Quantum Science Seminar

March 25 2021
online

Quantum Magnetism of Cold-Atom SU(N) Fermi-Hubbard Model

Kyoto University
Yoshiro Takahashi

Outline

1.Quantum Simulation of Fermi Hubbard Model

Quantum magnetism of Fermi Hubbard model
SU(N) Fermi Hubbard Model
Pomeranchuk cooling

2.Quantum Magnetism of SU(N) Fermi Hubbard Model

Observation of antiferromagnetic spin correlation of SU(N) Fermions
Dissipative Fermi-Hubbard model
Formation of SU(4)-Singlet in a plaquette lattice

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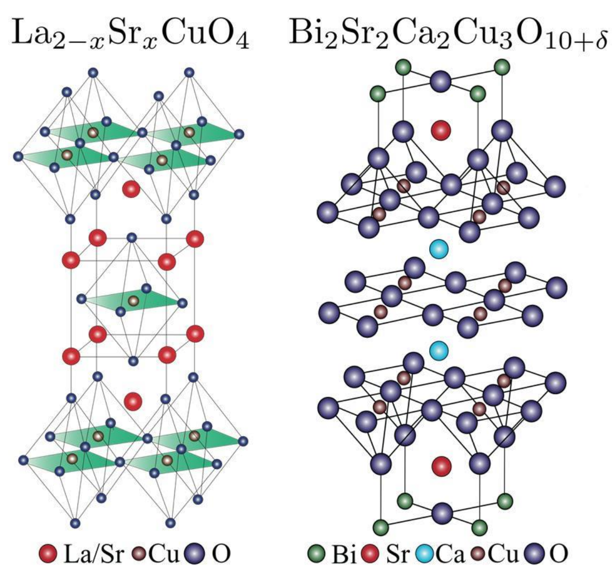
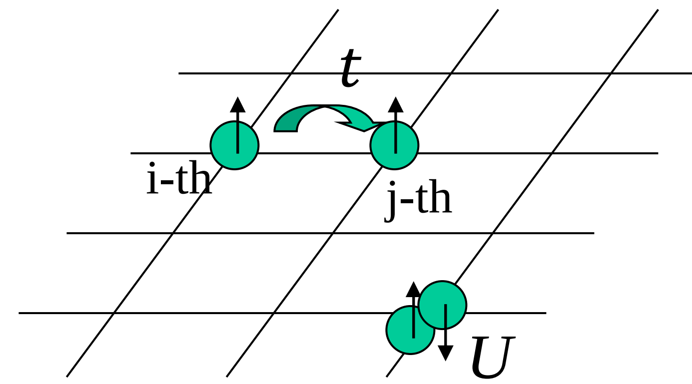
Quantum Simulation of Fermi Hubbard Model

$$H = -t \sum_{<i,j>} (c_i^+ c_j + c_j^+ c_i) + U \sum_i n_{i,\uparrow} n_{i,\downarrow}$$

→ Superconductivity, Magnetism,…





We need **Quantum Simulator**

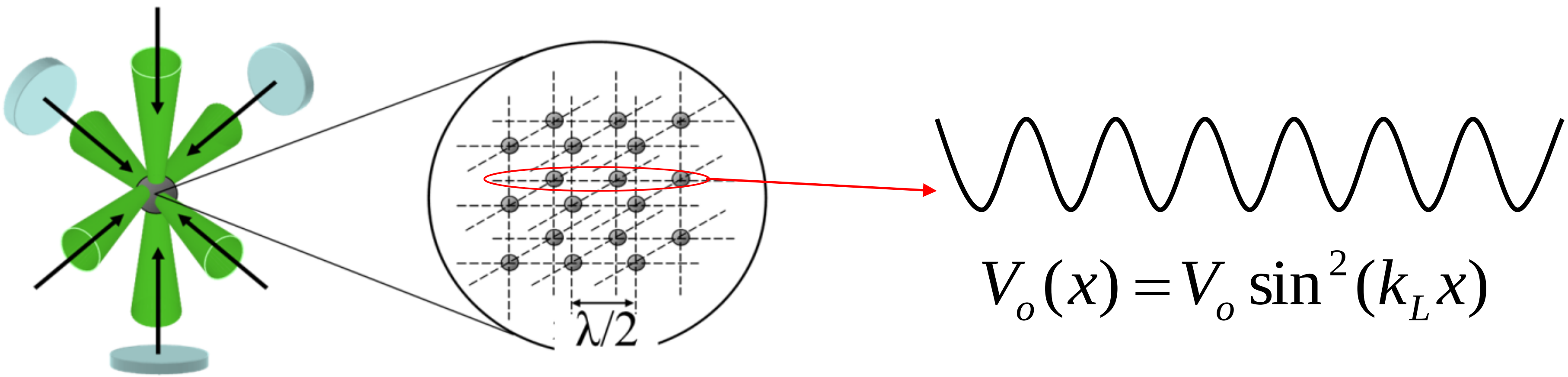
→ Difficult to solve by numerical simulation

DMFT, Gutzwiller, QMC, DMRG, FLEX, Exact Diagonalization, …

Quantum Simulation of Fermi Hubbard Model

$$H = -t \sum_{<i,j>} (c_i^+ c_j + c_j^+ c_i) + U \sum_i n_{i,\uparrow} n_{i,\downarrow}$$

"Ultracold atoms in an optical lattice"



$$V_o(x) = V_o \sin^2(k_L x)$$

Clean system (no lattice defects, impurities)

High controllability of Hubbard parameters t & U

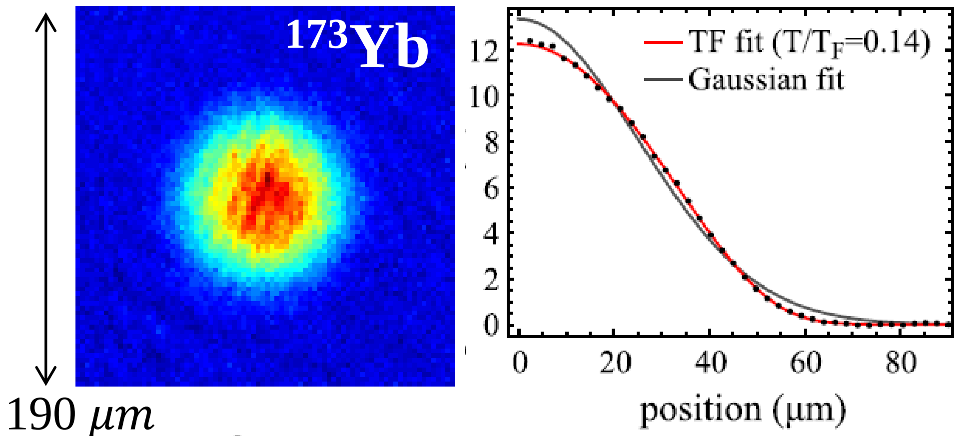
Various lattice geometries

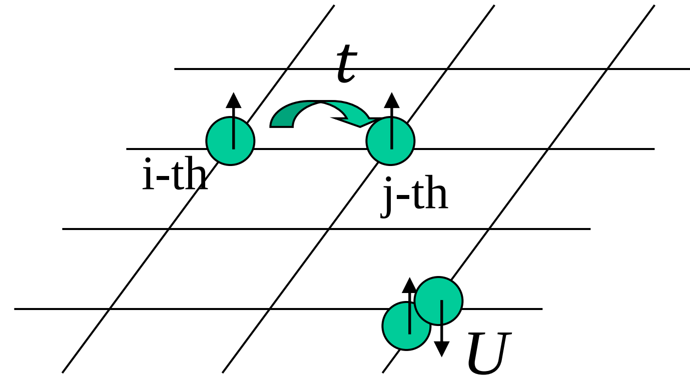
…

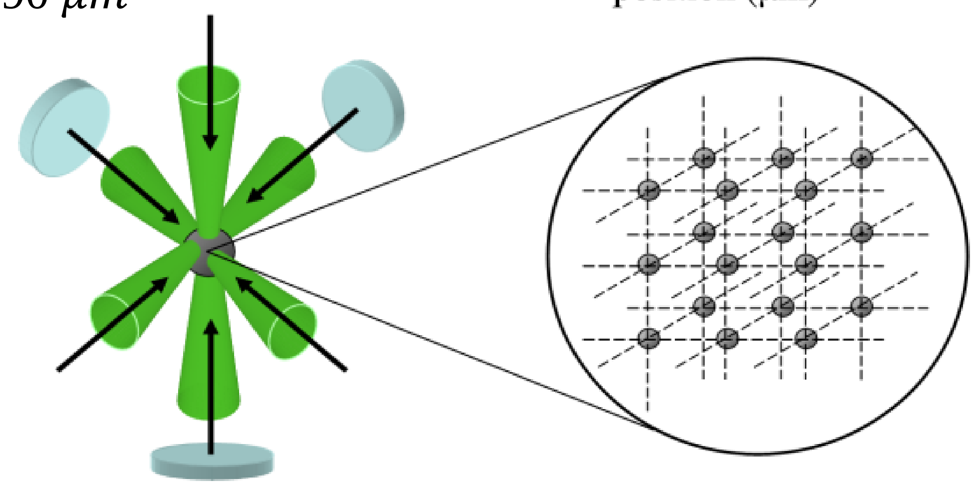
Quantum Simulation of Fermi Hubbard Model

$$H = -t \sum_{<i,j>} (c_i^+ c_j + c_j^+ c_i) + U \sum_i n_{i,\uparrow} n_{i,\downarrow}$$

Ultracold Fermi Gas: $T/T_F \ll 1$







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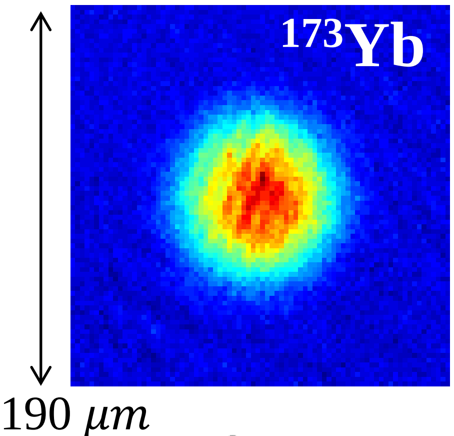
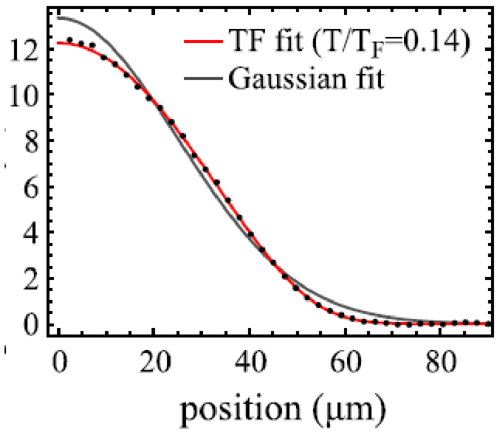
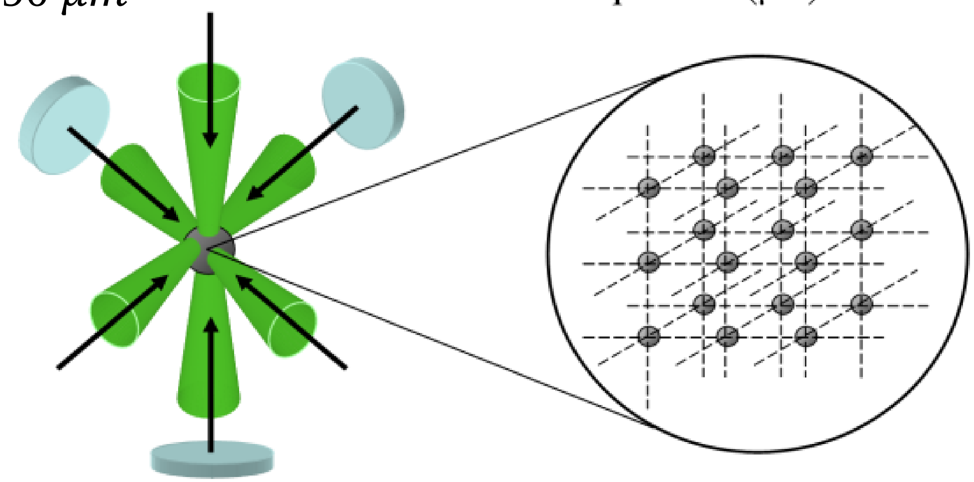
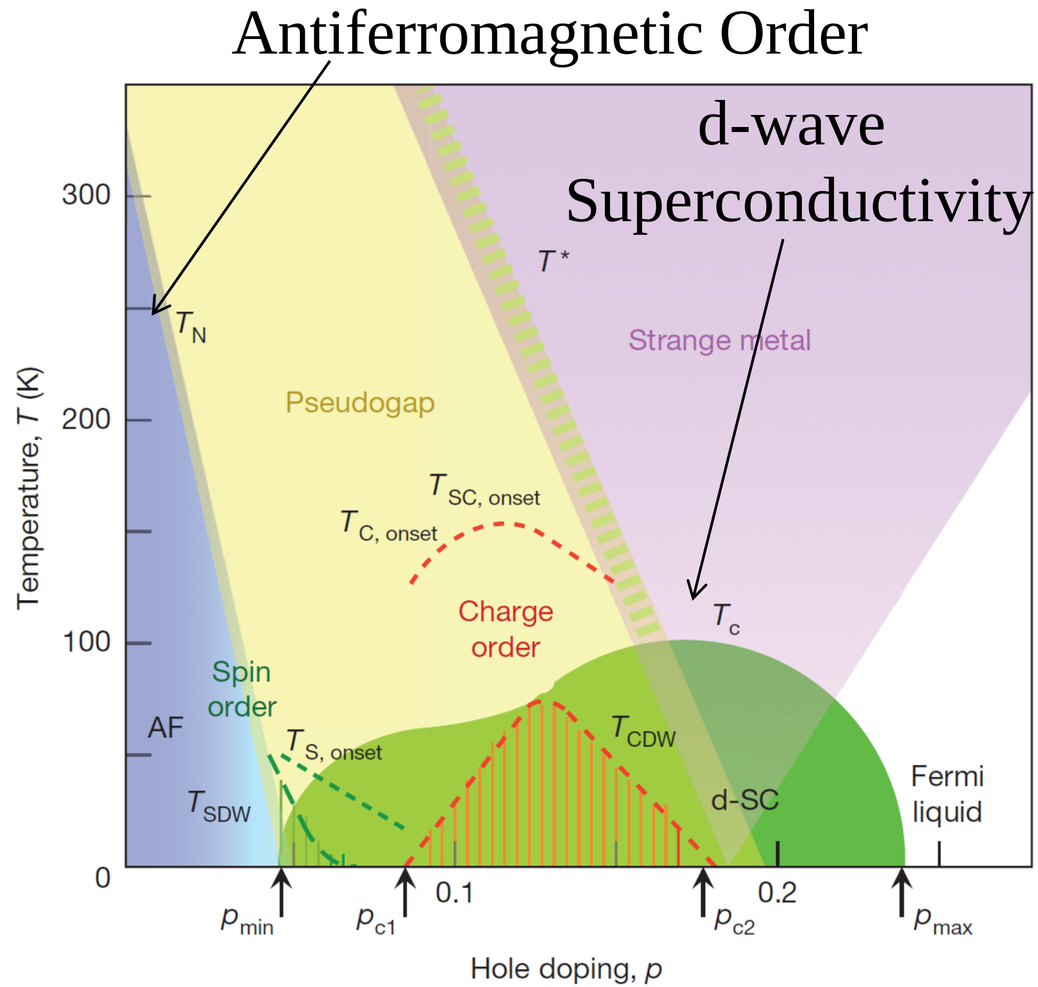








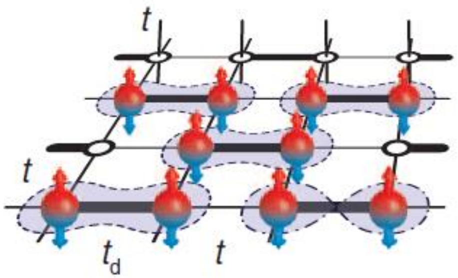
[Nature, **518**, 179(2015)]

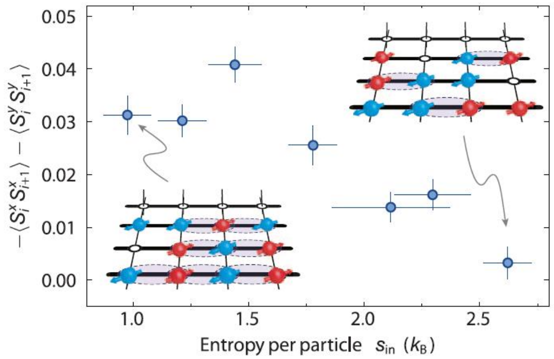
Quantum Magnetism of Fermi Hubbard Model

^{6}Li or ^{40}K : two-component fermions

ETH group (Dimer-1D, 2D, 3D lattice)

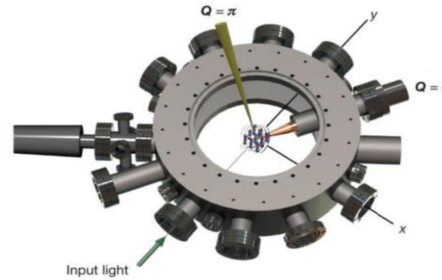
Science **340**, 1307 (2013) / PRL **115**, 260401(2015)

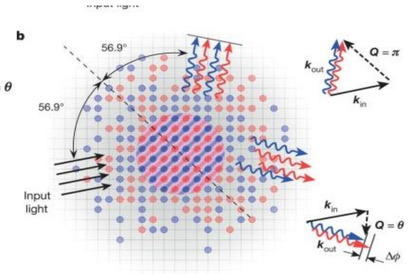




Rice group (3D lattice)

