# Observation of the Supersolid Stripe Phase in Spin-orbit Coupled Bose-Einstein Condensates

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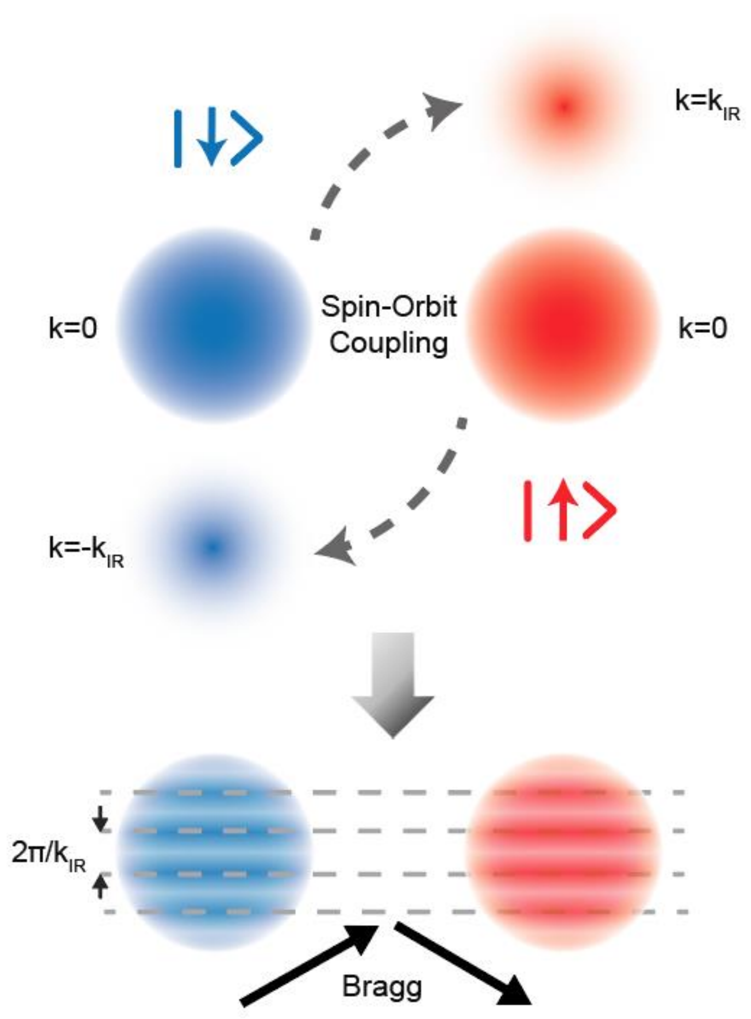
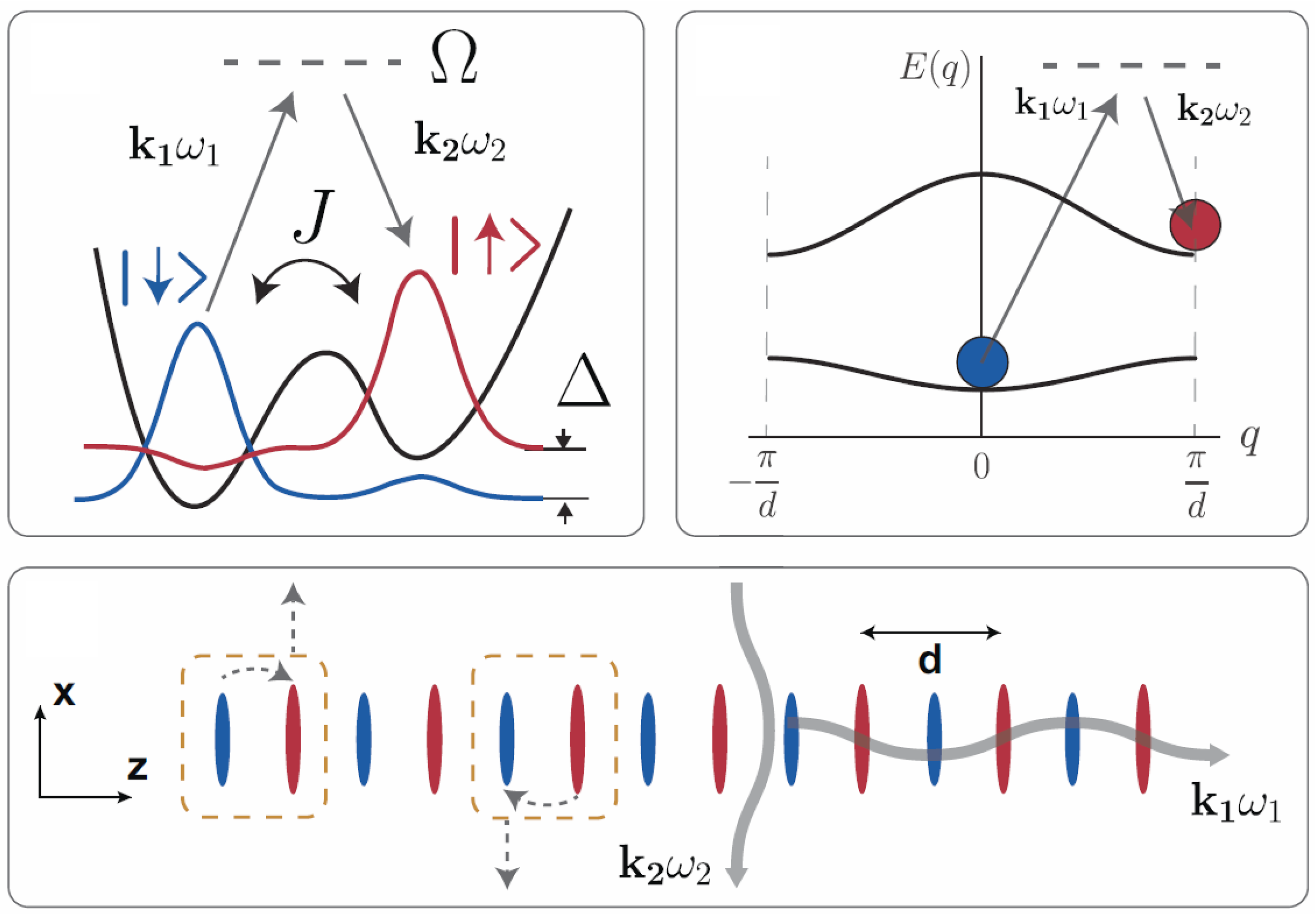
## Supersolid phase in Spin Orbit coupled (SOC) BEC




