Quantum condensed matter physics: organic insulators and ultracold atoms

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Outline

1. Organic insulators:
antiferromagnets on the triangular lattice

2. Ultracold atoms:
bosons in tilted Mott insulators

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2. Ultracold atoms:
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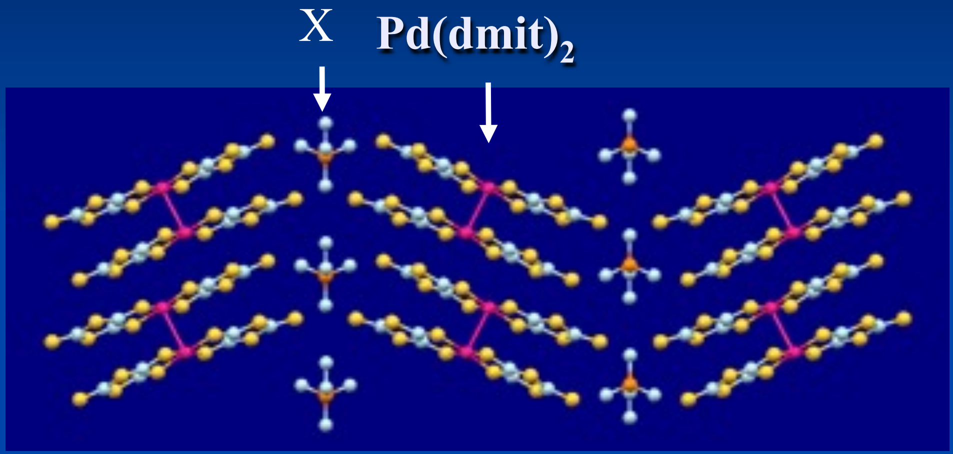
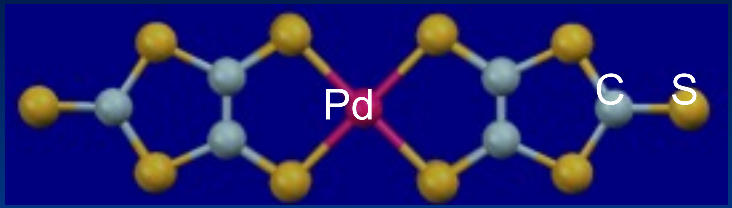
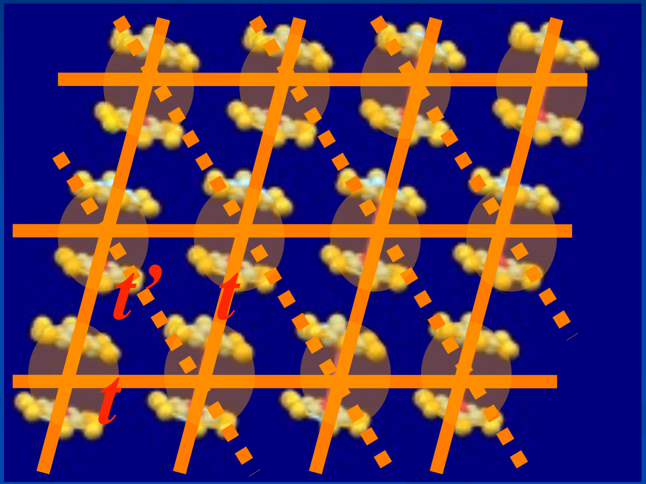
$X[Pd(dmit)_2]_2$







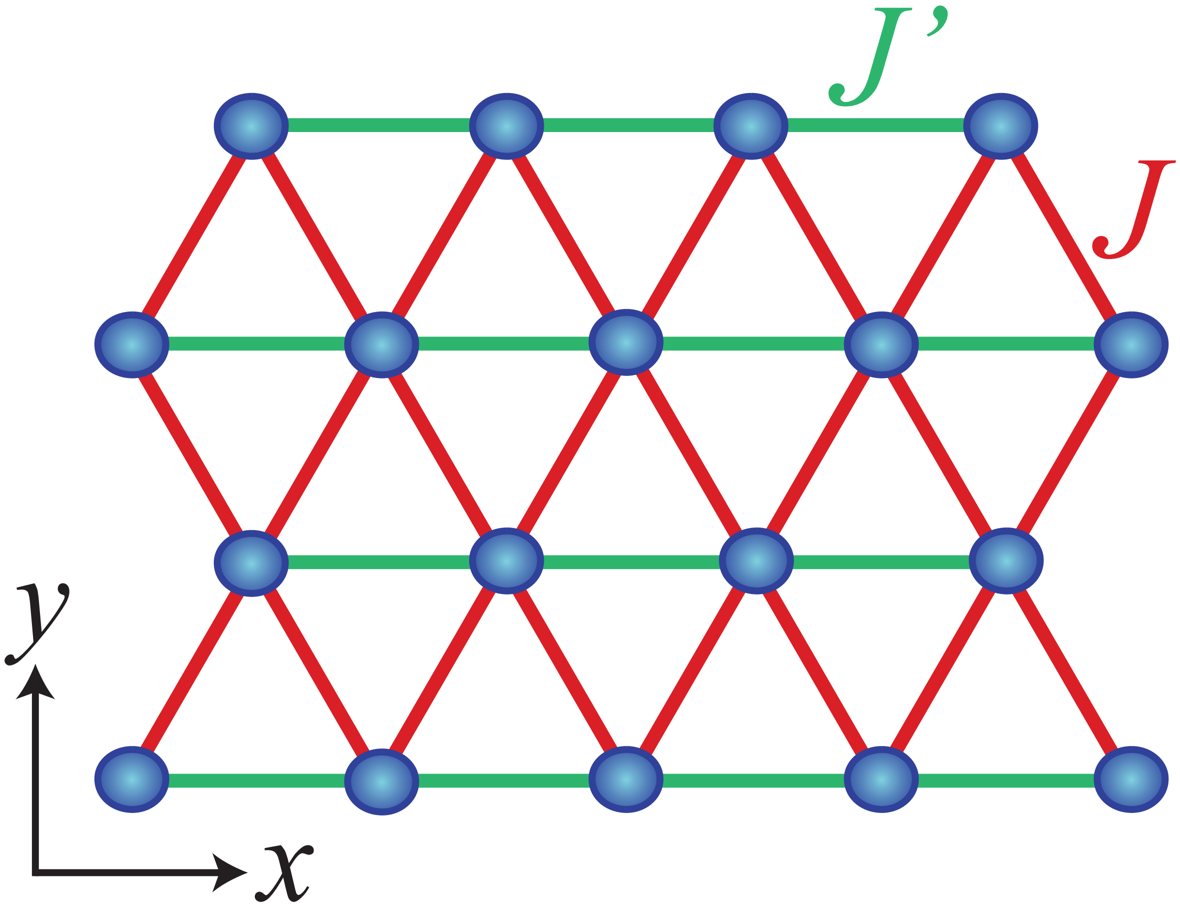
Half-filled band → Mott insulator with spin S = 1/2

Triangular lattice of $[Pd(dmit)_2]_2$

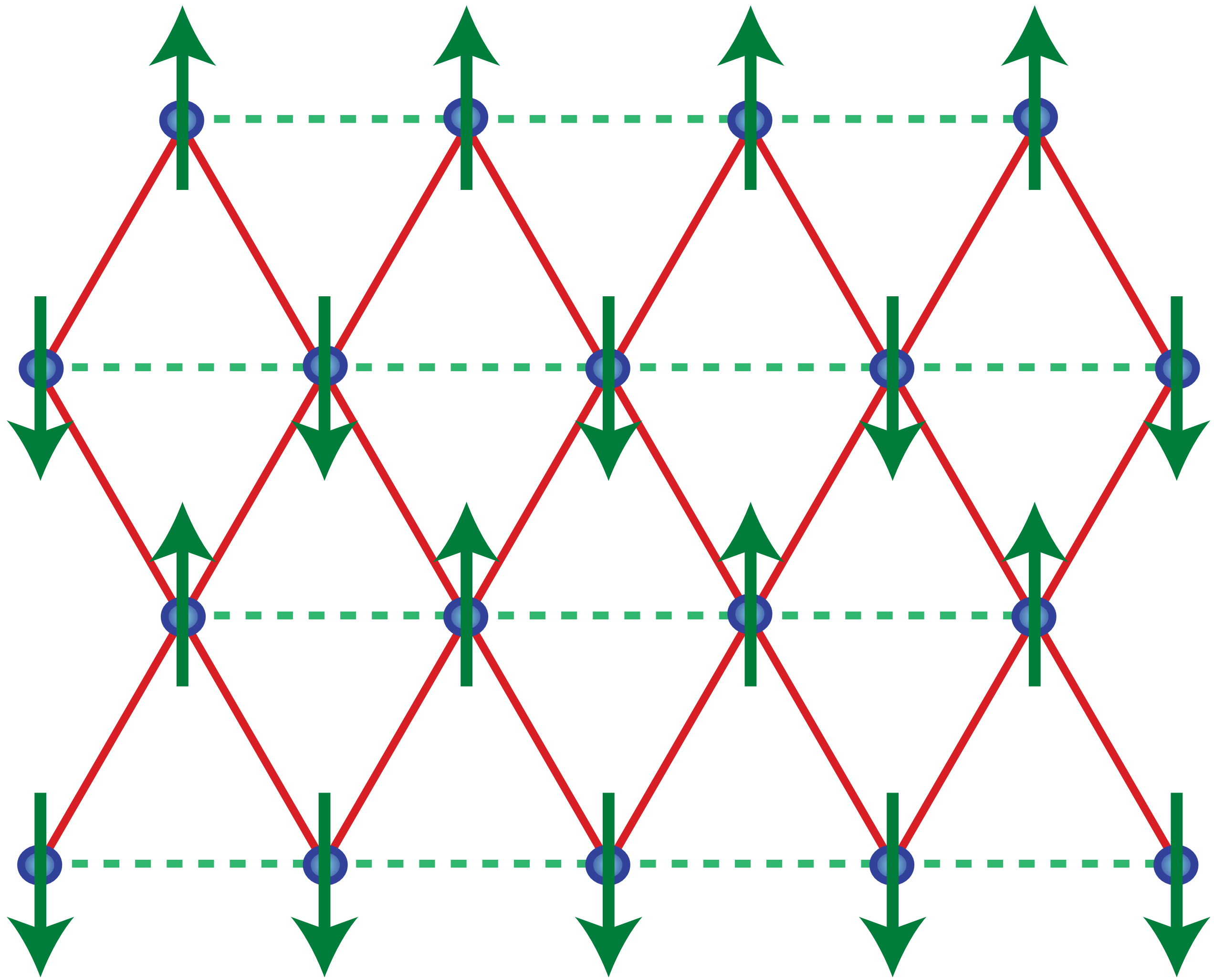
→ frustrated quantum spin system

$$H = \sum_{\langle ij \rangle} J_{ij} \vec{S}_i \cdot \vec{S}_j + \ldots$$

$\vec{S}_i \Rightarrow$ spin operator with $S = 1/2$



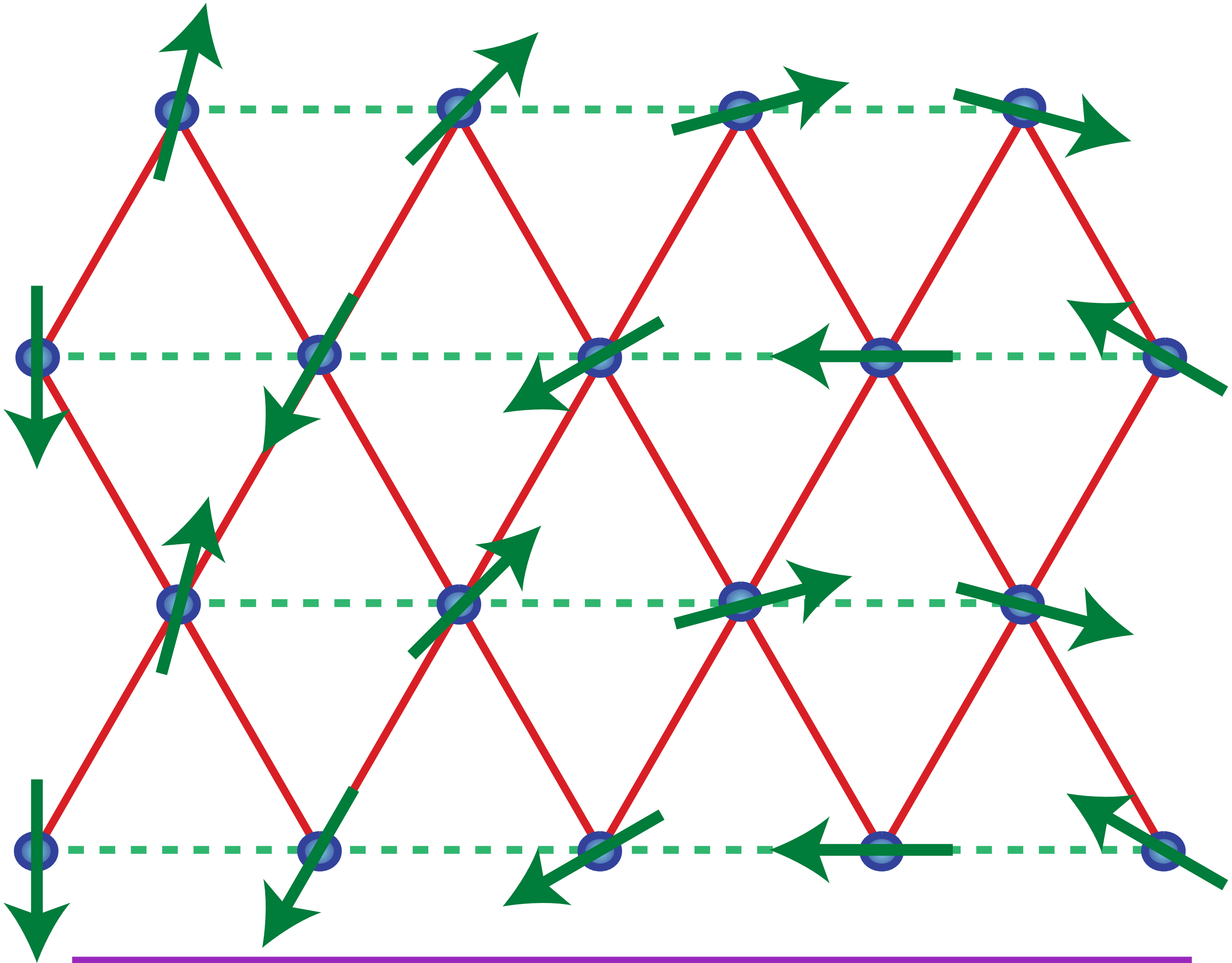
Anisotropic triangular lattice antiferromagnet



Classical ground state for small J'/J

Found in κ-$(ET)_2Cu[N(CN)_2]Cl$

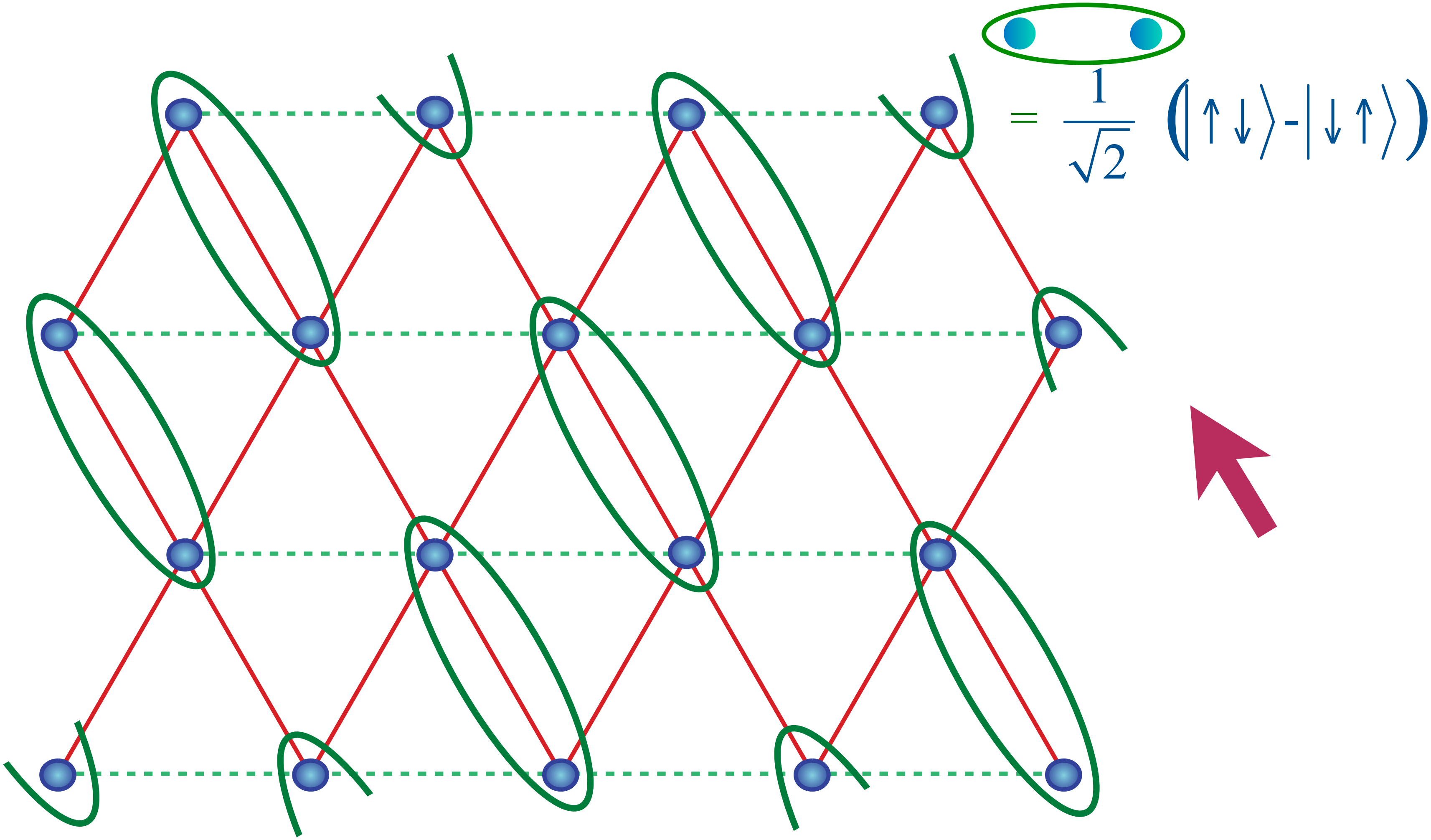
Anisotropic triangular lattice antiferromagnet



Classical ground state for large J'/J

Found in Cs_2CuCl_4

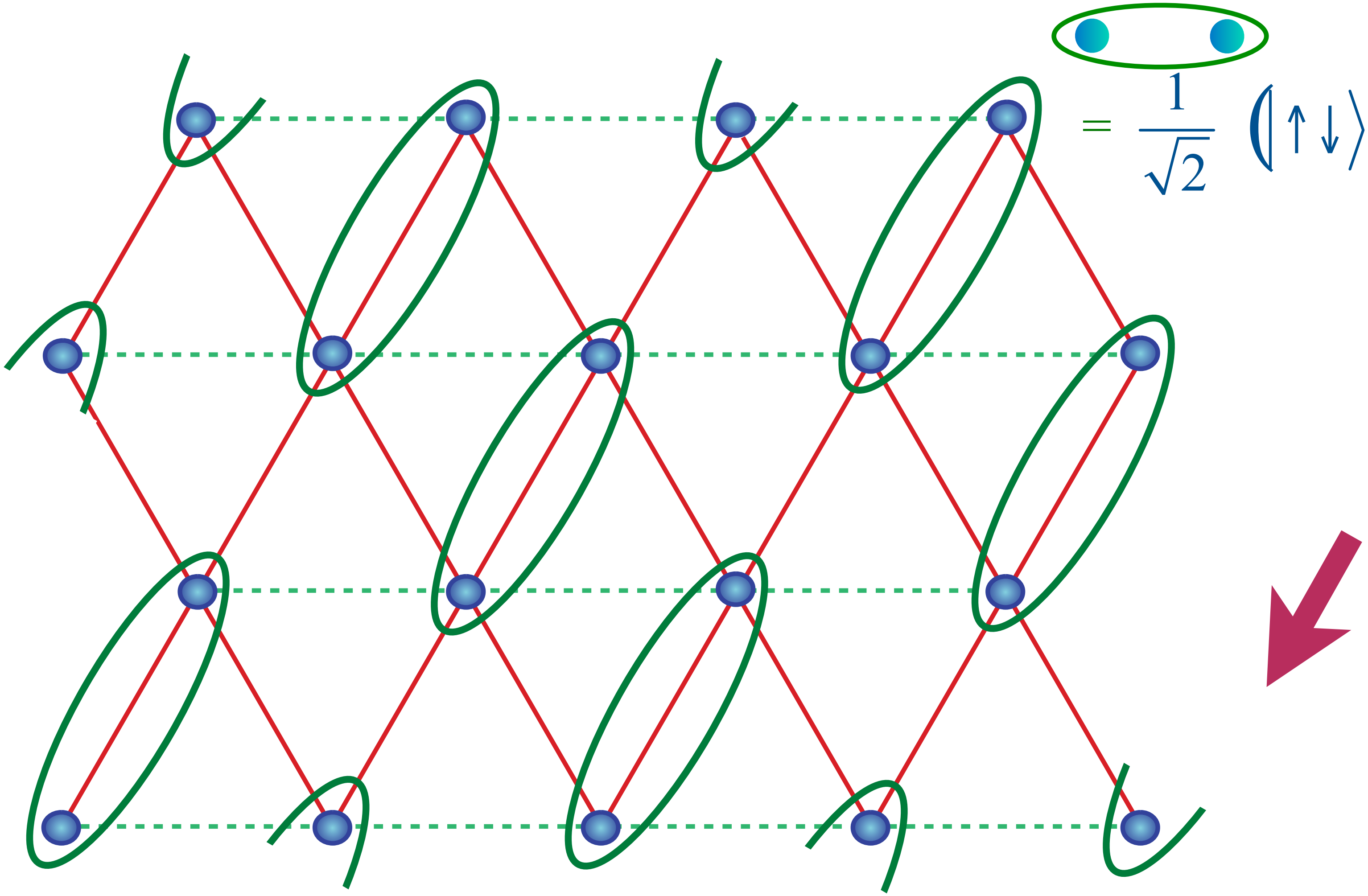
Anisotropic triangular lattice antiferromagnet



Valence bond solid

N. Read and S. Sachdev, *Phys. Rev. Lett.* **62**, 1694 (1989)

Anisotropic triangular lattice antiferromagnet



$$= \frac{1}{\sqrt{2}} \left(\left| \uparrow \downarrow \right\rangle - \left| \downarrow \uparrow \right\rangle \right)$$

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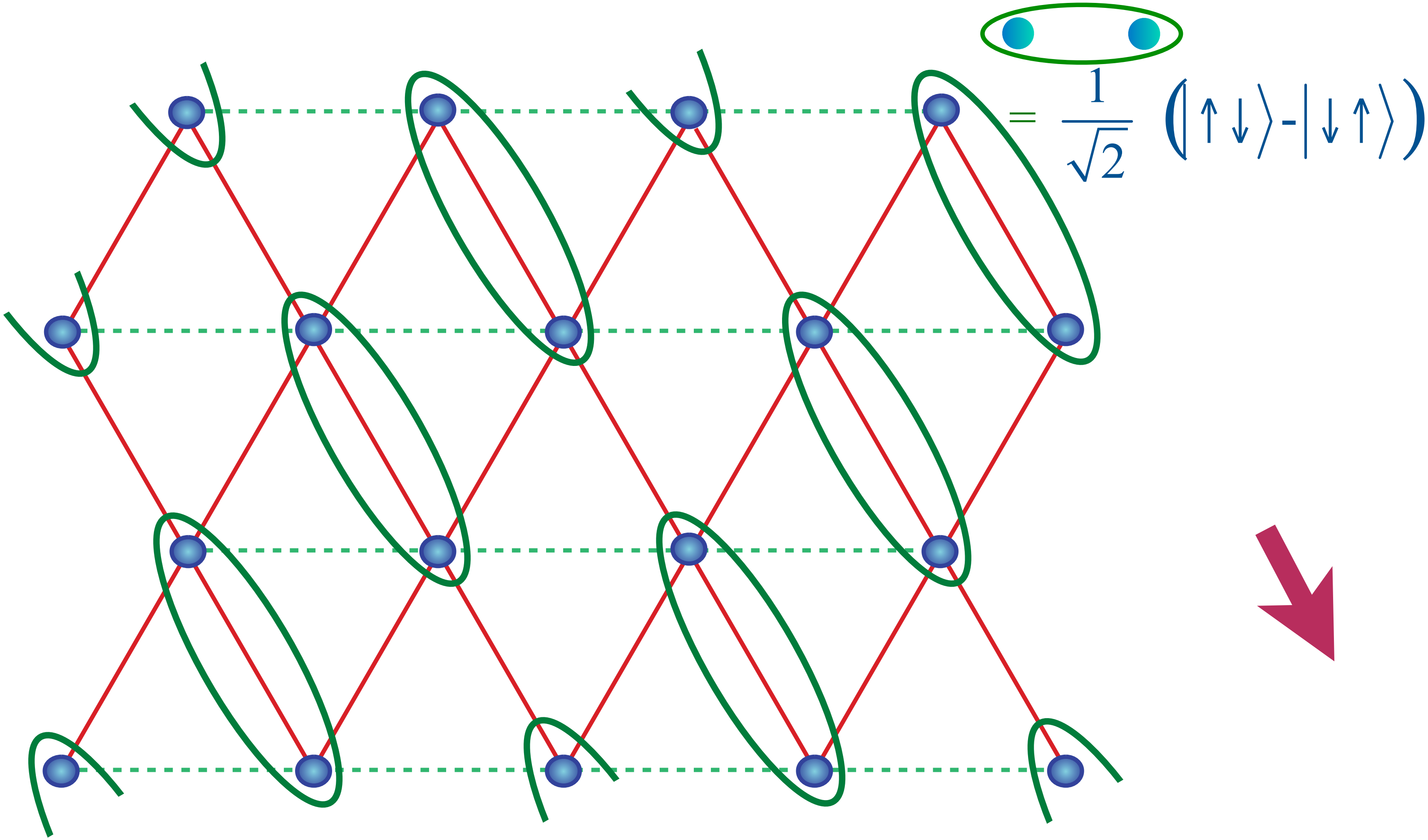

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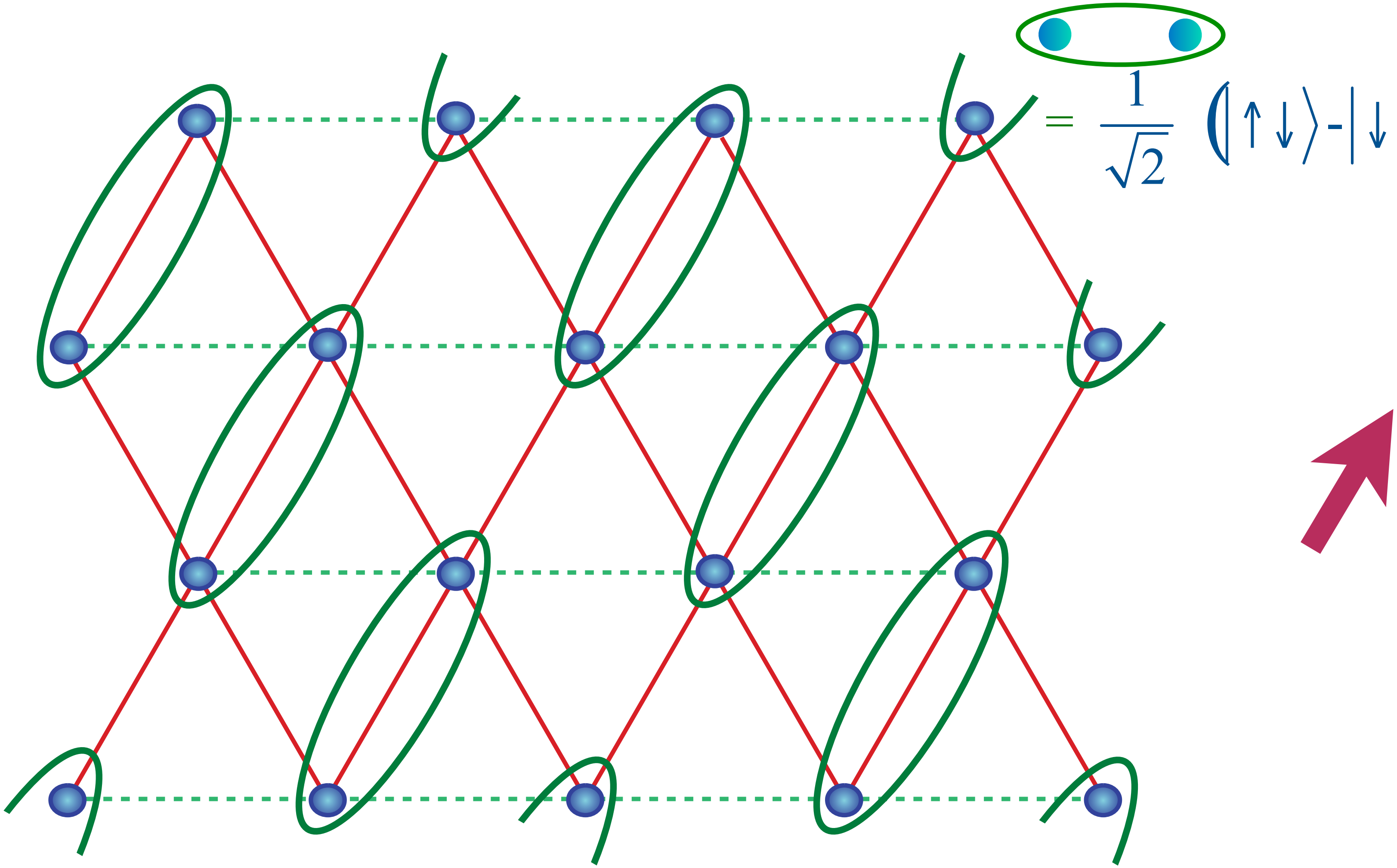

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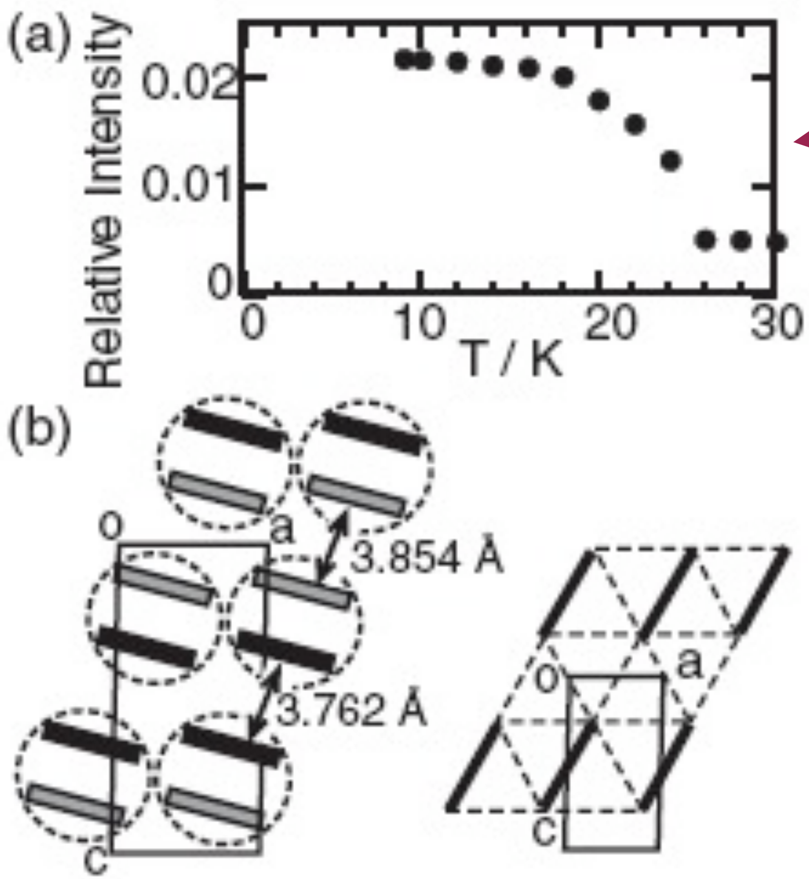
Observation of a valence bond solid (VBS) in $ETMe_3P[Pd(dmit)_2]_2$