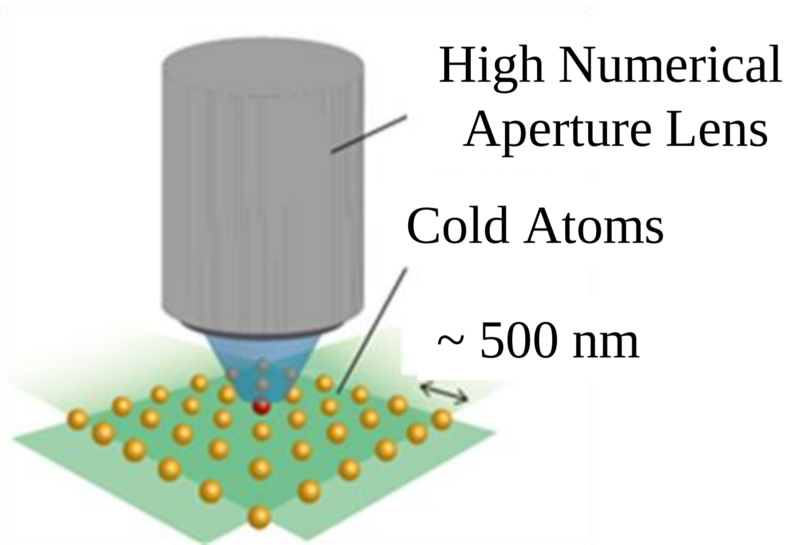
Nature **519**, 211 (2015)

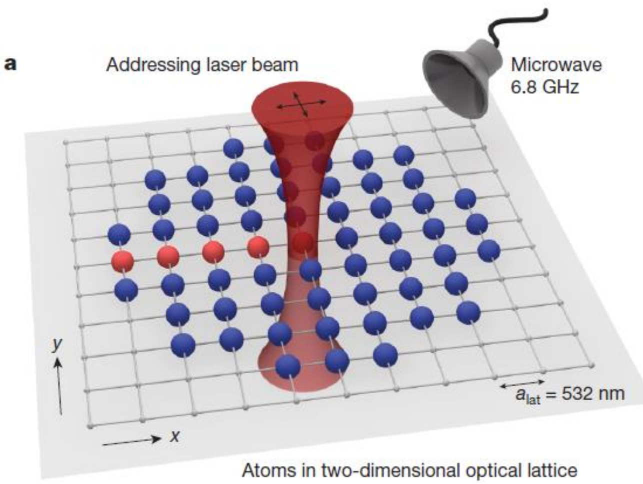




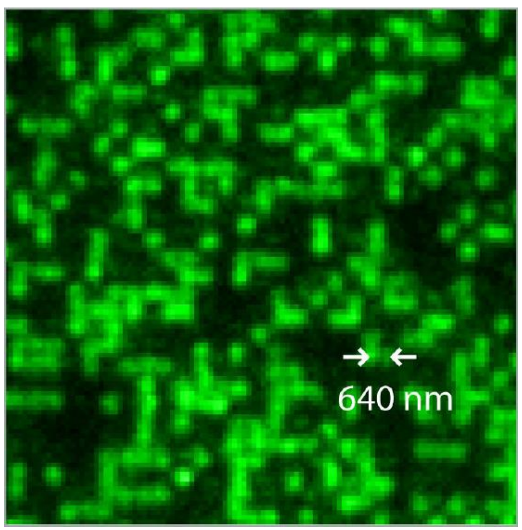
Quantum Gas Microscope

"detect and manipulate ***single atoms*** with ***single site resolution***"

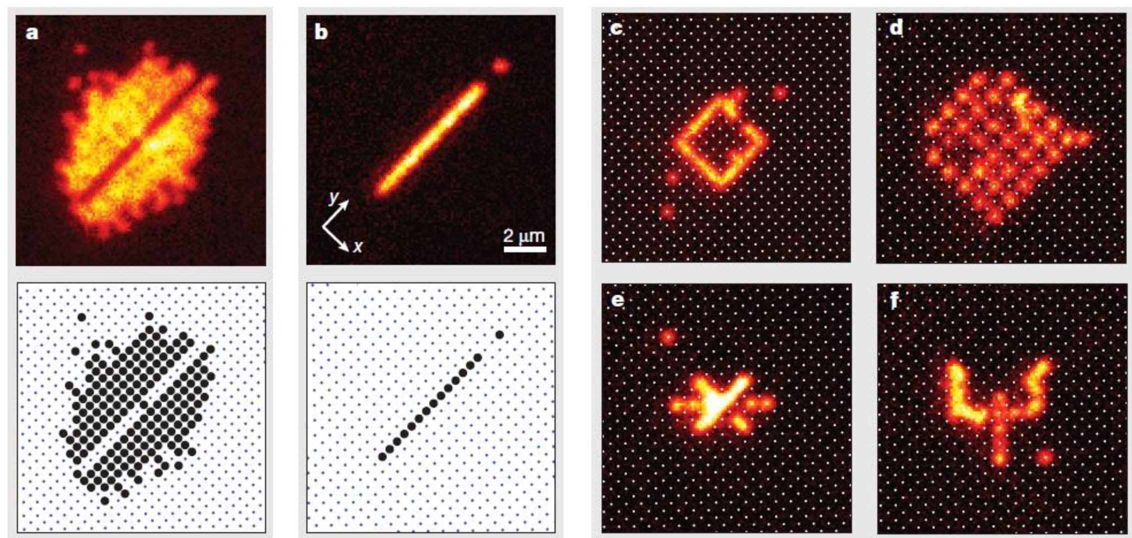




MPQ



Harvard



Harvard, MPQ, MIT, Princeton, Toronto, Strathclyde, TIT, Kyoto, …

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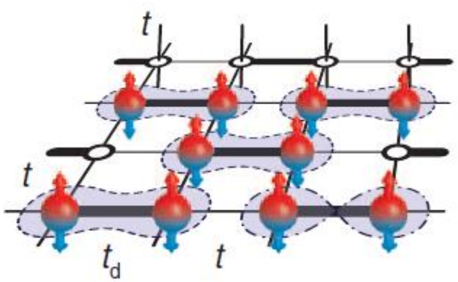

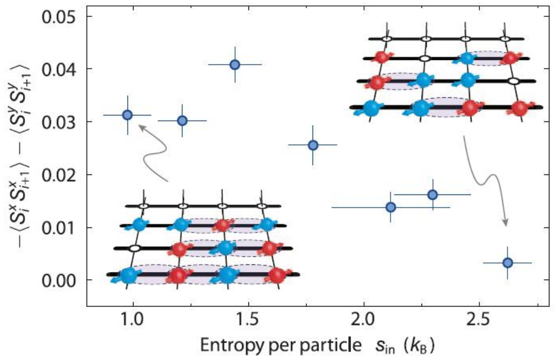

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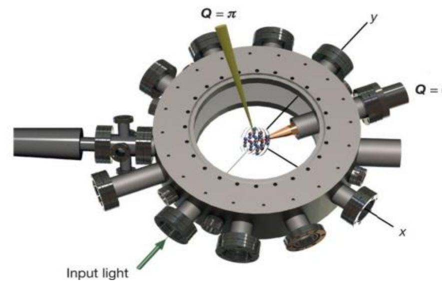
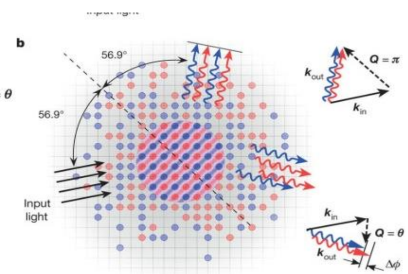
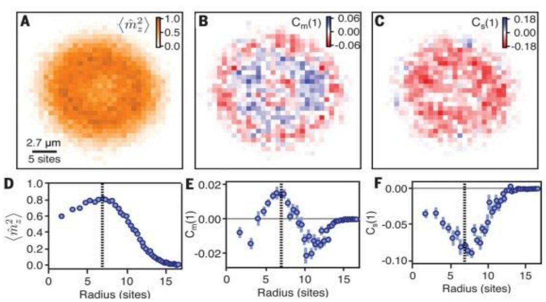




MIT group (2D lattice)

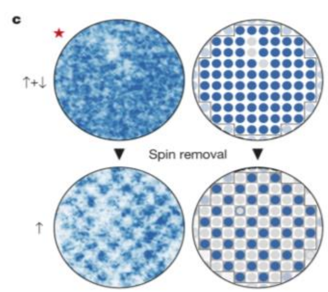
Science **353**, 1260 (2016)

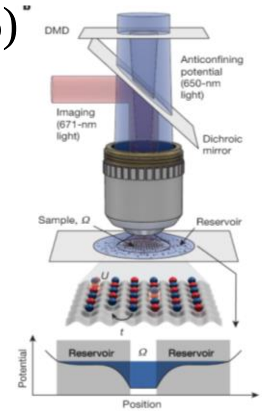


Harvard group (2D lattice)

Science **353**, 1253(2016)

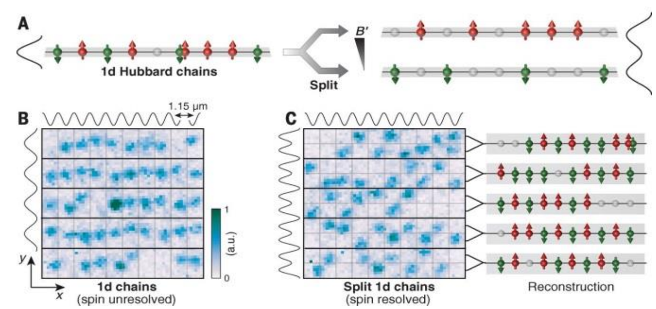
Nature **545**, 462(2017)





MPQ group (1D,2D lattice)

Science **353**, 1257 (2016)

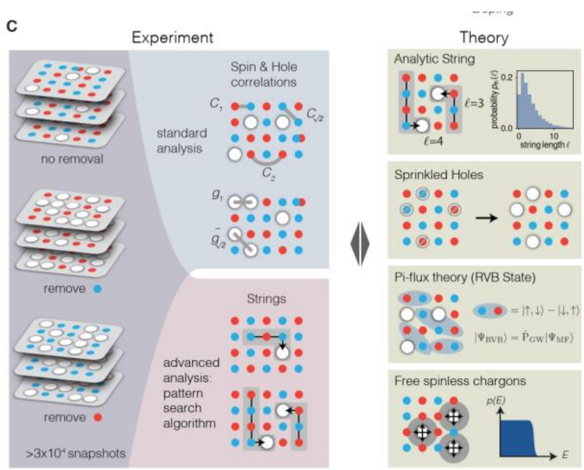


Princeton group (2D lattice), …

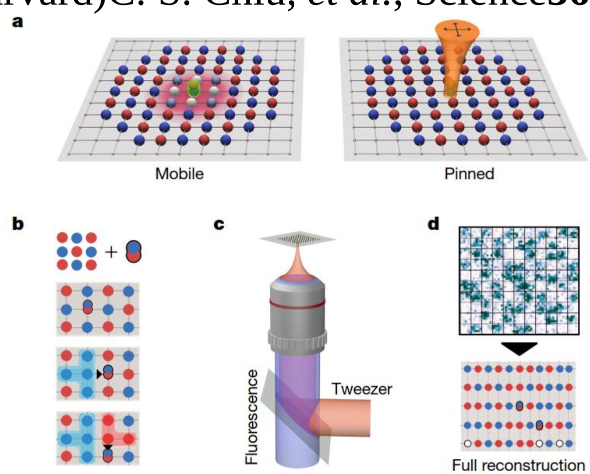
Quantum Magnetism of Fermi Hubbard Model

^{6}Li or ^{40}K : two-component fermions

Doped Fermi Hubbard model

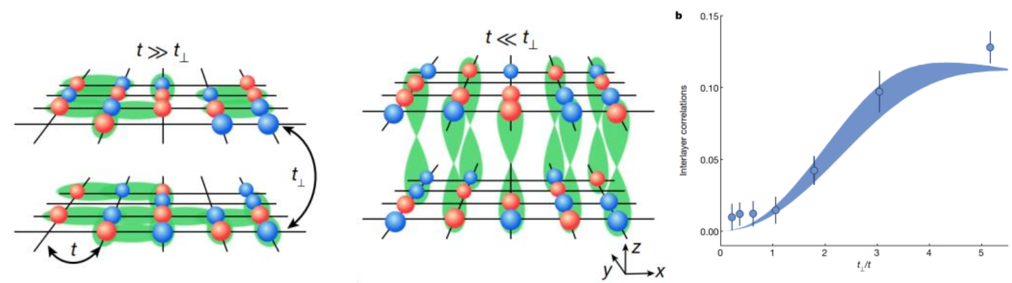


(Harvard)C. S. Chiu, *et al.*, Science**365** 251(2019)]

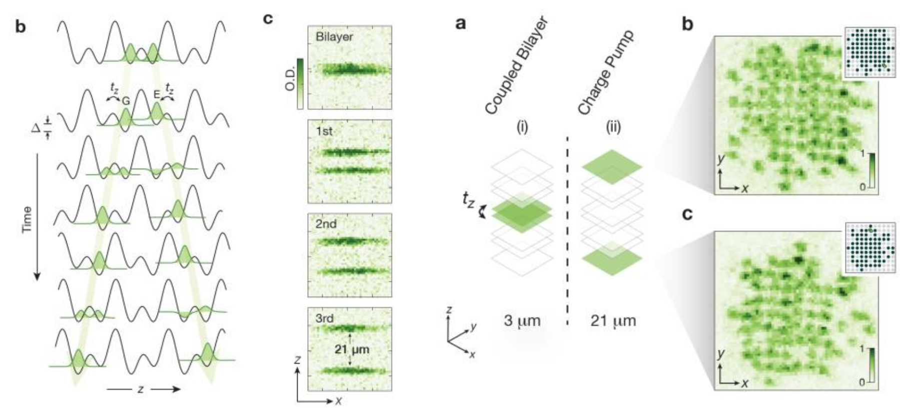


(MPQ) J. Koepsell *et al.*, Nature **572** 358(2019)]

Bilayer Fermi Hubbard Model



(Univ. of Bonn) M. Gall *et al.*, Nature **589**, 40 (2021)

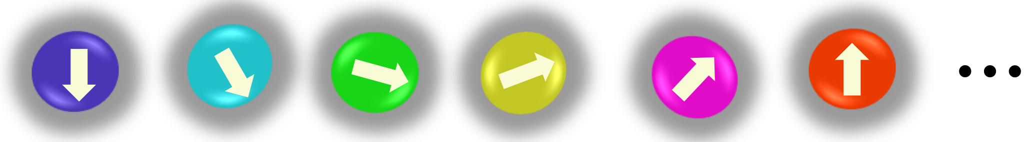


(MPQ) J. Koepsell *et al.*, PRL125, 010403 (2020)

Also (MIT) T. Hartke, *et al.*,PRL**125**, 113601 (2020)

“Two-Electron Atoms (Sr, Yb) with nuclear spin *I* ”

“Fermi Hubbard Model with SU(N>2) spin symmetry”



$$H = -t \sum_{<i,j>,\sigma} (c^+_{i,\sigma} c_{j,\sigma} + c^+_{j,\sigma} c_{i,\sigma}) + U \sum_{i,\sigma\neq\sigma'} n_{i,\sigma} n_{i,\sigma'}$$

$\sigma, \sigma' = -I, \ldots +I,$

N=2I+1

$^1\mathbf{S}_0$, $^3\mathbf{P}_0$ $(\boldsymbol{I} \cdot \boldsymbol{J} = 0)$

<u>Nuclear spin permutation operators:</u> $S^m_n \equiv c^+_n c_m = |n\rangle\langle m|$

SU(N) algebra : $[S^m_n, S^p_q] = \delta_{mq} S^p_n - \delta_{pn} S^m_q$

SU(N) symmetry: $[H, S^m_n] = 0$

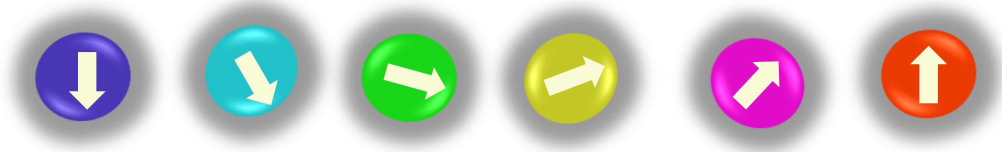
SU(N) Hubbard model $\rightarrow$ SU(N) Heisenberg model: $H = \dfrac{2t^2}{U} \sum_{\langle i,j\rangle m,n} S^m_n(i) S^n_m(j)$
$(U >> t)$

Theory of SU(N) FHM:

I. Affleck & J. B. Marston(1988); C. Honerkamp &W. Wofstetter(2004), C. Wu (2005),..
M. A. Cazalilla, *et al*,(2009), A.V. Gorshkov, *et al*, (2010),...

