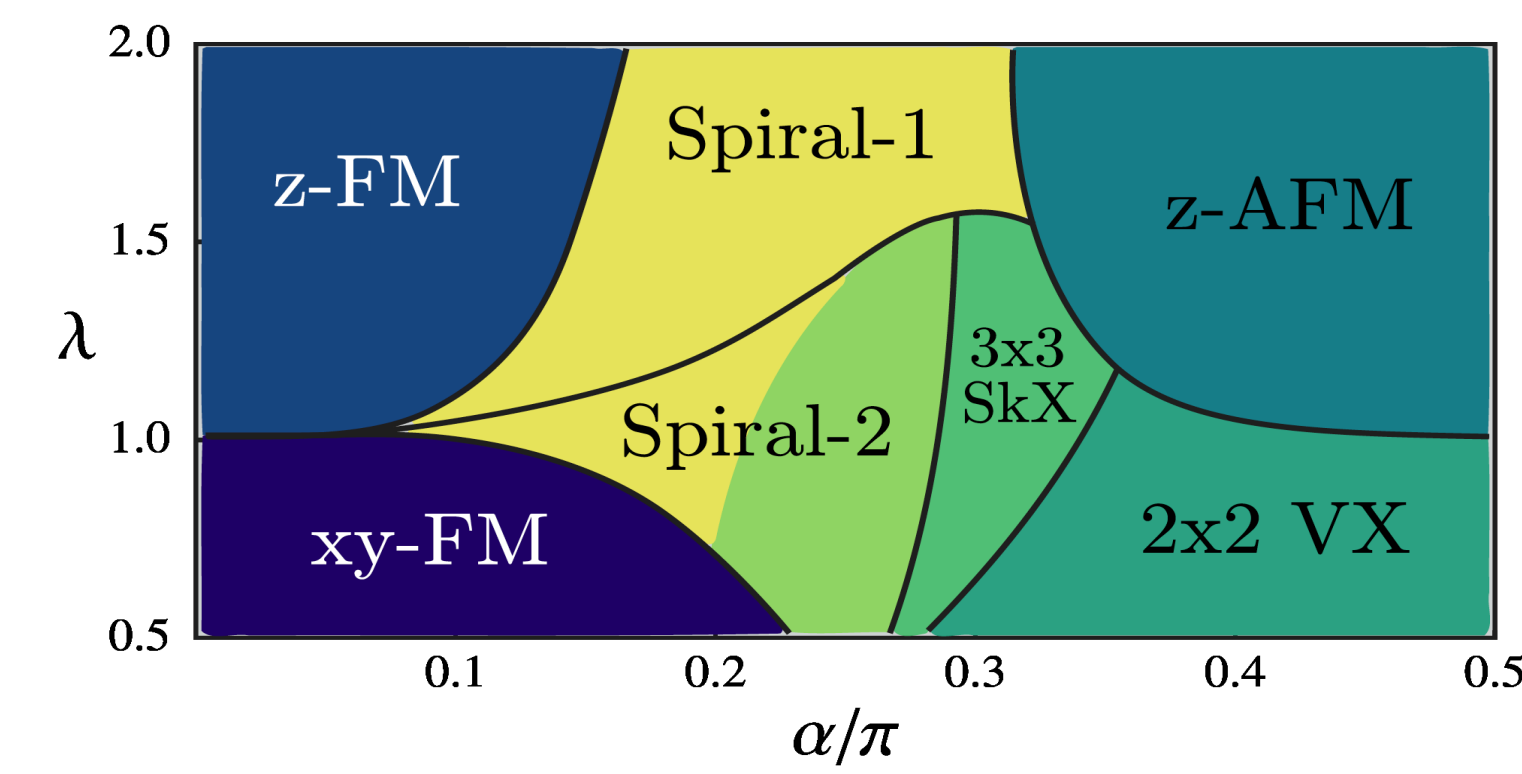


Quantum Simulation

- ❖ Engineer Hamiltonians through laser field dressing of atomic states, together with strong/tuneable interatomic scattering interactions [1-4].
- ❖ Create bipartite ultracold gas (^{87}Rb & ^{39}K) with interactions tuneable via Feshbach resonances.
- ❖ Interesting phases of matter: Spin-Hall effect; topological systems; magnetic systems... [5-7].

