Non-Fermi liquid behavior in metallic quasicrystals with local magnetic moments

Eric C. Andrade

Instituto de Física Teórica/Universidade Estadual Paulista (São Paulo)

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Anu Jagannathan (Paris)
Eduardo Miranda (Campinas)
Matthias Vojta (Dresden)
Vlad Dobrosavljević (Tallahassee)
Jose Garcia (São Paulo)

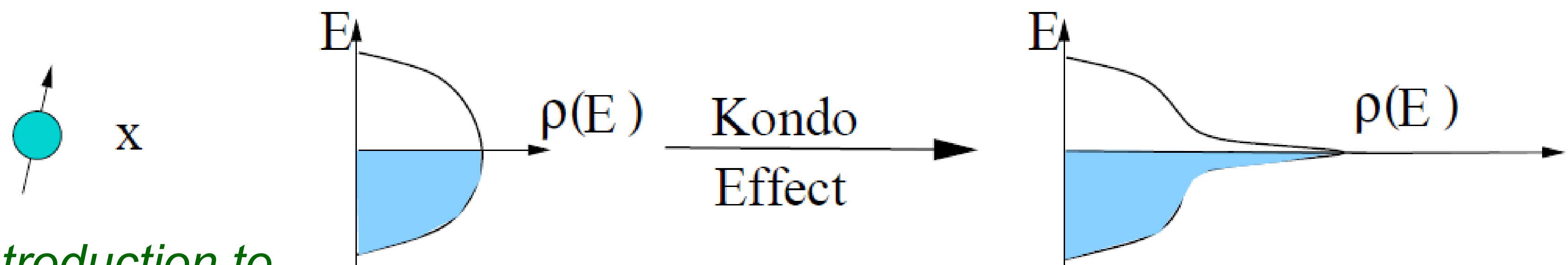
FAPESP

Outline

- **Introduction**
  - FL theory and NFL behavior
  - Experiments in the $Au_{51}Al_{34}Yb_{15}$ quasicrystal
- **Tiling models and quasicrystals**
  - Geometrical and electronic properties
- **Kondo effect in metallic quasicrystals**
  - Power-law distribution of Kondo temperatures
  - NFL behavior
- **Conclusions**

Fermi-liquid (FL)

- Ground state of interacting fermions: akin to Fermi gas
- Adiabaticity + Pauli principle
- Metals at low-T, core of neutron stars, ^{3}He, <u>Kondo problem</u>...

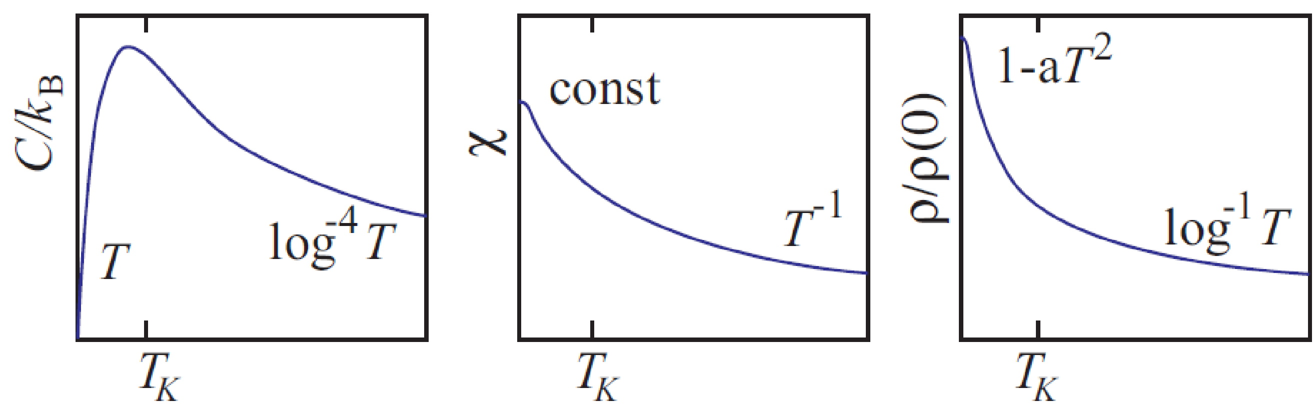


$T \lesssim T_K$ (Kondo temperature)

Coleman, *Introduction to Many Body Physics*

Schofield, *Non-Fermi Liquids*

Nozières, J. Low Temp. Phys. **17**, 31 (1974)



Impurity contribution to C, χ, and ρ

Non-Fermi-liquid (NFL)

- FL known instabilities: Superconductivity, Magnetism, Band insulator, Mott insulator, Anderson insulator...
- Phase transitions or Metal-Insulator transitions: No adiabaticity
- Can the Fermi liquid can fail within the normal metallic state?

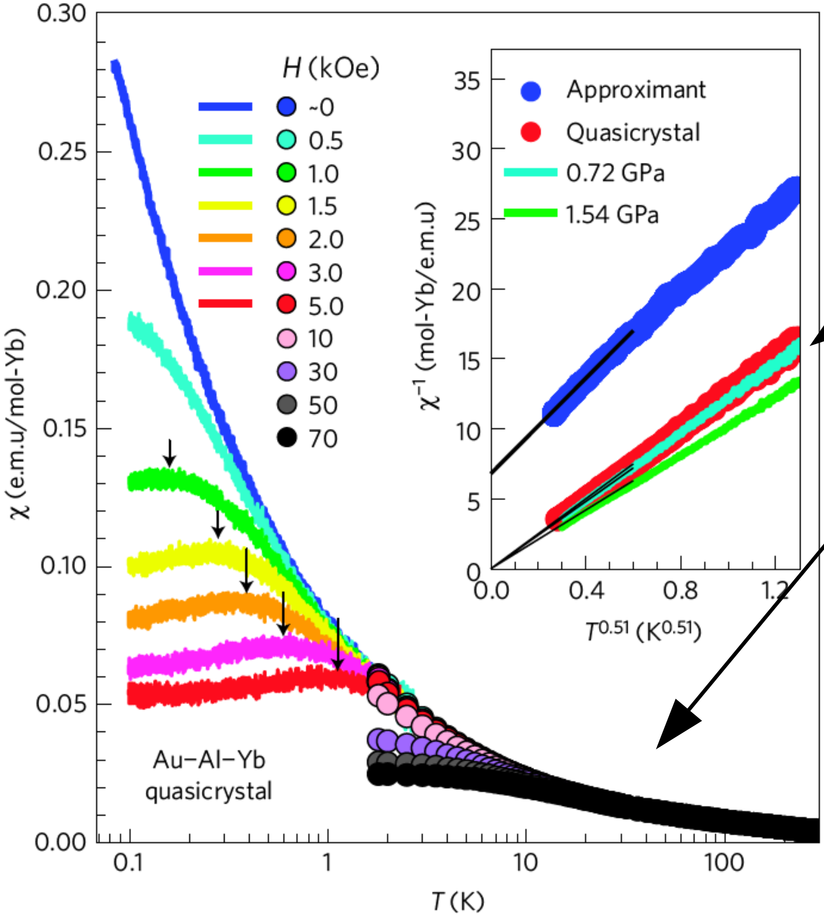
  Yes! Known examples of *non-Fermi-liquid behavior*

  - Metals in 1D: Luttinger liquid
  - Two-channel Kondo models
  - Metals close to a quantum critical point (QCP)
  - Disordered Kondo models
  - *Quasiperiodic Heavy Fermions*

NFL behavior in the $Au_{51}Al_{34}Yb_{15}$ quasicrystal

- NFL without tunning any parameter!

$$\chi \propto T^{-0.51}$$



Quenched by H
but not by P

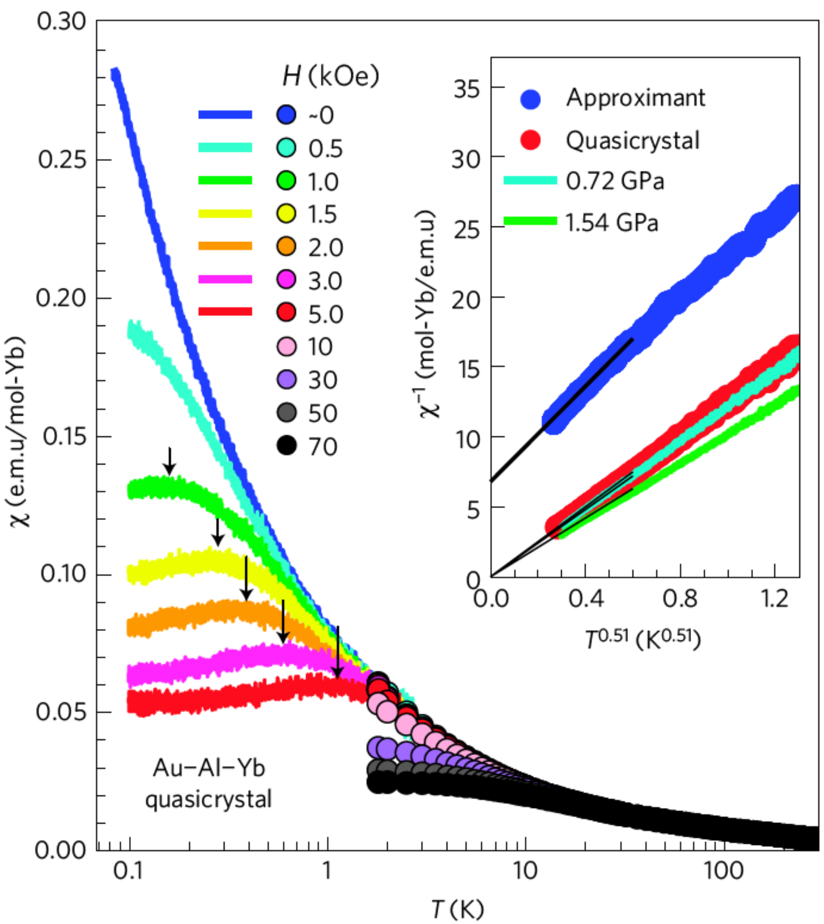
Deguchi *et al.* Nat. Mater. **11**, 1013 (2012)
Watanuki *et al.* PRB **86**, 094201 (2012)

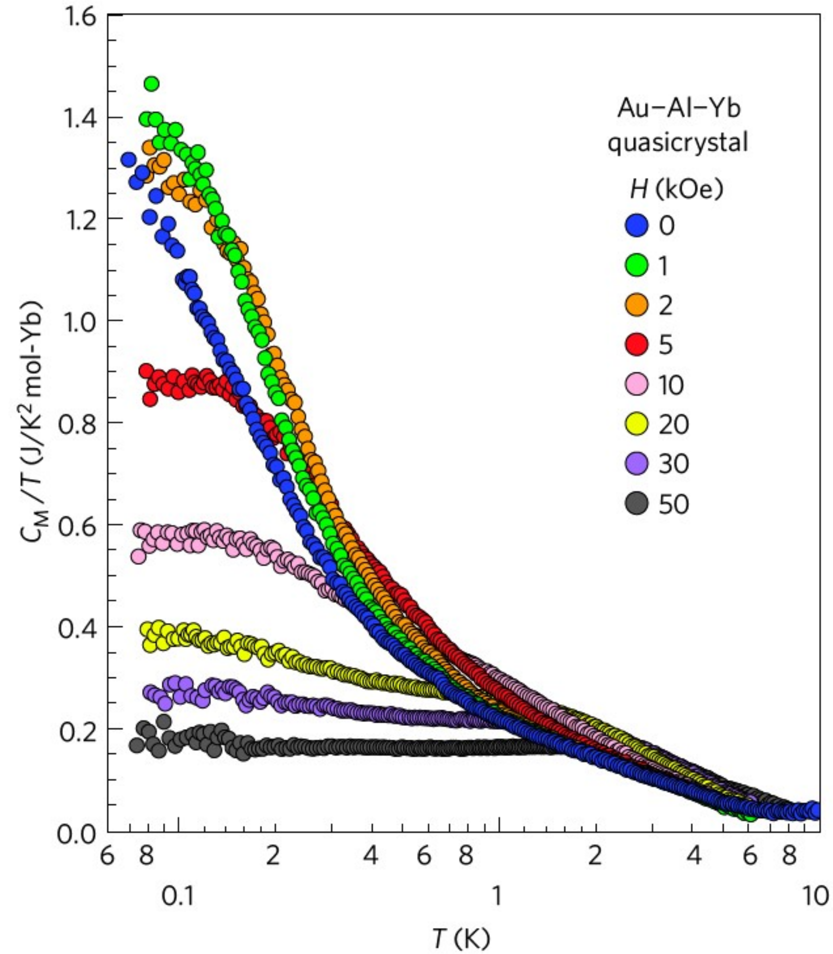
NFL behavior in the $Au_{51}Al_{34}Yb_{15}$ quasicrystal

