The saga of chiral transitions in arrays of Rydberg atoms

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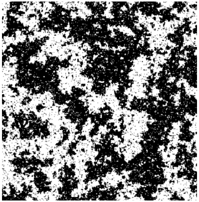
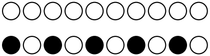
Universality classes:

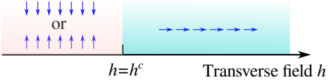
Family of phase transitions characterized by the universal scaling

quantum Ising model

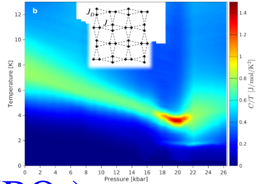
classical 2D





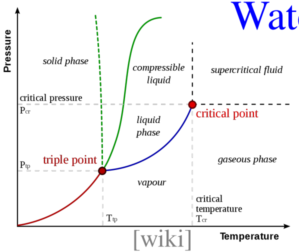


Ising



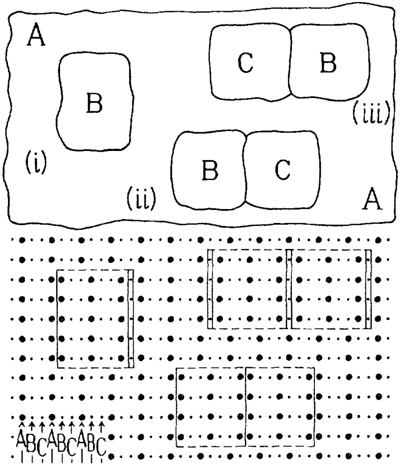
$SrCu_2(BO_3)_2$ [Nature 2021]

Water



[wiki]

Classical chiral transition in adsorbed monolayers?



Huse, Fisher, 1982

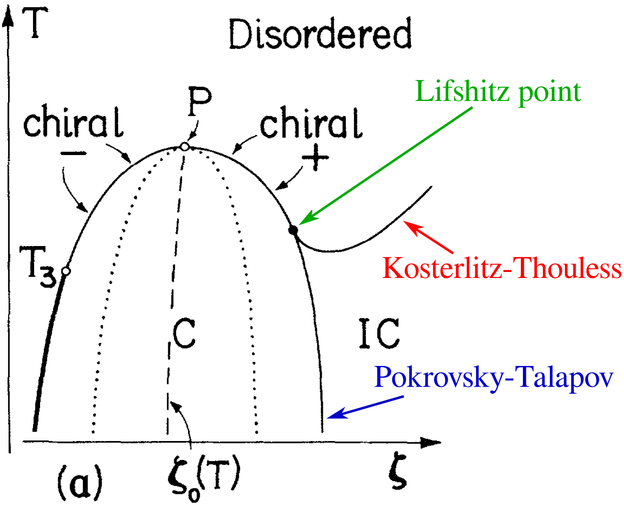
3 types of domains
⇓
3-state Potts?

Not that simple!

"Heavy" and "light" domain walls

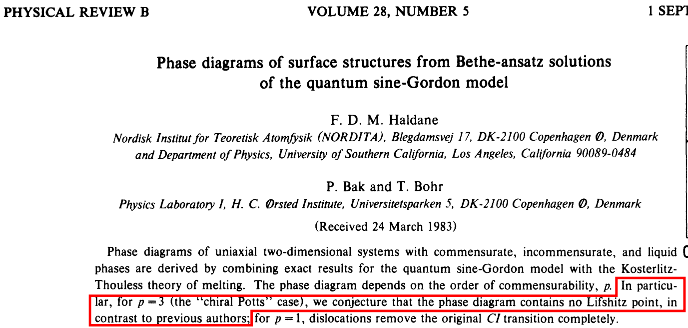
ABC ≠ ACB
⇓
Chiral perturbations

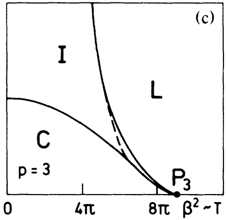
Possibility of a new chiral transition



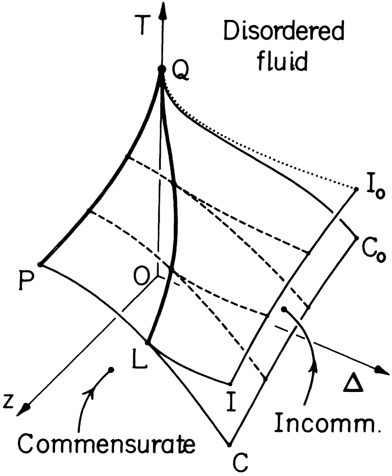
Huse, Fisher, 1982

Field theory argument





Chiral transition is still possible



Huse, Fisher, 1984

If dislocations are allowed a floating phase does not have to emerge immediately

Theoretical problem remained open for decades...

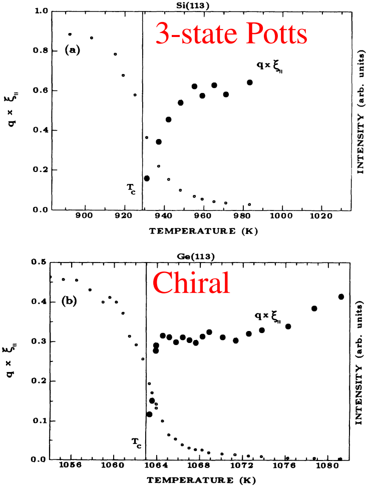
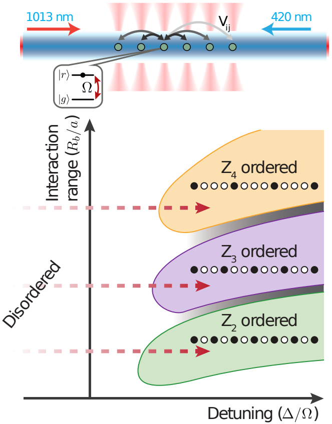
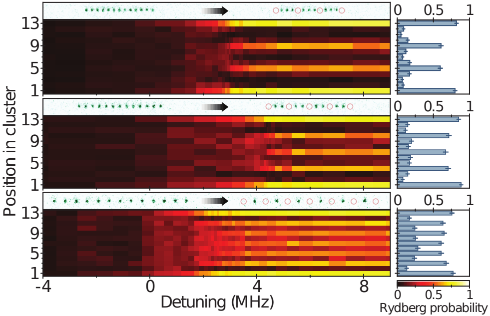


FIG. 11. Temperature dependence of $q\xi_\parallel$ (full dots) for Si(113) (a) and Ge(113) (b). The open dots show the temperature dependence of the 3×1 $(\bar{1},1)$ spot intensity.

Experimental evidence of chiral melting of the Ge(113) and Si(113) 3×1 surface phases
J.Schreiner, K.Jacobi, W.Selke, PRB 1994

Quantum phase transitions out of period-p phases





$$H = \sum_i -\frac{\Omega}{2}(d_i + d_i^\dagger) - \Delta n_i + \sum_{j>i} V_{i,j} n_i n_j$$

van der Waals interaction $V_{i,j} \propto |i-j|^{-6}$ $\longrightarrow$ Rydberg blockade

H. Bernien et al., Nature 2017

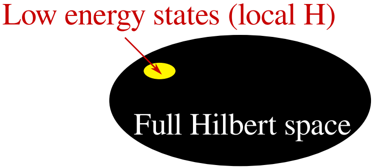
The same problem in a different context!

