What can the Wiedemann-Franz law tell us about strange metals?

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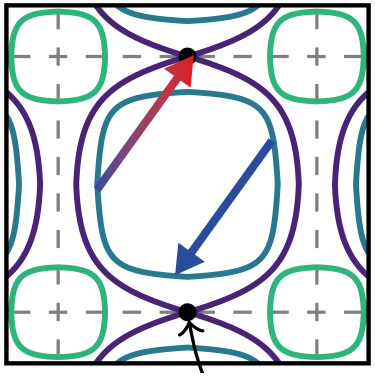
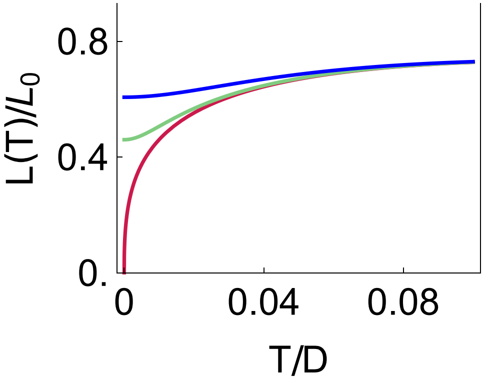
Outline

- A (not so strange) quantum critical metal: Tuning to a Van Hove singularity



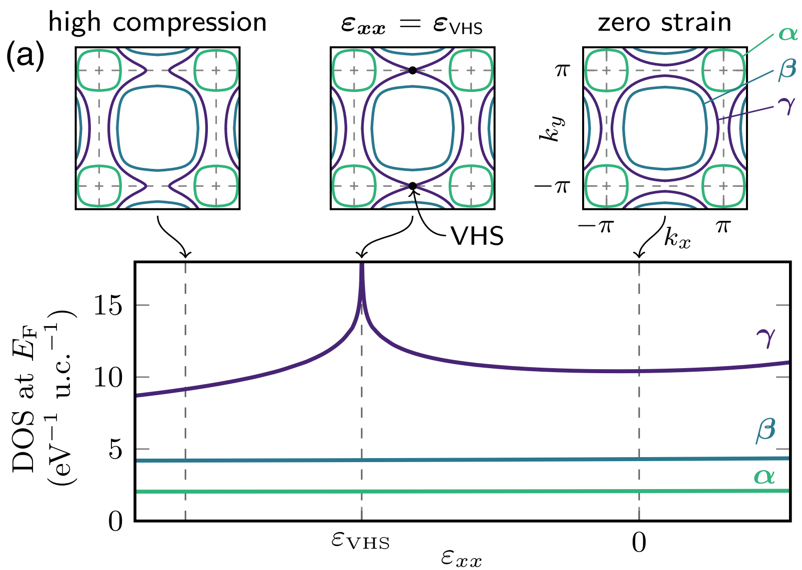
- Weidemann-Franz and its breakdown



- What can we learn from WF about scattering in strange metals?

