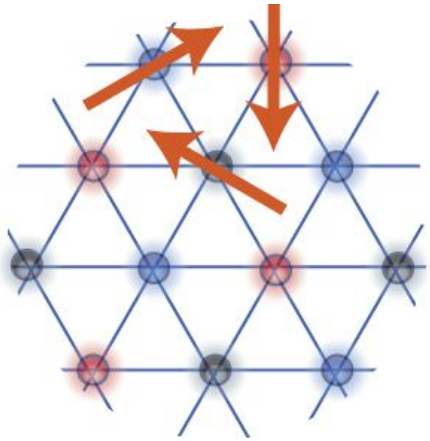
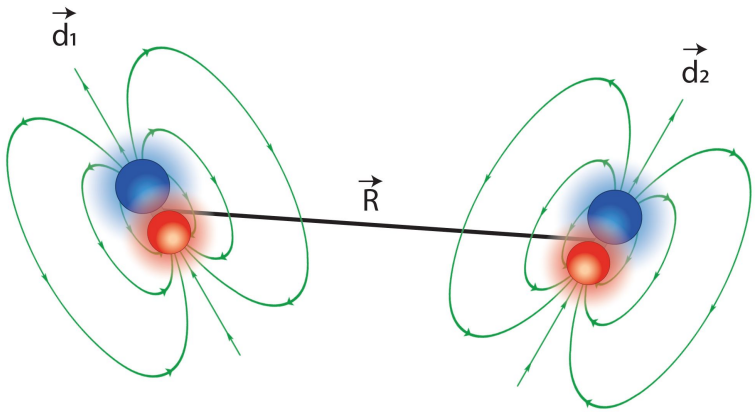
Quantum gas microscopy of correlated systems with new ingredients: kinetic frustration and dipolar interactions

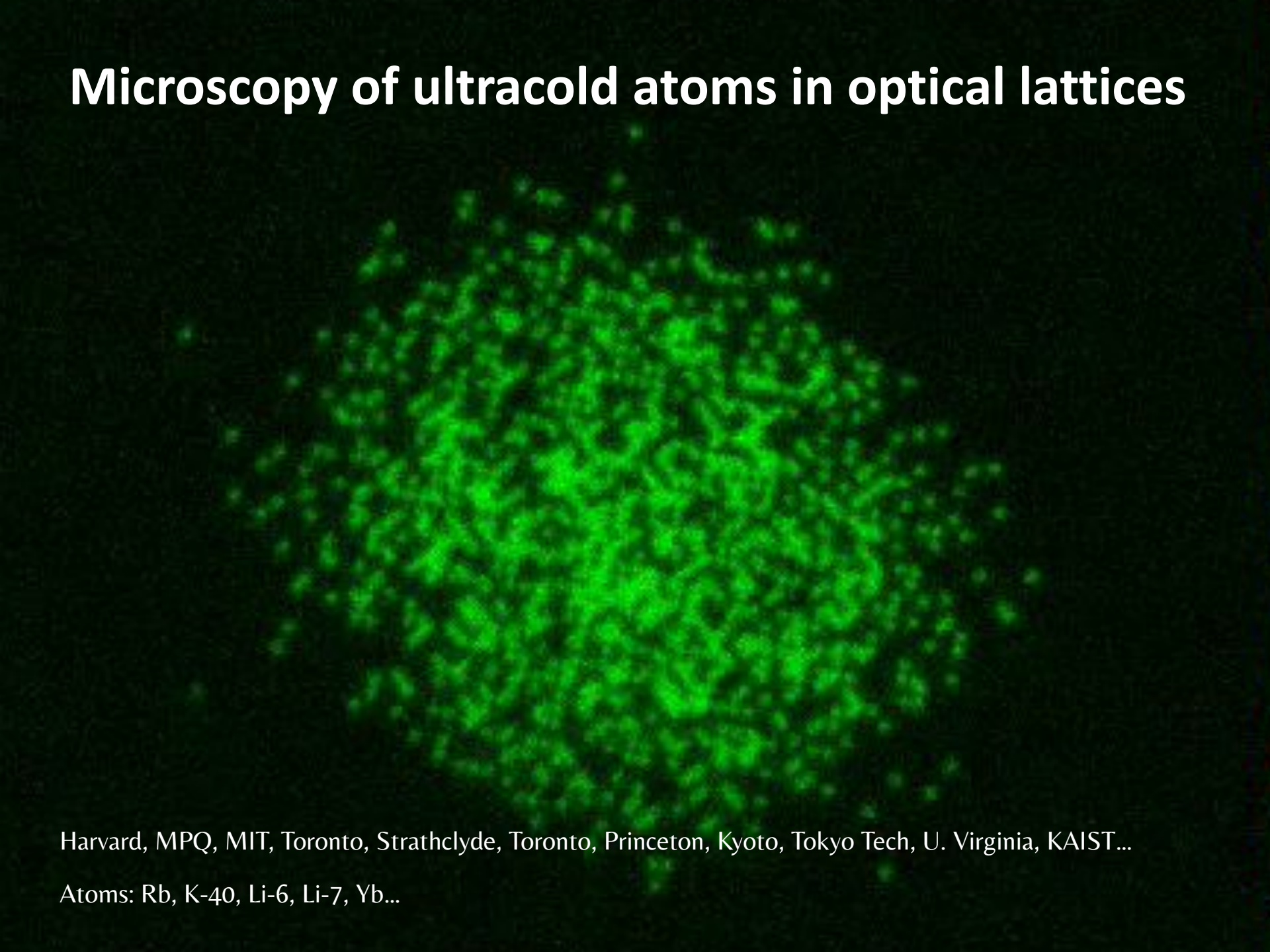




Waseem Bakr

PRINCETON UNIVERSITY

Microscopy of ultracold atoms in optical lattices

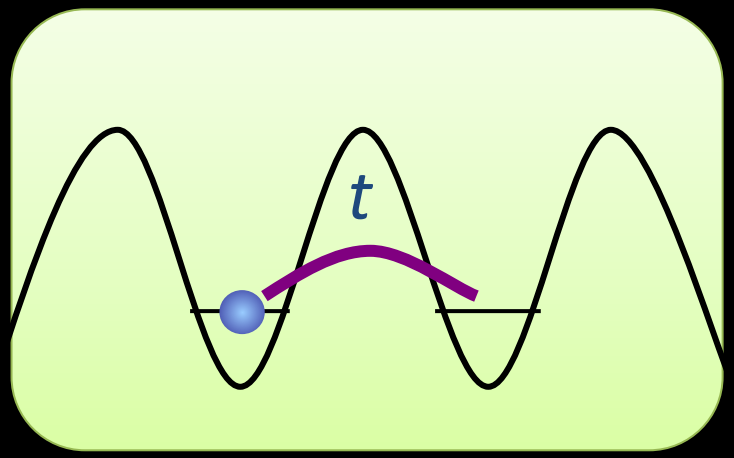


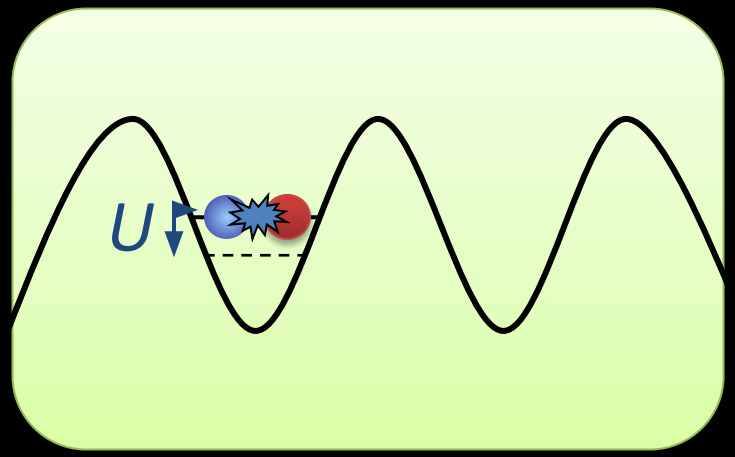
Harvard, MPQ, MIT, Toronto, Strathclyde, Toronto, Princeton, Kyoto, Tokyo Tech, U. Virginia, KAIST…

Atoms: Rb, K-40, Li-6, Li-7, Yb…

The Fermi-Hubbard model

$$H = -t \sum_{\langle i,j \rangle, \sigma} \left(c^{\dagger}_{i,\sigma} c_{j,\sigma} + h.c. \right) + U \sum_{i} n_{i,\uparrow} n_{i,\downarrow}$$





On the square lattice: a basic model for high T_c superconducting cuprates

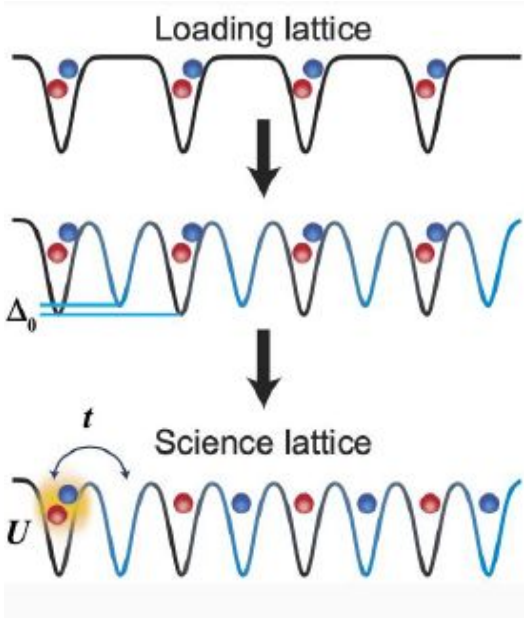
Microscopes have been stuck with square lattices for a while…

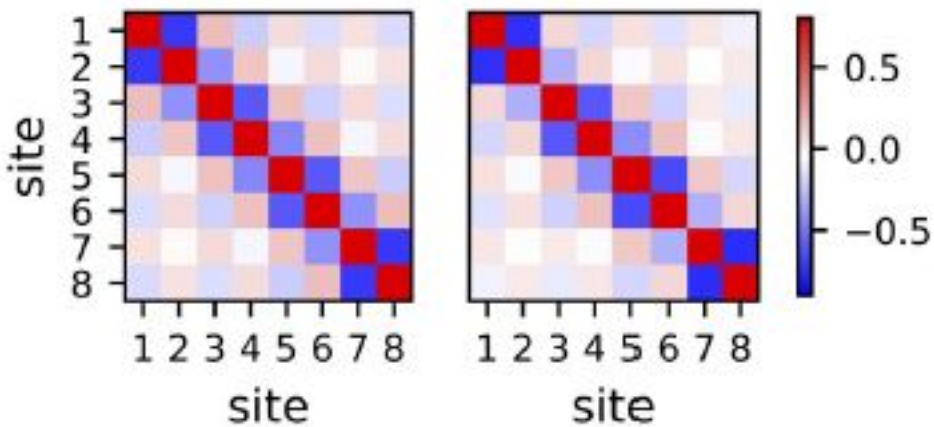
Novel geometries add new ingredients:

1. Spin/kinetic frustration.
2. Novel dispersions, e.g. relativistic fermions near Dirac cones, flat bands.
3. Topology, e.g. SSH type models.

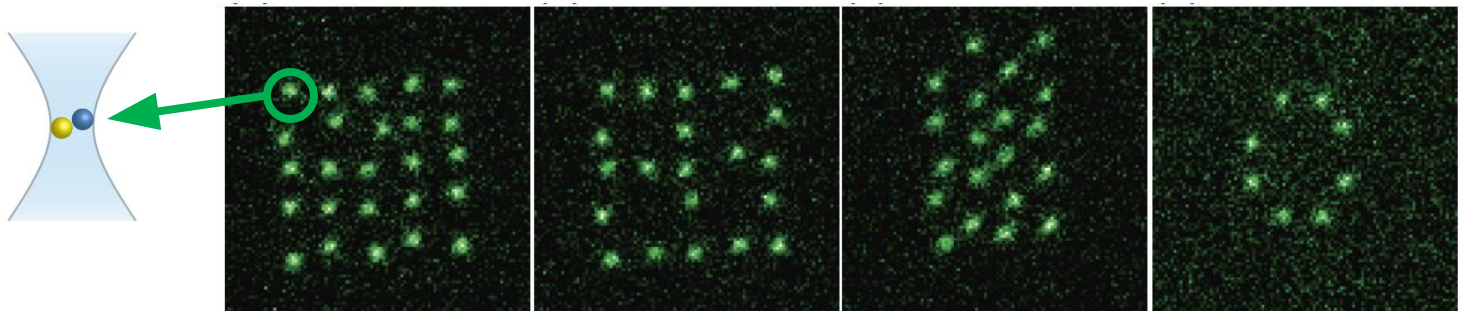
Programmable lattices for electronic simulations are highly desirable.

