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Superfluid disorder in He-4: from edges and interfaces to superglass

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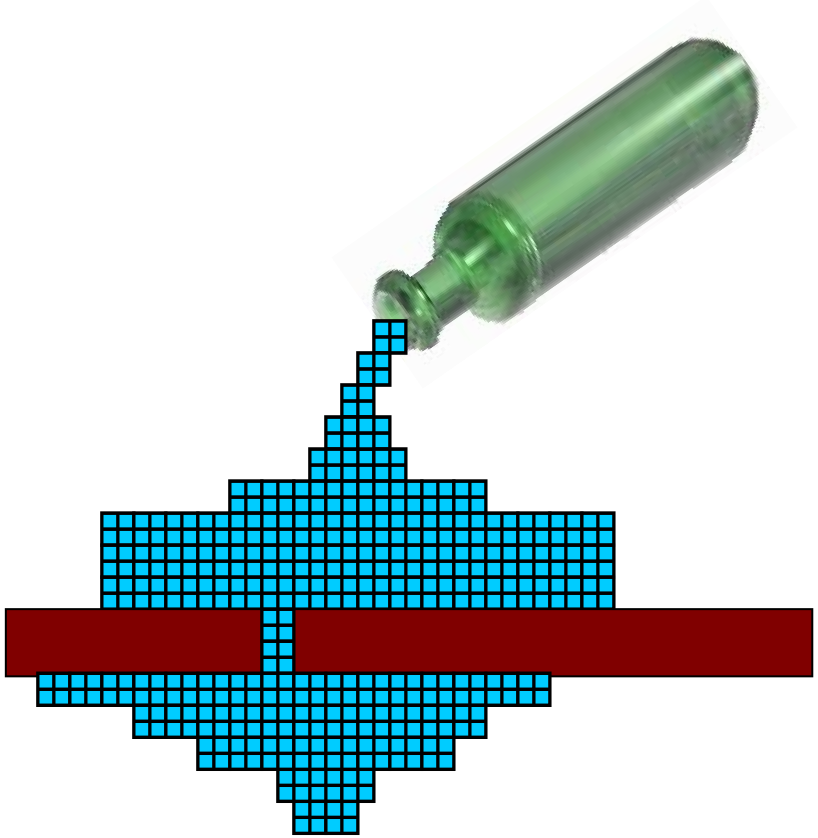
Superfluid disorder in He-4.

From edges and interfaces to superglass



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Boris Svistunov	UMass, Amherst
Evgeni Burovski	UMass, Amherst
Evgeni Kozik	UMass, Amherst
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Matthias Troyer	ETH
Anatoly Kuklov	CSI CUNY

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WHERE DISCOVERIES BEGIN

Trieste
July 3-7 (2006)

Outline

- Andreev-Lifshitz & Chester scenario for supersolids

- Experimental facts.

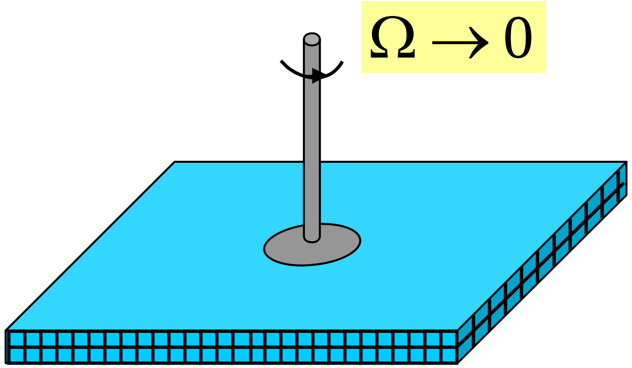
- Theorem: Continuous-space supersolids are always incommensurate
- He-4 *hcp* crystals are commensurate and insulating.
- Vacancies and interstitials are activated; vacancy gas is unstable

- Superfluid interfaces in lattice models (proof of principle)

- He-4 superglass

- Superfluid grain boundaries and ridges in polycrystalline samples

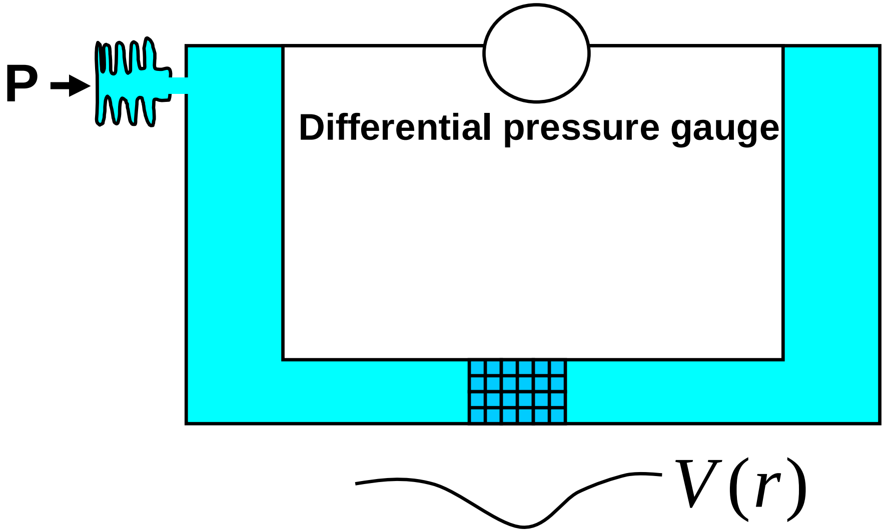
What is supersoilid?



$$E = \frac{1}{2} I \Omega^2$$

$$I \neq I_0 = \int \rho(r) r^2 dV$$

Non classical moment of inertia. Some of the crystal mass is not rotating with the lattice



Solid plug

Superflow or persistent current through the solid state; pressure Equilibration, etc.

SUPERSOLID = **Crystalline average density distribution** **.AND.** **frictionless liquid component**

$\rho(r)$ $\rho_S(r)$

Topology of lattice sites, shear modulus, Bragg peaks, etc …

Persistent currents, quantized velocity of circulation …

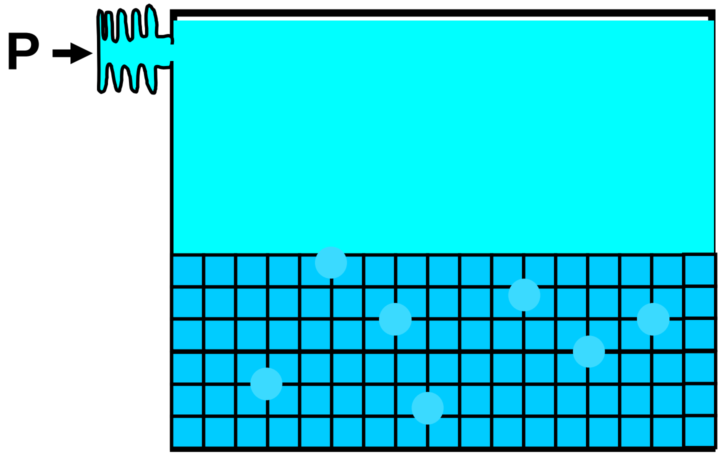
Same atoms participate in both

How can this happen?

