Vortex Lattice Formation in Bose-Condensed Gases in Rotating Potentials

Tetsuro Nikuni (Tokyo University of Science)

Toshihiro Sato (University of Tokyo)

Tomohiko Ishiyama (Tokyo University of Science)

Motivation

- BEC in rotating lattice potential

  Vortex lattice structure
  Weak lattice potential
  →Abrikosov Lattice

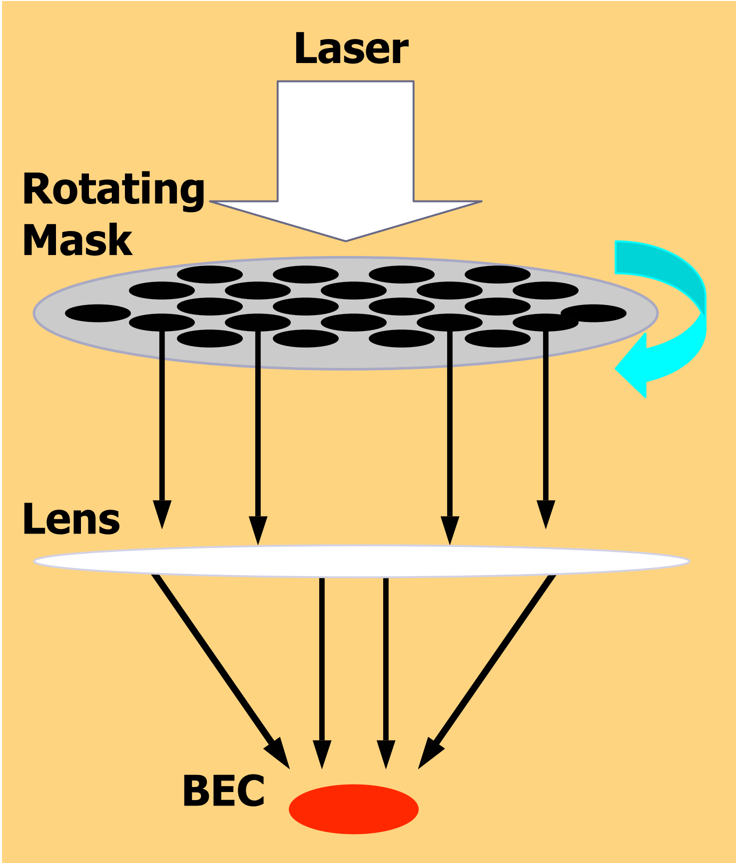
  Strong lattice potential
  →Vortex pinning

- Theory on the rotating square lattice potential

Reijnders and Duine, PRL 93, 060401 (2004)

Pu et al., PRL 94, 190401 (2005)

Bhat et al., PRL 96, 060405 (2006)



Bhat, Carr, and Holland., PRL 96, 060405 (2006)

Triangular Lattice Potential

- We consider the rotating **triangular lattice** potential generated by the **blue-detuned laser beam.**

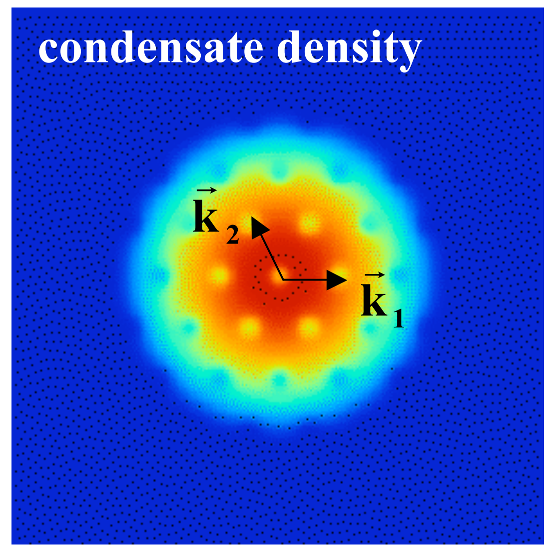
$$V_{\text{lattice}} = \sum_{n_1,n_2} V_0(\mathbf{r}-\mathbf{r}_{n_1,n_2}) = \sum_{n_1,n_2} V_0 \exp\left\{-\left[\frac{\left|\mathbf{r}-\mathbf{r}_{n_1,n_2}\right|^2}{(\sigma/2)^2}\right]\right\}$$

$$\mathbf{r}_{n_1,n_2} = n_1\mathbf{k}_1 + n_2\mathbf{k}_2$$

$$\mathbf{k}_1 = (a,0)$$

$$\mathbf{k}_2 = \left(-\frac{a}{2}, \frac{\sqrt{3}}{2}a\right)$$

a : lattice constant



a = 2.2 , V_0 = 7.0 , σ = 0.65
(ground state)

Gross-Pitaevskii Equation

- We use the 2D Gross-Pitaevskii equation in the rotating frame

$$(i-\gamma)\hbar\frac{\partial}{\partial t}\Phi(x,y,t)=\left[-\frac{\hbar^2}{2m}\nabla^2+V(x,y)+g|\Phi(x,y,t)|^2-\Omega\hat{L}_z\right]\Phi(x,y,t)$$