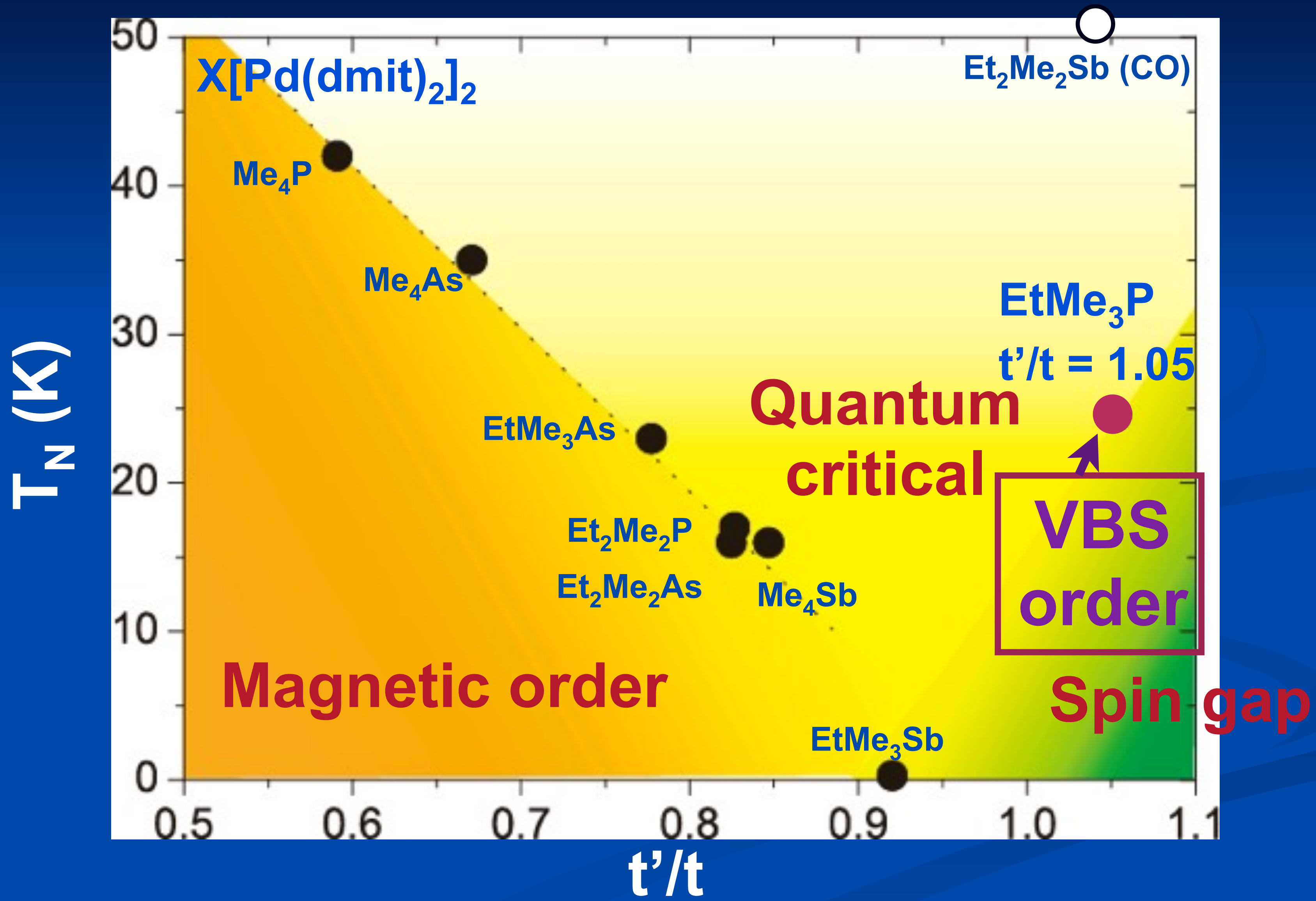


X-ray scattering

Spin gap ~ 40 K
J ~ 250 K

M. Tamura, A. Nakao and R. Kato, *J. Phys. Soc. Japan* **75**, 093701 (2006)
Y. Shimizu, H. Akimoto, H. Tsujii, A. Tajima, and R. Kato, *Phys. Rev. Lett.* **99**, 256403 (2007)

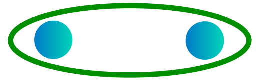
Magnetic Criticality



Y. Shimizu, H. Akimoto, H. Tsujii, A. Tajima, and R. Kato, *J. Phys.: Condens. Matter* **19**, 145240 (2007)

Triangular lattice antiferromagnet

Z_2 spin liquid



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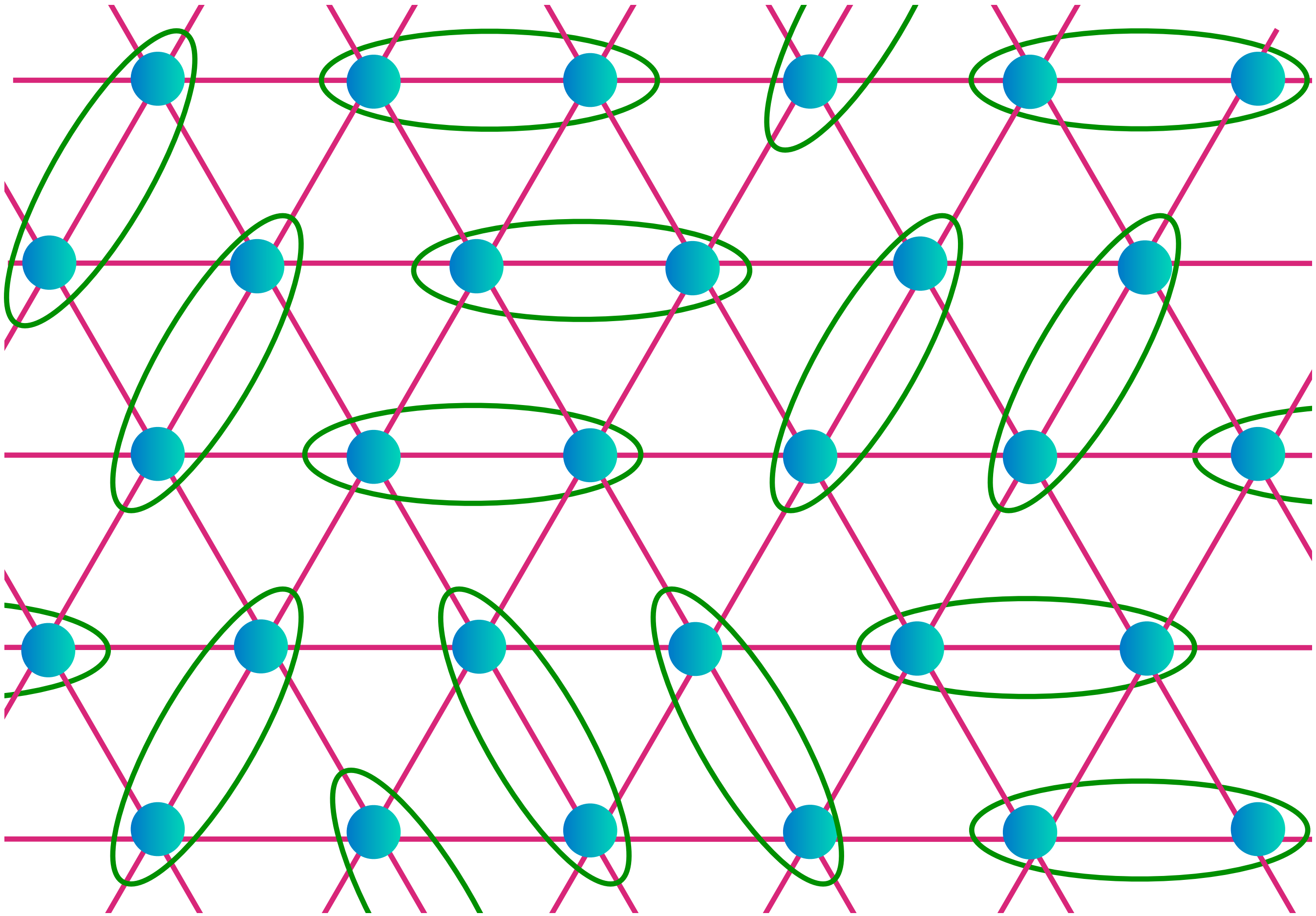

P. Fazekas and P. W. Anderson, *Philos. Mag.* **30**, 23 (1974).
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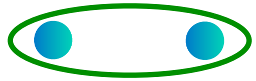

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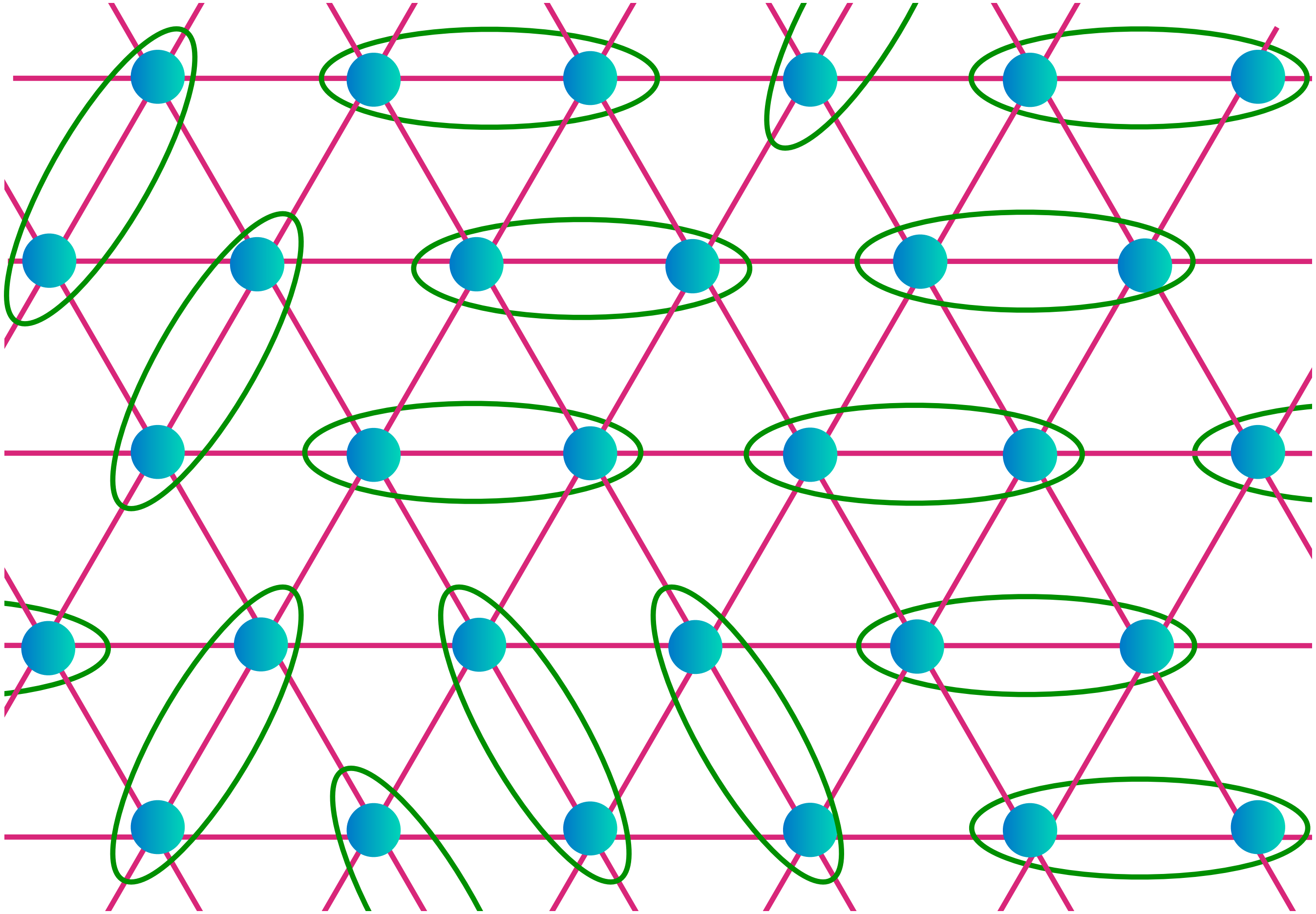

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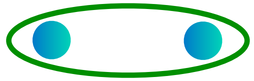

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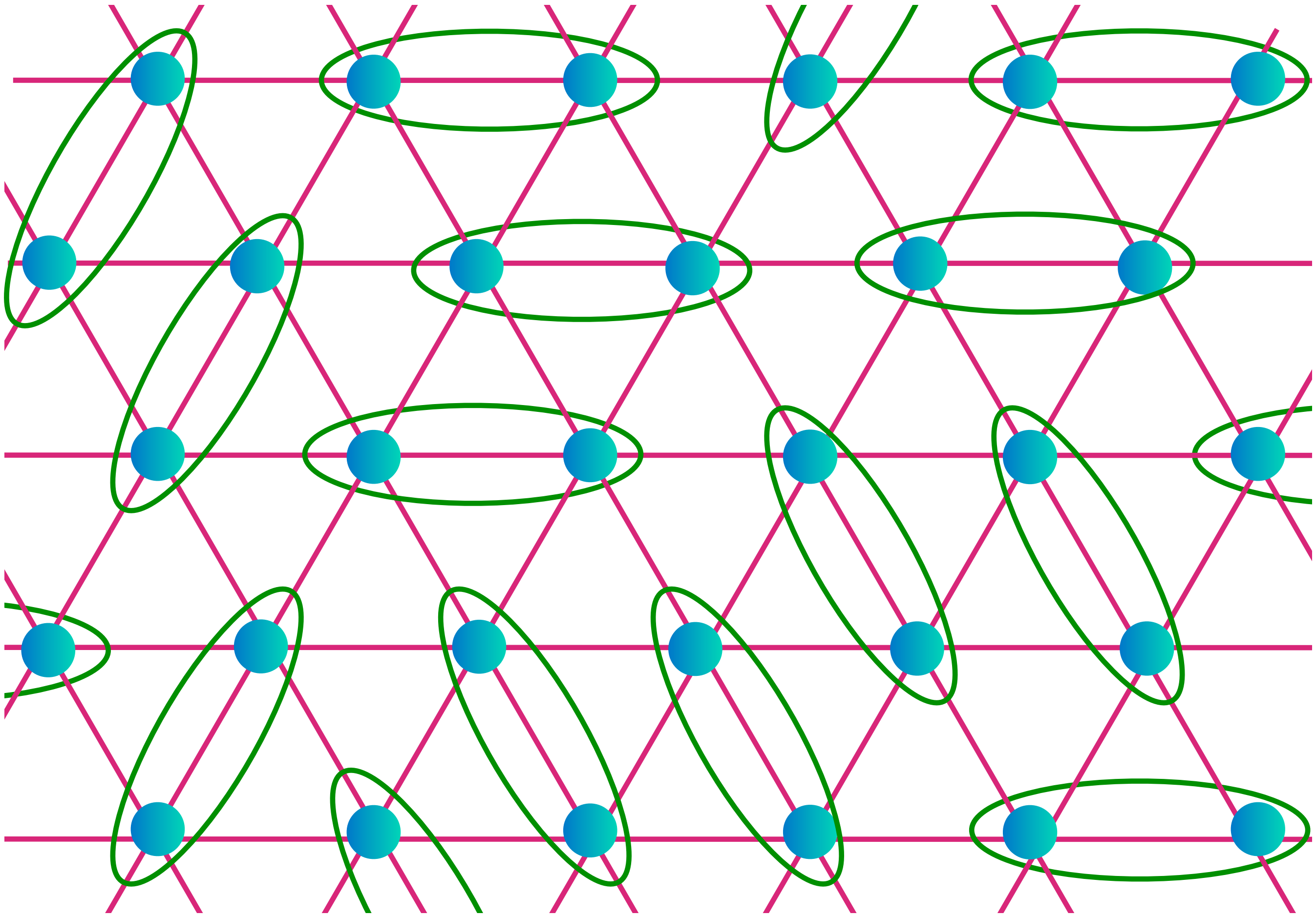

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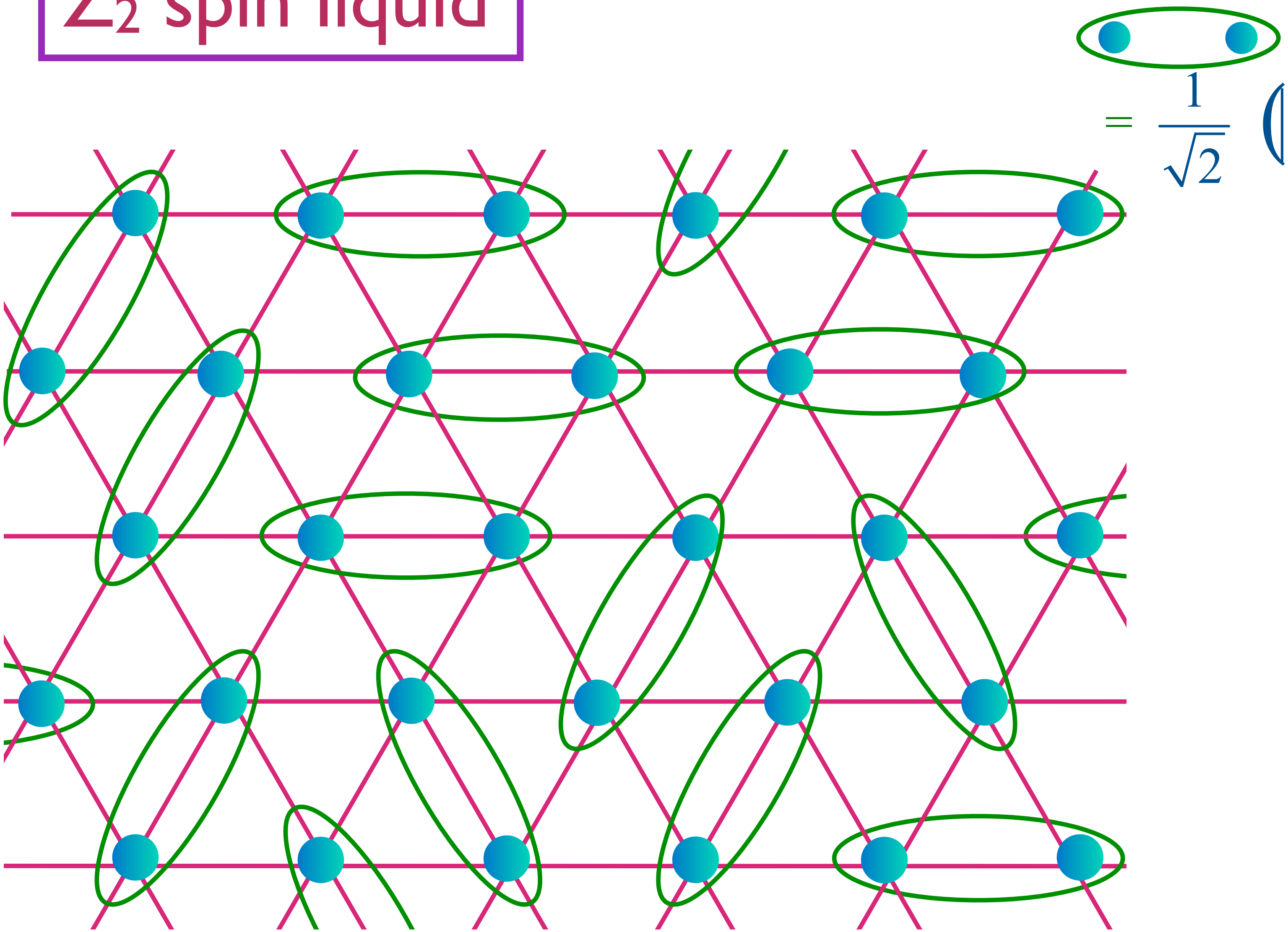

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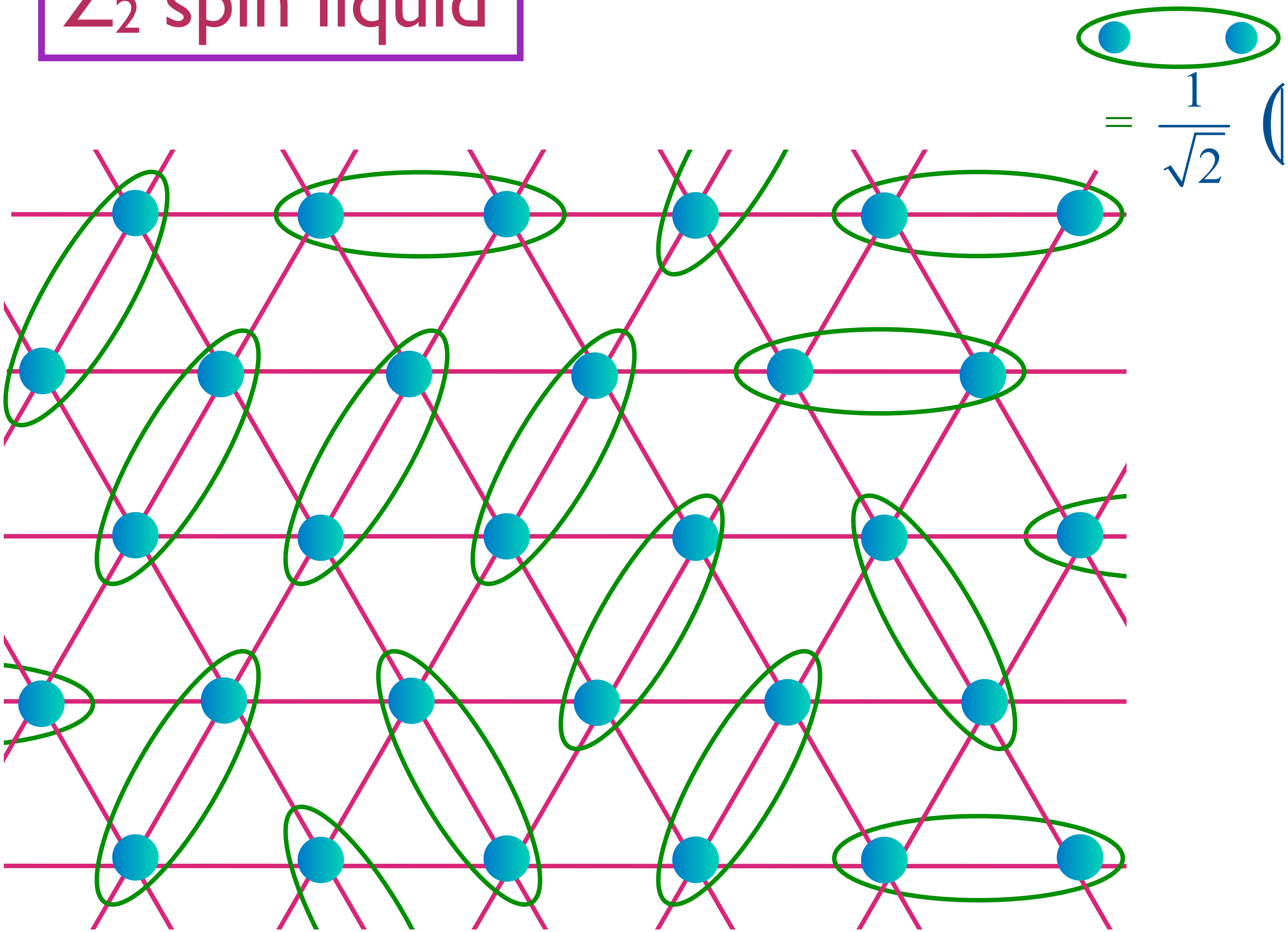

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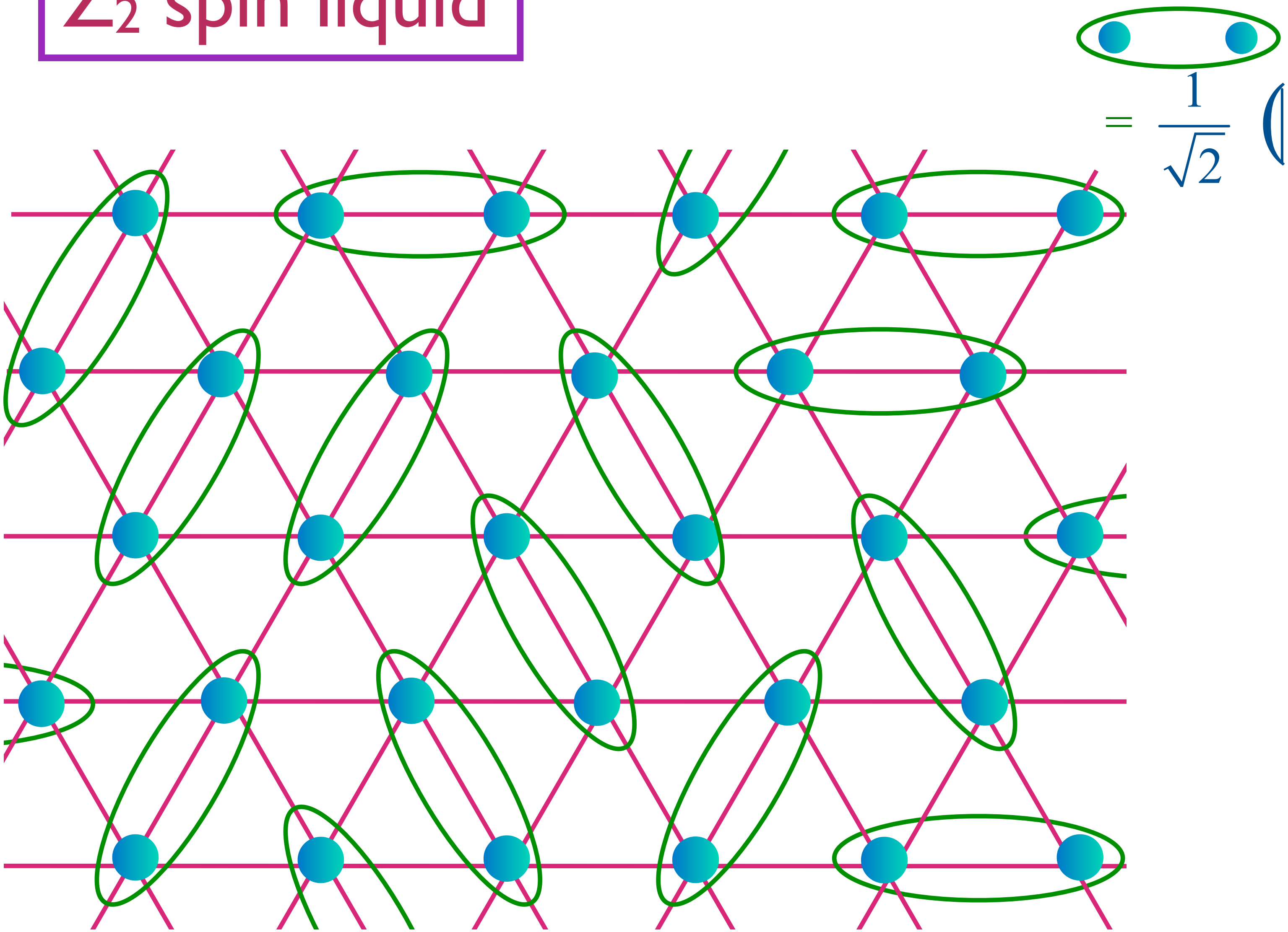

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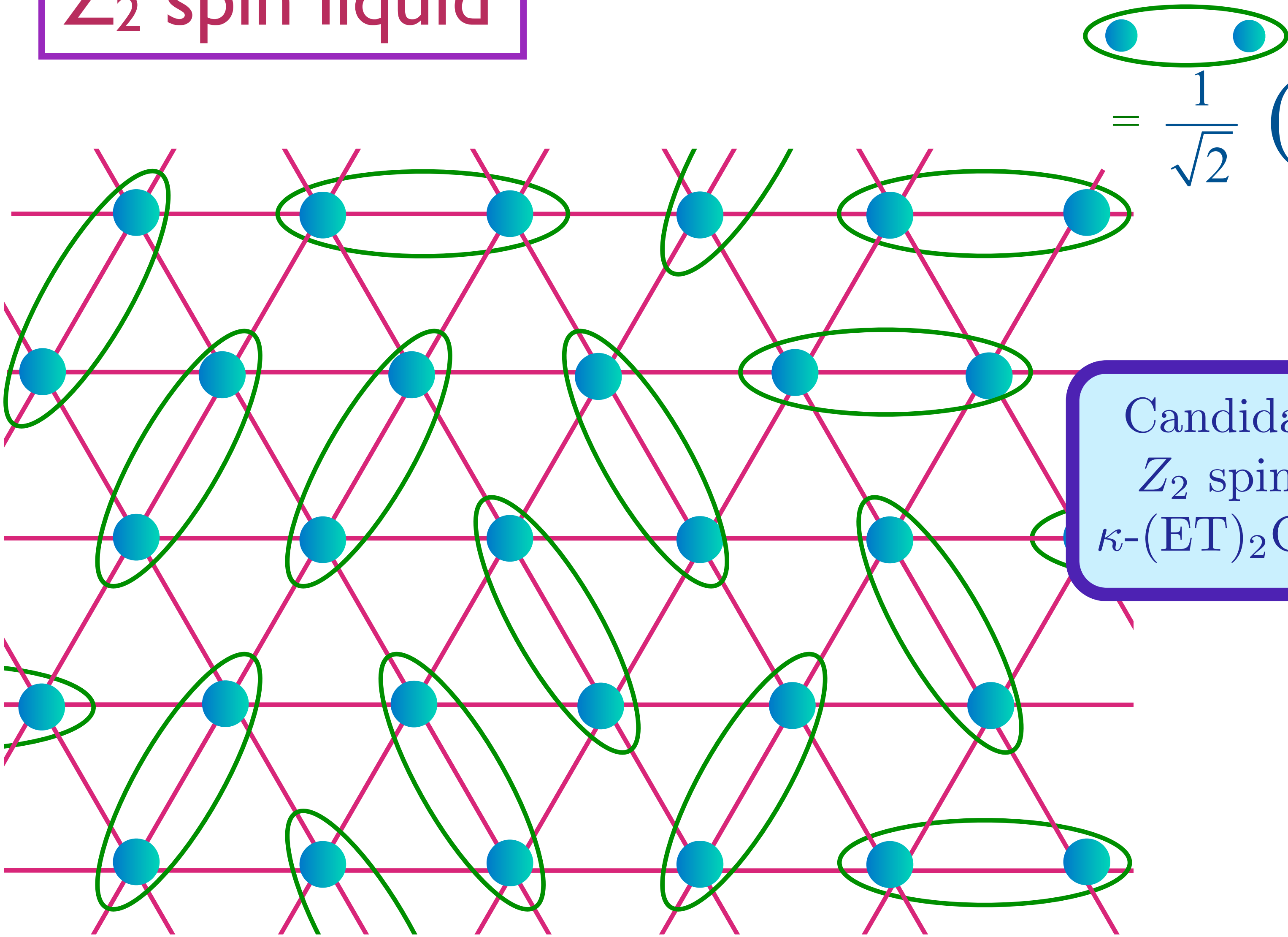

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Candidate for a Z_2 spin liquid: κ-$(ET)_2Cu_2(CN)_3$

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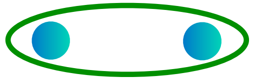
N. Read and S. Sachdev, *Phys. Rev. Lett.* **66**, 1773 (1991)

