Title: Research Talk

Speakers: Fakher Assaad

Collection: Quantum Criticality: Gauge Fields and Matter

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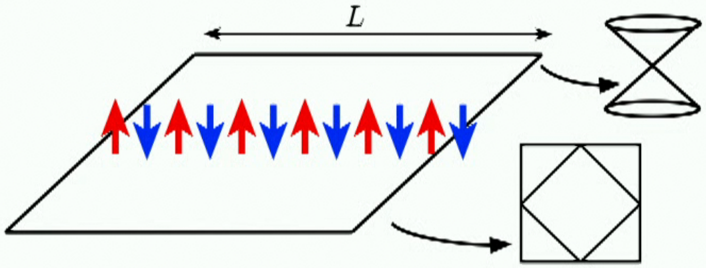
WÜRZBURG

Spin chains on metallic surfaces: Kondo destruction and magnetic order-disorder transitions

Fakher F. Assaad, Quantum Criticality: Gauge Fields and Matter, Perimeter ITP, 16th May 2022

Introduction Kondo systems. From experiments to models to field theories and quantum Monte Carlo simulations.

Topics



Kondo breakdown transitions and phases

Dissipation induced magnetic order-disorder transitions

Conclusions

DFG

SFB1170
ToCoTronics

FOR 1807

Center of excellence – complexity and topology in quantum matter

NIC

lrz Leibniz-Rechenzentrum
der Bayerischen Akademie der Wissenschaften

GCS
Gauss Centre for Supercomputing

TGCC

KONWIHR

Spin chains on metallic surfaces: Kondo destruction and magnetic order-disorder transitions

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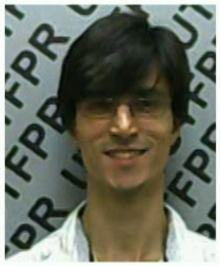
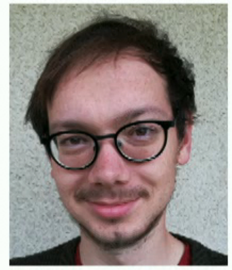
Many thanks to


M. Raczkowski


T. Sato

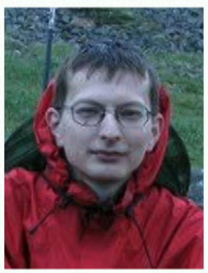

J. S.E. Portela


A. Götz


G. Rein


T. Grover


M. Vojta


M. Ulybyshev

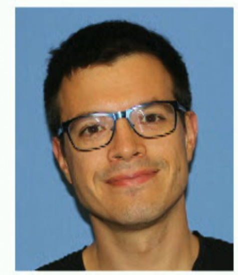

F. Parisen Toldin


J. Schwab

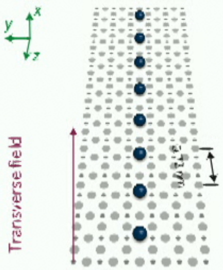

B. Danu


Z. Liu


M. Weber


D. Luitz

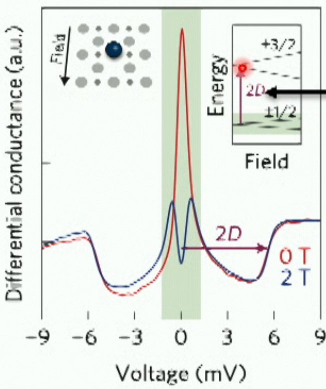
Kondo systems



Co atoms on Cu_2N/Cu(100) in magnetic field.

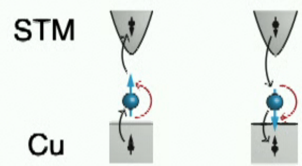
R. Toskovic, R. van den Berg, A. Spinelli, I. S. Eliens, B. van den Toorn, B. Bryant, J. S. Caux, and A. F. Otte, Nature Physics 12 (2016), 656

Single impurity limit

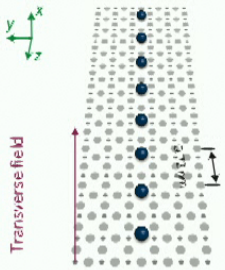


$D(S^z_{Co})^2$

Cu_2N decoupling layer, co-tunneling through Co-d orbital.



Kondo systems



Co atoms on $Cu_2N/Cu(100)$ in magnetic field.

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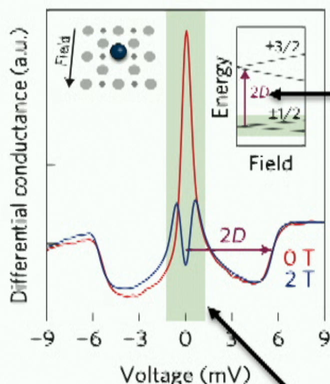

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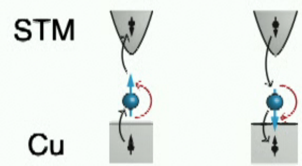
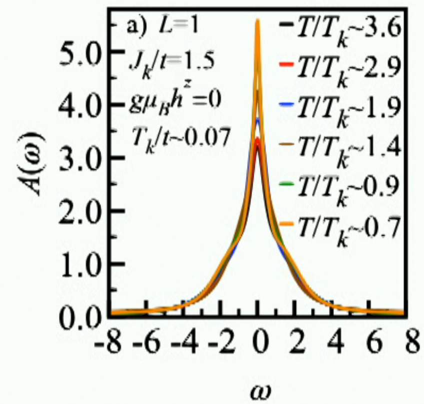




$T_k \sim 0.2$ meV

$\mu_B \sim 0.06$ meV/T

$$\hat{H} = -t\sum_{\langle \boldsymbol{i},\boldsymbol{j}\rangle}(\hat{\boldsymbol{c}}^\dagger_{\boldsymbol{i}}\hat{\boldsymbol{c}}_{\boldsymbol{j}} + h.c) + \frac{J_k}{2}\hat{\boldsymbol{c}}^\dagger_{\boldsymbol{r}=0}\boldsymbol{\sigma}\hat{\boldsymbol{c}}_{\boldsymbol{r}=0}\cdot\hat{\boldsymbol{S}} - g\mu_B h^{\boldsymbol{z}}\hat{S}^z$$

$$\hat{\boldsymbol{c}}^\dagger_{\boldsymbol{i}} = \left(\hat{c}^\dagger_{\boldsymbol{i},\uparrow}, \hat{c}^\dagger_{\boldsymbol{i},\downarrow}\right)$$

$$A(\omega) = -\mathrm{Im}G^{\mathrm{ret}}(\omega), \quad G^{\mathrm{ret}}(\omega) = -i\int_0^\infty dt e^{i\omega t}\sum_\sigma \langle\{\hat{\psi}_\sigma(t), \hat{\psi}^\dagger_\sigma(0)\}\rangle$$

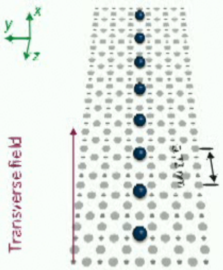
$$\hat{\boldsymbol{\psi}}^\dagger = e^{-S}\hat{\boldsymbol{d}}^\dagger e^S = \hat{\boldsymbol{c}}^\dagger_{\boldsymbol{r}=0}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{S}}$$

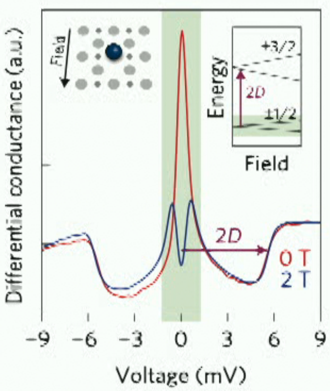
(S: Schrieffer Wolff transformation)

T.A. Costi, Phys. Rev. Lett. 85, 1504 (2000).

Kondo systems

Chain of impurities

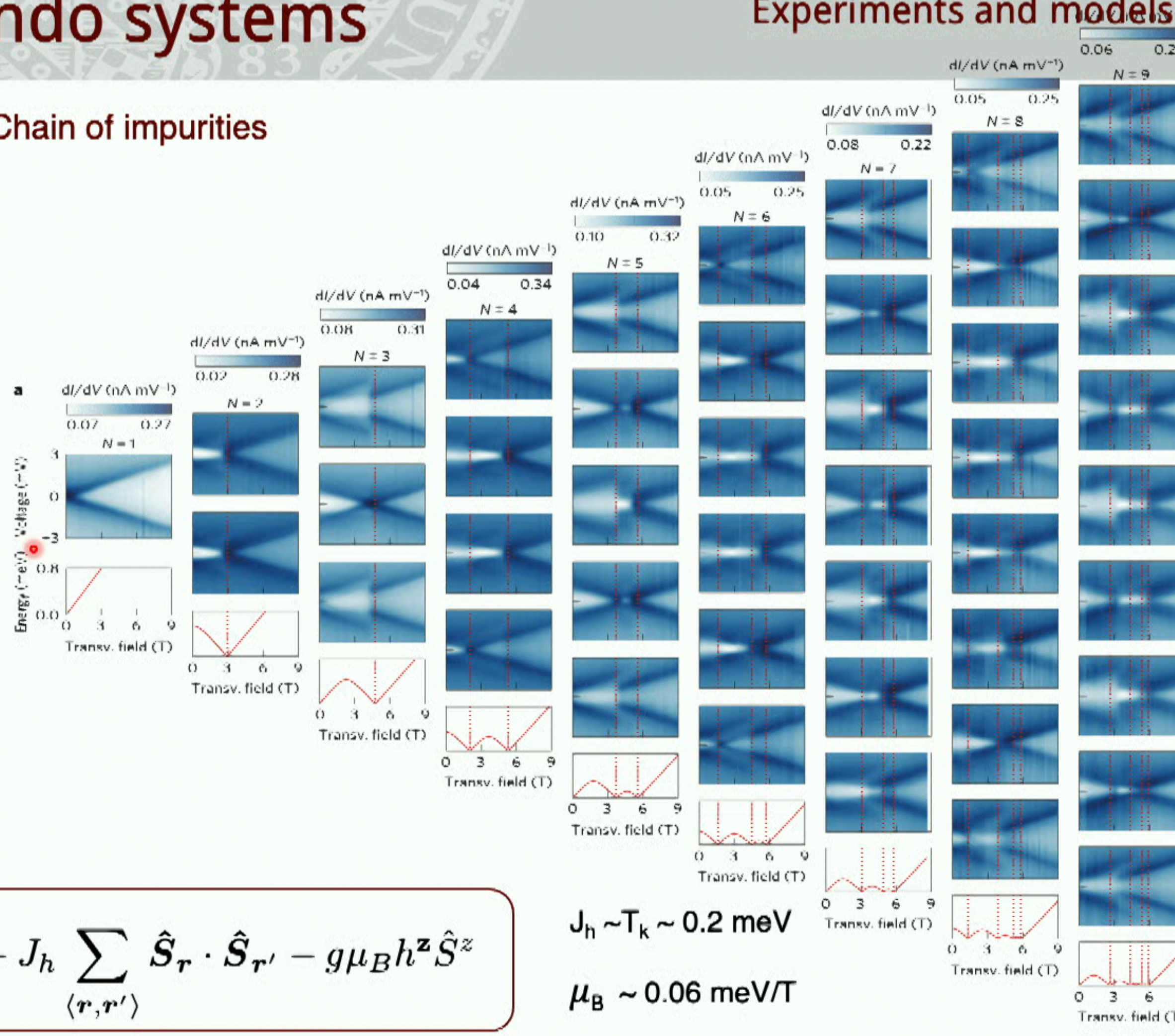




Site dependent

field induced

"Kondo resonance"



$$\hat{H} = -t\sum_{\langle i,j\rangle}(\hat{c}_i^\dagger \hat{c}_j + h.c) + \frac{J_k}{2}\sum_{r}\hat{c}_r^\dagger \boldsymbol{\sigma}\hat{c}_r \cdot \hat{\boldsymbol{S}}_r + J_h\sum_{\langle r,r'\rangle}\hat{\boldsymbol{S}}_r \cdot \hat{\boldsymbol{S}}_{r'} - g\mu_B h^{\mathbf{z}}\hat{S}^z$$

