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Extremely Correlated Fermi Liquids

Compilation of Reprints *

With Comments

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Preface

This volume contains a compilation of papers on the *Extremely Strongly Correlated Fermi Liquid* (ECFL) theory. The theory provides a systematic framework for calculating the properties of a fermions on a lattice, when the interaction strength is so large that standard perturbation techniques based on Feynman diagrams, are rendered invalid. The models solved in the ECFL theory allow the local interaction to diverge, thereby eliminating or projecting out a finite fraction of states in the Hilbert space. This elimination turns the usual fermions into non-canonical *projected* fermions. These satisfy an anti-commuting non-canonical algebra, whereby Wick's theorem is irretrievably lost. The theory now uses the Schwinger-Tomonaga method of source fields to set up exact non-linear functional differential equations for Greens functions. Solving these equations is challenging, and several innovations are further necessary before one can find practical solutions that are testable by experiments. This package of essential steps forms the core of the ECFL formalism.

After the [initial paper](#) in 2011, we‡ have worked on finding explicit solutions and comparing with a few known, but rare exact solutions, found by other means. These include the $d = 0$ Anderson impurity model (using the numerical renormalization group), the $d = \infty$, $U = \infty$ Hubbard model (using the dynamical mean field theory), the 1 dimensional t - J model (using the density matrix renormalization group), and also with high temperature series expansions. After this extensive testing, we have recently applied the theory to the 2-dimensional t - t' - J model, and calculated several measurables in the density range relevant to cuprate superconductors. Recent papers in 2020-21 address two central issues of cuprate superconductivity, the [quasi-linear resistivity](#) and the [mechanism of superconductivity](#). At this stage it appears that a compilation of the (several) published papers from the ECFL theory providing some additional context could be helpful. Towards that goal, this compilation contains a topic-wise breakup of the papers, and also brief comments on each paper. Extensive hyperlinks are provided to enable easy paper-hopping.

Co-authors‡

My grateful thanks to colleagues whose works are included here.

- *Graduate Students and Postdocs:* Michael Arciniaga, Wenxin Ding, Daniel Hansen, Peizhi Mai, Kazue Matsuyama, Edward Perepelitsky.
- *Senior Collaborators:* Professors Antoine Georges (Collège de France, Paris), G-H Gweon (UC Santa Cruz), Alex Hewson (Imperial College, London), Rok Žitko and Jernej Mravlje (Jožef Stefan Institute, Ljubljana), Ehsan Khatami (SJSU), Marcos Rigol (Penn State), Steven R White (UC Irvine) and H R Krishnamurthy (IISc, Bangalore).

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I Topics (With Comments)

I.1 Basic Formalism

1. Extremely Correlated Fermi Liquids

B. S. Shastry, arXiv:1102.2858 (2011), Phys. Rev. Letts. **107**, 056403 (2011). ...Page(16)

§This paper lays the foundations of the ECFL theory. A core issue in formulating a non canonical theory is to generalize Dyson's self energy of the canonical theory. This requires one to identify an object Φ that can be tucked into the denominator of the Greens function. A subtle and important requirement is that Φ must spawn a sensible (i.e. non-growing) vertex function (upon differentiating by a bosonic source). The vertex also defines the self energy through a closure relation. Thus a self-consistent loop of equations is set up, to be solved by a suitable iterative procedure. An earlier paper ([Extremely Correlated Quantum Liquids](#), B Sriram Shastry, Phys. Rev. **B 81**, 045121 (2010)) discusses this issue and proposes an alternate solution. However that solution leads inevitably to a fermi surface differing in volume from that of the free fermi gas, thereby violating the Luttinger-Ward theorem. While this may yet be relevant very close to the Mott insulating state, one would like to retain the volume at lower particle densities.

This work finds another possible route for identifying the self energy, while maintaining continuity with the fermi gas, and thus avoiding the volume violation. Here the basic factorization of the physical Greens function is introduced, into an auxiliary Greens function g and a [caparison](#) function μ through $\mathcal{G}(k, \omega) = g(k, \omega)\mu(k, \omega)$. The two Greens functions $\mathcal{G}$ and g describe the fully interacting and a related canonical theory, with identical particle number sum-rules. This decomposition leads to a sensible self energy for the auxiliary Greens function $g(k, \omega)$, and $\mu(k, \omega)$ is a second self energy, but now in the *numerator* of the physical $\mathcal{G}$. An iterative scheme is proposed here by introducing a parameter $\lambda \in [0, 1]$ connecting the free fermi gas with the fully interacting problem. Exact formal equations for the two self energies are given and systematically expanded in λ to $\mathcal{O}(\lambda^2)$.

The paper also contains a phenomenological model for the two self energies which captures many features of the spectral line shapes.

2. Anatomy of the Self Energy

B. S. Shastry, arXiv:1104.2633; Phys. Rev. B **84**, 165112 (2011); Phys. Rev. B **86**, 079911(E) (2012). ...Page(18)

§The non-standard Greens function of the extremely correlated electrons proposed in the [paper\(1\)](#), is structurally very different from the Dyson construction for canonical fermions. This paper explores the difference, its consequences for the line shapes, and further refines the phenomenological spectral function proposed above.

This paper also contains a discussion of the Mori formalism. It can be used to define a Dyson-Mori self energy, if the moments of the spectral function are available from an independent calculation.

3. Extremely Correlated Fermi Liquids: The Formalism

B. S. Shastry, arXiv:1207.6826 (2012); Phys. Rev. **B 87**, 125124 (2013). ...Page(20)

§This paper introduces two *shift identities* for the t - J model, and the use of a second Lagrange multiplier, required in addition to the thermodynamic chemical potential, to fulfill the number sum-rule on the physical as well as the auxiliary Greens functions. The paper also details a systematic procedure for computing the self energies and vertices to high order using functional derivatives on the lower order ones.

4. **Theory of extreme correlations using canonical Fermions and path integrals**
B. S. Shastry, arXiv:1312.1892 (2013), Ann. Phys. **343**, 164 (2014). (Erratum) **373**, 717 (2016). ...Page(26)

§This paper shows the analogy between the λ expansion of the correlated electrons, and the large spin expansion using the Dyson-Maleev representation for spins. It also has a formulation of the theory in terms of novel λ fermions satisfying a λ dependent (deformed) fermi algebra, and also a path integral representation in terms of canonical fermions. This paper also simplifies the treatment using the *minimal equations of motion*, discarding extra symmetrizing terms employed earlier (in the [paper\(1\)](#) and in [paper \(3\)](#)). Later work has used only the minimal equations.

5. **Diagrammatic λ series for extremely correlated Fermi liquids**
E. Perepelitsky and B. S. Shastry, arXiv:1410.5174, Ann. Phys. **357**, 1 (2015).
...Page(28)

§This paper contains a detailed diagrammatic expansion of the Schwinger equations of motion in terms of the λ parameter. The rules for diagrams enable one to write down a complete set of distinct diagrams to any order, without recourse to functional differentiation as in the formalism [paper \(3\)](#). The diagrams contain a Feynman diagram subset, extended by adding certain additional (Schwinger) diagrams.

6. **Fermi Surface Volume of Interacting Systems**
B. S. Shastry, arXiv:1808.00405v4; Annals of Physics **405**, 155 (2019). ...Page(37)

§This work provides an alternate proof of the theorem asserting the invariance of the Fermi surface volume at $T=0$ upon turning on interactions, using the novel concept of *isothermal continuity*. For Fermi liquids this theorem is an important ingredient of Landau's argument, who used adiabatic continuity. It was demonstrated in the well known work of Luttinger and Ward, who assumed that perturbation theory is convergent. The new proof, motivated by [the results of ECFL\(30\)](#), extends the theorem to arbitrarily strong interactions, 1-d non-Fermi liquid systems, and to singlet superconductors. The sum-rule is expressed in terms of photoemission accessible spectral functions, and its rich T dependence is illustrated in [paper\(23\)](#).

I.2 ECFL- Comparisons: Numerical Renormalization Group - Anderson Impurity Model and Dynamical Mean Field theory

7. **Extremely Correlated Fermi Liquid study of the $U = \infty$ Anderson Impurity Model**
B. S. Shastry, E. Perepelitsky and A. C. Hewson, arXiv:1307.3492 [cond-mat.str-el], Phys. Rev. B **88**, 205108 (2013). ...Page(23)

§In this work the single impurity Anderson model is solved by the ECFL method, using the λ expansion to $\mathcal{O}(\lambda^2)$. For impurity density $n_d \lesssim 0.7$ and the spectral properties

are shown to compare well with the numerically exact results from the numerical renormalization group method of Wilson. For higher densities $n_d \gtrsim 0.7$ good agreement is also found provided the frequencies are scaled by a corrected quasiparticle weight Z .

