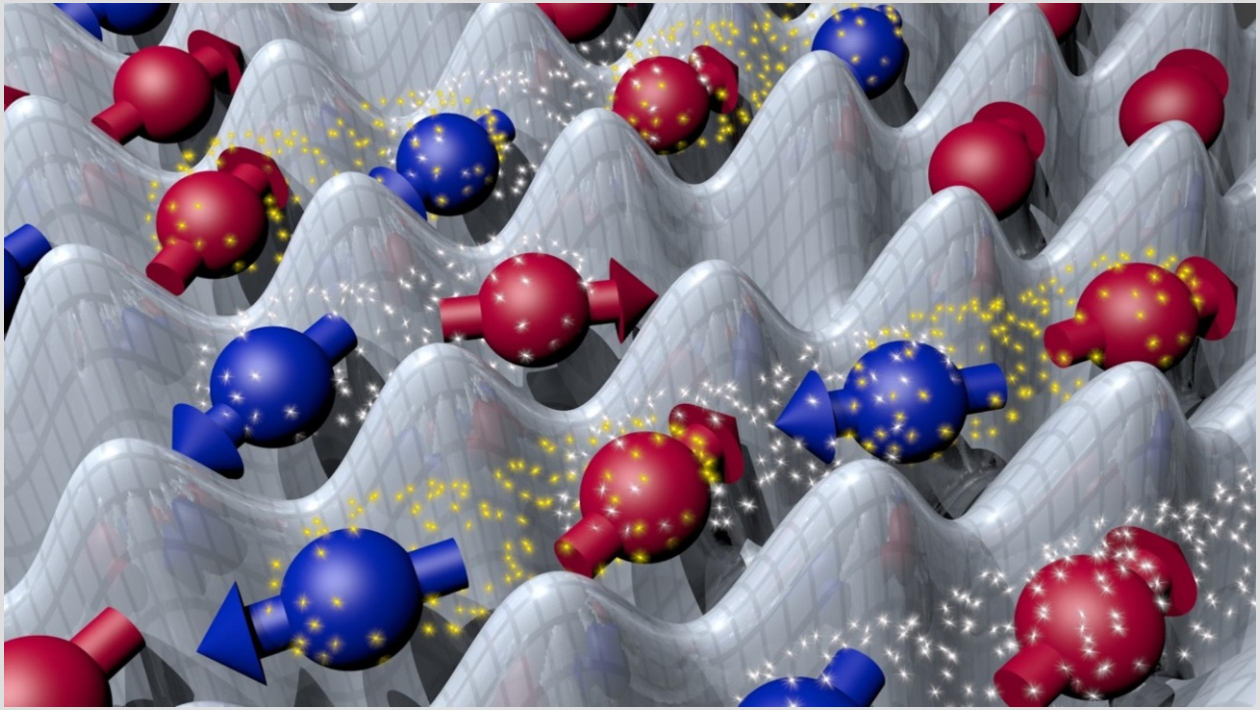
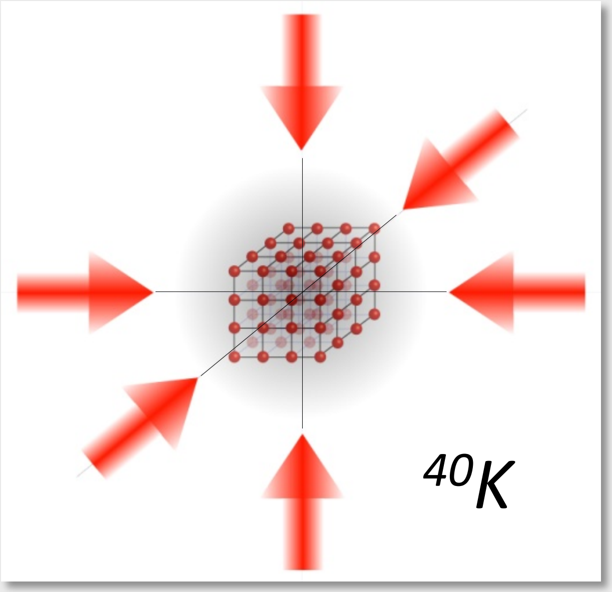
Short-range quantum magnetism of ultracold fermions in an optical lattice

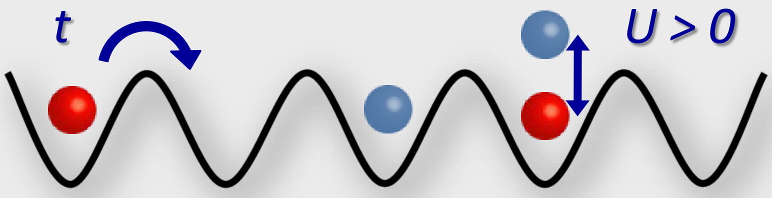


Leticia Tarruell

Aahrus – 26/06/2014

The repulsive Fermi-Hubbard model



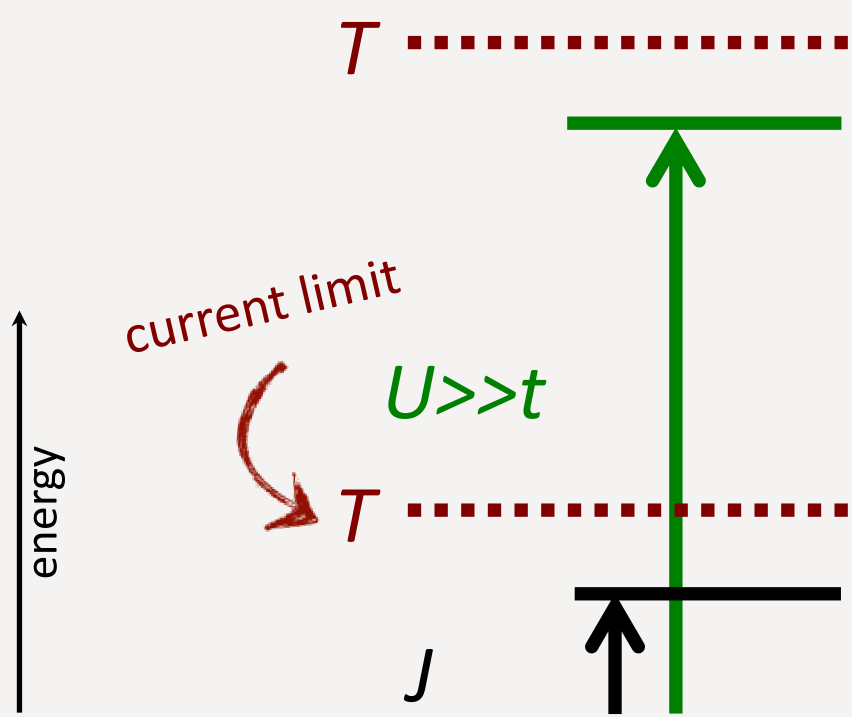


$$H_{\mathrm{F-H}} = -t \sum_{\langle i,j \rangle,\, \sigma} \left(c^{\dagger}_{i\sigma} c_{j\sigma} + \mathrm{h.c.} \right) + U \sum_{i} n_{i\uparrow} n_{i\downarrow}$$