Excitations of the Z_2 Spin liquid

A vison



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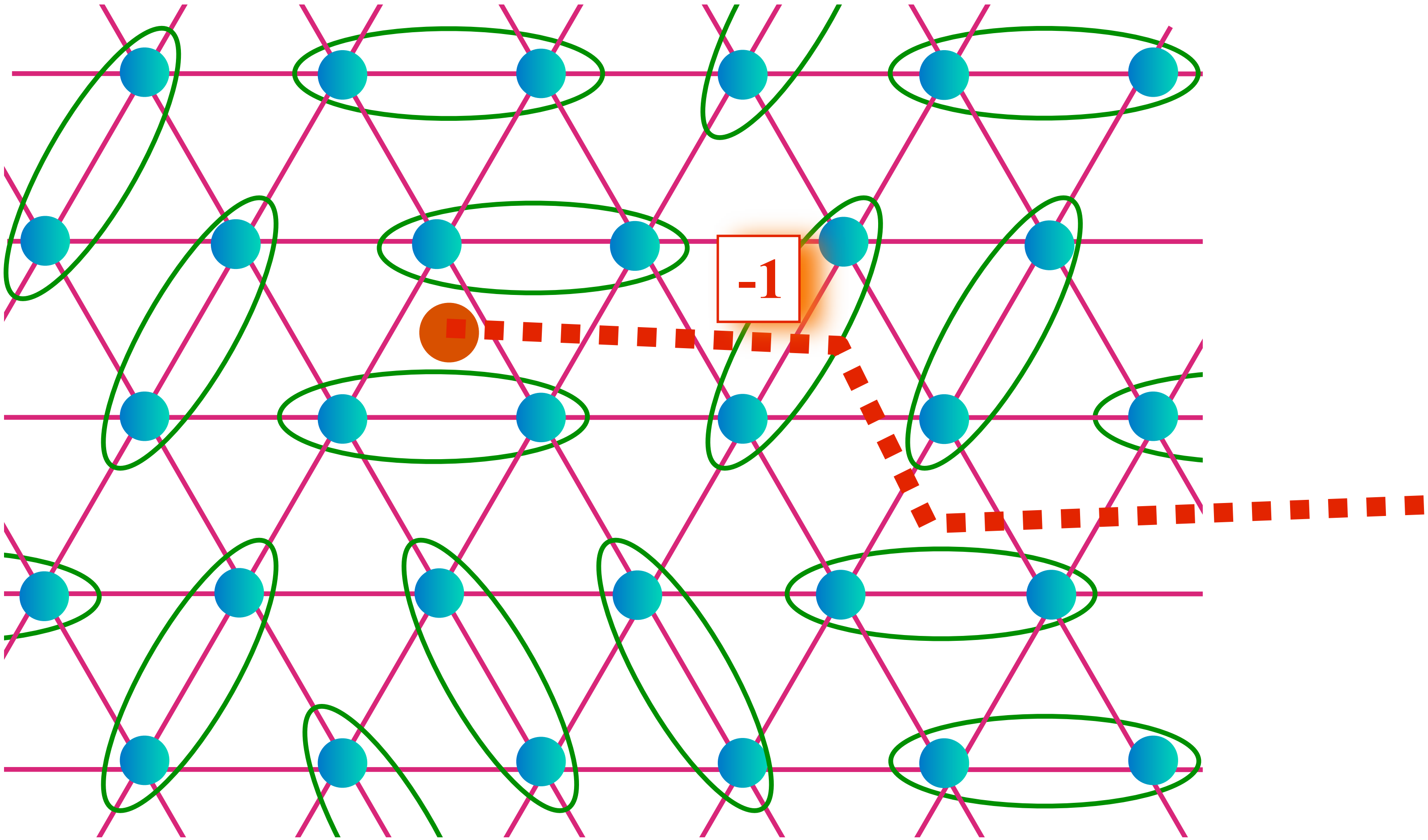

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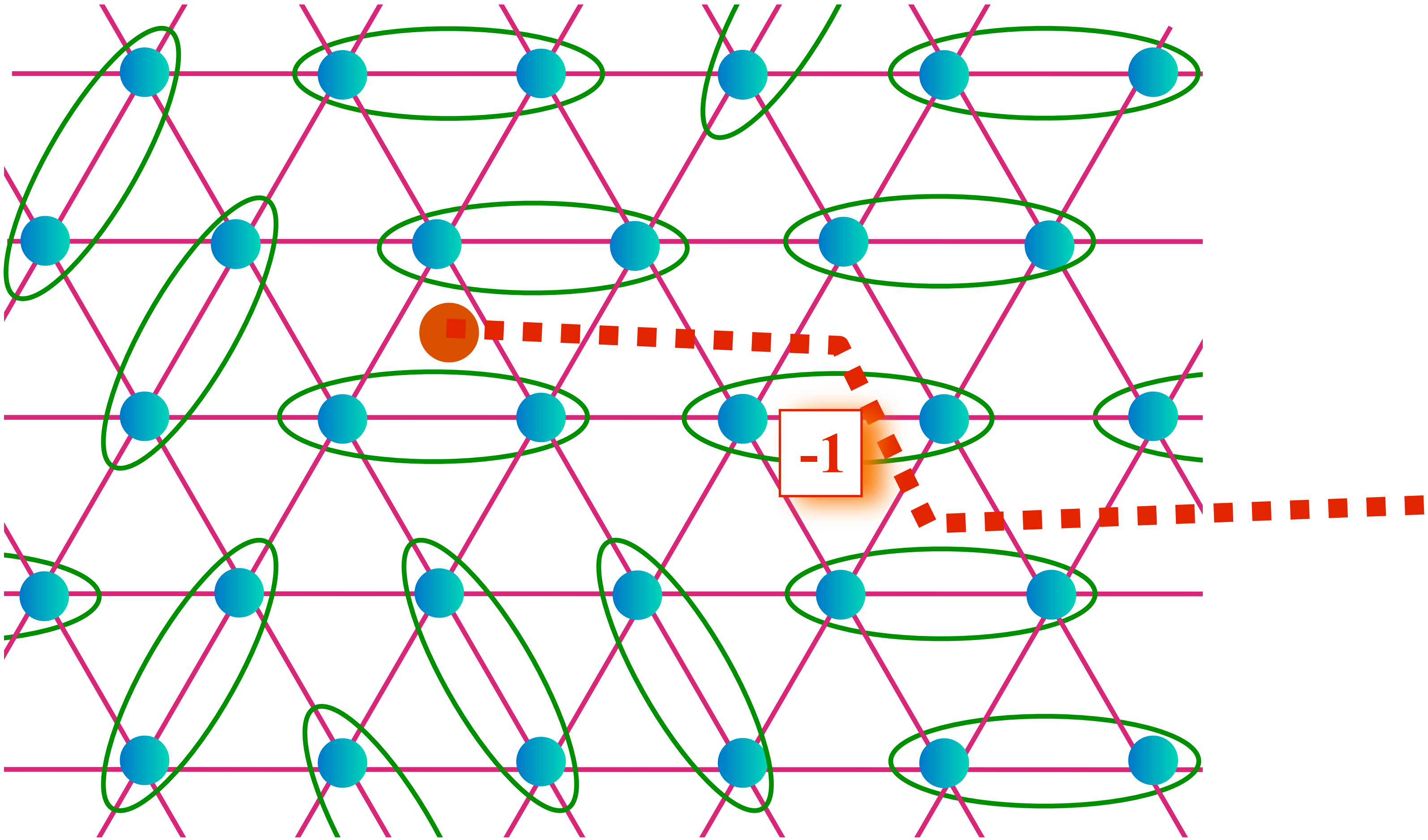

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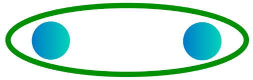

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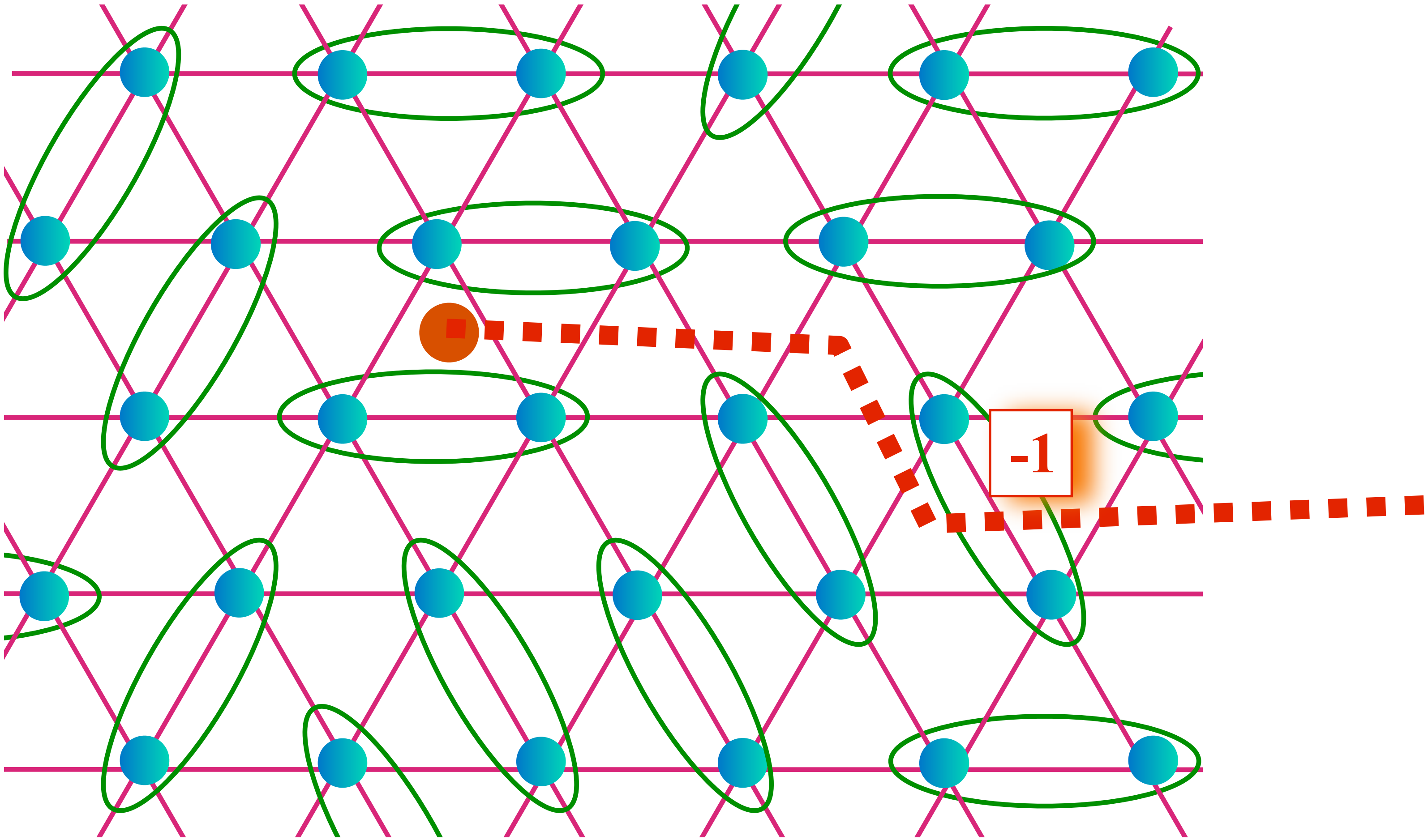

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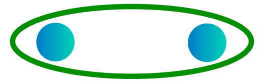

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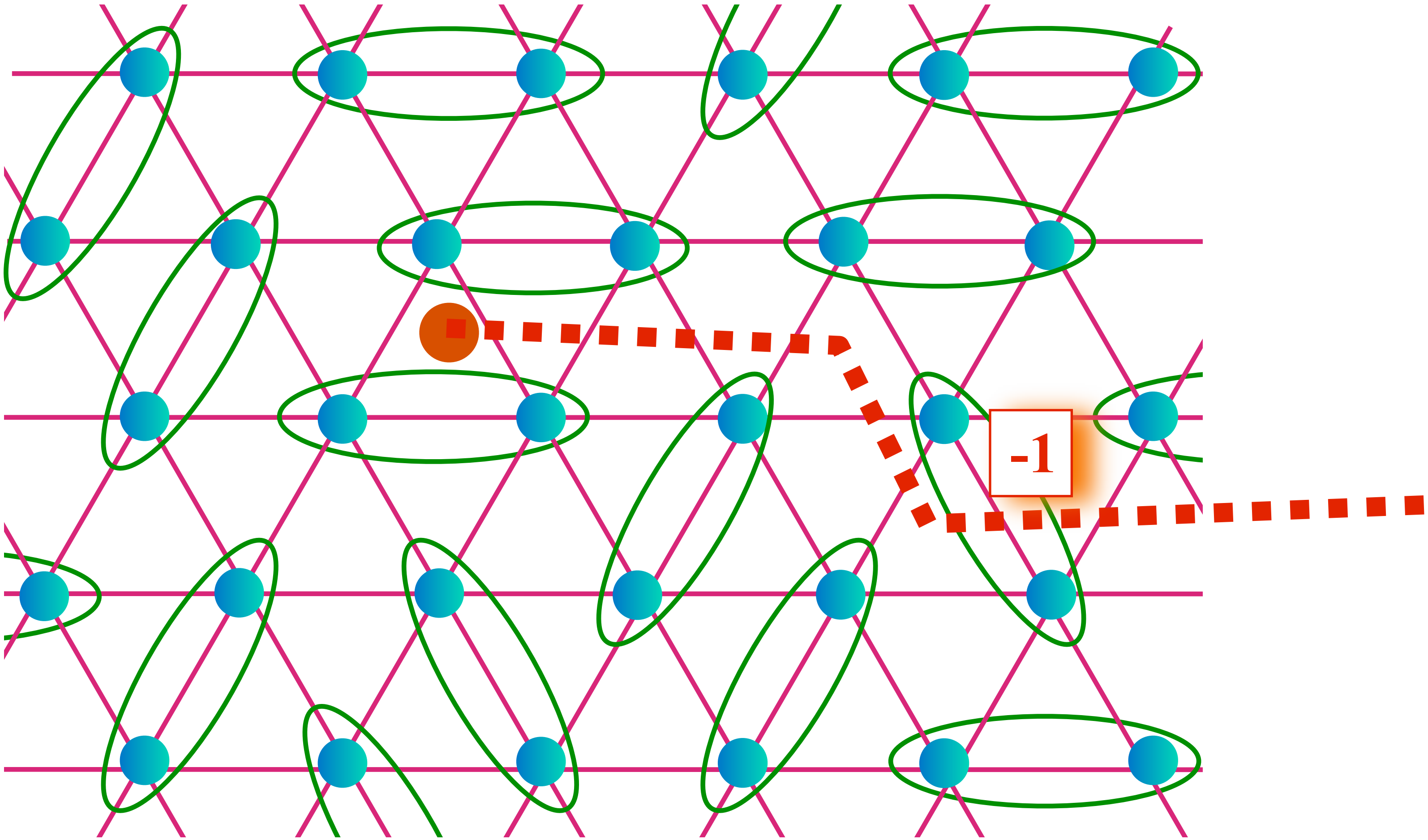

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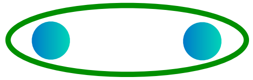

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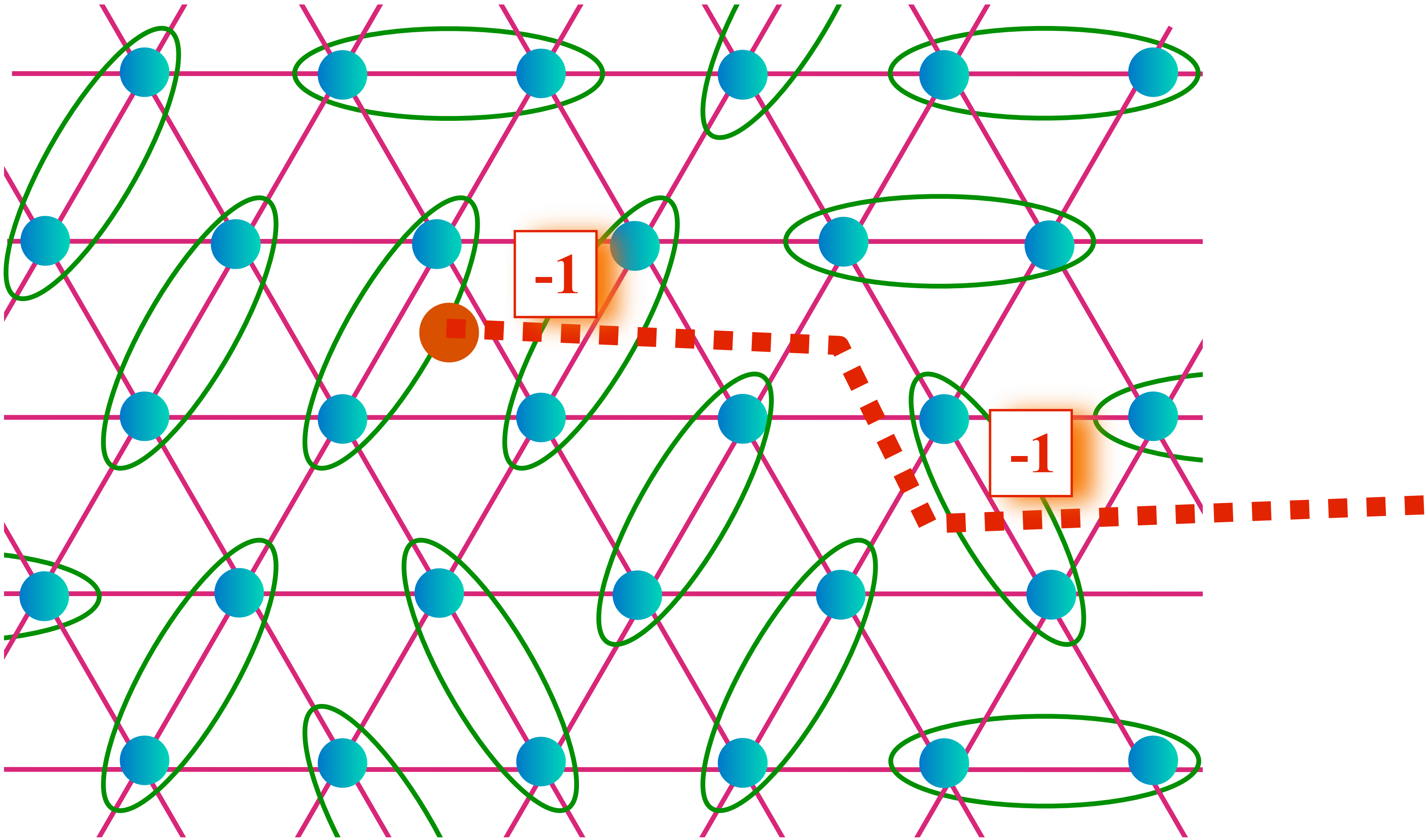

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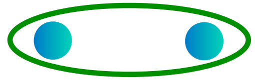

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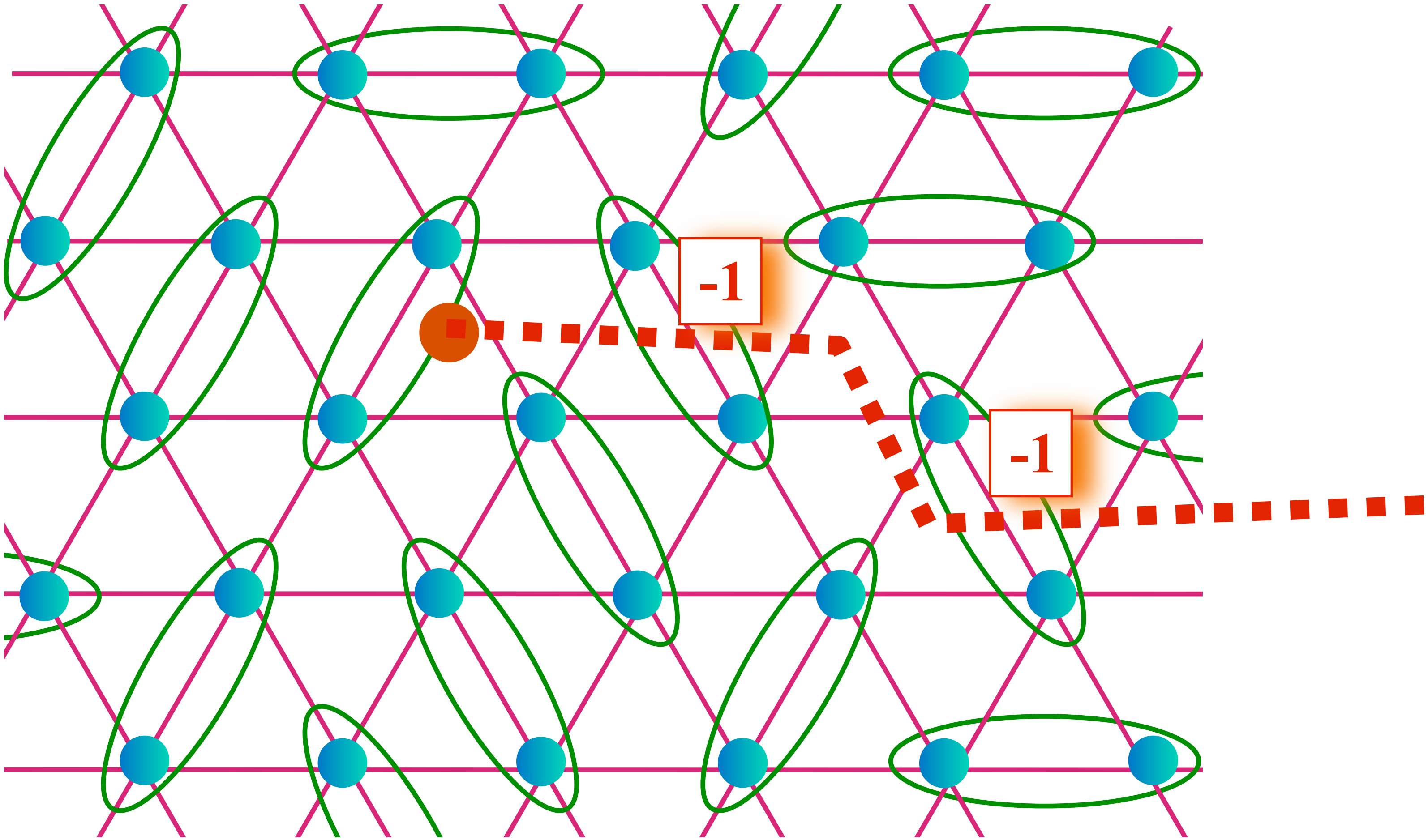


N. Read and S. Sachdev, *Phys. Rev. Lett.* **66**, 1773 (1991)

Excitations of the Z_2 Spin liquid

A vison

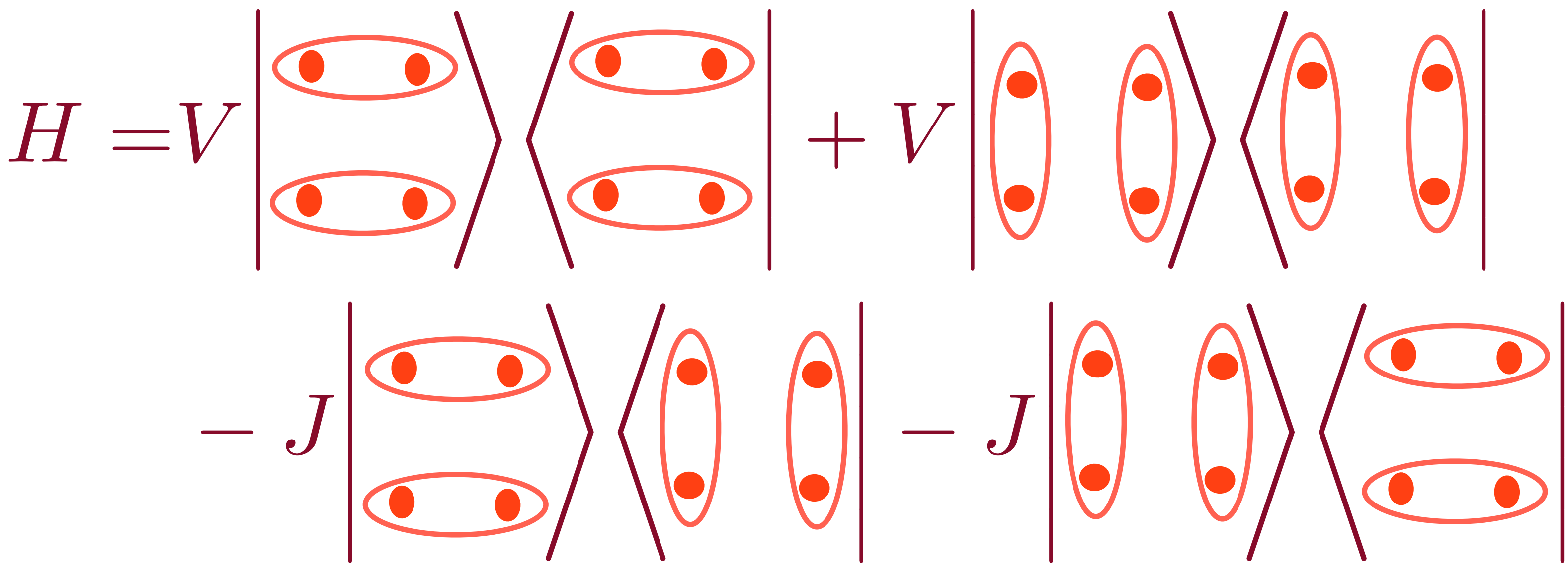
- A characteristic property of a Z_2 spin liquid is the presence of a spinon pair condensate
- A vison is an Abrikosov vortex in the pair condensate of spinons
- Visons are are the **dark matter** of spin liquids: they likely carry most of the energy, but are very hard to detect because they do not carry charge or spin.

N. Read and S. Sachdev, *Phys. Rev. Lett*. **66**, 1773 (1991)

Effective description of Z_2 spin liquids, their visons and valence bond solids

Quantum dimer model:

Hilbert space - set of dimer coverings of triangular/square lattice



D. Rokhsar and S. A. Kivelson, *Phys. Rev. Lett.* **61**, 2376 (1988)
R. Moessner and S. L. Sondhi, *Phys. Rev. Lett.* **86**, 1881 (2001)

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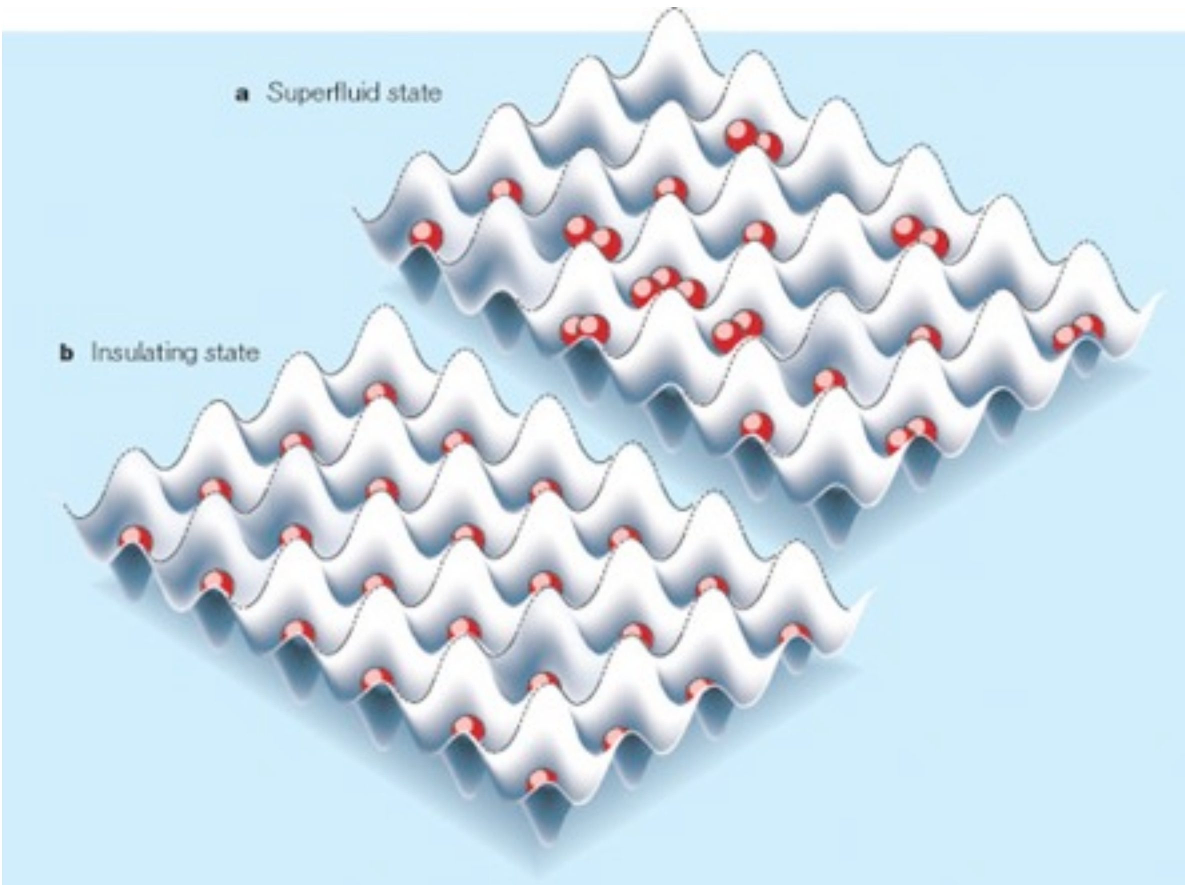
Takuya
Kitagawa

Erez
Berg

S. Sachdev, K. Sengupta, and S.M. Girvin, Phys. Rev. B 66, 075128 (2002)
S. Pielawa, T. Kitagawa, E. Berg, S. Sachdev, arXiv:1101.2897

Superfluid-insulator transition of ^{87}Rb atoms in a magnetic trap and an optical lattice potential



M. Greiner, O. Mandel, T. Esslinger, T. W. Hänsch, and I. Bloch, *Nature* **415**, 39 (2002).

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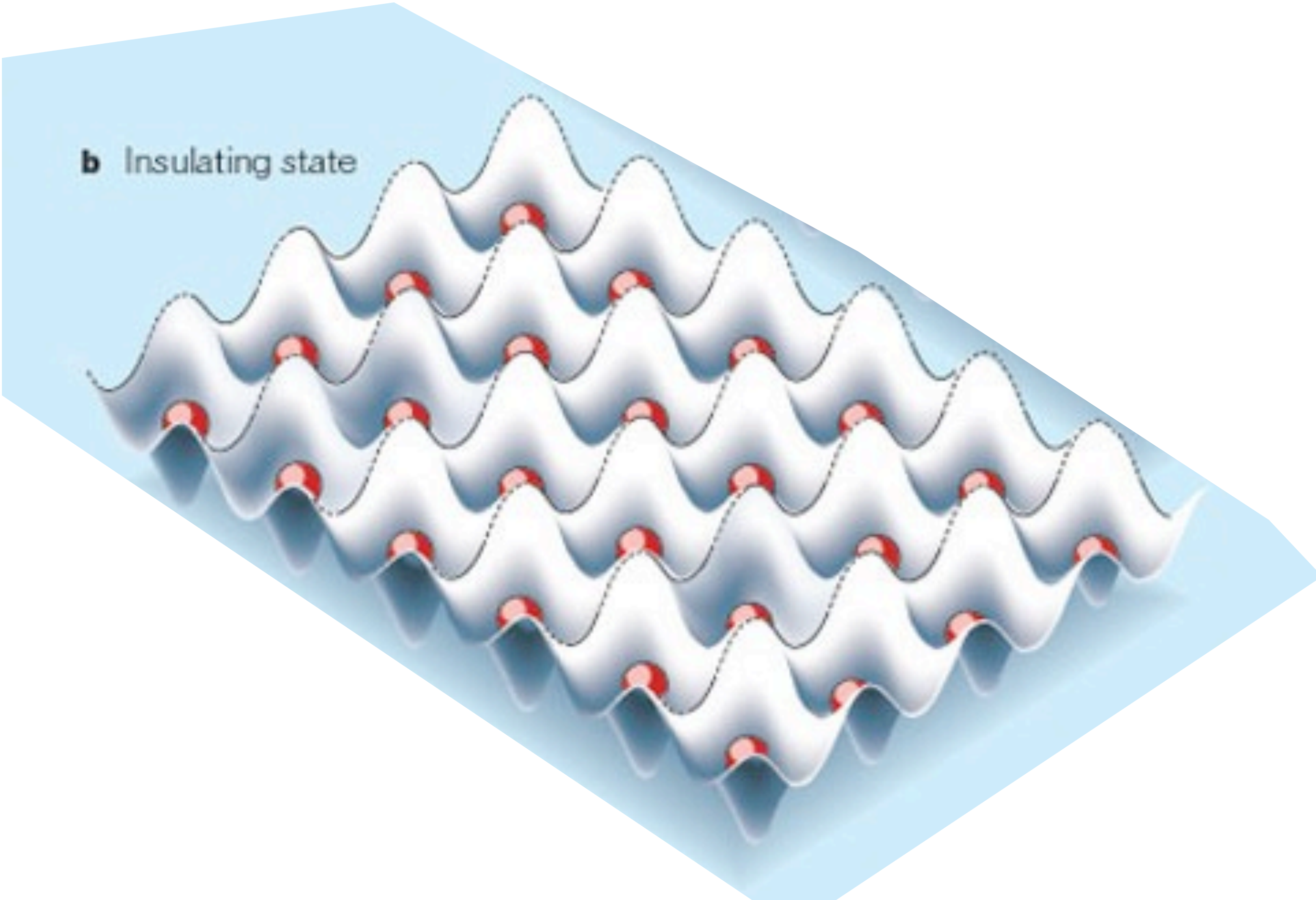