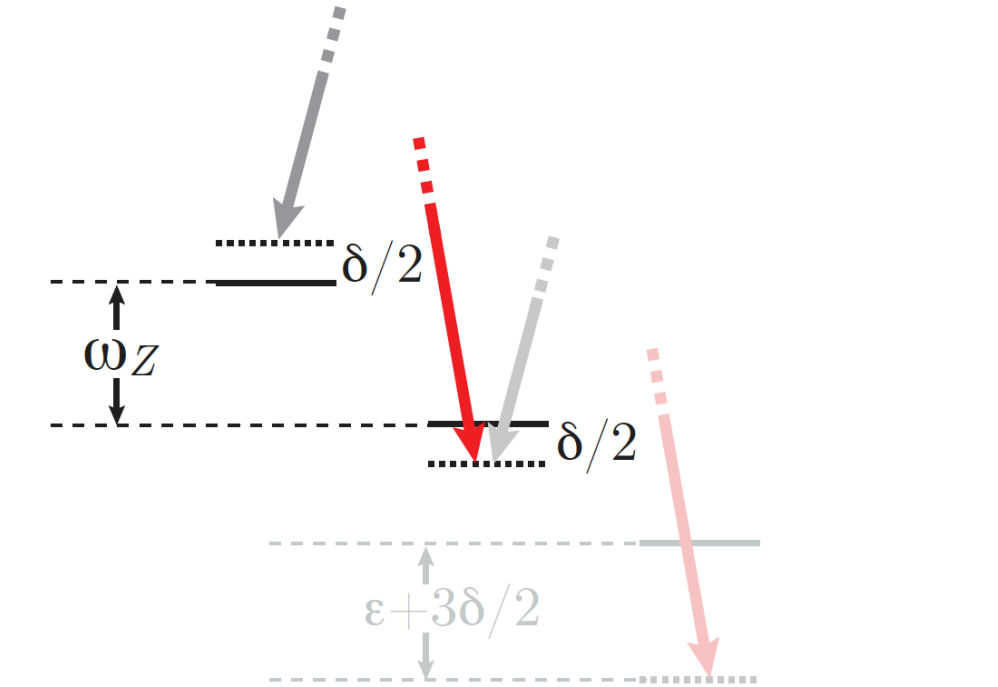


Implementing SOC (α) with tunable interactions (λ) provides access to many exotic states, including magnetic and superfluid phases. Figure from [7].

Raman Coupling Scheme

Raman Coupling

- ❖ Raman beams with wavevector k_L couple the three Zeeman states of the $F = 1$ ground state [8,9].
- ❖ Two-photon Raman coupling simultaneously splits and mixes the dispersion relations $E(k)$ of the atomic spin states.



Raman coupling scheme for an $F = 1$ ground state, with ω_Z the Zeeman shift, δ the Raman detuning, and ϵ the quadratic Zeeman shift. Figure from [1].

$$\hat{H}_R = \begin{pmatrix} \frac{\hbar^2(k_x + k_R)^2}{2m} - \hbar\delta & \hbar\Omega/2 & 0 \\ \hbar\Omega/2 & \frac{\hbar^2 k_x^2}{2m} - \hbar\epsilon & \hbar\Omega/2 \\ 0 & \hbar\Omega/2 & \frac{\hbar^2(k_x - k_R)^2}{2m} + \hbar\delta \end{pmatrix}$$

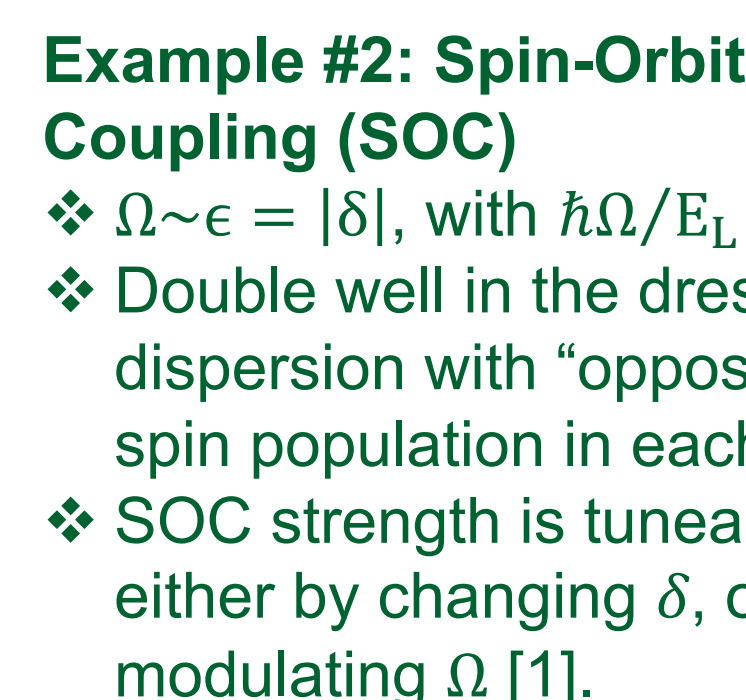
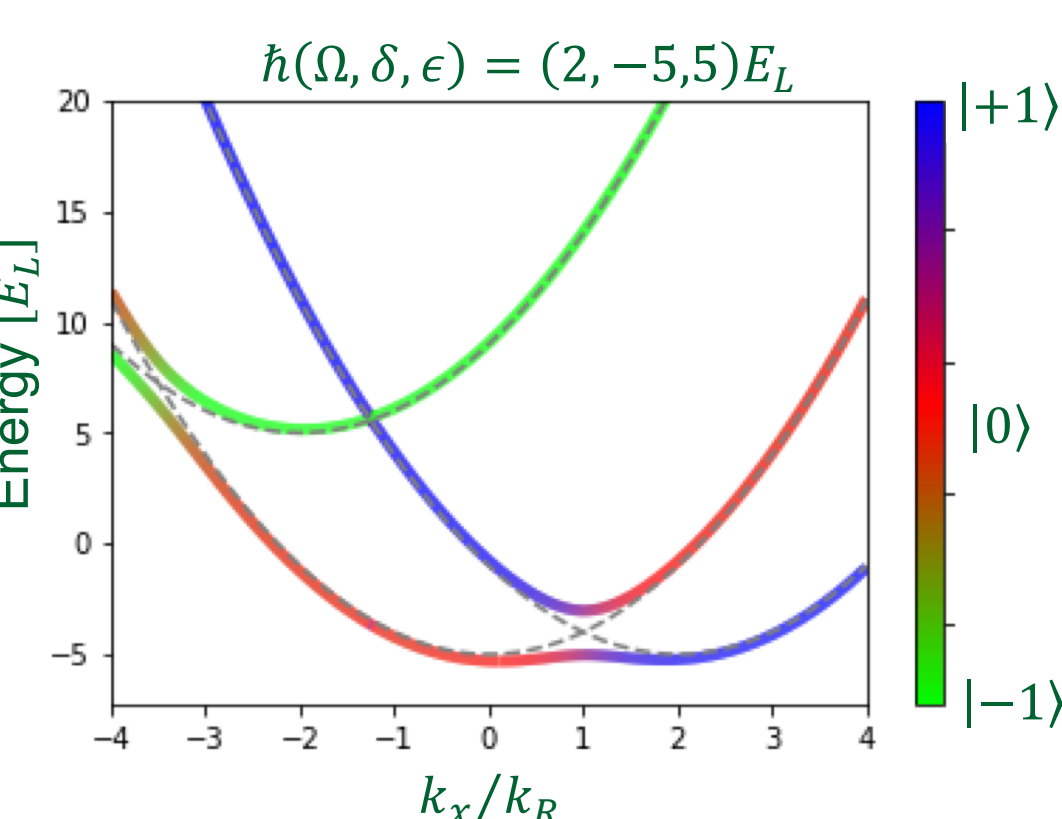
Example #1: Artificial Gauge Fields

