Universal Fermi liquid crossover and quantum criticality in a mesoscopic device

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Collaborators:

Experiments:	Stanford:	**Andrew Keller**
		Lucas Peeters
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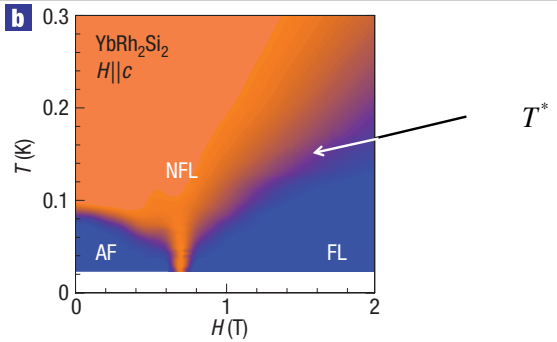
	Weizmann:	**D. Mahalu and V. Umansky**
Theory:	Budapest:	**Pascu Moca**
	Poznan:	**Ireneusz Weymann**

A. Keller et al, preprint arxiv.org/1504.07620

NPSMP Symposium, Tokyo, 2015

MOTIVATION



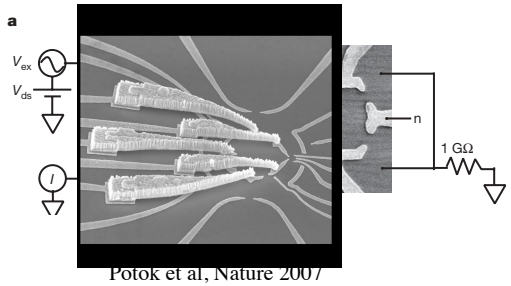
Gegenwart, Si, Steglich, Nature Physics (2008)

Goal: control/investigate QPT in a nano-device and address

⇨ **fate of FL scale** (T^*) ???

⇨ **universal cross-over** ???

Choice of device



Potok et al, Nature 2007

2015

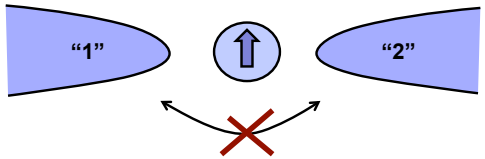
Tunable charge and spin 2-channel Kondo effect

Other possibilities:

Dissipative transitions: Mebrahtu et al, Nature Physics (2013)

2-channel device (Frederic Pierre's group, 2015)

The 2-channel Kondo „phase diagram"



Kondo Hamiltonian

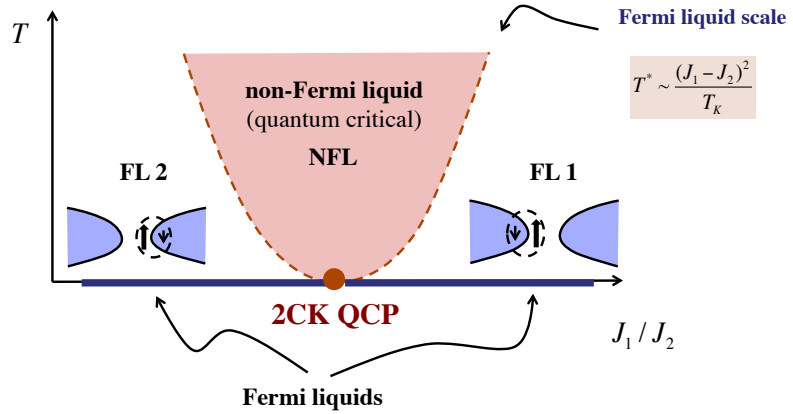
$$H_{\rm int} = J_1\, \underline{S}\cdot\underline{\sigma}_1 + J_2\, \underline{S}\cdot\underline{\sigma}_2$$

- No charge transfer between "1" and "2"
- Competition between channels "1" and "2"

⇨ **Quantum phase transition**

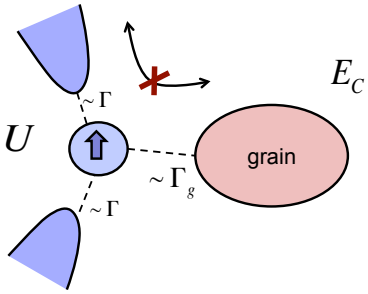
The 2-channel Kondo quantum criticality (2)

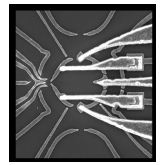
"Phase diagram"



Universal non-FL to FL cross-over at T^* !

