From Superfluid Interfaces to Superglass

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KITP, Santa Barbara, 2006

Outline

Theorem: No supersolidity without vacancies, interstitials, or both

Corollary: Continuous-space supersolids are generically incommensurate

HCP He-4 crystal as a clear-cut insulator (Worm MC)

Superfluid interfaces in lattice models

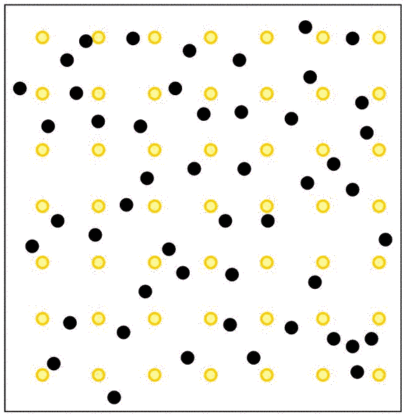
The superglass of He-4

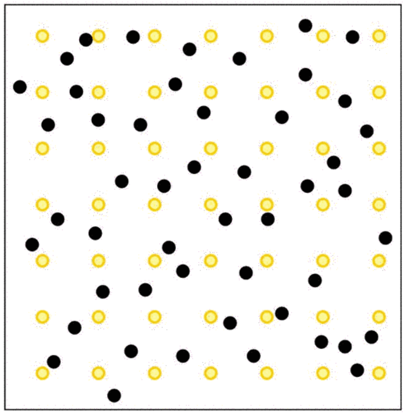
“Superfluid molasses”

Preliminary results for grain boundaries and ridges in He-4

“UMass Sandwich” (an experimental setup)

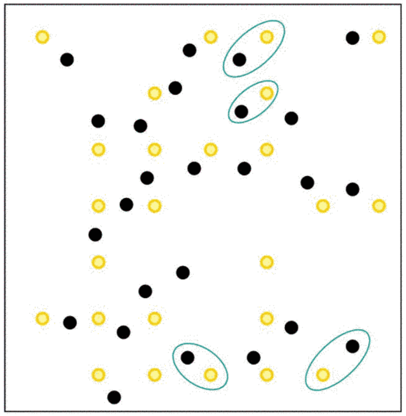
Revealing Vacancies and Interstitials in a Commensurate Crystal

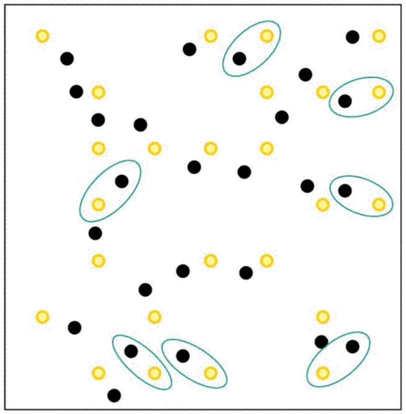




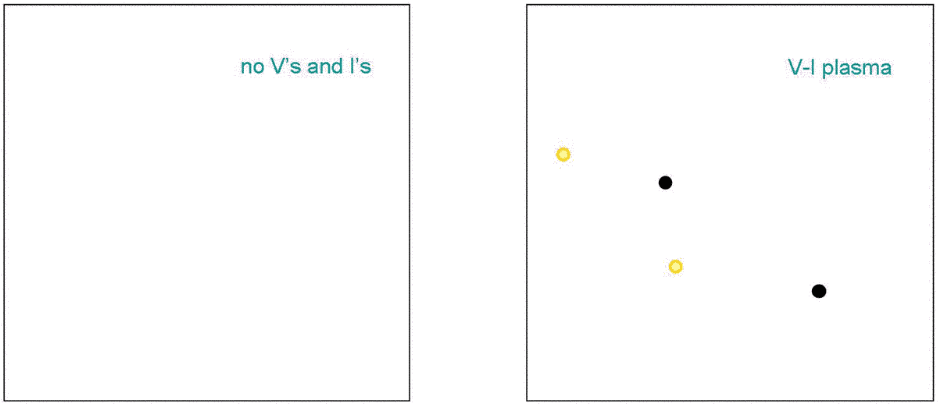
Revealing Vacancies and Interstitials in a Commensurate Crystal

