Quantum Critical Metals: From Loss of Quasiparticles to High T_c Superconductivity

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Cargèse, Corse, June 22, 2022

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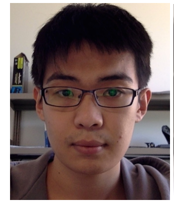


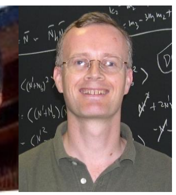
Rutgers University:

Jed Pixley

University of Florida:

Ananth Kandala
Lili Deng
Kevin Ingersent





Zhejiang University:

Stefan Kirchner

Vienna University of Technology:

Silke Paschen, Lukas Prochaska


Frank Steglich, Joe D. Thompson, Hilbert v. Löhneysen

Outline

- Quantum critical metals and the loss of quasiparticles

  --theoretical aspects, building on S. Paschen's lectures; in particular:

  A. Kandala, H. Hu, QS, K. Ingersent, arXiv:2206.01174

- High-T_c superconductivity out of the quantum critical metals

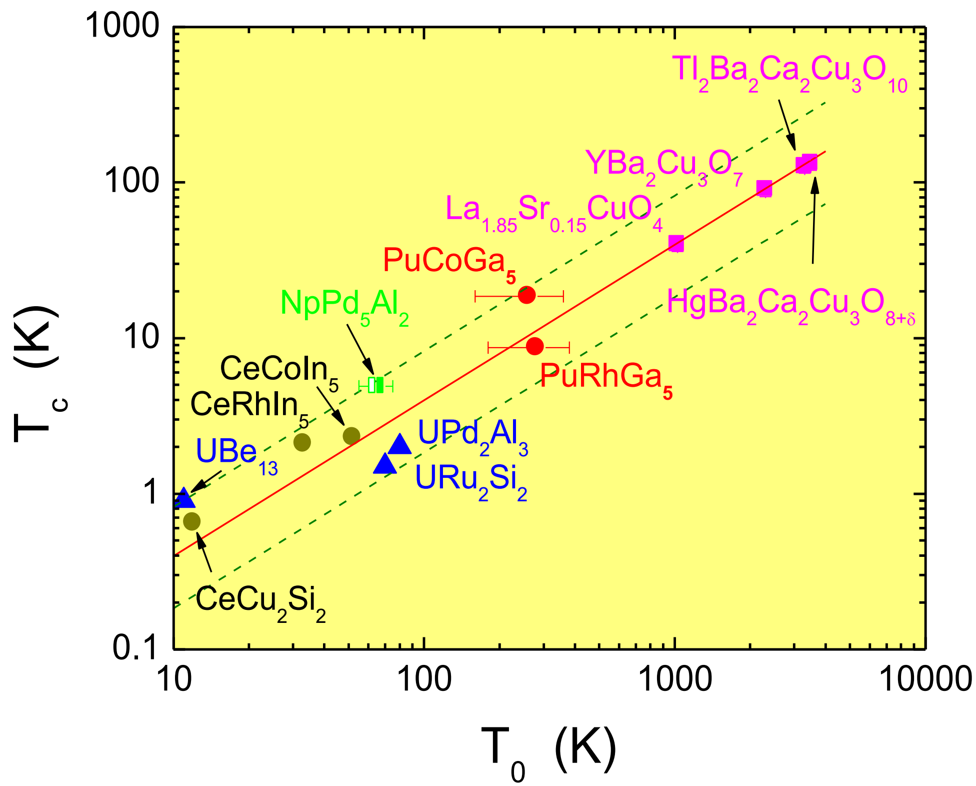
  H. Hu, A. Cai, L. Chen, L. Deng, J. Pixley, K. Ingersent & QS, arXiv:2109.13224

Notes and References

- "The many faces (phases) of stropng correlations", S. Paschen & QS, Europhysics News (EPN) 52/4, 30-32 (2021) (non-technical write-up).
- "Quantum phases driven by strong correlatons", S. Paschen & QS, Nat. Rev. Phys. 3, 9-26 (2021) (connecting different correlated platforms).
- "Heavy-electron quantum criticality and single-particle spectroscopy", S. Kirchner, S. Paschen, Q. Chen, S. Wirth, D. L. Feng, J. D. Thompson, QS, Rev. Mod. Phys. 92, 011002 (2020) (large and small Fermi surfaces).
- "Quantum criticality and the Kondo lattice", arXiv:1012.5440; in "Understanding quantum phase transitions", L. D. Carr, editor (CRC press, 2010) (a brief overview on the theoretical models and concepts).
- "Heavy fermions and quantum phase transitions", QS and F. Steglich, Science 329, 1161 (2010) (an emphasis on the global phase diagram).
- "Quantum criticality in heavy-fermion metals", P. Gegenwart, QS, F. Steglich, Nat. Phys. 4, 186 (2008) (an earlier comprehensive review).

Goalpost of the Talk

- Can, and how does, a quantum critical metal lacking quasiparticles lead to high-T_c superconductivity?



Courtesy J. D. Thompson

Quantum Criticality

Quantum critical point

enhanced
entropy

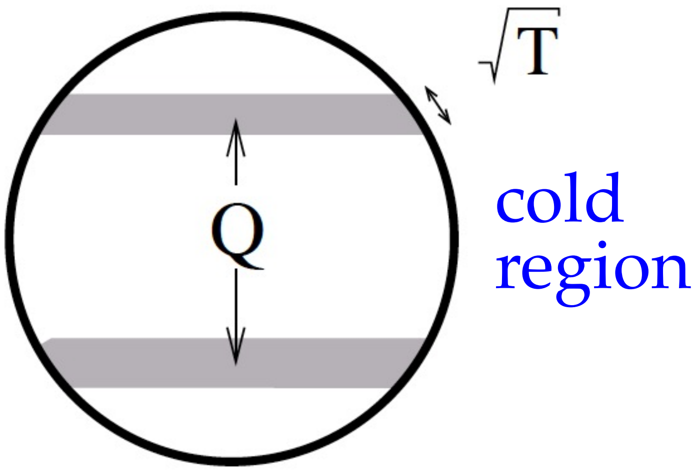
unusual excitations;
emergent phases

Quantum Critical Metals

- Landau framework (Hertz, Millis)

  --Fluctuations of the order parameter

  --O.P. fluctuations leave well-defined quasiparticles (c.f., SDW QCP)

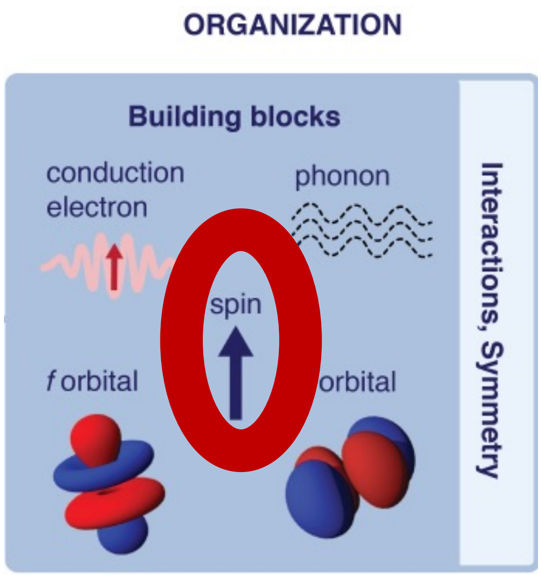


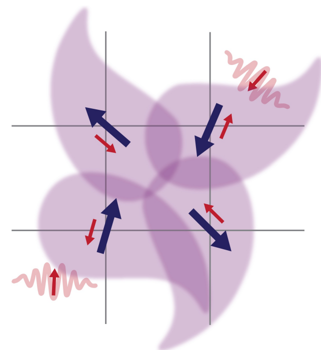
- Or beyond-Landau?

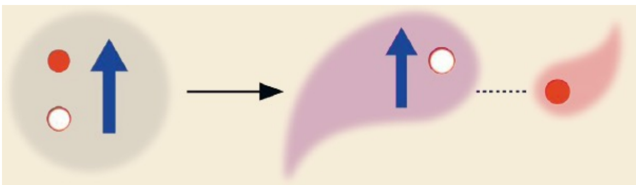
  --Are there critical modes beyond the order-parameter fluctuations?

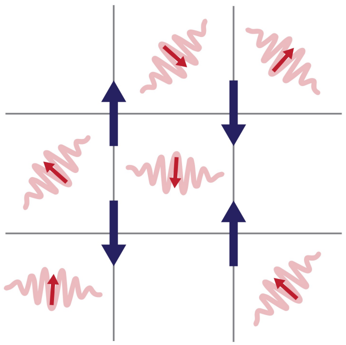
Heavy Fermion Metals

Strong Coulomb repulsion → spins are a part of the building blocks for the low-energy physics







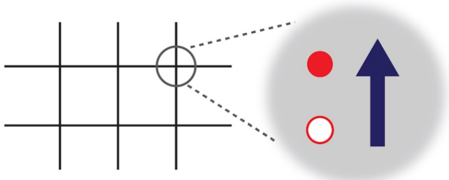


Introduction and status summary:

S. Paschen and QS, Nat. Rev. Phys. 3, 9 (2021)

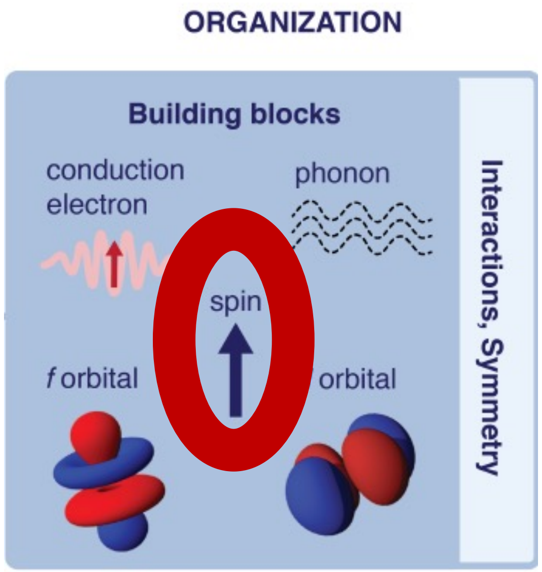
Kondo Lattice Systems

$$H = \sum_{ij} I_{ij}\mathbf{S}_i \cdot \mathbf{S}_j + \sum_{ij,\sigma} t_{ij} c^\dagger_{i\sigma} c_{j\sigma} + \sum_i J_K \mathbf{S}_i \cdot \mathbf{s}_{c,i}$$



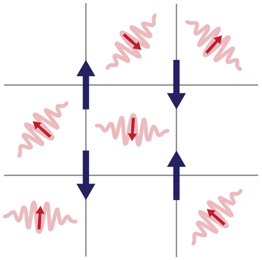
$J_K S c^\dagger \sigma c$

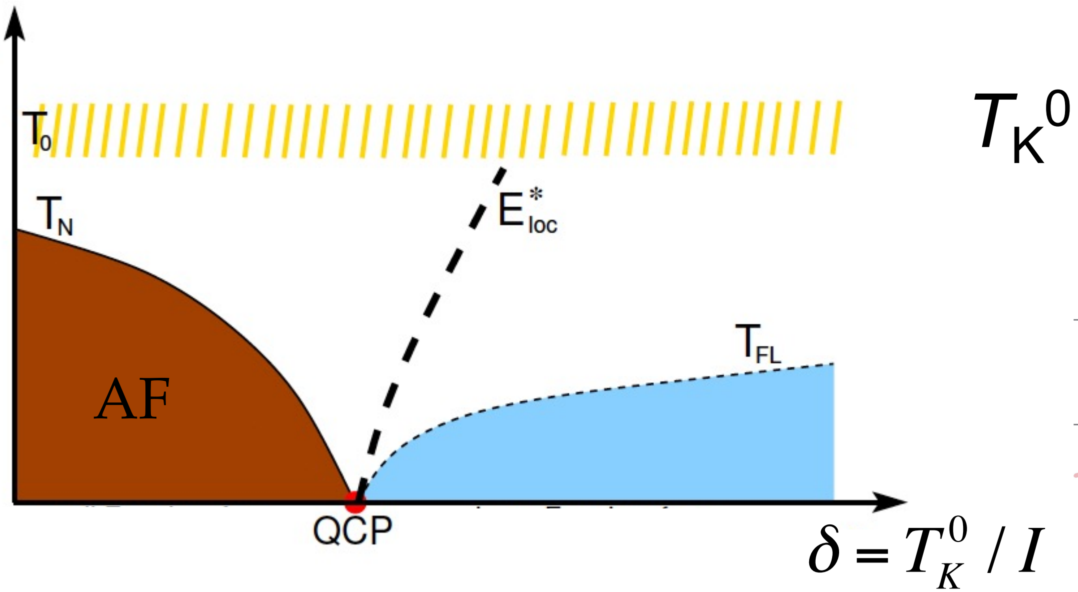
- Fate of local moments
  – end up fluctuating
  or forming order:
  Kondo entanglement,
  quantum magnetism, ...,

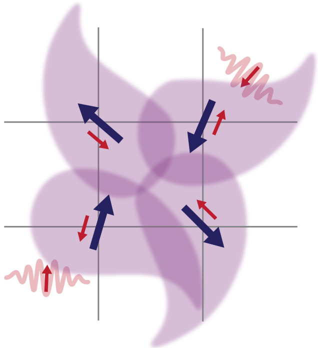


Quantum Criticality from Kondo Destruction

Critical destruction of Kondo singlet
at the T=0 onset of antiferromagnetic order