- ❖ $\Omega > \delta, \epsilon$, with $\hbar\Omega/E_L > 4$.
- ❖ Single dispersion minimum.
- ❖ Free particle Hamiltonian approximated as:

$$\frac{\hbar^2}{2m}(k - qA)^2 \rightarrow \frac{\hbar^2}{2m^*}(k - k_{min})^2$$

- ❖ If k_{min} is spatially-dependent, an artificial magnetic field $\vec{B}^* = \nabla \times \vec{A}$, may generate vortices.

- ❖ Simulates a physical rotation of the BEC [10].



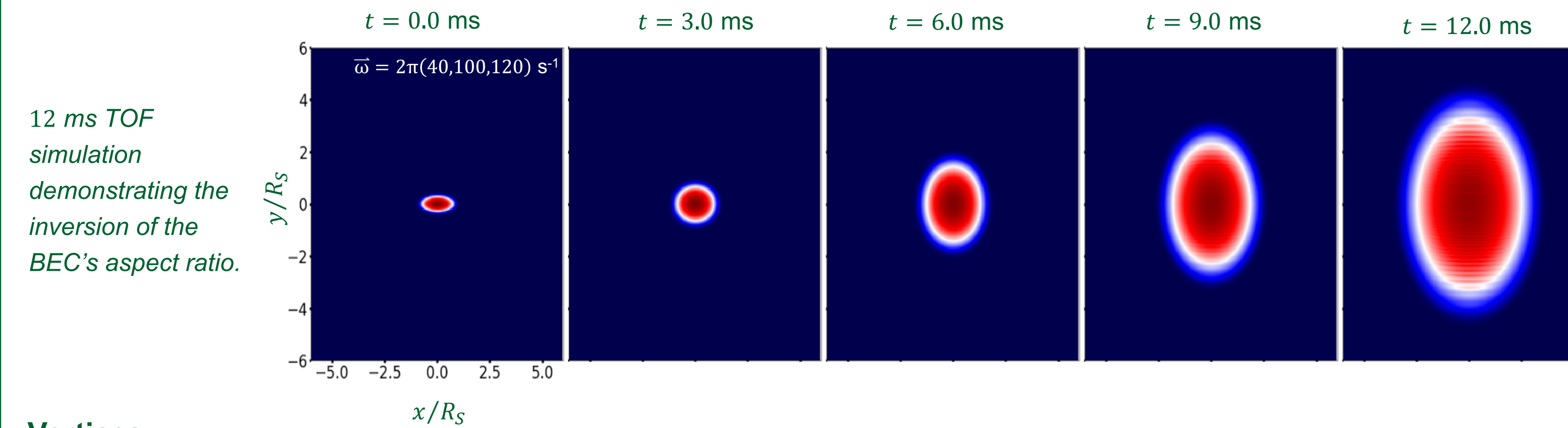
Example #2: Spin-Orbit Coupling (SOC)

- ❖ $\Omega \sim \epsilon = |\delta|$, with $\hbar\Omega/E_L < 4$.
- ❖ Double well in the dressed dispersion with "opposite" spin population in each.
- ❖ SOC strength is tuneable either by changing δ , or by modulating Ω [1].