Antiferromagnetic spin interaction from super-exchange

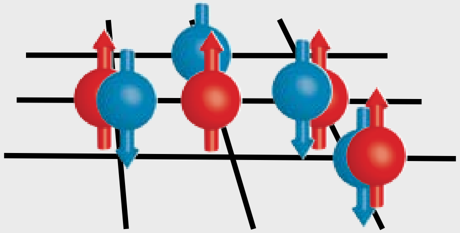
$J = 4t^2/U$

A temperature challenge

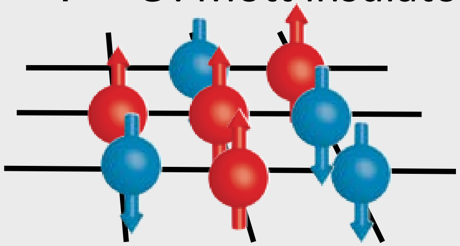


R. Jördens *et al.*, Phys. Rev. Lett. **104**, 180401 (2010)

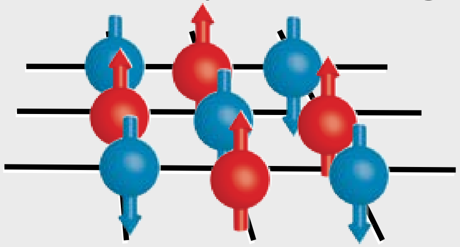
$T > U$: metallic behaviour



$T < U$: Mott insulator

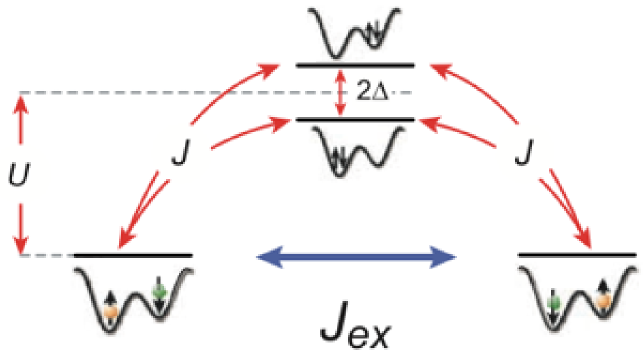


$T < J$: spin ordering



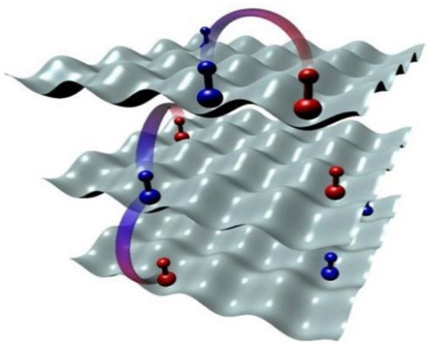
Approaches to magnetism

Isolated double-wells or plaquettes (Munich)



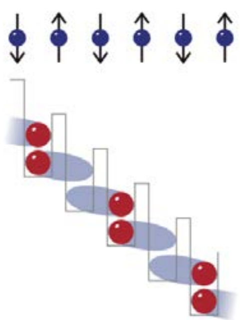
S. Trotzky *et al.,* Science **319**, 295 (2008)
S. Nascimbène *et al.*, Phys. Rev. Lett**. 108**, 205301 (2012)

Dipolar interactions (JILA, Paris)



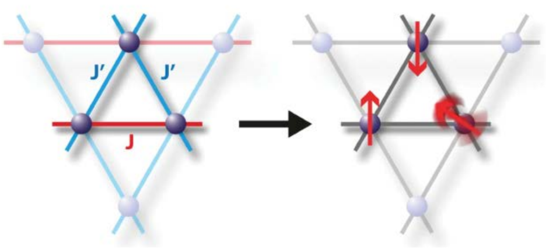
B. Yan *et al.*, Nature **501**, 521-525 (2013)
A. de Paz *et al.*, Phys. Rev. Lett. **111** , 185305 (2013)

Mapping: Ising spin chains (Harvard)



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

Classical magnetism (Hamburg)