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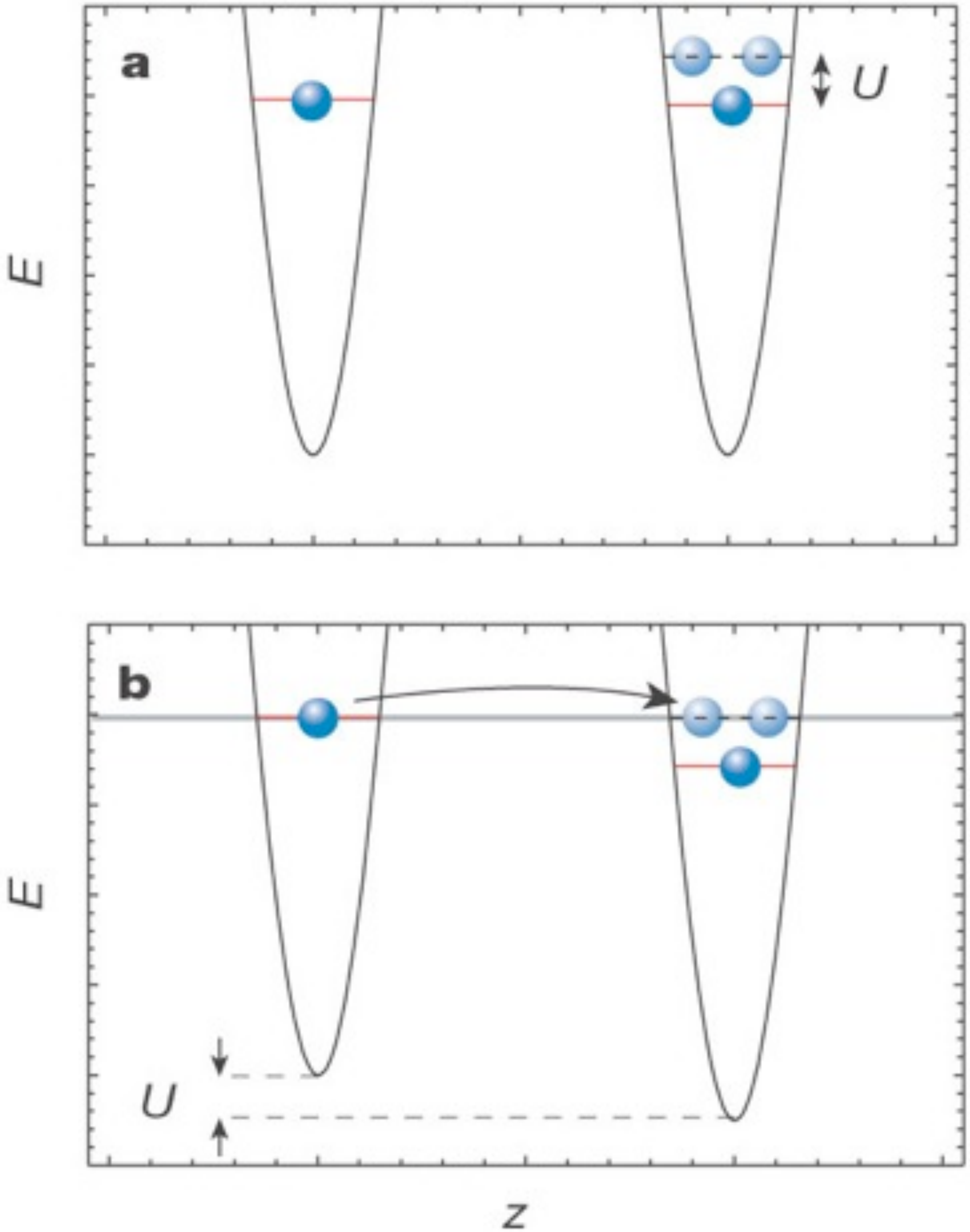
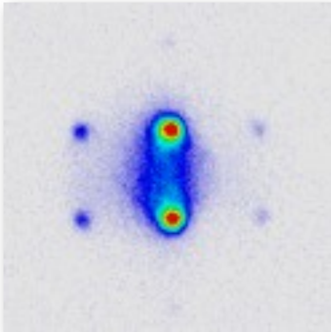
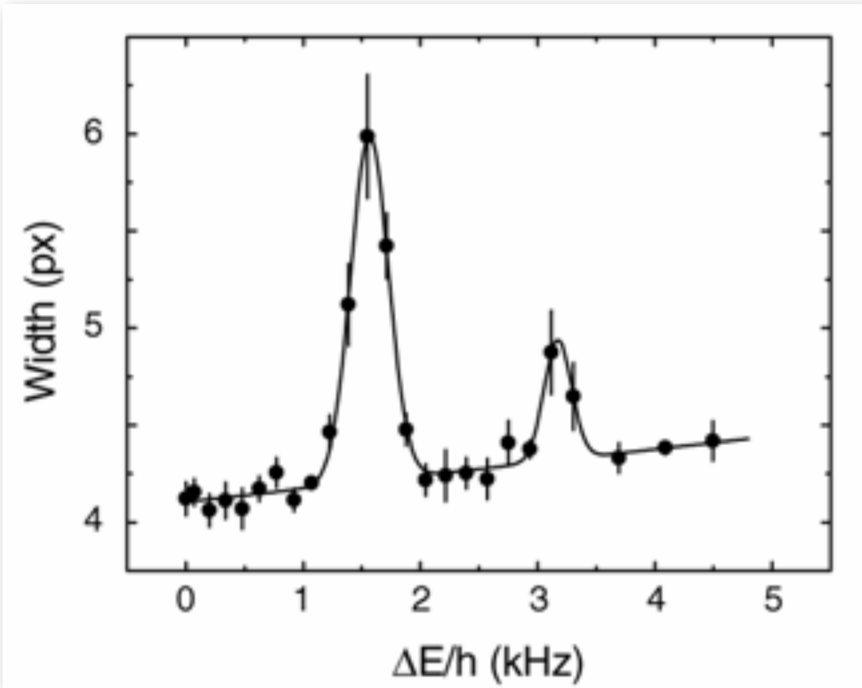
Applying an "electric" field to the Mott insulator



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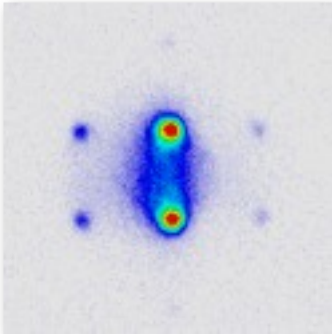
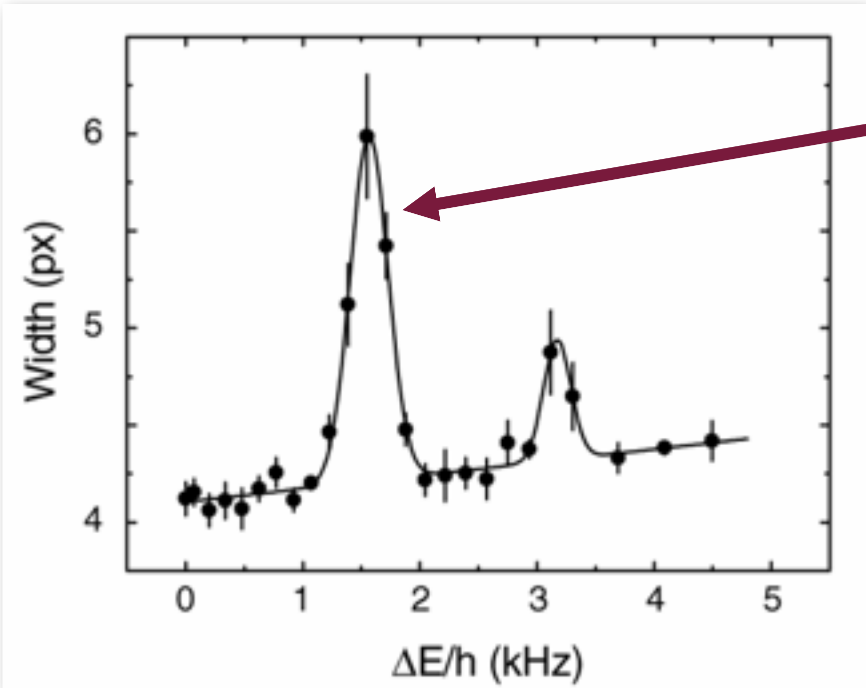
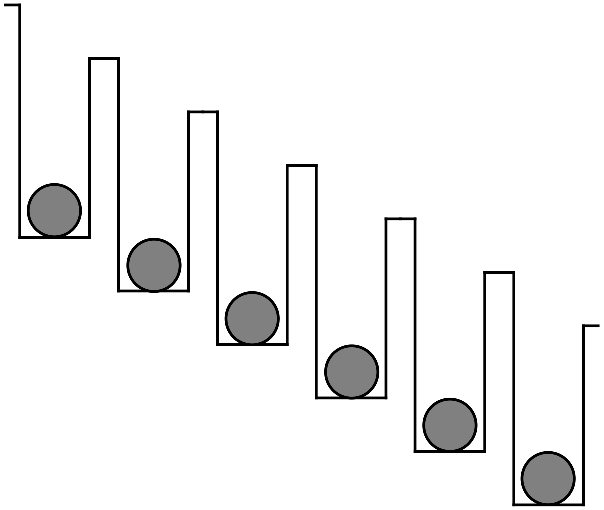
ΔE/h (kHz)





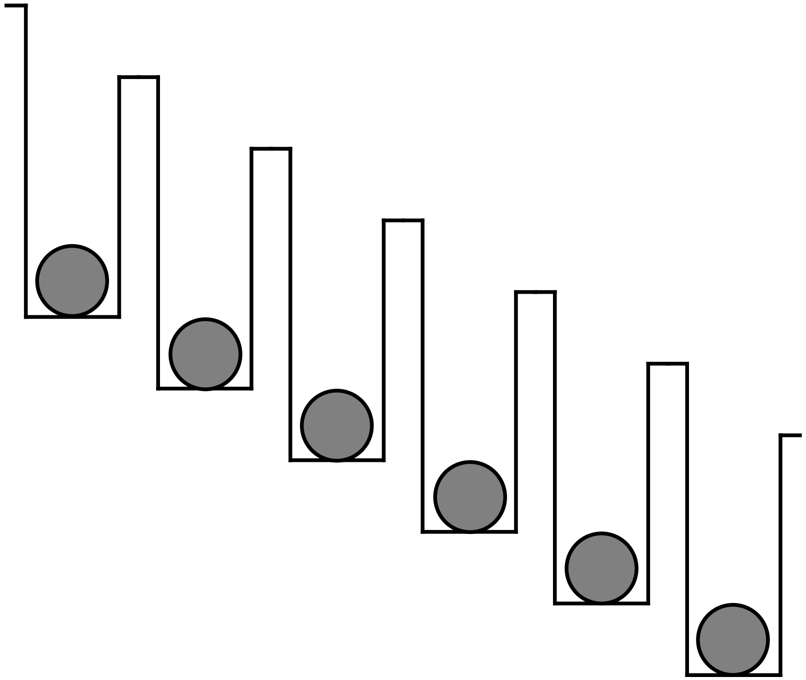
Why is there a peak (and not a threshold) when E = U ?

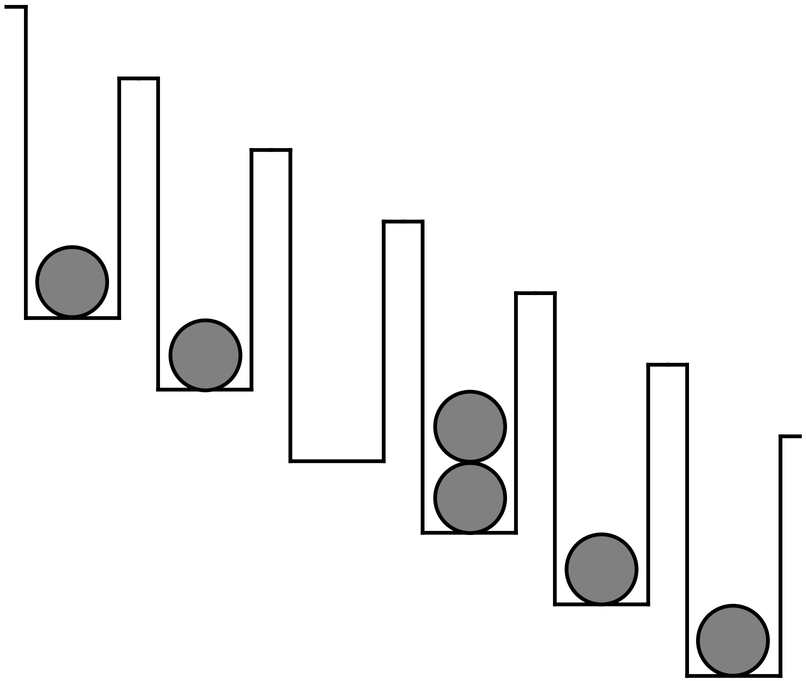


$$H = -t \sum_{\langle ij \rangle} \left(b_i^\dagger b_j + b_j^\dagger b_i \right) + \frac{U}{2} \sum_i n_i \left(n_i - 1 \right) - \sum_i \boldsymbol{E} \cdot \boldsymbol{r}_i n_i$$

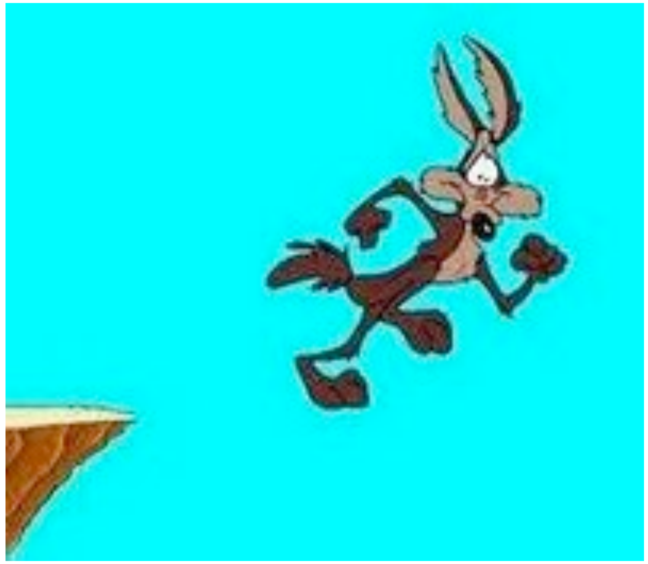
$$n_i = b_i^\dagger b_i$$

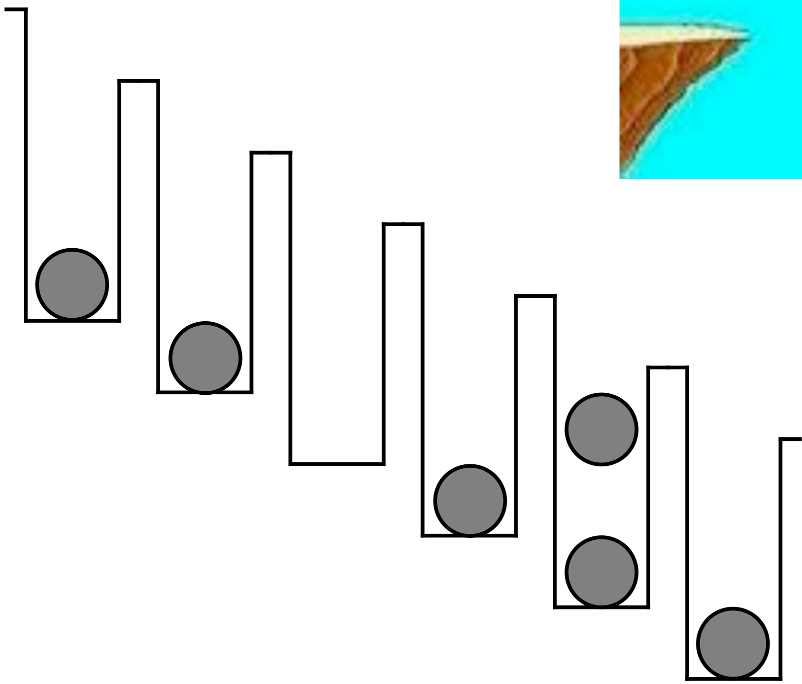
$$\left| U - E \right|, t \ll E, U$$



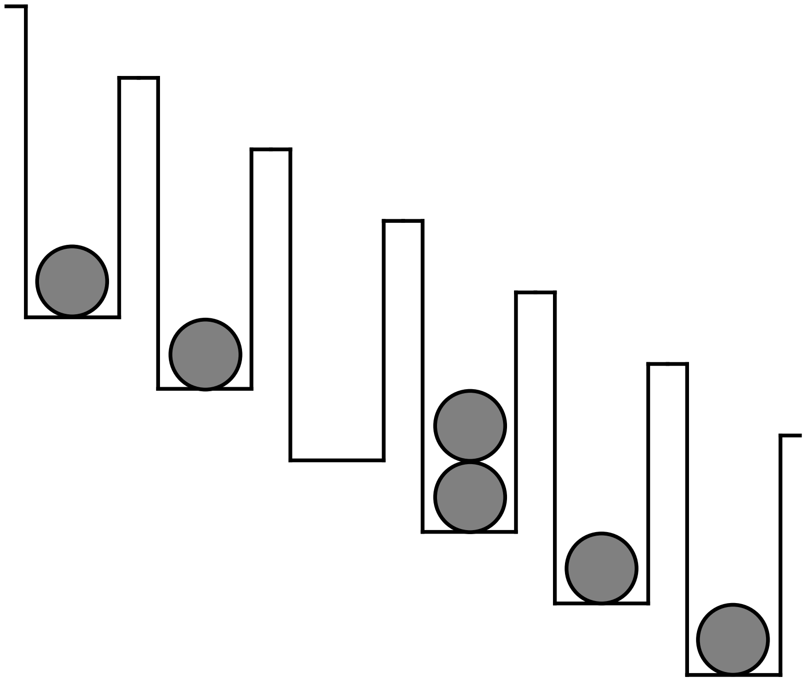


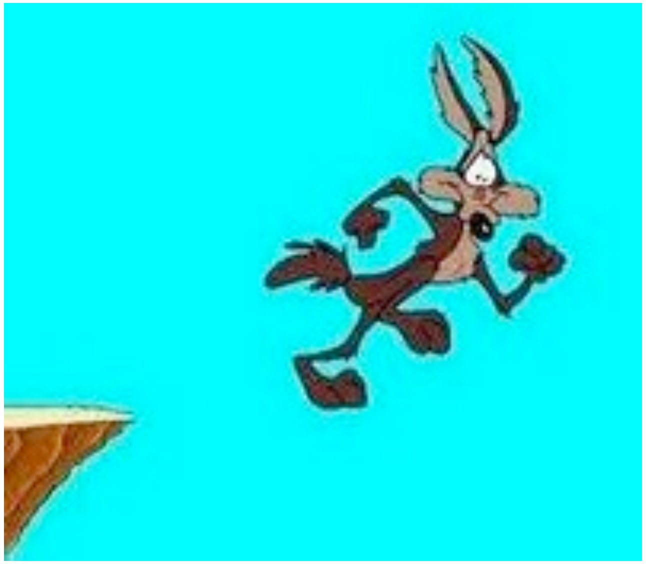
Resonant transition when $E \approx U$

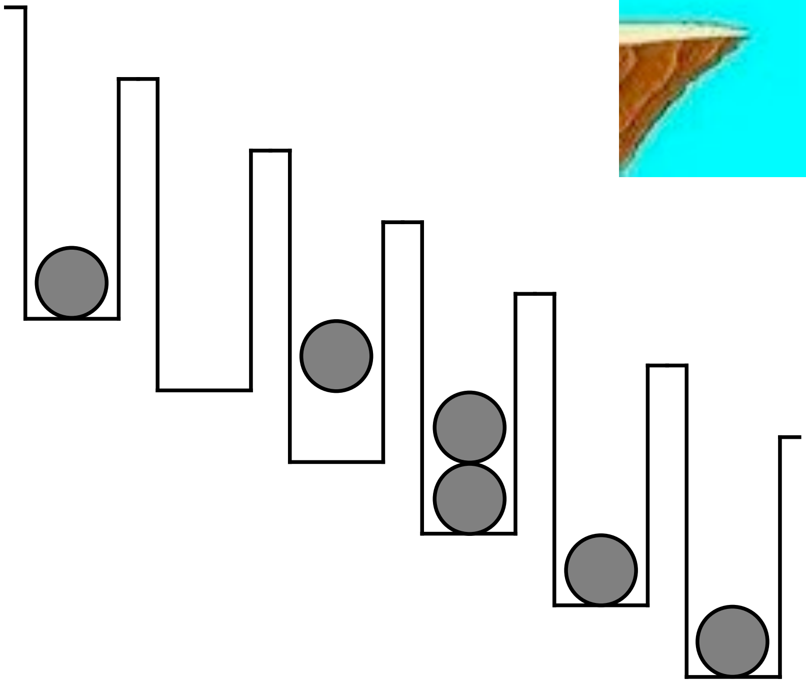




Virtual state







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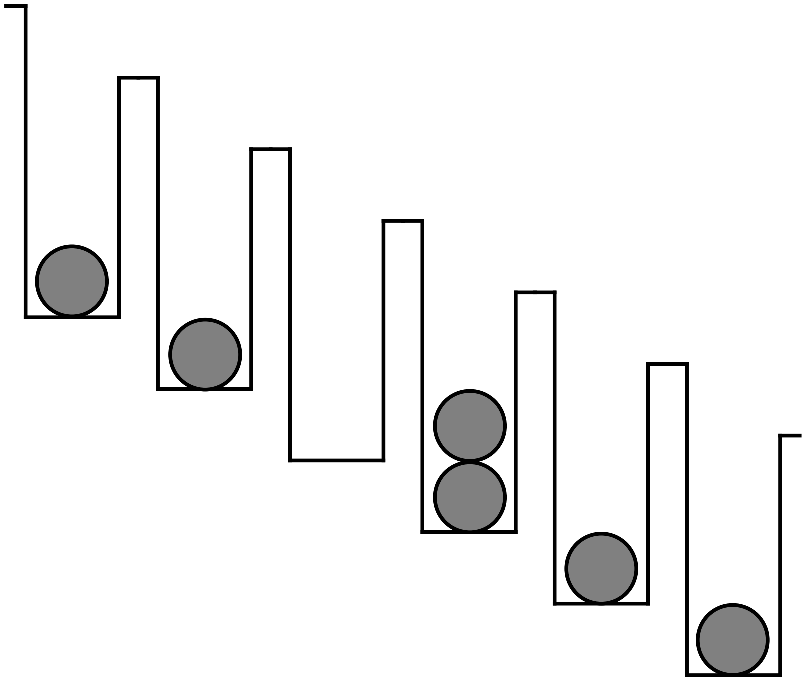

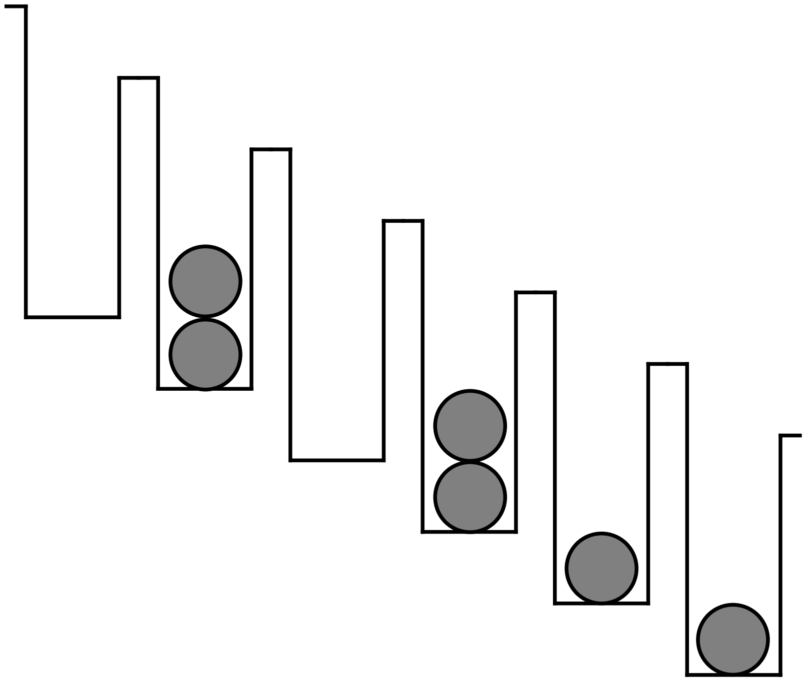

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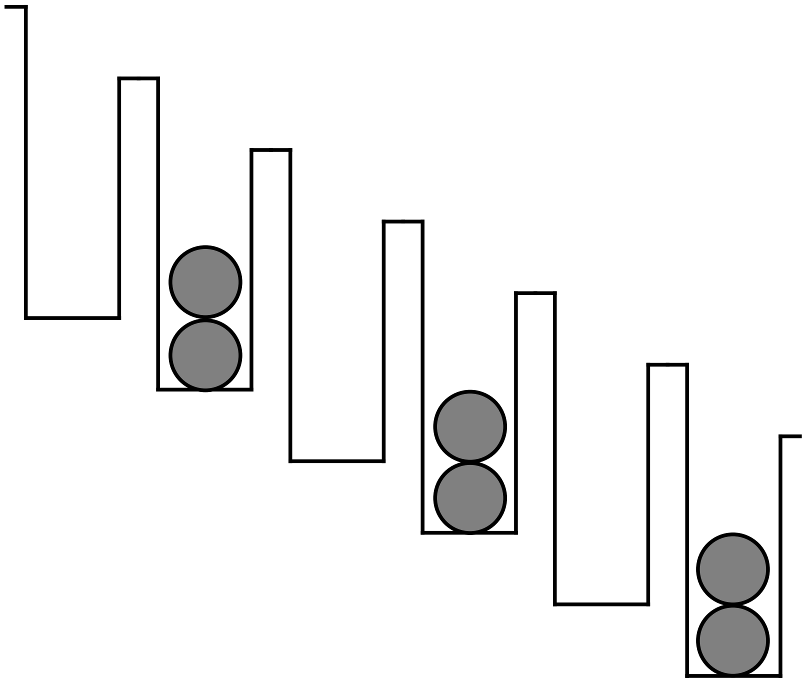
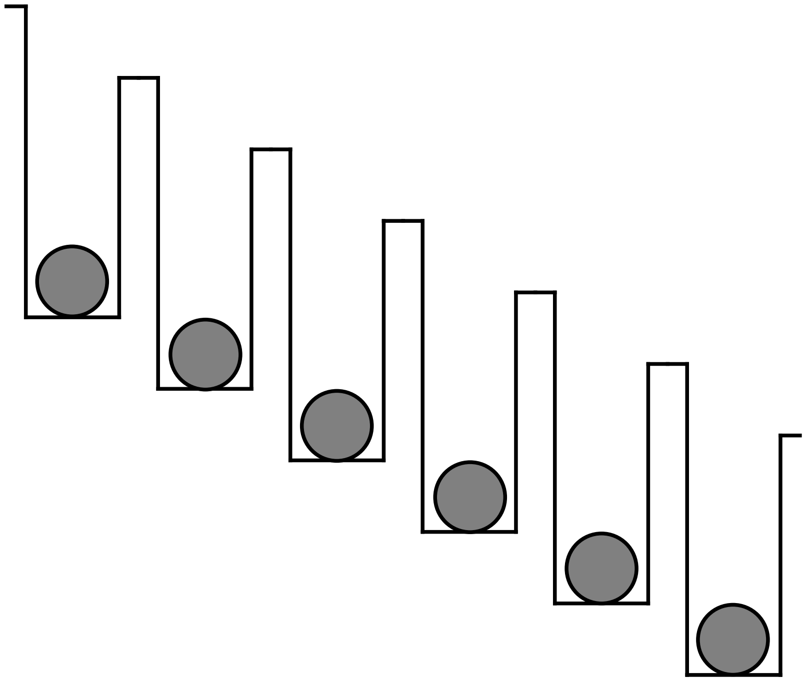
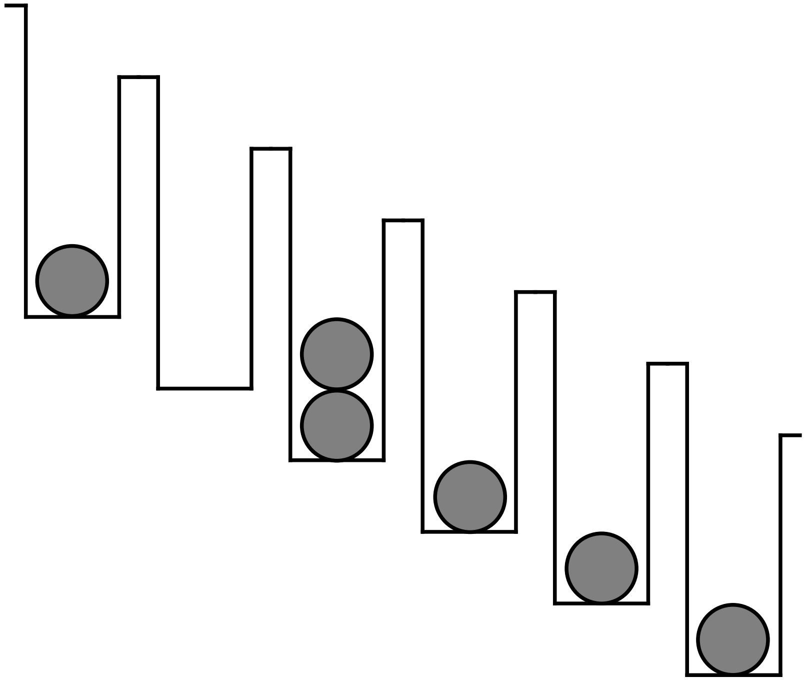
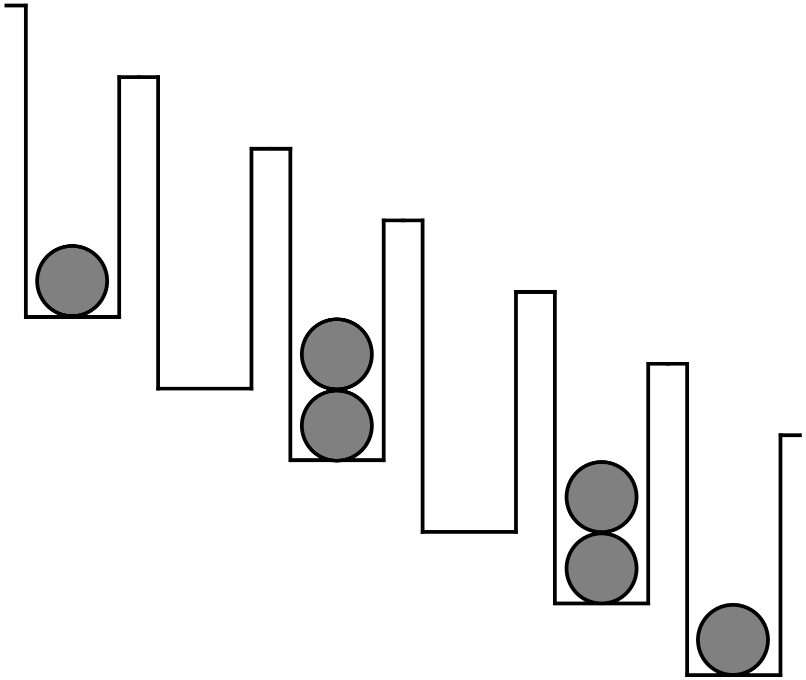
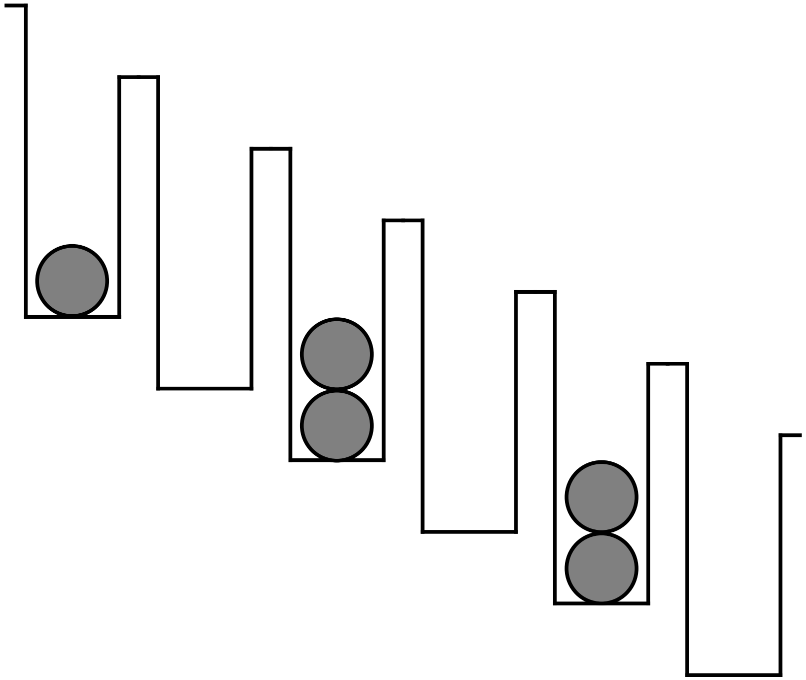