The situation becomes quite clear (cf. vortex pairs vs free vortices in K-T theory)

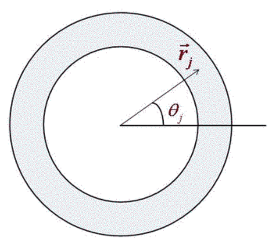




Revealing Vacancies and Interstitials in a Commensurate Crystal



Theorem: A state without both V's and I's is normal.



Proof:

Let Ψ_{ground} be a groundstate wavefunction without V's and I's…

$$\tilde{\Psi} = \begin{cases} \Psi_{ground}, & \text{for physical configurations} \\ 0, & \text{for configurations with V's and I's} \end{cases}$$

Wave function describing rotation with classical moment of inertia:

$$\Psi_{rot} = \tilde{\Psi} e^{\frac{i}{N}\sum_{j=1}^{N}\theta_j}$$

A. Leggett, PRL, **25**, 1543, (1970)

Corollary: Continuous-space supersolid is generically incommensurate

Proof:

Effective long-wave Hamiltonian for free V's and I's

$$H_{\text{eff}} = H_V[\Psi_V] + H_I[\Psi_I] + H_{\text{int}}^{(1)}[\Psi_V, \Psi_I] + H_{\text{int}}^{(2)}[|\Psi_V|, |\Psi_I|]$$

$$H_{\text{int}}^{(1)}[\Psi_V, \Psi_I] \propto \int \left(\Psi_V \Psi_I + \Psi_V^\dagger \Psi_I^\dagger\right) d\mathbf{r}$$

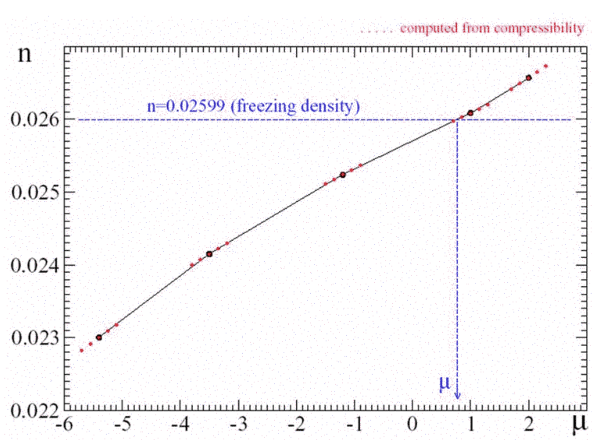
This is the only relevant constraint. It reduces the number of order parameters to just one.

$$N_V = \int \Psi_V^\dagger \Psi_V \, d\mathbf{r}, \qquad N_I = \int \Psi_I^\dagger \Psi_I \, d\mathbf{r}$$

are free variational parameters.

Hence, $X = N_V - N_I$ is a free variational parameter. The probability that it takes on the zero value, or, to these purposes, any ***given*** value, is zero.

Worm Algorithm Path Integral Monte Carlo: $n(\mu)$

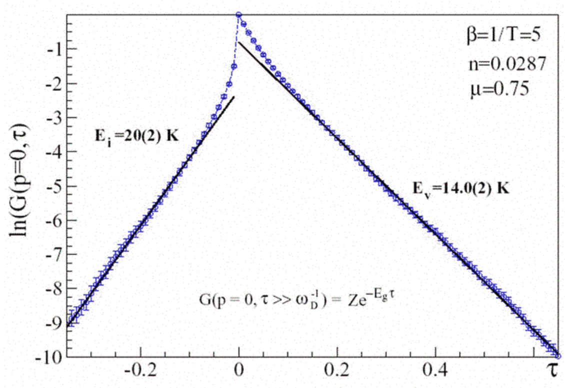


For the algorithm, see talk by Massimo Boninsegni;
and also Prokof'ev, Boninsegni, and BS, cond-mat/0510214 (to appear in PRL).