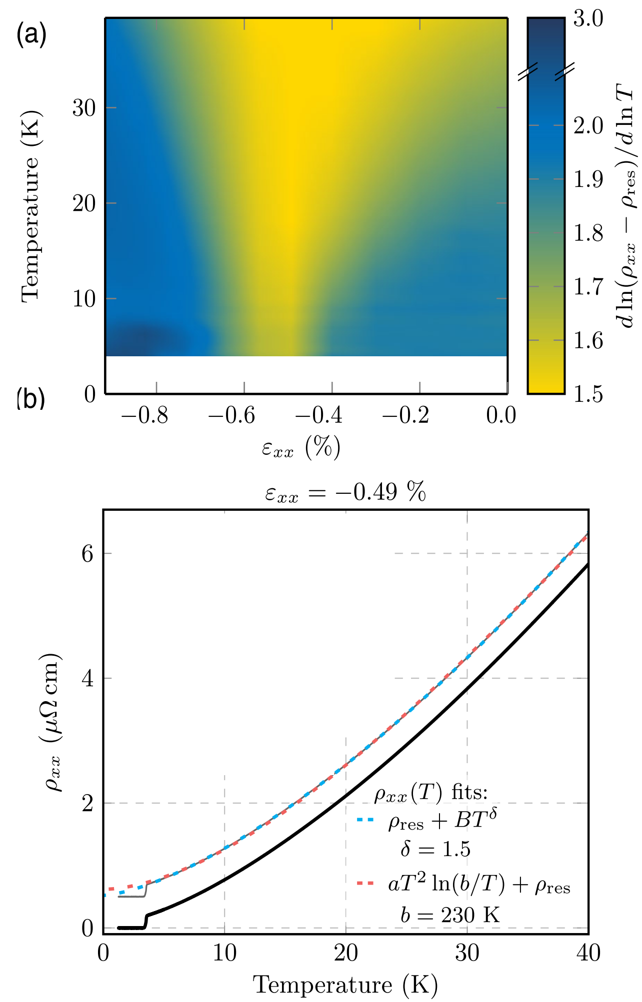
Turning through the Van Hove singularity in Sr_2RuO_4

Barber, Hicks et al. (2018)



Resistivity at $\varepsilon_{\mathrm{VHS}}$ consistent with

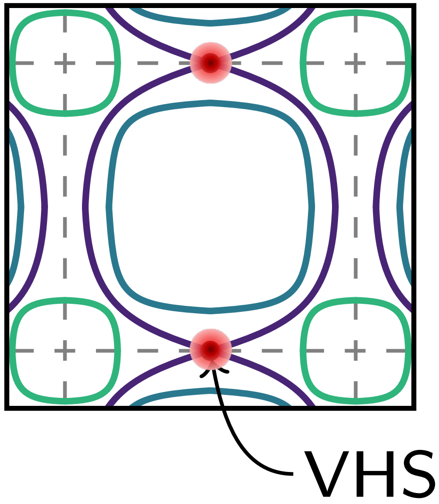
$\rho \sim T^2 \log(1/T)$



Turning through the Van Hove singularity in Sr_2RuO_4

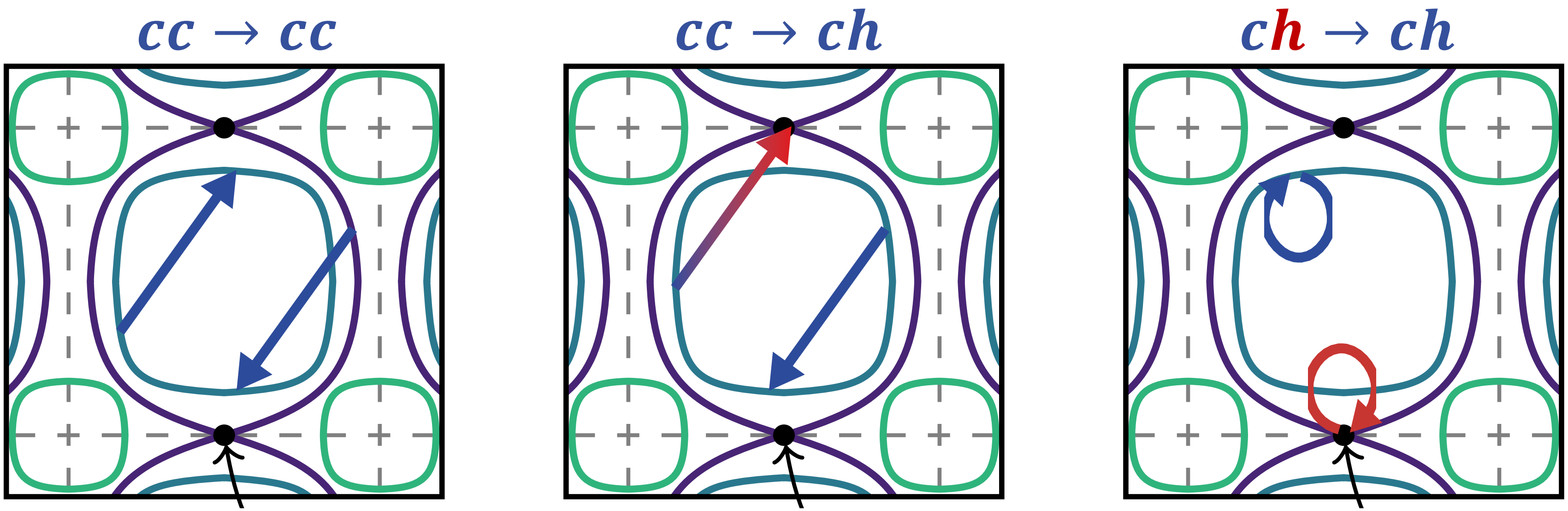
Why no “short circuiting”?

