Can inhomogeneities enhance superconductivity?

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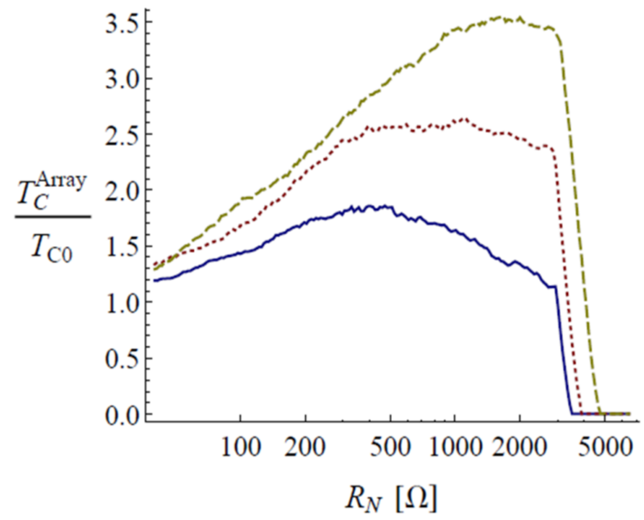
Global critical temperature in inhomogeneous superconductors induced by multifractality

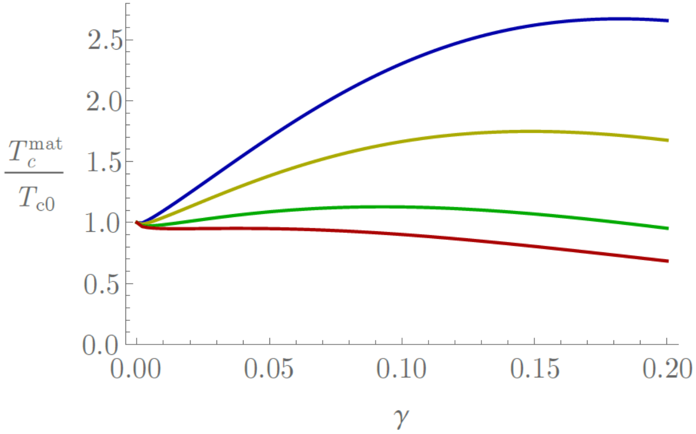
arxiv:1412.0029

Strong enhancement of bulk superconductivity by engineered nanogranularity

Phys. Rev. B 90, 134513 (2014)



James Mayoh



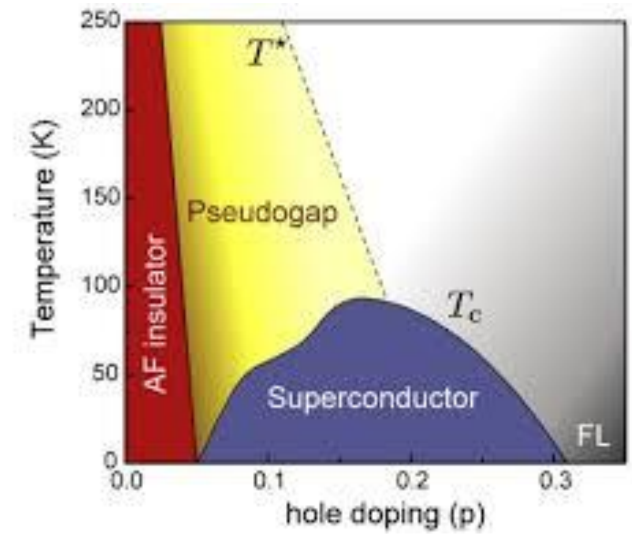
FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

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

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

Experimental Control → Enhancement Tc?; Understanding Tc?

Mavericks meet Librarians

Learning to design SC

Control on conventional SC

FeSe

LAO/STO

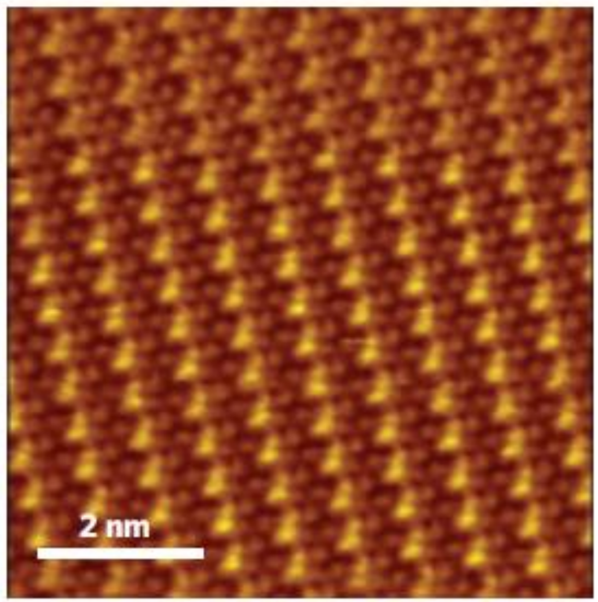
LETTERS
PUBLISHED ONLINE: 10 JANUARY 2010 | DOI:10.1038/NPHYS1499
nature physics

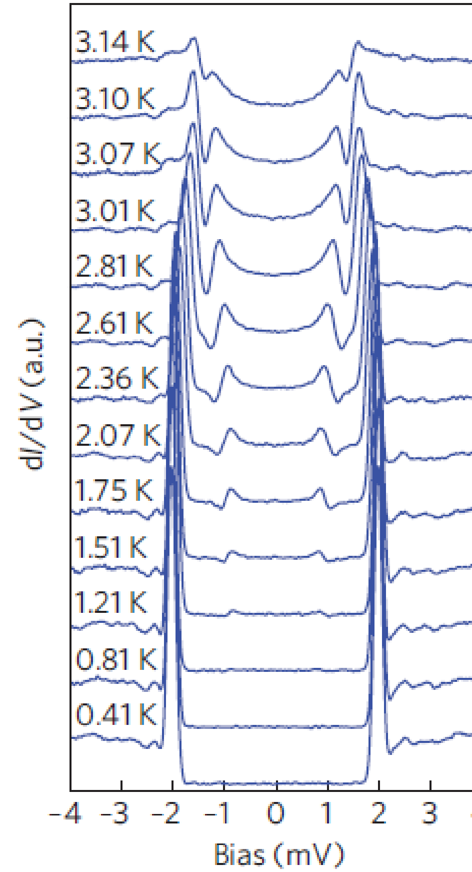
Superconductivity in one-atomic-layer metal films grown on Si(111)

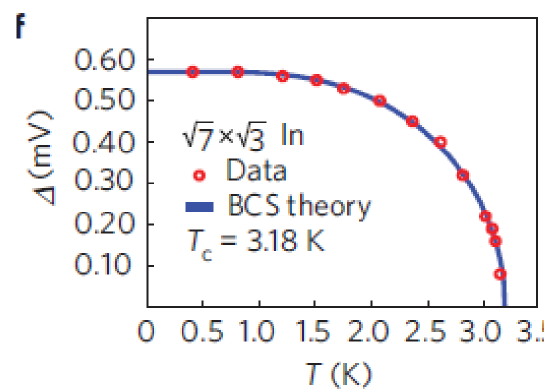
Epitaxial growth

STM

No impurities



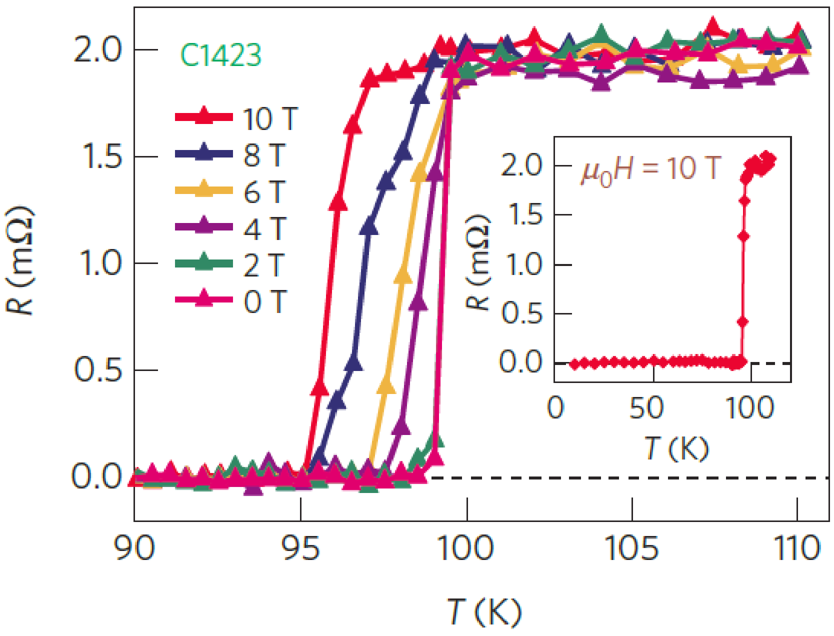




nature materials
LETTERS
PUBLISHED ONLINE: 24 NOVEMBER 2014 | DOI: 10.1038/NMAT4153