8. **Reversal of particle-hole scattering-rate asymmetry in Anderson impurity model**

Rok Žitko, H. R. Krishnamurthy and B. Sriram Shastry, arXiv:1807.11343. Phys. Rev. B **98**, 161121 (R) (2018). ...Page(36)

§In **this work**, motivated by a suggestion from the strong coupling solution in **paper (7)**, the single impurity Anderson model is shown to have a novel separatrix in the density- U plane, demarcating regions of weak and strong correlations. These regions are distinguished by opposite signs of the ω^3 term correction to $\Im m \Sigma(\omega)$, beyond the leading ω^2 Fermi liquid behavior.

9. **Extremely correlated Fermi liquid theory meets Dynamical mean-field theory: Analytical insights into the doping-driven Mott transition**

R. Žitko, D. Hansen, E. Perepelitsky, J. Mravlje, A. Georges and B. S. Shastry, arXiv:1309.5284 (2013), Phys. Rev. B **88**, 235132 (2013). ...Page(24)

§The ECFL spectral results for $d = \infty$ at $\mathcal{O}(\lambda^2)$, are compared with the exact solution of the Hubbard model in the same limit, with varying values of density and the interaction U . For $U \gtrsim 2D$ -the bandwidth, the two theories give a similar behavior at low frequencies, with a strong particle hole-asymmetry in the imaginary part of self energy. This benchmarking shows that the $\mathcal{O}(\lambda^2)$ ECFL theory gives spectral functions that extend to higher energies compared to the exact results. The value of the quasiparticle weight Z is also over-estimated for densities $n \gtrsim 0.75$, similar to the impurity model results in **paper (7)**. Once again, scaling the frequency by a corrected Z improves the agreement at high densities considerably.

10. **ECFL in the limit of infinite dimensions**

E. Perepelitsky and B. S. Shastry, arXiv:1309.5373 (2013), Annals of Physics **338**, 283-301 (2013). ...Page(25)

§The ECFL equations are analyzed in the limit of $d \rightarrow \infty$. The resulting Dysonian self energy, found by inverting the physical Greens function, is shown to be momentum independent, as in the exact result. An expansion in λ is developed, giving the equations used in the DMFT comparison **paper(9)**.

I.3 High T expansion and ECFL comparison

11. **Electronic spectral properties of the two-dimensional infinite-U Hubbard model**

E. Khatami, D. Hansen, E. Perepelitsky, M. Rigol, B. S. Shastry, arXiv:1303.2657 [cond-mat.str-el] (2013), Phys. Rev. B **87**, 161120 (R) (2013). ...Page(22)

§The 2-d $U = \infty$ Hubbard model electron Greens function is studied here. Several types of (low order) moments of the Greens functions are calculated here using high Temperature cumulant expansion. In this formalism non canonical fermions can be treated in a straightforward but laborious fashion. The comparison with ECFL spectra is found to be possible at low densities $n \lesssim 0.75$, and not too low T, and several useful results are compiled.

12. [Linked-Cluster Expansion for the Green's function of the Infinite-U Hubbard Model](#)
E. Khatami, E. Perepelitsky, M. Rigol and B. S. Shastry, arXiv: 1310.8029 (2013),
Phys. Rev. **E 89**, 063301 (2014). ...Page(27)

§The high T series for the $U = \infty$ Hubbard model Greens function is calculated to eighth order in t using a linked cluster expansion. The electronic spectral function, the thermopower and quasiparticle weight are calculated and compared to the ECFL results. The electron Greens function is tabulated up to $\mathcal{O}(t^4)$ in k-space, and (the long) higher order terms up to $\mathcal{O}(t^8)$ are available on request.

I.4 Angle Resolved Photoemission Spectroscopy (ARPES) related

13. [Extremely Correlated Fermi Liquid Description of Normal State ARPES in Cuprates](#)
G.-H. Gweon, B. S. Shastry and G. D. Gu, arXiv:1104.2631 (2011), Phys. Rev. Letts.
107, 056404 (2011). ...Page(17)

§The ECFL spectral lines are compared with experiments on several cuprate materials. The ARPES experiments done at different incident photon energies give quite different looking spectra, this work shows that varying an elastic scattering parameter together with the line shapes from ECFL theory fit experiments very closely. This paper observes that a low energy kink $\omega \sim 60\text{meV}$ present in the ECFL spectrum, is in close accord with experimental kinks.

14. [Dynamical Particle Hole Asymmetry in Cuprate Superconductors](#)
B. S. Shastry, arXiv:1110.1032 (2011), Phys. Rev. Letts. **109**, 067004 (2012). ...Page(19)

§This work emphasizes the occurrence of a distinct skew or asymmetry of ECFL spectral lines, also seen in experiments. This implies the absence of particle hole symmetry in the self energy at even modestly frequencies $\hbar\omega \sim 40\text{ meV}$. Further tests for establishing this asymmetry in experiments is proposed.

15. [Origin of Kinks in Energy Dispersion of Strongly Correlated Matter](#)
Kazue Matsuyama, Edward Perepelitsky and B Sriram Shastry, arXiv:1610.08079,
Phys. Rev. **B 95**, 165435 (2017). ...Page(30)

§This work provides a review of the kinks in ARPES, and contrasts two competing view points for explaining it, along with precise tests for each of them. One view of the kinks locates some bosonic degree of freedom at the kink energy, and leads to specific predictions for the energy dispersion of the electrons. Another view, initiated in [paper\(13\)](#) and developed further in [paper\(2\)](#), and [paper\(4\)](#) ascribes these to extremely strong correlations, and comes with another set of predictions. Considerable data is analyzed using the theory and several testable predictions made.

I.5 Infinite dimensions redux, optical and Hall response, resistivity

16. [Low energy physics of the \$t\$ - \$J\$ model in \$d = \infty\$ using Extremely Correlated Fermi Liquid theory: Cutoff Second Order Equation](#)
B. S. Shastry and E. Perepelitsky, arXiv:1605.08213. Phys. Rev. **B 94**, 045138 (2016).
...Page(29)

§Explores the origin and provides one convenient prescription for managing the high energy tails that the $\mathcal{O}(\lambda^2)$ equations develop in the two (distinct limits) of high T at any density, and at high density $n \rightarrow 1$ at low T. A cutoff procedure using a Tukey window confines the spectrum to roughly twice the (bare) bandwidth. Further the physical Greens function for the lower Hubbard band is required to satisfy the exact normalization $1 - \frac{n}{2}$ (without λ corrections as in earlier work), and argued to be essential for getting the right quasiparticle weight. With these ingredients, the resulting quasiparticle weight Z is close to the exact value from DMFT to fairly high $n \lesssim 0.9$.

17. [A Strange Metal from Gutzwiller correlations in infinite dimensions](#)

Wenxin Ding, Rok Žitko, Peizhi Mai, Edward Perepelitsky and B. Sriram Shastry, arXiv:1703.02206v2; Phys. Rev. **B 96**, 054114 (2017). DOI: 10.1103/PhysRevB.96.054114

...Page(31)

§The cutoff introduced in the above [paper \(16\)](#) is used to compute the resistivity, heat capacity and entropy at low T, and compared against exact results from DMFT. The different regimes of resistivity are reviewed, these include the fermi liquid, the strange metal, the bad metal and the high T metal, with three distinct crossovers between them. All these regimes follow from the Gutzwiller (i.e. large U) limit.

18. [A Strange Metal from Gutzwiller correlations in infinite dimensions II: Transverse Transport, Optical Response and Rise of Two Relaxation Rates](#)

Wenxin Ding, Rok Žitko, and B. Sriram Shastry, arXiv:1705.01914; Phys. Rev **B 96**, 115153 (2017).

...Page(33)

§This examines the T dependence of the Hall constant and the cotangent Hall angle, as well as the optical conductivity, using the same methods as in the [paper \(17\)](#) above. A noticeable *kink*, i.e. crossover between two linear regimes in the cotangent Hall angle versus T^2 plot is noted at the effective fermi liquid scale, and the transverse time scale is extracted from the frequency dependent conductivities. Such a kink seems present in many experiments.

19. [Extremely Correlated Fermi Liquid theory for \$U = \infty\$, \$d = \infty\$ Hubbard model to \$\mathcal{O}\(\lambda^3\)\$,](#)

Samantha Shears, Edward Perepelitsky, Michael Arciniaga and B Sriram Shastry, arXiv:2204.08599, Phys. Rev. B **106**, **035108** (2022).

DOI: 10.1103/PhysRevB.106.035108

...Page(43)

§This paper extends the λ expansion to $\mathcal{O}(\lambda^3)$ for the $d = \infty$ Hubbard model, from the lower order expansion reported in the above papers. This extension is noted to have greater sensitivity to the details of the iteration procedure and slightly limited in the range of densities as compared to the $\mathcal{O}(\lambda^2)$ expansion. In general the results seem closer to the exact results from exact numerical results from DMFT. We also explore the use of exact sum-rules for the electronic spectral function as constraints.