- **What is a supersolid? [1]:**
  - Phase of matter which displays simultaneously crystalline order and dissipationless flow
  - System that breaks two continuous U(1) symmetries –> internal gauge / translational
- **Search for supersolids in $^4$He [2]:**
  - Initial discovery of non-classical rotational inertia of solid $^4$He in torsion oscillator
  - Turned out to be caused by unusual elastic properties, which revealed quantum plasticity and mass supertransport
- **Search for supersolids in cold atom:**
  - BEC with dipolar interactions [3]
  - BEC with Rydberg interactions [4]
  - BEC with superradiant Rayleigh scattering [5]
  - BEC with spin orbit coupling [6]

## Our scheme: Orbital Pseudospins in Optical Superlattice



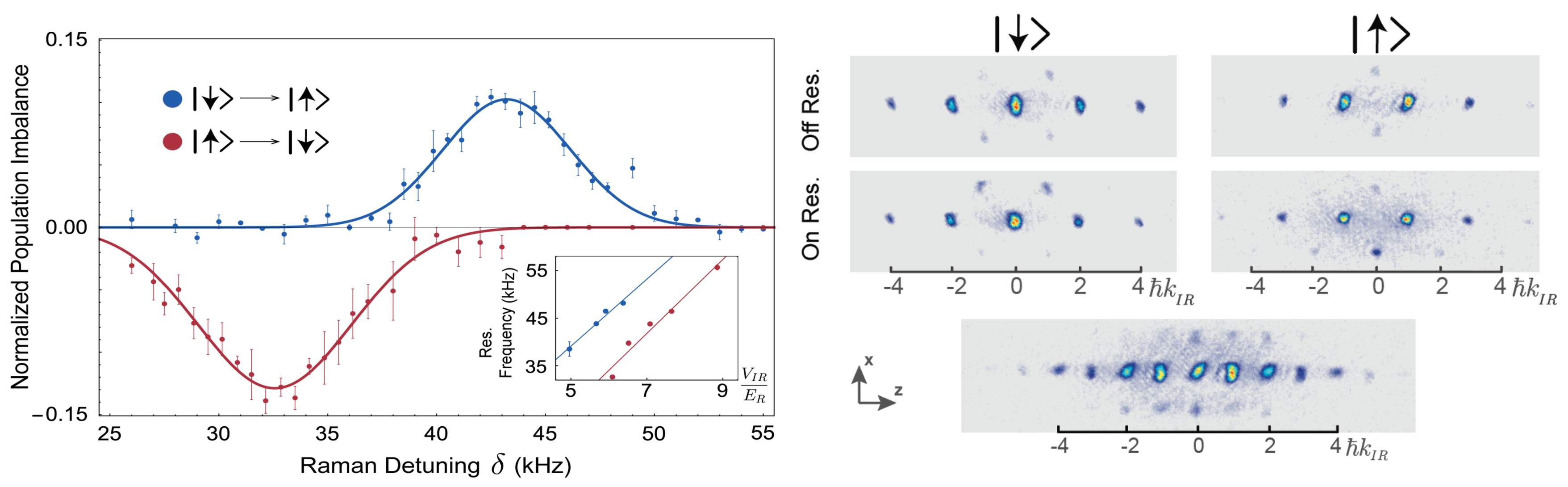

$$H = \frac{p^2}{2m} - \underbrace{\frac{1}{2}V_R\cos(2k_R x)}_{\text{IR lattice}} - \underbrace{\frac{1}{2}V_G\cos(4k_R x + \phi)}_{\text{Green lattice}} + \underbrace{\Omega\cos(\delta\mathbf{k}\cdot\mathbf{r} - \delta\omega t)}_{\text{Raman potential}}$$