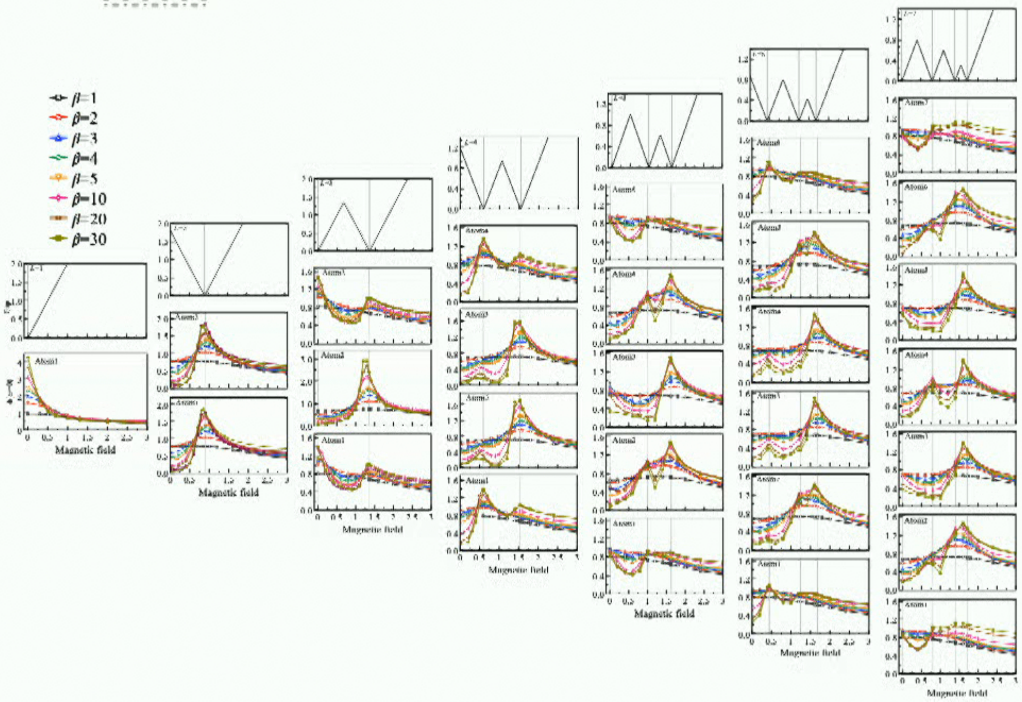
$J_h \sim T_k \sim 0.2$ meV

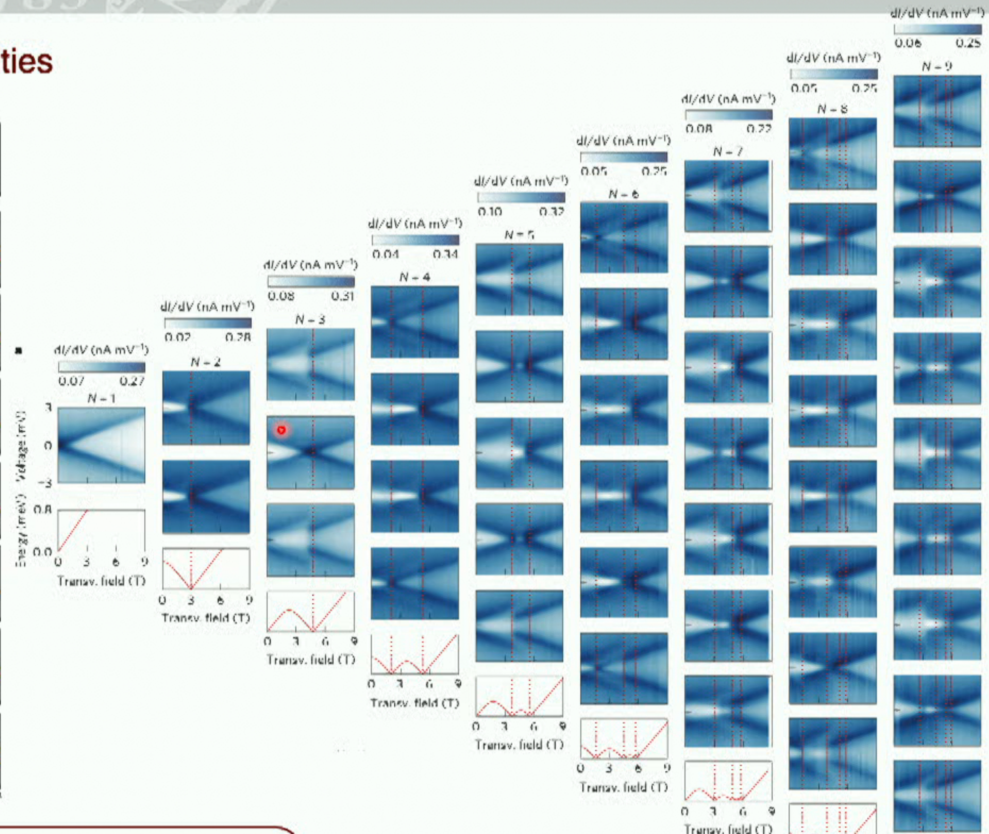
$\mu_B \sim 0.06$ meV/T

Kondo systems

Experiments and models

Chain of impurities





$$\hat{H} = -t\sum_{\langle i,j\rangle}(\hat{c}_i^\dagger \hat{c}_j + h.c) + \frac{J_k}{2}\sum_{r}\hat{c}_r^\dagger \sigma \hat{c}_r \cdot \hat{S}_r + J_h \sum_{\langle r,r'\rangle}\hat{S}_r \cdot \hat{S}_{r'} - g\mu_B h^z \hat{S}^z$$

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Kondo systems

Experiments and models

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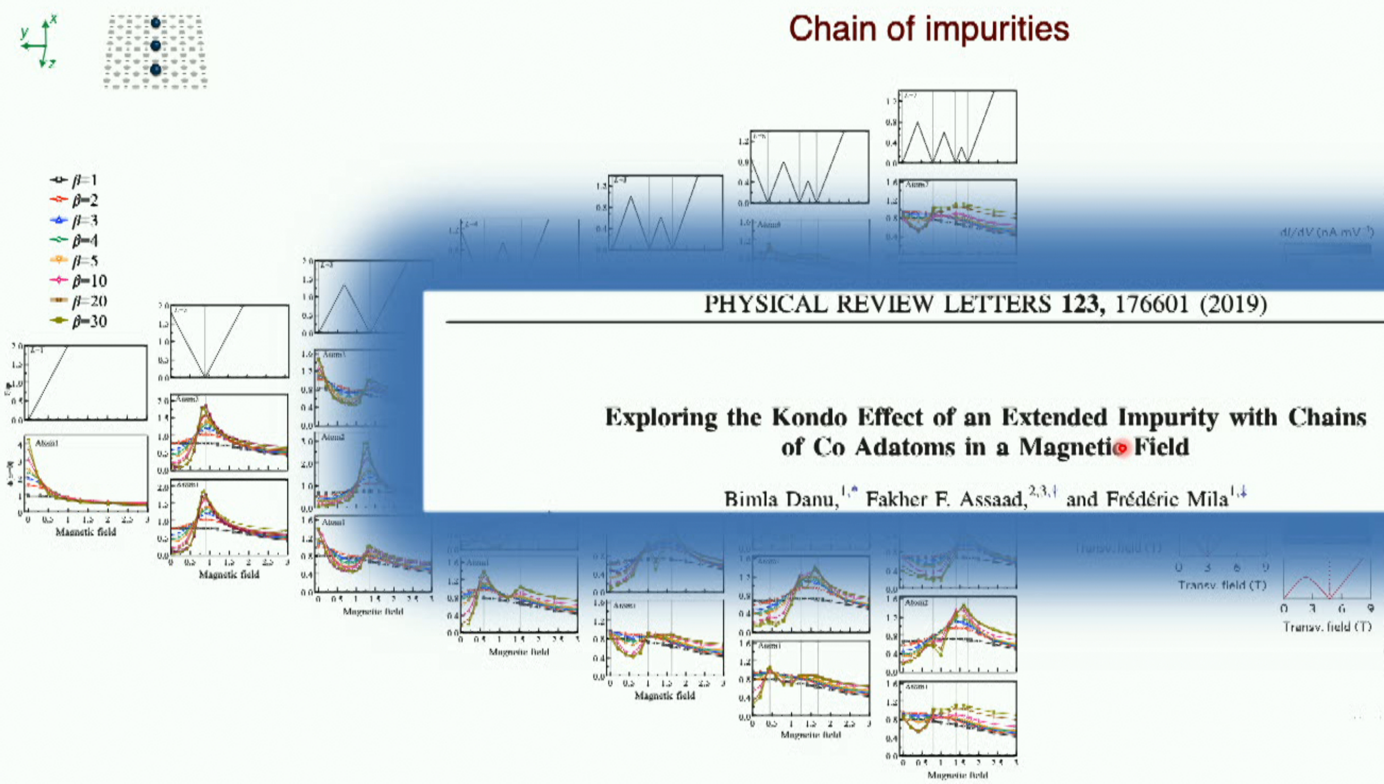
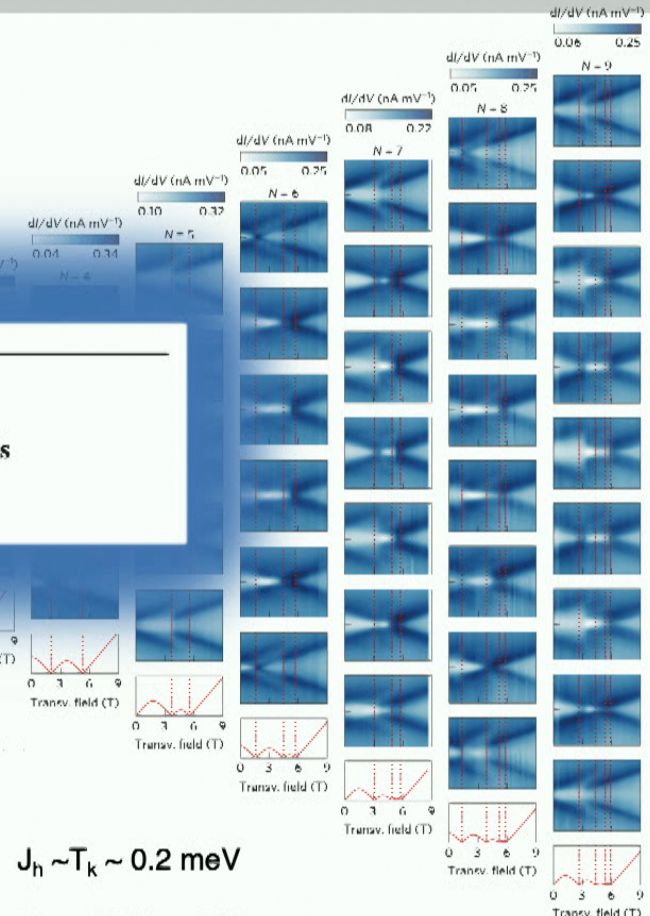




PHYSICAL REVIEW LETTERS 123, 176601 (2019)

Exploring the Kondo Effect of an Extended Impurity with Chains of Co Adatoms in a Magnetic Field

Bimla Danu,[1,*] Fakher F. Assaad,[2,3,†] and Frédéric Mila[1,‡]

$$\hat{H} = -t\sum_{\langle i,j\rangle}(\hat{c}_i^\dagger \hat{c}_j + h.c) + \frac{J_k}{2}\sum_{r}\hat{c}_r^\dagger \boldsymbol{\sigma}\hat{c}_r\cdot\hat{S}_r + J_h\sum_{\langle r,r'\rangle}\hat{S}_r\cdot\hat{S}_{r'} - g\mu_B h^z \hat{S}^z$$