The Oreg - Goldhaber-Gordon (OGG) device



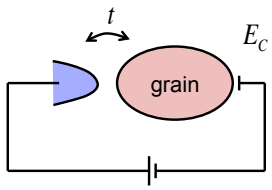


- charge transfer to grain forbidden at energies $\varepsilon, T << E_C$
- grain (Γ_g) and leads (Γ) compete to screen the spin

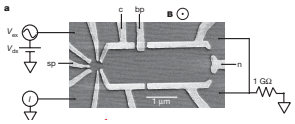
Oreg and Goldhaber-Gordon, PRL (2003); Potok et al., Nature (2007)

Other (possible) 2-channel Kondo realizations

- **Heavy fermion (U and Ce-based) materials**
  large SO coupling + crystal field
- **Matveev's mapping**
  charge 2-channel Kondo effect
  $N = 0 \leftrightarrow 1$
  spin = channel index

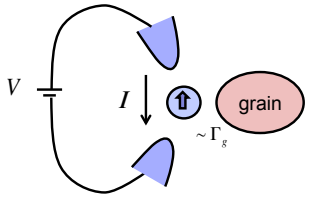


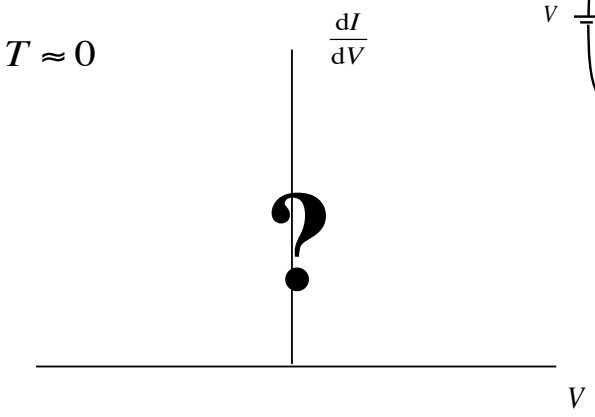
- **Two-level systems ?**
- **Oreg – Goldhaber-Gordon (OGG) proposal**



The Oreg - Goldhaber-Gordon device (2): transport in 1 electron limit

operate in 1 electron regime





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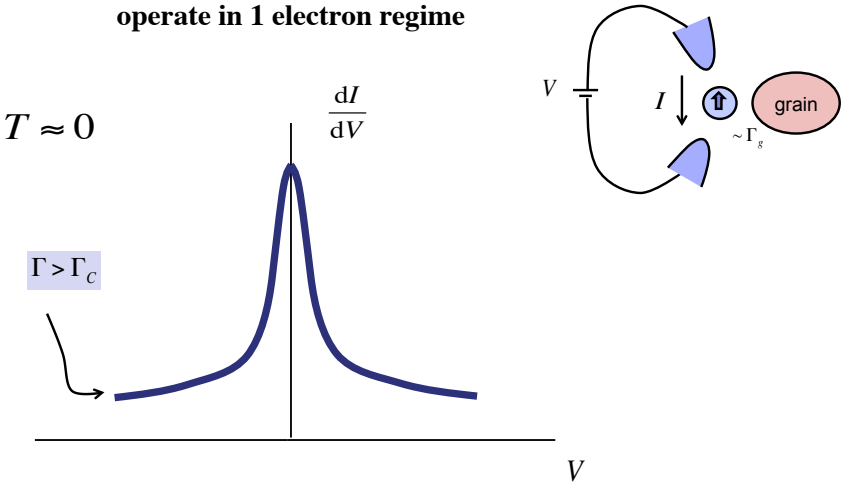