DMRG

Density Matrix Renormalization Group algorithm

Area law

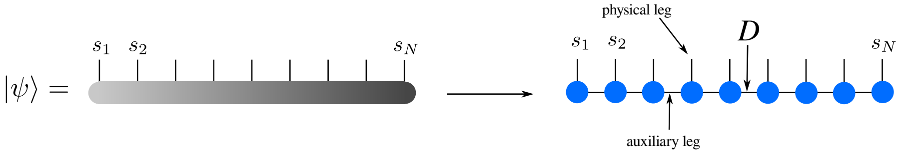
The Hilbert space grows exponentially $\dim H = d^N$



Ground states
of local Hamiltonians
are less entangled
than a random state in the Hilbert space

Tensor networks

Tensor networks is a different way of writing a quantum state

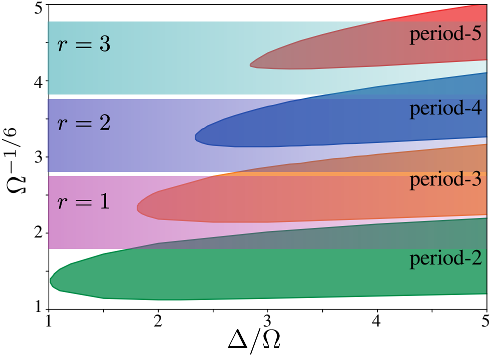


- The tensors are variationally optimized
- The Hilbert space is optimally truncated
- Bond dimension D controls the accuracy and complexity
- ... but the area law is violated at criticality

Constrained tensor networks: Rydberg blockade

$$H = \sum_i -\frac{\Omega}{2}(d_i^\dagger + d_i) - \Delta n_i + V_{r+1} n_i n_{i+r+1},$$

$$n_i(n_i - 1) = n_i n_{i+1} = ... = n_i n_{i+r} = 0$$



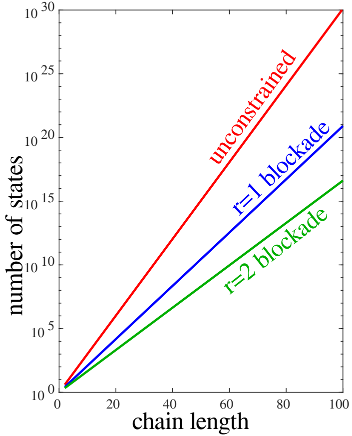
Costrained DMRG: NC, Mila, SciPost Phys. **6**, 033 (2019)

Figure credits: Rader, Läuchli, arXiv:1908.02068; NC, Mila, Nature Communications, **12**, 414 (2021)

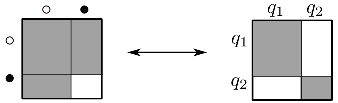
The size of the restricted Hilbert space

$$H = \sum_i -w(d_i^\dagger + d_i) + U n_i + V_{r+1} n_i n_{i+r+1}$$

$$n_i(1 - n_i) = n_i n_i + 1 = ... = n_i n_{i+r} = 0$$



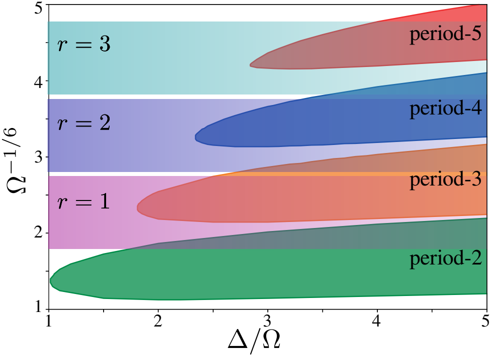
Constrained MPS
fully profit from the
restricted Hilbert space



At the critical point we can reach up to **9000** sites

Let's probe the $\mathbb{Z}_3$ transition

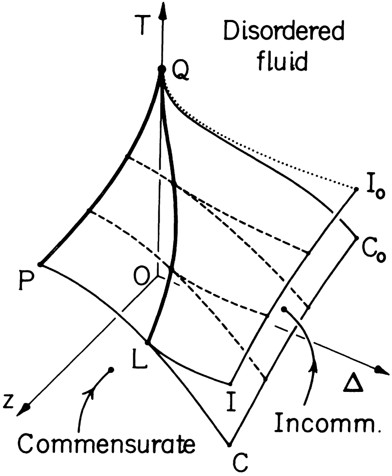
$$H = \sum_i -\frac{\Omega}{2}(d_i^\dagger + d_i) - \Delta n_i + V_{r+1} n_i n_{i+r+1},$$
$$n_i(n_i - 1) = n_i n_{i+1} = ... = n_i n_{i+r} = 0$$



Costrained DMRG: NC, Mila, SciPost Phys. **6**, 033 (2019)

Figure credits: Rader, Läuchli, arXiv:1908.02068; NC, Mila, Nature Communications, **12**, 414 (2021)

How to distinguish the three regimes?

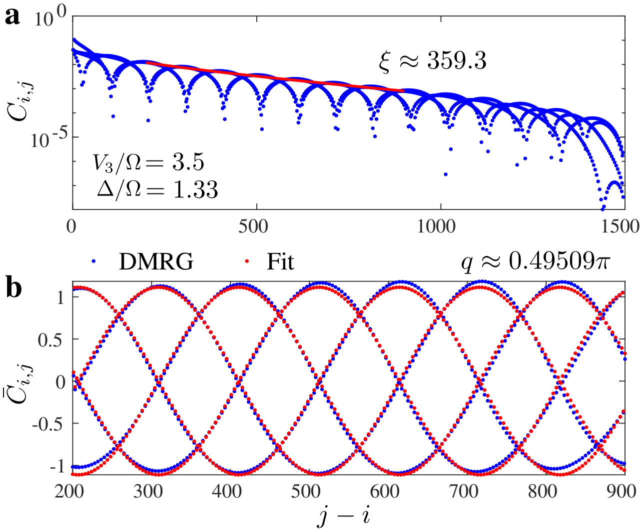


Huse, Fisher, 1984

Δq - distance to $q = 2\pi/3$;
ξ - correlation length

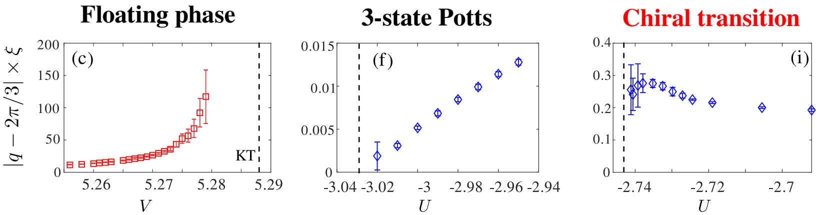
- Conformal:
  $\Delta q \cdot \xi \to 0$
- Chiral:
  $\Delta q \cdot \xi \to \text{const}$
- Floating phase:
  $\Delta q \cdot \xi \to \infty$

Extracting ξ and q



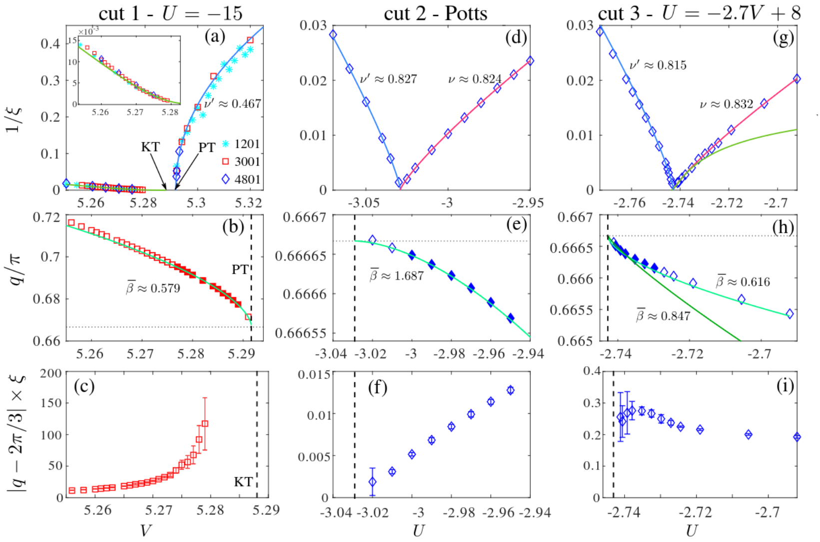
NC, Mila, Nature Communications, **12**, 414 (2021)

RESOLVED with constrained DMRG

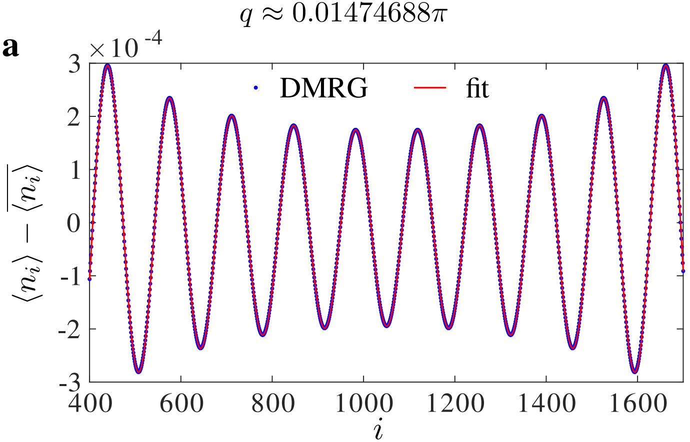


NC, Mila, Phys. Rev. Lett. **122**, 017205 (2019)
NC, Mila, SciPost Phys. **6**, 033 (2019)

Why constrained DMRG was a key?