Andreev & Lifshitz '69
Chester '70

Zero-point vacancies = "incommensurate" solid

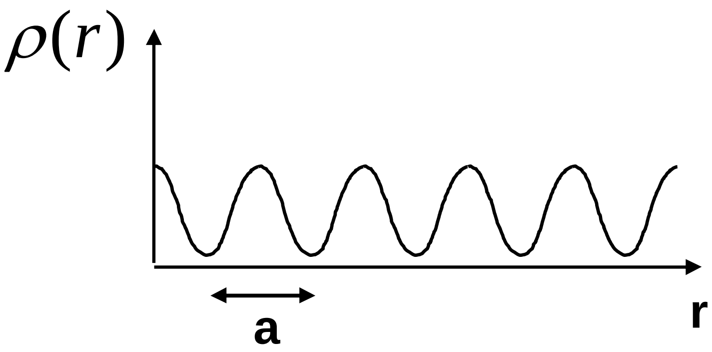
↓



Number of lattice points

$\neq$

Number of atoms in the ground state



Perfectly periodic, but $\dfrac{\int_o^{am} \rho(r)dr}{m} \neq 1$ **(integer)**

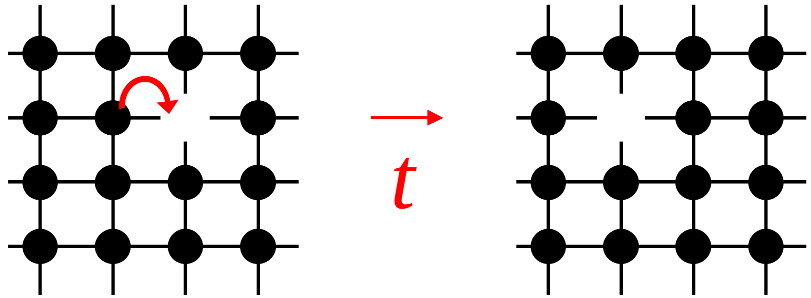
Start from a perfect structure

1. Create a static vacancy; $\delta\varepsilon = E_0 > 0$

2. Let the vacancy move around; $\delta\varepsilon = -zt < 0$

Reduction of kinetic energy of n.n. atoms

$$\delta p \sim h / \delta r$$

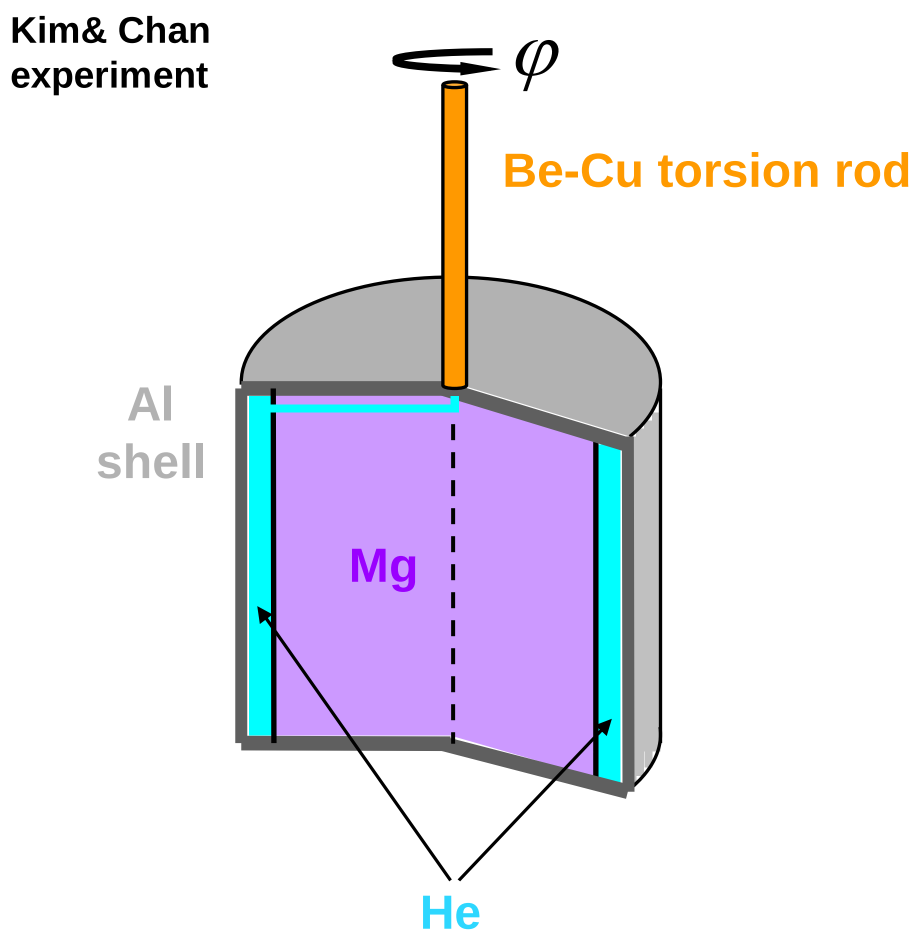


3. IF $\varepsilon_V = E_0 - zt < 0$ **, making vacancies is favorable for the structure.**

$$E \approx \varepsilon_V n_V + \frac{U}{2} n_V^2 \rightarrow n_V = \frac{|\varepsilon_V|}{U}$$