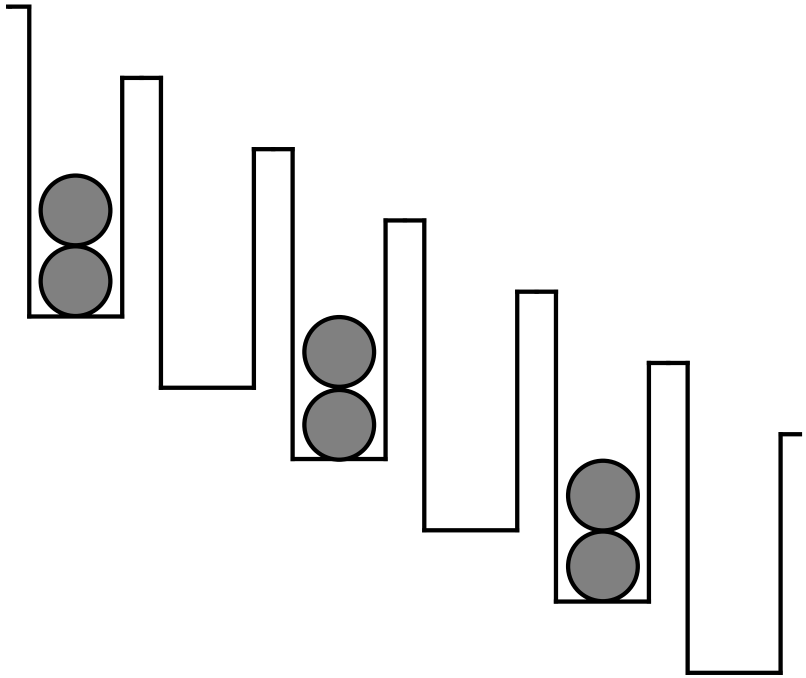
Resonant transition when $E \approx U$



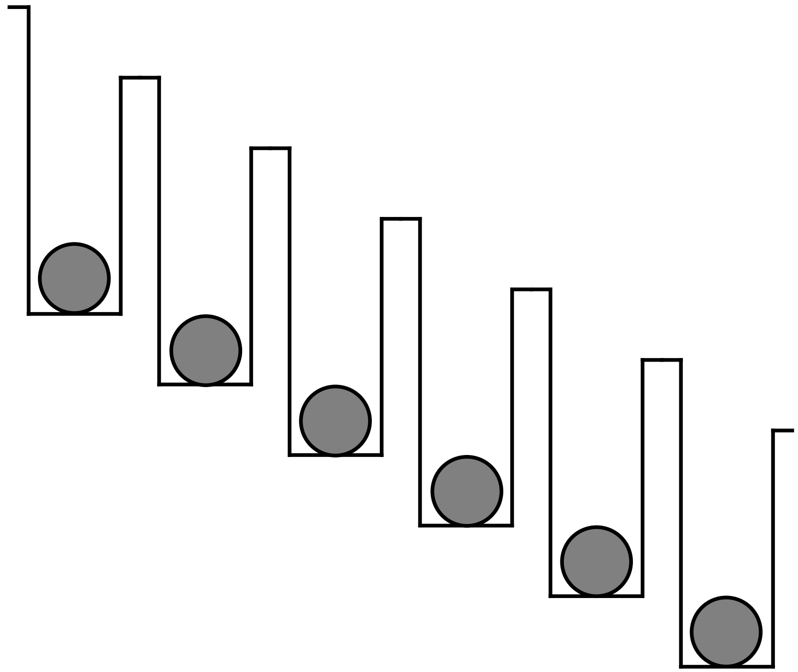








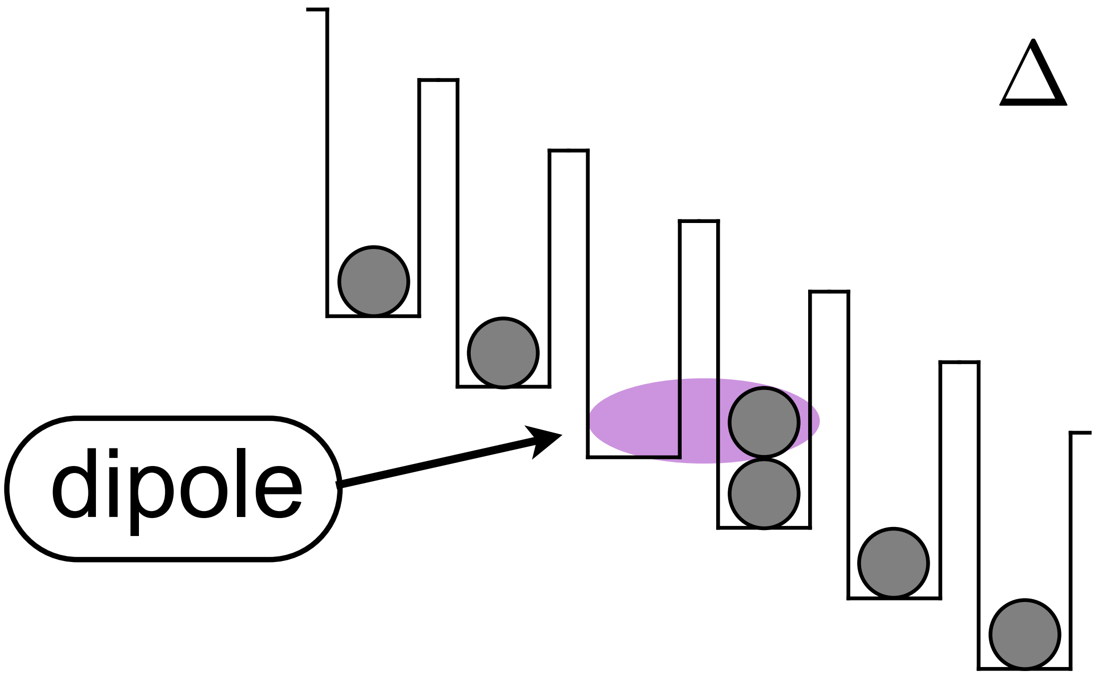
Hamiltonian of resonant subspace



Hamiltonian of resonant subspace

$$\hat{H} = -\sqrt{2}t \sum_i \left(\hat{d}_i^\dagger + \hat{d}_i \right) + \Delta \sum_i \hat{d}_i^\dagger \hat{d}_i$$

$$\Delta = U - E$$



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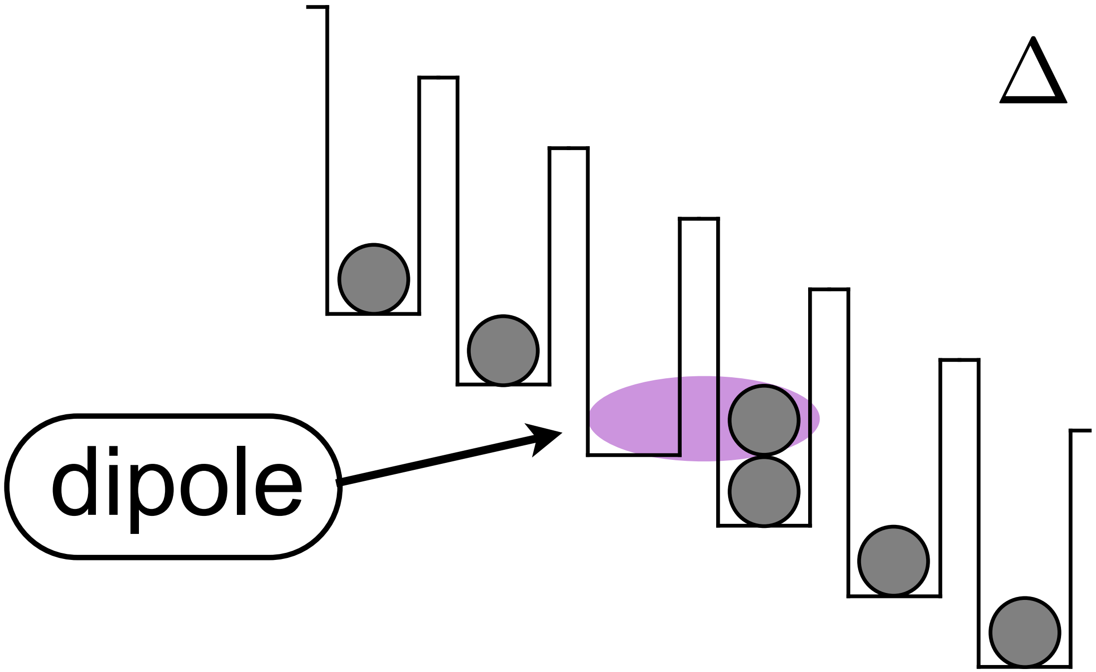

$$\Delta = U - E$$

Constraints:

max one dipole per site:

$$\hat{d}_i^\dagger \hat{d}_i \leq 1$$

no neighboring dipoles:

$$\hat{d}_i^\dagger \hat{d}_i \hat{d}_{i+1}^\dagger \hat{d}_{i+1} = 0$$

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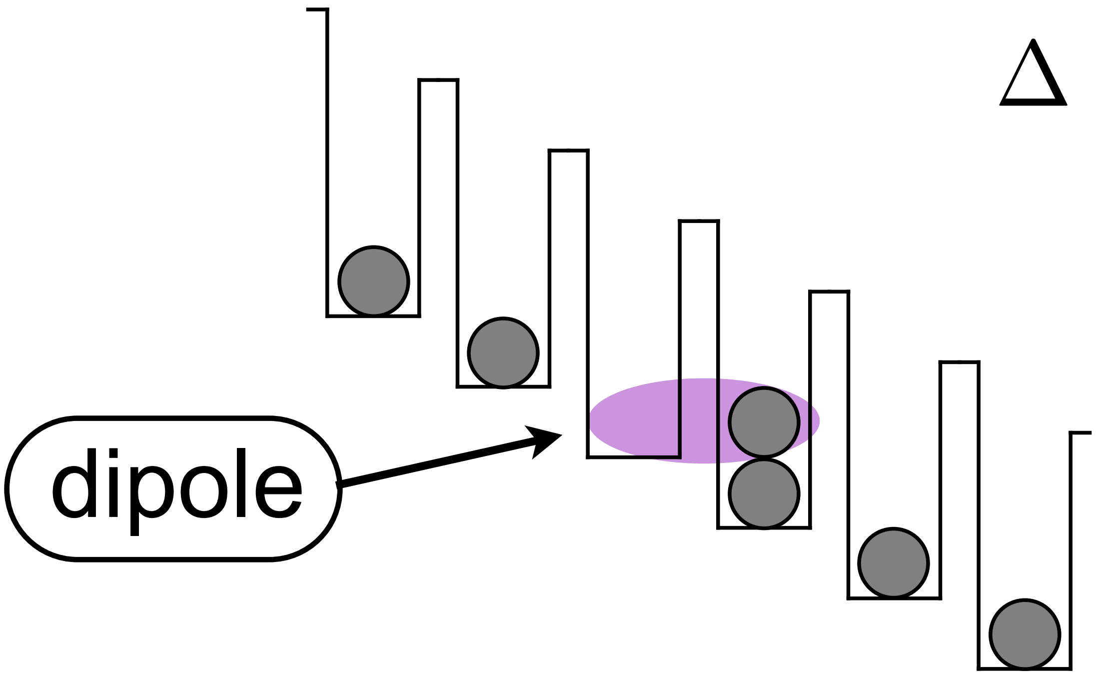

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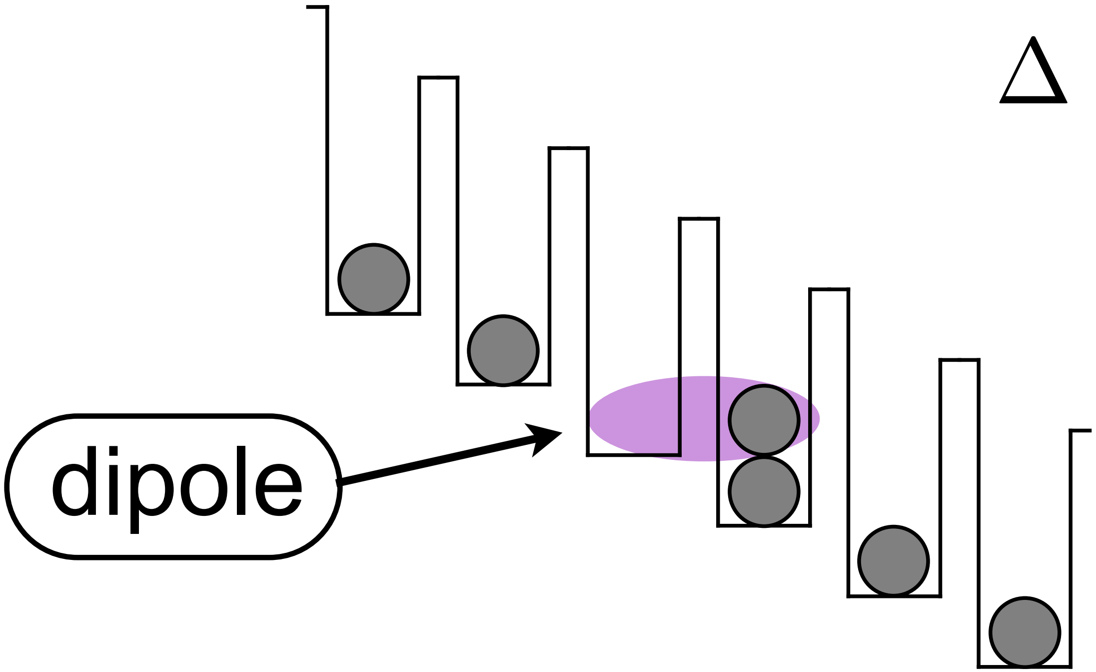


$$\Delta = U - E$$

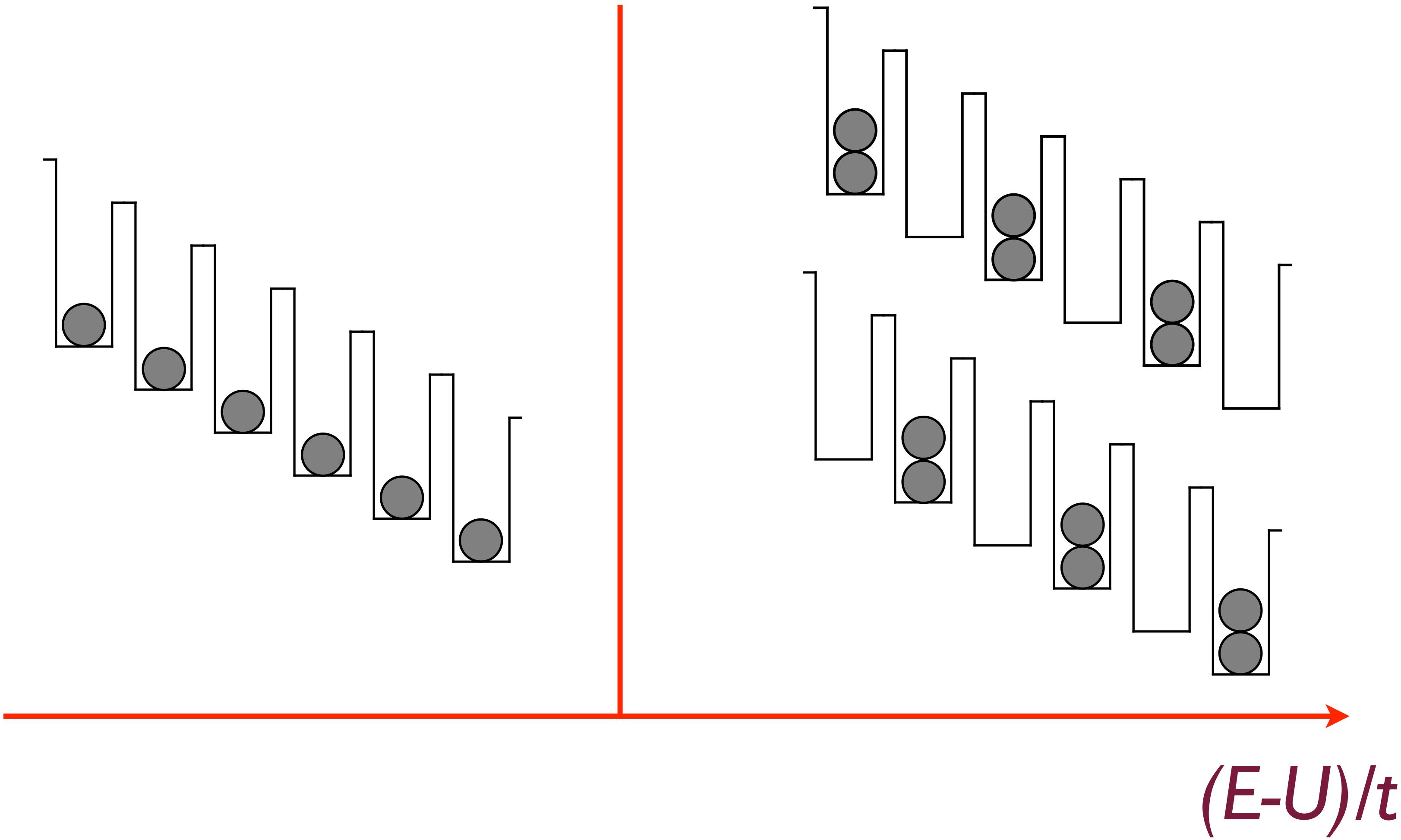
Strong off-site quantum correlations

Constraints:

max one dipole per site: $\hat{d}_i^\dagger \hat{d}_i \leq 1$

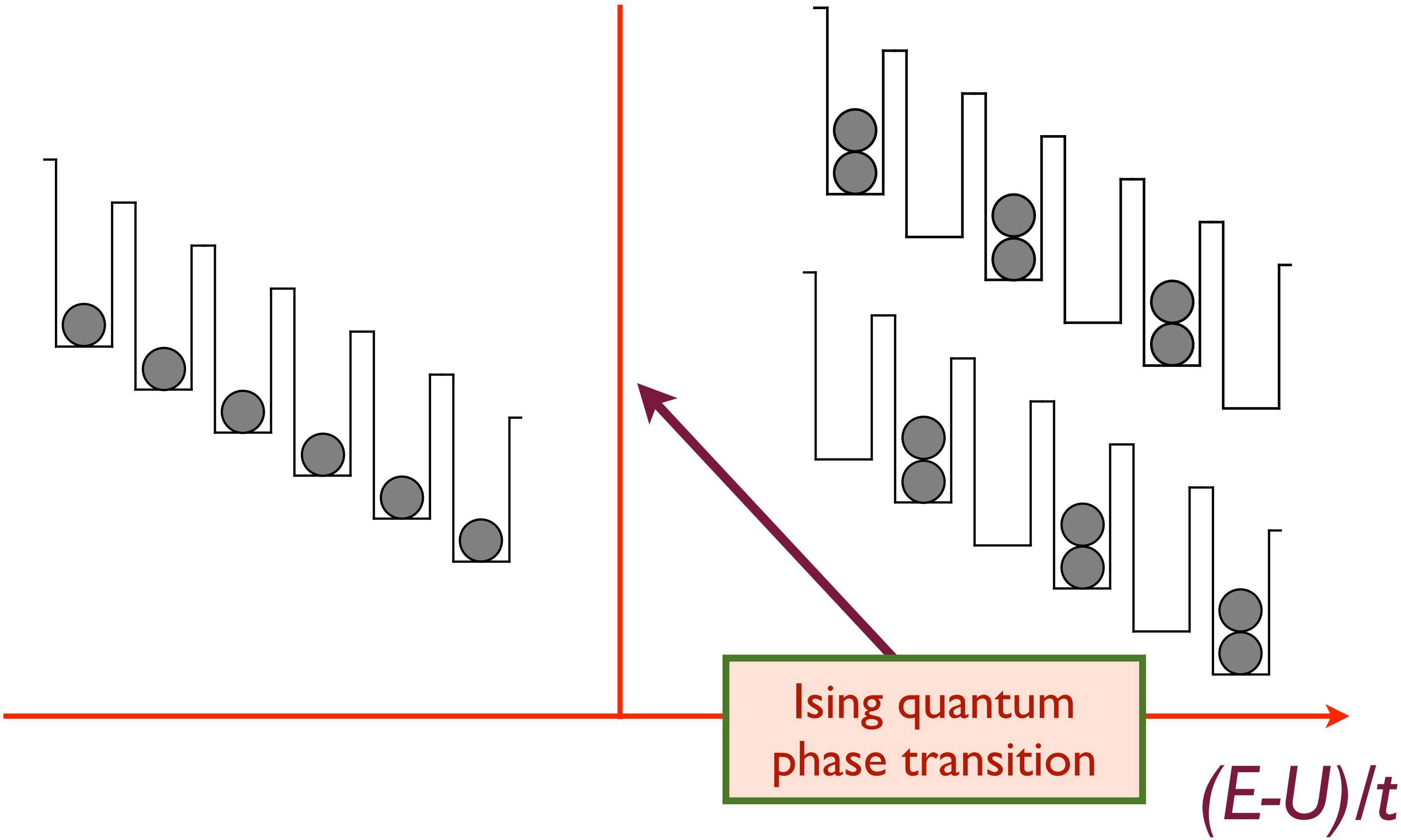
no neighboring dipoles: $\hat{d}_i^\dagger \hat{d}_i \hat{d}_{i+1}^\dagger \hat{d}_{i+1} = 0$

Phase diagram of dipole model



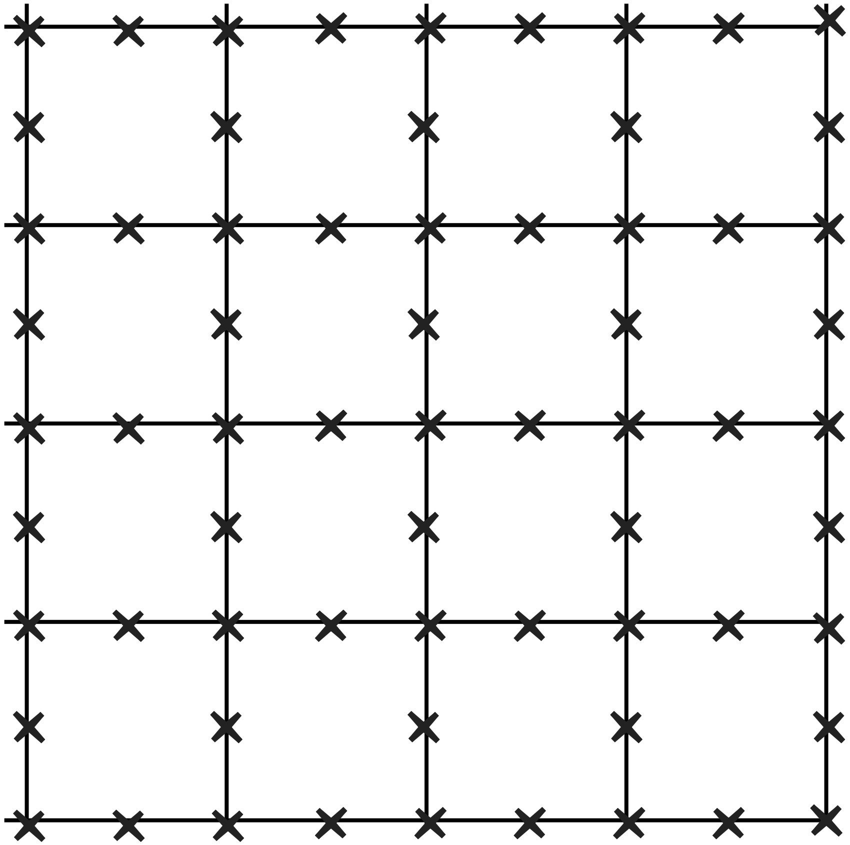
S. Sachdev, K. Sengupta, and S.M. Girvin, Phys. Rev. B 66, 075128 (2002)