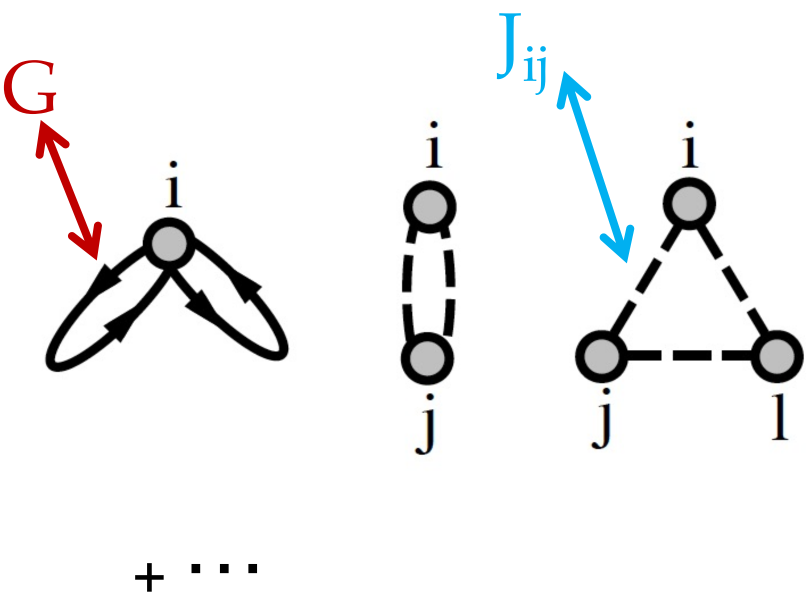


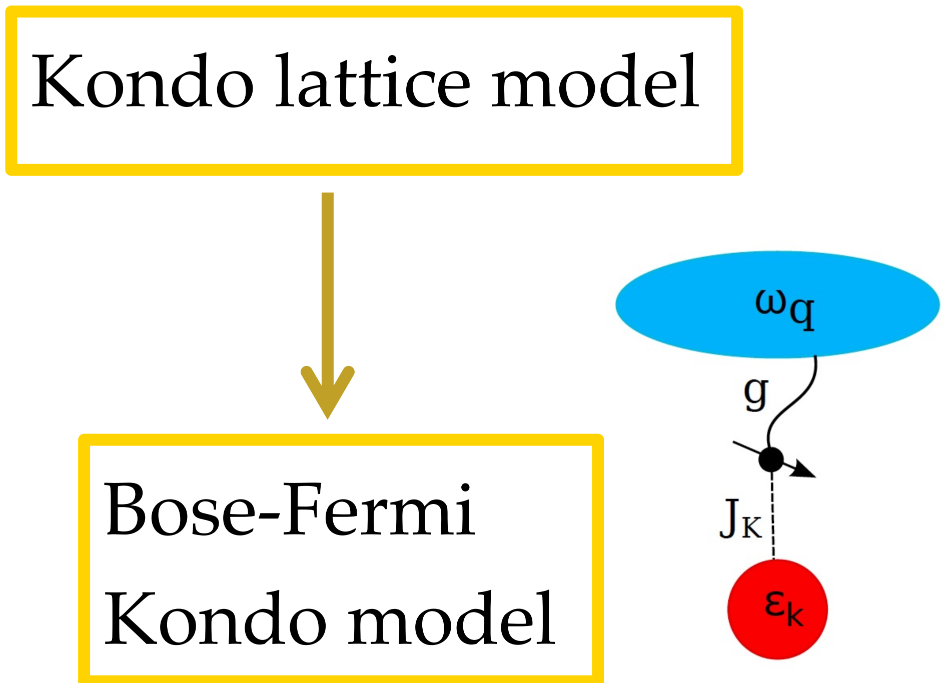
QS, S. Rabello, K. Ingersent & J. L. Smith, Nature 413, 804 (2001)

S. Kirchner, S. Paschen, Q. Y. Chen, S. Wirth, D. L. Feng,
J. D. Thompson, QS, Rev. Mod. Phys. 92, 011002 (2020)

Quantum Criticality from Kondo Destruction

EDMFT:



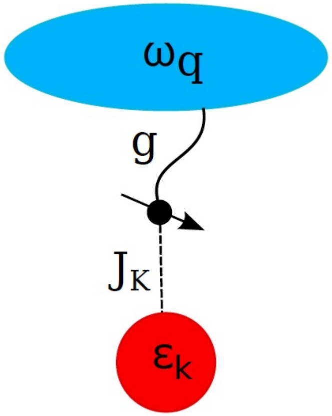


QS & J. L. Smith, PRL 77, 3391 ('96);
J. L. Smith & QS, PRB 61, 5184 ('00);
R. Chitra & G. Kotliar, PRB 63, 115110 ('01)

Quantum Criticality from Kondo Destruction

EDMFT:

Kondo lattice model → Bose-Fermi Anderson/Kondo



$$S_{BFA} = \int_0^\beta d\tau \left[\sum_\sigma f_\sigma^\dagger \partial_\tau f_\sigma + U n_{d,\uparrow} n_{d,\downarrow} - \mu n_d \right] - \int_0^\beta d\tau d\tau' \sum_\sigma f_\sigma^\dagger(\tau) V^2 G_{c,0}(\tau - \tau') f_\sigma(\tau')$$

$$+ \frac{1}{2} \int_0^\beta d\tau \int_0^\beta d\tau' \sum_{\alpha \in \{x,y,z\}} : S^\alpha : (\tau) [\chi_0^\alpha]^{-1} (\tau - \tau') : S^\alpha : (\tau') + \int_0^\beta d\tau h_{loc} S^z$$

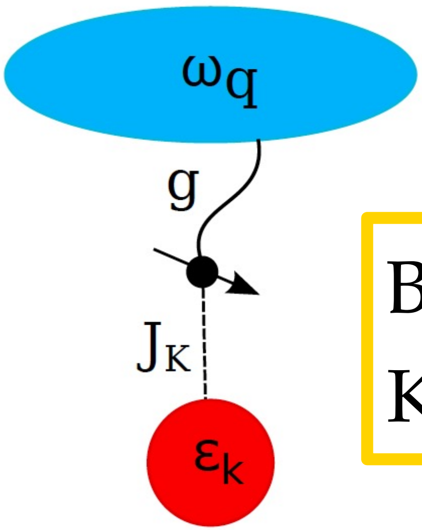
QS & J. L. Smith, PRL 77, 3391 ('96);
J. L. Smith & QS, PRB 61, 5184 ('00);
R. Chitra & G. Kotliar, PRB 63, 115110 ('01)

$$\chi_{loc}^\alpha(i\omega) = \sum_q \frac{1}{I_q + M^\alpha(i\omega)}$$

$$h_{loc} = I_Q \langle S^z \rangle$$

$$G_{c,loc}(i\omega) = \sum_k \frac{1}{i\omega - \epsilon_k - \Sigma_c(i\omega)}$$

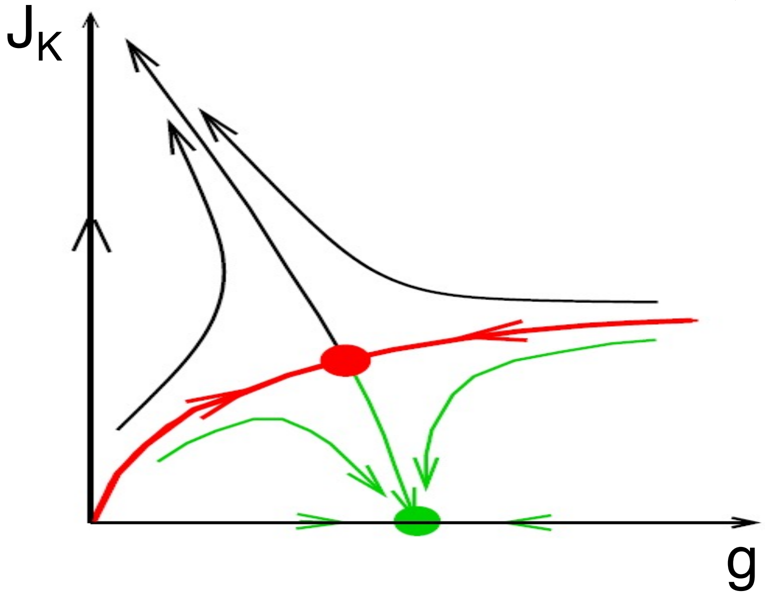
Quantum Criticality from Kondo Destruction



Bose-Fermi
Kondo model

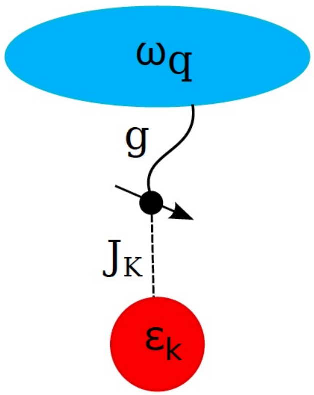
RG via ε-expansion

(1-ε: power-law spectrum of the bosonic bath)



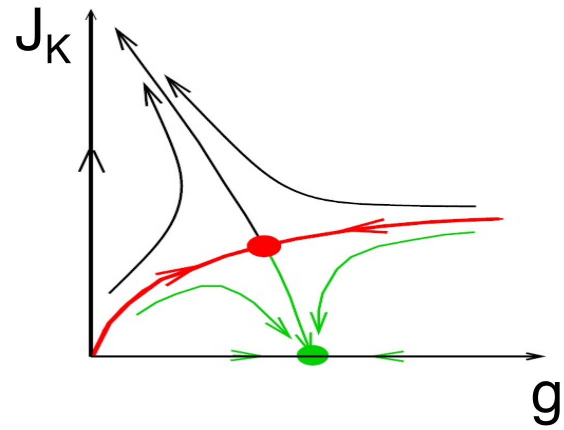
QS & J.L. Smith, PRL 77, 3391 ('96); QS, J.L. Smith & K. Ingersent, IJMPB 13, 2331 (1999);
J. L. Smith & QS, EPL 45, 228 ('99), cond-mat/9705140;
A.M. Sengupta, PRB 61, 4041 ('00), cond-mat/9707316;
L. Zhu & QS, PRB 66, 024426 ('02); G. Zarand & E. Demler, PRB 66, 024427 ('02)

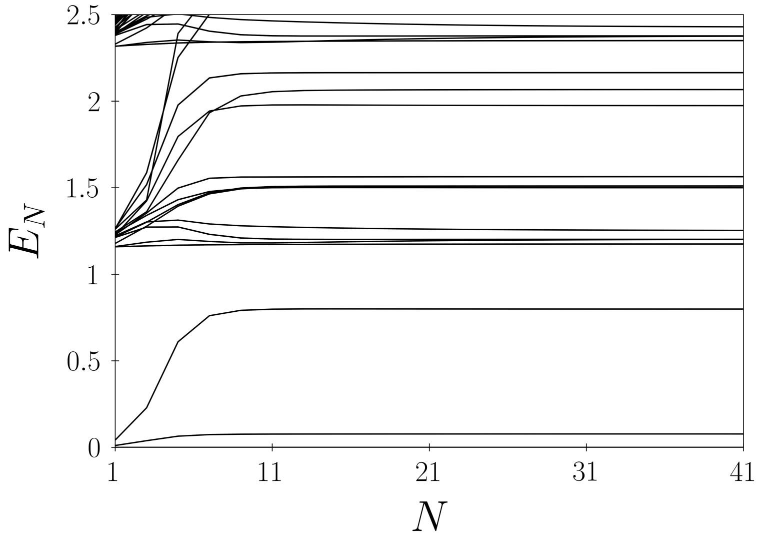
Loss of Quasiparticles

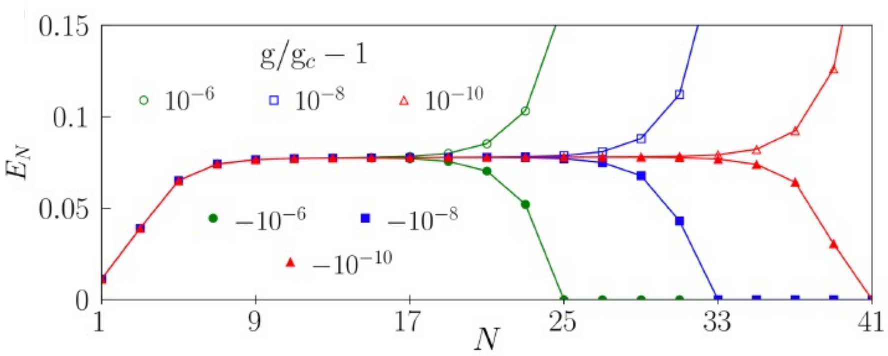


Quasiparticle weight $Z \rightarrow 0$

RG via ε-expansion



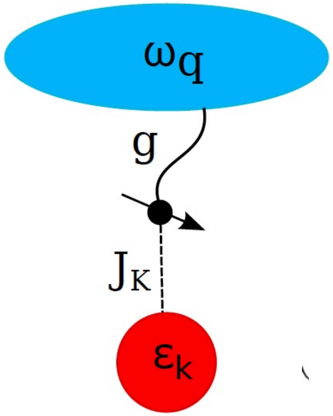




Critical spectrum at g=g_c does not have a Fermi liquid form

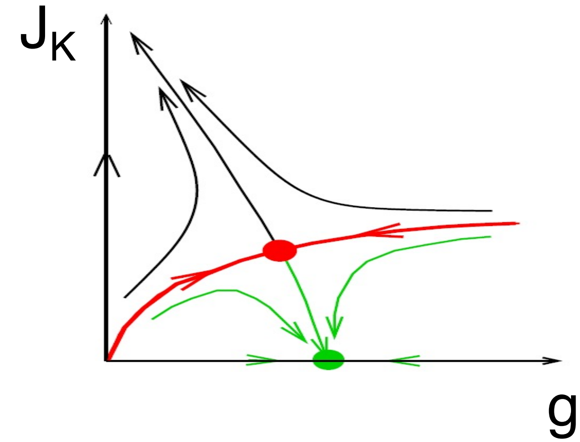
A.Kandala, H. Hu, QS, K. Ingersent, arXiv:2206.01174

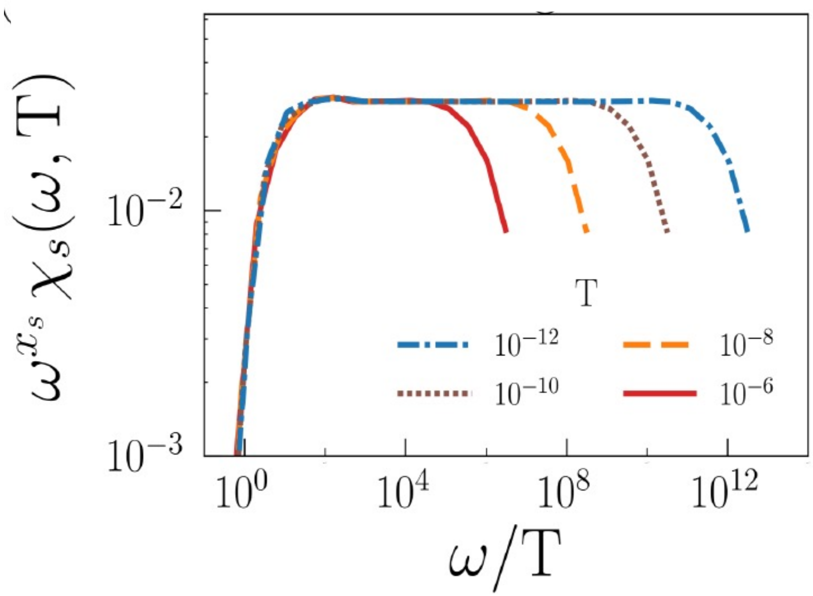
Interacting Fixed Point → Dynamical Planckian ($\hbar\omega / k_B T$) Scaling