$\varepsilon_{xx} = \varepsilon_{\mathrm{VHS}}$



Scattering processes: "Cold" and "Hot" fermions

Scattering processes:



$\rho \sim T^2 \log(1/T)$

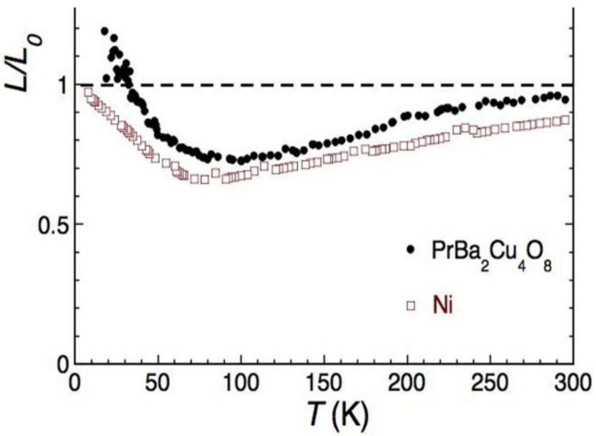
Stronger peak in DOS gives marginal FL with $\rho \propto T$, $c \propto -T\log T$: Explains $Sr_3Ru_2O_7$?

C. Mousatov, EB, S. Hartnoll, PNAS *(2020)*

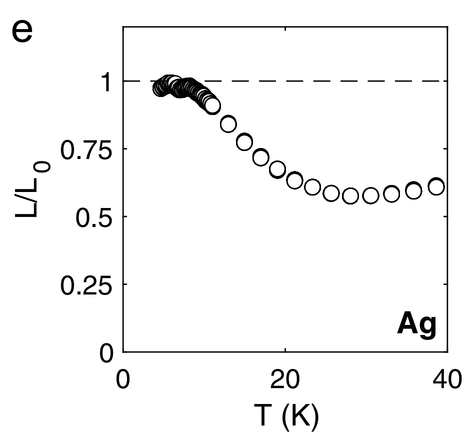
Reminder: Wiedemann-Franz

G. Wiedemann and R. Franz (1853)

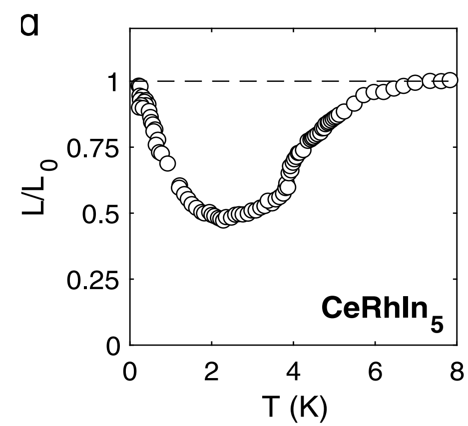
$$L = \frac{\kappa}{T\sigma} \qquad L_0 = \frac{\pi^2}{3}\left(\frac{k_B}{e}\right)^2$$



