Periodic orbit theory

Balian,Bloch. Gutzwiller

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

JJ Array

Open grain

Cutoff long orbits

Mean field

Tunneling

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

Schoen, Zaikin,Fazio.

Charging Hopping

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

Quasiparticles

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

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

INHOMOGENEOUS

HOMOGENEOUS

↑ T

↓ #SCG

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

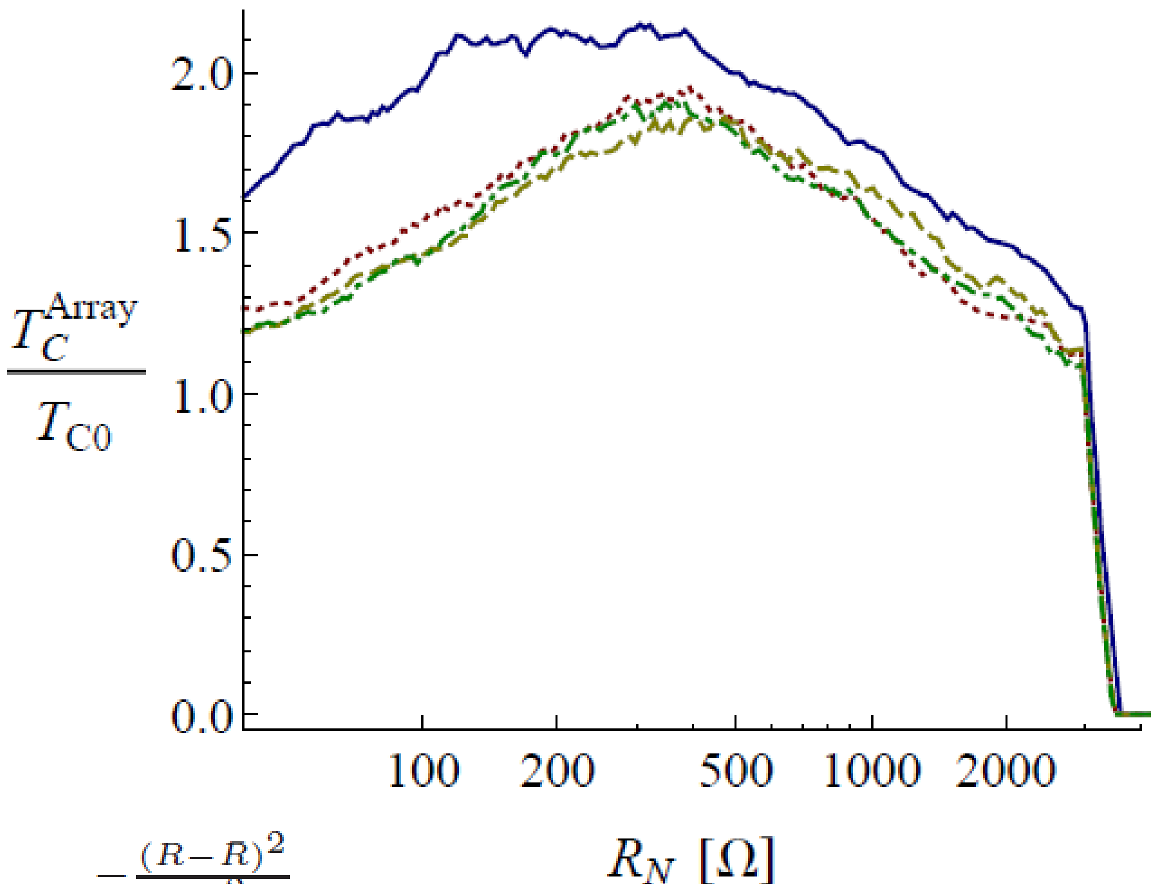
$$\bar{z} = zp$$

Percolation ?