Superconductivity above 100 K in single-layer FeSe films on doped $SrTiO_3$

Jian-Feng Ge[1], Zhi-Long Liu[1], Canhua Liu[1,2*], Chun-Lei Gao[1,2], Dong Qian[1,2], Qi-Kun Xue[3*], Ying Liu[1,2,4] and Jin-Feng Jia[1,2*]



Top equipment

Top expertise

Seminal:

Wang Qing-Yan et al 2012 Chinese Phys. Lett. 29 037402

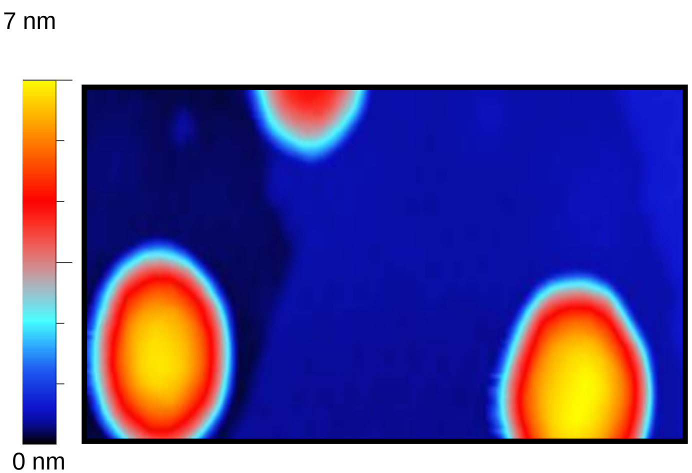
nature materials

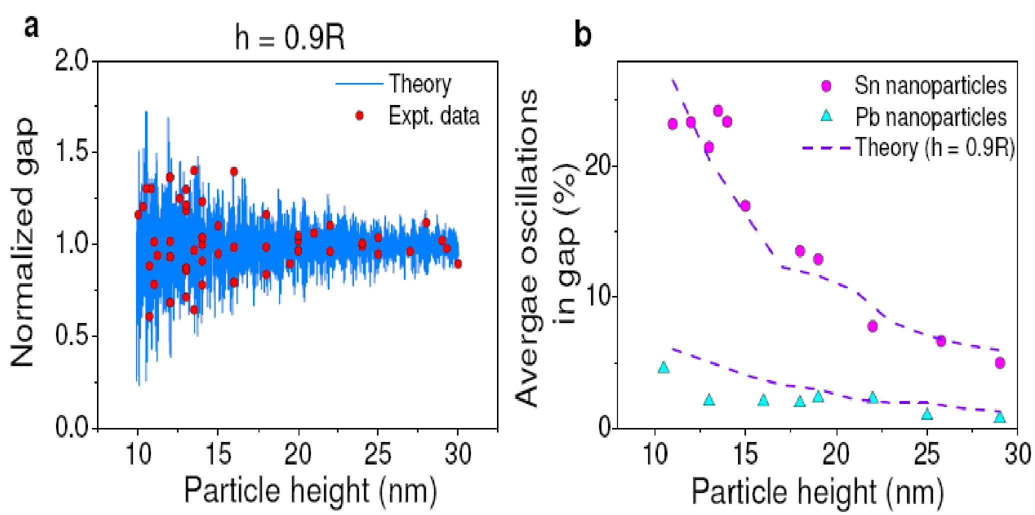
LETTERS

PUBLISHED ONLINE: 30 MAY 2010 | DOI:10.1038/NMAT2768

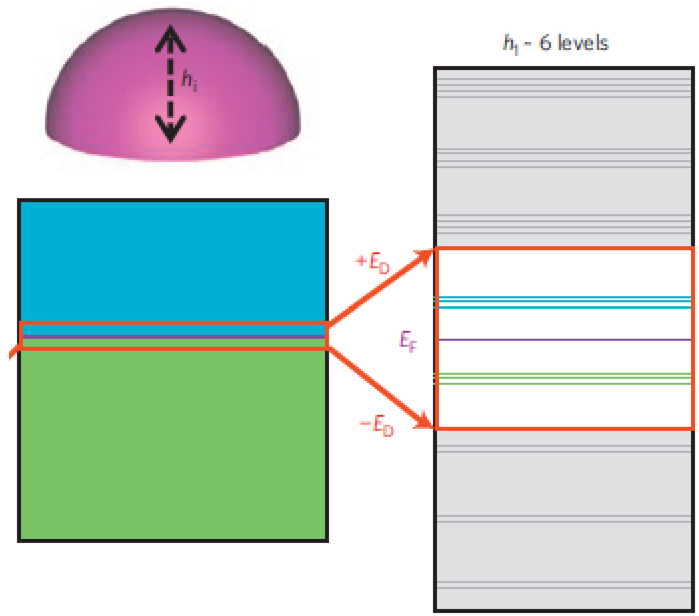
Observation of shell effects in superconducting nanoparticles of Sn

Sangita Bose[1]*, Antonio M. García-García[2]*, Miguel M. Ugeda[1,3], Juan D. Urbina[4], Christian H. Michaelis[1], Ivan Brihuega[1,3]* and Klaus Kern[1,5]



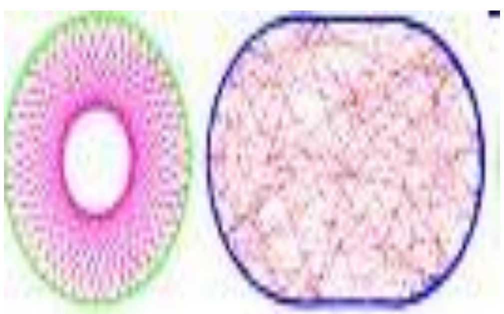


Δ >> δ L ~ 10nm



$$I(\epsilon_n, \epsilon_{n'}) = \lambda V \delta \int \psi_n^2(\vec{r}) \psi_{n'}^2(\vec{r}) d\vec{r}$$

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



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

Expansion in $1/k_F L$, δ/Δ_0

Parmenter, Blatt, Bianconi, Thompson, Perali, Croitoru, Shanenko

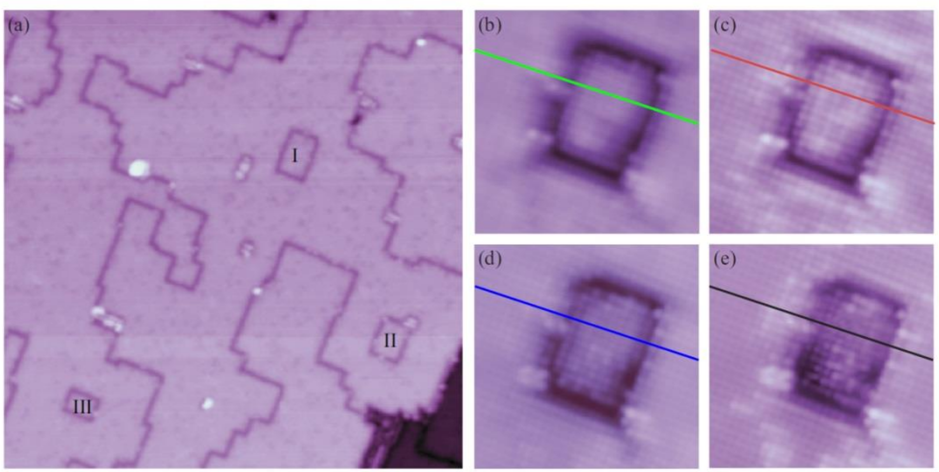
AGG, Altshuler, PRL 100, 187001 (2008)
AGG, Altshuler, PRB 83, 014510 (2011)

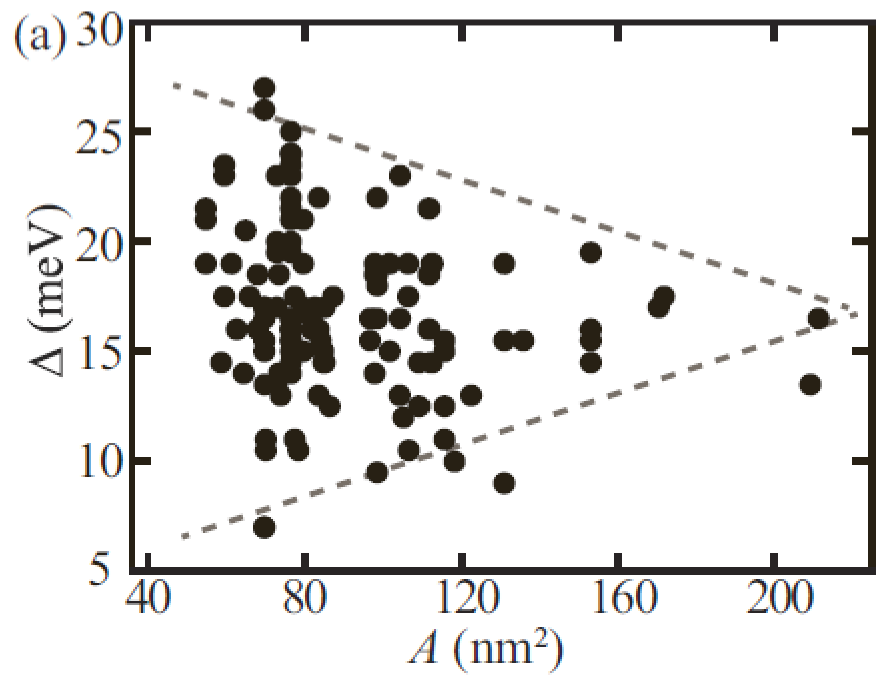
RAPID COMMUNICATIONS

PHYSICAL REVIEW B **91**, 060509(R) (2015)