Bangura, Hussey et al. (13')



Jaoui, Behnia et al. (18')



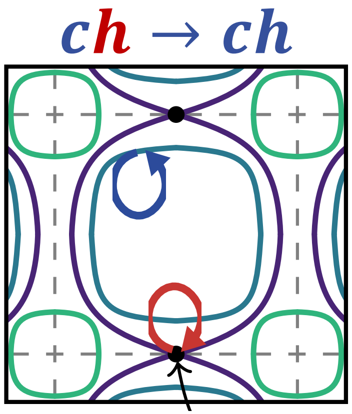
Paglione, Canfield et al. (05')

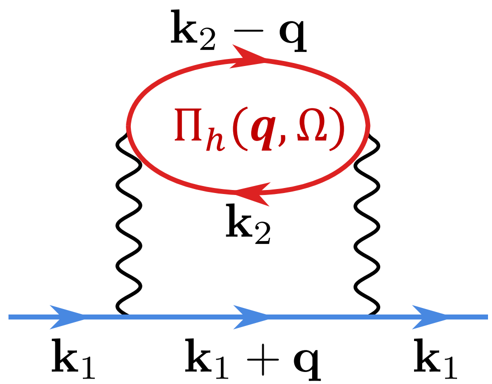
$L \to L_0$ when the scattering is effectively *elastic*

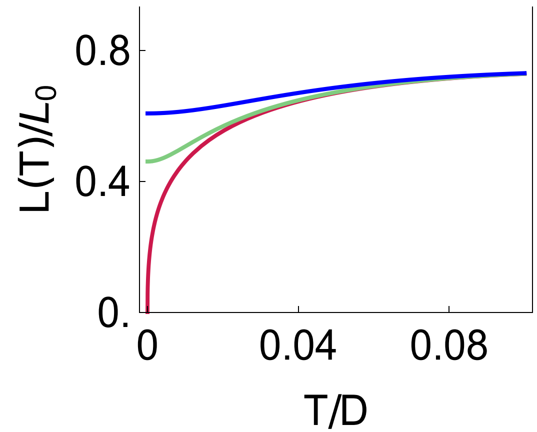
$$J_e = e\int_{\boldsymbol{k}} n_{\boldsymbol{k}} v_{\boldsymbol{k}}$$

$$J_Q = \int_{\boldsymbol{k}} (\varepsilon_{\boldsymbol{k}} - \mu) n_{\boldsymbol{k}} v_{\boldsymbol{k}}$$

Breakdown of
WF Law near Van Hove singularity







$$\mathrm{Im}\Pi_h(\boldsymbol{q}, \Omega) = -\frac{m}{2\pi} \min\left[\frac{2m\omega}{|q_x^2 - q_y^2|}, 1\right]$$

$$\frac{\kappa}{T} \sim \frac{1}{T^{3/2}} \quad \sigma \sim \frac{1}{T^2 \log(1/T)}$$

$$\Sigma''_c(\boldsymbol{k}, \omega) \sim \max\left[T^{\frac{3}{2}}, \omega^{\frac{3}{2}}\right]$$

$$\boldsymbol{\frac{L}{L_0} \sim \sqrt{T} \log(1/T)}$$

Gopalan, Gunnarson, Andersen (92')

Clean 2D FL: $\frac{L}{L_0} \sim \frac{1}{\log(1/T)}$ *Lyakhov, Mishchenko (03')*

