

# Towards an Experimental Realisation of Synthetic Dimensions in a Shaking Harmonic Trap

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## Abstract

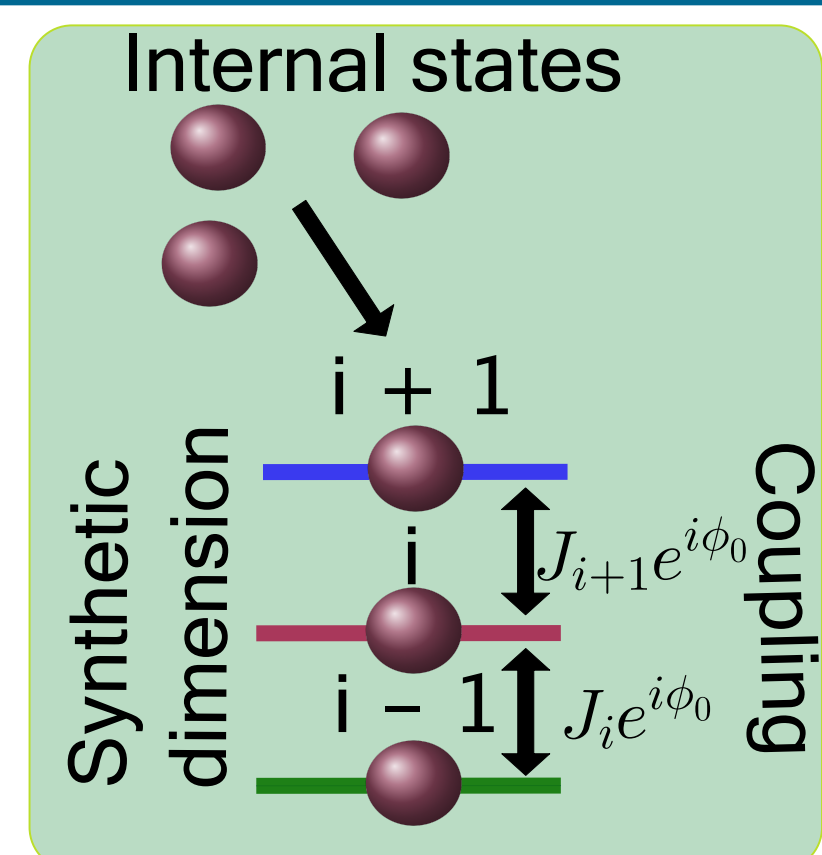
We introduce **dynamical simulations** of topological edge-states in a **harmonic synthetic dimension** [1].

Our work hopes to prepare a University of Birmingham experiment to explore such states in this tunable platform.

## What is a synthetic dimension?

Synthetic dimensions [2][3] are a tool used in **quantum simulation of topological models** [4].

They are **a set of states coupled together** to emulate a 1D spatial dimension [4].



## A harmonic synthetic dimension

Consider a 1d **atomic cloud in a harmonic potential** with frequency  $\omega$  [5]

$$\hat{H}_0 = \frac{\hat{p}_x^2}{2m} + \frac{1}{2} m \omega^2 x^2 = \omega \sum_{\lambda} \lambda |\lambda\rangle \langle \lambda|$$