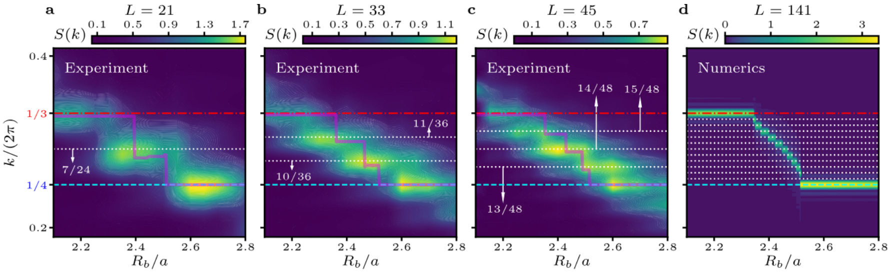


Inside the floating phase here: dual model of Rydberg atoms



NC, Mila, PRR, (2021)

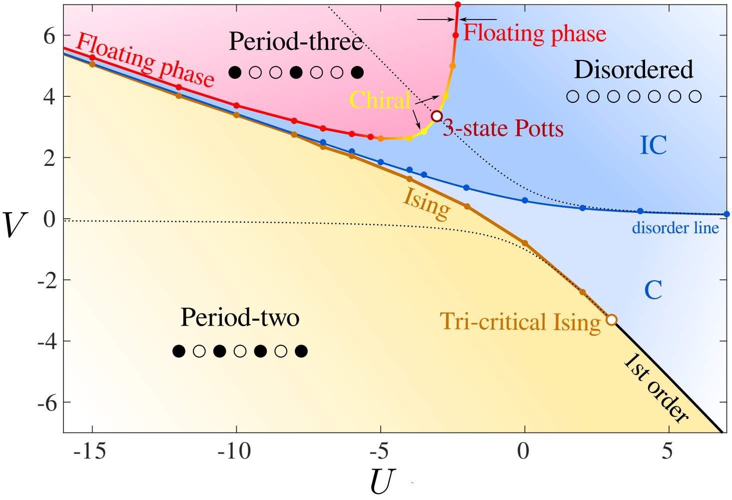
Inside the floating phase in experiments here: for a tall ladder



Wave-vector q (k) changes continuously - **floats** - inside the phase

Zhang et al., Nat.Comm., (2025)

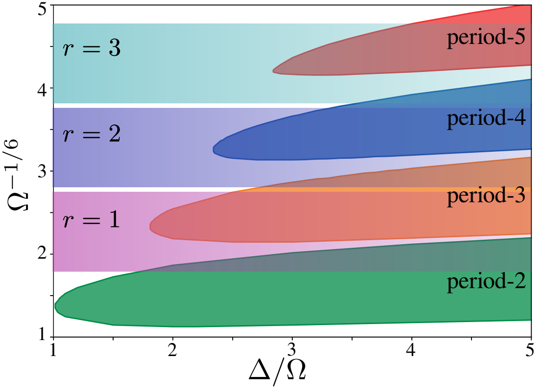
Chiral transition vs floating phase



NC, Mila, PRL (2019); NC, Mila, SciPost Phys. (2019); Fendley, Sengupta, Sachdev, PRB (2004)

What about melting of the $p = 4$ phase?

$$H = \sum_i -\frac{\Omega}{2}(d_i^\dagger + d_i) - \Delta n_i + V_{r+1} n_i n_{i+r+1},$$
$$n_i(n_i - 1) = n_i n_{i+1} = ... = n_i n_{i+r} = 0$$

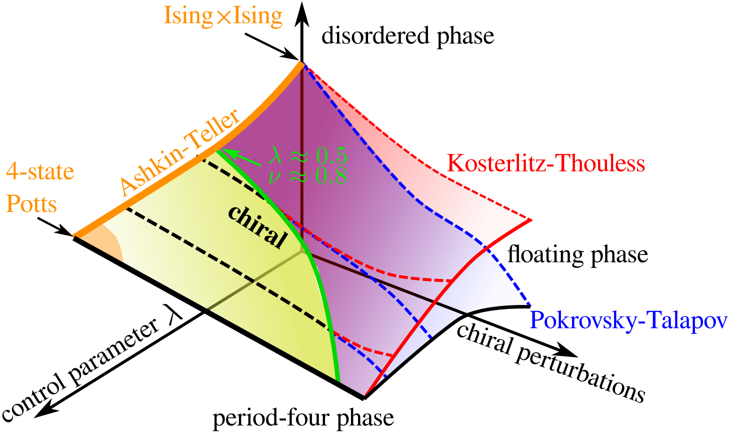


Rader, Läuchli, arXiv:1908.02068; NC, Mila, Nature Communications, **12**, 414 (2021)

Transition out of the period-four phase:

the situation is even richer because chiral perturbations are **not always relevant** [M. den Nijs, 1988]

Chiral transition out of period-4 phase

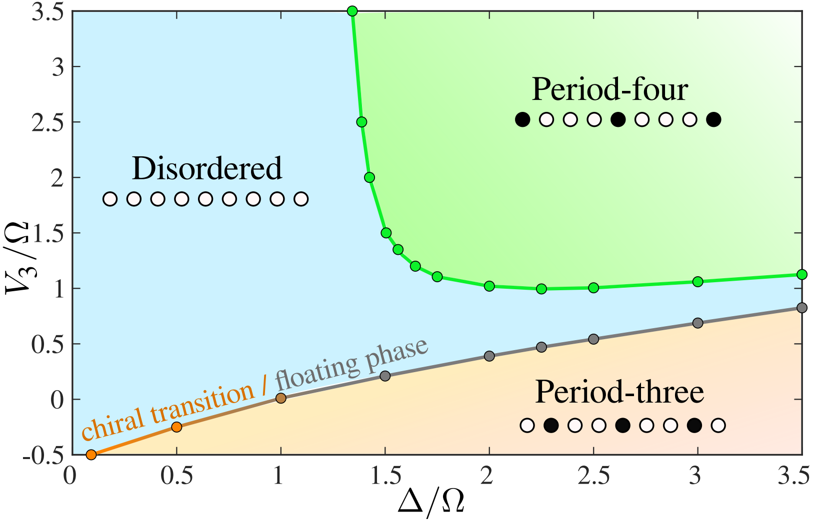


Parameter λ in the Ashkin-Teller Hamiltonian:

$$H_{AT} = -\sum_{j=1}^{N} \left(\sigma_j^x + \tau_j^x + \lambda \sigma_j^x \tau_j^x\right) - \beta \sum_{j=1}^{N-1} \left(\sigma_j^z \sigma_{j+1}^z + \tau_j^z \tau_{j+1}^z + \lambda \sigma_j^z \tau_j^z \sigma_{j+1}^z \tau_{j+1}^z\right)$$

