Quantum Phases of Dipolar Molecules

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Institute of Physics (Belgrade): July 18th, 2011

ZAHVALNOST

- ZELIM DA SE ZAHVALIM ANTUN BALAZ, STO MI JE OMOGUCIO DA ODRZIM PREDAVANJE NA INSTITUTU ZA FIZIKU U PRELEPOM BEOGRADU. IAKO BIH ZELEO DA MOGU DA ODRZIM PREDAVANJE NA SRPSKOM, MOJE ZNANJE SRPSKOG JEZIKA JE NA ZALOST OGRANICENO, ZATO CU SADA MORATI DA SE PREBACIM NA ENGLESKI.

Outline

- Introduction: heteronuclear molecules
- What are dipolar superfluids?
- Quantum phases of dipolar bosons in 2D.
- Conclusions.

Conclusions

- The possible quantum phases of dipolar bosons in 2D include:
- Superfluid, Wigner crystal, and hexatic and normal liquid phases.
- Supersolid and hexatic superfluid.

Some of our efforts on dipolar molecules.

PRL 103, 225301 (2009) PHYSICAL REVIEW LETTERS week ending 27 NOVEMBER 2009

Stability of Superfluid and Supersolid Phases of Dipolar Bosons in Optical Lattices

Ippei Danshita[1] and Carlos A. R. Sá de Melo[2]
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(Received 3 April 2008; revised manuscript received 3 November 2009; published 24 November 2009)

Time-Reversal-Breaking and *d*-Wave Superfluidity of Ultracold Dipolar Fermions in Optical Lattices

Li Han and C. A. R. Sá de Melo
School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332, USA
(Dated: June 11, 2010)

arXiv:1006.2072v1 [cond-mat.quant-gas] 10 Jun 2010

Main References for Talk

PRL 99, 110402 (2007) PHYSICAL REVIEW LETTERS week ending 14 SEPTEMBER 2007

Ultracold Heteronuclear Molecules and Ferroelectric Superfluids

M. Iskin and C. A. R. Sá de Melo
School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332, USA
(Received 13 October 2006; revised manuscript received 19 April 2007; published 13 September 2007)

Hexatic, Wigner Crystal, and Superfluid Phases of Dipolar Bosons

Kaushik Mitra, C. J. Williams and C. A. R. Sá de Melo
Joint Quantum Institute, University of Maryland, College Park, Maryland 20742, and National Institute of Standards and Technology, Gaithersburg, Maryland 20899
(Dated: March 26, 2009)

arXiv:0903.4655v1 [cond-mat.other] 26 Mar 2009

+ UNPUBLISHED
(in preparation 2011).

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Introduction: Heteronuclear Molecules

H_2

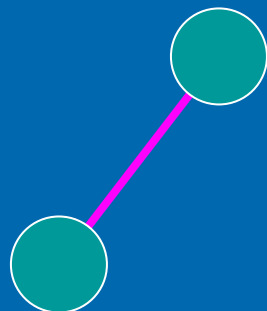
Li_2

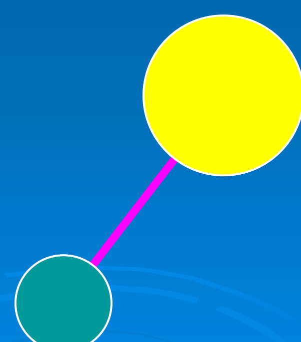
K_2

Na_2

Rb_2

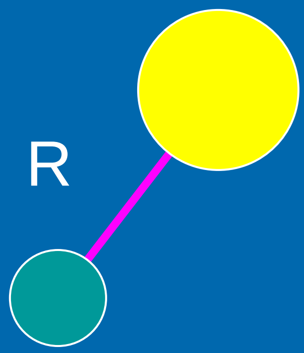
Cs_2





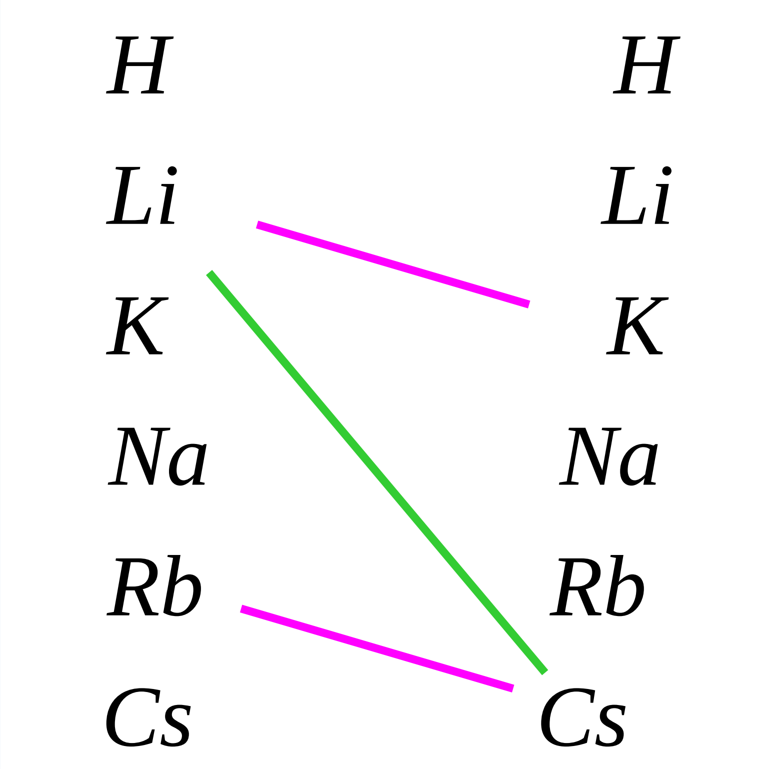
H	H
Li	Li
K	K
Na	Na
Rb	Rb
Cs	Cs

Introduction: Dipole Moment of Heteronuclear Molecules

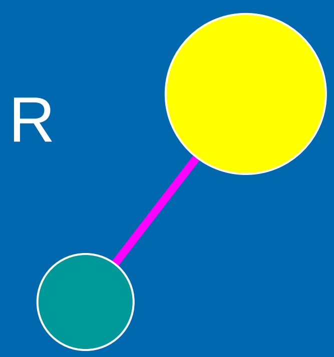


Rigid Quantum Rotor

$$\hat{H} = \frac{\hat{L}^2}{2\mu R^2}$$



Introduction: Dipole Moment of Heteronuclear Molecules

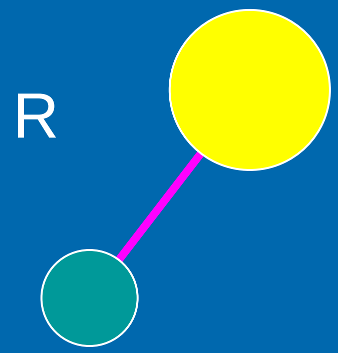


Eigenstates :

