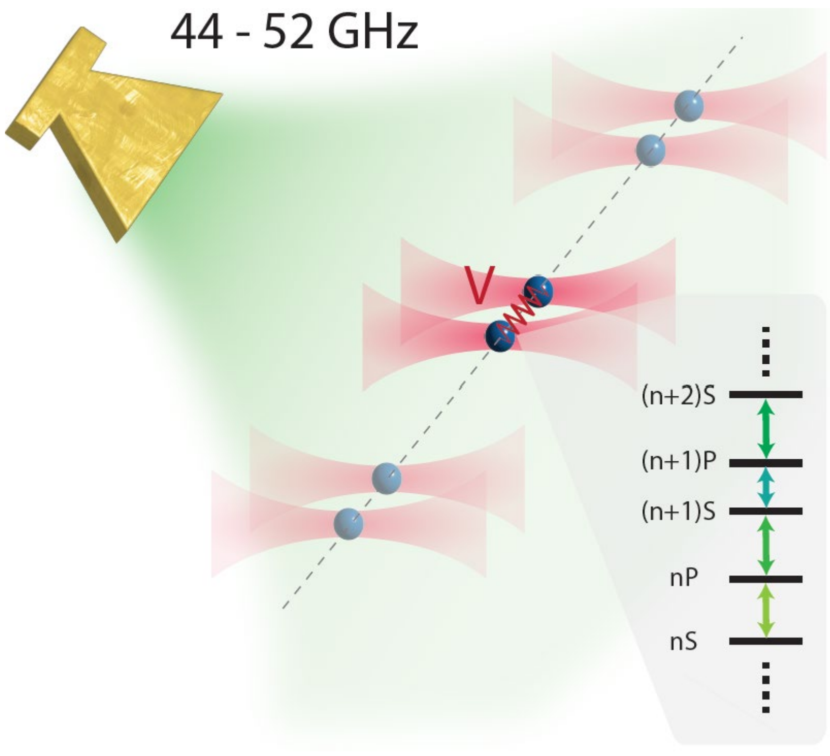
interacting topological pumps
in Rydberg synthetic dimensions

Bryce Gadway

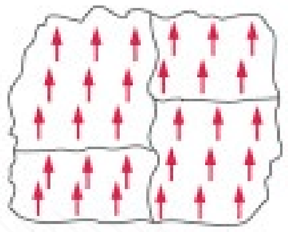
Penn State University

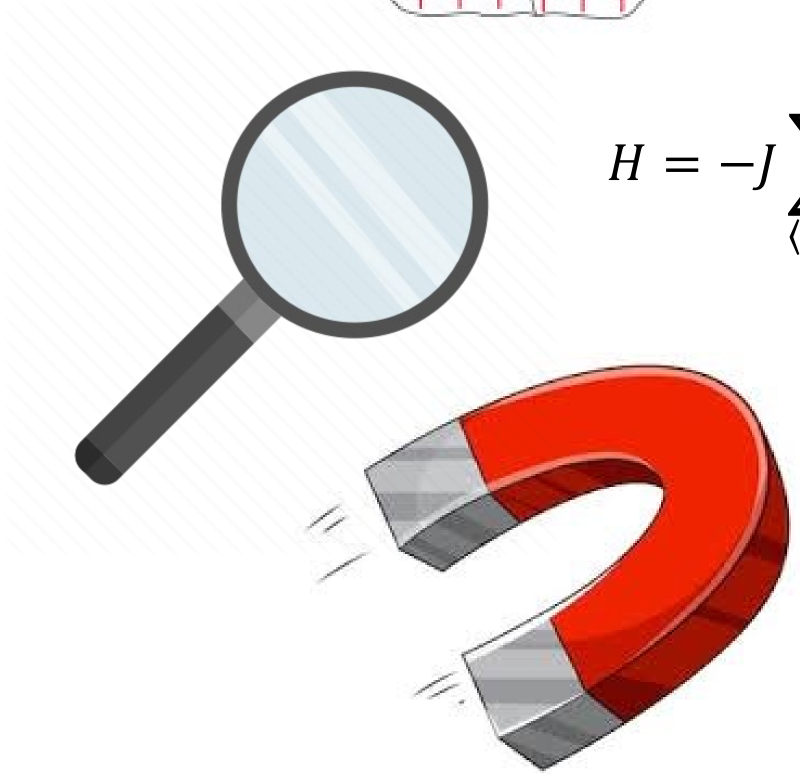


QSQW2025 (Napoli)

January 14, 2025

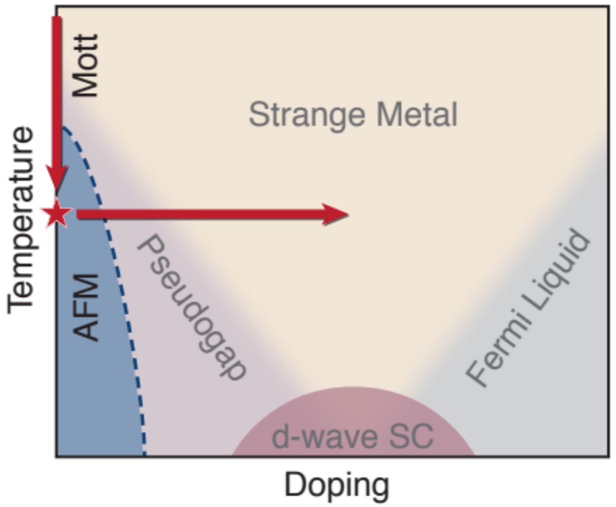
emergent phenomena by design





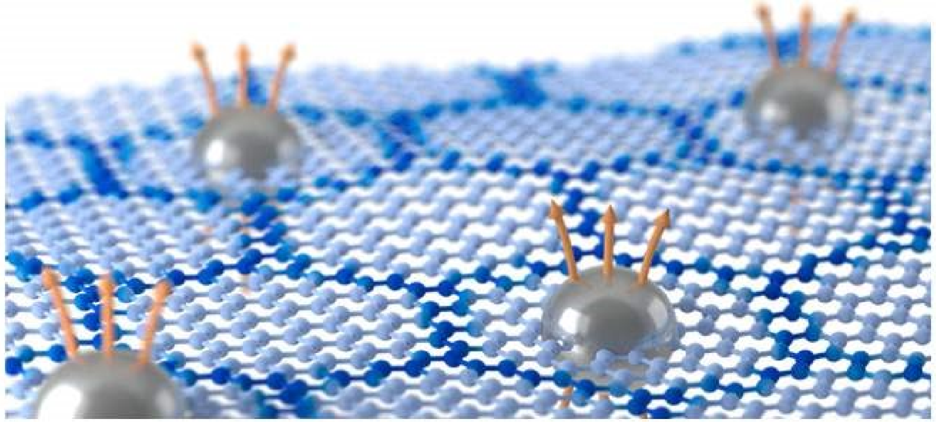
$$H = -J \sum_{\langle i,j \rangle} \sigma_i^z \, \sigma_j^z$$

+ new terms
with competing
order / symmetry

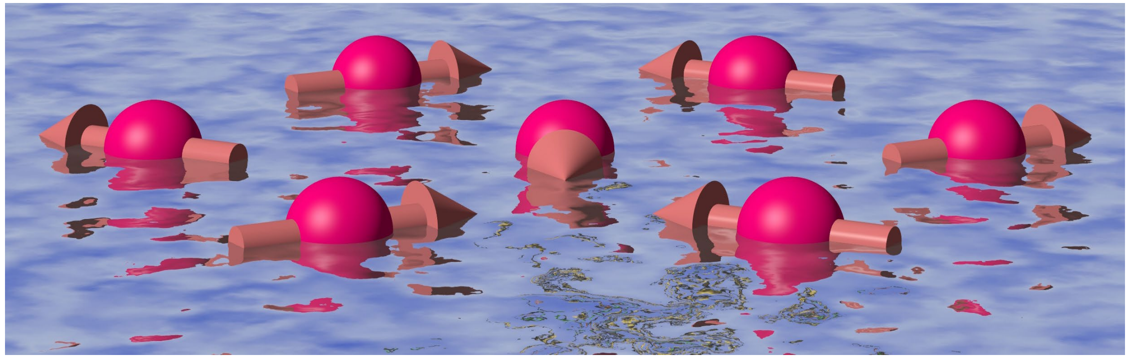


Mazurenko *et al.*, Nature (2017)

emergent phenomena by design



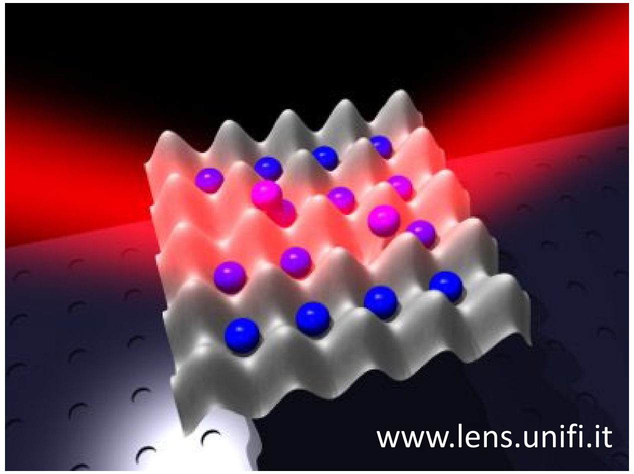
fractional quantum Hall (FQH) states



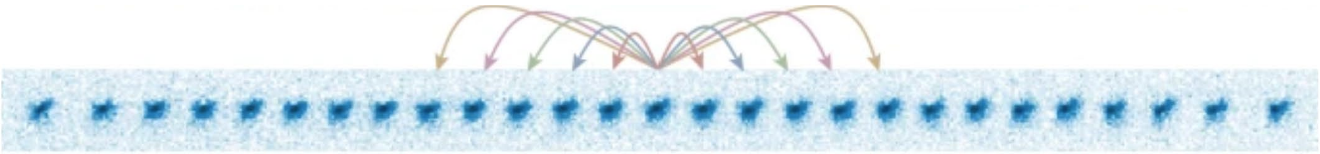
quantum spin liquids (QSL)

start with **frustration** as a central ingredient (and add interactions)

synthetic quantum matter – lattice networks

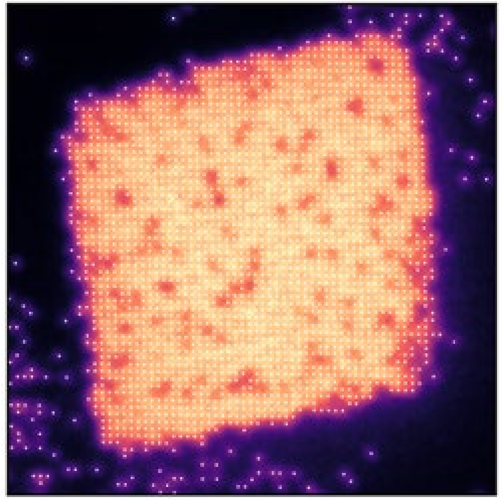


neutral atoms in optical lattices

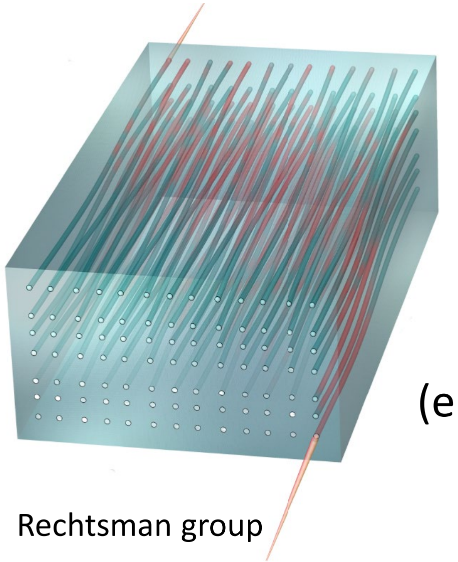


Feng, *et al*. Nature (2023)

spin excitations on a lattice of ions
(or Rydbergs/molecules/qubits/…)



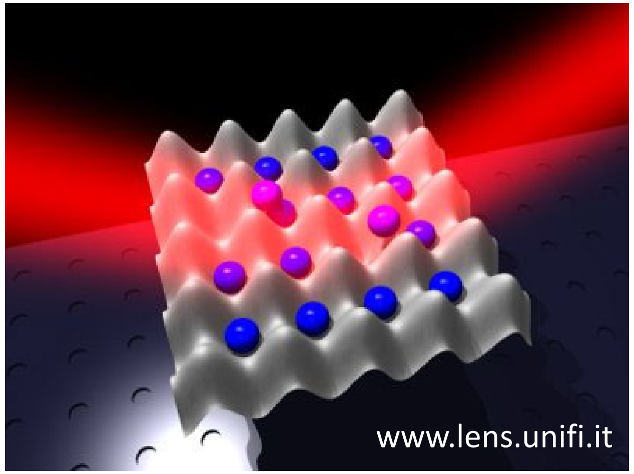
Cs QGM
Aidelsburger group



Rechtsman group

photonic arrays
(e.g., waveguide arrays)

synthetic quantum matter – lattice networks



$$\hat{H} = \sum_i \epsilon_i \hat{c}_i^\dagger \hat{c}_i - t \sum_i \left(\hat{c}_{i+1}^\dagger \hat{c}_i + \hat{c}_i^\dagger \hat{c}_{i+1} \right)$$

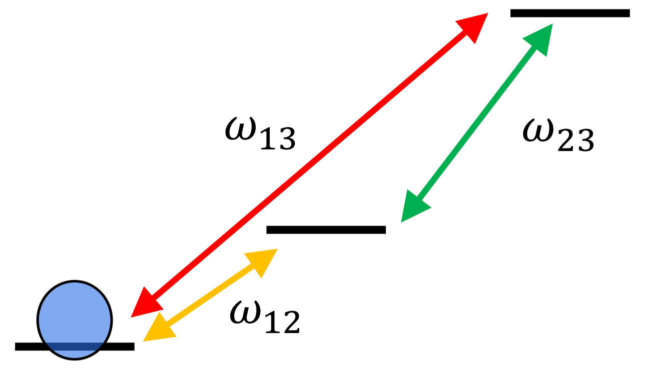
site orbital energies (diagonal)

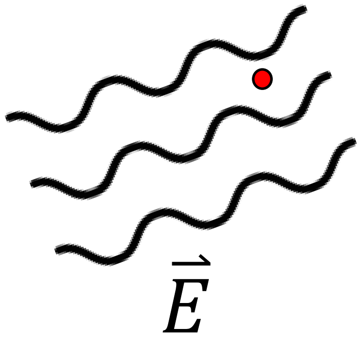
tunneling terms (off-diagonal)

some typical constraints

- atoms / excitations are neutral
  - natural hopping is real-valued, so hard to mimic **effective magnetic fields (kinetic frustration)**
- “hopping” graphs have some physical constraints

synthetic tight-binding models (i.e., a lattice of internal states)





particles pick up the <u>phase</u> of driving fields when undergoing transitions

<u>some typical constraints</u>

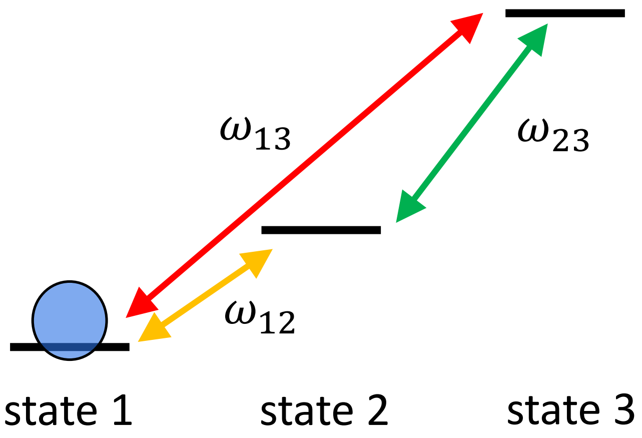
- atoms / excitations are neutral
  - natural hopping is real-valued, so hard to mimic **effective magnetic fields (kinetic frustration)**

→ **can *naturally* implement complex hopping and artificial gauge fields**

- "hopping" graphs have some physical constraints

→ **some constraints (e.g., dipole selection rules), but more flexibility**

synthetic tight-binding models (i.e., a lattice of internal states)



$$\hat{H} = -\vec{d} \cdot \vec{E}$$

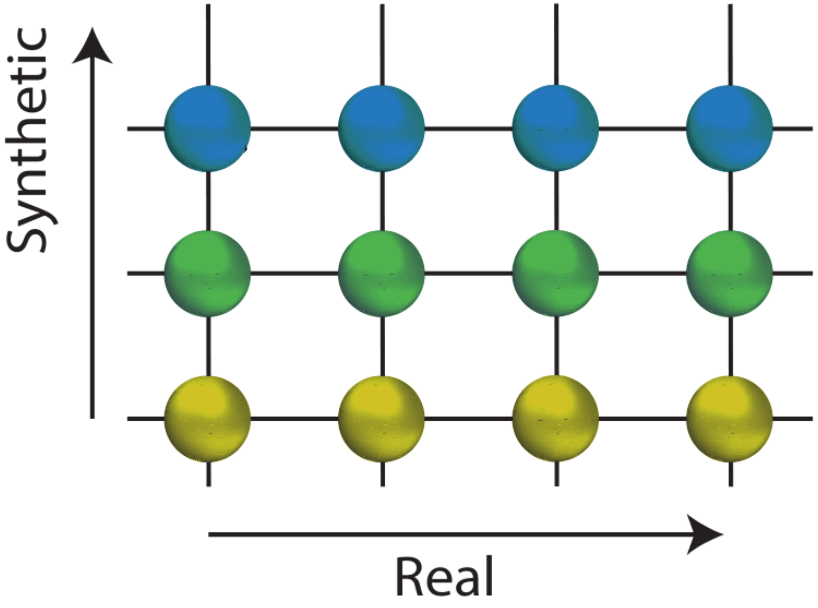
$$\vec{E} = \hat{\epsilon}\, E(t) \propto \sum_{i<j} E_{ij} \cos\left(\left(\omega_{ij} - \delta_{ij}\right)t + \varphi_{ij}\right)$$