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

$\sigma = 0.1, 0.6, 1, 1.4\,nm$

$\bar{R} = 5nm \quad \lambda = 0.25$

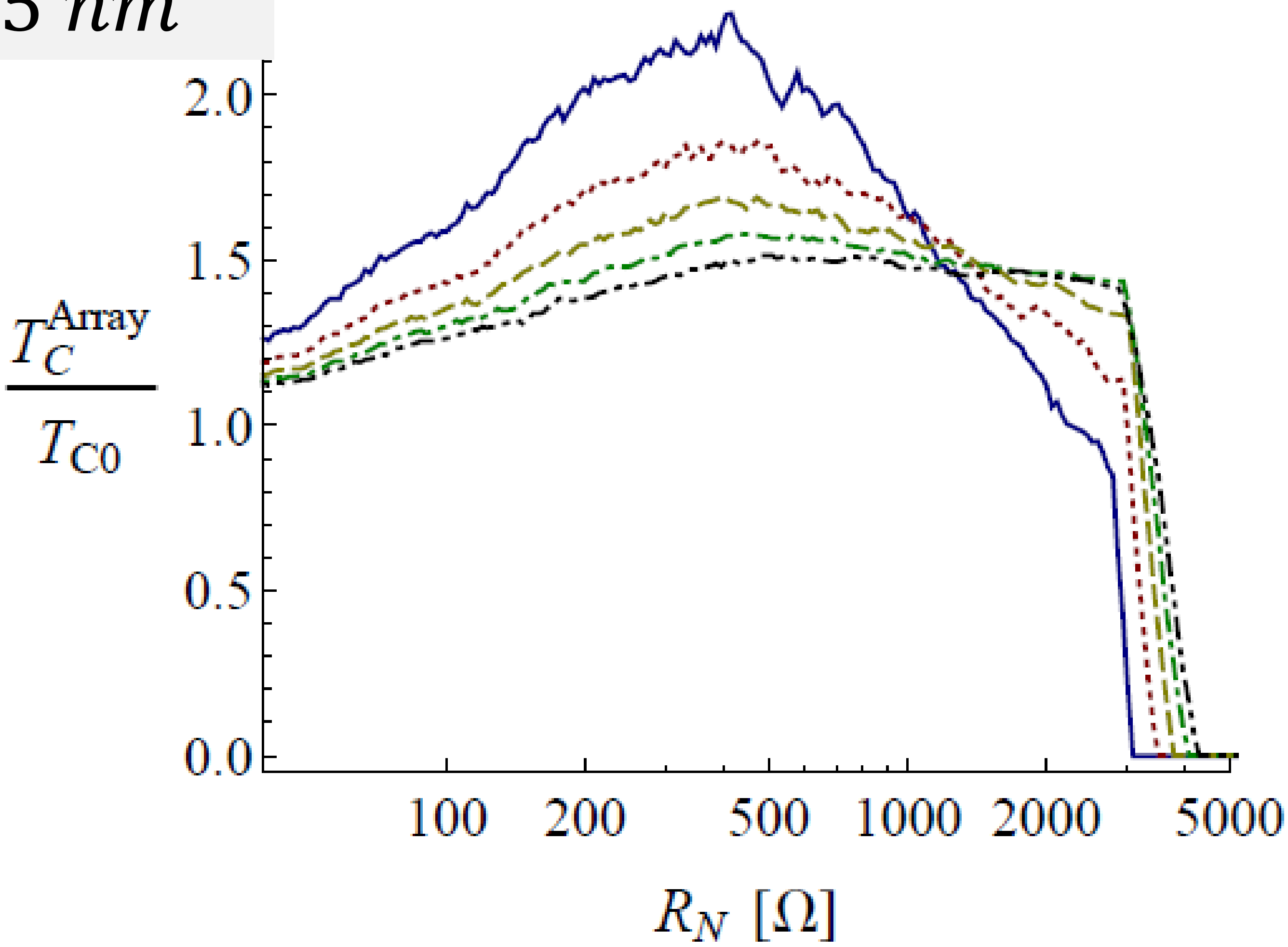


$$P(R) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(R-R)^2}{2\sigma^2}}$$