- NFL without tunning any parameter!

$$C_M/T \propto -\log(T)$$

$$\chi \propto T^{-0.51}$$

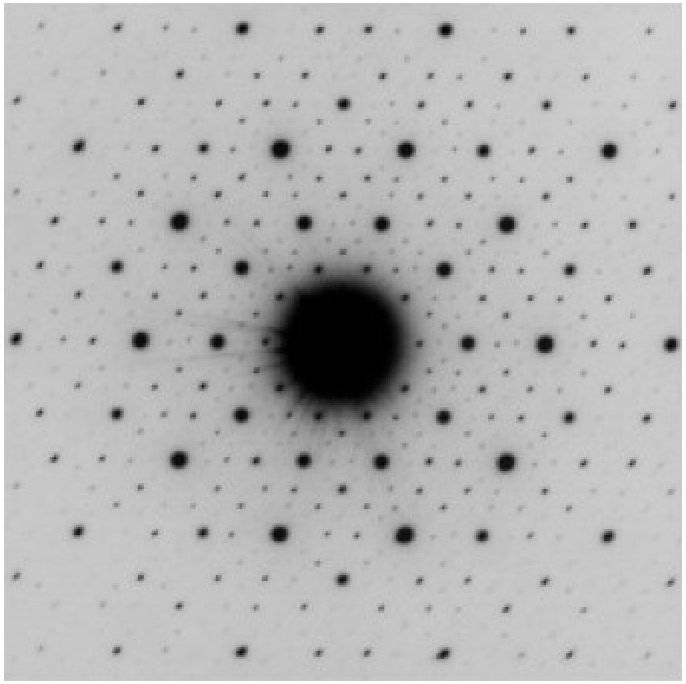


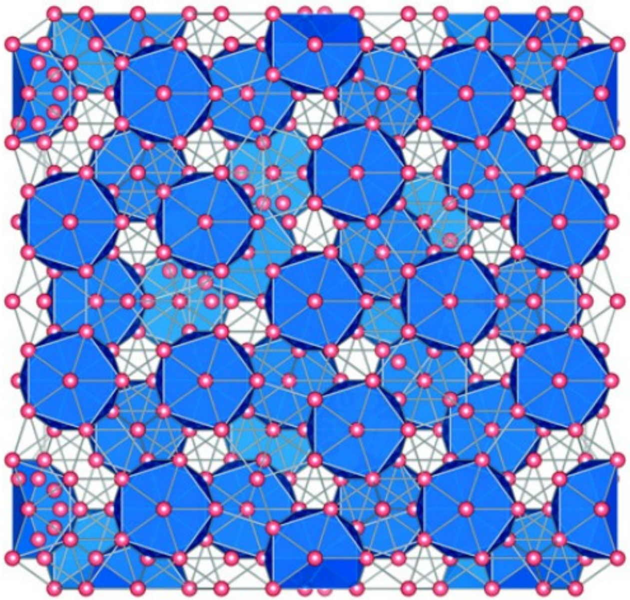


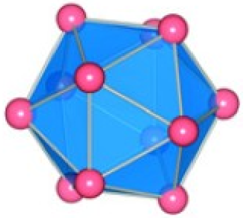
Deguchi *et al.* Nat. Mater. **11**, 1013 (2012)
Watanuki *et al.* PRB **86**, 094201 (2012)

$Au_{51}Al_{34}Yb_{15}$ quasicrystal

- $Au_{51}Al_{34}Yb_{15}$ *quasicrystal*
- 10-fold symmetry diffraction pattern
  - 12 Yb icosahedron
- Icosahedron QC (Tsai-type)
  - Projected positions of Yb atoms



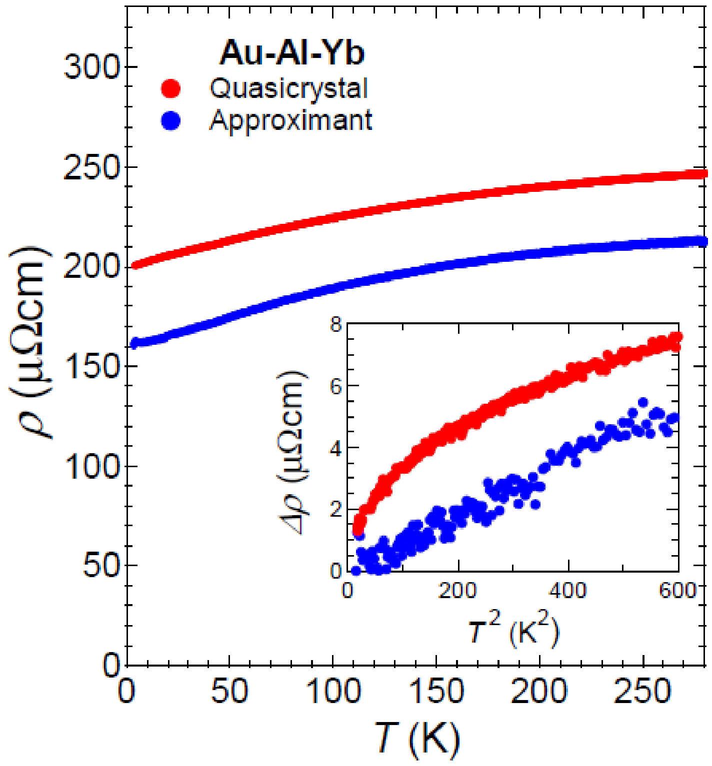




Ishimasa *et al.* Philos. Mag. 91, 4218 (2011)
Deguchi *et al.* Nat. Mater. **11**, 1013 (2012)
Watanuki *et al.* PRB **86**, 094201 (2012)

$Au_{51}Al_{34}Yb_{15}$ quasicrystal: Heavy Fermion

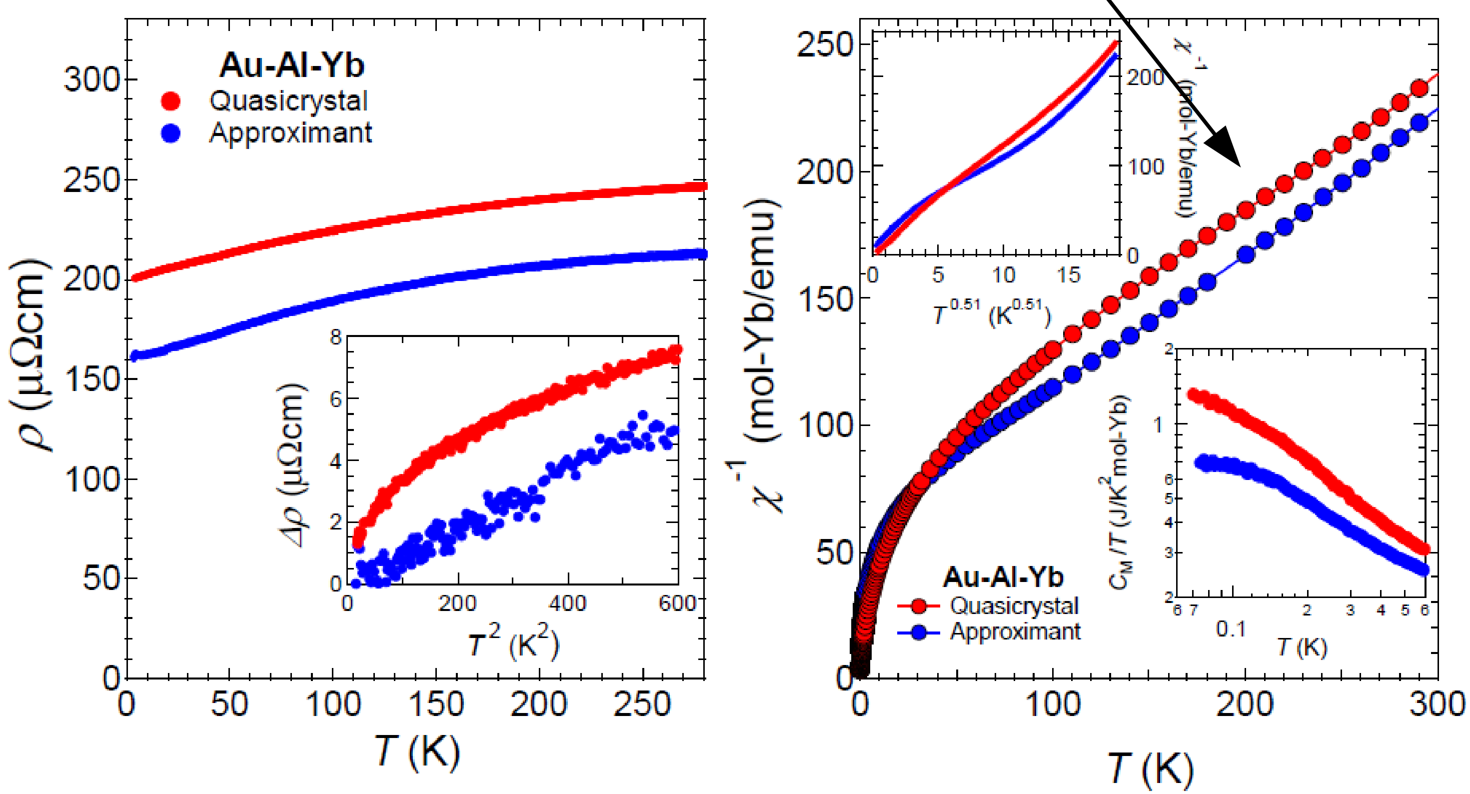
- *Metallic* system $\partial\rho\left(T\right)/\partial T > 0$



Deguchi *et al.* Nat. Mater. **11**, 1013 (2012)