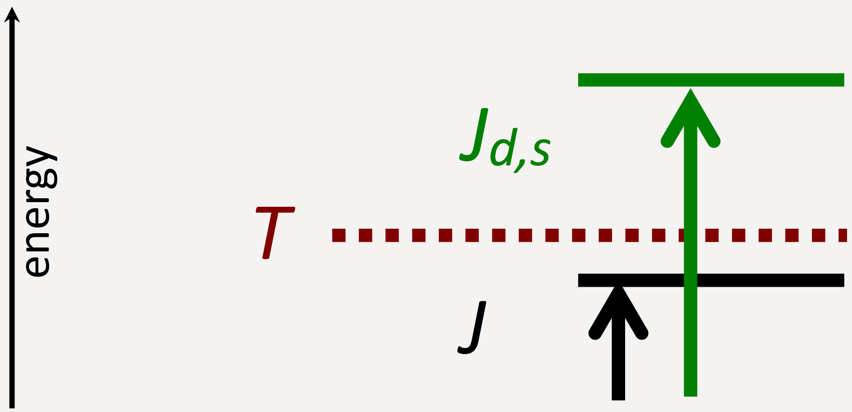


J. Struck *et al.,* Science **333**, 996 (2011)

Our approach: an energy trick

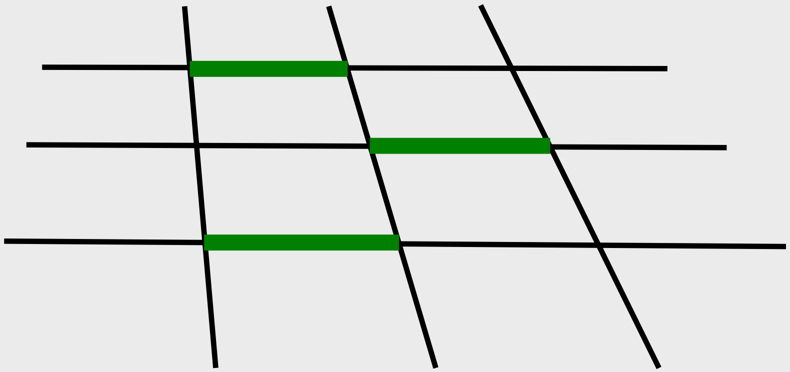
Quantum magnetism

$T < J$



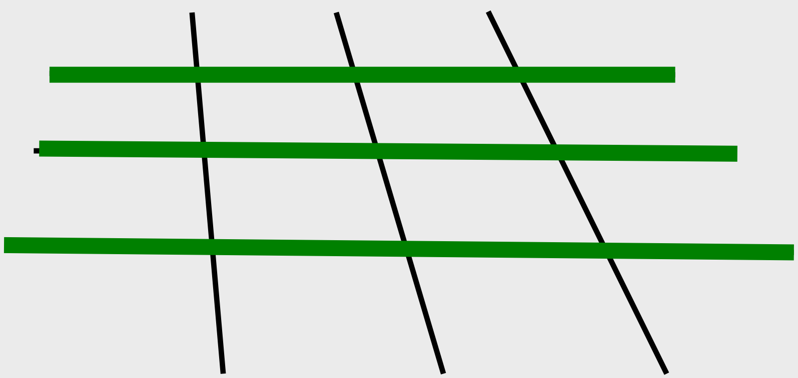
$J < T < J_{d,s}$

$J_d > J$



Dimerized lattice

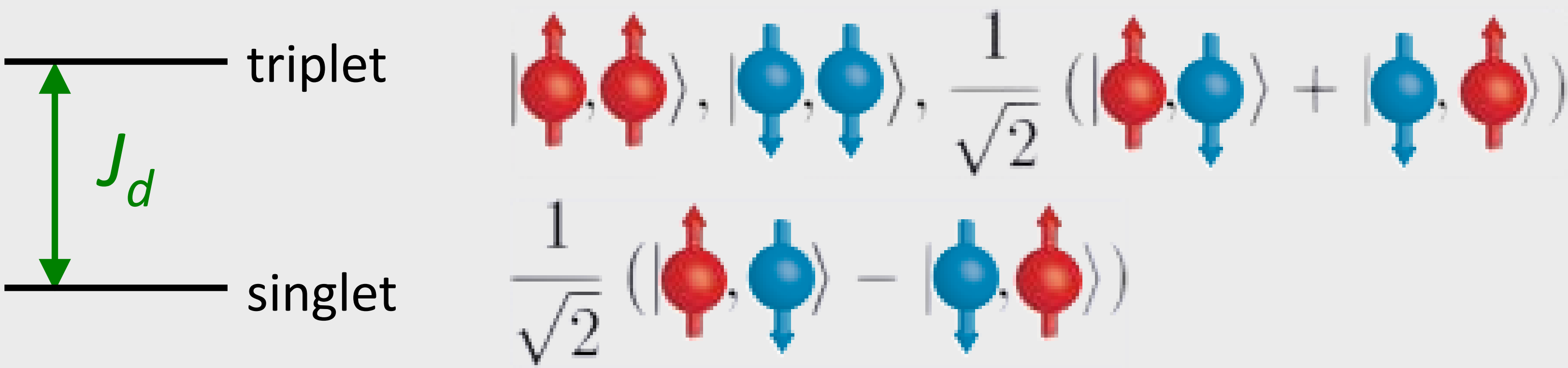
$J_s > J$



Anisotropic cubic lattice

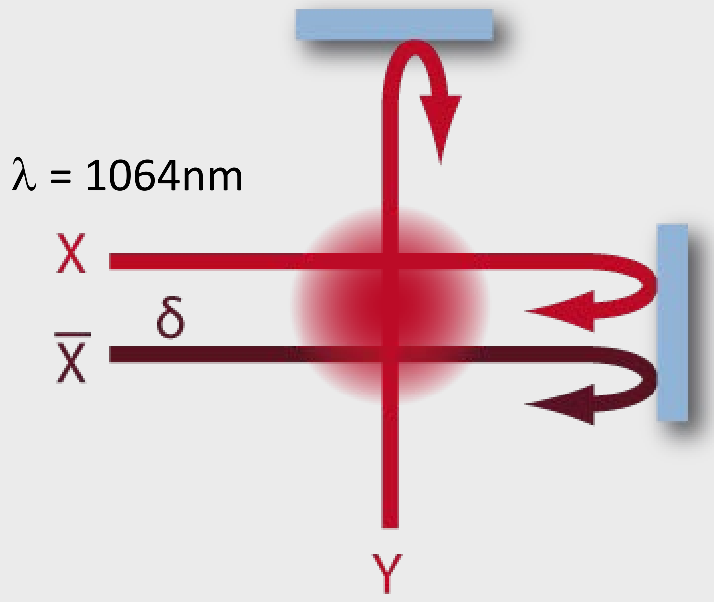
Detecting magnetic correlations

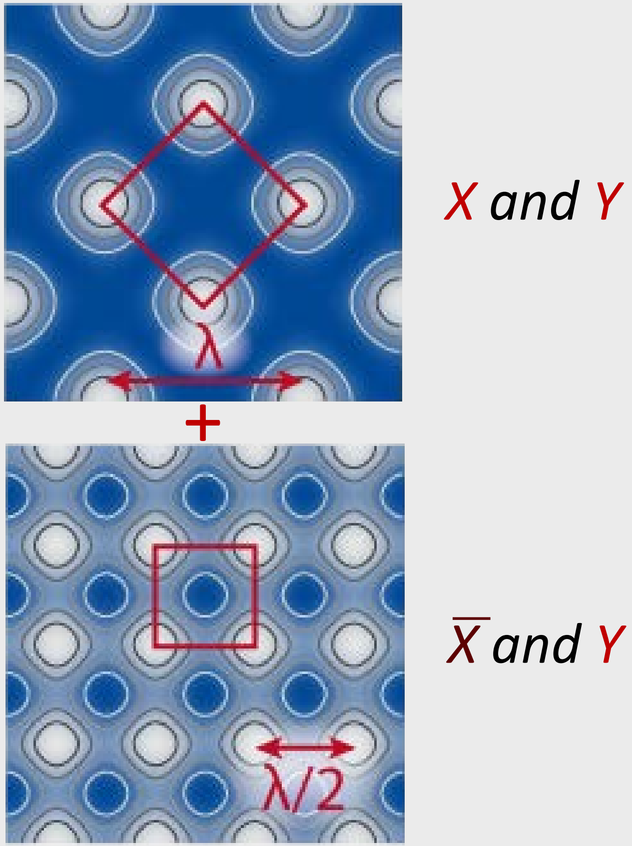
Spin correlations on neighboring sites



$T < J_d : N_S > N_T$

Our tool: tunable-geometry optical lattice

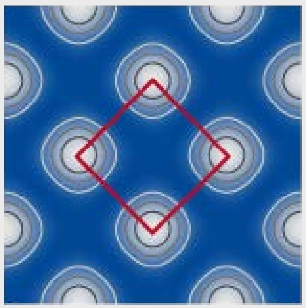




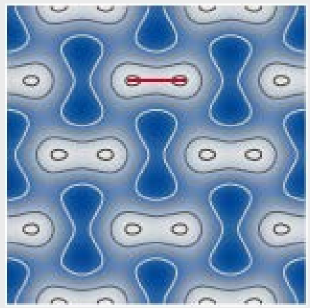
$$V(x,y) = \boxed{V_{\bar{X}} \cos^2(kx + \theta/2)} + \boxed{V_X \cos^2(kx) + V_Y \cos^2(ky) + 2\alpha\sqrt{V_X V_Y}\cos(kx)\cos(ky)}$$

Our tool: tunable-geometry optical lattice

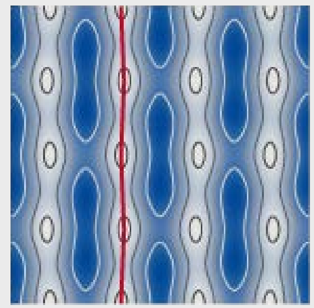
Chequerboard

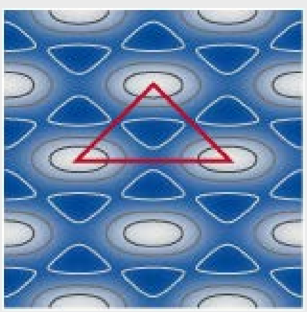


Dimer

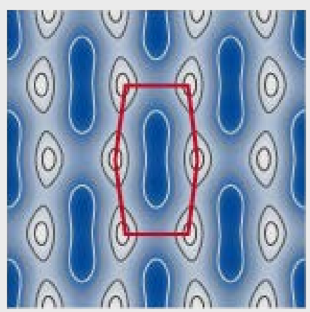


1D chains

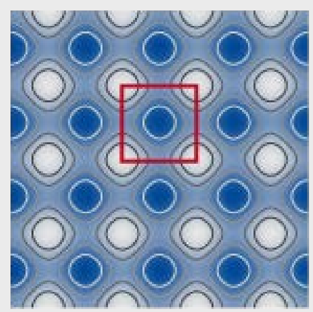




Triangular



Honeycomb



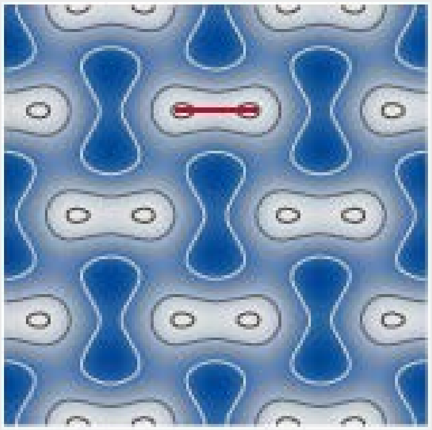
Square

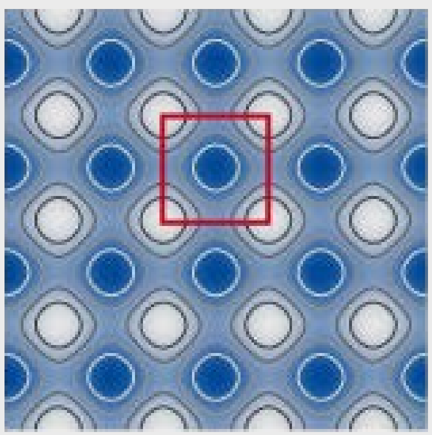
L. Tarruell *et al.*,
Nature **483**, 302 (2012)