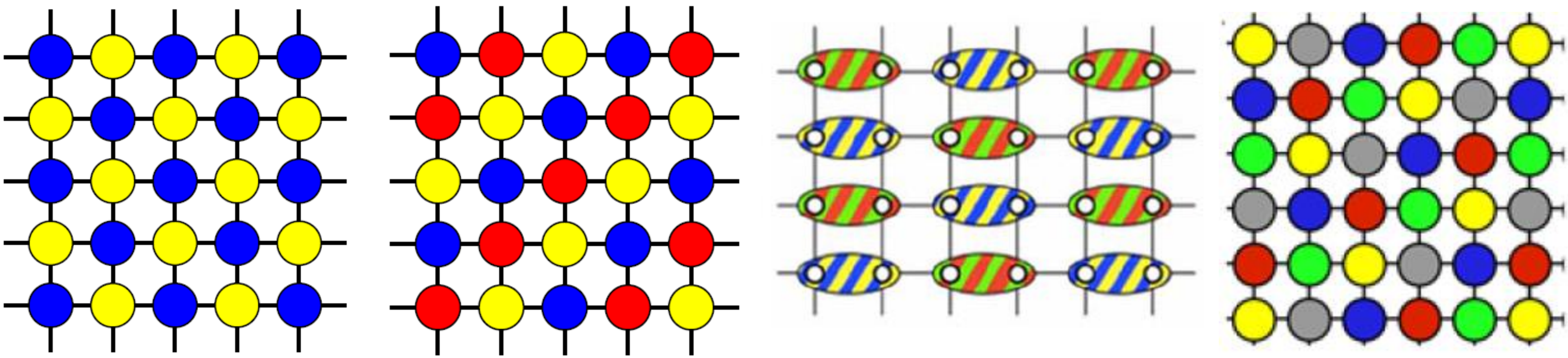
SU(N) Quantum Magnetism

$$H=\frac{2t^2}{U}\sum_{\langle i,j\rangle m,n}S_n^m(i)S_m^n(j)$$



…

SU(2) SU(3) SU(4) SU(5)

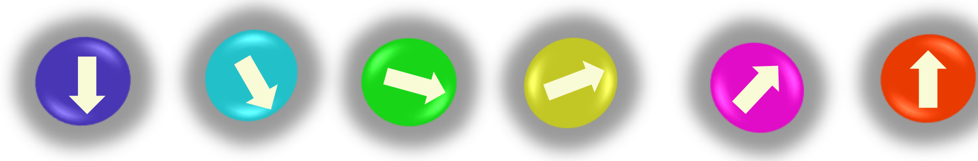


…

T. A. Toth *et al*, PRL(2010) P. Corboz *et al*, PRL(2011) P. Nataf & F. Mila,PRL(2014)

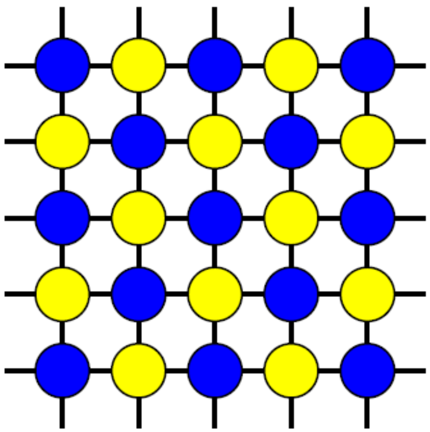
SU(N) Quantum Magnetism

$$H = \frac{2t^2}{U} \sum_{\langle i,j \rangle m,n} S_n^m(i) S_m^n(j)$$



…

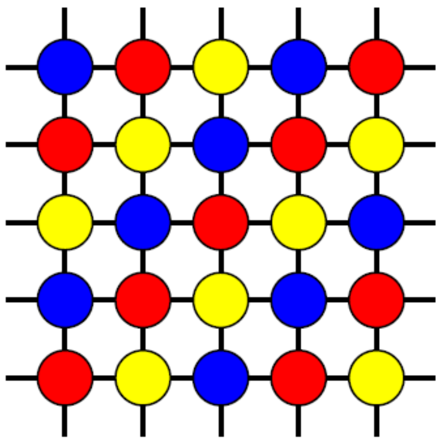
SU(2)



"doping"

d-wave superconductivity

SU(3)

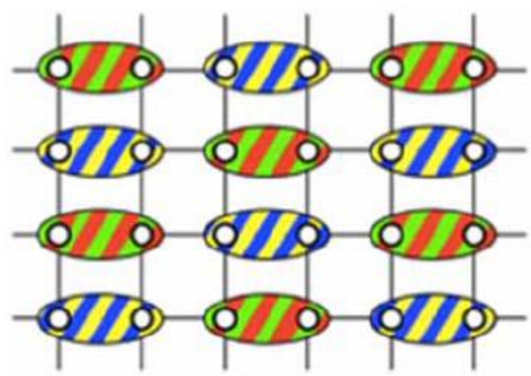


T. A. Toth *et al*, PRL(2010)

?

(C. Honerkamp &W. Wofstetter(2004)),..

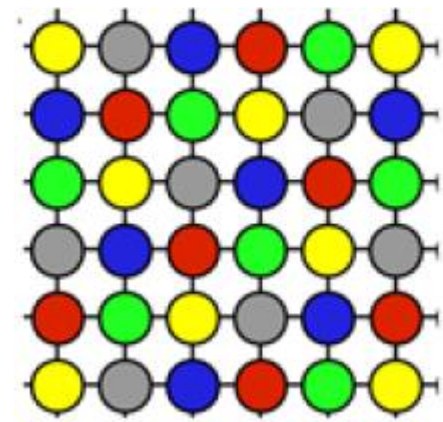
SU(4)



P. Corboz *et al*, PRL(2011)

?

SU(5)



…

P. Nataf & F. Mila,PRL(2014)

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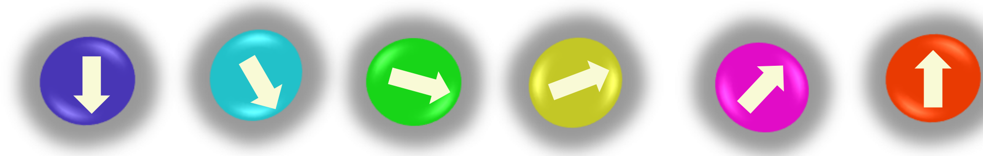
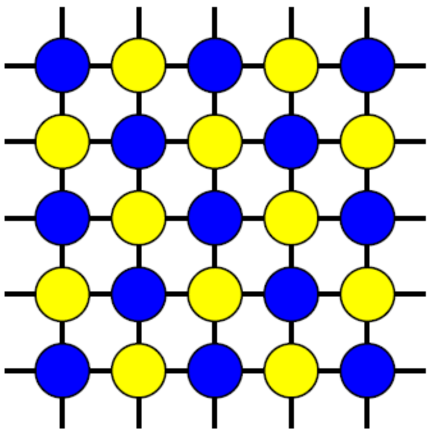


…

SU(2)



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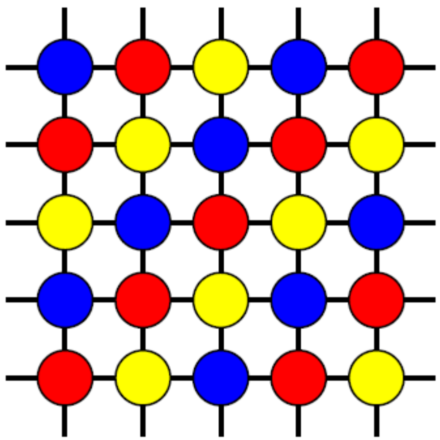

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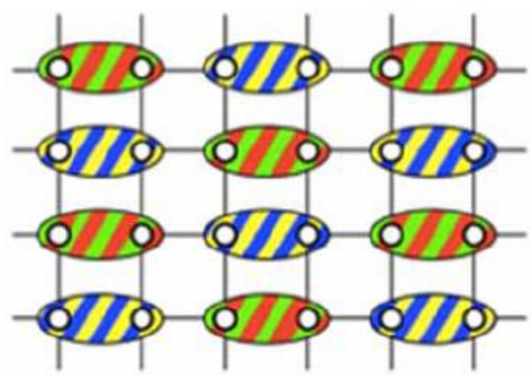

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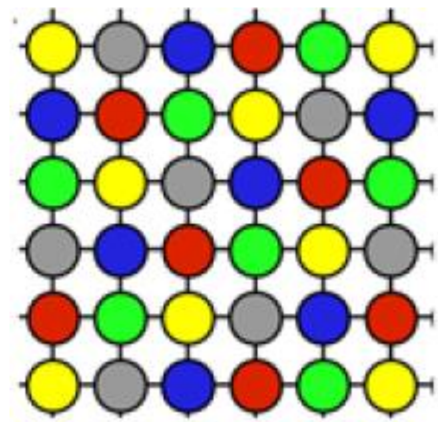


…

P. Nataf & F. Mila,PRL(2014)

?

"Spin-Imbalance"

Triangular SU(3) Heisenberg Model under Magnetic Fields,
D. Yamamoto, *et al.*, PRL**125**, 057204 (2020)

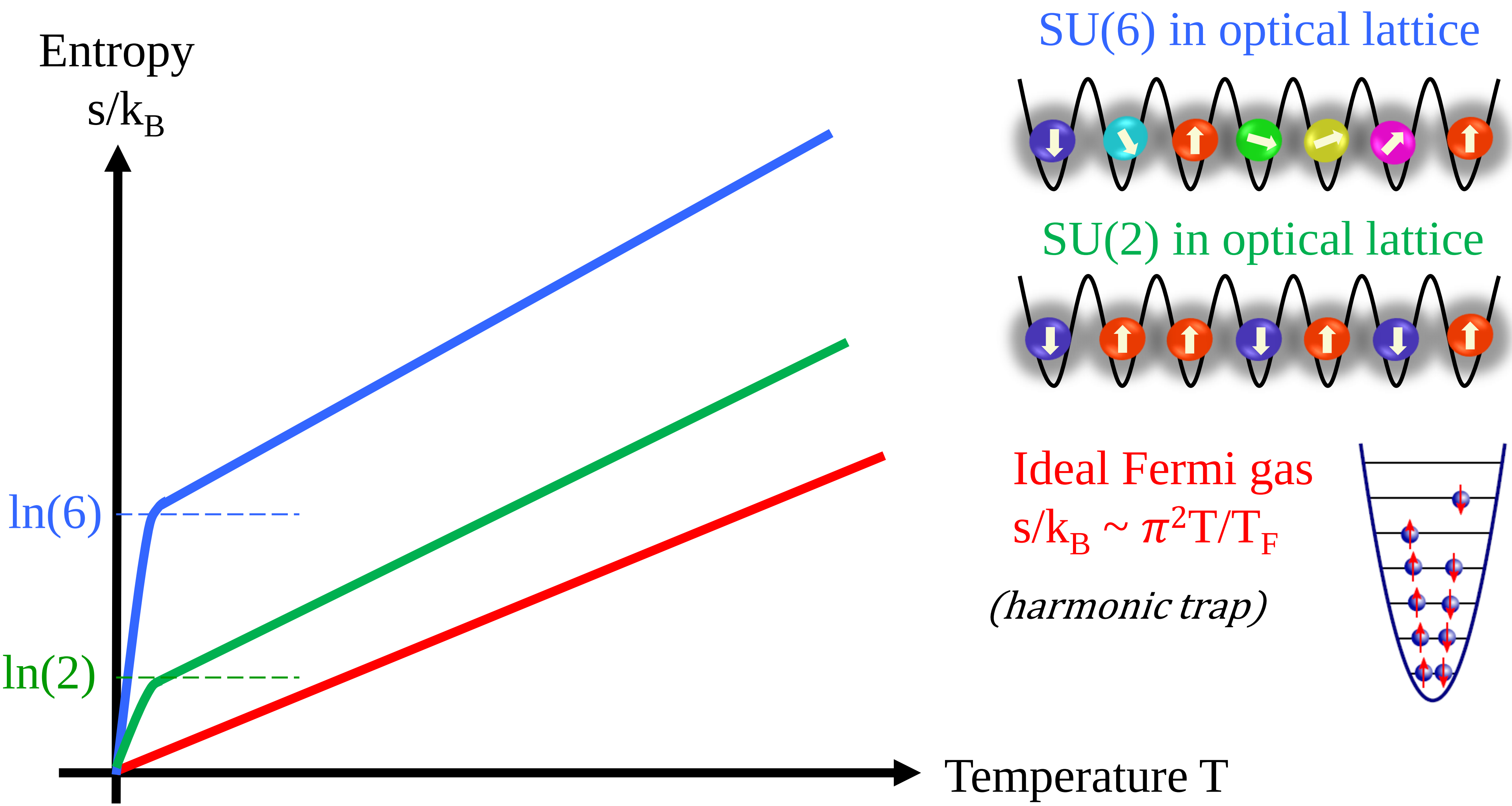
Pomeranchuk Cooling of an Atomic Gas

"colder temperature for SU(N) system than for SU(2) system"

[I. Pomeranchuk]

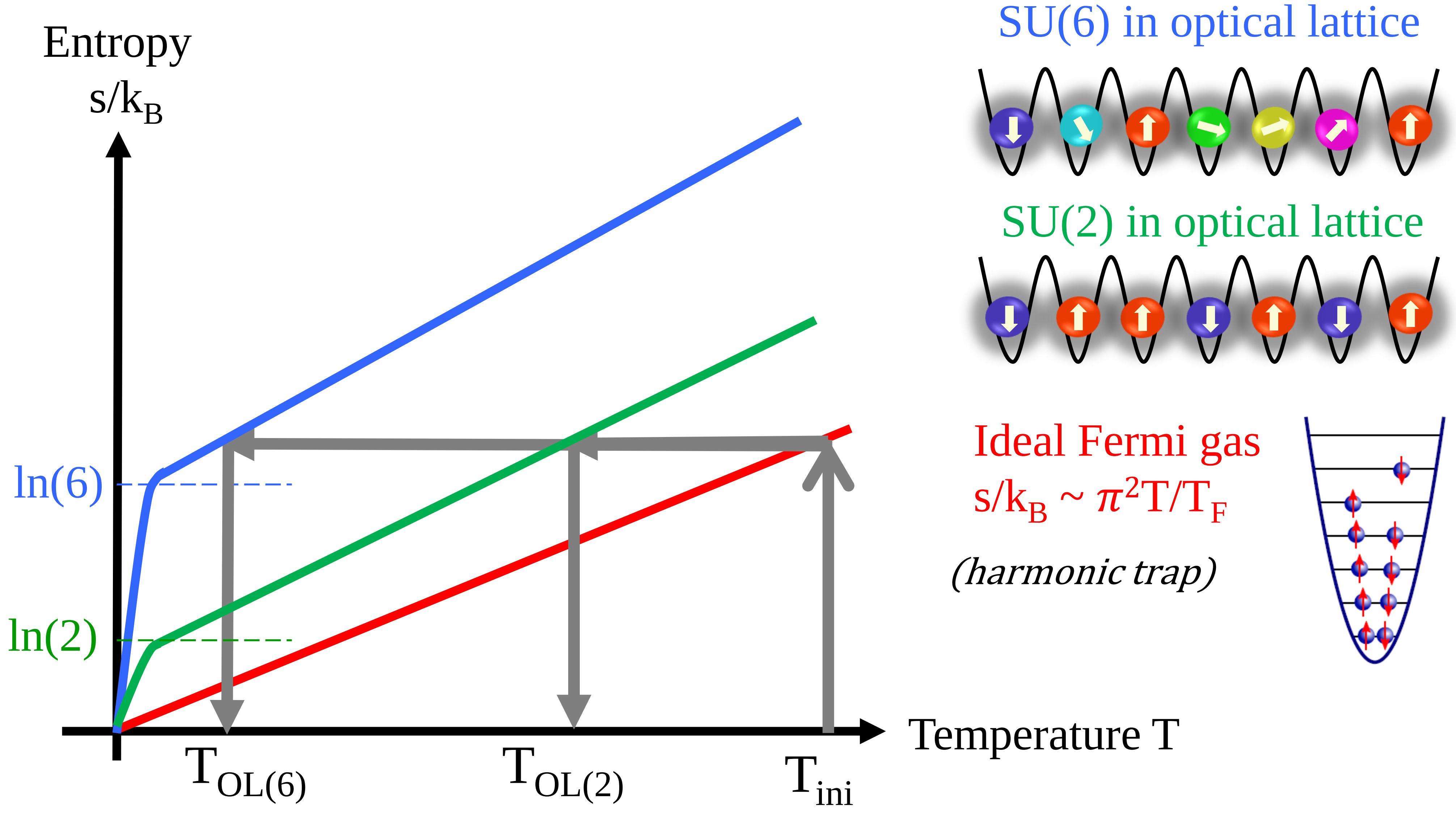
Pomeranchuk Cooling of an Atomic Gas

"colder temperature for SU(N) system than for SU(2) system"