$J_h \sim T_k \sim 0.2$ meV

$\mu_B \sim 0.06$ meV/T

Kondo systems

$$\hat{H} = -t\sum_{\langle \boldsymbol{i},\boldsymbol{j}\rangle}(\hat{\boldsymbol{c}}_{\boldsymbol{i}}^{\dagger}\hat{\boldsymbol{c}}_{\boldsymbol{j}} + h.c) + \frac{J_k}{2}\sum_{\boldsymbol{r}}\hat{\boldsymbol{c}}_{\boldsymbol{r}}^{\dagger}\boldsymbol{\sigma}\hat{\boldsymbol{c}}_{\boldsymbol{r}}\cdot\hat{\boldsymbol{S}}_{\boldsymbol{r}} + J_h\sum_{\langle \boldsymbol{r},\boldsymbol{r}'\rangle}\hat{\boldsymbol{S}}_{\boldsymbol{r}}\cdot\hat{\boldsymbol{S}}_{\boldsymbol{r}'}$$

<u>Question:</u> Field theory for i) Numerical simulations

ii) Classification of phases

Kondo systems

$$\hat{H} = -t \sum_{\langle \boldsymbol{i},\boldsymbol{j} \rangle} (\hat{\boldsymbol{c}}_{\boldsymbol{i}}^{\dagger} \hat{\boldsymbol{c}}_{\boldsymbol{j}} + h.c) + \frac{J_k}{2} \sum_{\boldsymbol{r}} \hat{\boldsymbol{c}}_{\boldsymbol{r}}^{\dagger} \boldsymbol{\sigma} \hat{\boldsymbol{c}}_{\boldsymbol{r}} \cdot \hat{\boldsymbol{S}}_{\boldsymbol{r}} + J_h \sum_{\langle \boldsymbol{r},\boldsymbol{r}' \rangle} \hat{\boldsymbol{S}}_{\boldsymbol{r}} \cdot \hat{\boldsymbol{S}}_{\boldsymbol{r}'}$$

Field theory: $\hat{\boldsymbol{S}}_{\boldsymbol{r}} = \frac{1}{2} \hat{\boldsymbol{f}}_{\boldsymbol{r}}^{\dagger} \boldsymbol{\sigma} \hat{\boldsymbol{f}}_{\boldsymbol{r}}$ with constraint $\hat{\boldsymbol{f}}_{\boldsymbol{r}}^{\dagger} \hat{\boldsymbol{f}}_{\boldsymbol{r}} = 1$ Def $\hat{\boldsymbol{f}}_{\boldsymbol{r}}^{\dagger} = \left(\hat{f}_{\boldsymbol{r},\uparrow}^{\dagger}, \hat{f}_{\boldsymbol{r},\downarrow}^{\dagger} \right)$

$$\hat{H} = -t \sum_{\langle \boldsymbol{i},\boldsymbol{j} \rangle} (\hat{\boldsymbol{c}}_{\boldsymbol{i}}^{\dagger} \hat{\boldsymbol{c}}_{\boldsymbol{j}} + h.c) \quad - \frac{J_k}{8} \sum_{\boldsymbol{r}} \left[\left(\hat{V}_{\boldsymbol{r}} + \hat{V}_{\boldsymbol{r}}^{\dagger} \right)^2 + \left(i\hat{V}_{\boldsymbol{r}} - i\hat{V}_{\boldsymbol{r}}^{\dagger} \right)^2 \right]$$

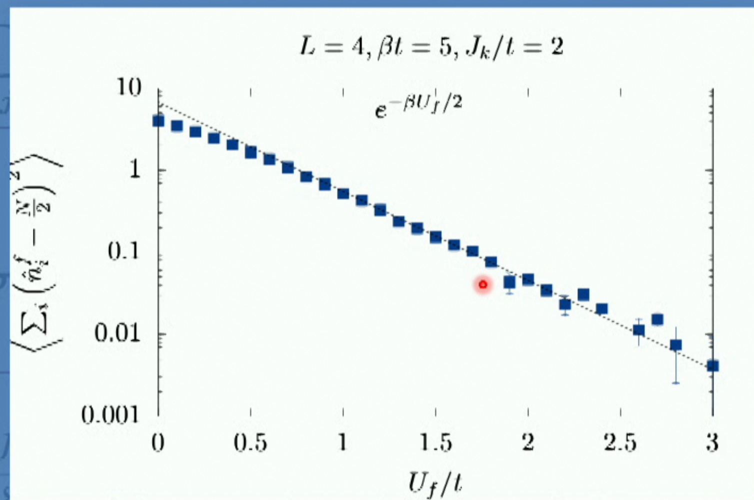
$$- \frac{J_h}{8} \sum_{b=\langle \boldsymbol{r},\boldsymbol{r}' \rangle} \left[\left(\hat{D}_b + \hat{D}_b^{\dagger} \right)^2 + \left(i\hat{D}_b - i\hat{D}_b^{\dagger} \right)^2 \right] + \underbrace{U \sum_{\boldsymbol{r}} \left(\hat{\boldsymbol{f}}_{\boldsymbol{r}}^{\dagger} \hat{\boldsymbol{f}}_{\boldsymbol{r}} - 1 \right)^2}_{= \hat{H}_U}$$

$$\hat{D}_b = \hat{\boldsymbol{f}}_{\boldsymbol{r}}^{\dagger} \hat{\boldsymbol{f}}_{\boldsymbol{r}'}, \quad \hat{V}_{\boldsymbol{r}} = \hat{\boldsymbol{f}}_{\boldsymbol{r}}^{\dagger} \hat{\boldsymbol{c}}_{\boldsymbol{r}}$$

Exact in the limit $U \to \infty$. But since $\left[\hat{H}_U, \hat{H} \right] = 0$ the constraint is imposed very efficiently.

Kondo systems

$\hat{H} = -t \sum_{\langle i,j \rangle}$ ... $\hat{S}_{r} \cdot \hat{S}_{r'}$



Field theory: $\hat{S}_{r} = \frac{1}{2}\hat{f}^{\dagger}_{r}\sigma$ ... Def $\hat{f}^{\dagger}_{r} = \left(\hat{f}^{\dagger}_{r,\uparrow}, \hat{f}^{\dagger}_{r,\downarrow}\right)$

$$\hat{H} = -t \sum_{\langle i,j \rangle} (\hat{c}^{\dagger}_{i}\hat{c}_{j} + h.c) \quad - \frac{J}{8} \sum_{r} \left[\ldots \right]$$

$$- \frac{J_h}{8} \sum_{b=\langle r,r' \rangle} \left[\left(\hat{D}_b + \hat{D}^{\dagger}_b\right)^2 + \left(i\hat{D}_b - i\hat{D}^{\dagger}_b\right)^2 \right] + \underbrace{U \sum_{r} \left(\hat{f}^{\dagger}_{r}\hat{f}_{r} - 1\right)^2}_{= \hat{H}_U}$$

$\hat{D}_b = \hat{f}^{\dagger}_{r}\hat{f}_{r'}, \quad \hat{V}_r = \hat{f}^{\dagger}_{r}\hat{c}_{r}$

Exact in the limit $U \to \infty$. But since $\left[\hat{H}_U, \hat{H}\right] = 0$ the constraint is imposed very efficiently.

Kondo systems

$$b_{\boldsymbol{r}} = |b_{\boldsymbol{r}}|e^{i\varphi_{\boldsymbol{r}}}$$

$$\hat{H} = -t\sum_{\langle \boldsymbol{i},\boldsymbol{j}\rangle}(\hat{\boldsymbol{c}}_{\boldsymbol{i}}^{\dagger}\hat{\boldsymbol{c}}_{\boldsymbol{j}} + h.c) \qquad -\frac{J_k}{8}\sum_{\boldsymbol{r}}\left[\left(\hat{V}_{\boldsymbol{r}} + \hat{V}_{\boldsymbol{r}}^{\dagger}\right)^2 + \left(i\hat{V}_{\boldsymbol{r}} - i\hat{V}_{\boldsymbol{r}}^{\dagger}\right)^2\right]$$

$$-\frac{J_h}{8}\sum_{b=\langle \boldsymbol{r},\boldsymbol{r}'\rangle}\left[\left(\hat{D}_b + \hat{D}_b^{\dagger}\right)^2 + \left(i\hat{D}_b - i\hat{D}_b^{\dagger}\right)^2\right] + U\sum_{\boldsymbol{r}}\left(\hat{\boldsymbol{f}}_{\boldsymbol{r}}^{\dagger}\hat{\boldsymbol{f}}_{\boldsymbol{r}} - 1\right)^2$$

$$\hat{D}_b = \hat{\boldsymbol{f}}_{\boldsymbol{r}}^{\dagger}\hat{\boldsymbol{f}}_{\boldsymbol{r}'}, \quad \hat{V}_{\boldsymbol{r}} = \hat{\boldsymbol{f}}_{\boldsymbol{r}}^{\dagger}\hat{\boldsymbol{c}}_{\boldsymbol{r}} \qquad \chi_b = |\chi_b|e^{i\int_{\boldsymbol{r}}^{\boldsymbol{r}'}\boldsymbol{a}\cdot d\boldsymbol{l}} \qquad a_0$$

Partition function, $Z \equiv \mathrm{Tr}\, e^{-\beta\hat{H}} = \int D\{f^{\dagger}f\}\, D\{c^{\dagger}c\}\, D\{z_b\}\, D\{b_{\boldsymbol{r}}\}\, D\{a_{0,\boldsymbol{r}}\}\, e^{-S}$ with, for $U \to \infty$

$$S = \int_0^{\beta} d\tau \quad \Bigg\{\frac{2}{J_h}\sum_b |\chi_b(\tau)|^2 + \frac{2}{J_k}\sum_{\boldsymbol{r}}|b_{\boldsymbol{r}}(\tau)|^2 + \sum_{\boldsymbol{i},\boldsymbol{j}}\boldsymbol{c}_{\boldsymbol{i}}^{\dagger}(\tau)\left[\partial_\tau\delta_{\boldsymbol{i},\boldsymbol{j}} - T_{\boldsymbol{i},\boldsymbol{j}}\right]\boldsymbol{c}_{\boldsymbol{j}}(\tau)$$

$$+\sum_{\boldsymbol{r}}|b_{\boldsymbol{r}}(\tau)|\left[e^{i\varphi_{\boldsymbol{r}}(\tau)}\boldsymbol{f}_{\boldsymbol{r}}^{\dagger}(\tau)\boldsymbol{c}_{\boldsymbol{r}}(\tau) + h.c.\right]$$

$$+\sum_{\boldsymbol{r}}\boldsymbol{f}_{\boldsymbol{r}}^{\dagger}(\tau)\left[\partial_\tau - ia_{0,\boldsymbol{r}}(\tau)\right]\boldsymbol{f}_{\boldsymbol{r}}(\tau) + ia_{0,\boldsymbol{r}}(\tau) + \sum_{b=\langle \boldsymbol{r},\boldsymbol{r}'\rangle}|\chi_b(\tau)|\left[\boldsymbol{f}_{\boldsymbol{r}}^{\dagger}(\tau)e^{-i\int_{\boldsymbol{r}}^{\boldsymbol{r}'}\boldsymbol{a}(\boldsymbol{l},\tau)d\boldsymbol{l}}\boldsymbol{f}_{\boldsymbol{r}'}(\tau) + h.c.\right]$$