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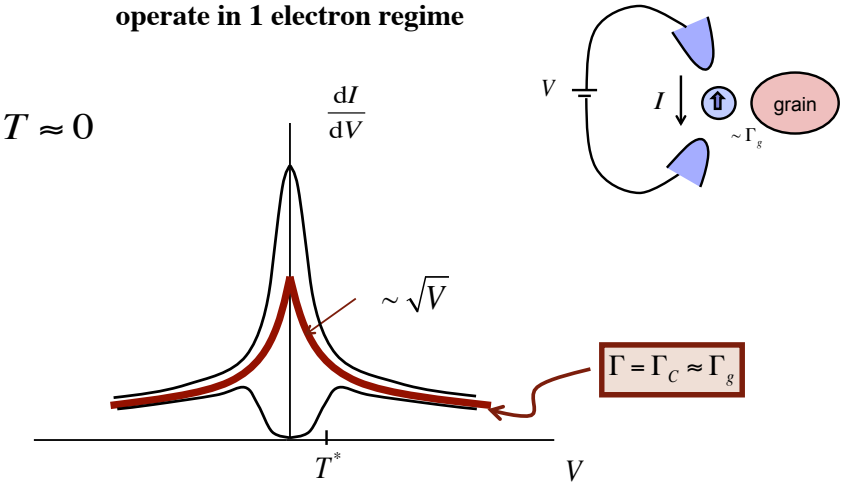

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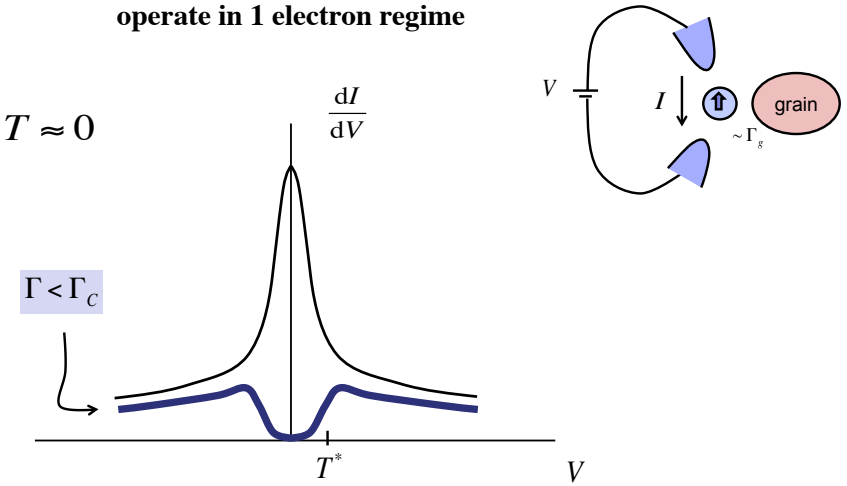
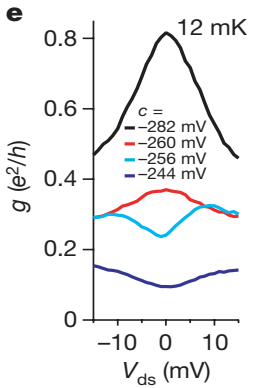
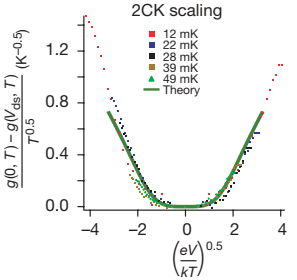