RWA…

full, spectroscopic control of Hamiltonian

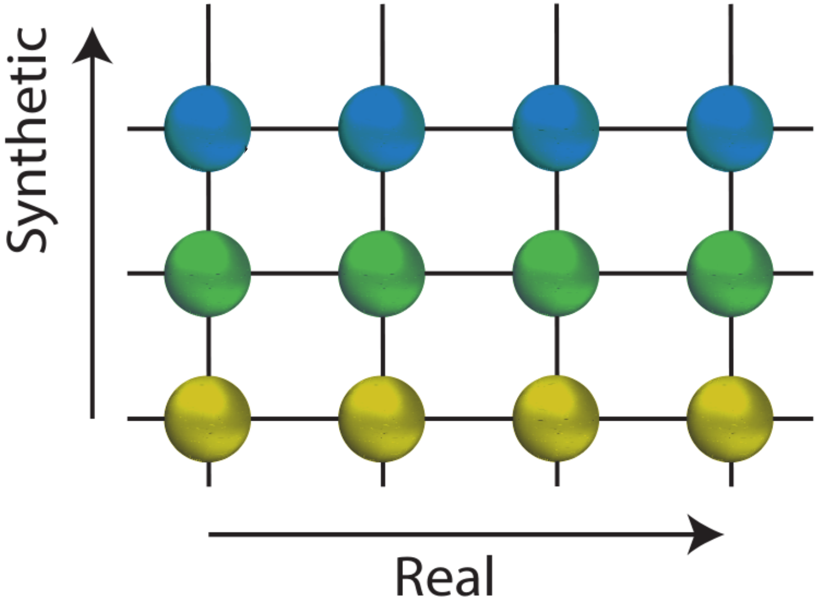
$$\hat{H} = \sum_i \epsilon_i \hat{c}_i^\dagger \hat{c}_i - \sum_{i<j} \left(t_{ij} e^{i\varphi_{ij}} \hat{c}_j^\dagger \hat{c}_i + \text{h.c.} \right)$$

synthetic dimensions in cold atoms



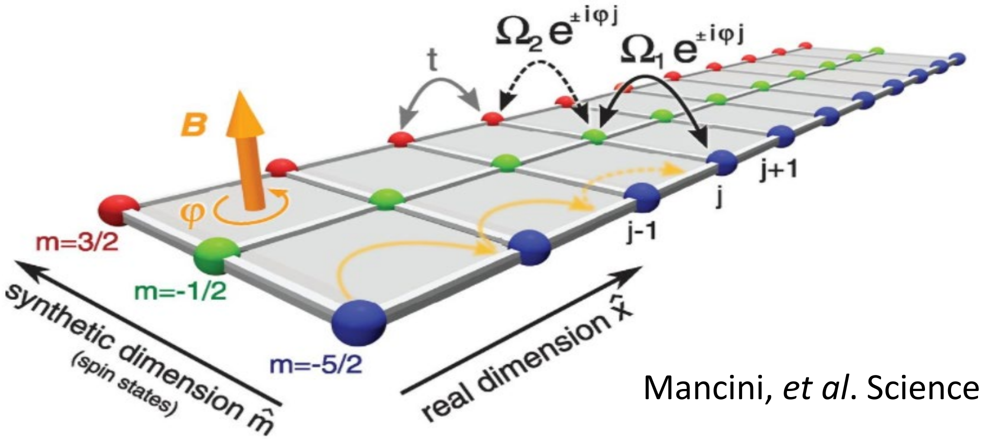
Ozawa & Price, Nat. Rev. Phys. (2019)

synthetic dimensions in cold atoms

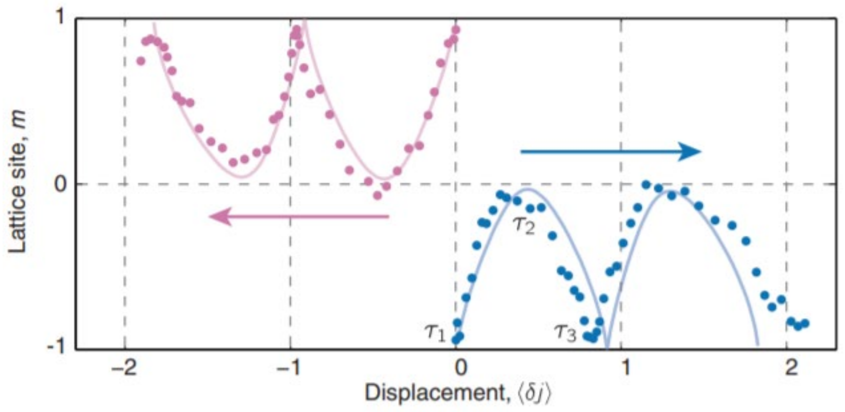


Ozawa & Price, Nat. Rev. Phys. (2019)

- hyperfine states

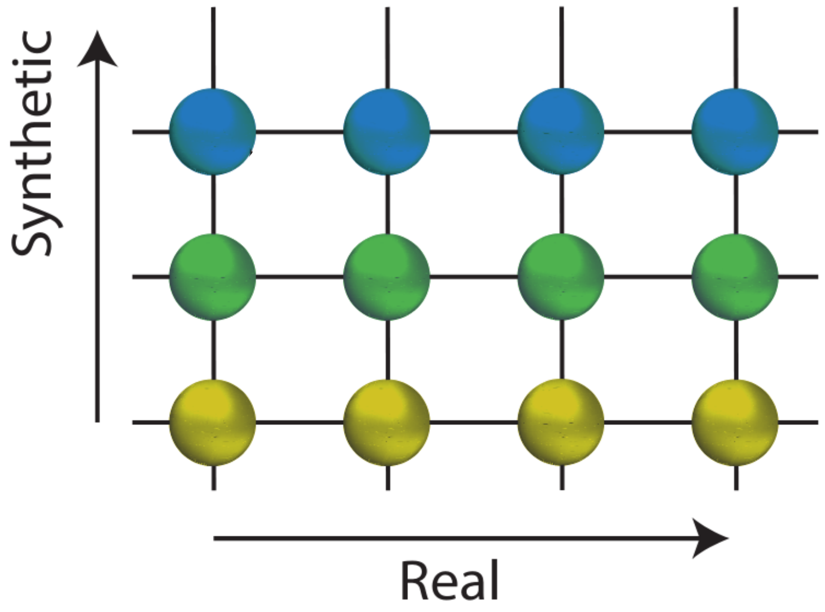


Mancini, *et al*. Science (2015)

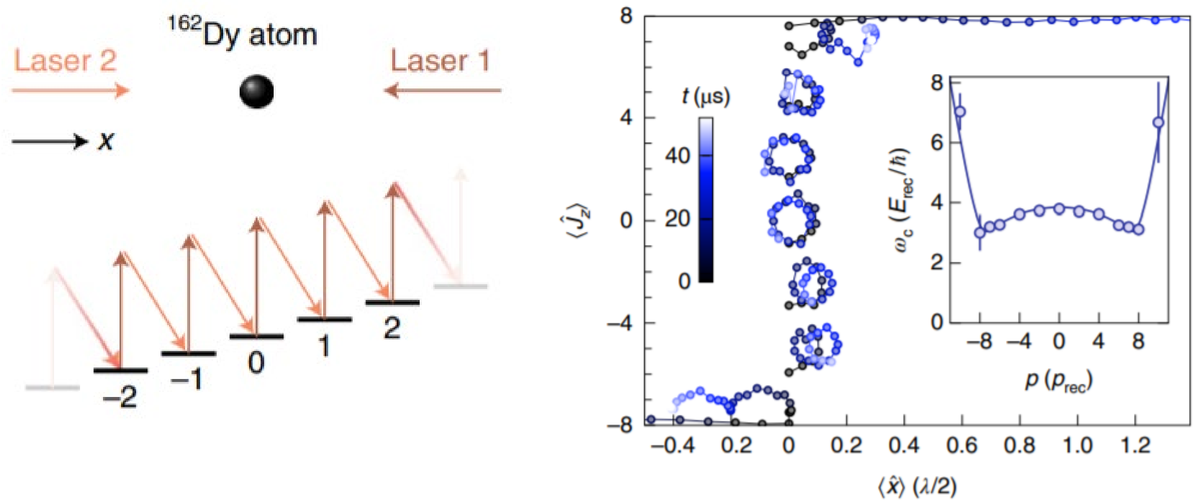


Stuhl, *et al*. Science (2015)

synthetic dimensions in cold atoms



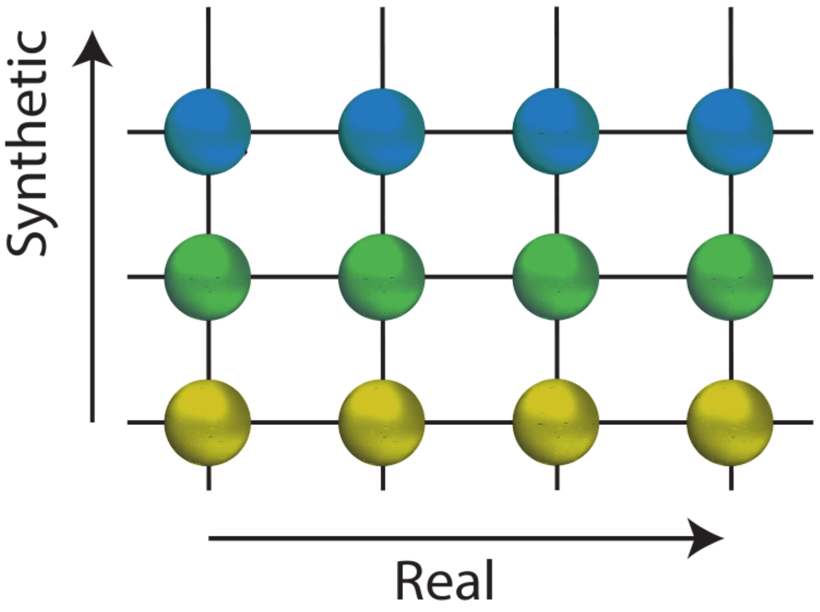
Ozawa & Price, Nat. Rev. Phys. (2019)



Chalopin, *et al.* (Nat. Phys., 2019)

- hyperfine states

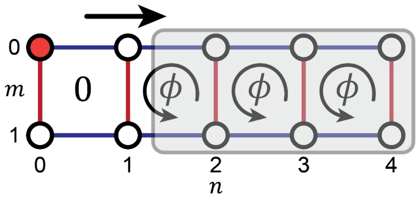
synthetic dimensions in cold atoms



Ozawa & Price, Nat. Rev. Phys. (2019)

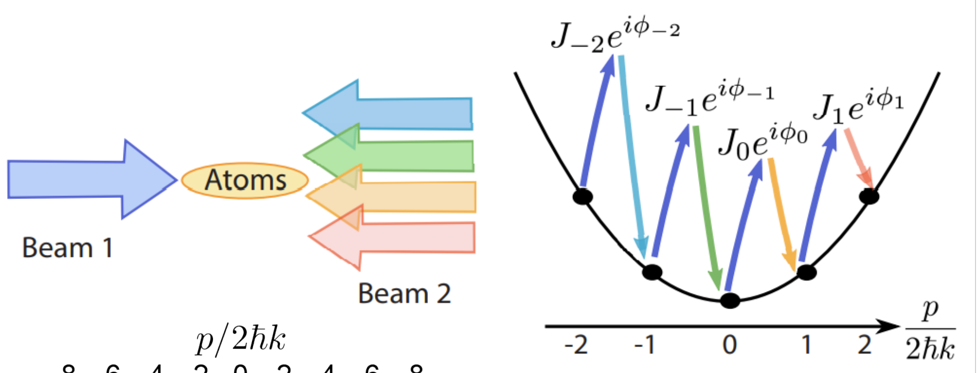
- hyperfine states
- momentum states
- + more

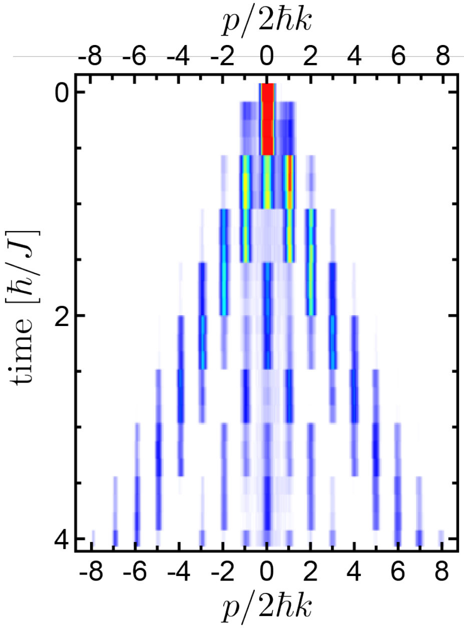
Tunable gauge fields



An, Meier, and BG, *Sci. Adv.* (2017)

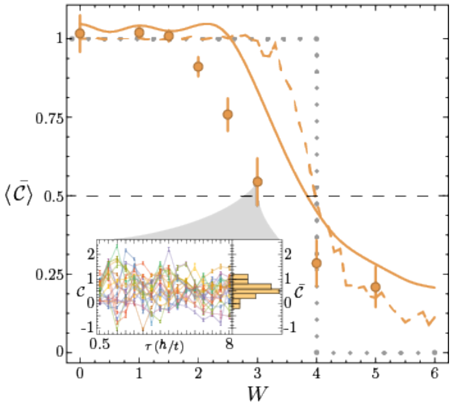
Ozawa and Price
Nat. Rev. Phys. (2019)





An & Meier, *et al.*

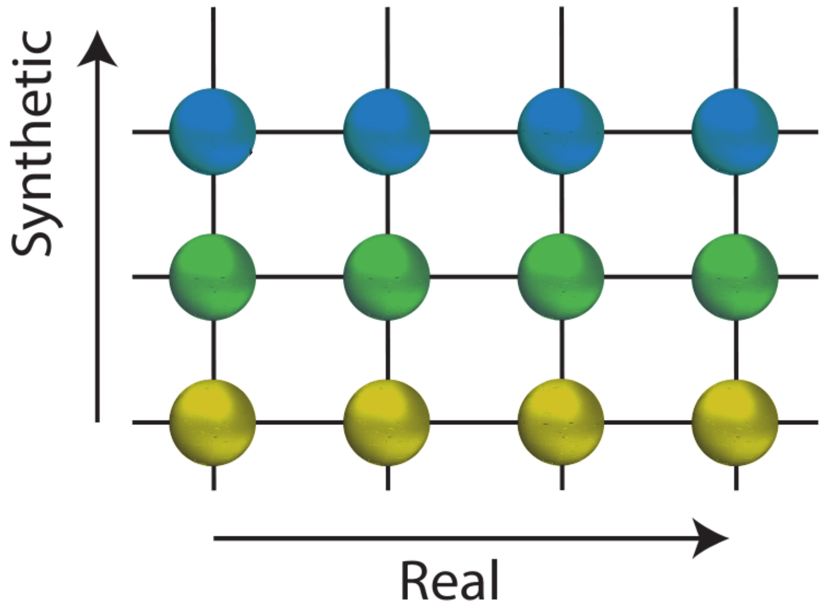
Disorder-induced topology



E.J. Meier *et al.*, *Science* (2018)

[see also Cardano, et al. 2017]

synthetic dimensions in cold atoms

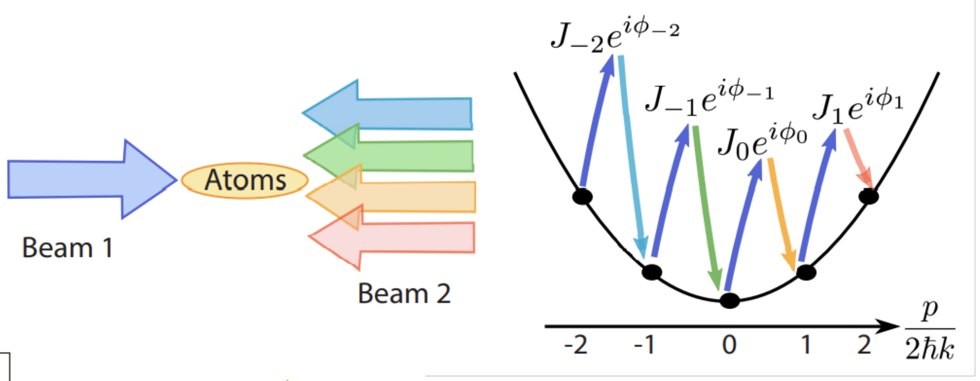


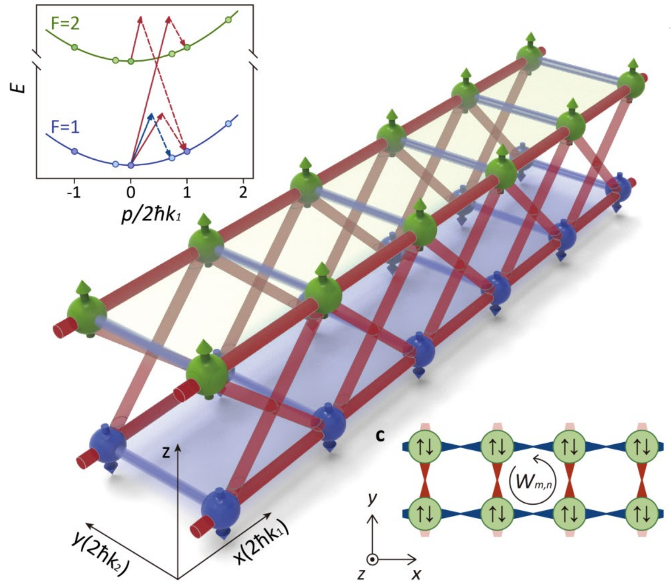
Ozawa & Price, Nat. Rev. Phys. (2019)

- hyperfine states
- momentum states
- + more

group of **Bo Yan**
Zhejiang Univ.
Raman-MSLs

Ozawa and Price
Nat. Rev. Phys. (2019)





Qian Liang, *et al.*
Nature Physics (2024)

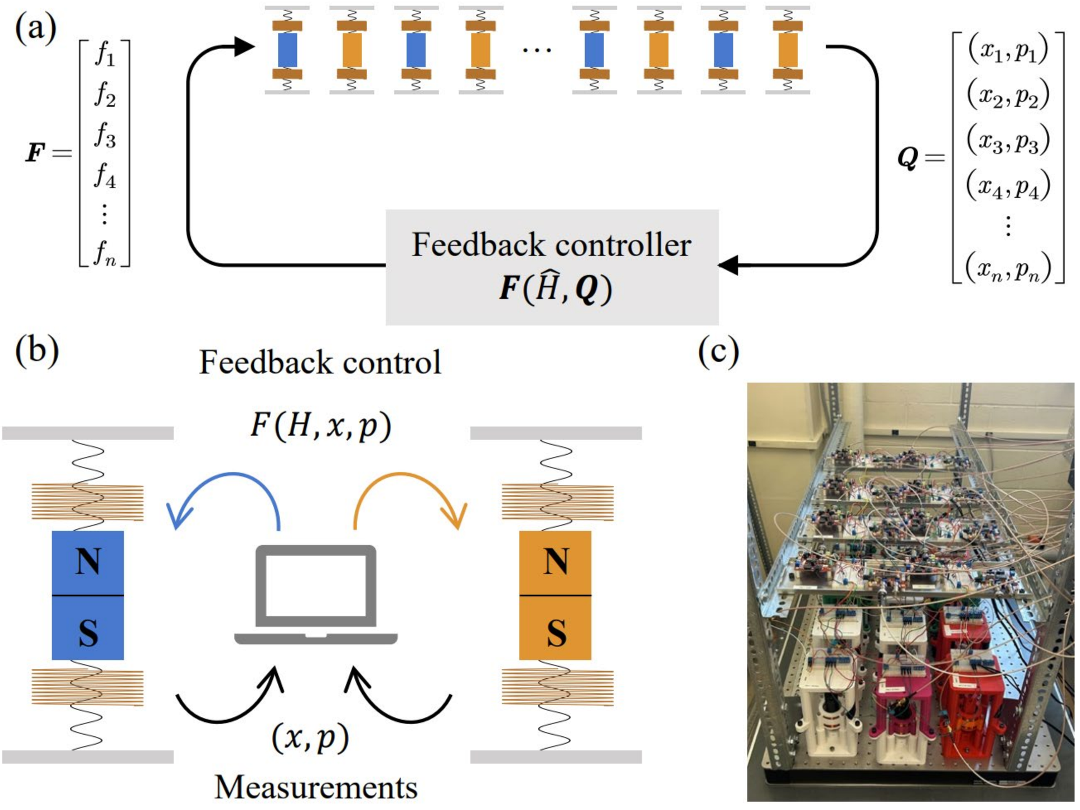
non-Abelian gauge fields

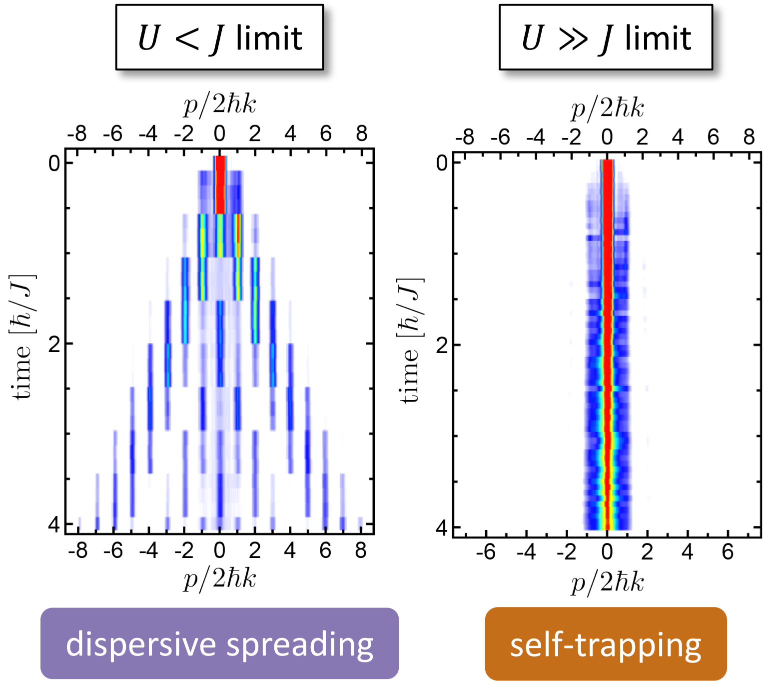
cf.
non-Hermitian skin effect in synthetic dimensions

Qian Liang, *et al.*
PRL (2022)

synthetic dimensions in cold atoms

interactions: mostly messy, measly, or mean-field

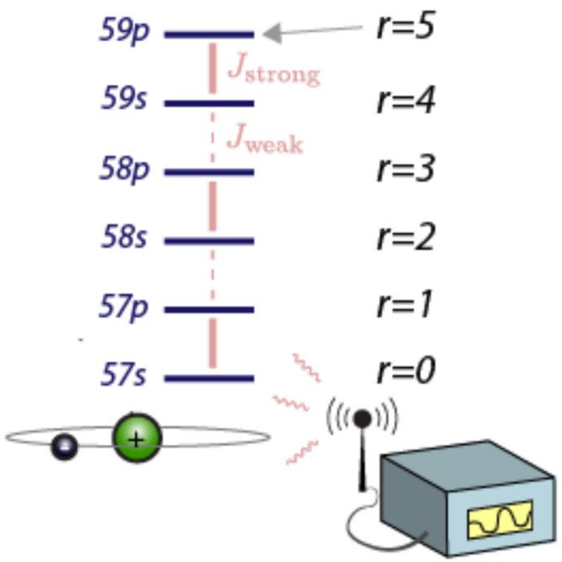




An, *et al.* PRL (2021)

nonlinear Schrödinger dynamics are ***classical*** – can we go stronger?