Other non-standard lattices: NIST, Munich, Bonn, Hamburg, Berkeley

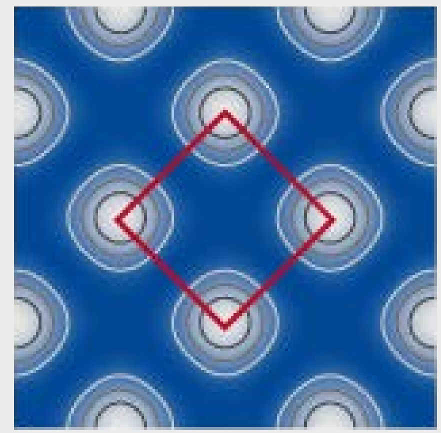
Merging lattice sites

Dimer



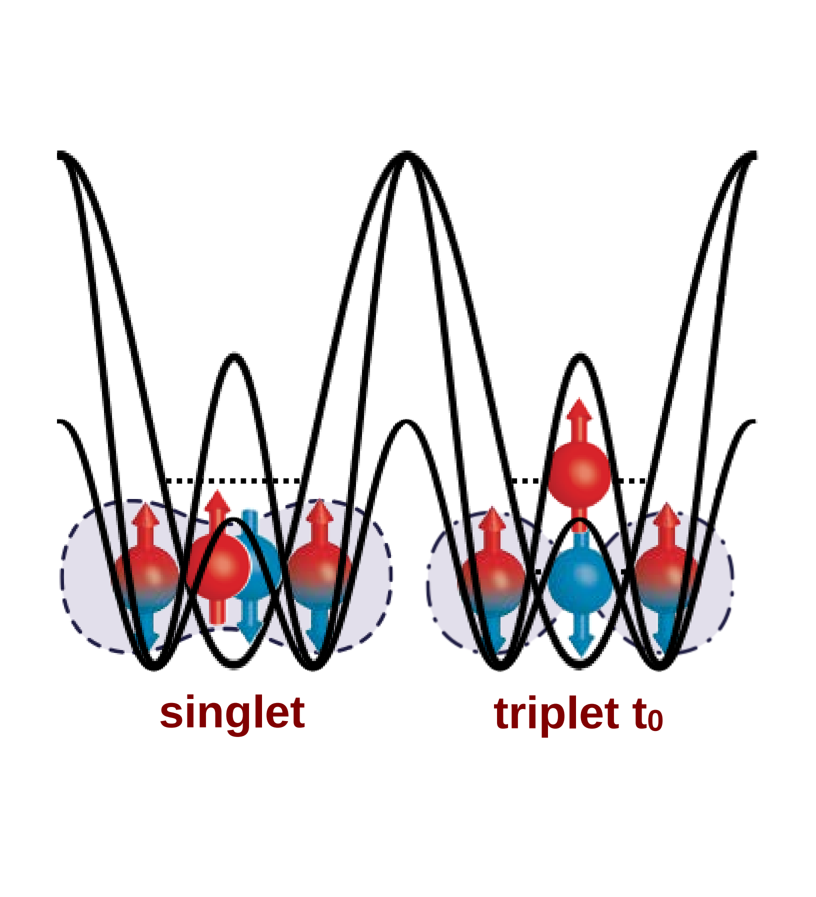


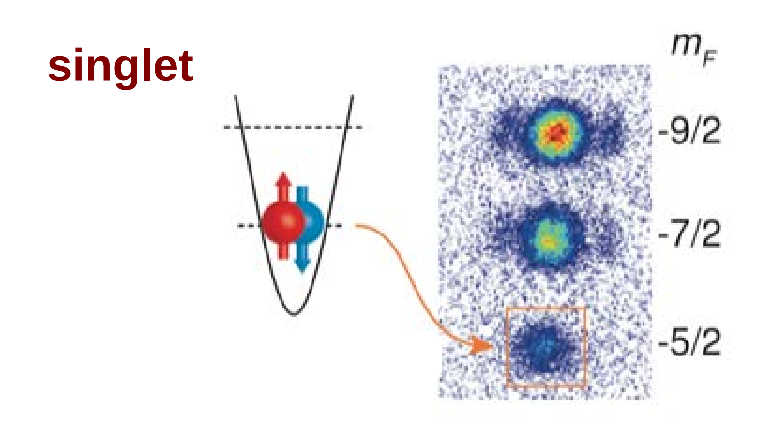
Square

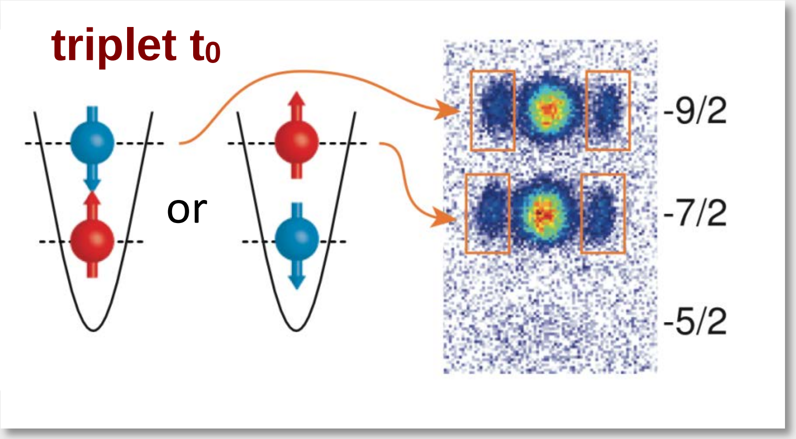


Chequerboard

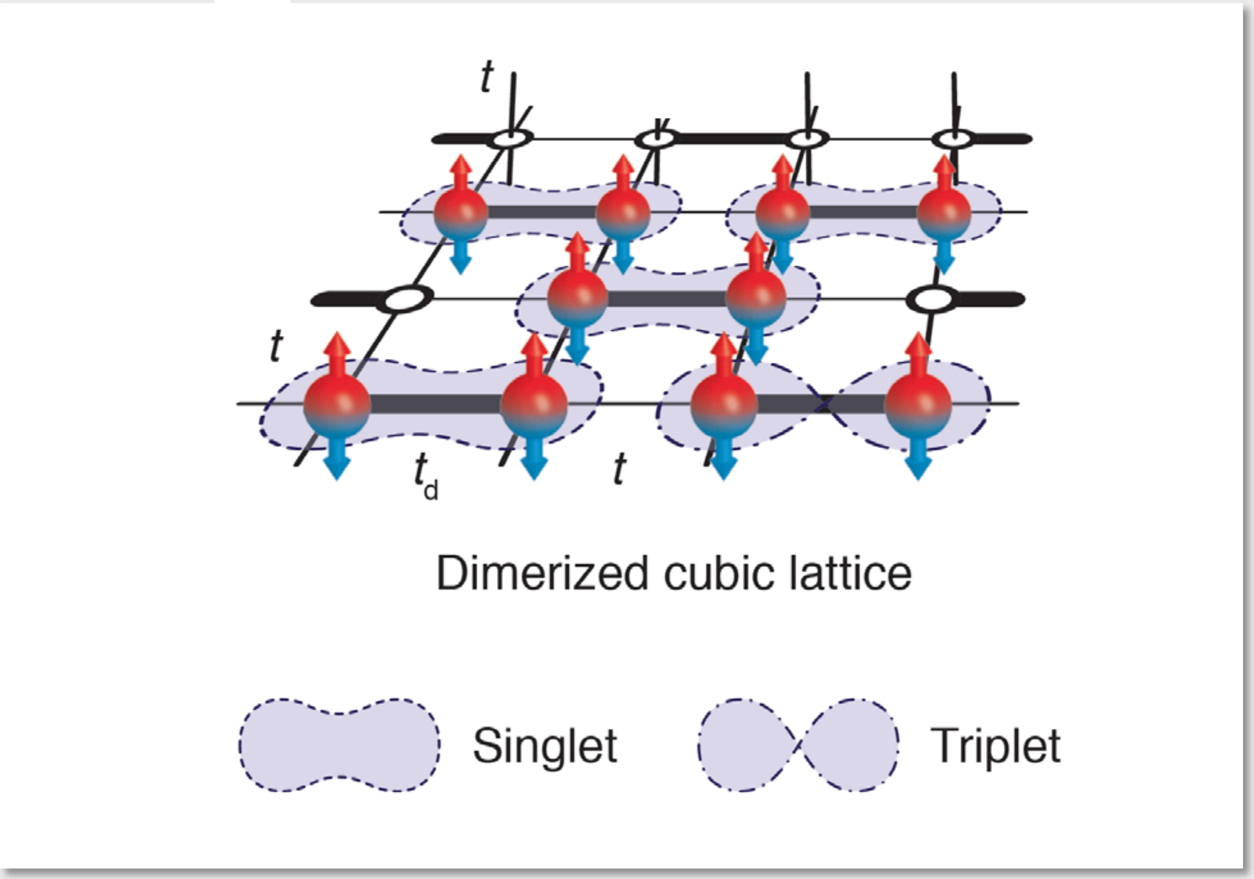
Detecting magnetic correlations





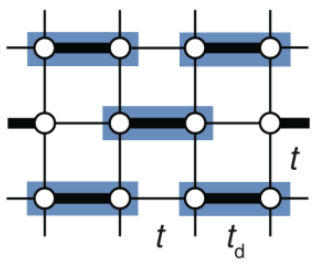


Dimerized lattice