Numerical Gross-Pitaevskii Equation (GPE) Simulations of BECs with Artificial Gauge Fields

Finding the Ground State

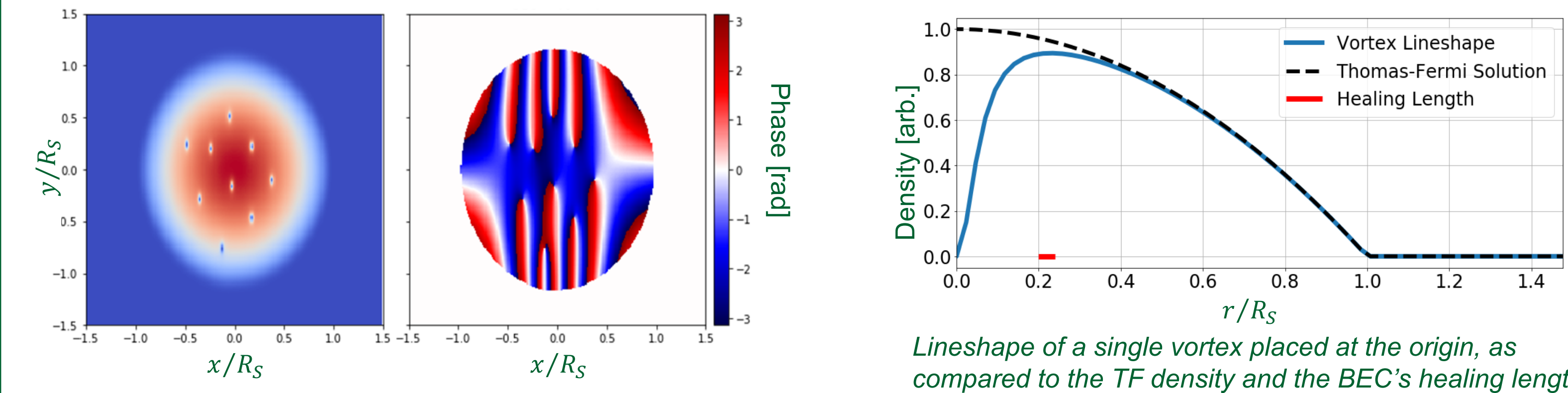
- ❖ For a given potential (trapping, gauge, etc...) we can compute the ground state in 2D through unitary evolution of the Thomas-Fermi (TF) ground state in imaginary time, using the time-splitting spectral method (TSSM) [11,12].
- ❖ Propagation in real time follows the same TSSM, allowing the study of real-time dynamics.



12 ms TOF simulation demonstrating the inversion of the BEC's aspect ratio.