$$\frac{\hat{L}^2}{2\mu R^2} Y_{lm}(\theta,\varphi) = \frac{l(l+1)\hbar^2}{2\mu R^2} Y_{lm}(\theta,\varphi)$$

$$\Delta E_{10} = \frac{\hbar^2}{2\mu R^2}$$

Introduction: Dipole Moment of Heteronuclear Molecules

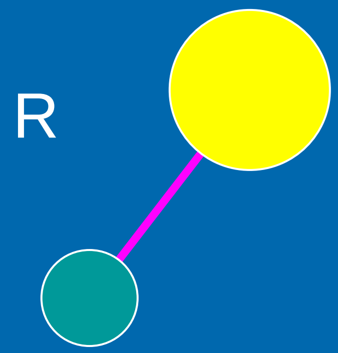


Eigenstates:

$$\frac{\hat{L}^2}{2\mu R^2} Y_{lm}(\theta,\varphi) = \frac{l(l+1)\hbar^2}{2\mu R^2} Y_{lm}(\theta,\varphi)$$

Spherical Harmonics have well defined parity, thus the expectation value of the dipole operator in any eigenstate (and in particular the ground state) is zero.

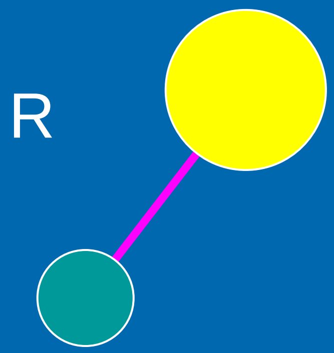
Introduction: Dipole Moment of Heteronuclear Molecules



$$T << \Delta E_{10} = \frac{\hbar^2}{2\mu R^2}$$

At low T there little admixture of states with different parity: need electric field!

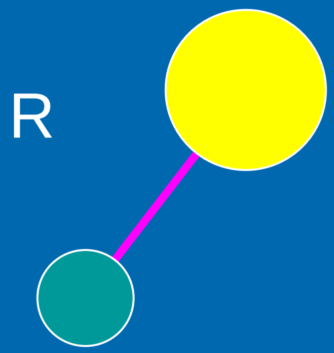
Dipole Moment of Heteronuclear Molecules

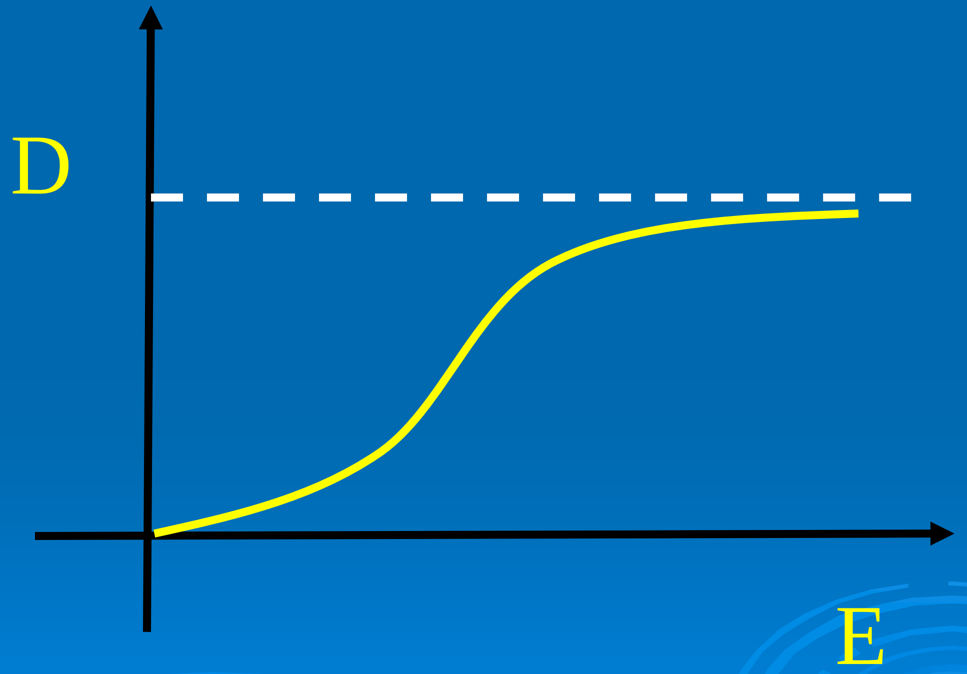


Electric dipole moments of molecules at very low T are not intrinsic, as they would require spontaneous breaking of parity.

In contrast, magnetic dipolar moments associated with spin are intrinsic.

Dipole Moment of Heteronuclear Molecules





Outline

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- What are dipolar superfluids?.
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- Conclusions.

What is a dipolar superfluid?

- A superfluid with dipolar internal degrees of freedom.