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

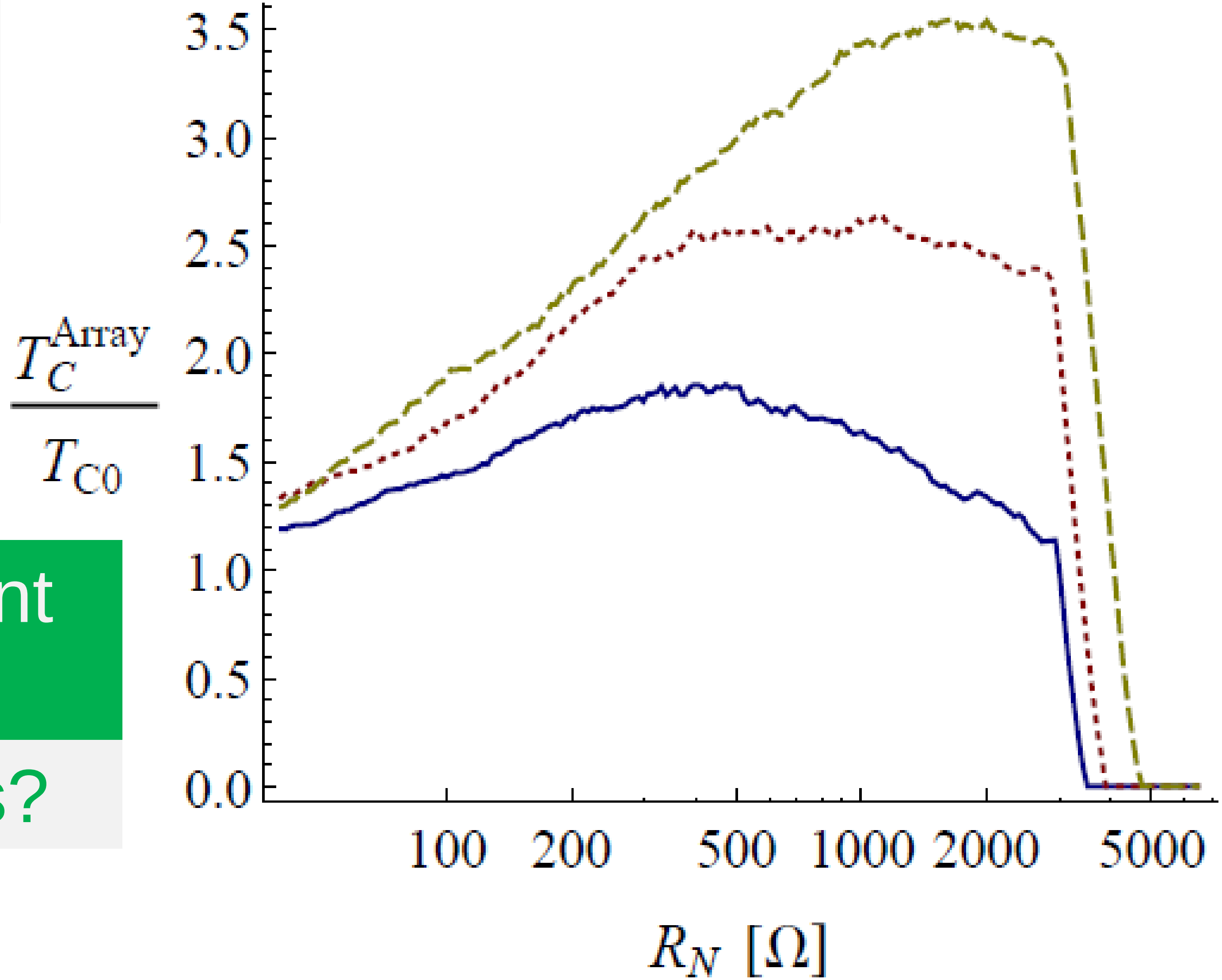
$\sigma = 1\ nm$

$\bar{R} = 5\ nm$



$$Packing = Cubic, BCC, FCC$$

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



Enhancement is possible!

Experiments?

Origin

Percolation?

