The metals and insulators contained in massive gravity

Oriol Pujolàs

IFAE & Universitat Autònoma de Barcelona

Based on arXiv:1411.1003
with Matteo Baggioli

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Motivation

1) Massive Gravity

Many consistent phases of MG in the market.

- dRGT – Lorentz Invariant (??)

- Rubakov-Dubovsky 2004 – Lorentz-breaking

Relevance for cosmology (3+1 gravity) dubious-unclear

Relevant for 'anti-cosmology' i.e. AdS/CFT duality without Lorentz-inv → Cond Matt

Motivation

2) Condensed Matter

Finite density (ρ) and strong interactions => tough problem

∃ plethora of puzzling materials. Often layered (2+1)

HTSC
- **Strange metals (Non Fermi-liquids),**
- Interaction-driven **insulators (Mott, Anderson localization)**

Strong dynamics crucial → AdS/CMT

Plan

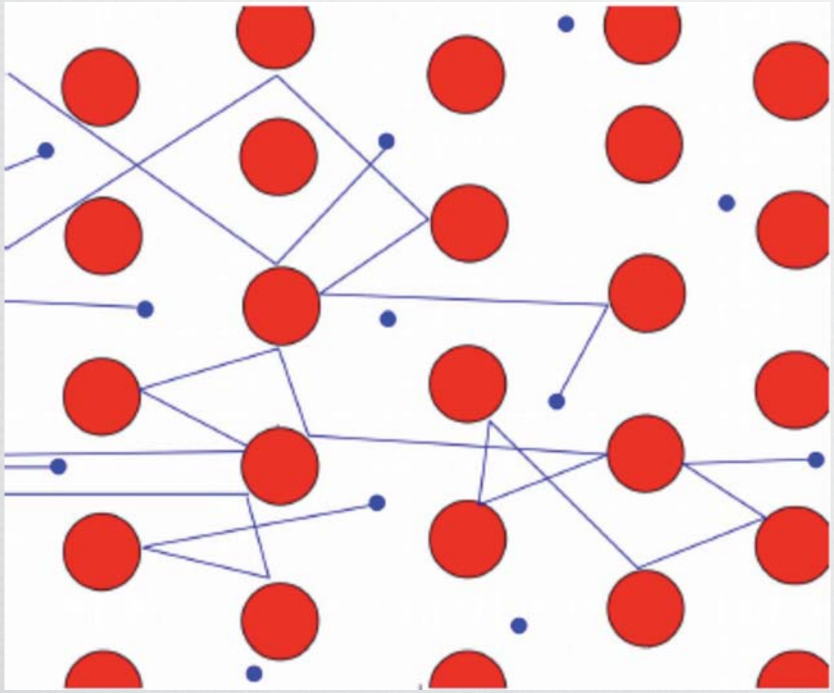
- Motivation
- Cond Matt crash course
- AdS/CFT crash course
- Massive Gravity renders AdS/CMT realistic
- Metal-Insulator transitions

CM crash course

Electrical conductivity (metals, insulators, …)

CM crash course

Drude model



$$m_*\left[\dot{\vec{v}}+\frac{\vec{v}}{\tau}\right]=e\vec{E}$$

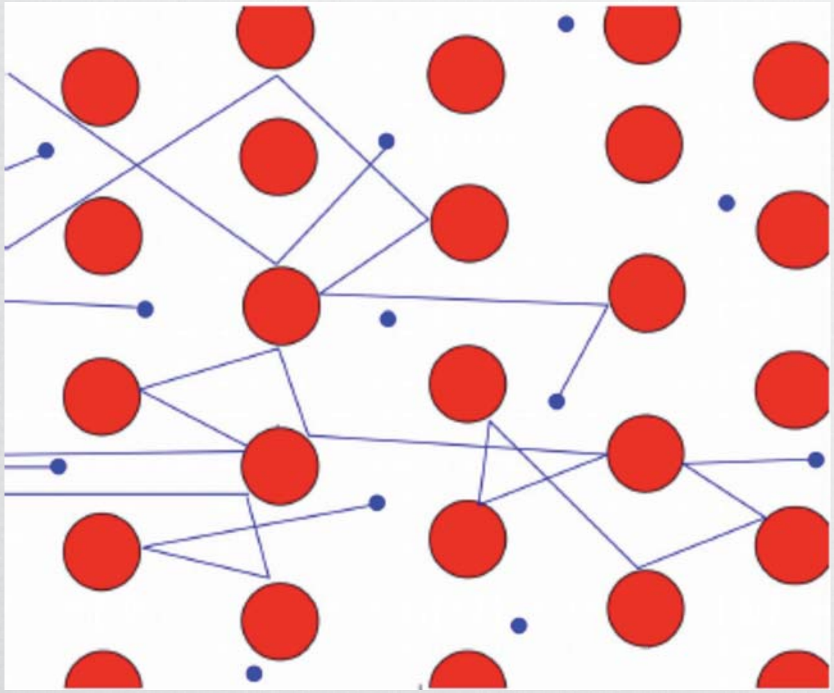
$$\Rightarrow \qquad \left(\vec{J}=\rho\,\vec{v}\right)$$