$$g=\frac{4\pi a_s\hbar^2}{m}$$

a_s : s-wave scattering length

m : atomic mass

γ : dissipative term

Ω : angular velocity of the rotating potential

$$V(x,y)=\frac{1}{2}m\omega_0^2(x^2+y^2)+V_{\text{lattice}}(x,y)$$

energy and length scales

$$a_{\text{ho}}=\sqrt{\frac{\hbar}{m\omega_0}}=1.01\ \mu\text{m}$$

$$\hbar\omega_0=7.55\times10^{-25}\ \text{erg}$$

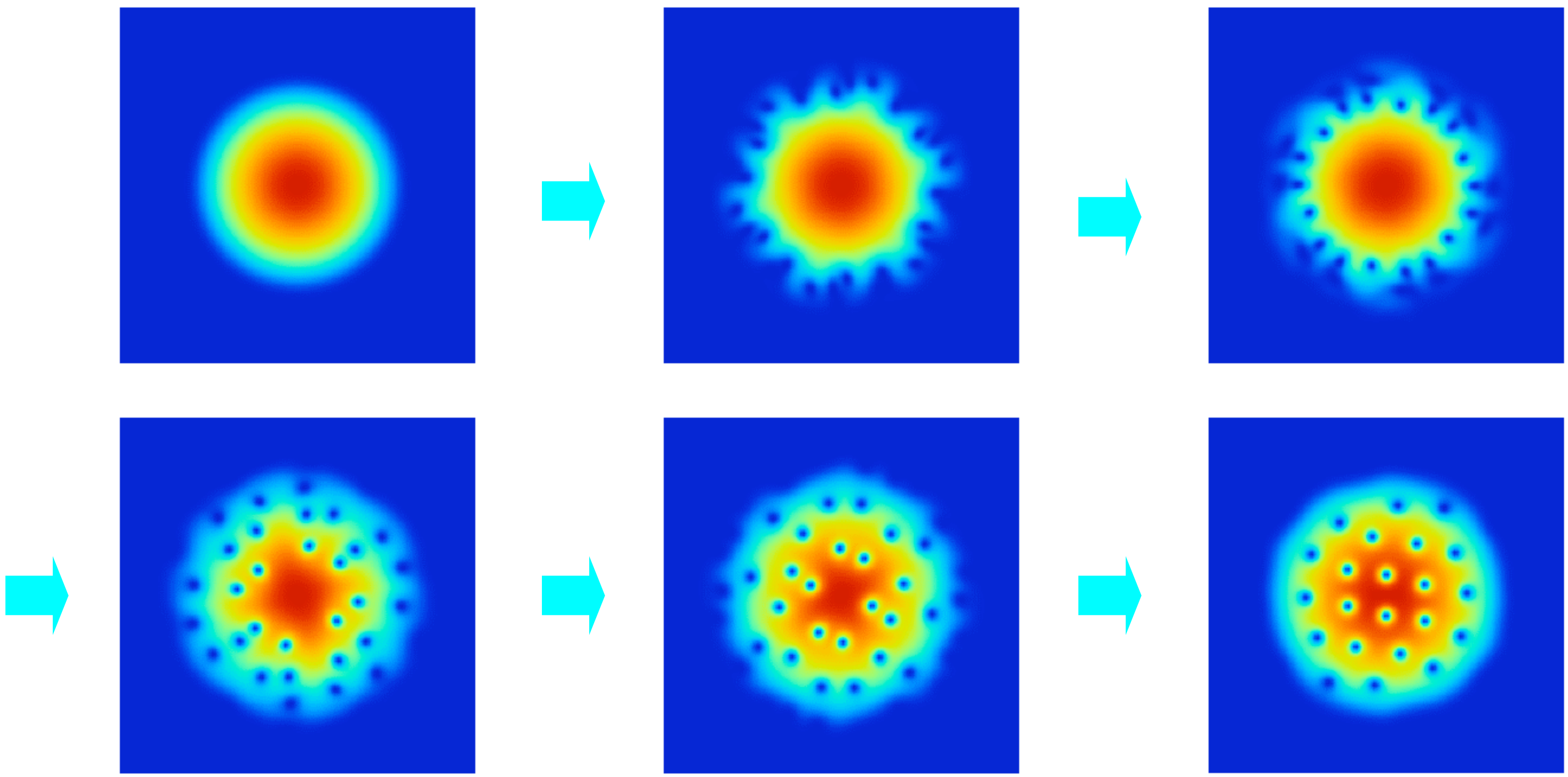
$$\xi=0.12\ \mu m$$

- We are interested in:
  - Dynamics of the vortex lattice formation.
  - Vortex lattice structure.

Numerical Result

Lattice constant a/a_{ho}=2.2 $\underline{\Omega=0.70\omega_0}$

1) Weak lattice potential (V_0=0.1)