Visualizing superconductivity in FeSe nanoflakes on $SrTiO_3$ by scanning tunneling microscopy

Zhi Li,[1] Jun-Ping Peng,[1] Hui-Min Zhang,[1] Can-Li Song,[2,3,*] Shuai-Hua Ji,[2,3] Lili Wang,[2,3] Ke He,[2,3] Xi Chen,[2,3]
Qi-Kun Xue,[2,3] and Xu-Cun Ma[1,2,3,†]





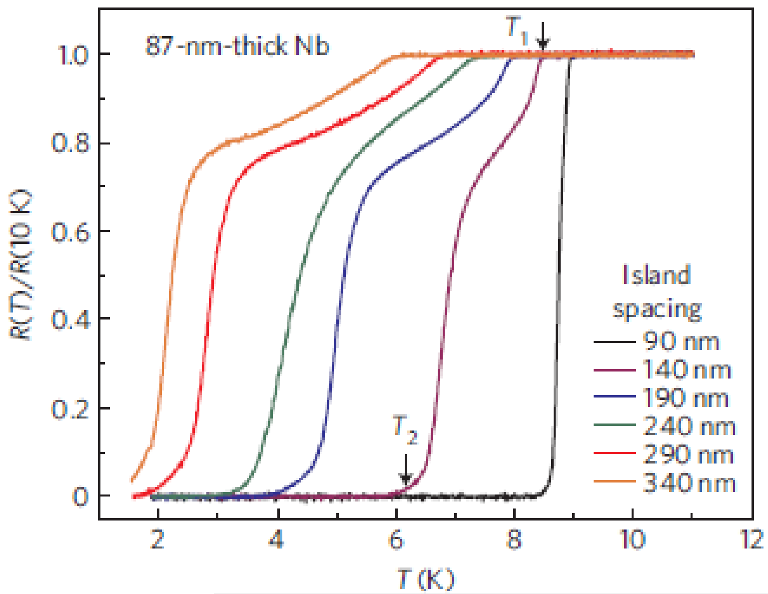
True phase coherence in single nanograins?

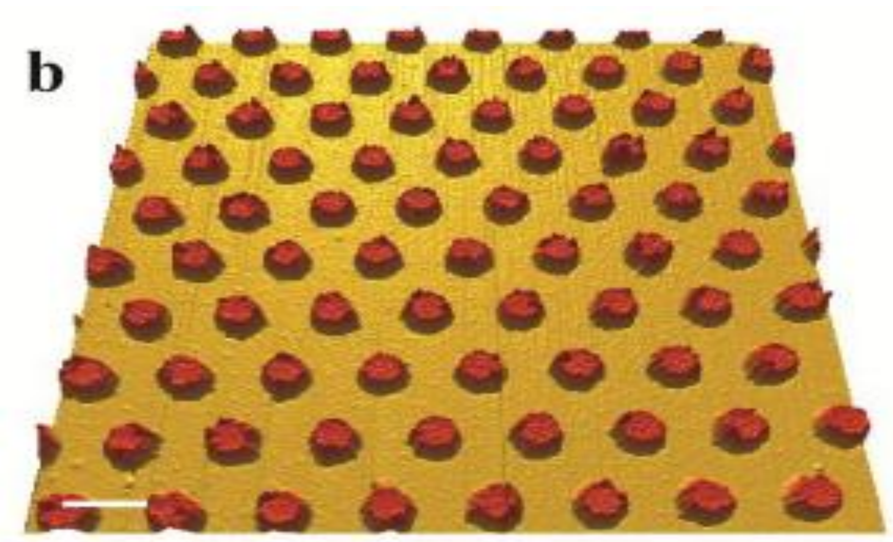
No

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

Josephson array?

Maybe

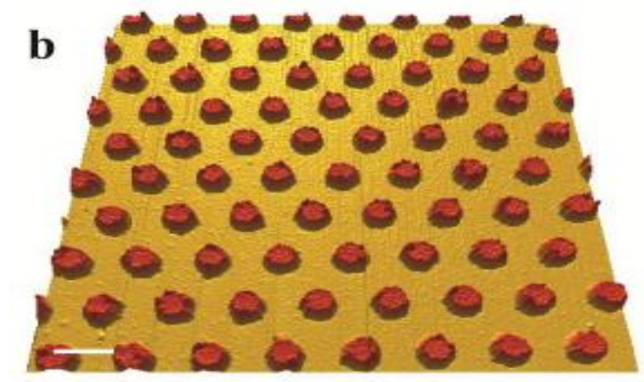




Mason, et al, Nature Physics 8 59 (2012)

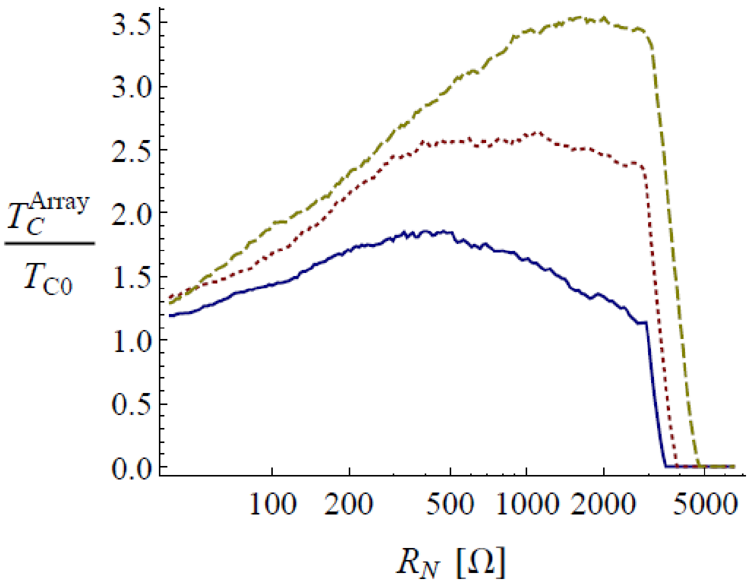
Engineering granular materials

Optimal but realistic



Size | **Variance** | **Packing**

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

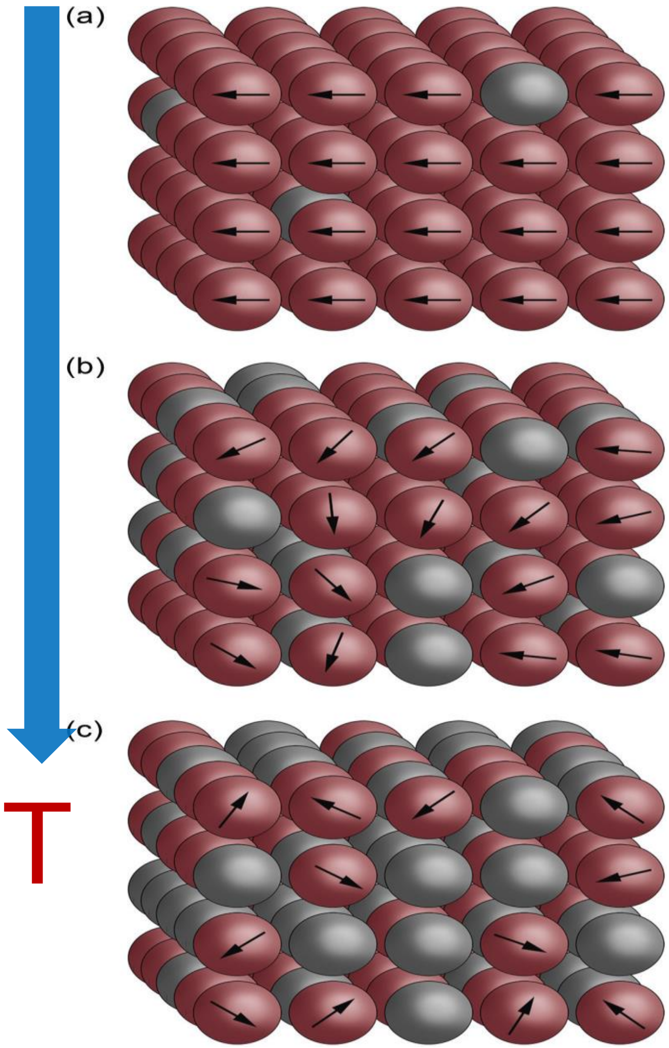


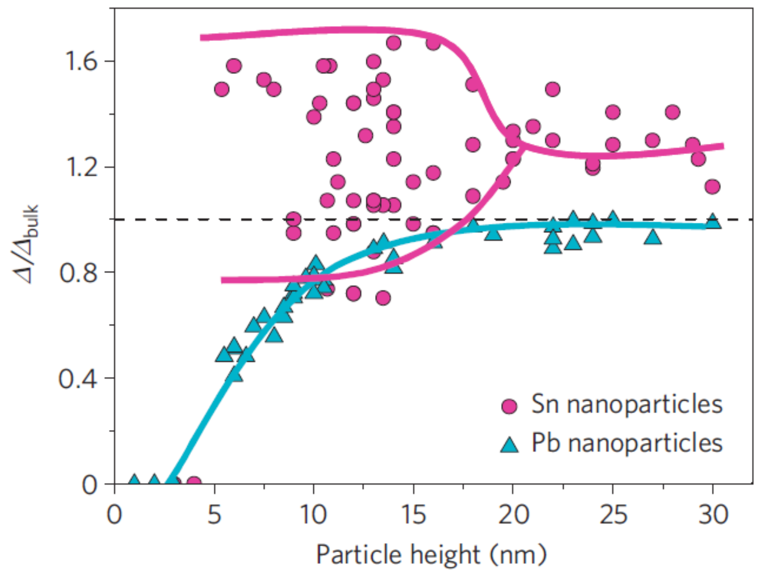
Mayoh, AGG, Phys. Rev. B 90, 134513 (2014)

Global T_c ?