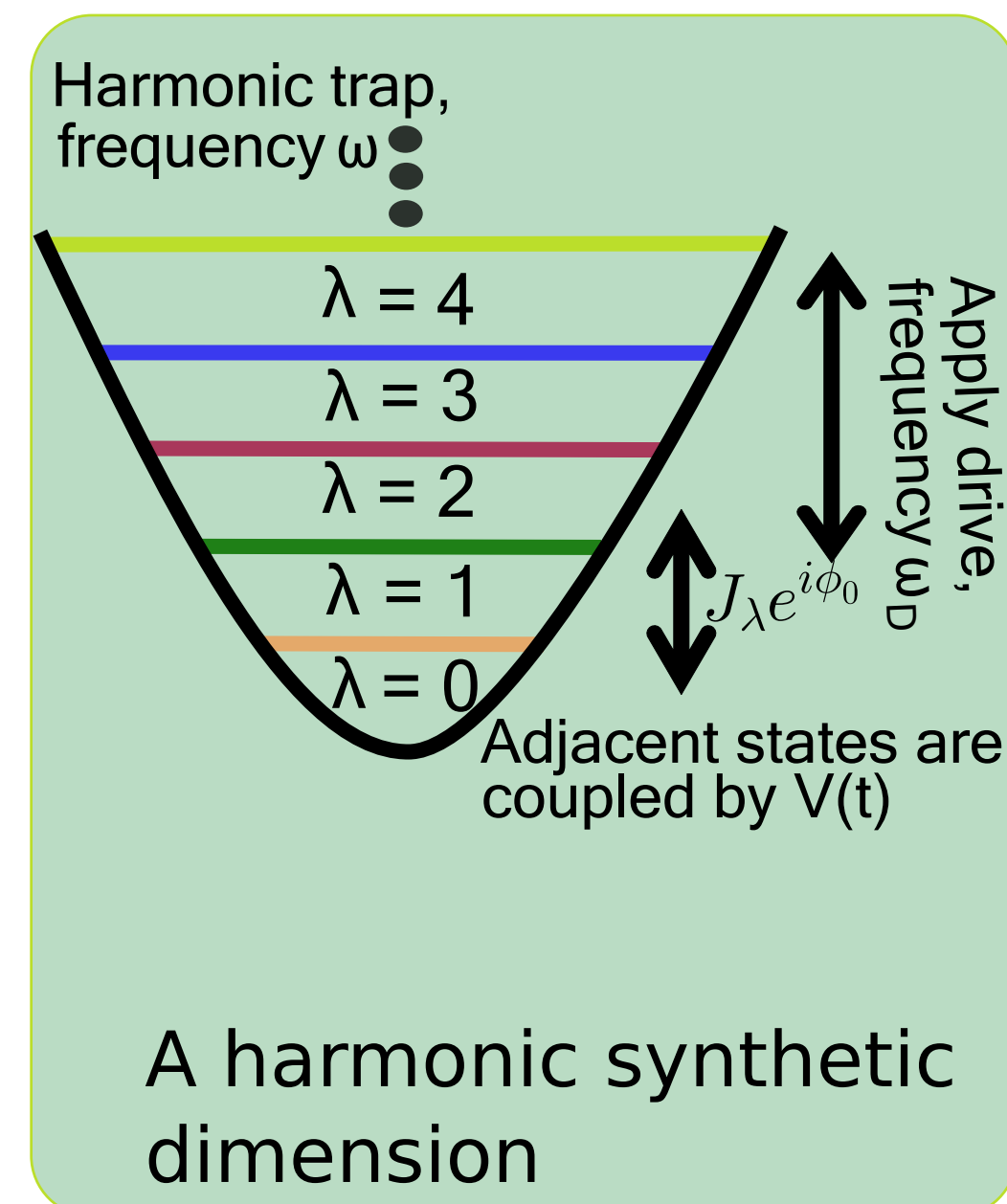
$\lambda$  is the harmonic state index,  $\hbar = 1$ .

Applying a **driving potential**  $V(t)$  with frequency  $\omega_D$  **couple adjacent trap states together**.

In the limit  $\omega \gg \Delta$  where a static Floquet Hamiltonian can capture the physics

$$\hat{H}_f = \Delta \sum_{\lambda} \lambda |\lambda\rangle \langle \lambda| + \sum_{\lambda} J_{\lambda} [|\lambda-1\rangle \langle \lambda| e^{i\phi_0} + h.c.] \quad (\text{Eqn. 1})$$

$J_{\lambda}$  is  $V(t)$  dependent and forms a synthetic dimension. The detuning acts as a force.