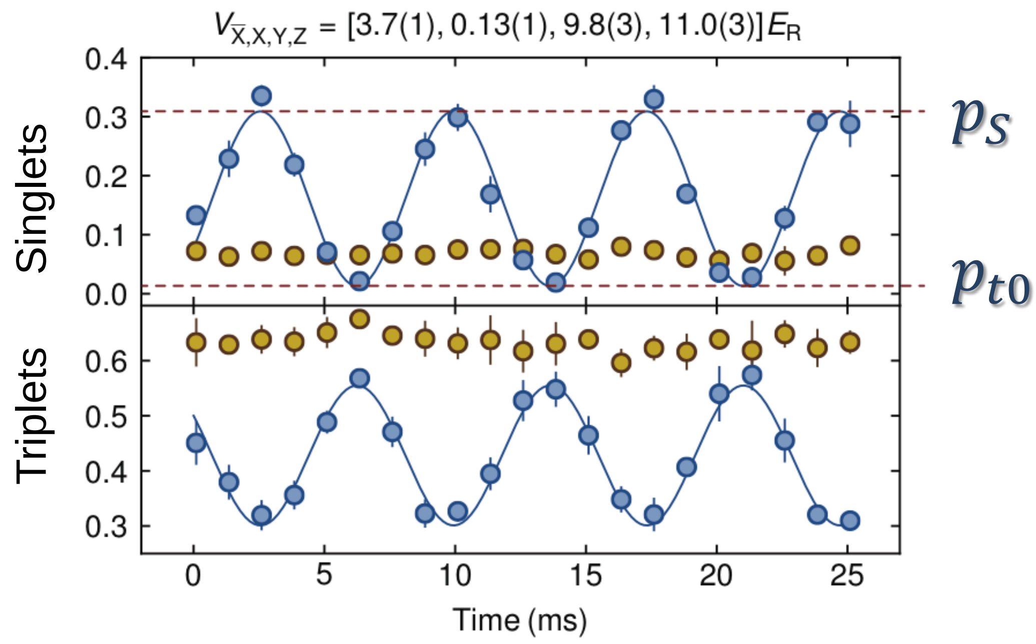


Measuring singlets and triplets

Merging neighboring sites



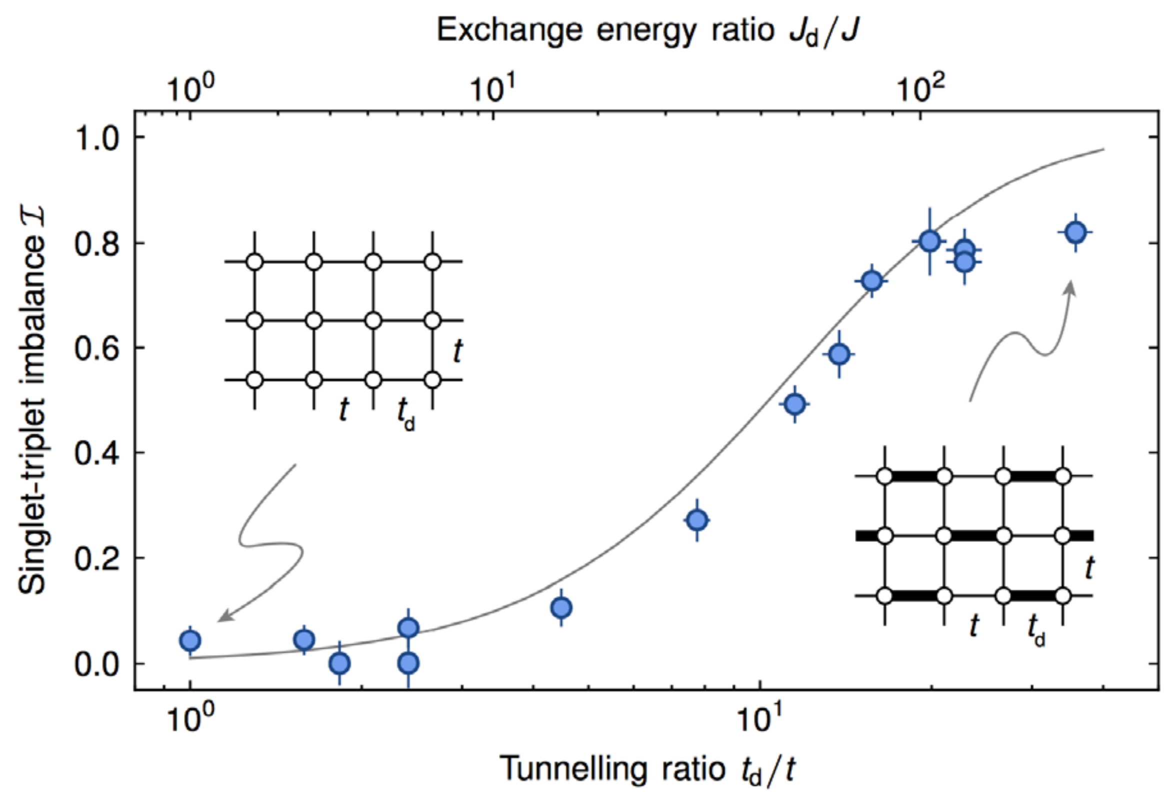
Singlet-triplet oscillations



Singlet-Triplet Imbalance $$\mathcal{I} = \frac{p_\mathrm{s} - p_{\mathrm{t}_0}}{p_\mathrm{s} + p_{\mathrm{t}_0}}$$

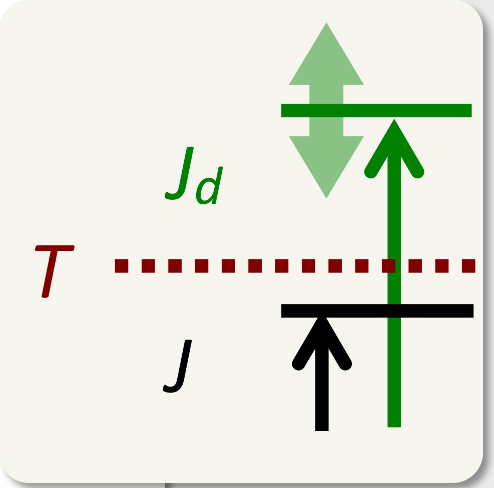
Singlet-triplet oscillations: S. Trotzky *et al*., Phys. Rev. Lett. **105**, 265303 (2010)