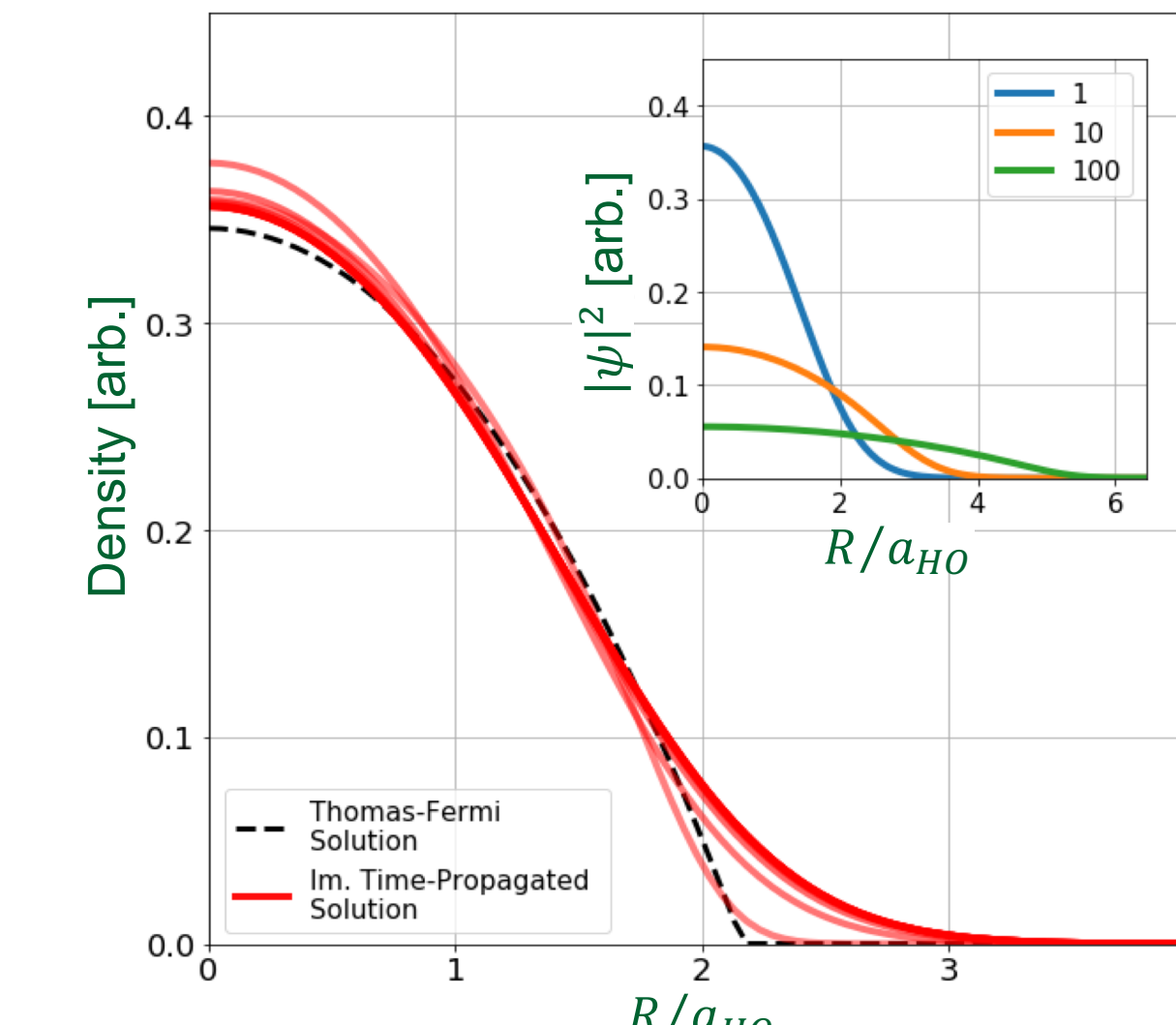
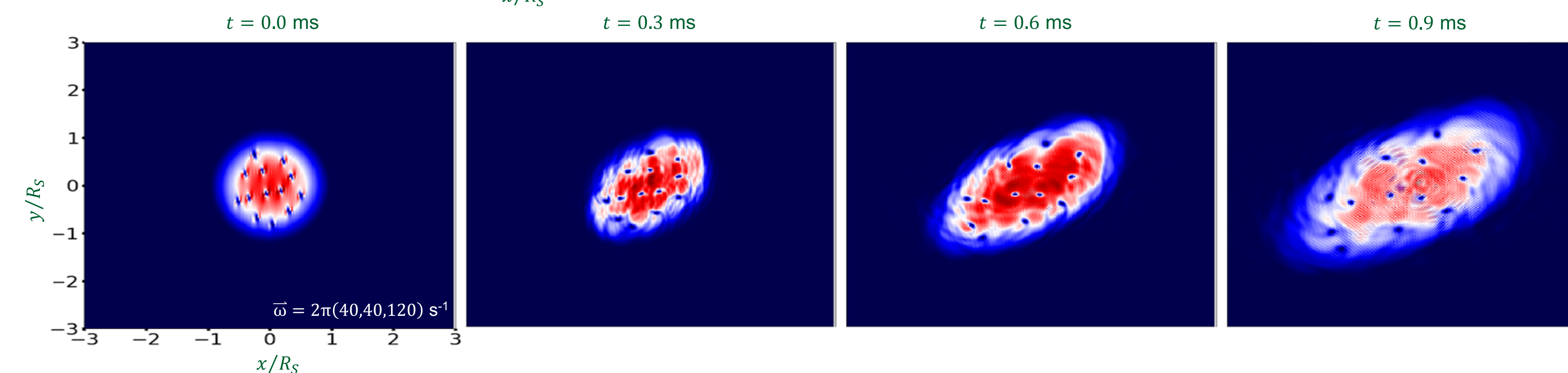
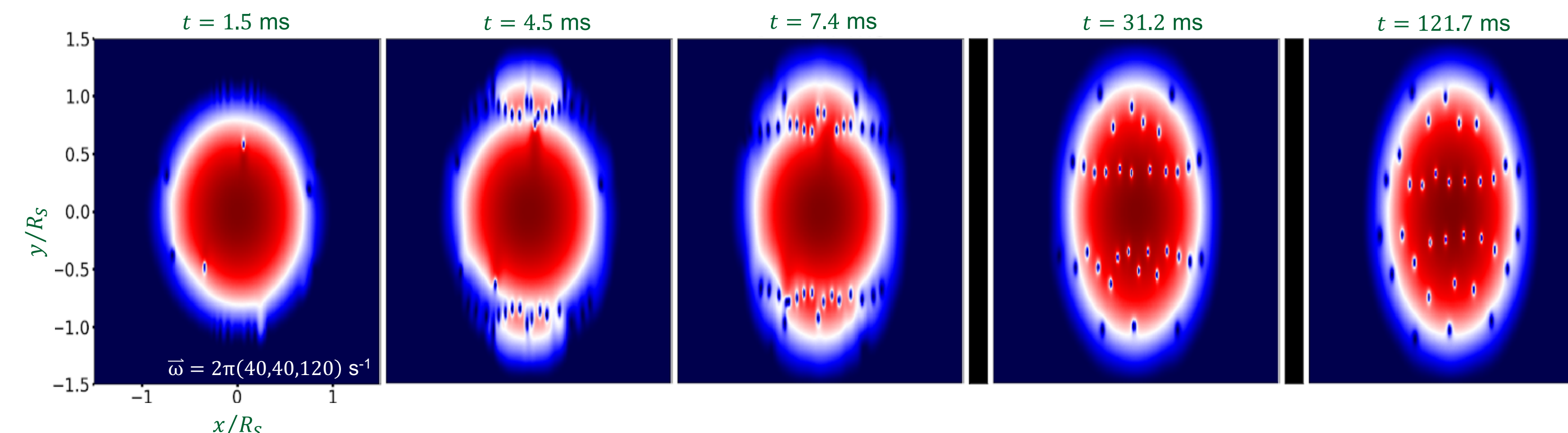
Vortices