Kondo systems

$$S = \int_0^\beta d\tau \quad \Big\{ \frac{2}{J_h} \sum_b |\chi_b(\tau)|^2 + \frac{2}{J_k} \sum_{\boldsymbol{r}} |b_{\boldsymbol{r}}(\tau)|^2 + \sum_{\boldsymbol{i},\boldsymbol{j}} \boldsymbol{c}_{\boldsymbol{i}}^\dagger(\tau) \left[\partial_\tau \delta_{\boldsymbol{i},\boldsymbol{j}} - T_{\boldsymbol{i},\boldsymbol{j}} \right] \boldsymbol{c}_{\boldsymbol{j}}(\tau)$$

$$+ \sum_{\boldsymbol{r}} |b_{\boldsymbol{r}}(\tau)| \left[e^{i\varphi_{\boldsymbol{r}}(\tau)} \boldsymbol{f}_{\boldsymbol{r}}^\dagger(\tau) \boldsymbol{c}_{\boldsymbol{r}}(\tau) + h.c. \right]$$

$$+ \sum_{\boldsymbol{r}} \boldsymbol{f}_{\boldsymbol{r}}^\dagger(\tau) \left[\partial_\tau - i a_{0,\boldsymbol{r}}(\tau) \right] \boldsymbol{f}_{\boldsymbol{r}}(\tau) + i a_{0,\boldsymbol{r}}(\tau) + \sum_{b=\langle \boldsymbol{r},\boldsymbol{r}' \rangle} |\chi_b(\tau)| \left[\boldsymbol{f}_{\boldsymbol{r}}^\dagger(\tau) e^{-i\int_{\boldsymbol{r}}^{\boldsymbol{r}'} \boldsymbol{a}(\boldsymbol{l},\tau) d\boldsymbol{l}} \boldsymbol{f}_{\boldsymbol{r}'}(\tau) + h.c. \right]$$

Local U(1) gauge invariance: $\boldsymbol{f}_{\boldsymbol{r}}^\dagger(\tau) \rightarrow \boldsymbol{f}_{\boldsymbol{r}}^\dagger(\tau) e^{i\eta_{\boldsymbol{r}}(\tau)}$

$$\begin{bmatrix} a_{0,\boldsymbol{r}}(\tau) & \rightarrow a_{0,\boldsymbol{r}}(\tau) + \partial_\tau \eta_{\boldsymbol{r}}(\tau) \\ \boldsymbol{a}_{\boldsymbol{r}}(\tau) & \rightarrow \boldsymbol{a}_{\boldsymbol{r}}(\tau) + \boldsymbol{\nabla}_{\boldsymbol{r}} \eta_{\boldsymbol{r}}(\tau) \\ \varphi_{\boldsymbol{r}}(\tau) & \rightarrow \varphi_{\boldsymbol{r}}(\tau) + \eta_{\boldsymbol{r}}(\tau) \end{bmatrix}$$

Other symmetry allowed terms, such as U(1) flux, and dynamics of the b-field, will be dynamically generated.

Kondo systems

$$S = \int_0^\beta d\tau \quad \Big\{ \frac{2}{J_h} \sum_b |\chi_b(\tau)|^2 + \frac{2}{J_k} \sum_{\boldsymbol{r}} |b_{\boldsymbol{r}}(\tau)|^2 + \sum_{\boldsymbol{i},\boldsymbol{j}} \boldsymbol{c}^\dagger_{\boldsymbol{i}}(\tau) \left[\partial_\tau \delta_{\boldsymbol{i},\boldsymbol{j}} - T_{\boldsymbol{i},\boldsymbol{j}} \right] \boldsymbol{c}_{\boldsymbol{j}}(\tau)$$

$$+ \sum_{\boldsymbol{r}} |b_{\boldsymbol{r}}(\tau)| \left[e^{i\varphi_{\boldsymbol{r}}(\tau)} \boldsymbol{f}^\dagger_{\boldsymbol{r}}(\tau) \boldsymbol{c}_{\boldsymbol{r}}(\tau) + h.c. \right]$$

$$+ \sum_{\boldsymbol{r}} \boldsymbol{f}^\dagger_{\boldsymbol{r}}(\tau) \left[\partial_\tau - i a_{0,\boldsymbol{r}}(\tau) \right] \boldsymbol{f}_{\boldsymbol{r}}(\tau) + i a_{0,\boldsymbol{r}}(\tau) + \sum_{b=\langle \boldsymbol{r},\boldsymbol{r}' \rangle} |\chi_b(\tau)| \left[\boldsymbol{f}^\dagger_{\boldsymbol{r}}(\tau) e^{-i\int_{\boldsymbol{r}}^{\boldsymbol{r}'} \boldsymbol{a}(\boldsymbol{l},\tau) d\boldsymbol{l}} \boldsymbol{f}_{\boldsymbol{r}'}(\tau) + h.c. \right]$$

Numerical simulations

$$Z \equiv \mathrm{Tr}\, e^{-\beta \hat{H}} = \int D\left\{ f^\dagger f \right\} D\left\{ c^\dagger c \right\} D\left\{ z_b \right\} D\left\{ b_{\boldsymbol{r}} \right\} D\left\{ a_0 \right\} e^{-S} = \int D\left\{ z_b, b_{\boldsymbol{r}}, a_0 \right\} e^{-(S_0 - \log \det M)}$$

For our specific case, the action is real ! → No sign problem. Absence of sign problem is shown on the basis of symmetry arguments.
(T. Sato, FFA, and T. Grover, Phys. Rev. Lett. 120 (2018), 107201)

The integration over the fields is carried out with Monte Carlo importance sampling.

Algorithms for Lattice fermions @ http://alf.physik.uni-wuerzburg.de/

ALF 1.0: SciPost Phys. 3 (2017), 013 ALF 2.0 https://arxiv.org/abs/2012.11914

Kinetic

Potential (sum of perfect squares)

$$\hat{H} = \sum_{k=1}^{M_T}\sum_{\sigma=1}^{N_{\rm col}}\sum_{s=1}^{N_{\rm fl}}\sum_{x,y}^{N_{\rm dim}} \hat{c}^{\dagger}_{x\sigma s} T^{(ks)}_{xy} \hat{c}_{y\sigma s} + \sum_{k=1}^{M_V} U_k \left\{ \sum_{\sigma=1}^{N_{\rm col}}\sum_{s=1}^{N_{\rm fl}} \left[\left(\sum_{x,y}^{N_{\rm dim}} \hat{c}^{\dagger}_{x\sigma s} V^{(ks)}_{xy} \hat{c}_{y\sigma s} \right) + \alpha_{ks} \right] \right\}^2$$

Coupling of fermions to bosonic fields with predefined dynamics

$$+ \sum_{k=1}^{M_I} \hat{Z}_k \left(\sum_{\sigma=1}^{N_{\rm col}}\sum_{s=1}^{N_{\rm fl}}\sum_{x,y}^{N_{\rm dim}} \hat{c}^{\dagger}_{x\sigma s} I^{(ks)}_{xy} \hat{c}_{y\sigma s} \right) + \hat{H}_{\rm Ising}$$

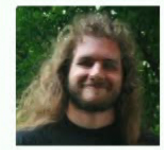
- Block diagonal in flavors, $N_{\rm fl}$
- SU($N_{\rm col}$) symmetric in colors $N_{\rm col}$
- Arbitrary Bravais lattice for d=1,2
- Model can be specified at minimal programming cost
- Fortran 2003 standard
- MPI implementation
- Global and local moves, Parallel tempering, Langevin
- Projective and finite T approaches
- pyALF: easy access python interface
- Predefined models


F. Goth

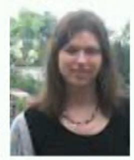

M. Bercx


J. Hoffmann

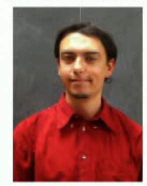

J. S.E. Portela


J. Schwab


Z. Liu


E. Huffman


A. Götz


F. Parisen Toldin

DFG Wissenschaftliche Literaturversorgungs und Informationssysteme (LIS)

KONWIHR

Kondo systems

$$S = \int_0^\beta d\tau \left\{ \frac{2}{J_h} \sum_b |\chi_b(\tau)|^2 + \frac{2}{J_k} \sum_{\boldsymbol{r}} |b_{\boldsymbol{r}}(\tau)|^2 + \sum_{\boldsymbol{i},\boldsymbol{j}} \boldsymbol{c}_{\boldsymbol{i}}^\dagger(\tau) \left[\partial_\tau \delta_{\boldsymbol{i},\boldsymbol{j}} - T_{\boldsymbol{i},\boldsymbol{j}}\right] \boldsymbol{c}_{\boldsymbol{j}}(\tau) \right.$$
$$+ \sum_{\boldsymbol{r}} |b_{\boldsymbol{r}}(\tau)| \left[e^{i\varphi_{\boldsymbol{r}}(\tau)} \boldsymbol{f}_{\boldsymbol{r}}^\dagger(\tau) \boldsymbol{c}_{\boldsymbol{r}}(\tau) + h.c. \right]$$
$$+ \sum_{\boldsymbol{r}} \boldsymbol{f}_{\boldsymbol{r}}^\dagger(\tau) \left[\partial_\tau - i a_{0,\boldsymbol{r}}(\tau)\right] \boldsymbol{f}_{\boldsymbol{r}}(\tau) + i a_{0,\boldsymbol{r}}(\tau) + \sum_{b=\langle \boldsymbol{r},\boldsymbol{r}'\rangle} |\chi_b(\tau)| \left[\boldsymbol{f}_{\boldsymbol{r}}^\dagger(\tau) e^{-i\int_{\boldsymbol{r}}^{\boldsymbol{r}'} \boldsymbol{a}(\boldsymbol{l},\tau) d\boldsymbol{l}} \boldsymbol{f}_{\boldsymbol{r}'}(\tau) + h.c. \right]$$

Classification of Phases	$\langle \boldsymbol{f}_{\boldsymbol{r}}^\dagger \boldsymbol{\sigma} \boldsymbol{f}_{\boldsymbol{r}} \rangle \neq 0$	$\langle b_{\boldsymbol{r}} \rangle \neq 0$	Gauge field
Kondo	✗	✓	confined
SDW	✓	✗	confined
Kondo + SDW	✓	✓	confined
FL*	✗	✗	De-confined
SDW*	✓	✗	De-confined

Kondo systems

$$S = \int_0^\beta d\tau \quad \left\{ \frac{2}{J_h} \sum_b |\chi_b(\tau)|^2 + \frac{2}{J_k} \sum_{\boldsymbol{r}} |b_{\boldsymbol{r}}(\tau)|^2 + \sum_{\boldsymbol{i},\boldsymbol{j}} \boldsymbol{c}_{\boldsymbol{i}}^\dagger(\tau) \left[\partial_\tau \delta_{\boldsymbol{i},\boldsymbol{j}} - T_{\boldsymbol{i},\boldsymbol{j}}\right] \boldsymbol{c}_{\boldsymbol{j}}(\tau) \right.$$

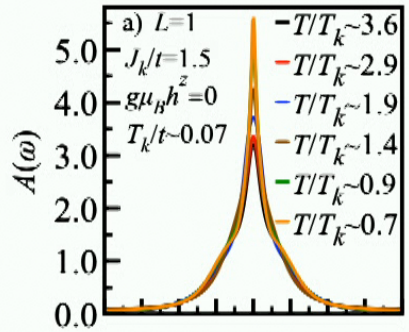
$$+ \sum_{\boldsymbol{r}} |b_{\boldsymbol{r}}(\tau)| \left[e^{i\varphi_{\boldsymbol{r}}(\tau)} \boldsymbol{f}_{\boldsymbol{r}}^\dagger(\tau) \boldsymbol{c}_{\boldsymbol{r}}(\tau) + h.c. \right]$$

$$+ \sum_{\boldsymbol{r}} \boldsymbol{f}_{\boldsymbol{r}}^\dagger(\tau) \left[\partial_\tau - i a_{0,\boldsymbol{r}}(\tau)\right] \boldsymbol{f}_{\boldsymbol{r}}(\tau) + i a_{0,\boldsymbol{r}}(\tau) + \sum_{b=\langle \boldsymbol{r},\boldsymbol{r}'\rangle} |\chi_b(\tau)| \left[\boldsymbol{f}_{\boldsymbol{r}}^\dagger(\tau) e^{-i\int_{\boldsymbol{r}}^{\boldsymbol{r}'} \boldsymbol{a}(\boldsymbol{l},\tau) d\boldsymbol{l}} \boldsymbol{f}_{\boldsymbol{r}'}(\tau) + h.c. \right]$$