$$\sigma_{DC}=\frac{e\tau}{m_*}\rho \qquad \sigma(w)=\frac{\sigma_{DC}}{1-iw\tau}$$

CM crash course

τ : collision time
momentum non-conservation

Drude model



$$m_* \left[\dot{\vec{v}} + \frac{\vec{v}}{\tau} \right] = e\vec{E}$$

$$\Rightarrow \qquad \left(\vec{J} = \rho \vec{v} \right)$$

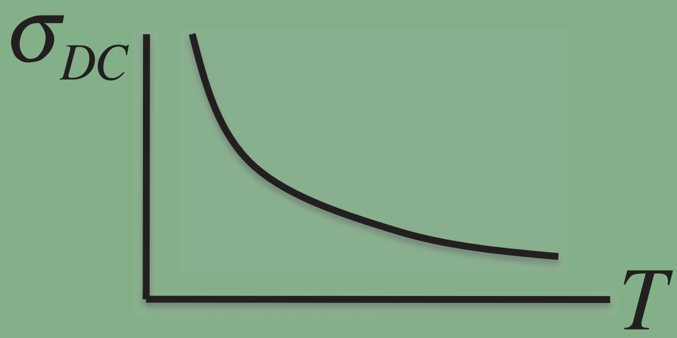
$$\sigma_{DC} = \frac{e\tau}{m_*}\rho \qquad \sigma(w) = \frac{\sigma_{DC}}{1 - iw\tau}$$

CM crash course

$$\sigma_{DC} = \frac{e\,\tau}{m_*}\rho$$

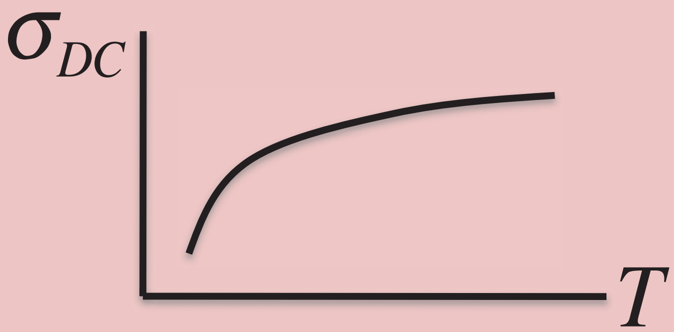
Metal: σ large

$$\frac{d\sigma}{dT} < 0$$



Insulator: σ small

$$\frac{d\sigma}{dT} > 0$$



CM crash course

Question marks: $\left(\sigma_{DC} = \frac{e\tau}{m_*}\rho\right)$

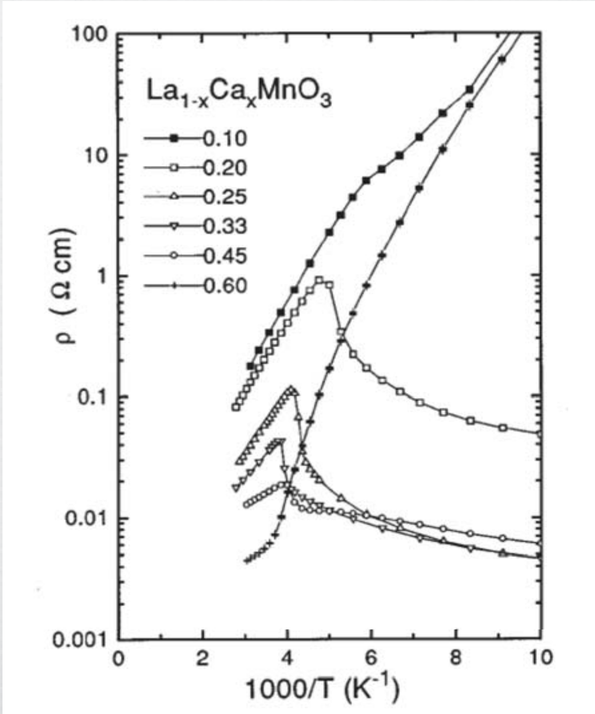
- *Correlated* insulator: ρ large but σ small
- Materials with Metal-Insulator transition