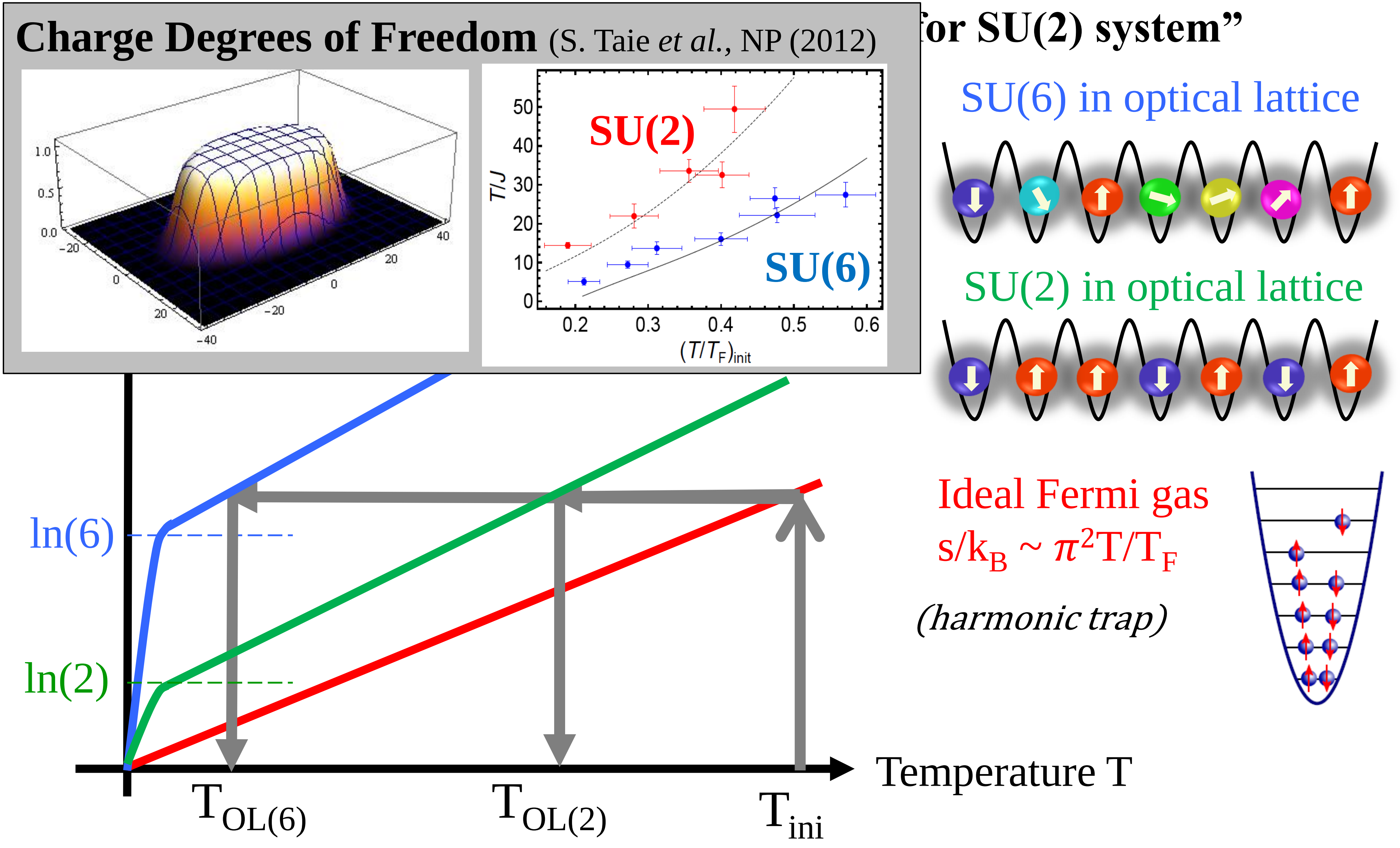


Pomeranchuk Cooling of an Atomic Gas

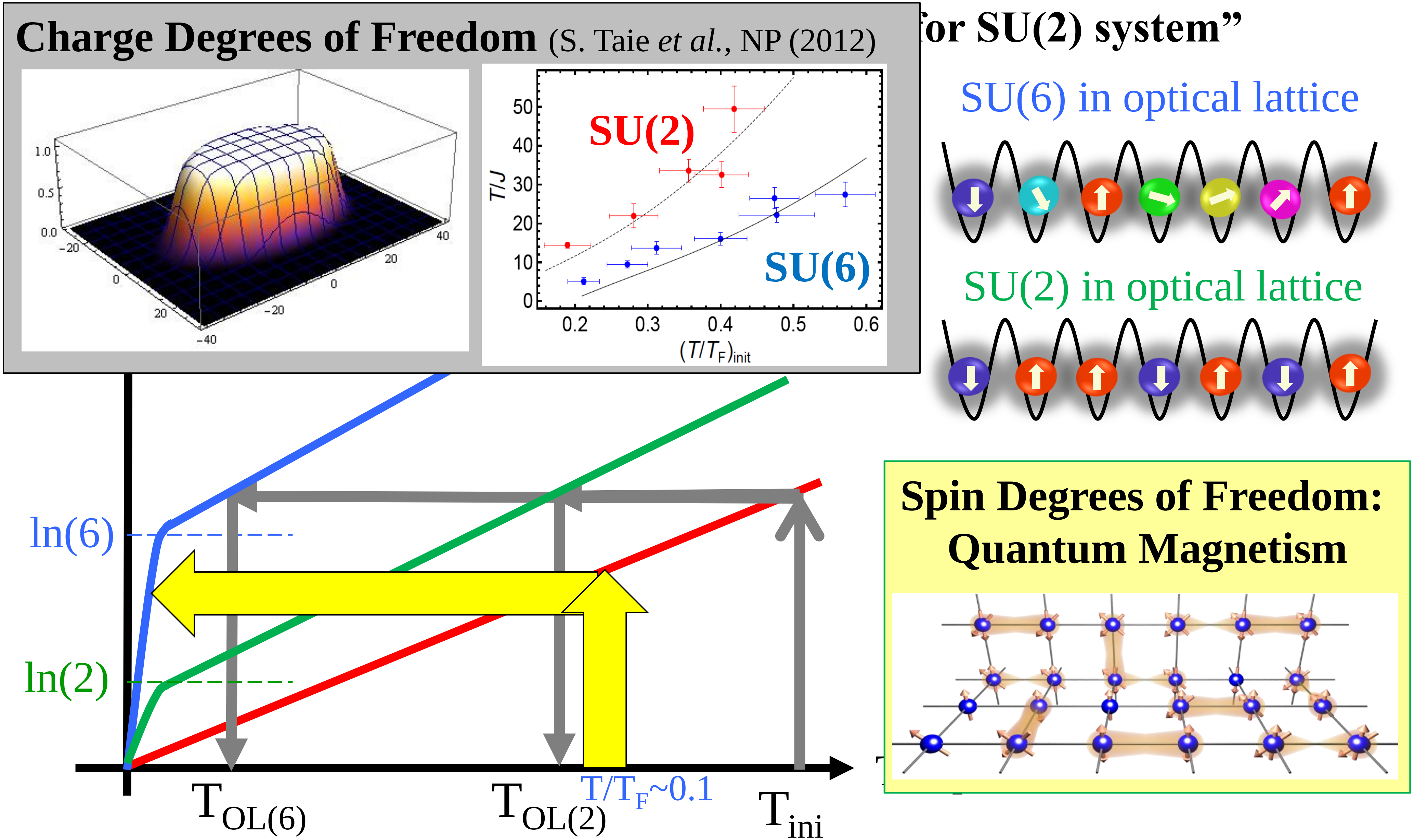
"colder temperature for SU(N) system than for SU(2) system"



Pomeranchuk Cooling of an Atomic Gas



Pomeranchuk Cooling of an Atomic Gas



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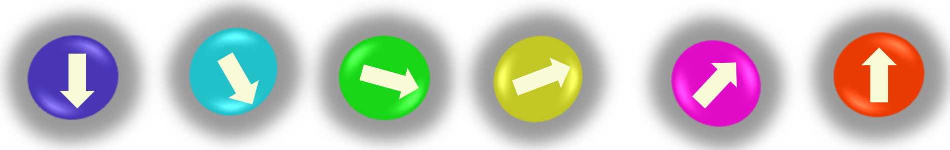
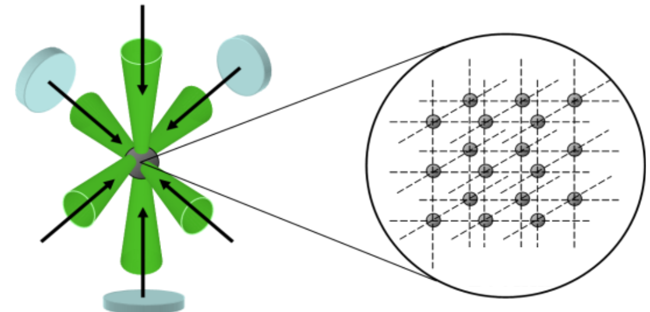
^{173}Yb SU(N=6) Fermi Hubbard Model

$^1S_0$



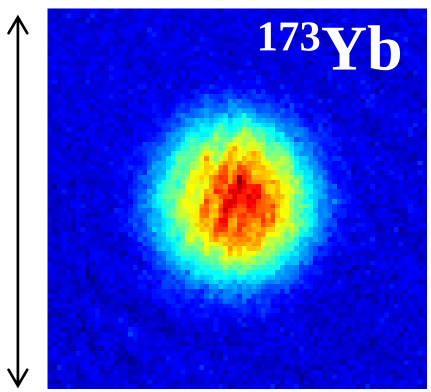


$I=5/2, \;\; a_s = +199.4\, a_0$

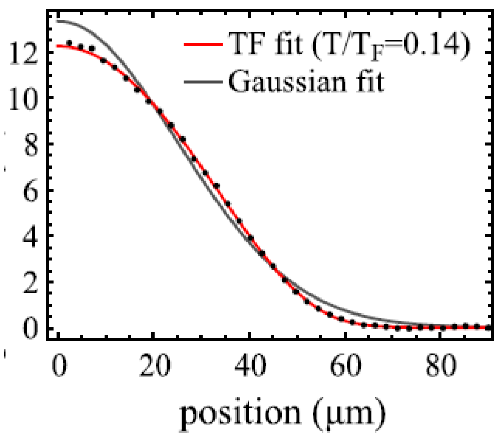
$$H = -t \sum_{<i,j>,\sigma} \left(c^{+}_{i,\sigma} c_{j,\sigma} + c^{+}_{j,\sigma} c_{i,\sigma}\right) + U \sum_{i,\sigma \neq \sigma'} n_{i,\sigma} n_{i,\sigma'}$$

t,U: nuclear-spin σ-independent

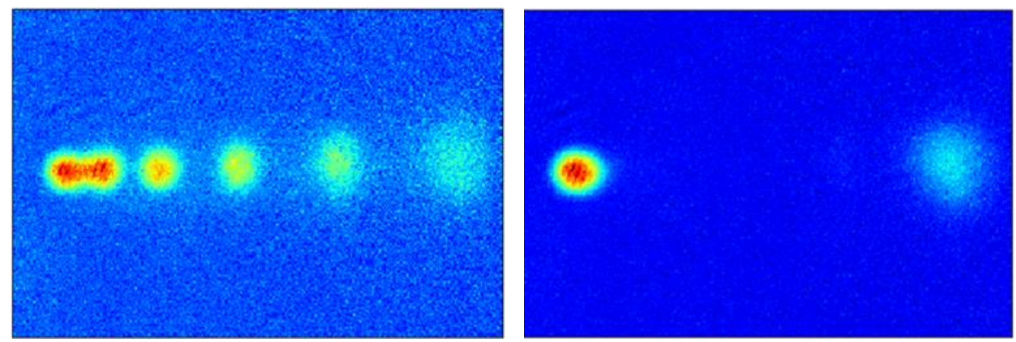
Ultracold Fermi Gas



190 μm



SU(6) SU(2)

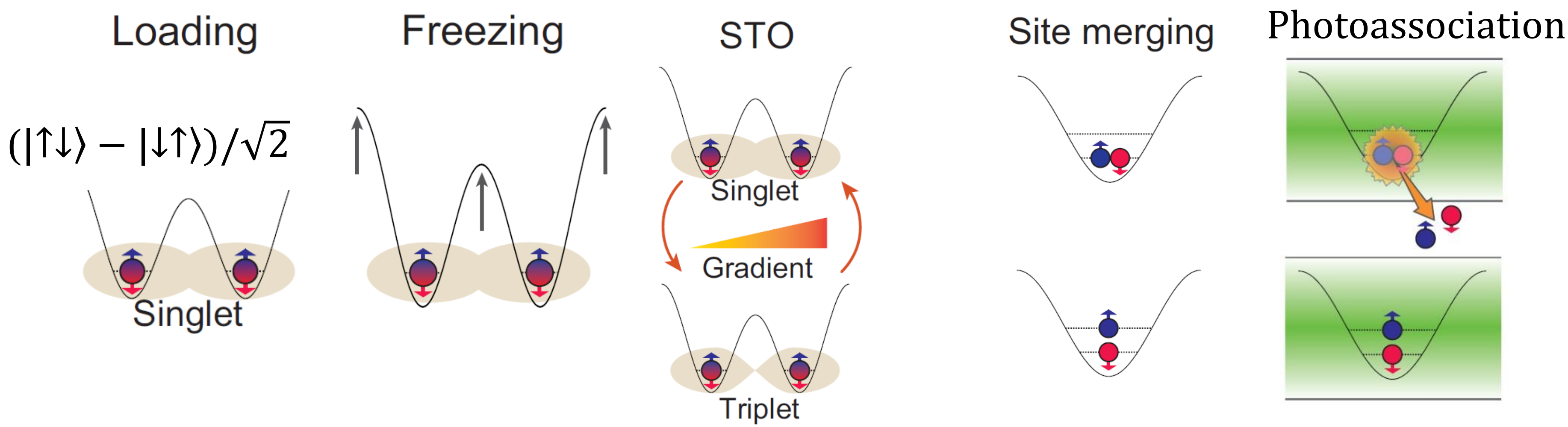


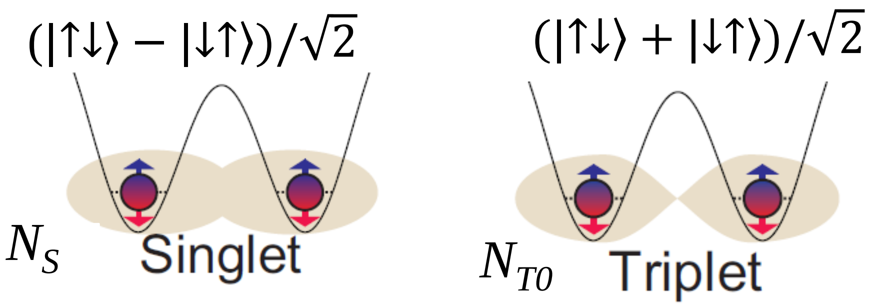
Optical Pumping &
Optical Stern-Gerlach imaging

First Step of SU(N) Quantum Magnetism Study: Measuring Nearest Neighbor Spin Correlation

STO: Singlet-Triplet Oscillation method

[cf. ^{87}Rb :S. Trotzky *et al.*, PRL (2010), ^{40}K :D. Greif *et al.*, Science (2013)]





$$|\Psi(t)\rangle = \{|\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle e^{-i\delta t/\hbar}\}/\sqrt{2}$$

Normalized STO Amplitude:

$$A=(N_S - N_{T0})/N_{total}$$

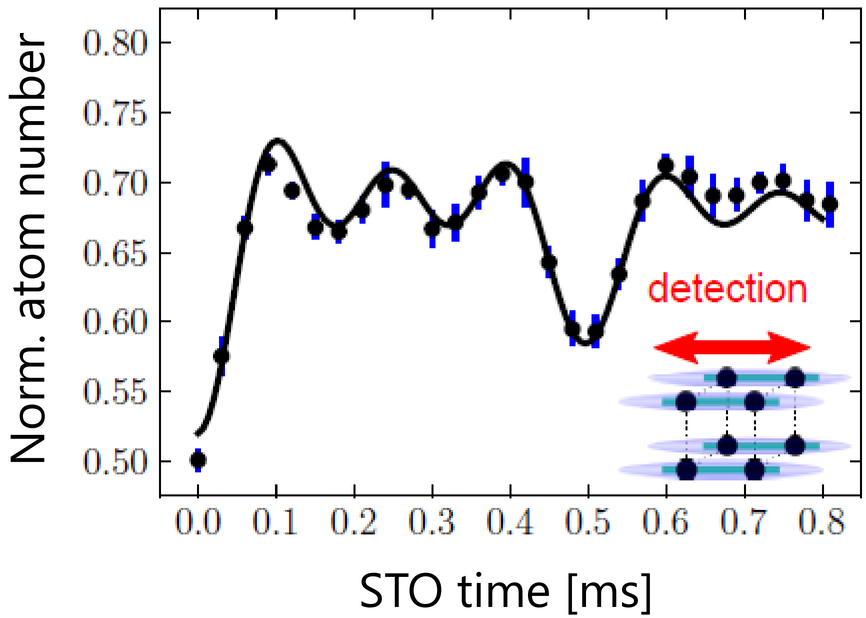
Singlet-Triplet Imbalance:

$$I = \frac{N_S - N_{T0}}{N_S + N_{T0}}$$

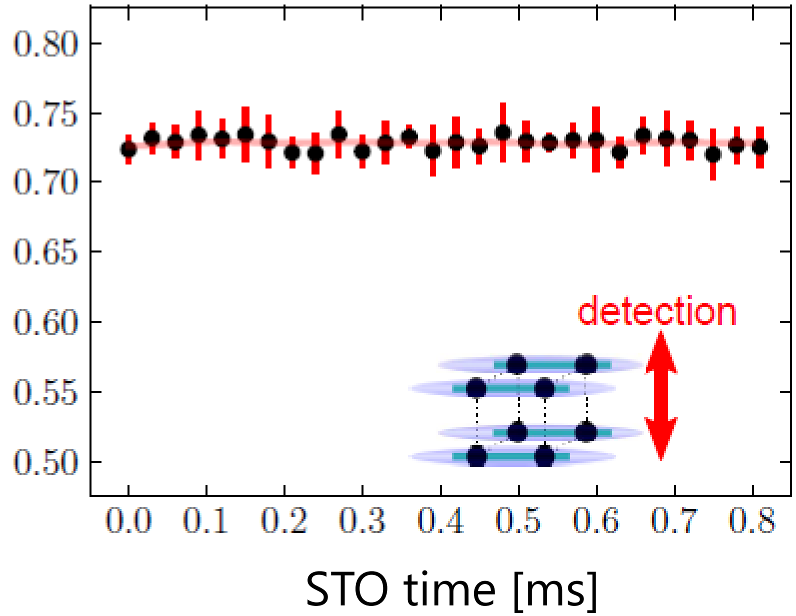
Singlet-Triplet Oscillation of SU(6) Fermions

Typical STO Signal : 1D chain (U/t = 15.3, t/h = 270 [Hz])

"Strong link" (intra-chain)



"Weak link" (inter-chain)



Fitting function

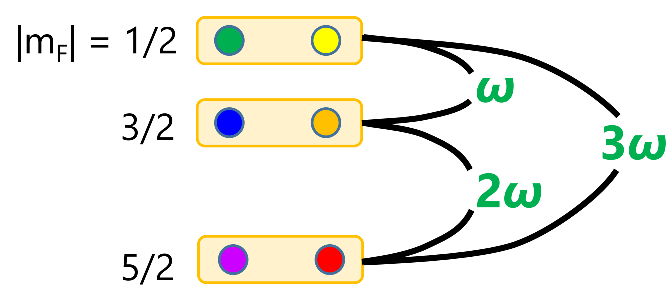
$$N(t) = -a \exp(-t/\tau) \left[\cos \omega t + \cos 2\omega t + \cos 3\omega t\right] + b$$