I.6 ECFL Solutions in $d = 1$ at $\mathcal{O}(\lambda^2)$ and preliminary solution in $d = 2$

20. [Extremely Correlated Fermi Liquids: Self consistent solution of the second order theory](#)

D. Hansen and B. S. Shastry, arXiv:1211.0594, (2012), Phys. Rev. **B 87**, 245101 (2013).

...Page(21)

§The first set of numerical results from the theory for the t - J model in 2-d. The equations for the self energies are truncated to $\mathcal{O}(\lambda^2)$, and explicit results for electronic densities in the highly overdoped regime of cuprates $n \leq 0.75$, are found. The quasi-particle weight is larger than expected for $n \gtrsim 0.75$, since the normalization condition for the Greens function is different from the one later emphasized in [paper\(16\)](#), and employed in recent work.

21. [The t-t'-J model in one dimension using extremely correlated Fermi liquid theory and time dependent density matrix renormalization group](#)

Peizhi Mai, Steven R. White and B. Sriram Shastry, arXiv:1712.05396. ...Page(34)

§An application of the equations reported in the [paper \(16\)](#) and in [paper \(22\)](#) to the case of the 1-d t - t' - J model are made and the results compared with those from the density matrix renormalization group (DMRG). The physics of anomalous exponents, spin-charge separation, and the (non-fermi) Tomonaga-Luttinger liquid state brought about by quantum fluctuations in 1-d are captured by the ECFL equations, and also the DMRG solution. The DMRG and ECFL theories yield a self energy with strong k dependence of a similar nature.

I.7 ECFL Solutions in $d = 2$ at $\mathcal{O}(\lambda^2)$: Basic Papers

22. [Extremely Correlated Fermi Liquid theory of the \$t\$ - \$J\$ model in 2 dimensions: Low energy properties](#)

B Sriram Shastry and Peizhi Mai, arXiv:1703.08142, N. Jour. Phys. **20** 013027 (2018).
...Page(32)

§An application of the equations reported in the [paper \(16\)](#), to the case of the 2-d t - t' - J model is made, at experimentally interesting densities $.8 \leq n \leq .9$. The quasiparticle weight is typically very small, and very sensitive to the sign of the second neighbor hopping t'/t . The effective fermi temperature is calculated to be 2 or 3 orders of magnitude smaller than the bandwidth. The resistivity changes from a quadratic T^2 to a linear T variation. The Hall number, cotangent Hall angle are calculated.

23. [Extremely correlated fermi liquid of \$t\$ - \$J\$ model in two dimensions](#)

Peizhi Mai and B. Sriram Shastry, arXiv:1808.09788, Phys. Rev. B **98**, 205106 (2018).
...Page(38)

§This work is a continuation of [paper \(22\)](#), and reports detailed calculations of the spectral functions, EDC and MDC dispersion relations, the Hall constant and Hall number and illustrates the Fermi surface sum-rule reported in [paper \(30\)](#).

I.8 ECFL Solutions in $d = 2$ at $\mathcal{O}(\lambda^2)$: Applications to Raman scattering, Momentum resolved electron energy loss and Superconductivity

24. [Non-resonant Raman Scattering in Extremely Correlated Fermi Liquids](#)

Peizhi Mai and B. Sriram Shastry, arXiv:1805.09935, Phys. Rev. **B 98**, 115101 (2018).
...Page(35)

§A detailed study of the non-resonant Raman scattering in a 2-d t - J model is presented, using the ECFL equations developed in [paper \(22\)](#). A quartet of closely related variables

are presented, three from standard polarization geometries and the optical conductivity. Together they reveal the role played by the model parameters, and the importance of using correct vertices in narrow band metals.

25. **Extremely correlated superconductors,**

B. Sriram Shastry, arXiv:2102.08395; Annals of Physics **434**, 168614 (2021)....Page(41)

§Superconductivity in the t - J model is studied by generalizing the Gor'kov equations to include very strong correlations. Systematic equations for the superconducting instability are formulated within the λ expansion. The leading order equation is studied using a phenomenological spectral function for the metallic state. A superconducting phase appears away from half filling, and persists for a range of densities. A simple formula for the T_c is obtained, where the interplay between Mott-Hubbard localization, Cooper pairing due to the exchange energy J , and its dependence on the band parameters are made explicit.

26. **Dielectric response of electrons with strong local correlations and long-ranged Coulomb interactions,**

B Sriram Shastry and Michael Ariciniaga, arXiv:2111.04891, Ann. Pays. **442**, 168924 (2022).

<https://doi.org/10.1016/j.aop.2022.168924>

...Page(42)

§Motivated by recent experiments in momentum resolved electron energy loss spectroscopy (M-EELS) in layered (i.e. quasi 2-dimensional) strongly correlated systems, we studied the t - J model within the ECFL theory, by adding long range Coulomb interactions. This challenging theoretical problem requires adding suitable vertex corrections, in order to satisfy current conservation laws. New formulas for the dielectric function in such systems are developed, following Nozières's results for a weakly correlated systems.

I.9 ECFL Solutions in $d = 2$ at $\mathcal{O}(\lambda^2)$: Applications to resistivity

27. **Theory of anisotropic elasto-resistivity of 2-D extremely strongly correlated metals**

Michael Arciniaga, Peizhi Mai and B Sriram Shastry, arXiv:1909.06471; Phys. Rev. B **101**, 245149 (2020). ...Page(39)

§The effect of anisotropic strain on resistivities is calculated from equations generalizing those in [paper \(22\)](#) to include the effect of anisotropic strain. The elastoresistivity tensor is calculated and predictions for the magnitude of this effect are made for cuprate superconductors. The anisotropic response of a few other measurables (the local density of states and optical sum-rule) are calculated.

28. **Aspects of the Normal State Resistivity of Cuprate Superconductors**

B. Sriram Shastry and Peizhi Mai, arXiv:1911.09119; Phys. Rev. B **101**, 115121 (2020). ...Page(40)

29. **Aspects of the normal state resistivity of cuprate superconductors $Bi_2Sr_2CuO_{6+x}$, $Tl_2Ba_2CuO_{6+x}$ and $HgBa_2CuO_{4+x}$,**

Samantha Shears, Michael Arciniaga and B. Sriram Shastry, arXiv:2502.00293, Phys. Rev. B **111**, 245146 (2025);

<https://DOI: 10.1103/89cj-5qhs>

...Page(45)

§In [paper \(28\)](#) and [paper\(29\)](#) the published electrical resistivity of all single layer cuprate superconductors are compared with the ECFL theory, as a function of temperature and density. In [paper \(28\)](#) the data on the hole-doped compounds $La_{2-x}Sr_xCuO_4$ (LSCO) and $Bi_2Sr_{2-x}La_xCuO_6$ (BSLCO) are compared with ECFL modeled with $t'/t < 0$, while the two electron-doped compounds $Nd_{2-x}Ce_xCO_4$ (NCCO) and $La_{2-x}Ce_xCuO_4$ (LCCO), which are modeled with $t'/t > 0$. The observed quadratic temperature dependence of the electron-doped compounds is well described by the theory, as is the almost linear in T dependence of the hole-doped compounds, with otherwise identical equations. In [paper \(29\)](#) the data on the recent hole-doped compounds $Bi_2Sr_2CuO_{6+x}$ (Bi2201), $Tl_2Ba_2CuO_{6+x}$ (Tl2201) and $HgBa_2CuO_{4+x}$ (Hg1202) is compared with the ECFL theory. Overall all seven families of compound display resistivities that compare favorably with theory[‡].

I.10 General results on Fermi surface volume theorem and Extraction of self energy from spectral function

30. [Fermi Surface Volume of Interacting Systems](#)

B. S. Shastry, arXiv:1808.00405v4; Annals of Physics **405**, 155 (2019). ...Page(37)

§This work provides an alternate proof of the Luttinger-Ward theorem on the interaction independence of the Fermi surface volume. This proof extends the theorem to new situations such as very strong interactions, and to 1-dimensional interacting fermions. For this purpose it uses a new sum-rule expressible in terms of experimentally accessible spectral functions. The sum-rule is also applicable to singlet superconductors, in their superconducting phase, where it would reveal the underlying Fermi surface of the parent normal system.

31. [Method for reconstructing the self-energy from the spectral function](#),

B. Sriram Shastry, arXiv:2408.07682, Phys. Rev. B **110**, 155149 (2024);
https://doi.org/10.1103/PhysRevB.110.155149 ...Page(44)

§The intense focus of the community on resistivity, stems from the expectation that it could reveal whether the correlated systems are Fermi liquids or non-Fermi liquids. The considerable subtleties involved in calculating and interpreting the resistivity, suggest alternate ways to address this question are needed. This work develops an important and hitherto unused formula for extracting the imaginary part of the self energy from the spectral function, where the fractional error is theoretically shown to shrink at low energies. A case is made for further ARPES work in this promising direction.

[‡]The code used in these papers is openly available on

Github: <https://github.com/marcinia-sudo/2DECFL2ndOrder>

Zenodo: <https://doi.org/10.5281/zenodo.18085923>

ECFL results for resistivity and spectral function data for these systems with an added interpolation scheme are made available in

Aspects of the normal state resistivity of cuprate superconductors Bi2201, Tl2201, and Hg1201 (Data set), S. Shears, M. Arciniaga, and B. S. Shastry, Zenodo (2025), <https://doi.org/10.5281/zenodo.15306960>.