Grey = No SC

L ~ 5nm





Highly inhomogenous

Local T_c sensitive to L

Fine not all grains SC

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

Deutscher 73'

Packing

How?

Single grain

$$\Delta \gg \delta$$

BCS

$$L \sim 5nm$$

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

Periodic orbit theory

Balian,Bloch,Gutzwiller

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

Open grain

Tunneling

Cutoff long periodic orbits

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 ?

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

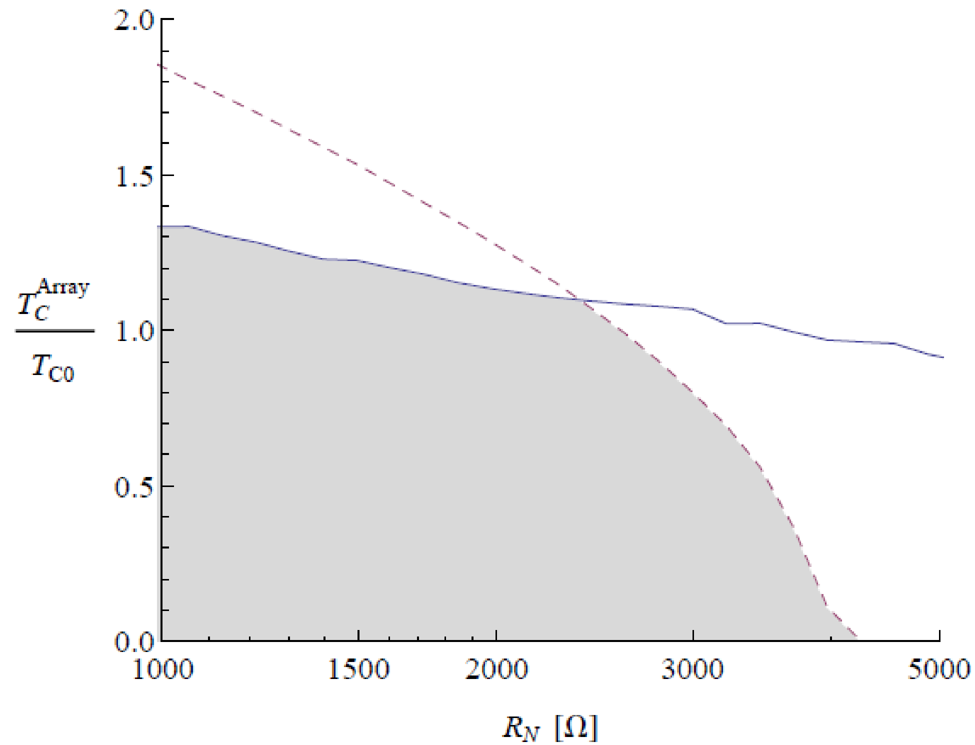
Percolation?

Phase fluctuations?

T

#SCgrains

T_c?