Programmable Hubbard tweezer arrays in 2D





Theory Experiment

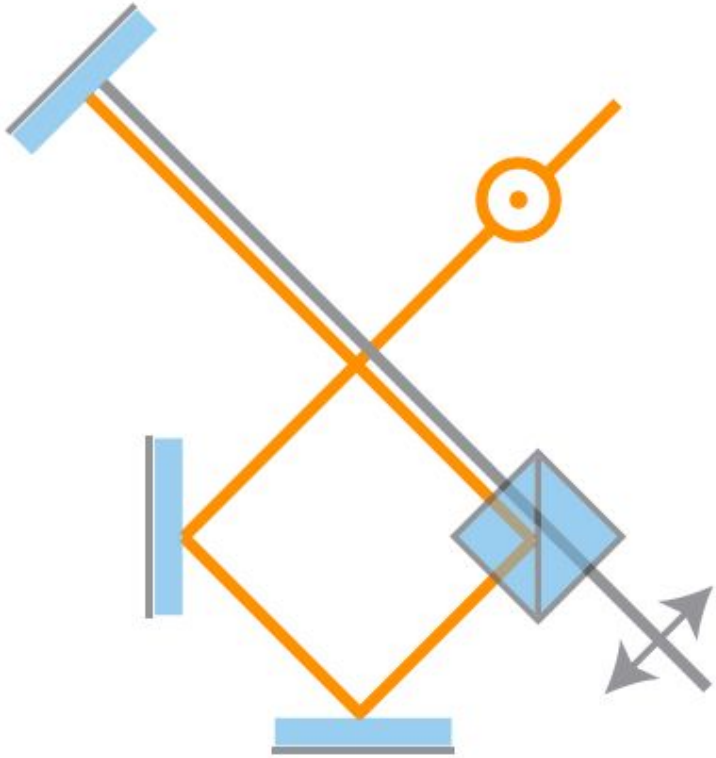


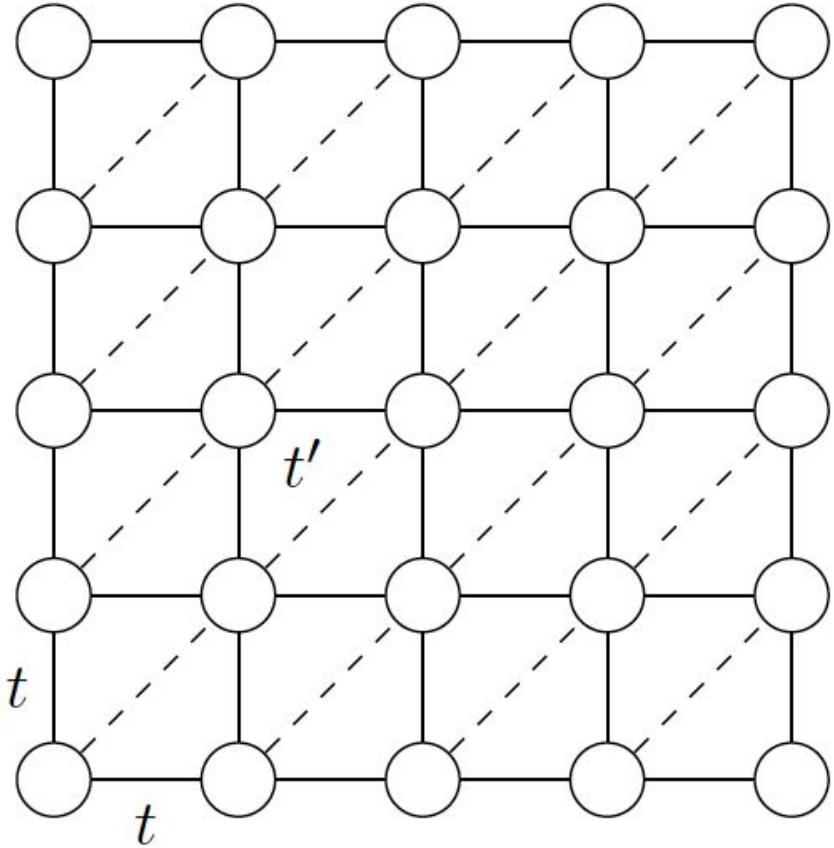
Up to 50 fermions in a band insulating state (one spin state shown here).

Ben Spar *et al.,* PRL 128, 223202 (2022)

Zoe Yan, Ben Spar *et al.,* PRL 129, 123201 (2022)

Programmable interferometric lattice



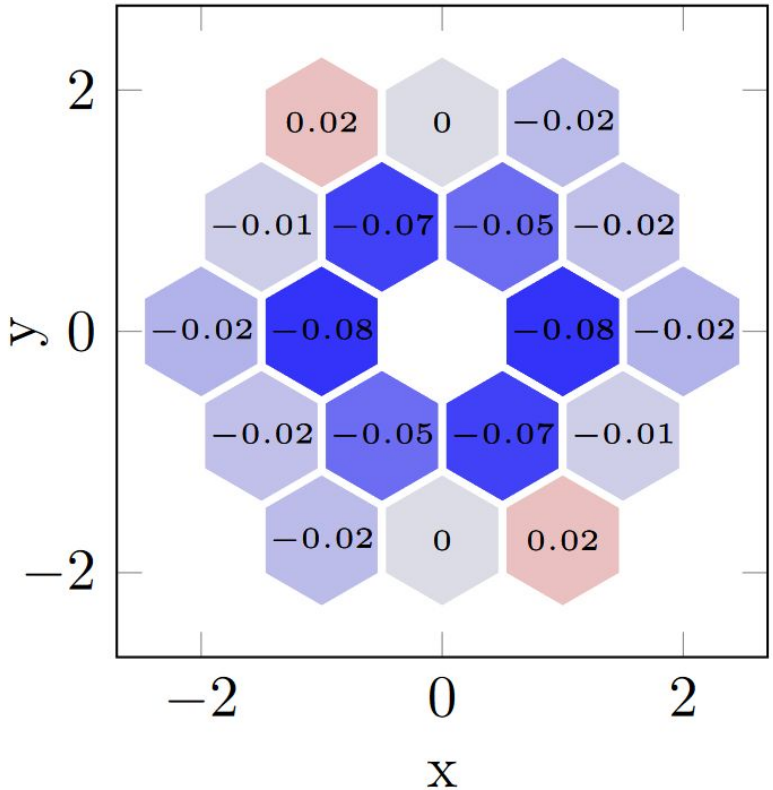


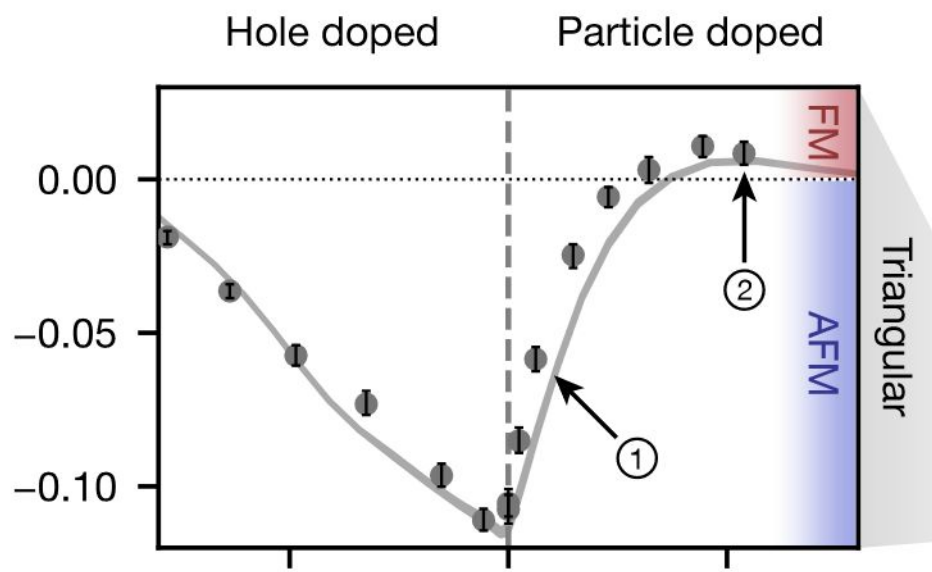
Wei…Bloch, Zeiher, arxiv 2301.11869 (2023), also used to generate Lieb, Kagome lattices in combination with DMD to block out sites

Related schemes: Esslinger, Porto/Johnson, Greiner groups

Triangular Hubbard simulators

Cold atom microscopes
Mott insulators with spiral AFM correlations

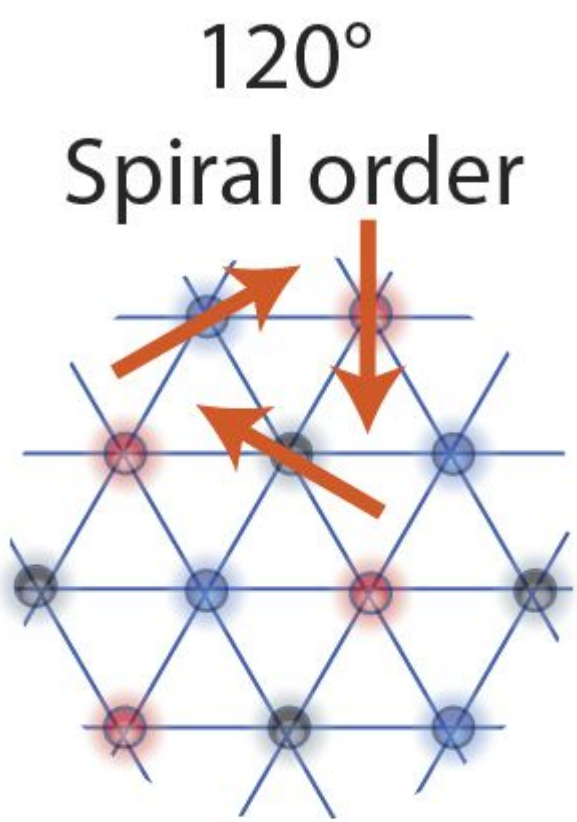


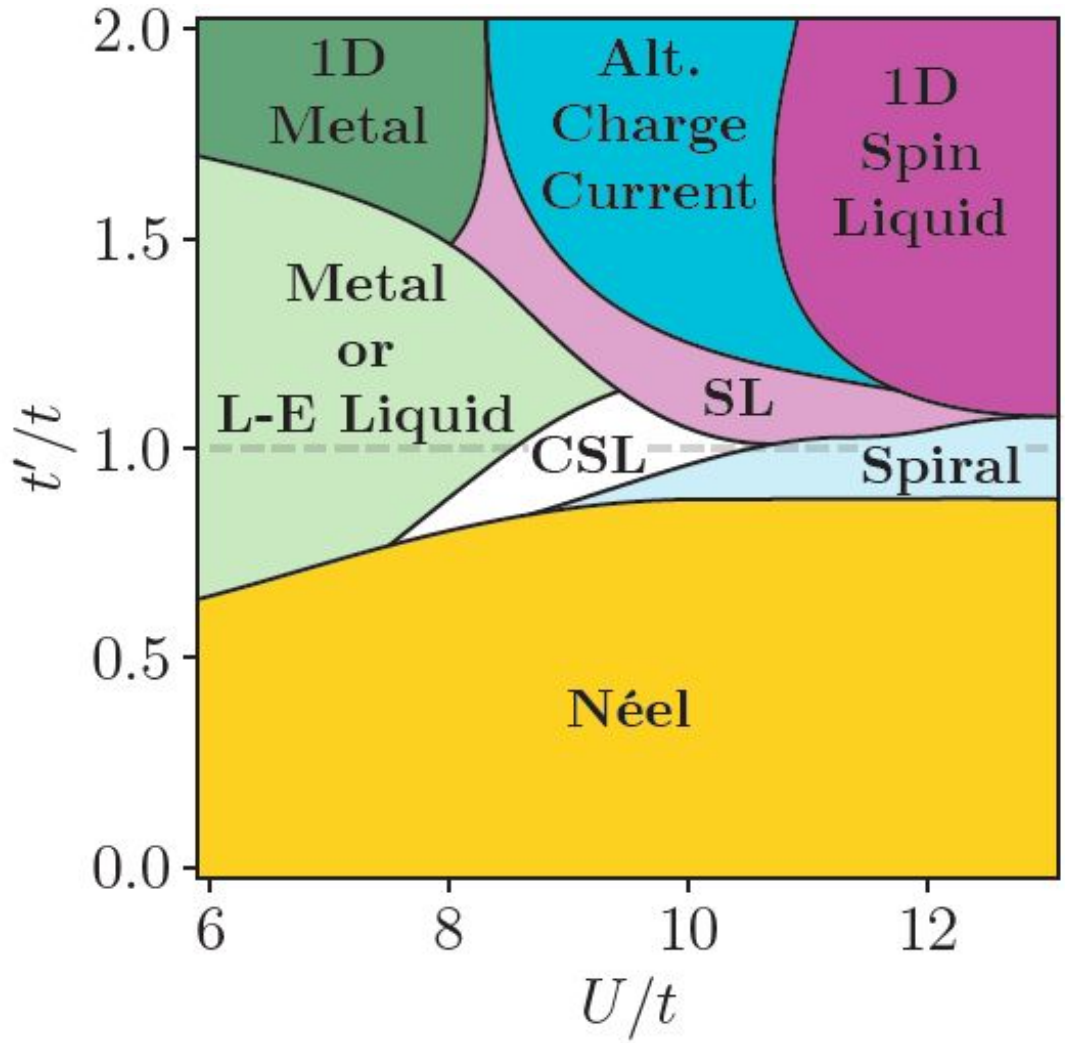


Mongkolkiattichai … Schauss,
arXiv: 2210.14895 (2022)

Xu … Greiner,
arXiv: 2212.13983 (2022)

The triangular Hubbard model at half-filling

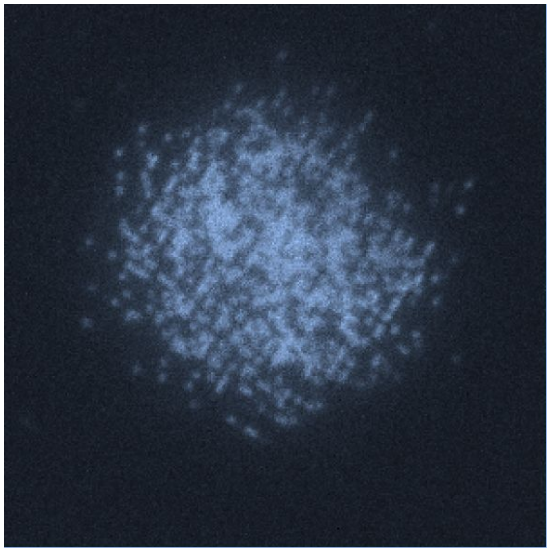


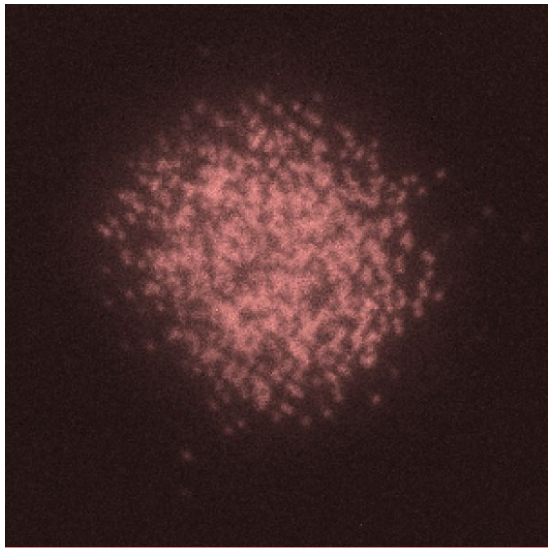


Szasz and Motruk, PRB 103, 235132 (2021)