II Included papers (most recent first)

- Aspects of the normal state resistivity of cuprate superconductors $Bi_2Sr_2CuO_{6+x}$, $Tl_2Ba_2CuO_{6+x}$ and $HgBa_2CuO_{4+x}$,
Samantha Shears, Michael Arciniaga and B. Sriram Shastry, arXiv:2502.00293, Phys. Rev. B **111**, 245146 (2025);
<https://DOI: 10.1103/89cj-5qhs> ...Page(45)
- Method for reconstructing the self-energy from the spectral function,
B. Sriram Shastry, arXiv:2408.07682, Phys. Rev. B **110**, 155149 (2024);
<https://doi.org/10.1103/PhysRevB.110.155149> ...Page(44)
- Extremely Correlated Fermi Liquid theory for $U = \infty$, $d = \infty$ Hubbard model to $\mathcal{O}(\lambda^3)$,
Samantha Shears, Edward Perepelitsky, Michael Arciniaga and B. Sriram Shastry, arXiv:2204.08599, Phys. Rev. B **106**, **035108** (2022).
DOI: 10.1103/PhysRevB.106.035108 ...Page(43)
- Dielectric response of electrons with strong local correlations and long-ranged Coulomb interactions,
B. Sriram Shastry and Michael Ariciniaga, arXiv:2111.04891, Ann. Pays. **442**, 168924 (2022).
<https://doi.org/10.1016/j.aop.2022.168924> ...Page(42)
- Extremely correlated superconductors,
B. Sriram Shastry, arXiv:2102.08395; Annals of Physics **434**, 168614 (2021).
<https://doi.org/10.1016/j.aop.2021.168614> ...Page(41)
- Aspects of the normal state resistivity of cuprate superconductors,
B. Sriram Shastry and Peizhi Mai, arXiv:1911.09119; Phys. Rev. B **101**, 115121 (2020).
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B. S. Shastry, arXiv:1102.2858 (2011), Phys. Rev. Letts. **107**, 056403 (2011).
DOI: 10.1103/PhysRevLett.107.056403

...Page(16)

Title: Extremely Correlated Fermi Liquids

Author: B Sriram Shastry

Abstract:

We present the theory of an extremely correlated Fermi liquid (ECFL) with $U \rightarrow \infty$. This liquid has an underlying Fermi liquid (FL) Greens function that is further caparisoned. The theory leads to two parallel hierarchies of equations that permit iterative approximations in a certain parameter. Preliminary results for the spectral functions display a broad background and a distinct T dependent left skew. An important energy scale $\Delta(k,x)$ emerges as the average inelasticity of the FL Greens function, and influences the photoemission spectra profoundly. A duality is identified wherein an apparent loss of coherence of the ECFL results from an excessively sharp FL.

Ref: Physical Review Letters, vol 107, 056043 (2011)

DOI: <https://doi.org/10.1103/PhysRevLett.107.056403>

Arxiv.org Reference: arxiv:1102.2858v3

Arxiv.org DOI: <https://doi.org/10.48550/arXiv.1102.2858>

Title: Extremely Correlated Fermi-Liquid Description of Normal-State ARPES in Cuprates

Author: G. H. Gweon, B S. Shastry and G. D. Gu

Abstract:

The normal-state single particle spectral function of the high temperature superconducting cuprates, measured by the angle-resolved photoelectron spectroscopy (ARPES), has been considered both anomalous and crucial to understand. Here, we report an unprecedented success of the new extremely correlated Fermi liquid theory by one of us [B. S. Shastry, Phys. Rev. Lett. 107, 056403 (2011)] to describe both laser and conventional synchrotron ARPES data (nodal cut at optimal doping) on $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ and synchrotron data on $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_4$. It fits all data sets with the same physical parameter values, satisfies the particle sum rule and successfully addresses two widely discussed kink anomalies in the dispersion

Ref: Physical Review Letters, vol 107, 056404 (2011)

DOI: <https://doi.org/10.1103/PhysRevLett.107.056404>

Arxiv.org Reference: arxiv:1104.2631v3

Arxiv.org DOI: <https://doi.org/10.48550/arXiv.1104.2631>

Title: Anatomy of the self-energy

Author: B Sriram Shastry

Abstract:

The general problem of representing the Greens function $G(k,z)$ in terms of self energy, in field theories lacking Wick's theorem, is considered. A simple construction shows that a Dyson like representation with a self energy $\Sigma(k,z)$ is always possible, provided we start with a spectral representation for $G(k,z)$ for finite sized systems and take the thermodynamic limit. The self energy itself can then be iteratively expressed in terms of another higher order self energy, capturing the spirit of Mori's formulation. We further discuss alternative and more general forms of $G(k,z)$ that are possible. In particular, a recent theory by the author of extremely correlated Fermi liquids at density "n", for Gutzwiller projected non canonical Fermi operators obtains a new form of the Greens function:

$$G(k, z) = \frac{(1 - \frac{n}{2} + \Psi(k, z))}{z - E_k - \Phi(k, z)}$$

with a pair of self energies $\Phi(z)$ and $\Psi(z)$. Its relationship with the Dyson form is explored. A simple version of the two self energy model was shown recently to successfully fit several data sets of photoemission line shapes in cuprates. We provide details of the unusual spectral line shapes that arise in this model, with the characteristic skewed shape depending upon a single parameter. The EDC and MDC line shapes are shown to be skewed in opposite directions, and provide a testable prediction of the theory.

Ref: Physical Review B **84**, 165112 (2011), Phys. Rev. **B** 86, 079911(E) (2012).

DOI: <https://doi.org/10.1103/PhysRevB.84.165112>

Arxiv.org Reference: arxiv:1104.2633

Arxiv.org DOI: <https://doi.org/10.48550/arXiv.1104.2631>

Title: Dynamical Particle-Hole Asymmetry in High-Temperature Cuprate Superconductors

Author: B Sriram Shastry

Abstract:

Motivated by the form of recent theoretical results, a quantitative test for an important dynamical particle-hole asymmetry of the electron spectral function at low energies and long wavelengths is proposed. The test requires the decomposition of the angle resolved photo emission intensity, after a specific Fermi symmetrization, into odd and even parts to obtain its ratio **R**. A large magnitude **R** is implied in recent theoretical fits at optimal doping around the chemical potential, and I propose that this large asymmetry needs to be checked more directly and thoroughly. This processing requires a slightly higher precision determination of the Fermi momentum relative to current availability.

Ref: Physical Review Letters **109**, 067004 (2012)

DOI: <https://doi.org/10.1103/PhysRevLetters.109.067004>

Arxiv.org Reference: arxiv:1110.1032

Arxiv.org DOI: <https://doi.org/10.48550/arXiv.1110.1032>

Title: Extremely correlated Fermi liquids: The formalism

Author: B Sriram Shastry

Abstract:

We present the detailed formalism of the extremely correlated Fermi liquid theory, developed for treating the physics of the t-J model. We start from the exact Schwinger equation of motion for the Green's function for projected electrons, and develop a systematic expansion in a parameter λ , relating to the double occupancy. The resulting Green's function has a canonical part arising from an effective Hamiltonian of the auxiliary electrons, and a caparison part playing the role of a frequency-dependent adaptive spectral weight. This adaptive weight balances the requirement at low ω of the invariance of the Fermi volume, and at high ω of decaying as $c_0/i\omega$, with a correlation-depleted $c_0 < 1$. The effective Hamiltonian H_{eff} describing the auxiliary fermions is given a natural interpretation with an effective interaction V_{eff} containing both the exchange J_{ij} and the hopping parameters t_{ij} . It is made Hermitian by adding suitable terms that ultimately vanish, in the symmetrized theory developed in this paper. Simple but important shift invariances of the t-J model are noted with respect to translating its parameters uniformly. These play a crucial role in constraining the form of V_{eff} and also provide checks for further approximations. The auxiliary and physical Green's function satisfy two sum rules, and the Lagrange multipliers for these are identified. A complete set of expressions for the Green's functions to second order in λ is given, satisfying various invariances. A systematic iterative procedure for higher order approximations is detailed. A superconducting instability of the theory is noted at the simplest level with a high transition temperature

Ref: Physical Review B **87**, 125124 (2013)

DOI: <https://doi.org/10.1103/PhysRevB.87.125124>

Arxiv: arXiv.1207.6826 (2012)

Arxiv DOI: <https://doi.org/10.48550/arXiv.1207.6826>

Title: Extremely correlated Fermi liquids: Self-consistent solution of the second-order theory

Authors: Daniel Hansen, B Sriram Shastry

Abstract:

We present detailed results from a recent microscopic theory of extremely correlated Fermi liquids, applied to the t-J model in two dimensions, developed recently by Shastry [Phys. Rev. Lett. 107, 056403 (2011); Phys. Rev. B 87, 125124 (2013)]. The second-order theory in the parameter λ , related to the density, is argued to be quantitatively valid in the overdoped regime for $0 < n < 0.75$, with n denoting the particle density. The calculation involves the self-consistent solution of equations for an auxiliary Fermi liquid Green's function and an adaptive spectral weight. We present numerical results at low as well as high T , at various low to intermediate densities in the normal phase, using a minimal set of band parameters relevant to the cuprate superconductors. We display the momentum space occupation function m_k , energy dispersion curves locating the peaks of spectral functions, the optical conductivity, relaxation rates for quasiparticles, and the electronic spectral functions on an absolute scale. The line shapes have an asymmetric shape and a broad background that is also seen in experiments, and our calculations validate approximate recent versions of the theory. The results also display the experimentally noted high-energy kink and provide an in-depth understanding of its origin and dependence on band parameters.