- **Orbital pseudospins:** Two lowest eigenstates of the double-well potential, where one well lifted with respect to another, can be considered as a two-level system with pseudo-spin up and down states.
- **Optical superlattice:** We create a one-dimensional superlattice by overlapping Infrared ($\lambda$ =1064nm) lattice and green ($\lambda$ =532nm) lattice, resulting in the periodic array of double wells. By controlling the relative phase between green and infrared lattices we can control the shape of double-well.
- **Advantages**

I. No internal spin-flip: Since only one hyperfine state is involved, far-off resonant light can be used. As a result, lifetime is improved.

II. Adjustable inter-spin interaction: Double well potential can be controlled to change the overlap between pseudo-spin states, which gives tunable interactions. Especially the case of $g_{\uparrow\downarrow}^2 < g_{\uparrow\uparrow}g_{\downarrow\downarrow}$ is favorable for detection of stripe phase.

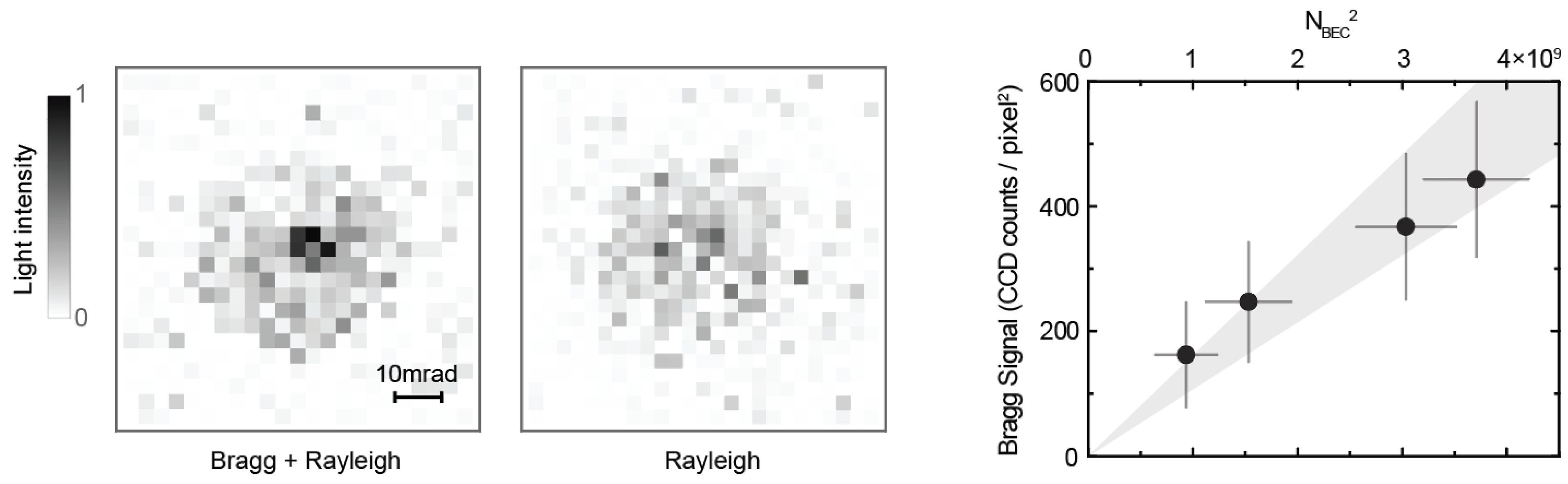
## Spin-Orbit Coupling of Orbital Pseudospins [7]