The Oreg - Goldhaber-Gordon device (2): transport in 1 electron limit

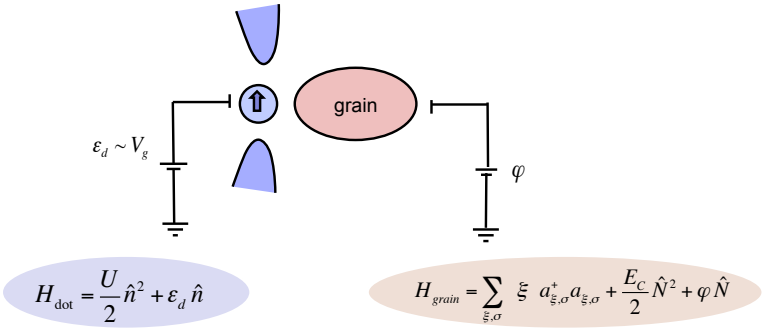


scaling collapse
(~conformal field theory)



Potok et al., Nature (2007)

Phase diagram of OGG device ??

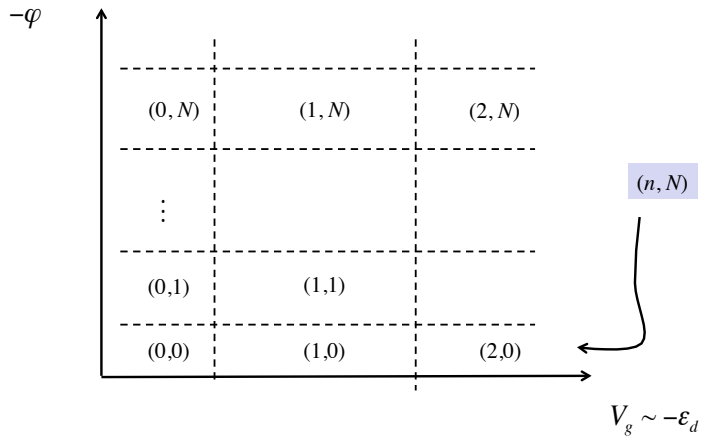


- no dot-grain Coulomb coupling
- many parameters

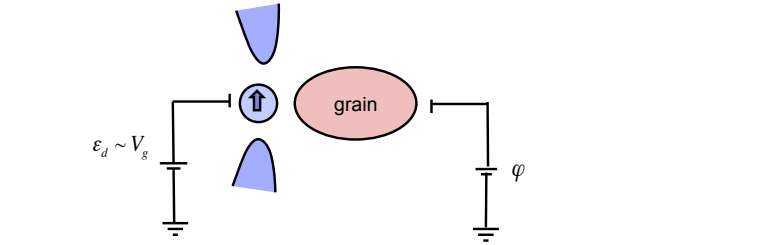
$$V_g \sim \varepsilon_d, \quad \varphi, \quad \Gamma, \quad \Gamma_g, \ldots$$

Stability diagram and predicted phases

$$\Gamma, \Gamma_g \approx 0$$



Phase diagram of OGG device ??



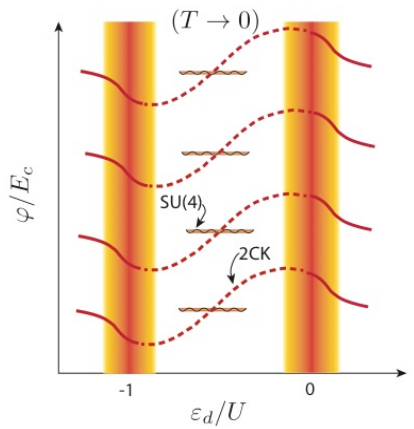
rich phase diagram...

SU(4) physics ? **Spin 2-channel Kondo ?** **Charge 2-channel Kondo ?**

WHERE ARE THESE ???