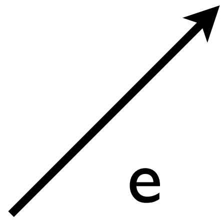
Phase diagram of dipole model



S. Sachdev, K. Sengupta, and S.M. Girvin, Phys. Rev. B 66, 075128 (2002)

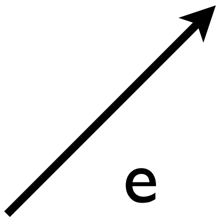
Tilting a decorated square lattice

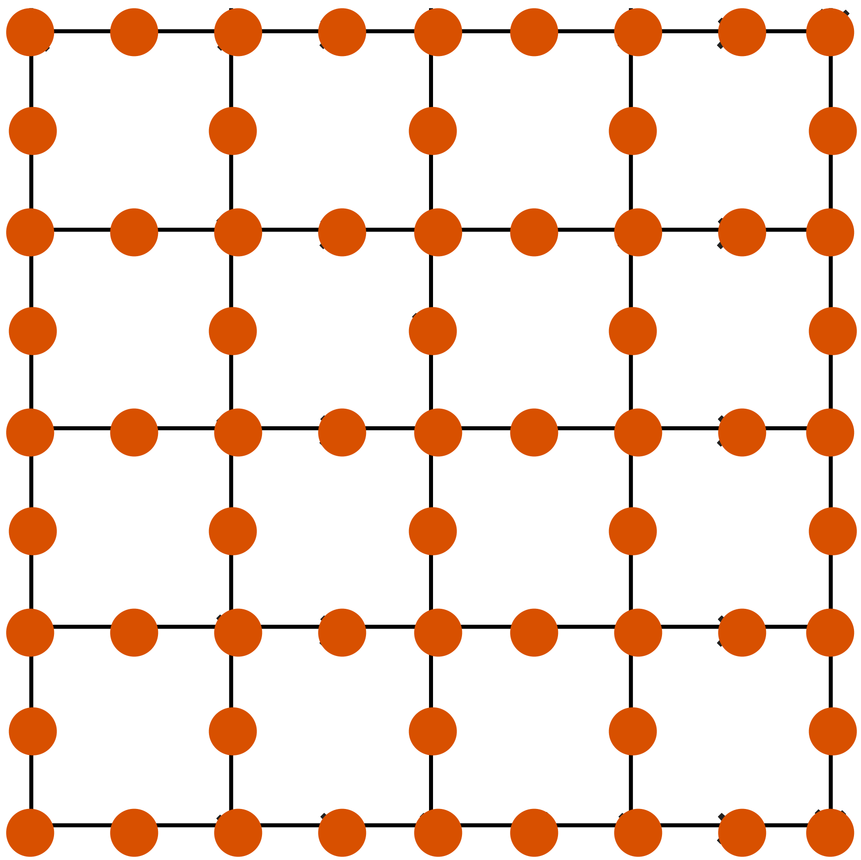




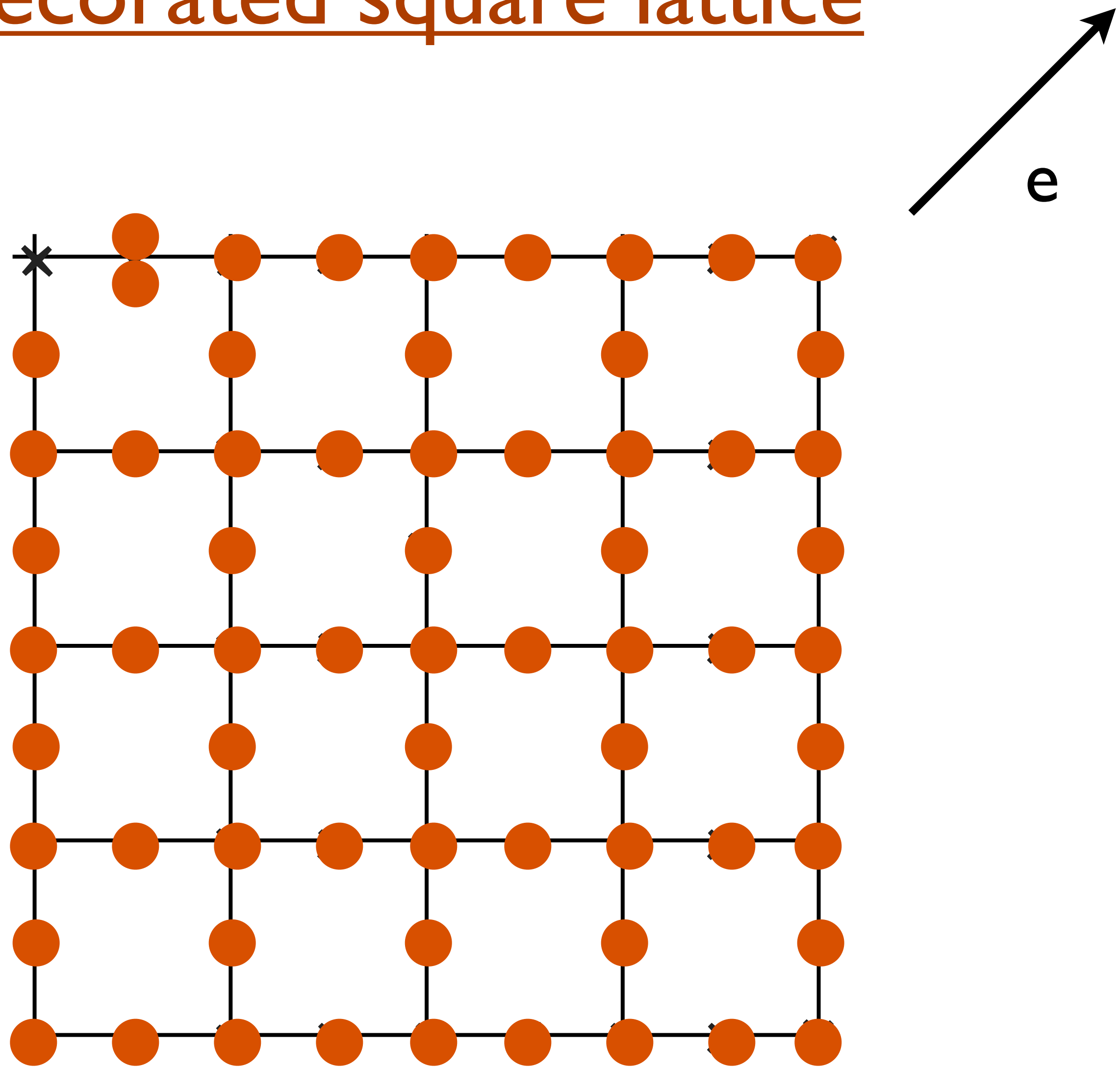
Susanne Pielawa

Tilting a decorated square lattice





Tilting a decorated square lattice



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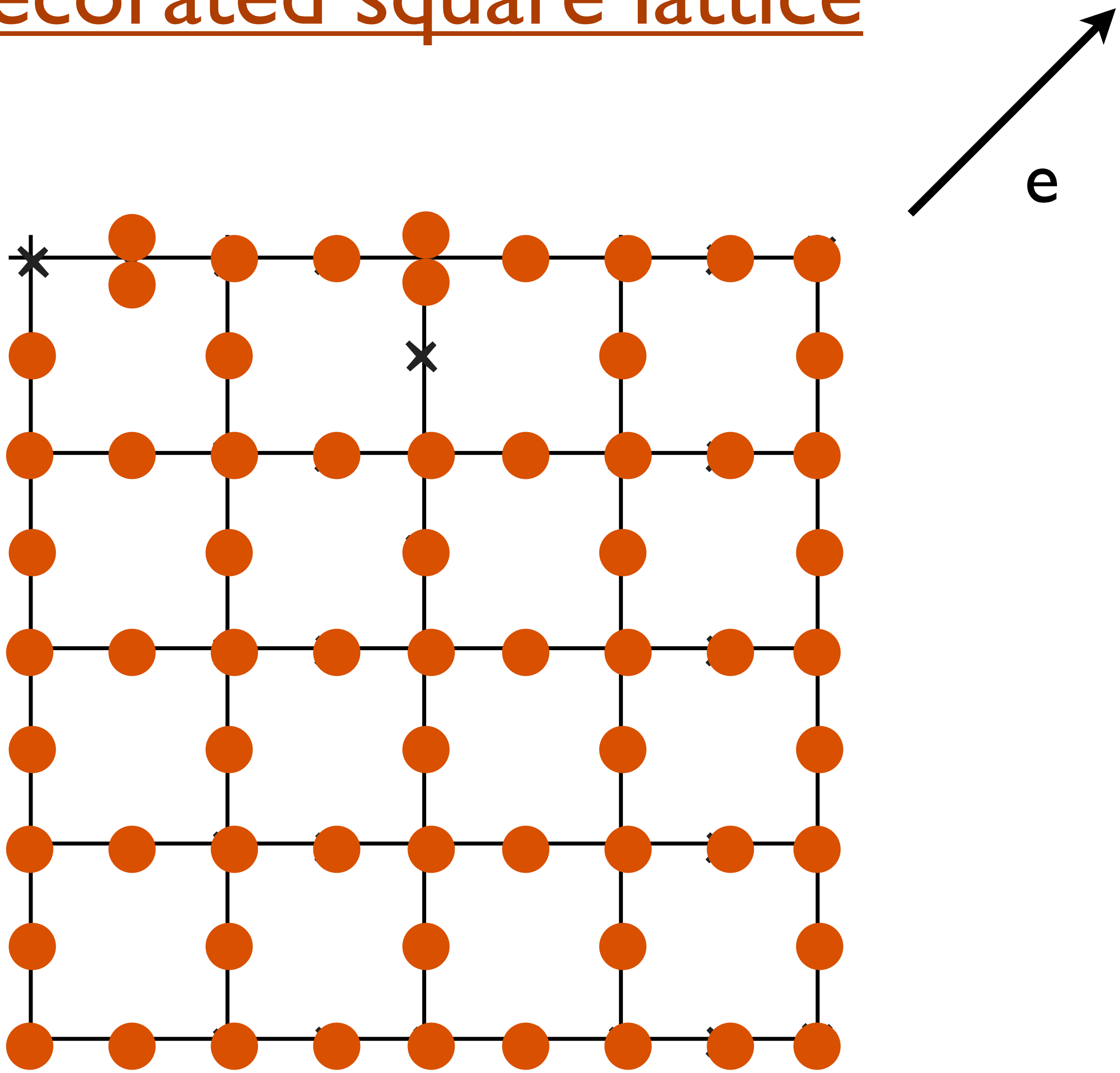
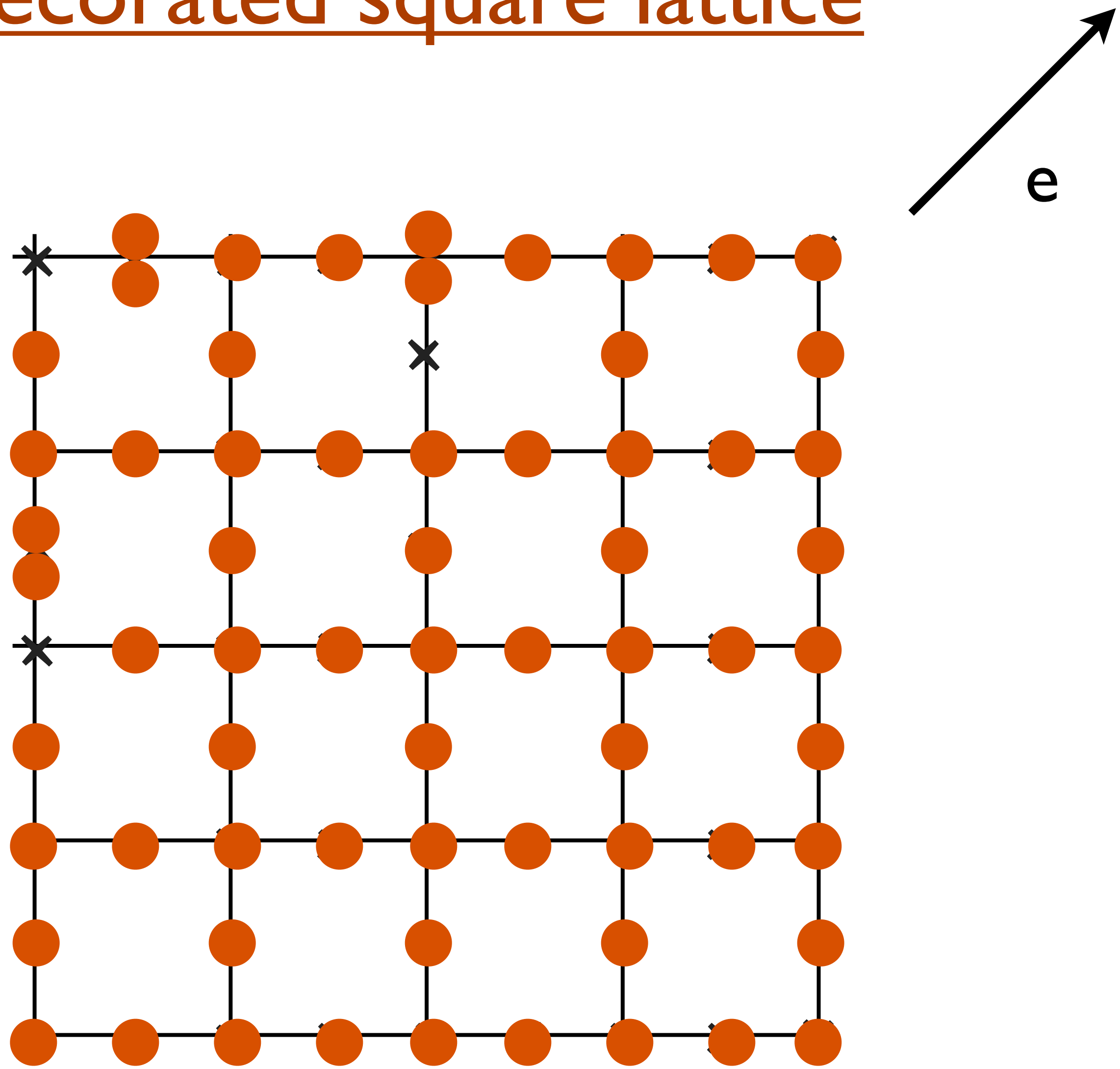


Strong tilt: maximize sites with 2 bosons

Tilting a decorated square lattice



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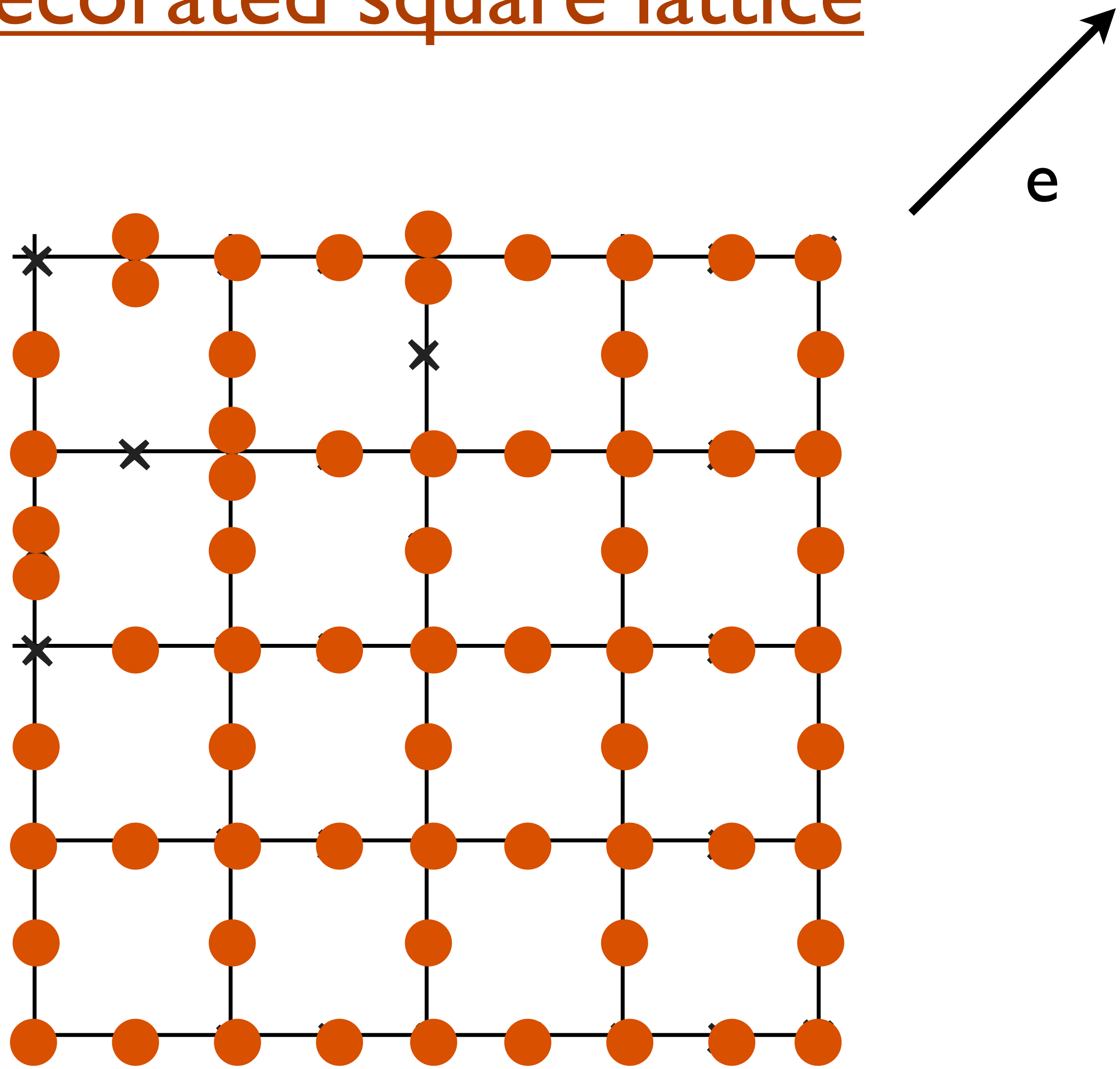

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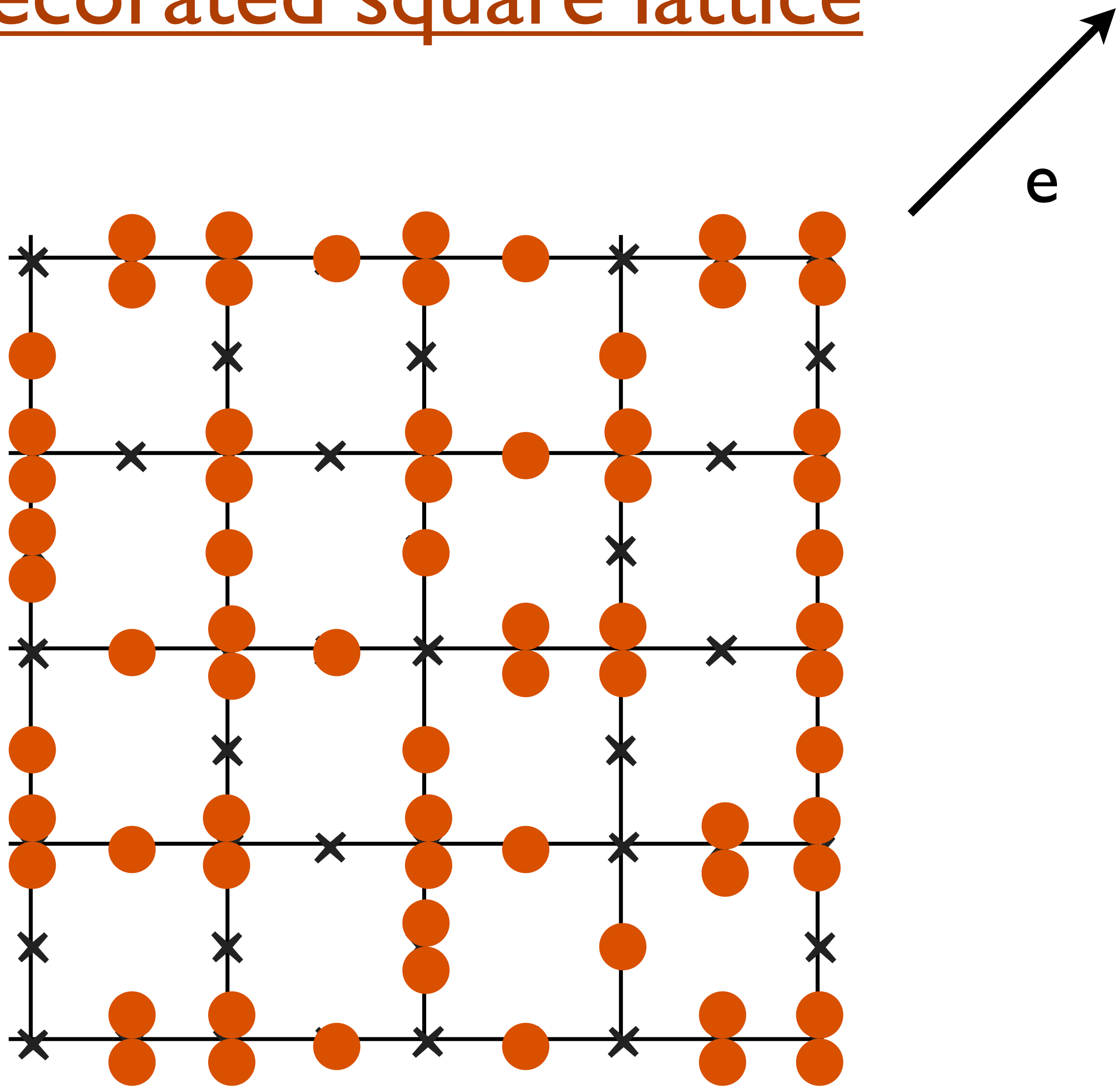
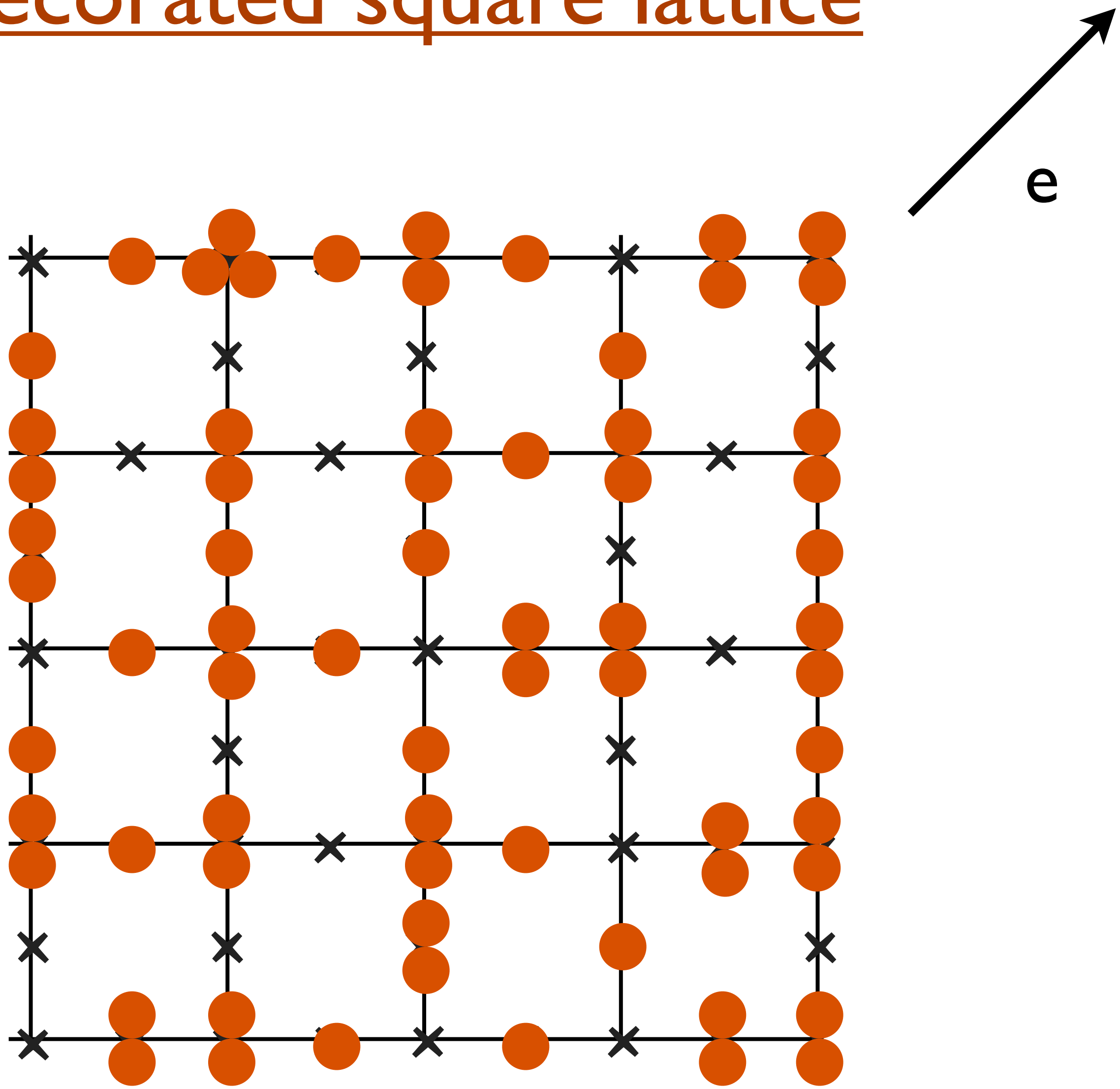


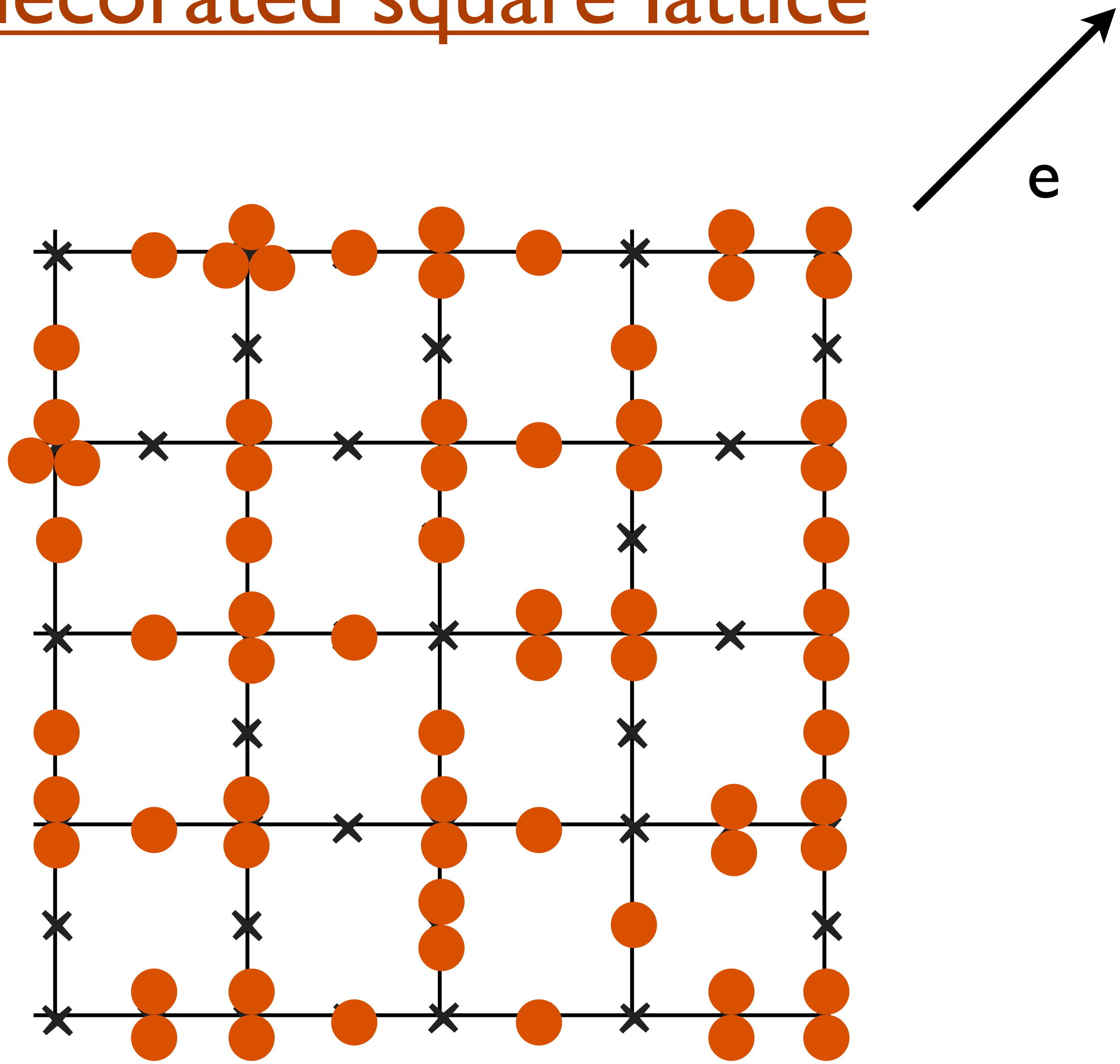
Maximum number of 2's

Tilting a decorated square lattice



Can also get some 3's from neighboring 2's.

Tilting a decorated square lattice



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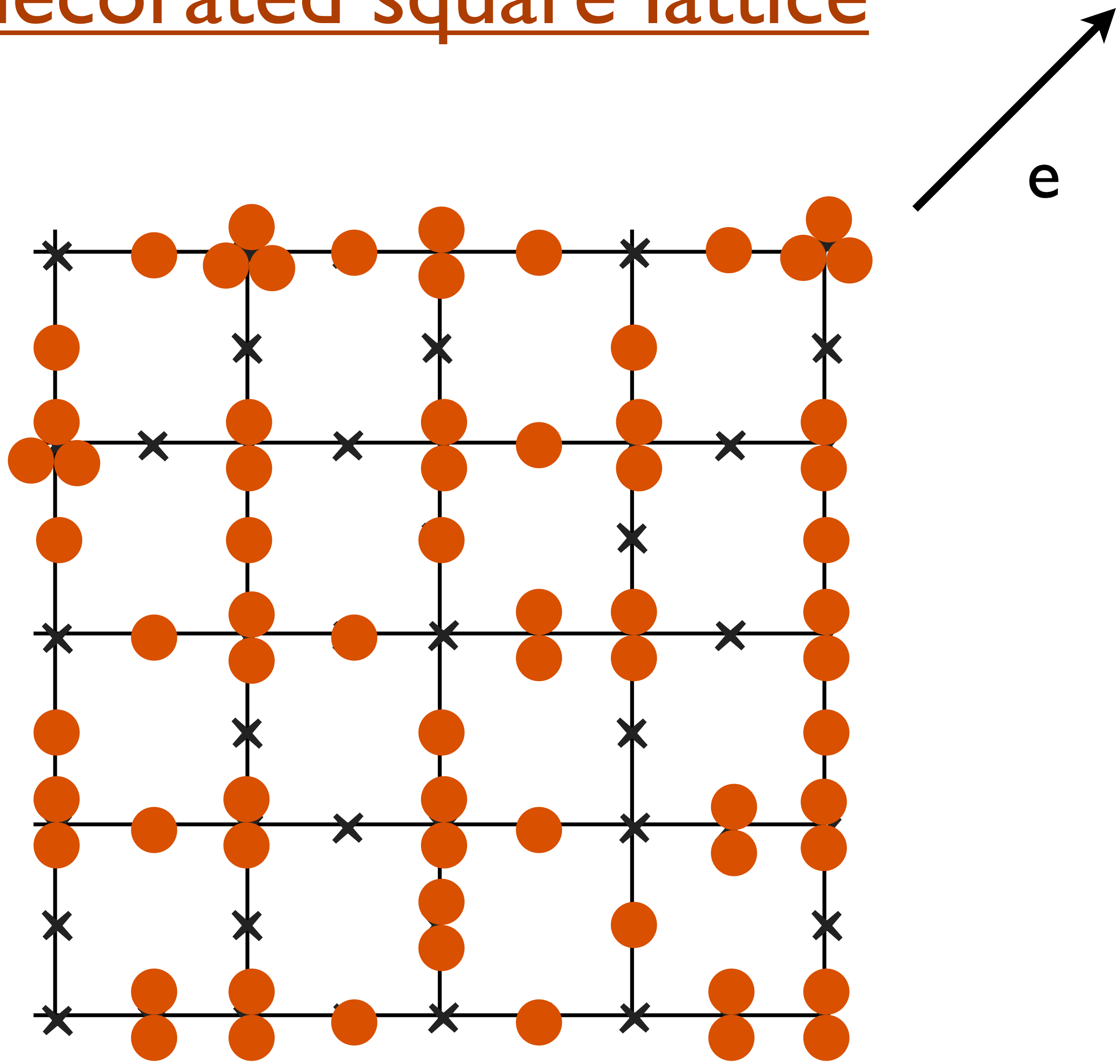

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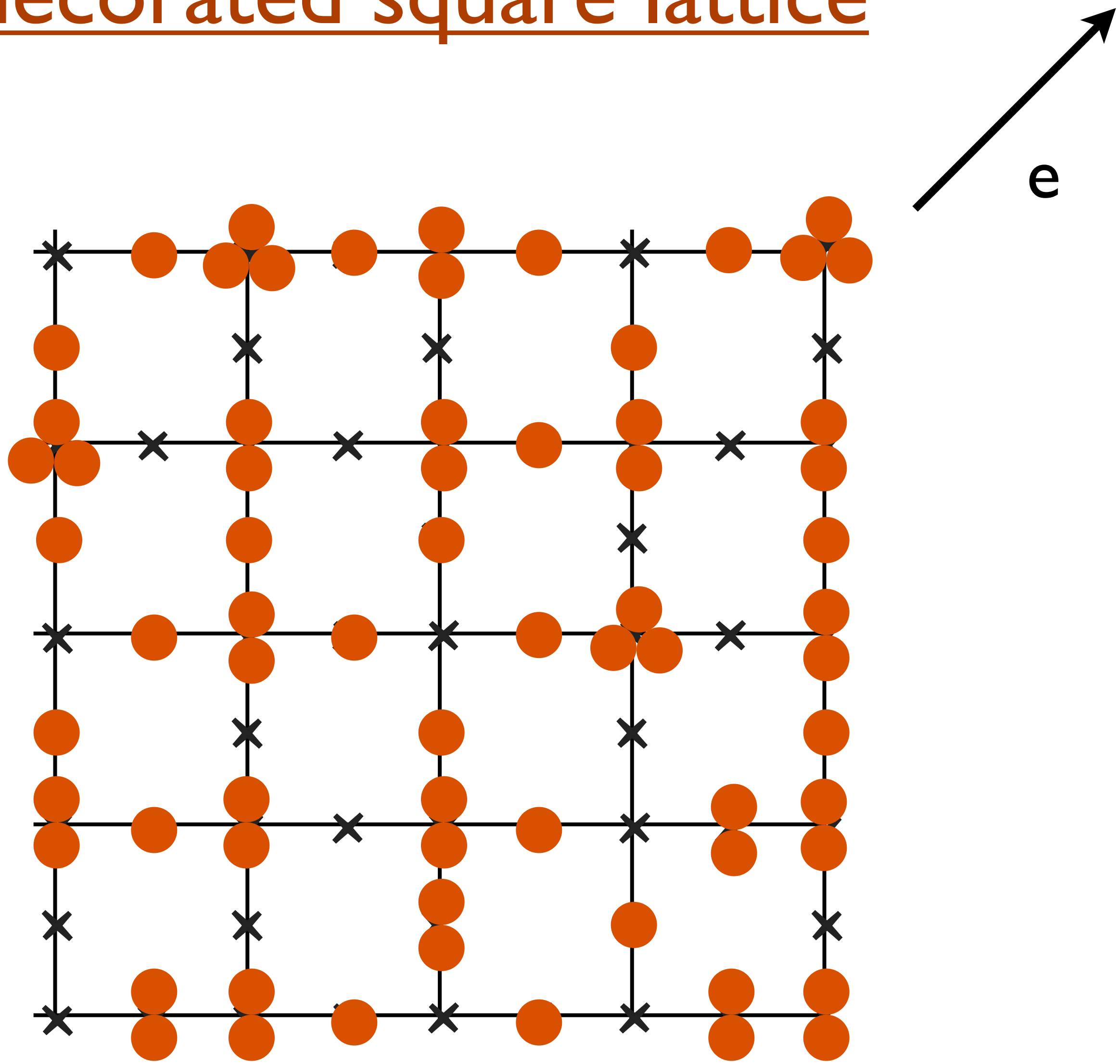

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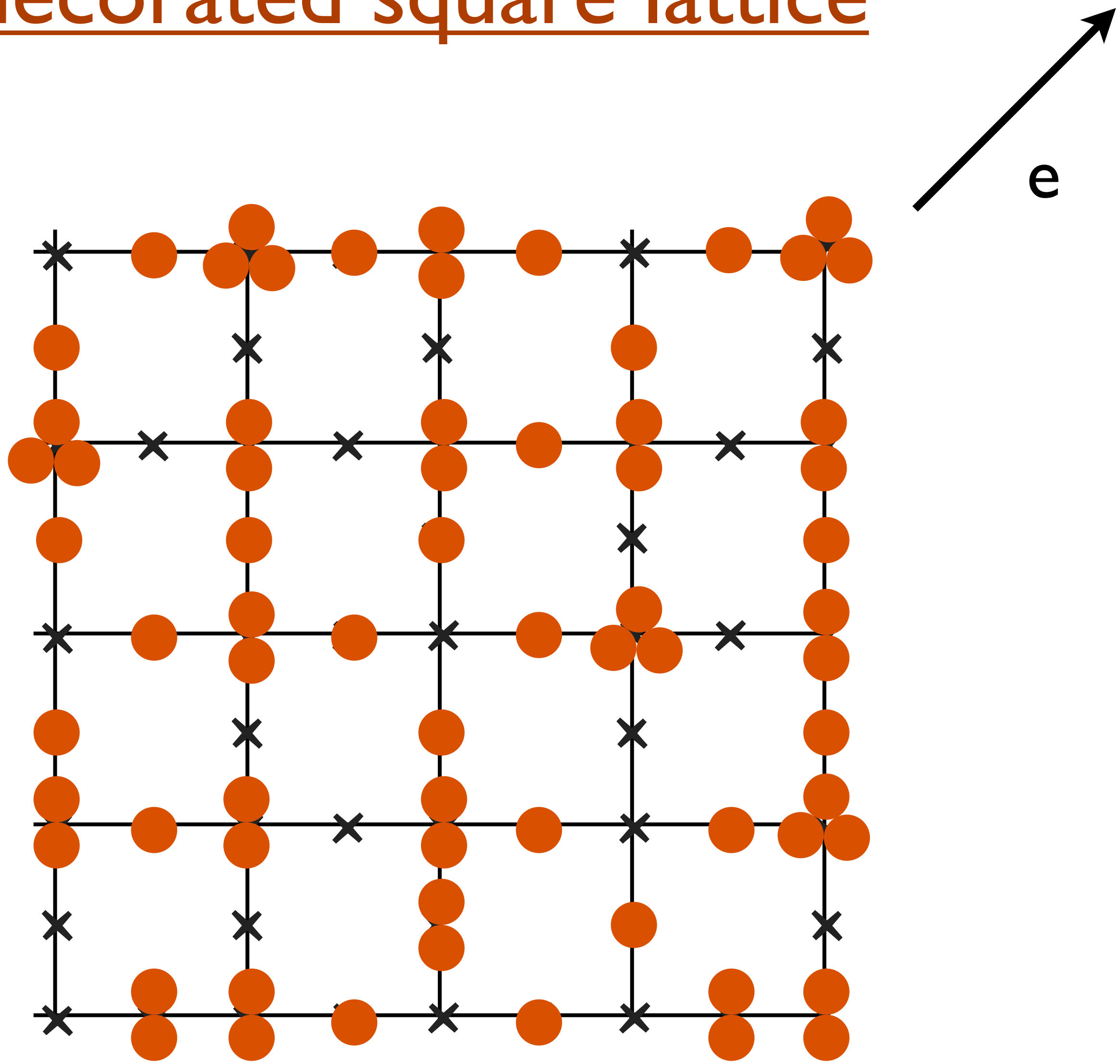