Lüscher, Mila, NC, PRB (2023); Nyckees, Mila, PRResearch 4, 013093 (2022)

Phase diagram for the model with NNN blockade

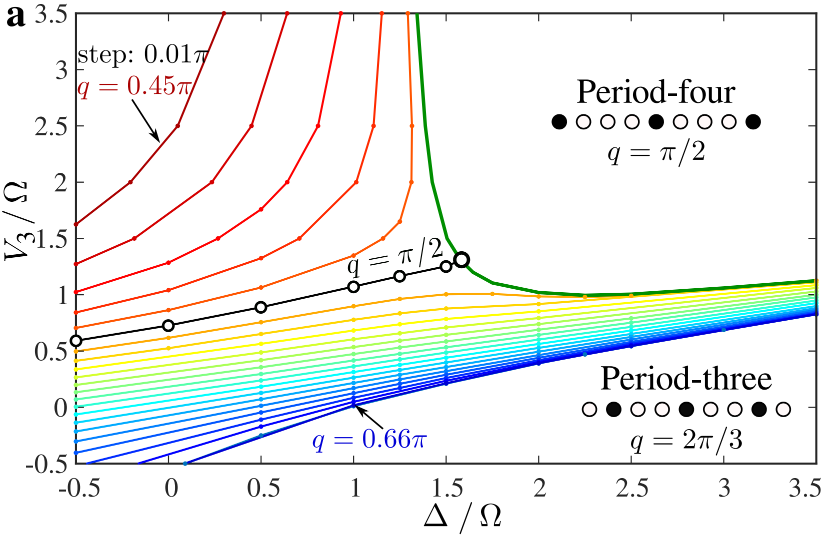


NC, Mila, Nature Communications, **12**, 414 (2021)

No integrable line...

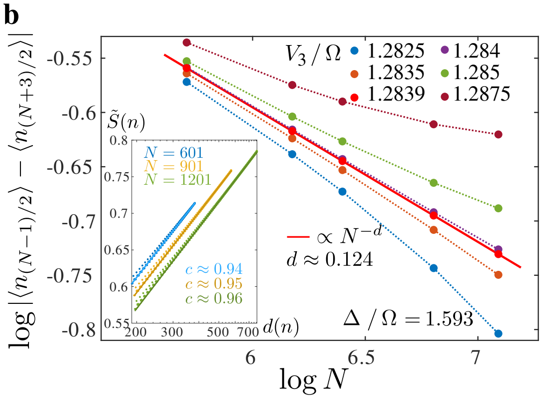
How to find the conformal point?

Commensurate line



NC, Mila, Nature Communications, **12**, 414 (2021)

Conformal point

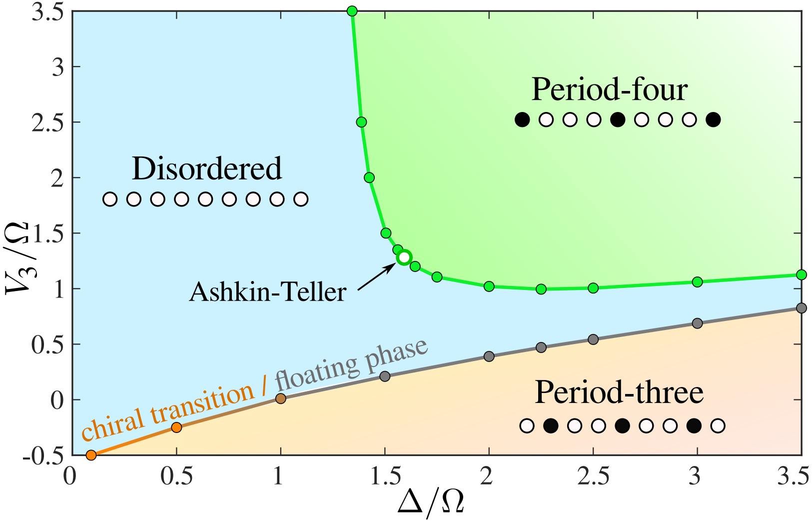


NC, Mila, Nature Communications, **12**, 414 (2021)

CFT predictions:

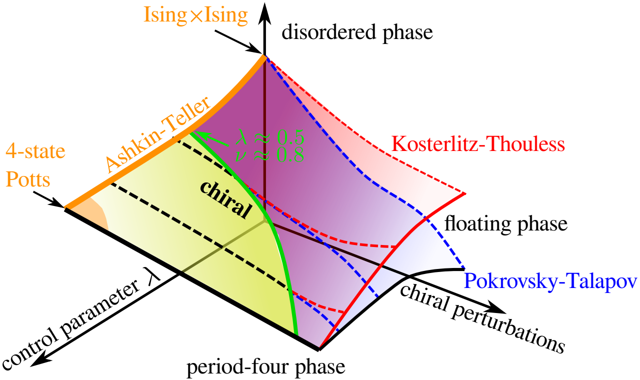
- $d = \beta/\nu = 1/8$
- $c = 1$

Basic phase diagram

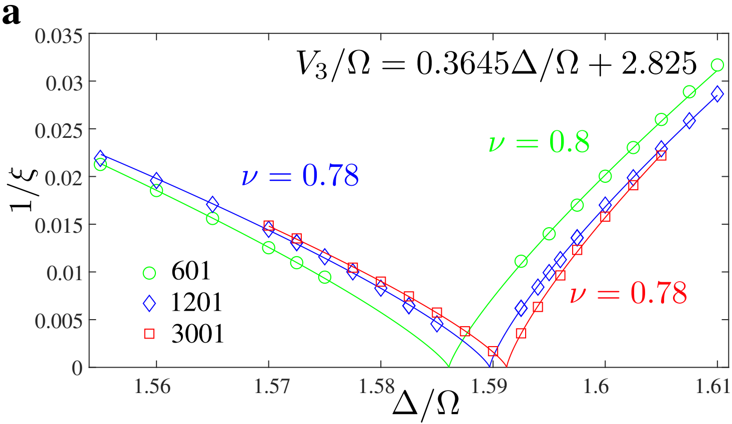


NC, Mila, Nature Communications, **12**, 414 (2021)

Next step: identify λ



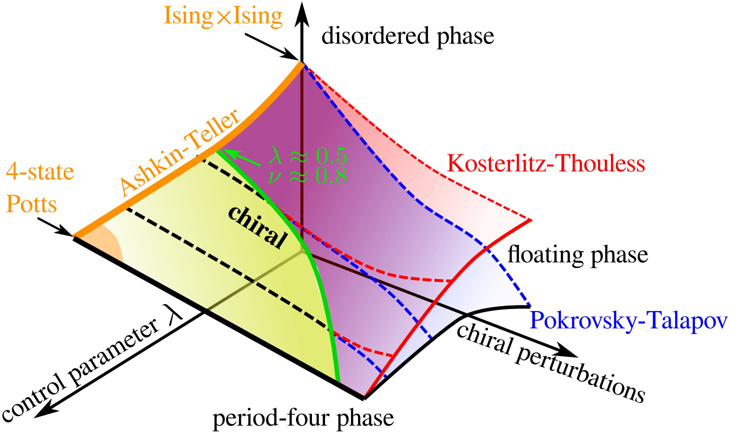
Correlation length along the commensurate line



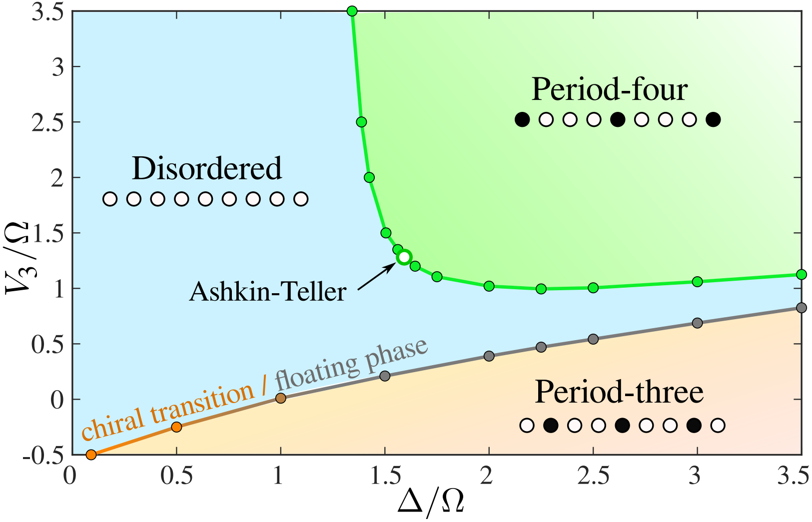
$\nu \approx 0.78$ implies $\lambda \approx 0.57$

NC, Mila, Nature Communications, **12**, 414 (2021)

$\lambda \approx 0.57$: we might see a chiral transition!