some HTSCs

cuprates,

manganites,

perovskites, …

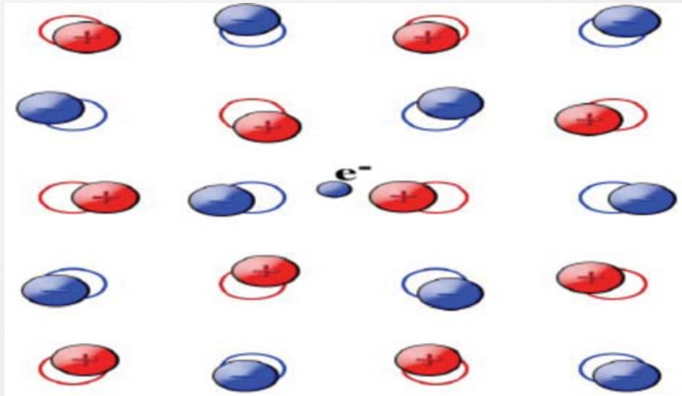


PhysRev B56, 5104

CM crash course

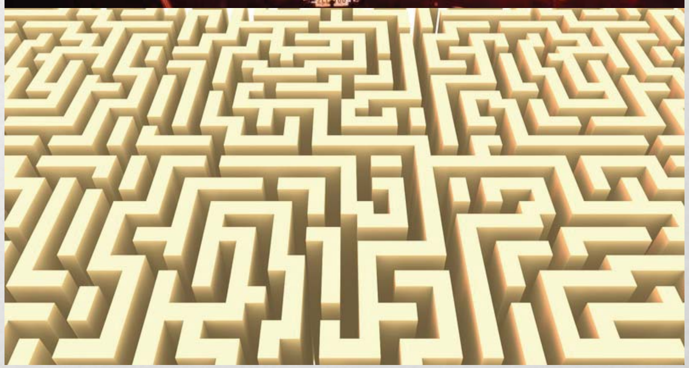
Various mechanisms:

i) Polaron (electron-phonon int.)



ii) Mott-Wigner (electron-electron)

iii) Disorder / Anderson localization

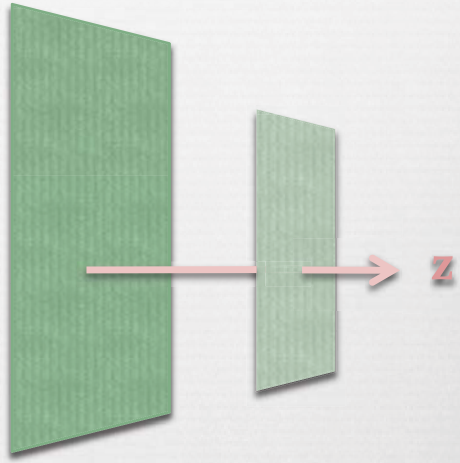


AdS/CFT crash course

AdS/CFT crash course

Physics (boundary conditions) in AdS ??

$$ds^2_{(d+1)} = \frac{dz^2 + \eta_{\mu\nu} dx^\mu dx^\nu}{z^2}$$



$$\Phi(z,x) \simeq \Phi_-(x)\, z^{\Delta_-} + \Phi_+(x)\, z^{\Delta_+} + \ldots$$

$J(x)$ $\qquad$ $\hat{O}(x)$

$$\Delta_+ + \Delta_- = d$$

$$S_{on-shell} = \int d^d x \sqrt{h} \left(\ldots + \Phi_- \Phi_+ + \ldots \right) \quad = \log\left[Z(J) \right]$$