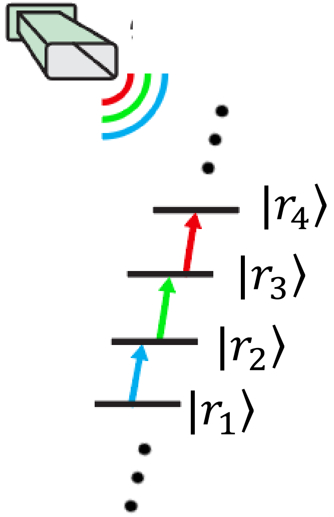
Rydberg synthetic dimensions



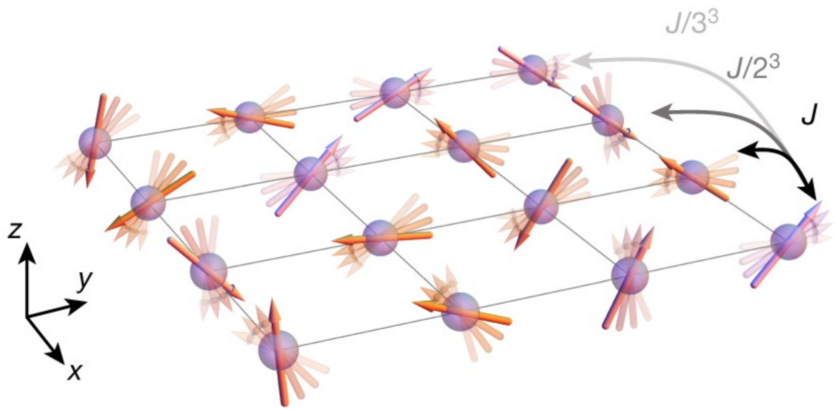
Hazzard & Gadway,
Physics Today (2023)

synthetic lattices for dipolar Rydberg arrays

- start with strong, stable, long-ranged interactions + many internal states
- connect states with coherent microwaves
- entanglement/correlations due to dipole-dipole interactions



dipolar Rydbergs



C. Chen, *et al. Nature* **616**, 691–695 (2023)

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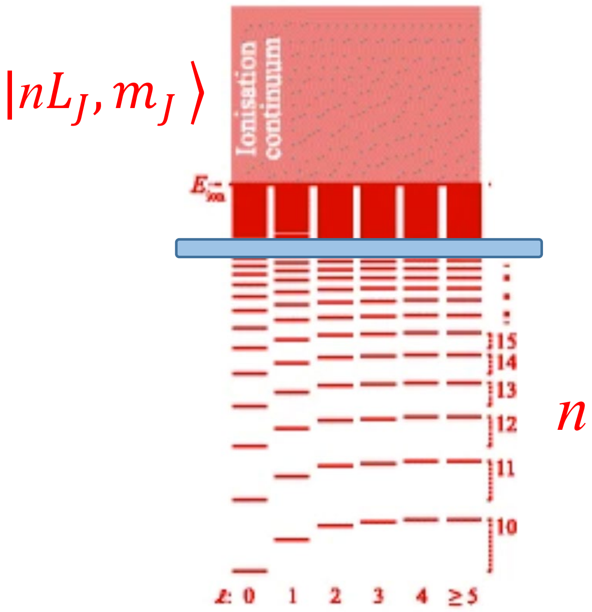
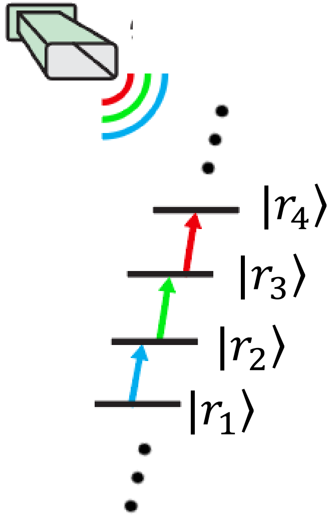
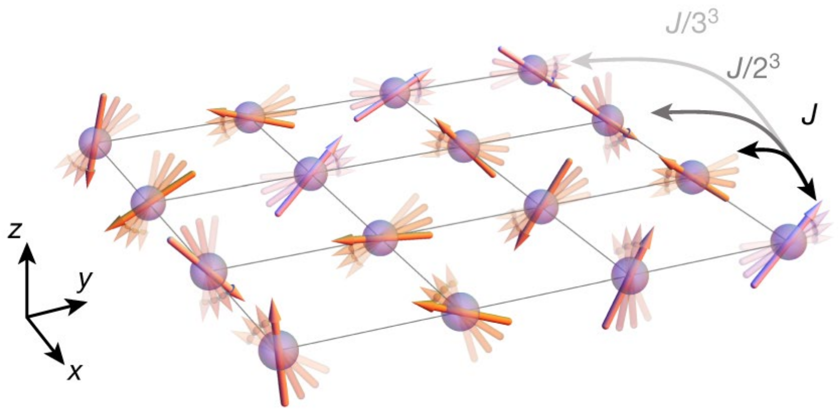


10s to 100s of states ("sites") for the lattice

From S. Hogan
EPJ Techniques and Instrumentation **3**, 2 (2016)



dipolar Rydbergs



C. Chen, *et al. Nature* **616**, 691–695 (2023)

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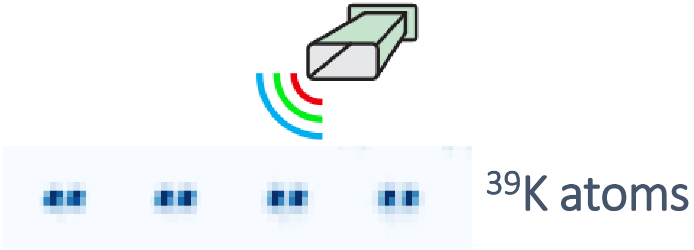
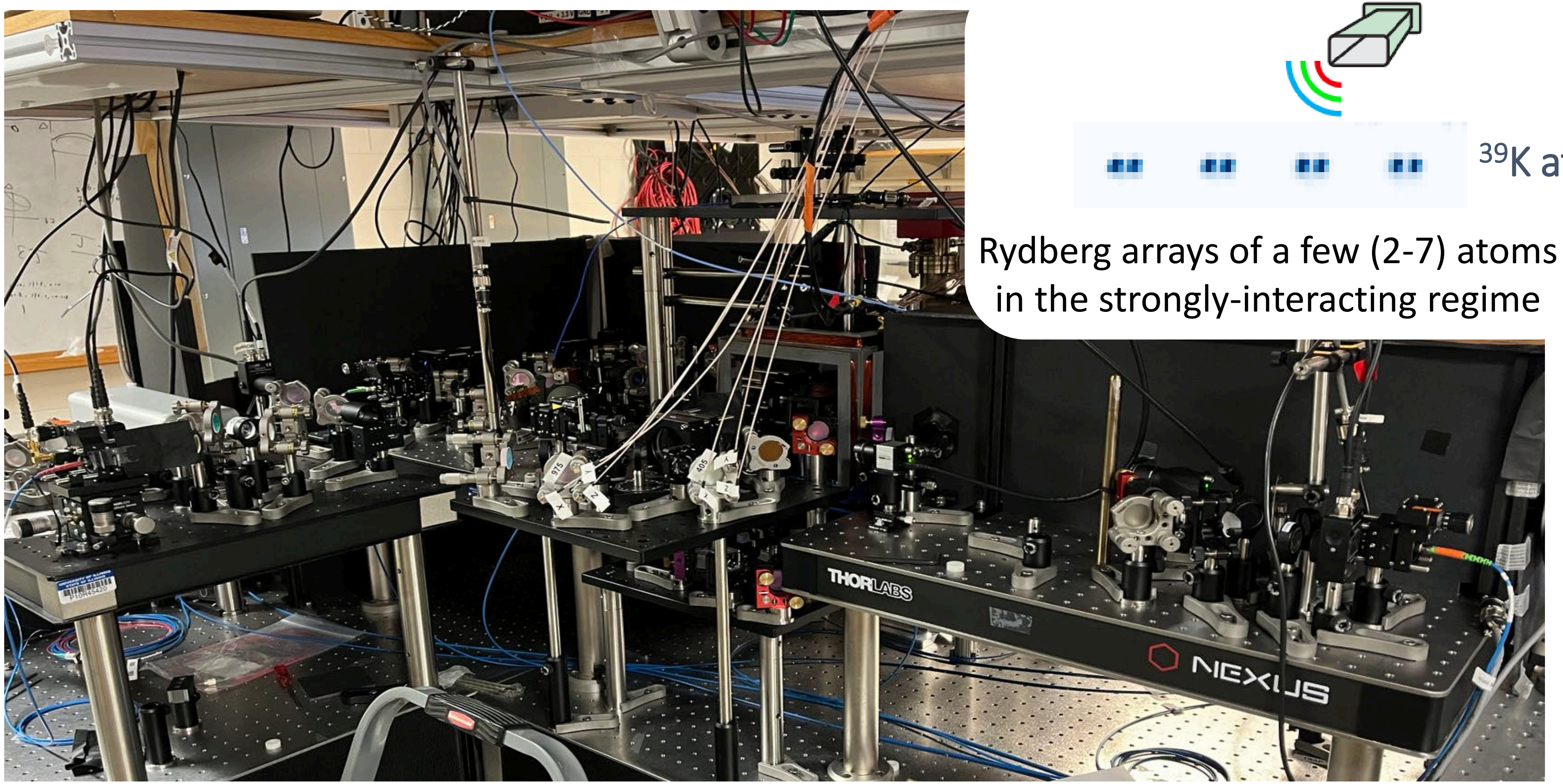


Rydberg arrays of a few (2-7) atoms
in the strongly-interacting regime

synthetic lattices for dipolar Rydberg arrays

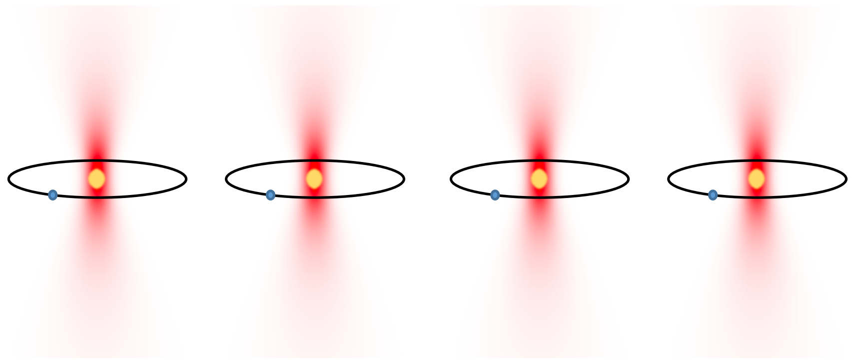
^{39}K atoms

Rydberg arrays of a few (2-7) atoms
in the strongly-interacting regime

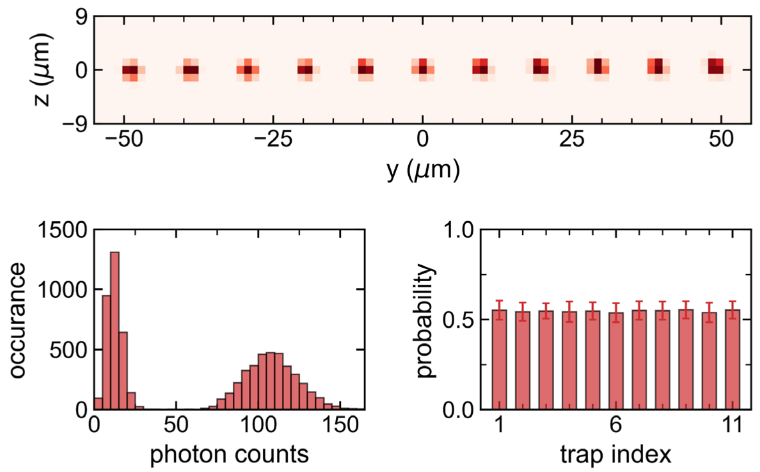


Rydberg synthetic lattices in tweezer arrays

← real space →

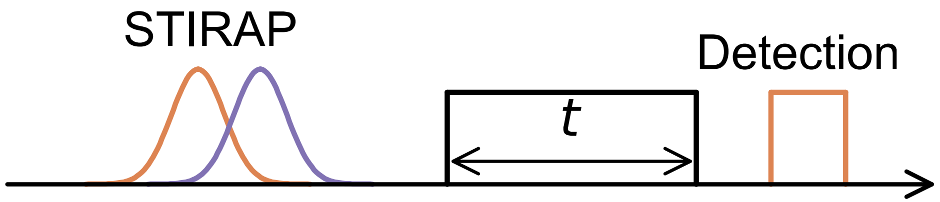


our experiments - ^{39}K atoms

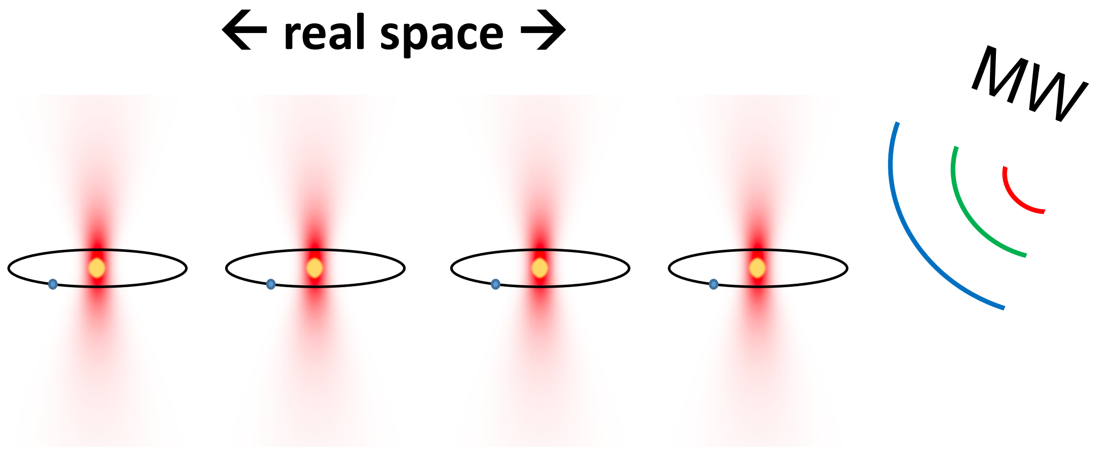


Rydberg synthetic lattices in tweezer arrays

“science” portion of experiment



microwave-controlled dynamics in the synthetic space



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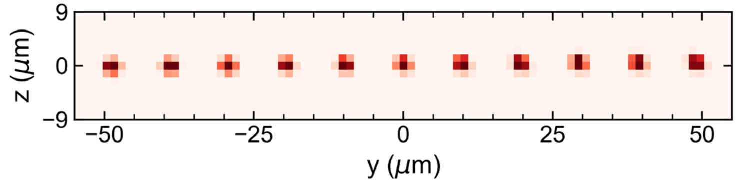


current limitation:
imperfect Rydberg excitation

→ **start with few-body studies (1-6 atoms)**

Rydberg synthetic lattices

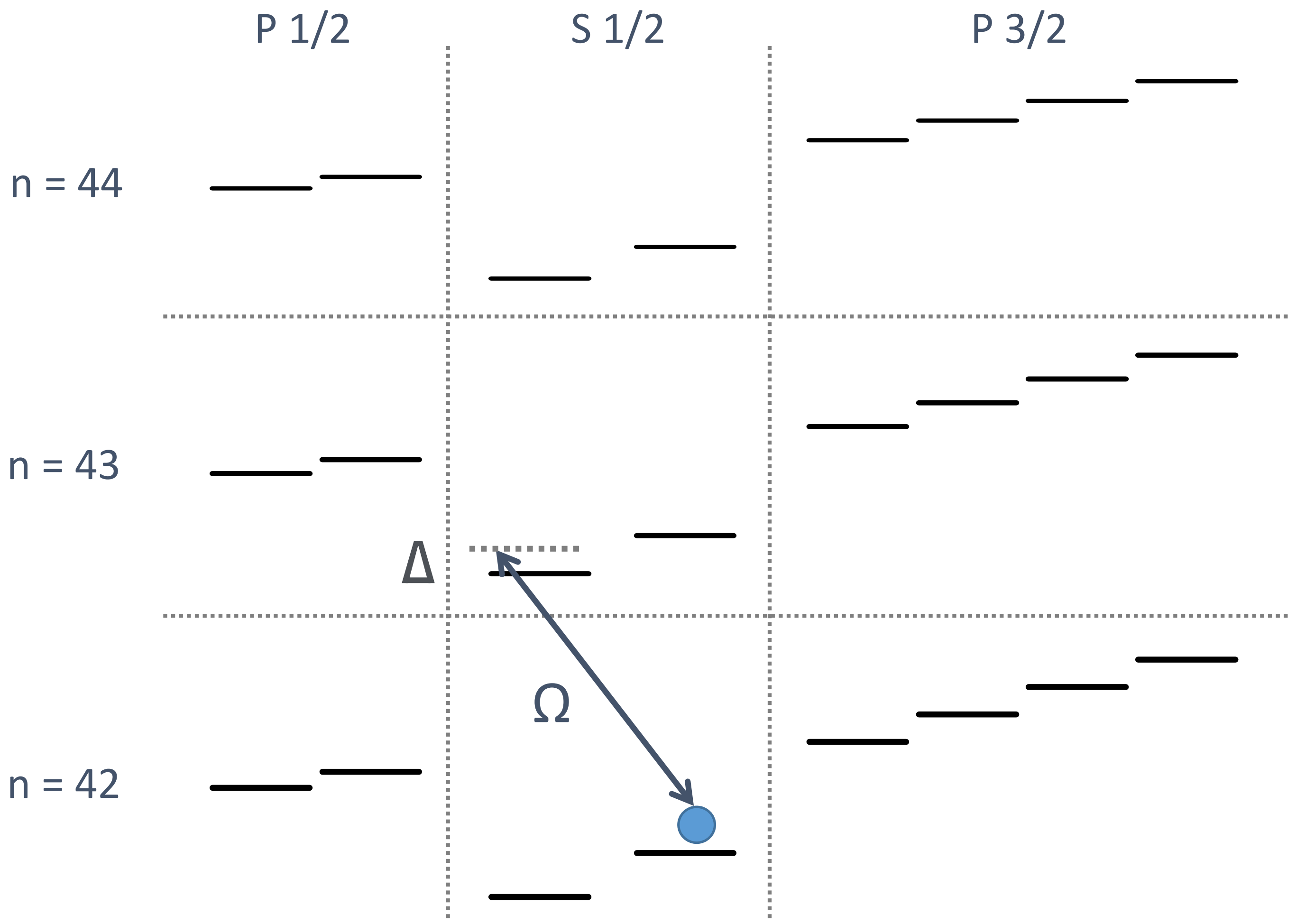
see also work from Killian group:

S.K. Kanungo, *et al. Nat Commun* **13**, 972 (2022)
Lu. *et al*. PRA **109**, 032801 (2024)

& Haroche group:

A. Signoles, *et al. Nat Phys.* **10**, 715 (2014)

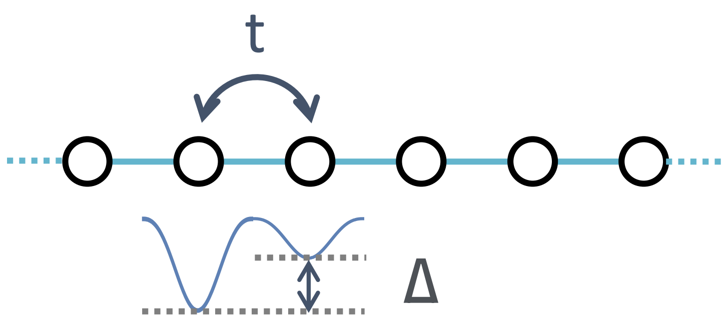
$$nL_{J,m_J}$$

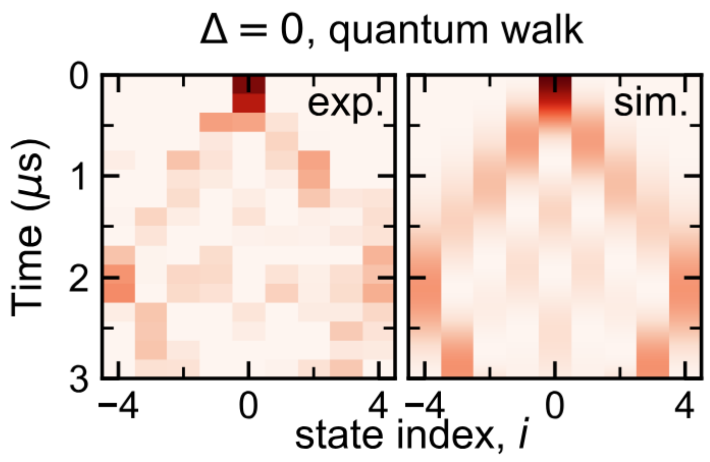


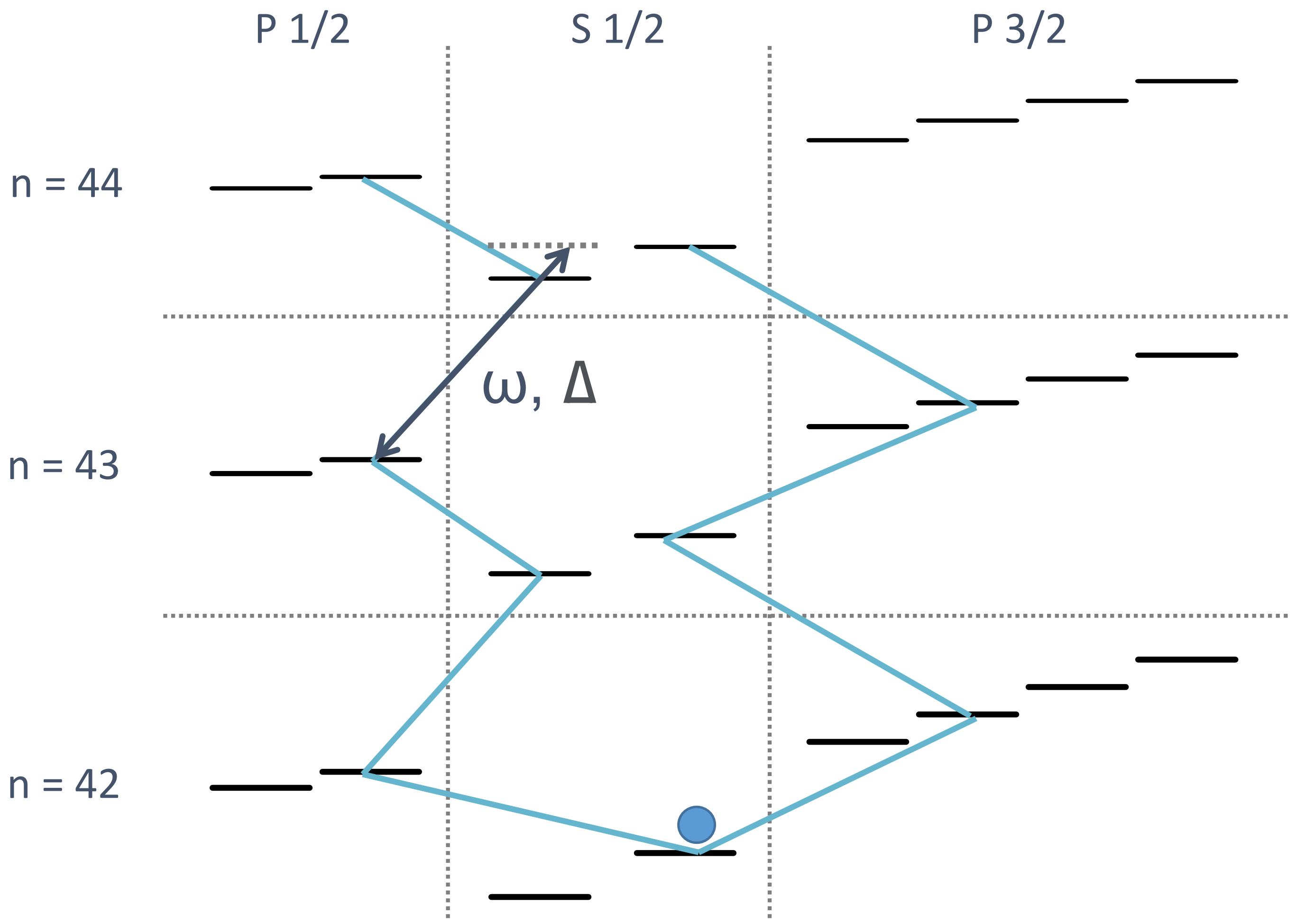
underlying concept:

two coupled states maps onto a double-well

Rydberg synthetic lattices

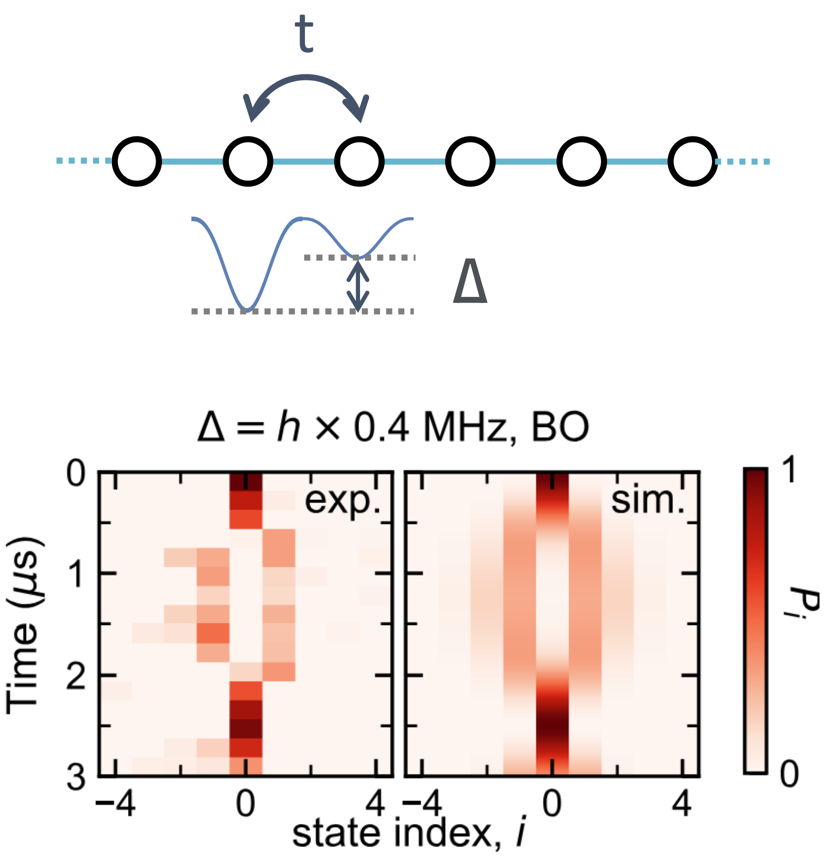


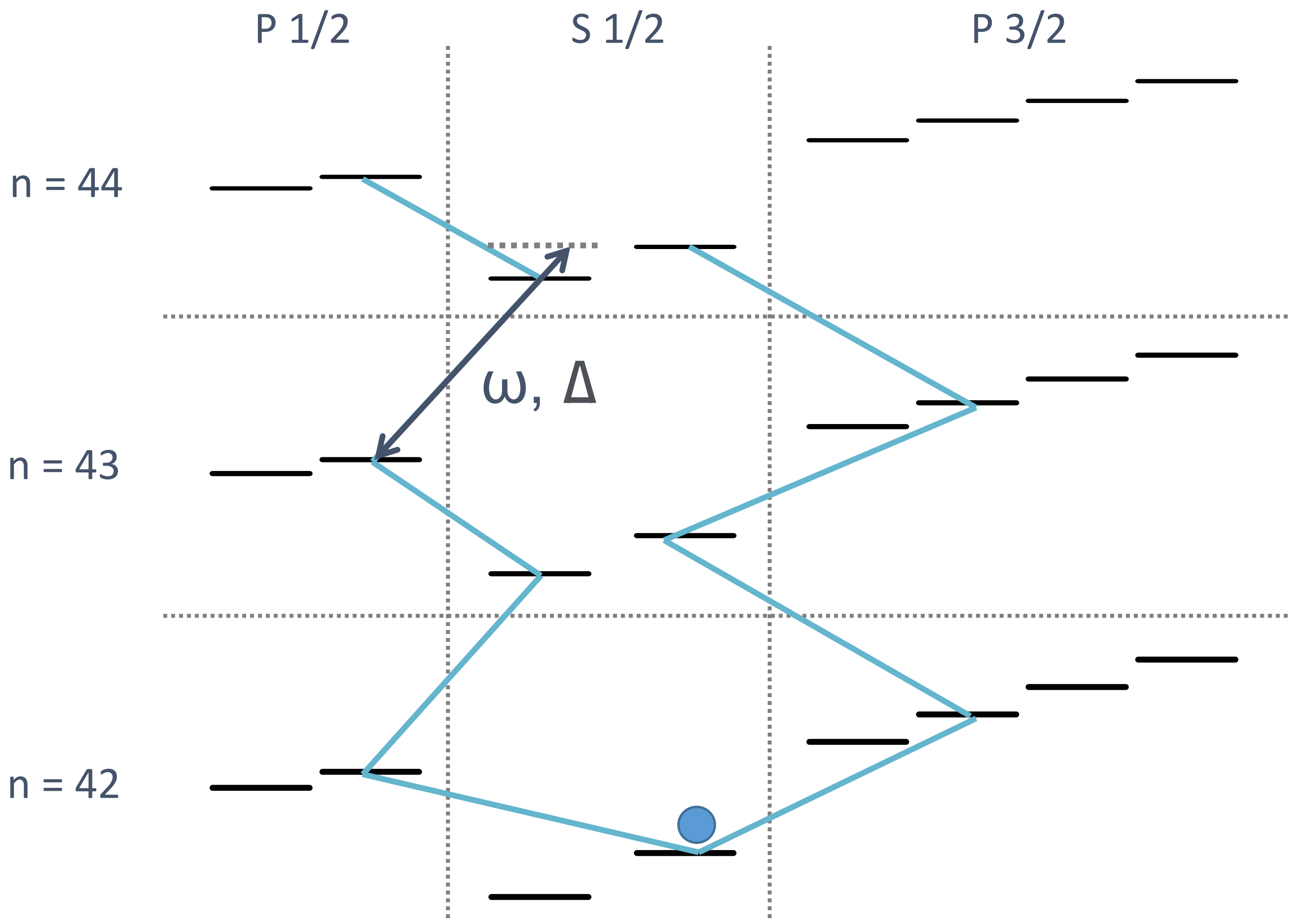




T. Chen, C. Huang, *et al.* PRL (2024)

Rydberg synthetic lattices





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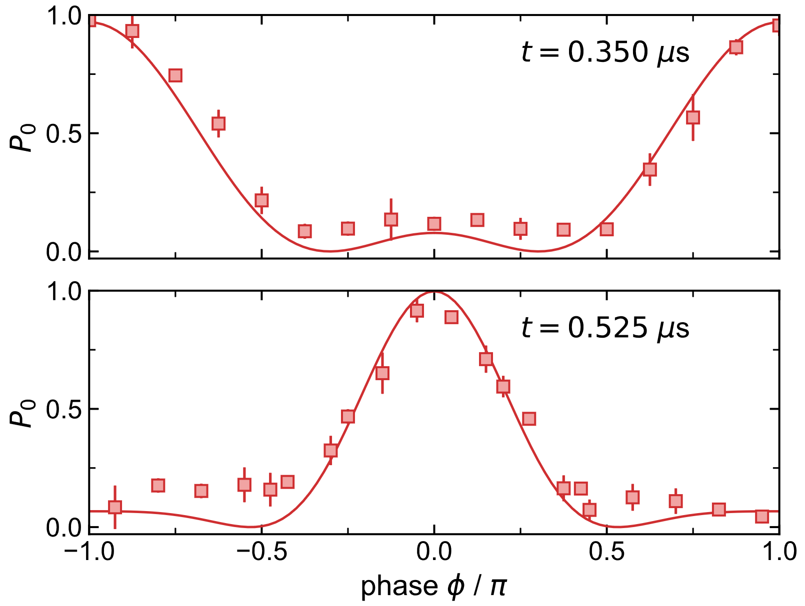
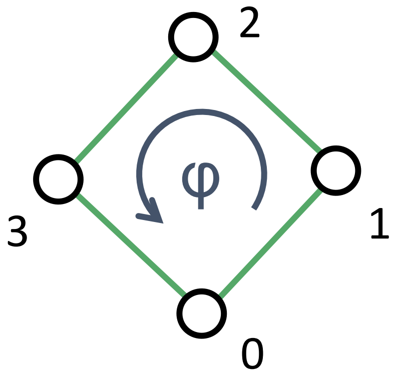
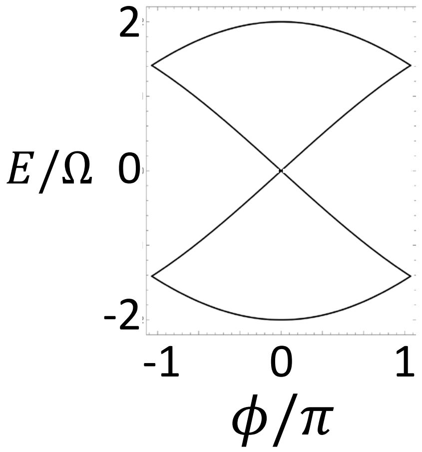
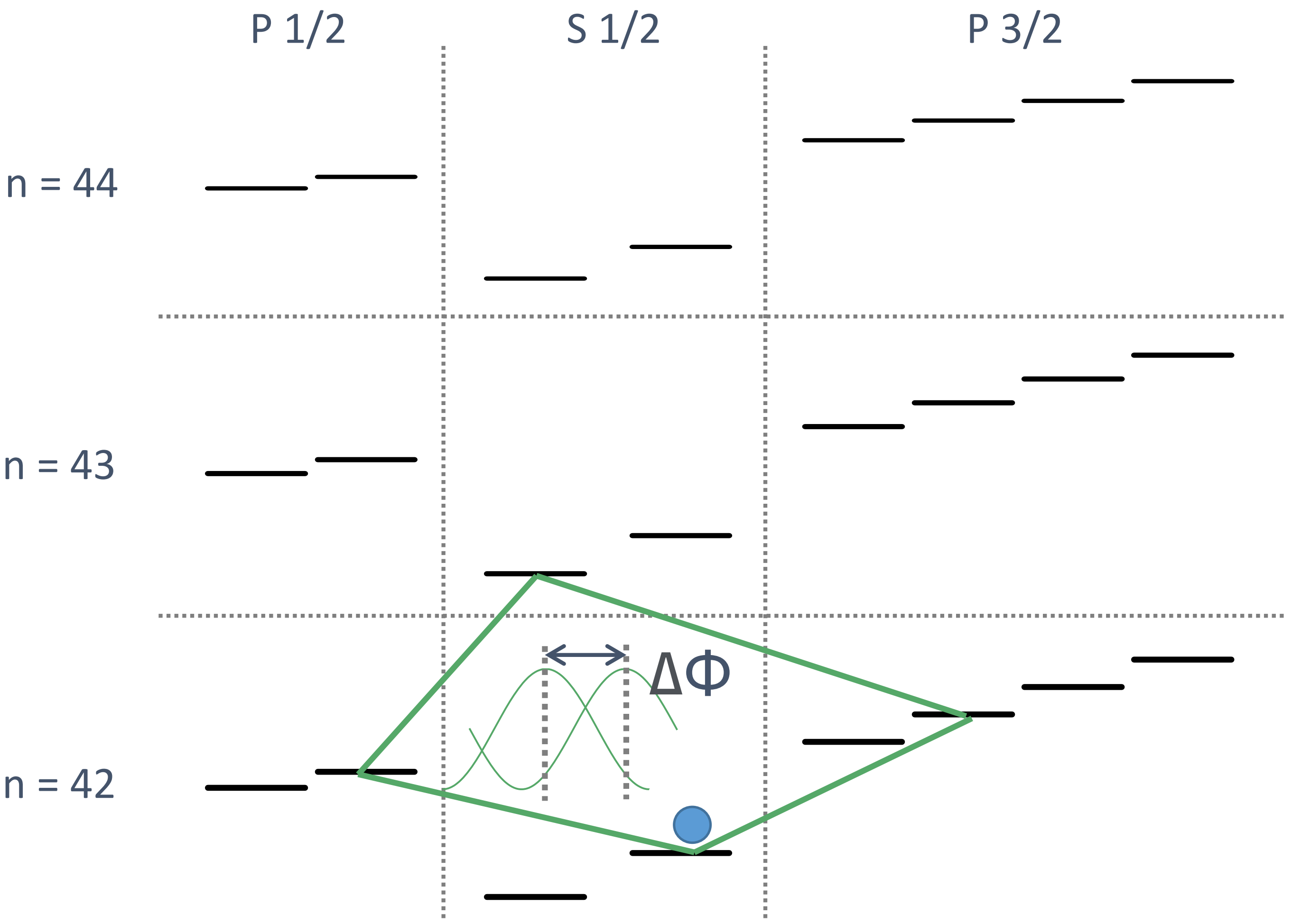
Rydberg synthetic lattices