$Au_{51}Al_{34}Yb_{15}$ quasicrystal: Heavy Fermion

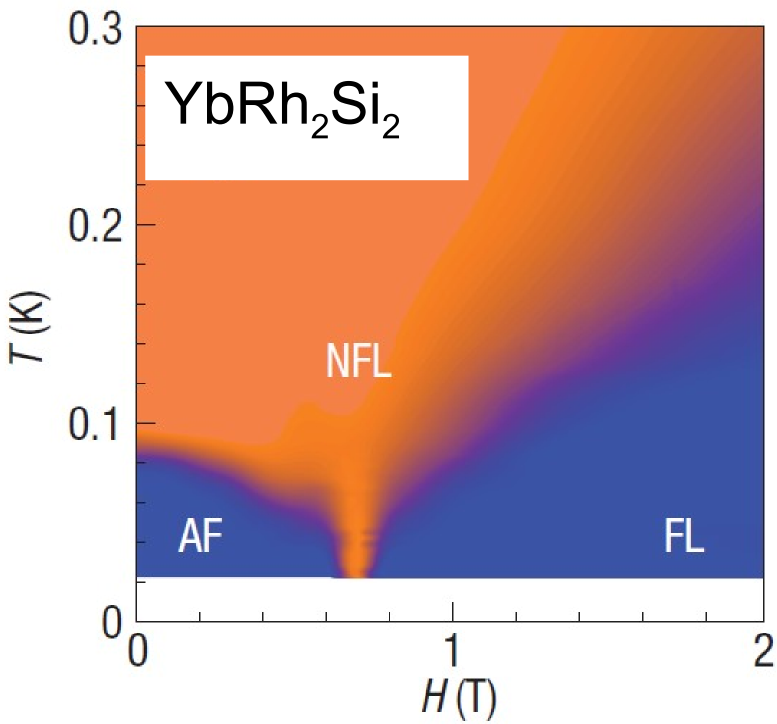
- Metallic system $\partial\rho(T)/\partial T > 0$
- Local moments at high-T: Curie law with $\mu = 3.92\mu_B$
- Mixed-valence (2.61): Yb^{2+} (μ = 0) – Yb^{3+} ($\mu = 4.52\mu_B$)



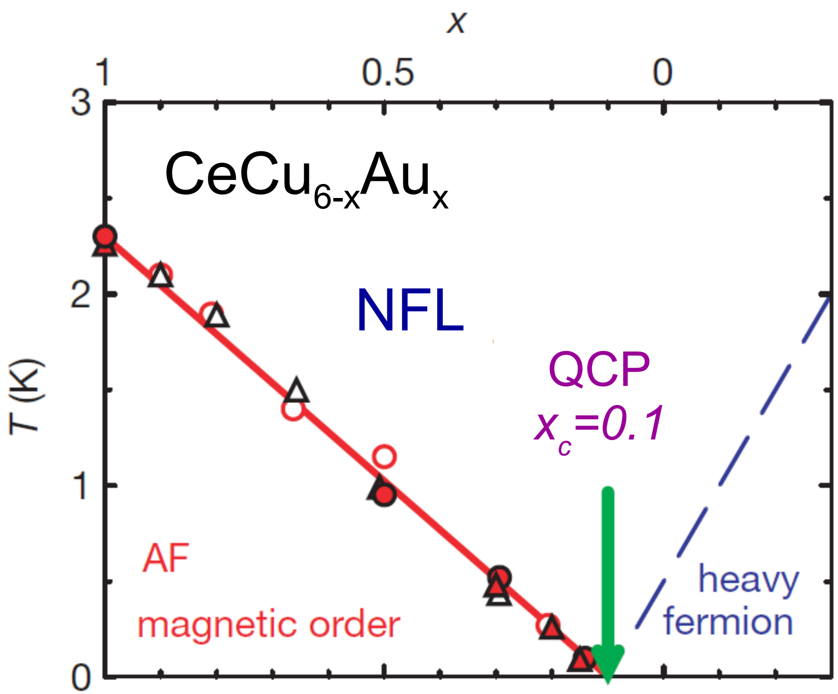
Deguchi *et al.* Nat. Mater. **11**, 1013 (2012)

Quantum critical point scenario

- NFL behavior observed in several other Heavy Fermions
- Proximity to Quantum Critical Point
- Tuning of external parameter: field, doping, pressure, ...



Clusters *et al.*, Nature, **424**, 524 (2003)



Schröder *et al.*, Nature, **407**, 351 (2000)

Intrinsic NFL: $Au_{51}Al_{34}Yb_{15}$ quasicrystal

- Conventional QCP approaches:
  - Quantum valence criticality

    Watanabe *et al.* J. Phys. Soc. Jpn. **82**, 083704 (2013)
  - Fermion condensation quantum phase transition

    Shaginyan *et al.* PRB **87**, 245122 (2013)
- *Parameter* driven QCP (pressure, doping, field): Fine-tuning
- Quasicrystalline environment of the light electrons considered only minimally

Our Goal: Study the Kondo problem in a quasicrystal

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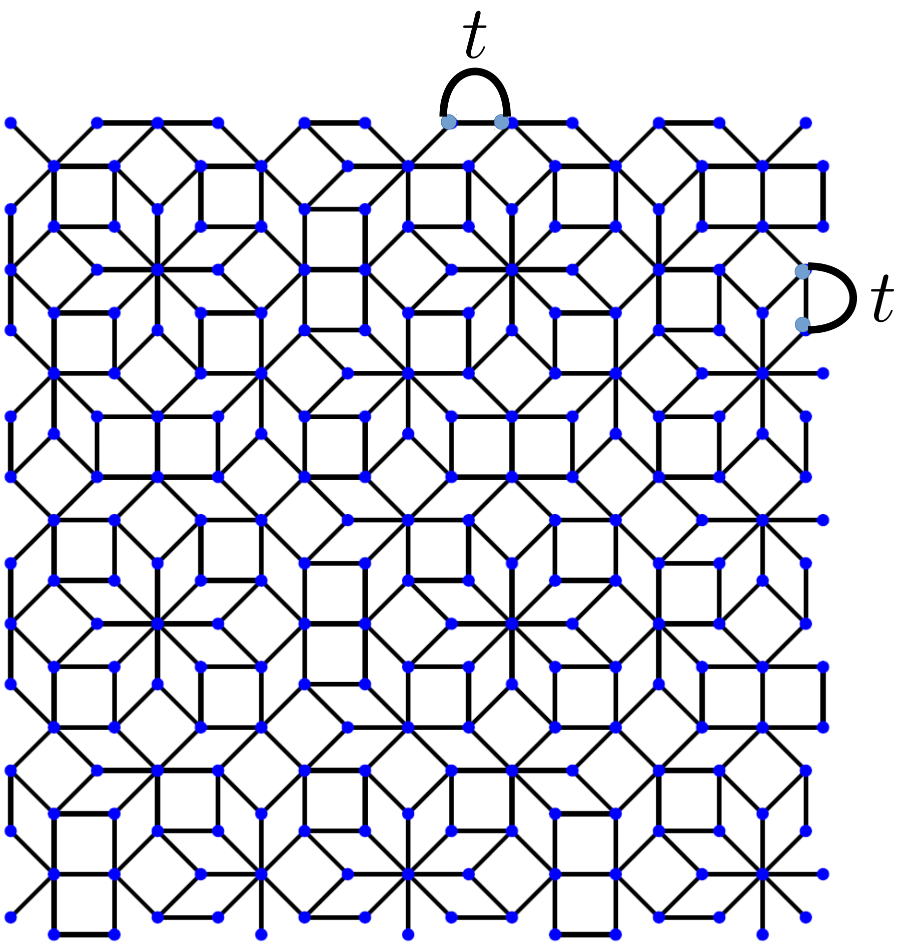
Octagonal tiling (Ammann-Beenker)

- Nearest neighbor tight-biding model. Non-interacting electrons hopping in a *quasiperiodic* potential

$$\mathcal{H}_c = -t \sum_{\langle ij \rangle, \sigma} \left(c^{\dagger}_{i\sigma} c_{j\sigma} + c^{\dagger}_{j\sigma} c_{i\sigma} \right)$$



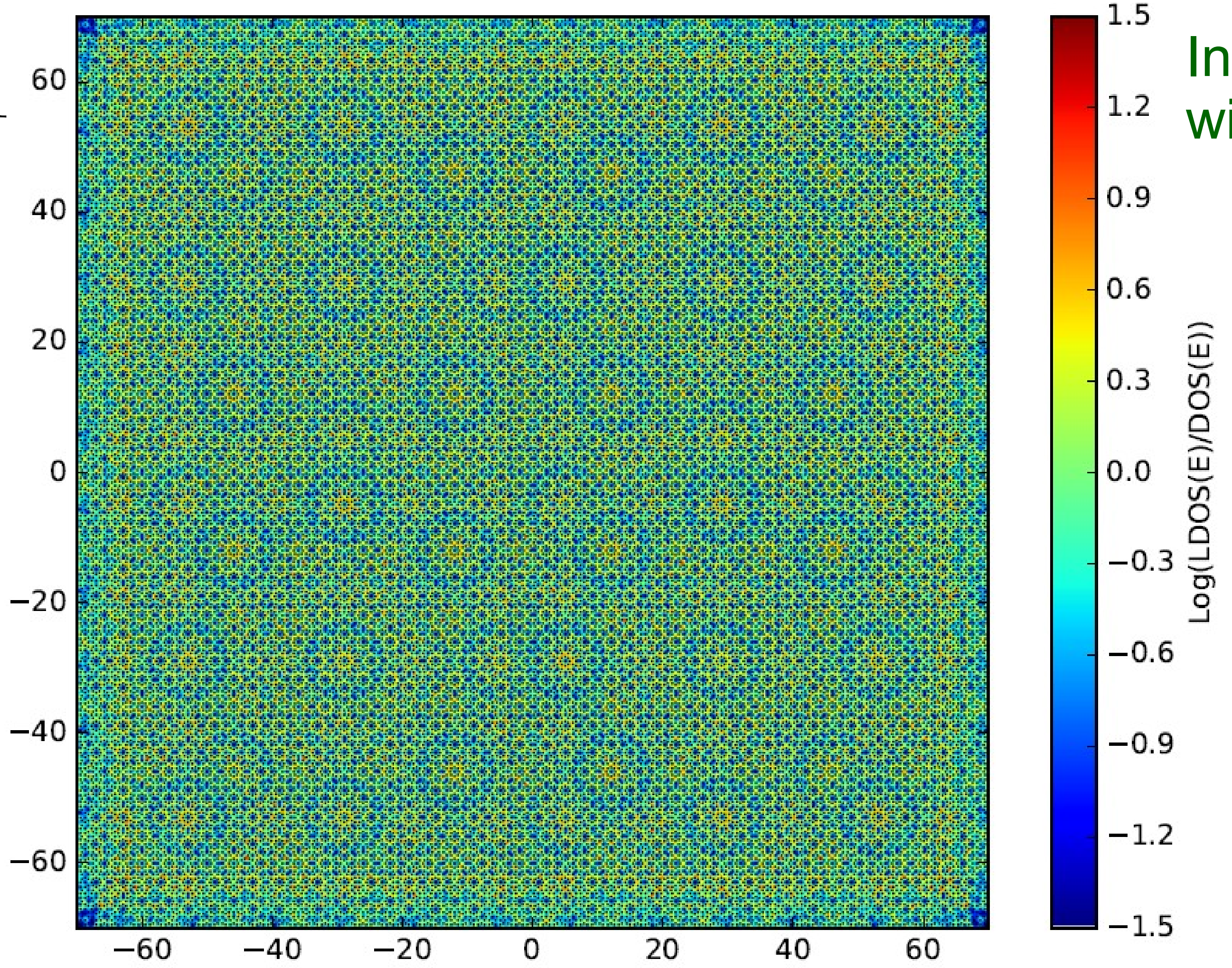
- Socolar, PRB **39**, 10519 (1989)
- Duneau, J. Phys. A **22**, 4549 (1989)
- Benza/Sire, PRB **44**, 10343 (1991)
- Grimm/Schreiber, in Quasicrystals—Structure and Physical Properties
- Jagannathan/Piéchon, Philos. Mag. **87**, 2389 (2007)
- ...

Octagonal tiling – Local density of states

- Unique for each different site.

