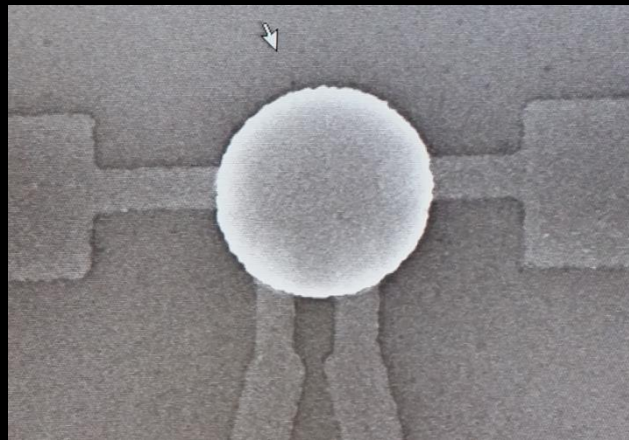


Large variance of T_c at long length scales in granular mesoscopic Nb islands

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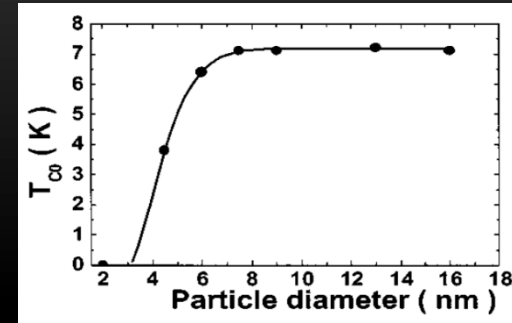
Superconductivity in Granular Systems

- For an **isolated grain**, superconductivity is destroyed when level spacing $>$ gap size, or

$$dE > D$$

- For Nb, superconductivity is suppressed at:

$$L = 4.3 \text{ nm and } \Delta = 3.05 \text{ meV}$$

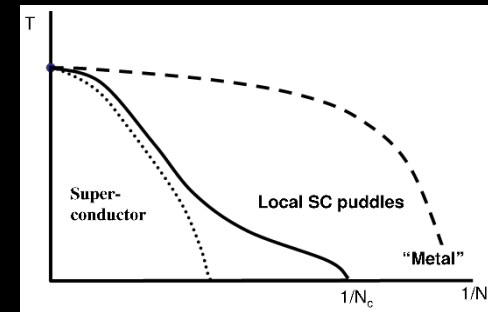


W.H. Li, C. C. Yang, F. C. Tsao, K. C. Lee, *Phys. Rev. B* **68**, 184597 (2003)

- For a **SC grain embedded in a normal metal**: Coherence length is relevant (due to inverse proximity effect)

Nb: Dirty limit coherence length

$$\xi_{SC} \sim 38 \text{ nm}$$

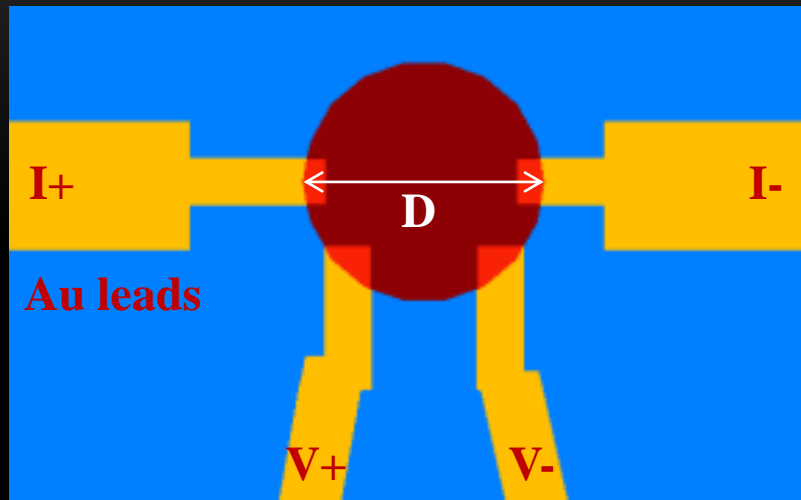


B. Spivak, P. Oretto, and S. A. Kivelson, *Phys. Rev. B* **77**, 214523 (2008).

- For **system of grains embedded in a normal metal**: Expect S-N transition.