- Normalized STO amplitude

$$A = \frac{N_S - N_{T0}}{N_a} = \frac{15a}{2N_{\mathrm{atom}}}$$

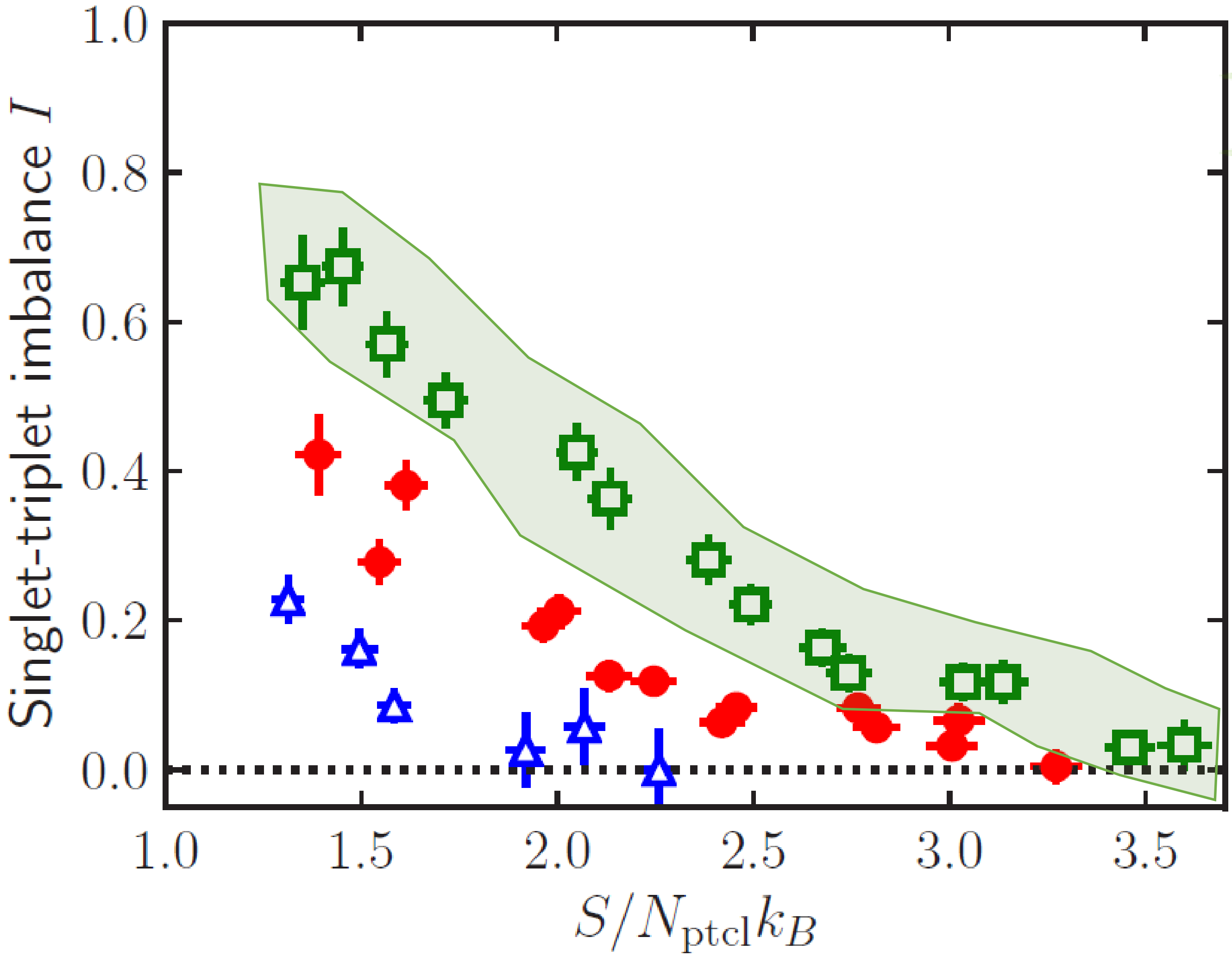
- Singlet-Triplet imbalance

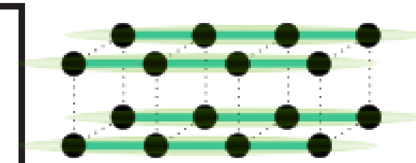
$$I = \frac{N_S - N_{T0}}{N_S + N_{T0}} = \frac{15a}{3a + 4b - 4N_{\mathrm{atom}}}$$



Spin Correlation vs Entropy: $S/N_{\text{ptcl}}k_B$

$U/t = 15.3$

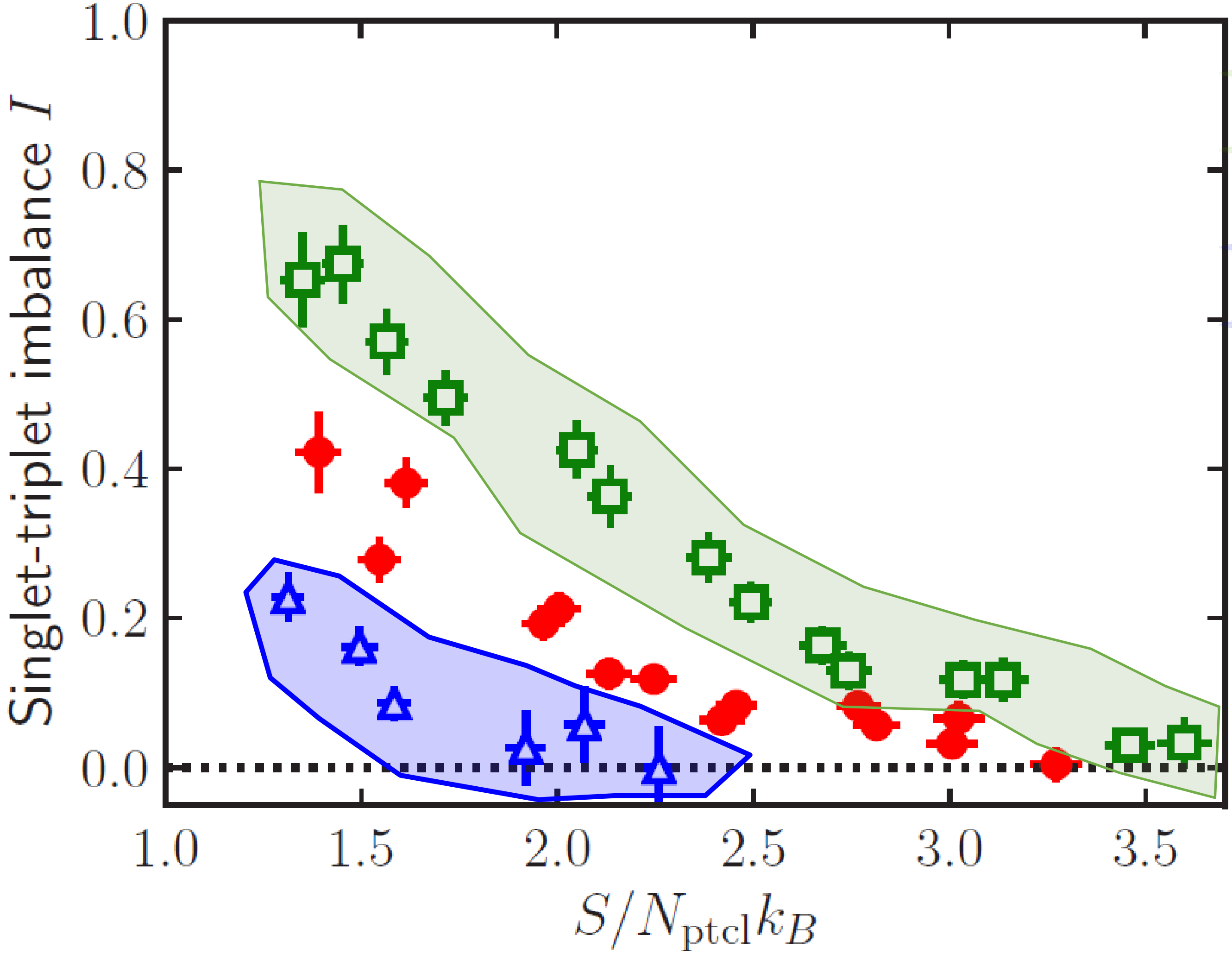


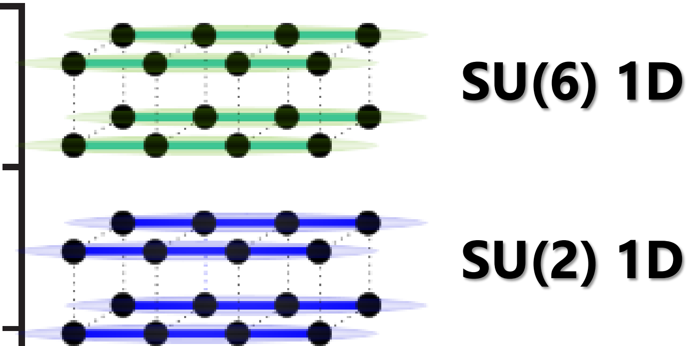


SU(6) 1D

Spin Correlation vs Entropy: $S/N_{\text{ptcl}}k_B$

$U/t = 15.3$



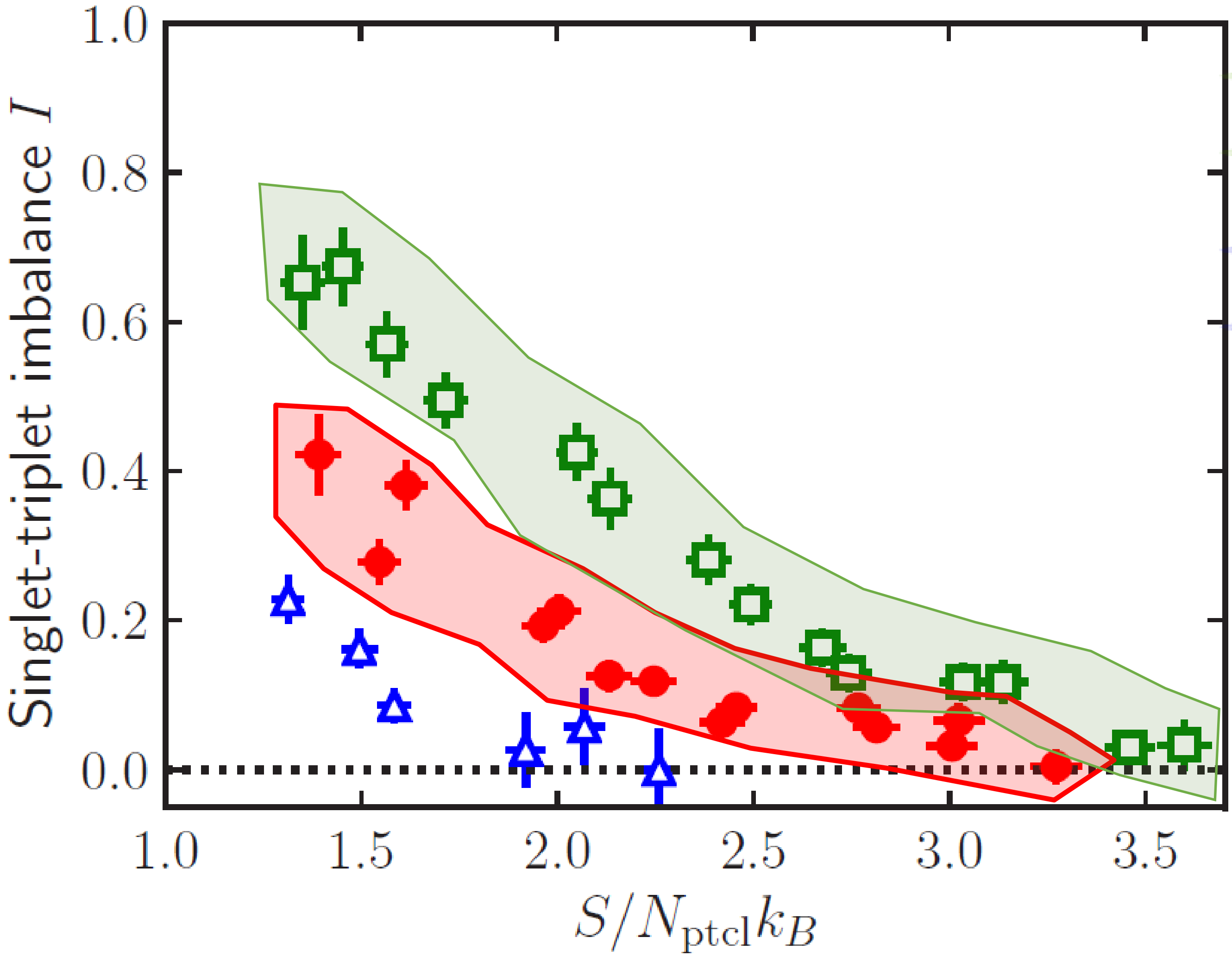


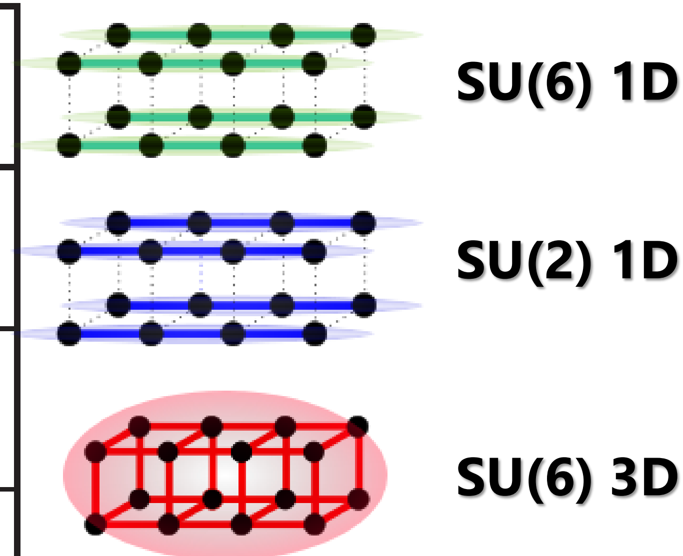
Enhancement with increasing N from 2 to 6

"Pomeranchuk cooling for quantum magnetism"

Spin Correlation vs Entropy: $S/N_{\mathrm{ptcl}}k_B$

$U/t = 15.3$





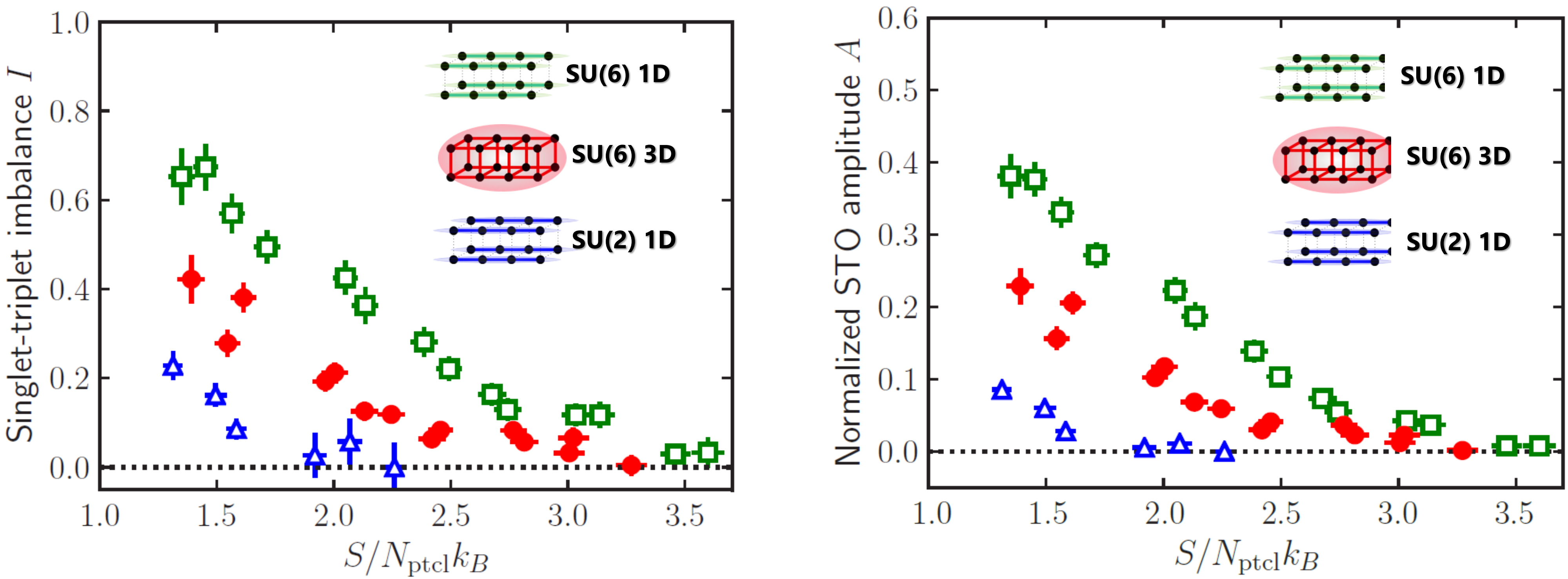
Enhancement for lower dimension

"entropy redistribution in weak links"

cf. Greif et al., PRL **115**, 260401 (2015)