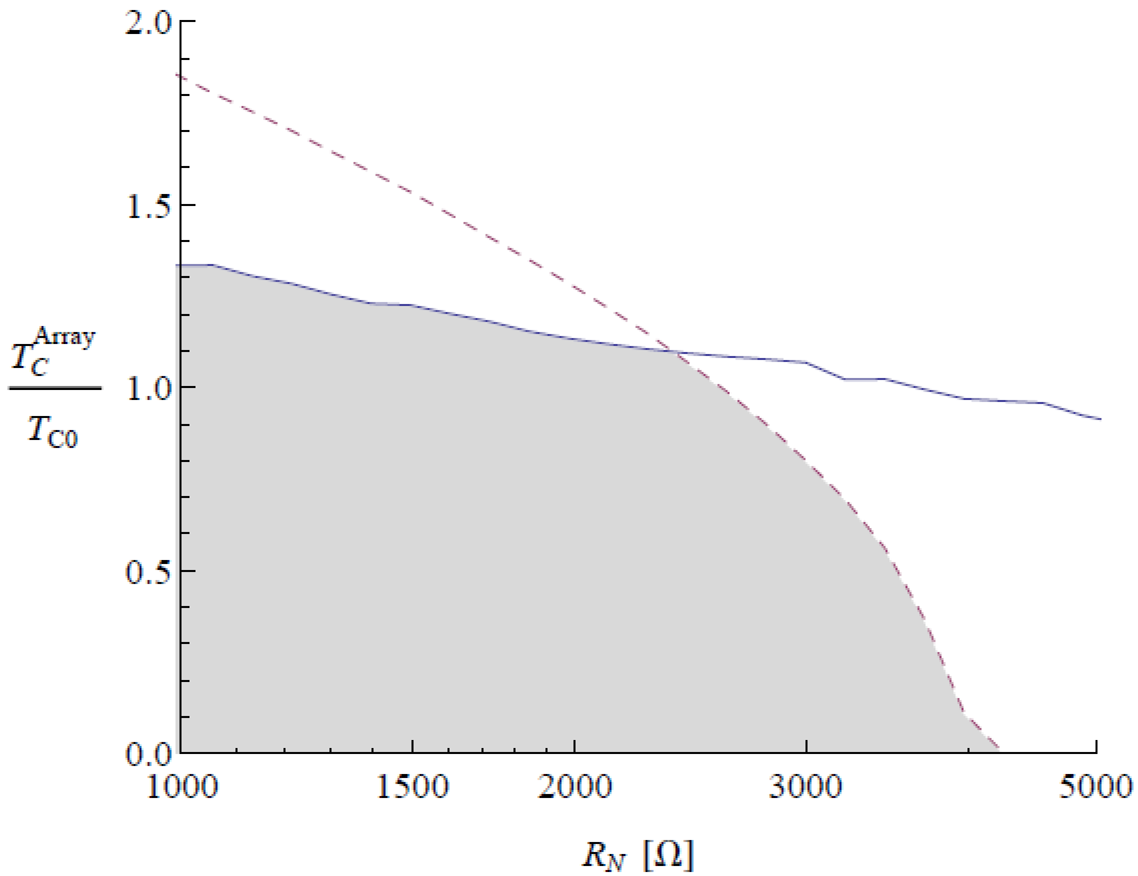
T_c

$\uparrow$ T

Phase dynamics?

$\downarrow$ #SCG

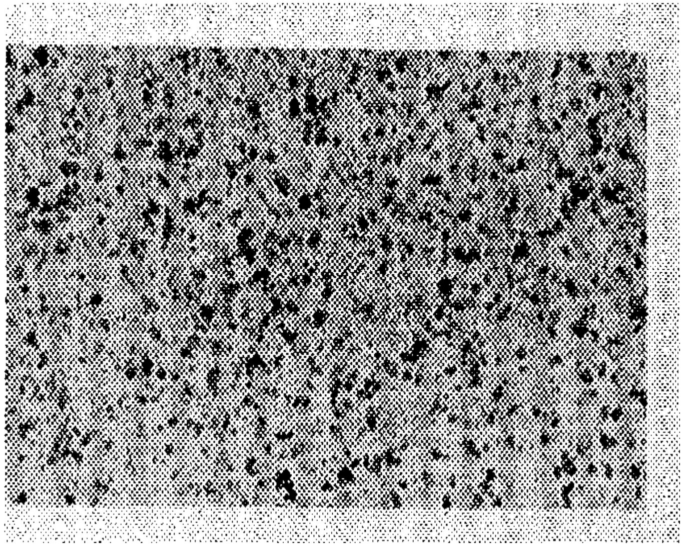
Percolation ?? Phase fluctuations



R=5nm σ=1nm λ=0.3

Experiments:

1960

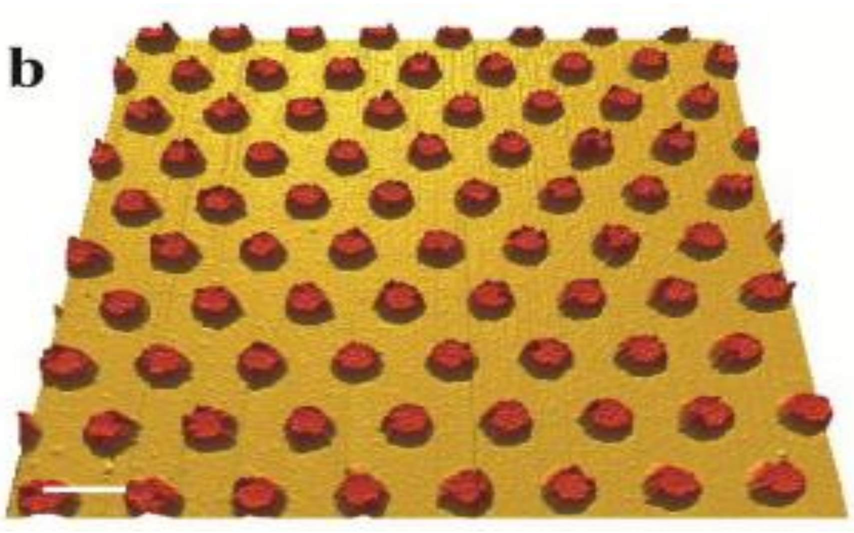


Abeles, Cohen, Cullen, PRL17, 632 (1966)

L ~ 5nm

No Control

2012



Control

L ~ 50nm

L ~ 5nm?

Thanks!