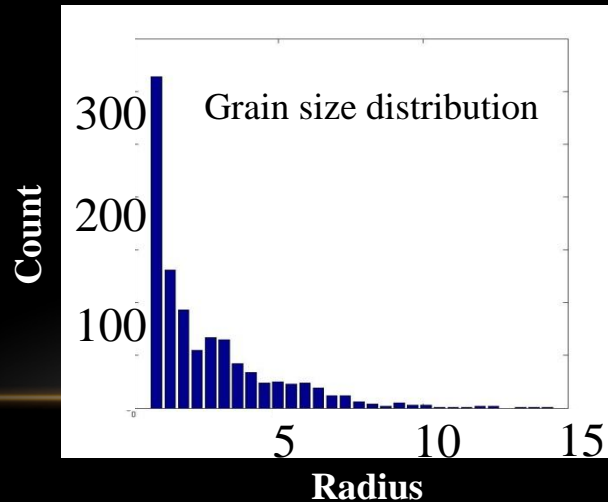
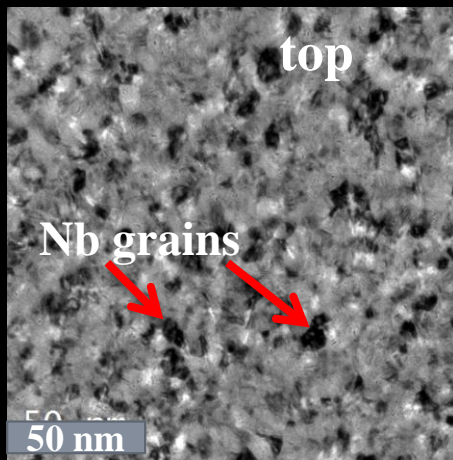
- Open question:** What determines the **onset** of superconductivity in S-N system?
 - Study transport in mesoscopic granular islands

Mesoscopic Granular Nb Islands



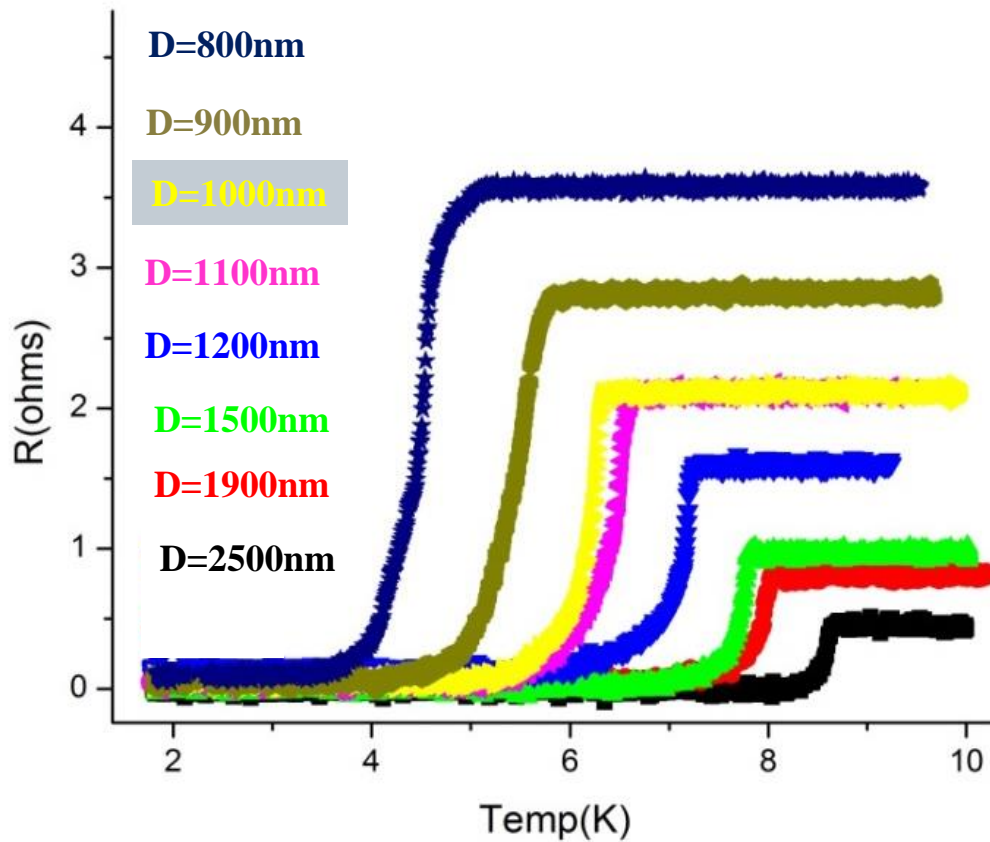
- Nb islands (70 nm thickness) contacted to Ti/Au (1 nm/10nm) leads.
- Vary diameter between:
700nm \longleftrightarrow 2600nm
~600 grains $\hspace{15em}$ ~10,000 grains
- Key length scale:

$$\xi_{SC}^{Nb} (T_c \approx 9.1 \text{ K}) \approx 27 \text{ nm}$$



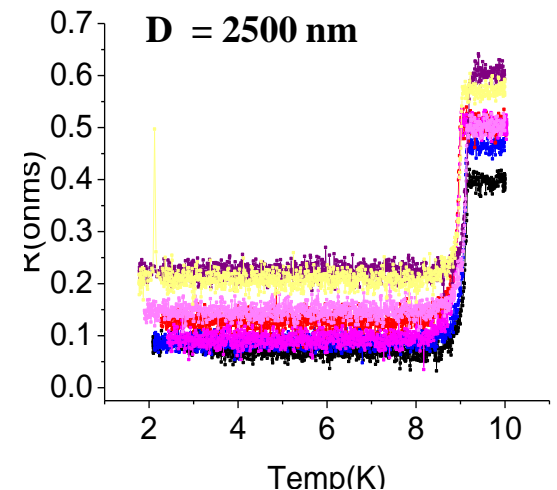
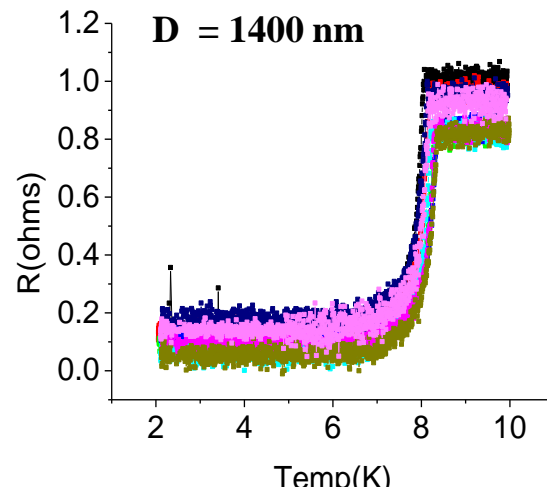
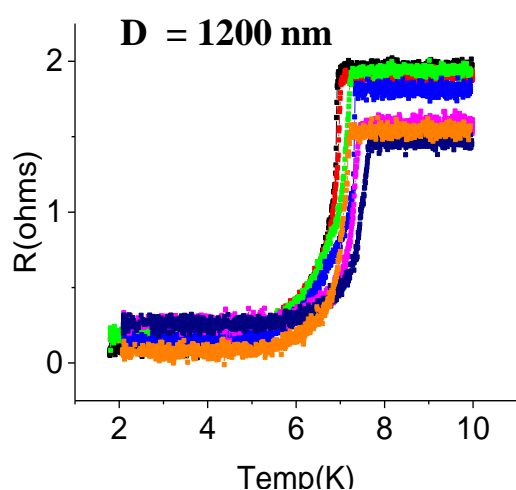
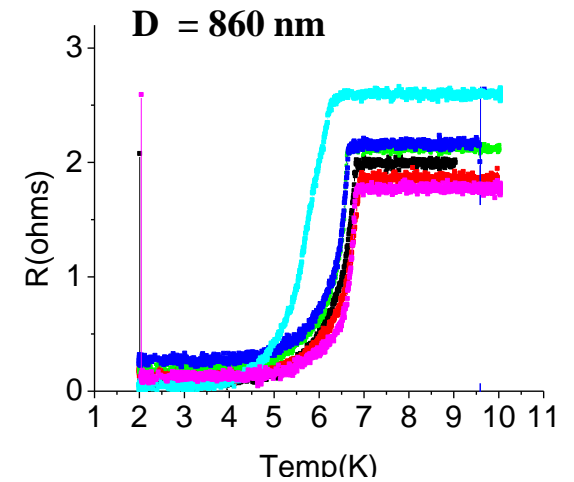
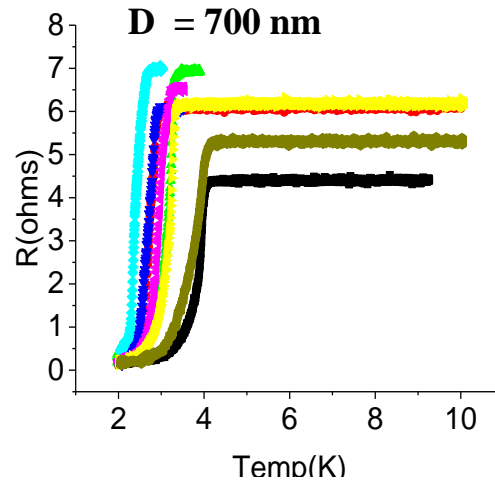
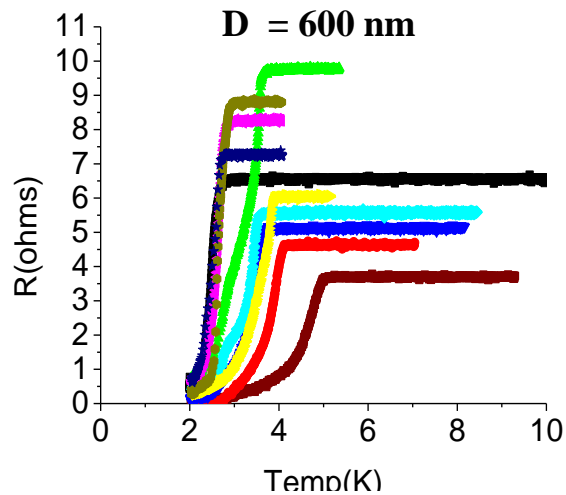
- TEM shows two types of Nb: **granular Nb** (superconducting) and **amorphous non-superconducting Nb** (metallic matrix).