Dependence on dimerization



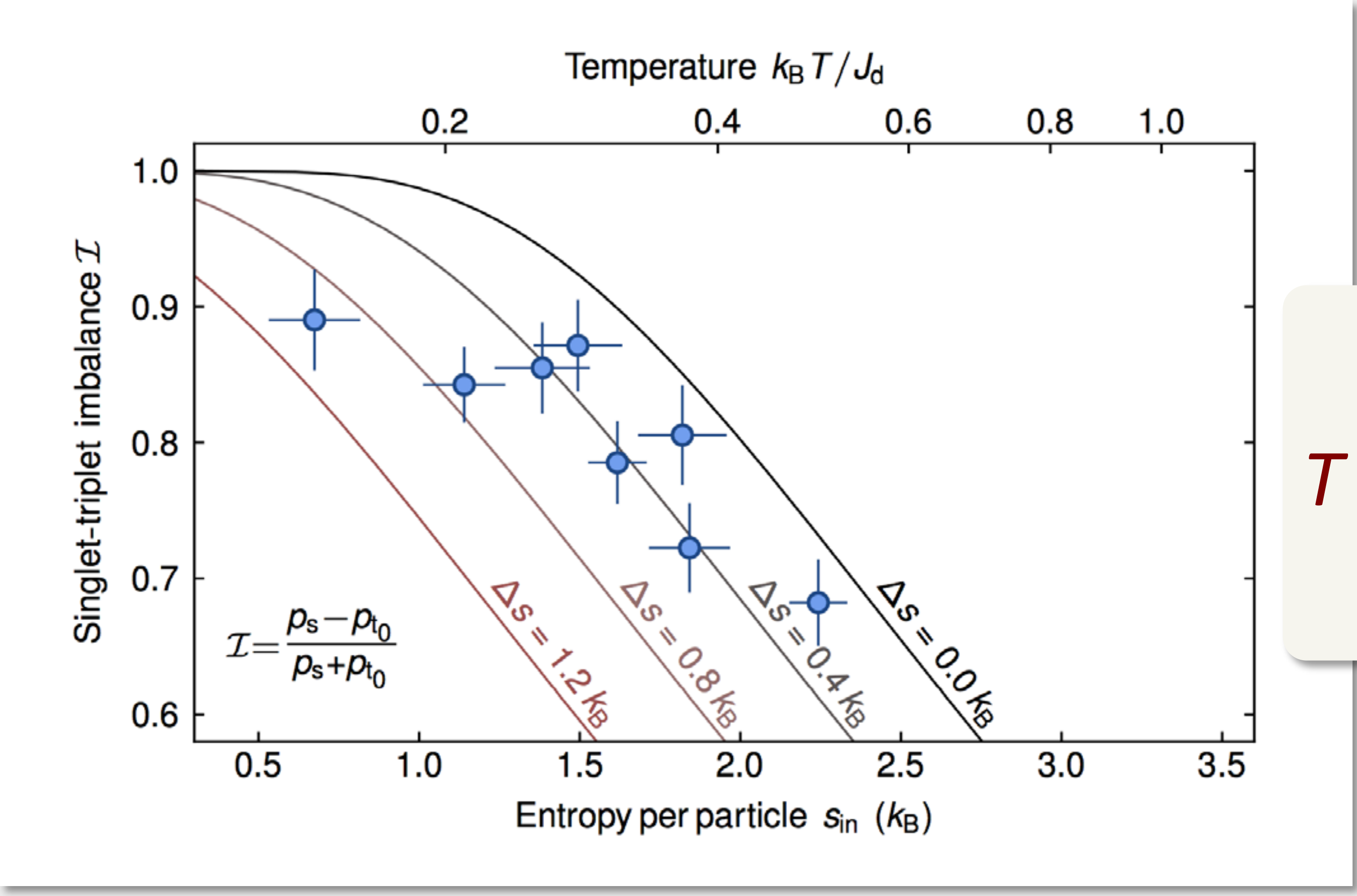
isotropic

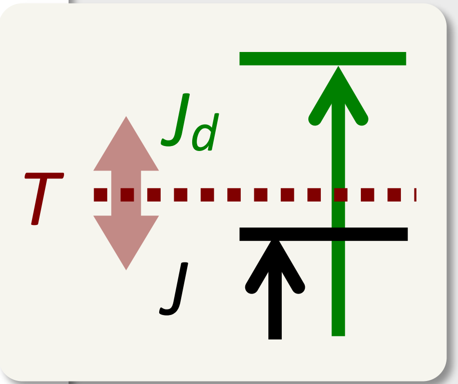
strongly dimerized



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

Dependence on entropy

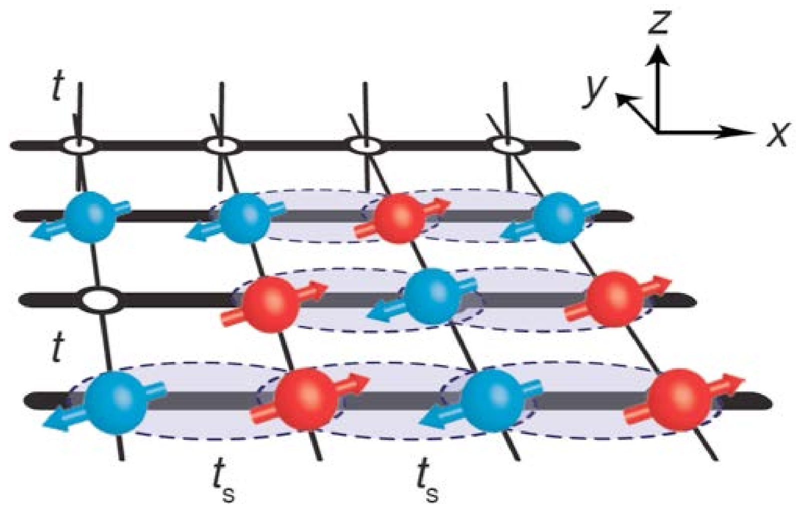




$U/t = 11.0(8)$
$t_d/t = 22(2)$
$t/h = 67(3)$ Hz

Theory: second order high-temperature series expansion of coupled dimers

Anisotropic cubic lattice



Anisotropic cubic lattice

Effective 1D chains

AFM correlations along *x*

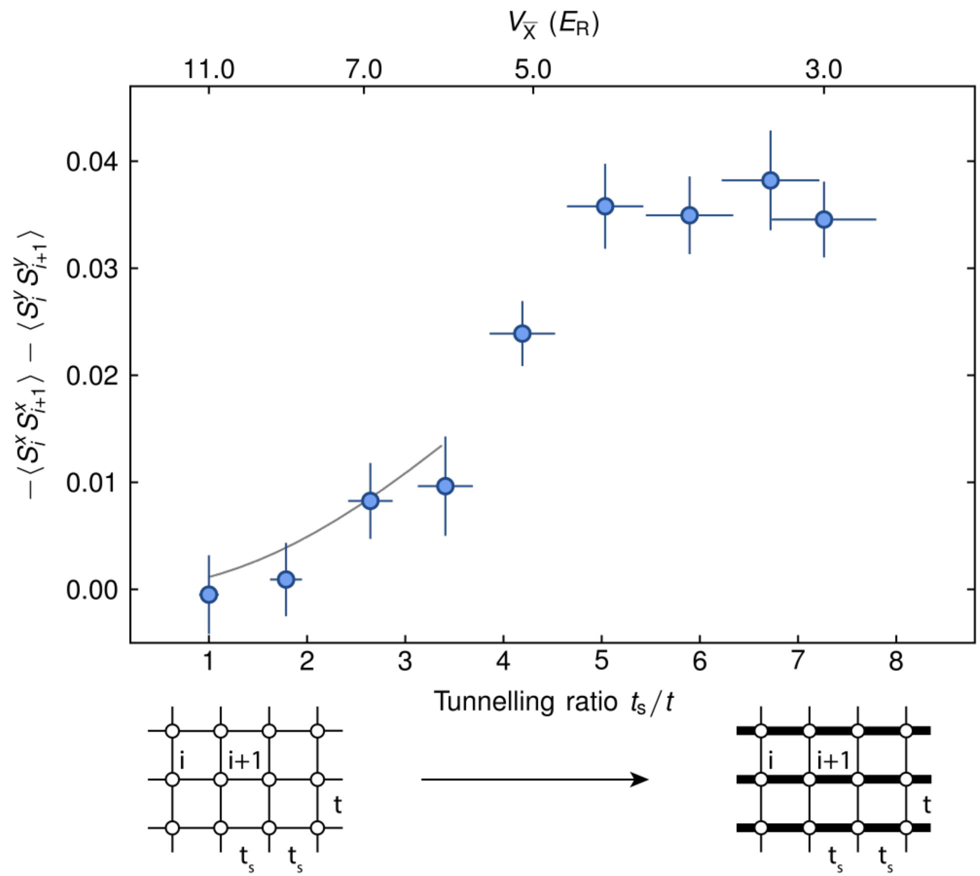
$$\langle \mathbf{S}_i \cdot \mathbf{S}_{i+1} \rangle \neq 0$$

transverse spin correlator ⟺ population difference

$$-\langle S_i^x S_{i+1}^x \rangle - \langle S_i^y S_{i+1}^y \rangle = \left(p_{\mathrm{s}} - p_{\mathrm{t_0}}\right)/2$$