- ❖ Applying a magnetic field gradient over the BEC creates a spatial dependence of the Raman detuning. This gives a variation in the dressed state momentum across the cloud [3].
- ❖ Vortices can be "planted" in the initial TF wavefunction and may persist through imaginary time propagation; new vortices also emerge during real-time propagation [13-15].

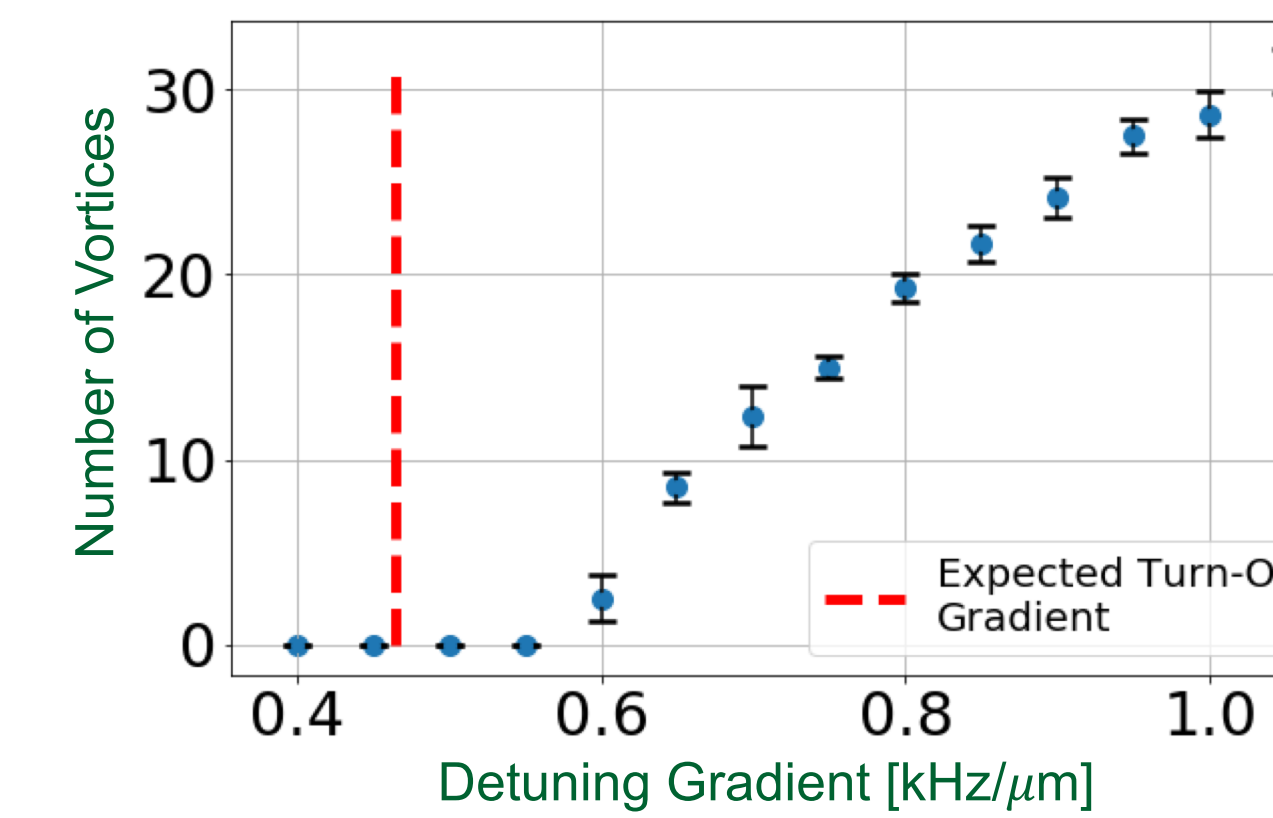


Lineshape of a single vortex placed at the origin, as compared to the TF density and the BEC's healing length.

- ❖ For a particular trap configuration, there is a critical Raman detuning gradient required to sustain vortices. Steeper gradients create more vortices.
- ❖ The presence of vortices in the BEC can be detected in TOF images through a shearing effect on the cloud [16].