$N_a = 47321$

$\omega = -1.5t$



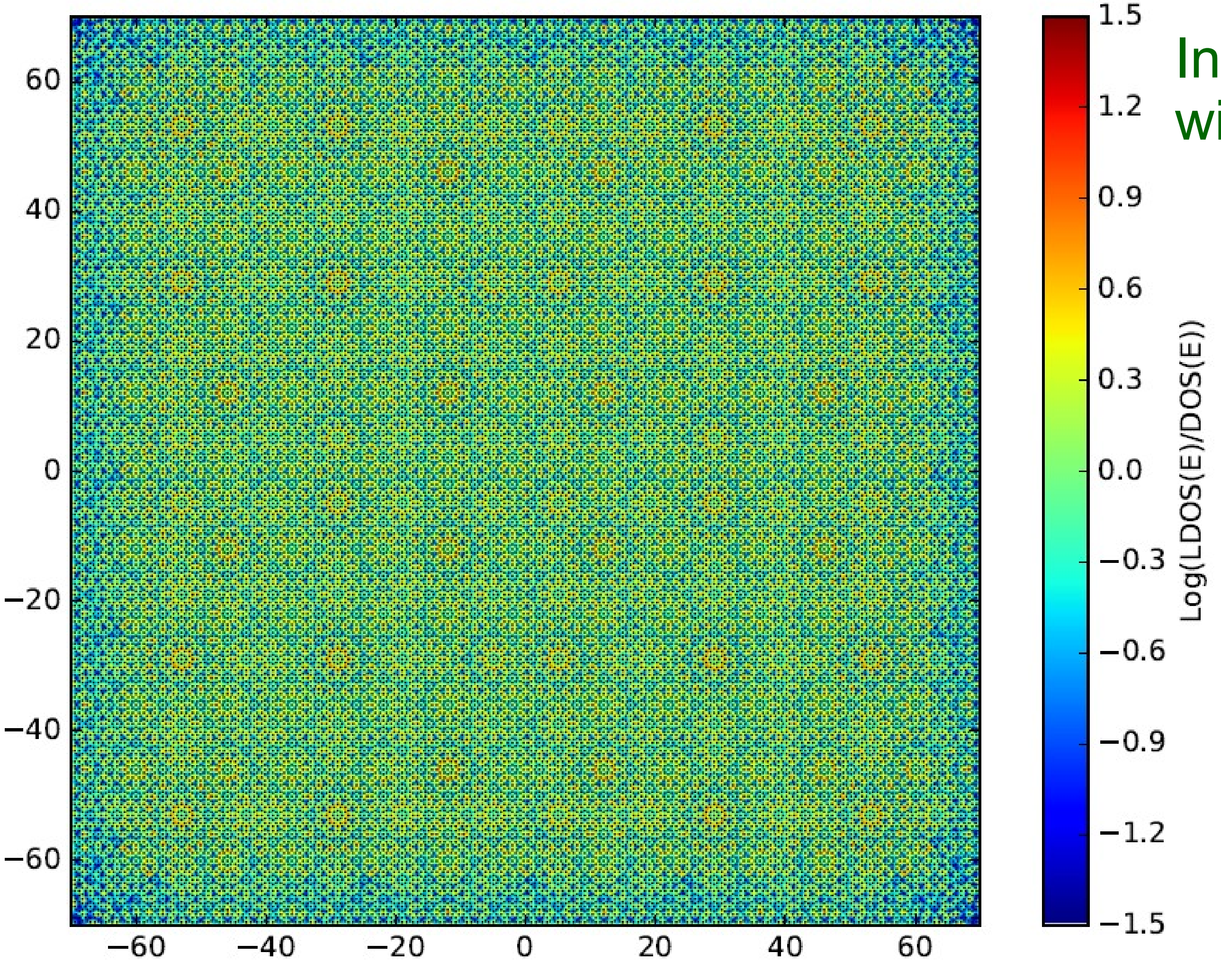
In collaboration with Jose Garcia

Octagonal tiling – Local density of states

- Unique for each different site. Strong energy dependence

$N_a = 47321$

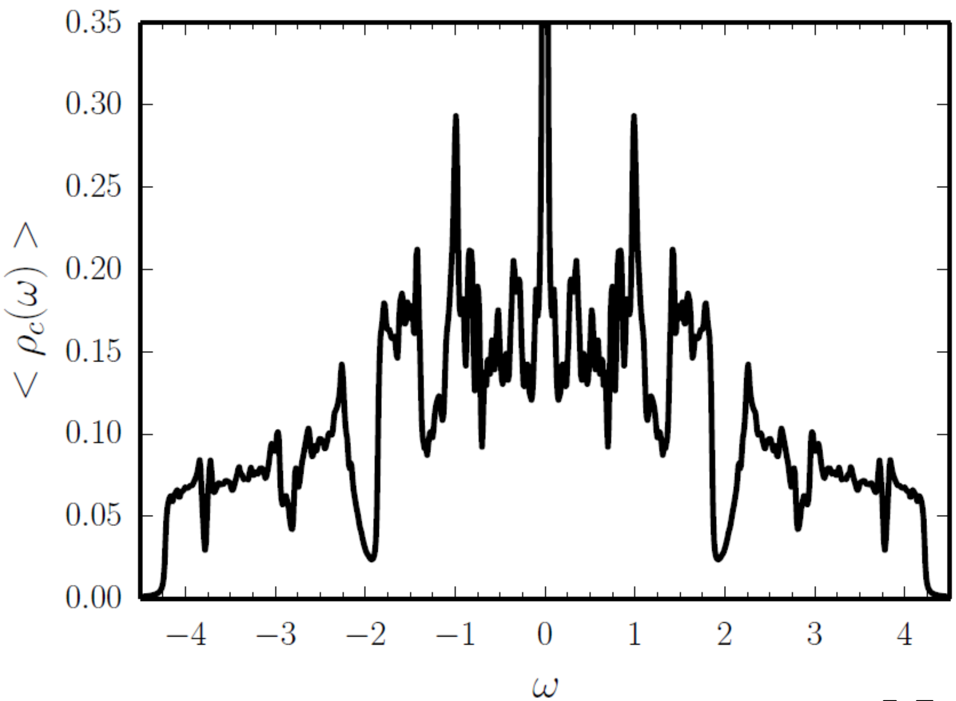
$\omega = -2.2t$

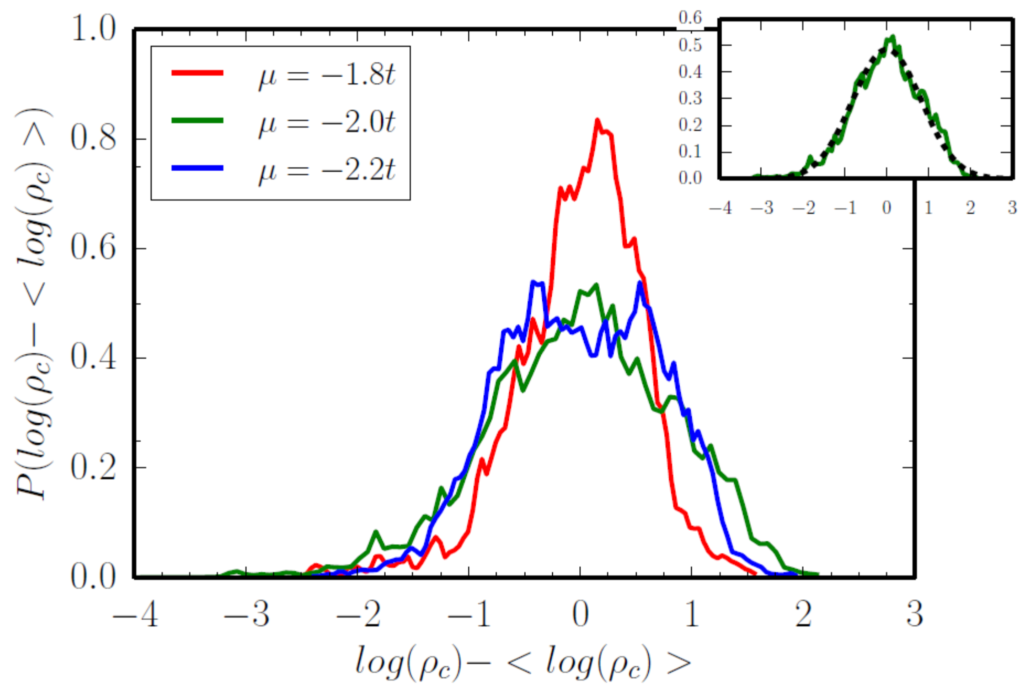


In collaboration with Jose Garcia

Octagonal tiling – Density of states

- Averaged value (energy) and distribution (real space)
- Spiked in energy domain (averaged value over all sites)
- Approximately log-normal distribution in real space (fixed ω)





$N_a = 8119$

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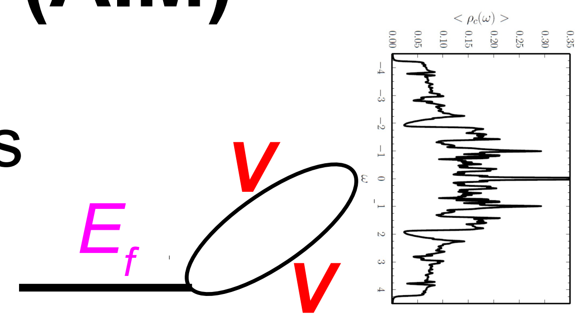
Anderson impurity model (AIM)

- Localized *f*-orbital hybridizes with *c*-electrons
- $U \to \infty$ AIM: Mixed-valence ($n_f \leq 1$)



- Slave-boson MF approach

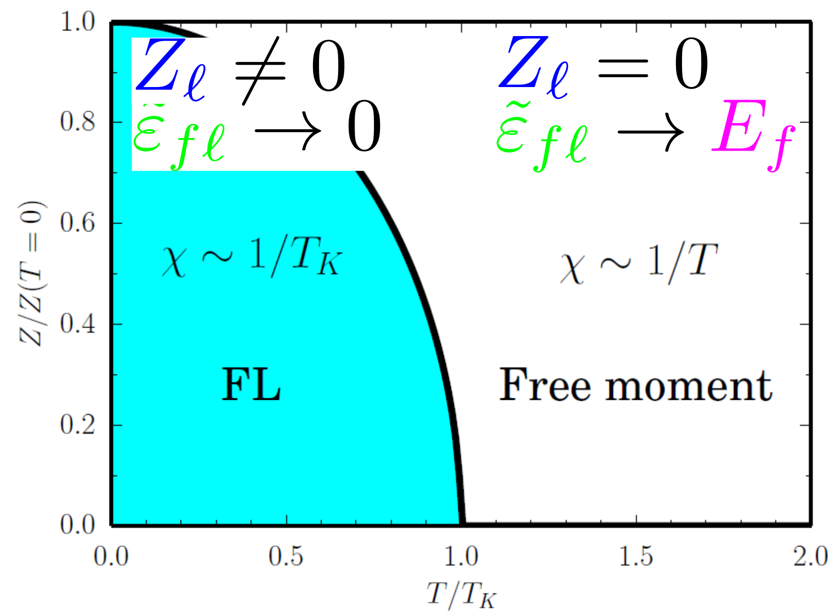
$$\mathcal{H} = \mathcal{H}_c + \tilde{\varepsilon}_{f\ell} \sum_{\sigma} n_{f\sigma} + V\sqrt{Z_\ell} \sum_{\sigma} \left(f^\dagger_{\ell\sigma} c_{\ell\sigma} + c^\dagger_{\ell\sigma} f_{\ell\sigma} \right) + \left(\tilde{\varepsilon}_{f\ell} - E_f \right) \left(Z_\ell - 1 \right)$$