Weakly-interacting gas goes superfluid in 3D below

$$T_C \sim n_V^{2/3}$$



$$H = \frac{\kappa\varphi^2}{2} + \frac{I\dot{\varphi}^2}{2}$$

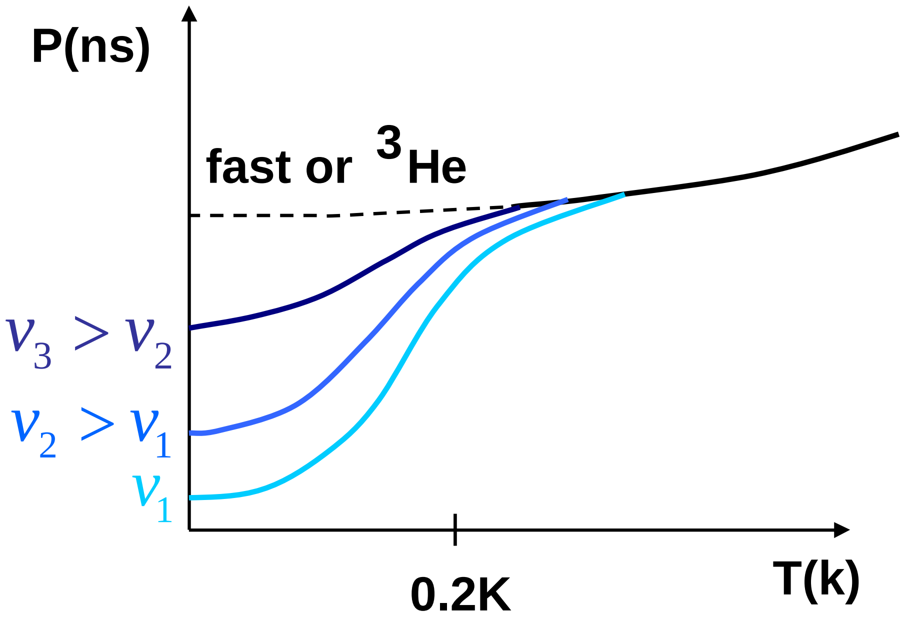
$$\Omega = \sqrt{\kappa / I}$$

$$I = I_{classical} \quad \text{if} \quad \rho_S = 0$$

$$I < I_{classical} \quad \text{if} \quad \rho_S > 0$$

Oscillation period drop = onset of superfluidity

$v = \Omega R$ - linear velocity

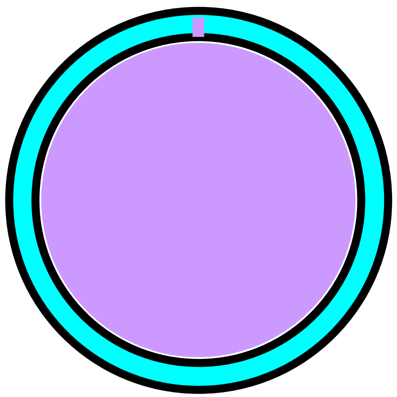


Systems
- ^{4}He in Vycor
- ^{4}He in porous gold
- ^{4}He frozen in bulk

⇩

1-2 % of ^{4}He did not follow the rotation

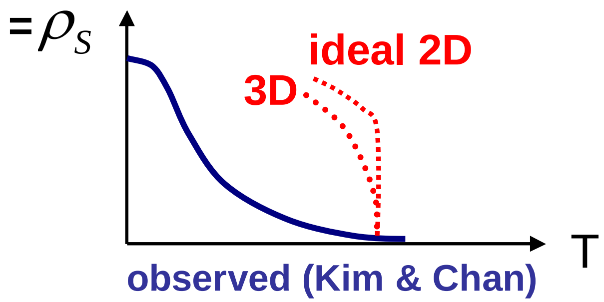
cut the channel



$\rho_S \rightarrow$ reduced by nearly two orders of magnitude

Problems with homogeneous 3D interpretation

- **Decoupled mass**



Strongly disordered system with a broad distribution of $T_C(\vec{r})$

- **He-3 impurities:** $\rho_3 / \rho_S \sim 10^{-3}$!

  impossible to understand in the homogeneous bulk state

physics of Josephson-junctions or weak-links cutting the flow is involved

- **"Elimination of the supersolid state through crystal annealing"**

Rittner & Reppy '06. Supersolid samples are far more disspative !

- $C(T) \propto T$ **at low temperatures < 0.1 K**

Kim & Chan measurements. Typical for a glass (or 1D superfluid).

Theorem: The state without vacancies and interstitials is normal.

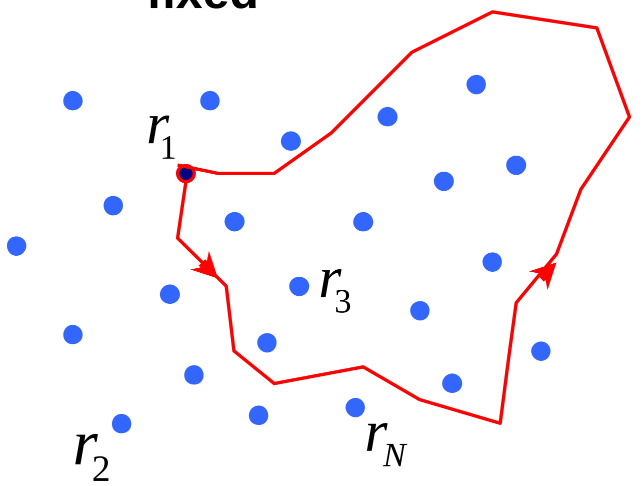
(**Groundstate wave function; Path-integrals**)

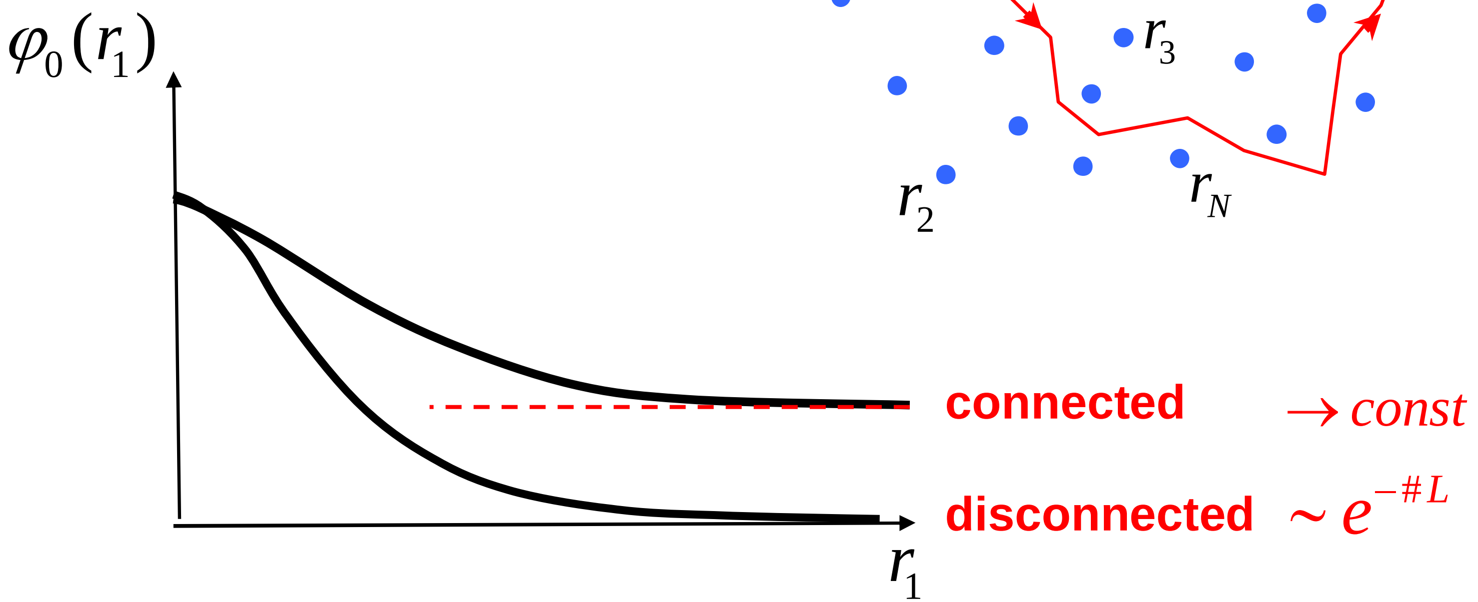
NP, Svistunov '04

Only "connected"ground states are superfluid !

$$\varphi_0(\underbrace{r_1, r_2, \ldots, r_N}_{\text{fixed}})$$

Leggett '1970





Insulating *hcp* crystals of He-4

No interstitial-vacancy symmetry in the supersolid $\longrightarrow$ $n_V \neq n_i$.
Thus, supersolids are always incommensurate

Experiments:

He-4 is a commensurate solid, X-ray (accuracy 0.1%)

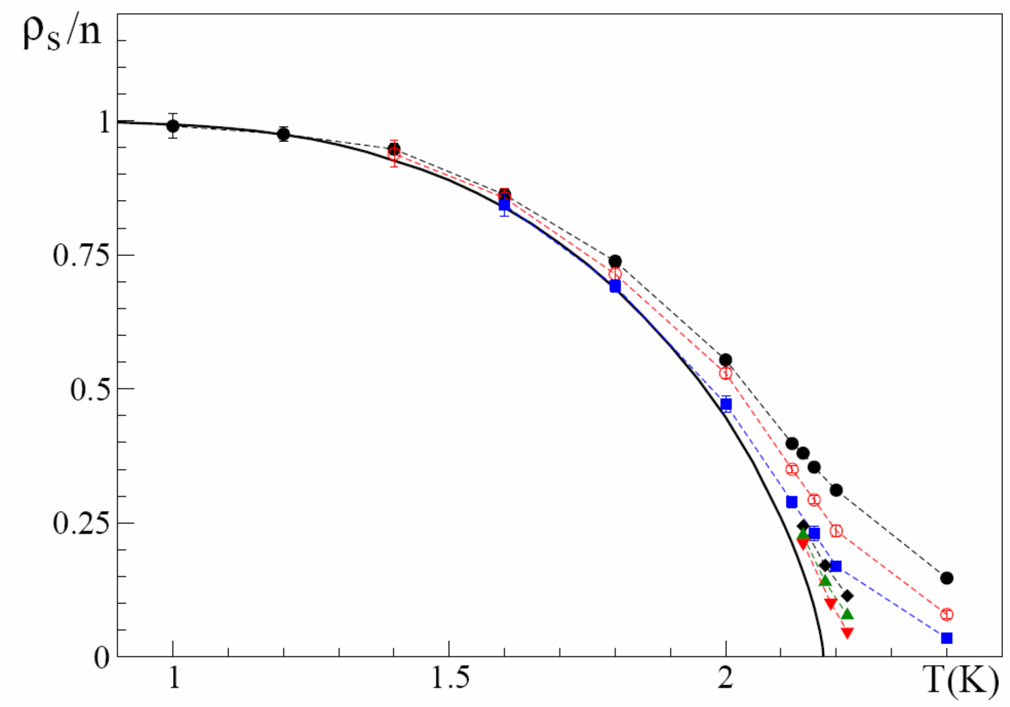
Vacancies and interstitials are activated, X-ray, ion and He-3 mobilities