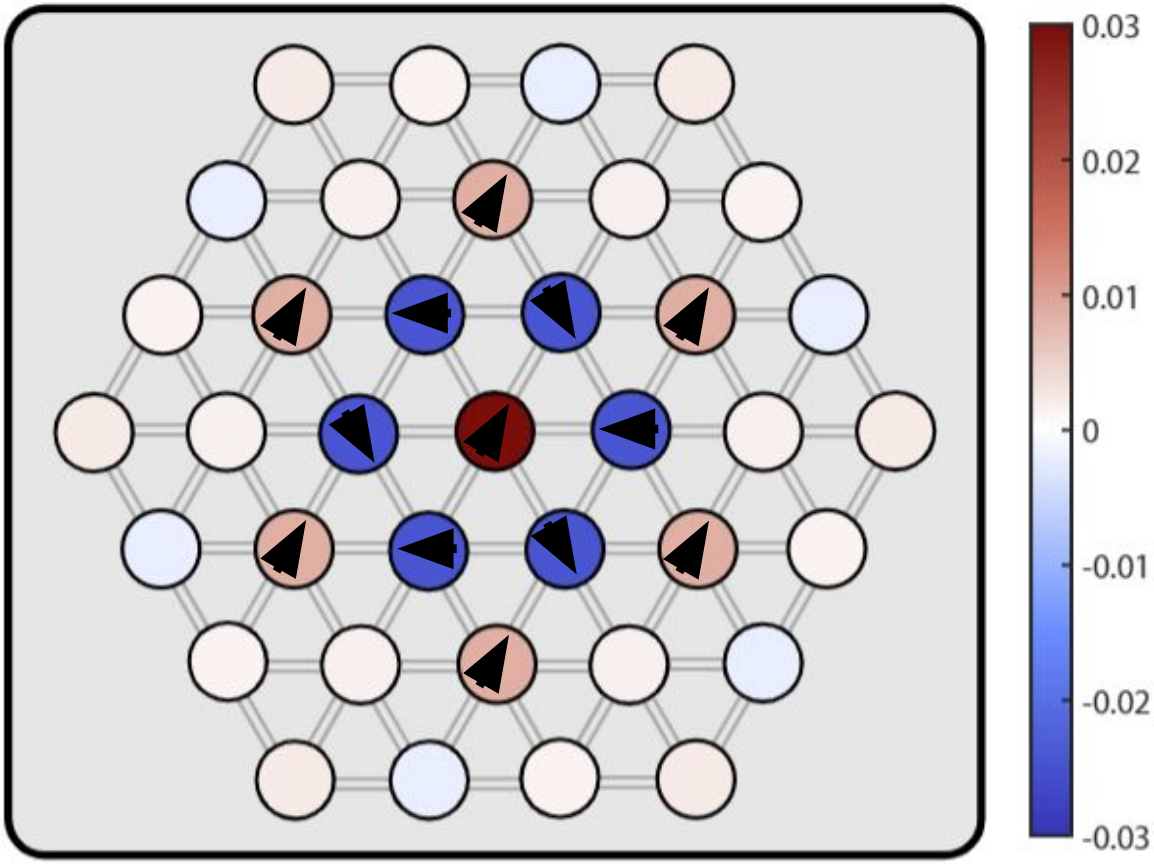
Two-point spin correlations (Princeton)

Raw images of
Antiferromagnetic order





Correlations consistent with spiral order



Kinetic Antiferromagnetism in the Triangular Lattice

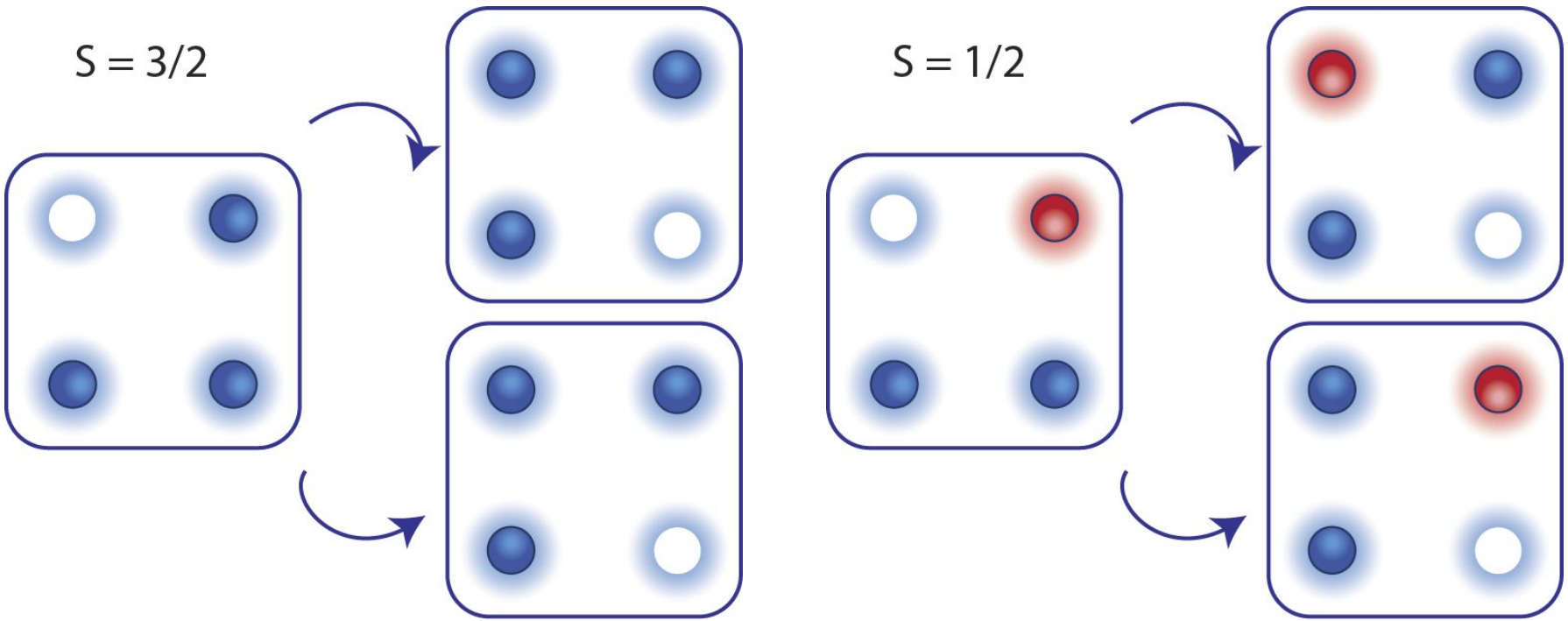
Jan O. Haerter and B. Sriram Shastry
Physics Department, University of California, Santa Cruz, California 95064, USA
(Received 25 May 2005; published 19 August 2005)

We show that the motion of a single hole in the infinite-U Hubbard model with frustrated hopping leads to weak metallic antiferromagnetism of kinetic origin. An intimate relationship is demonstrated between the simplest versions of this problem in one and two dimensions, and two of the most subtle many body problems, namely, the Heisenberg Bethe ring in one dimension and the two-dimensional triangular lattice Heisenberg antiferromagnet.

- Infinite-U: superexchange vanishes
- But hole motion mediates an effective exchange coupling between spins in the Mott insulator.
- A new kind of antiferromagnetism: kinetic antiferromagnetism!

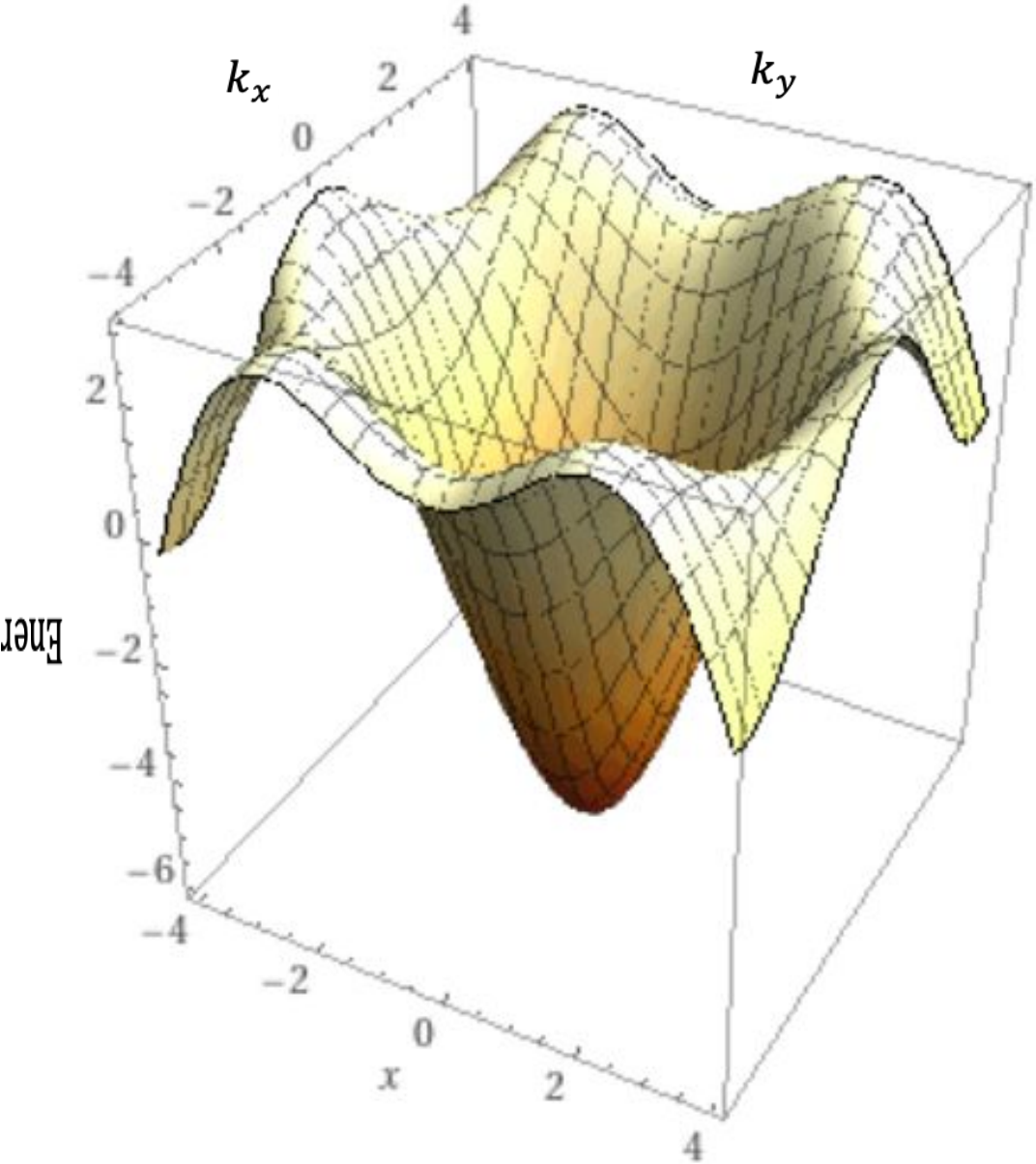
Reminiscent of the setup for Nagaoka ferromagnetism on the square lattice…

Nagaoka's itinerant magnetism (1966): infinite U, one hole from half filling
Interference on a square plaquette favors S=3/2 ferromagnetic state

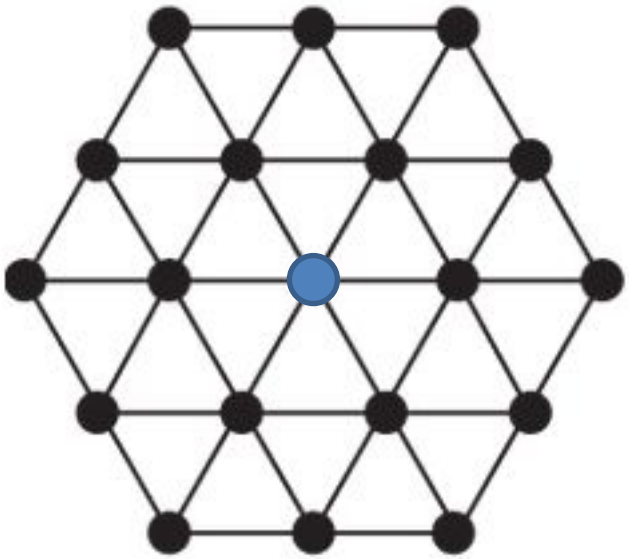


Constructive interference of hole motion in polarized background lowers kinetic energy and favors ferromagnetism.
Recently observed 2x2 quantum dot array: Dehollian et al, *Nature* 579, 528 (2020)