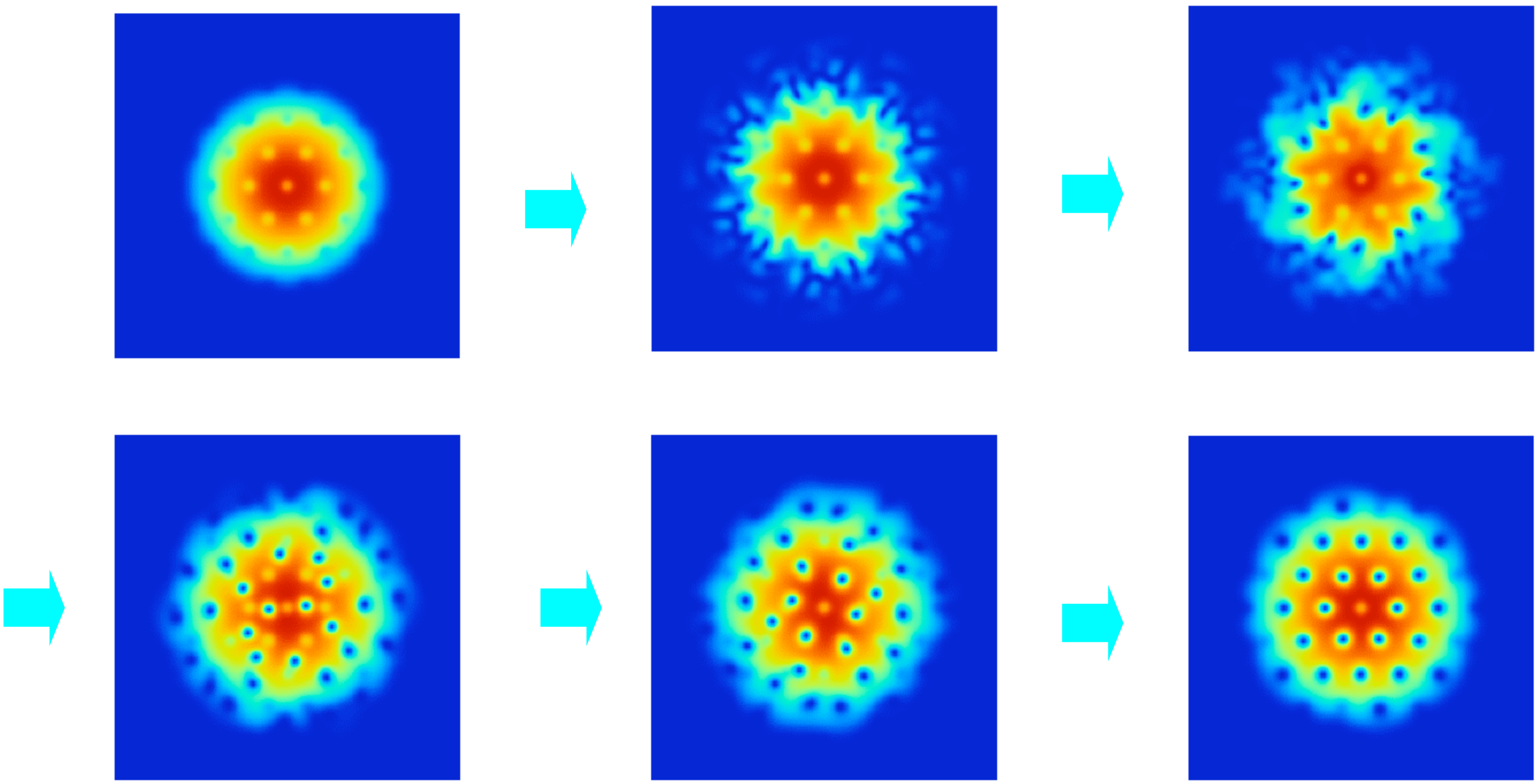


Time evolution of the condensate density

Numerical Result

Lattice constant a/a_{ho}=2.2 $\underline{\Omega=0.70\omega_0}$

2) Strong lattice potential (V_0=5.0) ⇒perfect pinning

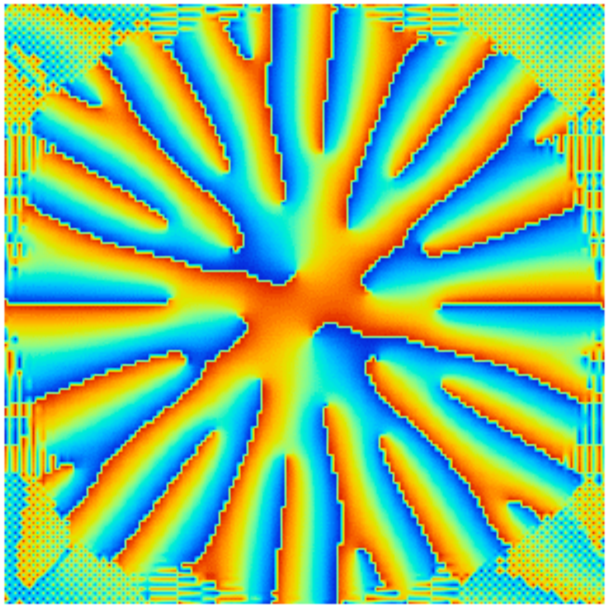


Time evolution of the condensate density

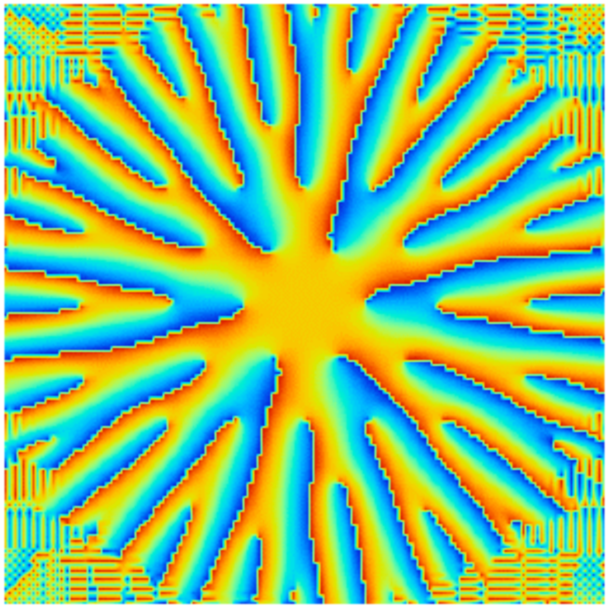
Phase of the Condensate

Lattice constant a/a_{ho}=2.2 $\underline{\Omega=0.70\omega_0}$

1) Weak lattice potential



2) Strong lattice potential



Quantities Characterizing the Vortex Pinning

- Lattice potential energy

$$E_{\text{lattice}} = \langle V_{\text{lattice}} \rangle = \int dxdy \Phi * (x,y) V_{\text{lattice}} \Phi(x,y)$$

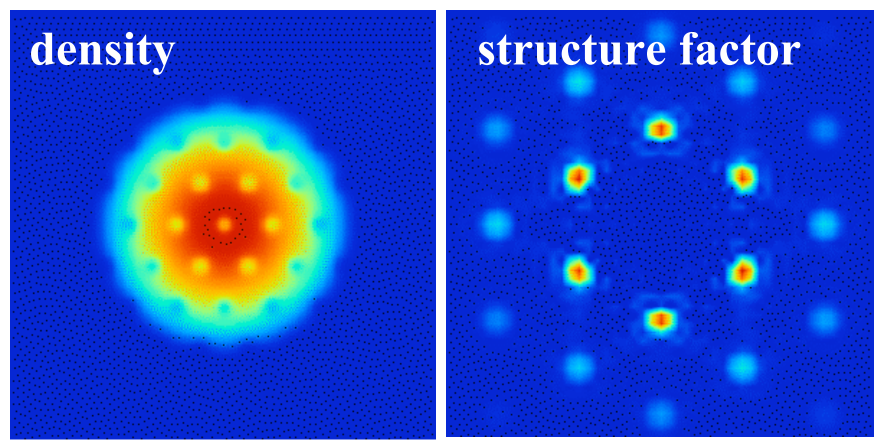
$$V_{\text{lattice}} = \sum_{n_1,n_2} V_0(\mathbf{r} - \mathbf{r}_{n_1,n_2})$$

- Structure factor

(Fourier transform of the condensate density)