Real phase diagram (from detailed NRG)

$$\Gamma > \Gamma_g$$



Flexible open access Budapest DM-NRG code: http://www.phy.bme.hu/~dmnrg/

Numerical Renormalization Group (NRG) calculations

Consider $\hat{N} = \sum_{\xi,\sigma} : a^{+}_{\xi,\sigma} a_{\xi,\sigma} :$ as independent variable

Introduce ladder operator: $\Lambda^{+} |N\rangle = |N+1\rangle$

Rewrite tunneling: $t_g a^{+}_{\xi,\sigma} d_\sigma \rightarrow t_g \Lambda^{+} a^{+}_{\xi,\sigma} d_\sigma$

Do NRG with $SU(2) \times U(1) \times U(1)$ symmetry

Remarks

- ladder operator ~ pseudospin of Matveev

$$\Lambda^{\pm} \leftrightarrow T^{\pm}$$

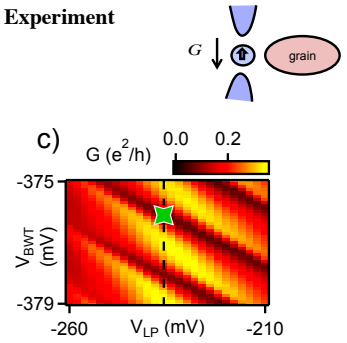
- Multiple Fock spaces (atrificial)

⇒ projection to physical subspace !

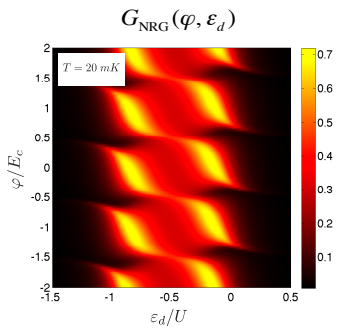
$$\hat{Q} \equiv \hat{N} - \sum_{\xi,\sigma} : a^{+}_{\xi,\sigma} a_{\xi,\sigma} : \; = 0$$

Locating non-Fermi liquid lines ???

Experiment



Theory



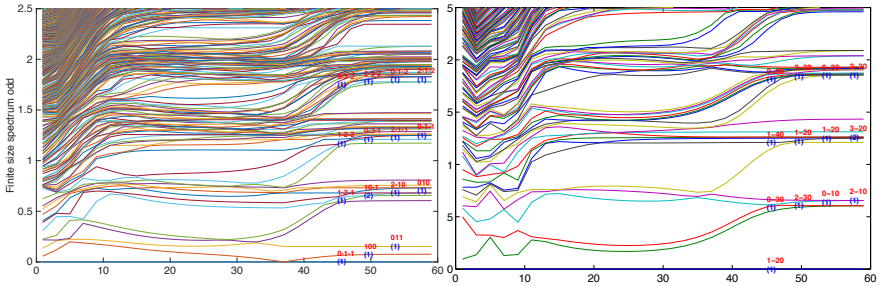
Find non-Fermi liquid lines:

- compute / measure spectral functions or G(T) ⇨ check scaling collapse
- use finite size spectrum

Projection to physical subspace

unprojected finite size spectrum

projected finite size spectrum (2CK)



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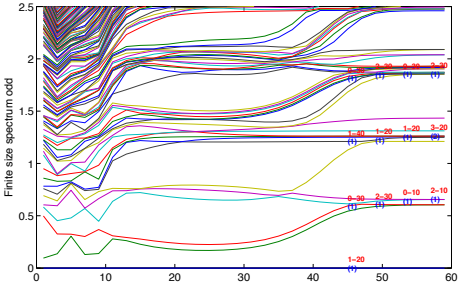
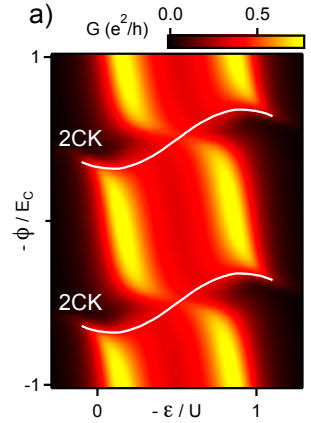
A. I. Toth, C. P. Moca, O. Legeza, and G.Z., PRB 78, 245109 (2008);
C. P. Moca, A. Alex, J. v. Delft, and G.Z., PRB 86, 195128 (2012).