Kinetic frustration



$$H = -t \sum_{n.n.} c_i^\dagger c_j + h.c.$$

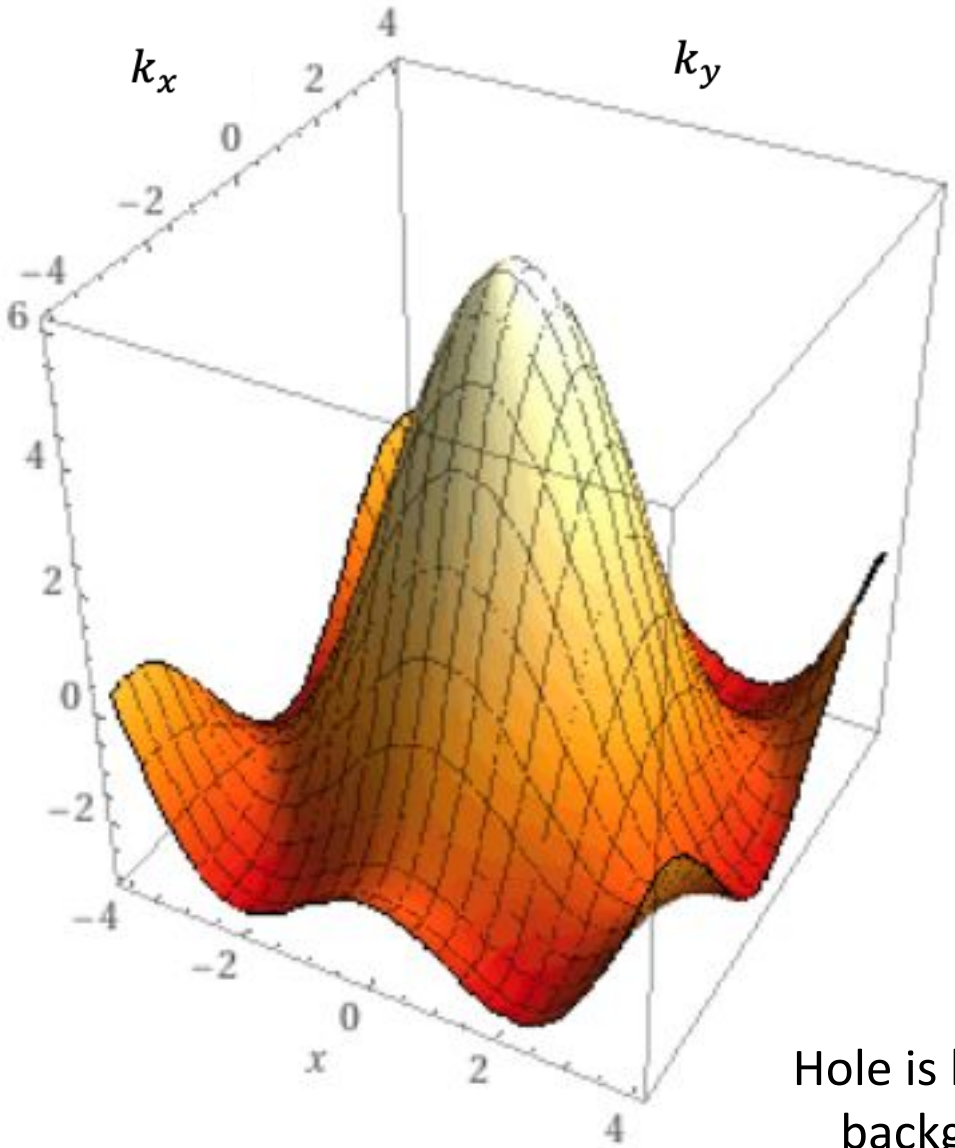


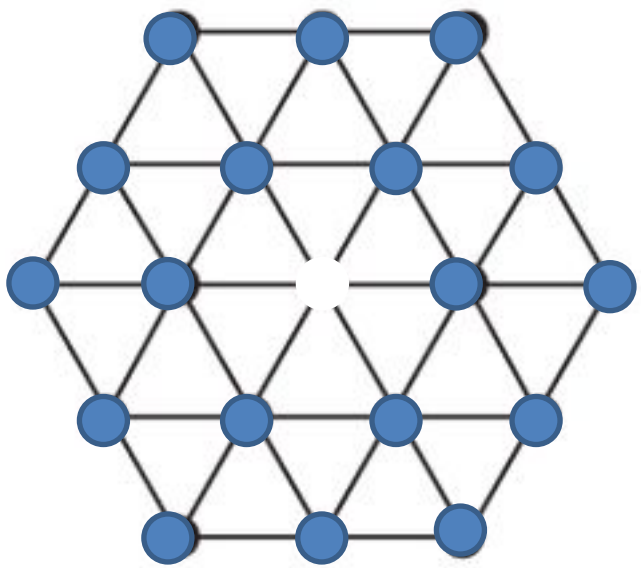
Minimum energy of particle is -6*t*

Kinetic frustration

$$h_i^\dagger = c_i$$

$$H = +t \sum_{n.n.} h_j^\dagger h_i + h.c.$$

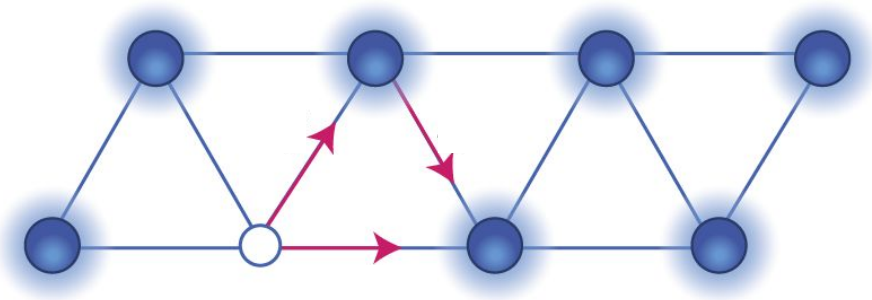




Minimum energy of particle is -3*t*

Hole is kinetically frustrated in spin polarized background due to destructive quantum interference.

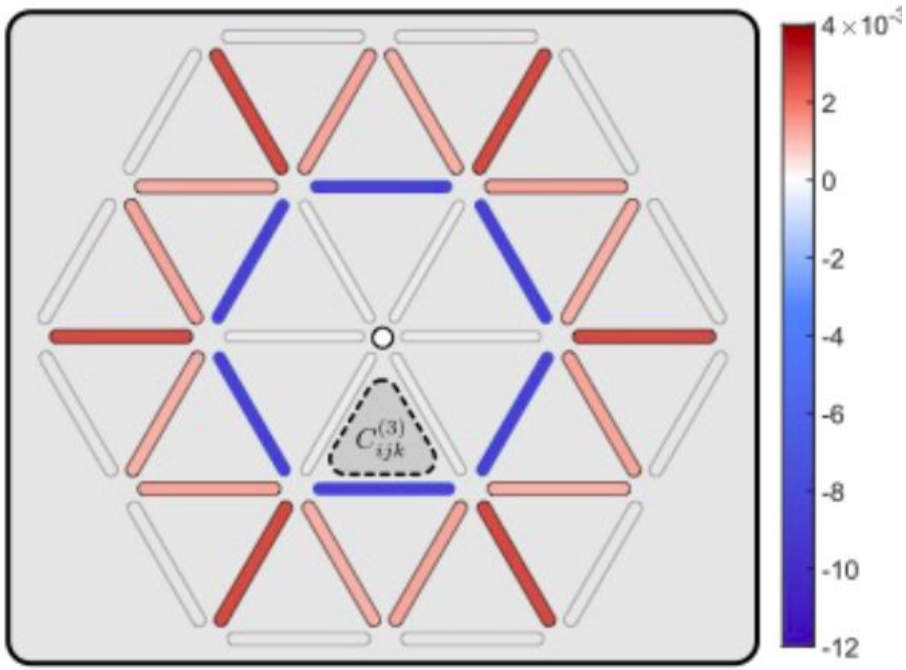
Magnetic polaron with *t* scale binding energy



A hole likes to bind to an antiferromagnetic bond to release kinetic frustration and lower kinetic energy by an amount of order *t*.

Predictions of this polaron:
Zhang … Batista, PRB 97, 140507(R) (2018)
Morera … Demler, arxiv:2106.09600 (2021)
Morera … Demler, arxiv:2209.05398 (2022)
Davydova … Liang Fu, arxiv:2206.01221 (2023)
Schlomer … Grusdt, arxiv:2305.02342 (2023)
Samajdar … Bhatt, arxiv:2305.05683 (2023)

Experimental “images” of the polaron through three-point correlators

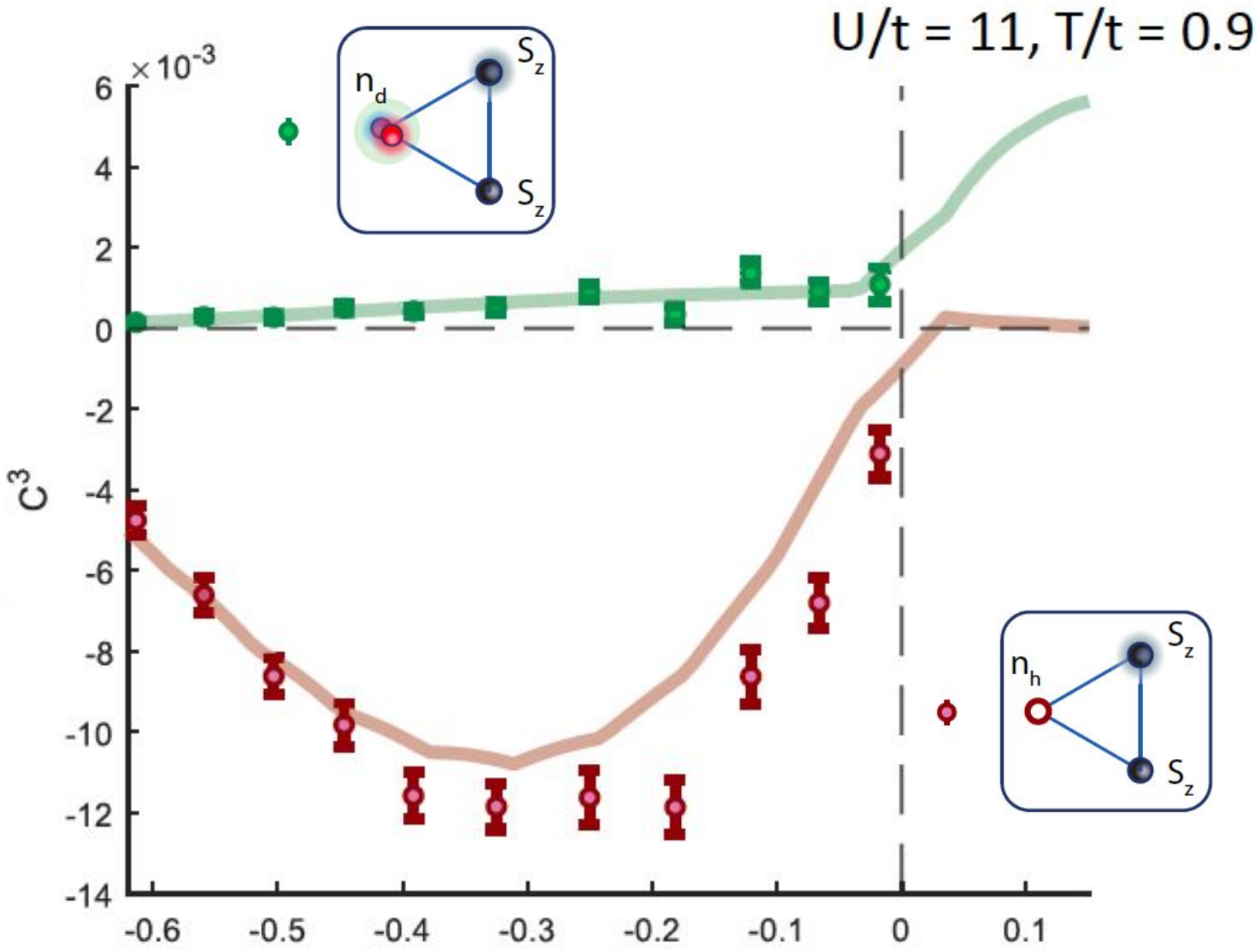


$$4 < S_i^z S_j^z h_k >_C$$

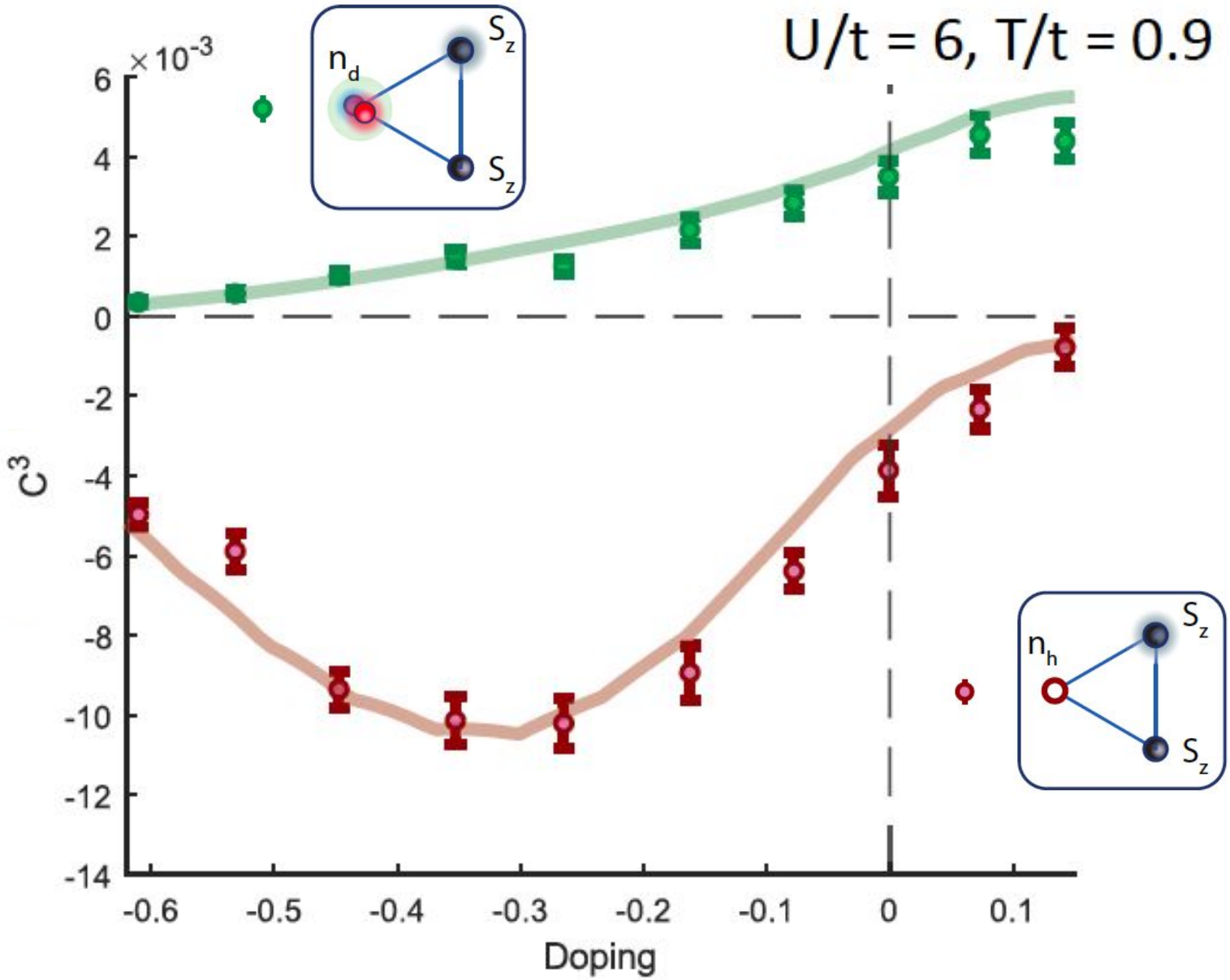
Holes cluster with antiferromagnetic bonds

