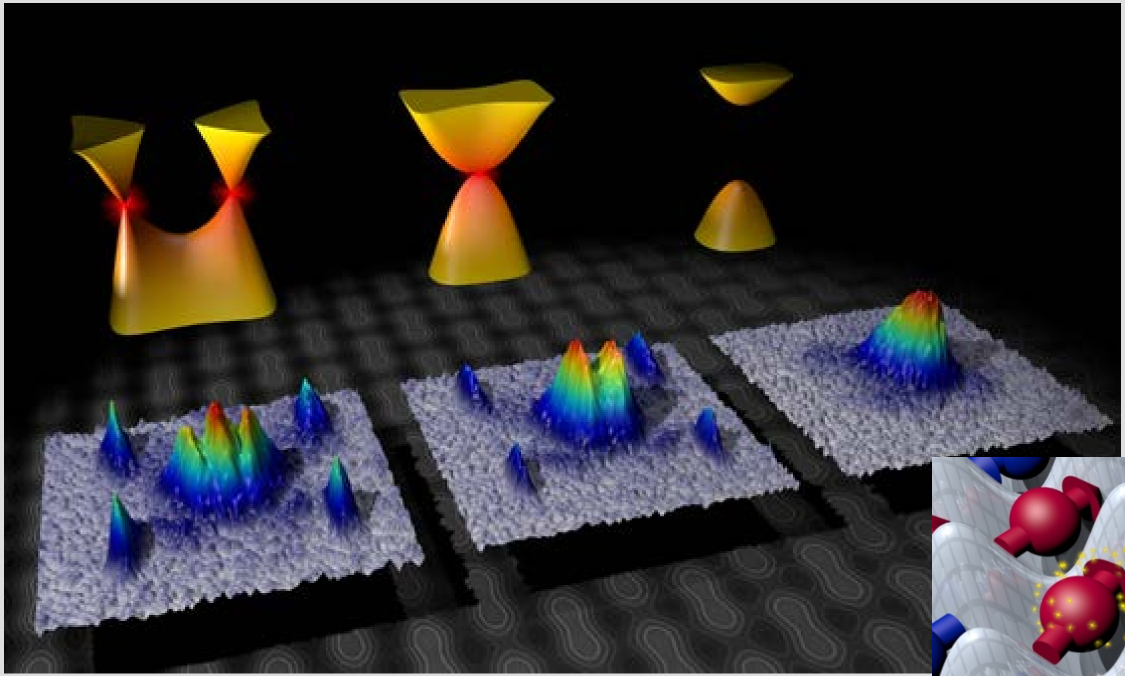
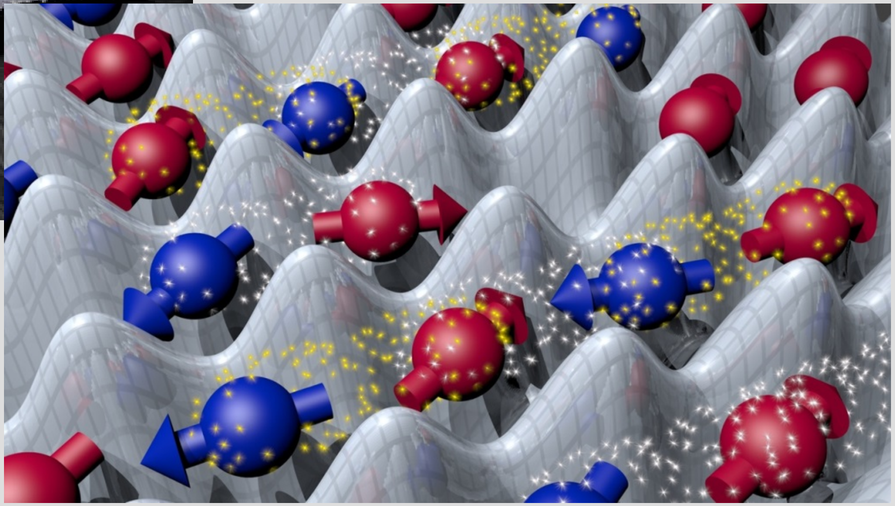
Ultracold fermions in tunable-geometry optical lattices

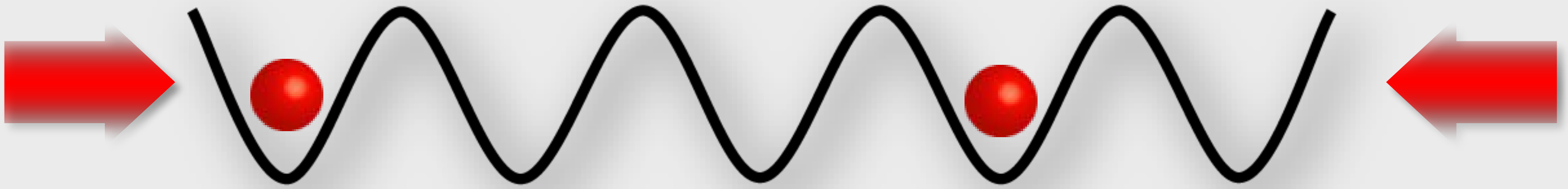




Leticia Tarruell

Okinawa, 15/04/2014

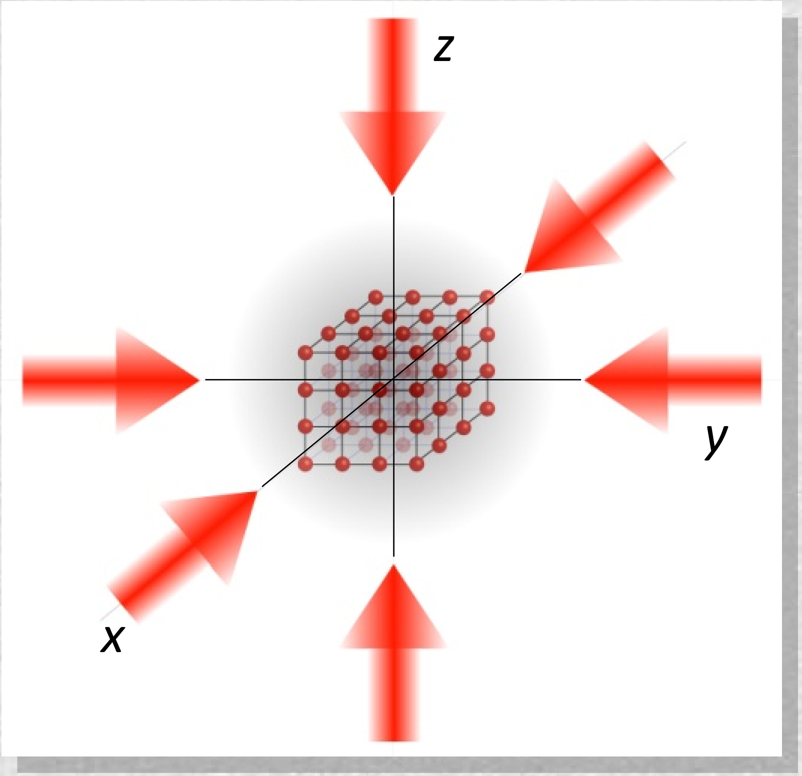
Ultracold fermions in optical lattices

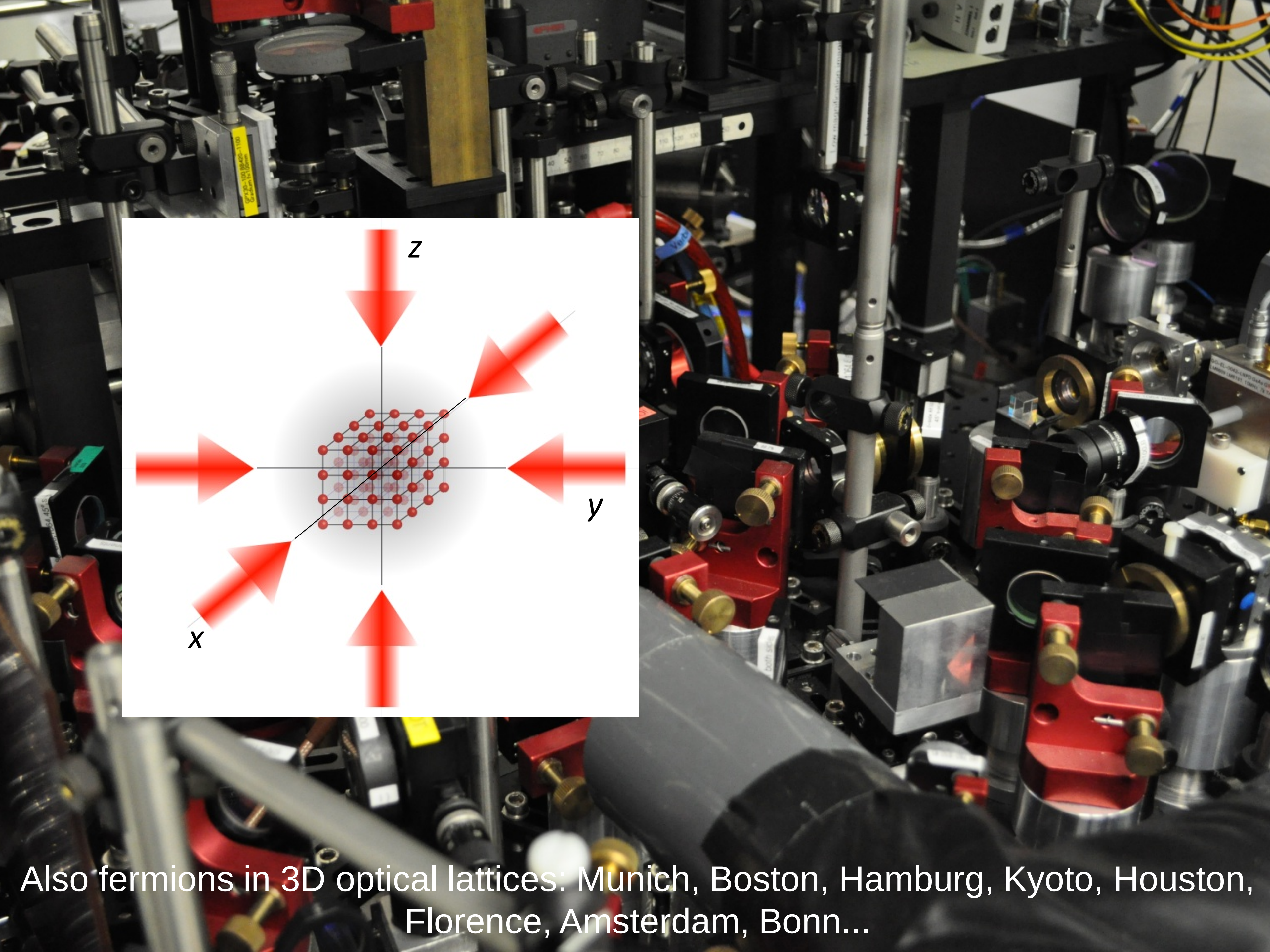


- Ultracold fermionics atoms (^{40}K)
- Interfering laser beams (optical lattice)

Fermions in optical lattices
as condensed matter model systems

Ultracold fermions in optical lattices



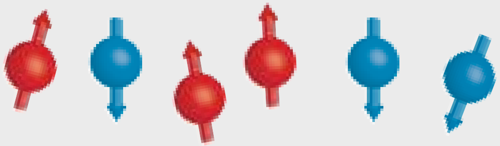

z
y
x
Also fermions in 3D optical lattices: Munich, Boston, Hamburg, Kyoto, Houston, Florence, Amsterdam, Bonn...