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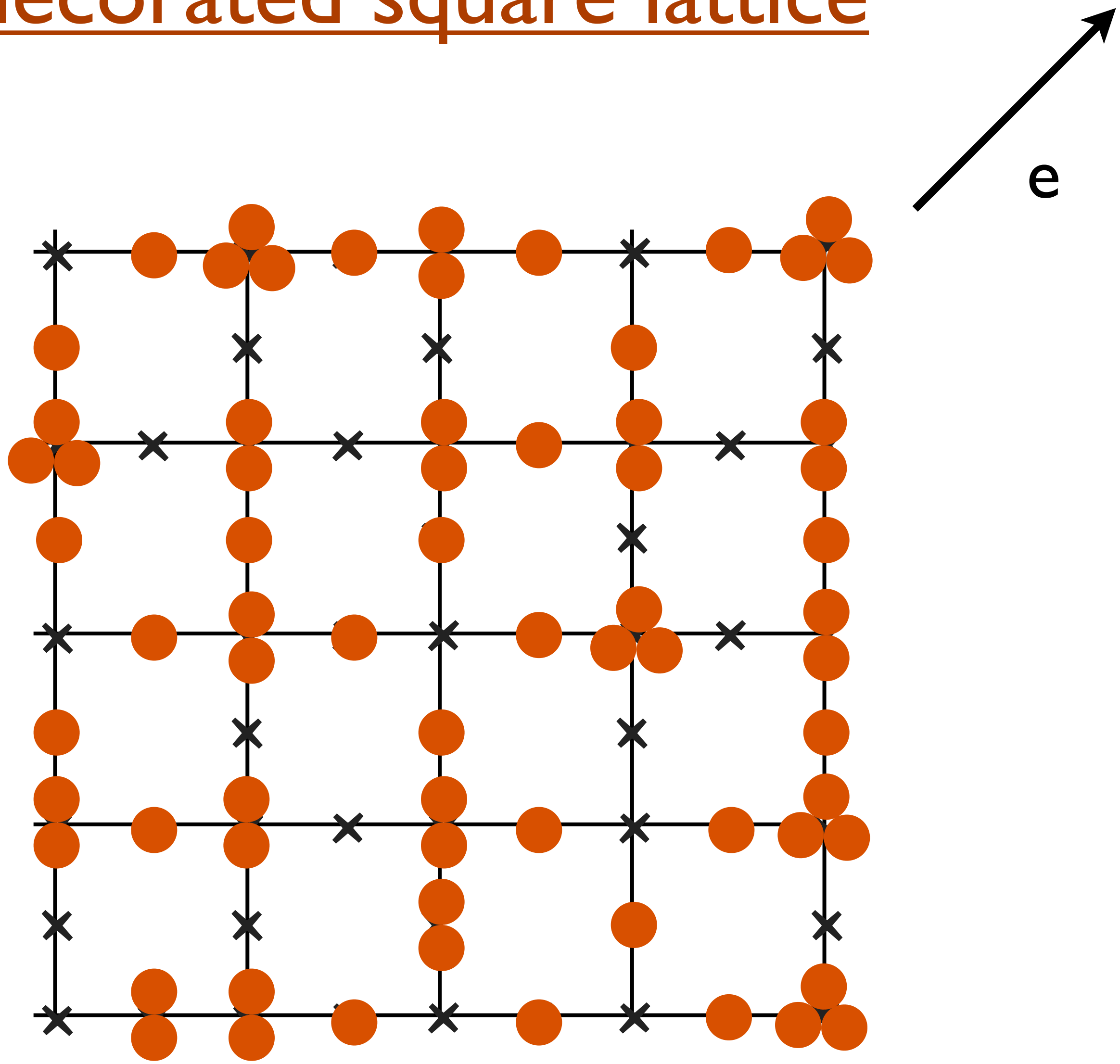

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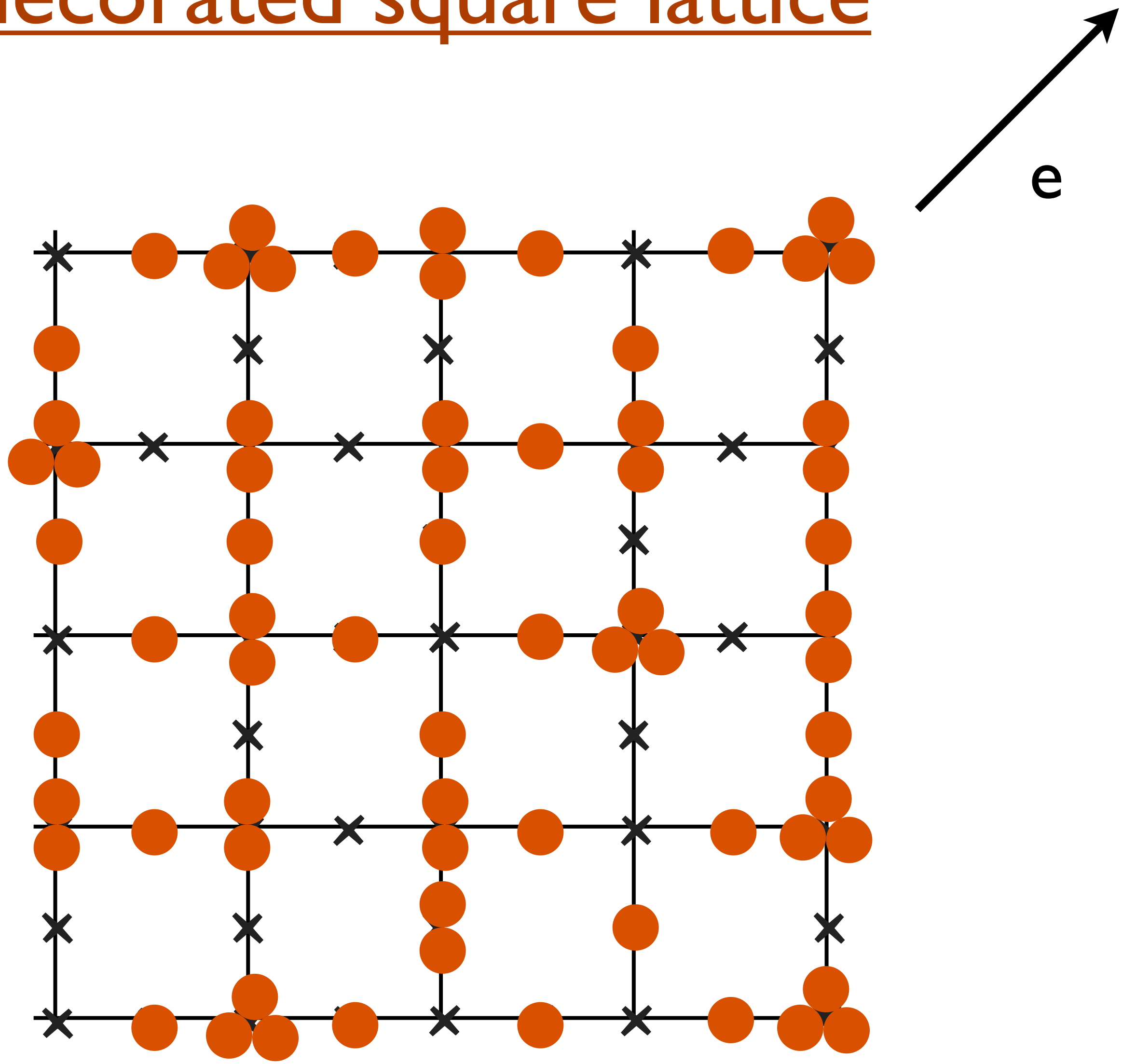

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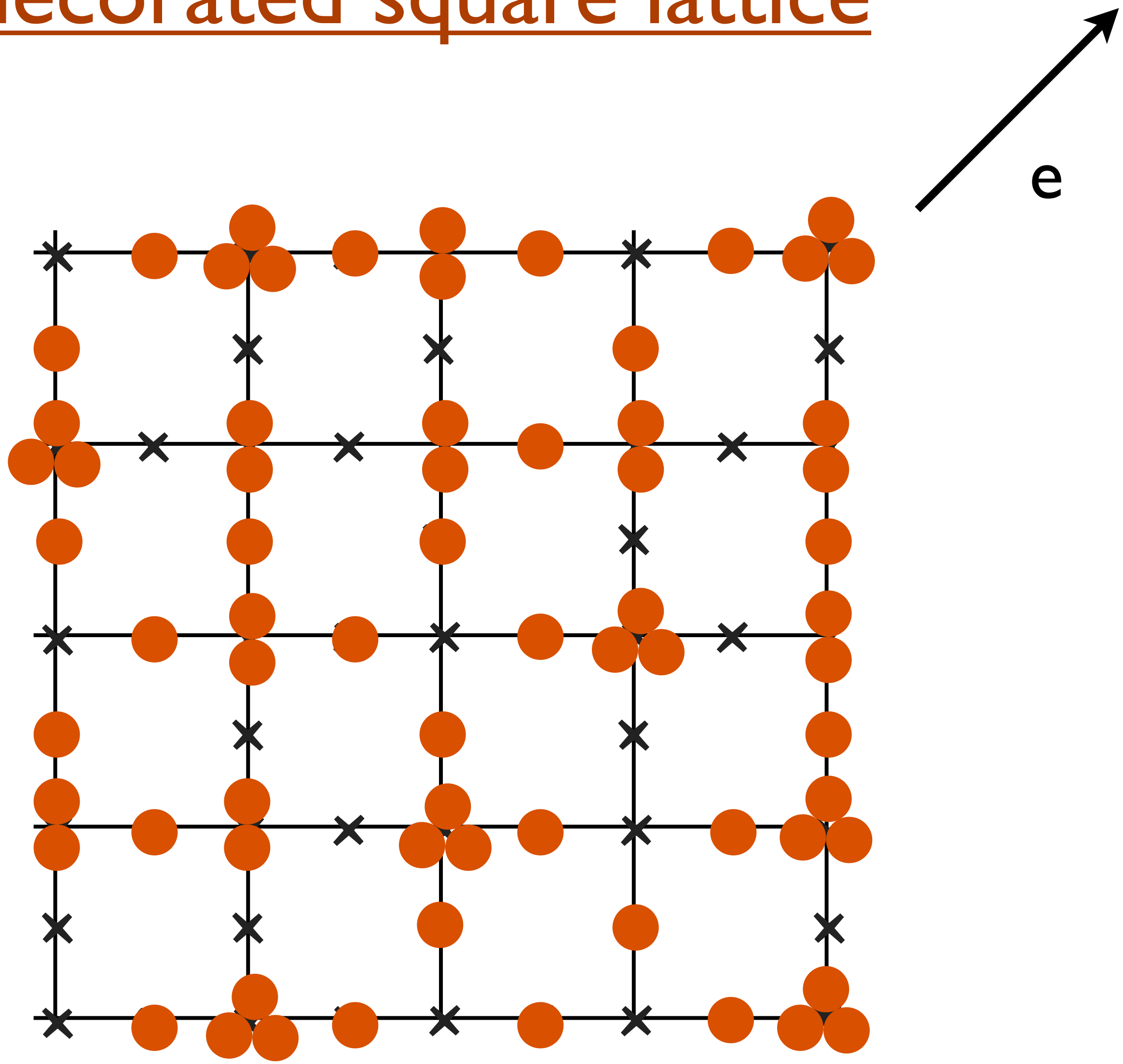
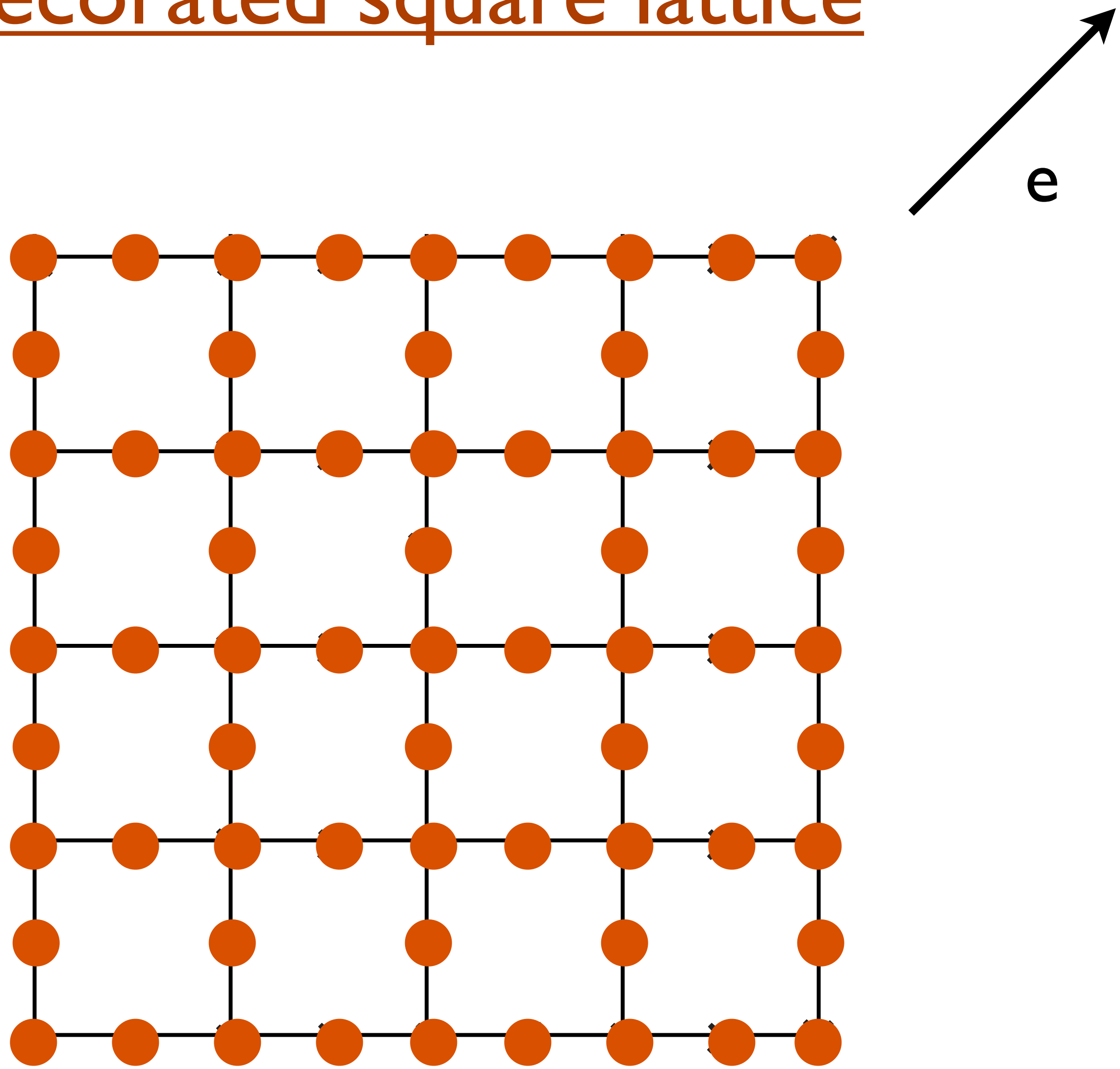


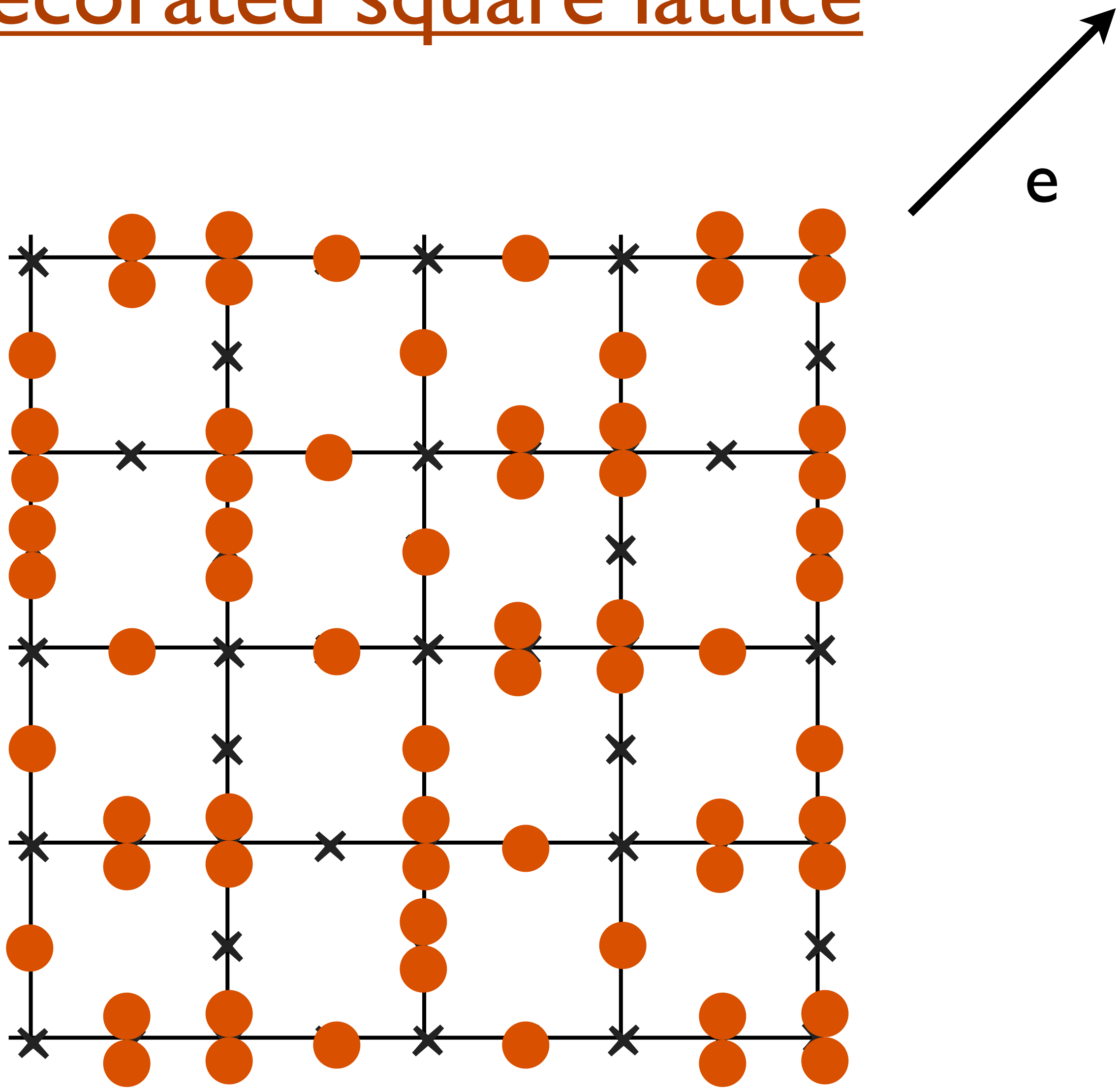
No more 3's are possible, but some 2's are left over

Tilting a decorated square lattice



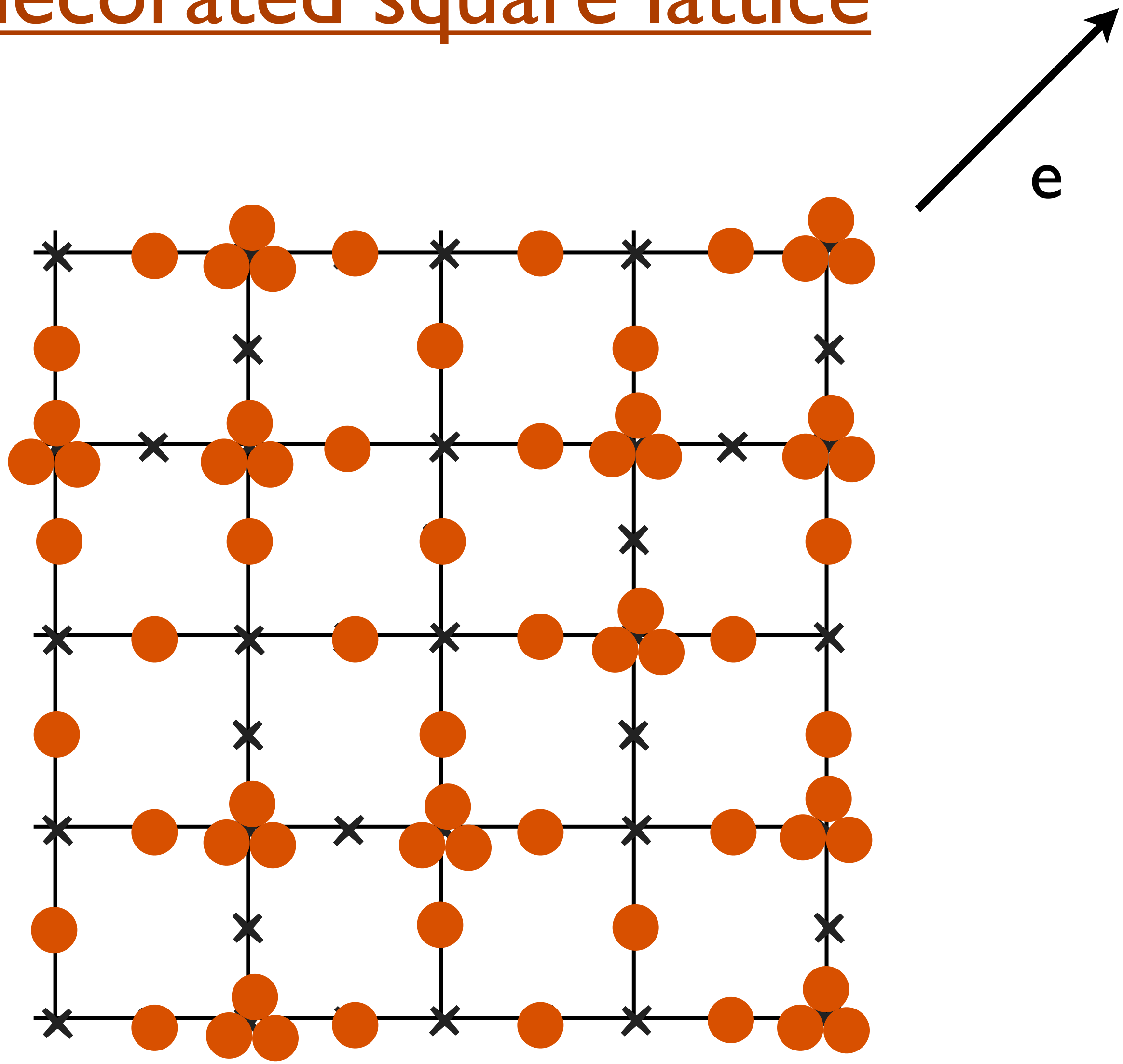
Start again

Tilting a decorated square lattice



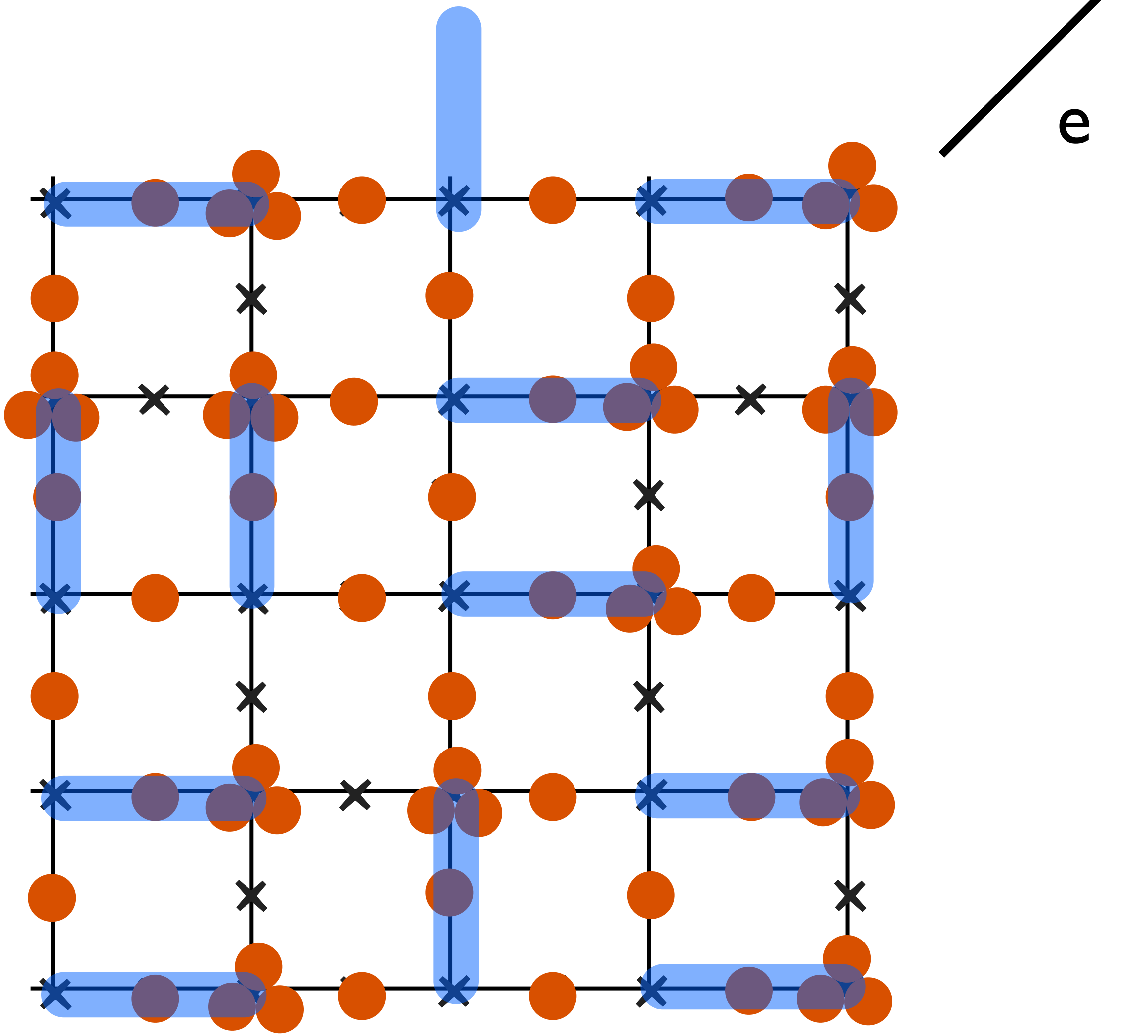
Another maximal set of 2's

Tilting a decorated square lattice



Maximum number of 3's with no 2's left over

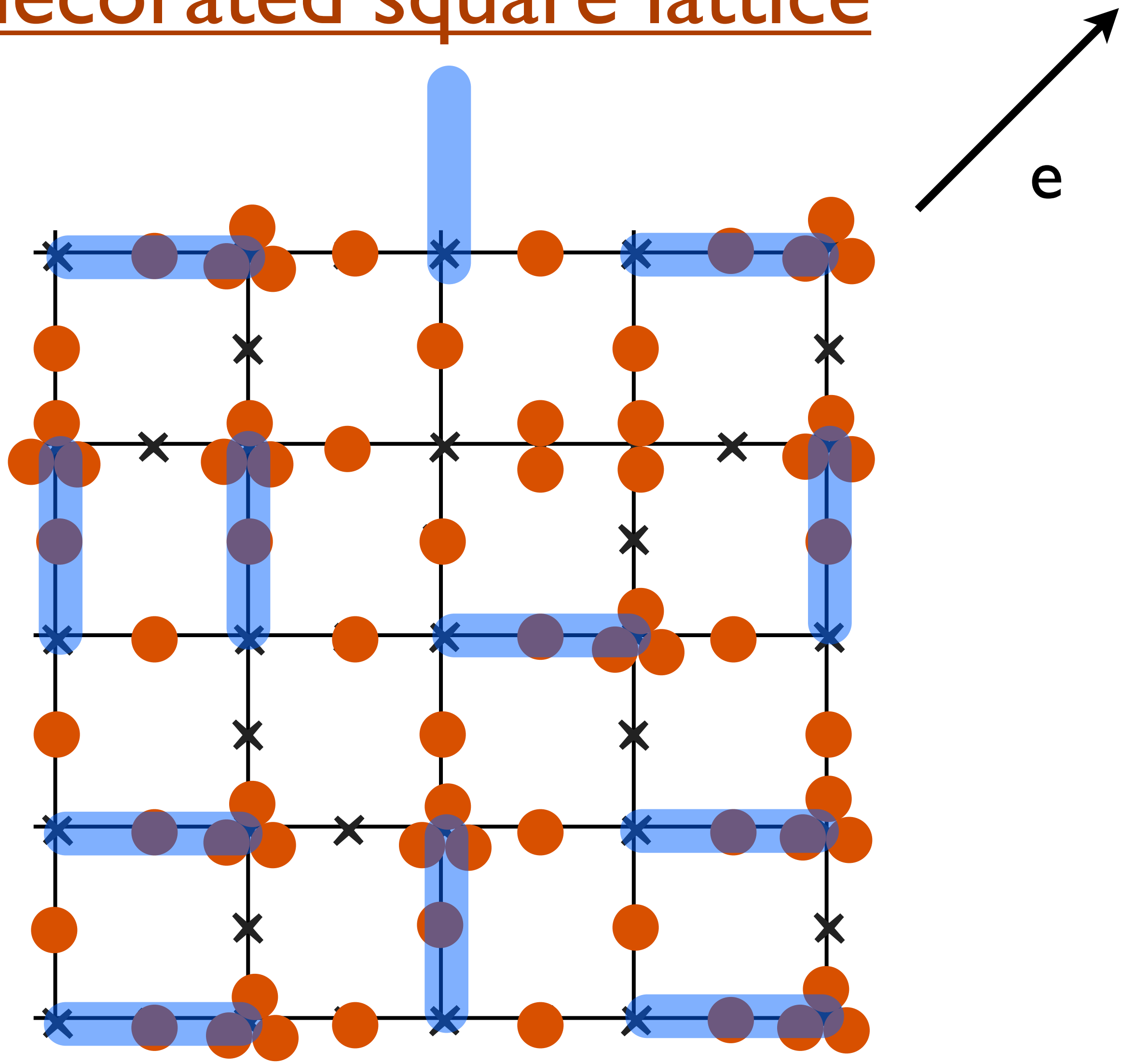
Tilting a decorated square lattice



Susanne Pielawa

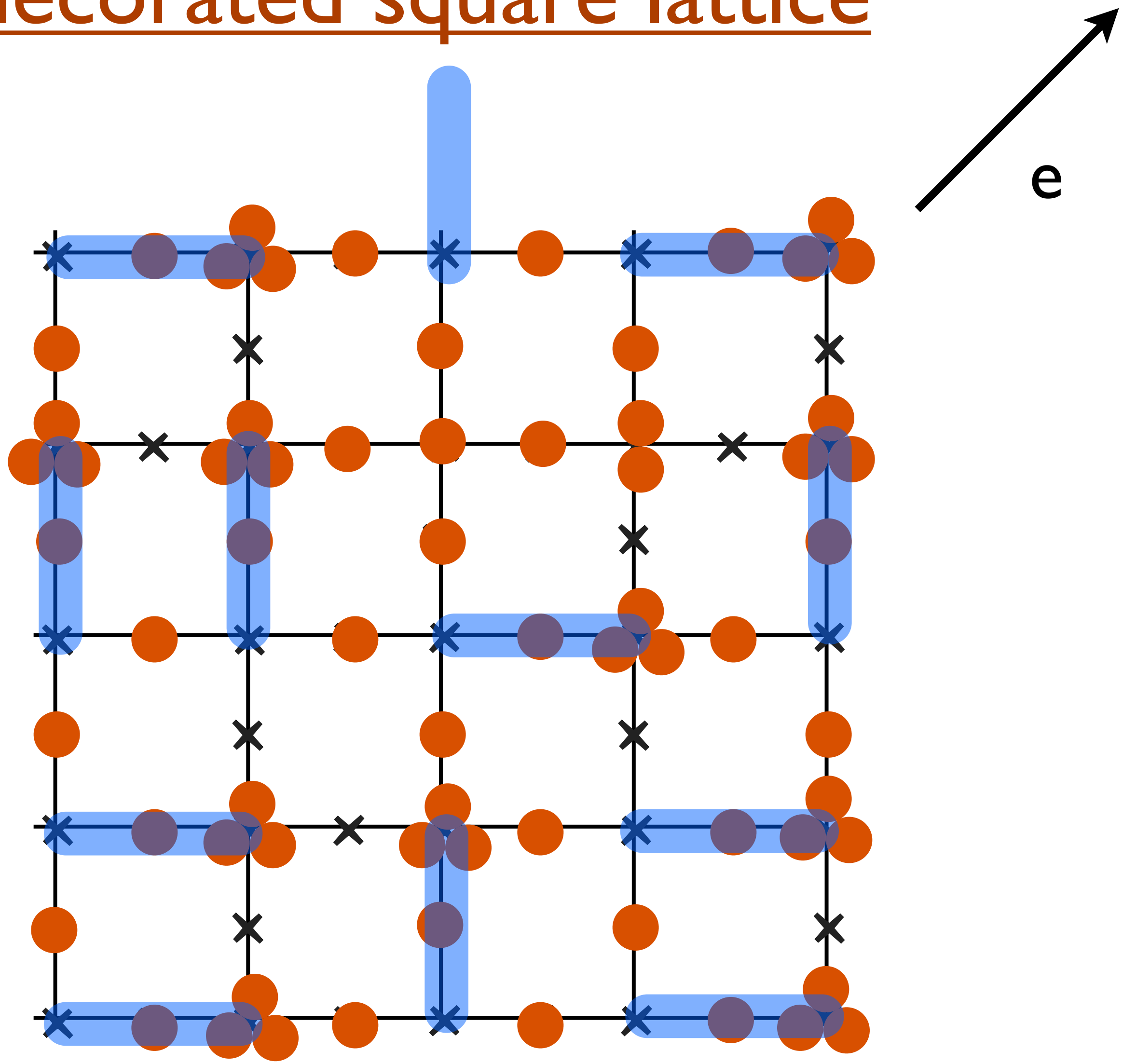
Configurations map onto dimer coverings of the square lattice !