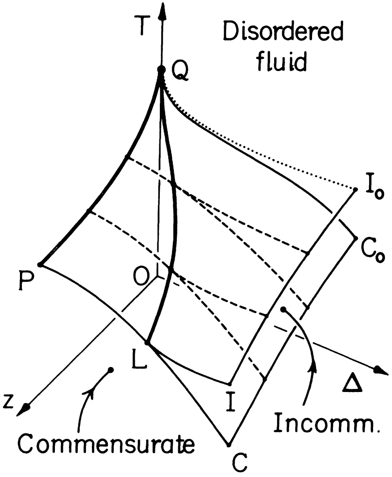


Explore the vicinity of the Ashkin-Teller point



NC, Mila, Nature Communications, **12**, 414 (2021)

How to distinguish the three regimes?



Huse, Fisher, 1984

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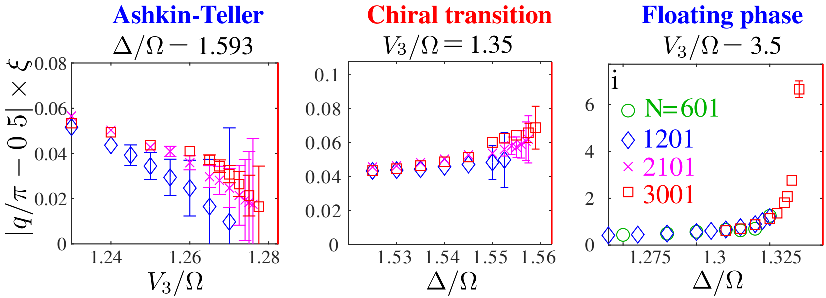
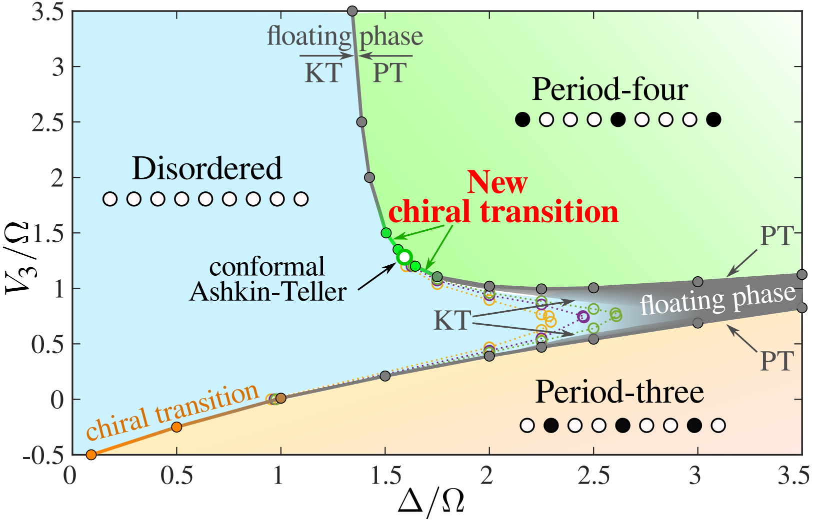
Three cuts - three different transitions



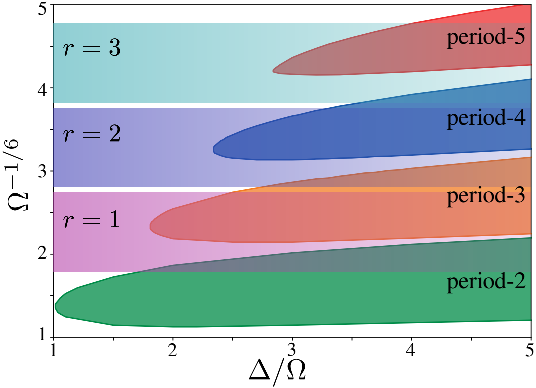
NC, Mila, Nature Communications, **12**, 414 (2021)

Phase diagram



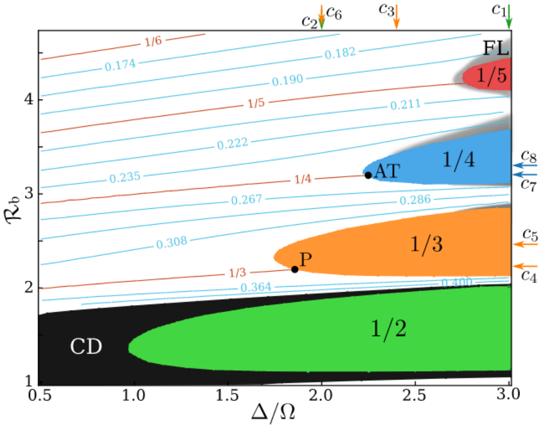
NC, Mila, Nature Communications, **12**, 414 (2021)

Back to Rydberg



Back to Rydberg

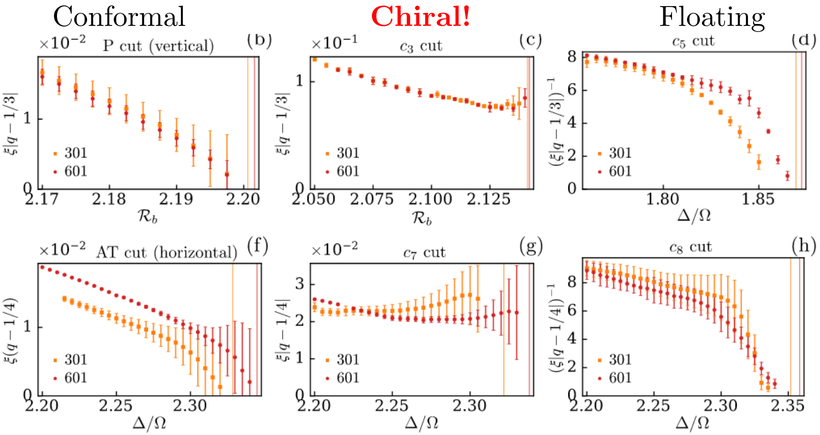
$$\mathcal{H} = \sum_i -\Delta \hat{n}_i + \Omega \hat{\sigma}_i^x + \sum_{j>i} \frac{\hat{n}_i \hat{n}_j}{(i-j)^6},$$



Maceira, NC, Mila, PRResearch 4, 043102 (2022)

Back to Rydberg

$$\mathcal{H} = \sum_i -\Delta\hat{n}_i + \Omega\hat{\sigma}_i^x + \sum_{j>i} \frac{\hat{n}_i\hat{n}_j}{(i-j)^6},$$