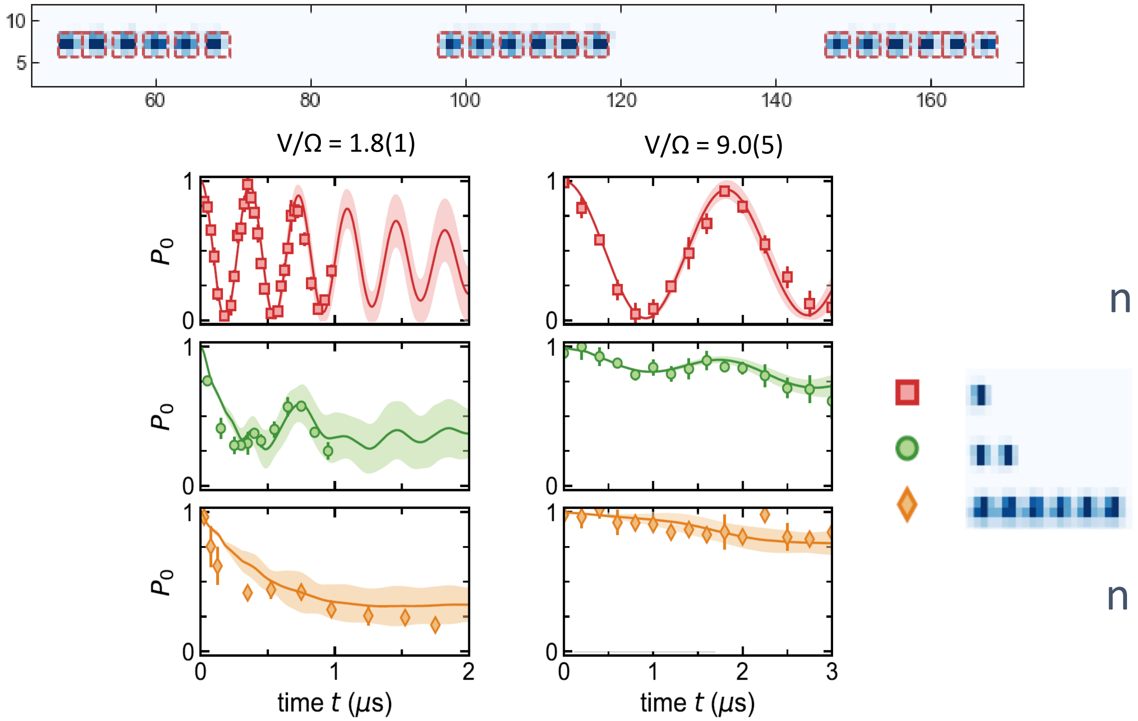


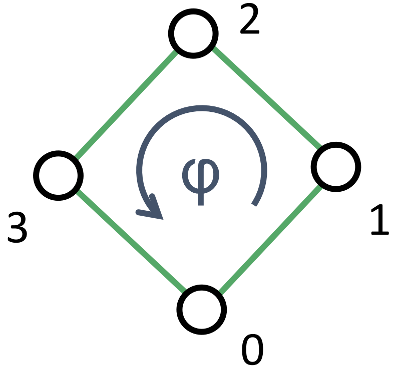


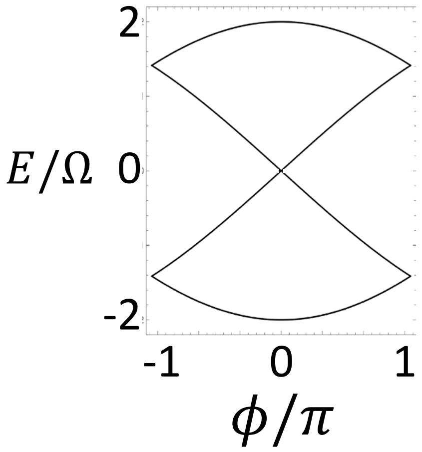


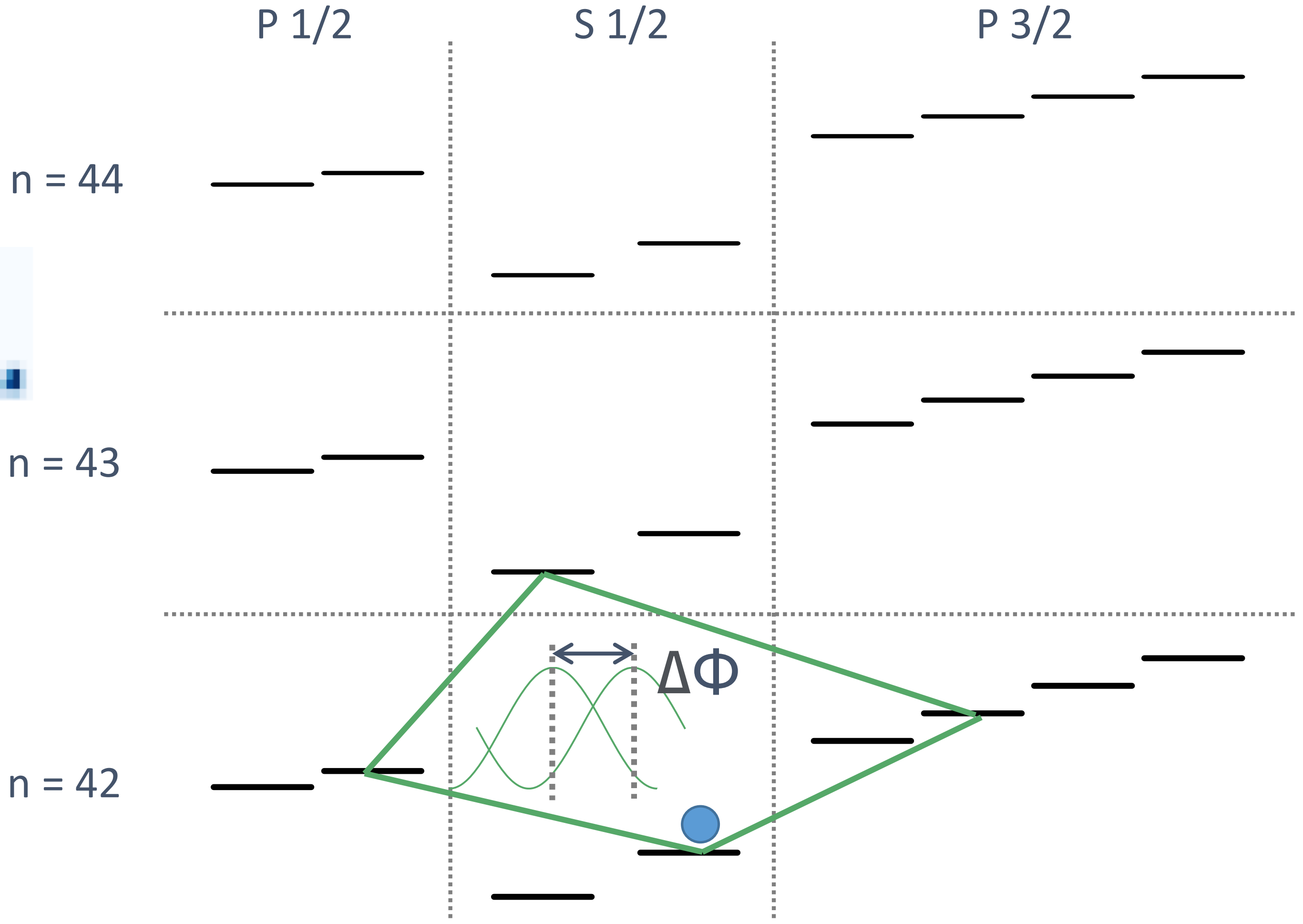
T. Chen*, C. Huang*, *et al. Nat. Comm.*(2024)

Rydberg synthetic lattices – **interactions**





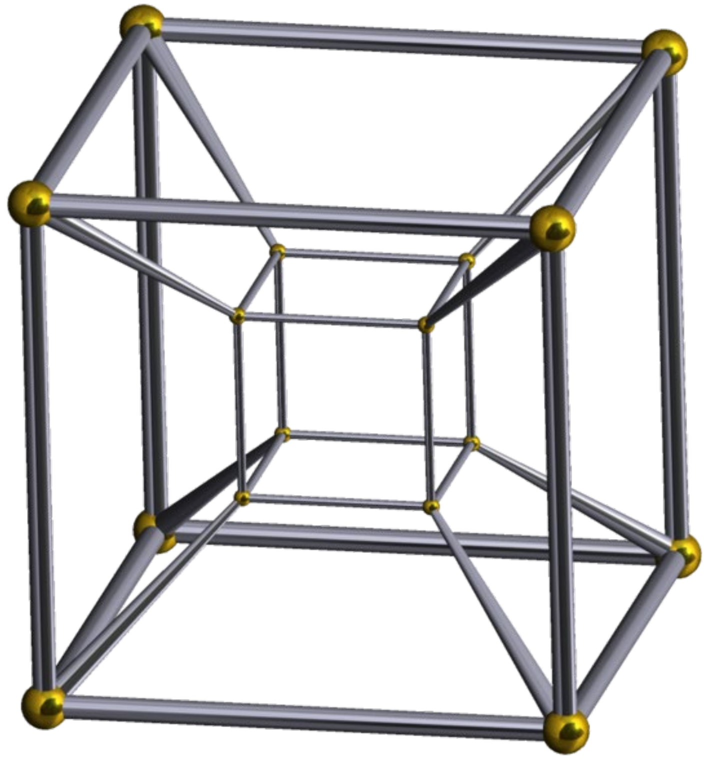


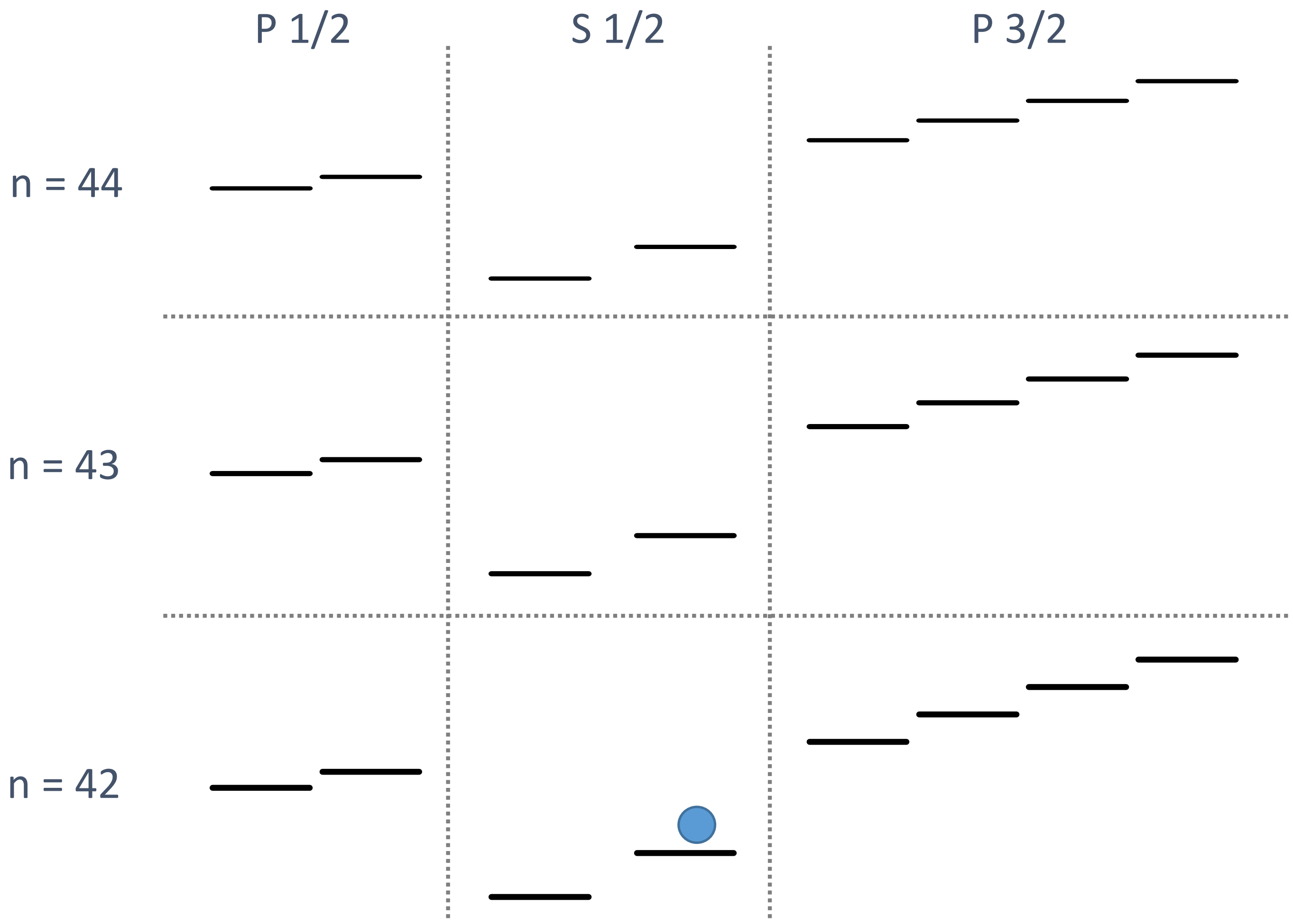


T. Chen*, C. Huang*, *et al. Nat. Comm.*(2024)

Rydberg synthetic lattices

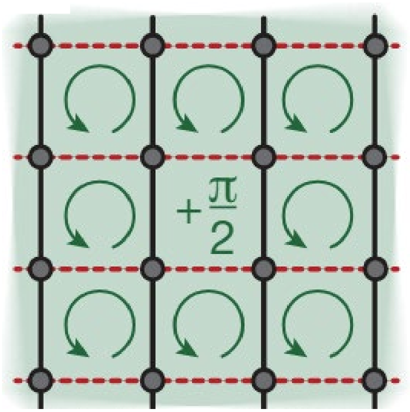
4D hypercube
Robert Webb, wikipedia



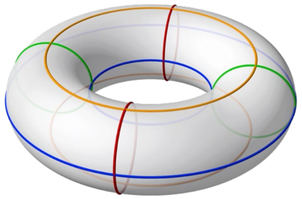


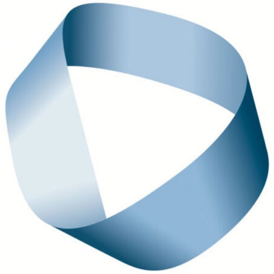
Rydberg synthetic lattices

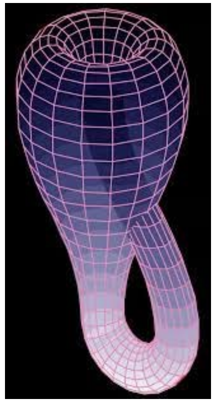
2D Hofstadter models and more

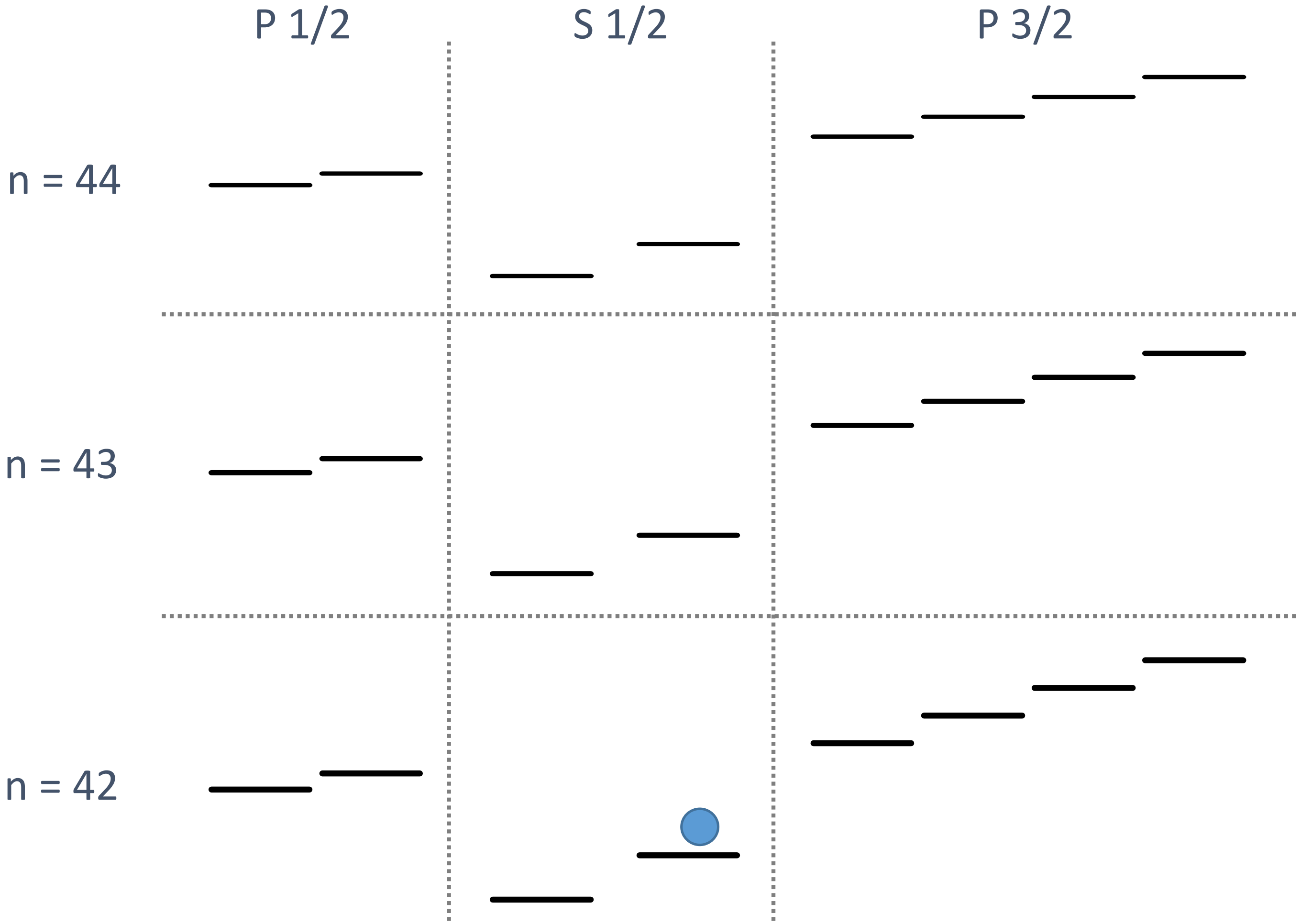


Aidelsburger, *et al* (2013)