Condensed matter model systems

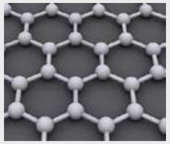
Ultracold fermions
in optical lattices

Strongly correlated materials
(Mott insulators,
high-T_c superconductors)

Spin systems
(quantum phase transitions,
frustration, spin-liquids)



Novel materials
(graphene,
topological insulators)



ETH approach: tunable-geometry optical lattice

Outline

An optical lattice of tunable geometry

Engineering Dirac points in a honeycomb lattice

Short-range quantum magnetism

Outline

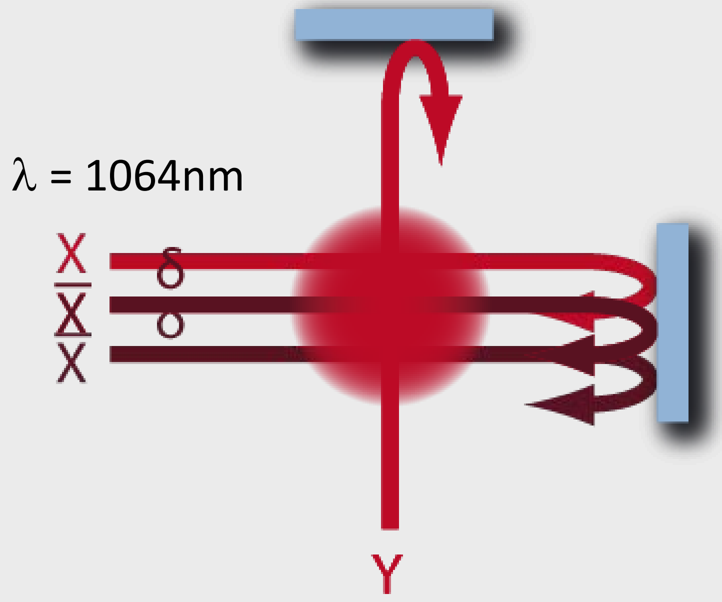
An optical lattice of tunable geometry

Engineering Dirac points in a honeycomb lattice

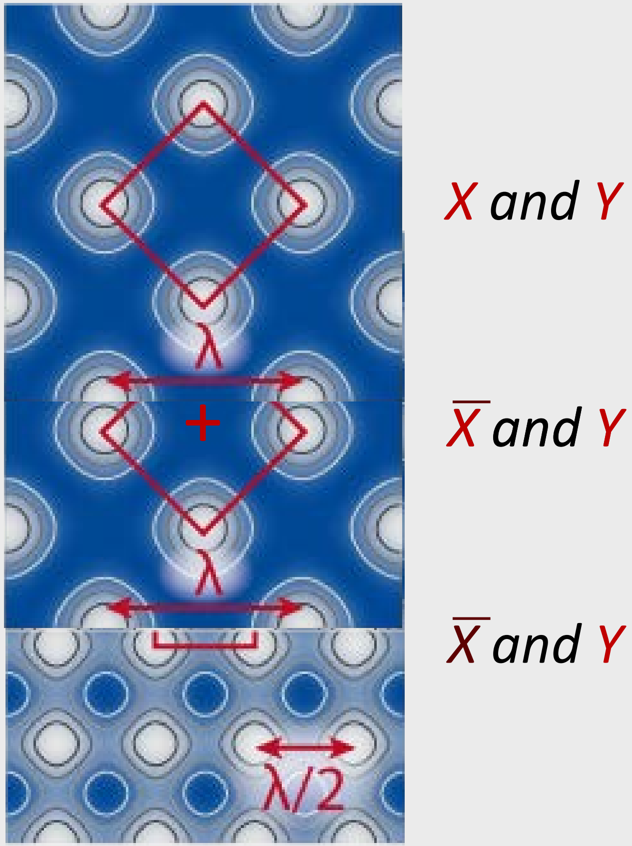
Short-range quantum magnetism

The tunable-geometry optical lattice

Setup

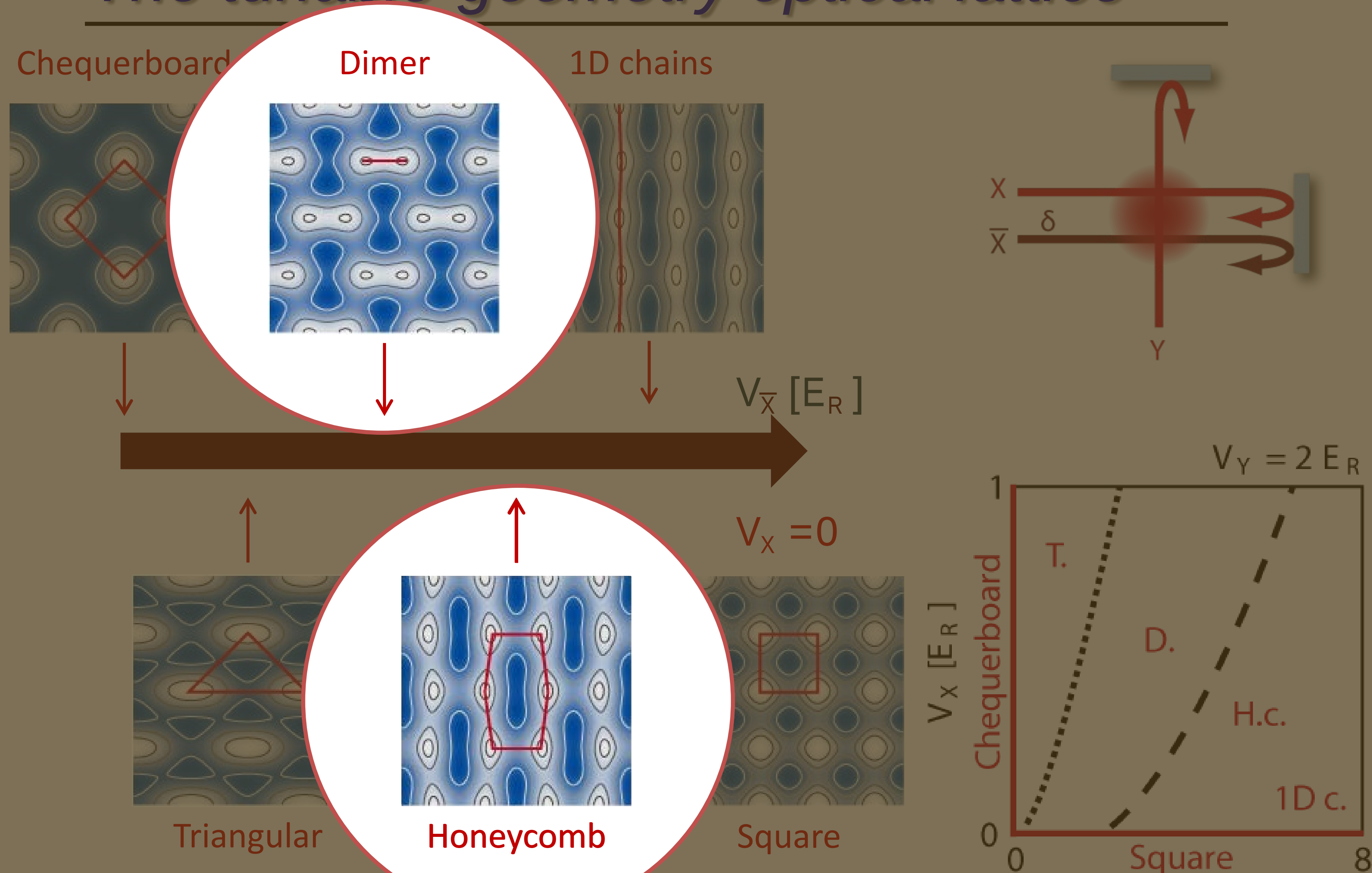


Optical potential



$$V(x,y) = \boxed{V_{\bar{X}} \cos^2(kx+\theta/2)} + \boxed{V_X \cos^2(kx) + V_Y \cos^2(ky) + 2\alpha\sqrt{V_X V_Y}\cos(kx)\cos(ky)}$$

The tunable-geometry optical lattice



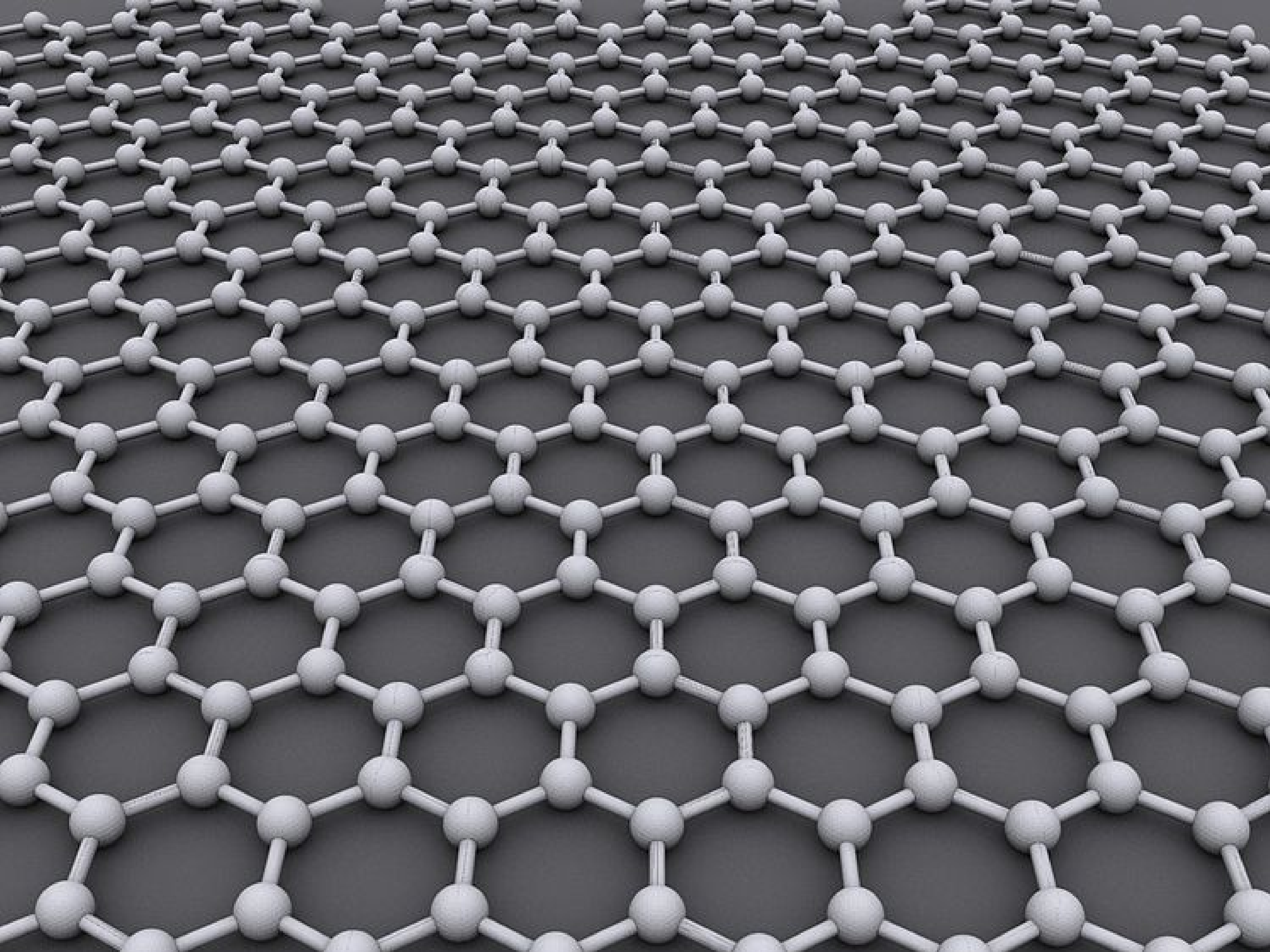
Other non-standard lattices: … en, Bonn, Hamburg, Berkeley