Spin Correlation vs Entropy: $S/N_{\mathrm{ptcl}}k_B$

$U/t = 15.3$

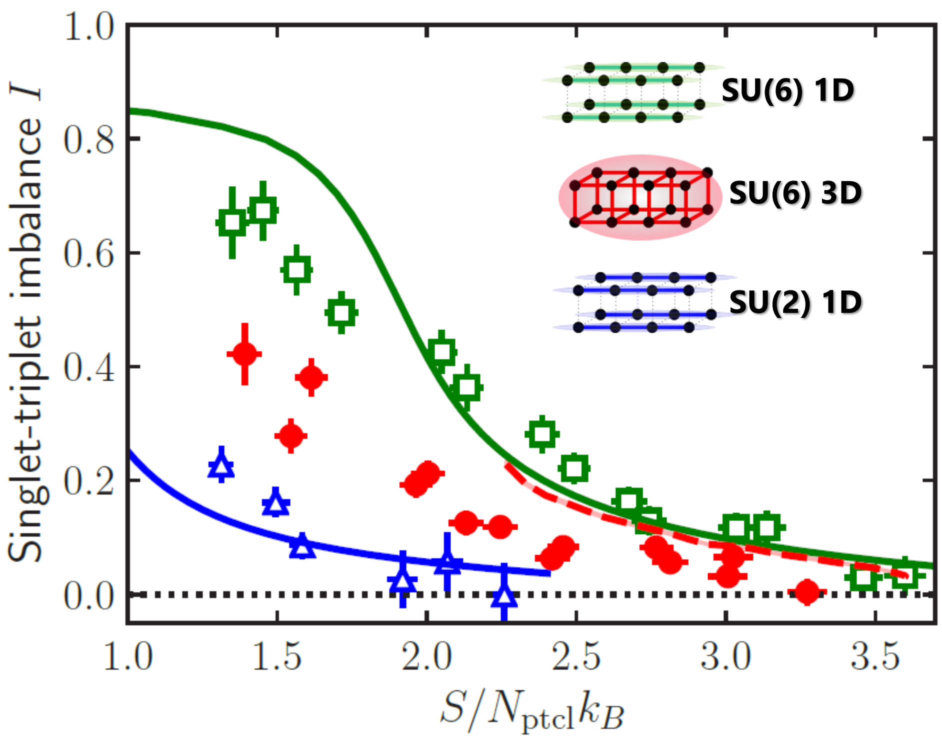


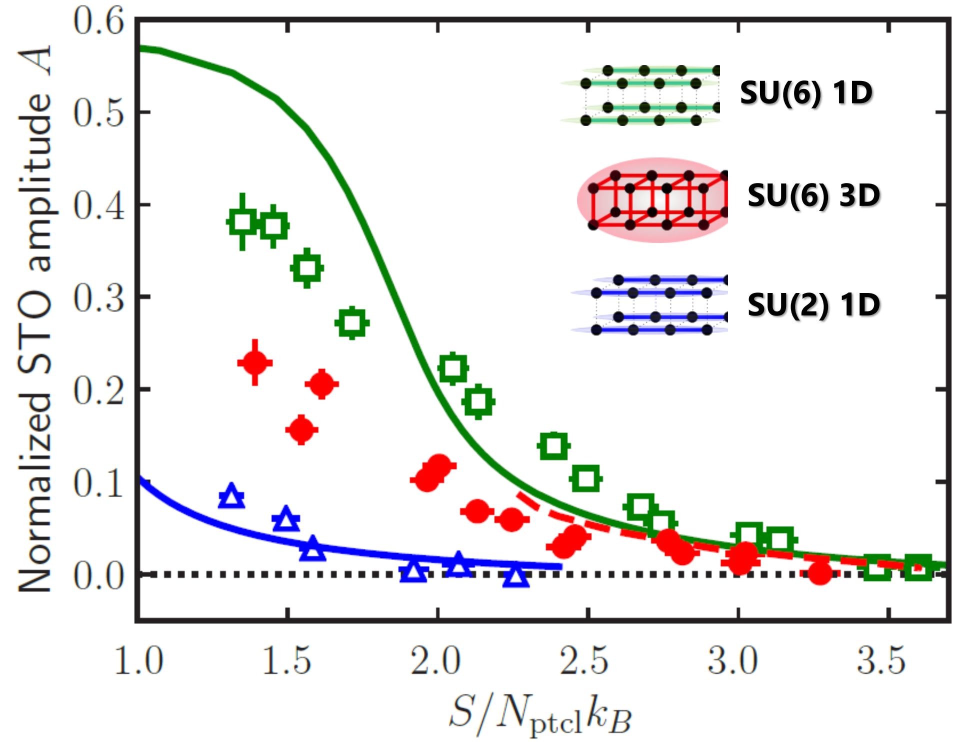
Spin Correlation vs Entropy: $S/N_{\mathrm{ptcl}}k_B$

SU(N) theory calculations

U/t = 15.3

K. Hazzard, R. Scalettar, E. Ibarra-García-Padilla, H.-T. Wei





1D: Exact Diagonalization in 8 site Chain & fss + LDA

3D: Determinantal QMC in 4×4×4 sites geometry + LDA

⟶ **Agreement between Exp. and Cal. with no fitting parameters**

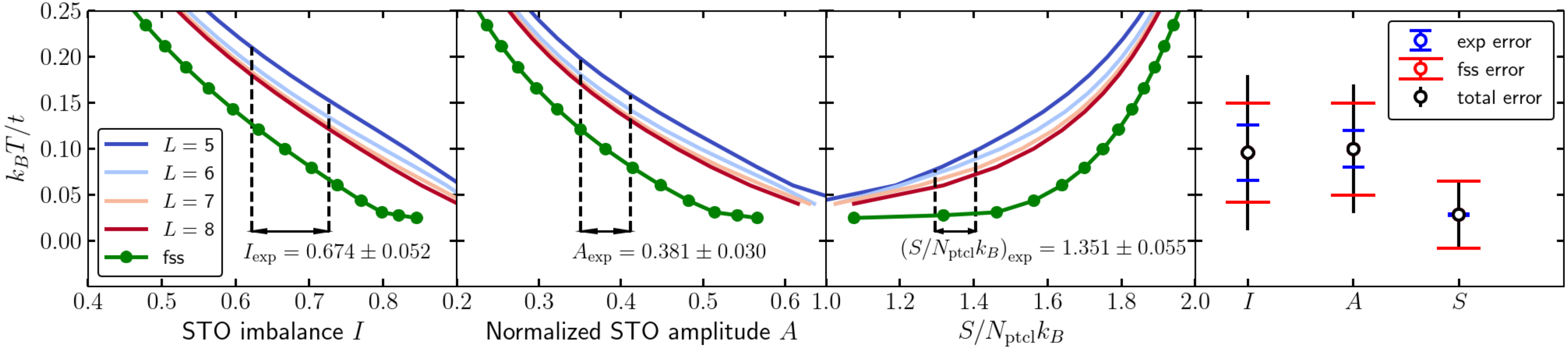
⟶ **SU(6) in 3D at low temperature: Quantum Simulation manifests its usefulness**

Spin Correlation vs Entropy: $S/N_{ptcl}k_B$

Extracting the temperature of SU(6) in 1D lattice

$U/t = 15.3$

K. Hazzard, R. Scalettar, E. Ibarra-García-Padilla, H.-T. Wei



$k_BT_{lattice}/t = 0.096 \pm 0.054$ (cal.) $\pm$ 0.030(exp.)

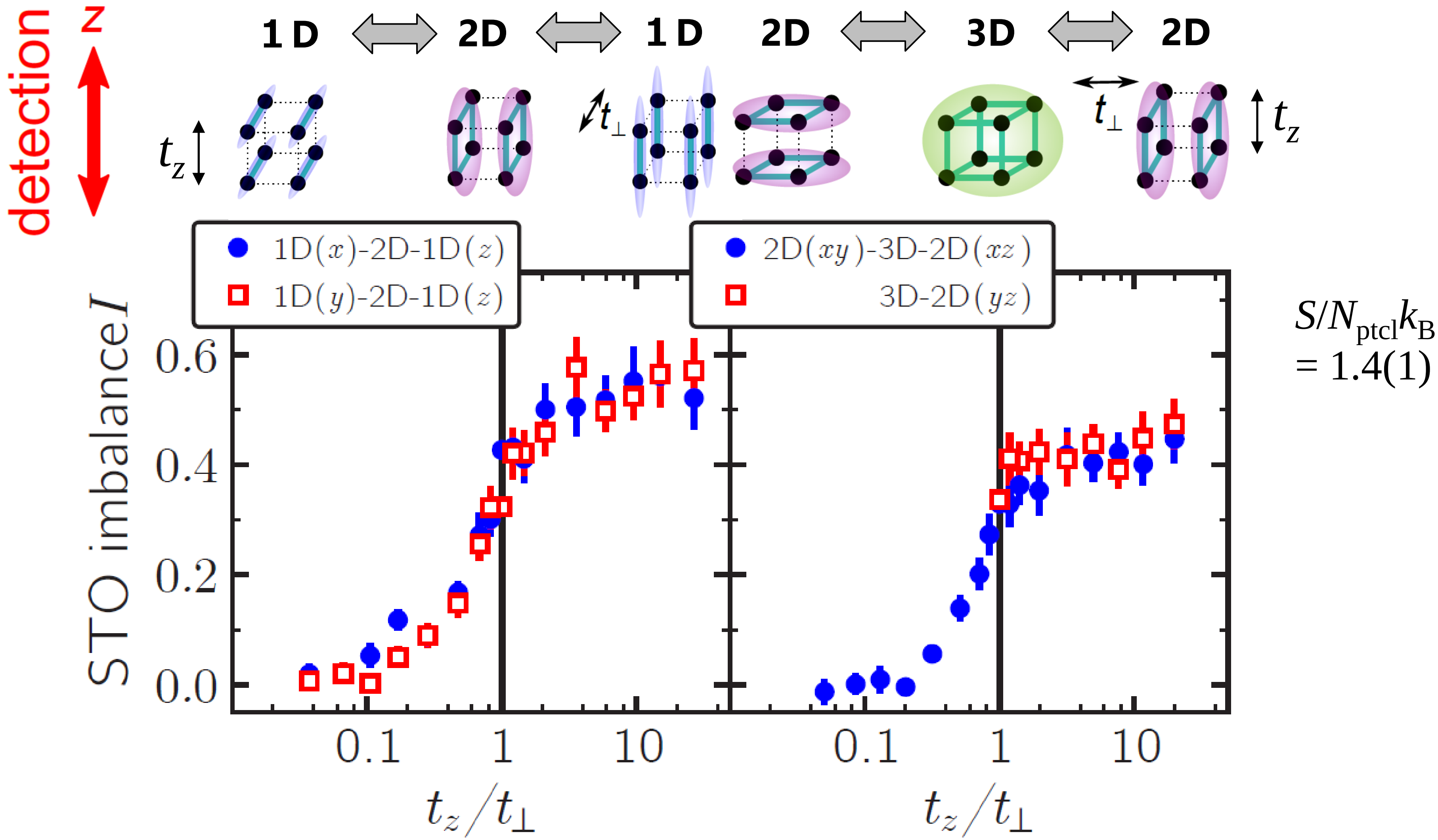
SU(2) 1D case[our exp.]
$k_BT_{lattice}/t = 1.008 \pm 0.073$ (cal.) $\pm$ 0.001(exp.)

SU(2) 2D case[A. Mazurenko, *et al.*,(2017)]
$k_BT_{lattice}/t \sim 0.25(2)$

Achieved lowest temperature of cold-atom FHM !

→ outlook: further low temperature by spatial entropy-redistribution technique

Dependence of *continuous* lattice deformation



Continuous enhancement for lower dimensions

cf. Greif et al., PRL **115**, 260401 (2015)

Quantum Magnetism
in an Open Dissipative Fermi Hubbard System

[M. Nakagawa, N. Tsuji, N. Kawakami, M. Ueda, PRL.**124,** 147203(2020)]

2-site FHM:

$$H = J_{spin}(\mathbf{S}^{i}\cdot\mathbf{S}^{i+1}-1/4)$$

$$J_{spin} = \frac{4t^2}{U}, \quad U \gg t$$

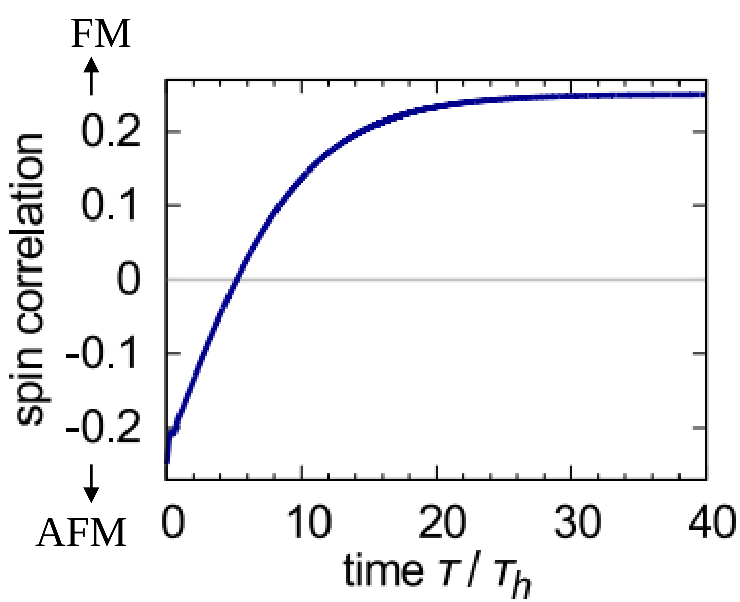
Two-body Dissipation γ_{2B}

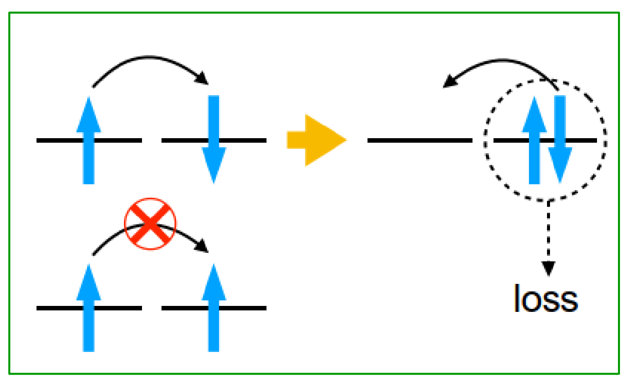
$$H_{eff} = (J_{eff} + i\Gamma)(\mathbf{S}^{i}\cdot\mathbf{S}^{i+1}-1/4)$$

$$J_{eff} = \mathrm{Re}\left[\frac{4t^2}{U-i\gamma_{2B}}\right] = \frac{4t^2U}{U^2+\gamma_{2B}{}^2}$$

$$\Gamma = \mathrm{Im}\left[\frac{4t^2}{U-i\gamma_{2B}}\right] = \frac{4t^2\gamma_{2B}}{U^2+\gamma_{2B}{}^2}$$

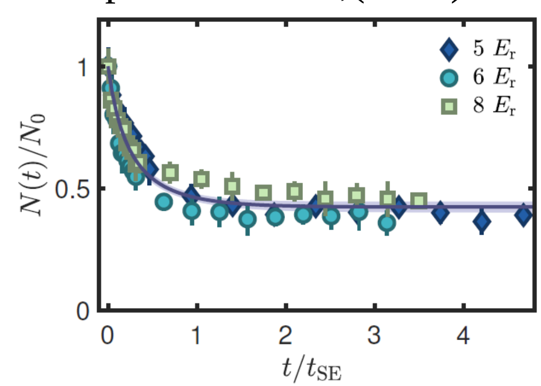
[also S. K. Bauer and E. J. Mueller (2010)]





$$\begin{cases} -\mathrm{Im}\,[E_s] = \Gamma \\ -\mathrm{Im}\,[E_t] = 0 \end{cases}$$

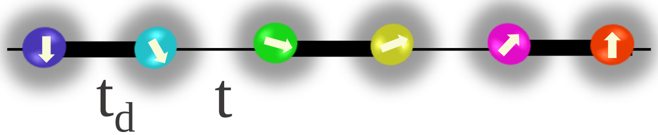
Theory:
M. Foss-Feig, *et al*, (2012)
Experiment:
K Sponselee *et al*,(2019)



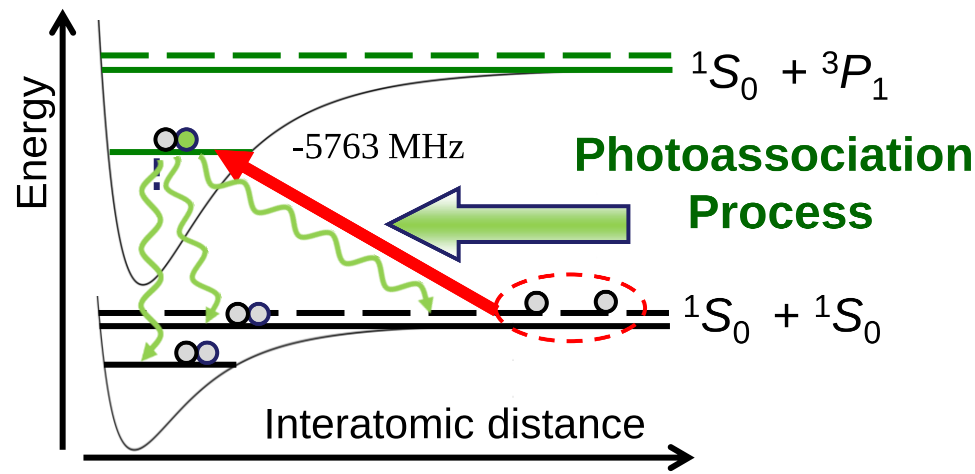
Quantum Magnetism
in an Open Dissipative Fermi Hubbard System

^{173}Yb : $^{1}S_0$ state   SU(6)