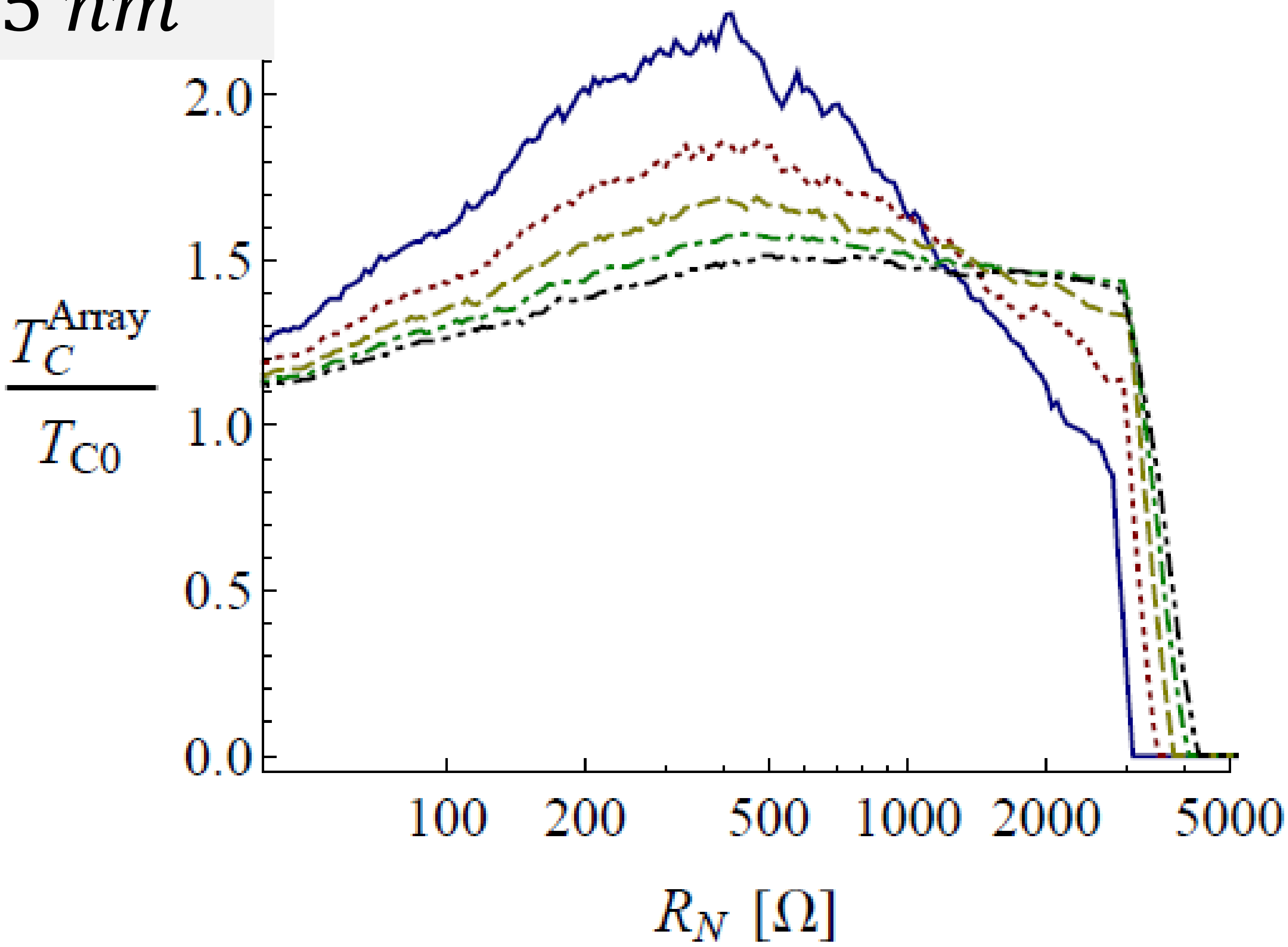


R=5nm σ=1nm λ=0.3

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

$\sigma = 1\ nm$

$\bar{R} = 5\ nm$

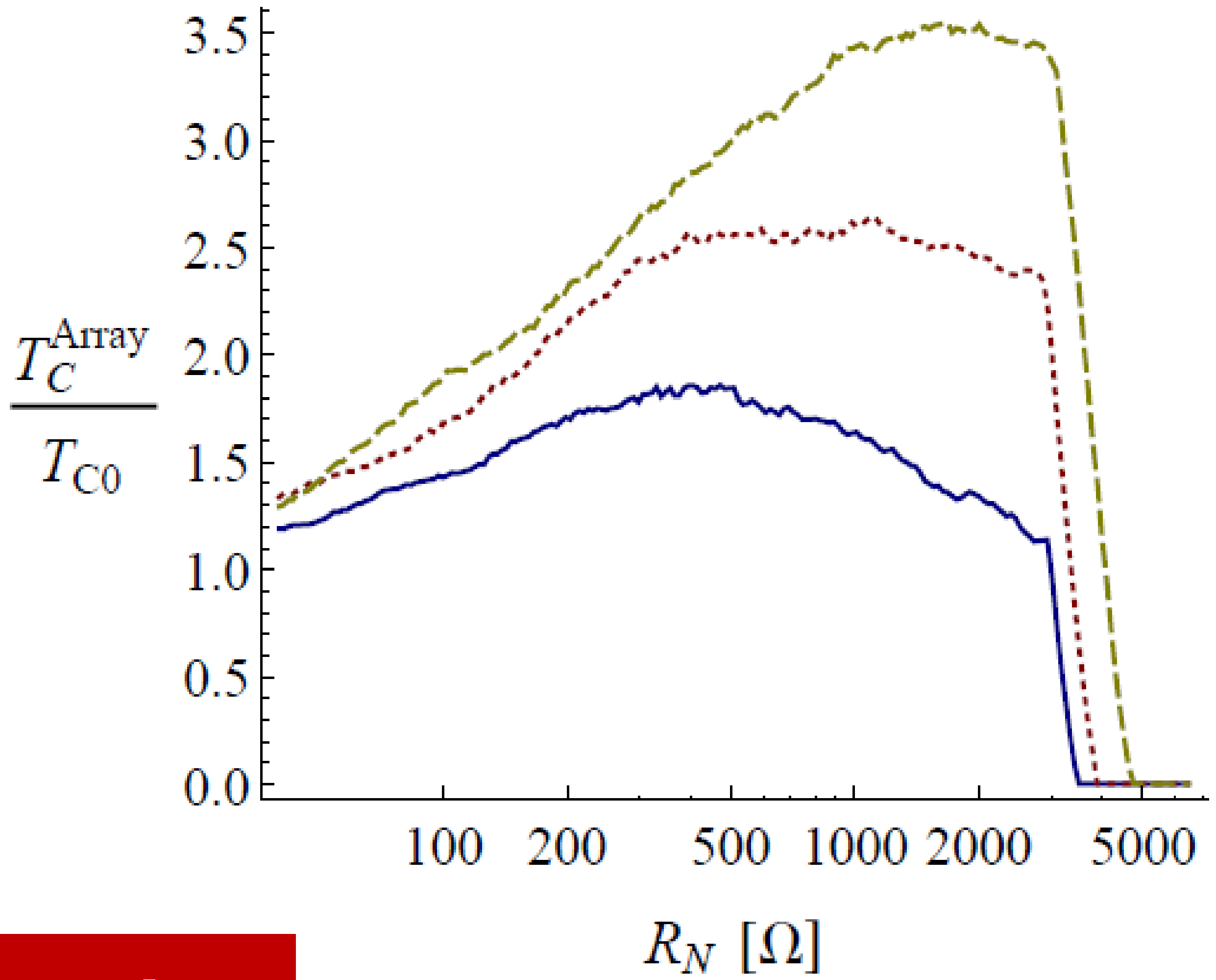


Packing = Cubic, BCC, FCC

$\sigma = 1\, nm$

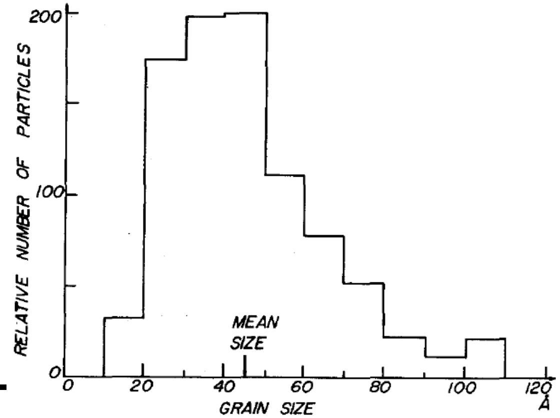
$\bar{R} = 5\, nm$

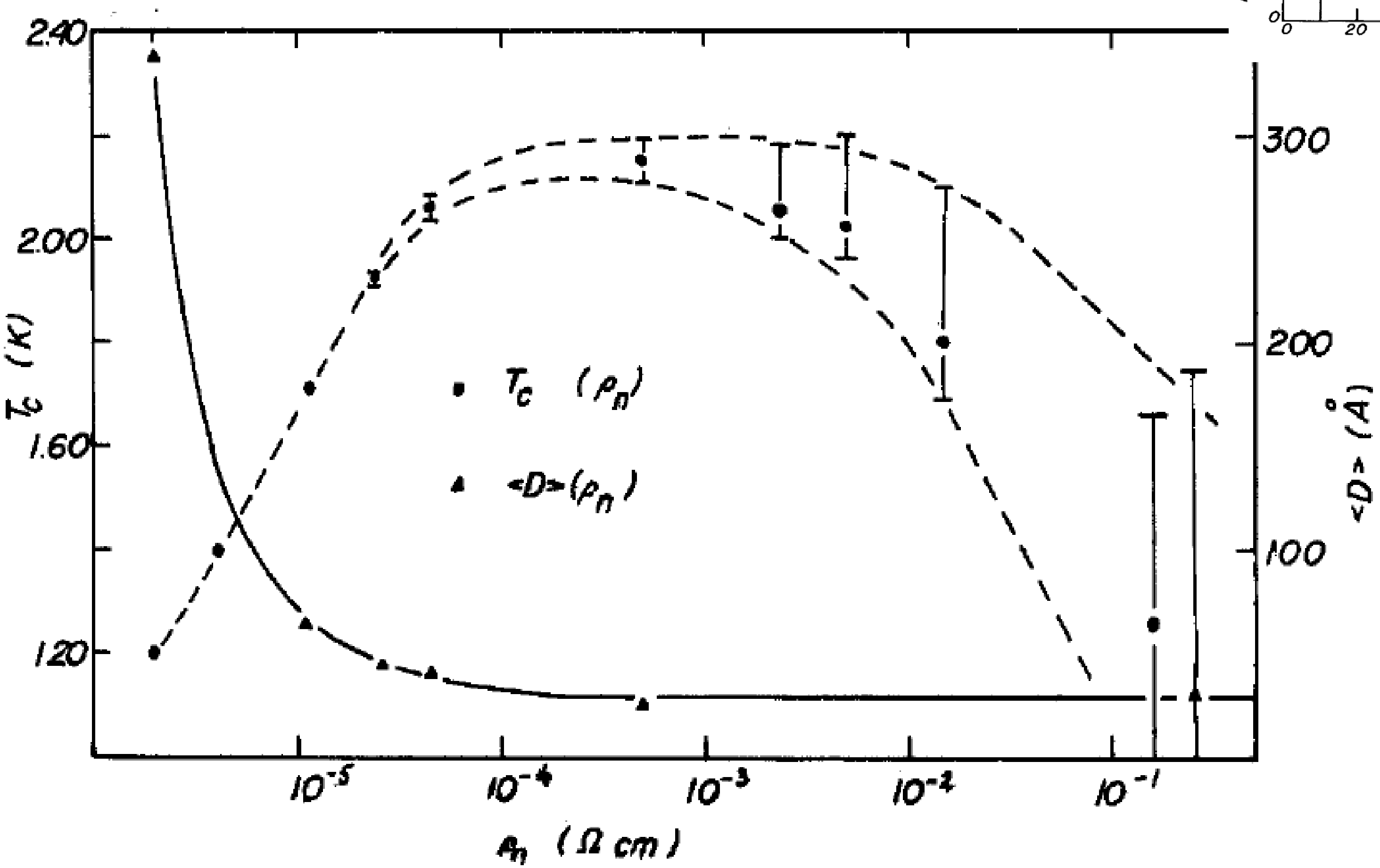
$\lambda = 0.25$



Enhancement!

Al evaporated on a glass substrate





Deutscher 73’

Disorder and enhancement of superconductivity?

Are you crazy?

Gor'kov and Abrikosov

Anderson theorem

Anderson, J. Phys. Chem. Solids 11, 26 (1959)

Finkelstein A M, 1987

Weak localization corrections

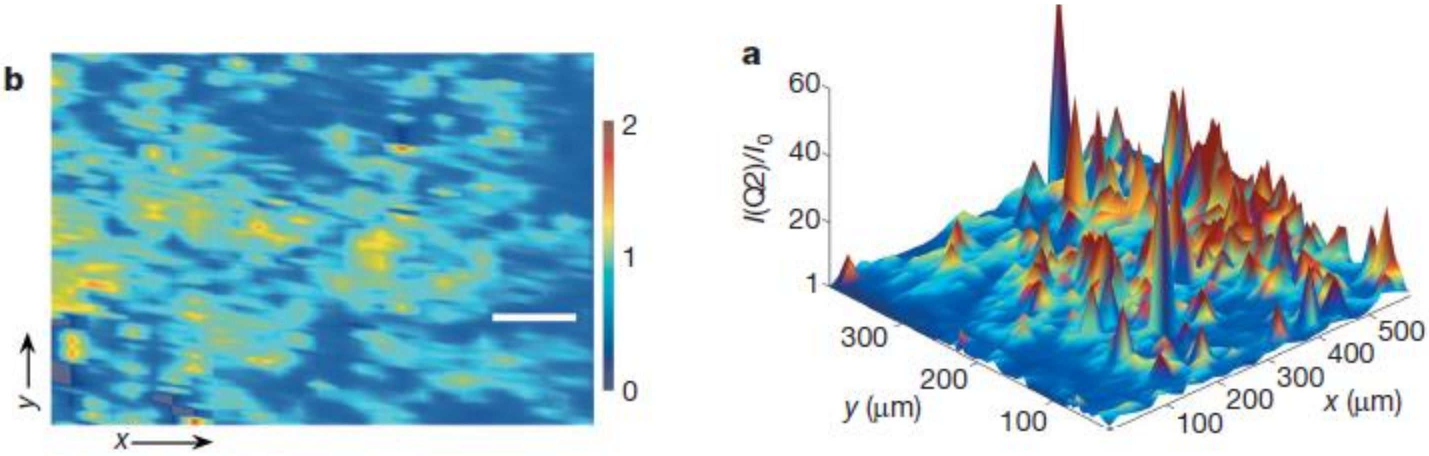
Maekawa S, Fukuyama H, 1982
J.Phys.Soc. Jpn. 51 1380.