Outline

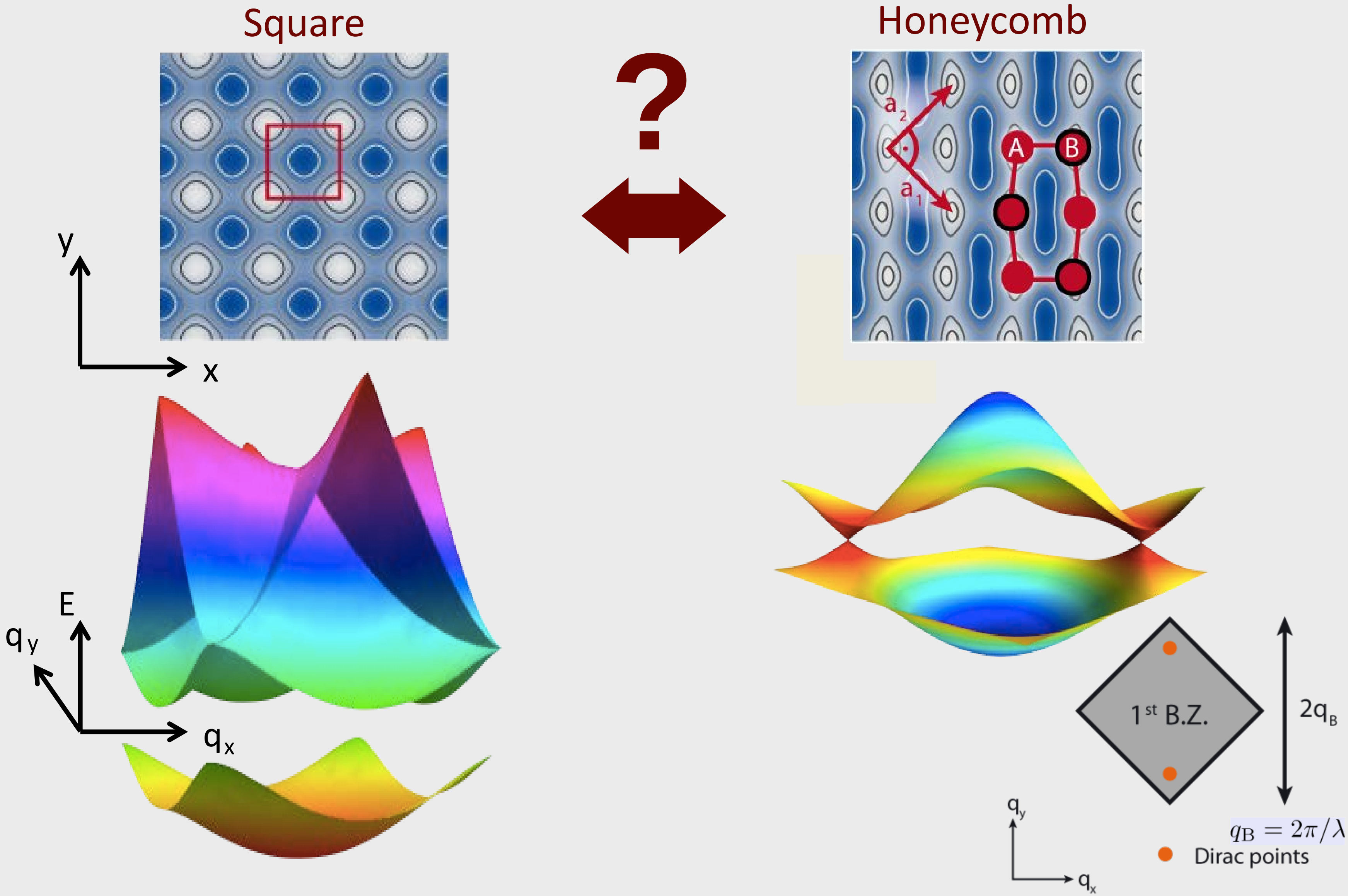
An optical lattice of tunable geometry

Engineering Dirac points in a honeycomb lattice

Short-range quantum magnetism



Deforming the band structure



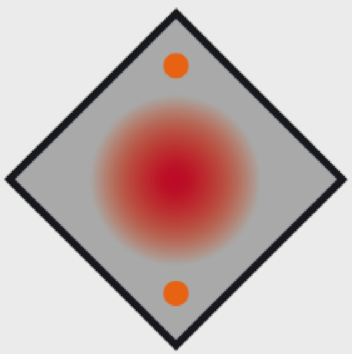
Probing the Dirac points

Challenges: vanishing density of states
small energy scales

Probe energy splitting of
the bands **dynamically**

T. Salger *et al.*, Phys. Rev. Lett. 99, 190405 (2007)

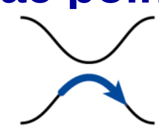
Bloch oscillations + interband transitions