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Back to Rydberg

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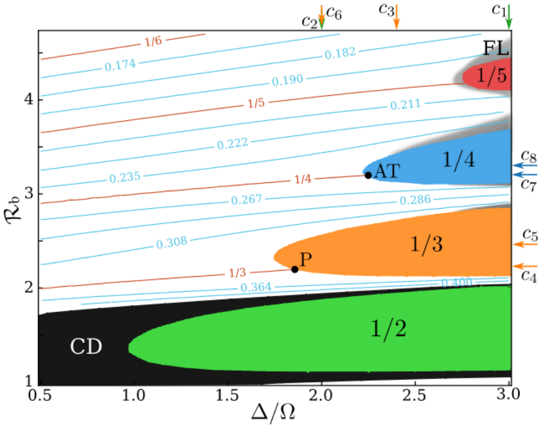
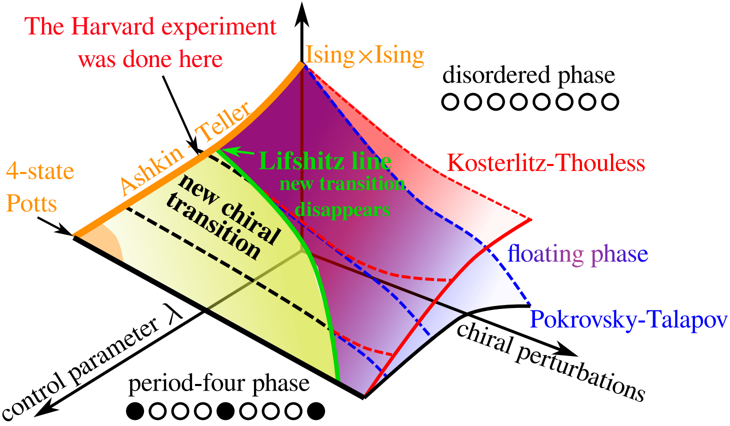


Maceira, NC, Mila, PRResearch 4, 043102 (2022)

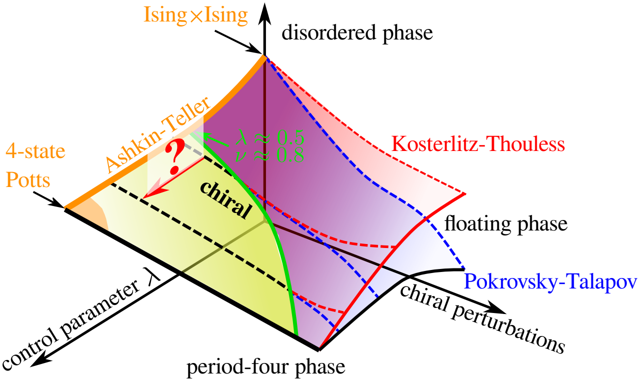
Ashkin-Teller point in the Rydberg array is
very close to the **Lifshitz point**

Result: an extremely short interval of chiral transitions



How to **zoom in**
with a quantum simulator?

Is there a way to tune the Ashkin-Teller point?

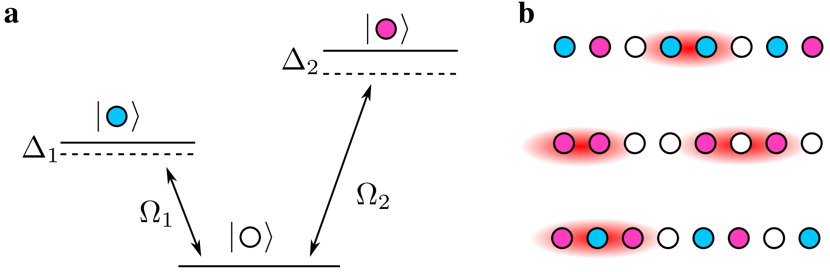


This is a 3D phase diagram. Two independent parameters $(\mathcal{R}_b, \Delta)$ are insufficient.

Tunable quantum criticality

in multi-component Rydberg arrays

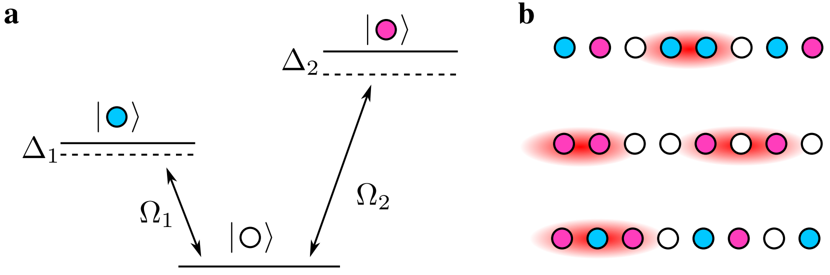
Multi-component Rydberg arrays



- Two Rydberg levels
- One - weakly interacting with nearest-neighbor blockade
- The second one - strong - with next-nearest-neighbor blockade
- Two components interact only via statistics

NC, PRL (2024); Levi, Minar, Garrahan, Lesanovsky, NJP (2015)

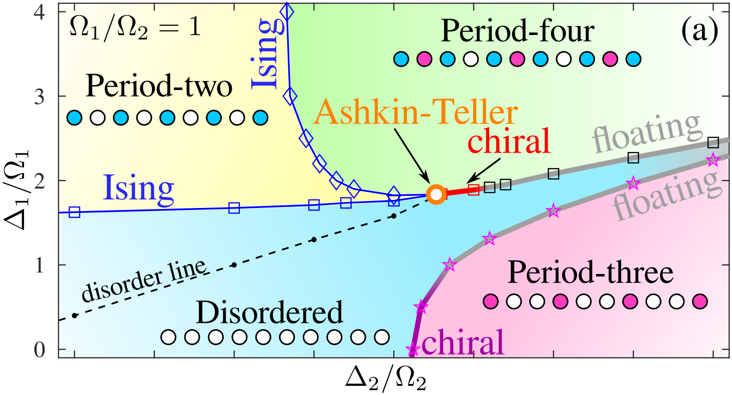
Multi-component Rydberg arrays



$$H_{\mathrm{MC}} = \sum_{\alpha=1,2} \sum_{i} \left[-\Omega_\alpha (d^\dagger_{\alpha,i} + d_{\alpha,i}) - \Delta_\alpha n_{\alpha,i} \right]$$

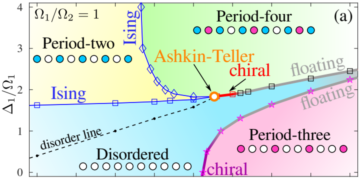
Simple model with 3 independent parameters. Exactly as we need!

Basic phase diagram

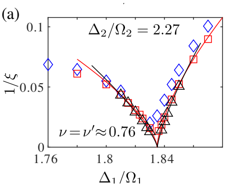


NC, PRL (2024)