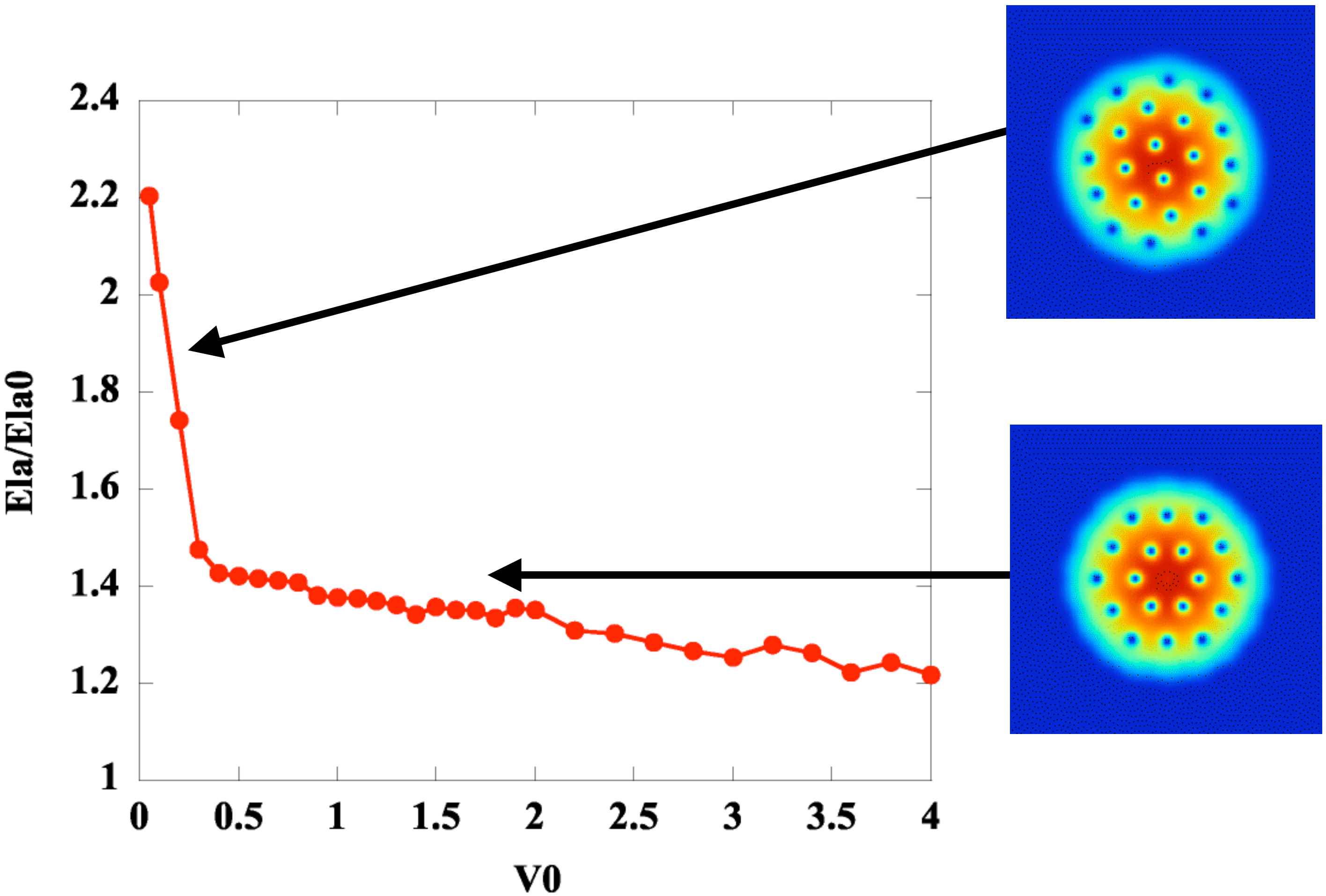
$$S(k_x, k_y) = F\{n(x,y)\}$$

$$n(x,y) = |\Phi(x,y)|^2$$

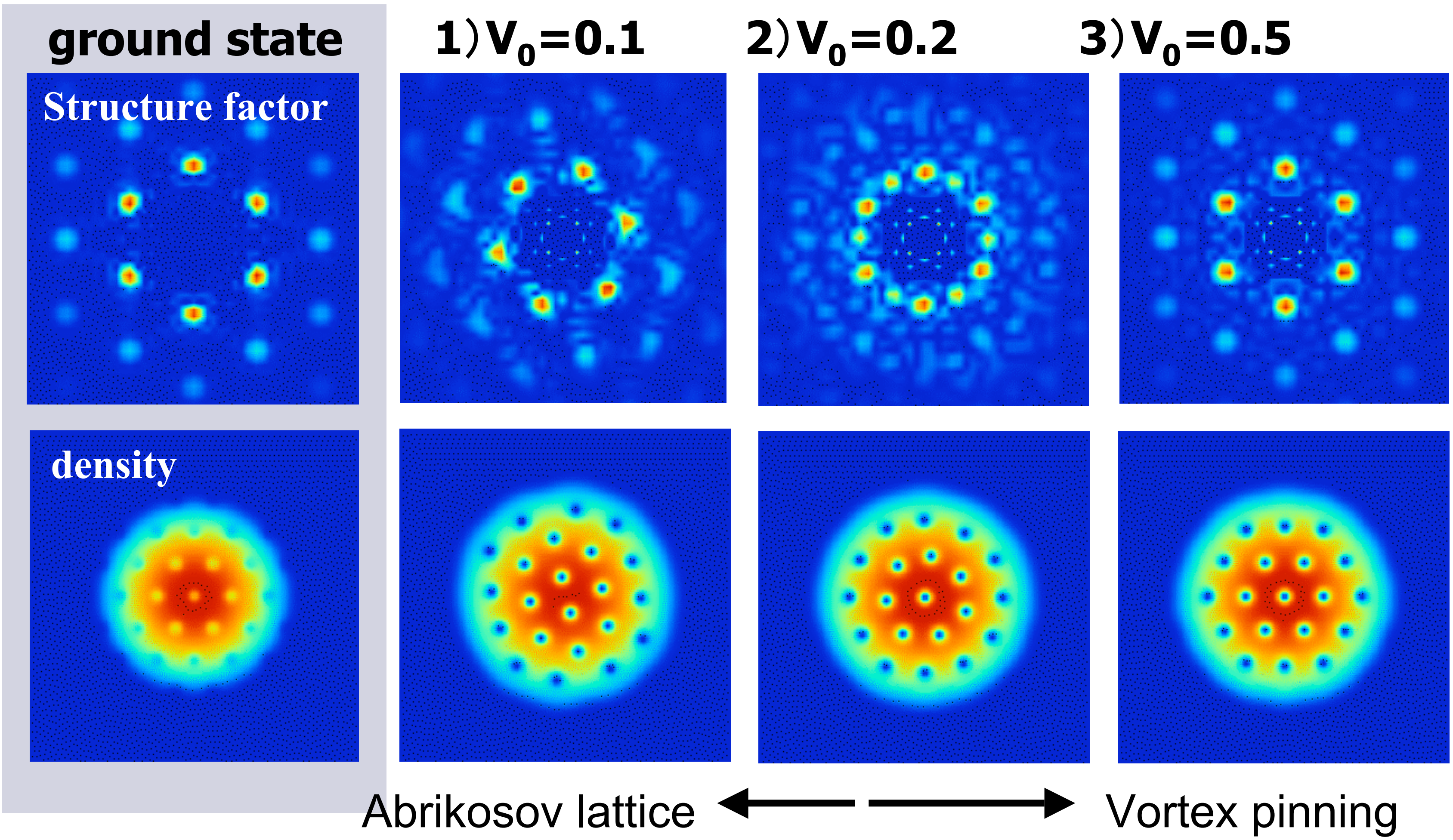


$a = 2.2$, $V_0 = 7.0$, $\sigma = 0.65$
(ground state)