Redistribution of entropy: incoherent spin chains, entropy stored in between

Dependence on anisotropy



isotropic

strongly anisotropic

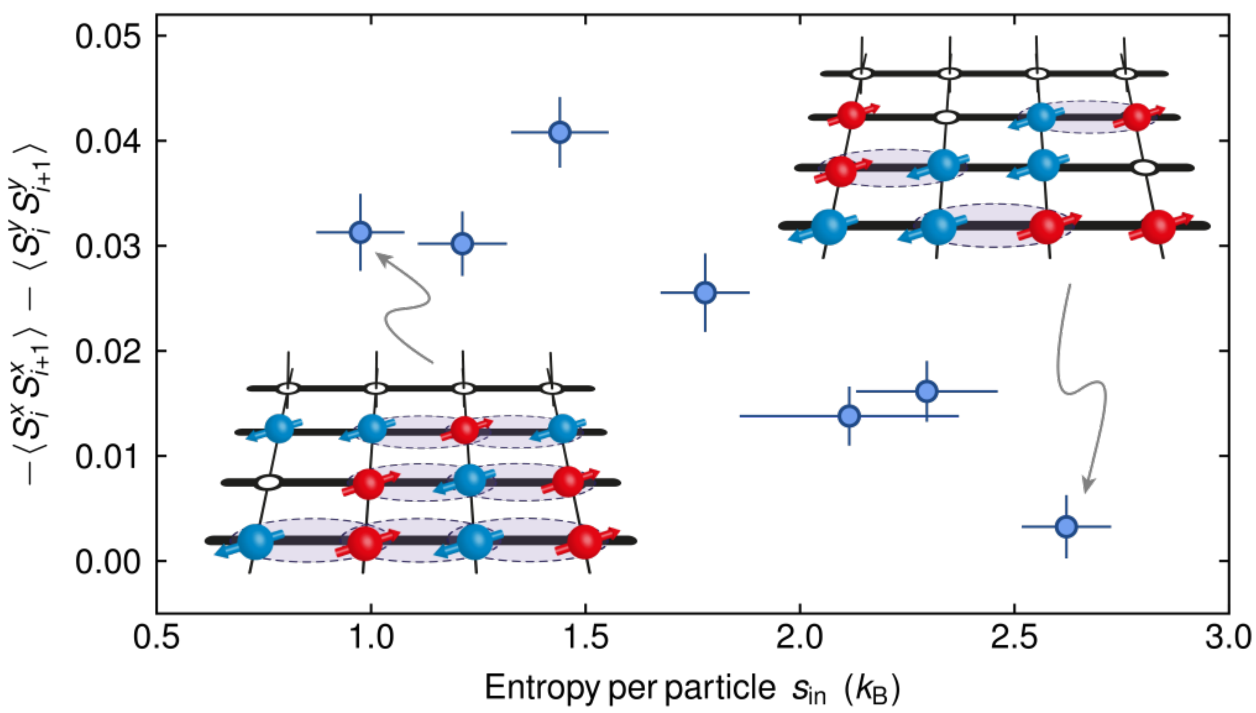
normalized spin correlator

$$\mathcal{S} = \frac{-4\langle S_i^z S_{i+1}^z \rangle}{\langle n_i^s n_{i+1}^s \rangle} = \frac{p_s - p_{t_0}}{p_s + 3p_{t_0}}$$