- Low-energy description

$$\tilde{V} = V\sqrt{Z_\ell}$$

$$T_K^\ell = D\exp\left[-1/J\rho_\ell^c(0)\right]$$

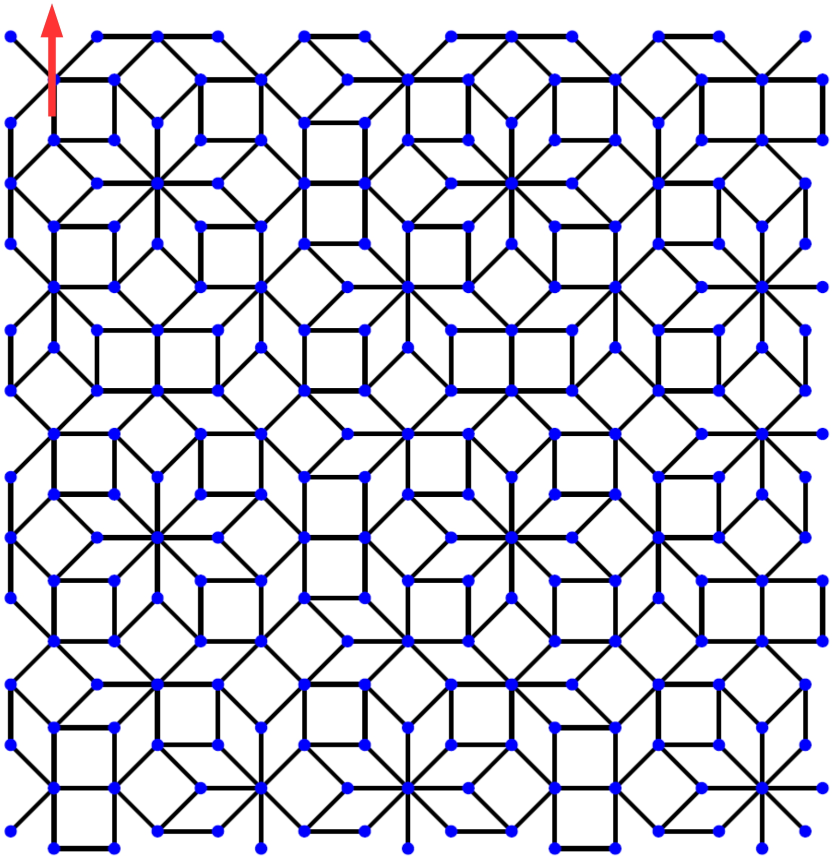
$$J = 2V^2/|E_f|$$



Read/Newns, J. Phys. C **16**, L1055 (1983)
Coleman, PRB **29**, 3035 (1984)

Kondo impurities in a quasicrystal

- Quasicrystal → Different environments: $\Delta_{f\ell}(\omega) = V^2 G^c_{\ell\ell}(\omega)$
- One Kondo impurity at each site. N_a values of T_K: $P(T_K)$



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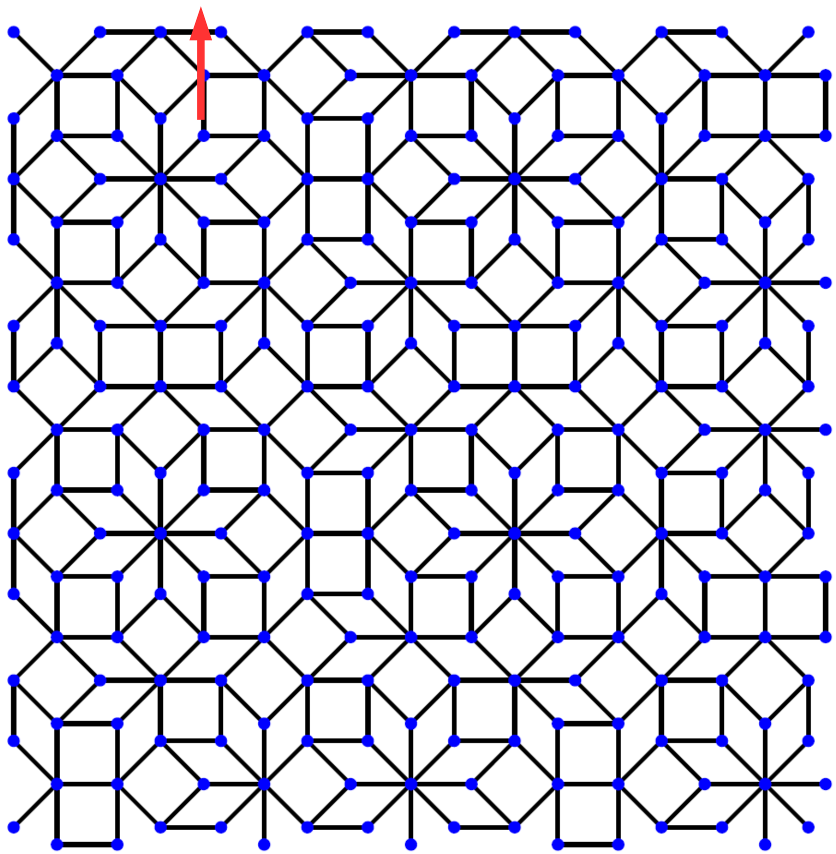

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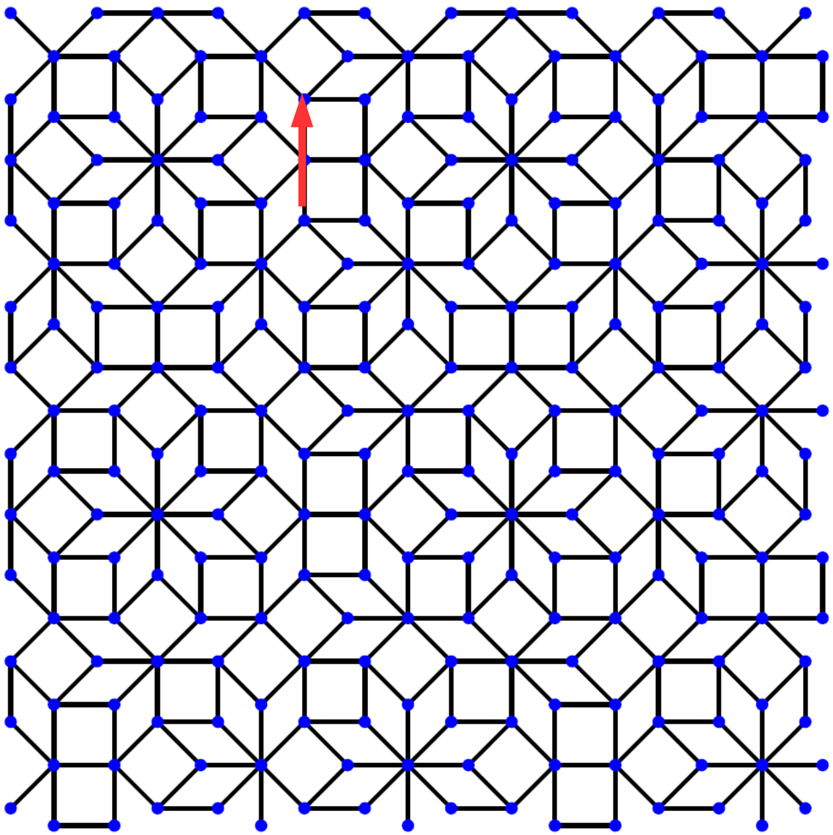
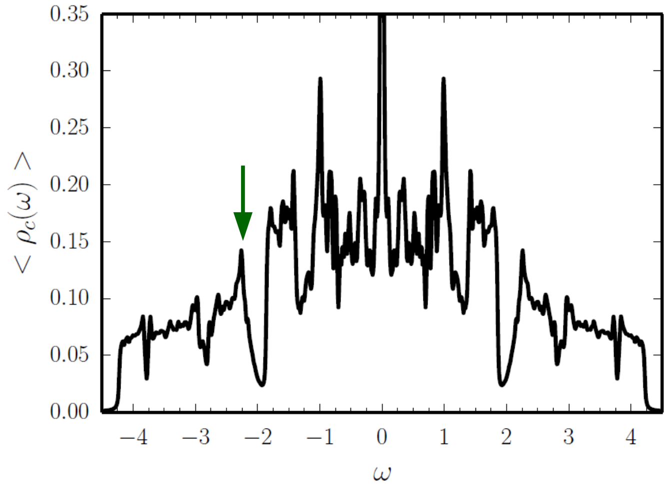
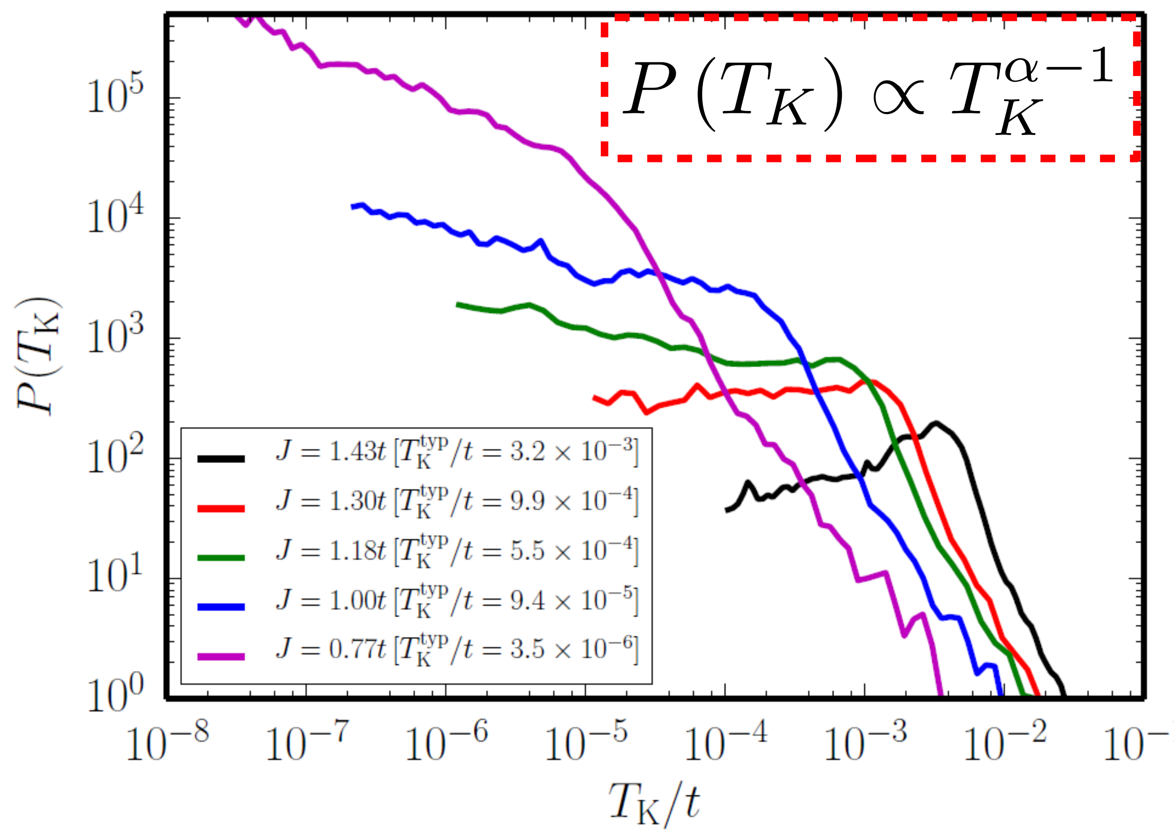


Power-law distribution of Kondo temperatures

- Quasicrystal → Different environments: $\Delta_{f\ell}(\omega) = V^2 G^c_{\ell\ell}(\omega)$
- One Kondo impurity at each site. N_a values of T_K: $P(T_K)$
- Remarkably, we get a power-law distribution at low-T_K