Rydberg synthetic lattices

toy examples from last year or so

- **Gauge fields, strings, and scrambling**
  T. Chen*, C. Huang*, et al. Nat Comm. (2024)
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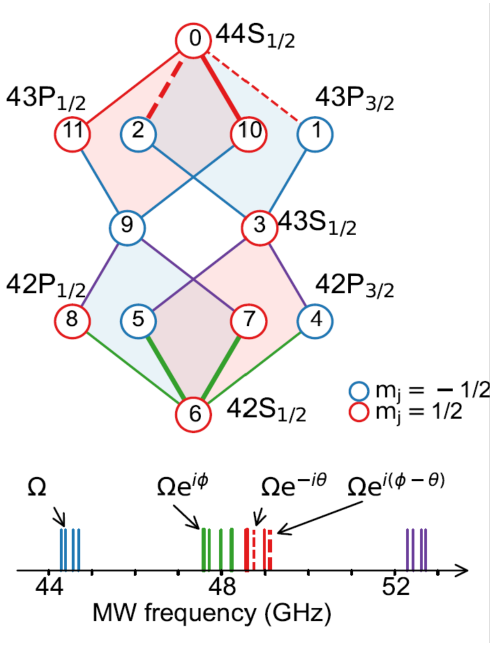
Rydberg synthetic lattices

flat-band lattices
+ interactions



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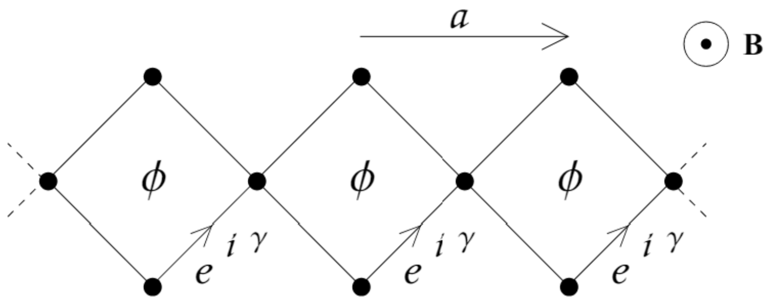
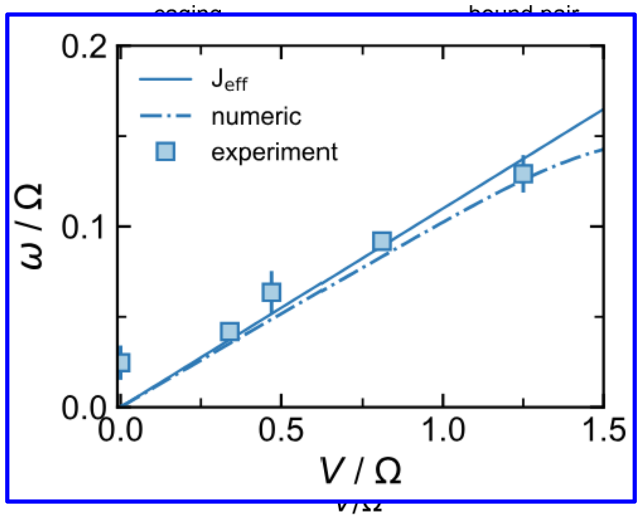
Rydberg synthetic lattices

flat-band lattices
+ interactions

Interaction Induced Delocalization for Two Particles in a Periodic Potential

Julien Vidal, Benoît Douçot, Rémy Mosseri, and Patrick Butaud
Phys. Rev. Lett. **85**, 3906 – Published 30 October 2000





<u>toy examples from last year or so</u>

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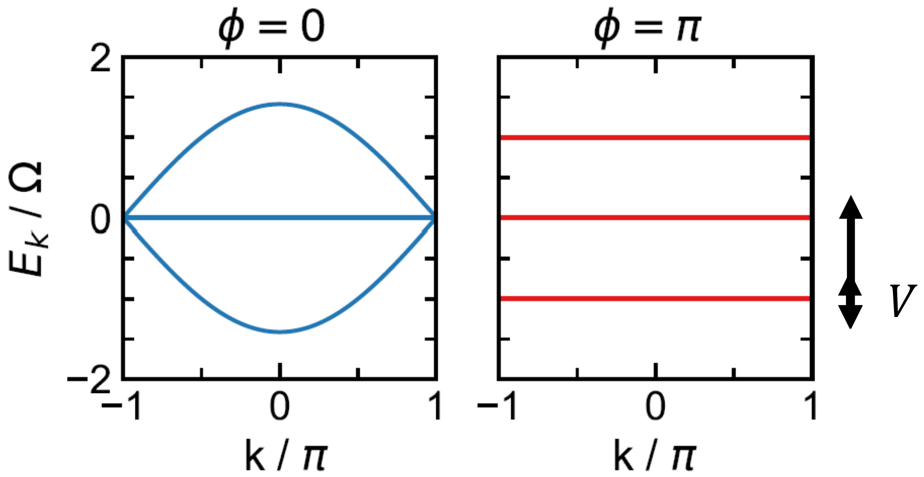

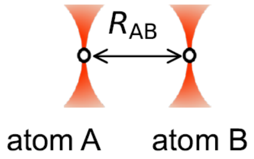

Rydberg synthetic lattices

flat-band lattices
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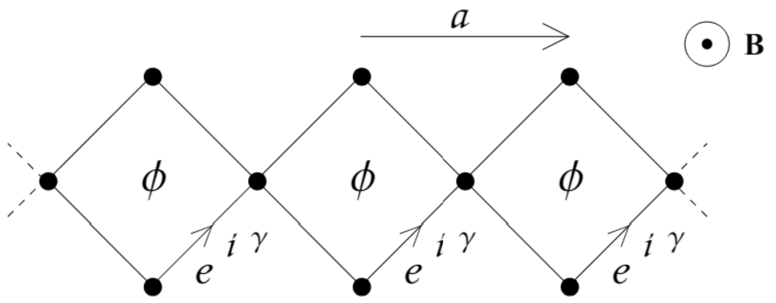

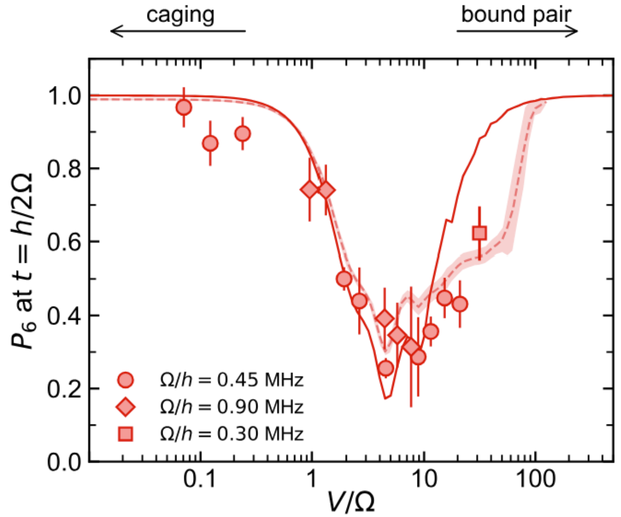

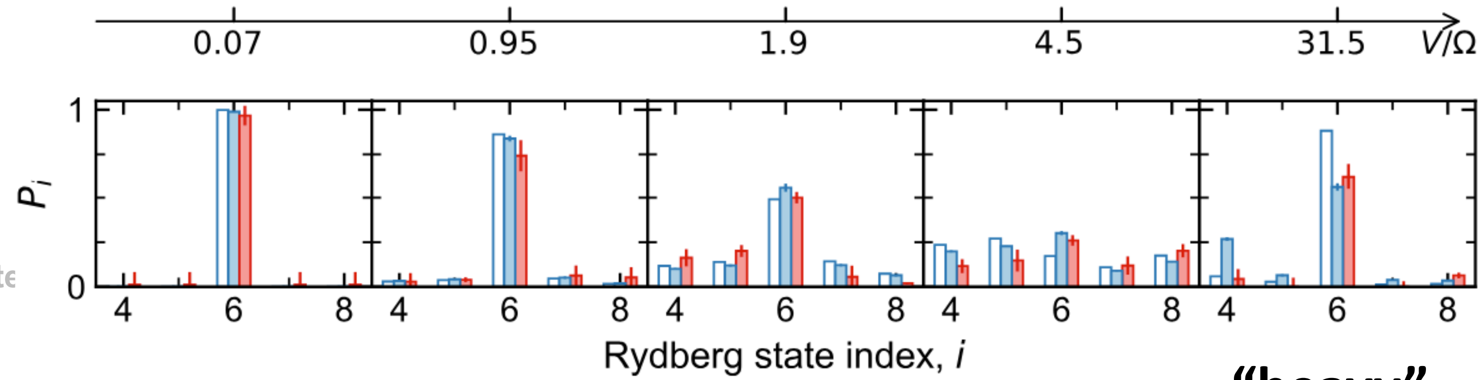

caged

delocalized

"heavy" bound state

toy examples from last year or so

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  T. Chen*, C. Huang*, arXiv:2404.00737 (accepted to Nat. Phys.)
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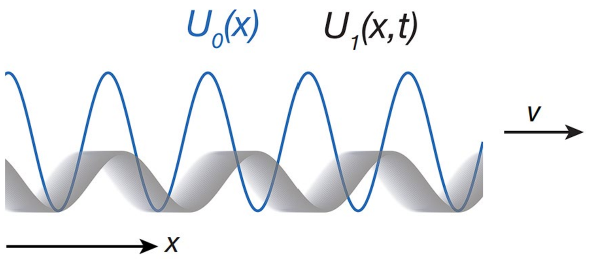
topological pumps

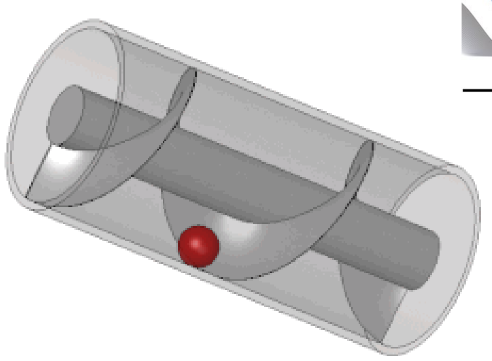
want to explore interacting topological systems – let's start simple, working in 1D

$$Q = \frac{e}{\pi}\int_A dX_1 dX_2 \sum_\beta \sum_{\alpha\in m} \Im \frac{\partial S^\star_{\alpha\beta}}{\partial X_1}\frac{S_{\alpha\beta}}{\partial X_2}$$

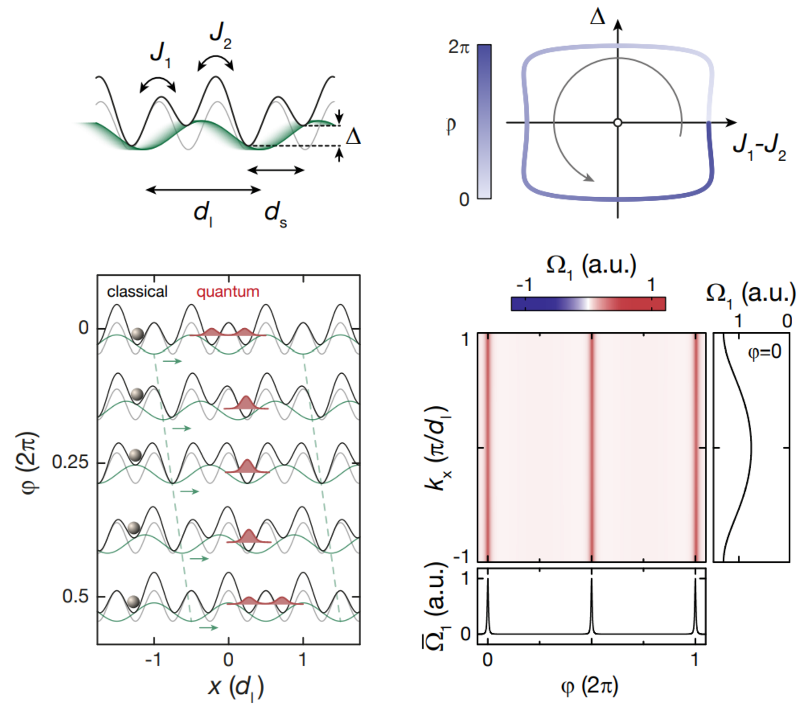
D. Thouless et al, Phys. Rev. Lett. 49, 405 (1982)
D. Thouless Phys. Rev. B 27, 6083 (1983)
R. Citro & M. Aidelsburger, Nat. Rev. Phys. 5, 87 (2023)

"quantum pumps": quantized charge pumping is related to the topology of lattice bands





Archimedes screw animation (Wikipedia)



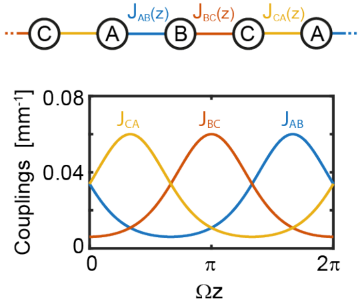
Lohse, *et al*. Nature Physics (2016)

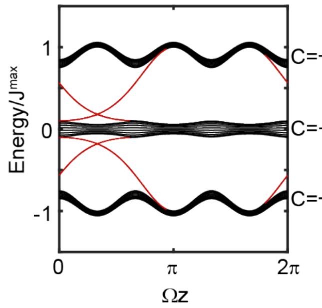
interacting topological pumps

Nature, 2021

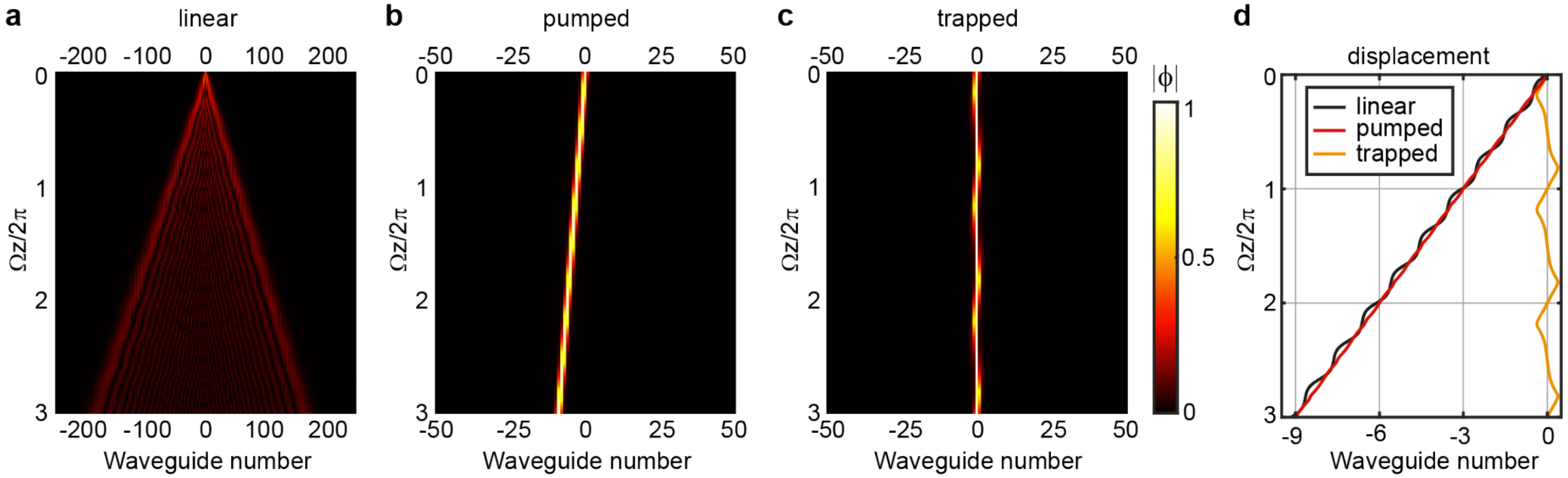
Quantized Nonlinear Thouless Pumping

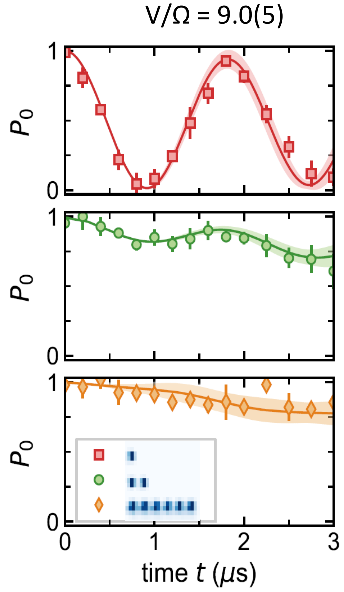
Marius Jürgensen,* Sebabrata Mukherjee, and Mikael C. Rechtsman†
Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA
(Dated: June 29, 2021)





increasing nonlinearity



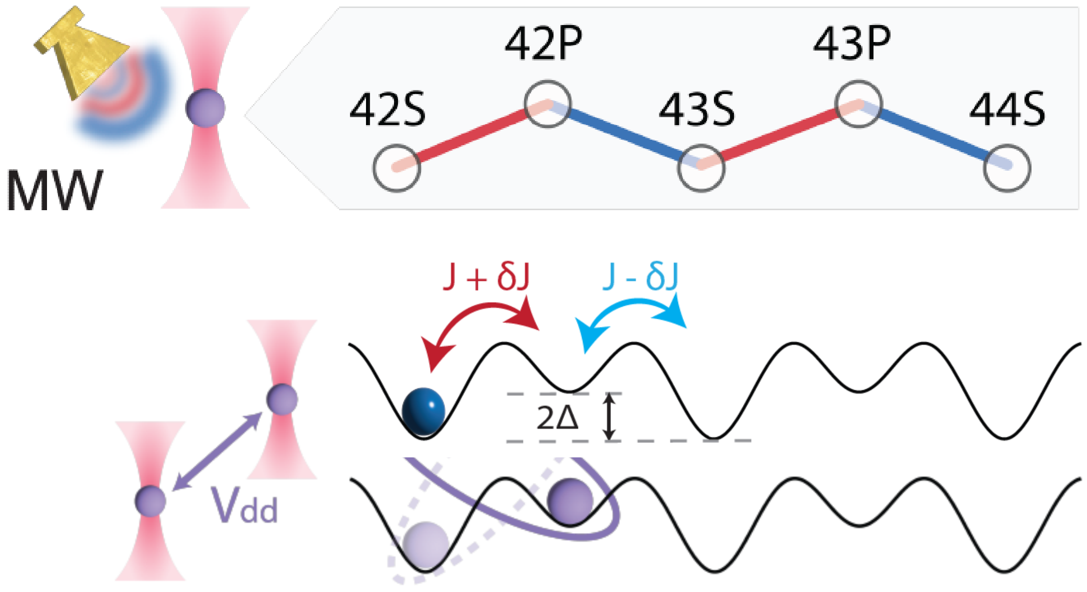


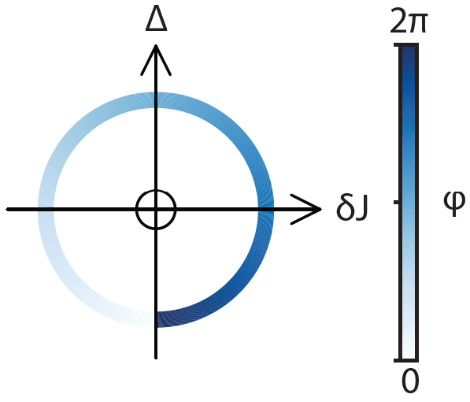
does this classical bound-state pumping persist in the few-body quantum limit?