T = 0.2K

~ 1000 particles

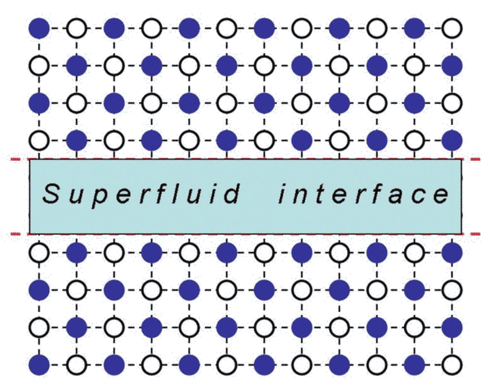
HCP He-4 crystal is a clear-cut insulator (Worm MC)



To rule out possible non-linear effects, we make sure that if we add ~ 0.6% of vacancies, by shifting chemical potential, and then returning back to the melting curve, ***all vacancies disappear***.

Here, for all practical purposes T=0 because during all the time of collecting statistics we ***never*** hit $\tau \sim 1/T$.

Superfluid Interfaces in Lattice Models

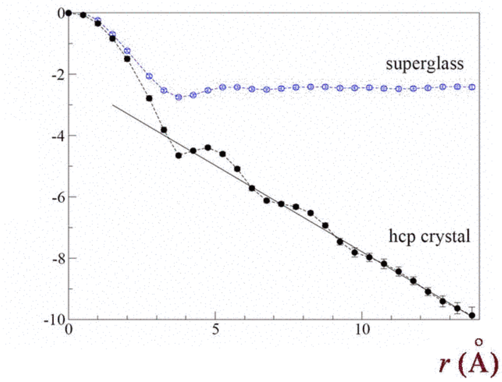


Superglass state of He-4

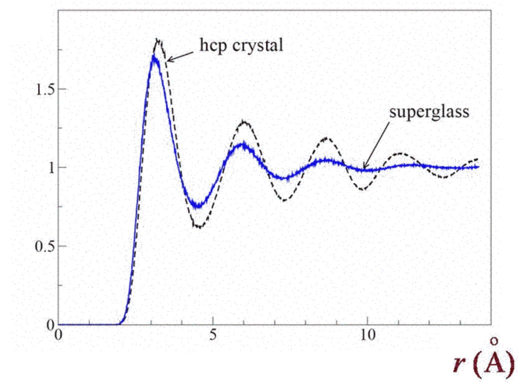
Boninsegni, Prokof'ev, and BS, cond-mat/0512103 (PRL)

$n = 0.0359\,\mathring{A}^{-3}$ $T = 0.2K$ $N = 800$

$\log_{10}$ of single-particle density matrix



density-density correlator

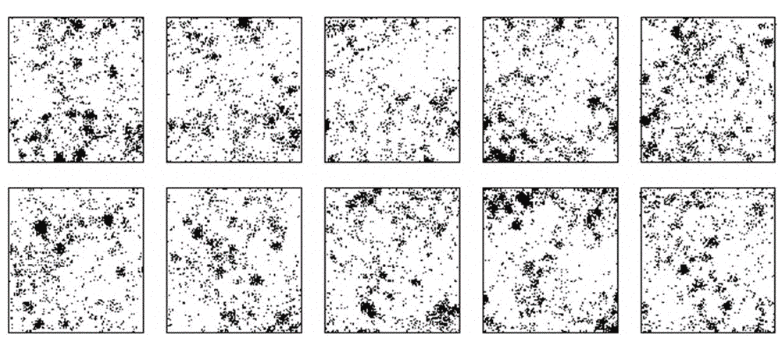


$\rho_s = 0.07(2)$

Map of the condensate wave function reveals the superglass

$n = 0.0359\,\mathring{A}^{-3}$ $T = 0.2K$ $N = 800$

10 slices across the z-axis



$t_{relax} > 10^4 \omega_D^{-1} \sim 10^{-9}$ s   (a rough estimate)

What do we mean by 'superglass' ?