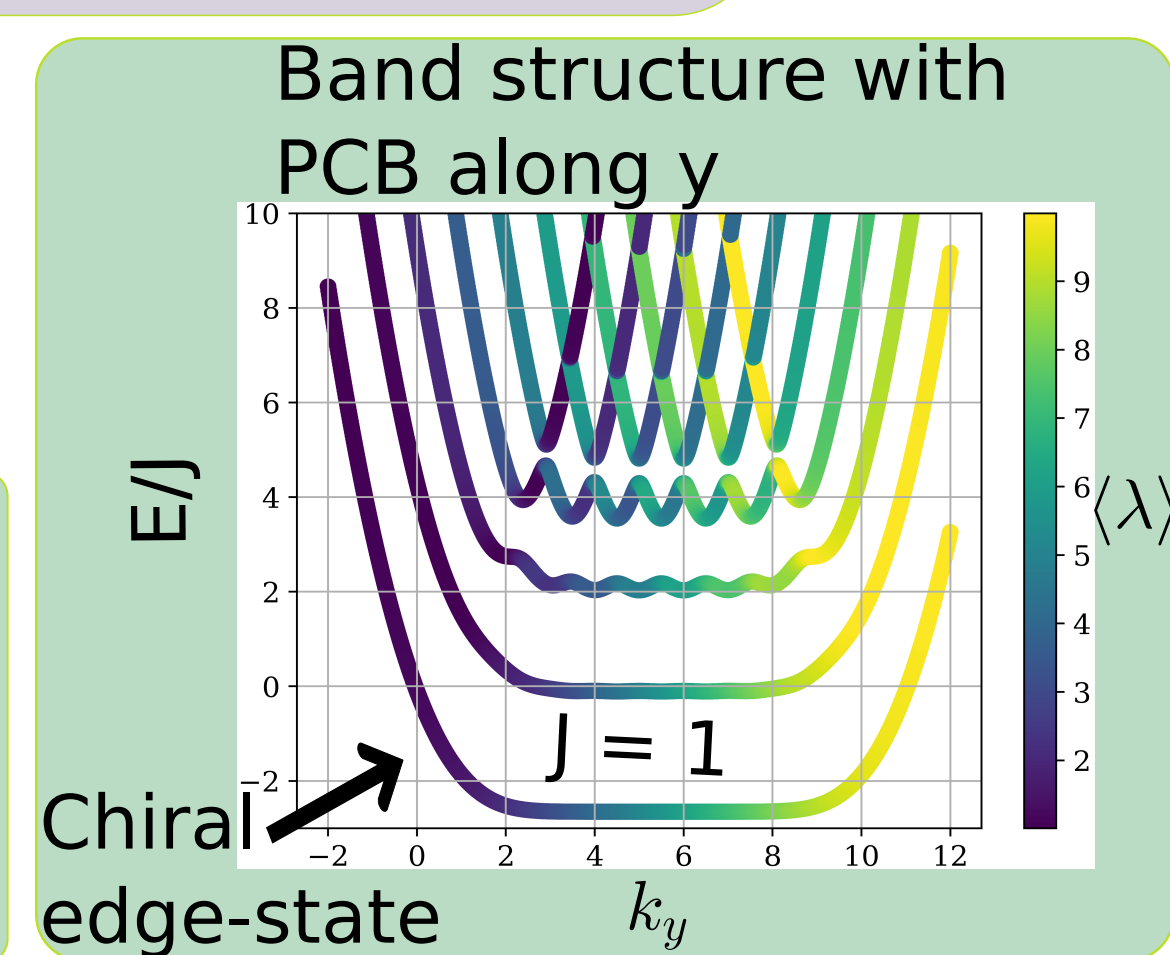