<u>Kondo:</u> composite fermion $e^{i\varphi_i(\tau)} \boldsymbol{f}_{\boldsymbol{i}}(\tau) \propto \boldsymbol{\psi}_{\boldsymbol{i}} = \boldsymbol{S}_{\boldsymbol{i}} \cdot \boldsymbol{\sigma} \boldsymbol{c}_{\boldsymbol{i}}.$

Single impurity.

$$A(\omega) = -\mathrm{Im} G^{\mathrm{ret}}(\omega), \quad G^{\mathrm{ret}}(\omega) = -i \int_0^\infty dt e^{i\omega t} \sum_\sigma \langle \{ \hat{\psi}_\sigma(t), \hat{\psi}_\sigma^\dagger(0) \} \rangle$$



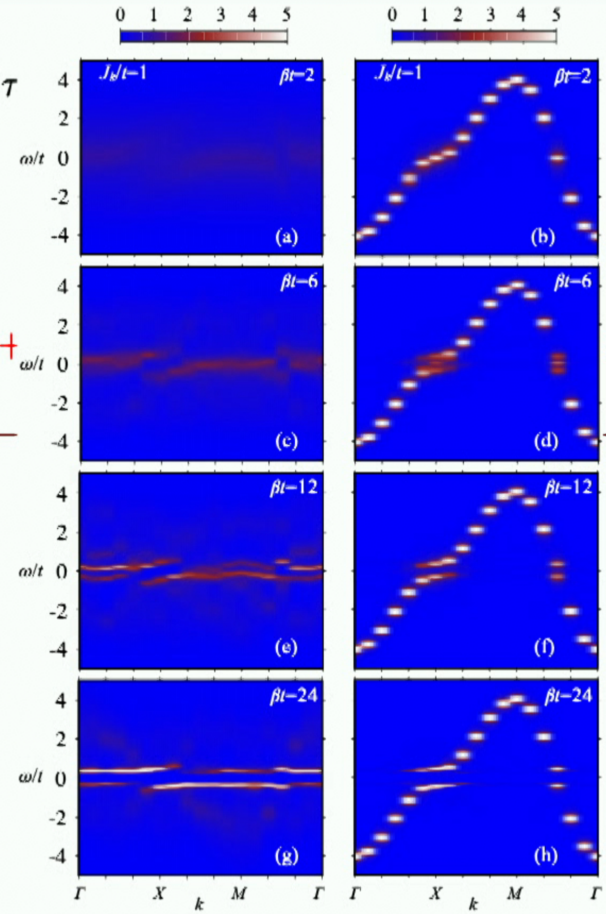
B. Danu, FFA, and F. Mila, Phys. Rev. Lett. 123 (2019), 176601.

Kondo systems

$$S = \int_0^\beta d\tau \quad \Bigg\{ \frac{2}{J_h} \sum_b |\chi_b(\tau)|^2 + \frac{2}{J_k} \sum_{\boldsymbol{r}} |b_{\boldsymbol{r}}(\tau)|^2 + \sum_{\boldsymbol{i},\boldsymbol{j}} \boldsymbol{c}_{\boldsymbol{i}}^\dagger(\tau$$

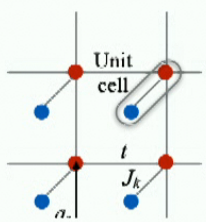
$$+ \sum_{\boldsymbol{r}} |b_{\boldsymbol{r}}(\tau)| \left[e^{i\varphi_{\boldsymbol{r}}(\tau)} \boldsymbol{f}_{\boldsymbol{r}}^\dagger(\tau) \boldsymbol{c}_{\boldsymbol{r}}(\tau) + h.c. \right]$$

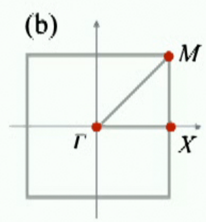
$$+ \sum_{\boldsymbol{r}} \boldsymbol{f}_{\boldsymbol{r}}^\dagger(\tau) \left[\partial_\tau - i a_{0,\boldsymbol{r}}(\tau) \right] \boldsymbol{f}_{\boldsymbol{r}}(\tau) + i a_{0,\boldsymbol{r}}(\tau) + \quad \boldsymbol{f}_{\boldsymbol{r}'}(\tau) + h.c. \Big]$$



Kondo: composite fermion $\quad e^{i\varphi_i(\tau)} \boldsymbol{f}_{\boldsymbol{i}}(\tau) \propto \boldsymbol{\psi}_{\boldsymbol{i}} = \boldsymbol{S}_{\boldsymbol{i}} \cdot \boldsymbol{\sigma} \boldsymbol{c}_{\boldsymbol{i}}.$

Square Lattice





$$A_\psi(\boldsymbol{k},\omega) = -\frac{1}{\pi} \mathrm{Im} G_\psi^{ret}(\boldsymbol{k},\omega) \qquad G_\psi^{ret}(\boldsymbol{k},\omega) = -i \int_0^\infty dt e^{i\omega t} \sum_\sigma \langle \{ \tilde{\psi}_{\boldsymbol{k},\sigma}(t), \tilde{\psi}_{\boldsymbol{k},\sigma}^\dagger(0) \} \rangle$$

B. Danu, Z. Liu, FFA, and M. Raczkowski, Phys. Rev. B 104 (2021), 155128.

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Spin chains on metallic surfaces: Kondo destruction and magnetic order-disorder transitions

Fakher F. Assaad, Quantum Criticality: Gauge Fields and Matter, Perimeter ITP, 16th May 2022

Topics Kondo breakdown transitions and phases

PHYSICAL REVIEW LETTERS **125**, 206602 (2020)

Kondo Breakdown in a Spin-1/2 Chain of Adatoms on a Dirac Semimetal

Bimla Danu,[1,*] Matthias Vojta,[2,†] Fakher F. Assaad,[1,‡] and Tarun Grover[3,§]

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TGCC
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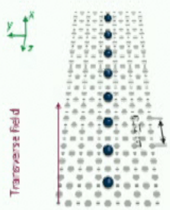
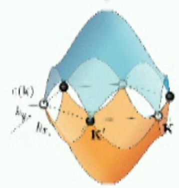
Spin chain on semi-metal

Lattice model

$$\hat{H} = -t \sum_{\langle \boldsymbol{i},\boldsymbol{j} \rangle,\sigma} \left(e^{\frac{2\pi i}{\Phi_0}\int_i^j \boldsymbol{A} d\boldsymbol{l}}\, \hat{c}^\dagger_{\boldsymbol{i},\boldsymbol{\sigma}} \hat{c}_{\boldsymbol{j},\boldsymbol{\sigma}} + h.c\right) + J_k \sum_{l=1}^{L} \hat{\boldsymbol{S}}^c_{\boldsymbol{l}} \cdot \hat{\boldsymbol{S}}_{\boldsymbol{l}} + J_h \sum_{l=1}^{L} \hat{\boldsymbol{S}}_{\boldsymbol{l}} \cdot \hat{\boldsymbol{S}}_{\boldsymbol{l}+\Delta \boldsymbol{l}}$$

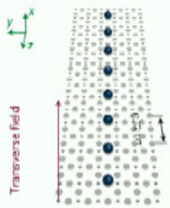




Spin chain on semi-metal

Lattice model

$$\hat{H} = -t \sum_{\langle i,j \rangle, \sigma} (e^{\frac{2\pi i}{\Phi_0} \int_i^j \boldsymbol{A} d\boldsymbol{l}} \hat{c}^{\dagger}_{\boldsymbol{i},\boldsymbol{\sigma}} \hat{c}_{\boldsymbol{j},\boldsymbol{\sigma}} + h.c) + J_k \sum_{l=1}^{L} \hat{\boldsymbol{S}}^c_{\boldsymbol{l}} \cdot \hat{\boldsymbol{S}}_{\boldsymbol{l}} + J_h \sum_{l=1}^{L} \hat{\boldsymbol{S}}_{\boldsymbol{l}} \cdot \hat{\boldsymbol{S}}_{\boldsymbol{l}+\Delta \boldsymbol{l}}$$



Weak Coupling

Scaling dimensions of fermion and spin: $\Delta_\psi = \frac{d}{2}$ $\Delta_s = \frac{1}{2}$

→ Kondo term has scaling dimension, $2 - 2\Delta_\Psi - \Delta_s = -1/2$

→ Irrelevant

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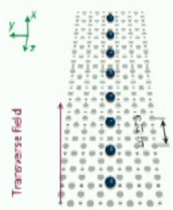
Spin chain on semi-metal

Lattice model

$$\hat{H} = -t \sum_{\langle i,j\rangle,\sigma} \left(e^{\frac{2\pi i}{\Phi_0}\int_i^j \boldsymbol{A} d\boldsymbol{l}}\, \hat{c}^\dagger_{i,\sigma}\hat{c}_{j,\sigma} + h.c\right) + J_k \sum_{l=1}^{L} \hat{\boldsymbol{S}}^c_l \cdot \hat{\boldsymbol{S}}_l + J_h \sum_{l=1}^{L} \hat{\boldsymbol{S}}_l \cdot \hat{\boldsymbol{S}}_{l+\Delta l}$$



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→ Kondo term has scaling dimension, $2 - 2\Delta_\Psi - \Delta_s = -1/2$

→ Irrelevant

Strong coupling

Each spin captures a conduction electron and forms a singlet.

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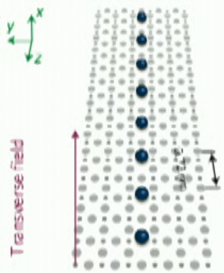
Spin chain on semi-metal

Lattice model

$$\hat{H} = -t \sum_{\langle i,j\rangle,\sigma} \left(e^{\frac{2\pi i}{\Phi_0}\int_i^j \boldsymbol{A}d\boldsymbol{l}}\, \hat{c}^\dagger_{i,\sigma}\hat{c}_{j,\sigma} + h.c\right) + J_k \sum_{l=1}^{L} \hat{\boldsymbol{S}}^c_{\boldsymbol{l}} \cdot \hat{\boldsymbol{S}}_{\boldsymbol{l}} + J_h \sum_{l=1}^{L} \hat{\boldsymbol{S}}_{\boldsymbol{l}} \cdot \hat{\boldsymbol{S}}_{\boldsymbol{l}+\Delta \boldsymbol{l}}$$



Weak Coupling

Scaling dimensions of fermion and spin: $\Delta_\psi = \frac{d}{2}$ $\Delta_s = \frac{1}{2}$

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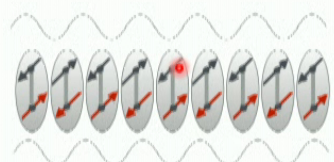
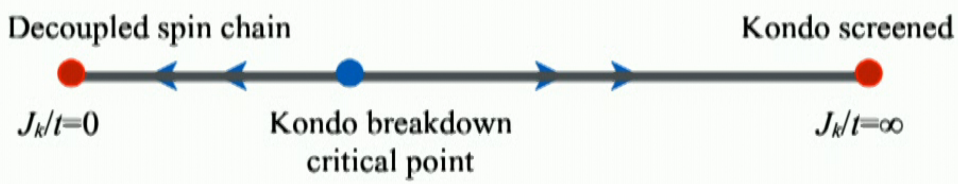


Each spin captures a conduction electron and forms a singlet.