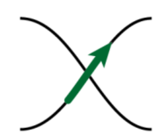
+

Pot. Gradient ≙ Force

Passing away from Dirac point:
stay in lowest band



Passing through Dirac point:
transfer to 2nd band

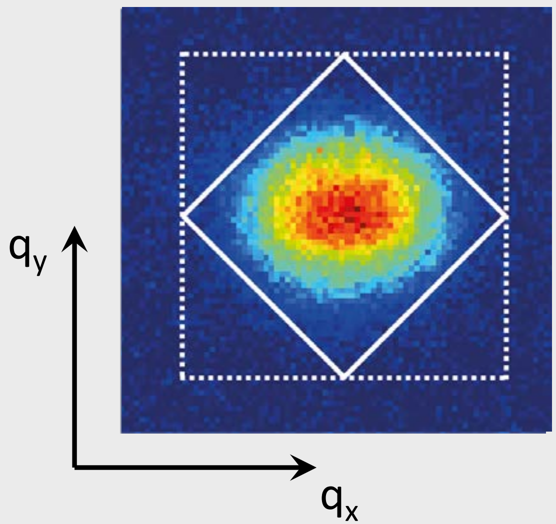


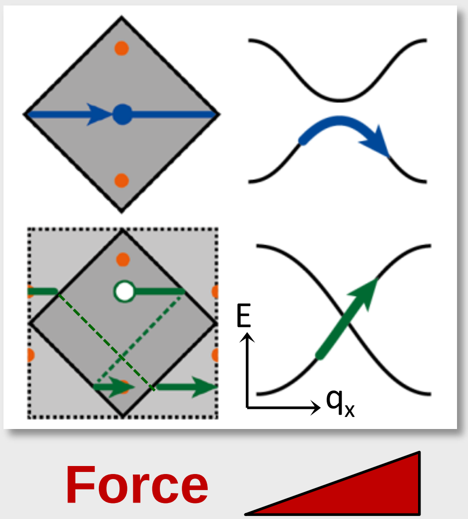
Observable: quasi-momentum distribution

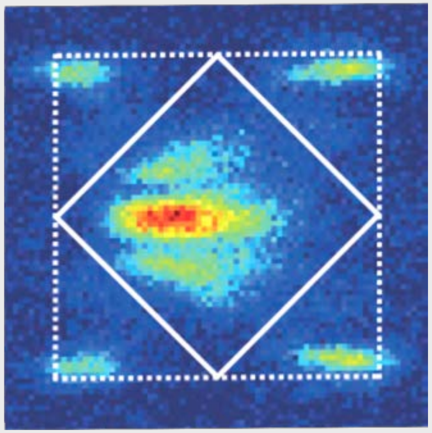
Interband transitions

Spin-polarized ^{40}K gas

After a Bloch cycle: $t=T_B$



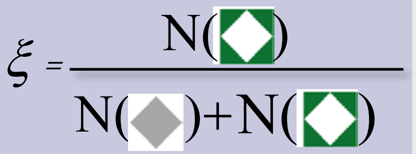




Transfer to 2nd band at the position of the Dirac points

Quantitative measurements

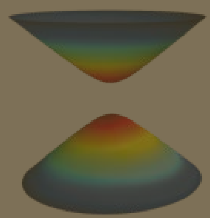
Higher band fraction



Engineering Dirac points

Tunability

Gap



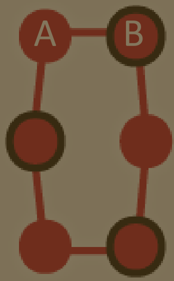
Cone shape

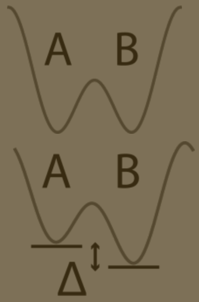
Position

Merging

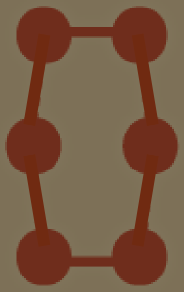
Tools

Inversion symmetry

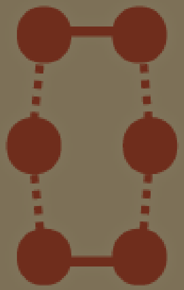




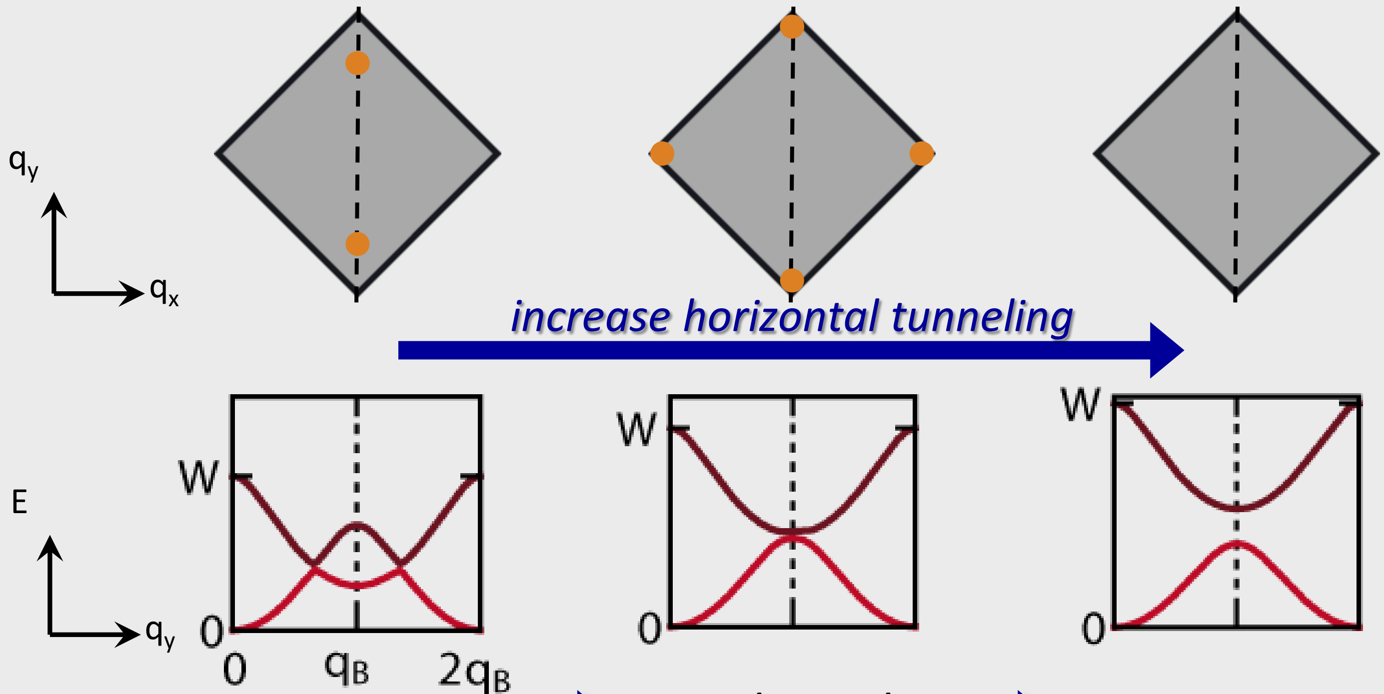
Tunneling imbalance



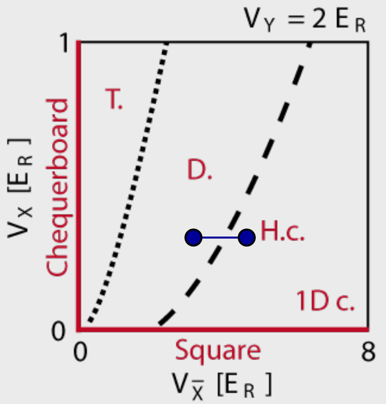
vs.



Merging Dirac points



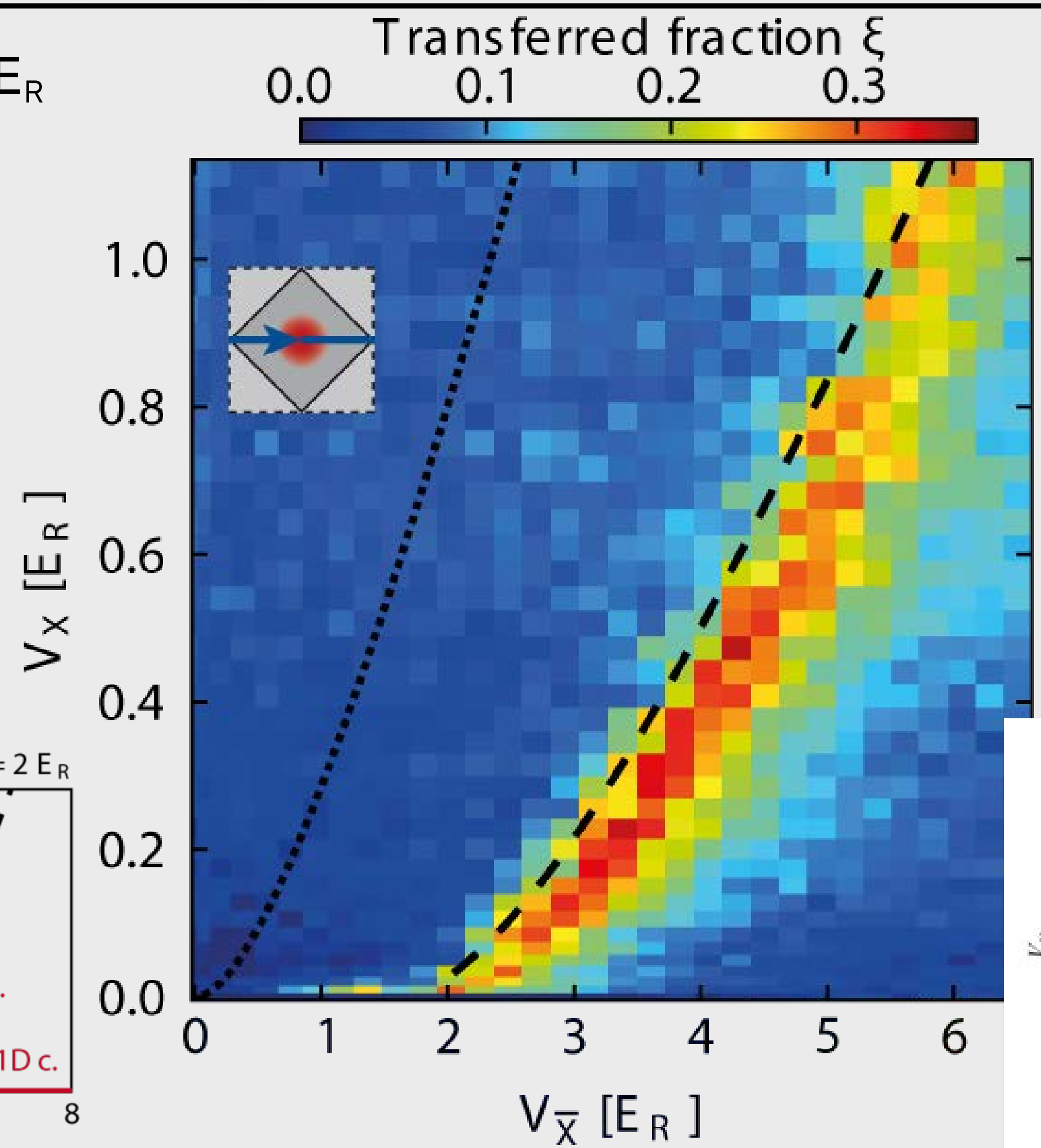
Dirac points → *Topological Transition* → *No Dirac points*

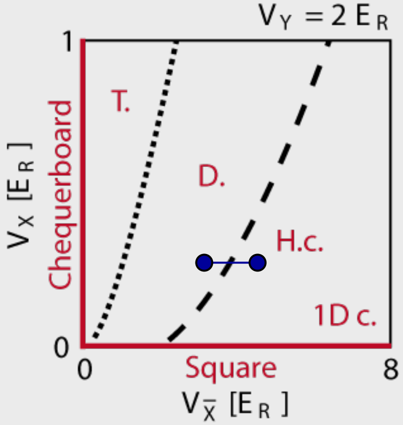


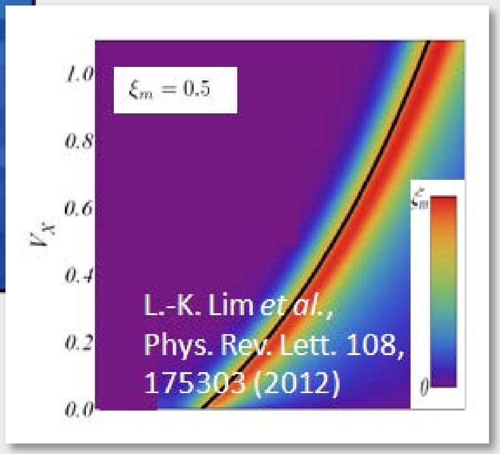
Lifshitz transition, Sov. Phys. JETP **11**, 1130 (1960)

The topological transition

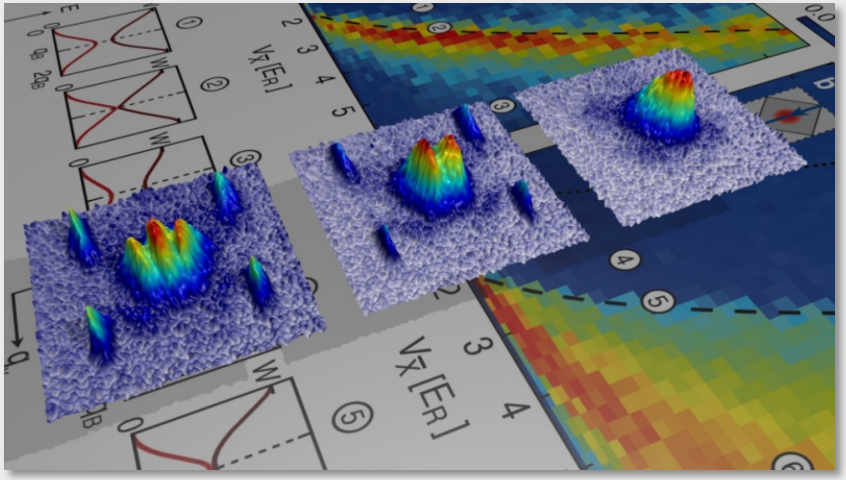
$V_Y = 1.8\ E_R$







Engineering Dirac points



L. Tarruell, D. Greif, T. Uehlinger, G. Jotzu, and T. Esslinger, Nature **483**, 302 (2012)
T. Uehlinger, D. Greif, G. Jotzu, L. Tarruell, T. Esslinger, L. Wang, and M. Troyer, EPJ ST **217**, 121 (2013)

Combination of honeycomb lattice and interactions (Mott insulator)

T. Uehlinger, G. Jotzu, M. Messer, D. Greif, U. Bissbort, W. Hoffstetter, and T. Esslinger,

Phys. Rev. Lett. **111**, 185307 (2013).