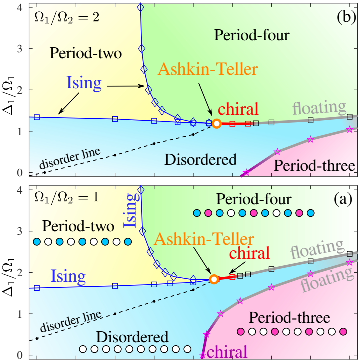
Tunable Ashkin-Teller point



$$\Omega_1/\Omega_2 = 1$$

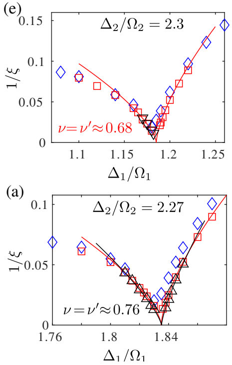


Tunable Ashkin-Teller point

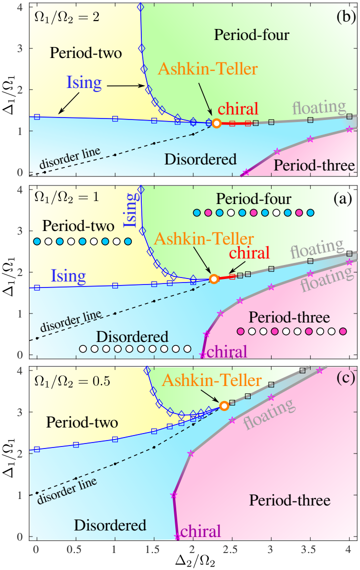


$$\Omega_1/\Omega_2 = 2$$

$$\Omega_1/\Omega_2 = 1$$



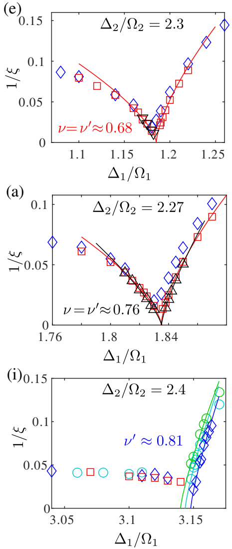
Tunable Ashkin-Teller point



$\Omega_1/\Omega_2 = 2$

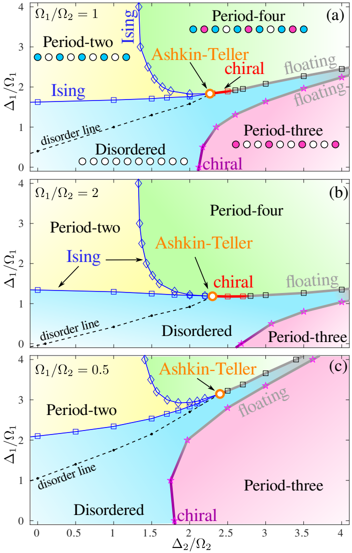
$\Omega_1/\Omega_2 = 1$

$\Omega_1/\Omega_2 = 0.5$

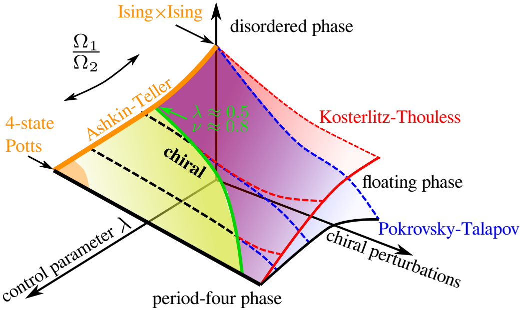


○ $N = 91$ ○ $N = 127$ ◇ $N = 199$ □ $N = 451$ △ $N = 607$ ▽ $N = 907$

Tunable Ashkin-Teller point

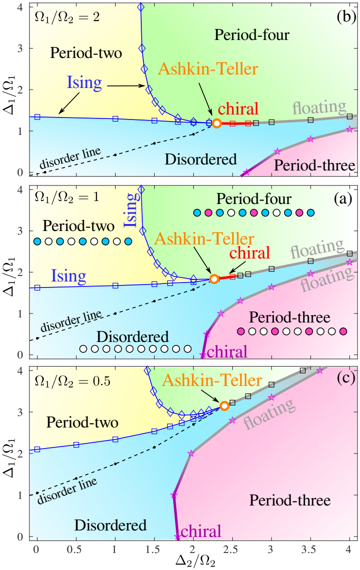


NC, PRL (2024)



Ratio Ω_1/Ω_2 tunes conformal point along the Ashkin-Teller line

Tunable chiral transition



$\Omega_1/\Omega_2 = 2$

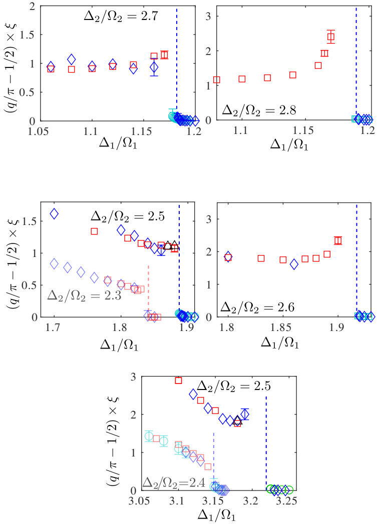
$W \approx 0.45$

$\Omega_1/\Omega_2 = 1$

$W \approx 0.25$

$\Omega_1/\Omega_2 = 0.5$

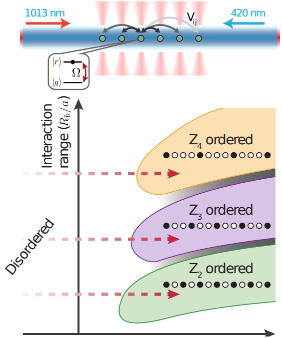
$W < 0.1$

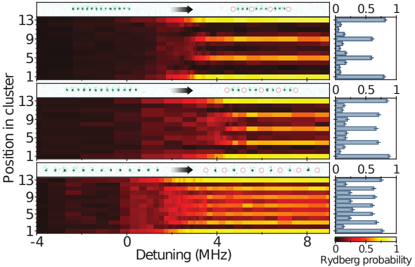


○ $N = 91$ ○ $N = 127$ ◇ $N = 199$ □ $N = 451$ △ $N = 607$ ▽ $N = 907$

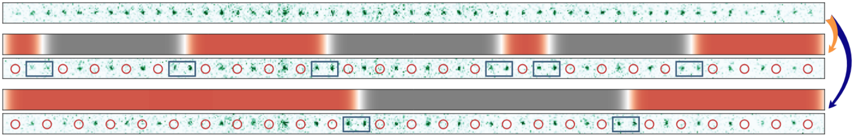
So, can we really observe chiral transitions?

Dynamical probes of quantum phase transitions: Kibble-Zurek





$$H = \sum -\frac{\Omega}{2}(d_i + d_i^\dagger) - \Delta n_i + \sum V_{i,j} n_i n_j$$

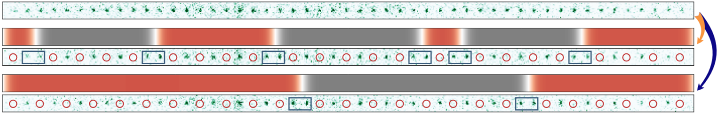


Keesling et al., Nature 2019

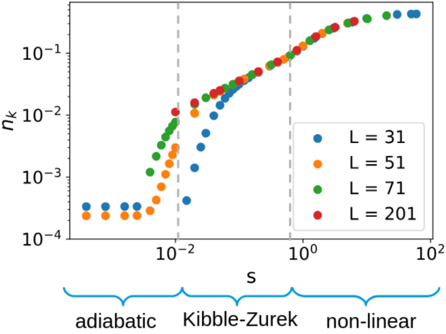
Non-adiabatical sweeping through a transition creates **kinks**

Dynamical probes of quantum phase transitions: Kibble-Zurek

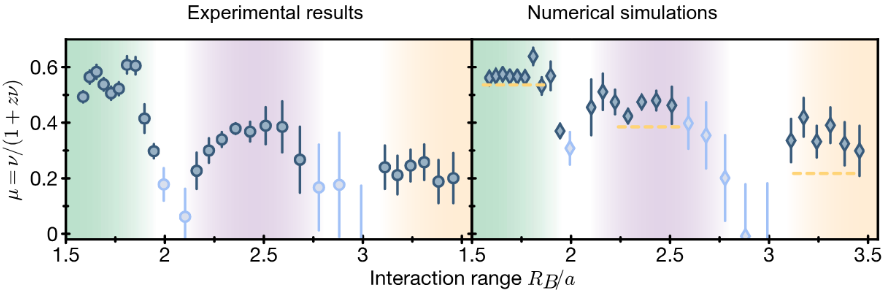
Non-adiabatical sweeping through a transition creates **kinks**