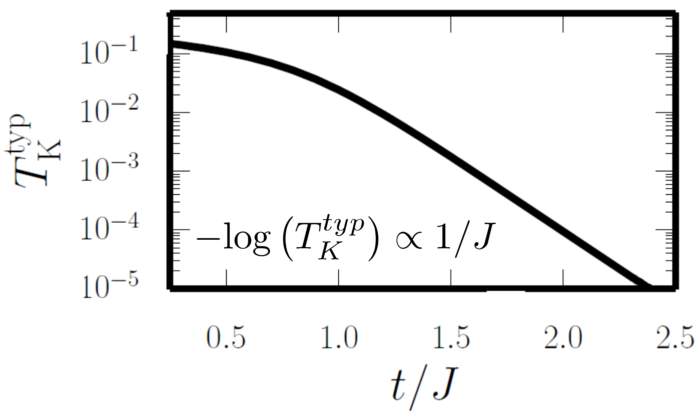
$$\mu = -2.2t$$
$$N_a = 1393$$
$$J = 2V^2 / |E_f|$$



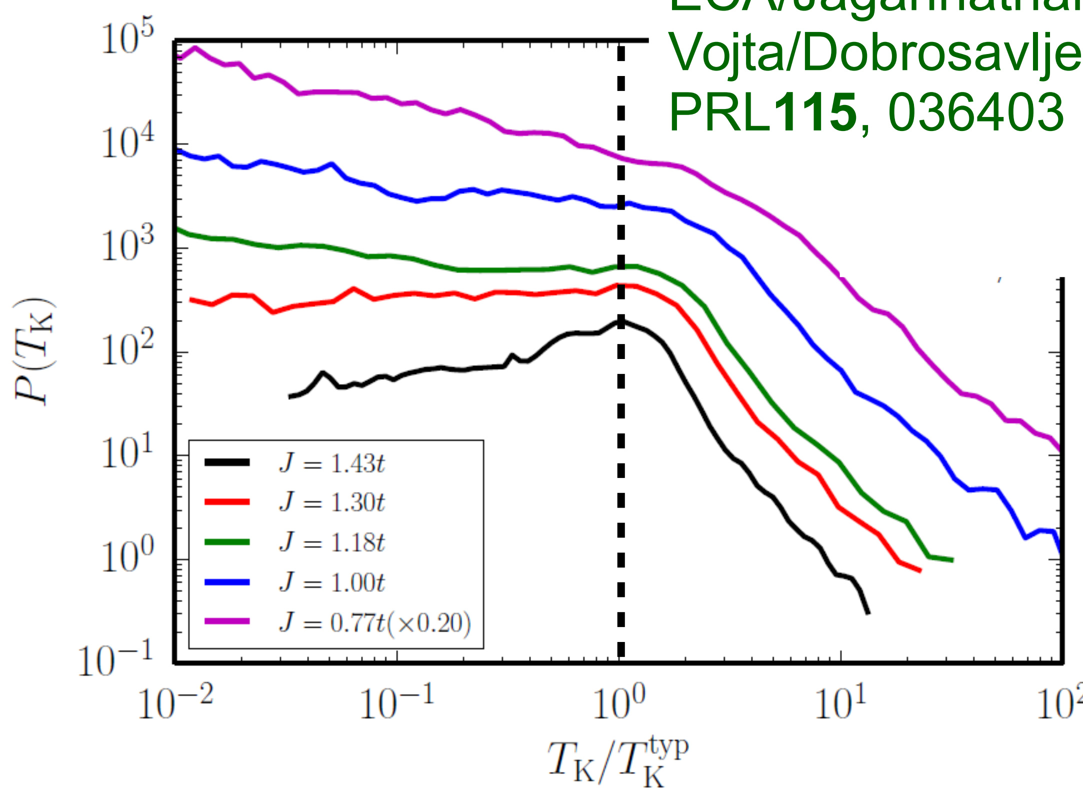
Power-law distribution of Kondo temperatures

- Quasicrystal → Different environments: $\Delta_{f\ell}(\omega) = V^2 G^c_{\ell\ell}(\omega)$
- One Kondo impurity at each site. N_a values of T_K: $P(T_K)$
- Remarkably, we get a power-law distribution below T_K^{typ}

$$T_K^{typ} \equiv \exp\left[\langle \ln(T_K)\rangle\right]$$



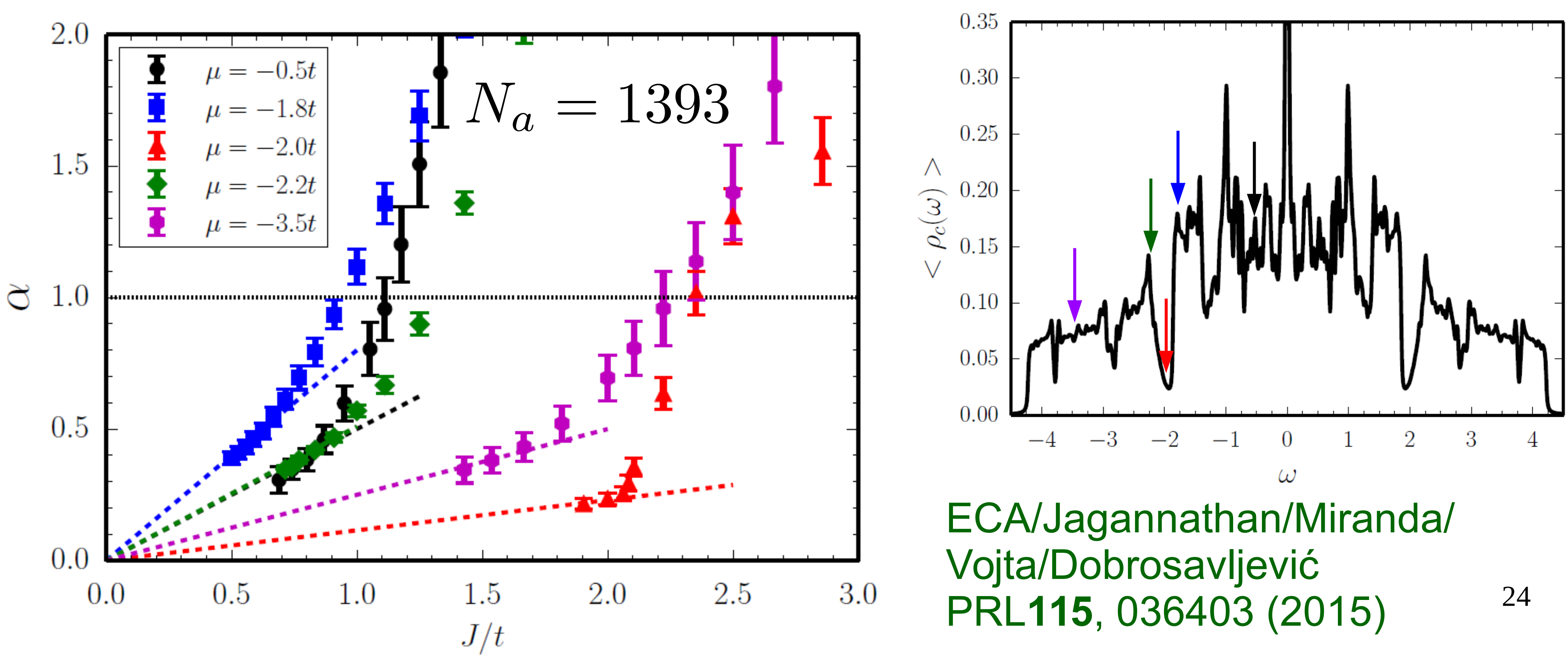
ECA/Jagannathan/Miranda/Vojta/Dobrosavljević PRL **115**, 036403 (2015)



$$\mu = -2.2t$$
$$N_a = 1393$$
$$J = 2V^2/|E_f|$$

Non-universal power-law exponent α

- $P(T_K) \propto T_K^{\alpha-1}$ for all μ, with $\alpha \propto J\langle\rho_c(0)\rangle$ as $J \to 0$
- As the DOS, α has huge energy dependence
- NFL liquid behavior for $\alpha < 1$. Unquenched spins: $T_K \to 0$



ECA/Jagannathan/Miranda/
Vojta/Dobrosavljević
PRL**115**, 036403 (2015)

Free spins at low-T: route to NFL

- Number of free local moments at a given *T*

$$n_{free}(T) = \int_0^T P(T_K)\, dT_K \sim \int_0^T T_K^{\alpha-1} dT_K \sim T^{\alpha}$$

Spins with $T_K < T$: essentially free

- Susceptibility

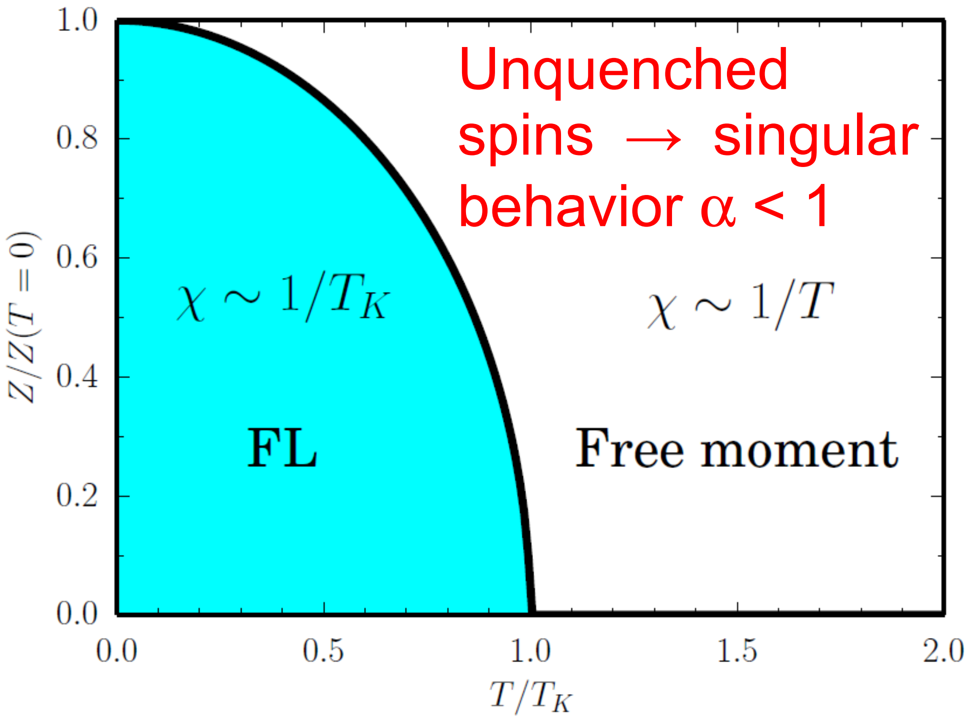
$$\chi(T) \sim n_{free}(T)/T \sim T^{\alpha-1}$$

- Entropy

$$S(T) \sim n_{free}(T)\, ln2 \sim T^{\alpha}$$

- Sommerfeld coefficient

$$\gamma(T) = \frac{C(T)}{T} = \frac{\partial S}{\partial T} \sim T^{\alpha-1}$$



NFL behavior – Free spins at T → 0

- Single energy scale: $\begin{cases} T \lesssim T_K, & \text{Fermi-liquid} \\ T \gtrsim T_K, & \text{Free spin} \end{cases}$ $\quad \chi(T, T_K) = \frac{1}{T_K} f\left(\frac{T}{T_K}\right)$