Quasiparticle weight Z→0

RG via ε-expansion

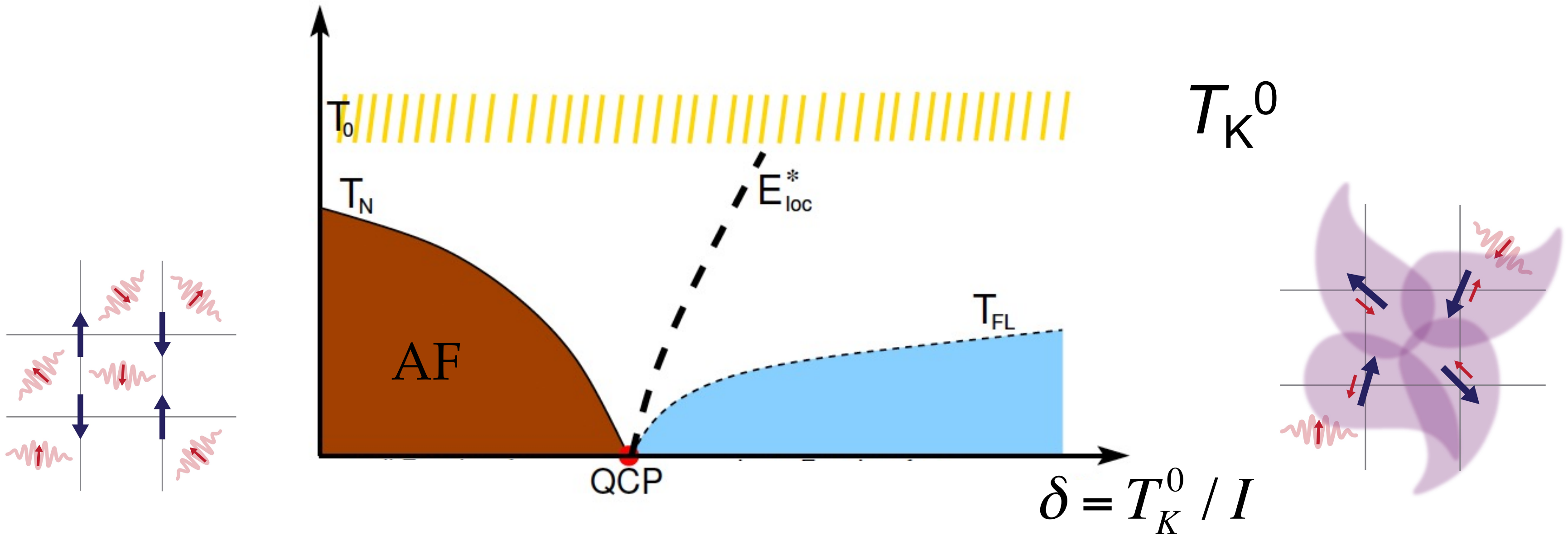




A. Kandala, H. Hu, QS, K. Ingersent, arXiv:2206.01174

Kondo Destruction via EDMFT

Critical destruction of Kondo singlet
at the T=0 onset of antiferromagnetic order



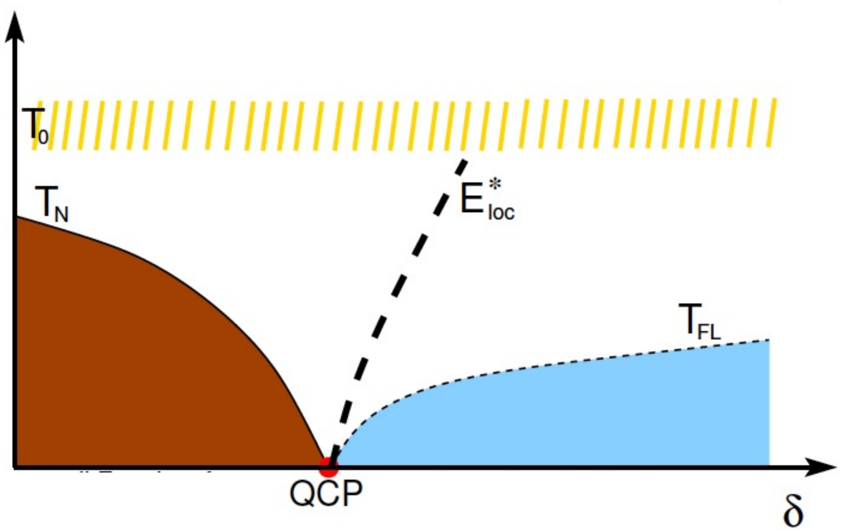
QS, S. Rabello, K. Ingersent & J. L. Smith, Nature 413, 804 (2001)

S. Kirchner, S. Paschen, Q. Y. Chen, S. Wirth, D. L. Feng,
J. D. Thompson, QS, Rev. Mod. Phys. 92, 011002 (2020)

Dynamical Scaling

Dynamical Planckian ($\hbar\omega/k_{\mathrm{B}}T$) scaling:

$$\chi(\mathbf{Q},\omega) \sim \frac{1}{(-i\hbar\omega)^{\alpha}} W^{-1}\left(\frac{\hbar\omega}{k_{\mathrm{B}}T}\right)$$



--The QCP is interacting (instead of Gaussian), from Kondo destruction

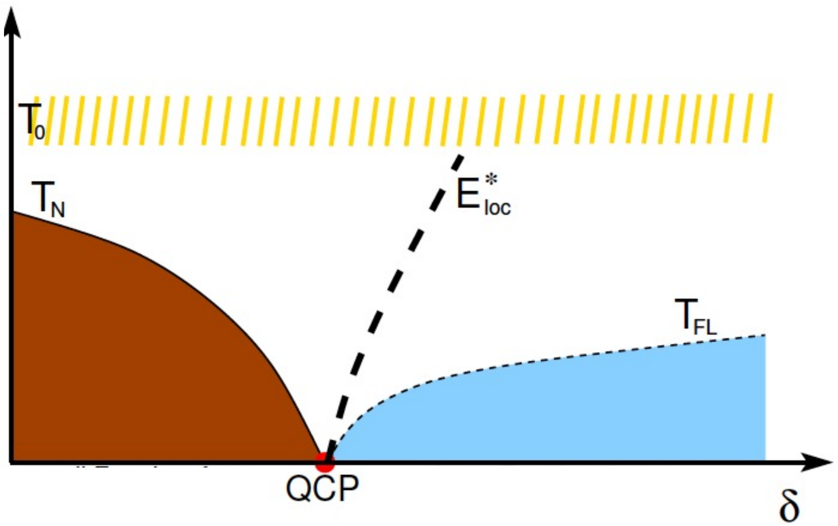
--$k_{\mathrm{B}}T$ is the only energy scale

QS, S. Rabello, K. Ingersent & J. L. Smith, Nature 413, 804 (2001)

Dynamical Scaling

Dynamical Planckian ($\hbar\omega/k_B T$) scaling:

$$\chi(\mathbf{q},\omega) \sim \frac{1}{(I_{\mathbf{q}} - I_{\mathbf{Q}}) + A(-i\hbar\omega)^{\alpha}\, W(\hbar\omega/k_B T)}$$



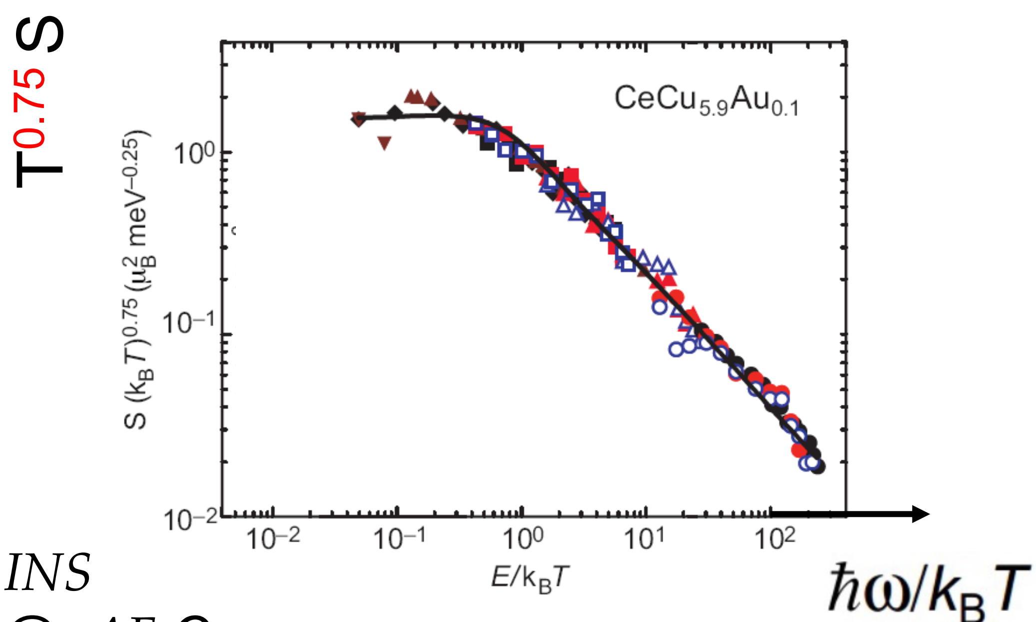
QS, S. Rabello, K. Ingersent
& J. L. Smith, Nature 413, 804 (2001)

α = 0.72-0.78

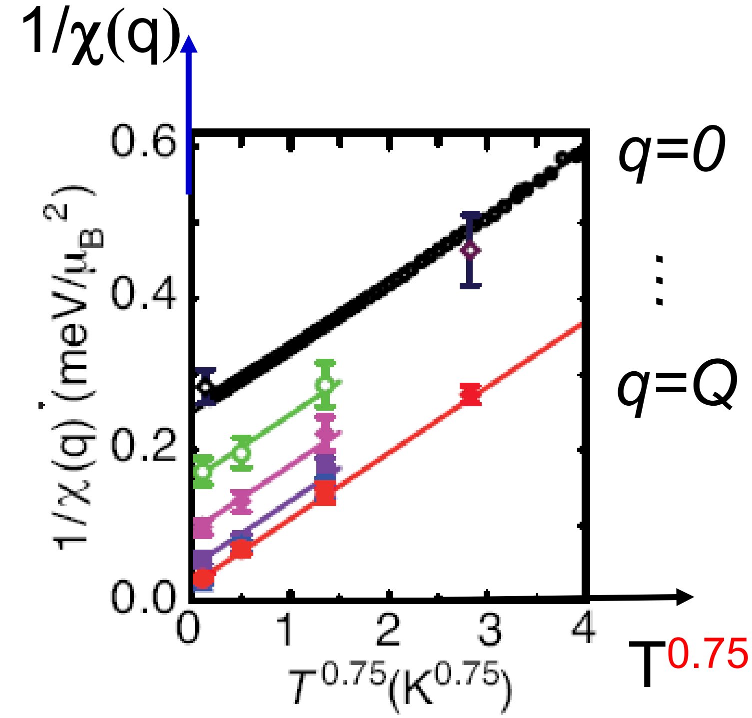
- D. Grempel & QS, PRL (2003)
- J-X Zhu, D. Grempel & QS, PRL (2003)
- M. Glossop & K. Ingersent, PRL (2007)
- J-X Zhu, S. Kirchner, R. Bulla, QS, PRL (2007)

Dynamical Scaling of Spin Responses in $CeCu_{5.9}Au_{0.1}$

Fractional exponent α=0.75-0.80



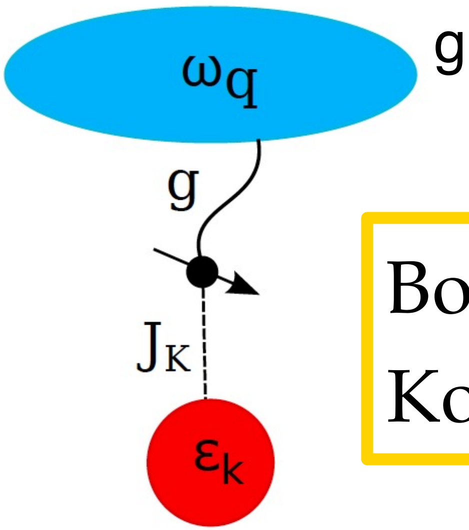
INS
@ *AF Q*



INS and M/H

inelastic neutron scattering expts:
A. Schröder et al. ($CeCu_{5.9}Au_{0.1}$);
M. Aronson et al.

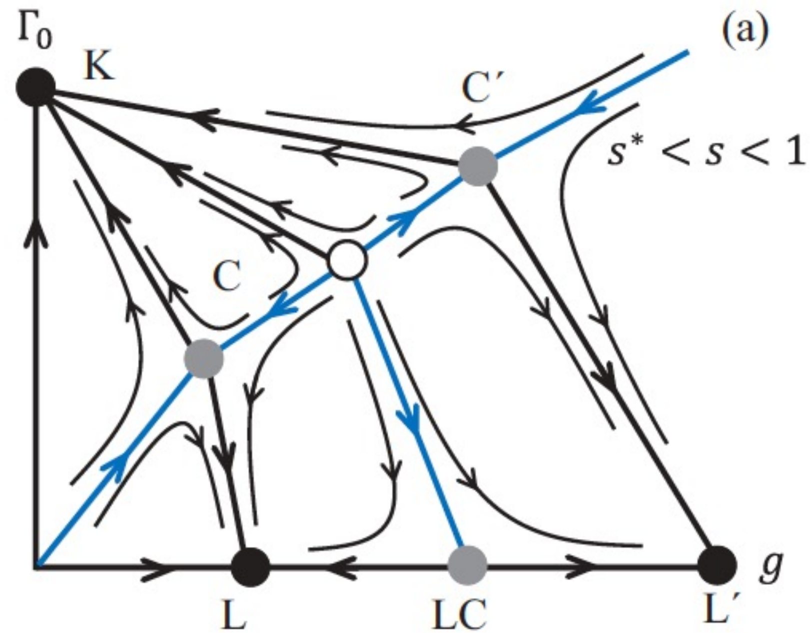
SU(2)-symmetric Model



Bose-Fermi
Kondo model

RG flow:

$(1\text{-}\varepsilon \equiv s)$

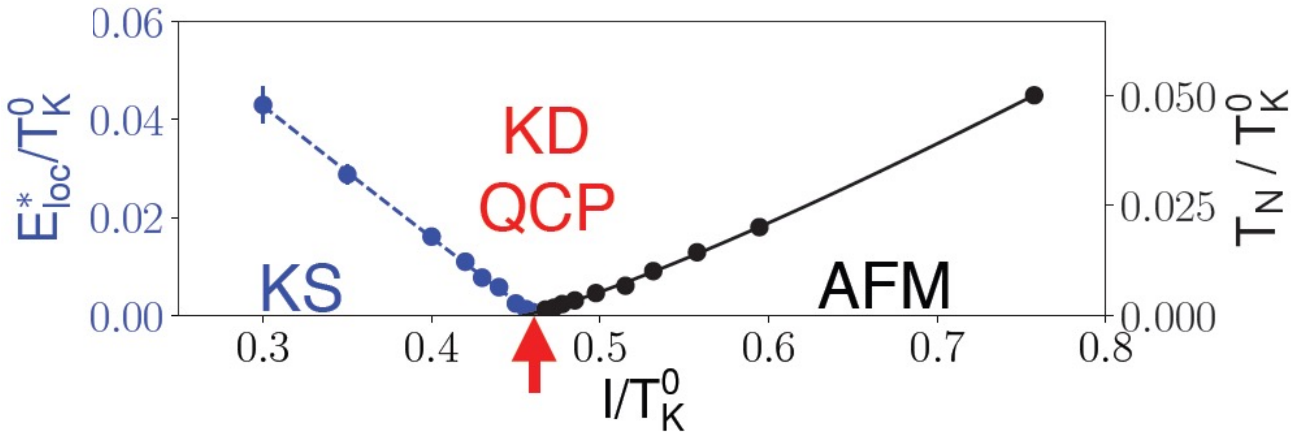


(Fixed-point annihilation)

A.Cai & QS, Phys. Rev. B100, 014439 (2019)

See also A. Nahum, arXiv:2202.08431

SU(2) Kondo Lattice: Loss of Quasiparticles, and Dynamical Quantum Scaling



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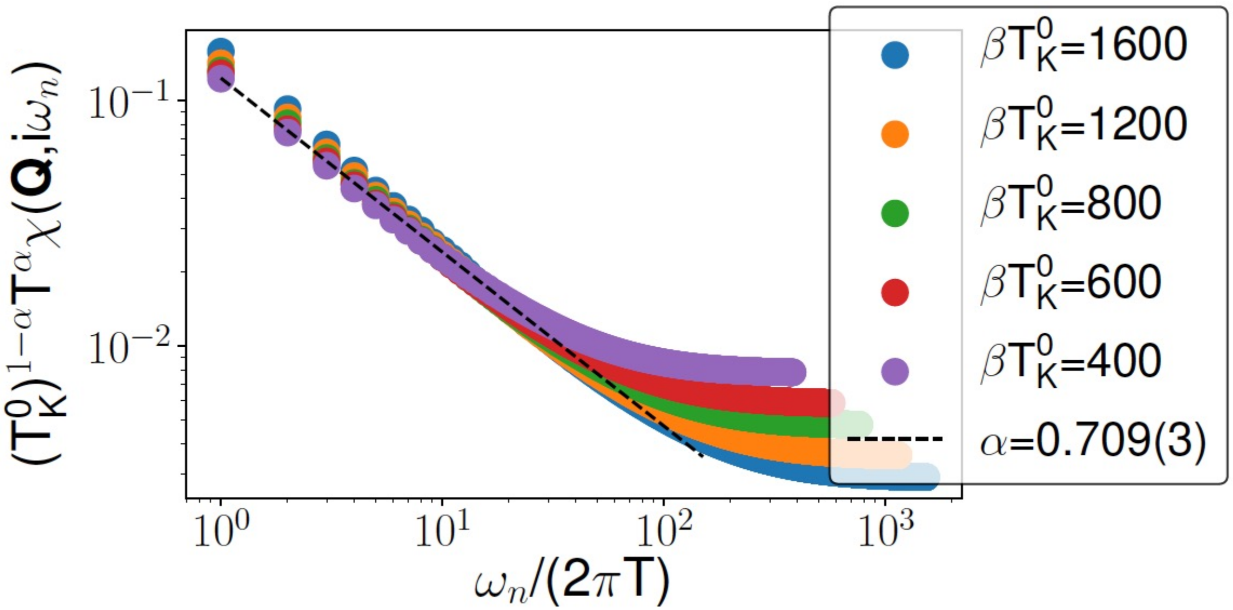


H. Hu, A. Cai & QS (2020)

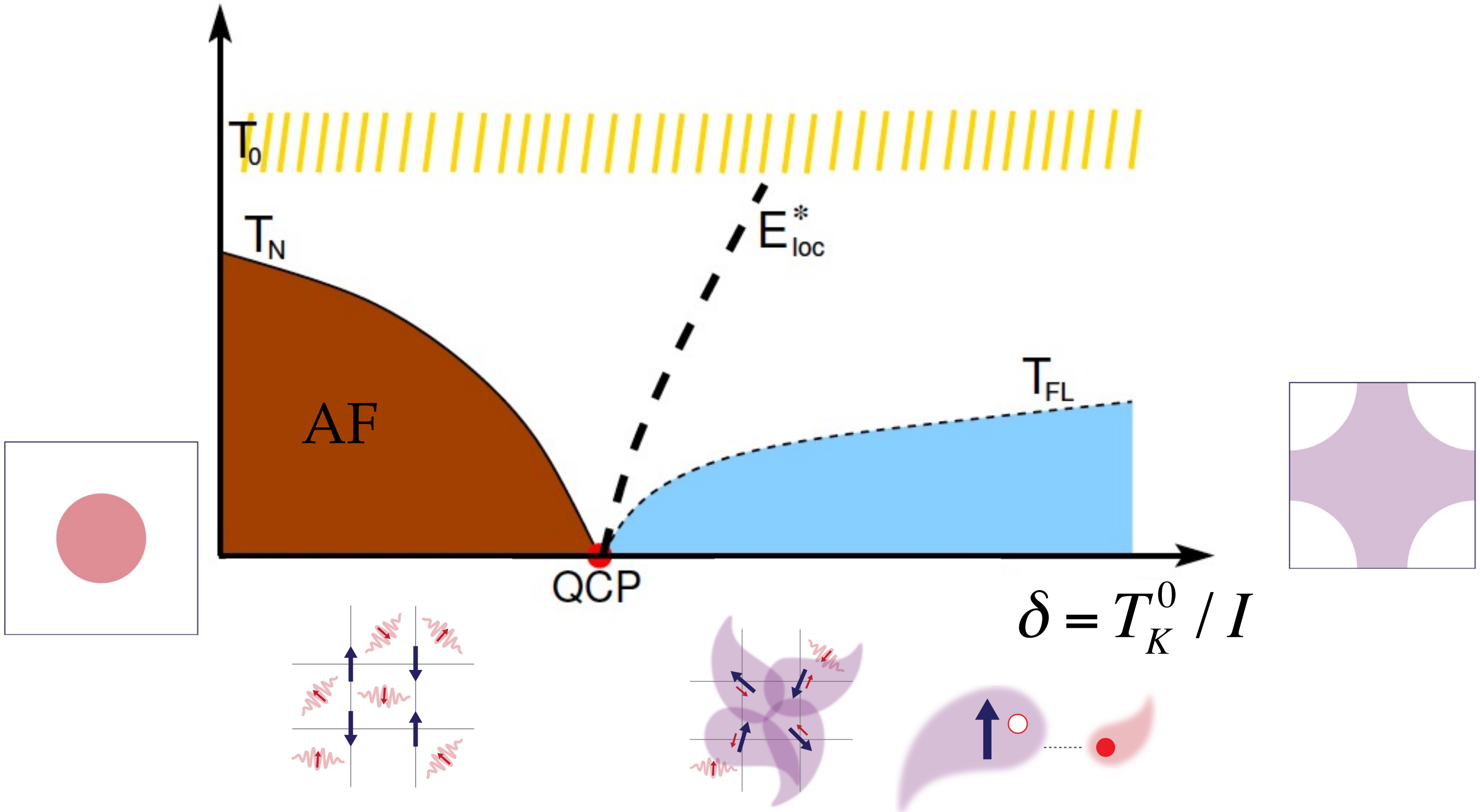
Kondo Destruction

$\leftrightarrow$

"Large"-to-"Small" Fermi Surface Fluctuations

Quantum Criticality from Kondo Destruction

Sudden reconstruction of
Fermi surface from large to small



QS, S. Rabello, K. Ingersent & J. L. Smith, Nature 413, 804 (2001)

Quantum Criticality from Kondo Destruction

- Loss of quasiparticles via the suppression of the Kondo-destruction energy scale E^*_{loc}

- Suppression of the Kondo scale ←→ the suppression of a pole in the conduction-electron self-energy:

$$\Sigma(\mathbf{k}, \omega) = \frac{(b^*)^2}{\omega - \varepsilon_f^*}$$

QS, S. Rabello, K. Ingersent & J. L. Smith, Nature 413, 804 (2001)

Quantum Criticality from Kondo Destruction

- Loss of quasiparticles via the suppression of the Kondo-destruction energy scale E^*_{loc}

- Suppression of the Kondo scale ←→ the suppression of a pole in the conduction-electron self-energy:

$$\Sigma(\mathbf{k}, \omega) = \frac{(b^*)^2}{\omega - \varepsilon^*_f}$$

- Kondo destruction—Prediction: large-to-small Fermi surface transformation across the QCP

QS, S. Rabello, K. Ingersent & J. L. Smith, Nature 413, 804 (2001)

Quantum Criticality from Kondo Destruction

- **Fermi-surface jump based on Hall measurements ($YbRh_2Si_2$, $Ce_3Pd_{20}Si_6$):**

S. Paschen, T. Luhmann, S. Wirth, P. Gegenwart, O. Trovarelli, C. Geibel, F. Steglich, P. Coleman, QS, Nature 432, 881 (2004)

S. Friedemann, N. Oeschler, S. Wirth, C. Krellner, C. Geibel, F. Steglich, S. Paschen, S. Kirchner, and QS, PNAS 107, 14547 (2010)

P. Gegenwart, T. Westerkamp, C. Krellner, Y. Tokiwa, S. Paschen, C. Geibel, F. Steglich, E. Abrahams, QS, Science 315, 969 (2007)

V. Martelli, A. Cai, E. M. Nica, M. Taupin, A. Prokofiev, C. C. Liu, H.-H. Lai, R. Yu, K. Ingersent, R. Kuchler, A. M. Strydom, D. Geiger, J. Haenel, J. Larrea, QS, S. Paschen, PNAS 116, 17701 (2019).

- **Fermi-surface jump based on quantum oscillations ($CeRhIn_5$):**

H. Shishido, R. Settai, H. Harima, & Y. Onuki, JPSJ 74, 1103 ('05)

L. Jiao, Y. Chen, Y. Kohama, D. Graf, E. D. Bauer, J. Singleton, J.-X. Zhu, Z. F. Weng, G. M. Pang, T. Shang, J. L. Zhang, H. O. Lee, T. Park, M. Jaime, J. D. Thompson, F. Steglich, QS, H. Q. Yuan, PNAS 112, 673 (2015).

Quantum Criticality from Kondo Destruction

- Fermi-surface jump based on Hall measurements ($YbRh_2Si_2$, $Ce_3Pd_{20}Si_6$)

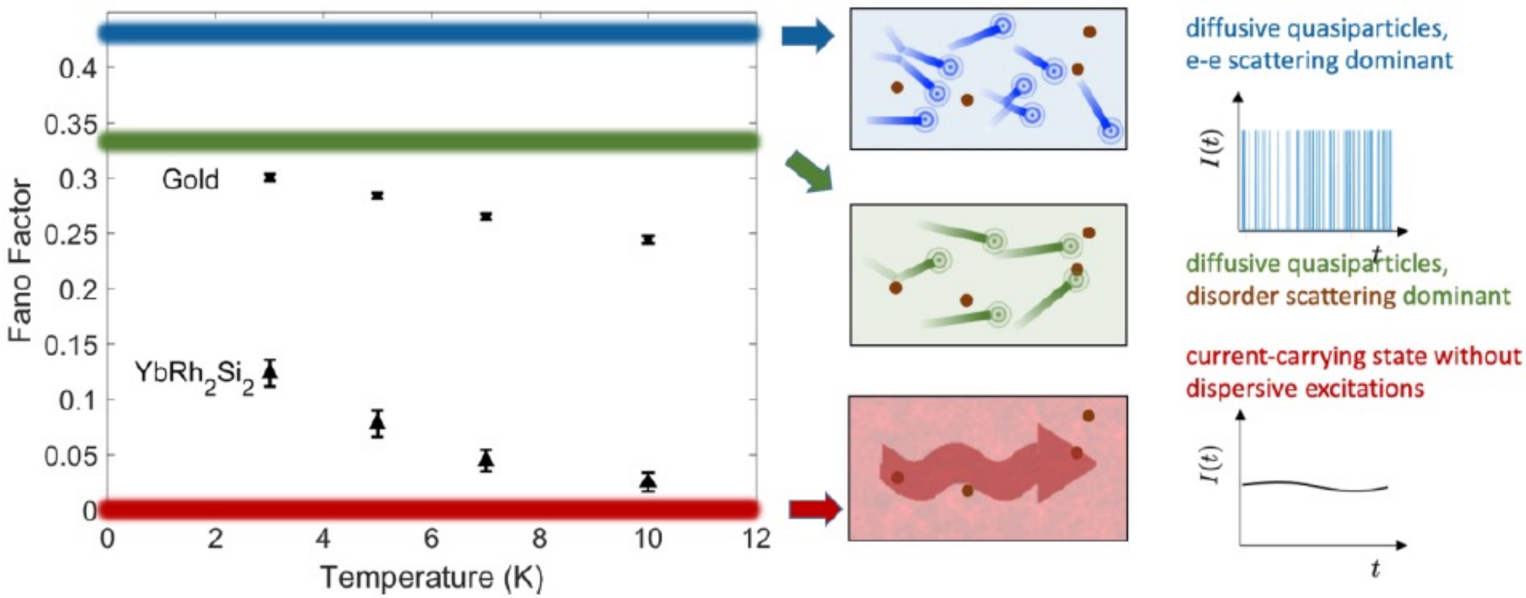
- Fermi-surface jump based on quantum oscillations ($CeRhIn_5$)

- Cf. Status report on Fermi-surface jump and localization-delocalization across the QCP:

  "Heavy-electron quantum criticality and single-particle spectroscopy", S. Kirchner, S. Paschen, Q. Chen, S. Wirth, D. L. Feng, J. D. Thompson, QS, Rev. Mod. Phys. 92, 011002 (2020).