Doublons cluster with ferromagnetic bonds

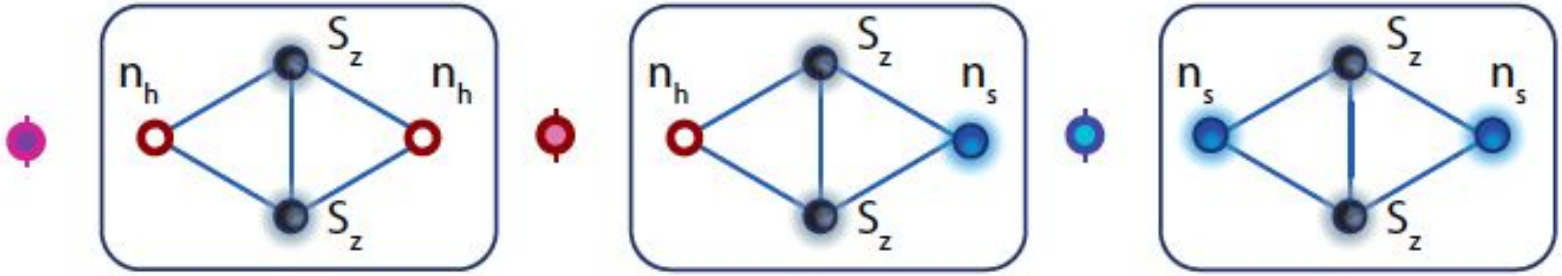
Doping dependence of polarons

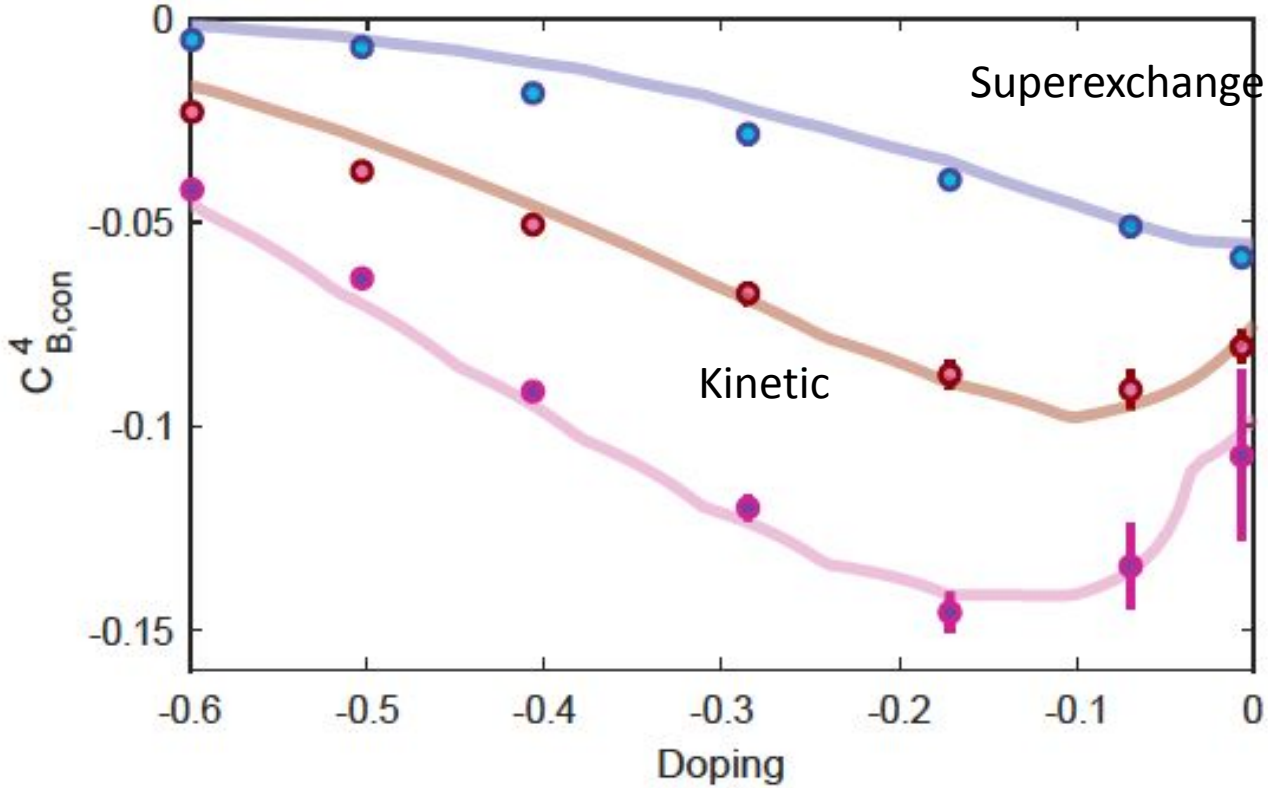


Polarons in the metallic regime



Kinetic magnetism vs. superexchange magnetism



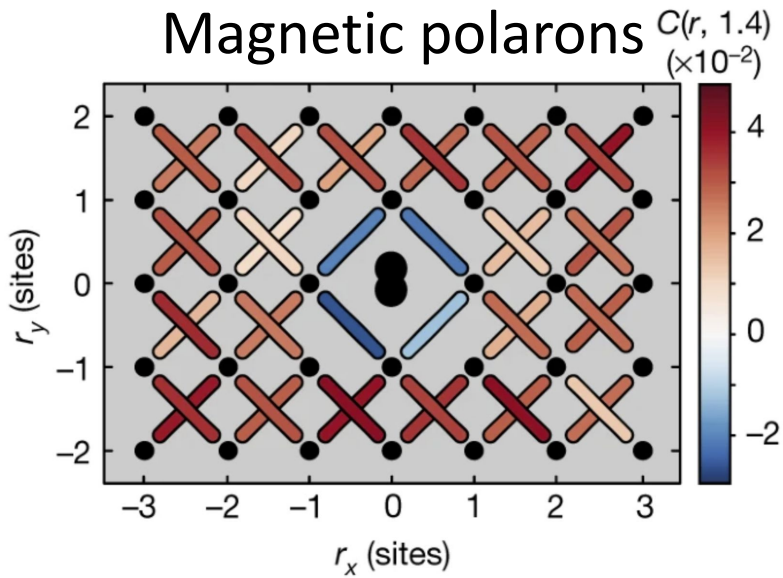


$$C^4_{B,con}(O_1, O_2) = \frac{4 < O_1 S_z S_z O_2 >}{< O_1 O_2 >}$$

U/t = 11, T/t = 0.9

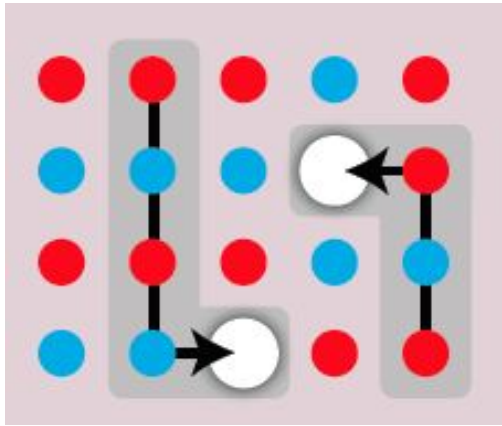
Comparison with square lattice magnetic polarons

Magnetic polarons



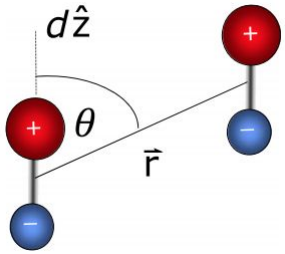
Koepsell … Bloch, Gross,
Nature 572, 358 (2019)

Geometric strings



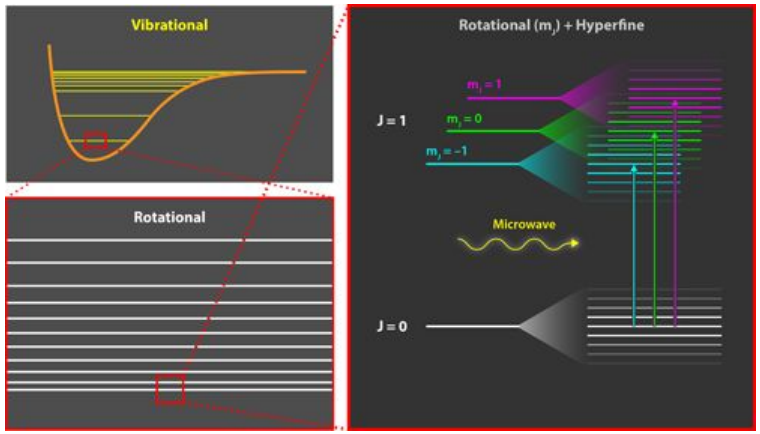
Chiu … Greiner, Greif,
Science 365, 251 (2019)

Why quantum simulation with molecules?

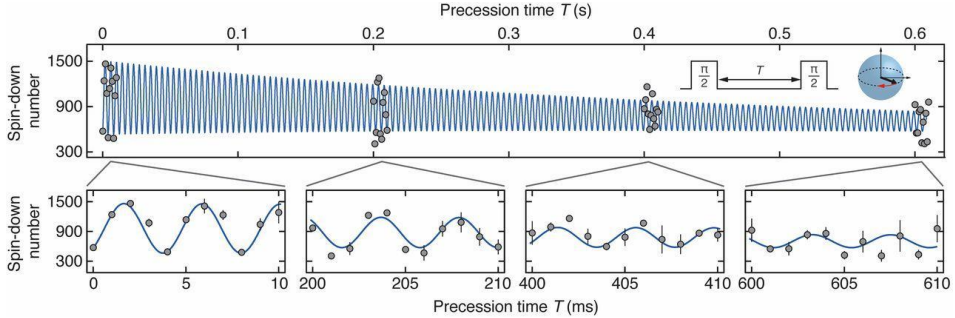


$$V_{dd}(\vec{r}) = \frac{d^2}{4\pi\epsilon_0}\frac{(1-3\cos^2\theta)}{r^3}$$

- Long ranged, anisotropic interactions
- new types of many-body Hamiltonians
- Wide range of energy levels with different control knobs (electric, magnetic, optical fields)
- Long hyperfine and rotational coherence times



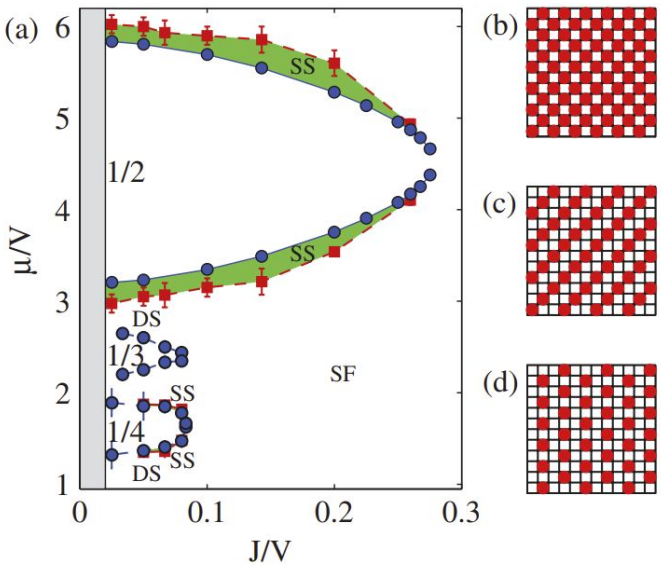
Yelin, Susanne. "Taming Ultracold Molecules." *Physics* 9 (2016): 60.



Park, J. W., et al. *Science*, *357*(6349), 372-375, (2017).
Burchesky, S., *et al. Physical Review Letters*, *127*(12), 123202, (2021).

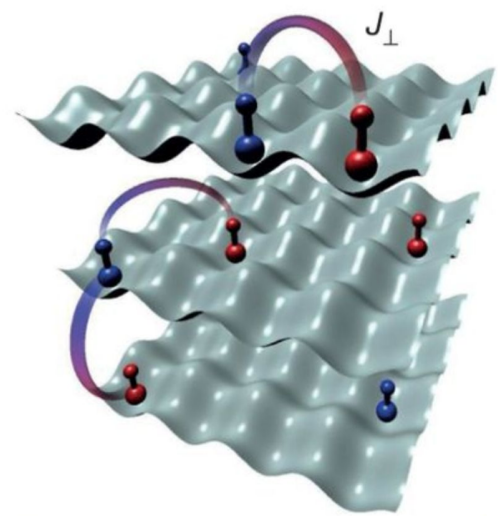
Correlated matter with molecules

Extended Hubbard physics



Capogrosso-Sansone et al,
Phys. Rev. Lett. **104**, 125301 (2010)

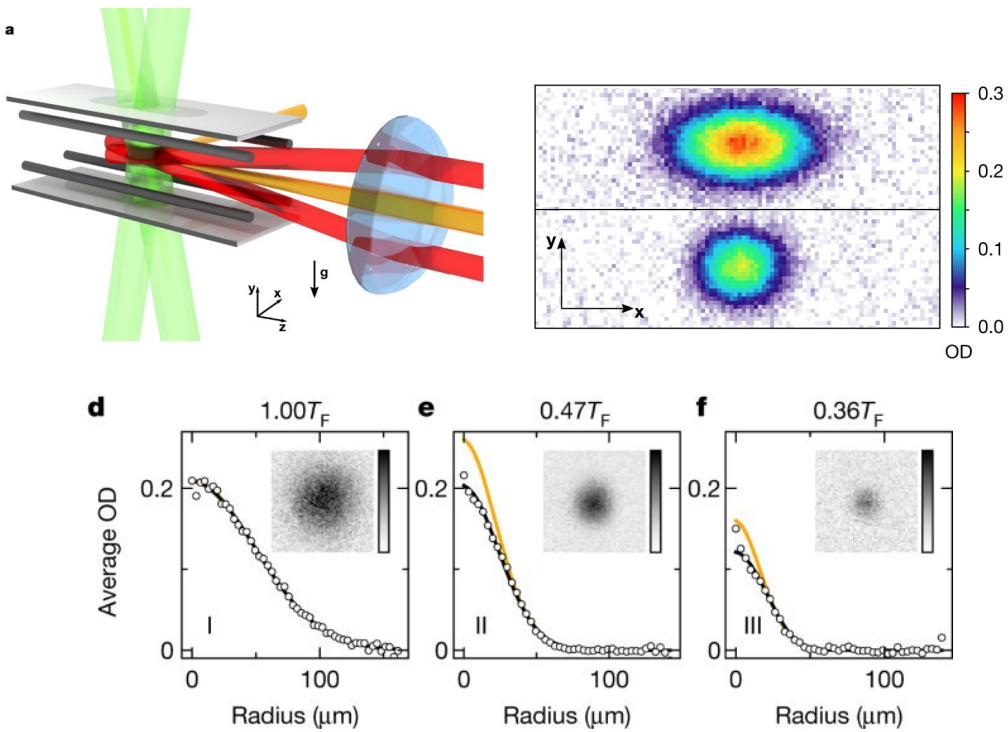
Quantum spin models



Yan... Jin, Ye, et al. *Nature* **501**, 521 (2013)

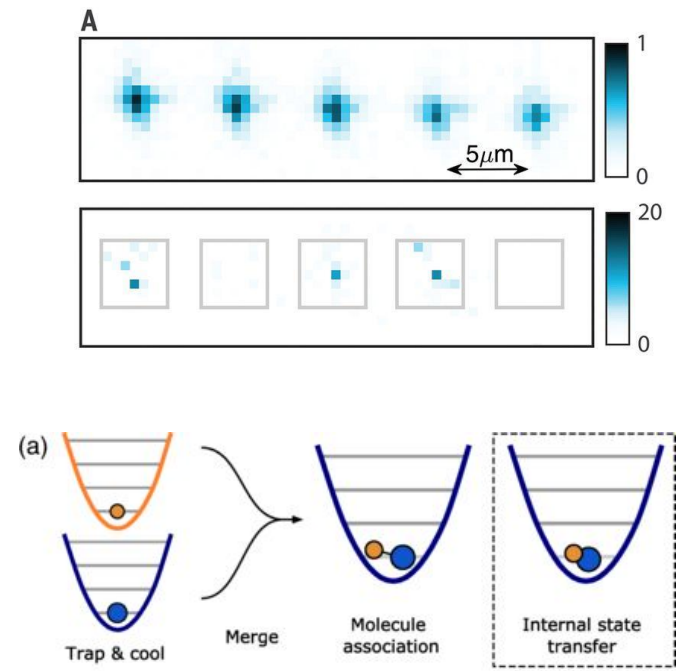
Experimental progress with ultracold molecules

Quantum gases in bulk traps



Valtolina, G., *et al*. *Nature* **588**, 239–243 (2020).
Schindewolf, A., *et al.* *Nature* **607**, 677–681 (2022).