ϵ-expansion



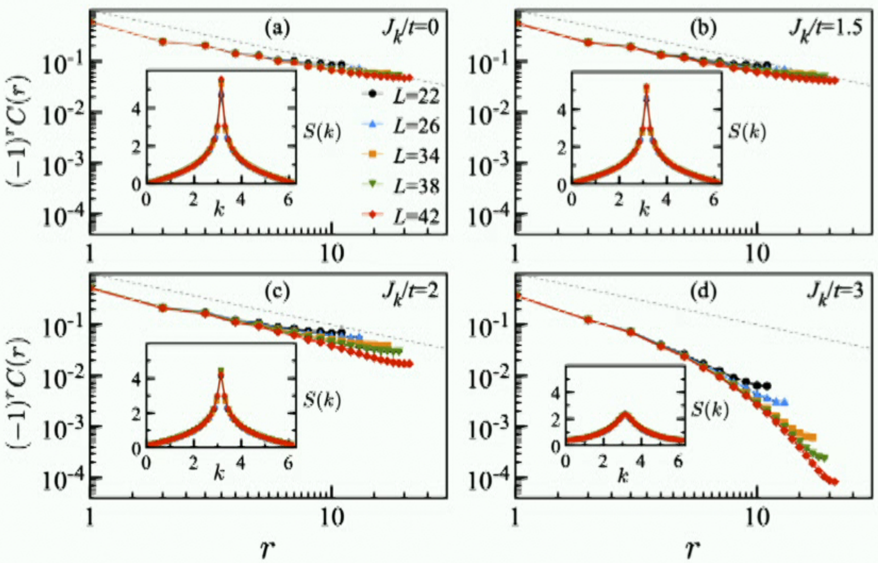
$$\frac{dj_k}{d\ln\Lambda} = \epsilon j_k - \frac{j_k^2}{2}$$

Spin chain on semi-metal

Spin-spin correlations along the Heisenberg chain

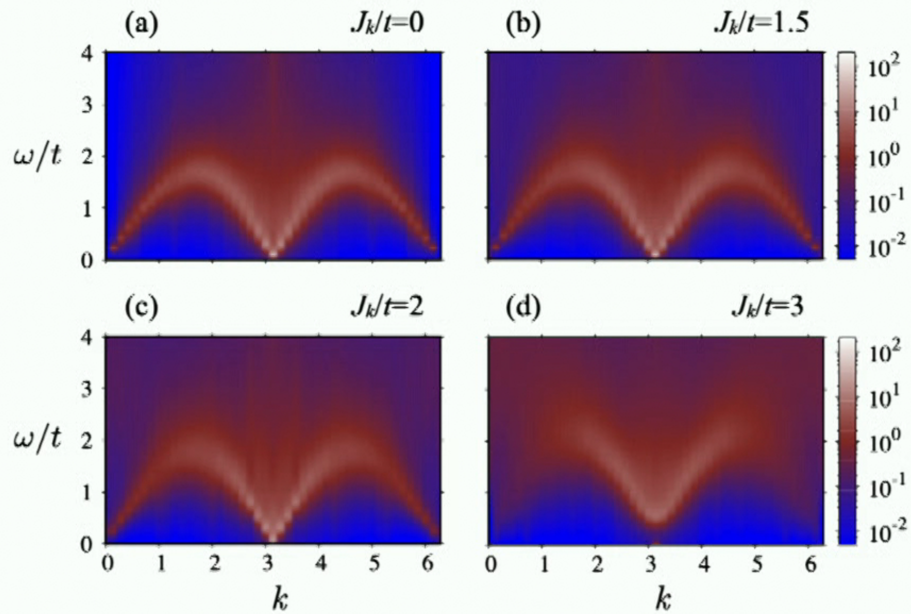
For isolated chain, SU(2) spin symmetry enforces

$$C(\boldsymbol{r}) = \langle \hat{\boldsymbol{S}}_l \hat{\boldsymbol{S}}_{l+\boldsymbol{r}} \rangle \simeq (-1)^{|\boldsymbol{r}|}/|\boldsymbol{r}|$$



Two spinon continuum

$$S(\boldsymbol{q},\omega) = \frac{\chi''(\boldsymbol{q},\omega)}{1-e^{-\beta\omega}}$$



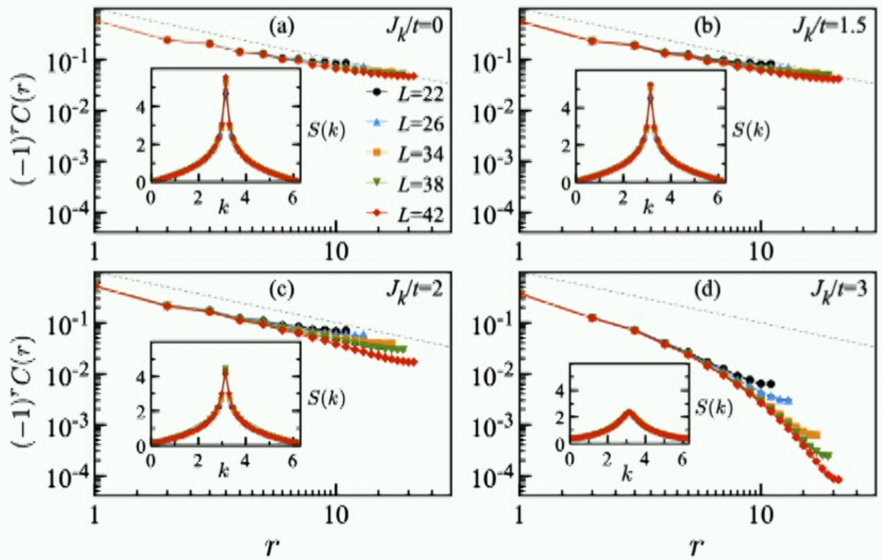
Spin chain on semi-metal

Interpretation

Gapping out of two-spinon continuum corresponds to confinement transition.

$$C(\boldsymbol{r}) = \langle \hat{\boldsymbol{S}}_l \hat{\boldsymbol{S}}_{l+\boldsymbol{r}} \rangle \simeq (-1)^{|\boldsymbol{r}|}/|\boldsymbol{r}|$$

$$\langle f_{\boldsymbol{r}}^\dagger \, e^{i \int_{\boldsymbol{r}}^{\boldsymbol{r}'} \boldsymbol{a}(\boldsymbol{l}) \cdot d\boldsymbol{l}} \, f_{\boldsymbol{r}'} \rangle \propto \begin{cases} \frac{1}{|\boldsymbol{r}-\boldsymbol{r}'|^\alpha} & J_k < J_k^c \\ e^{-|\boldsymbol{r}-\boldsymbol{r}'|/\xi} & J_k > J_k^c \end{cases}$$



At large Kondo coupling, the spins inherit the low energy properties of the conduction electrons.

$$\langle b_{\boldsymbol{r}} \rangle = 0 \quad J_k < J_k^c$$
$$\langle b_{\boldsymbol{r}} \rangle \neq 0 \quad J_k > J_k^c$$

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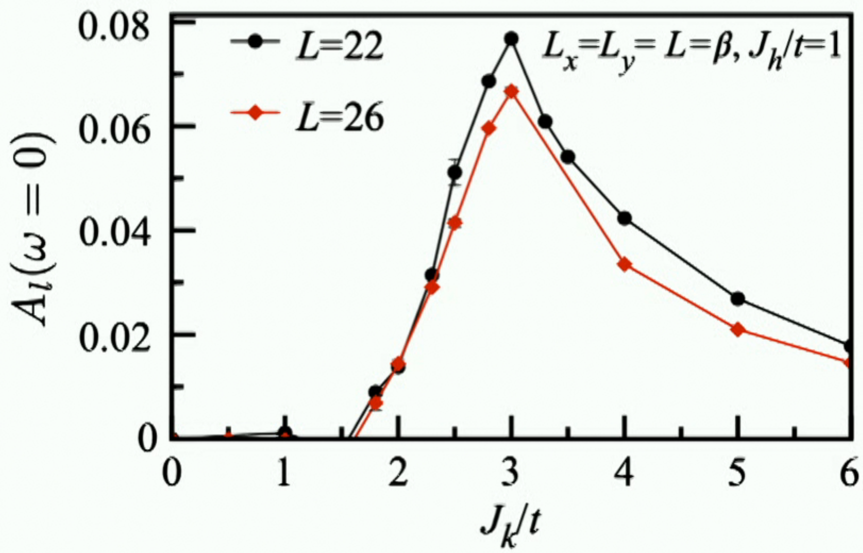
Spin chain on semi-metal

Zero bias tunneling through the magnetic adatom as a measure of the Higgs condensate.



$$A(\omega) = -\mathrm{Im}G^{\mathrm{ret}}(\omega), \quad G^{\mathrm{ret}}(\omega) = -i\int_0^\infty dt e^{i\omega t}\sum_\sigma \langle\{\hat{\psi}_\sigma(t), \hat{\psi}^\dagger_\sigma(0)\}\rangle$$

$$\hat{\boldsymbol{\psi}}^\dagger = e^{-S}\hat{\boldsymbol{d}}^\dagger e^S = \hat{\boldsymbol{c}}^\dagger_{\boldsymbol{r}=0}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{S}}$$

(S: Schrieffer Wolff transformation)

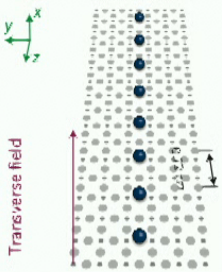
T.A. Costi, Phys. Rev. Lett. 85, 1504 (2000).

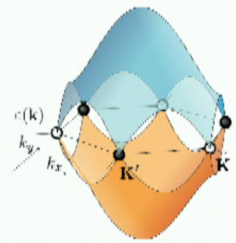
In the large-N limit: $\hat{\boldsymbol{\psi}}^\dagger_{\boldsymbol{r}} \propto \hat{\boldsymbol{f}}^\dagger_{\boldsymbol{r}} b_{\boldsymbol{r}}$

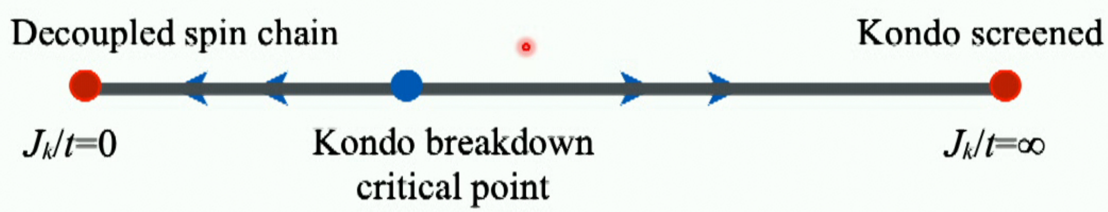
Spin chain on semi-metal

Lattice model

$$\hat{H} = -t \sum_{\langle \boldsymbol{i},\boldsymbol{j}\rangle,\sigma} \left(e^{\frac{2\pi i}{\Phi_0}\int_{\boldsymbol{i}}^{\boldsymbol{j}} \boldsymbol{A} d\boldsymbol{l}}\, \hat{c}^{\dagger}_{\boldsymbol{i},\boldsymbol{\sigma}} \hat{c}_{\boldsymbol{j},\boldsymbol{\sigma}} + h.c\right) + J_k \sum_{l=1}^{L} \hat{\boldsymbol{S}}^{c}_{\boldsymbol{l}} \cdot \hat{\boldsymbol{S}}_{\boldsymbol{l}} + J_h \sum_{l=1}^{L} \hat{\boldsymbol{S}}_{\boldsymbol{l}} \cdot \hat{\boldsymbol{S}}_{\boldsymbol{l}+\Delta \boldsymbol{l}}$$







FL* phase	Kondo phase
Spinons are deconfined	Spinons are confined
No Higgs condensate	Higgs condensate

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Spin chains on metallic surfaces: Kondo destruction and magnetic order-disorder transitions

Fakher F. Assaad, Quantum Criticality: Gauge Fields and Matter, Perimeter ITP, 16th May 2022

Topics

Spin chain on a metallic surface: Dissipation-induced order vs. Kondo entanglement

Bimla Danu,[1] Matthias Vojta,[2] Tarun Grover,[3] and Fakher F. Assaad[1]

arXiv:2204.00029v1

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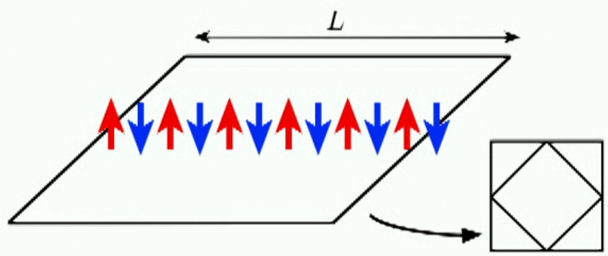
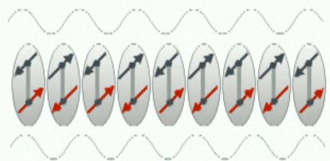
Spin chain on metallic surface



$$\hat{H} = -t \sum_{\langle \boldsymbol{i},\boldsymbol{j} \rangle} (\hat{\boldsymbol{c}}_{\boldsymbol{i}}^{\dagger} \hat{\boldsymbol{c}}_{\boldsymbol{j}} + h.c) + \frac{J_k}{2} \sum_{\boldsymbol{r}} \hat{\boldsymbol{c}}_{\boldsymbol{r}}^{\dagger} \boldsymbol{\sigma} \hat{\boldsymbol{c}}_{\boldsymbol{r}} \cdot \hat{\boldsymbol{S}}_{\boldsymbol{r}} + J_h \sum_{\langle \boldsymbol{r},\boldsymbol{r}' \rangle} \hat{\boldsymbol{S}}_{\boldsymbol{r}} \cdot \hat{\boldsymbol{S}}_{\boldsymbol{r}'}$$

Strong coupling



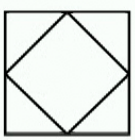
Spins are screened by conduction electrons and inherit the properties of the metal. → Heavy fermion metal.