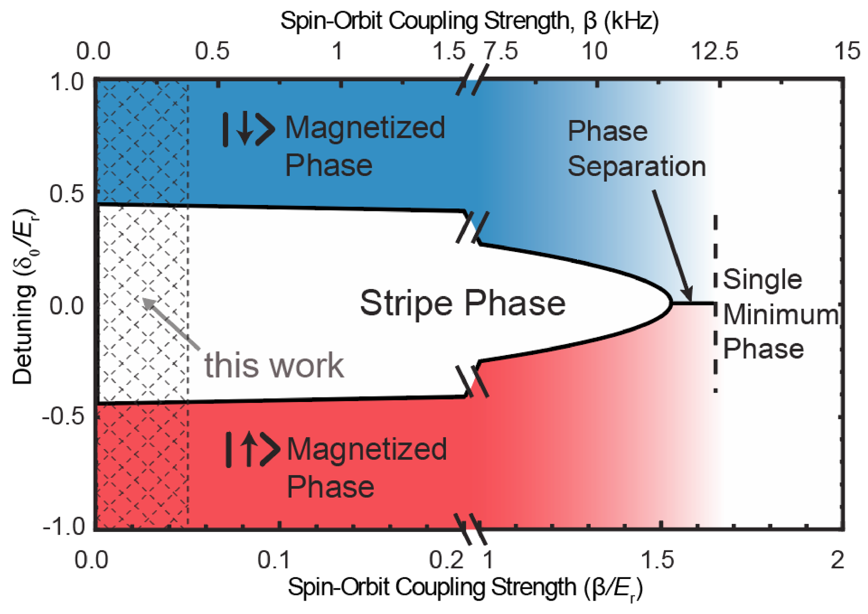


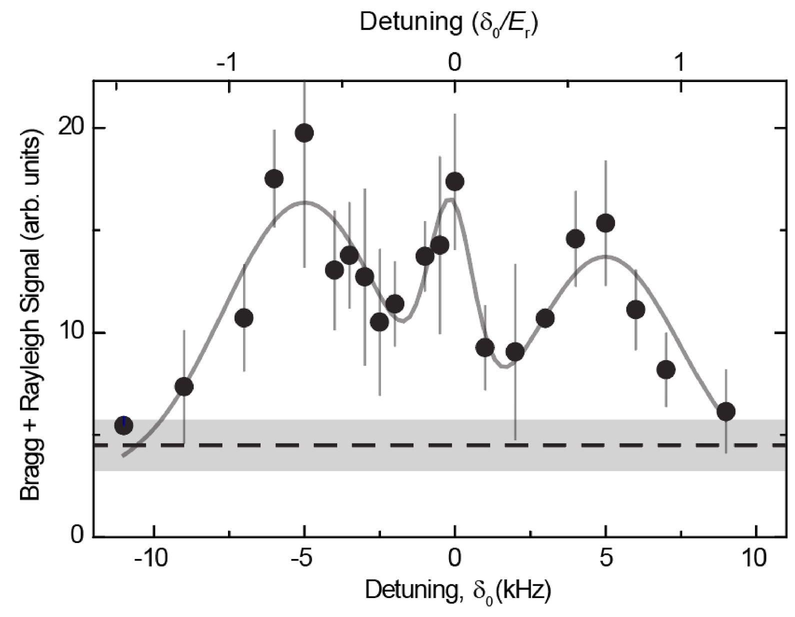

$$\hat{H}_{SOC} = \frac{(\hat{p} + \alpha\hat{\sigma}_z)^2}{2m} + \beta\hat{\sigma}_x + \delta_0\hat{\sigma}_z \qquad \alpha = -k_x/2,\ \beta = (1/\sqrt{2})\Omega J/\Delta, \text{ and } \delta_0 = (\delta - \Delta)/2$$

- **Time-of-flight detection:** Pseudo-spin up and down states are orthogonal to each other, therefore becomes separated in ballistic expansion.
- **Raman-induced spin-orbit coupling scheme:** Two-photon Raman coupling of pseudo-spin states results in spin dependent momentum kick.
- **Resonant feature:** There are both off-resonant on-site coupling, and resonant spin-orbit coupling. By scanning the detuning between the Raman beams, we observe that Up to Down and Down to Up resonances are $2E_R$ apart.