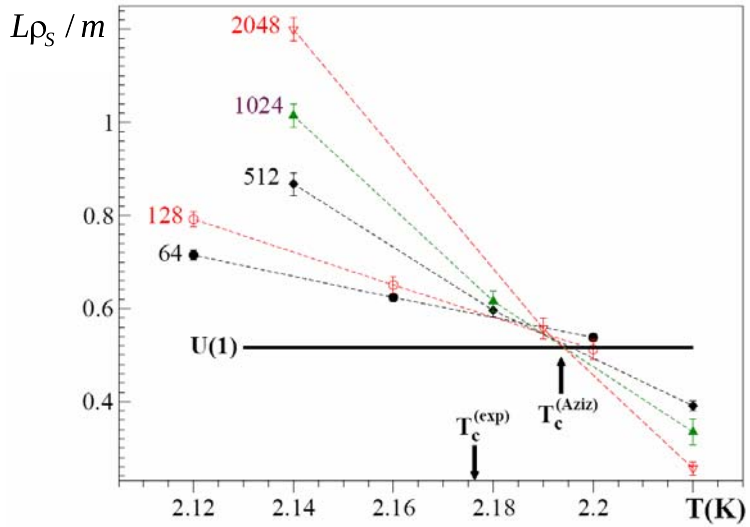
Simulations: Density matrix (or ODLRO) $n(r) = \left\langle \psi^+(r,+0)\psi(0,0) \right\rangle$

Green function $G(p=0,\tau) = \int dr \left\langle \psi^+(r,\tau)\psi(0,0) \right\rangle$

Why should we trust simulations?

No free parameters; helium mass + V(r) and go …





$T_C = 2.193$ calculated

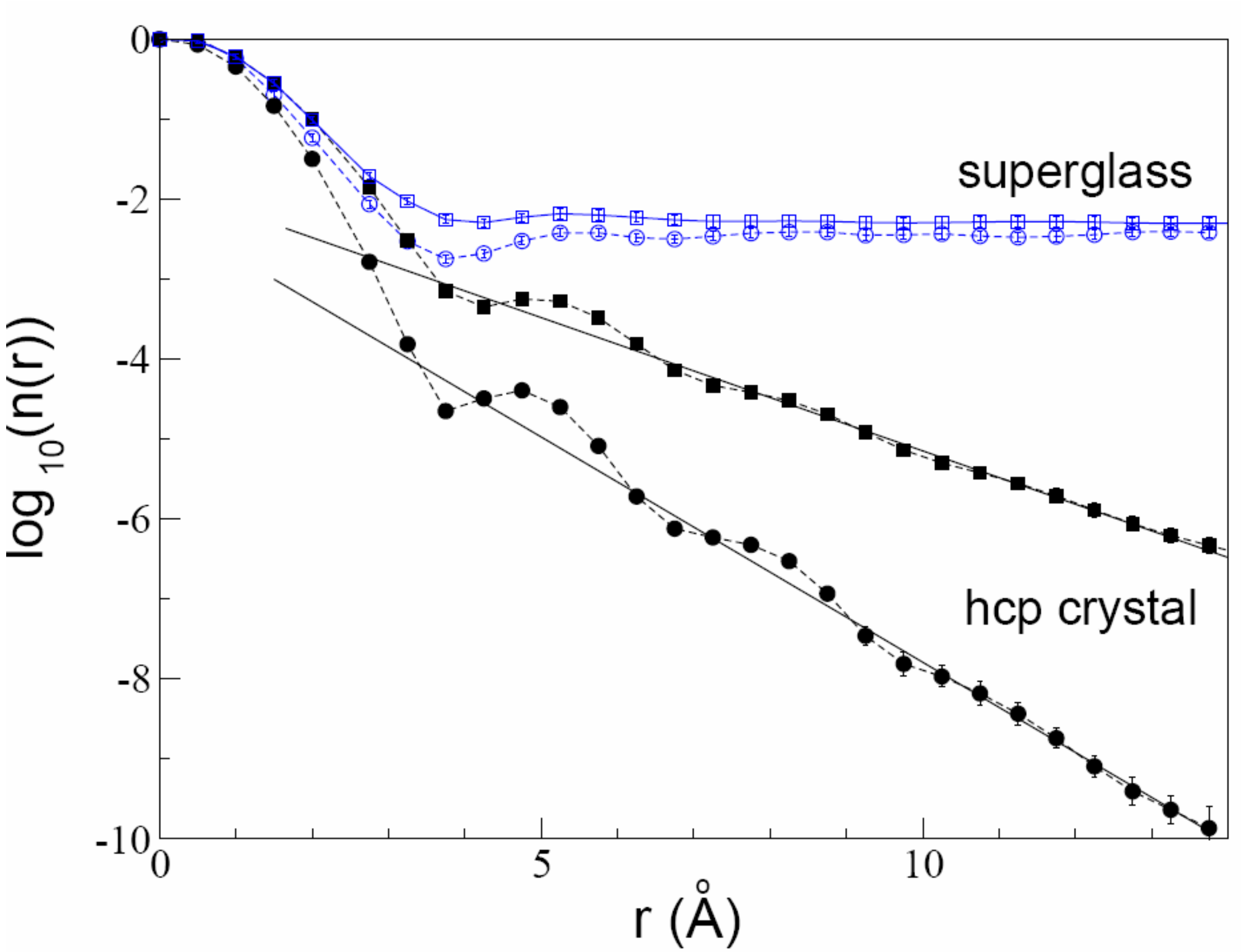
$T_C = 2.177$ experiment

Up to 2048 atoms
(path-integral MC
worm algorithm updates)