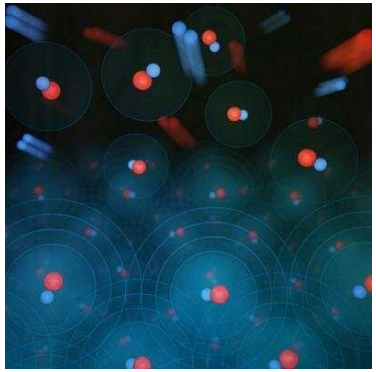
Optical tweezer arrays



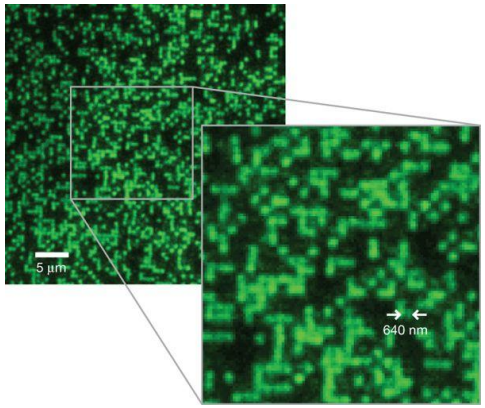
Anderegg, L. et al. Science 365, 1156–1158 (2019).
Cairncross, W. B., *et al*. *Physical Review Letters*, *126* (12), 123402, (2021).

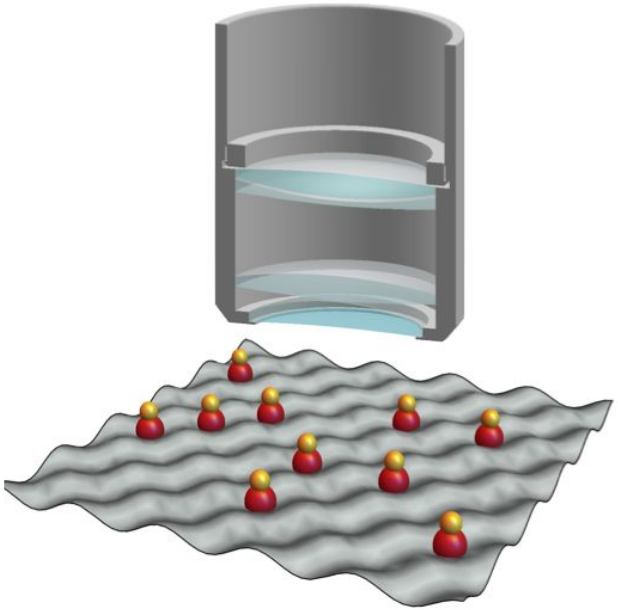
Ultracold molecule microscope

Ultracold polar molecules



Quantum gas microscopy



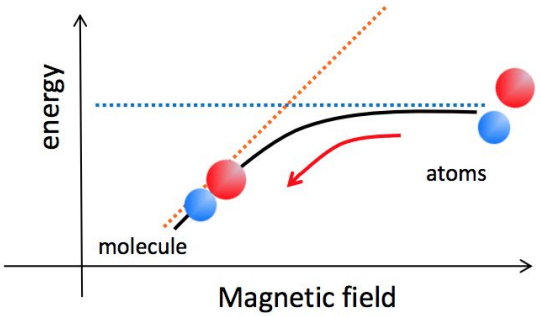


Assembly of Ultracold NaRb Molecules

PRL 116, 205303 (2016) PHYSICAL REVIEW LETTERS week ending 20 MAY 2016

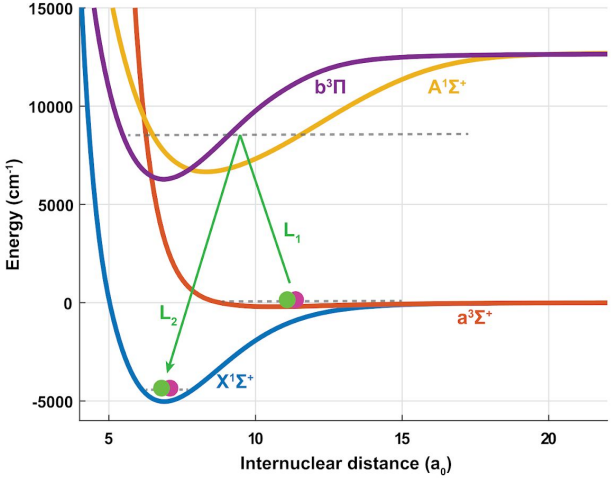
Creation of an Ultracold Gas of Ground-State Dipolar $^{23}Na^{87}Rb$ Molecules

Mingyang Guo,[1] Bing Zhu,[1] Bo Lu,[1] Xin Ye,[1] Fudong Wang,[1] Romain Vexiau,[2] Nadia Bouloufa-Maafa,[2] Goulven Quéméner,[2] Olivier Dulieu,[2] and Dajun Wang[1,3,*]
[1]*Department of Physics, The Chinese University of Hong Kong, Hong Kong, China*
[2]*Laboratoire Aimé Cotton, CNRS, Université Paris-Sud, ENS Cachan, Université Paris-Saclay, 91405 Orsay Cedex, France*
[3]*The Chinese University of Hong Kong Shenzhen Research Institute, 518057, Shenzhen, China*
(Received 11 February 2016; published 19 May 2016)

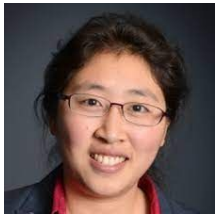


Step 1: Sweep interspecies Feshbach resonance

- Large dipole moment: d = 3.3 D
- Bosonic

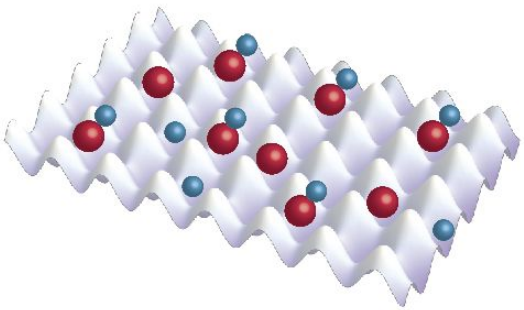


Step 2: Two-photon transfer (STIRAP) to absolute ground state

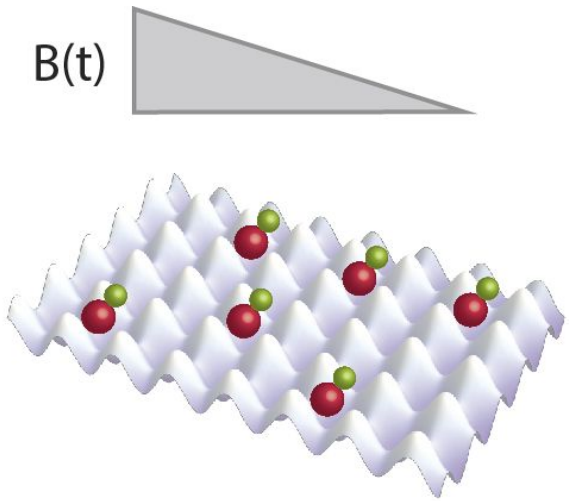


Ni, K. K., et al. *Science*, *322*(5899), 231-235, (2008).