Def. 1: A solid is a state with broken translational symmetry.

Def. 2: A quasi-solid is a state which is indistinguishable from a solid during time $t \ll t_*$ provided t_* is much larger than inverse Debye frequency.

Def. 3: A glass is a disordered solid.

Def. 4. A superglass is a glass that supports a superflow of its particles.

For practical purposes, superglass works like a sponge soaked with a superfluid, both sponge and superfluid formed by the atoms of the same sort.

"Quantum molasses"

(What do we know of quantum jamming?)

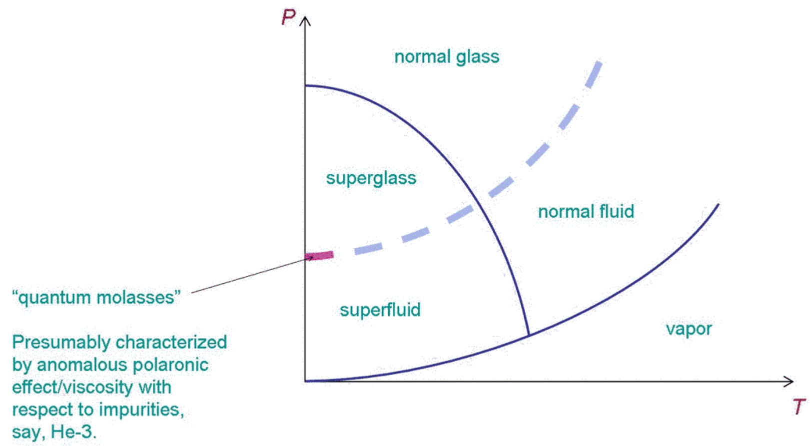
$n = 0.0292\,\text{Å}^{-3}$ $\quad T = 0.2K \quad N = 800$

Condensate wavefunction is homogeneous, **but**:

Convergence of the Worm algorithm gets extremely poor !

$\rho_s \ll 1$ with the error of ~ 100%.

Hypothetic Phase Diagram



The superglass/quantum molasses can explain the strange outcome of the known experiment:

Liquid Helium up to 160 bar

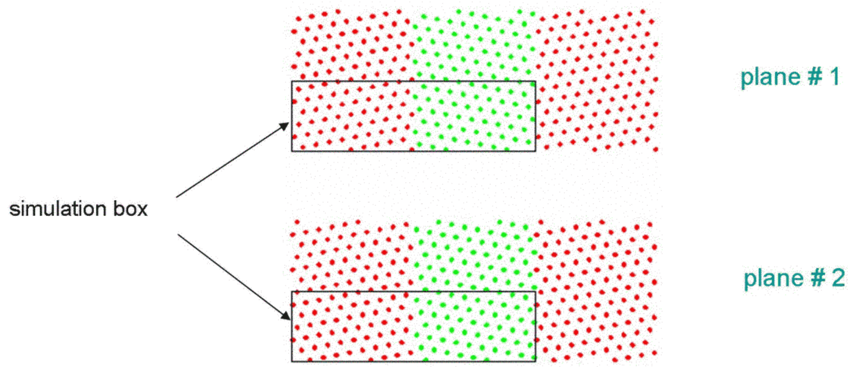
F. Werner, G. Beaume, A. Hobeika, S. Nascimbene, C. Herrmann, C. Caupin, and S. Balibar

J. Low Temp. Phys., Vol. 136, Nos. ½, 2004

Liquid helium was pressurized by an acoustic technique in order to observe a bulk nucleation of solid, which was expected to inevitably occur at ~ 65 bar.

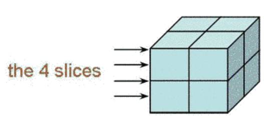
The outcome was negative.