Quantum Criticality from Kondo Destruction

- ➢Fermi-surface jump based on Hall measurements
- ➢Fermi-surface jump based on quantum oscillations
- ➢Loss of quasiparticles: Shot-noise reduction



L. Chen, D. T. Lowder, E. Bakali, A. M. Andrews, W. Schrenk, M. Waas, R. Svagera, G. Eguchi, L. Prochaska, QS, S. Paschen, D. Natelson, arXiv:2206.00673

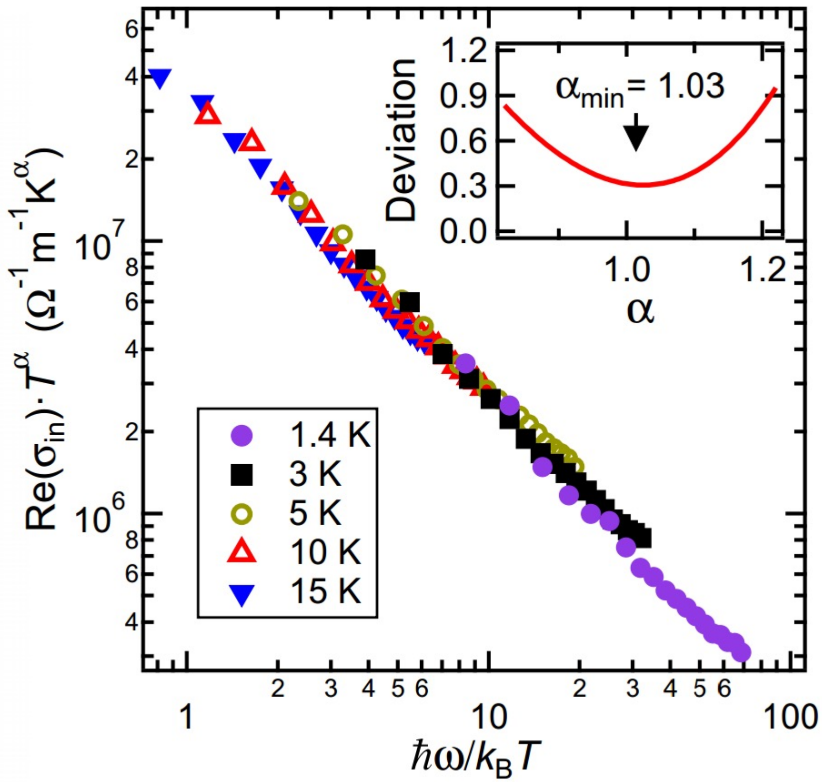
Charge Response with Dynamical Scaling

QUANTUM CRITICALITY

Singular charge fluctuations at a magnetic quantum critical point

L. Prochaska[1*], X. Li[2*†], D. C. MacFarland[1,3*‡], A. M. Andrews[3], M. Bonta[4], E. F. Bianco[5§], S. Yazdi[6¶], W. Schrenk[7], H. Detz[7#], A. Limbeck[4], Q. Si[8], E. Ringe[6**], G. Strasser[3,7], J. Kono[2,6,8], S. Paschen[1,8††]

$\hbar\omega/k_B T$ scaling of optical conductivity



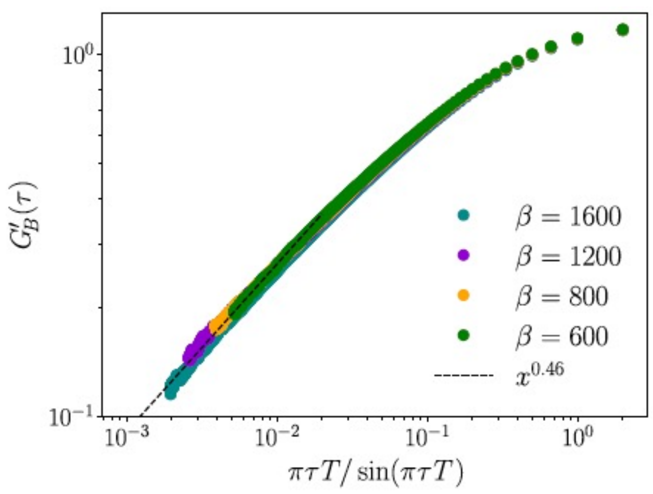
Science 367, 285 (2020)

Dynamical Quantum Scaling of Charge Response at a Kondo-destruction QCP

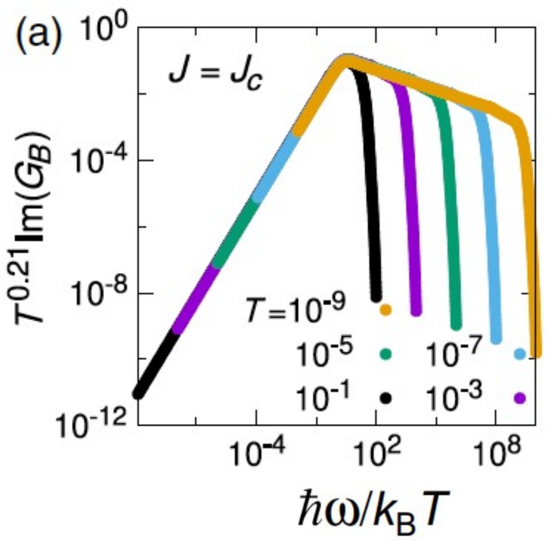
$$\mathrm{J_K}\sum_{\alpha} S\cdot s_{\alpha} = \mathrm{J_K}\sum_{\sigma\sigma'}(f_{\sigma}^{\dagger}f_{\sigma'} - \delta_{\sigma\sigma'})c_{\alpha\sigma'}^{\dagger}c_{\alpha\sigma} \xrightarrow{H.S.\,transform} B_{\alpha}^{\dagger}\sum_{\sigma} c_{\alpha\sigma}^{\dagger}f_{\sigma} + h.c.$$

Chargon

Kondo lattice via EDMFT SU(2):



BFK model at large-N:



A. Cai, Z. Yu, H. Hu, S. Kirchner, QS, PRL 124, 027205 (2020)

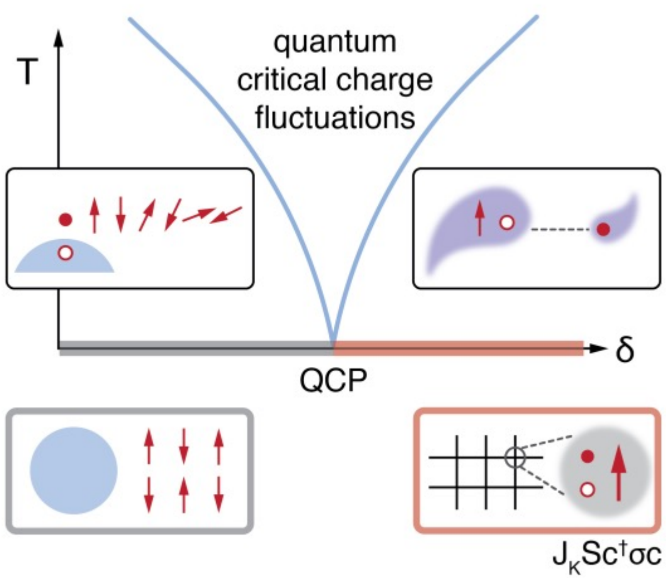
Dynamical Quantum Scaling of Charge Response at a Kondo-destruction QCP

Qualitative picture:

- QCP involves the destruction of Kondo singlet: localization-delocalization of f electrons

  → electronic d.o.f. is critical
- Interacting QCP

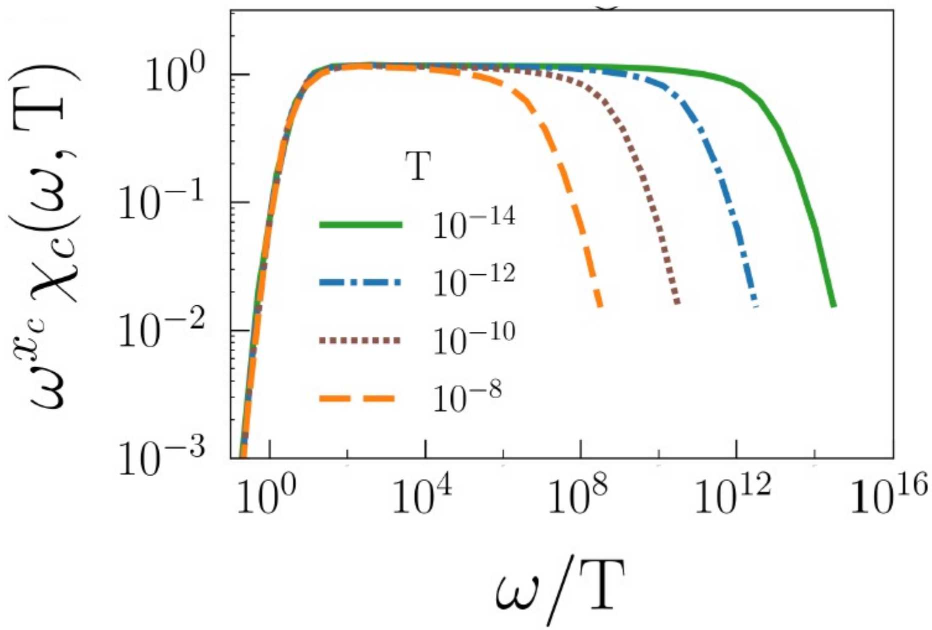
Charge response also satisfies $\hbar\omega/kBT$ scaling



- ➢ Captures a dynamical Kondo effect at the Kondo-destruction QCP
- ➢ Implications for superconductivity

Dynamical Quantum Scaling of Charge Response at a Kondo-destruction QCP

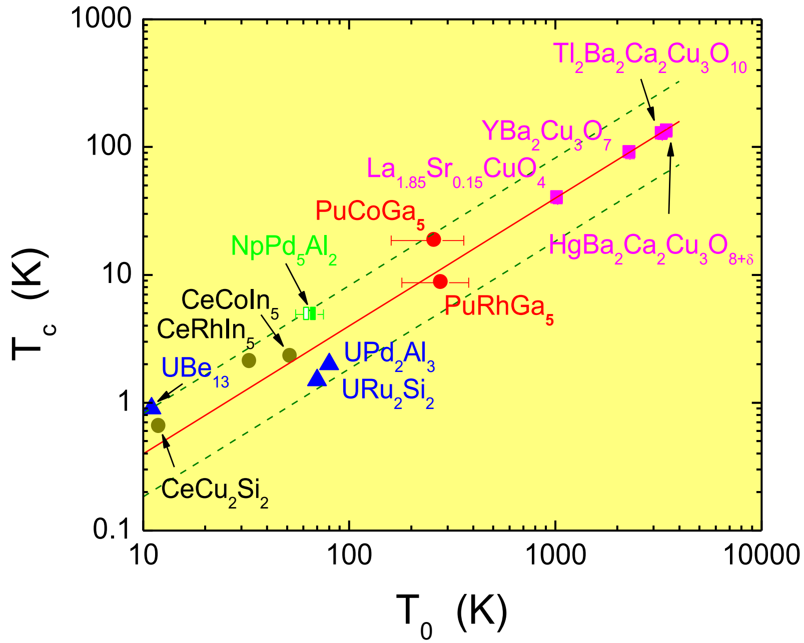
The regime of particle-hole asymmetry (Bose-Fermi Anderson, mixed-valence) (the case for CeRhSn, CeIrSn)



A. Kandala, H. Hu, QS, K. Ingersent, arXiv:2206.01174

From Loss of Quasiparticles
to
High T_c Superconductivity

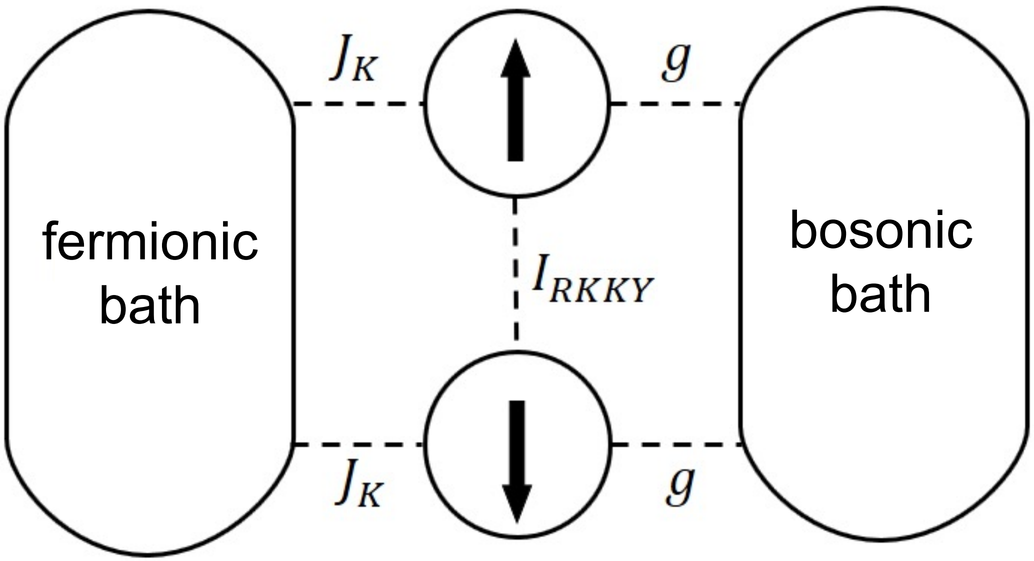
- **Heavy-fermion superconductivity: ~50 members**
- **Most of them with antiferromagnetic correlations**
- **Modern understanding of quantum criticality has not been treated in driving superconductivity**



Cluster-EDMFT

$$H = \sum_{i,j,\sigma} t_{ij} \left(c_{i\sigma}^{\dagger} c_{j\sigma} + \text{h.c.} \right) + \sum_{i} \left(\epsilon_f n_{fi} + U n_{fi\uparrow} n_{fi\downarrow} \right)$$
$$+ \sum_{i,\sigma} \left(V c_{i\sigma}^{\dagger} f_{i\sigma} + \text{h.c.} \right) + \sum_{i,j} I_{ij} \mathbf{S}_{fi} \cdot \mathbf{S}_{fj}$$