Ref: Physical Review B **87**, 245101 (2013)

DOI: <https://doi.org/10.1103/PhysRevB.87.245101>

Arxiv: arXiv:1211.0594

Arxiv DOI: <https://doi.org/10.48550/arXiv.1211.0594>

Title: Electronic spectral properties of the two-dimensional infinite- U Hubbard model

Authors: Ehsan Khatami, Daniel Hansen, Edward Perepelitsky, Marcos Rigol and: B Sriram Shastry

Abstract:

A strong-coupling series expansion for the Green's function and the extremely correlated Fermi liquid (ECFL) theory are used to calculate the moments of the electronic spectral functions of the infinite- U Hubbard model. Results from these two complementary methods agree very well at both low densities, where the ECFL solution is the most accurate, and at high to intermediate temperatures, where the series converge. We find that a modified first moment, which underestimates the contributions from the occupied states and is accessible in the series through the time-dependent Green's function, best describes the peak location of the spectral function in the strongly correlated regime. This is examined by the ECFL results at low temperatures, where it is shown that the spectral function is largely skewed towards the occupied states.

Ref: Physical Review B 87, 161120 (R) (2013)

DOI: <https://doi.org/10.1103/PhysRevB.87.161120>

Arxiv Ref: arXiv:1303.2657

Arxiv.org DOI: <https://doi.org/10.48550/arXiv.1303.2657>

Title: Extremely Correlated Fermi liquid study of the $U=\infty$ Anderson impurity model

Authors: B Sriram Shastry, Edward Perepelitsky and Alex C. Hewson

Abstract:

We apply the recently developed extremely correlated Fermi liquid (ECFL) theory to the Anderson impurity model, in the extreme correlation limit $U \rightarrow \infty$. We develop an expansion in a parameter λ , related to n_d , the average occupation of the localized orbital, and find analytic expressions for the Green's functions to $O(\lambda^2)$. These yield the impurity spectral function and also the self-energy $\Sigma(\omega)$ in terms of the two self-energies of the ECFL formalism. The imaginary parts of the latter have roughly symmetric low-energy behavior ($\propto \omega^2$), as predicted by Fermi liquid theory. However, the inferred impurity self-energy $\Sigma''(\omega)$ develops asymmetric corrections near $n_d \rightarrow 1$, leading in turn to a strongly asymmetric impurity spectral function with a skew towards the occupied states. Within this approximation, the Friedel sum rule is satisfied but we overestimate the quasiparticle weight z relative to the known exact results, resulting in an overbroadening of the Kondo peak. Upon scaling the frequency by the quasiparticle weight z , the spectrum is found to be in reasonable agreement with numerical renormalization group results over a wide range of densities.

Ref: Physical Review B 88, 205108 (2013)

DOI: <https://doi.org/10.1103/PhysRevB.88.205108>

Arxiv Ref: arXiv:1307.3492

Arxiv.org DOI: <https://doi.org/10.48550/arXiv.1307.3492>

Title: Extremely Correlated Fermi Liquid theory meets dynamical mean-field theory: Analytical insights into the doping-driven Mott transition

Author: R. Zitko, D. Hansen, E. Perepelitsky, J. Mravlje, A. Georges and B S. Shastry

Abstract:

We consider a doped Mott insulator in the large dimensionality limit within both the recently developed extremely correlated Fermi liquid (ECFL) theory and the dynamical mean-field theory (DMFT). We show that the general structure of the ECFL sheds light on the rich frequency dependence of the DMFT self-energy. Using the leading Fermi liquid form of the two key auxiliary functions introduced in the ECFL theory, we obtain an analytical ansatz, which provides a good quantitative description of the DMFT self-energy down to hole doping level $\delta \approx 0.2$. In particular, the deviation from Fermi liquid behavior and the corresponding particle-hole asymmetry developing at a low-energy scale are well reproduced by this ansatz. The DMFT being exact at large dimensionality, our study also provides a benchmark of the ECFL in this limit. We find that the main features of the self-energy and spectral line shape are well reproduced by the ECFL calculations in the $O(\lambda^2)$ minimal scheme, for not too low doping level $\delta \approx 0.3$. The DMFT calculations reported here are performed using a state-of-the-art numerical renormalization-group impurity solver, which yields accurate results down to an unprecedentedly small doping level $\delta \approx 0.001$.

Ref: Physical Review B 88, 235132 (2013).

DOI: <https://doi.org/10.1103/PhysRevB.88.235132>

Arxiv.org Reference: arXiv:1309.5284

arxiv.org <https://doi.org/10.48550/arXiv.1309.5284>

Title: Extremely Correlated Fermi Liquid theory in the limit of infinite dimensions

Authors: Edward Perepelitsky and B Sriram Shastry

Abstract:

We study the infinite spatial dimensionality limit ($d \rightarrow \infty$) of the recently developed Extremely Correlated Fermi Liquid (ECFL) theory (Shastry 2011, 2013) [17,18] for the t - J model at $J=0$. We directly analyze the Schwinger equations of motion for the Gutzwiller projected (i.e. $U = \infty$) electron Green's function G . From simplifications arising in this limit $d \rightarrow \infty$, we are able to make several exact statements about the theory. The ECFL Green's function is shown to have a momentum independent Dyson (Mori) self energy. For practical calculations we introduce a partial projection parameter λ , and obtain the complete set of ECFL integral equations to $O(\lambda^2)$. In a related publication (Zitko et al. 2013) [23], these equations are compared in detail with the dynamical mean field theory for the large U Hubbard model. Paralleling the well known mapping for the Hubbard model, we find that the infinite dimensional t - J model (with $J=0$) can be mapped to the infinite- U Anderson impurity model with a self-consistently determined set of parameters. This mapping extends individually to the auxiliary Green's function g and the capacitor factor μ . Additionally, the optical conductivity is shown to be obtainable from G with negligibly small vertex corrections. These results are shown to hold to each order in λ .

Ref: Annals of Physics 338 (2013) 283-301

DOI: <http://dx.doi.org/10.1016/j.aop.2013.09.010>

Arxiv.org Reference: arXiv:1309.5373

arxiv.org DOI: <https://doi.org/10.48550/arXiv.1309.5373>

Title: Theory of extreme correlations using canonical Fermions and path integrals Extremely Correlated Fermi Liquid theory in the limit of infinite dimensions

Authors: B Sriram Shastry

Abstract:

The t-J model is studied using a novel and rigorous mapping of the Gutzwiller projected electrons, in terms of canonical electrons. The mapping has considerable similarity to the Dyson-Maleev transformation relating spin operators to canonical Bosons. This representation gives rise to a non Hermitean quantum theory, characterized by minimal redundancies. A path integral representation of the canonical theory is given. Using it, the salient results of the extremely correlated Fermi liquid (ECFL) theory, including the previously found Schwinger equations of motion, are easily rederived. Further a transparent physical interpretation of the previously introduced auxiliary Greens functions and the caparison factor is obtained. The low energy electron spectral function in this theory with a strong intrinsic asymmetry, is summarized in terms of a few expansion coefficients. These include an important emergent energy scale Δ_0 that shrinks to zero on approaching the insulating state, thereby making it difficult to access the underlying low energy Fermi liquid behavior. The scaled low frequency ECFL spectral function is related simply to the Fano line shape. The resulting energy dispersion (EDC or MDC) is a hybrid of a massive and a massless Dirac spectrum $E_Q^* \sim \gamma Q - \sqrt{(Q^2 + \Gamma_0^2)}$, where the vanishing of Q , a momentum like variable, locates the kink. Therefore the quasiparticle velocity interpolates between the limits $(\gamma \mp 1)$ over a width Γ_0 on the two sides of $Q=0$. The resulting kink strongly resembles a prominent low energy feature seen in angle resolved photoemission spectra (ARPES) of cuprate materials. We also propose novel ways of analyzing the ARPES data to isolate the predicted asymmetry between particle and hole excitations.