- Averaged value of the single-impurity susceptibility

$$\langle \chi(T) \rangle = \int dT_K P(T_K) \chi(T, T_K) = \chi_r + \underbrace{\int_0^{\Lambda} dT_K T_K^{\alpha-1} \frac{1}{T_K} f\left(\frac{T}{T_K}\right)}_{\propto T^{\alpha-1}}$$

Regular + Singular

- Miranda/Dobrosavljević/Kotliar, J. Phys. Cond. Mat **8**, 9871 (1996)
- Rappoport/Boechat/Saguia/Continentino, EPL **61**, 831 (2003)
- Cornaglia/Grempel/Balseiro, PRL **96**, 117209 (2006)
- Kettemann/Mucciolo/Varga, PRL **103**, 126401 (2009)
- Miranda/Dias da Silva/Lewenkopf, PRB **90**, 201101 (2014)
- ...

$$\chi(T) \sim N(T)/T \propto T^{\alpha-1}$$

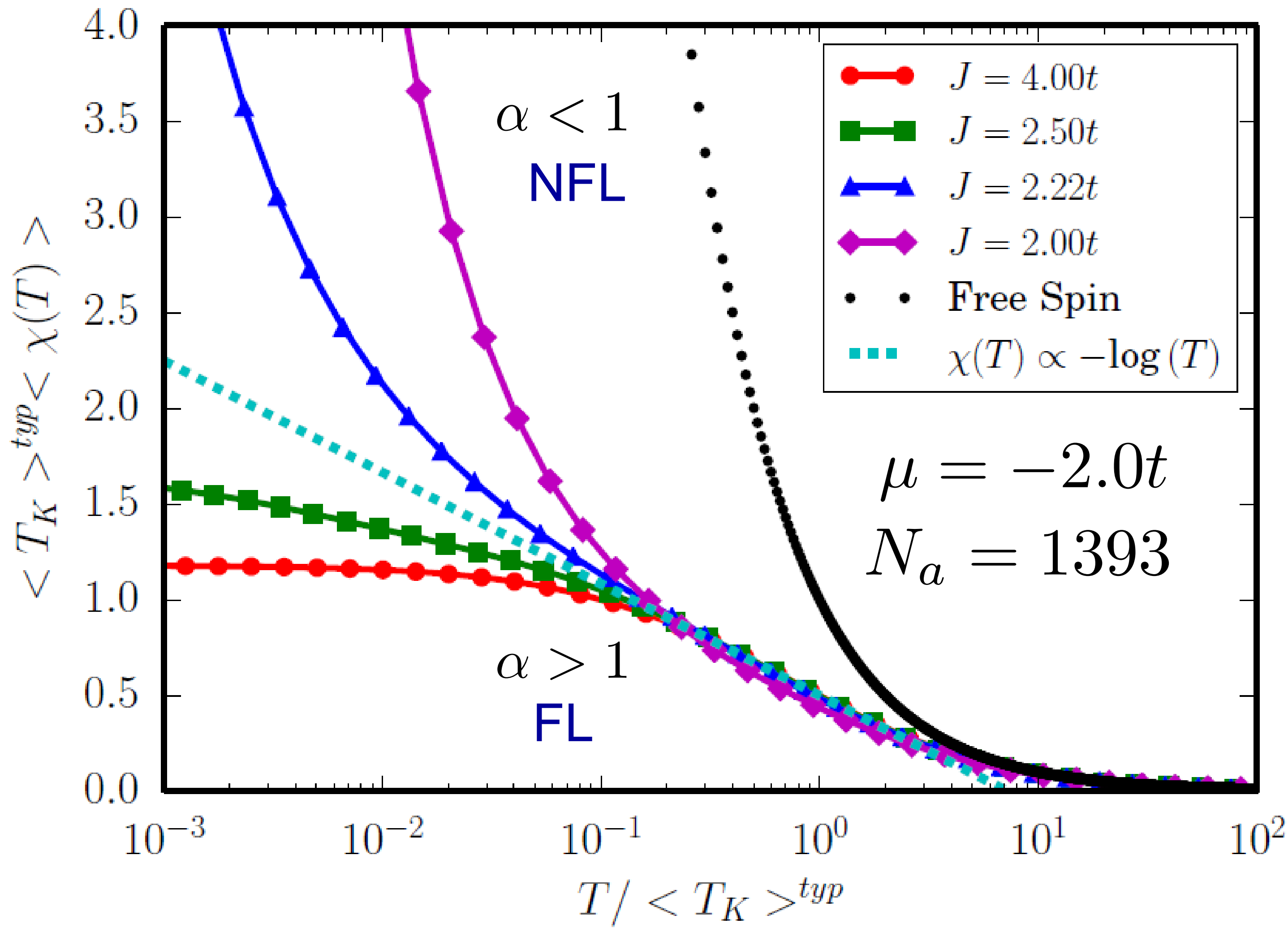
$$C/T = \gamma(T) \propto T^{\alpha-1}$$

$$\chi/\gamma \sim cte$$

$$1/T_1 T \propto T^{\alpha-2}$$

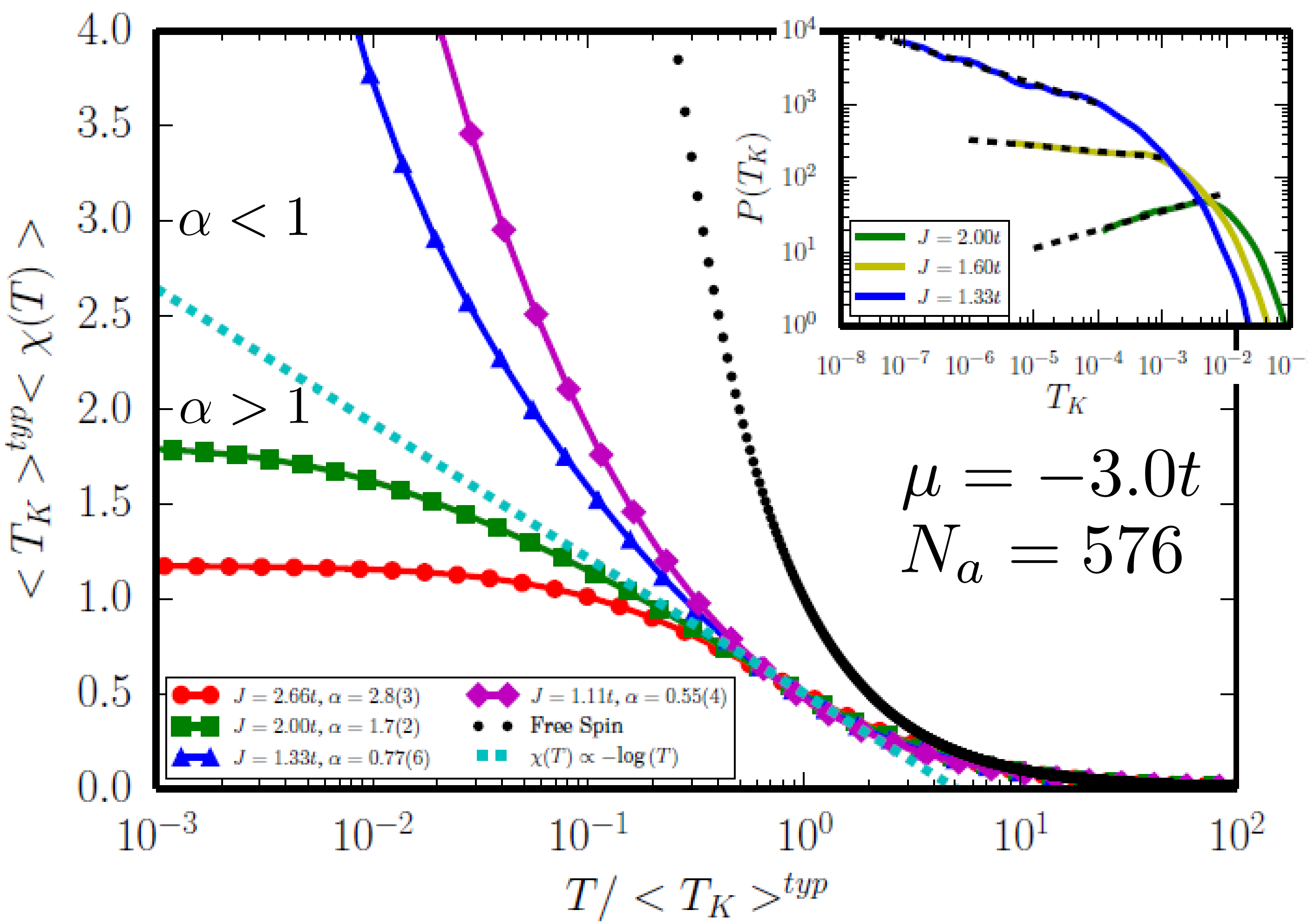
NFL behavior – Octagonal tiling

A power-law distribution of Kondo temperatures, leads to a power-law susceptibility

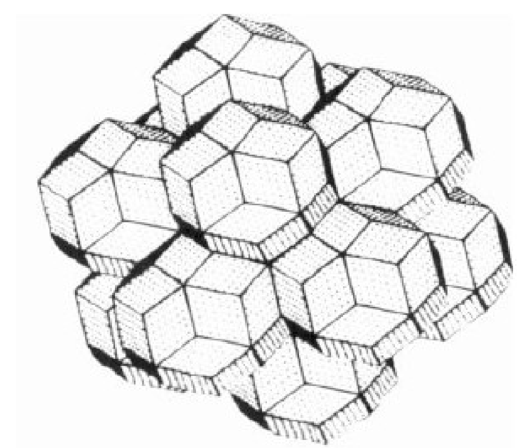


NFL behavior – Three dimensions

- Similar behavior in 3D: rhombohedra (Ammann-Kramer) tiling
- There seems to be little dimensionality dependence (*D* = *2,3*)



Provided by M. Mihalkovic



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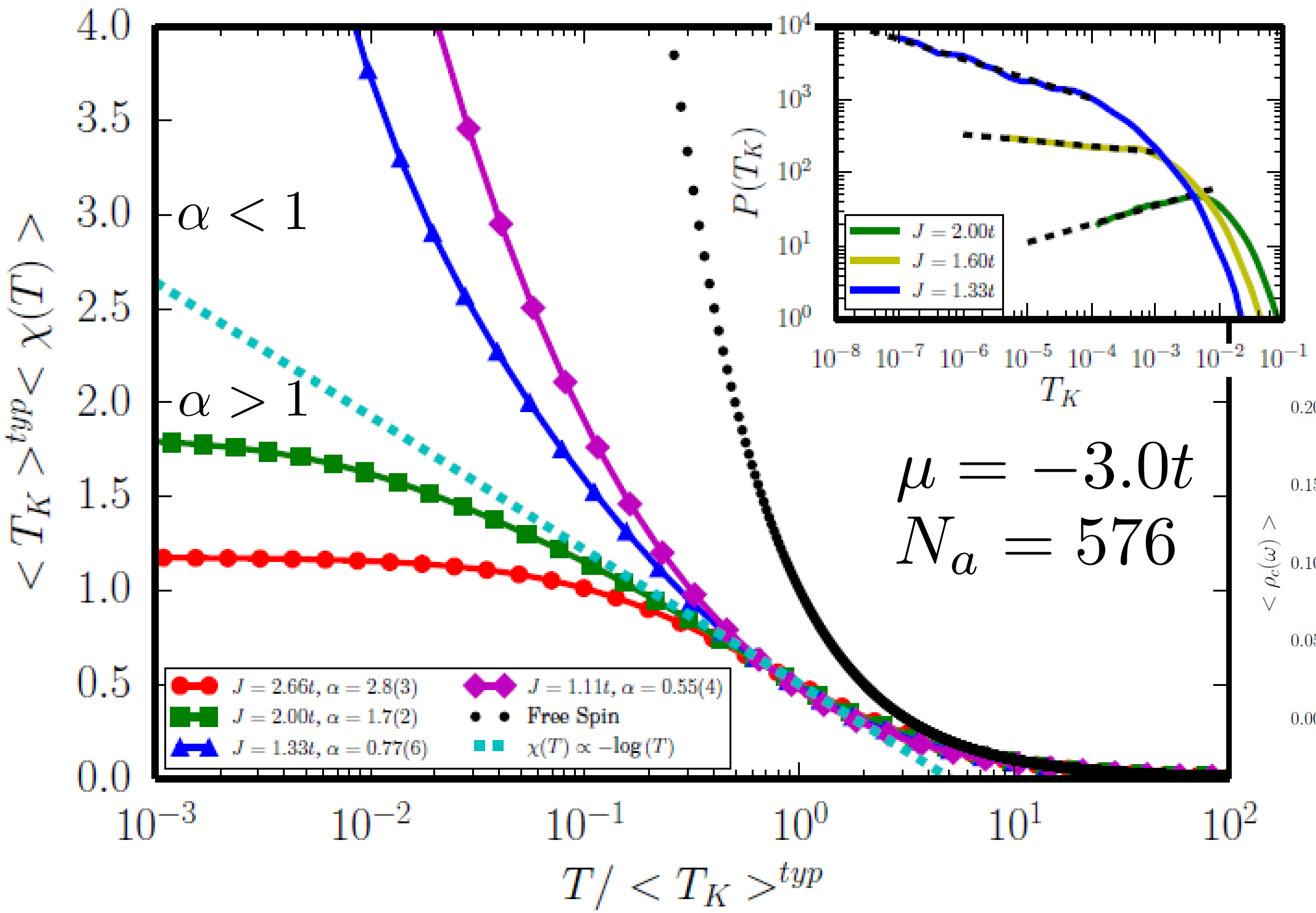