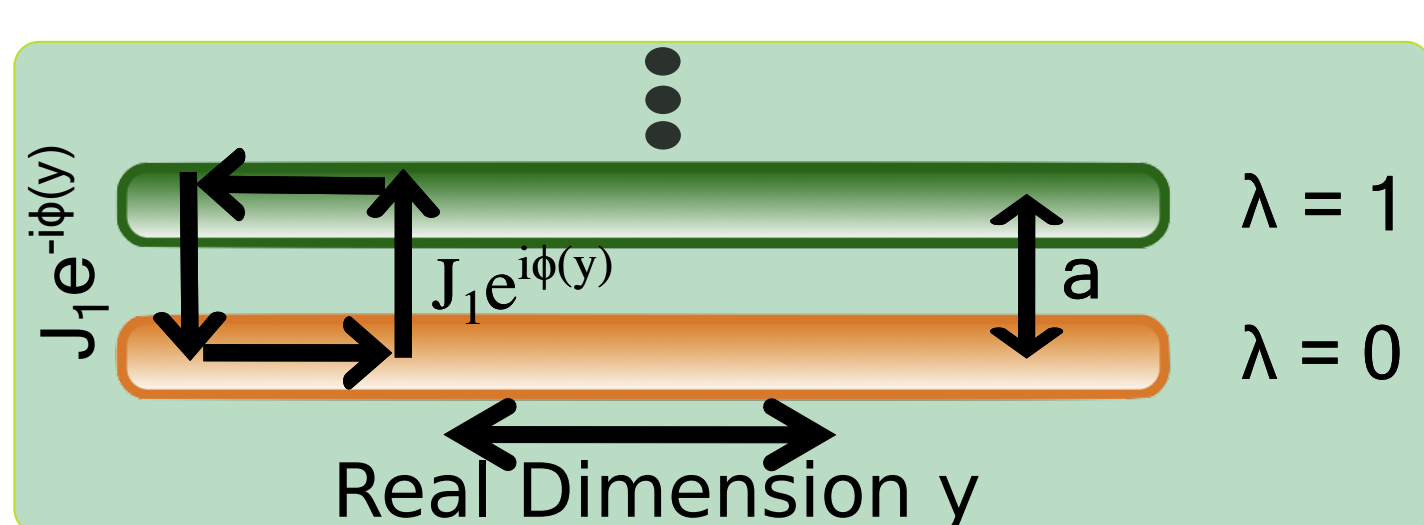