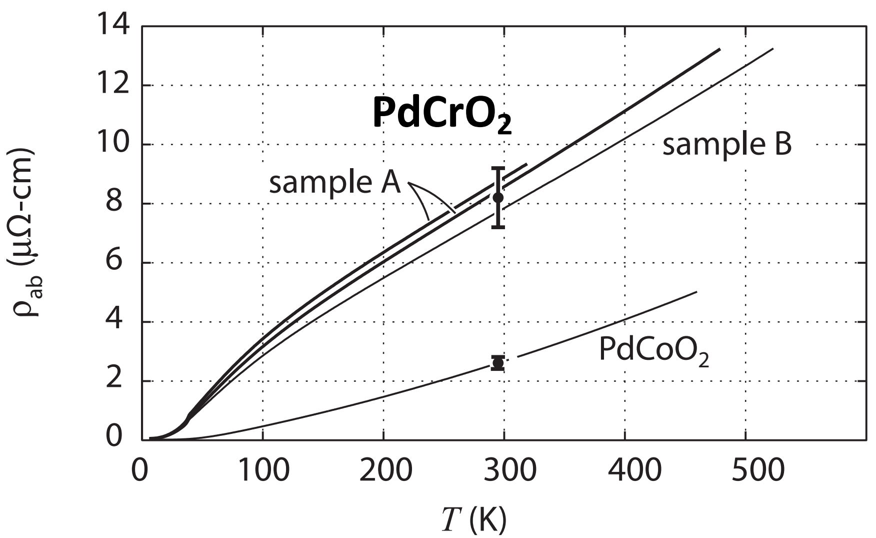
Clean FL, el-ph: $\frac{L}{L_0} \sim T^2$ *Lavasani, Bulmash, Das Sarma (19')*

Analogous violations in hydrodynamic and quantum critical metals

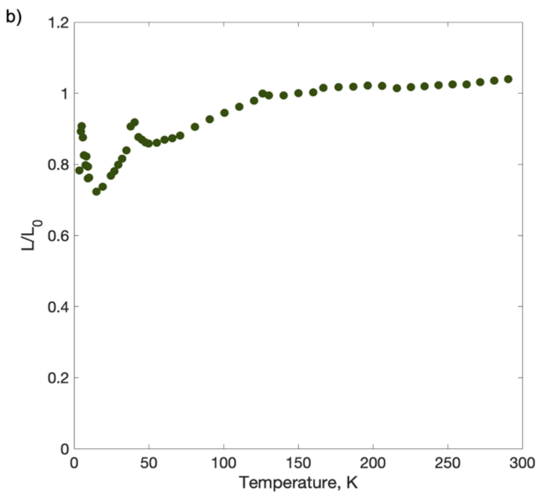
Mahajan, Barkeshli, Hartnoll (13')

Veronika Stangier, EB, J. Schmalian, PRB *(2022)*

What does the Lorenz ratio tell us about strange metals?



Hicks, Yelland et al. (15')



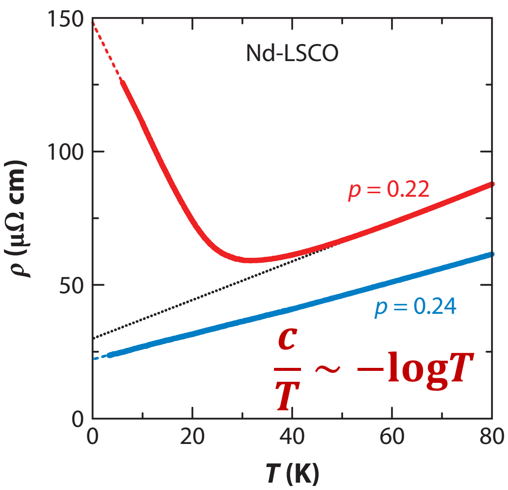
Zhakina, Mackenzie et al. (unpublished)

$\rho \propto T$ from **quasi-elastic** scattering (probably phonons)