Lattice Potential Energy

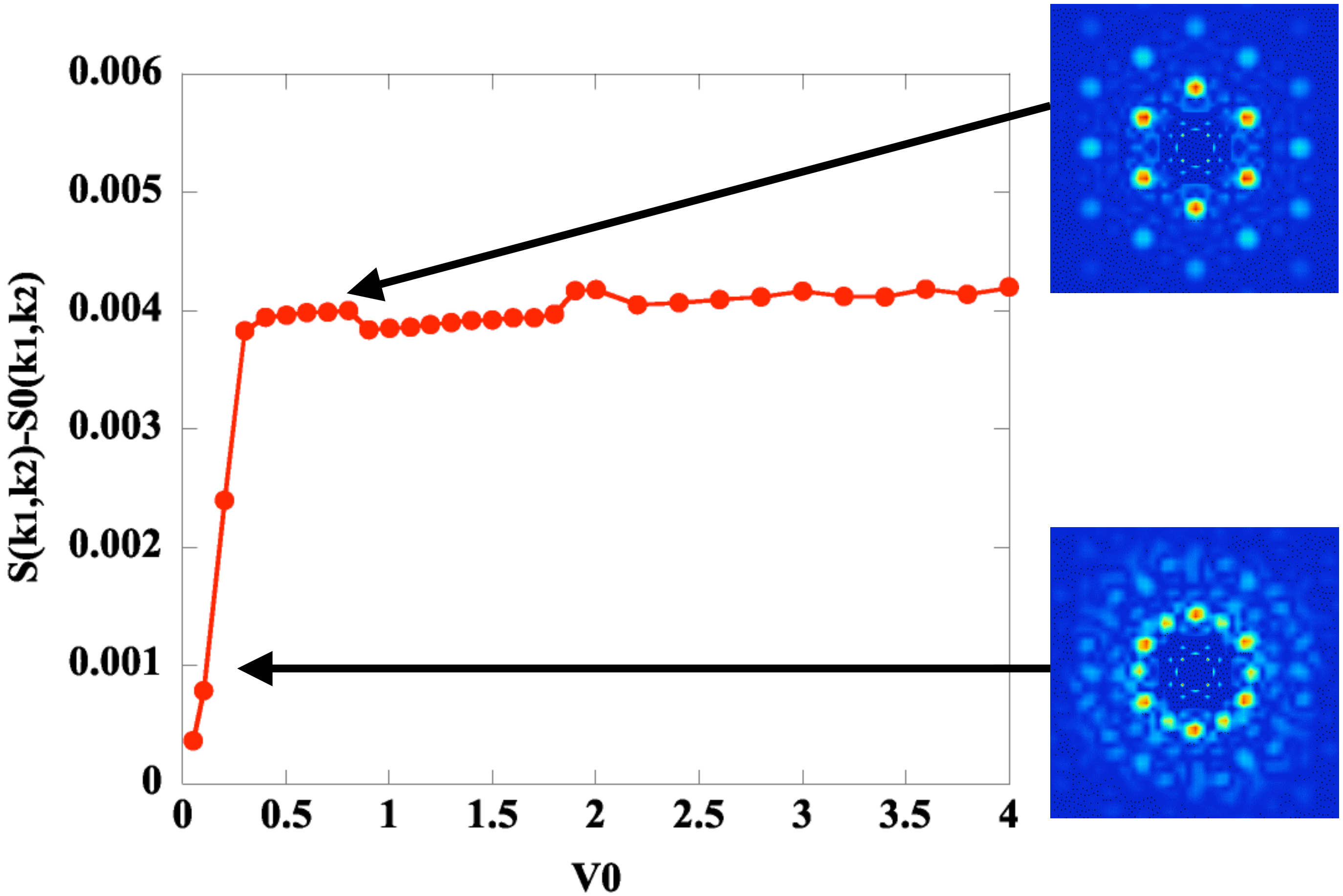


Structure Factor