Locating non-Fermi liquid lines

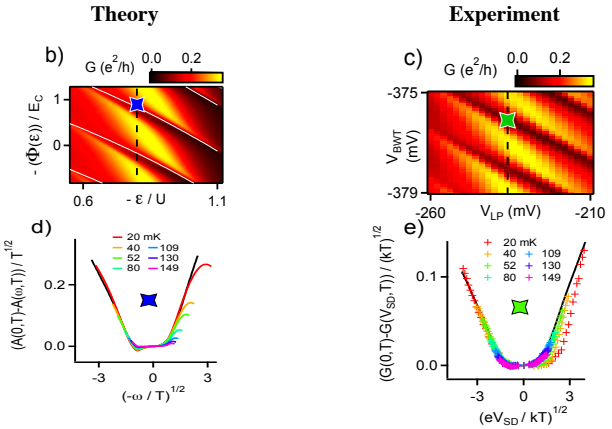




Remarks

- Phase shifts visible
- Not simple 2CK spectrum...

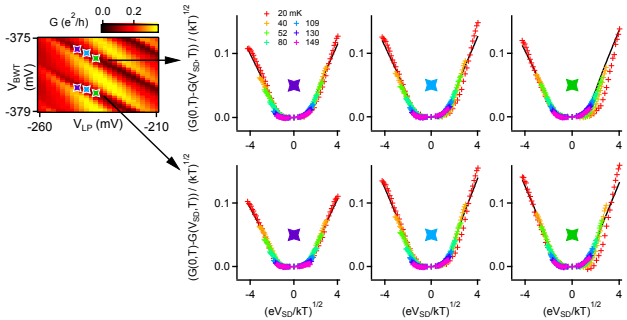
Check universal scaling



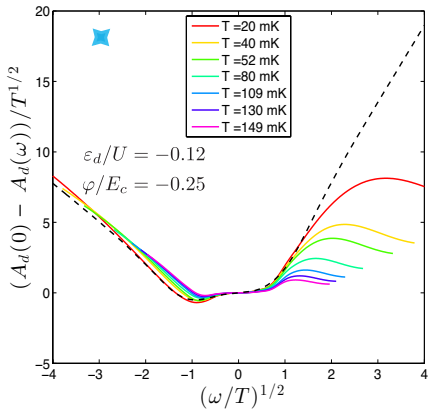
Asymmetry ⟺ **potential scattering** (phase shift)

CFT by Affleck and Ludwig: $S_{2CK}(\omega,T) \rightarrow e^{2i\delta} S_{2CK}(\omega,T)$

Critical lines...



Phase shifted universal scaling

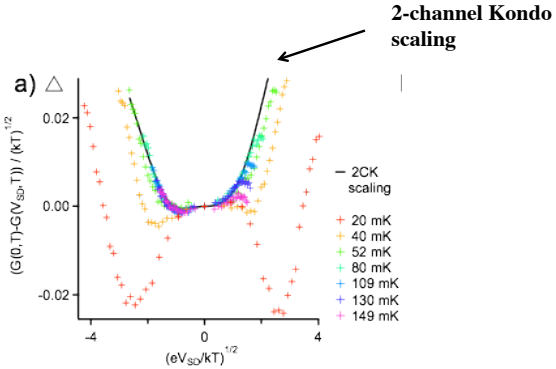


Asymmetry ⟺ **potential scattering** (phase shift)

$S_{2CK}(\omega,T) \rightarrow e^{2i\delta} S_{2CK}(\omega,T)$

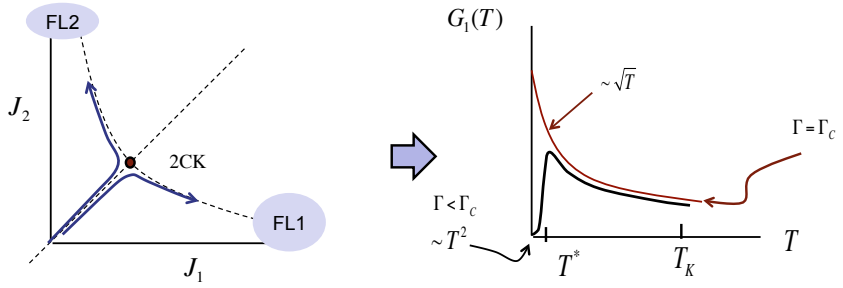
Deviations from universal scaling...