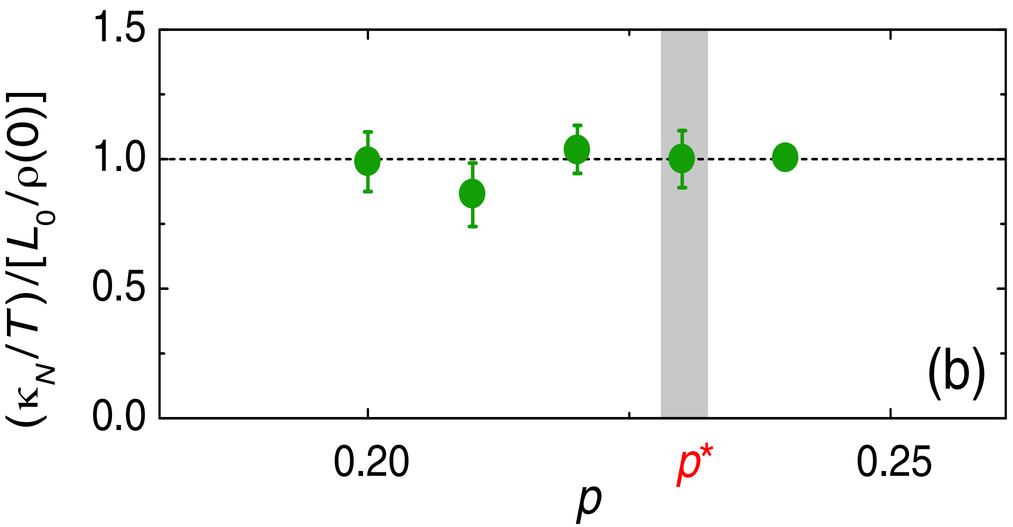
Difference between $PdCrO_2$ and $PdCoO_2$? Specific heat?

Why Planckian?

What does the Lorenz ratio tell us about strange metals?



Proust, Taillefer (18')



Michon, Taillefer et al. (18')

For $p \geq p^*$, WF obeyed also by σ_{xy}/κ_{xy}

Grissonnanche, Taillefer et al. (19')

Strange/marginal Fermi liquid or conventional metal with strange scatterers?

See Kivelson talk

Lorenz ratio of a marginal Fermi liquid

Marginal Fermi liquid

$$\Sigma(k,\omega) \quad \sim \lambda\left[\omega \log\left(\frac{\Lambda}{\omega}\right) + \frac{i\pi}{2}\max(T,\omega)\right]$$

$$\rho \propto T \qquad c \propto T \log\left(\frac{1}{T}\right)$$

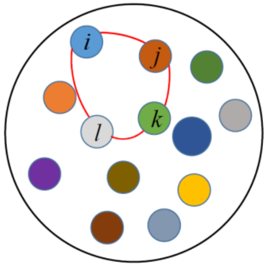
Varma, Littlewood, Abrahams, Schmitt-Rink, Ruckenstein (89')

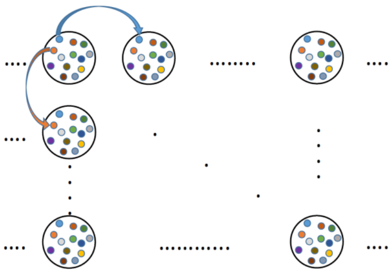
Planckian! $$\frac{1}{\tau} \sim \frac{\Sigma''(k,\omega)}{d\Sigma'/d\omega} \sim \frac{T}{\log(\Lambda/T)}$$ (λ independent)

Lorenz ratio?

Lorenz ratio of a marginal Fermi liquid

Model: lattice of Sachdev-Ye-Kitaev (SYK) dots





$$H_c = \sum_{i=1,\mathbf{k}}^{N} \varepsilon_{\mathbf{k}} c_{\mathbf{k}i}^{\dagger} c_{\mathbf{k}i} + \sum_{ijkl=1,\mathbf{r}}^{N} \frac{U_{ijkl}}{N^{3/2}} c_{\mathbf{r}i}^{\dagger} c_{\mathbf{r}j}^{\dagger} c_{\mathbf{r}k} c_{\mathbf{r}l} + \sum_{ij=1,\mathbf{r}}^{N} \frac{W_{ij,\mathbf{r}}}{N^{1/2}} c_{\mathbf{r}i}^{\dagger} c_{\mathbf{r}j}$$