Electric Dipoles

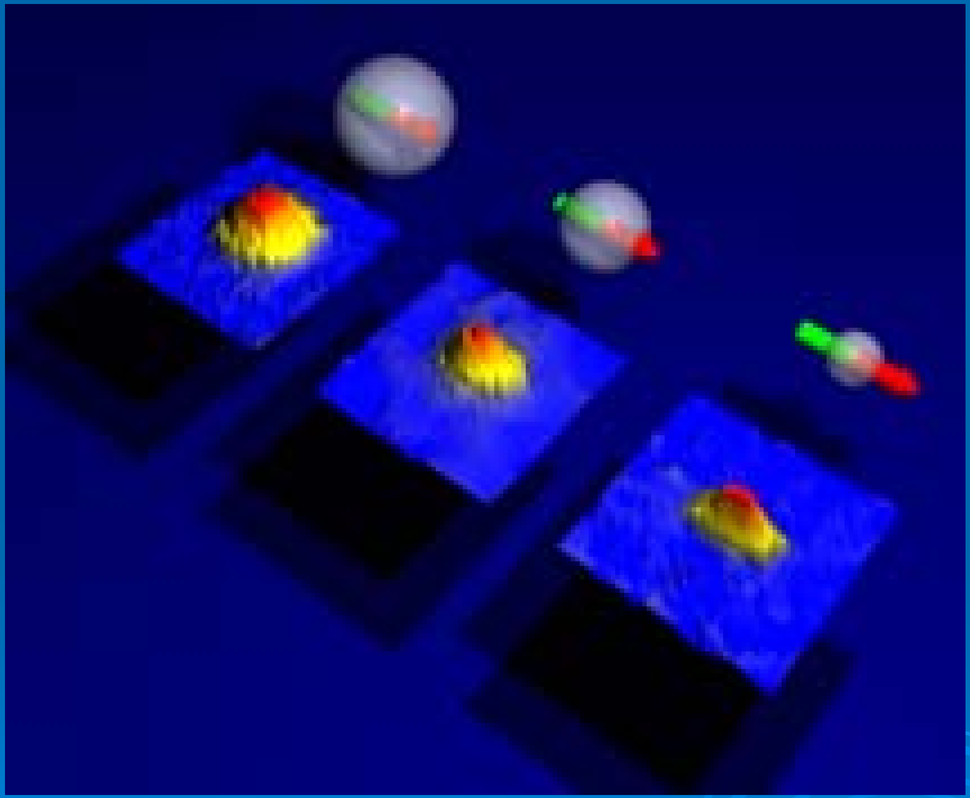
Magnetic Dipoles

Candidates for dipolar superfluids

- Atoms with large magnetic dipole moments.
- Heteronuclear molecules with permanent electric dipole moments.
- Rydberg atoms with large electric dipole moments.

Tuning the ratio of long-range to short-range interactions

Distortion of ^{52}Cr cloud via reduction of short range interactions



Th. Lahaye, T. Koch, B. Fröhlich, M. Fattori, J. Metz, A. Griesmaier, S. Giovanazzi, T. Pfau: "Strong dipolar effects in a quantum ferrofluid", Nature **448**; 672 (2007).

Dipolar Superfluids in 2D

$$H = T + V_{dipole} + V_{local} = -\sum_i \frac{\hbar^2}{2m}\nabla_i^2 + \frac{1}{2}\sum_{\langle i,j\rangle}\left(\frac{D^2}{|\mathbf{x}_i - \mathbf{x}_j|^3} + U\delta(\mathbf{x}_i - \mathbf{x}_j)\right).$$

1st approximation: BKT Physics…

$$H = \int d^2 r |\psi|^2 \frac{\hbar^2}{2m}\nabla^2\theta(\vec{r}) + |\psi|^4 \int d^2 r_1 d^2 r_2 V(\vec{r}_1 - \vec{r}_2)$$

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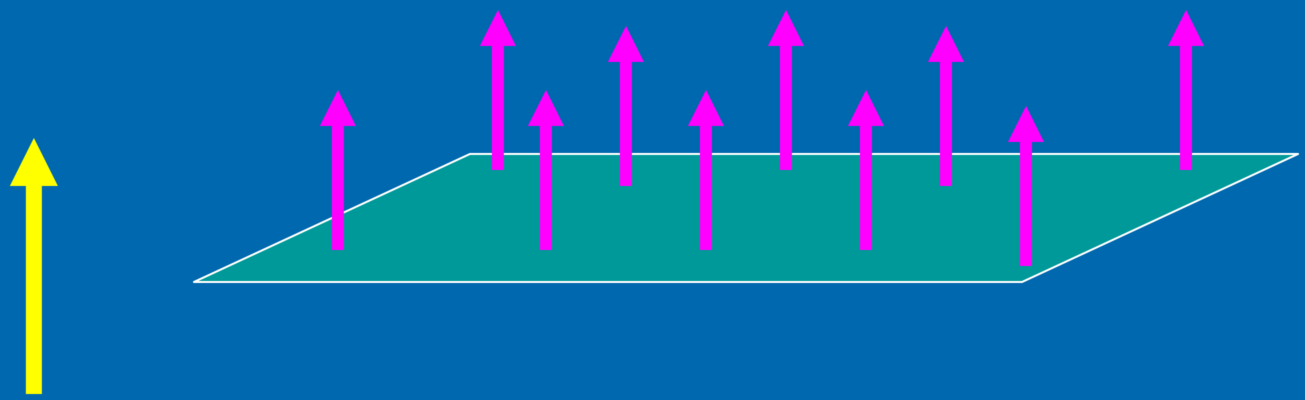
Dipolar Bosons Continuum



$$H = T + V_{dipole} + V_{local} = -\sum_i \frac{\hbar^2}{2m}\nabla_i^2 + \frac{1}{2}\sum_{\langle i,j\rangle}\left(\frac{D^2}{|\mathbf{x}_i - \mathbf{x}_j|^3} + U\delta(\mathbf{x}_i - \mathbf{x}_j)\right).$$

Relevant Parameters and Ratios of Energies

$$K = \hbar^2/(2ma^2)$$

$$E_D = D^2/a^3 \sim D^2\rho^{3/2}$$

$$E_U = U/a^2 \sim U\rho$$

$$r_D = E_D/K$$

$$r_D \sim 2mD^2\rho^{1/2}/\hbar^2$$

$$r_D = 2mD^2/\hbar^2 a$$

$$r_U = 2mU/\hbar^2$$

Dipolar Superfluid expected for $r_D << 1$

Dipolar Wigner Crystal expected for $r_D \gg 1$

Dipolar Superfluids in 2D: $r_D << 1$

$r_D = E_D/K << 1$

$$H = T + V_{dipole} + V_{local} = -\sum_i \frac{\hbar^2}{2m}\nabla_i^2 + \frac{1}{2}\sum_{\langle i,j\rangle}\left(\frac{D^2}{|\mathbf{x}_i - \mathbf{x}_j|^3} + U\delta(\mathbf{x}_i - \mathbf{x}_j)\right).$$

For small dipolar interactions

1st approximation: BKT Physics…

$$H = \int d^2 r |\psi|^2 \frac{\hbar^2}{2m}\nabla^2\phi(\vec{r}) + |\psi|^4 \int d^2 r_1 d^2 r_2 V(\vec{r}_1 - \vec{r}_2)$$

First set U = 0 ($r_U = 0$)