Cluster-EDMFT

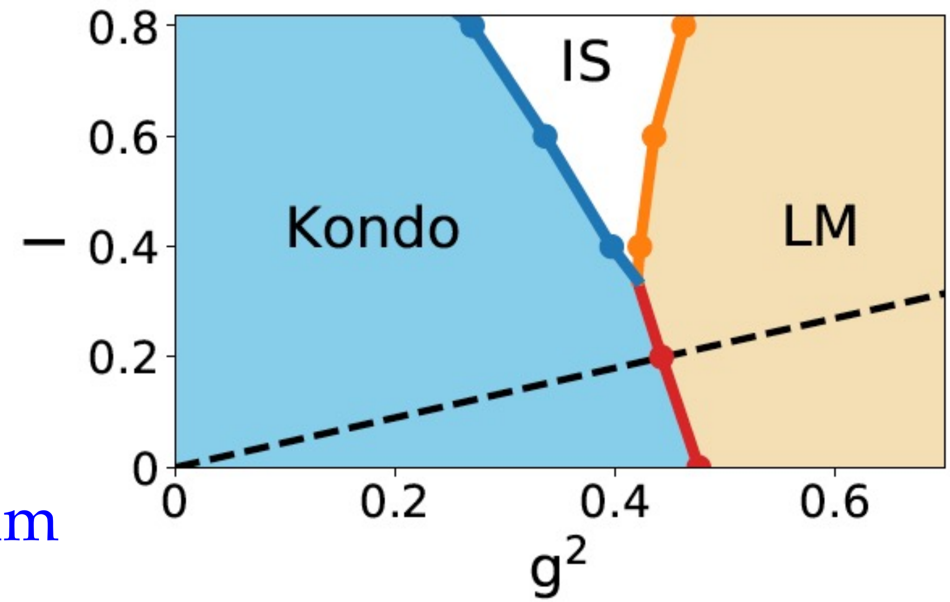


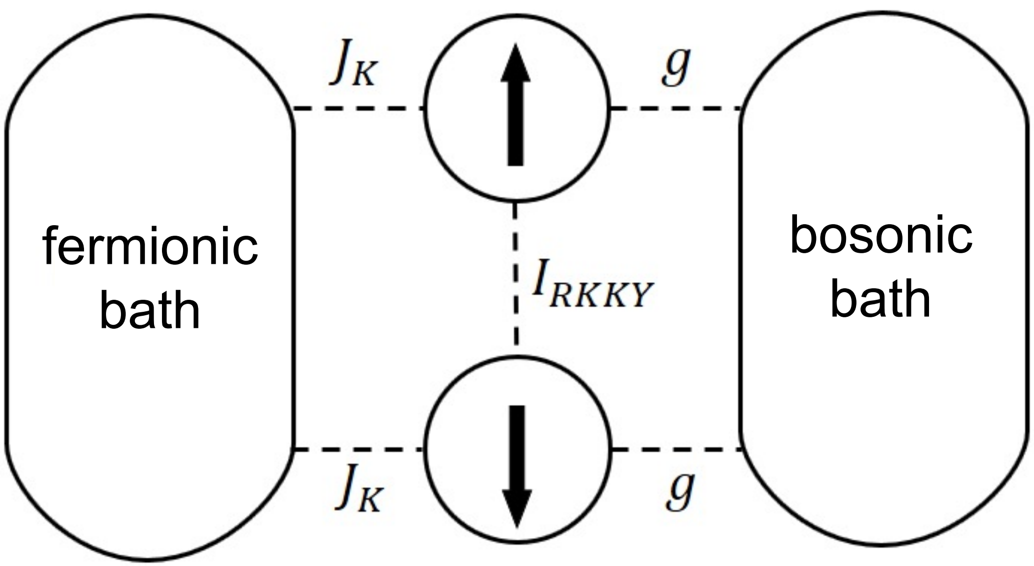
J. Pixley, A. Cai & QS, PRB 91, 125127 (2015)

Cluster-EDMFT

RKKY interaction generates spin-singlet correlations:

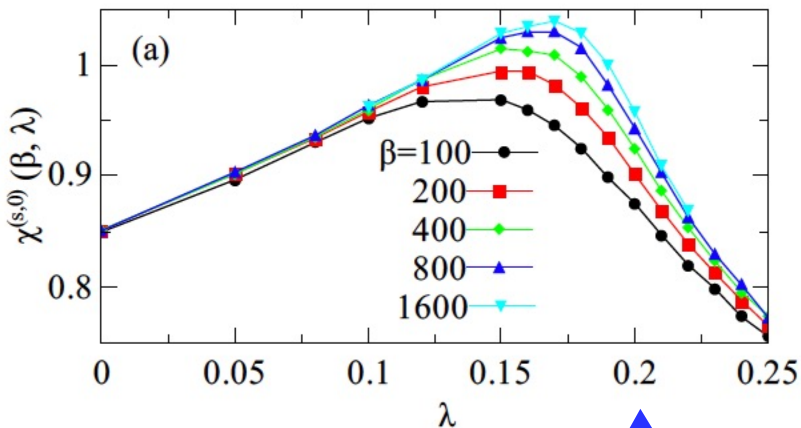
- bond-singlet correlations everywhere
- "intersite-singlet (IS)" regime in the phase diagram



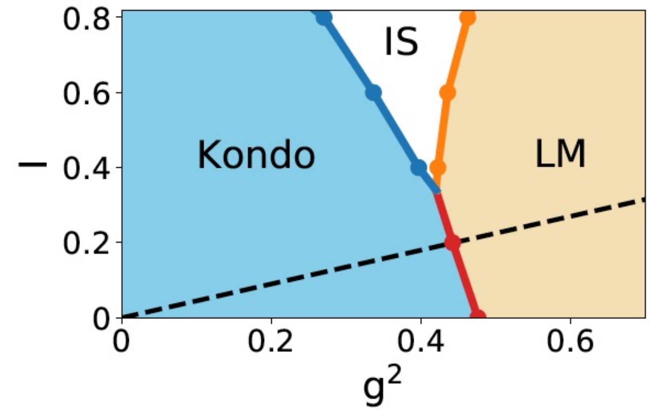


Pairing Correlations from RKKY Interactions

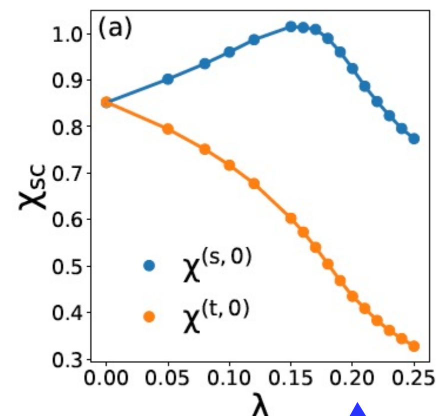
Spin-singlet pairing correlation



KD QCP



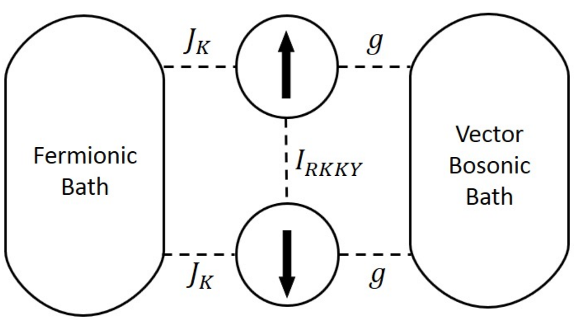
λ



singlet

triplet

KD QCP

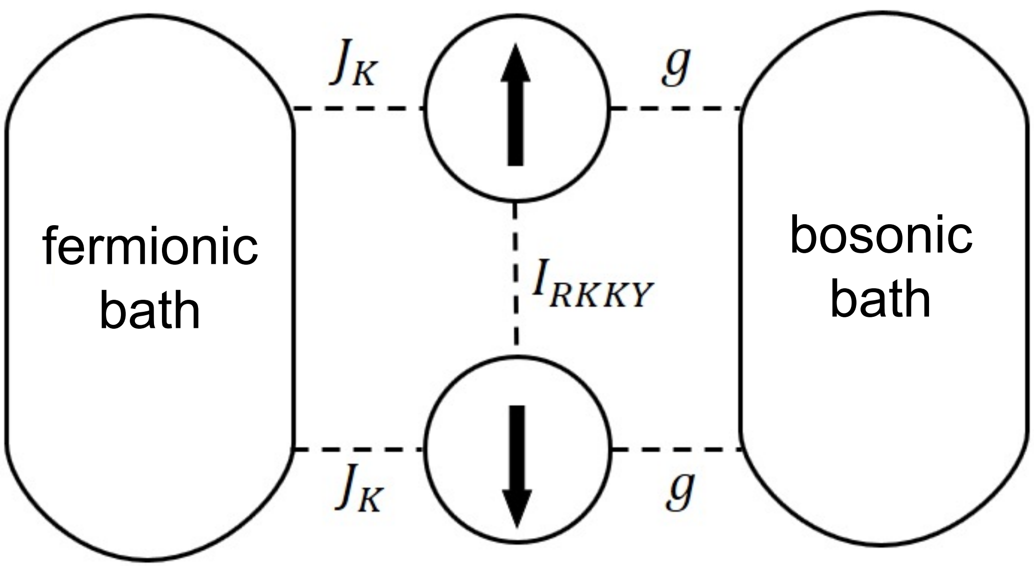


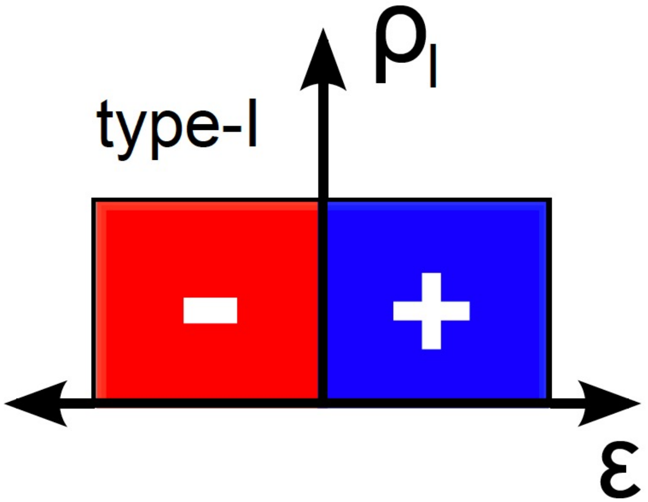
SU(2)

Cluster-EDMFT

- Type I model

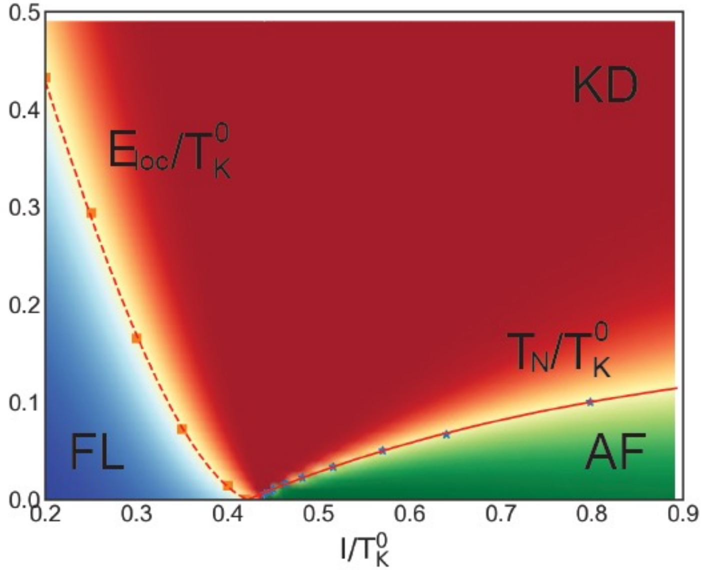
$$\chi^{\alpha}_{loc}(i\omega) = \sum_q \frac{1}{I_q + M^{\alpha}(i\omega)} = \int_{-\infty}^{\infty} \frac{\rho_I(\epsilon)}{\epsilon + M^{\alpha}(i\omega)} d\epsilon$$

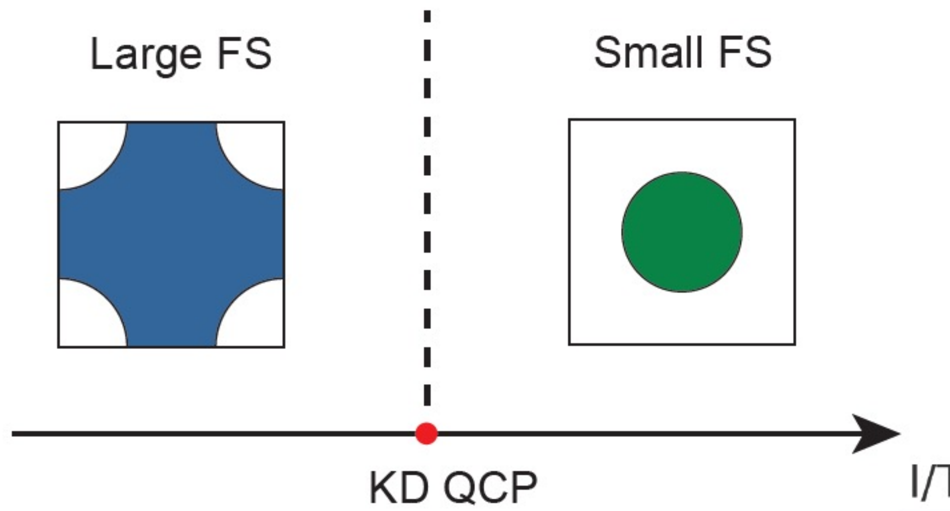




Kondo-destruction QCP

- Type I model





Cluster-EDMFT

EDMFT result robust: loss of quasiparticles at the QCP

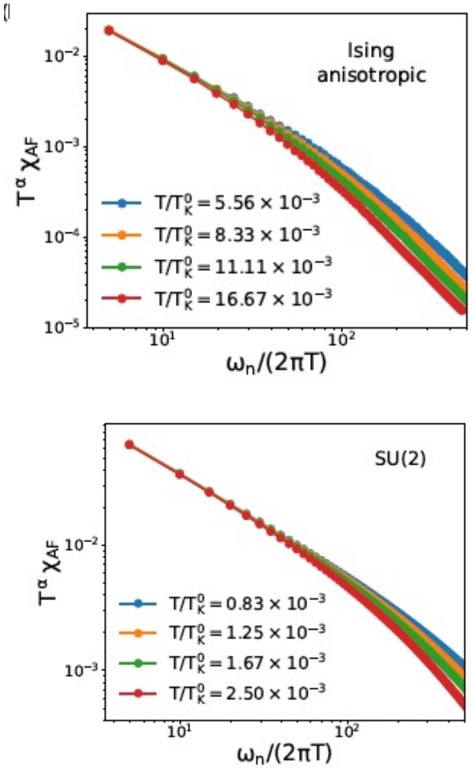
H. Hu, A. Cai, L. Chen, L. Deng, J. Pixley, K. Ingersent & QS, arXiv:2109.13224

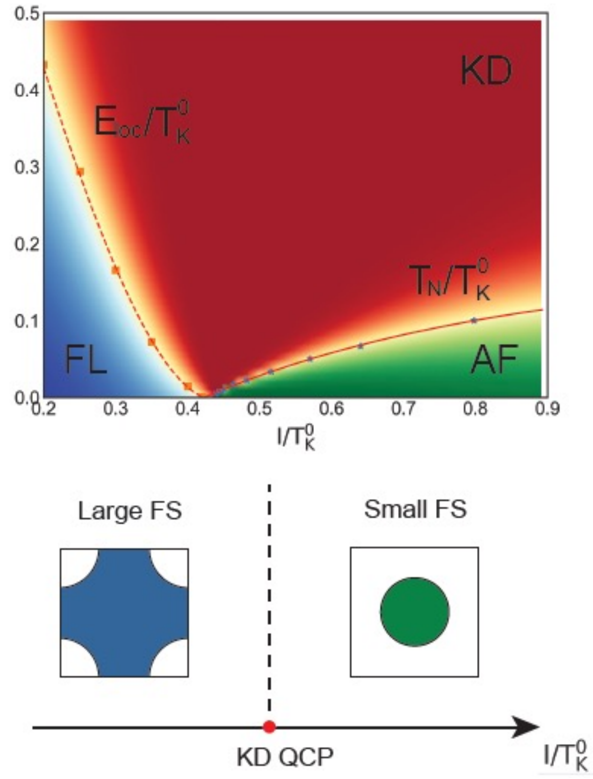
Kondo-destruction Quantum Critical Metal