Anderson theorem is all but a theorem

Be careful with BCS+Perturbation

Enhancement of Tc by disorder

Fractal distributions of dopants enhance Tc in cuprates



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

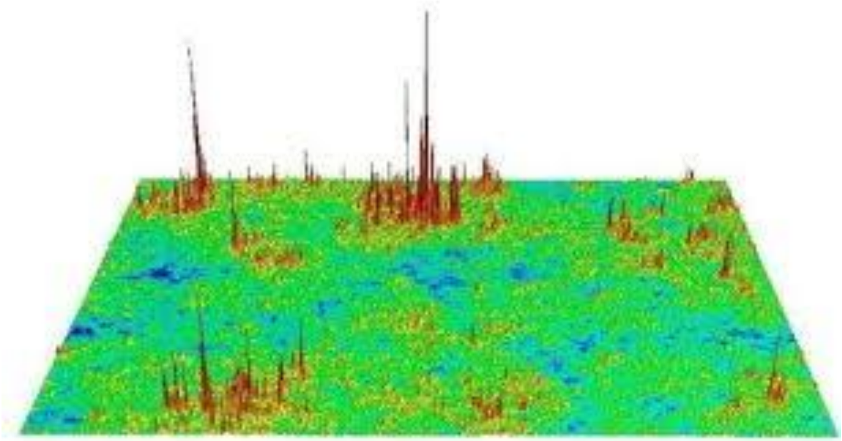
Inhomogeneities ⟷ Higher T_c

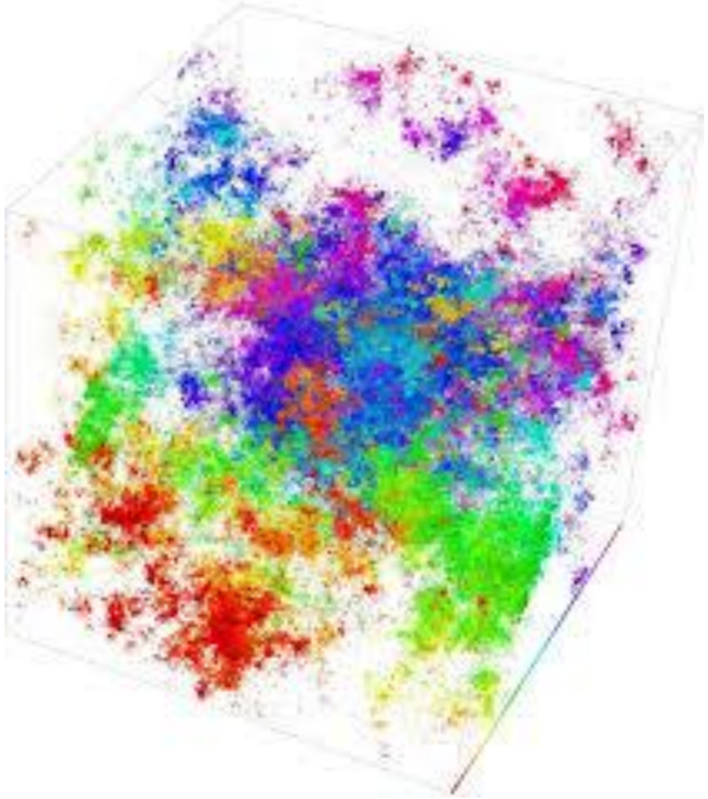
PRL 108, 017002 (2012)

Anderson Metal-Insulator Transitions

Multifractal eigenstates

Wegner, Aoki, Castellani, Efetov





$$P_q = \int d\mathbf{r} |\psi(\mathbf{r})|^{2q} \sim L^{d_q (q-1)}$$

Strong multifractality and superconductivity

Feigelman, Ioffe, Kravtsov, Yuzbashyan, Phys. Rev. Lett. 98, 027001 (2007)

I. S. Burmistrov, I. V. Gornyi, A. D. Mirlin, Phys. Rev. Lett. 108, 017002 (2012)

$$\Delta(\epsilon) = \frac{\lambda}{2} \int_{-\epsilon_D}^{\epsilon_D} \frac{I(\epsilon, \epsilon')\Delta(\epsilon')}{\sqrt{\epsilon'^2 + \Delta^2(\epsilon')}} \tanh\left(\frac{\beta\sqrt{\epsilon'^2 + \Delta^2(\epsilon')}}{2}\right) d\epsilon'$$

$$I(\epsilon, \epsilon') = \left(\frac{E_0}{|\epsilon - \epsilon'|}\right)^{\gamma}$$

$\epsilon_D \to \infty$?

$\epsilon = \epsilon_F$

$\gamma \sim 0.4$

$$V \int d\mathbf{r} |\psi(\epsilon, \mathbf{r})|^2 |\psi(\epsilon', \mathbf{r})|^2$$

$$\gamma = 1 - \frac{d_2}{d} \sim 0.4$$

$$T_c^0(\lambda, \gamma) = E_0 \lambda^{1/\gamma} C(\gamma)$$

$$P_q = \int d\mathbf{r} |\psi(\mathbf{r})|^{2q} \sim L^{d_q(q-1)}$$

$T_c \geq 1000K$

Weak multifractality and superconductivity

J. Mayoh and AGG, arxiv:1412.0029

Where?

(Ultra) Thin films

2D + Spin orbit

1D + Long Range

What?

$\Delta(\epsilon_F)$ spatial distribution

$\Delta(\epsilon)$ energy dependence

$\Delta(r)$ spatial distribution

Global T_c

How?

$\lambda, \gamma \ll 1$

$BCS, \epsilon_D\ fixed$

Percolation

$$\gamma = 1 - \frac{d_2}{d}$$

$$d_q \approx d(1 - \kappa q)$$

$$\kappa = \alpha/g$$

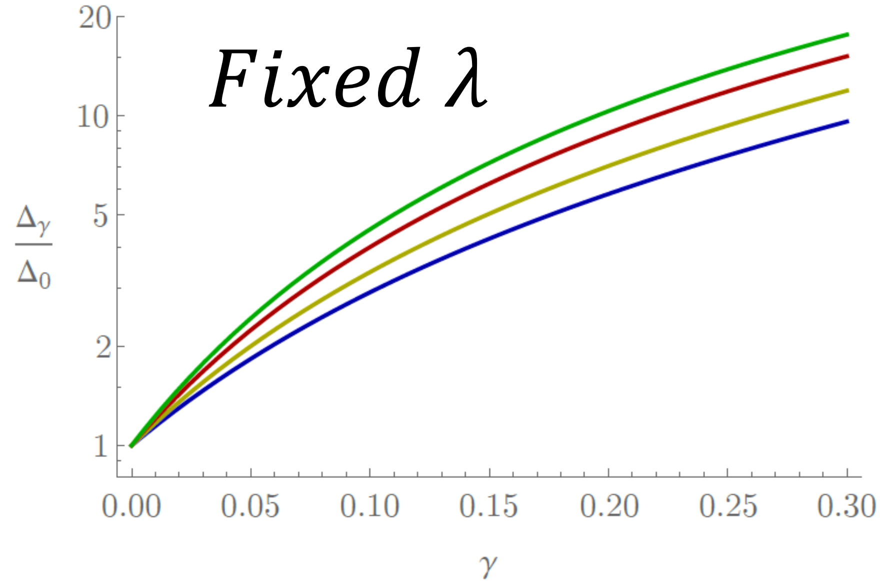
Can disorder enhance SC?