Dipolar Wigner crystal expected for: small masses, large dipole moments and high densities. Notice that the dependence on density is the opposite for the 2D Coulomb-Wigner crystal.

$$r_D = 2mD^2/\hbar^2 a$$

$$r_D \sim \rho^{1/2}$$

$$r_D \gg 1$$

$$K = \hbar^2/(2ma^2)$$

$$r_s \sim \rho^{-1/2}$$

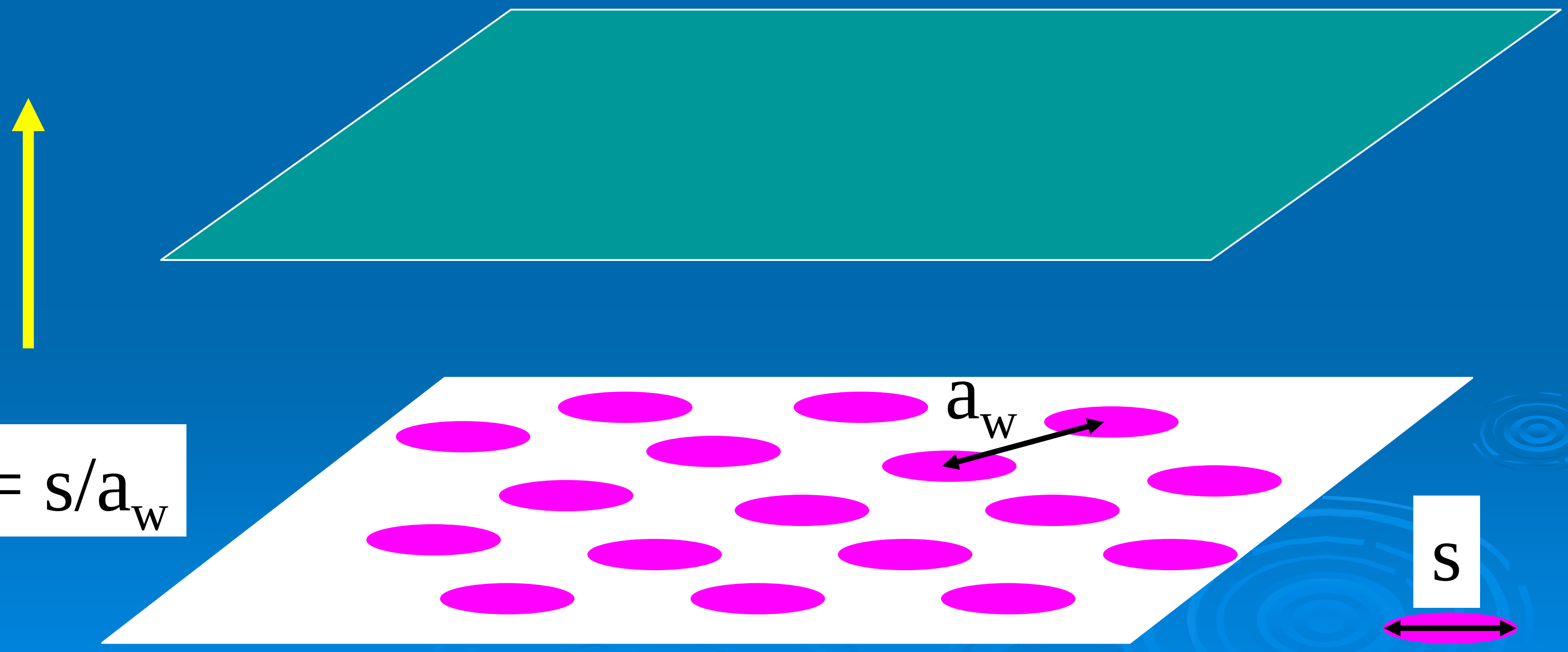
$$r_s >> 1$$

$$E_c = C/a$$

$$r_s = 2mCa/\hbar^2$$

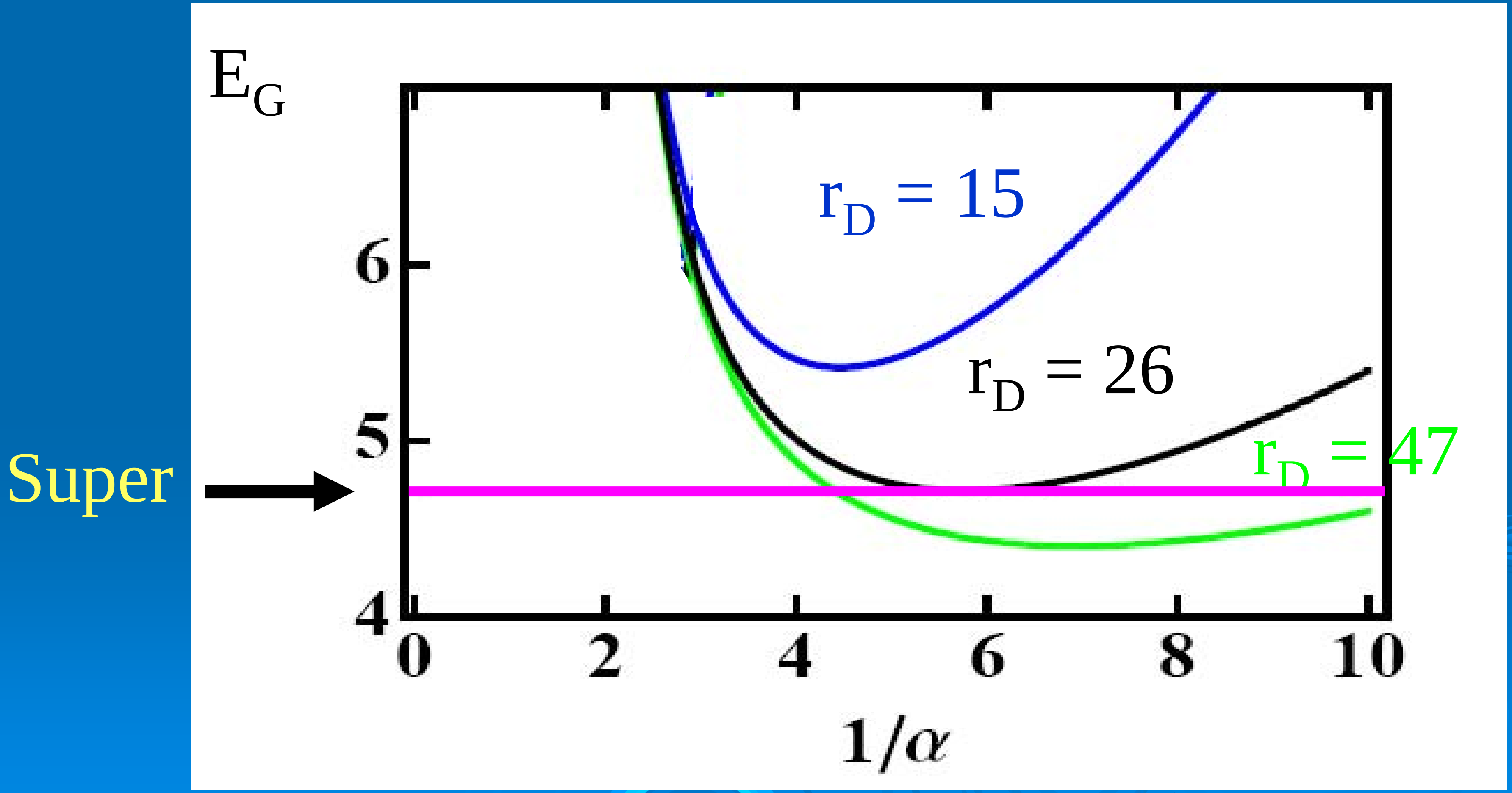