Lattice shaking to engineer the Haldane model

Outline

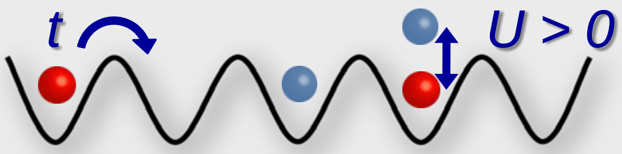
An optical lattice of tunable geometry

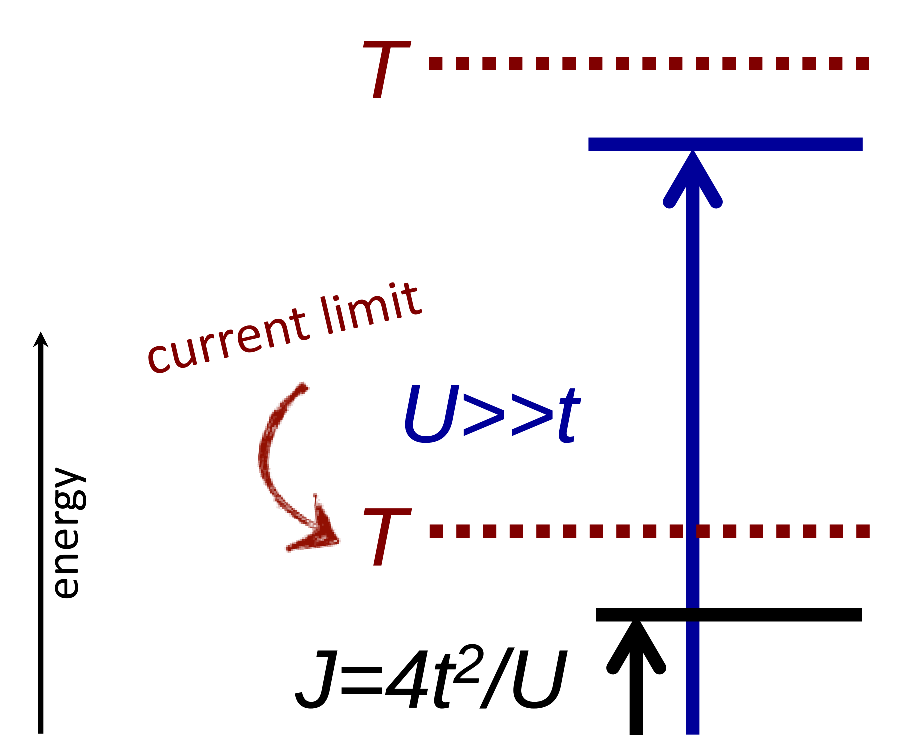
Engineering Dirac points in a honeycomb lattice

Short-range quantum magnetism

Magnetism: a temperature challenge

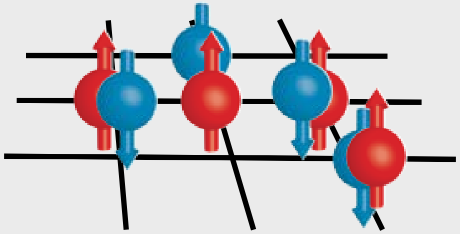
Fermi-Hubbard model



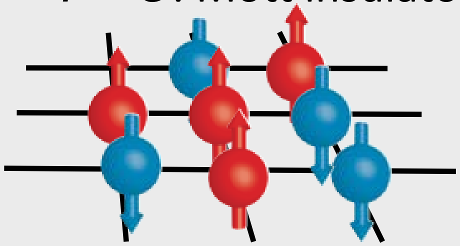


R. Jördens *et al.*, Phys. Rev. Lett. **104**, 180401 (2010)

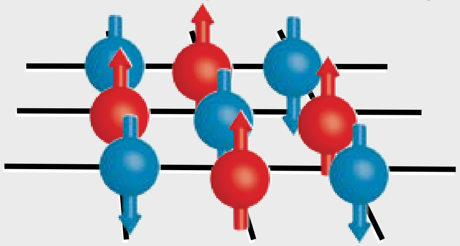
$T > U$: metallic behaviour



$T < U$: Mott insulator

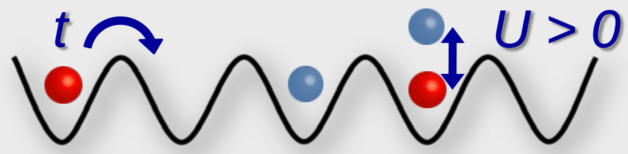


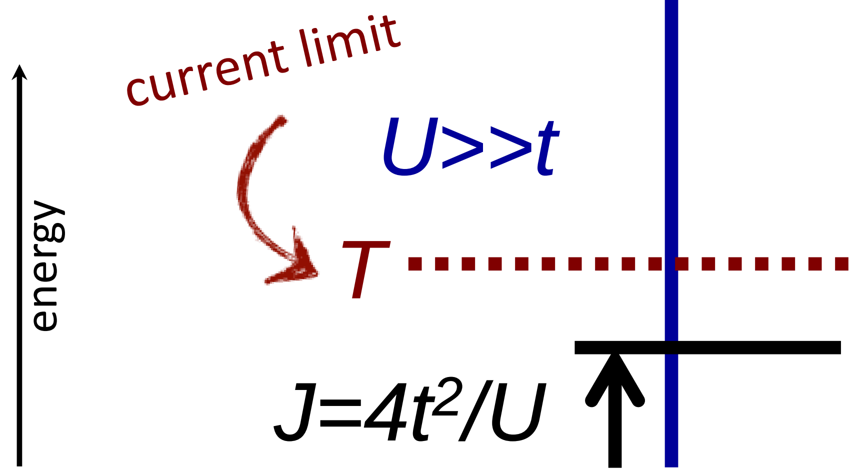
$T < J$: spin ordering



Magnetism: a temperature challenge

Fermi-Hubbard model





R. Jördens *et al.*, Phys. Rev. Lett. **104**, 180401 (2010)

State of the art

Isolated double-wells or plaquettes (Munich)

S. Trotzky *et al.*, Science **319**, 295-299 (2008)

S. Nascimbène *et al.*, Phys. Rev. Lett**. 108**, 205301 (2012)

Mappings

Ising spin chain (Harvard)

Classical magnets (Hamburg)

J. Simon *et al.*, Nature **472**, 307-312 (2011)

J. Struck *et al.*, Science **333**, 996-999 (2011)

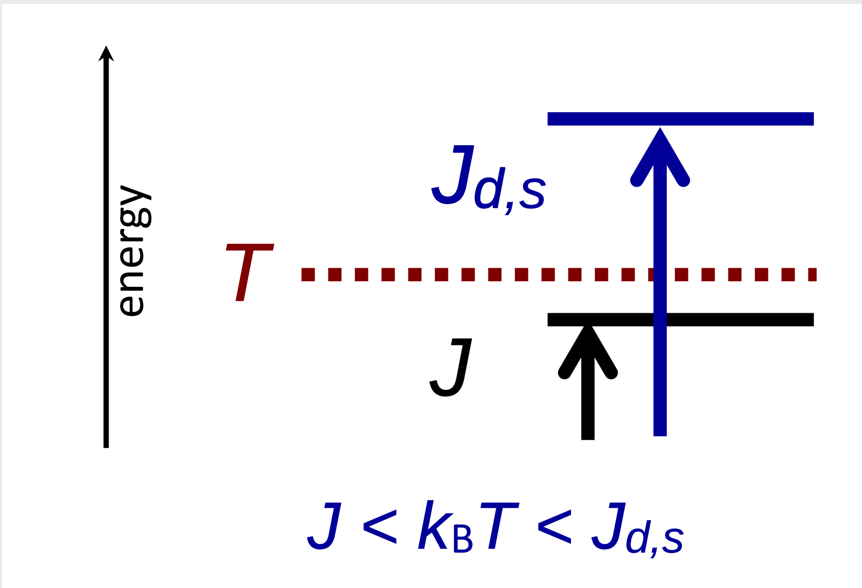
Dipolar interactions (JILA, Paris)

B. Yan *et al.*, Nature **501**, 521-525 (2013)

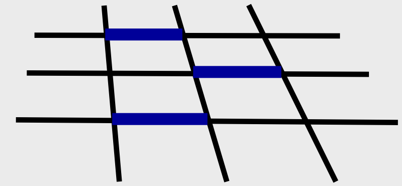
A. de Paz *et al.*, Phys. Rev. Lett. **111** , 185305 (2013)

Reaching magnetism: an energy trick

Reaching magnetic correlations:

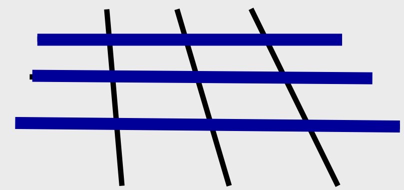


$t_d \Rightarrow J_d > J$ $\quad t \Rightarrow J$



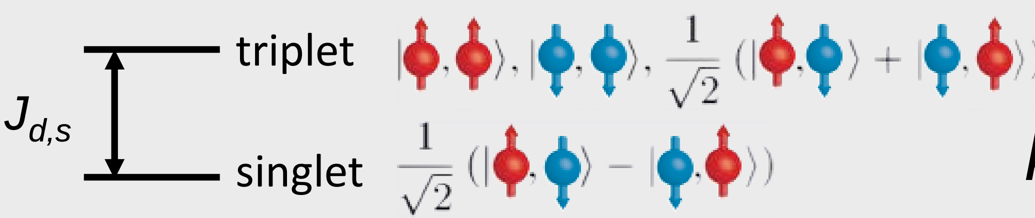
Dimerized lattice

$t_s \Rightarrow J_s > J$



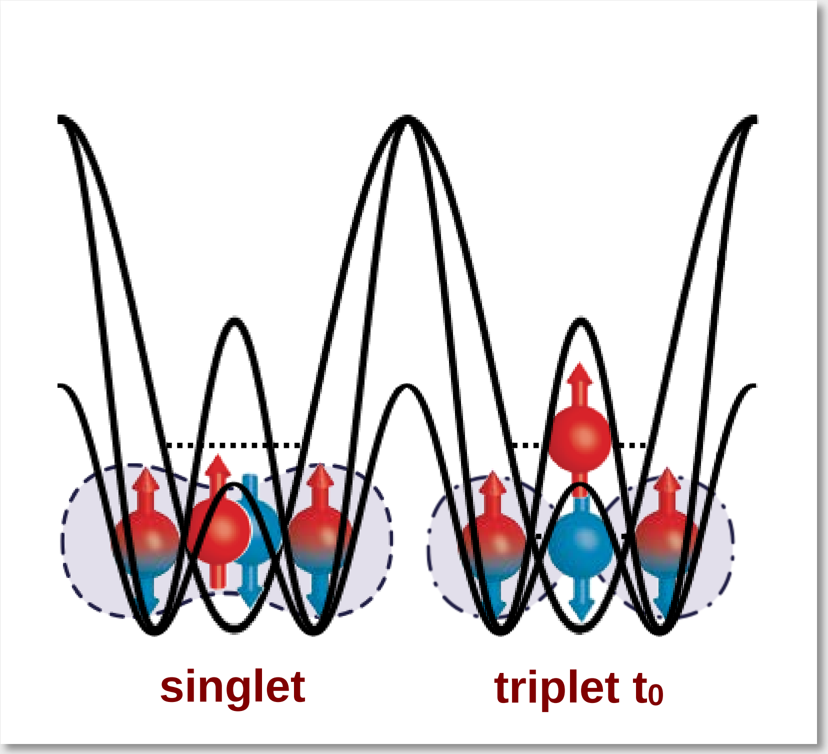
Anisotropic lattice

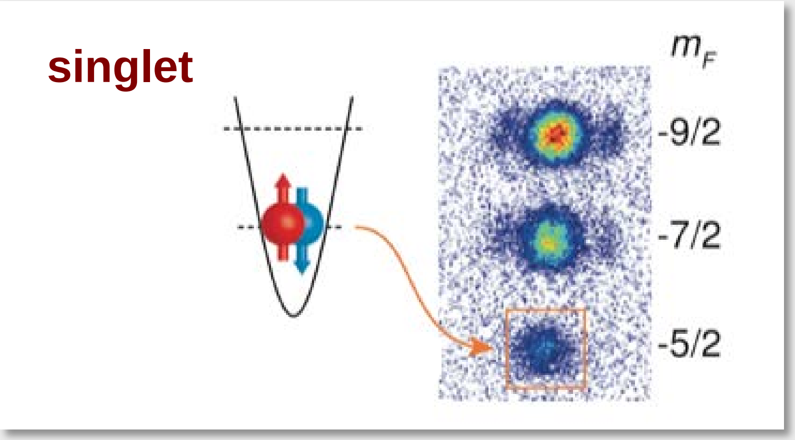
Probing: neighboring sites

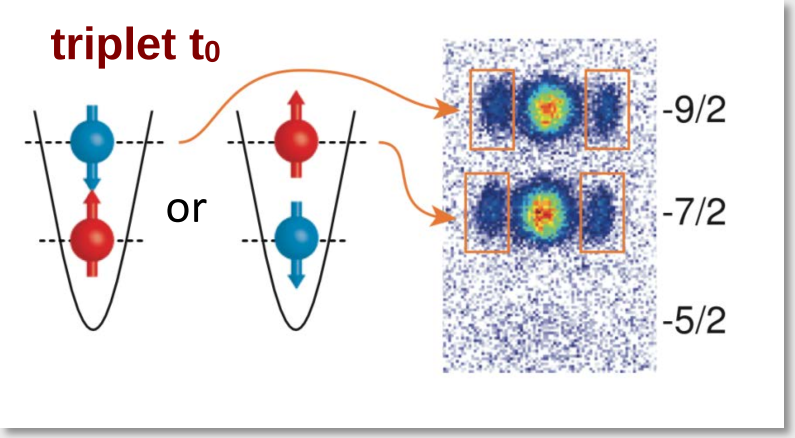


$k_B T < J_{d,s} : N_S > N_T$

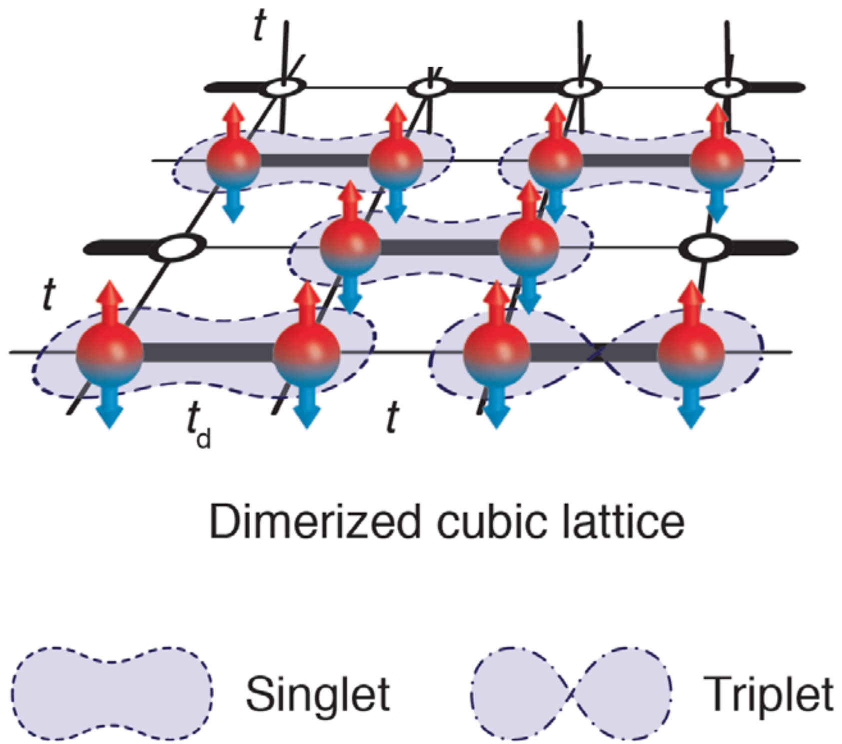
Detecting magnetic correlations





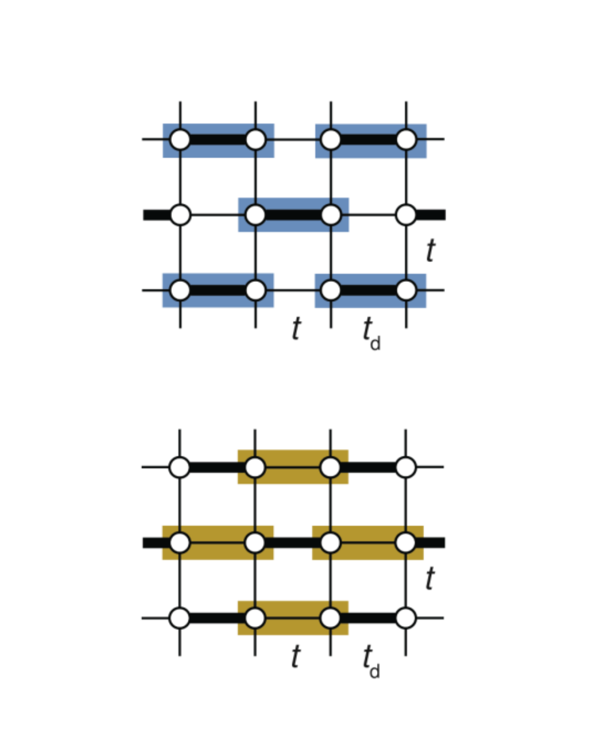


Dimerized lattice

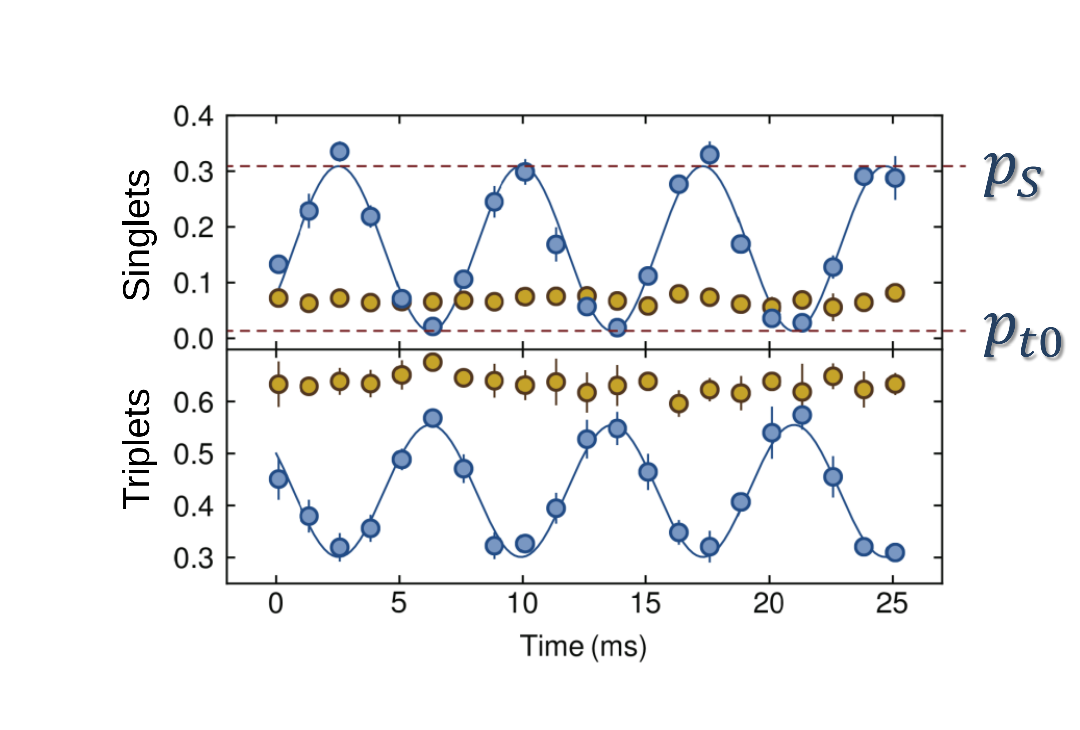


Measuring singlets and triplets

Merging neighboring sites



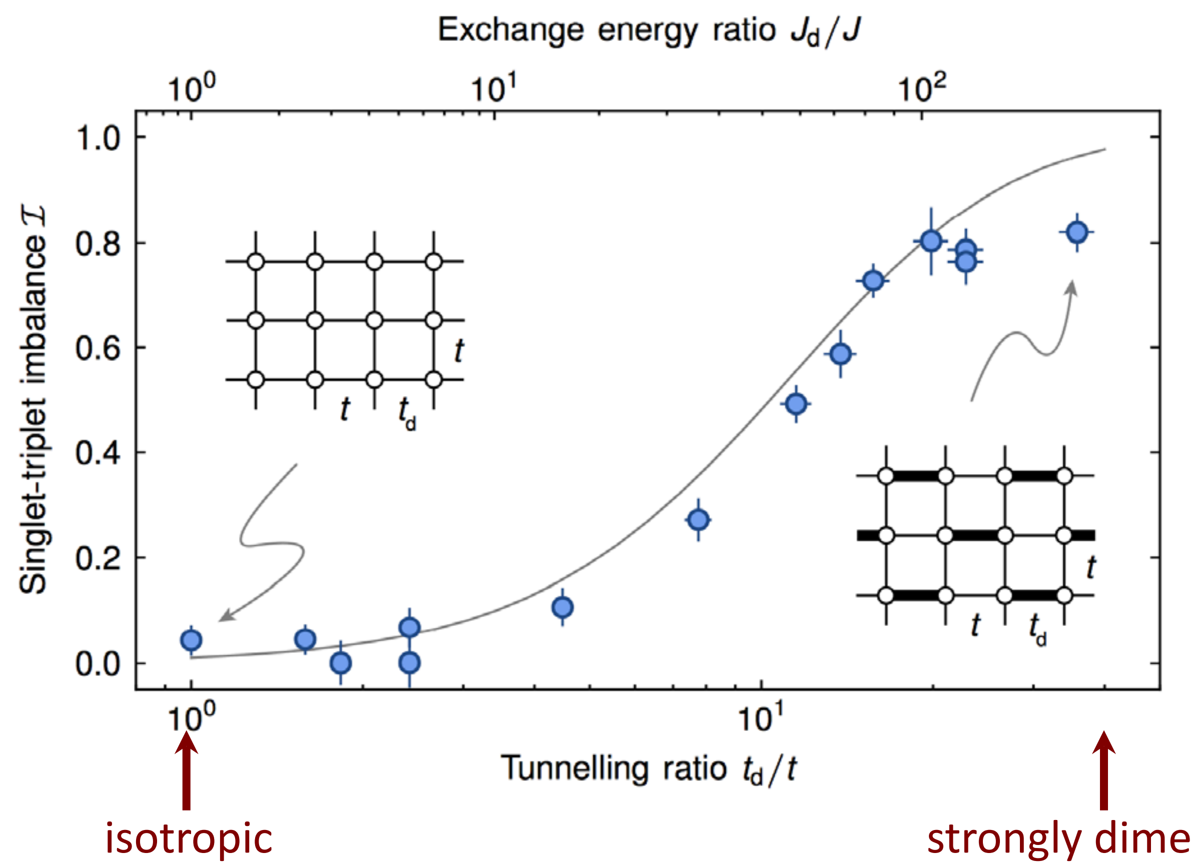
Singlet-triplet oscillations



Singlet-Triplet Imbalance $$\mathcal{I} = \frac{p_{\mathrm{s}} - p_{\mathrm{t_0}}}{p_{\mathrm{s}} + p_{\mathrm{t_0}}}$$