T_c suppression at long length scales



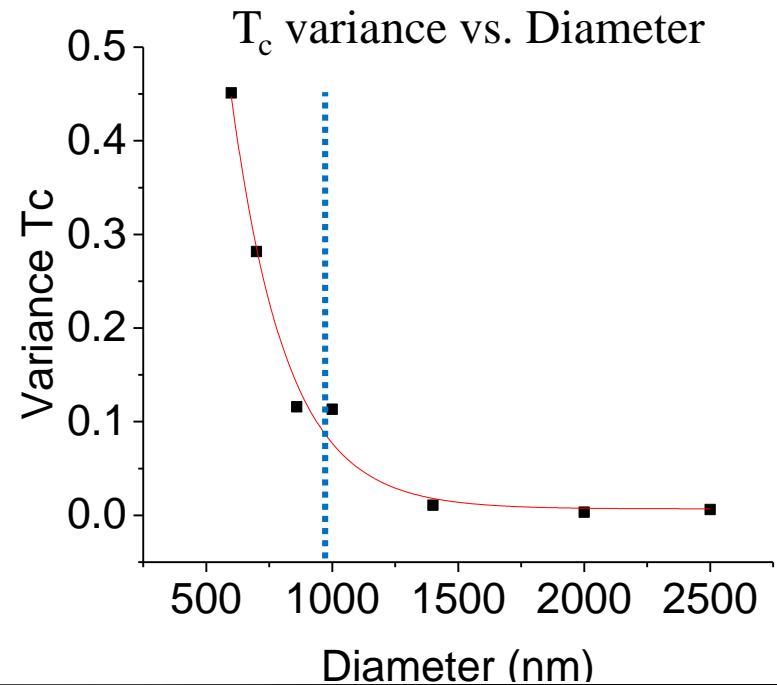
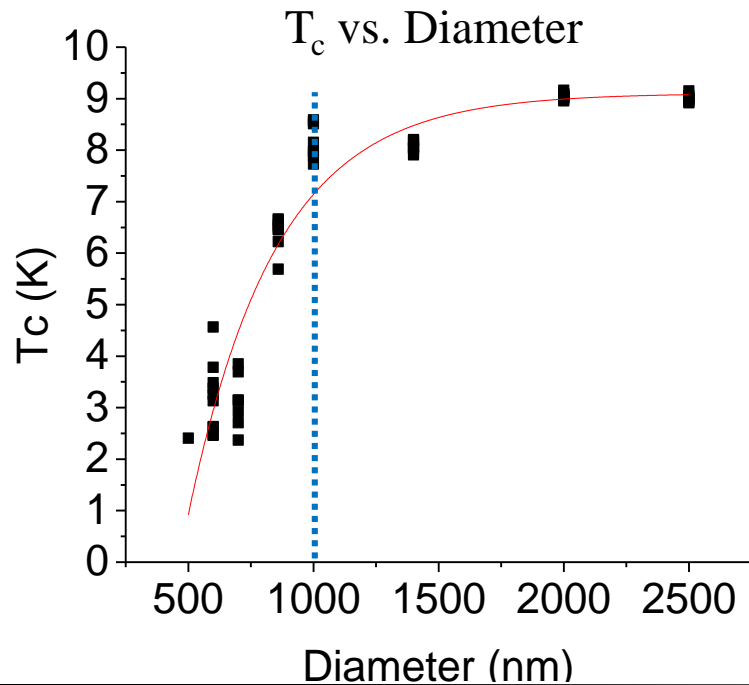
Variation of T_c with Diameter