Low densities

Transition from superfluid to dipolar Wigner crystal (T = 0)

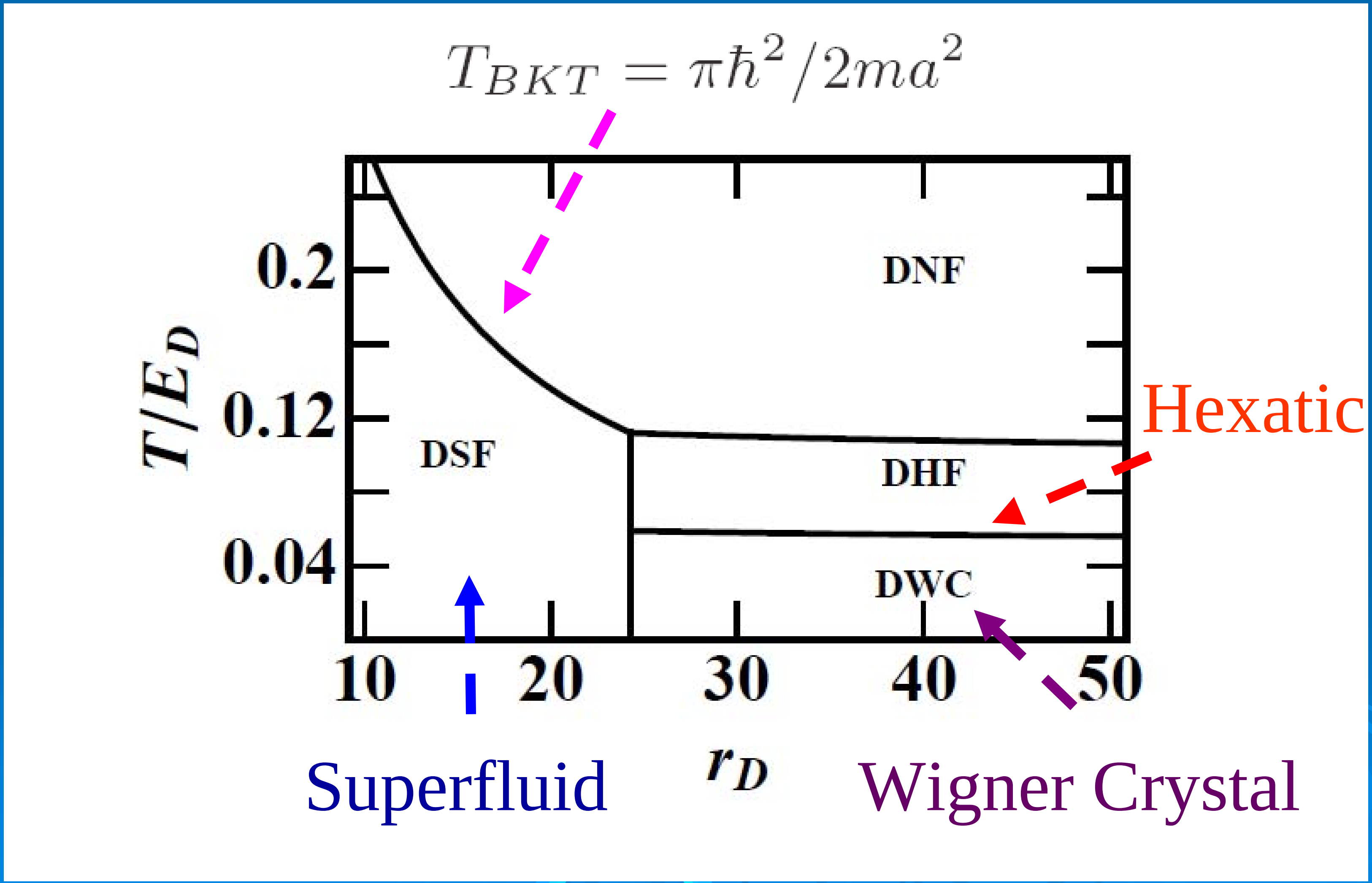


$\alpha = s/a_w$

Transition from Superfluid to dipolar Wigner crystal



Phase Diagram



Two-stage melting: emergence of the dipolar hexatic phase

Elastic energy

$$E_{\rm el} = \frac{1}{2}\int d\mathbf{r}\,\left[2\mu\epsilon^2_{\alpha\beta} + \lambda\epsilon^2_{\alpha\alpha}\right],$$