Better then 1%
agreement at all T
after finite-size scaling

Insulating *hcp* crystals of He-4

Exponential decay of the single-particle density matrix



$T = 0.2\ K, \quad N = 800$

$n = 0.0292\,\mathring{A}^{-3}$ **near melting**

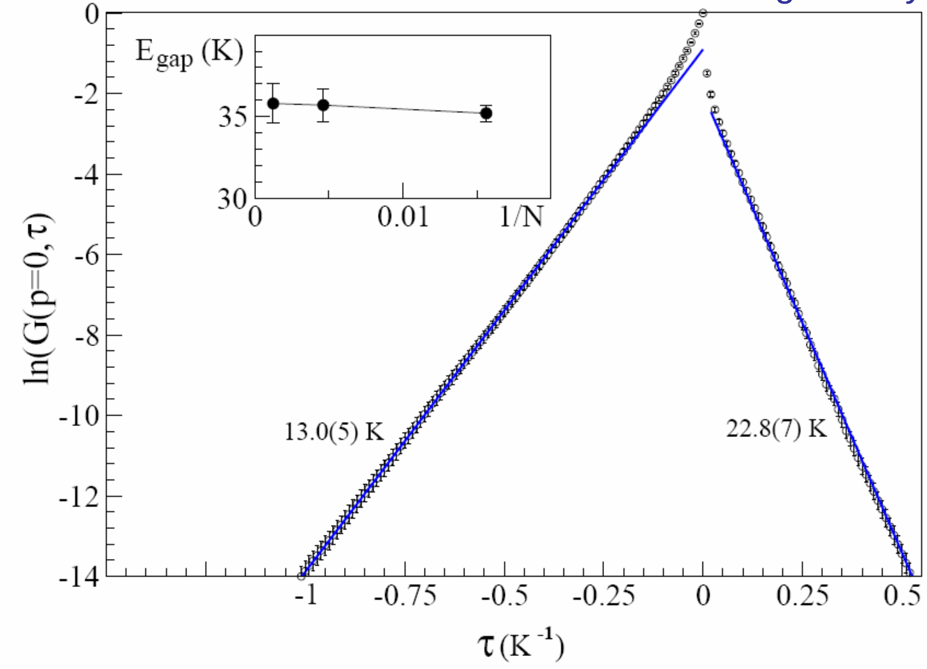
$n = 0.0359\,\mathring{A}^{-3}$

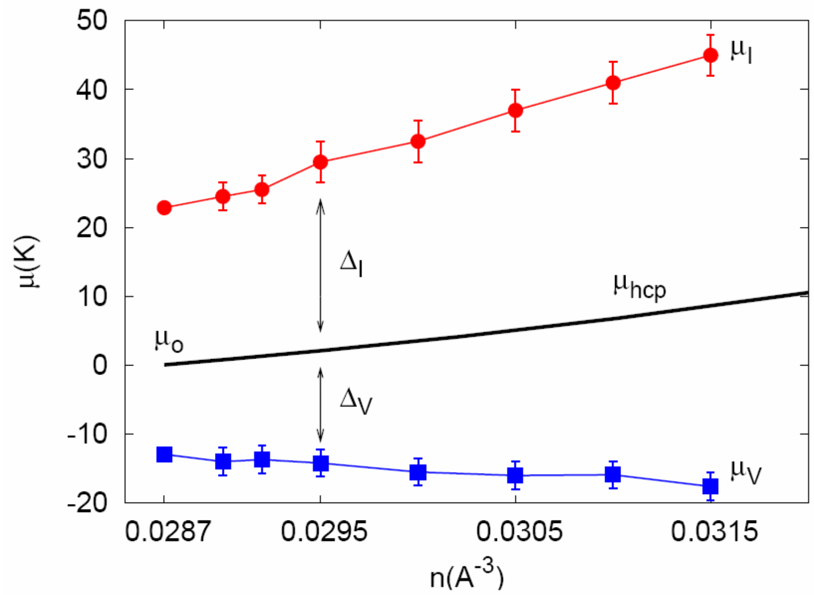
Insulating *hcp* crystals of He-4

Green function (polaron effect + gaps)

$$G(p,\tau \to \infty) \to Ze^{-E_{i,v}|\tau|}$$

melting density

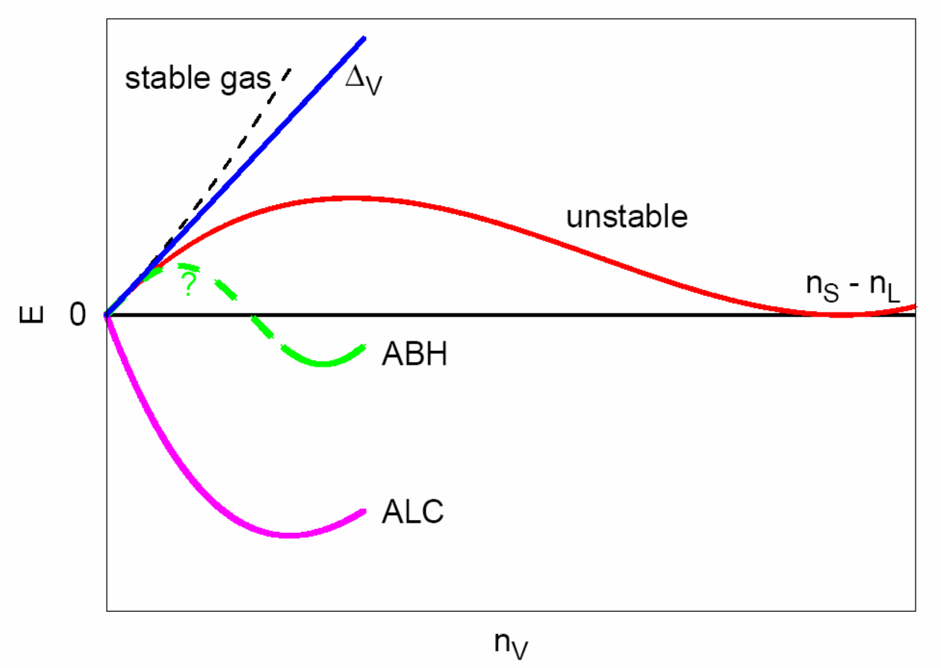




Large activation energies at all Pressures (thermodynamic limit)

Insulating *hcp* crystals of He-4

Various vacancy-induced supersolid scenarios



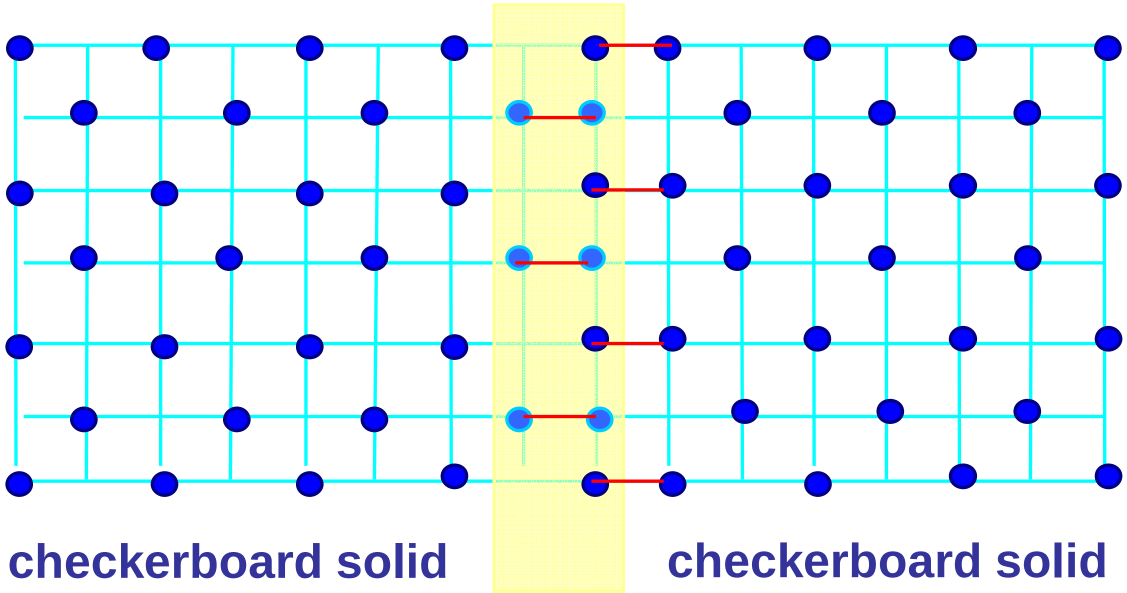
When introduced into the solid by hand vacancies form an unstable gas, cluster, and phase separate