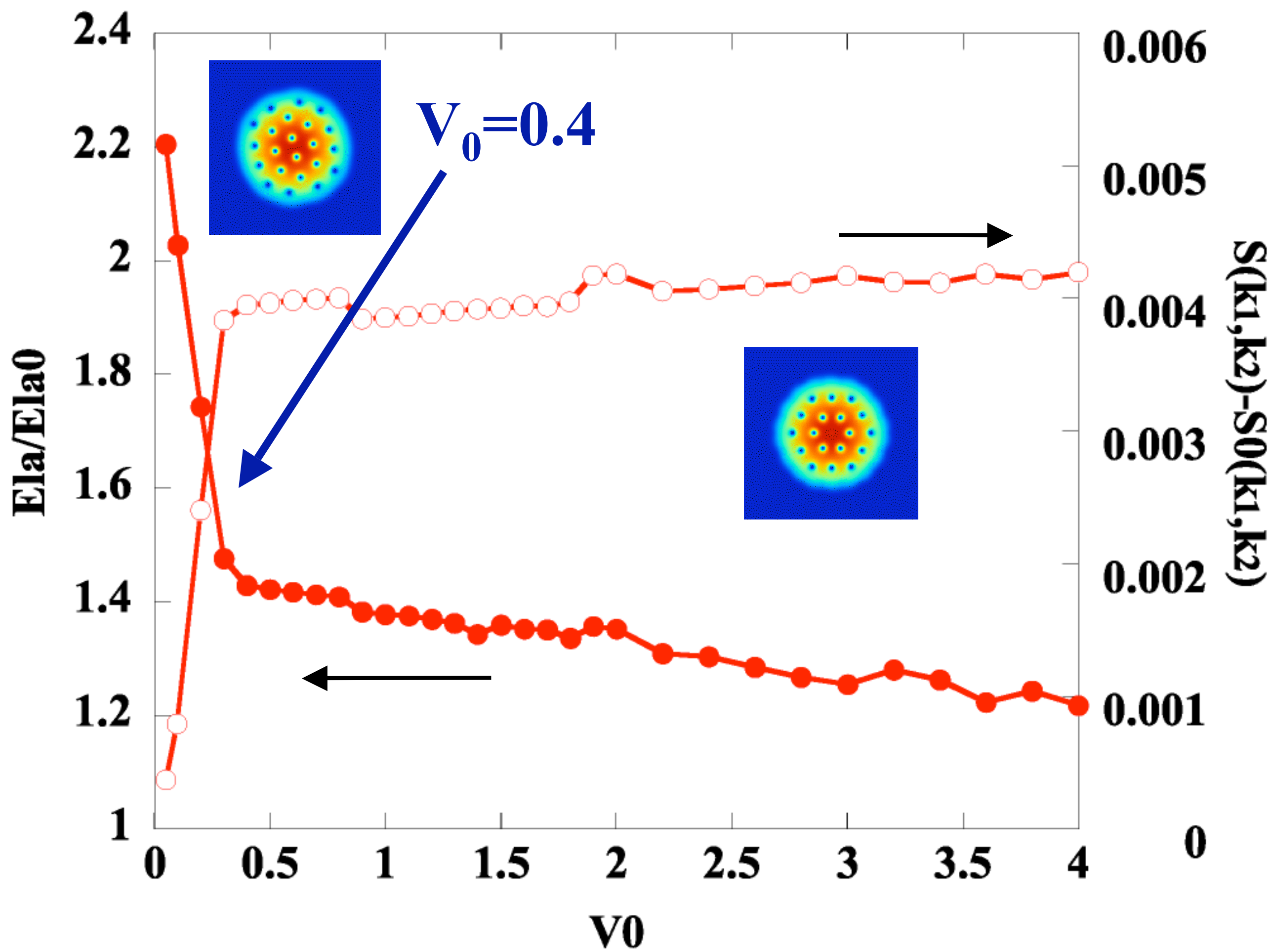


Vortex Pinning

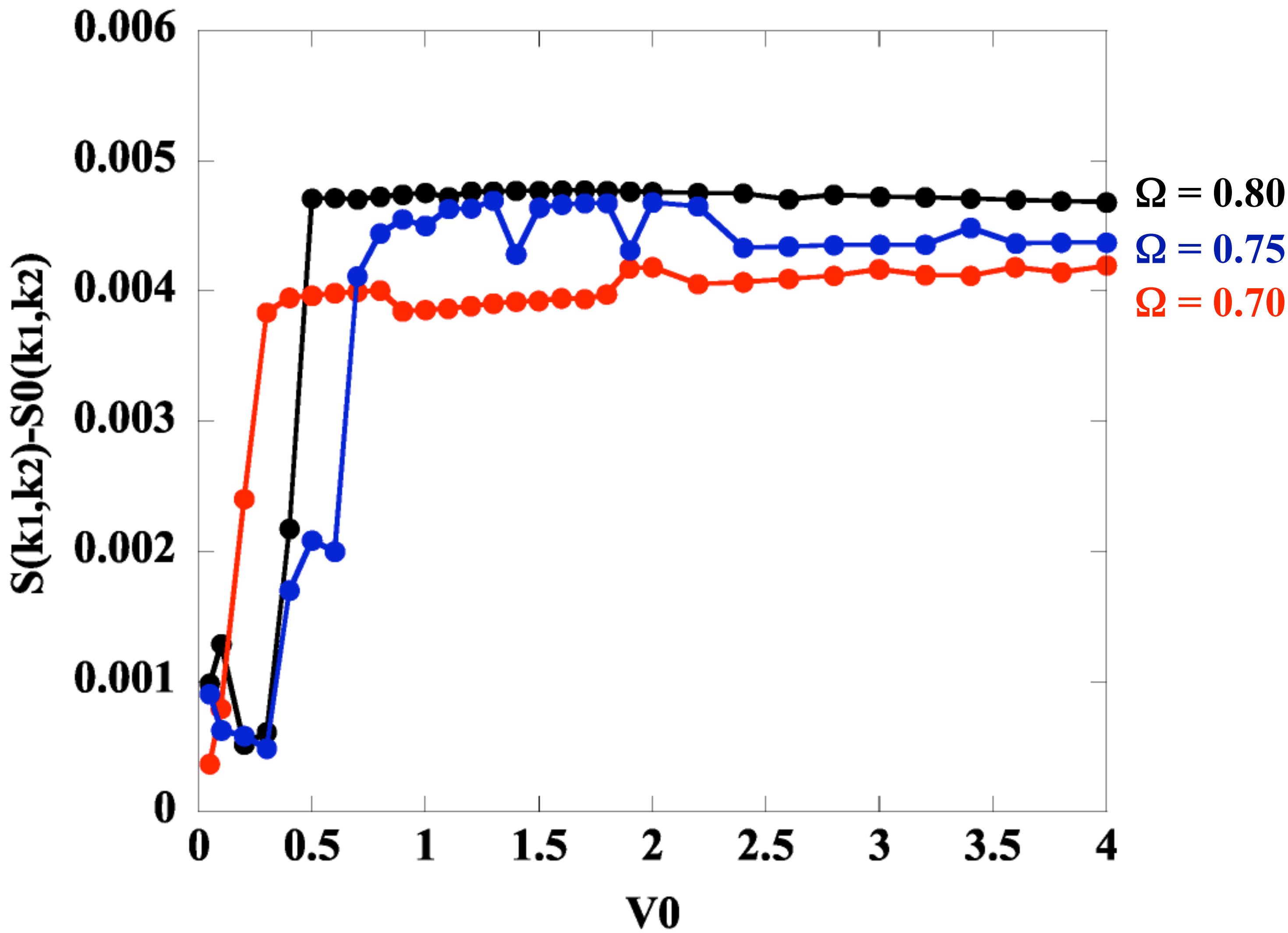
Structure factor $S(\mathbf{k})$