$U_{ijkl} = 0,\ \overline{U_{ijkl}^2} = U^2$ **Translationally invariant** in every realization

"Kondo lattice": Two bands c, f with bandwidths $W_f \ll W_c$

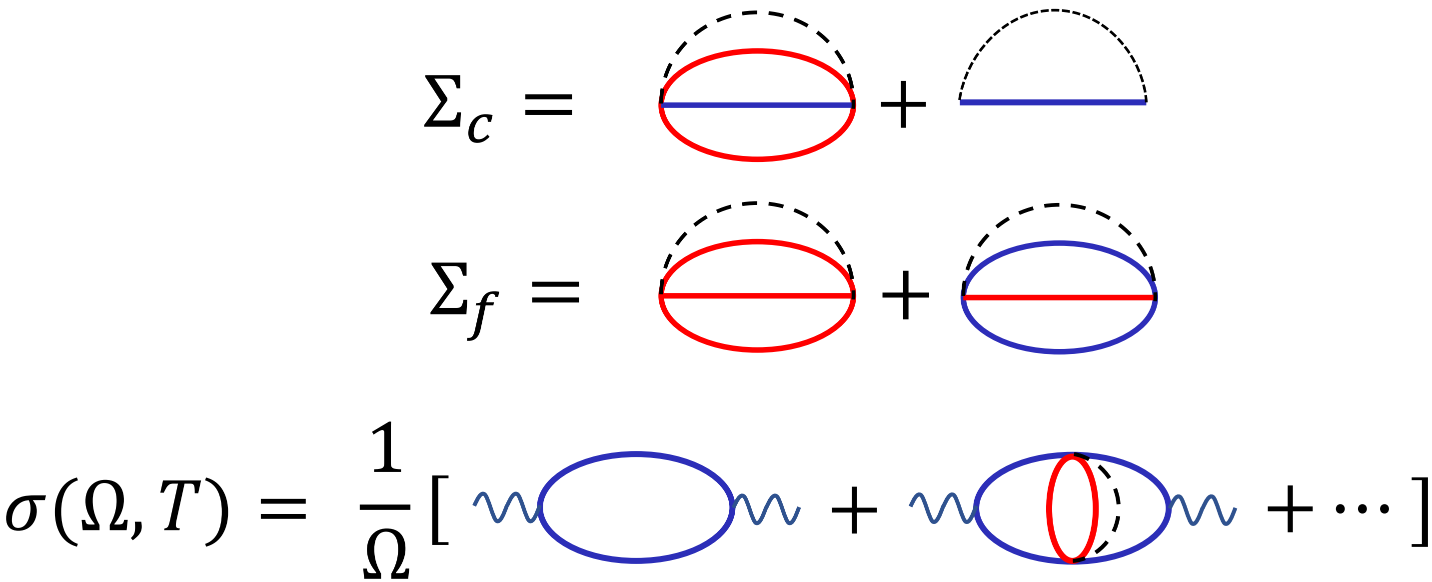
$$H = H_c + H_f + \sum_{ijkl=1,\mathbf{r}}^{N} \frac{V_{ijkl}}{N^{3/2}} c_{\mathbf{r}i}^{\dagger} c_{\mathbf{r}j} f_{\mathbf{r}k}^{\dagger} f_{\mathbf{r}l}$$

D. Chowdhury, Y. Werman, EB, T. Senthil, PRX (2018)

See also: A. Patel, J. McGreevy, D. Arovas, S. Sachdev, PRX (2018)

Lorenz ratio of a marginal Fermi liquid

Solvable in large N limit



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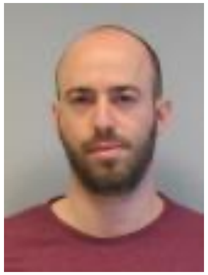