- Each trace within a single graph corresponds to a different Nb island of the same diameter.
- Each graph represents 10-12 islands.
- T_c varies even for same diameter islands.



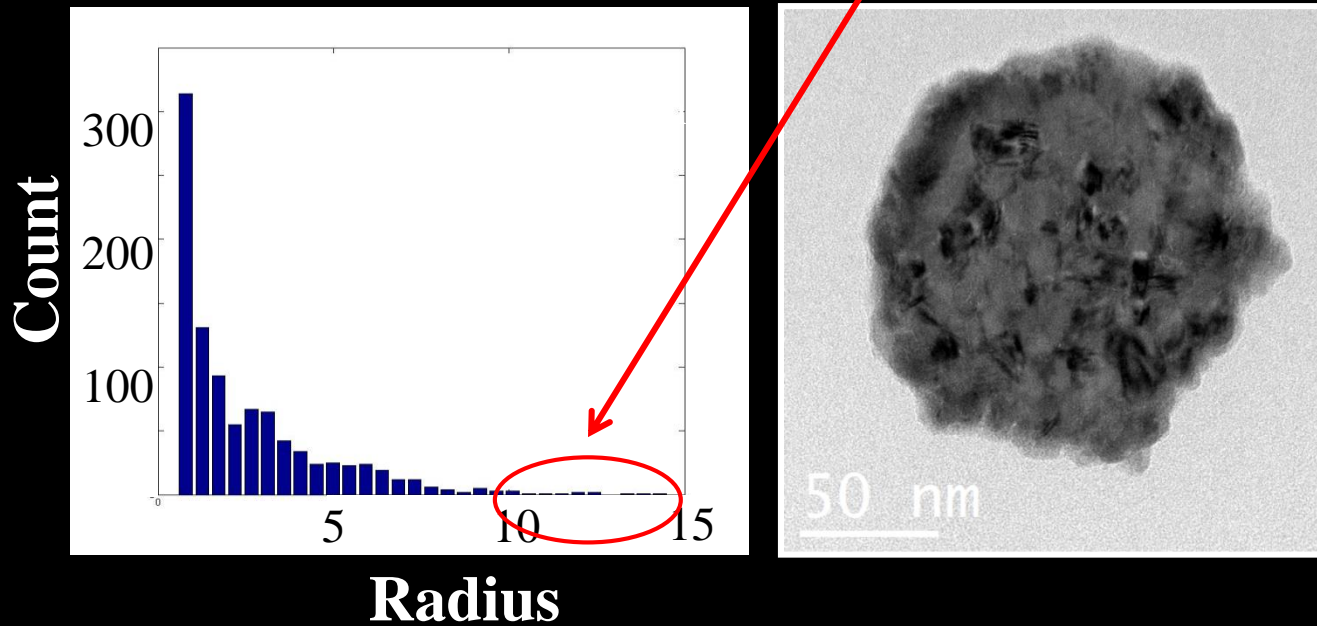
Variation of T_c with Diameter

- Exponential suppression of T_c with decreasing diameter.
- Exponential increase in T_c variation at small diameters.
- Note: 10-12 points for each diameter.



So...what is happening in our granular Nb islands?

- Onset of superconductivity driven by **largest grains** i.e. $L >$ coherence length.