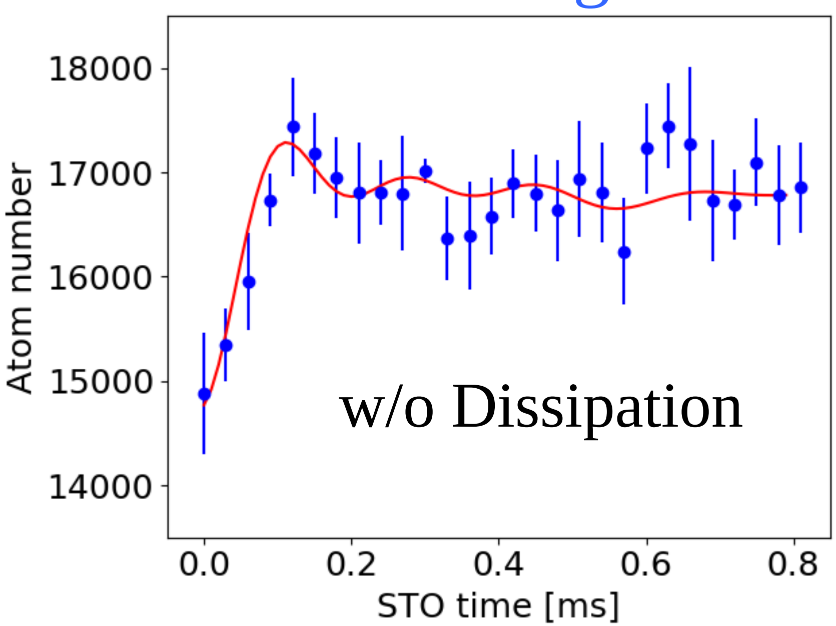
N_{total} =2.2(1) × 10^4



U/t_d=3.8, t_d/t=27

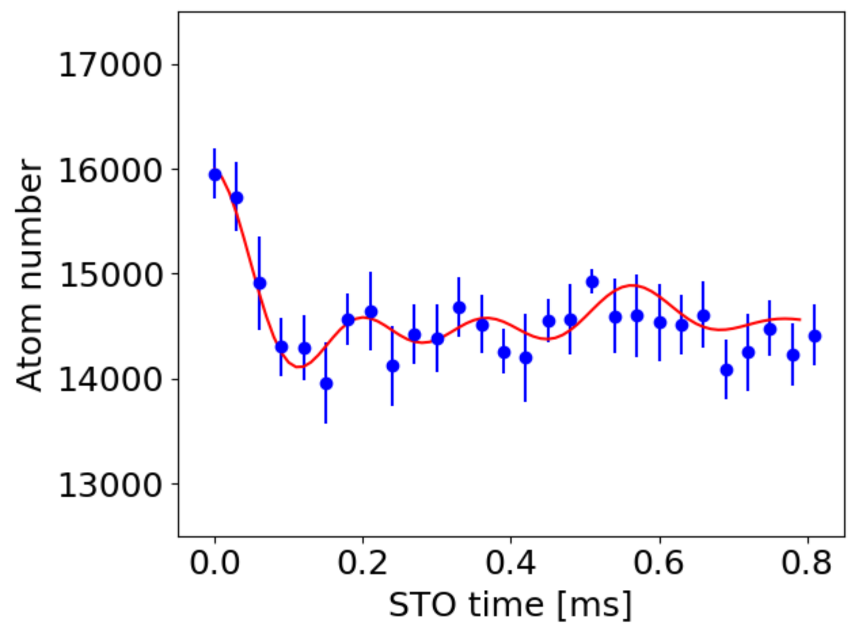


Antiferromagnetic



1.5 ms Dissipation

Ferromagnetic



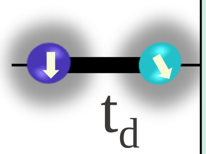
Quantum Magnetism
in an Open Dissipative Fermi Hubbard System

^{173}Yb : 1

N_{total} =

$^1S_0$ + $^3P_1$

association
Process



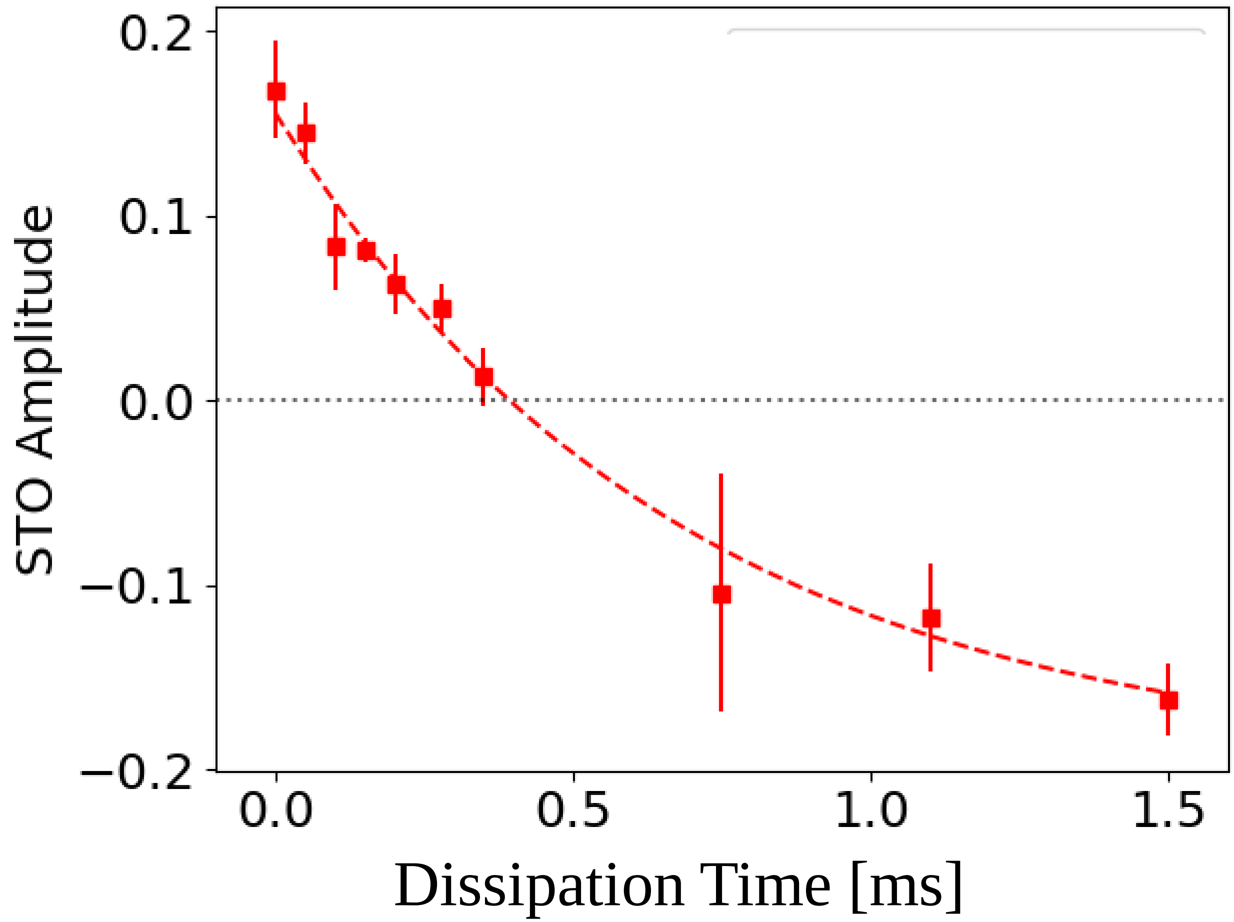
S_0 + $^1S_0$

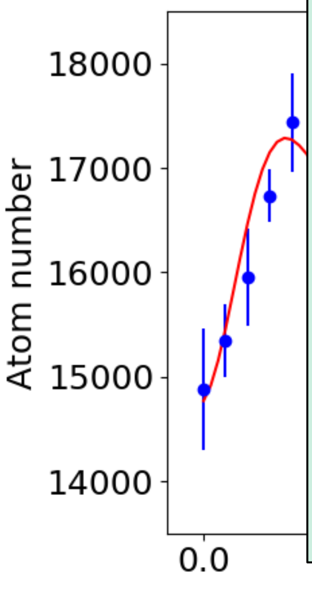
U/

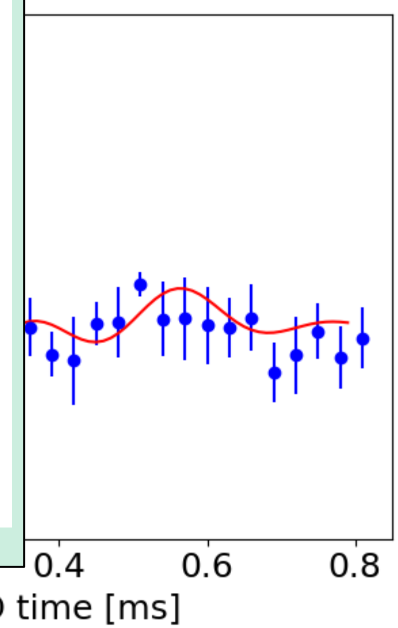
Ant

agnetic

Antiferromagnetic → Ferromagnetic

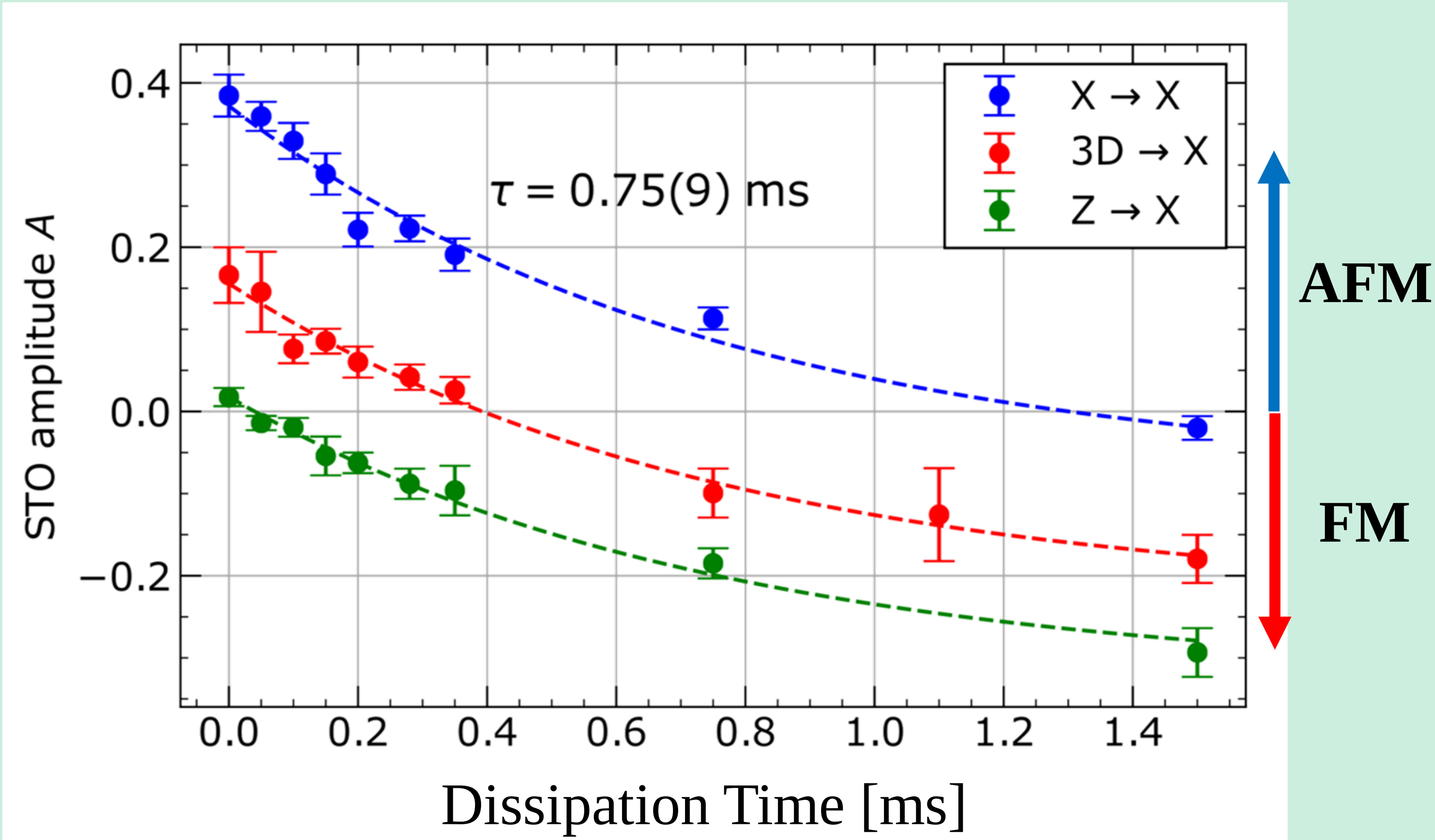






Quantum Magnetism
in an Open Dissipative Fermi Hubbard System

Antiferromagnetic → Ferromagnetic



Quantum Magnetism
in an Open Dissipative Fermi Hubbard System

^{173}Yb : $^{1}S_{0}$ state SU(6)

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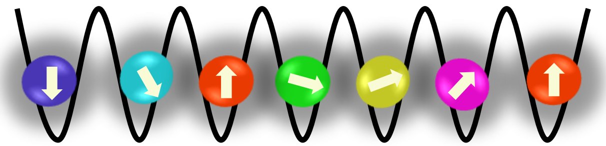
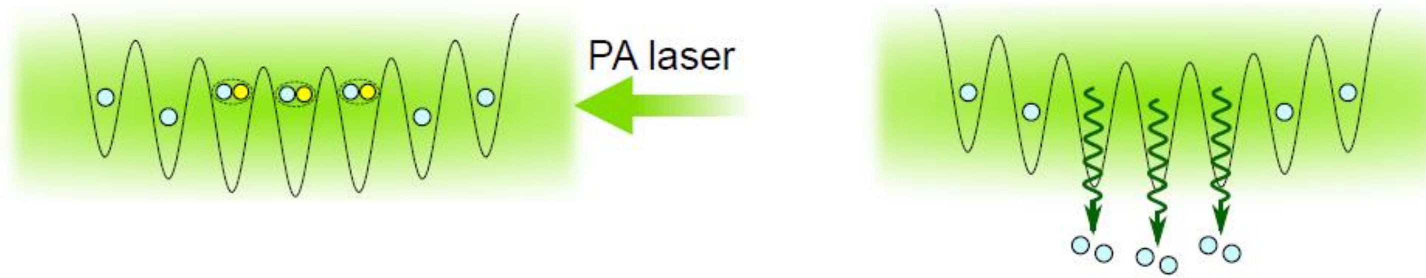