## Bragg Detection of the Supersolid Stripe Phase [8]

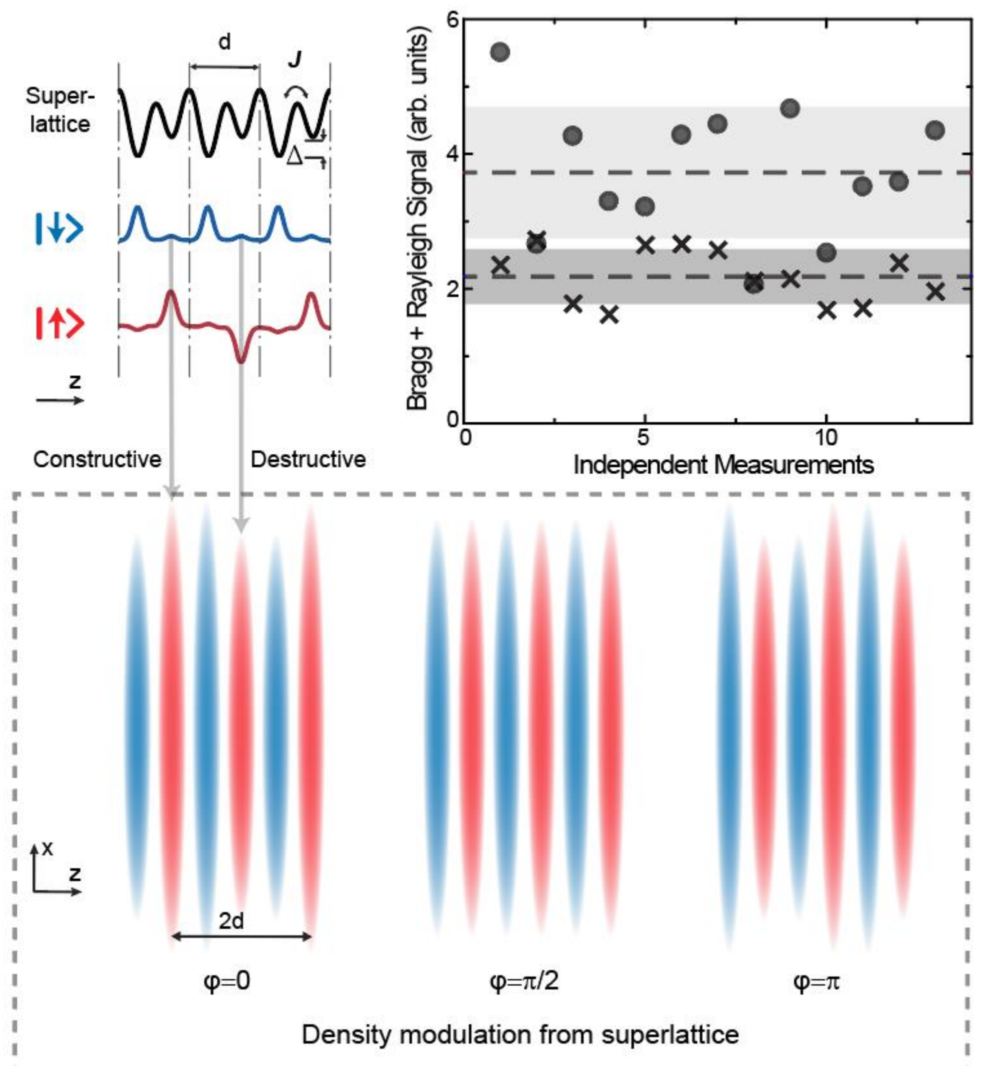



- **Bragg detection:** A sharp specular feature in the left panel is the Bragg signal due to the periodic density modulation. The diffuse signal is Rayleigh scattering filling the round aperture of the imaging system.
- **BEC number dependence:** We observed the expected Bragg signal ∝ $N_{bec}^2$ behavior. The prediction for the signal assumes that the stripes are long-range ordered throughout the whole cloud. If there were m domains, the signal would be m times smaller.
- **Large window for supersolid stripe phase:** Theoretical studies predict miscible (stripe), separated, and single-minimum phases for spin-orbit coupled BEC. As the pseudospin system becomes more miscible, $g_{\uparrow\downarrow}^2 < g_{\uparrow\uparrow}g_{\downarrow\downarrow}$, there is larger range of parameters for detection of the supersolid stripe phase.
- **Raman detuning dependence:** Due to slow population relaxation between the two spin states, the detection of the stripes are possible even for large detuning.

## Bragg Detection of the Lattice Supersolid [8]




- **Discrete breaking of translational symmetry:** Unrelated to the presence of spin-orbit coupling, our superlattice system also breaks a discrete translational symmetry along the lattice z-direction by forming a spatial period which is twice that of the external lattice.

## References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