Weak coupling

Integrate out electrons à la Hertz-Millis

$$\mathcal{S}(\boldsymbol{n}) = \mathcal{S}_{\text{chain}}(\boldsymbol{n}) + \mathcal{S}_{\text{diss}}(\boldsymbol{n})$$

$$\mathcal{S}_{\text{diss}}(\boldsymbol{n}) = \frac{J_k^2}{8} \int d\tau d\tau' \sum_{\boldsymbol{r},\boldsymbol{r}'} \boldsymbol{n}_{\boldsymbol{r}}(\tau) \chi^0(\boldsymbol{r} - \boldsymbol{r}', \tau - \tau') \boldsymbol{n}_{\boldsymbol{r}'}(\tau').$$



$$\chi^0(\mathbf{0}, \tau - \tau') \propto \frac{1}{v_F^2 (\tau - \tau')^2} \qquad \chi^0(r\boldsymbol{e}_x, 0) \propto \frac{1}{r^4}$$

At Heisenberg critical point ($\Delta_{\boldsymbol{n}} = \frac{1}{2}$) the coupling to electron in the temporal direction is marginal !

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Spin chain on metallic surface

DETOUR

$$\mathcal{S}(\boldsymbol{n}) = \mathcal{S}_{\text{chain}}(\boldsymbol{n}) + \mathcal{S}_{\text{diss}}(\boldsymbol{n})$$

$$\mathcal{S}_{\text{diss}}(\boldsymbol{n}) = \alpha \int d\tau d\tau' \sum_{\boldsymbol{r}} \frac{\boldsymbol{n}_{\boldsymbol{r}}(\tau)\boldsymbol{n}_{\boldsymbol{r}}(\tau')}{(\tau-\tau')^2}.$$

arXiv:2112.02124v1

Dissipation-induced order: the $S=1/2$ quantum spin chain coupled to an ohmic bath

Manuel Weber,[1] David J. Luitz,[1] and Fakher F. Assaad[2,3]

Hamiltonian

$$\hat{H} = J\sum_i \hat{\boldsymbol{S}}_i \cdot \hat{\boldsymbol{S}}_{i+1} + \sum_{i,q} \omega_q \hat{\boldsymbol{a}}^{\dagger}_{i,q}\hat{\boldsymbol{a}}_{i,q} + \sum_{i,q} \lambda_q \left(\hat{\boldsymbol{a}}^{\dagger}_{i,q} + \hat{\boldsymbol{a}}_{i,q}\right) \cdot \hat{\boldsymbol{S}}_i$$

$$J(\omega) = \pi \sum_q \lambda_q \delta(\omega - \omega_q) = 2\pi\alpha\,\omega$$

Conservation law

$$\hat{\boldsymbol{J}}_{tot} = \sum_{iq} \hat{\boldsymbol{Q}}_{iq} \times \hat{\boldsymbol{P}}_{iq} + \sum_i \hat{\boldsymbol{S}}_i$$

$$\hat{\boldsymbol{P}}_{iq} = \frac{1}{\sqrt{2}}\left(\hat{\boldsymbol{a}}^{\dagger}_{iq} - \hat{\boldsymbol{a}}_{iq}\right)$$

$$\hat{\boldsymbol{Q}}_{iq} = \frac{1}{\sqrt{2}}\left(\hat{\boldsymbol{a}}^{\dagger}_{iq} + \hat{\boldsymbol{a}}_{iq}\right)$$

A bath cannot screen

Spin chain on metallic surface

DETOUR

$$\mathcal{S}(\boldsymbol{n}) = \mathcal{S}_{\text{chain}}(\boldsymbol{n}) + \mathcal{S}_{\text{diss}}(\boldsymbol{n})$$

$$\mathcal{S}_{\text{diss}}(\boldsymbol{n}) = \alpha \int d\tau d\tau' \sum_{\boldsymbol{r}} \frac{\boldsymbol{n}_{\boldsymbol{r}}(\tau)\boldsymbol{n}_{\boldsymbol{r}}(\tau')}{(\tau-\tau')^2}.$$

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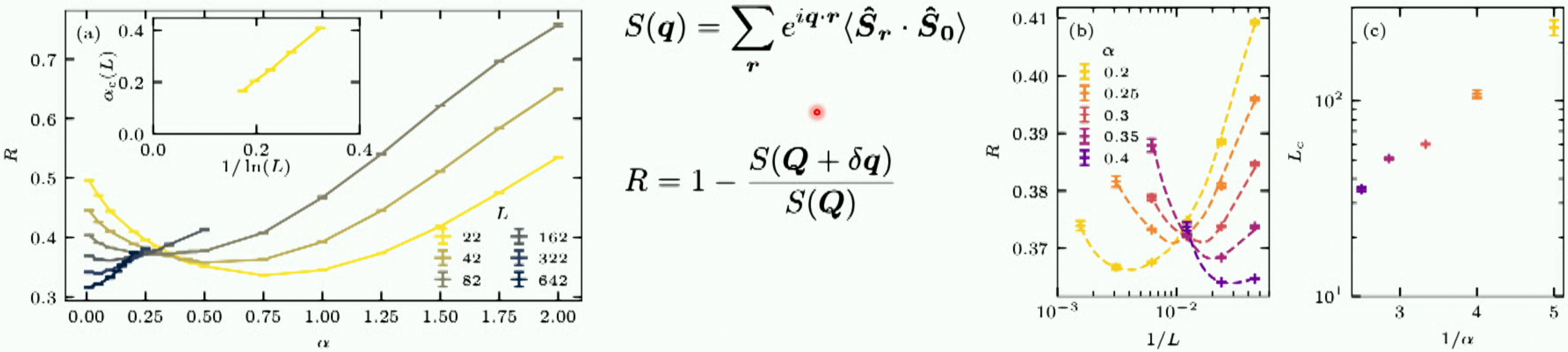
Dissipation-induced order: the $S = 1/2$ quantum spin chain coupled to an ohmic bath

Manuel Weber,[1] David J. Luitz,[1] and Fakher F. Assaad[2,3]



$$S(\boldsymbol{q}) = \sum_{\boldsymbol{r}} e^{i\boldsymbol{q}\cdot\boldsymbol{r}} \langle \hat{\boldsymbol{S}}_{\boldsymbol{r}} \cdot \hat{\boldsymbol{S}}_{\boldsymbol{0}} \rangle$$

$$R = 1 - \frac{S(\boldsymbol{Q}+\delta\boldsymbol{q})}{S(\boldsymbol{Q})}$$

Long ranged interaction along the imaginary time invalidates Mermin-Wagner theorem and triggers long-ranged order.
(Dissipation is marginally relevant)

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Spin chain on metallic surface

DETOUR

$$\mathcal{S}(\boldsymbol{n}) = \mathcal{S}_{\text{chain}}(\boldsymbol{n}) + \mathcal{S}_{\text{diss}}(\boldsymbol{n})$$

$$\mathcal{S}_{\text{diss}}(\boldsymbol{n}) = \alpha \int d\tau d\tau' \sum_{\boldsymbol{r}} \frac{\boldsymbol{n}_{\boldsymbol{r}}(\tau)\boldsymbol{n}_{\boldsymbol{r}}(\tau')}{(\tau-\tau')^2}.$$

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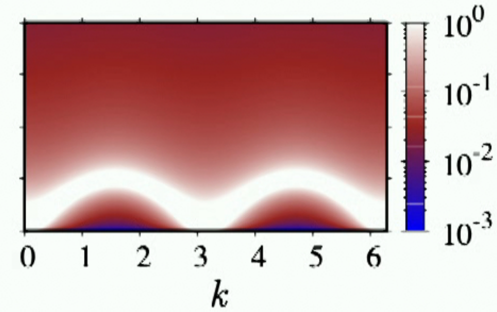
Dissipation-induced order: the $S = 1/2$ quantum spin chain coupled to an ohmic bath

Manuel Weber,[1] David J. Luitz,[1] and Fakher F. Assaad[2,3]

Spin structure factor: Landau damped Goldstone modes (z=2).

$$S(\boldsymbol{k},\omega) = \frac{\text{Im}\chi(\boldsymbol{k},\omega + i0^+)}{1 - e^{-\beta\omega}}$$

Spin-wave calculation (B. Danu)



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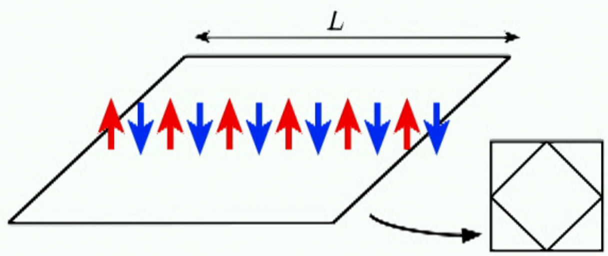
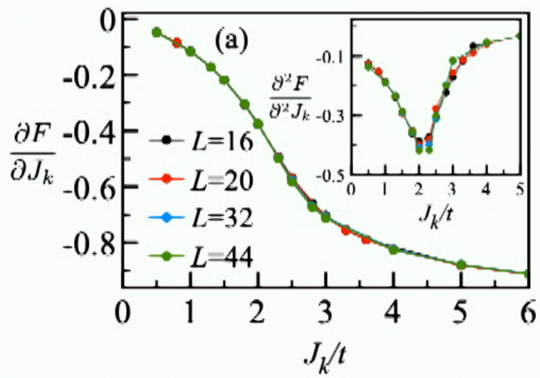
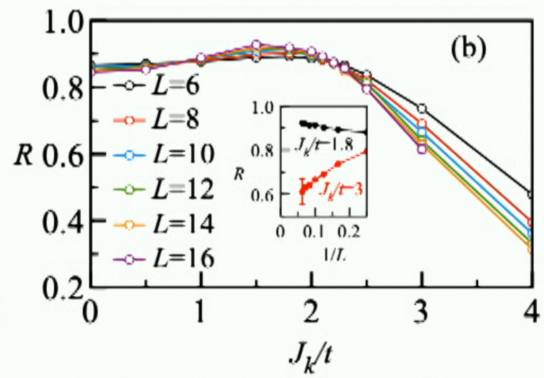
Spin chain on metallic surface



$$\hat{H} = -t \sum_{\langle \boldsymbol{i},\boldsymbol{j} \rangle} (\hat{\boldsymbol{c}}^{\dagger}_{\boldsymbol{i}} \hat{\boldsymbol{c}}_{\boldsymbol{j}} + h.c) + \frac{J_k}{2} \sum_{\boldsymbol{r}} \hat{\boldsymbol{c}}^{\dagger}_{\boldsymbol{r}} \boldsymbol{\sigma} \hat{\boldsymbol{c}}_{\boldsymbol{r}} \cdot \hat{\boldsymbol{S}}_{\boldsymbol{r}} + J_h \sum_{\langle \boldsymbol{r},\boldsymbol{r}' \rangle} \hat{\boldsymbol{S}}_{\boldsymbol{r}} \cdot \hat{\boldsymbol{S}}_{\boldsymbol{r}'}$$

Dissipation and Kondo singlet formation compete and trigger an order-disorder transition.