1D lattice

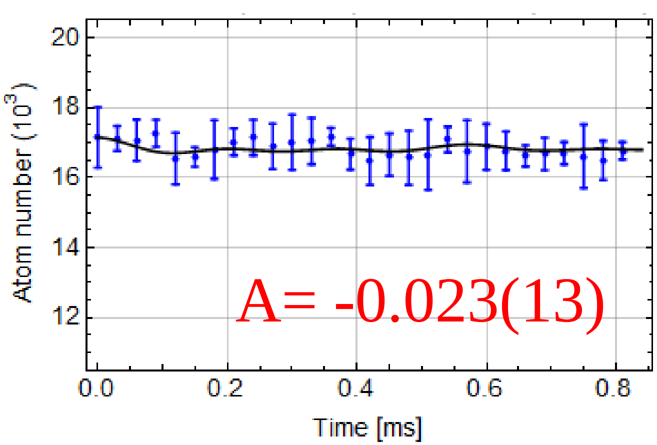
Photo-association(PA)
at -5763 MHz



preliminary

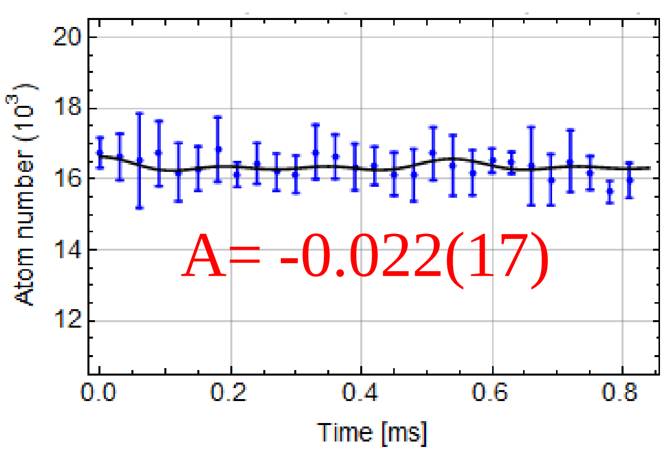
Ferromagnetic, indicating *Dicke state*

0.5 ms Dissipation



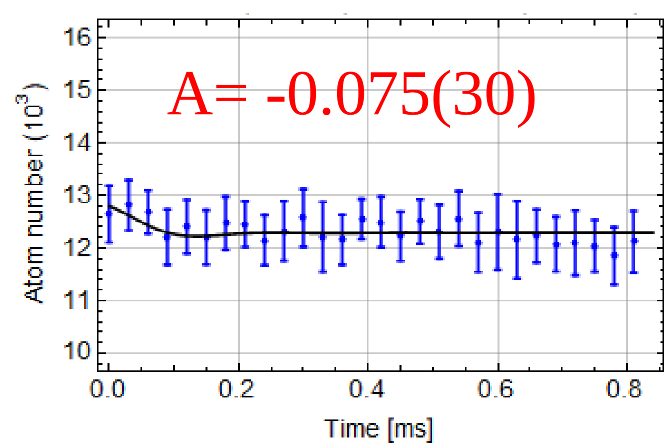
$2E_r$

1.5 ms Dissipation



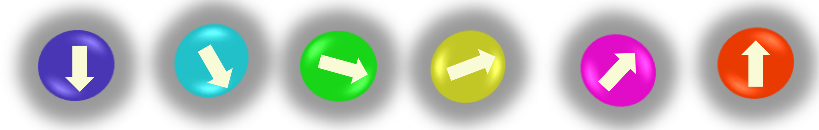
$4E_r$

2.0 ms Dissipation

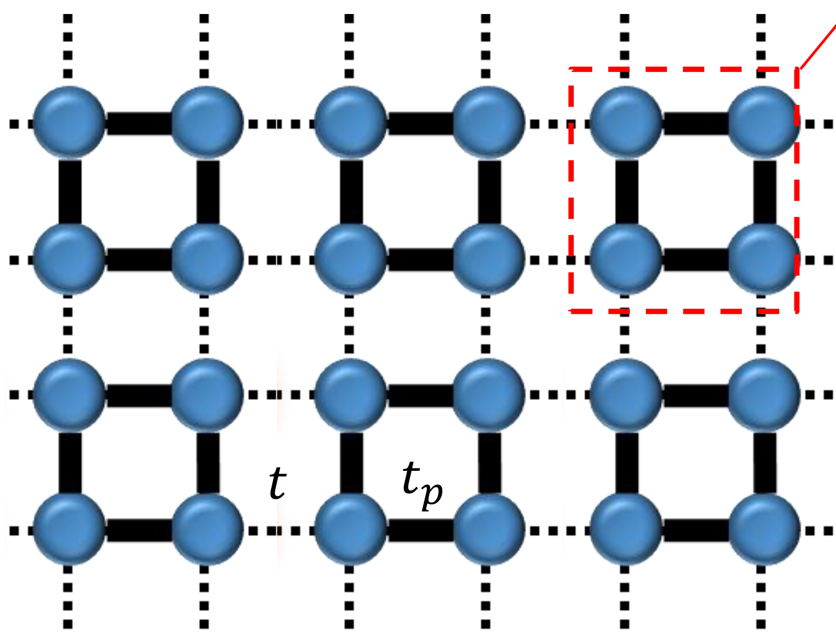


$4E_r$

Quantum Magnetism in a Plaquette Lattice

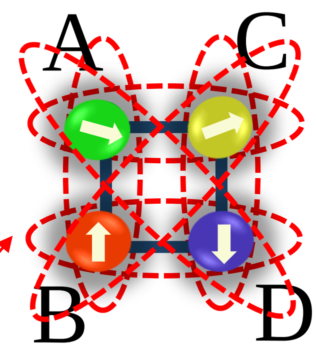
SU(N=6) Fermi gas 

isolated plaquette lattice



t/t_p = 0.043

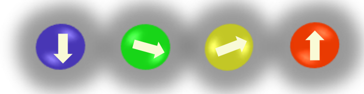
t/h = 43.7 Hz



SU(4)-singlet: $|SU(4)S\rangle$

$$= \frac{1}{\sqrt{24}} \sum_{\{ijkl\}} c^{\dagger}_{1i} c^{\dagger}_{2j} c^{\dagger}_{3k} c^{\dagger}_{4l} |0\rangle$$

i,j,k,l = A,B,C,D

1,2,3,4 = 

S. Sachdev, F. C. Zhang, C. Wu, …

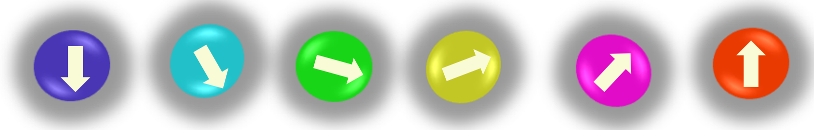
SU(4) in plaquette: SU(4)-singlet

$$|SU(4)S\rangle = \frac{1}{\sqrt{6}} \sum_{\{\sigma,\tau\}} |S^{AB}_{\mathrm{SU2}}(\sigma\tau), S^{CD}_{\mathrm{SU2}}(\overline{\sigma\tau})\rangle$$

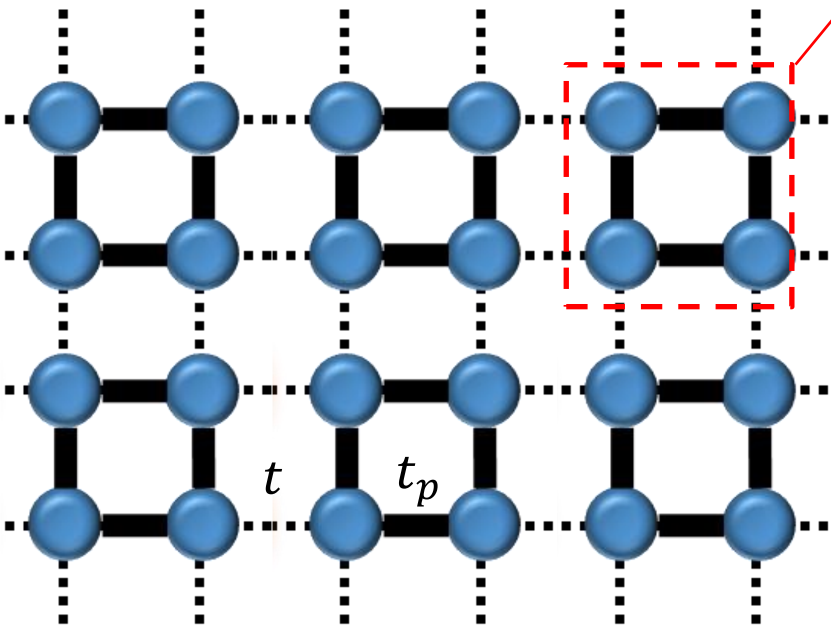
$$= \frac{1}{\sqrt{6}} \sum_{\{\sigma,\tau\}} |S^{AC}_{\mathrm{SU2}}(\sigma\tau), S^{BD}_{\mathrm{SU2}}(\overline{\sigma\tau})\rangle$$

Quantum Magnetism in a Plaquette Lattice

SU(N=6) Fermi gas



isolated plaquette lattice



$t/t_p = 0.043$

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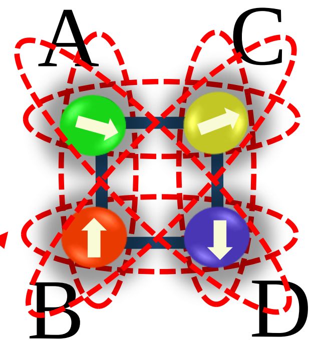

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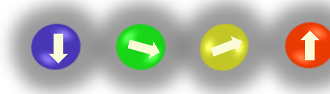
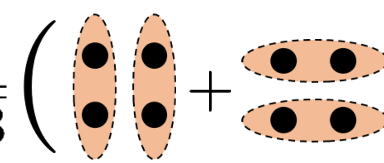
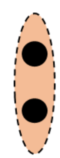
1,2,3,4 = 

S. Sachdev, F. C. Zhang, C. Wu, …

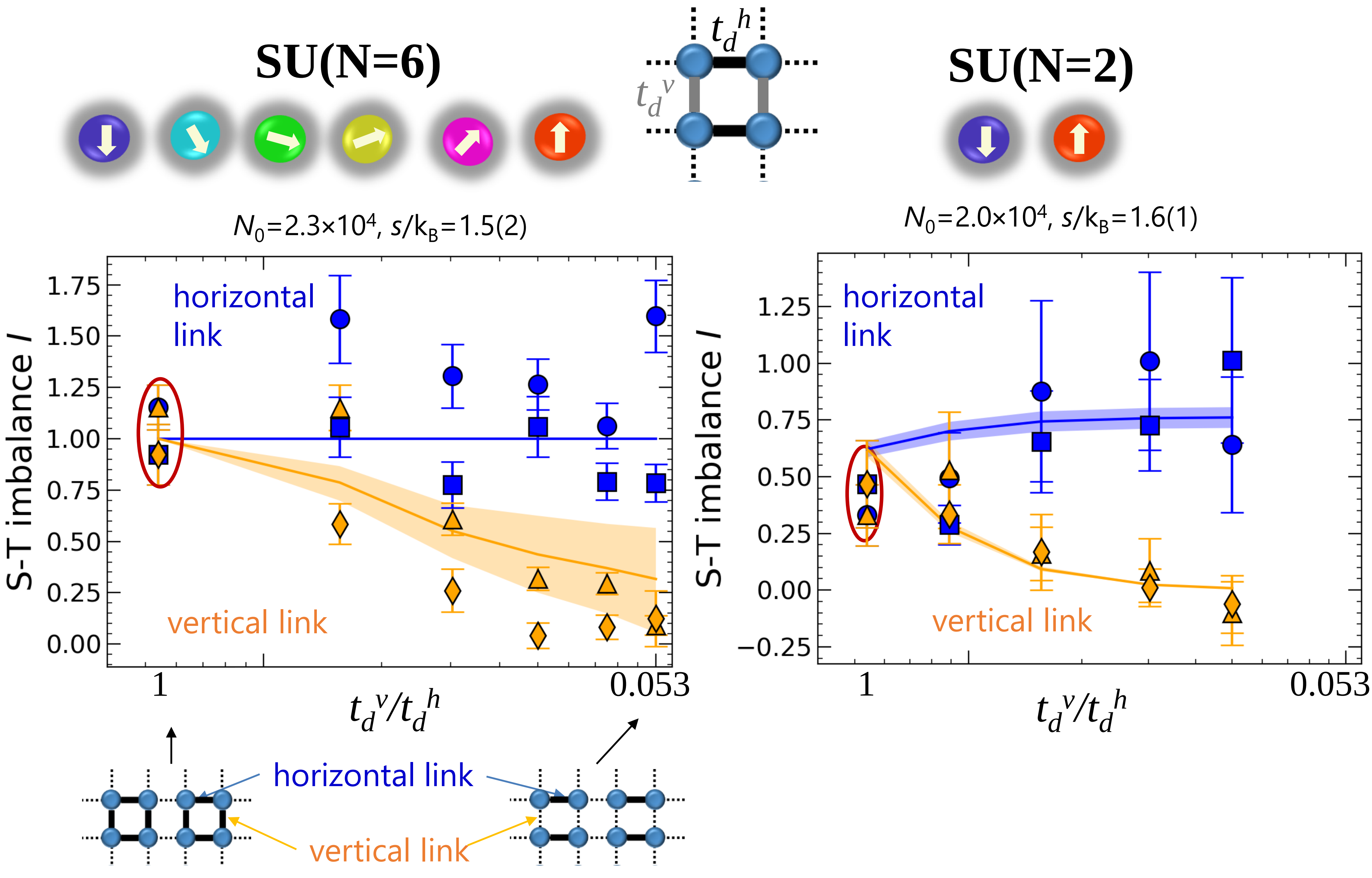
SU(2) in plaquette: s-wave RVB state

$|\mathrm{s-RVB}\rangle = \frac{1}{\sqrt{3}}\Big($  $\Big)$

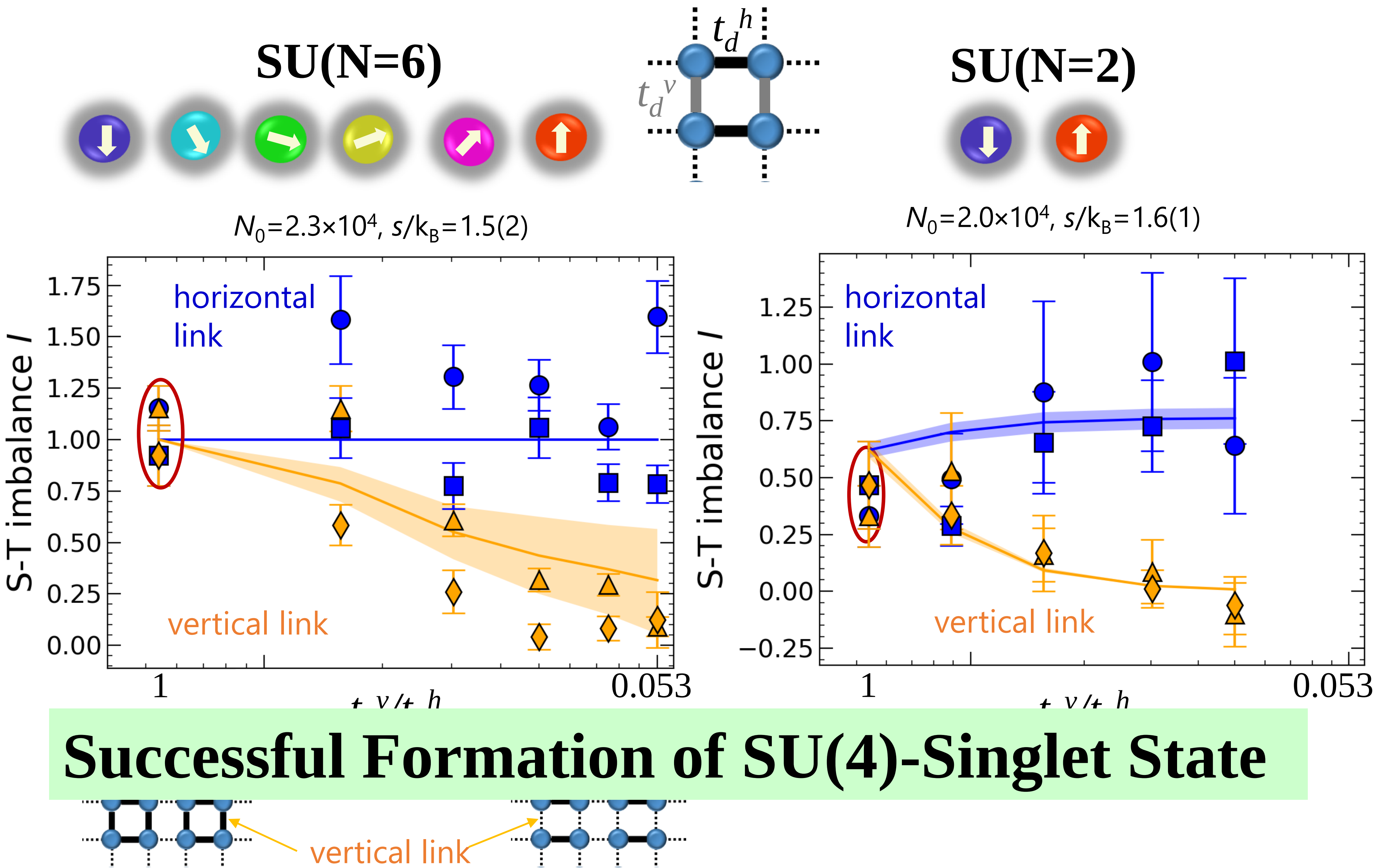
 $= \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$

$\rightarrow P_s = 3/4,\ P_{t0} = 1/12$

Quantum Magnetism in a Plaquette Lattice



Quantum Magnetism in a Plaquette Lattice



Successful Formation of SU(4)-Singlet State

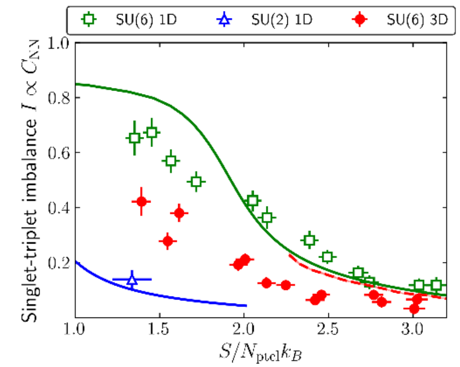
Summary

Spin correlation of SU(6) system for 1D, 2D, 3D lattices

agreement with SU(N) theoretical calculations

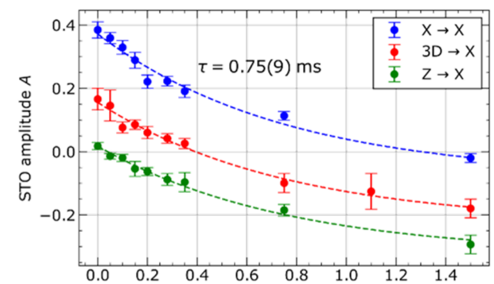
$\mathbf{k_B T_{lattice}/t = 0.096 \pm 0.054\ (cal.) \pm 0.030(exp.)}$

[S. Taie, *et al.*, arXiv:2010.07730]



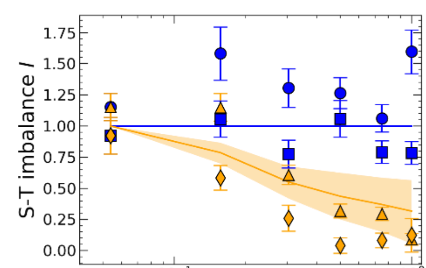
SU(6) quantum magnetism in open-dissipative system

transition from *antiferromagnetic*
to *ferromagnetic* spin correlations



SU(4)-singlet in a plaquette lattice

successful formation of SU(4)-singlet



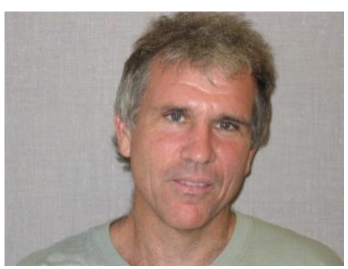
Development of Quantum Gas Microscope (^{173}Yb)

Quantum Optics Group @ Kyoto University

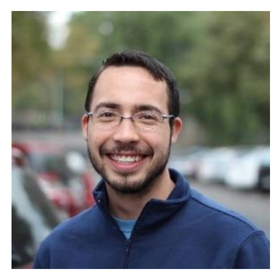
Former members: **N. Nishizawa** **Y. Kuno**

<u>SU(N) theory team</u>

K. Hazzard (Rice)



R. Scalettar (UC Davis)



E. Ibarra-García-Padilla (Rice)

Hao-Tian Wei (Fudan)

Thank you very much for attention

16 August   Mount Daimonji at Kyoto