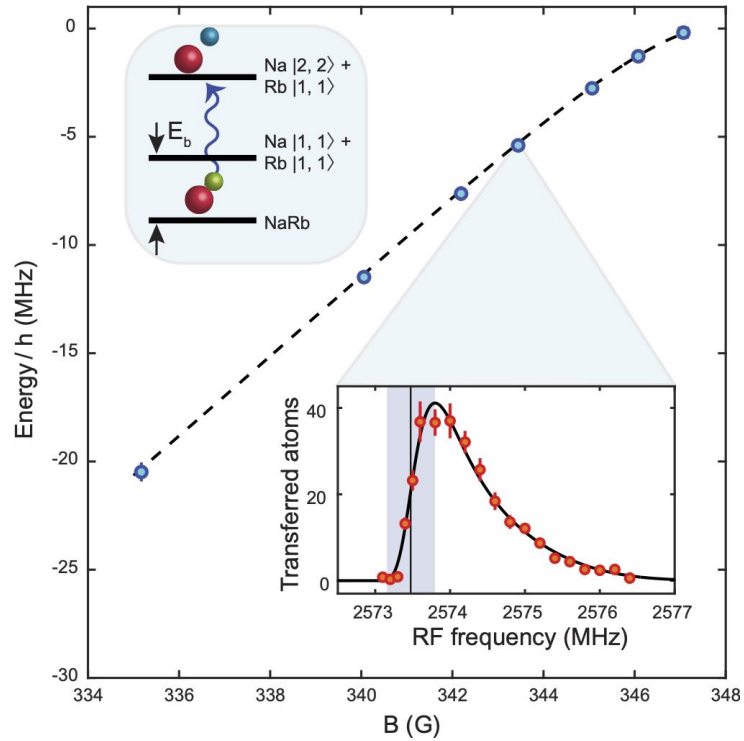
Creation of Feshbach Molecules



Turn on square 2D lattice

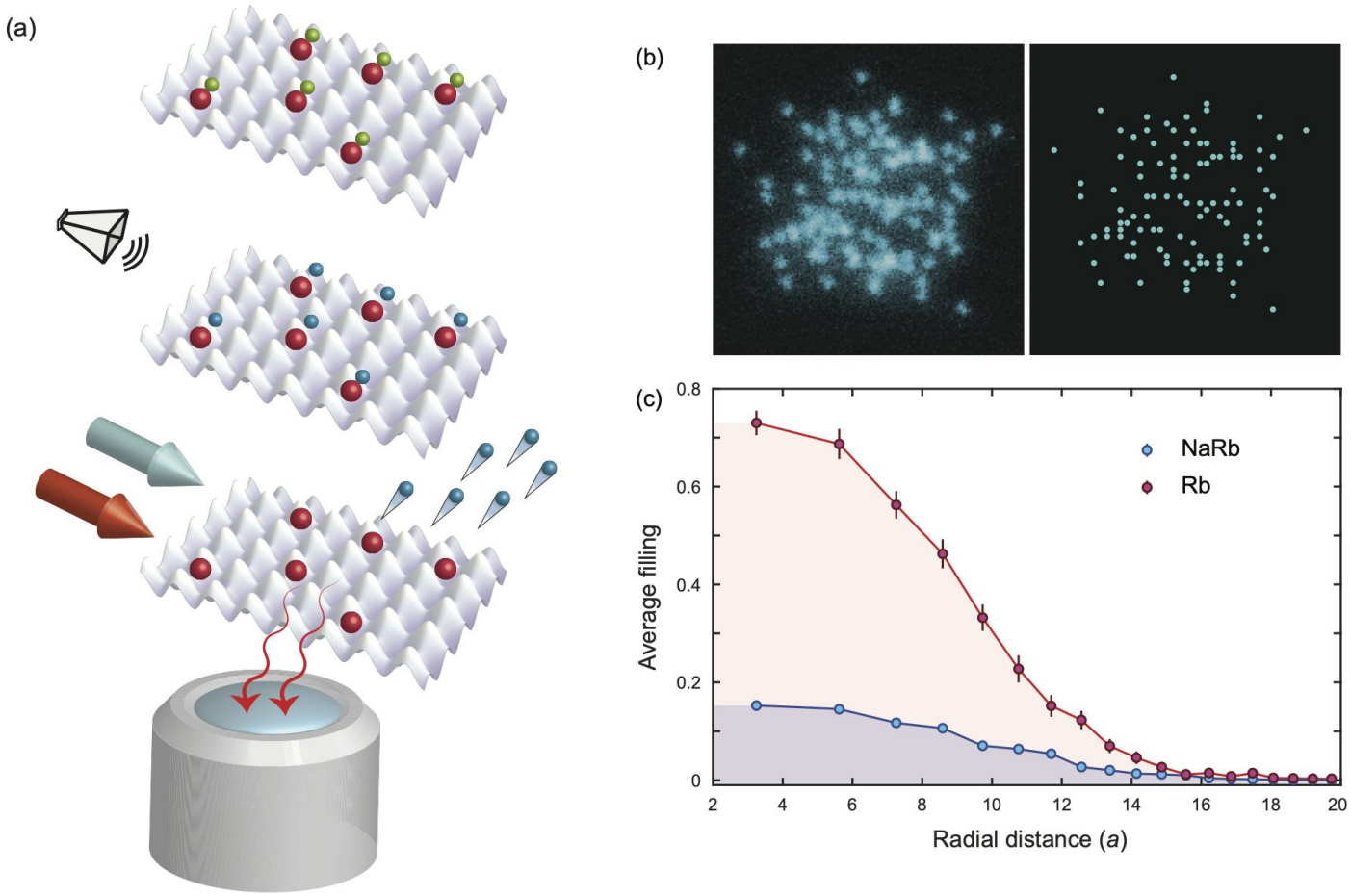


Sites with both species convert to molecules with ~100% efficiency

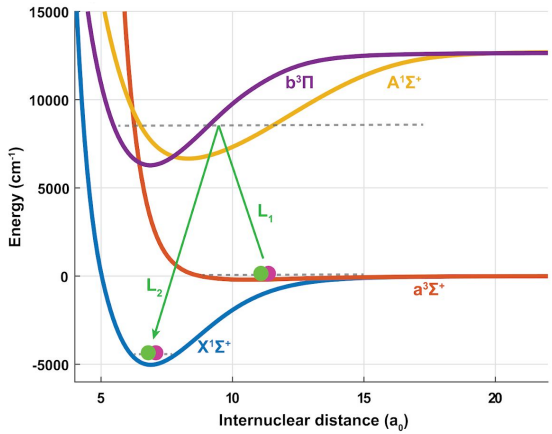


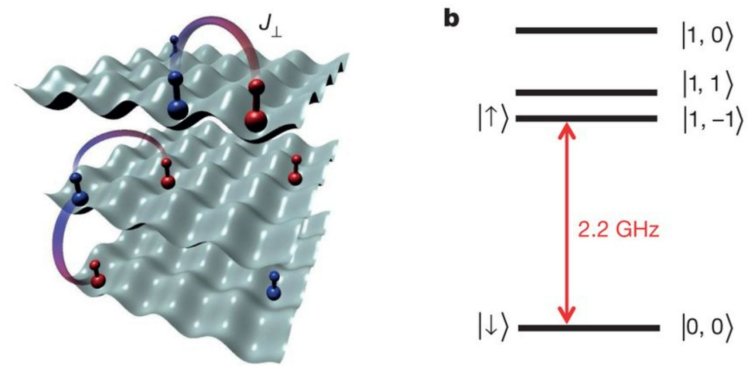
Rosenberg, J.S., Christakis, L.,. *et al.* Observation of the Hanbury Brown–Twiss effect with ultracold molecules. *Nat. Phys.* **18**, 1062–1066 (2022).

Microscopy of Feshbach Molecules



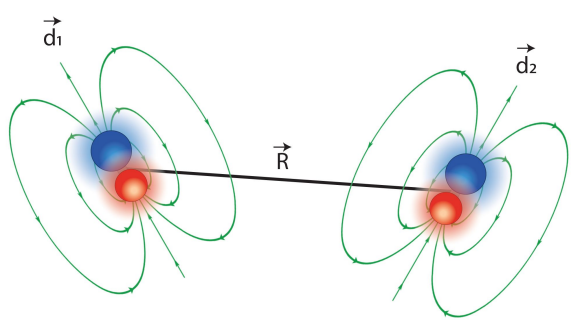
Quantum magnetism with polar molecules

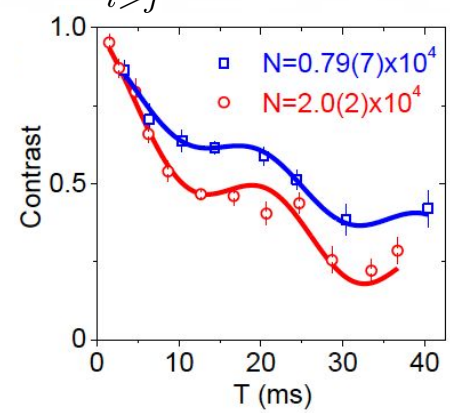




$$H_{XY} = \sum_{i>j} V_{dd}(\mathbf{r}_i - \mathbf{r}_j)(S_x^i S_x^j + S_y^i S_y^j)$$

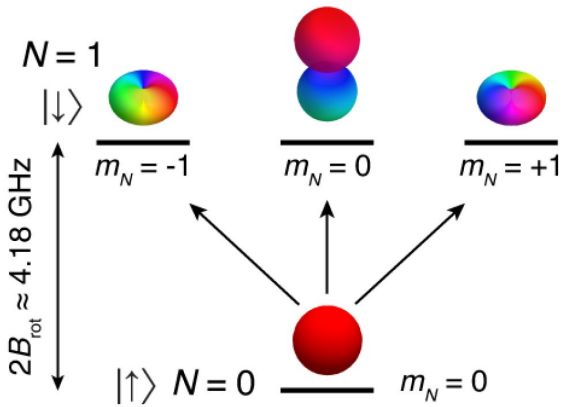
- 94% efficiency STIRAP transfer

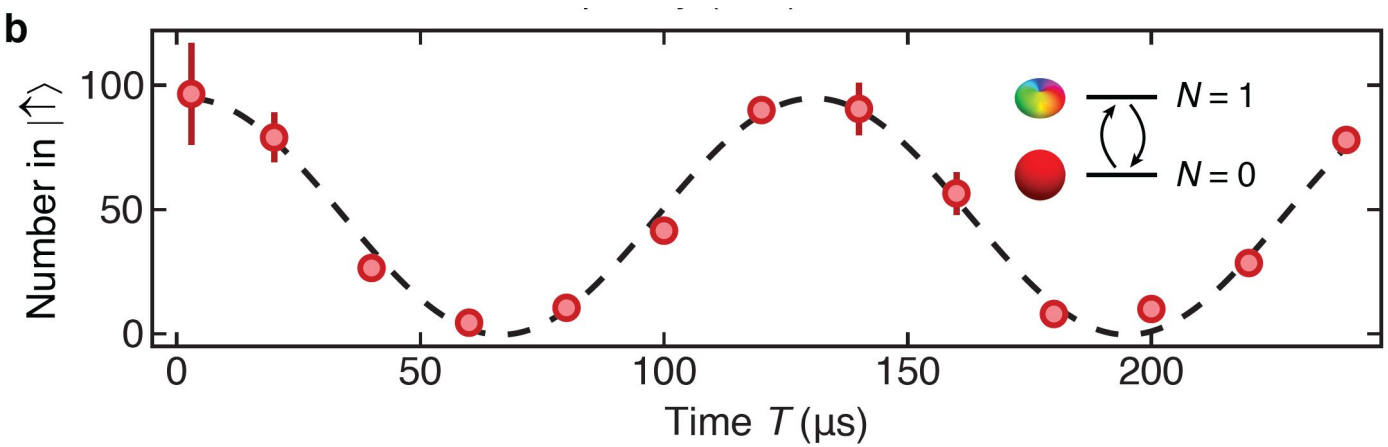




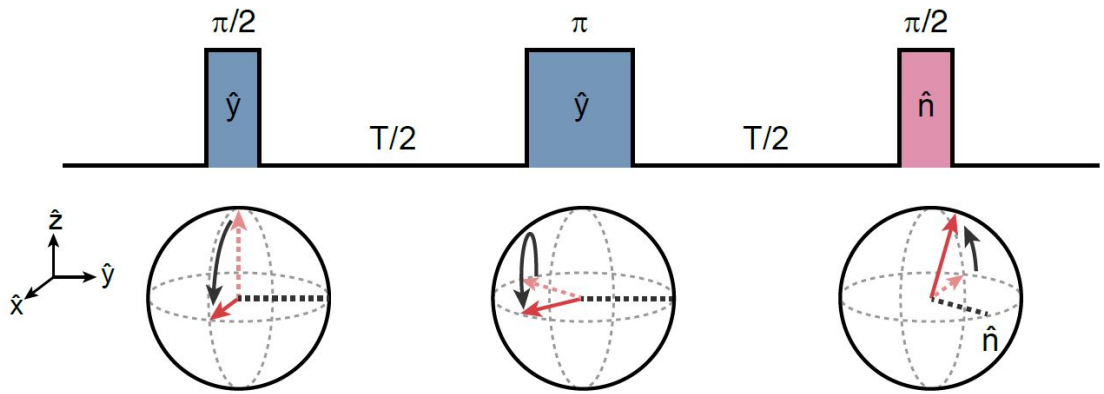
Yan, B., et al. *Nature* 501, 521 (2013).

Rotational states





Rotational state coherence



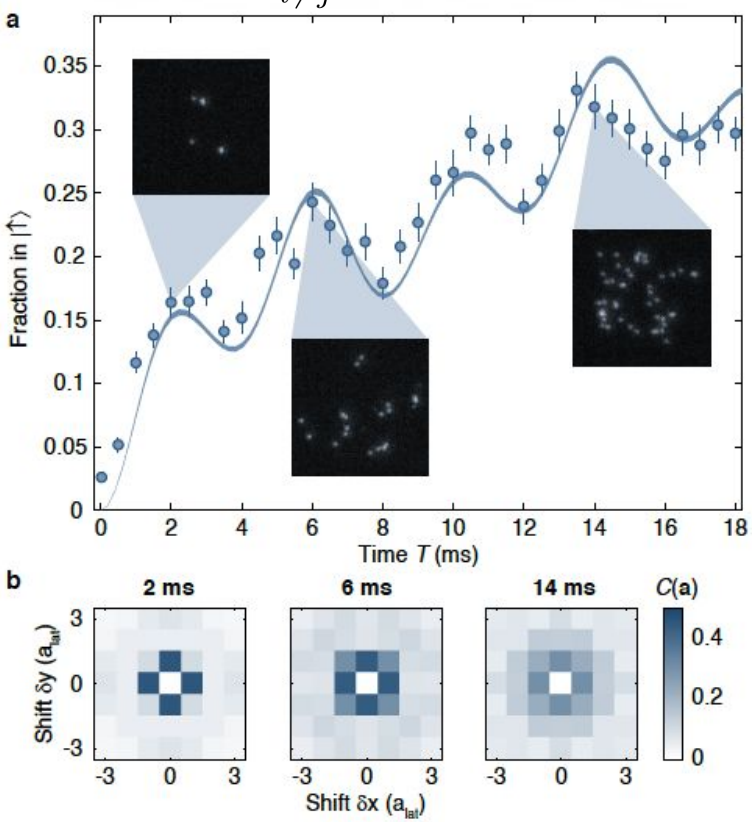
- Sources of decoherence:
  - AC stark shift
  - Varying magnetic/electric fields
  - dipolar interactions between molecules
- Work at very low filling (1%) to minimize dipolar interactions

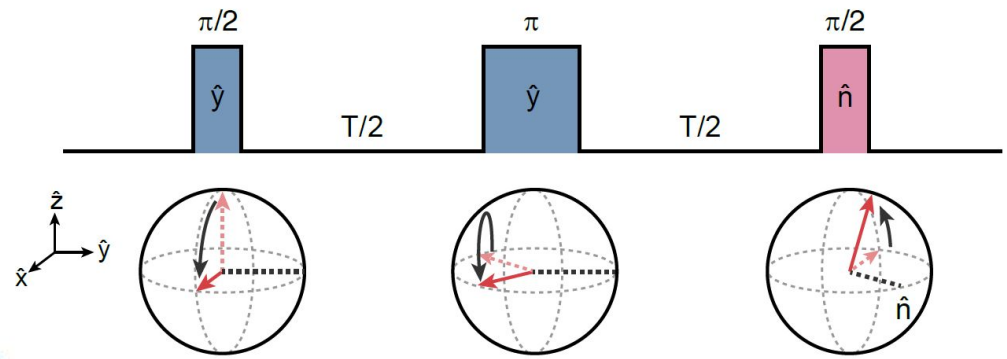
Christakis, L., Rosenberg, J. *et al. Nature* **614**, 64-69 (2023).

Correlation dynamics in an XY spin model

$$H_{\mathrm{XY}} = J \sum_{i \neq j} \frac{1}{r_{ij}^3} \left(S_x^i S_x^j + S_y^i S_y^j \right)$$

$$C(\mathbf{a}, T) = \mathcal{N} \sum_{\mathbf{r}} \left(\langle n_{\mathbf{r}}^{\uparrow} n_{\mathbf{r}+\mathbf{a}}^{\uparrow} \rangle - \langle n_{\mathbf{r}}^{\uparrow} \rangle \langle n_{\mathbf{r}+\mathbf{a}}^{\uparrow} \rangle \right)$$





Entangling-disentangling dynamics

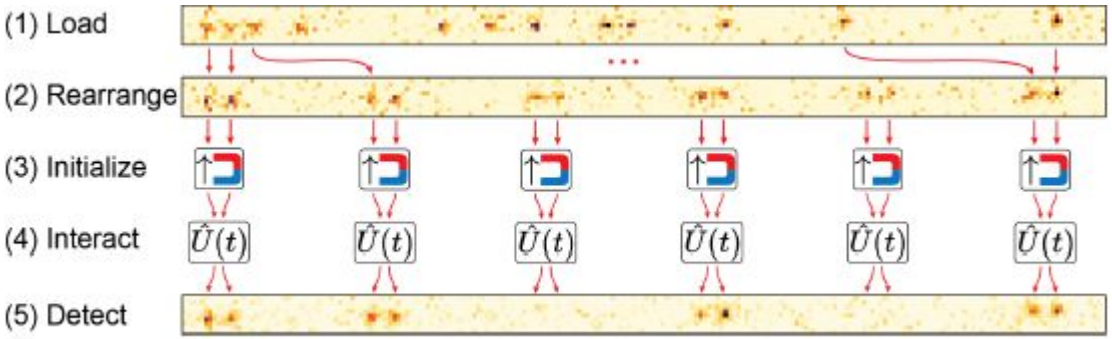
Dilute limit: consider a gas of pairs and single molecules.
Ramsey sequence arranged to have singles all end up in undetected state.

For pairs, the evolution at the end of a Ramsey sequence with evolution *T*:

$$\sin(V(\mathbf{a})T/4\hbar)\,|\uparrow\uparrow\rangle - i\cos(V(\mathbf{a})T/4\hbar)\,|\downarrow\downarrow\rangle$$

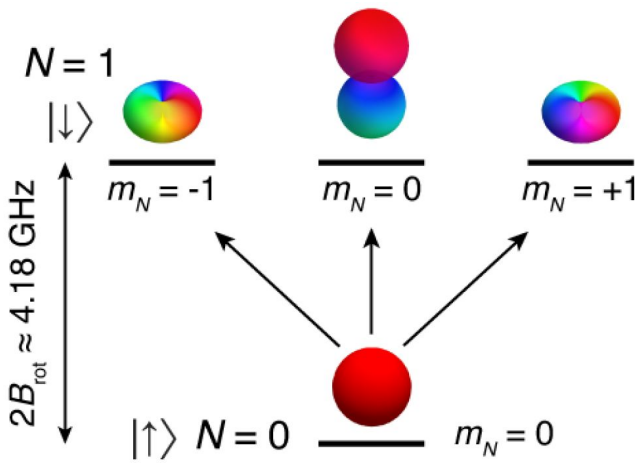
Bell states at certain times in evolution!