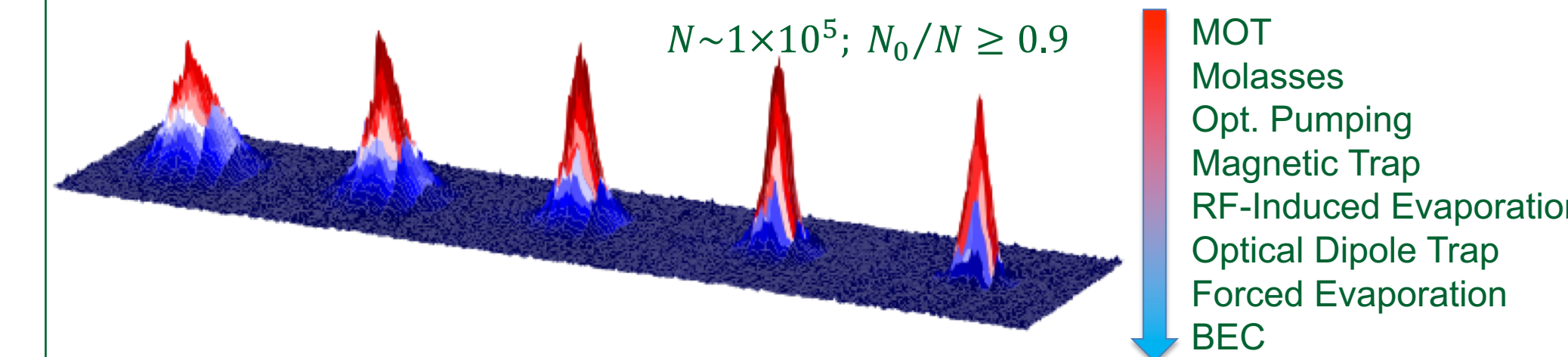
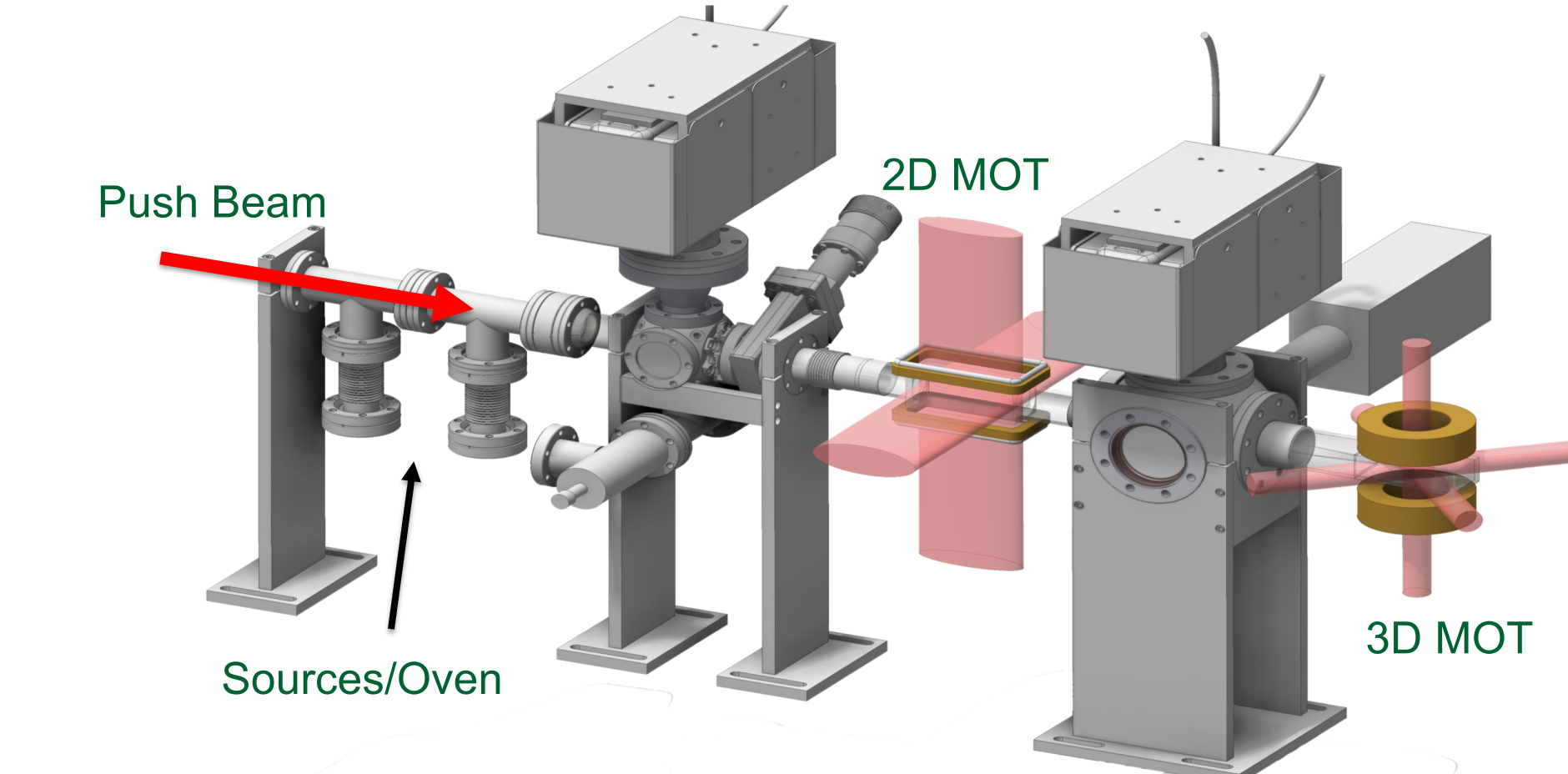
Convergence of the TF wavefunction to the true ground state through imaginary time propagation. Inset depicts ground states for various ratios of the BEC's interaction to kinetic energy. Adapted from [12].