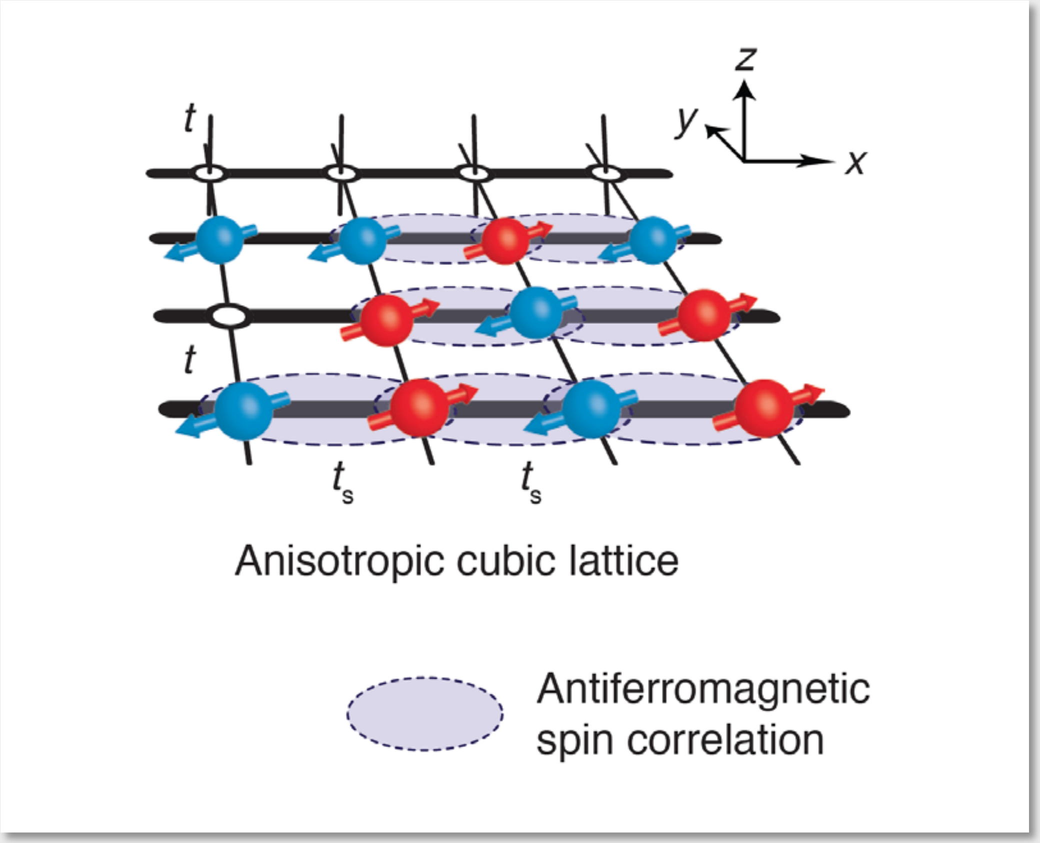
Singlet-Triplet Oscillations: S. Trotzky *et al.*, Phys. Rev. Lett. **105**, 265303 (2010)

Dimerization dependence



Theory: second order high-temperature series expansion of coupled dimers *s=1.7 k_B*

Anisotropic cubic lattice



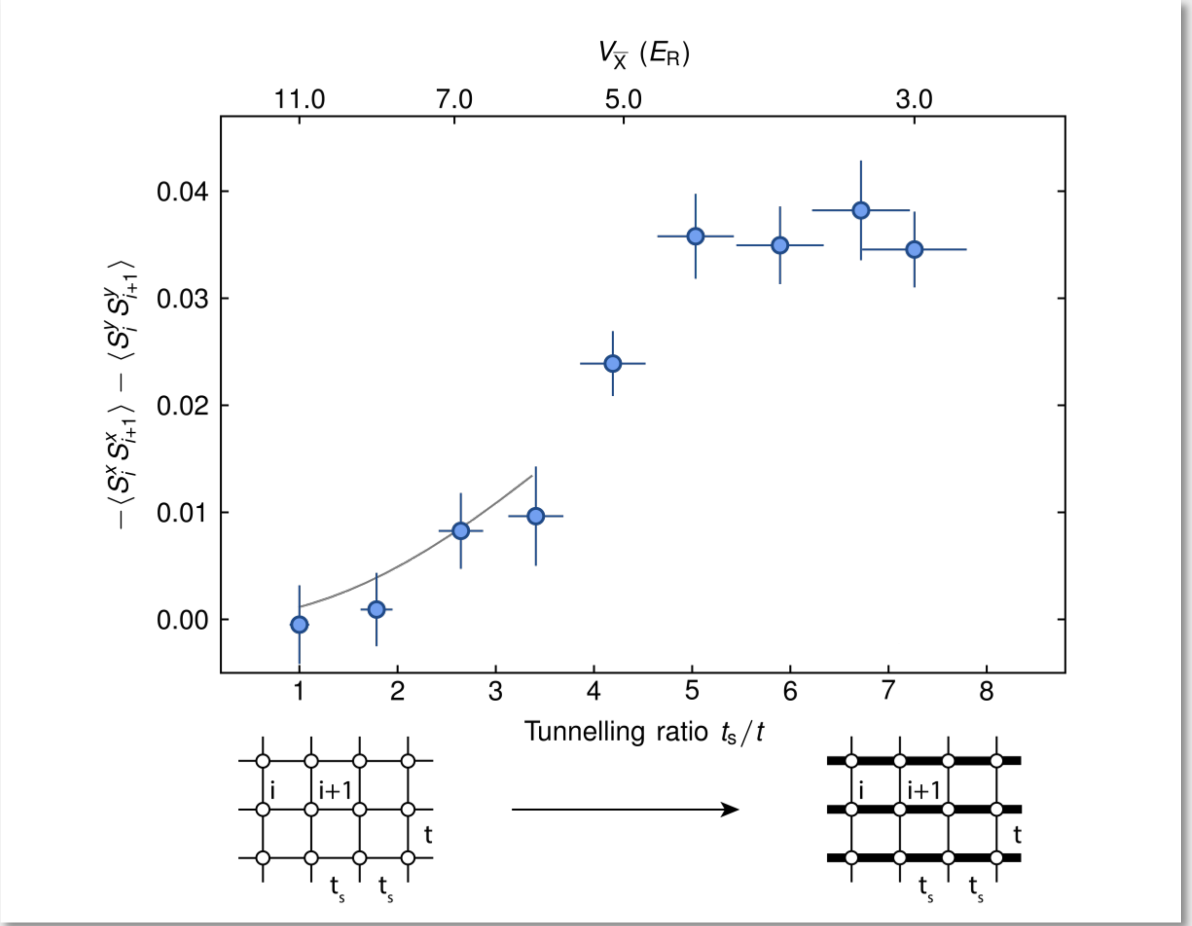
AFM correlations along *x*

$$\langle \mathbf{S}_i \cdot \mathbf{S}_{i+1} \rangle \neq 0$$

transverse spin correlator ⟺ population difference

$$-\langle S_i^x S_{i+1}^x \rangle - \langle S_i^y S_{i+1}^y \rangle = (p_{\mathrm{s}} - p_{\mathrm{t}_0})/2$$