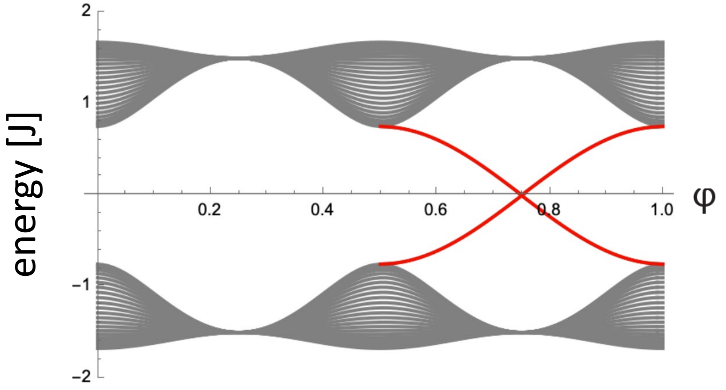
topological pumping with dipolar Rydberg atoms

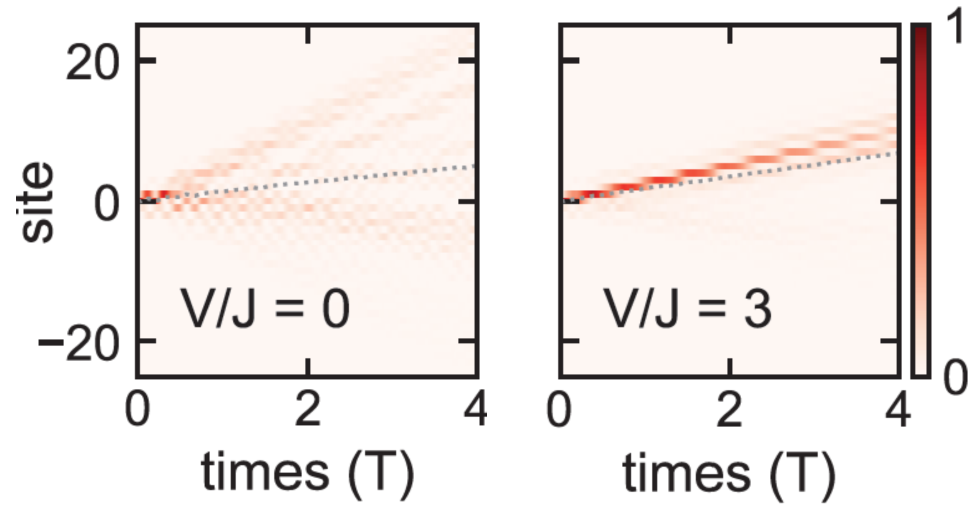
see also work from Deiglmayr group
arXiv: 2406.08551

C. Huang, T. Chen, *et al.* (*in prep*)



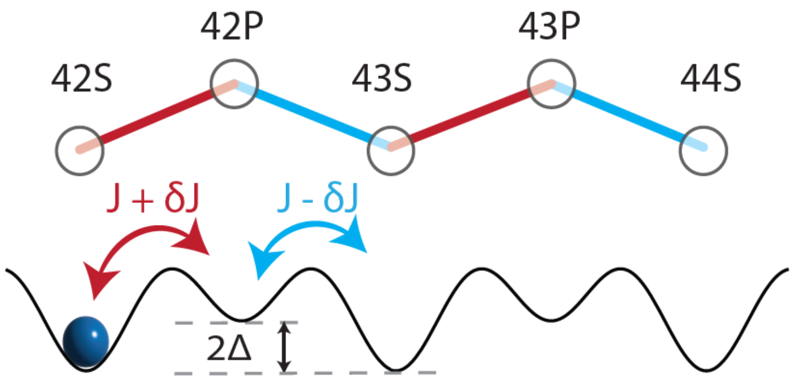






experimental pumping dynamics

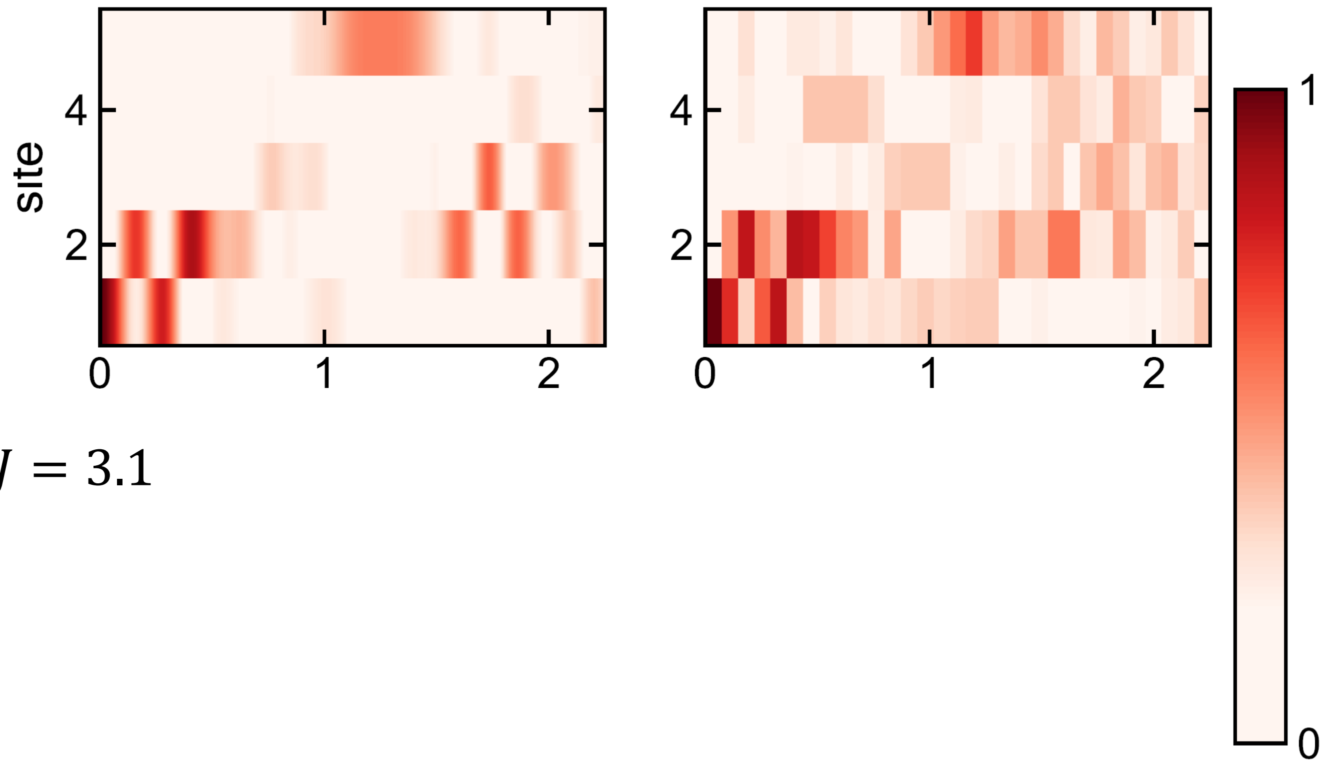
see also work from Deiglmayr group
arXiv: 2406.08551



atoms pump while
remaining bound together

C. Huang, T. Chen, *et al.* (*in prep*)

$V/J = 0$

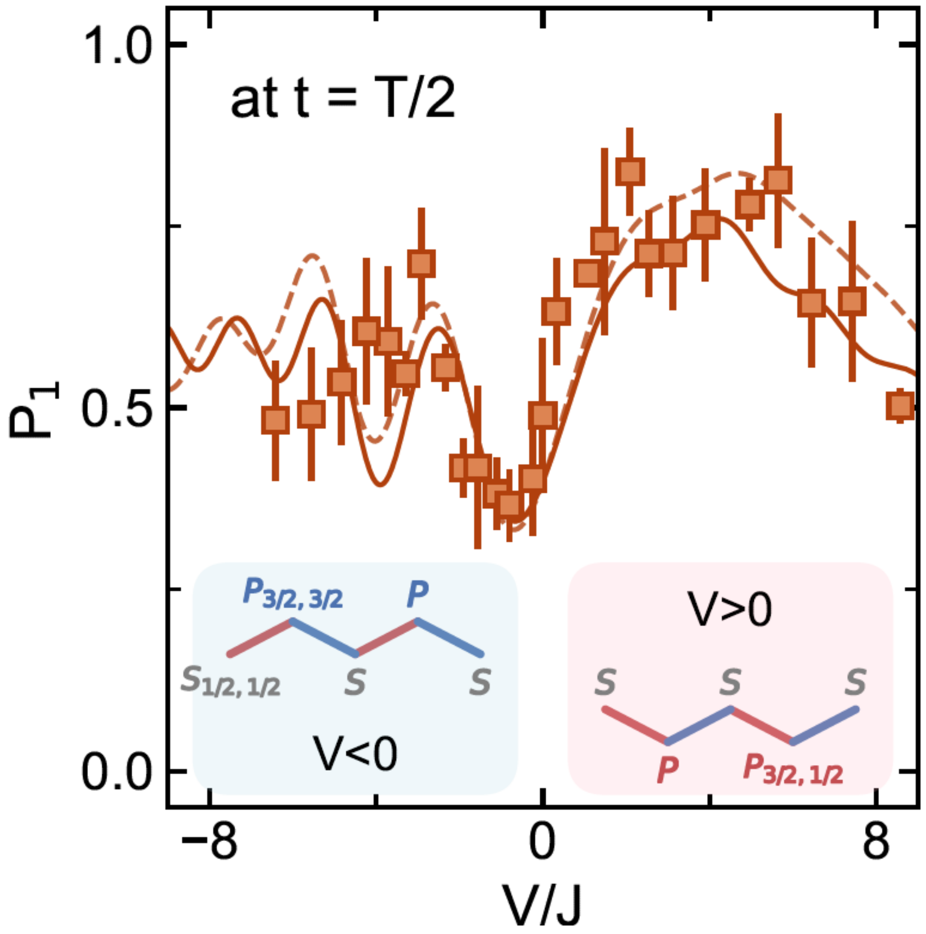


$V/J = 3.1$

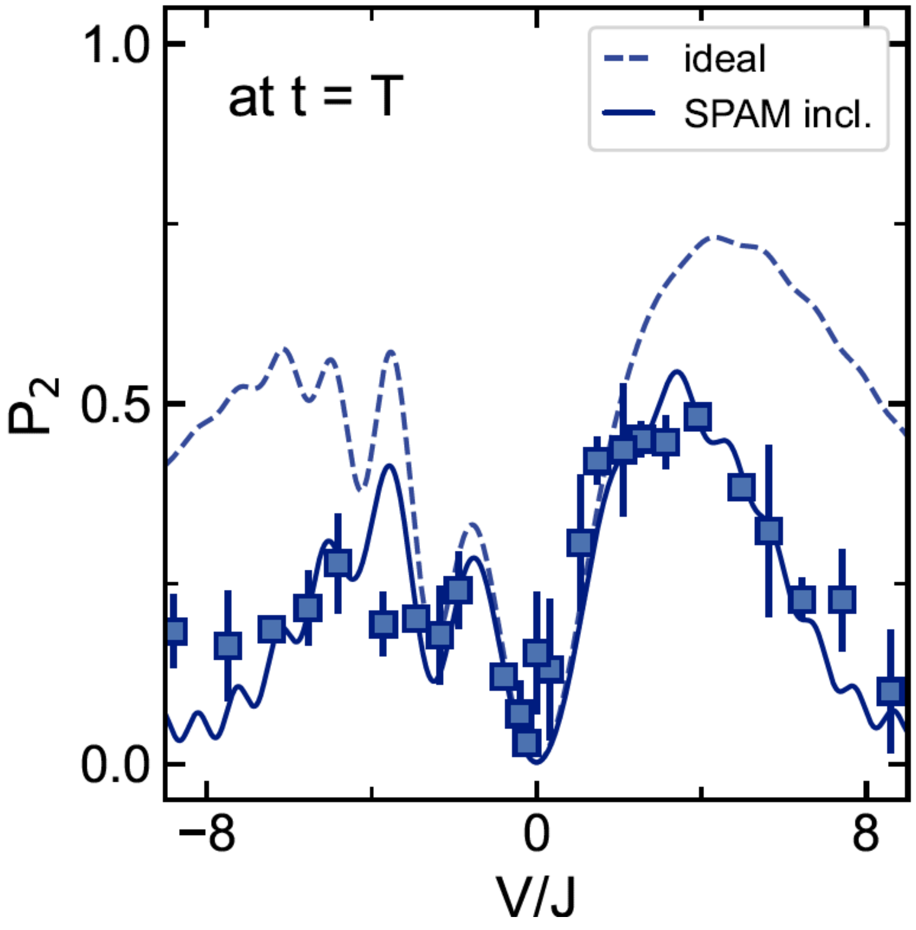
influence of interactions

C. Huang, T. Chen, *et al.* (*in prep*)

half a pump cycle

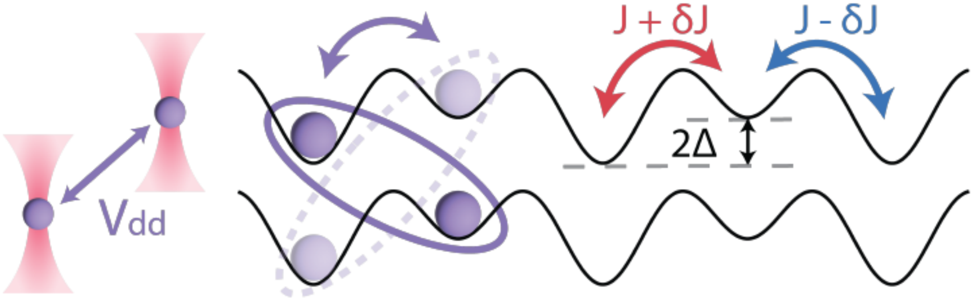


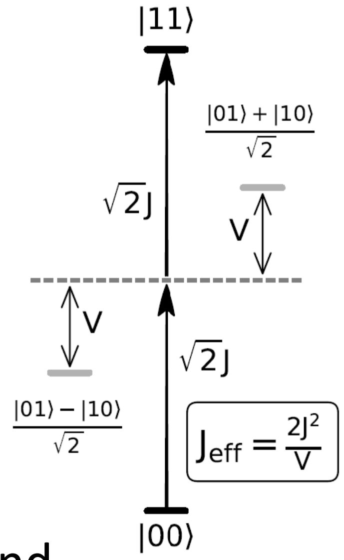
one full pump cycle

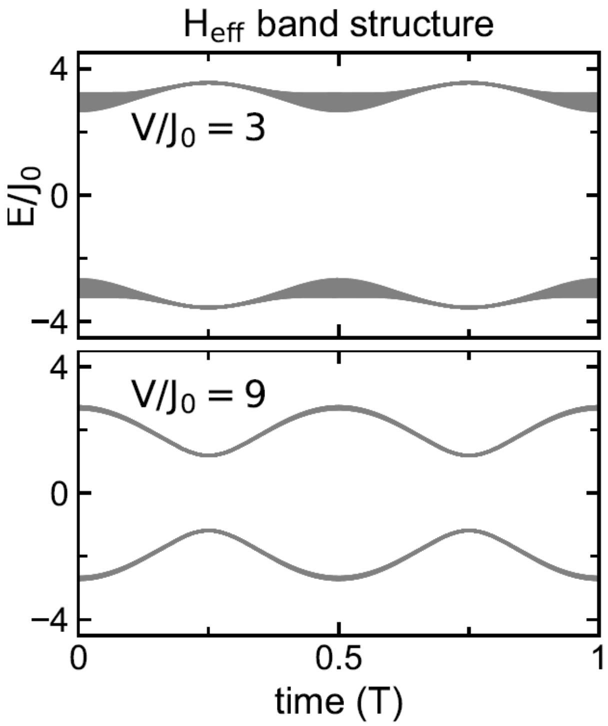


what's the mechanism?

C. Huang, T. Chen, *et al.* (*in prep*)







Two main effects:

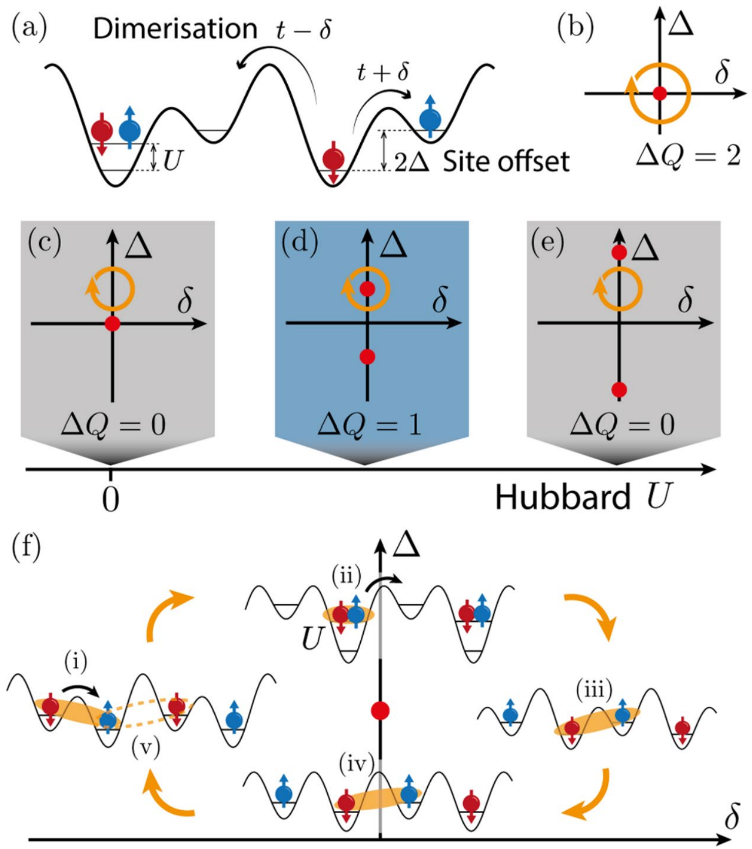
- positive interactions improve projection onto single band
- interactions restrict transport to within a basis of bound pairs (and the pumping path in this bound-pair basis prevents spreading)

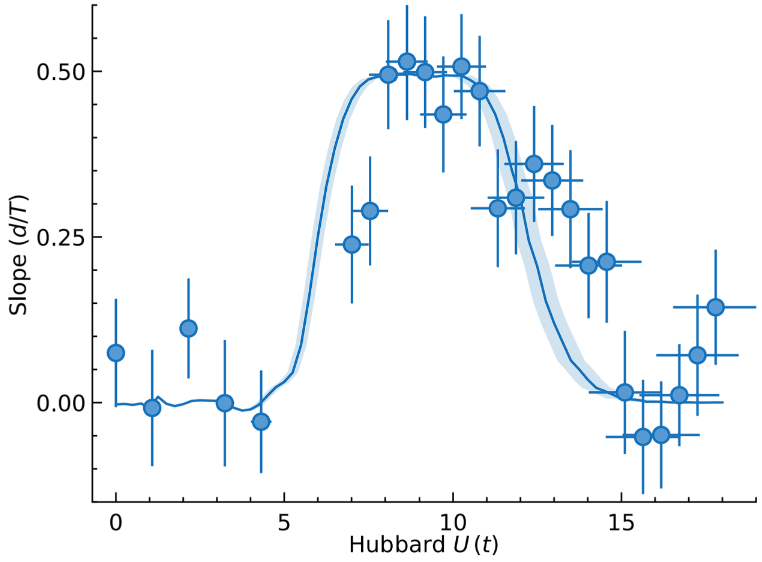
$$|j, j\rangle$$

interaction-induced topological pumping?

motivating experiments by Tilman Esslinger group

Fermions in superlattice implementation (T. Esslinger group) -- K. Viebahn et al, Phys. Rev. X 14, 021049 (2024)