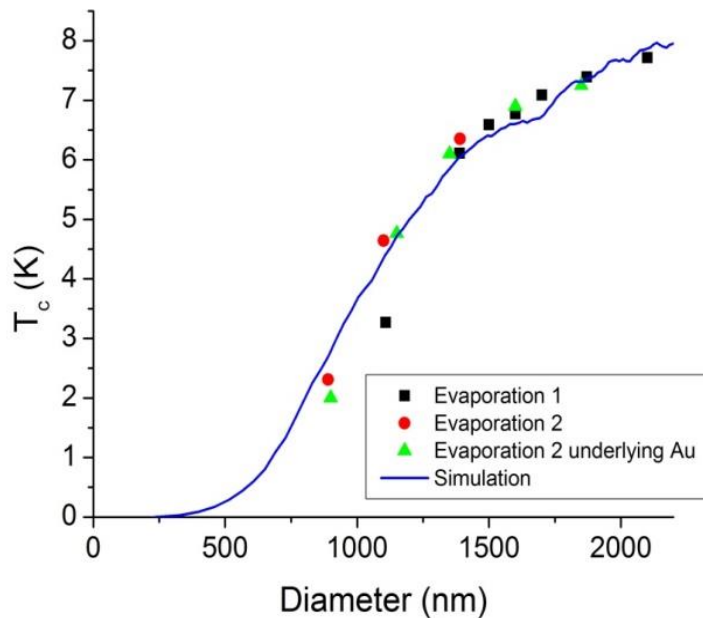


- Grain distribution does not depend on island diameter (measured via TEM).

Rare grain model predicts T_c fluctuations

- **Small diameter** \longrightarrow **Low probability of large grains** \longrightarrow **Large fluctuations in T_c**
- Simulations using an **exponential distribution** of grains (from TEM data) where the onset of superconductivity is set by largest grains supports experimental results.
 - Large grains go superconducting
 - Due to proximity effect, smaller grains go superconducting.

Simulation using largest grain to determine T_c



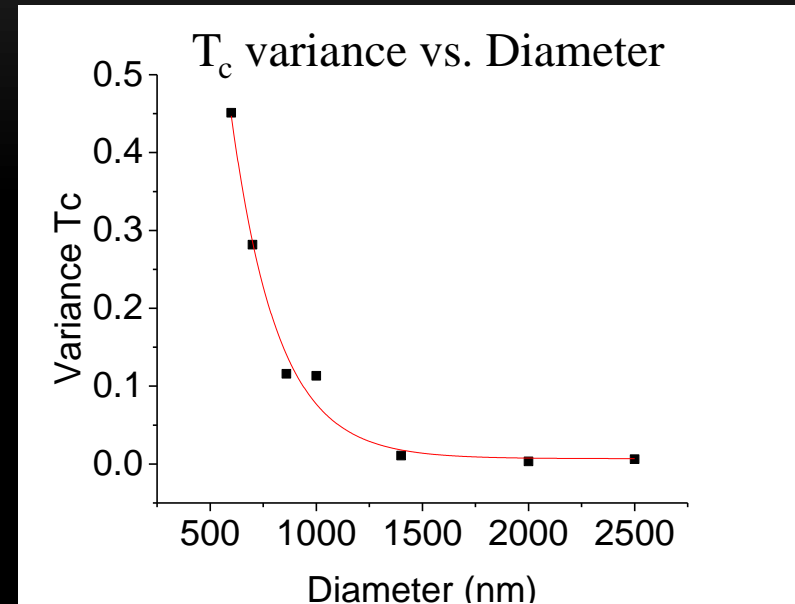
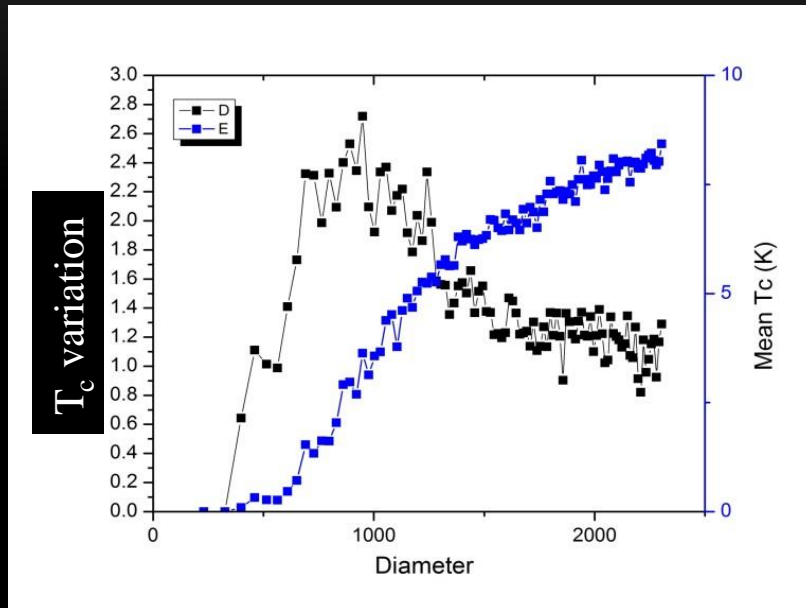
- Probability of largest grain:

$$e^{-(R_{larg}_{est} - R_{mean})/\sigma} = \frac{1}{N}$$

$$T_c \sim \sqrt{R_{largest} - x}$$

Rare grain model predicts T_c fluctuations

- Small diameter \longrightarrow Low probability of large grains \longrightarrow Large fluctuations in T_c

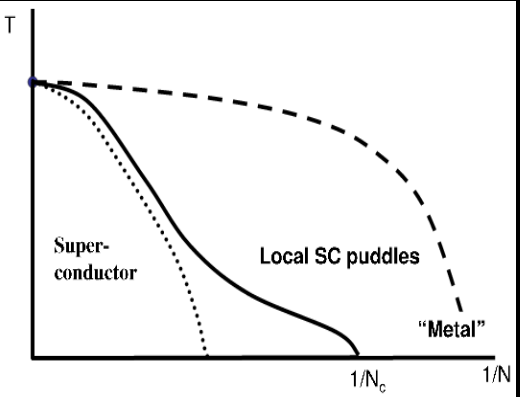


- T_c simulation from exponential grain distribution using the largest grain size generated by a pseudo random number generator:
 - Simulation outputs largest grain size fluctuation after various iterations for different diameters (Gumbel distribution).
 - Largest grain size fluctuation proportional to T_c variation.
 - Good agreement between simulation and experiment except for islands where $L <$ coherence length.

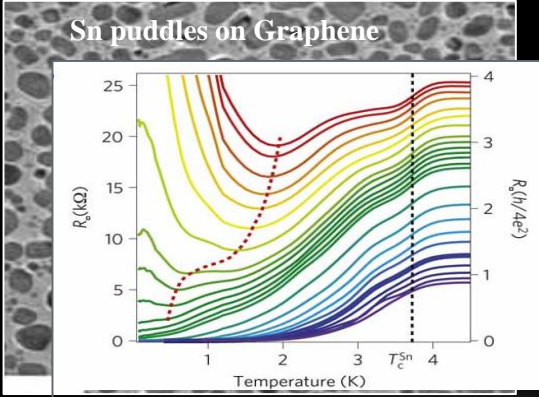
Conclusion

- T_c suppression at micron length scales due to onset of superconductivity of unusually large grains.
- Variance study of T_c supports rare large grain theory through a good fit to exponential decay (tail-end of Gumbel distribution) as a function of island diameter.

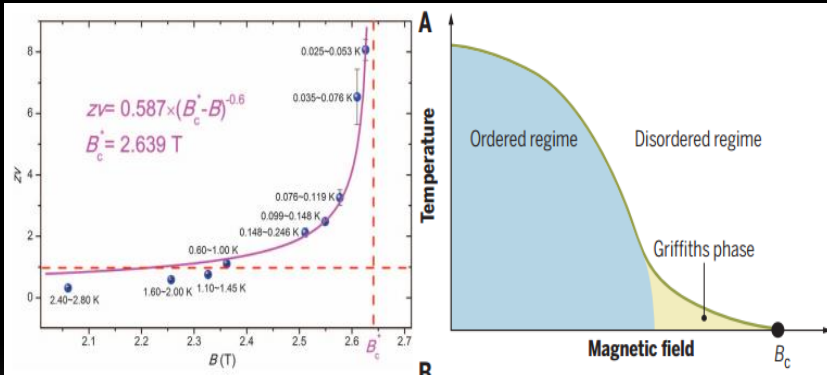
This understanding of how T_c emerges is relevant to a variety of granular systems:



B. Spivak, P. Oredo, and S. A. Kivelson, *Phys. Rev. B* **77**, 214523 (2008).



A. Allain, Z. Han, V. Bouchait, *Nat. Mater.* **11**, 590 (2012)



Y. Xing et al, *Science*, **350**, 542 (2015)
N. Markovic, *Science*, **350**, 509 (2015)