Slightly off the 2-channel Kondo points...



Deviations from critical scaling

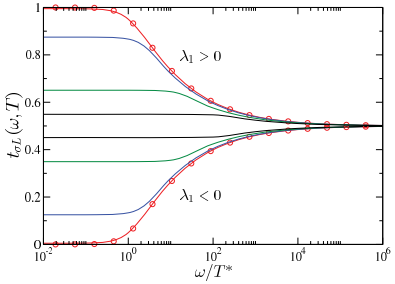
2-channel Kondo scaling



- Cross-over between two strong coupling fixed points

Universal cross-over to FL

Universal cross-over functions from CFT



$$2\pi i\nu\mathcal{T}_{\sigma\alpha,\sigma'\alpha'}(\omega,T)=\delta_{\sigma\sigma'}\delta_{\alpha\alpha'}-S_{\sigma\alpha,\sigma'\alpha'}\mathcal{G}\left(\frac{\omega}{T^*},\frac{T}{T^*}\right)$$

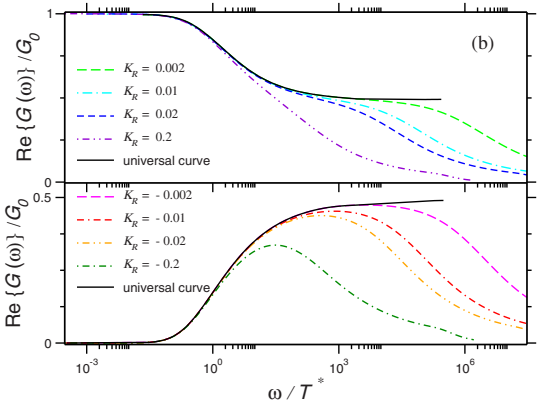
$$\mathcal{G}(\tilde{\omega},\tilde{T})=\frac{\frac{-i}{\sqrt{2\pi^3\tilde{T}}}}{\tanh\frac{\tilde{\omega}}{2\tilde{T}}}\frac{\Gamma\left(\frac{1}{2}+\frac{1}{2\pi\tilde{T}}\right)}{\Gamma\left(1+\frac{1}{2\pi\tilde{T}}\right)}\int_{-\infty}^{\infty}dx\frac{e^{\frac{ix\tilde{\omega}}{\pi\tilde{T}}}}{\sinh x}\times\mathrm{Re}\left[{}_2F_1\left(\frac{1}{2},\frac{1}{2};1+\frac{1}{2\pi\tilde{T}},\frac{1-\coth x}{2}\right)\right]$$

$$\Rightarrow\quad G\left(\frac{T}{T^*},\frac{eV}{T^*},\delta\right)$$

Sela, Mitchell, and Fritz , PRL (2011); Mitchell and Sela, PRB (2012).