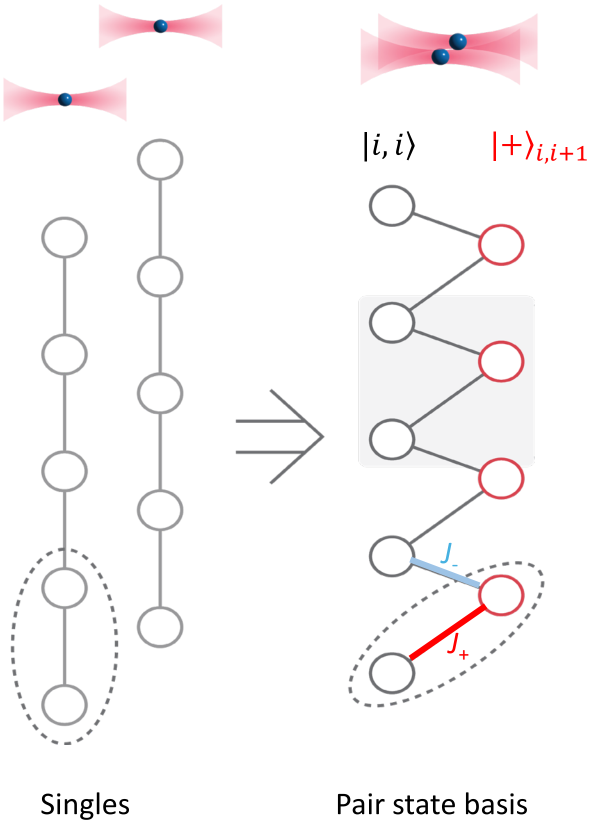


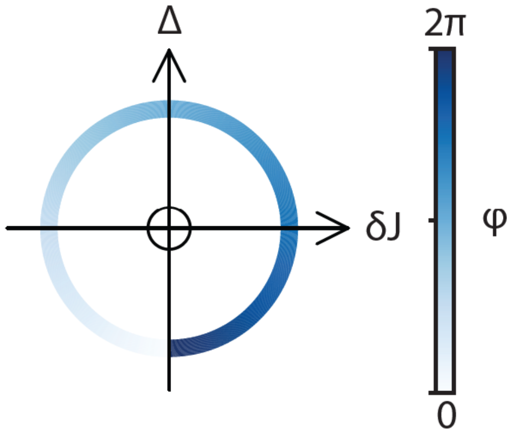
+ lots of motivating theory work

Yan & Zhou, PRL **120**, 235302 (2018)
Lin, Ke, and Lee, PRA 101, 023620 (2020)
Kuno & Hatsugai, PRR **2**, 042024(R) (2020)
Bertok, Heidrich-Meisner, and Aligia, PRB 106, 045141 (2022)
+ more

interaction-induced topological pumping of dipolar pairs

C. Huang, T. Chen, *et al.* (*in prep*)



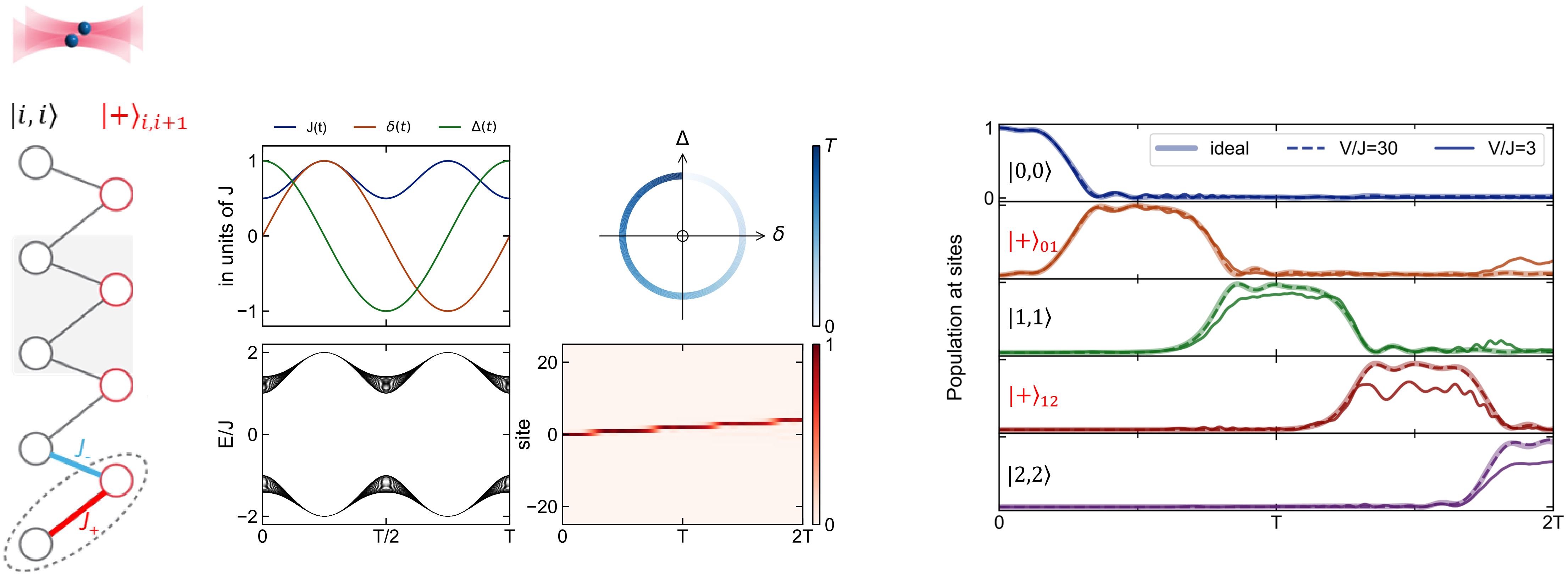


cyclic driving in the effective pair-state Rice-Mele model

because our synthetic lattice is biased away from dc,
we can separately address processes that form and break bound states

interaction-induced topological pumping of dipolar pairs

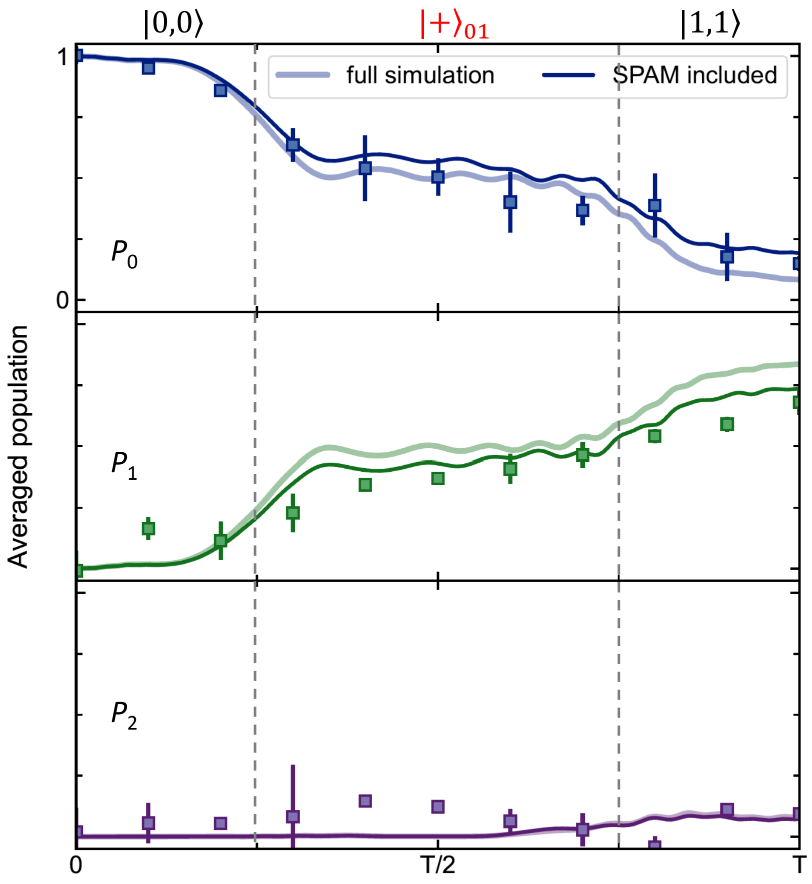
C. Huang, T. Chen, *et al.* (*in prep*)



Pair basis: $H_{\mathrm{RM}}(t) = -\sum_i [J(t) + (-1)^i \delta(t)] \left(\hat{c}_i^\dagger \hat{c}_{i+1} + \mathrm{h.c.} \right) + \Delta(t) \sum_i (-1)^i \hat{c}_i^\dagger \hat{c}_i$

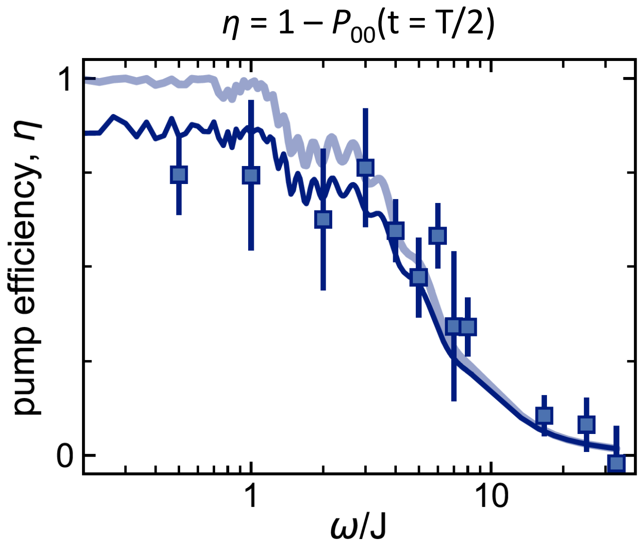
experimental pumping and adiabaticity

C. Huang, T. Chen, *et al.* (*in prep*)



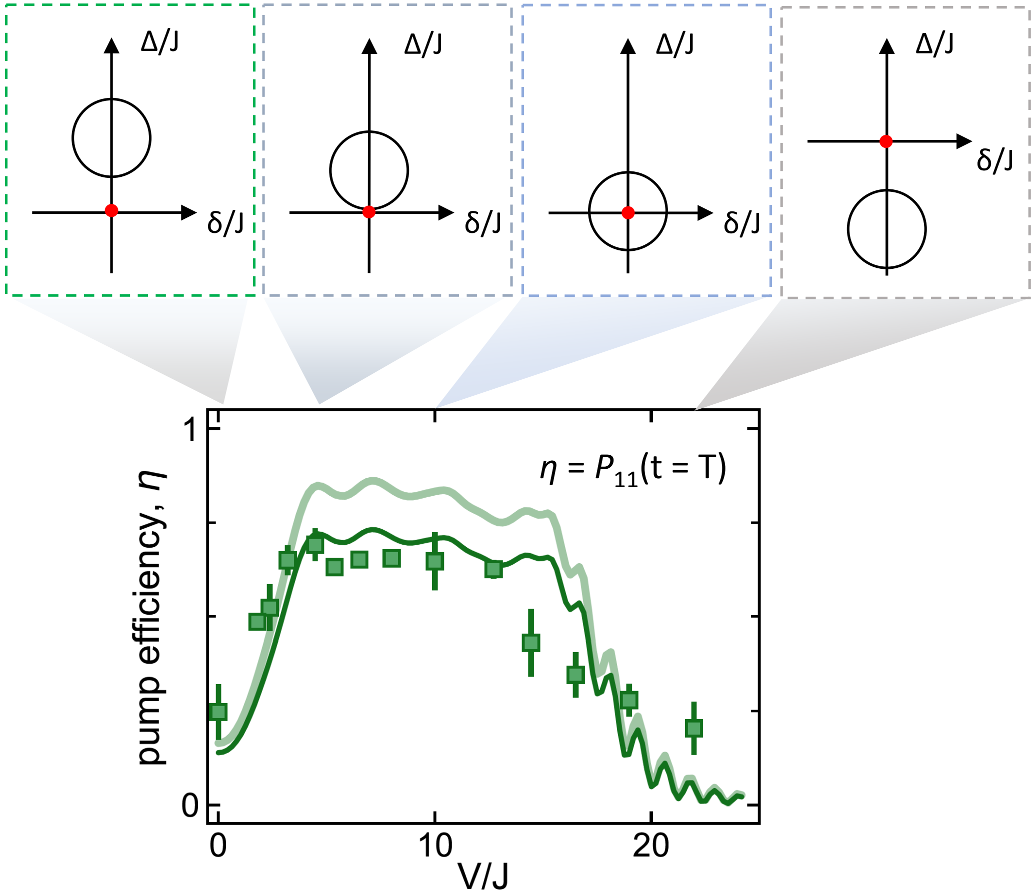
$\Delta_c/h = V/h = 3$ MHz, $\Delta_0/h = 1.2$ MHz, $J/h = 0.3$ MHz, $\delta_0/h = 0.3$ MHz, $\omega/2\pi = 0.3$ MHz

- Check adiabaticity – slower is better
- Smaller ω is limited by our release time window (~ 5 μs)
- Solid lines include contributions from single atoms (SPAM)



interaction-dependence and robustness to perturbations

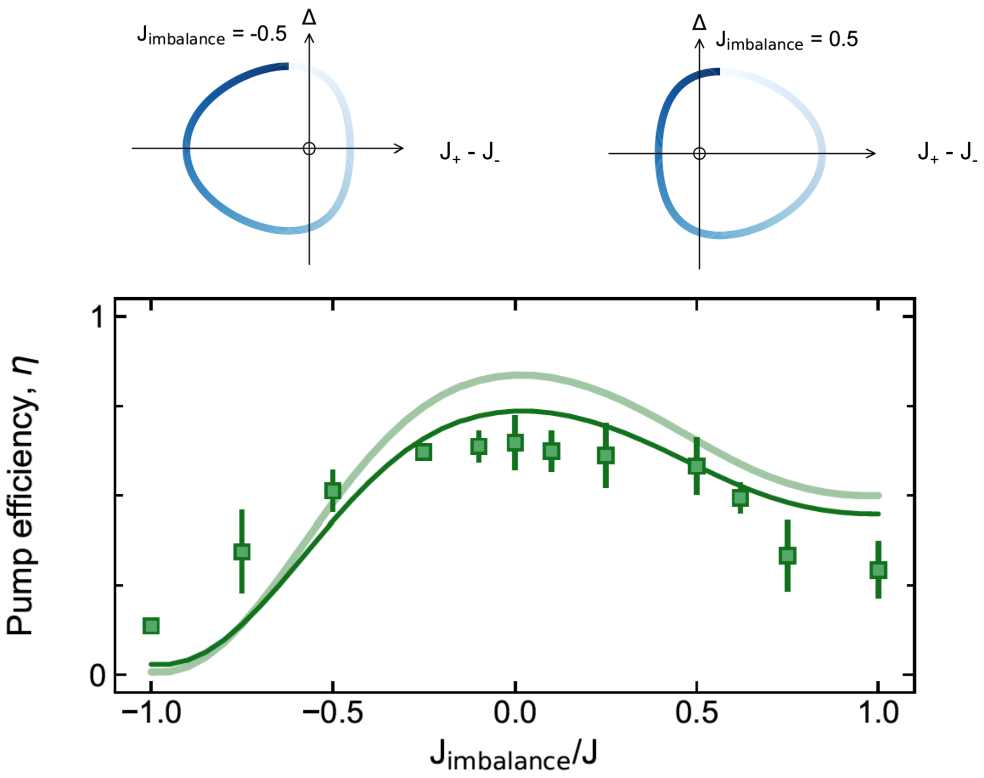
C. Huang, T. Chen, *et al.* (*in prep*)



$\Delta(t) = \Delta_c - V + \Delta_0 \cos \omega t$

J/h = 0.3 MHz, **fix Δ_c/J = 10**, scan V; Δ_0/J = 4, δ_0/J = 1, ω/2π = 0.3 MHz

Pair basis: $H_{\mathrm{RM}}(t) = -\sum_i [J(t) + (-1)^i \delta(t)] \left(\hat{c}_i^\dagger \hat{c}_{i+1} + \mathrm{h.c.}\right) + \Delta(t) \sum_i (-1)^i \hat{c}_i^\dagger \hat{c}_i$



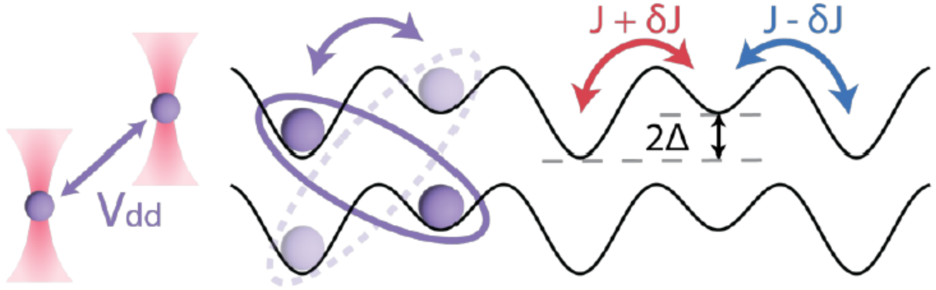
Vary J(t) form independently for two tones to generate irregular driving path

J/h = 0.3 MHz, Δ_c/J = 10, V = Δ_c; Δ_0/J = 4, δ_0/J = 1, ω/2π = 0.3 MHz

outlook

Rydberg state synthetic dimensions

new playground for exploring strong interactions in highly controllable lattices



outlook

Rydberg state synthetic dimensions

new playground for exploring strong interactions in highly controllable lattices

next steps

- expand to bigger lattices in internal space – 100s of states, 2D/3D lattices

outlook

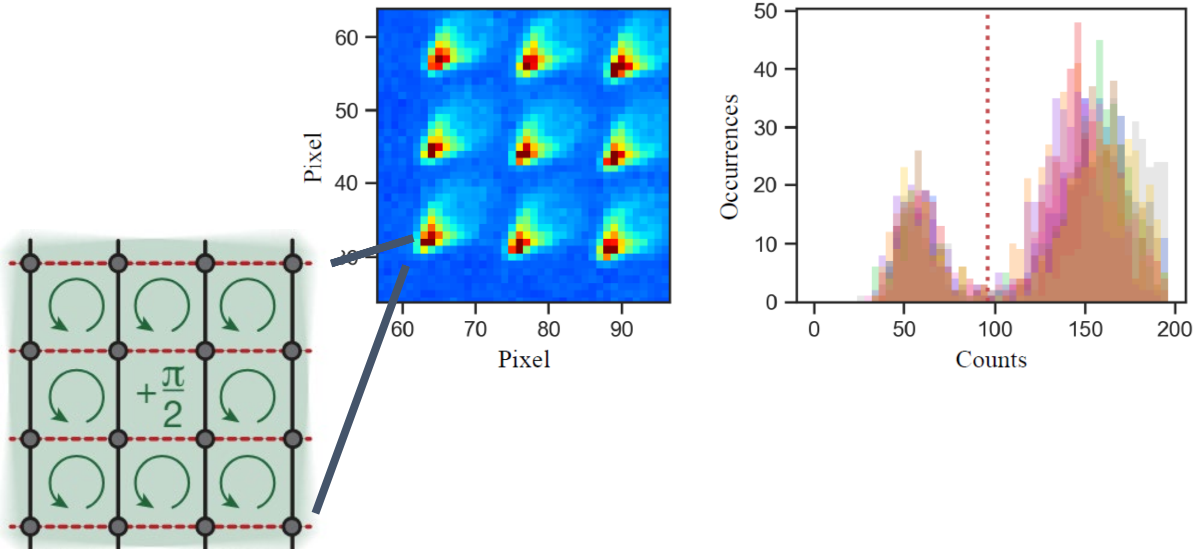
Rydberg state synthetic dimensions

new playground for exploring strong interactions in highly controllable lattices

next steps

- expand to bigger lattices in internal space – 100s of states, 2D/3D lattices
- expand to larger atom arrays – 100s of atoms

what is the ground state / what is the dynamics of this kind of system?



Aidelsburger, *et al* (2013)

thanks for your attention! any questions?

UIUC team

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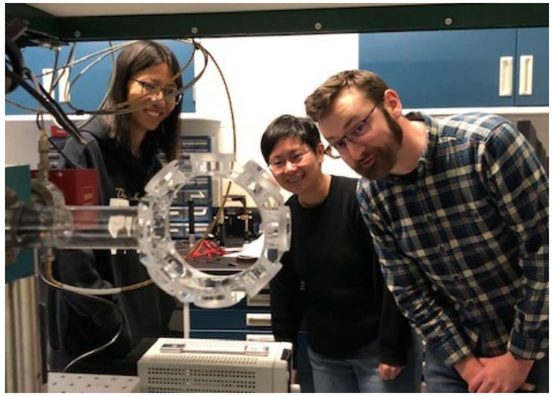
Chenxi Huang

Dr. Jackson Ang’ong’a (alum, Tubingen)

Dr. Sai Paladugu

Rishi Lohar

Shraddha Agrawal



Penn State team

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Ethan Springhorn
Ruiyu Li
Jungi Lee

Chenxi Huang
Mingsheng Tian

collaborations w/ Brian DeMarco & Jake Covey

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Dr Eric Meier – Los Alamos
Dr Jackson Ang’ong’a – Tübingen University
Dr Michael Highman – Toptica Photonics
+ Yaashnaa Singhal, Hannah Manetsch, Ritika Anandwade, Samantha Lapp, Michael Castle, & other former UGs

Theory collaborators:
Kaden Hazzard, Hannah Price, Tomoki Ozawa, Marcos Rigol, and many more