Ref: Annals of Physics 343 (2014) 164-199

DOI: <http://dx.doi.org/10.1016/j.aop.2014.02.005>

Arxiv.org Reference: arXiv:1312.1892

arxiv.org DOI: <https://doi.org/10.48550/arXiv.1312.1892>

Title: Linked-cluster expansion for the Green's function of the infinite- U Hubbard model

Authors: Ehsan Khatami, Edward Perepelitsky, Marcos Rigol and: B Sriram Shastry

Abstract:

We implement a highly efficient strong-coupling expansion for the Green's function of the Hubbard model. In the limit of extreme correlations, where the onsite interaction is infinite, the evaluation of diagrams simplifies dramatically enabling us to carry out the expansion to the eighth order in powers of the hopping amplitude. We compute the finite-temperature Green's function analytically in the momentum and Matsubara frequency space as a function of the electron density. Employing Padé approximations, we study the equation of state, Kelvin thermopower, momentum distribution function, quasiparticle fraction, and quasiparticle lifetime of the system at temperatures lower than, or of the order of, the hopping amplitude. We also discuss several different approaches for obtaining the spectral functions through analytic continuation of the imaginary frequency Green's function, and show results for the system near half filling. We benchmark our results for the equation of state against those obtained from a numerical linked-cluster expansion carried out to the eleventh order.

Ref: Physical Review E 89, 063301 (2014)

DOI: <https://doi.org/10.1103/PhysRevE.89.063301>

Arxiv Ref: arXiv:1310.8029

Arxiv.org DOI: <https://doi.org/10.48550/arXiv.1310.8029>

Title: Diagrammatic λ series for extremely correlated Fermi liquids

Authors: Edward Perepelitsky and B Sriram Shastry

Abstract:

The recently developed theory of extremely correlated Fermi liquids (ECFL), applicable to models involving the physics of Gutzwiller projected electrons, shows considerable promise in understanding the phenomena displayed by the t - J model. Its formal equations for the Greens function are reformulated by a new procedure that is intuitively close to that used in the usual Feynman–Dyson theory. We provide a systematic procedure by which one can draw diagrams for the λ -expansion of the ECFL introduced in Shastry (2011), where the parameter $\lambda \in (0,1)$ counts the order of the terms. In contrast to the Schwinger method originally used for this problem, we are able to write down the n^{th} order diagrams ($O(n)$) directly with the appropriate coefficients, without enumerating all the previous order terms. This is a considerable advantage since it thereby enables the possible implementation of Monte Carlo methods to evaluate the series directly. The new procedure also provides a useful and intuitive alternative to the earlier methods.

Ref: Annals of Physics 357 (2015)1-39

DOI: <http://dx.doi.org/10.1016/j.aop.2015.03.010>

Arxiv.org Reference: arXiv:1410.5174

arxiv.org DOI: <https://doi.org/10.48550/arXiv.1410.5174>

Title:

Low-energy physics of the t - J model in $d = \infty$ using extremely correlated Fermi liquid theory: Cutoff second-order equations

Authors: B. Sriram Shastry and Edward Perepelitsky

Abstract: We present the results for the low-energy properties of the infinite-dimensional t - J model with $J = 0$, using $O(\lambda^2)$ equations of the extremely correlated Fermi liquid formalism. The parameter $\lambda \in [0, 1]$ is analogous to the inverse spin parameter $1/(2S)$ in quantum magnets. The present analytical scheme allows us to approach the physically most interesting regime near the Mott insulating state $n \lesssim 1$. It overcomes the limitation to low densities $n \lesssim 0.7$ of earlier calculations, by employing a variant of the skeleton graph expansion, and a high-frequency cutoff that is essential for maintaining the known high- T entropy. The resulting quasiparticle weight Z , the low ω, T self-energy, and the resistivity are reported. These are quite close at all densities to the exact numerical results of the $U = \infty$ Hubbard model, obtained using the dynamical mean field theory. The present calculation offers the advantage of generalizing to finite T rather easily, and allows the visualization of the loss of coherence of Fermi liquid quasiparticles by raising T . The present scheme is generalizable to finite dimensions and a non-vanishing J .

Ref: Physical Review B 94, 045138 (2016).

DOI: <https://doi.org/10.1103/PhysRevB.94.045138>

Arxiv.org Reference: arXiv:1605.08213

[arxiv.org https://doi.org/10.48550/arXiv.1605.08213](https://doi.org/10.48550/arXiv.1605.08213)

Title: Origin of kinks in the energy dispersion of strongly correlated matter

Authors: Kazue Matsuyama, Edward Perepelitsky and B. Sriram Shastry

Abstract: We present the results for the low-energy properties of the infinite-dimensional t-J model with $J=0$, using $O(\lambda^2)$ equations of the extremely correlated Fermi liquid formalism. The parameter $\lambda \in [0,1]$ is analogous to the inverse spin parameter $1/(2S)$ in quantum magnets. The present analytical scheme allows us to approach the physically most interesting regime near the Mott insulating state $n \lesssim 1$. It overcomes the limitation to low densities $n \lesssim 0.7$ of earlier calculations, by employing a variant of the skeleton graph expansion, and a high-frequency cutoff that is essential for maintaining the known high-T entropy. The resulting quasiparticle weight Z , the low ω, T self-energy, and the resistivity are reported. These are quite close at all densities to the exact numerical results of the $U = \infty$ Hubbard model, obtained using the dynamical mean field theory. The present calculation offers the advantage of generalizing to finite T rather easily, and allows the visualization of the loss of coherence of Fermi liquid quasiparticles by raising T . The present scheme is generalizable to finite dimensions and a non-vanishing J .

Ref: Physical Review B 95, 165435 (2017).

DOI: <https://doi.org/10.1103/PhysRevB.95.165435>

Arxiv.org Reference: arXiv:1610.08079

arxiv.org <https://doi.org/10.48550/arXiv.1610.08079>

Title: Strange metal from Gutzwiller correlations in infinite dimensions

Authors:Wenxin Ding, Rok Zitko, Peizhi Mai , Edward Perepelitsky and B. Sriram Shastry

Abstract:

Recent progress in *extremely correlated Fermi liquid theory (ECFL)* and the *dynamical mean field theory (DMFT)* enables us to accurately compute in the $d \rightarrow \infty$ limit the resistivity of the t - J model after setting $J \rightarrow 0$. This is also the $U = \infty$ Hubbard model. Since J is set to zero, our study isolates the *dynamical effects* of the single occupation constraint enforced by the projection operator originally introduced by Gutzwiller. We study three densities $n = .75, .8, .85$ that correspond to a range between the overdoped and optimally doped Mott insulating state. We delineate four distinct regimes separated by three crossovers, which are characterized by different behaviors of the resistivity ρ . We find at the lowest temperature T a *Gutzwiller correlated Fermi liquid* regime with $\rho \propto T^2$ extending up to an effective Fermi temperature that is dramatically suppressed from the noninteracting value by the proximity to half filling, $n \sim 1$. This is followed by a *Gutzwiller correlated strange metal* regime with $\rho \propto (T - T_0)$, i.e., a linear resistivity extrapolating back to $\rho = 0$ at a positive T_0 . At a higher temperature scale this crosses over into the *bad metal* regime with $\rho \propto (T + T_1)$, i.e., a linear resistivity extrapolating back to a finite resistivity at $T = 0$ and passing through the Ioffe-Regel-Mott value where the mean free path is a few lattice constants. This regime finally gives way to the *high T metal* regime, where we find $\rho \propto T$, i.e., a linear resistivity extrapolating back to zero at $T = 0$. The present work emphasizes the first two, i.e., the two lowest temperature regimes, where the availability of an analytical ECFL theory is of help in identifying the changes in related variables entering the resistivity formula that accompanies the onset of linear resistivity, and the numerically exact DMFT helps to validate the results. We also examine thermodynamical variables such as the magnetic susceptibility, compressibility, heat capacity, and entropy and correlate changes in these with the change in resistivity. This exercise casts valuable light on the nature of charge and spin correlations in the Gutzwiller correlated strange metal regime, which has features in common with the physically relevant strange metal phase seen in strongly correlated matter.

Ref: Physical Review B 96, 054114 (2017).

DOI: <https://doi.org/10.1103/PhysRevB.96.054114>

Arxiv.org Reference: arXiv:1703.02206

arxiv.org <https://doi.org/10.48550/arXiv.1703.02206>

Title: Strange metal from Gutzwiller correlations in infinite dimensions

Authors: B. Sriram Shastry and Peizhi Mai

Abstract:

Low energy properties of the metallic state of the two-dimensional t - J model are presented for second neighbor hopping with hole-doping ($t' < 0$) and electron-doping ($t' > 0$), with various superexchange energy J . We use a closed set of equations for the Greens functions obtained from the extremely correlated Fermi liquid theory. These equations reproduce the known low energies features of the large U Hubbard model in infinite dimensions. The density and temperature dependent quasiparticle weight, decay rate and the peak spectral heights over the Brillouin zone are calculated. We also calculate the resistivity, Hall conductivity, Hall number and cotangent Hall angle. The spectral features display high thermal sensitivity at modest T for density $n > 0.8$, implying a suppression of the effective Fermi-liquid temperature by two orders of magnitude relative to the bare bandwidth. The cotangent Hall angle exhibits a T^2 behavior at low T , followed by an interesting kink at higher T . The Hall number exhibits strong renormalization due to correlations. Flipping the sign of t changes the curvature of the resistivity versus T curves between convex and concave. Our results provide a natural route for understanding the observed difference in the temperature dependent resistivity of strongly correlated electron-doped and hole-doped matter.