Numerics suggest a z=2 QCP such that we adopt a $\beta = L^2$ scaling.

$$\chi(\boldsymbol{k}, i\Omega_m) = \int_0^{\beta} \mathrm{d}\tau \sum_{\boldsymbol{r}} e^{i(\Omega_m \tau - \boldsymbol{k} \cdot \boldsymbol{r})} \langle \hat{S}^z_{\boldsymbol{r}}(\tau) \hat{S}^z_{\boldsymbol{0}}(0) \rangle$$

$$R = 1 - \frac{\chi(\boldsymbol{Q} - \delta \boldsymbol{k}, 0)}{\chi(\boldsymbol{Q}, 0)}$$

$$R = f([J_k - J_k^c] L^{1/\nu}, L^z/\beta, L^{-\omega})$$

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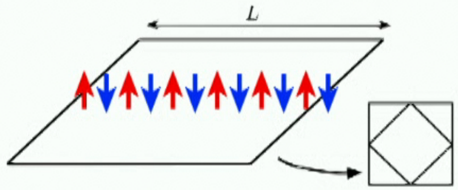
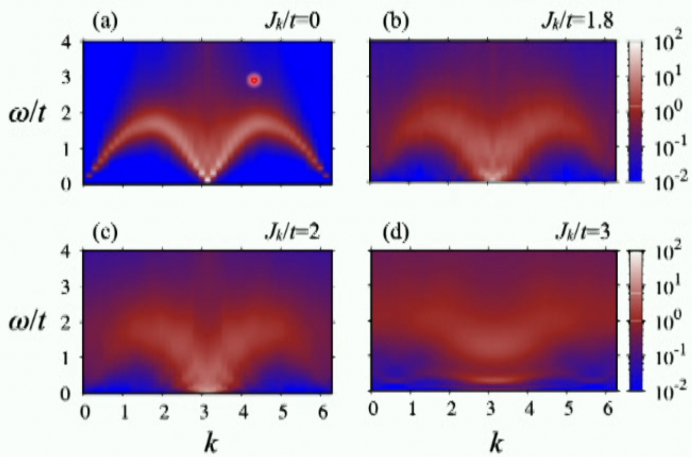
Spin chain on metallic surface



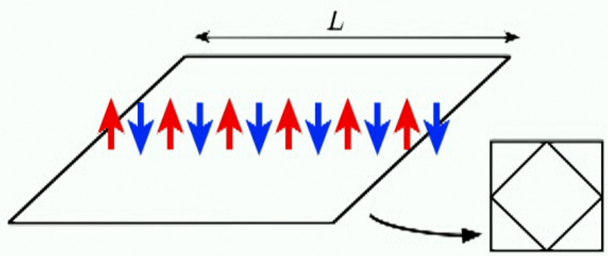
$$\hat{H} = -t \sum_{\langle i,j \rangle} (\hat{c}_i^\dagger \hat{c}_j + h.c) + \frac{J_k}{2} \sum_{r} \hat{c}_r^\dagger \boldsymbol{\sigma} \hat{c}_r \cdot \hat{\boldsymbol{S}}_r + J_h \sum_{\langle r,r' \rangle} \hat{\boldsymbol{S}}_r \cdot \hat{\boldsymbol{S}}_{r'}$$

Dissipation and Kondo singlet formation compete and trigger an order-disorder transition.

$$S(\boldsymbol{k},\omega) = \frac{\mathrm{Im}\chi(\boldsymbol{k},\omega + i0^+)}{1 - e^{-\beta\omega}}$$



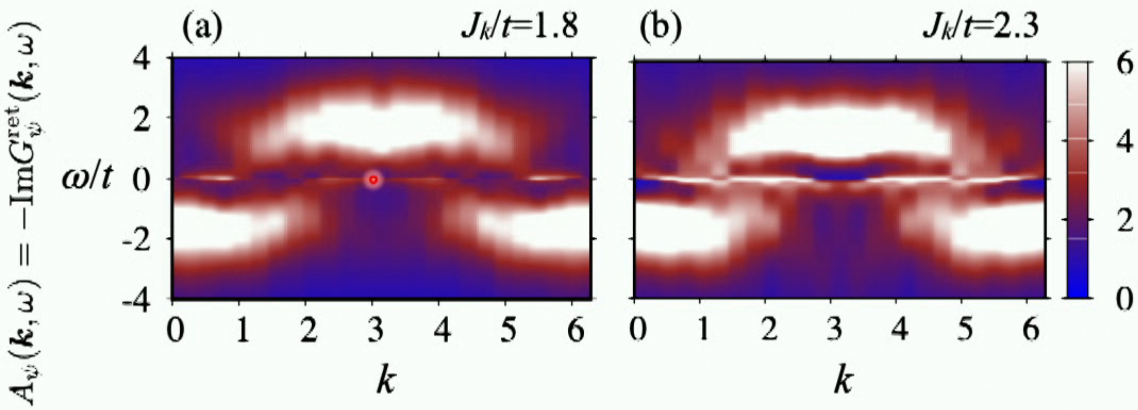
Spin chain on metallic surface

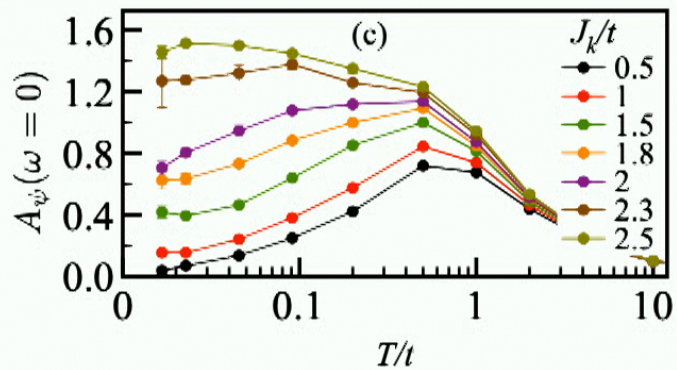


$$\hat{H} = -t\sum_{\langle i,j\rangle}(\hat{c}_i^\dagger \hat{c}_j + h.c) + \frac{J_k}{2}\sum_{r}\hat{c}_r^\dagger \boldsymbol{\sigma}\hat{c}_r \cdot \hat{S}_r + J_h \sum_{\langle r,r'\rangle}\hat{S}_r \cdot \hat{S}_{r'}$$

Single particle spectral function shows heavy bands in both phases.

Consistent with the absence of Kondo breakdown.

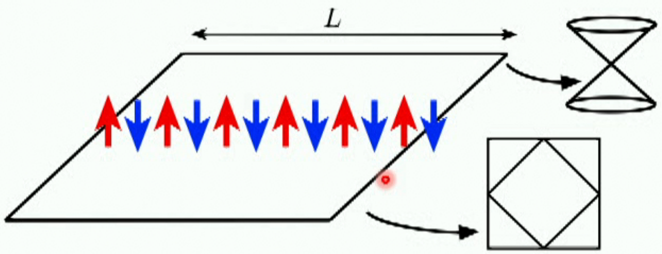




$$G_\psi^{\mathrm{ret}}(k,\omega) = -i\int_0^\infty dt e^{i\omega t}\sum_\sigma \langle\{\hat{\psi}_{k,\sigma}(t), \hat{\psi}_{k,\sigma}^\dagger(0)\}\rangle \qquad \hat{\psi}_{r,\sigma}^\dagger = 2\sum_{\sigma'}\hat{c}_{r,\sigma'}^\dagger \boldsymbol{\sigma}_{\sigma',\sigma}\cdot \hat{S}_r$$

Spin chains on metallic surfaces: Kondo destruction and magnetic order-disorder transitions

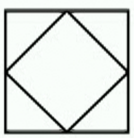
Conclusions



$$\hat{H} = -t\sum_{\langle \boldsymbol{i},\boldsymbol{j}\rangle}(\hat{\boldsymbol{c}}_{\boldsymbol{i}}^{\dagger}\hat{\boldsymbol{c}}_{\boldsymbol{j}} + h.c) + \frac{J_k}{2}\sum_{\boldsymbol{r}}\hat{\boldsymbol{c}}_{\boldsymbol{r}}^{\dagger}\boldsymbol{\sigma}\hat{\boldsymbol{c}}_{\boldsymbol{r}}\cdot\hat{\boldsymbol{S}}_{\boldsymbol{r}} + J_h\sum_{\langle \boldsymbol{r},\boldsymbol{r}'\rangle}\hat{\boldsymbol{S}}_{\boldsymbol{r}}\cdot\hat{\boldsymbol{S}}_{\boldsymbol{r}'}$$

U(1) gauge theory

$$S = \int_0^{\beta} d\tau \left\{ \frac{2}{J_h}\sum_{b}|\chi_b(\tau)|^2 + \frac{2}{J_k}\sum_{\boldsymbol{r}}|b_{\boldsymbol{r}}(\tau)|^2 + \sum_{\boldsymbol{i},\boldsymbol{j}} c_{\boldsymbol{i}}^{\dagger}(\tau)\left[\partial_\tau \delta_{\boldsymbol{i},\boldsymbol{j}} - T_{\boldsymbol{i},\boldsymbol{j}}\right] c_{\boldsymbol{j}}(\tau) \right.$$
$$+ \sum_{\boldsymbol{r}} |b_{\boldsymbol{r}}(\tau)| \left[e^{i\varphi_{\boldsymbol{r}}(\tau)} \boldsymbol{f}_{\boldsymbol{r}}^{\dagger}(\tau) \boldsymbol{c}_{\boldsymbol{r}}(\tau) + h.c. \right]$$
$$+ \sum_{\boldsymbol{r}} \boldsymbol{f}_{\boldsymbol{r}}^{\dagger}(\tau)\left[\partial_\tau - i a_{0,\boldsymbol{r}}(\tau)\right]\boldsymbol{f}_{\boldsymbol{r}}(\tau) + i a_{0,\boldsymbol{r}}(\tau) + \sum_{b=\langle \boldsymbol{r},\boldsymbol{r}'\rangle} |\chi_b(\tau)| \left[\boldsymbol{f}_{\boldsymbol{r}}^{\dagger}(\tau) e^{-i\int_{\boldsymbol{r}}^{\boldsymbol{r}'} a(l,\tau)dl} \boldsymbol{f}_{\boldsymbol{r}'}(\tau) + h.c. \right]$$

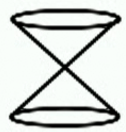


AFM metal
$\langle \boldsymbol{n} \rangle \neq 0, \langle b \rangle \neq 0$

Heavy fermion metal
$\langle \boldsymbol{n} \rangle = 0, \langle b \rangle \neq 0$

Dissipation versus Kondo screening.

Anti-ferromagnetic metal to heavy fermion metal QCP.



FL*
$\langle b \rangle = 0, \ \langle \boldsymbol{n} \rangle = 0$

Heavy fermion metal
$\langle b \rangle \neq 0, \ \langle \boldsymbol{n} \rangle = 0$

Spinons are deconfined
Kondo Breakdown phase

Heavy-fermion phase
Kondo screen