Tilting a decorated square lattice



Go backwards around a plaquette

Tilting a decorated square lattice



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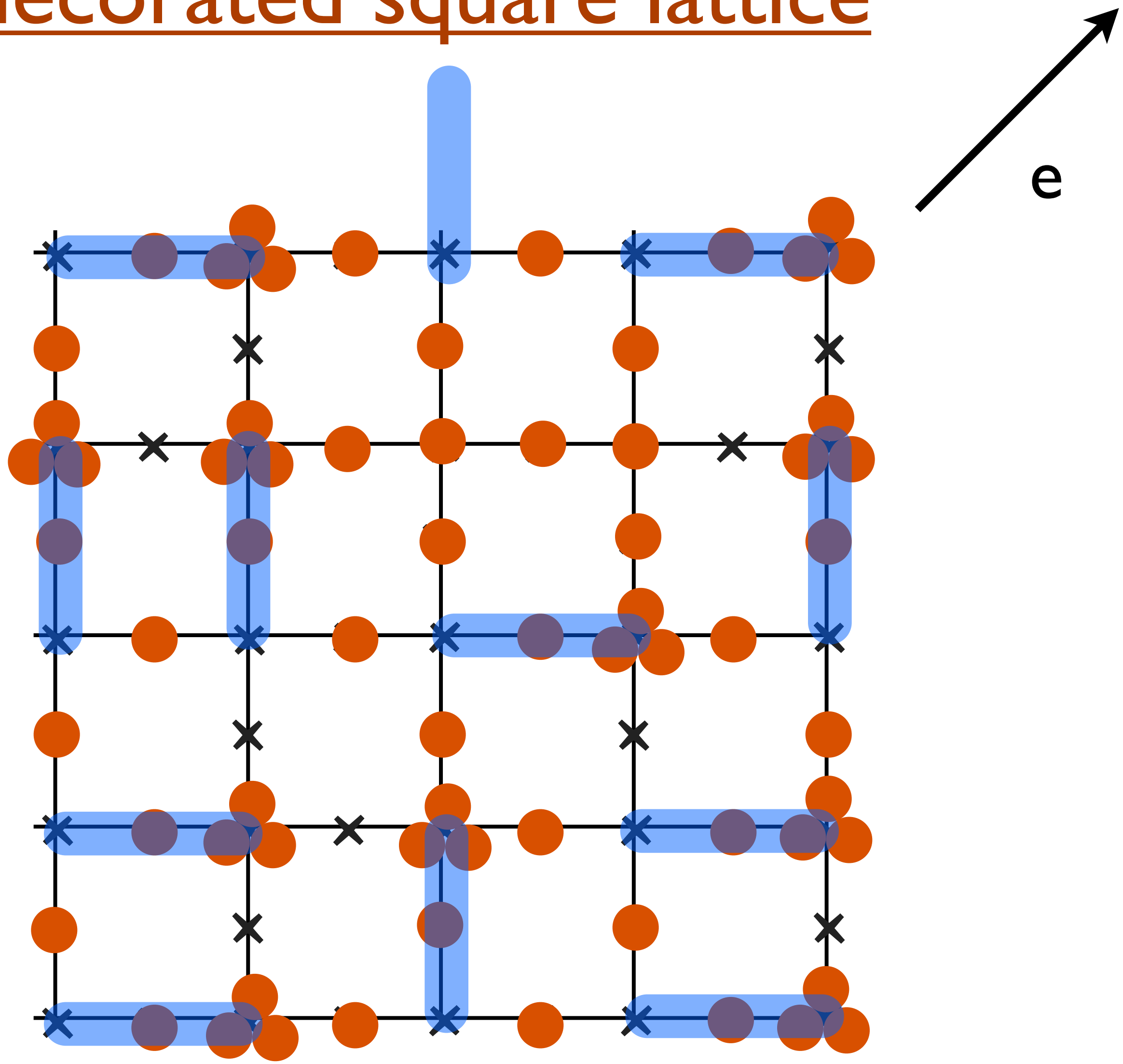

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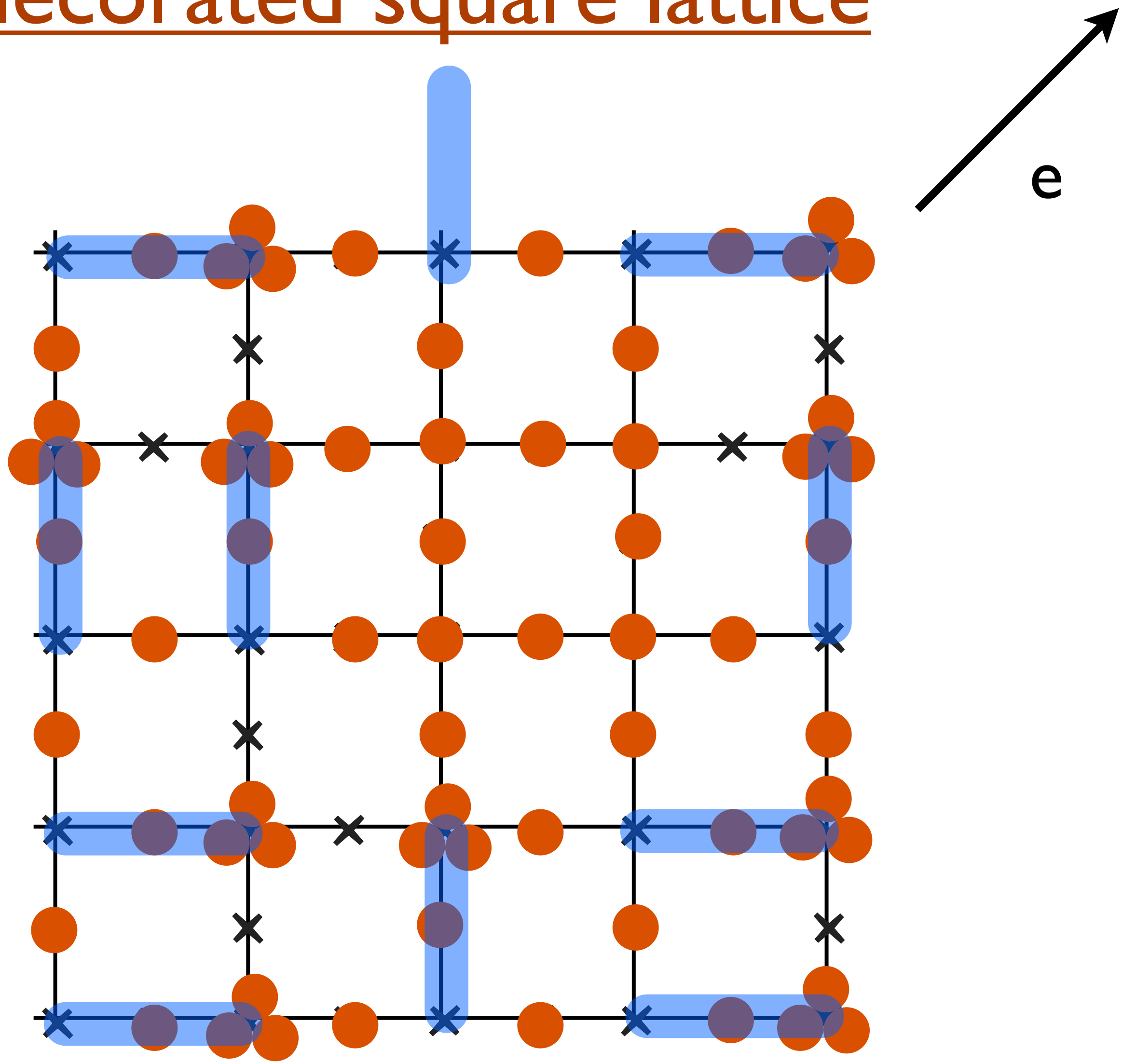

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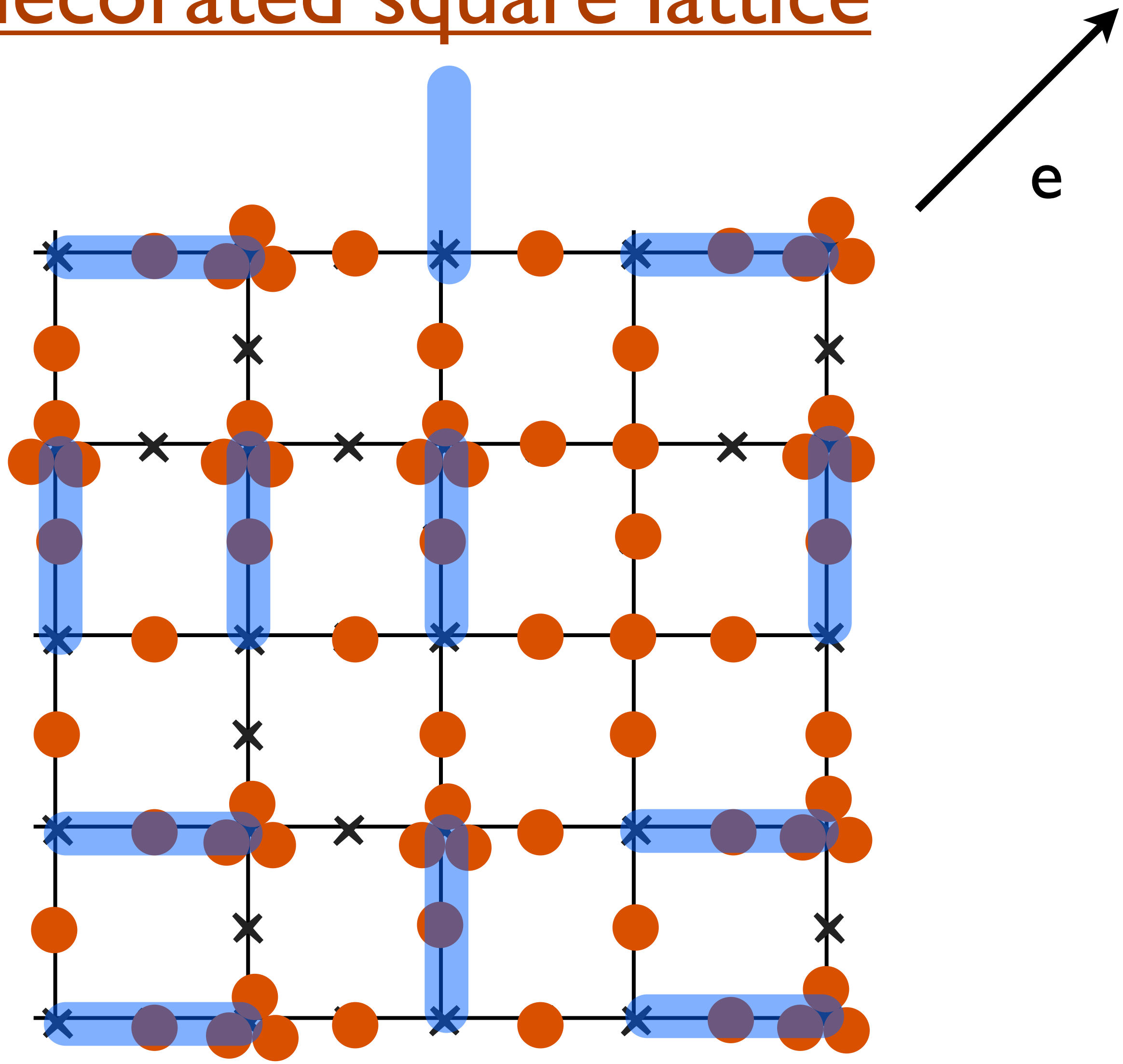
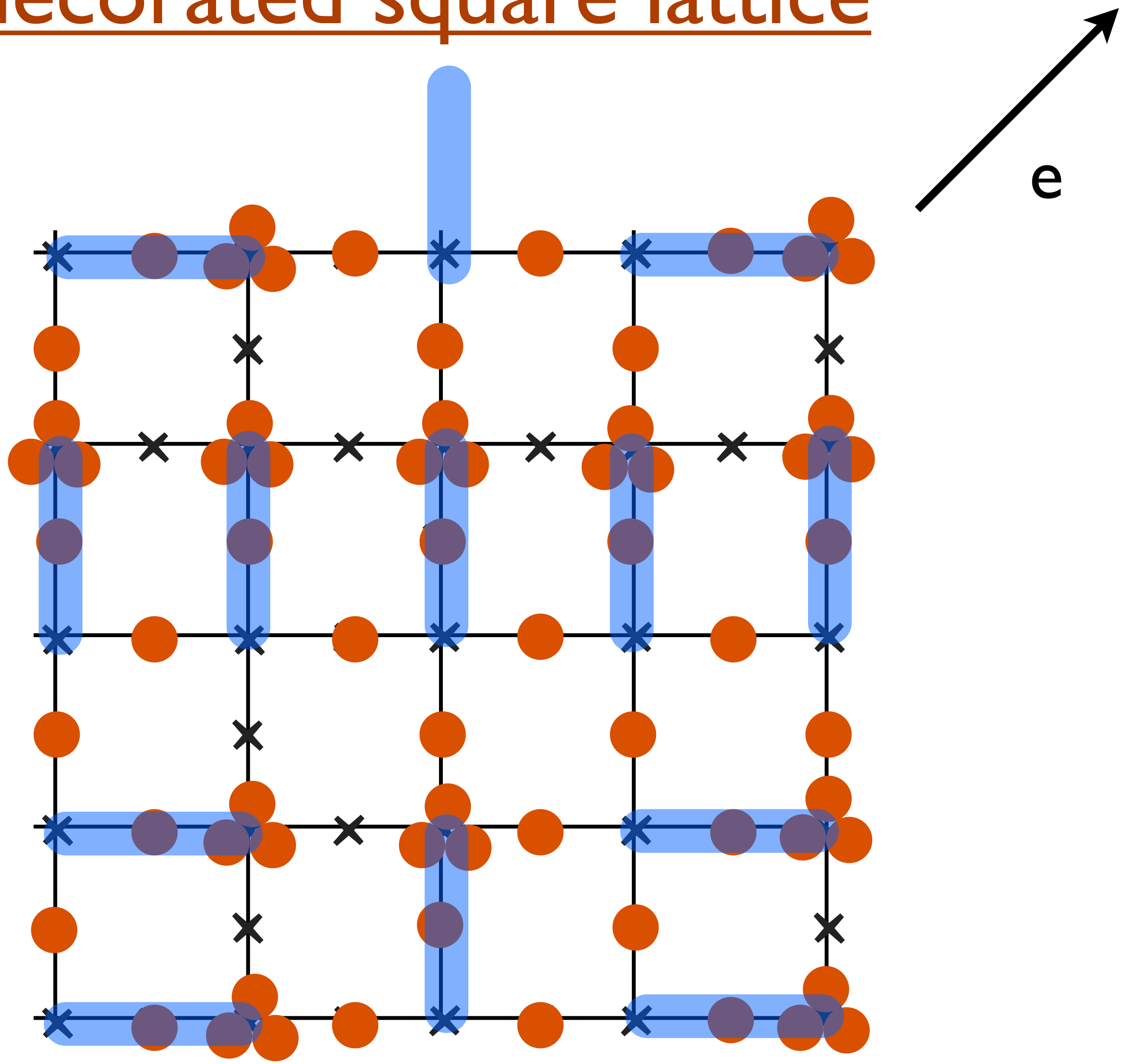


Then create a different set of 3's

Tilting a decorated square lattice



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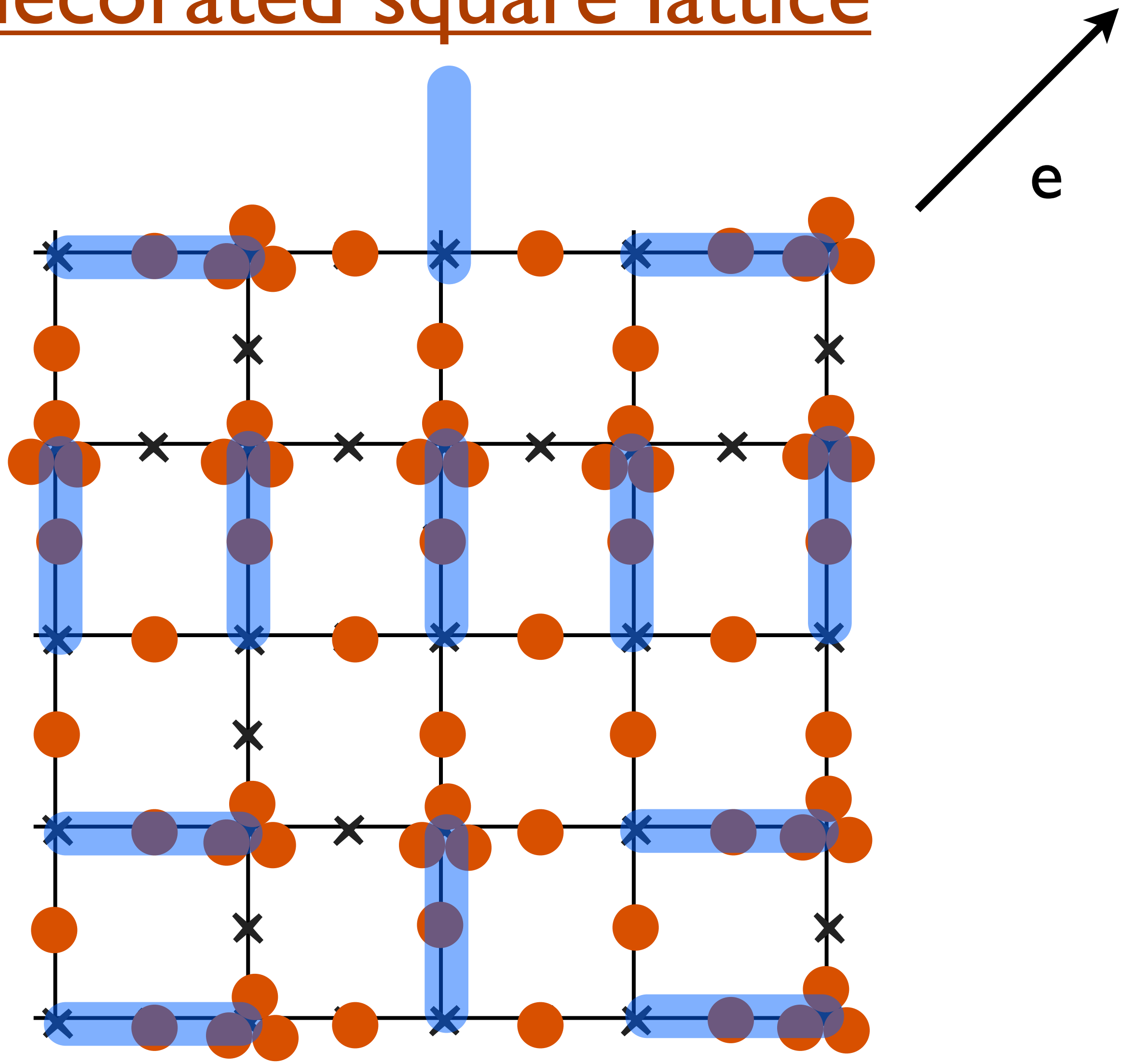
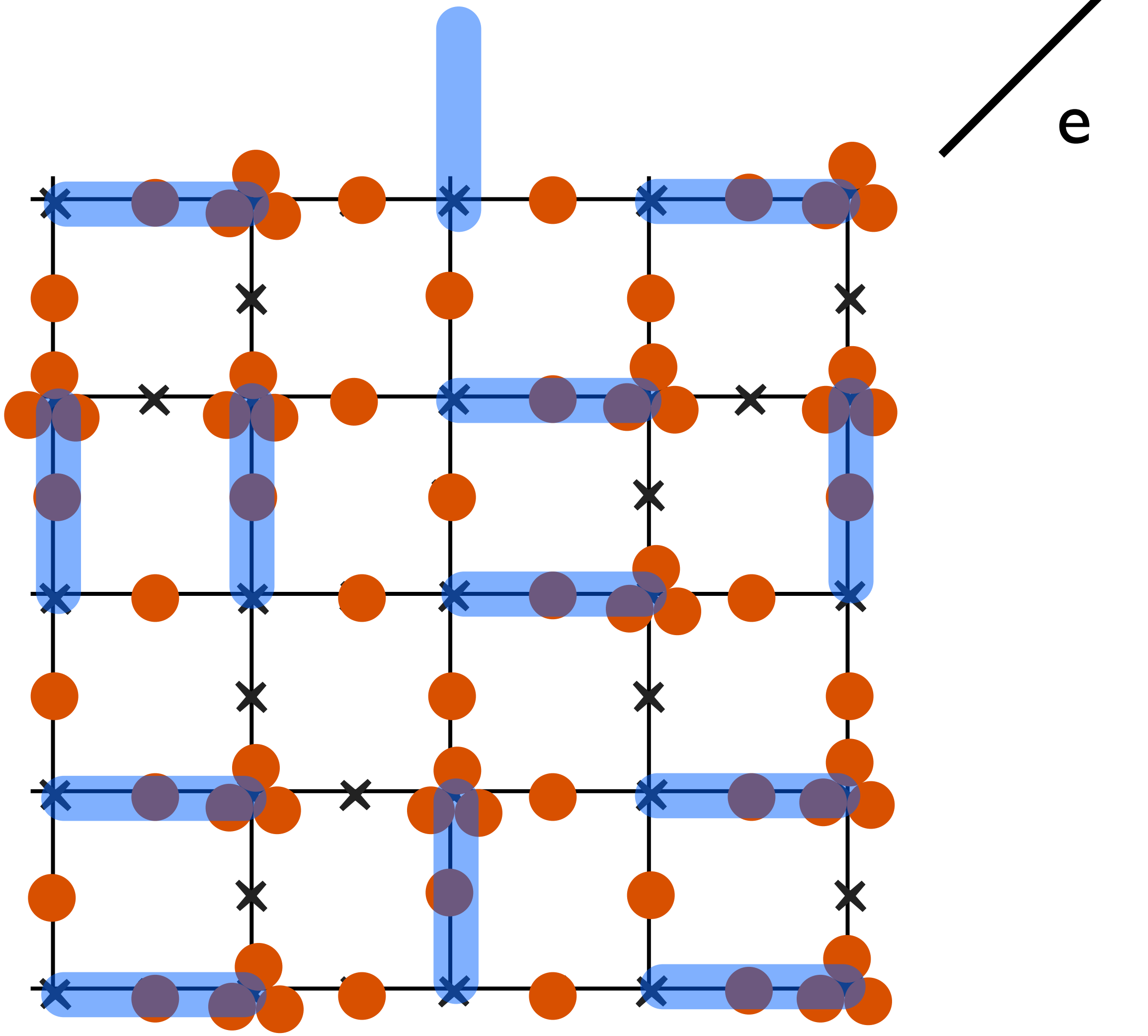
Tilting a decorated square lattice



A different dimer covering

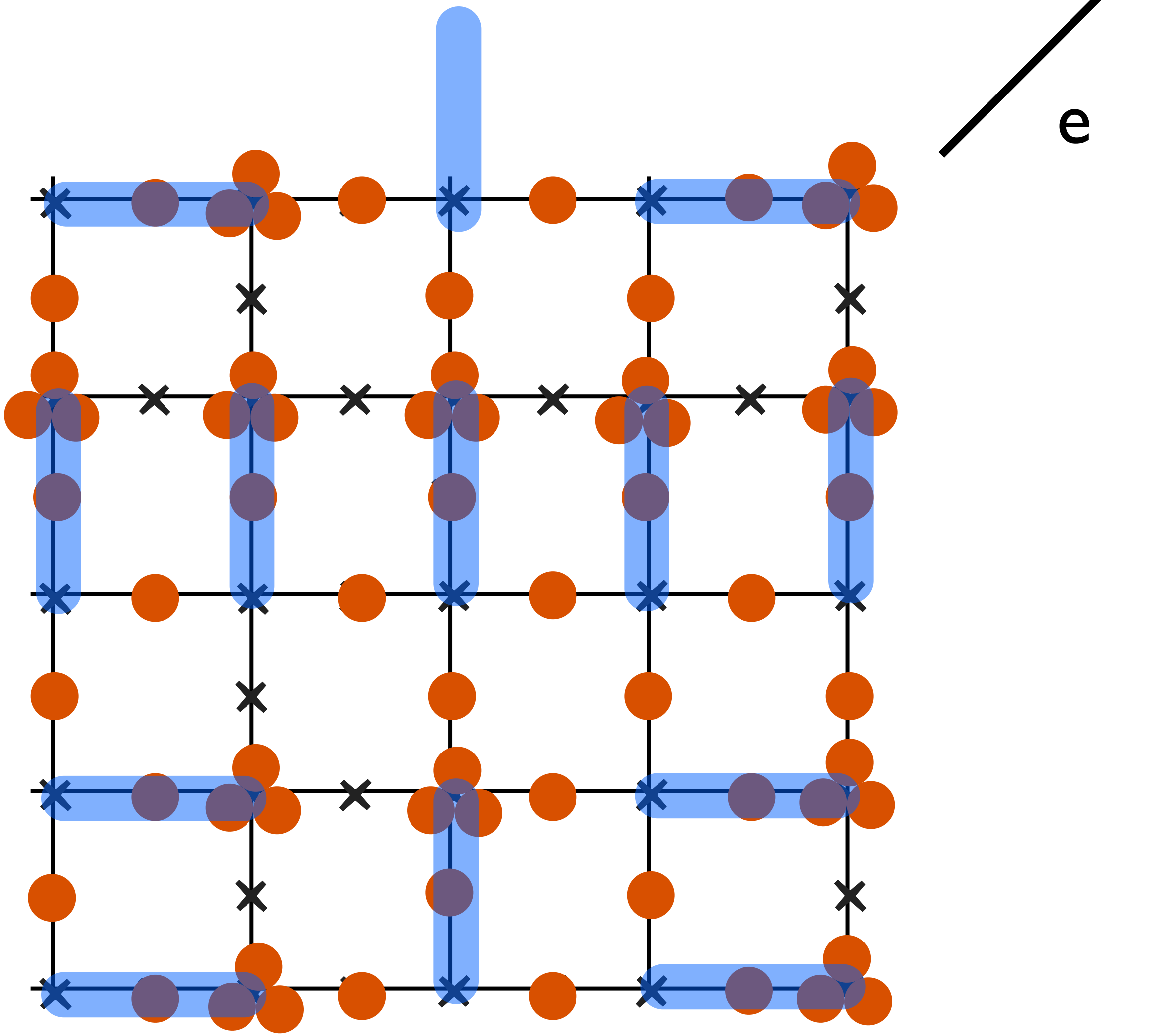
Tilting a decorated square lattice



Susanne Pielawa

Dimers can resonate around a plaquette

Tilting a decorated square lattice



Susanne
Pielawa

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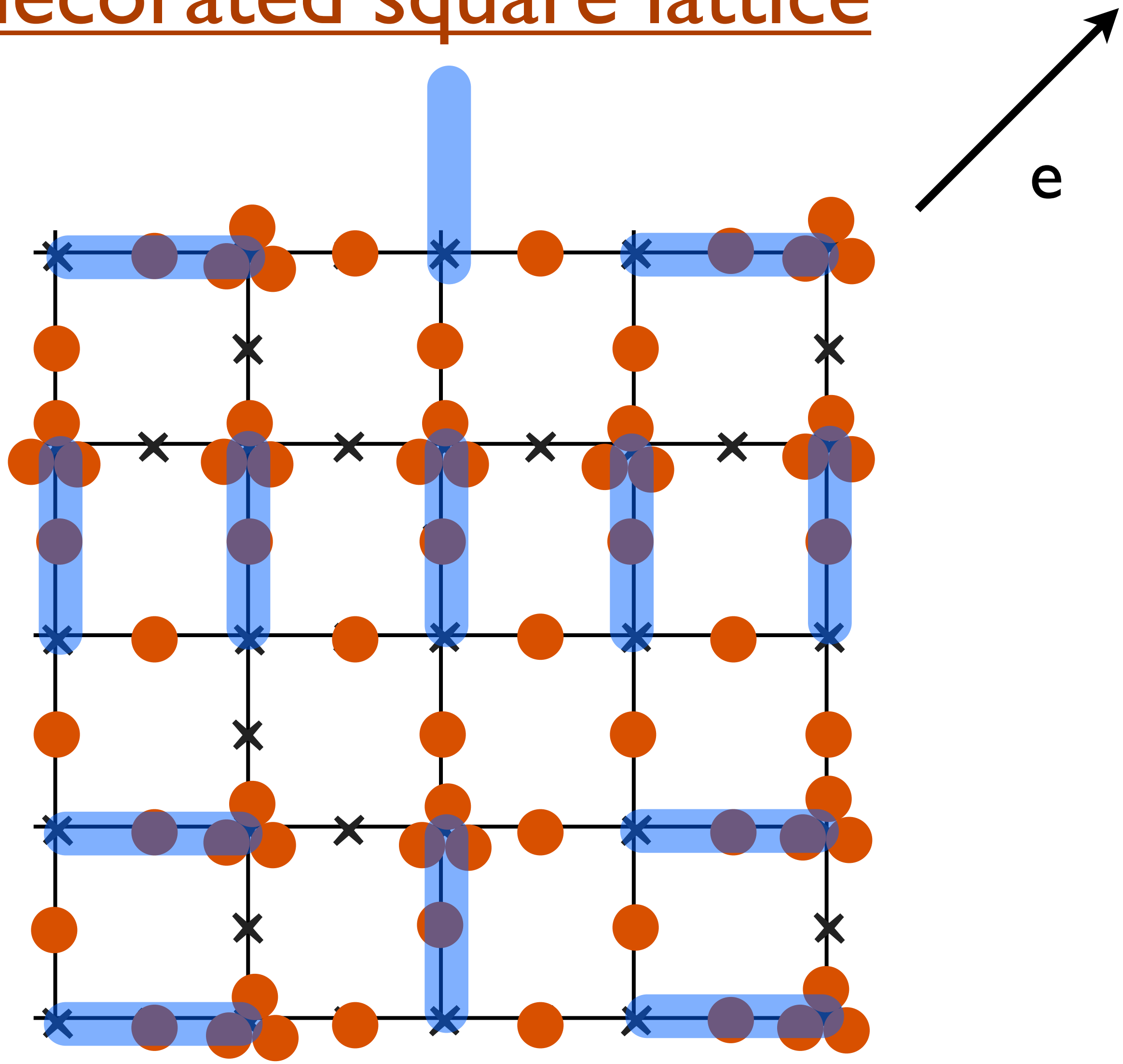

Susanne Pielawa

Strong tilt:
effective quantum dimer model

Conclusions

- Many common issues on many body quantum correlations in condensed matter and ultracold atoms

- Tilting Mott insulators can generate many interesting states with non-trivial quantum entanglement