Kondo-destruction quantum criticality:
dynamical scaling is robust

$$\chi_{AF}(T) \sim T^{-\alpha}$$

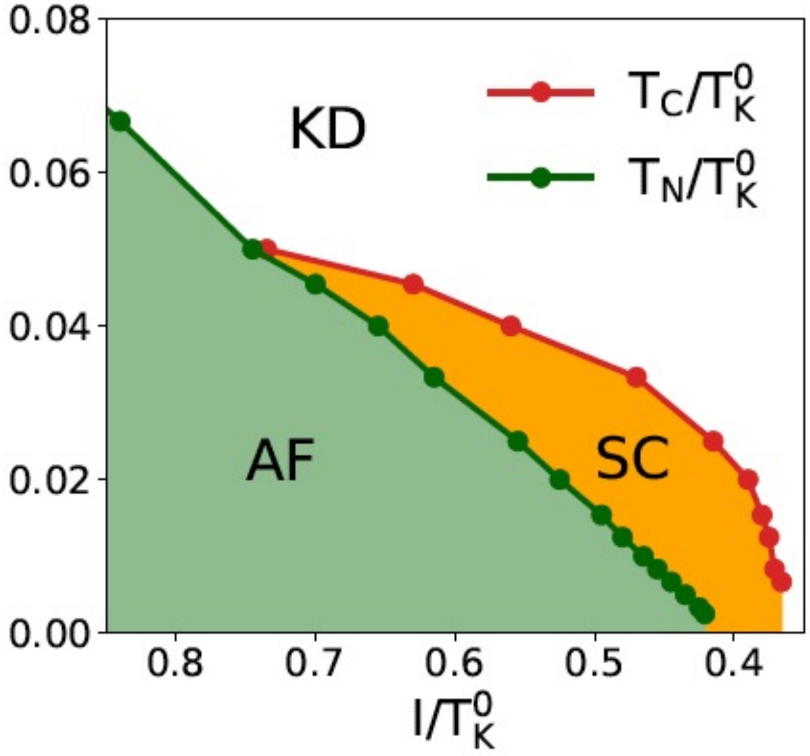
$\alpha = 0.81(4)$





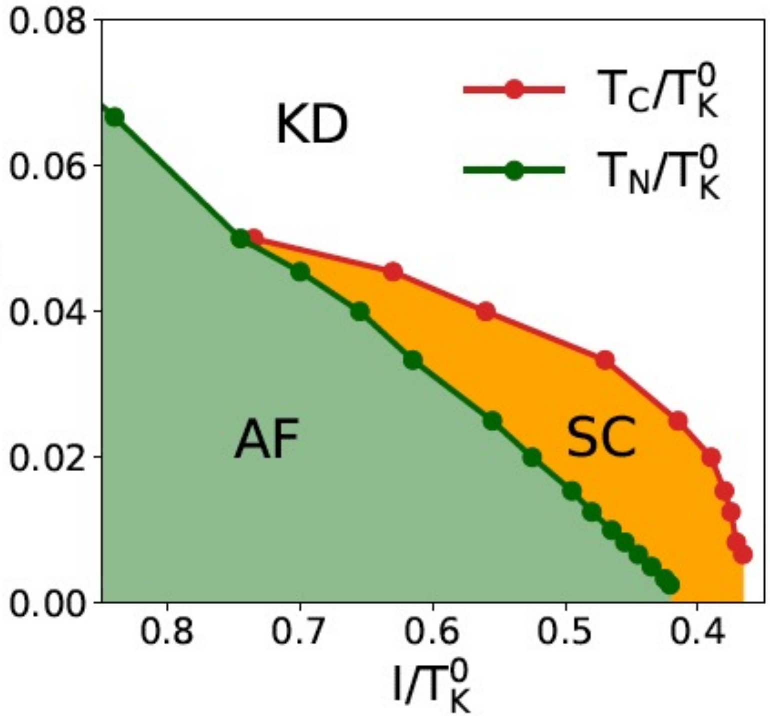
H. Hu, A. Cai, L. Chen, L. Deng, J. Pixley, K. Ingersent & QS,
arXiv:2109.13224

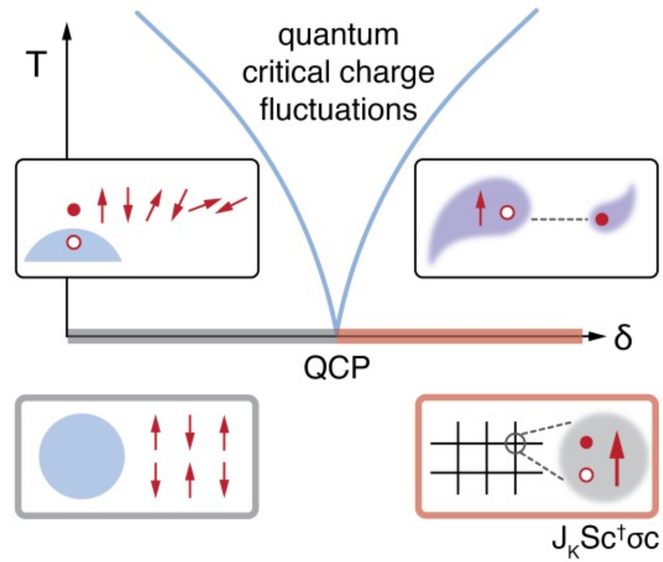
Development of Superconductivity



H. Hu, A. Cai, L. Chen, L. Deng, J. Pixley, K. Ingersent & QS, arXiv:2109.13224

Development of Superconductivity





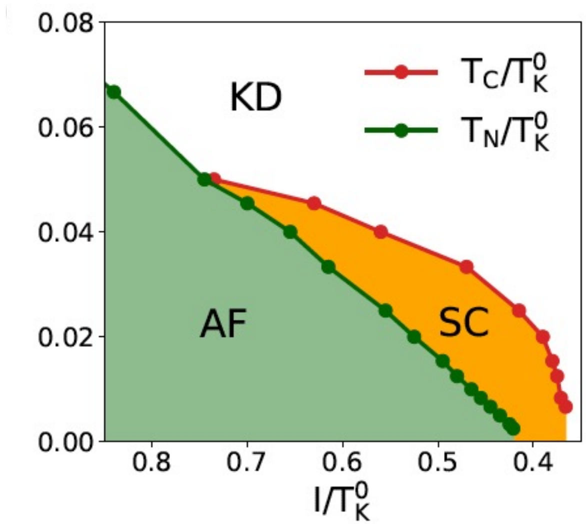
Superconductivity
driven by
Fermi surface fluctuations

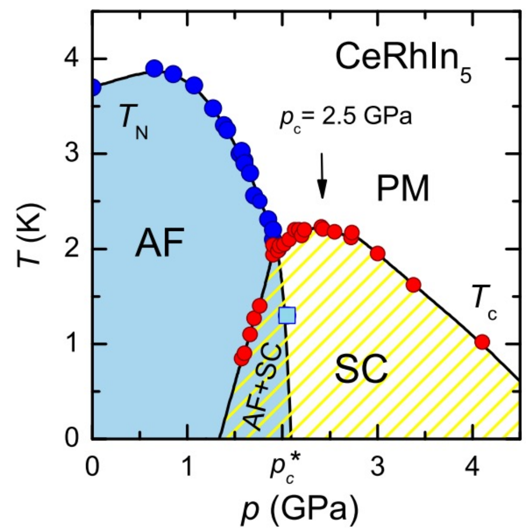
H. Hu, A. Cai, L. Chen, L. Deng, J. Pixley, K. Ingersent & QS,
arXiv:2109.13224

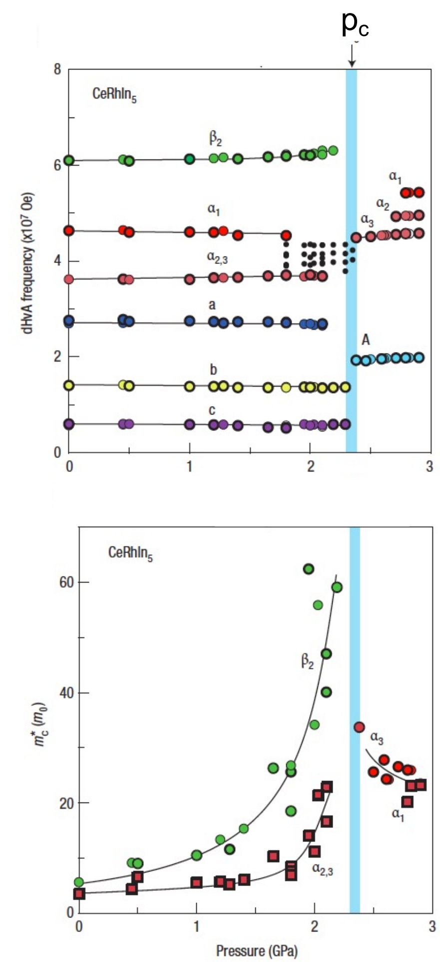
Superconductivity near Kondo-destruction QCP in $CeRhIn_5$

high T_c:

$T_c/T_K^0 \approx 0.03$





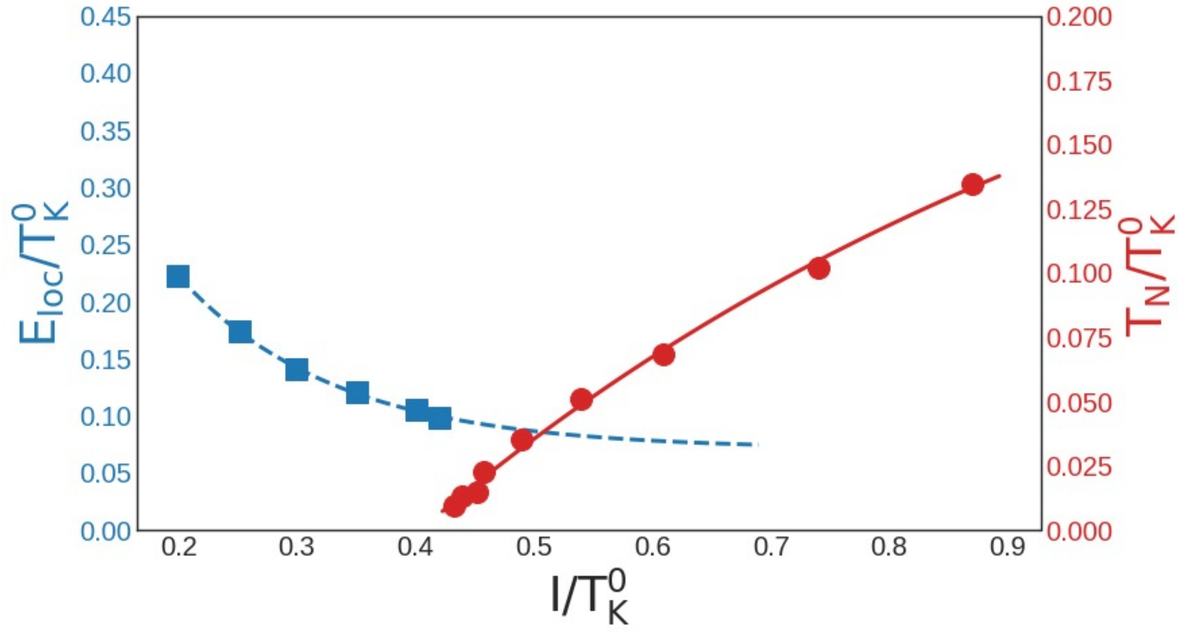


T. Park et al., Nature (2006);
G. Knebel et al., PRB (2006)

H. Shishido et al., JPSJ (2005)

SDW$_r$ QCP

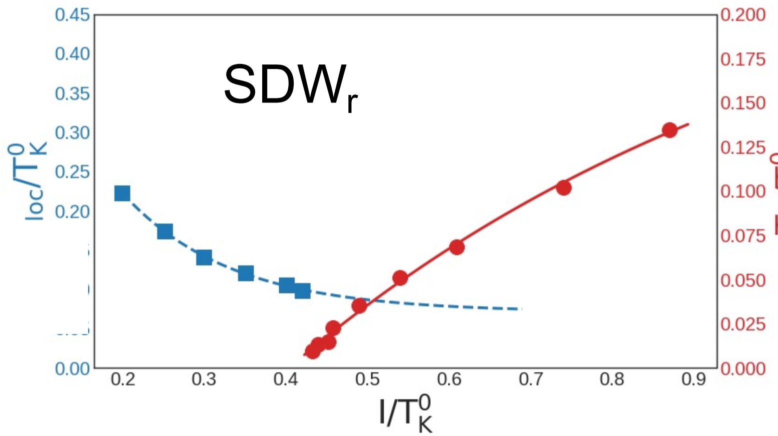
- Type II model: SDW$_r$ QCP

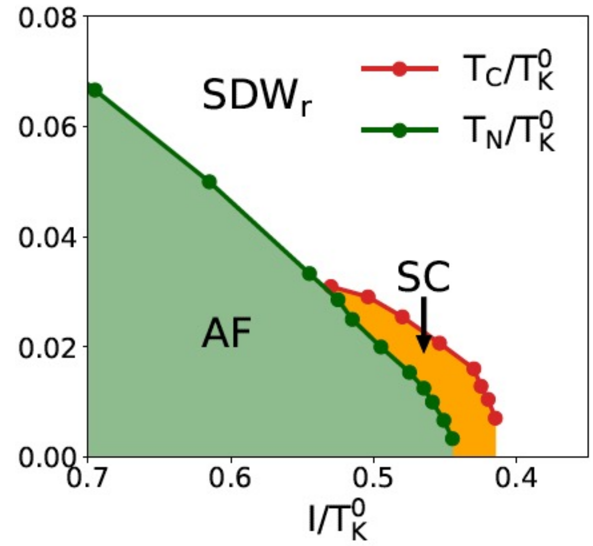


  - Loss of quasiparticles over an extended dynamical range

L. Chen, H. Hu, QS, unpublished (2022)

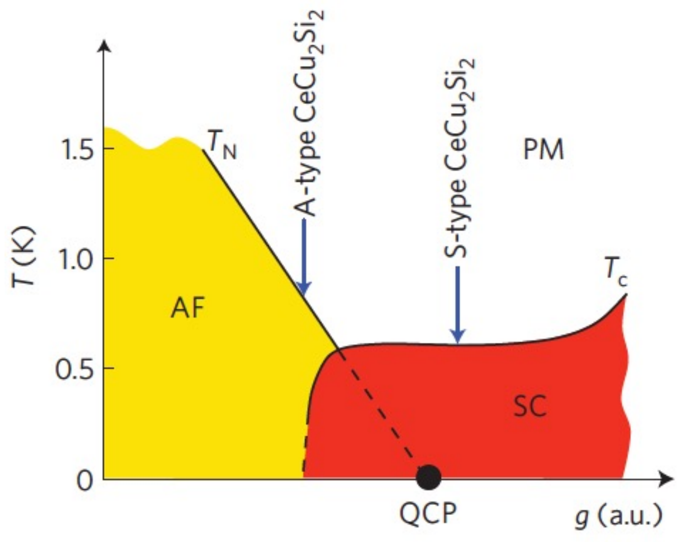
Superconductivity w/ a large dynamical range of Fermi-surface fluctuations in $CeCu_2Si_2$