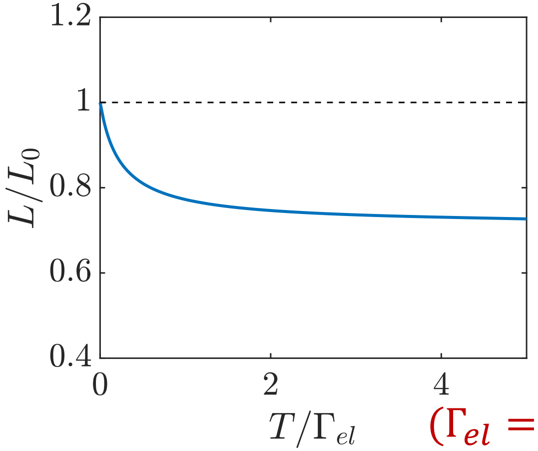
Evyatar Tulipman

Clean limit ($w = 0$):

$$\rho(T) = AT$$

$$\frac{L}{L_0} = 0.71306\ldots$$

Patel, McGreevy, Arovas, Sachdev (18')



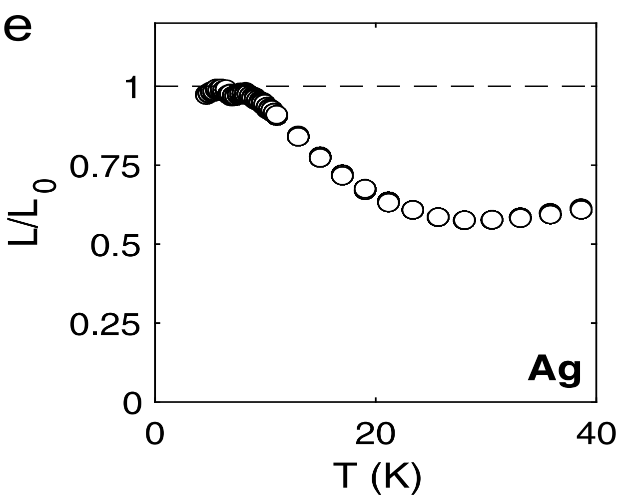
$(\Gamma_{el} = \pi\nu_0|w|^2)$

Disordered ($w > 0$):

$$\rho(T) = \rho_0 + AT$$

$$\frac{L}{L_0} = 1 - \alpha T + \cdots$$

Sharp signature of MFL!

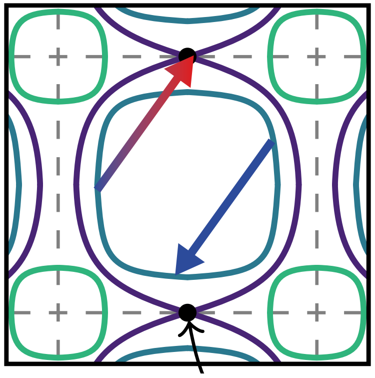


Summary

The Wiedemann-Franz law and its violation can serve as a probe for the nature of scattering

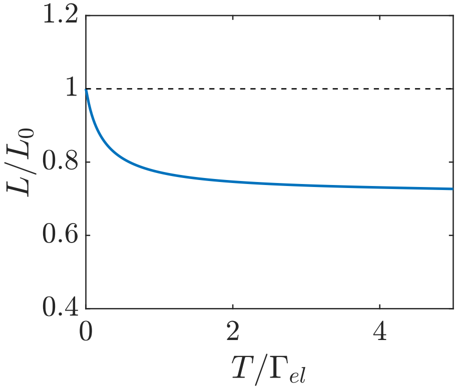
- **Clean metal near a VHS**

$$\frac{L}{L_0} \sim \sqrt{T}\log(1/T)$$



- **Disordered marginal Fermi liquid**

$$\frac{L}{L_0} = 1 - \alpha T + \cdots$$



Thank you!