QFT interpretation in terms of boundary data for a strongly coupled CFT

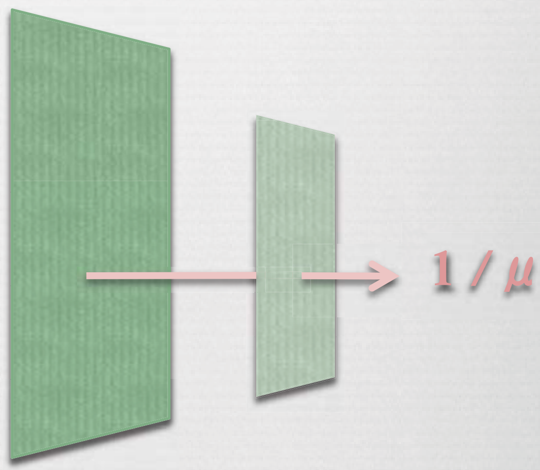
$$z \sim \frac{1}{\mu}$$

AdS/CFT crash course

- *QFTs with gravity dual* → **dynamics simplify enormously**

  few QFT operators= $\{T_{\mu\nu}, J_\mu, O, \ldots\}$

  → Finite T, ρ problems easily tractable



- Self-consistent dynamics:

  $T^{CFT}_{\mu\nu} \subset g_{\mu\nu}$

  $J^{CFT}_{\mu} \subset A_{\mu}$ with nonlinearities

- spacetime symmetries → holographic isometries

- Many non-trivial QFT effects: **nonperturbative RG flows, unparticle behaviour (broad resonances), collective effects, emergent symmetries & DOFs, dissipation in QFT, SSB, …**

Realistic AdS/CMT ?

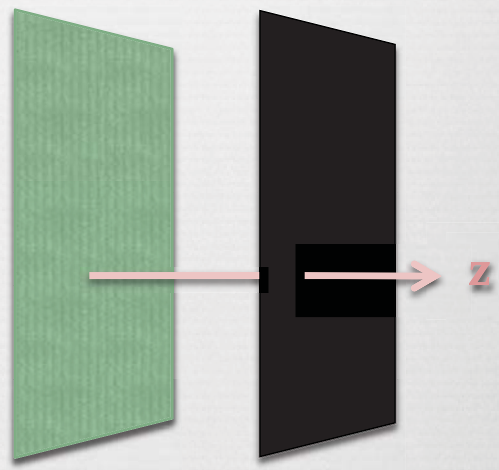
Unrealistic AdS/CMT

CFT at Finite T, ρ : RN AdS BB

$$ds^2 = \frac{\ell^2}{z^2}\left[\frac{dz^2}{f(z)} - f(z)\,dt^2 + dx_{d-1}^2\right]$$

$$f(z) = 1 - \varepsilon z^3 + \rho^2 z^4$$

$$A_t(z) = \mu - \rho\, z$$



charge-density (density of mobile charge-carriers)

Unrealistic AdS/CMT

CFT at Finite T, ρ : RN AdS BB

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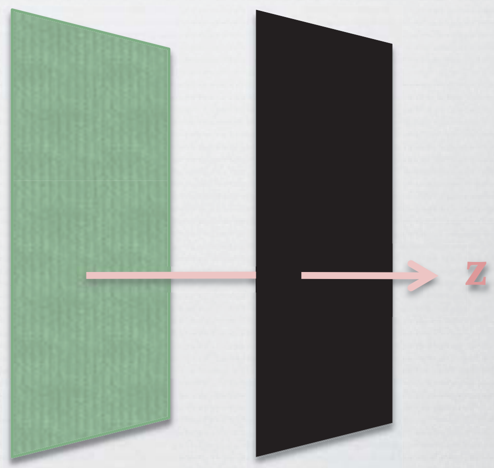

$$f(z) = 1 - \varepsilon z^3 + \rho^2 z^4$$

$$A_t(z) = \mu - \rho z$$

Conductivity: $A_i = A_i^{ext}(t) + z J_i + \ldots$

$$\sigma(w) = \frac{J}{iwA^{ext}} \quad \Rightarrow \quad \sigma(0) = \infty!!$$

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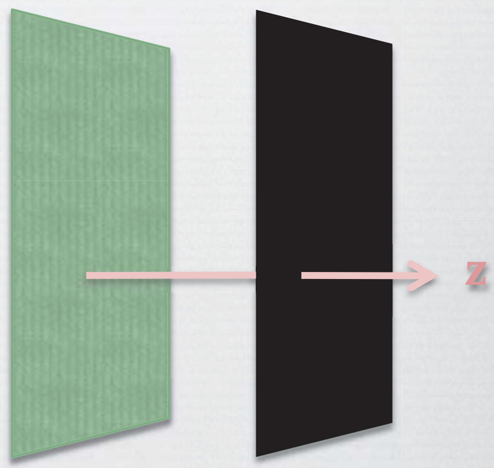