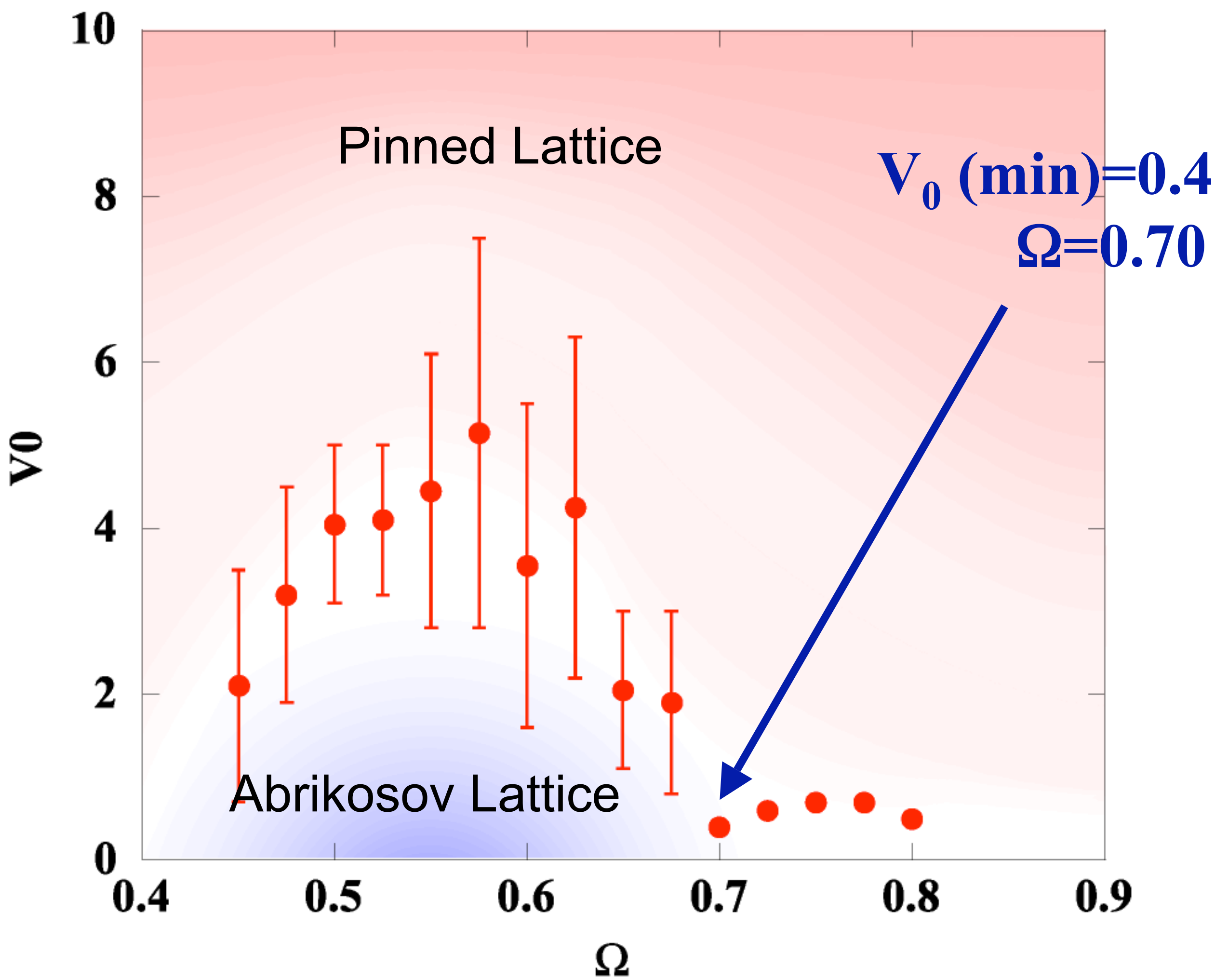
Lattice Potential Energy and Structure Factor