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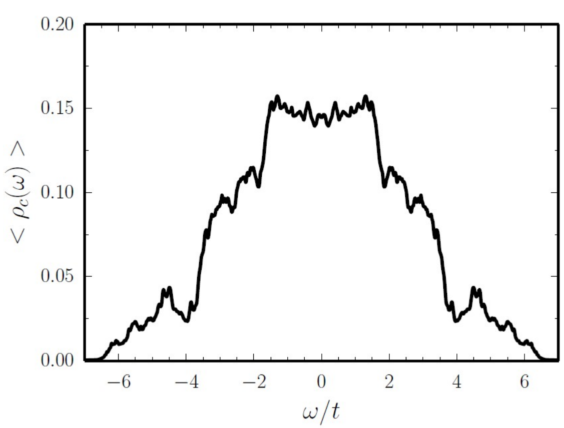
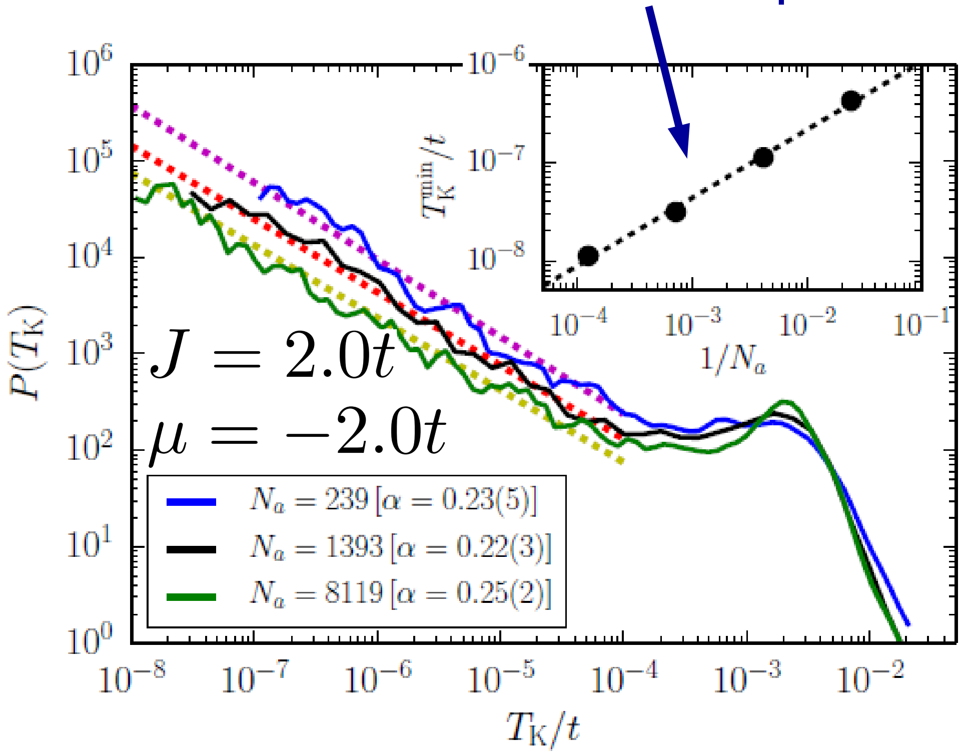
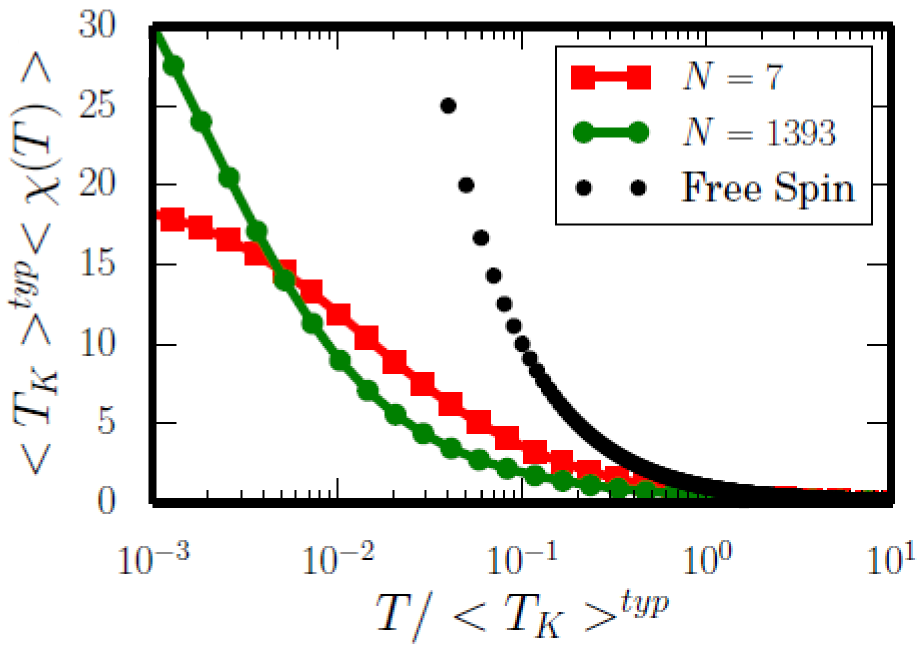


FL behavior in small approximants

- For any approximant, there is a finite number of T_K's, and therefore a minimum one.
- Below this T_K^{min} , FL behavior is recovered.
- Only in an infinite QC there is true NFL behavior.

Minimum value of Kondo temperature: T_K^{min}





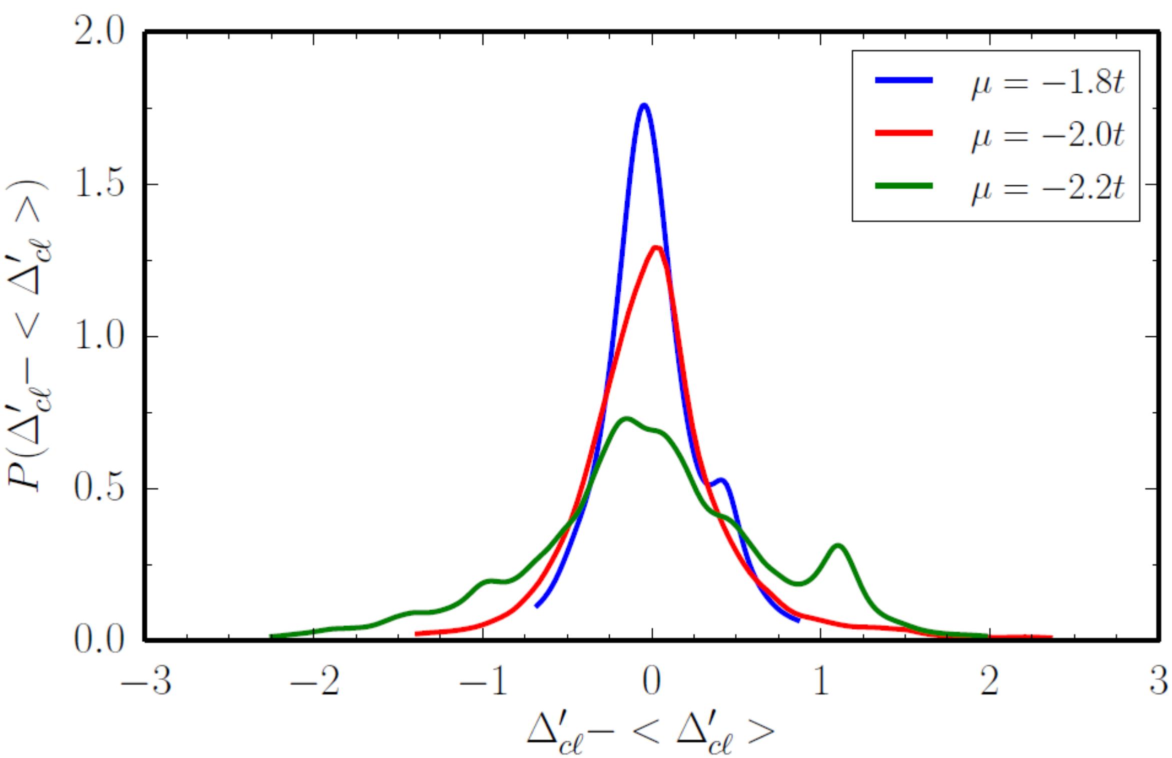
Why power-law? Metallic quasicrystal

- Define an "effective site energy" via the cavity function

$$G^c_{\ell\ell}(\omega) = 1/(\omega - \Delta_{c\ell}(\omega)) \qquad \tilde{\varepsilon}_\ell = \Delta'_{c\ell}(0)$$

$$T^\ell_K = T^0_K e^{-\tilde{\varepsilon}^2_\ell / J\langle\rho_c(0)\rangle t^2} \quad P(\tilde{\varepsilon}) \sim e^{-\tilde{\varepsilon}^2/2\sigma^2} \quad P(T_K) \propto T_K^{\alpha-1}$$

$$\alpha = J\langle\rho_c(0)\rangle t^2/2\sigma^2$$



Gaussian-like tails in *P(Δ'(0))* immediately leads to singular behavior in *P*(T_K)

Akin to disordered metals

Tanasković/Miranda/Dobrosavljević PRB **70**, 205108 (2004)

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Conclusions

- Experiments: NFL behavior in the $Au_{51}Al_{34}Yb_{15}$ quasicrystal
  - No tunning of external parameters. Approximant different from the quasicrystal. Quenched by H but not by P
- Diluted Kondo impurities in metallic quasicrystals: Power-law distribution of T_K. Akin to *weakly* disordered systems
- Strong energy dependence. NFL behavior changes/disappears in small approximants (observed experimentally)
- Lattice problem: Diluted impurity scenario survives? (Most likely yes for thermodynamics!), Effects of inter-site spin correlations; Kondo coherence; Transport ...

Thank you very much for your attention!

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