Keesling et al., Nature 2019

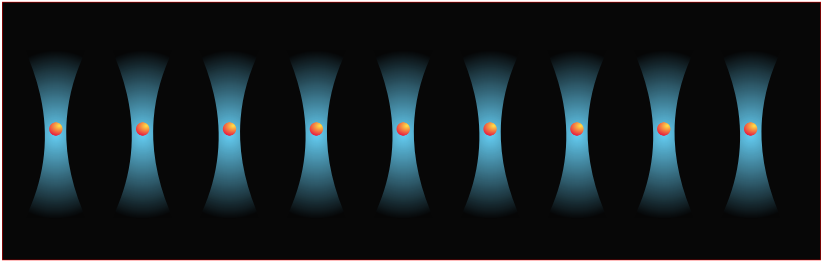


Numerical simulations systematically predict μ higher than in experiments

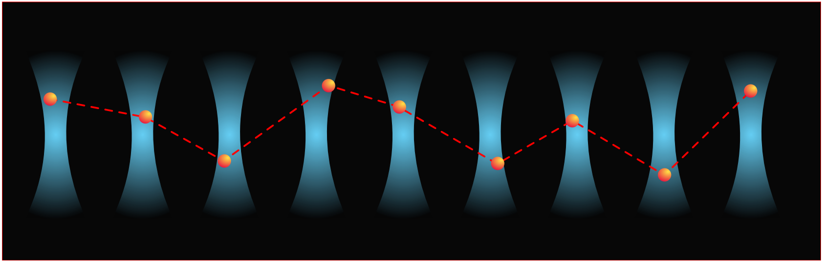


Keesling et al., Nature 2019

In numerical modeling tweezers are always assumed to be perfect



But nowadays they have a substantial width

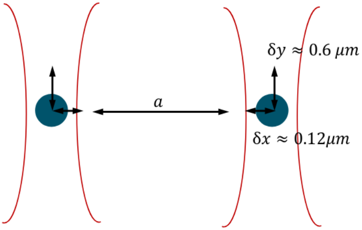


The trapping is not perfect and cause some lattice disorder

$$\frac{H}{\hbar} = \frac{\Omega}{2}\sum_i \left(d_i + d_i^\dagger\right) - \Delta\sum_i n_i + \sum_{i<j} V_i \frac{n_i n_j}{(i-j)^6}$$

This **alters** the nature of quantum phase transitions

Uncertainty in the location of the atoms



Very conservative error estimation:

- period 2: $a = 5.74\ \mu m,\ \ \delta V \approx 0.15\ V$
- period 3: $a = 3.95\ \mu m,\ \delta V \approx 0.25\ V$
- period 4: $a = 2.70\ \mu m,\ \delta V \approx 0.40\ V$

- van der Waals repulsion

$$V = V_0 \sum_{j>i} \frac{1}{a^6 |i-j|^6}$$

- linear error propagation

$$\delta V = \frac{6\delta a}{a} V$$

- First order error

$$\delta a = \sqrt{2}\delta x$$

- Rydberg Hamiltonian with random interactions

$$\frac{H}{\hbar} = \frac{\Omega}{2} \sum_i \left(d_i + d_i^\dagger \right) - \Delta \sum_i n_i + \sum_{i<j} V_i \frac{n_i n_j}{(i-j)^6},$$

$$V_i = V_0 \pm \delta V_i$$

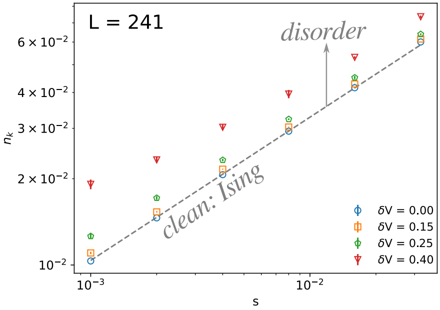
Phase transition is altered by the lattice disorder

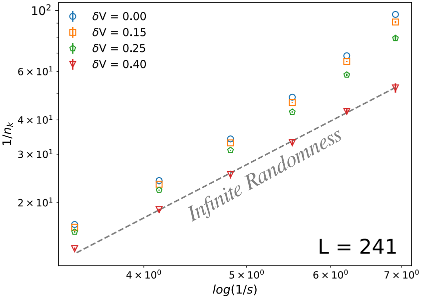
Clean Ising transition

$$n_k \propto s^{-\mu}\Big|_{\mu_{\text{Ising}}=0.5}$$

Infinite Randomness

$$1/n_k \propto \log^2(s^{-1})$$



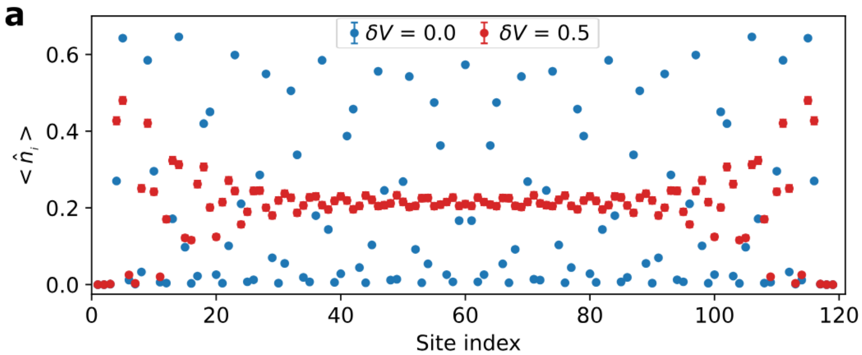


But is it the same infinite randomness as in the short-range random Ising model?

More visible for larger systems, smaller interatomic distances, slower sweep rates

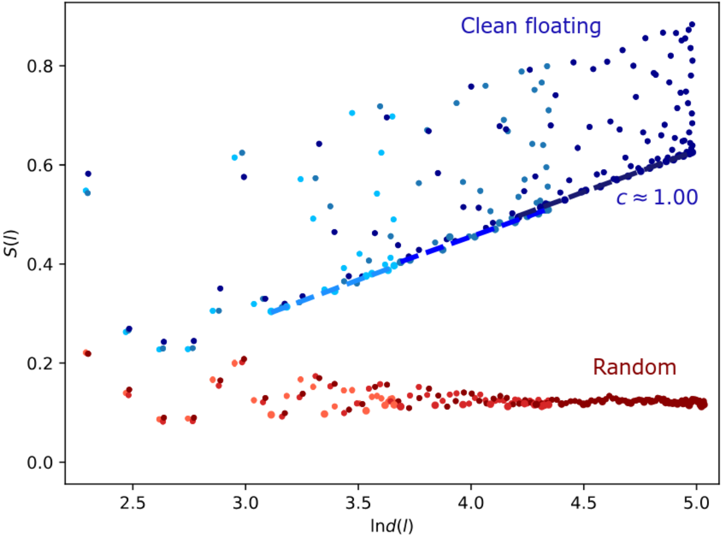
Soto Garcia, NC, PRL (26)

The floating phase is localized



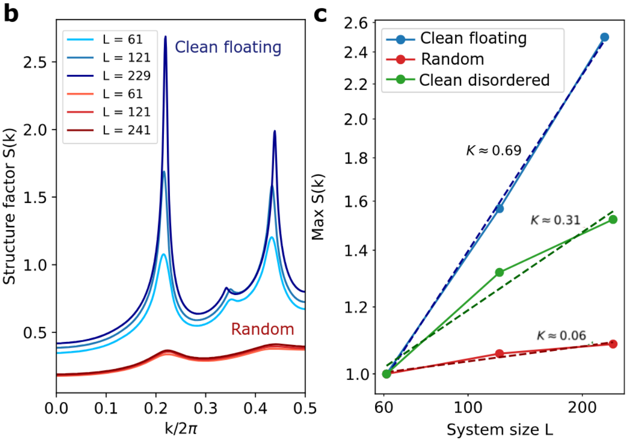
Soto Garcia, NC, PRL (2026)

The floating phase is localized



Soto Garcia, NC, PRL (2026)

The floating phase is localized... but incommensurate!



Incommensurability is not destroyed by the disorder*
Shall we then expect a disordered C-IC transition?

Soto Garcia, NC, PRL (2026);
* similar has been reported for interacting Majorana fermions, NC, Laflorencie, PRL (2024)

Conclusion

Chiral transition

- There is an exciting family QPT beyond conformal
- The transition can in principle be realized in Rydberg arrays...
- but first we have to refine the tweezers
- C-IC transition in random arrays?

Tensor Networks

- Constrained tensor networks
- Finally, sufficient accuracy to predict novel types of QPT
- Non-trivial fusion: anyons, quantum dimers/loops, hyperbolic lattices...

Multi-component Rydberg arrays

- Enlarged local Hilbert space
- Experimentally feasible, yet barely studied
- More knobs to tune without messing up with symmetries