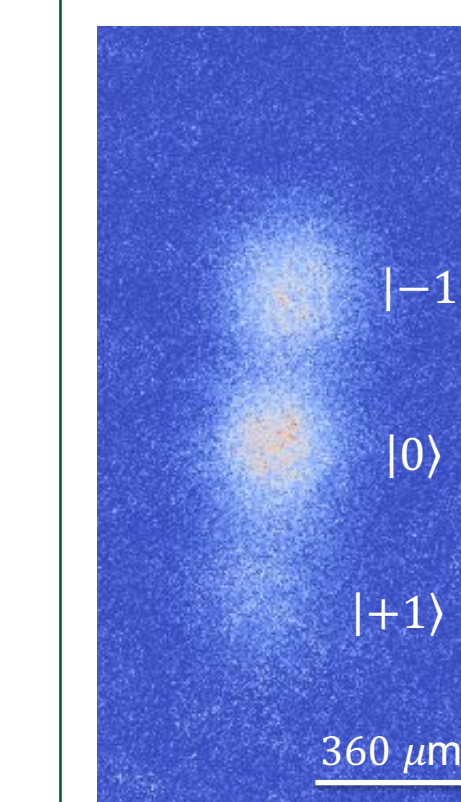
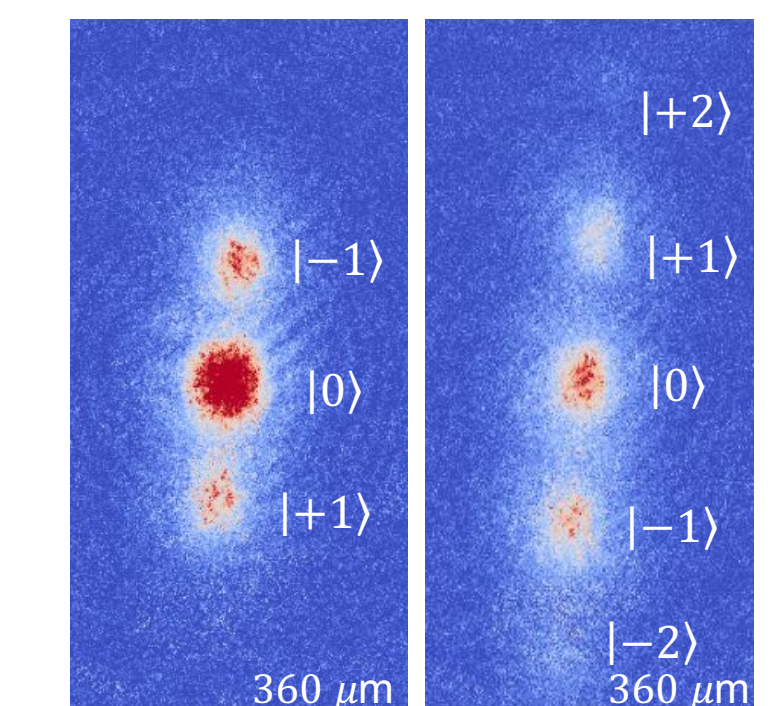
Based on the trap parameters and Ω , there exists a critical $\vec{B}^*$ for which vortices begin to emerge. Here, $\vec{\omega} = 2\pi(40,40,120) \text{ s}^{-1}$, and $\hbar\Omega/E_L = 16$.

Experimental Progress

- ❖ Oven contains metallic source of ^{87}Rb (and ^{39}K in the near future).
- ❖ Push beam directs atoms through the system.
- ❖ 2D MOT stage pre-cools atoms, and loads 3D MOT more efficiently.
- ❖ Differential pumping stage between 2D & 3D MOT keeps background pressure low.
- ❖ 3D MOT coils will be modified for Feshbach spectroscopy.



- ❖ We have the option of preparing a BEC in either the $F = 2$, $M_F = 2$ or $F = 1$, $M_F = -1$ ground states, via microwave population transfer.
- ❖ We can use the 3D MOT coils to apply a magnetic field gradient during TOF, for Stern-Gerlach imaging.



- ❖ Two Raman beams @790 nm aligned onto the BEC will dress atoms in the $F = 1$ manifold. Further characterization and setup is required.

Future Work

- ❖ Investigate how SOC changes the BEC transition temperature [17], with tuneable scattering interactions.
- ❖ Artificial gauge fields, SOC, fundamental thermodynamics, quantum memories [18], 2-species BECs, and beyond!

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