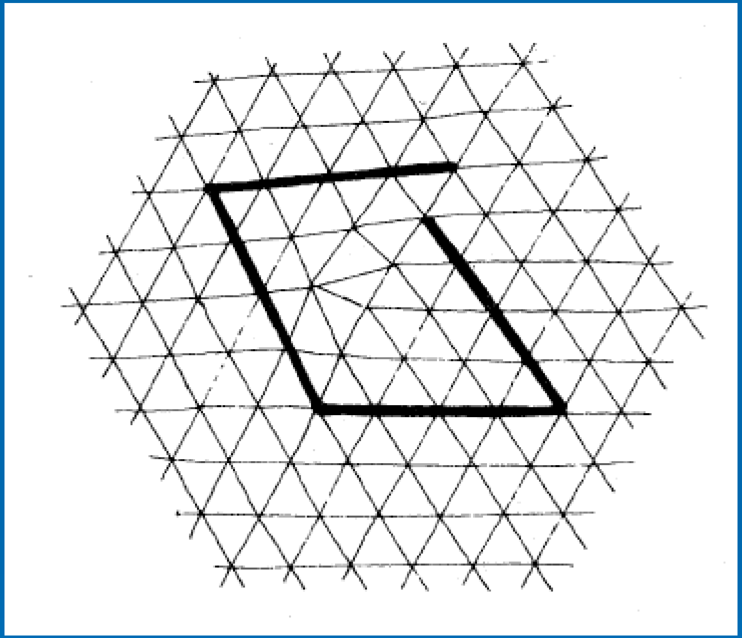
Lame coefficients

$$\mu = 15\sqrt{3}D^2/4a^5 \qquad \lambda = 3\mu$$

Strain tensor

$$\epsilon_{\alpha\beta}(\mathbf{r}) = \frac{1}{2}\left[\frac{\partial u_\alpha(\mathbf{r})}{\partial \mathbf{r}_\beta} + \frac{\partial u_\beta(\mathbf{r})}{\partial \mathbf{r}_\alpha}\right]$$

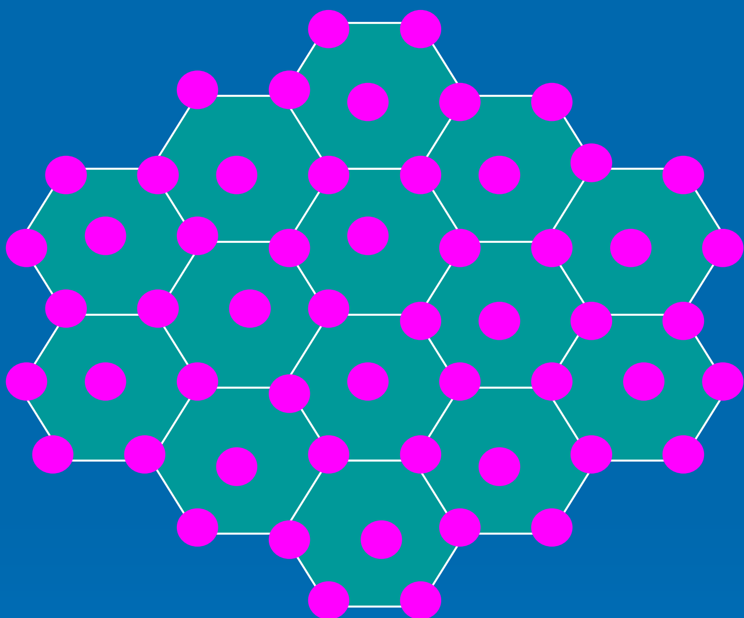
Dislocation mediated melting



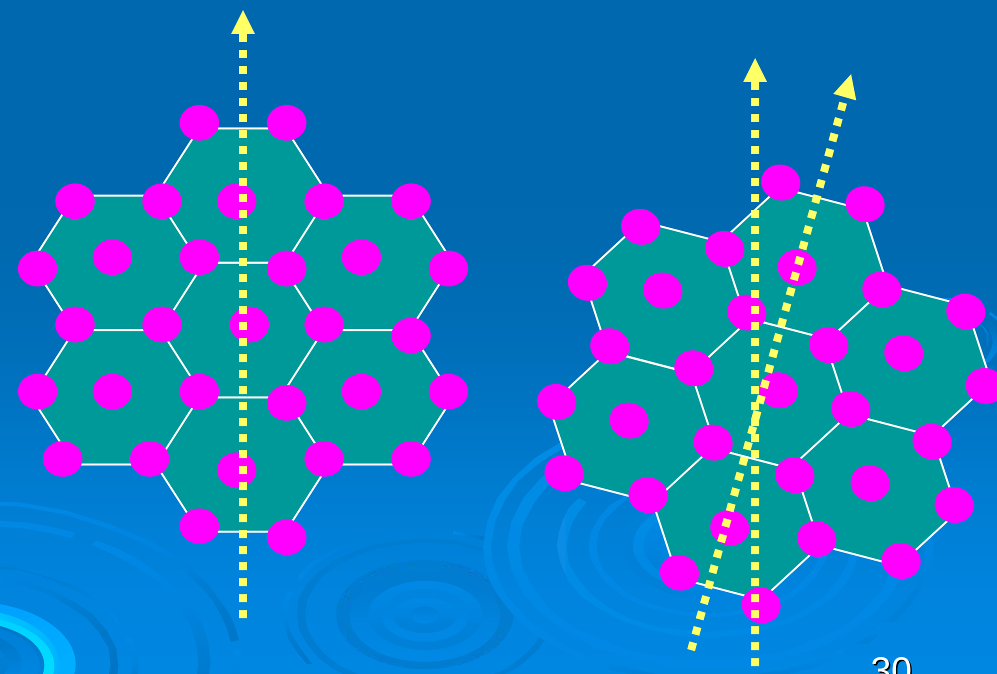
Elementary dislocation

Translational versus orientational (Wigner crystal versus hexatic)