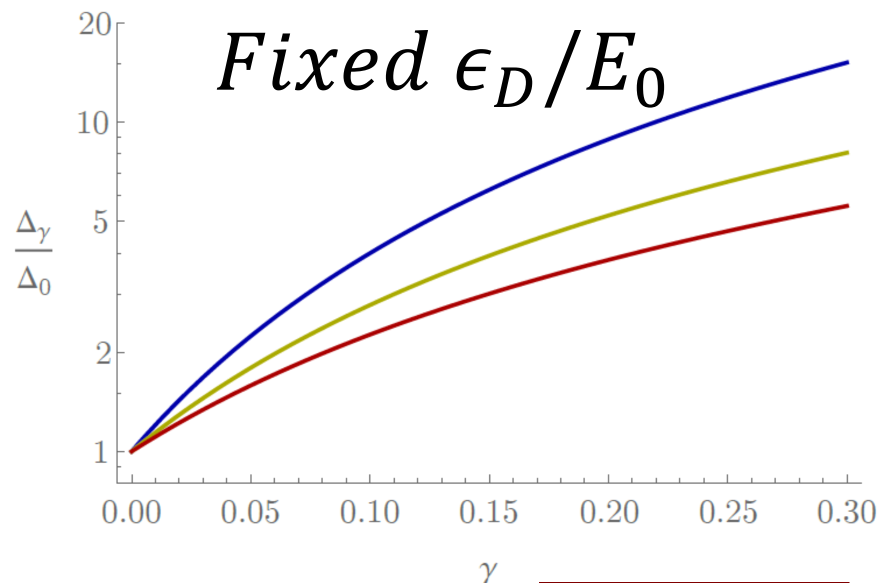
$$\Delta(\epsilon_F) = \Delta_\gamma$$

$$\Delta_\gamma = D(\gamma)\epsilon_D \left(1 + \frac{\gamma}{\lambda}\left(\frac{\epsilon_D}{E_0}\right)^\gamma\right)^{-\frac{1}{\gamma}}$$

$$\Delta_\gamma \approx D(\gamma)\epsilon_D e^{-\frac{1}{\lambda}\left(\frac{\epsilon_D}{E_0}\right)^\gamma}$$

$$\frac{2\Delta_\gamma}{k_B T_{c\gamma}} = \frac{2D(\gamma)}{C(\gamma)}$$





Still unrealistic

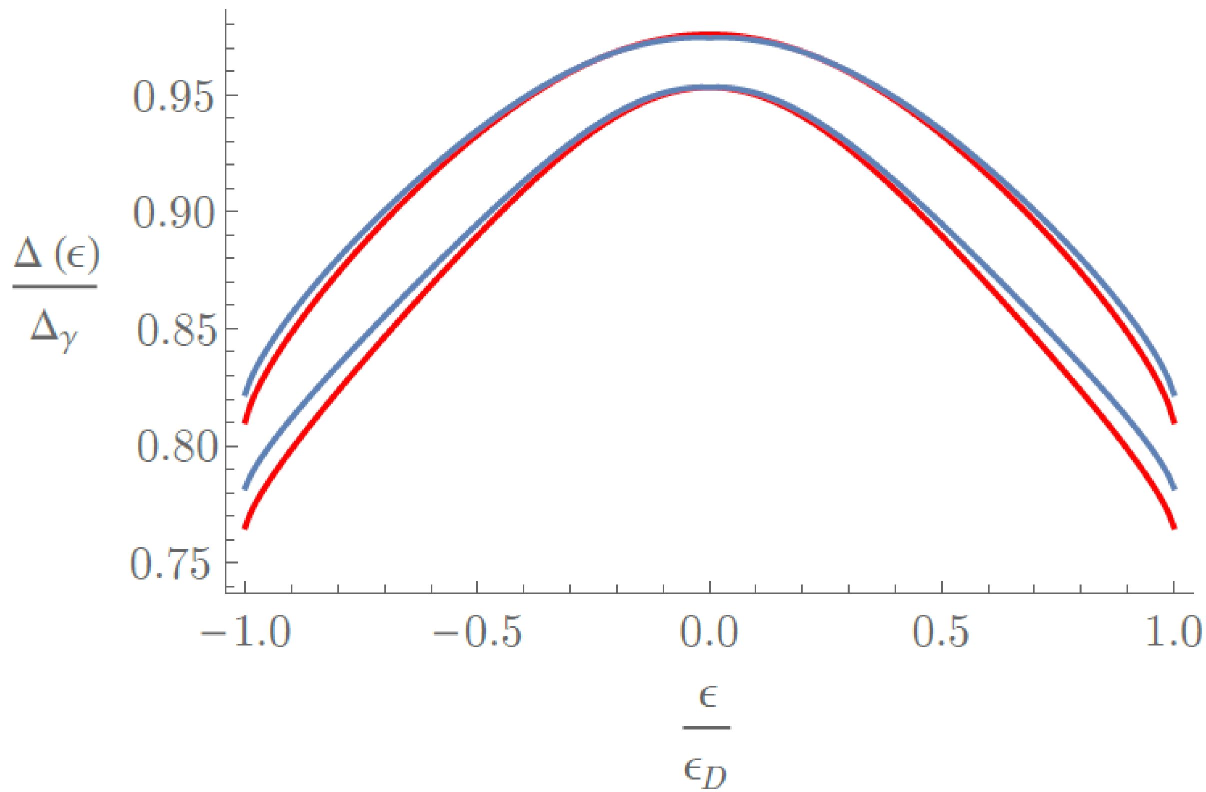
Why?

Inhomogenous SC → Not true Tc

Energy dependence of $\Delta(\epsilon)$

$$\Delta(\epsilon) = \Delta_\gamma\left(1 + \gamma f_1(\epsilon) + \gamma^2 f_2(\epsilon) + \ldots\right)$$

$$f_1(\epsilon) = \frac{\lambda}{2}\int_{-\epsilon_D}^{\epsilon_D}\left[\frac{\epsilon'^2 f_1(\epsilon')}{(\epsilon'^2+\Delta_\gamma^2)^{3/2}}\left|\frac{E_0}{\epsilon'}\right|^\gamma - \frac{\ln\left|1-\frac{\epsilon}{\epsilon'}\right|}{\sqrt{\epsilon'^2+\Delta_\gamma^2}}\left|\frac{E_0}{\epsilon'}\right|^\gamma\right]d\epsilon'$$



Spatial Distribution

$$\langle \Delta^n(\mathbf{r}) \rangle = \int d\mathbf{r} \prod_{j=1}^{n} \left(\frac{\lambda V}{2} \int \frac{\Delta(\epsilon_j)}{\sqrt{\Delta(\epsilon_j)^2 + \epsilon_j^2}} |\psi(\epsilon_j, \mathbf{r})|^2 d\epsilon_j \right)$$

Eq.137, Feigelman M V, Ioffe L B, Kravtsov V E, Cuevas E, 2010 Ann. Phys. 325 1368

$$\frac{\langle \Delta^n(\mathbf{r}) \rangle}{(\Delta_\gamma)^n} = e^{\kappa \ln(\epsilon_D/E_0)(3n - n^2)}$$

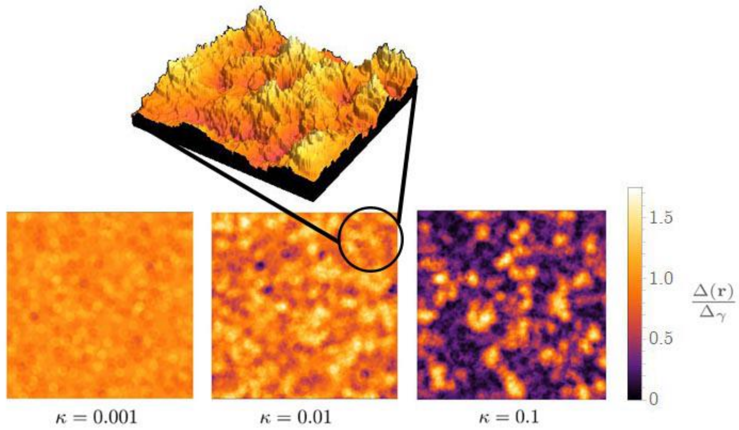
$$\mathcal{P}\left(\frac{\Delta(\mathbf{r})}{\Delta_\gamma}\right) = \frac{\Delta_\gamma}{\Delta(\mathbf{r})\sqrt{2\pi}\sigma} \exp\left[-\frac{\left(\ln\left(\frac{\Delta(\mathbf{r})}{\Delta_\gamma}\right) - \mu\right)^2}{2\sigma^2} \right]$$

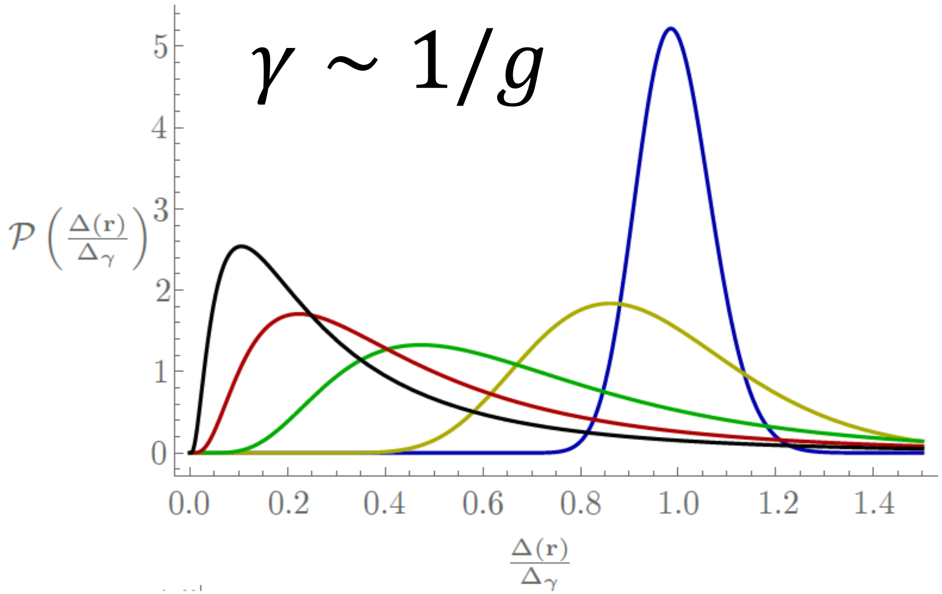
$$\mu = 3\kappa \ln(\epsilon_D/E_0)$$

Universal log-normal distribution!