## A 2D coupled-wire model

We generate a **2D coupled-wire model** [6] by unfreezing the trap along  $y$ , engineering a  $y$  dependent **Peierls phase**  $\phi(y)$  via  $V(t)$  and setting  $\Delta = 0$

$$\hat{H}_{2d} = \frac{\hat{p}_y^2}{2m} + \frac{1}{2} m \omega_y^2 y^2 + \sum_{\lambda} J_{\lambda} [|\lambda-1\rangle \langle \lambda| e^{i\phi_0 y} + h.c.] \quad (\text{Eqn. 2})$$

This model is known to lead to topological **edge-states**.

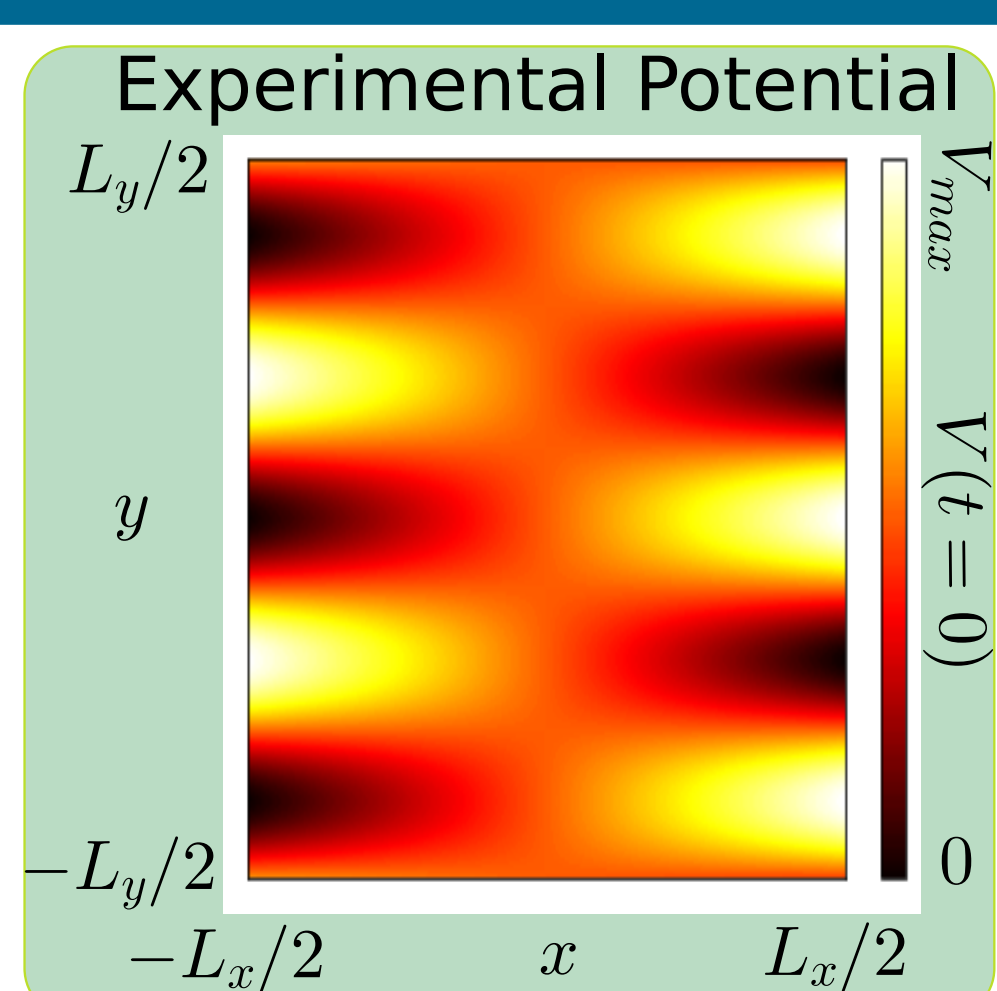


## Experimental implementation

The platform is a **ultracold Rb-87 gas confined in an optical dipole trap** with  $V(t)$  induced via a **digital micromirror device**.

Initial results for a 1D set-up have observed **Bloch oscillations** [7].

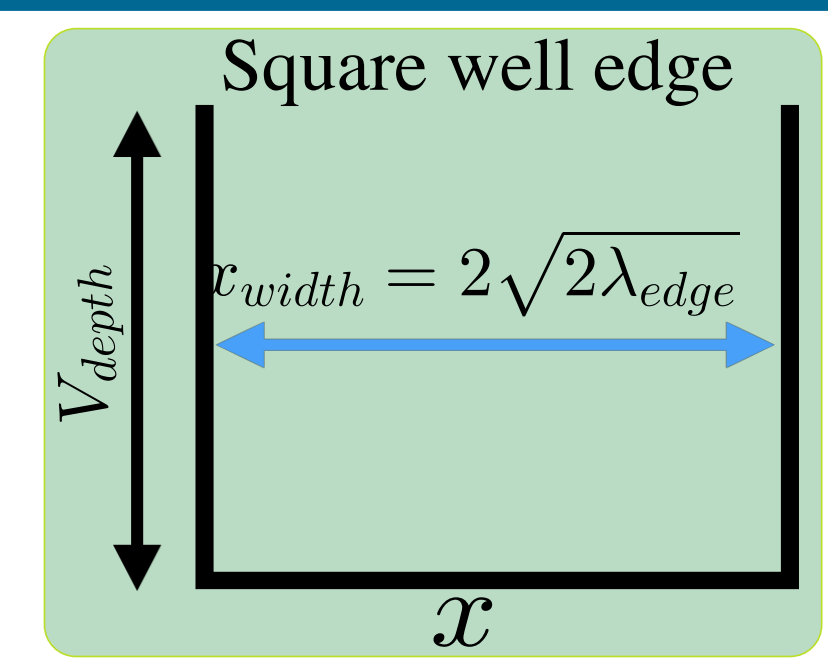
Currently setting up 2D system.



## Edges in synthetic space

The lowest energy state provides a **lower edge** in synthetic space. There is no clear upper edge.