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

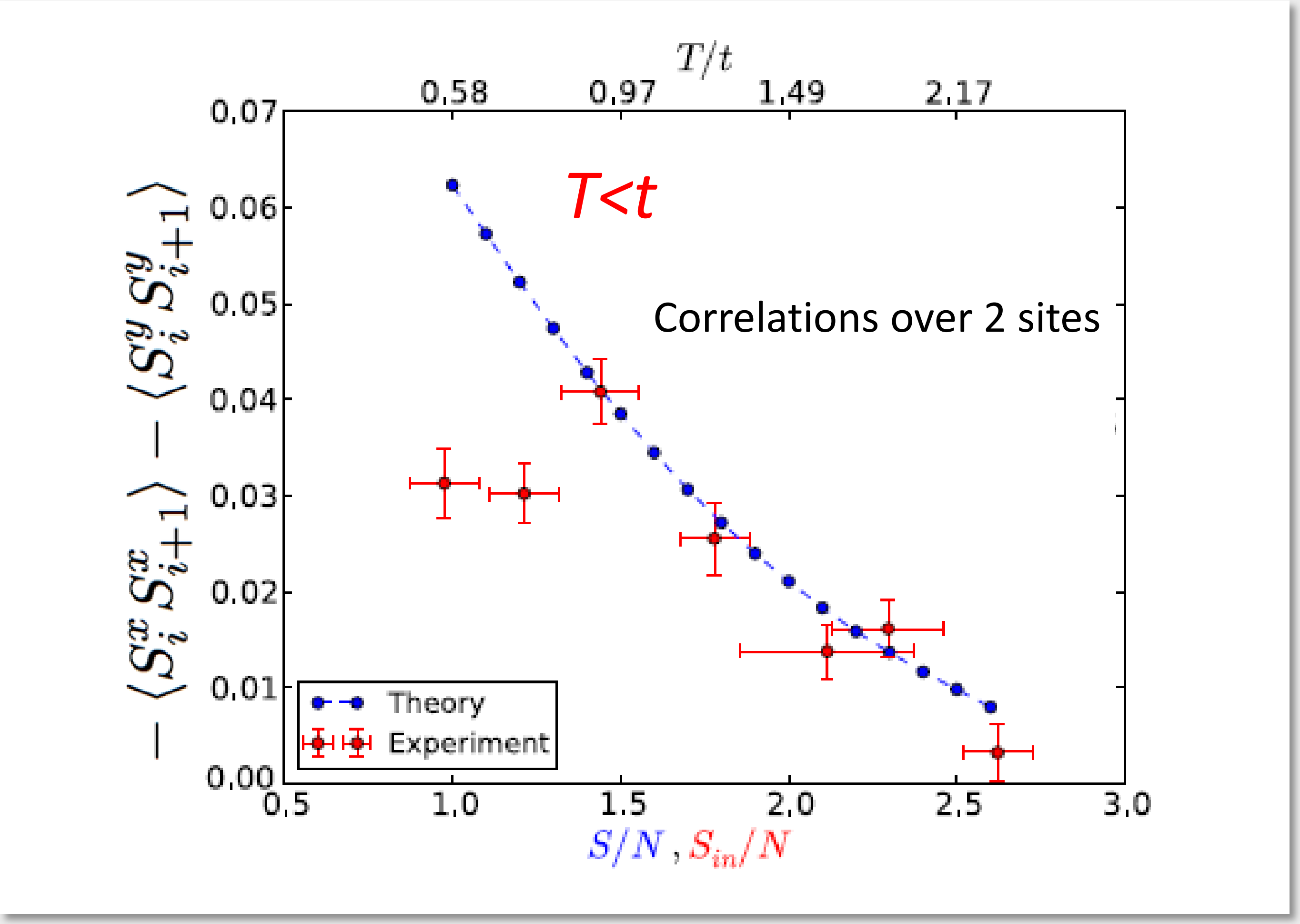
$s = 1.8\ k_B$

Dependence on entropy



$t_S/t=7.3$

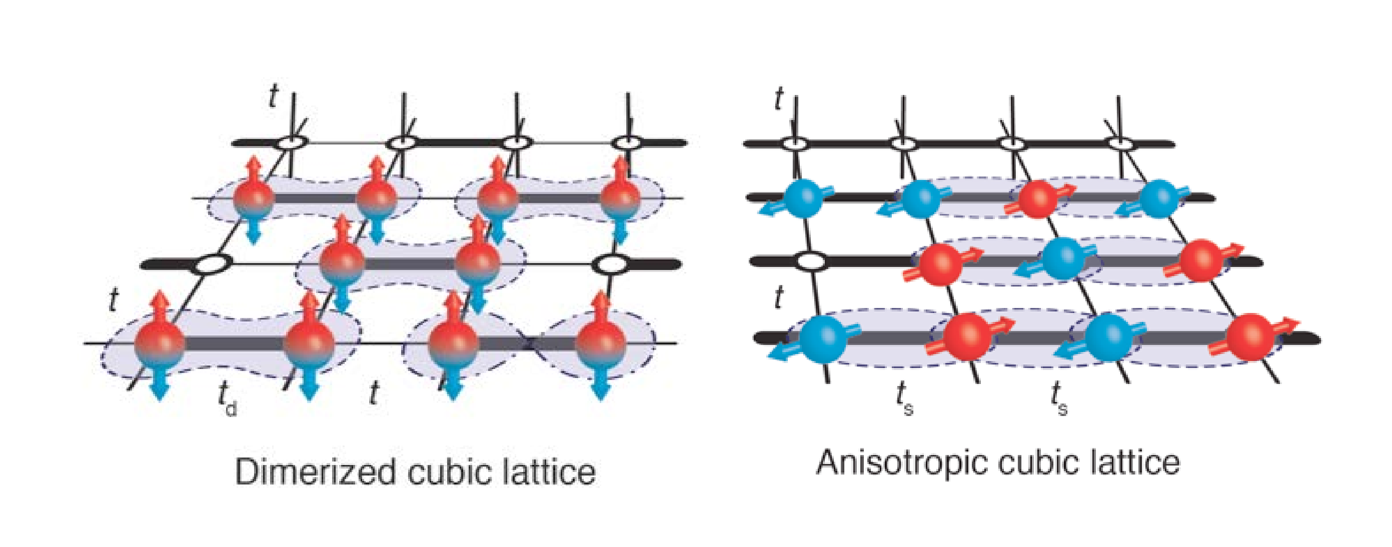
Comparison with theory



Theory: DCA+LDA for anisotropic simple cubic lattice

J. Imriška, M. Iazzi, L. Wang, E. Gull and M. Troyer – ETH Zurich

Short-range quantum magnetism



Nearest-neighbor magnetic correlations in thermalized ensembles

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

Comparison with numerical simulations: $T < t$ in effective 1D systems

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)

B. Sciolla, A. Tokuno, S. Uchino, P. Bartmettler, T. Giamarchi, and C. Kollath, Phys. Rev. A **88**, 063629 (2013)

The ETH lattice team' 2012

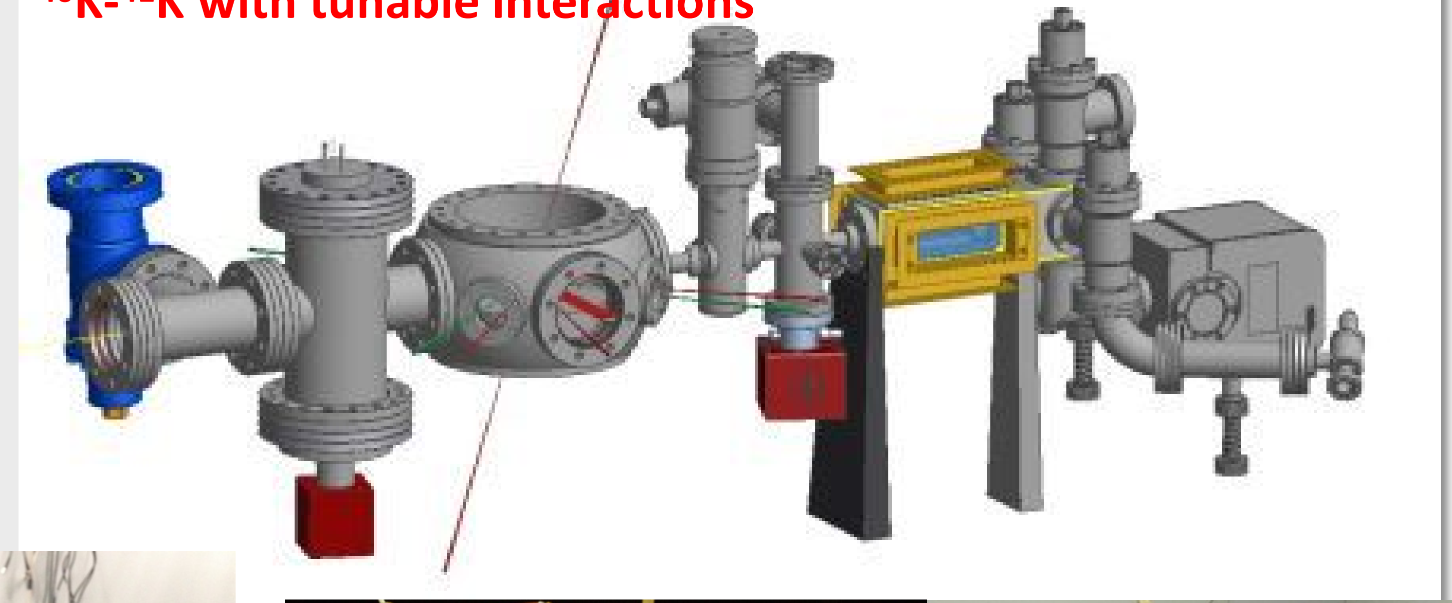
Theory: J. Imriška, M. Iazzi, L. Wang, E. Gull and M. Troyer

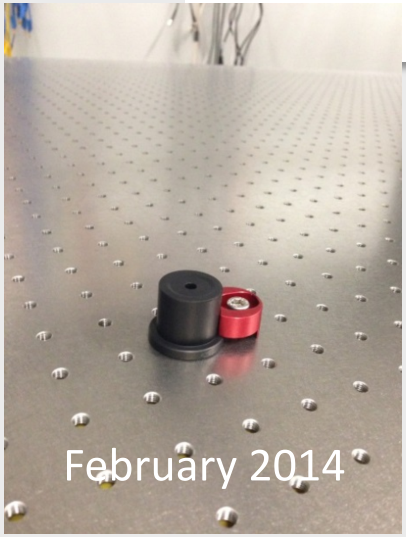
Many discussions with C. Kollath and T. Giamarchi's groups

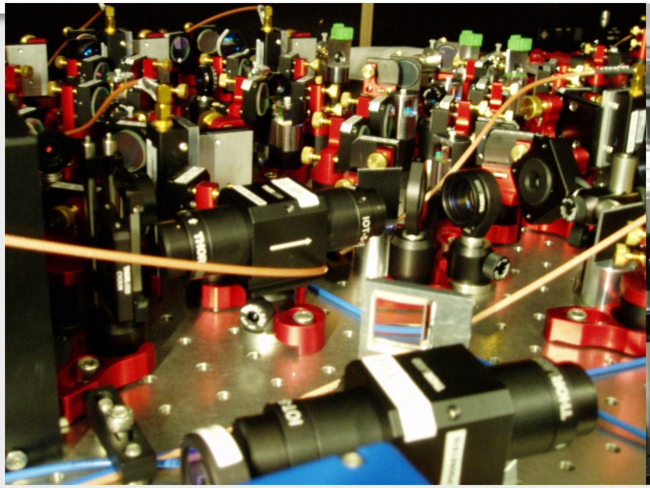
Funding: EU (ERC SQMS), SNF, NCCR QSIT, NCCR MaNEP

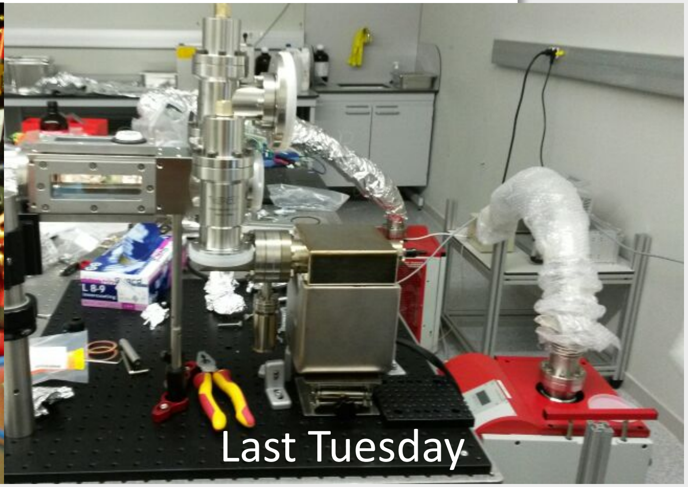
Towards isotopic potassium mixtures

^{40}K-^{41}K with tunable interactions









The ICFO quantum gases group' 2014

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EXCELENCIA SEVERO OCHOA
MARIE CURIE ACTIONS
SEVENTH FRAMEWORK PROGRAMME
Fundació Privada CELLEX