Ref: New J. Phys. **20** (2018) 013027

DOI: <https://doi.org/10.1088/1367-2630/aa9b74>

Arxiv.org Reference: arXiv:1703.08142

[arxiv.org https://doi.org/10.48550/arXiv.1703.08142](https://doi.org/10.48550/arXiv.1703.08142)

Title: Strange metal from Gutzwiller correlations in infinite dimensions: Transverse transport, optical response, and rise of two relaxation rates

Authors: Wenxin Ding, Rok Zitko and B. Sriram Shastry

Abstract:

Using two approaches to strongly correlated systems, the extremely correlated Fermi liquid theory and the dynamical mean field theory, we compute the transverse transport coefficients, namely, the Hall constants R_H and Hall angles θ_H , and the longitudinal and transverse optical response of the $U = \infty$ Hubbard model in the limit of infinite dimensions. We focus on two successive low-temperature regimes, the Gutzwiller-correlated Fermi liquid (GCFL) and the Gutzwiller-correlated strange metal (GCSM). We find that the Hall angle $\cot \theta_H$ is proportional to T^2 in the GCFL regime, while upon warming into the GCSM regime it first passes through a downward bend and then continues as T^2 . Equivalently, R_H is weakly temperature dependent in the GCFL regime, but becomes strongly temperature dependent in the GCSM regime. Drude peaks are found for both the longitudinal optical conductivity $\sigma_{xx}(\omega)$ and the optical Hall angles $\tan \theta_H(\omega)$ below certain characteristic energy scales. By comparing the relaxation rates extracted from fitting to the Drude formula, we find that in the GCFL regime there is a single relaxation rate controlling both longitudinal and transverse transport, while in the GCSM regime two different relaxation rates emerge. We trace the origin of this behavior to the dynamical particle-hole asymmetry of the Dyson self-energy, arguably a generic feature of doped Mott insulators.

Ref: Physical Review B 96, 115153 (2017).

DOI: <https://doi.org/10.1103/PhysRevB.96.115153>

Arxiv.org Reference: arXiv:1705.01914

arxiv.org <https://doi.org/10.48550/arXiv.1705.01914>

Title: t - t' - J model in one dimension using extremely correlated Fermi-liquid theory and time-dependent density matrix renormalization group

Authors: Peizhi Mai, Steven R. White and B. Sriram Shastry

Abstract:

We study the one-dimensional t - t' - J model for generic couplings using two complementary theories, the extremely correlated Fermi liquid theory and time dependent density matrix renormalization group over a broad energy scale. The two methods provide a unique insight into the strong momentum dependence of the self-energy of this prototypical non-Fermi liquid, described at low energies as a Tomonaga-Luttinger liquid. We also demonstrate its intimate relationship to spin-charge separation, i.e., the splitting of Landau quasiparticles of higher dimensions into two constituents, driven by strong quantum fluctuations inherent in one dimension. The momentum distribution function, the spectral function, and the excitation dispersion of these two methods also compare well.

Ref: Physical Review B 98, 035108 (2018).

DOI: <https://doi.org/10.1103/PhysRevB.98.035108>

Arxiv.org Reference: arXiv:1712.05396

[arxiv.org](https://arxiv.org/abs/1712.05396) <https://doi.org/10.48550/arXiv.1712.05396>

Title: Nonresonant Raman scattering in extremely correlated Fermi liquids

Authors: Peizhi Mai and B. Sriram Shastry

Abstract:

We present theoretical results for the optical conductivity and the nonresonant Raman susceptibilities for three principal polarization geometries relevant to the square lattice. The susceptibilities are obtained using the recently developed extremely correlated Fermi liquid theory for the two-dimensional t - t' - J model, where t and t' are the nearest- and second-neighbor hopping. Our results sensitively depend on t , t' . By studying this quartet of related dynamical susceptibilities, and their dependence on t , t' , doping, and temperature, we provide a useful framework of interpreting and planning future Raman experiments on strongly correlated matter.

Ref: Physical Review B 98, 115101 (2018).

DOI: <https://doi.org/10.1103/PhysRevB.98.115101>

Arxiv.org Reference: arXiv:1805.09935

arxiv.org <https://doi.org/10.48550/arXiv.1805.09935>

Title: Reversal of particle-hole scattering-rate asymmetry in the Anderson impurity model

Authors: R. Zitko, H. R. Krishnamurthy and B. Sriram Shastry

Abstract:

We study the particle-hole asymmetry of the scattering rate in strongly correlated electron systems by examining the cubic ω^3 and ωT^2 terms in the imaginary part of the self-energy of the Anderson impurity model. We show that the sign is opposite in the weak-coupling and strong-coupling limits, explaining the differences found in theoretical approaches taking the respective limits as the starting points. The sign change in fact precisely delineates the crossover between the weak- and strong-correlation regimes of the model. For weak interaction U the sign reversal occurs for small values of the doping $\delta = 1 - n$, while for interaction of order $U \approx 2\Gamma$, Γ being the hybridization strength, the crossover curve rapidly shifts to the large-doping range. This curve, based on the impurity dynamics, is genuinely different from other crossover curves defined through impurity thermodynamic and static properties.

Ref: Physical Review B 98, 161121 (R) (2018).

DOI: <https://doi.org/10.1103/PhysRevB.98.161121>

Arxiv.org Reference: arXiv:1807.11343

arxiv.org <https://doi.org/10.48550/arXiv.1807.11343>

Title: Fermi surface volume of interacting systems

Authors: B. Sriram Shastry

Abstract:

Three Fermion sumrules for interacting systems are derived at $T=0$, involving the number expectation $N(\mu)$, canonical chemical potentials $\mu(m)$, a logarithmic time derivative of the Greens function $\gamma_{k\sigma}$ and the static Greens function. In essence we establish at zero temperature the sumrules linking:

$$N(\mu) \leftrightarrow \sum_m \Theta(\mu - \mu(m)) \leftrightarrow \sum_{k,\sigma} \Theta(\gamma_{k\sigma}) \leftrightarrow \sum_{k,\sigma} \Theta(G_\sigma(k, 0)).$$

Connecting them across leads to the Luttinger and Ward sumrule, originally proved perturbatively for Fermi liquids. Our sumrules are nonperturbative in character and valid in a considerably broader setting that additionally includes non-canonical Fermions and Tomonaga-Luttinger models. Generalizations are given for singlet-paired superconductors, where one of the sumrules requires a testable assumption of particle-hole symmetry at all couplings. The sumrules are found by requiring a continuous evolution from the Fermi gas, and by assuming a monotonic increase of $\mu(m)$ with particle number m . At finite T a pseudo-Fermi surface, accessible to angle resolved photoemission, is defined using the zero crossings of the first frequency moment of a weighted spectral function.

Ref: Annals of Physics 405 (2019)155–175

DOI: <https://doi.org/10.1016/j.aop.2019.03.016>

Arxiv.org Reference: arXiv:1808.00405

arxiv.org <https://doi.org/10.48550/arXiv.1808.00405>

Title: Extremely correlated Fermi liquid of the t- J model in two dimensions

Authors: Peizhi Mai and B. Sriram Shastry

Abstract:

We study the two-dimensional t-J model with second-neighbor hopping parameter t' and in a broad range of doping δ using a closed set of equations from the extremely correlated Fermi liquid theory. We obtain asymmetric energy distribution curves and symmetric momentum distribution curves of the spectral function, consistent with experimental data. We further explore the Fermi surface and local density of states for different parameter sets. Using the spectral function, we calculate the resistivity, Hall number, and spin susceptibility. The curvature change in the resistivity curves with varying δ is presented and connected to intensity loss in angle-resolved photoemission spectroscopy experiments. We also discuss the role of the superexchange J in the spectral function and the resistivity in the optimal to overdoped density regimes.

Ref: Physical Review B 98, 205106 (2018)

DOI: <https://doi.org/10.1103/PhysRevB.98.205106>

Arxiv.org Reference: arXiv:1808.09788

arxiv.org <https://doi.org/10.48550/arXiv.1808.09788>

Title: Theory of anisotropic elastoresistivity of two-dimensional extremely strongly correlated metals

Authors: Michael Arciniaga, Peizhi Mai and B. Sriram Shastry

Abstract:

There is considerable recent interest in the phenomenon of anisotropic electroresistivity of correlated metals. While some interesting work has been done on the iron-based superconducting systems, not much is known for the cuprate materials. Here we study the anisotropy of elastoresistivity for cuprates in the normal state. We present theoretical results for the effect of strain on resistivity and additionally on the optical weight and local density of states. We use the recently developed extremely strongly correlated Fermi liquid theory in two dimensions, which accounts quantitatively for the unstrained resistivities for three families of single-layer cuprates. The strained hoppings of a tight-binding model are roughly modeled analogously to strained transition metals. The strained resistivity for a two-dimensional t - t' - J model are then obtained, using the equations developed in recent work. Our quantitative predictions for these quantities have the prospect of experimental tests in the near future, for strongly correlated materials such as the hole-doped and electron-doped high- T_c materials.