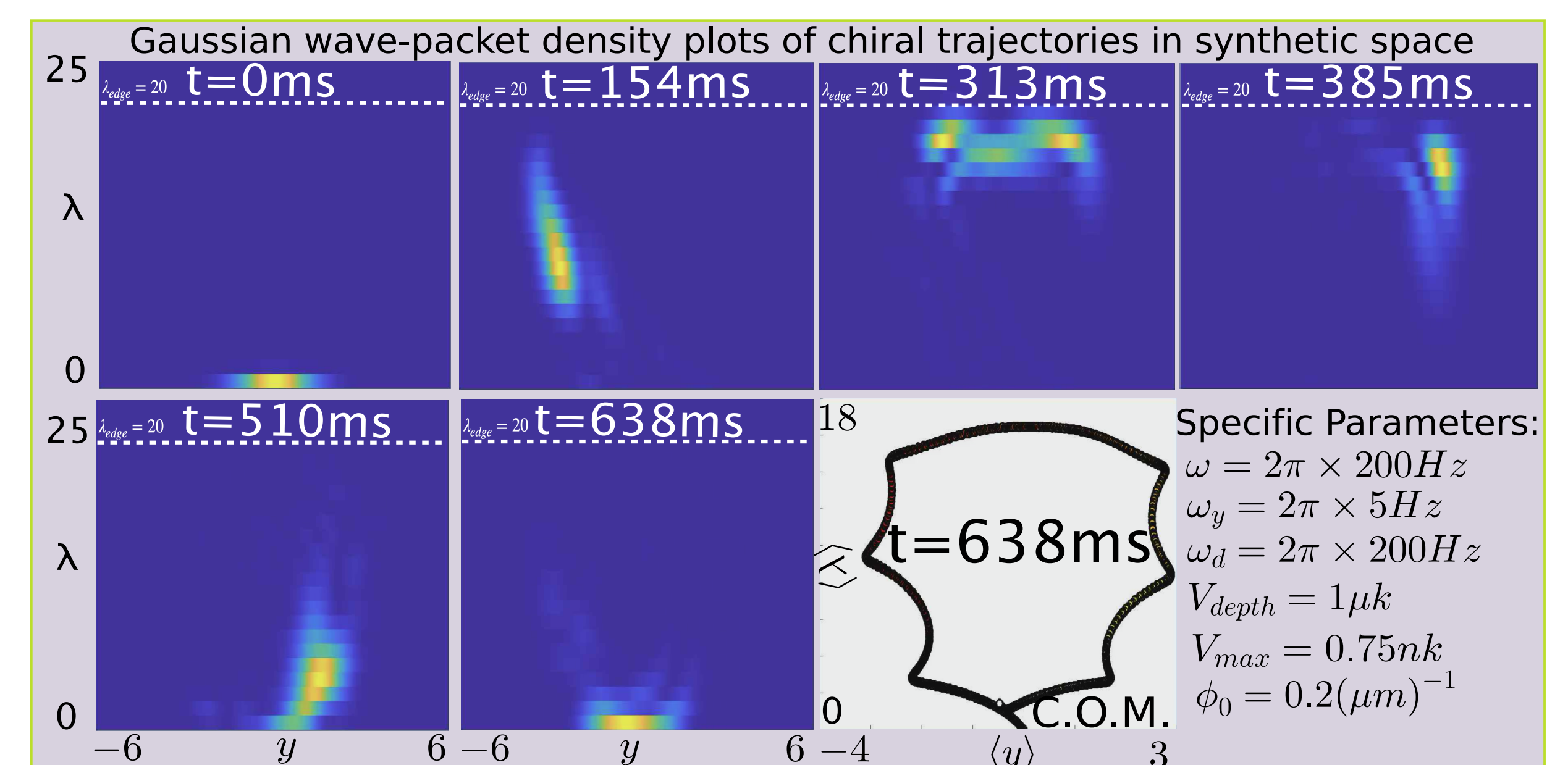
A square well in  $x$  can induce a **tunable edge**.