$$\left\langle \frac{\Delta(\mathbf{r})}{\Delta_\gamma} \right\rangle = \left(\frac{\epsilon_D}{E_0}\right)^{2\kappa}$$

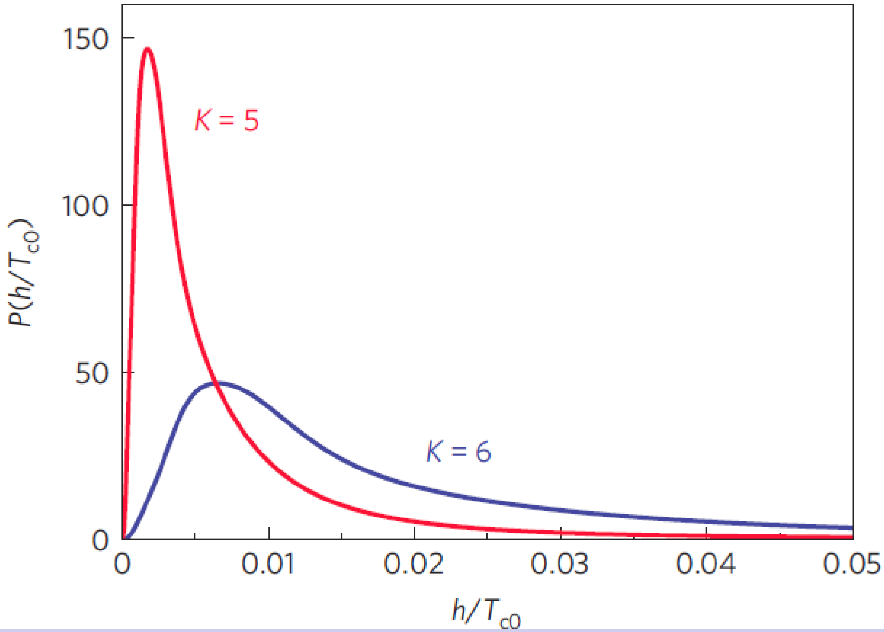
$$\sigma = \sqrt{2\kappa \ln(E_0/\epsilon_D)}$$





Global Tc?

$$\mathcal{P}\left(\frac{T_c(\mathbf{r})}{T_{c_\gamma}}\right) = \mathcal{P}\left(\frac{\Delta(\mathbf{r})}{\Delta_\gamma}\right)$$



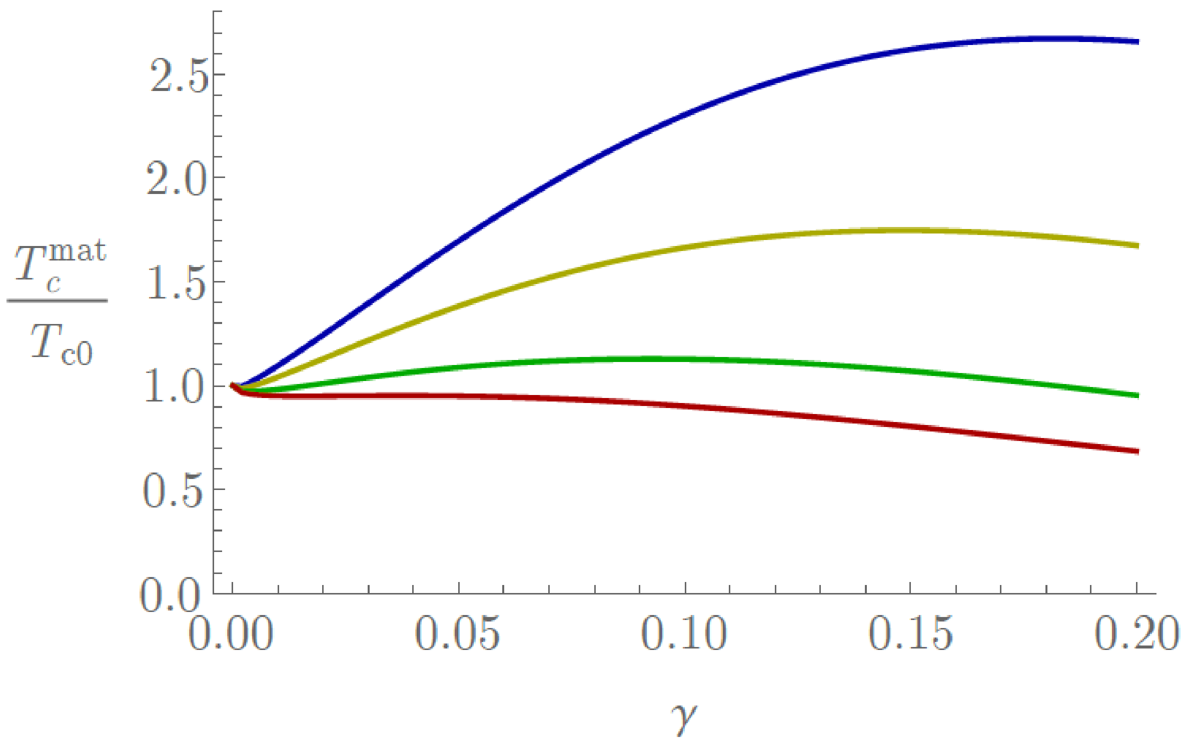
Sacepe et al., Nat. Phys. 7 239 (2011)

Global Tc

$$\int_0^{T_c^{\mathrm{mat}}} \mathcal{P}(T_c(\mathbf{r}))dT_c(\mathbf{r}) = 1 - \phi_c$$

Percolation

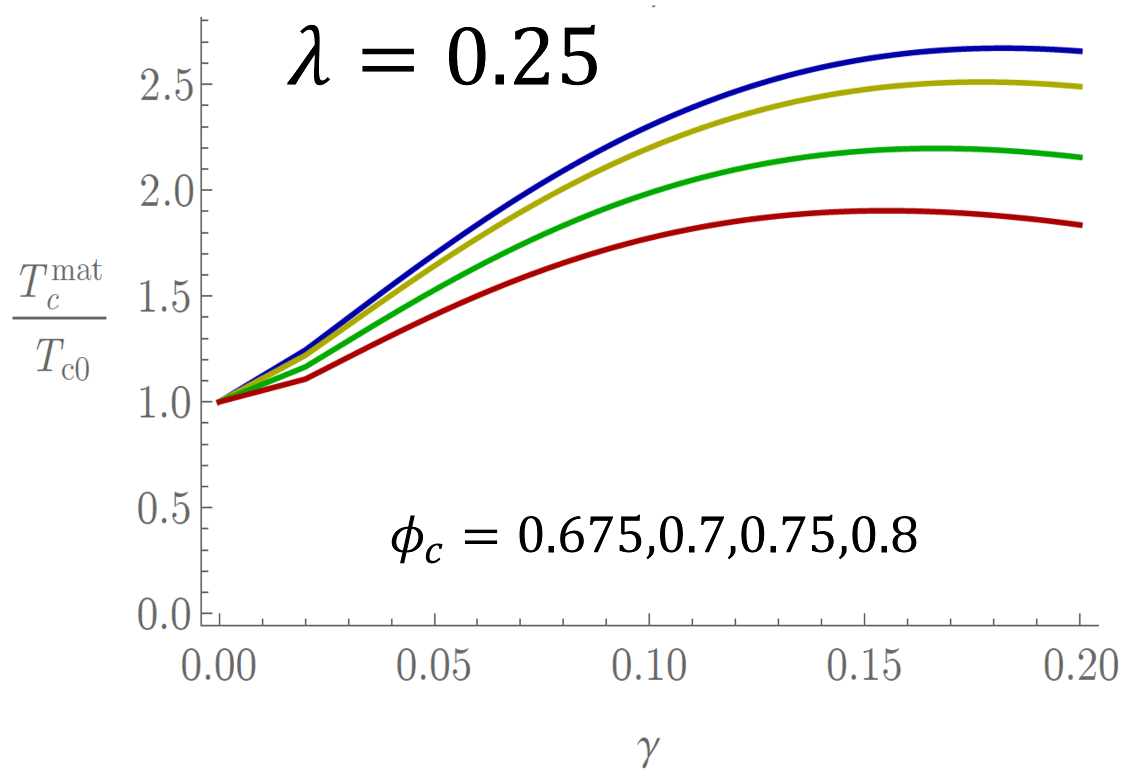
$$\phi \to \phi_c = 0.676$$



$\lambda = 0.25, 0.3, 0.4, 0.5$

Phase fluctuations?

$\phi > \phi_c$



Enhancement?

Yes But

$\lambda \leq 0.3$

Al is fine!

Experimental tests

Disorder

STM in thin films $\log^2$ distribution

Transport to test higher global Tc

Nano engineering

L ~ 5-10nm?

Conclusion:

Enhancement?

Sure

Only in boring materials?

FeSe?

MgB_2?

THANKS!