In real experiments will anneal at the grain boundaries, dislocations, and other crystalline defects …

Superfluid disorder

Burovski ,Kozik,
NP, Svistunov '05

Proof of concept for grain boundaries



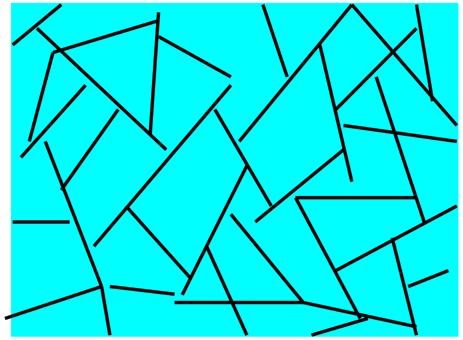
Superfluid domain walls
both in 2D and 3D crystals

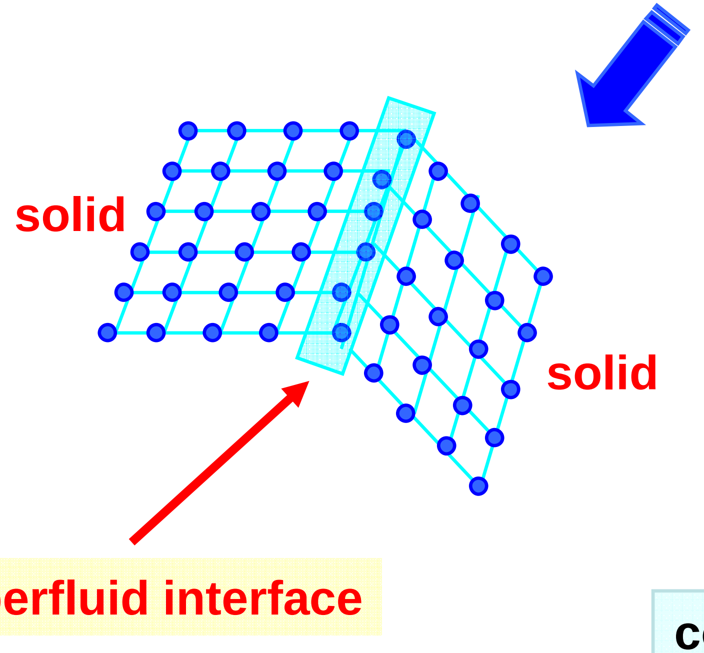
(SF = rough wall = solid-solid recrystallizartion waves)

Superfluid disorder

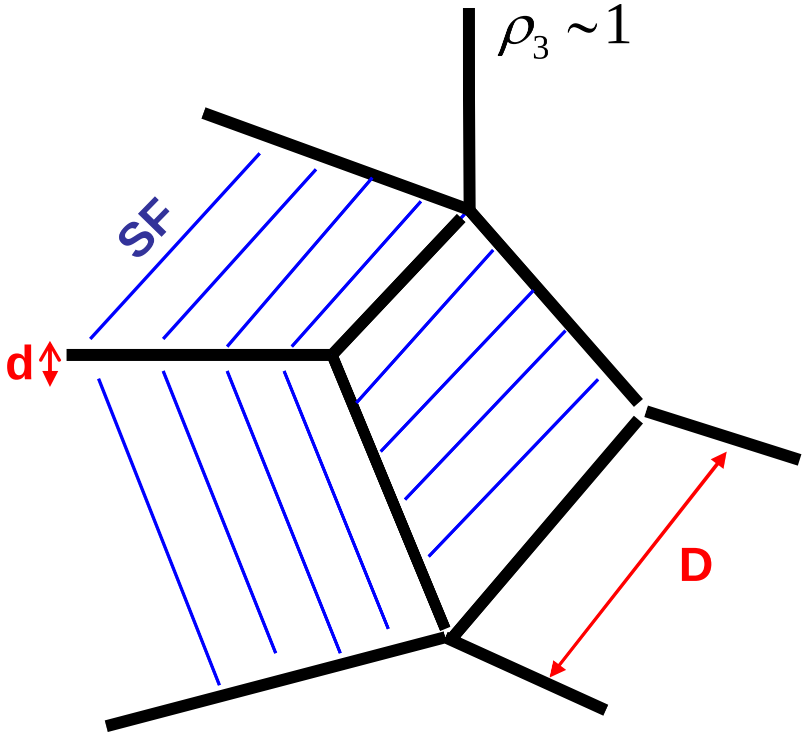
Quantum crystal, weak first-order liquid-solid transition

Frustrated crystalline interfaces





connected three-dimensional network of superfluid films (disordered ; ~ 2% volume)



3D network of superfluid interfaces and ridges. (disorder, different interfaces)

$T_C(\vec{r})$

He- 3 goes to interfaces and then to ridges connecting them.
Ridges → Josephson junctions

He- 3 at grain boundaries, ridges and corners prevents crystals from growing (stabilizes disorder)

Numbers: $\rho_S \sim d / D \longrightarrow D \sim \# \mu m$ "helium milk" (B. Hallock)

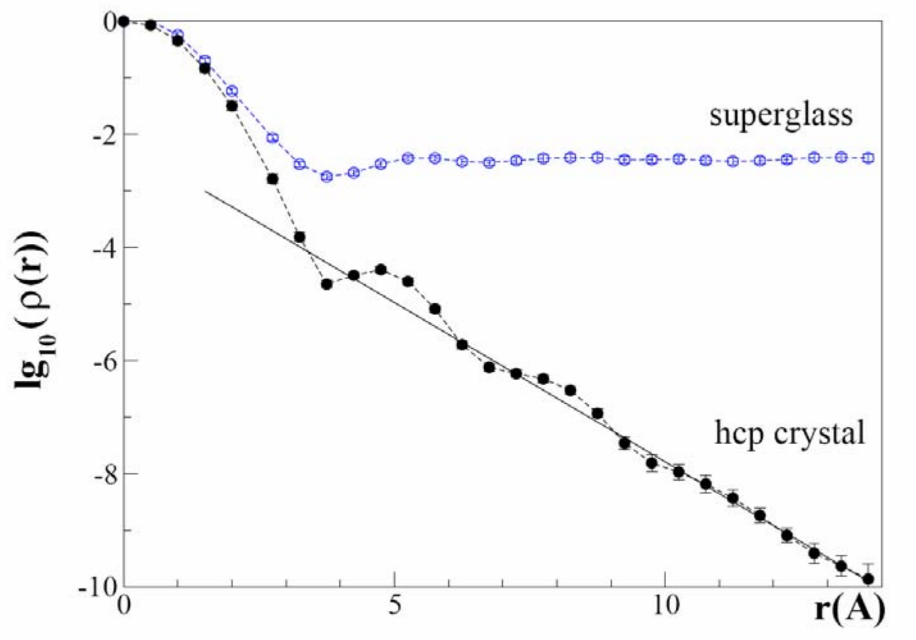
$$\rho_3 \sim (d / D)^2 \sim \rho_S^2 \longrightarrow \sim 10^{-4}$$