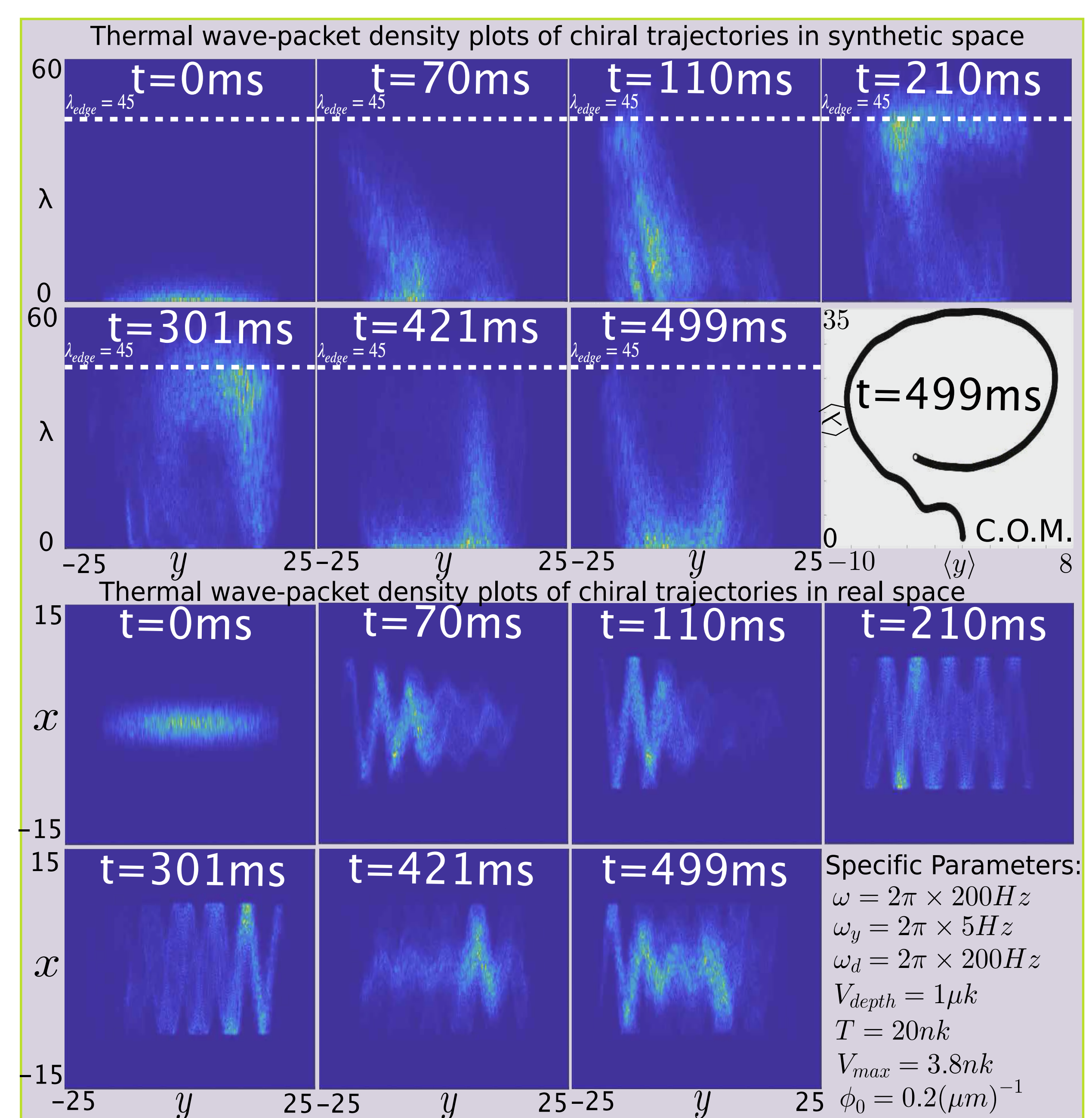
## Results

To prepare for the experiment we developed non-interacting simulations.

The following physics is seen by **excluding thermal effects**



Introducing **thermal effects** into the initial state and comparing synthetic and **real space** provides a more realistic picture,



These simulations provide a clear observable for the experiment to study these topological edge-states.

## Future Work

Effect of mean-field interactions in harmonic synthetic dimension on 2D vortices.

We will study how they alter the 2D vortex lattice for the Hofstadter and coupled-wire models.

## References

- [1] H.M. Price et al, Phys. Rev. A 95, 023607 (2017)
- [2] O. Boada et al, Phys. Rev. Lett. 108, 133001 (2012).
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- [6] J. C. Budich et al, Phys. Rev. A. 95, 043632 (2017)
- [7] C. Oliver et al. arXiv:2112.10648 (2021)