Not ***all*** the grain boundaries in He-4 are superfluid

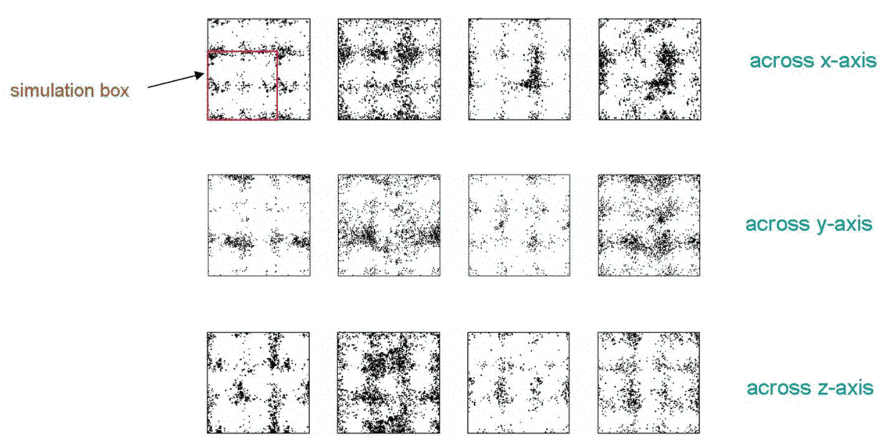


This and similar ones are found to be insulating.

8 Cubes: Condensate maps



Each of the 8 cubes is a randomly oriented crystallite



How about superfluid ridges ?

Experimental evidence for a disordered scenario

1. Absence of U(1)-universality-class features *- masked by non-universal behavior of the disordered superfluid network ?*

2. Special role of He-3:

   (a) Crucial role of small concentrations *- stabilizing disordered state ?*

   (b) Contaminating effect of larger concentrations *- by blocking bottlenecks of the superfluid network ?*

3. $C(T) \propto T$ *- cannot take place in 3D homogeneous superfluid; and typical for a glass !*

4. Limitingly small critical velocity *- quantum molasses ?*

Ongoing simulations

Liquid-glass phase diagram

Grain boundaries and ridges

Dislocation

A crystallite in a superglass. Superglass between crystallites

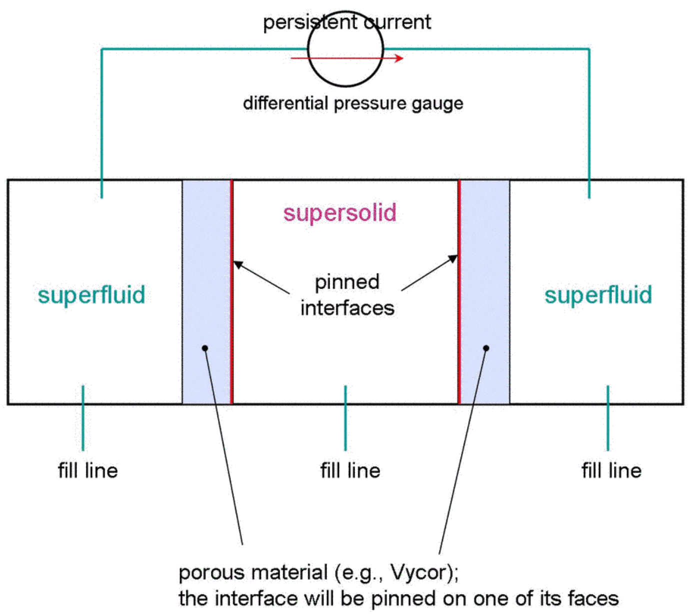
Planned simulations

He-3 in the superglass/quantum molasses and defect structures

"UMass Sandwich"

Idea: A pinned solid-liquid interface supports pressure jump

R. Hallock
M. Ray
N. Prokof'ev
B. Svistunov



Most important conclusions

HCP He-4 crystal is a clear-cut insulator.

Grain boundaries and other defects can be superfluid.

Superglass and quantum molasses: new challenging states of matter.

"UMass Sandwich": intriguing experimental geometry.