Dependence on geometry



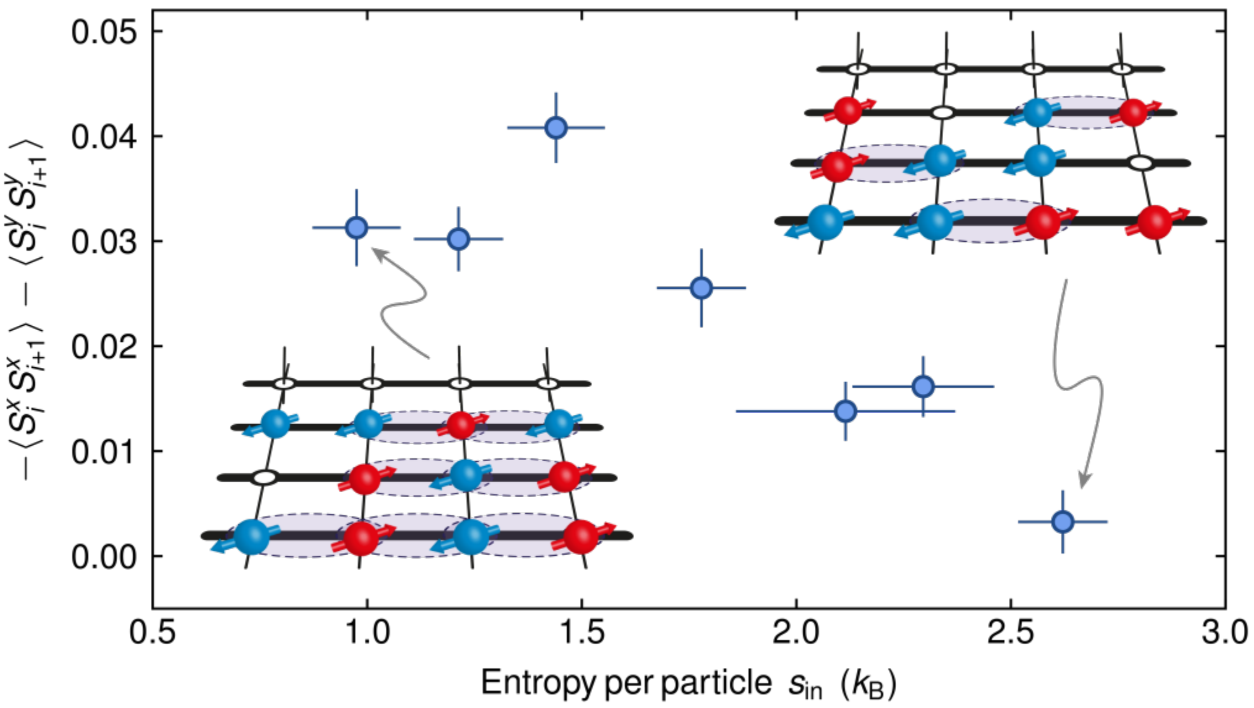
isotropic

strongly anisotropic

$V_{Y,Z}$ = 11.0(3) E_R

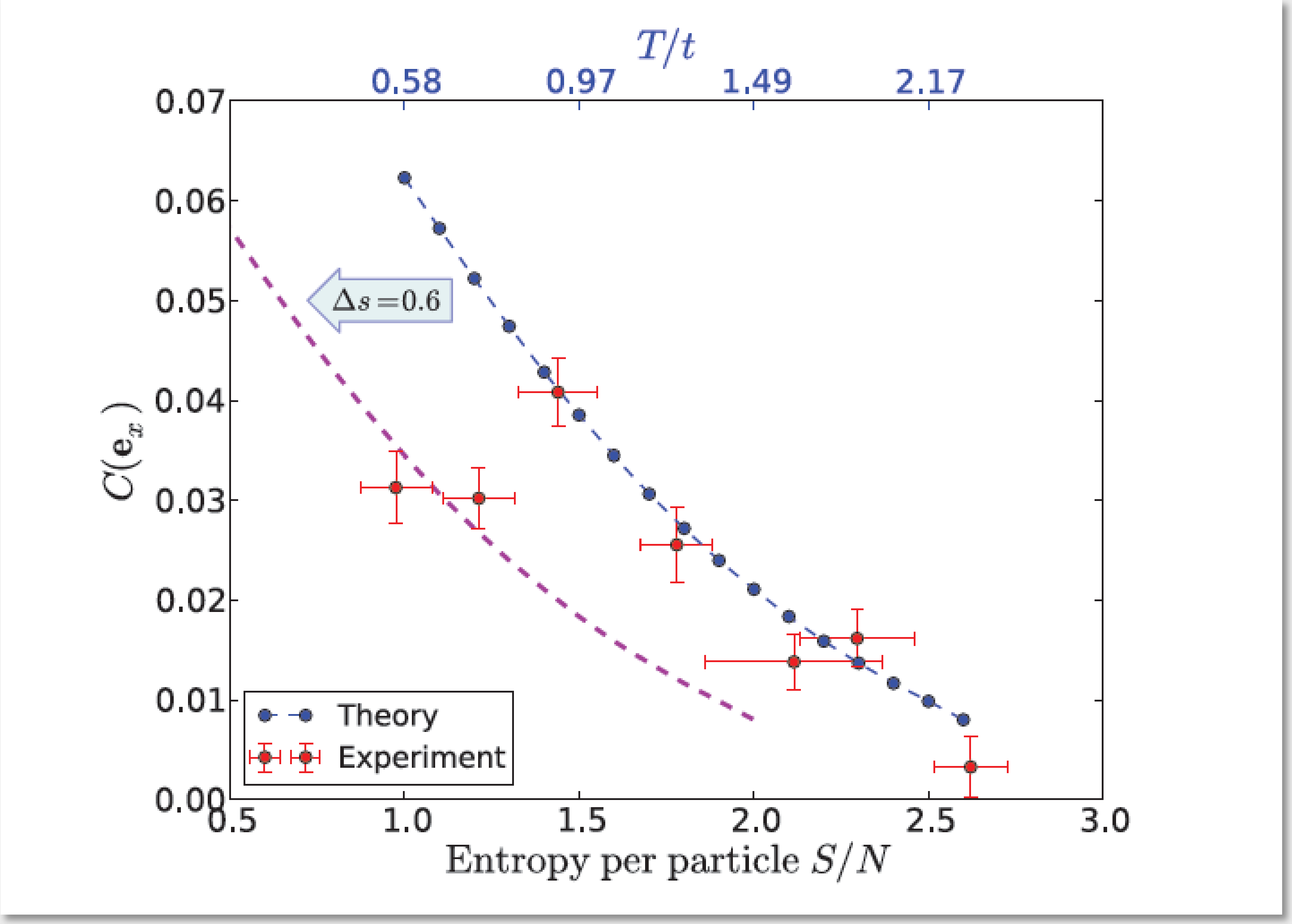
s = 1.8 k_B

Dependence on entropy



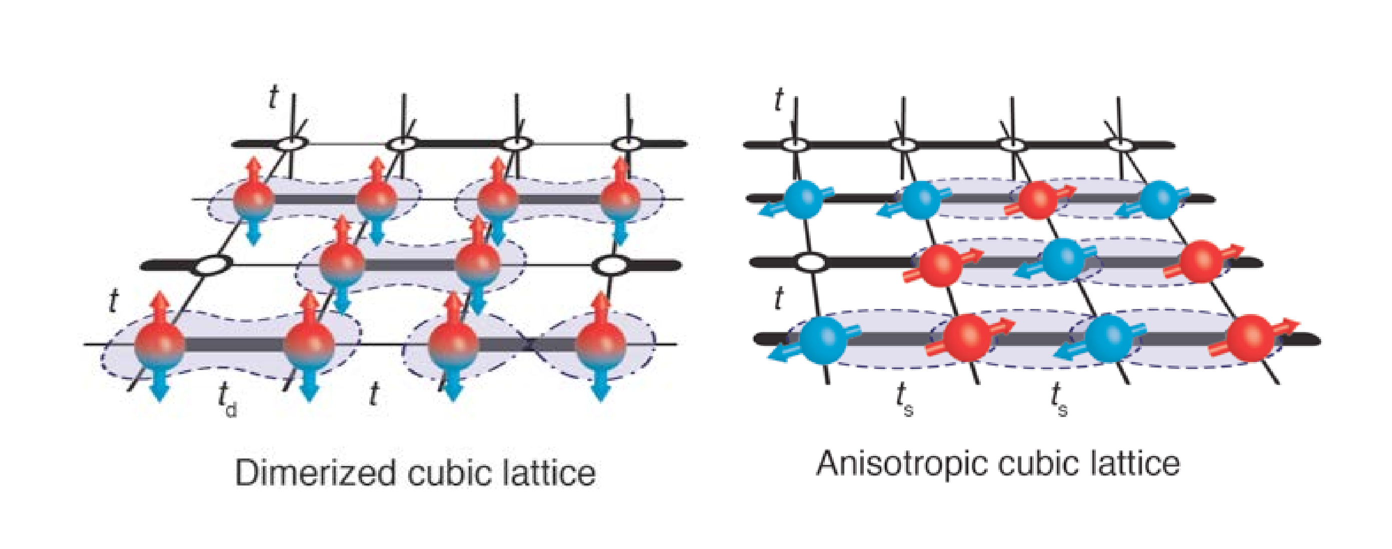
$t_S/t=7.3$

Comparison with theory



Theory (DCA+LDA): J. Imriška, M. Iazzi, L. Wang, E. Gull, and M. Troyer

Quantum magnetism



Nearest-neighbor magnetic correlations in thermalized ensembles

D. Greif, T. Uehlinger, G. Jotzu, L. Tarruell, and T. Esslinger, Science **340**, 1307 (2013)

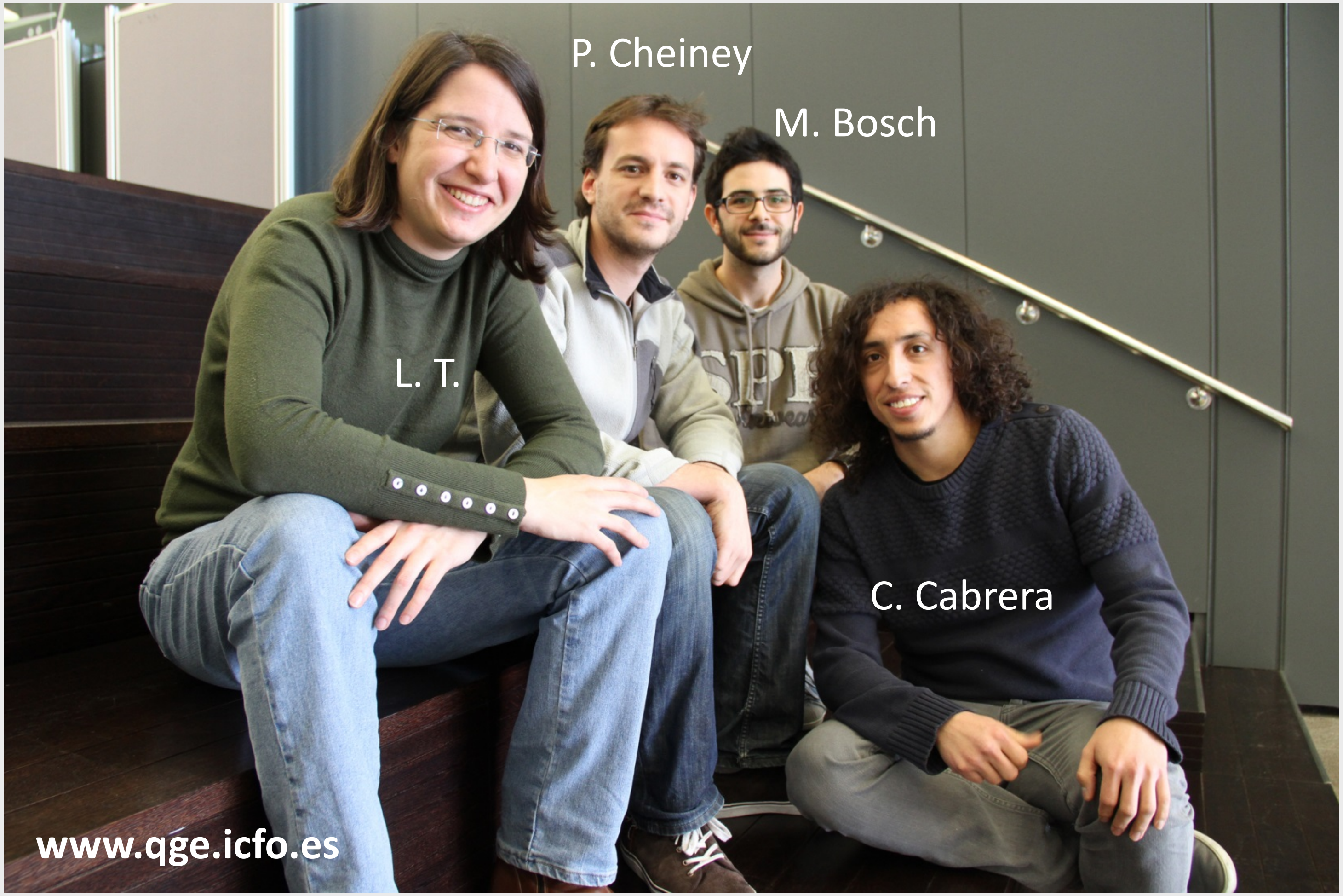
Quantitative comparison with theory

J. Imriška, M. Iazzi, L. Wang, E. Gull, D. Greif, T. Uehlinger, G. Jotzu, L. Tarruell, T. Esslinger, and M. Troyer, , Phys. Rev. Lett. **112**, 115301 (2014)

The ETH lattice team (fall 2012)

Magnetism theory: J. Imriška, M. Iazzi, L. Wang, E. Gull, M. Troyer

The ICFO Ultracold Quantum Gases group



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