Ref: Physical Review B 101, 245149 (2020)

DOI: <https://doi.org/10.1103/PhysRevB.101.245149>

Arxiv.org Reference: arXiv:1909.06471

arxiv.org <https://doi.org/10.48550/arXiv.1909.06471>

Title: Aspects of the normal state resistivity of cuprate superconductors

Authors: B. Sriram Shastry and Peizhi Mai

Abstract:

Planar normal state resistivity data taken from three families of cuprate superconductors are compared with theoretical calculations from the recent extremely correlated Fermi liquid theory (ECFL) [B. S. Shastry, Phys.Rev. Lett. 107, 056403 (2011)]. The two hole-doped cuprate materials LSCO and BSLCO and the electron-doped material LCCO have yielded rich data sets at several densities δ and temperatures T , thereby enabling a systematic comparison with theory. The recent ECFL resistivity calculations for the highly correlated t - t' - J model by us give the resistivity for a wide set of model parameters [B. S. Shastry and P. Mai, New J. Phys. 20, 013027 (2018); P. Mai and B. S. Shastry, Phys. Rev. B 98, 205106 (2018)]. After using x-ray diffraction and angle-resolved photoemission data to fix parameters appearing in the theoretical resistivity, only one parameter, the magnitude of the hopping t , remains undetermined. For each data set, the slope of the experimental resistivity at a single temperature-density point is sufficient to determine t , and hence the resistivity on absolute scale at all remaining densities and temperatures. This procedure is shown to give a fair account of the entire data.

Ref: Physical Review B 101, 115121 (2020)

DOI: <https://doi.org/10.1103/PhysRevB.101.115121>

Arxiv.org Reference: arXiv:1911.09119

arxiv.org <https://doi.org/10.48550/arXiv.1911.09119>

Title: Extremely correlated superconductors

Author: B. Sriram Shastry

Abstract:

Superconductivity in the t-J model is studied by extending the recently introduced extremely correlated fermi liquid theory. Exact equations for the Greens functions are obtained by generalizing Gor'kov's equations to include extremely strong local repulsion between electrons of opposite spin. These equation are expanded in a parameter λ representing the fraction of double occupancy, and the lowest order equations are further simplified near T_c , resulting in an approximate integral equation for the superconducting gap. The condition for T_c is studied using a model spectral function embodying a reduced quasiparticle weight Z near half-filling, yielding an approximate analytical formula for T_c . This formula is evaluated using parameters representative of single layer High- T_c systems. In a narrow range of electron densities that is necessarily separated from the Mott-Hubbard insulator at half filling, we find superconductivity with a typical $T_c \sim 10^2 K$.

Ref: Annals of Physics 434 (2021)168614

DOI: <https://doi.org/10.1016/j.aop.2021.168614>

Arxiv.org Reference: arXiv:2102.08395

[arxiv.org https://doi.org/10.48550/arXiv.2102.08395](https://doi.org/10.48550/arXiv.2102.08395)

Title: Dielectric response of electrons with strong local correlations and long-ranged Coulomb interactions

Author: B. Sriram Shastry and Michael Arciniaga

Abstract:

Motivated by recent experiments, we append long ranged Coulomb interactions to dominant strong local correlations and study the resulting t - J - V_C model for the 2-dimensional cuprate materials. This model includes the effect of short ranged Hubbard–Gutzwiller–Kanamori type correlations and long ranged Coulomb interactions on tight binding electrons. We calculate the $\{q, \omega\}$ dependent charge density fluctuations in this model using the extremely correlated Fermi liquid theory characterized by quasiparticles with very small weight Z . We develop a novel set of formulae to represent the dynamical charge susceptibility and the dielectric function, using a version of the charge-current continuity equation for a band system, valid for arbitrary q . Combining these ingredients, we present results for the irreducible dynamical charge susceptibility $\chi_{\rho\rho}(q, \omega)$, (longitudinal) dielectric function $\epsilon(q, \omega)$, current susceptibility $\chi_{JJ}(q, \omega)$, conductivity $\sigma(q, \omega)$, and the plasma frequency for any q . We also present calculations for the first moment of the structure function and discuss a characteristic energy scale $\Omega_p(q)$ which locates a peak in $\text{Im } \chi_{\rho\rho}(q, \omega)$.

Ref: Annals of Physics 442 (2022)168924

DOI: <https://doi.org/10.1016/j.aop.2022.168924>

Arxiv.org Reference: arXiv:2111.04891

arxiv.org <https://doi.org/10.48550/arXiv.2111.04891>

Title: Extremely correlated Fermi liquid theory for the $U = \infty$, $d = \infty$ Hubbard model to $O(\lambda^3)$

Author: S. Shears, E. Perepelitsky, M. Arciniaga and B. S. Shastry

Abstract:

We present the $O(\lambda^3)$ results from the λ expansion in the extremely correlated Fermi-liquid theory applied to the infinite-dimensional t-J model (with $J=0$) and compare the results with the earlier $O(\lambda^2)$ results as well as the results from the dynamical mean-field theory. We focus attention on the T dependence of the resistivity $\rho(T)$, the Dyson self-energy, and the quasiparticle weight Z at various densities. The comparison shows that all the methods display quadratic-in-T resistivity followed by a quasilinear-in-T resistivity characterizing a strange metal and gives an estimate of the different scales of these variables relative to the exact results.

Ref: Physical Review B 106, 035108 (2022)

DOI: <https://doi.org/10.1103/PhysRevB.106.035108>

Arxiv.org Reference: arXiv:2204.08599

arxiv.org <https://doi.org/10.48550/arXiv.2204.08599>

Title: Method for reconstructing the self-energy from the spectral function

Author: B Sriram Shastry

Abstract:

A fundamental question about the nature of quantum materials such as high- T_c systems remains open to date: it is unclear whether they are (some variety of) Fermi liquids, or (some variety of) non Fermi liquids. A direct avenue to determine their nature is to study the (imaginary part of the) self-energy at low energies. Here we present a method to extract this low- ω self-energy from experimentally derived spectral functions. The method seems suited for implementation with high-quality angle-resolved photoemission data. It is based on a helpful theorem proposed here, which assures us that the method has minimal (or vanishing) error at the lowest energies. We provide numerical examples showing that a few popular model systems yield distinguishably different low-energy self-energies.

Ref: Physical Review B 110, 155149 (2024)

DOI: <https://doi.org/10.1103/PhysRevB.110.155149>

Arxiv.org Reference: arXiv:2408.07682

arxiv.org <https://doi.org/10.48550/arXiv.2408.07682>

Title: Aspects of normal-state resistivity of the cuprate superconductors $\text{Bi}_2\text{Sr}_2\text{CuO}_{6+x}$, $\text{Tl}_2\text{Ba}_2\text{CuO}_{6+x}$, and $\text{HgBa}_2\text{CuO}_{4+x}$

Authors: Samantha Shears, Michael Arciniaga and B Sriram Shastry

Abstract:

Planar normal-state resistivity data from three families of hole-doped single-layer cuprate superconductors, i.e., Bi2201 ($\text{Bi}_2\text{Sr}_2\text{CuO}_{6+x}$), Tl2201 ($\text{Tl}_2\text{Ba}_2\text{CuO}_{6+x}$), and Hg1201 ($\text{HgBa}_2\text{CuO}_{4+x}$), are calculated using the extremely correlated Fermi liquid theory (ECFL). This theory was recently employed by us to compute the resistivity of three families of single-layer cuprate superconductors, i.e., $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ (LSCO), $\text{Bi}_2\text{Sr}_{2-x}\text{La}_x\text{CuO}_{6+\delta}$ (BSLCO), and $\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_4$ (NCCO), followed by a detailed comparison. Adding the three systems studied here accounts for all the remaining single-layer compounds, where data are available for a range of densities and temperatures, thereby providing a comprehensive study of one class of important cuprate superconductors. The added study of the material Bi2201 is of particular interest since it is the system where the almost linear in temperature resistivity was first reported in 1990. Only recently, in 2022, has a systematic doping analysis become available. The Tl2201 system has two distinct sets of band parameters that fit the same Fermi surface, providing new challenges and insights into the ECFL theory.

Ref: Physical Review B 111, 245146 (2025)

DOI: <https://doi.org/10.1103/89cj-5qhs>

Arxiv.org Reference: arXiv:2502.00293

arxiv.org <https://doi.org/10.48550/arXiv.2502.00293>