Conductivity: $A_i = A_i^{ext}(t) + z J_i + \ldots$

$$\sigma(w) = \frac{J}{iwA^{ext}} \Rightarrow \sigma(0) = \infty!!$$

need to relax $\vec{P}$
→ break translations

Realistic AdS/CMT

$$S=\int\sqrt{-g}\left\{R-2\Lambda-F_{\mu\nu}^2+m^2V(g^{\mu\nu})\right\}$$

graviton mass => new degrees of freedom

PHONONS

Realistic AdS/CMT

$$S = \int \sqrt{-g}\left\{R - 2\Lambda - F_{\mu\nu}^2 + m^2 V(X)\right\}$$

Phonon-dynamics

$$X \equiv \partial_\mu \Phi^I \, \partial_\nu \Phi^I \, g^{\mu\nu}$$

$$\left\langle \Phi^I \right\rangle = \delta_i^I x^i$$

Realistic AdS/CMT

$$S = \int \sqrt{-g}\left\{R - 2\Lambda - F_{\mu\nu}^2 + m^2 V(X)\right\}$$

Phonon-dynamics

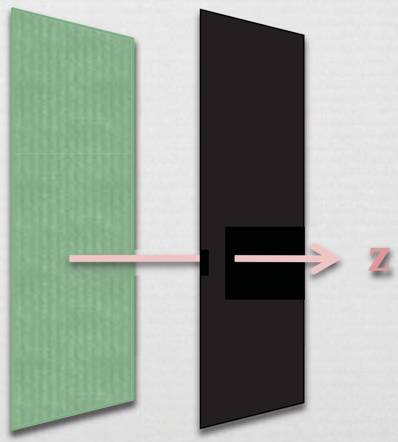
$$X \equiv \partial_\mu \Phi^I \, \partial_\nu \Phi^I \, g^{\mu\nu}$$

$$\left\langle \Phi^I \right\rangle = \delta_i^I x^i$$

There are BB solutions with 'hedgehog' scalar charge

$$ds^2 = \frac{\ell^2}{z^2}\left[\frac{dz^2}{f(z)} - f(z)dt^2 + dx_{d-1}^2\right]$$

$$f(z) = 1 - \varepsilon z^3 + \rho^2 z^4 + \ldots$$

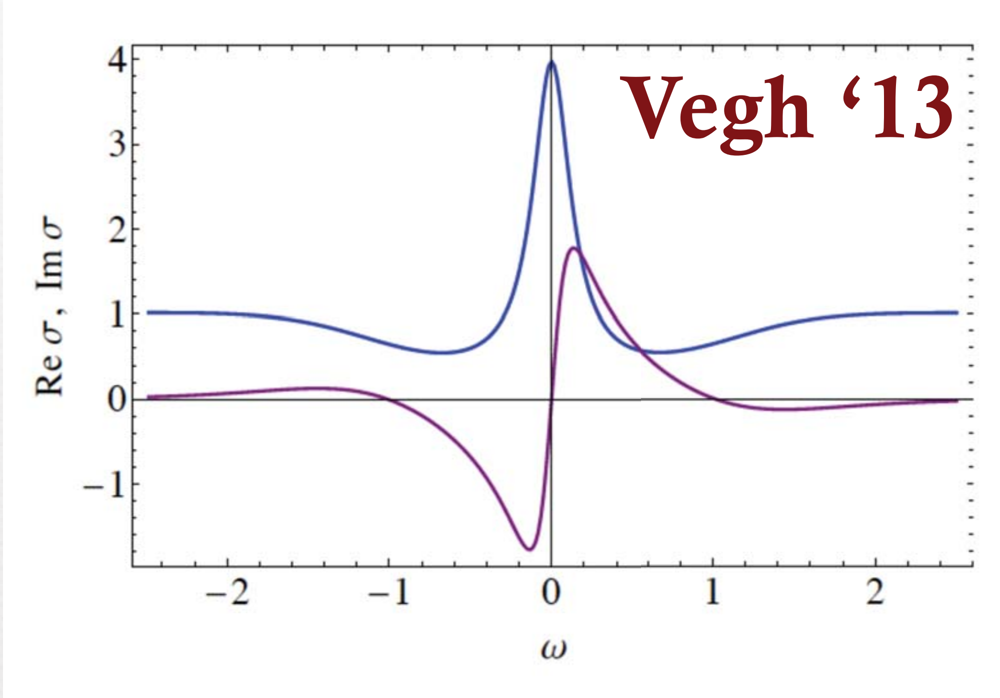


Realistic AdS/CMT

Conductivity:

$$\sigma(w) \simeq \frac{\sigma_{DC}}{1 - iw\tau}$$

$$\sigma_{DC} = 1 + \frac{\rho^2 z_H^2}{m^2}$$



Just with a graviton mass term, V(X)=X

$$\tau \sim \frac{1}{m^2}$$

Realistic AdS/CMT

Conductivity:

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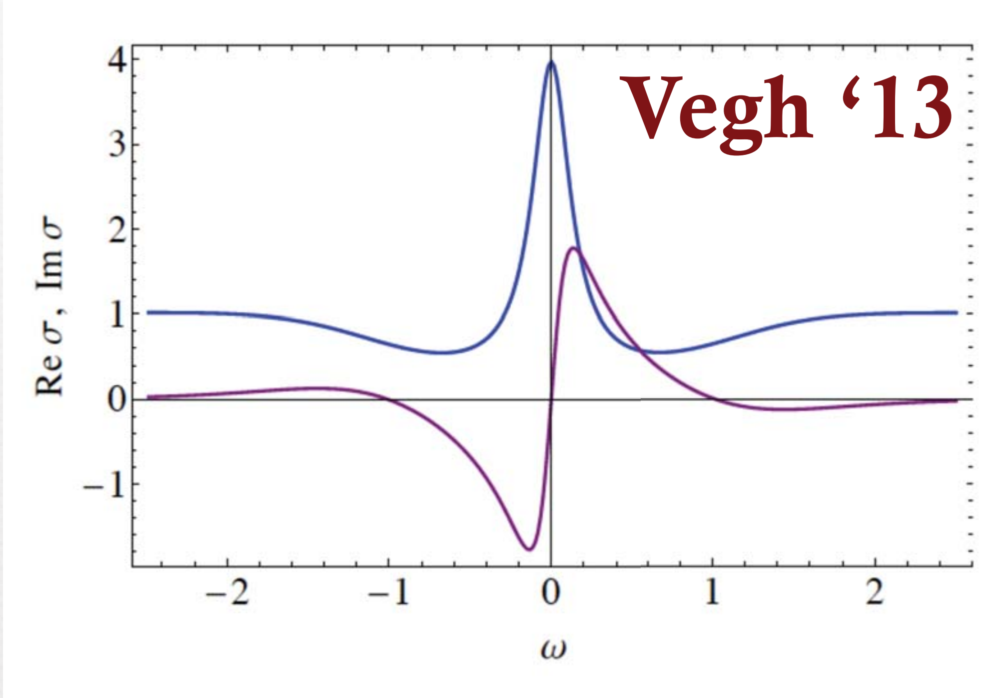
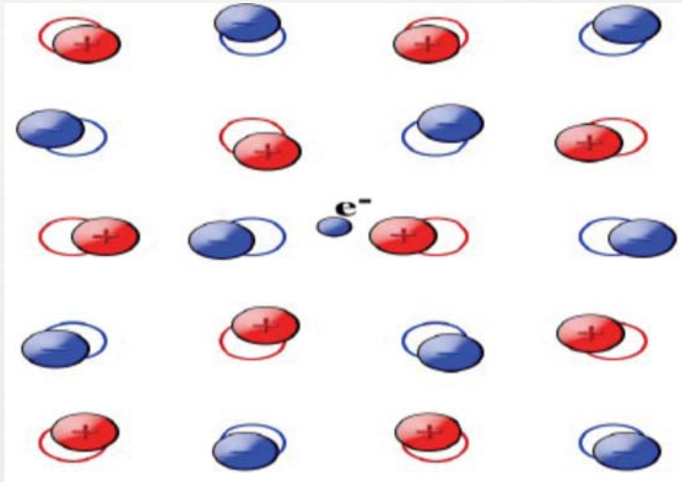