C. Holland, Y. Lu & L. Cheuk,
arxiv: 2210.06309 (2022)
Y. Bao … J. Doyle, 2211.09780 (2022)

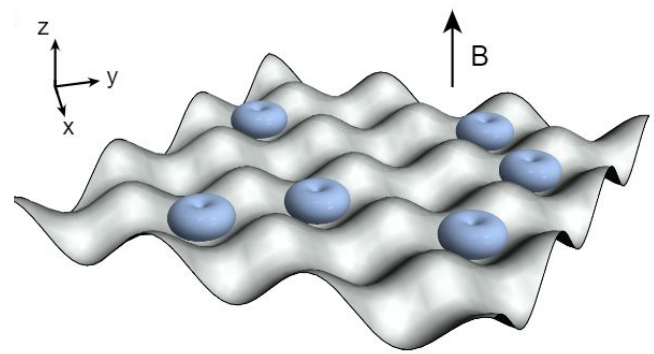


Tunable spatial anisotropy

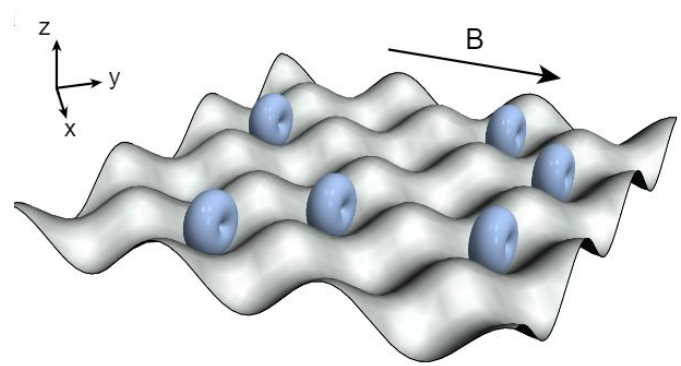
$$V_{dd}(\vec{r}) = \frac{d^2}{4\pi\epsilon_0}\frac{(1-3\cos^2\theta)}{r^3}$$



Isotropic

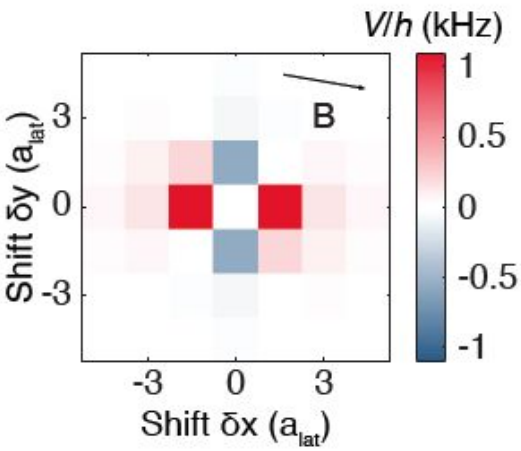


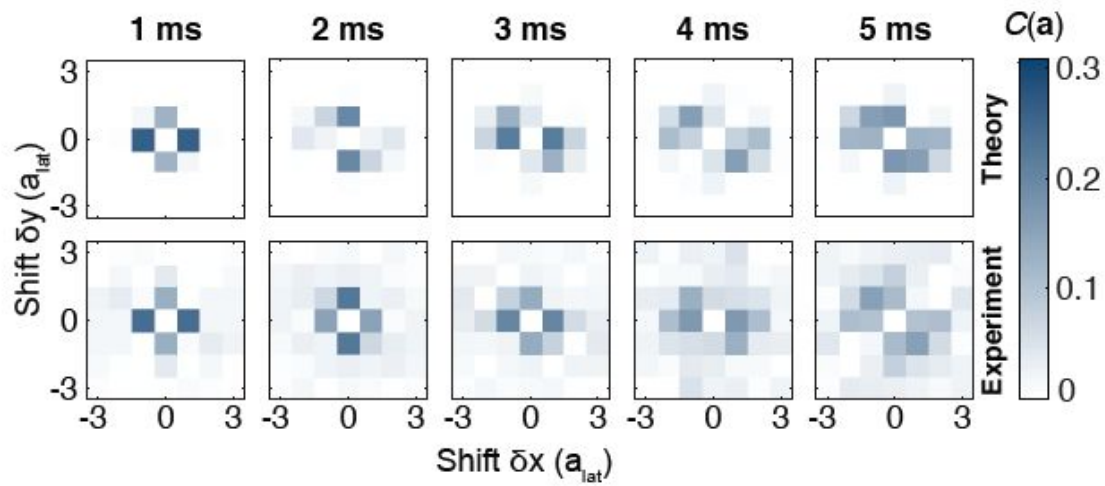
Anisotropic



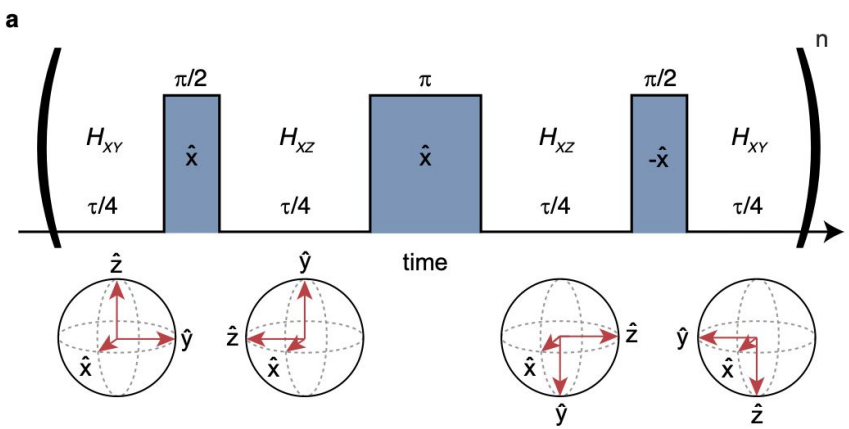
Tunable spatial anisotropy

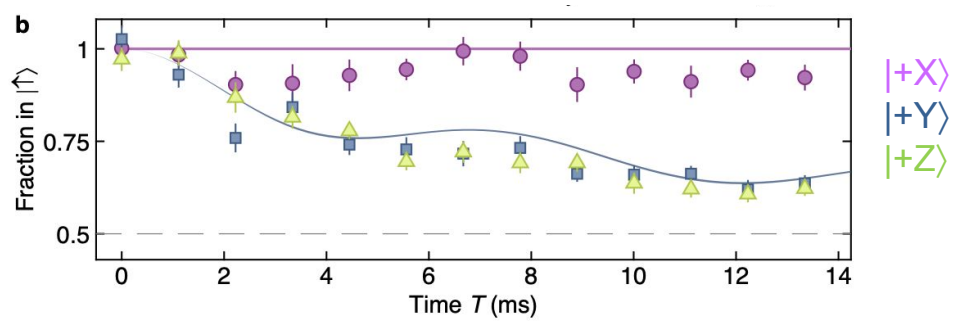
$$H_{\mathrm{XY}} = J \sum_{i \neq j} \frac{1 - 3\cos^2\theta_{ij}}{|\mathbf{r}_i - \mathbf{r}_j|^3} \left(S_x^i S_x^j + S_y^i S_y^j \right)$$

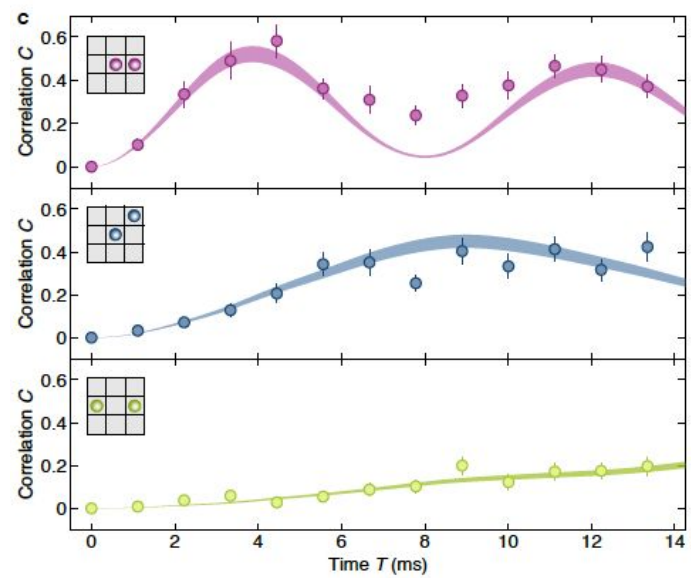




Floquet engineering of an anisotropic Heisenberg model





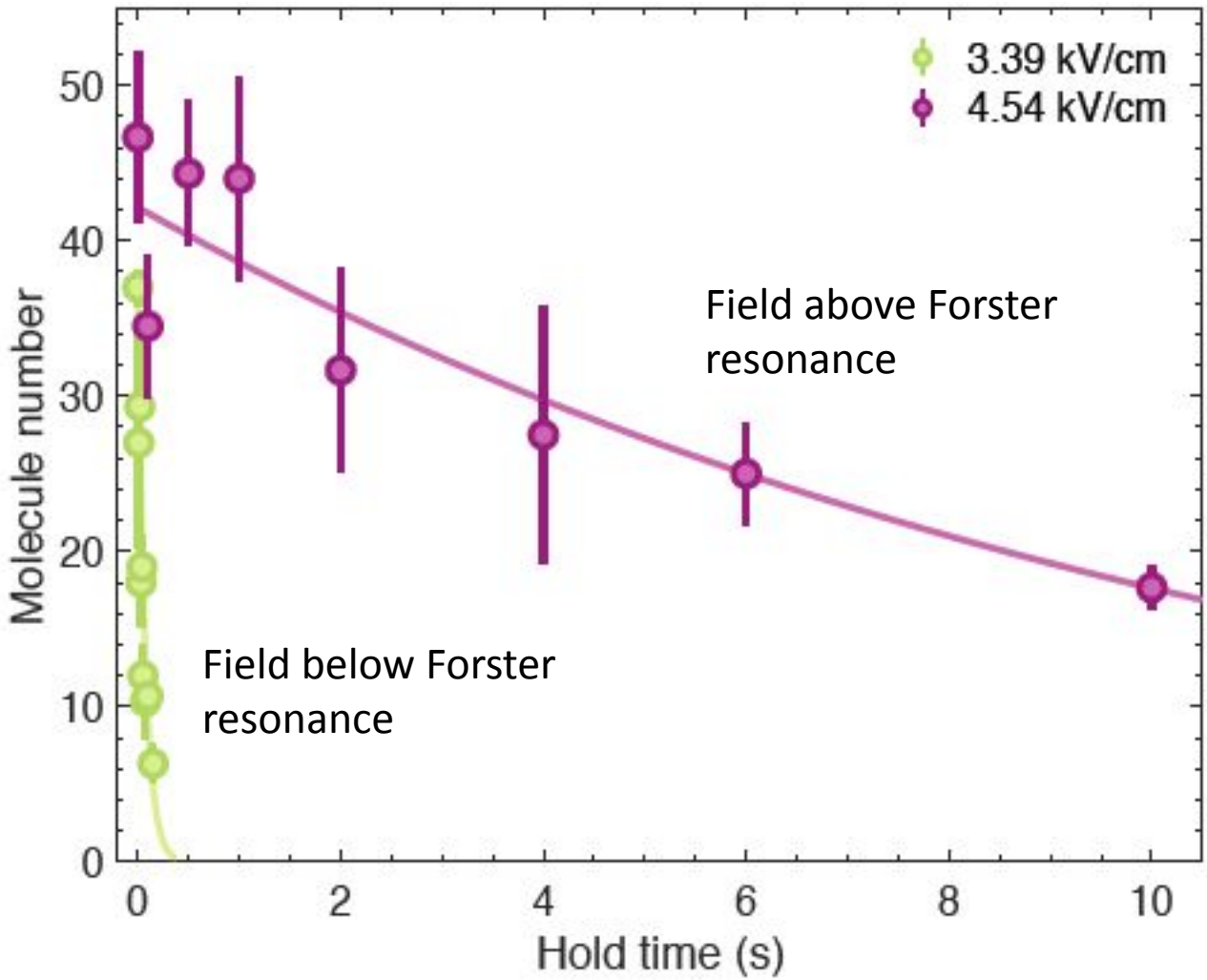


$$H_{\mathrm{XY}} = J \sum_{i \neq j} \frac{1}{r_{ij}^3} \left(S_x^i S_x^j + S_y^i S_y^j \right)$$

$$\downarrow$$

$$H_{\mathrm{XYY}} = J \sum_{i \neq j} \frac{1}{r_{ij}^3} \left(S_x^i S_x^j + \frac{1}{2} (S_y^i S_y^j + S_z^i S_z^j) \right)$$

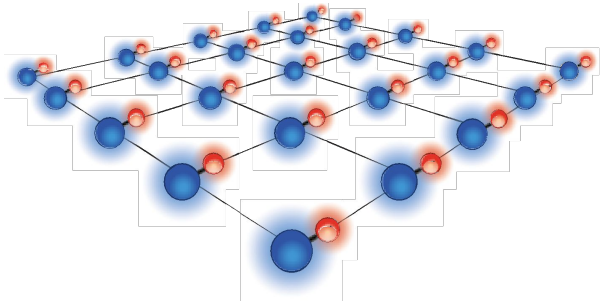
Preliminary results on DC electric field shielding with NaRb



Building on first demonstration of DC field shielding with KRb:
K. Matsuda … Jun Ye, Science 370, 1324 (2020), related work with microwave shielding:
Hong-Kong, Munich & Columbia

Conclusions

- ✔ Rich internal structure
- ✔ Long **rotational** and **nuclear spin coherence times** (100ms – 1s) compared to interaction timescale (~ kHz)
- ✔ Tunable interactions for quantum magnetism: spin-exchange, Ising, spatial anisotropy
- ✔ **Quantum gas microscopy** □ measurable quantum correlations
- ✔ Outlook: Dipolar Bose-Hubbard models with strong interactions



Thank you!

Fermi-Hubbard

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