T_c/T_K^0

≈ 0.02



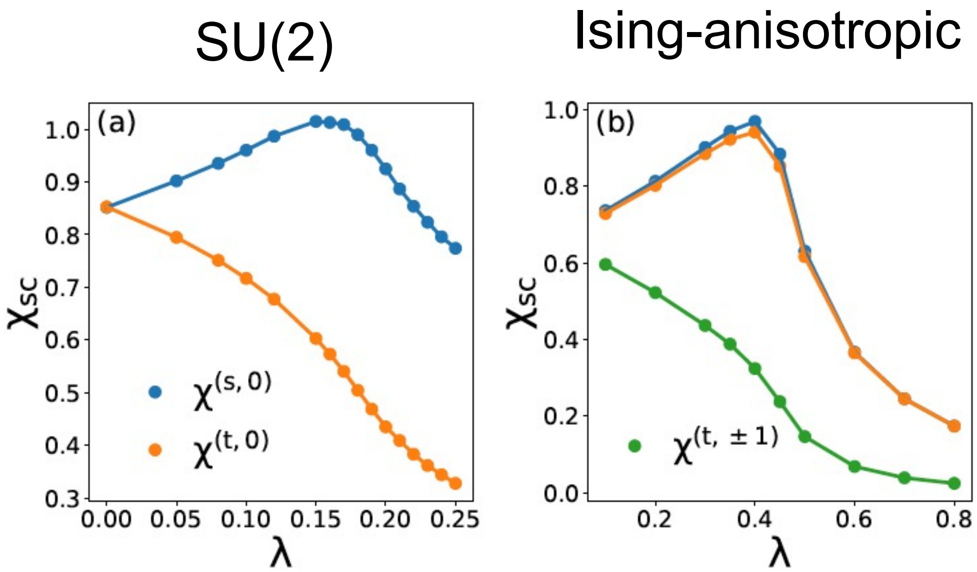
$T_{cr} \sim 1$ K

$T_K^0 \sim 20$ K

O. Stockert, F. Steglich et al.

Route towards Spin-Triplet Pairing

Cluster Bose-Fermi Anderson models:

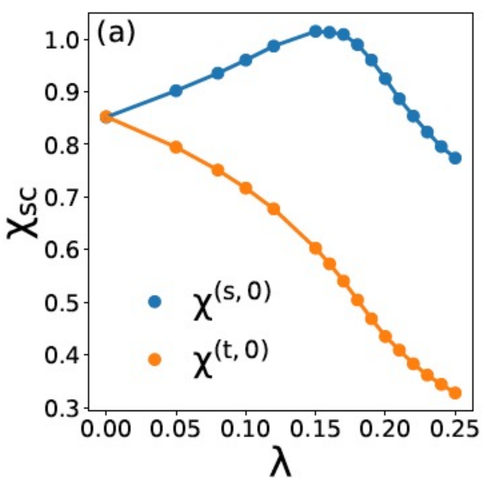


H. Hu, A. Cai, L. Chen & QS, arXiv:2109.12794

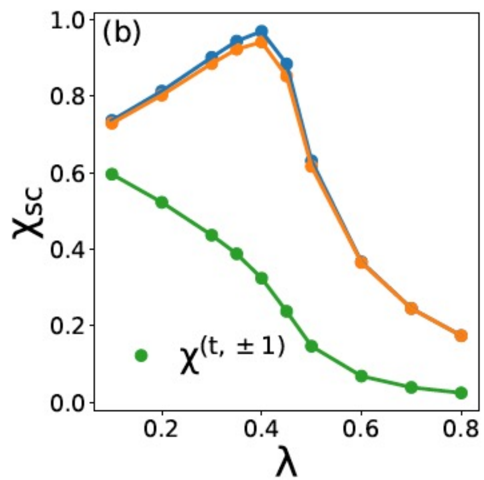
Route towards Spin-Triplet Pairing

$YbRh_2Si_2$ as a candidate setting:

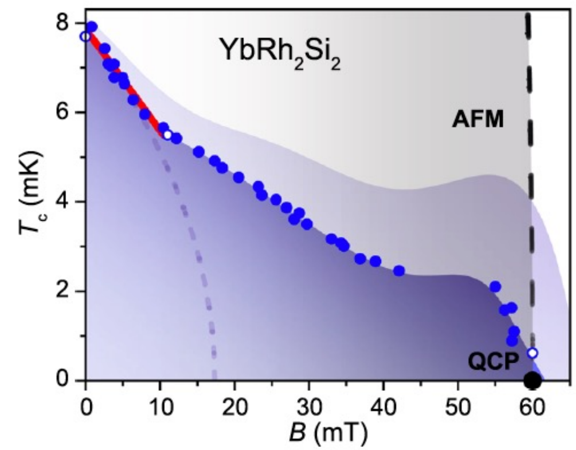
SU(2)



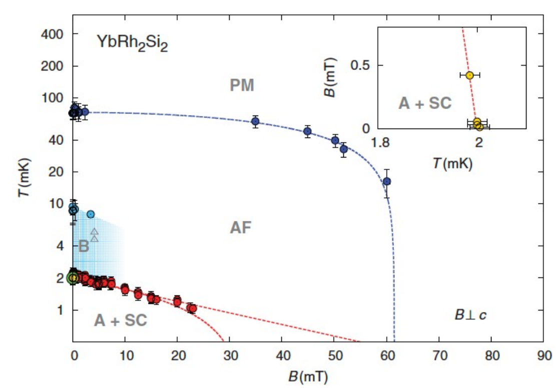
Ising-anisotropic



H. Hu, A. Cai, L. Chen & QS, arXiv:2109.12794



D. H. Nguyen et al., Nat. Comm. (2021)



E. Schuberth et al., Science (2016)

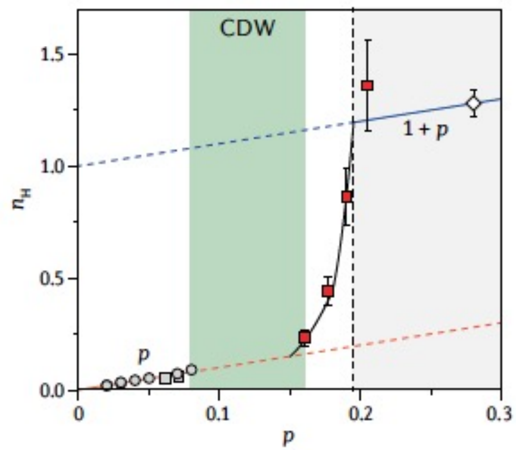
Broader Contexts

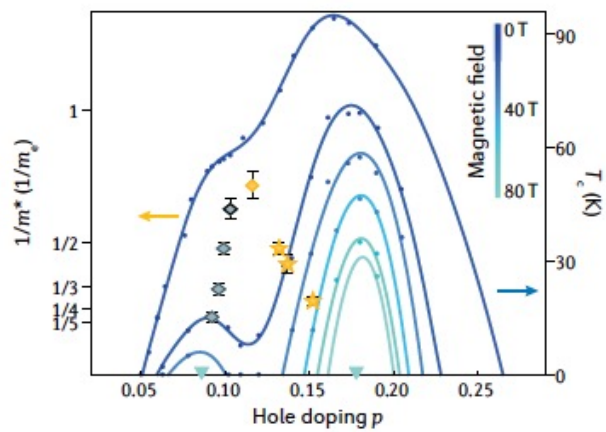
Quantum critical electrons bordering localization

-- Cf. connection w/ other correlated systems

S. Badoux et al ('16)

Y. Fang et al ('22)

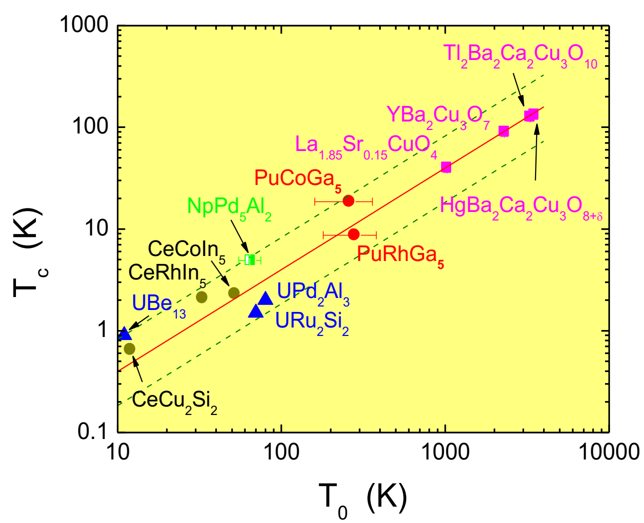




B. J. Ramshaw et al ('15)

See also

F. Balakirev et al ('03)



Broader Contexts

Quantum critical electrons bordering localization

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S. Badoux et al ('16)

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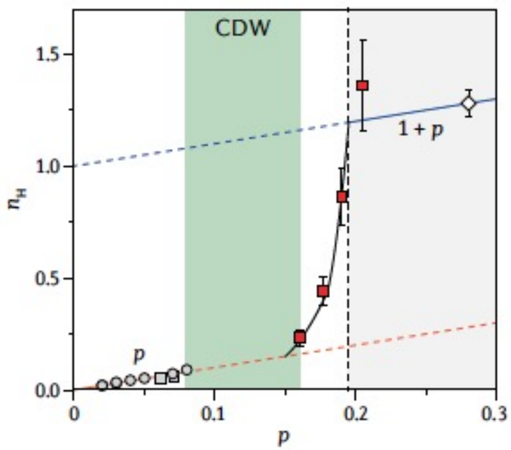
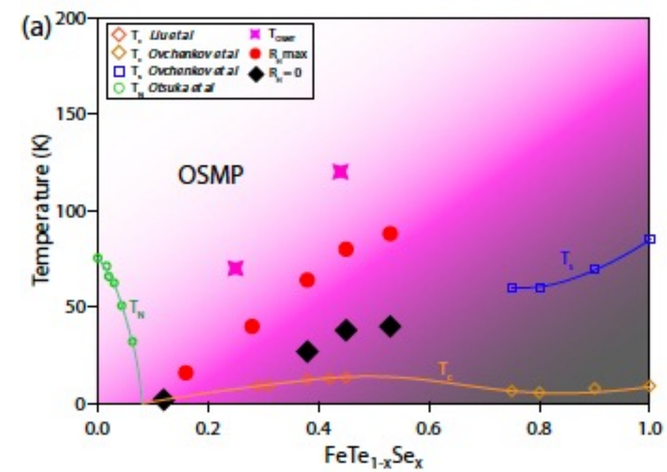
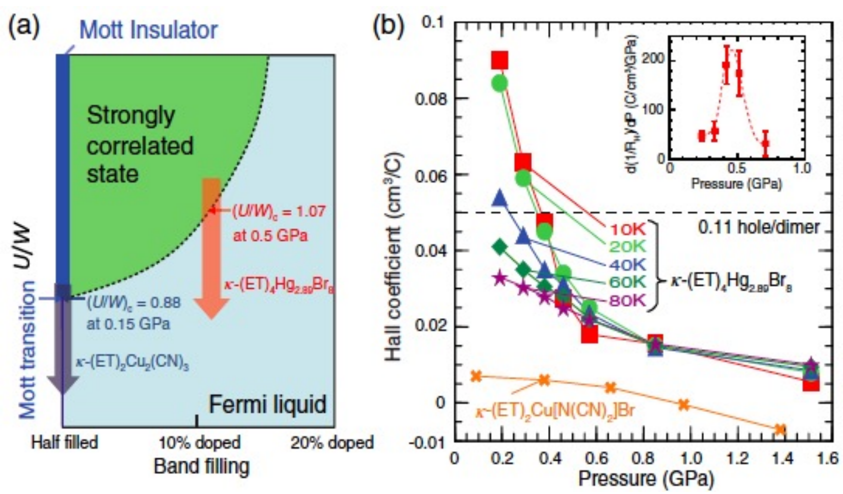
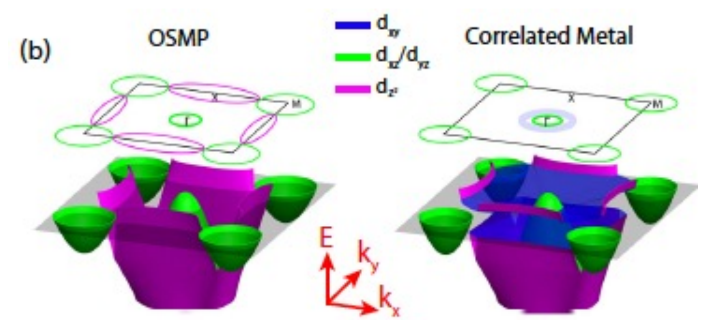




H. Oike et al. ('15)

K. Wakamatsu et al. ('22)





J. Huang et al. ('22)

SUMMARY

- **Quantum criticality from Kondo destruction:**
  - Loss of quasiparticles; dynamical Planckian scaling
  - Jump of Fermi surface from large to small
- **Singular charge response with $\hbar\omega/k_BT$ scaling:**
  - Captures the dynamical Kondo effect
- **Superconductivity of the QC metal:**
  - Kondo destruction ($CeRhIn_5$) and SDW_r ($CeCu_2Si_2$)
  - Route towards spin-triplet pairing (maybe $YbRh_2Si_2$)

Overview materials:

--S. Paschen and QS, Nat. Rev. Phys. 3, 9 (2021)

--S. Kirchner et al, Rev. Mod. Phys. 92, 011002 (2020)