Hexatic



Wigner Crystal



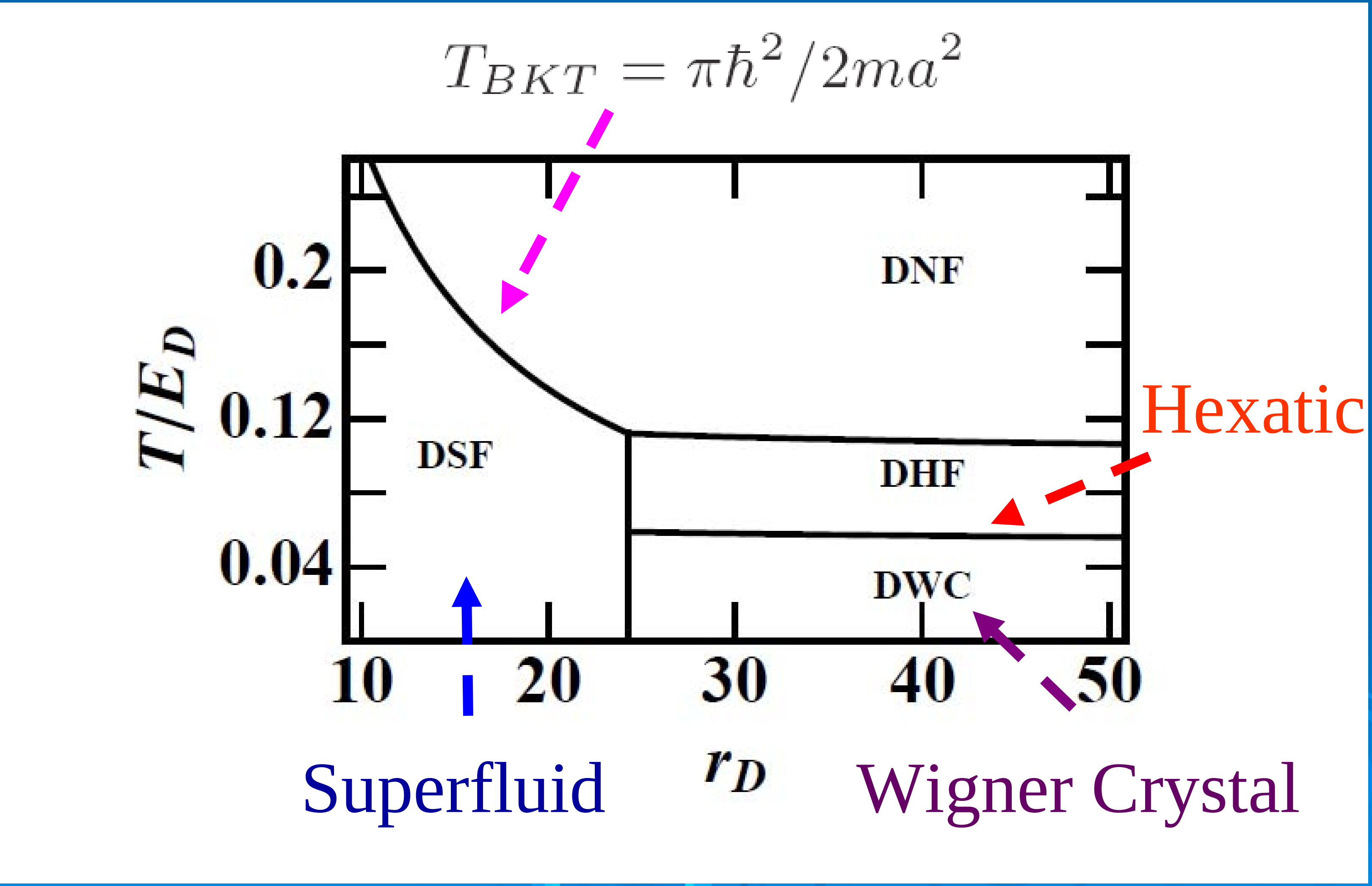
Two-stage melting: emergence of the normal phase

Bond angle field $\theta(\mathbf{r}) = \left[\partial_x u_y(\mathbf{r}) - \partial_y u_x(\mathbf{r})\right]/2$

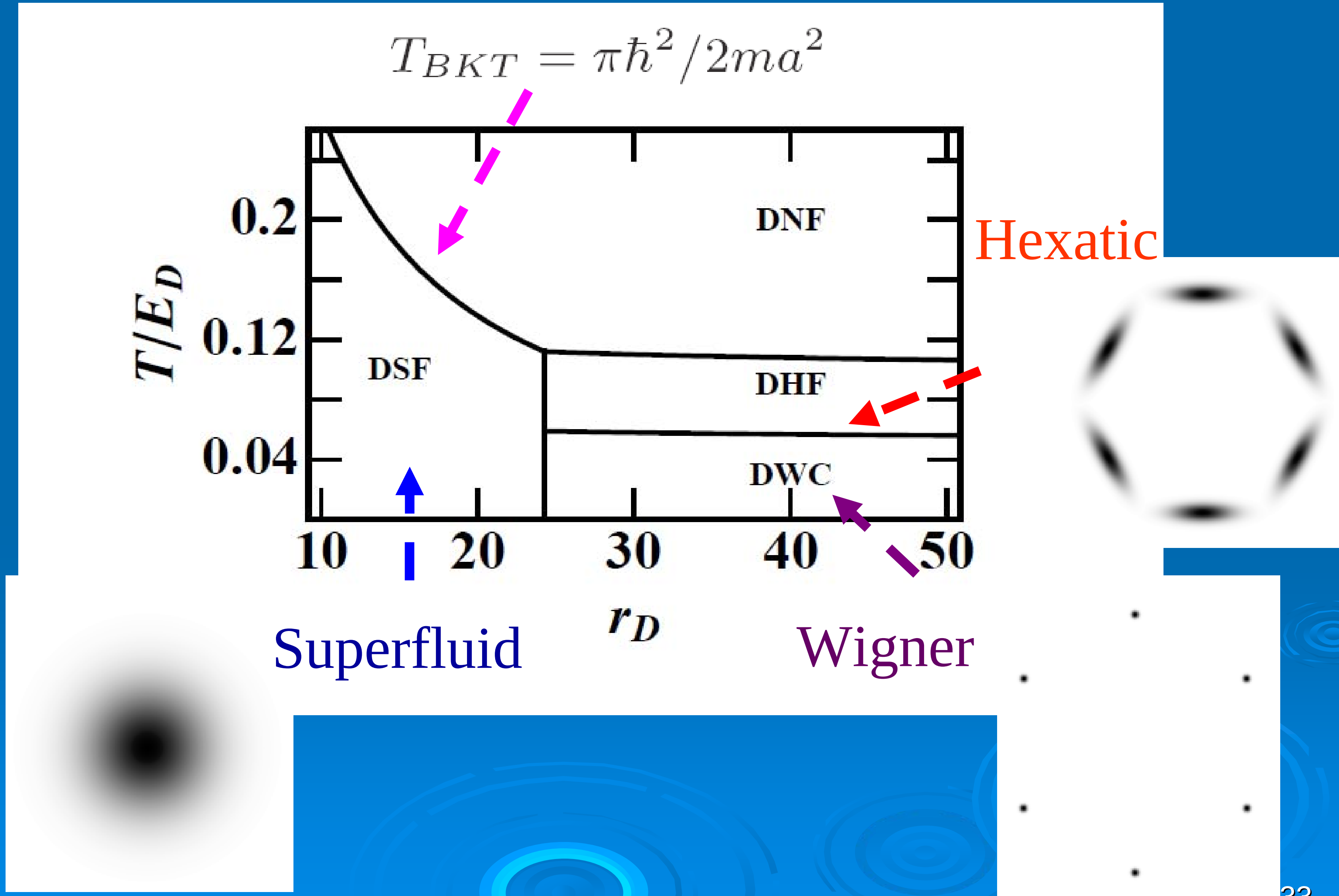
Energy $$E_{\rm he} = \frac{\Gamma_6}{2}\int \frac{d\mathbf{r}}{a^2}\left|\nabla\theta(\mathbf{r})\right|^2$$