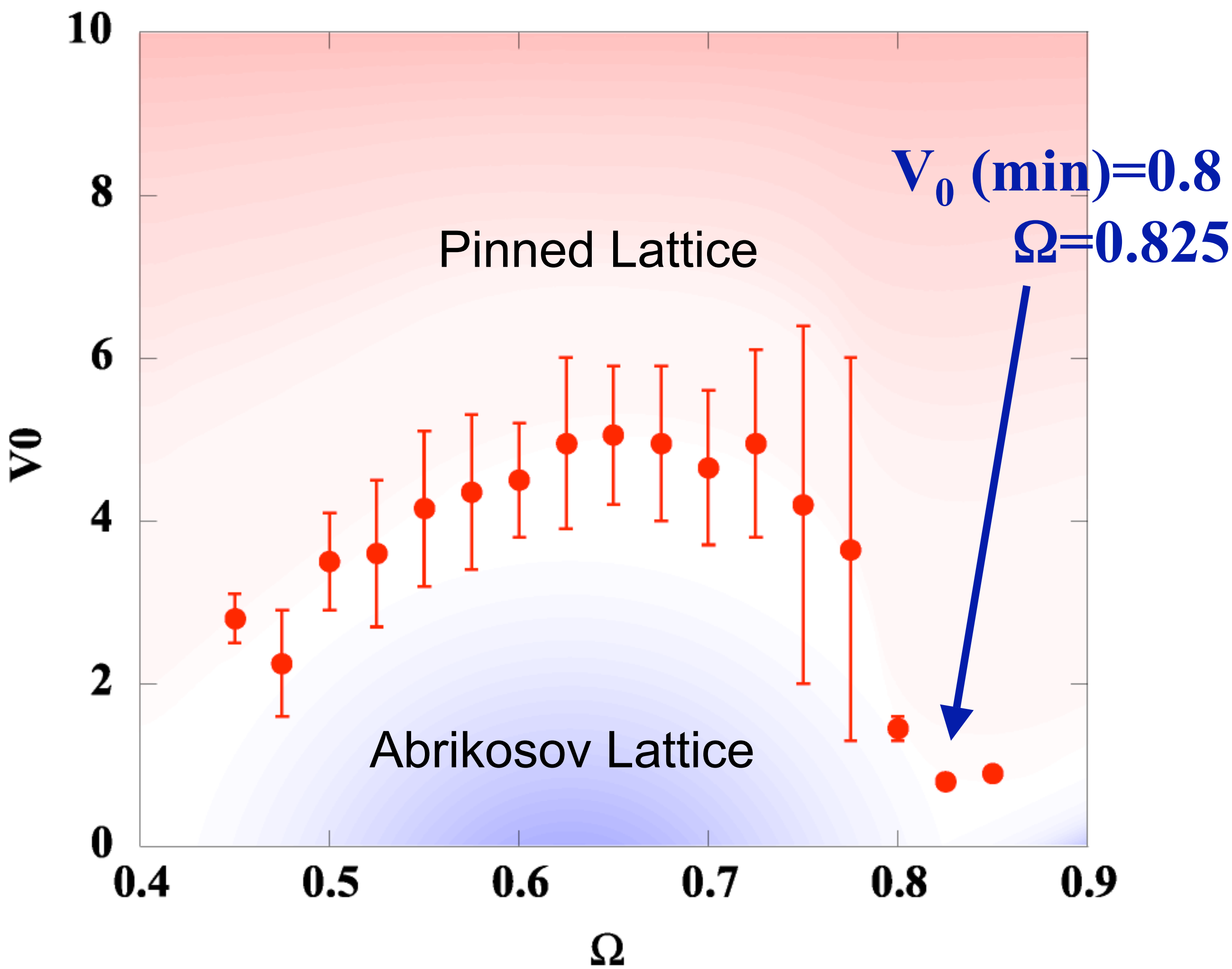
Structure Factor



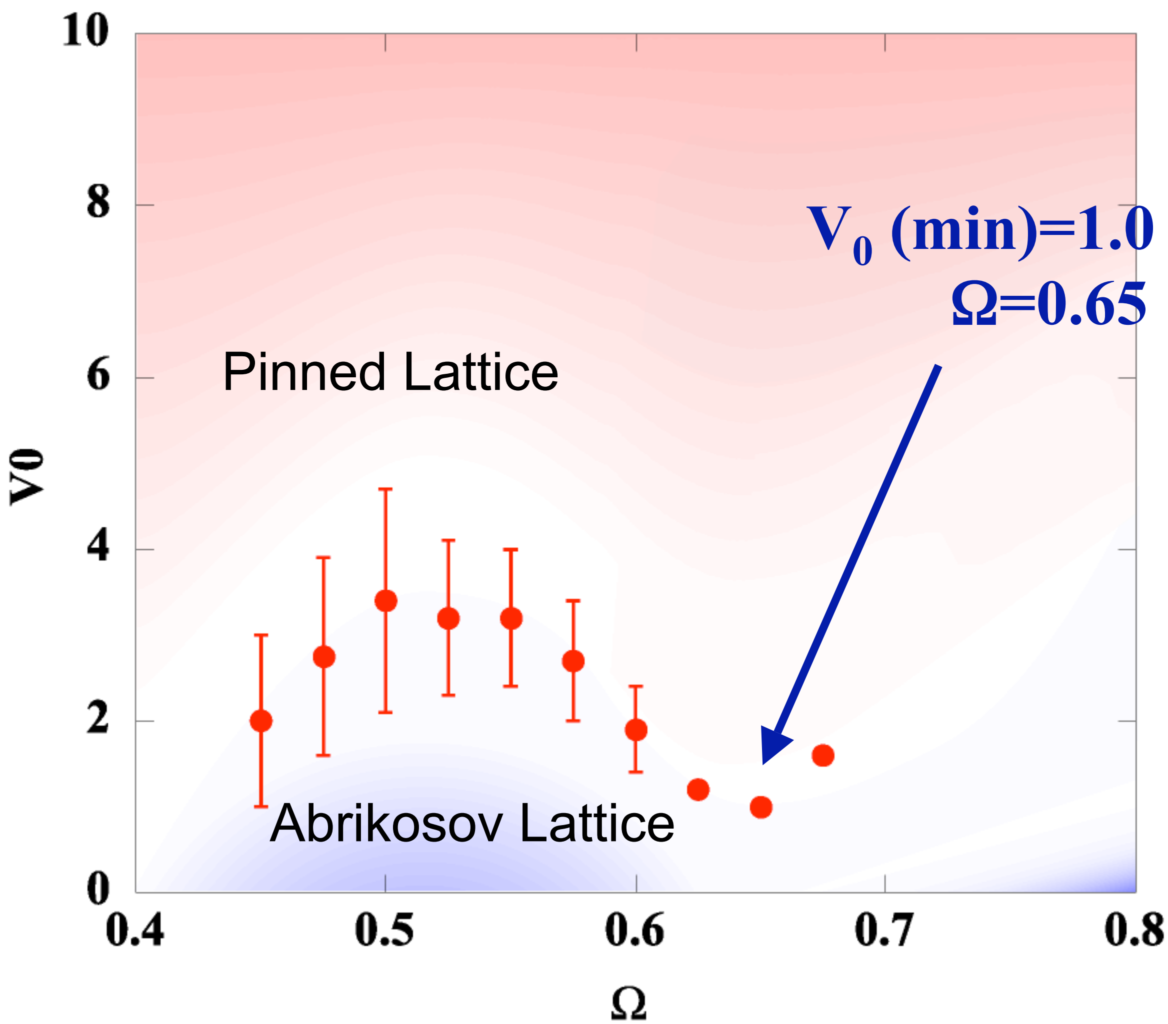
Vortex Lattice Structures (a/a_{ho}=2.2)



Vortex Lattice Structures (a/a_{ho}=2.0)



Vortex Lattice Structures (a/a_{ho}=2.4)



Summary

- We studied vortex lattice formation in BEC in the rotating triangular lattice potential.
- We calculated the structure factor of the condensate density to quantify the vortex lattice structures.
- We also studied vortex lattice formation in the rotating square lattice potential.