Superglass state of He-4

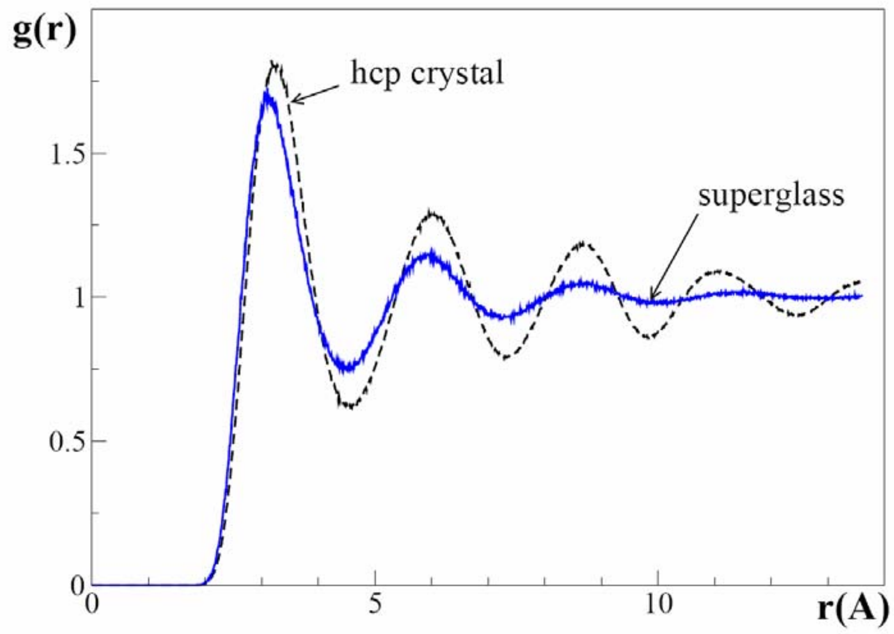
Monte Carlo temperature quench from normal liquid

$$n = 0.0359\ \overset{o}{A}^{-3}, \quad T = 100\ K \to 0.2\ K, \quad N = 800$$

Single-particle density matrix



density-density correlator

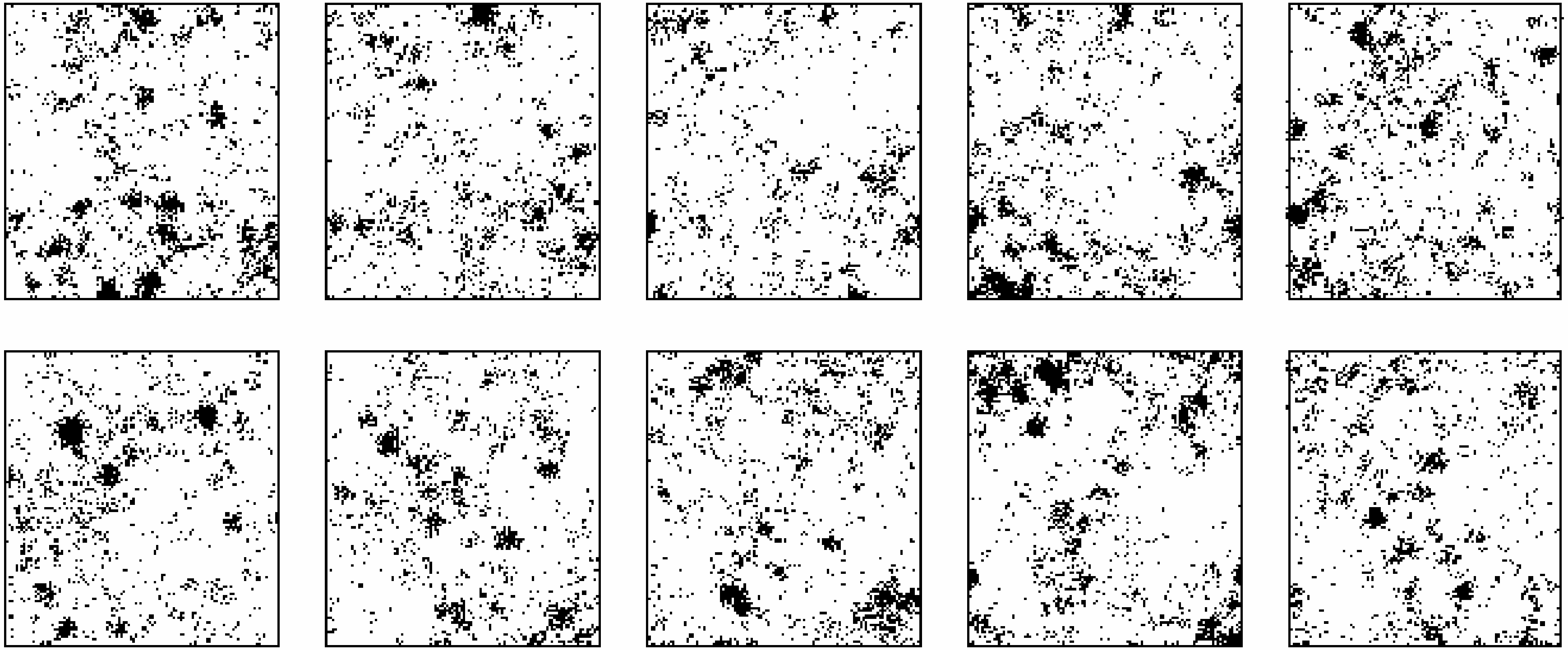


ODLRO, $\rho_S = 0.07(2)$

Superglass state of He-4

Condensate wave function maps
reveal broken translation symmetry $\varphi_0(r) \sim$ density of points

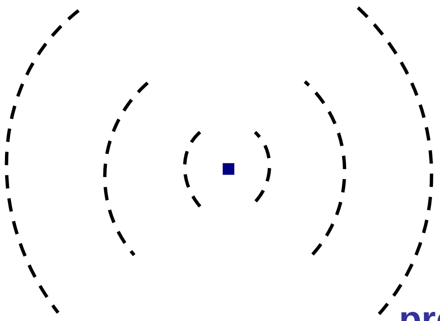
10 slices across the z-axis



A rough estimate of metastability: $t_{relax} > 10^4\, J_{4-4} \sim 10^{10}\, \omega_D^{-1} \sim 10^{-3}$ s

Superglass state of He-4

“Strange” outcome of the quantum-nucleation experiment



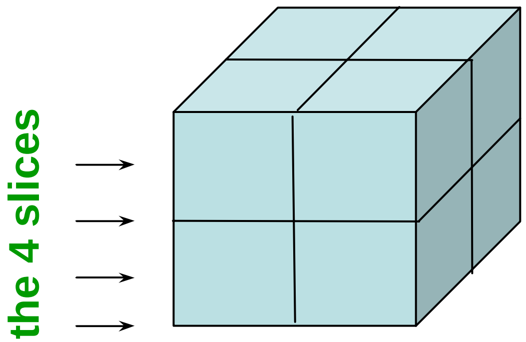
pressure wave, T=0.05 K

F. Werner, G. Beaume, A. Hobeika, S. Nascimbene,
C. Herrmann, C. Caupin, and S. Balibar
J. Low Temp. Phys., Vol. 136, Nos. ½, 2004

Bulk nucleation of a solid was predicted to occur at P~ 65 bar. Nothing was observed up to 160 bar !