Critical Temperature $\Gamma_6(T_n) = 72T_n/\pi$

Two-stage melting: emergence of the normal phase



Bragg Diffraction Patterns

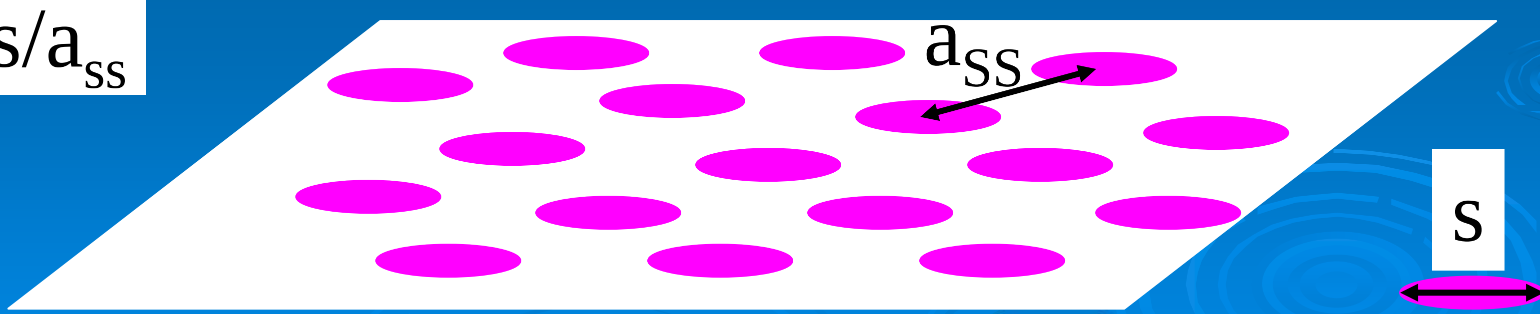


Are there any additional phases?

What about a supersolid phase:
coexistence of superfluid order
and density order, i.e.,
superfluid density is modulated.

 = superfluid regions

$$\alpha_{ss} = s/a_{ss}$$



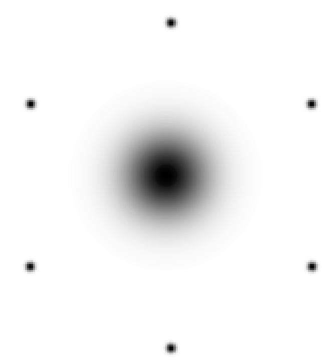
Comparison with ^{4}He

In ^{4}He the system is in a solid phase and the superfluid component is due to defects.

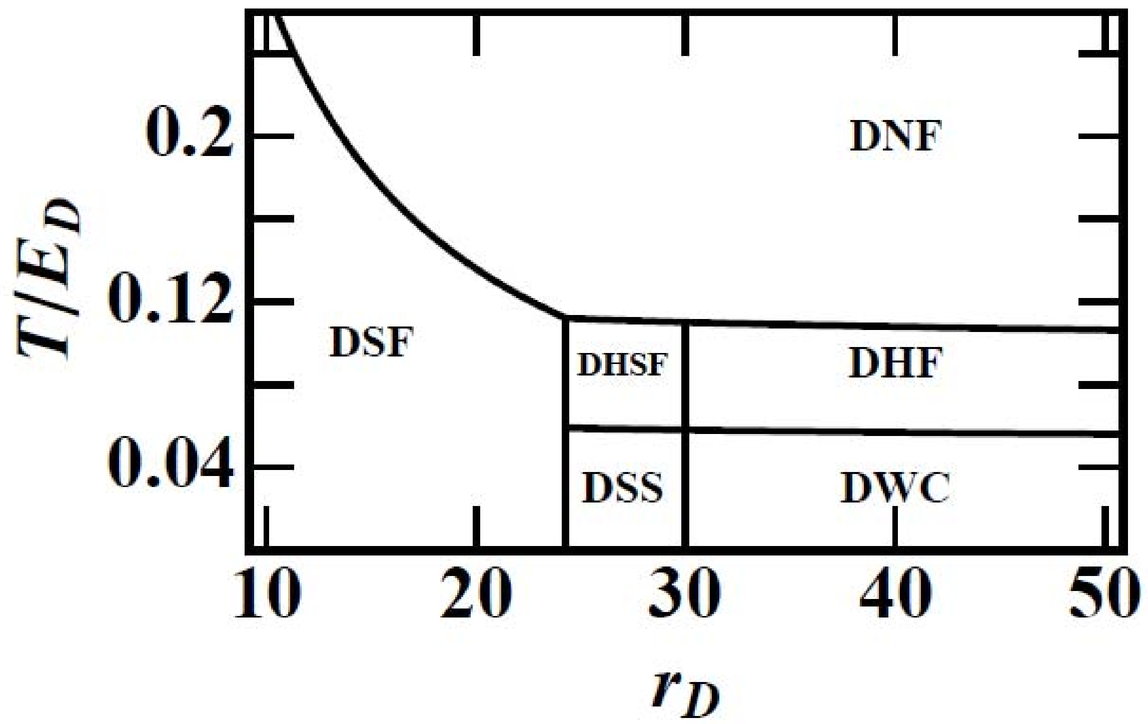
In ultra-cold gases there is no solid phase, but instead the coexistence between superfluid order and discrete translational order.

$\alpha_{ss} = s/a_{ss}$

Additional phases possible in continuum 2D dipolar problem.



DSS



DHSF

DSS = Dipolar Supersolid

DHSF = Dipolar Hexatic Superfluid

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(HVALA NA PAZNJI)

END OF TALK