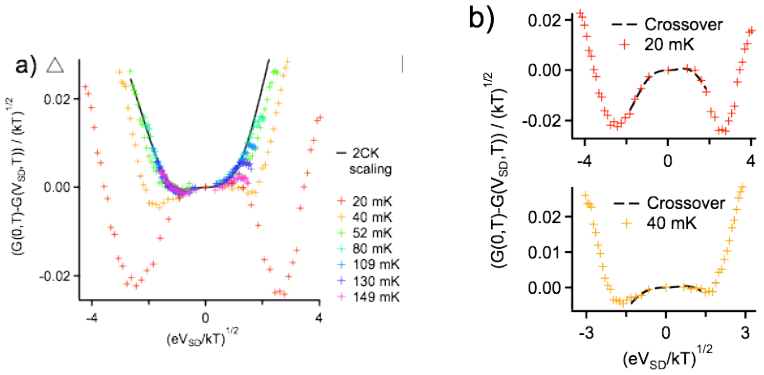
Universal cross-over functions from NRG

Optical conductivity rescaled by FL scale

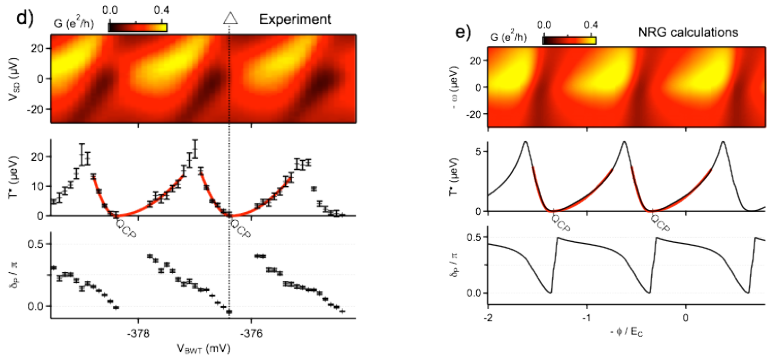


A.I Toth, L. Borda, J. vonDelft, and G.Z., PRB (2007); A.I Toth and G.Z., PRB (2008).

Extracting T^* from experimental data

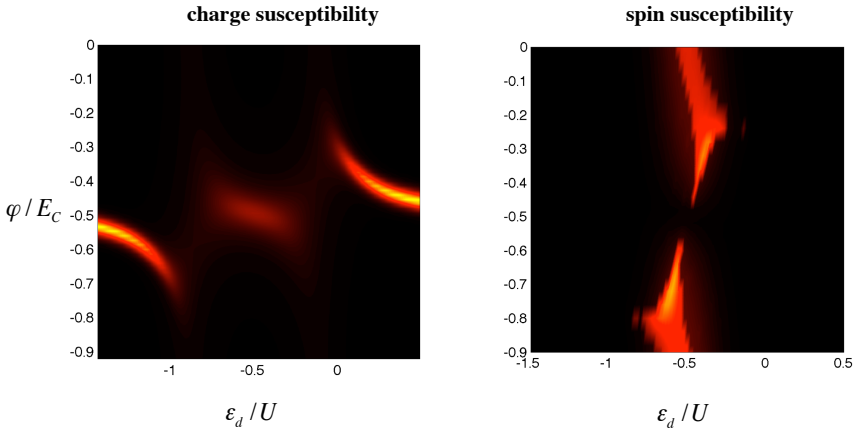


Extracting T^* from experimental data

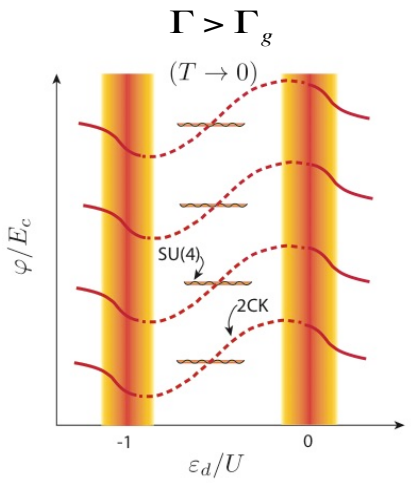


- FL scale vanishes at QCP: $T^* \sim (\varphi - \varphi_{QCP})^2$
- Phase shift jupms by $\delta \to \delta + \pi/2$

Charge and spin susceptibility



Real phase diagram (from detailed NRG)



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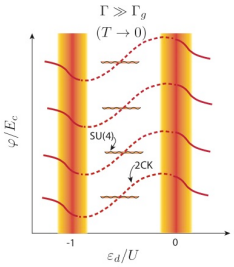
Conclusions

Theory

- Phase diagram: 2CK lines coexisting with SU(4) regions !
- Verification of phase shifted spectrum/scaling



Experiment

- FL scale vanishing at criticality
- Observation of universal 2CK -> FL cross-over
- Indications of charge Kondo state and SU(4) physics...

A. Keller et al, preprint arxiv.org/1504.07620

DM-NRG code: http://www.phy.bme.hu/~dmnrg/