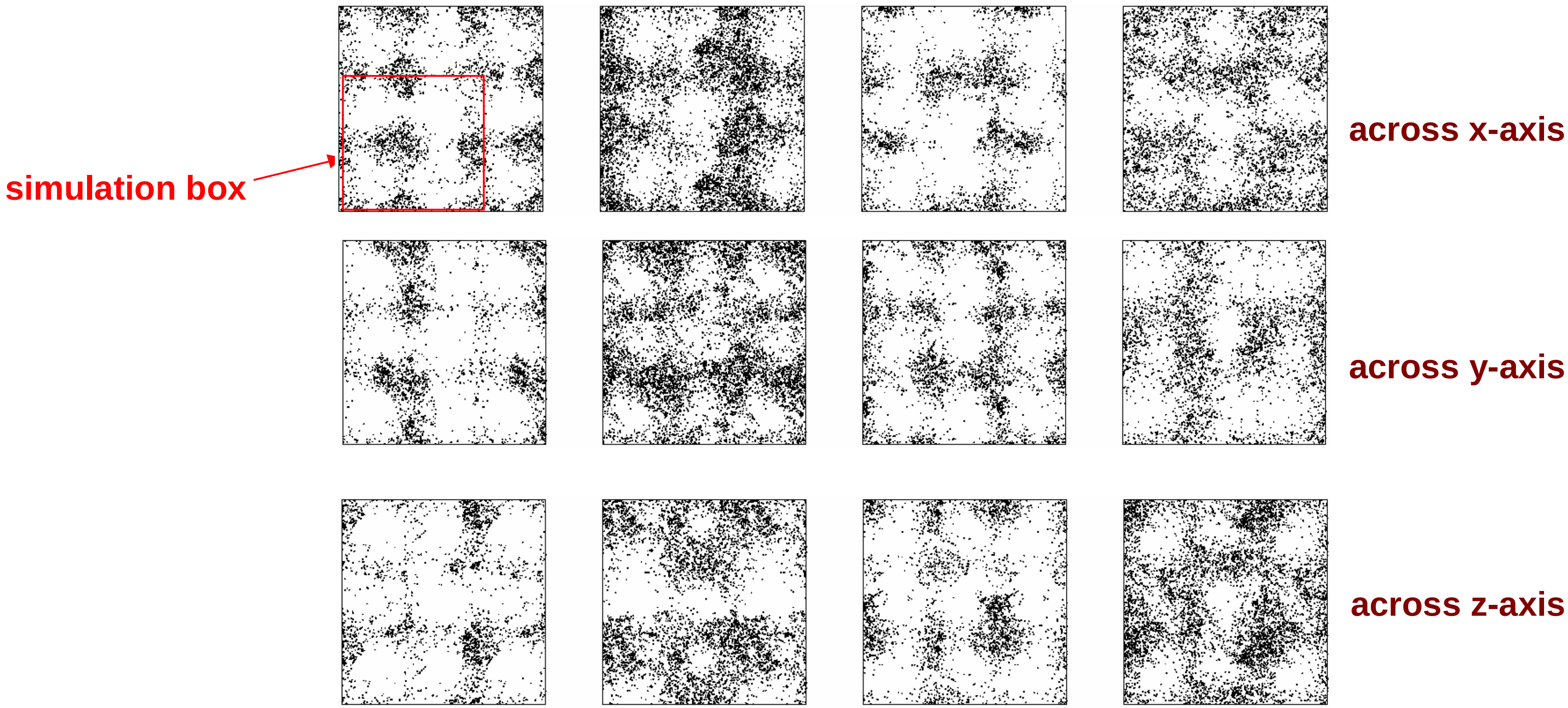
Authors → very viscous (glassy), normal liquid.

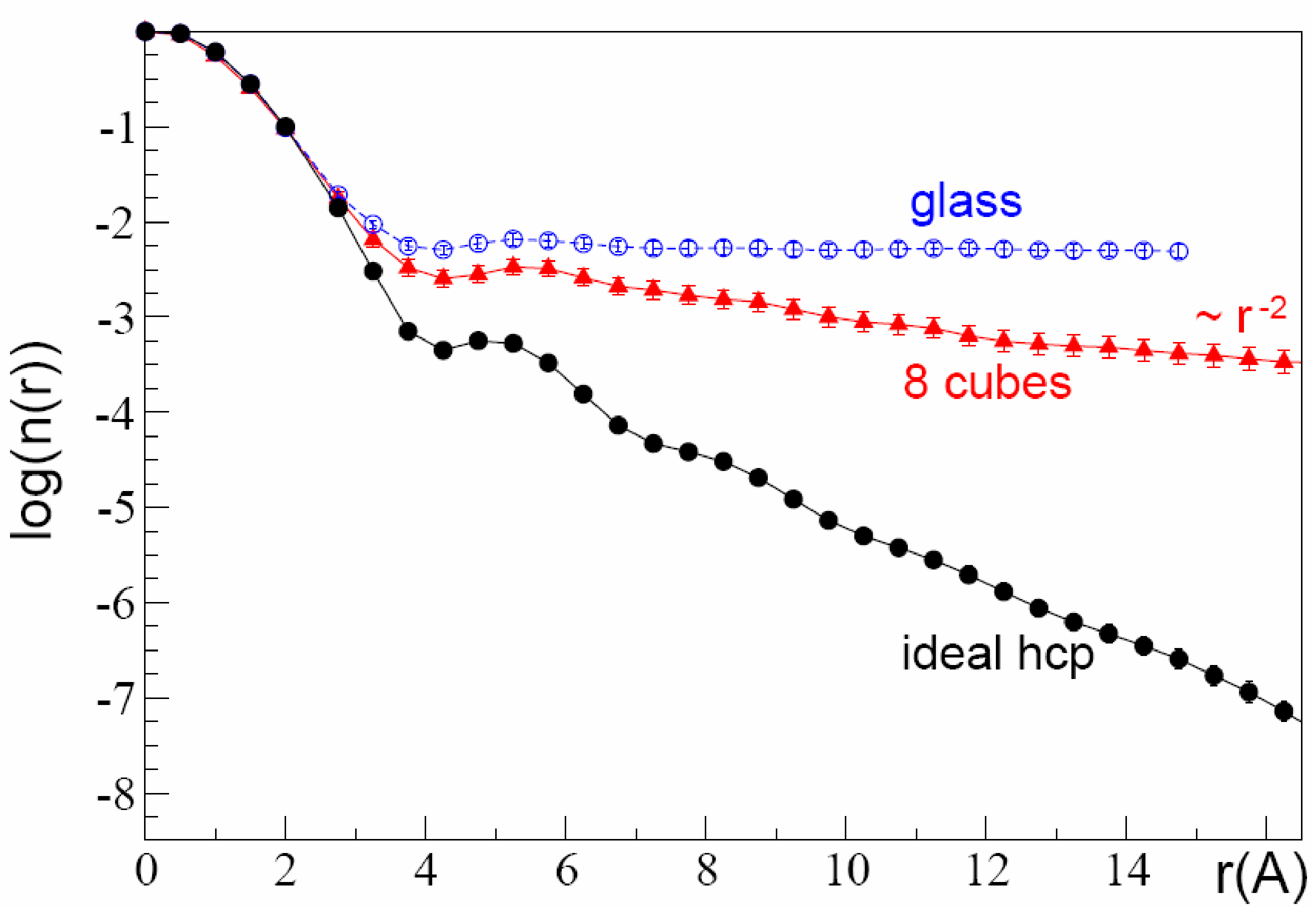
Superfluid ridges and interfaces in He-4



Each of the 8 cubes is a randomly oriented crystallite (24 interfaces)

Condensate maps





mostly 1D channels

Summary:

Ideal *hcp* crystals are not superfluid.
Large gaps for vacancies and interstitials at all pressures.

Non-equilibrium vacancies is an unstable, phase separating system.

Some (not all!) grain boundaries and ridges in helium are superfluid.

Helium can form a meta-stable superglass phase (very stable even in contact with crystals!).

Open questions: can easily fill next five slides!