Just with a graviton mass term

$$\tau \sim \frac{1}{m^2}$$

Metal-Insulator transitions

i) Polaronic



ii) Mott-Wigner

Metal-Insulator transitions

i) $S = \int \sqrt{-g}\left\{R - 2\Lambda - F_{\mu\nu}^2 + m^2 V(X)\right\}$

Quite general form of $V(X)$ allowed

$V'(X) > 0$

$XV''(X) + V'(X) > 0$

$\Rightarrow$

$\Phi^I = \langle \Phi^I \rangle + \delta\Phi^I \qquad M_{\delta\Phi}^2 \approx -\frac{V''(z_H^2)}{V'(z_H^2)} < 0$

Polaron formation

$\sigma_{DC} = 1 + \frac{\rho^2 z_H^2}{m^2 V'(z_H^2)}$

Metal-Insulator transition

Metal-Insulator transitions

Debye / plasma mass term

$$\partial_u \left(f\, \partial_u\, a_i\right) + \left[\frac{\omega^2}{f} - k^2 - 2u^2\rho^2\right] a_i = \frac{i\rho\, u^2(2\bar{m}^2 + k^2)}{\omega} U_i - \frac{i\, f\, \rho\, k^2}{\omega} \partial_u B_i\,,$$

$$\frac{1}{u^2}\partial_u \left[\frac{f u^2}{\bar{m}^2}\partial_u(\bar{m}^2 U_i)\right] + \left[\frac{\omega^2}{f} - k^2 - 2\bar{m}^2\right] U_i = -2i\,\rho\,\omega\, a_i + \frac{f' k^2}{u^2} B_i\,,$$

$$k\left\{u^2\partial_u\left(\frac{f}{u^2}\,\partial_u\, B_i\right) + \left[\frac{\omega^2}{f} - k^2 - 2\bar{m}^2\right] B_i = -2\frac{\bar{m}'}{\bar{m}} U_i\right\},$$

bulk liearized equations for vector modes

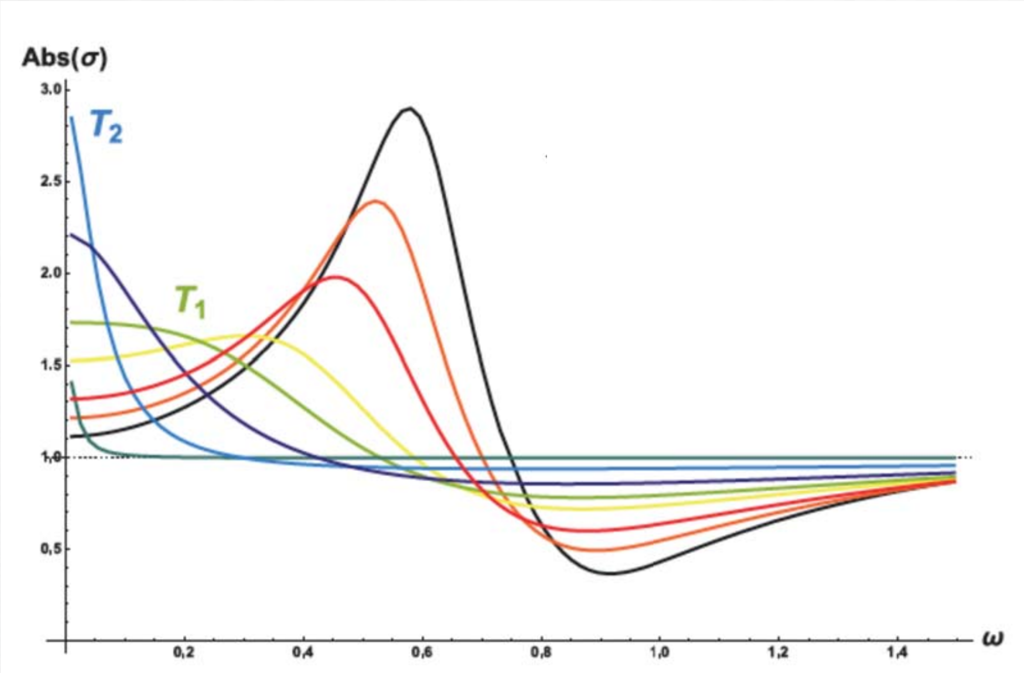
$$T_i \equiv u^2 h_{ti} - \frac{\partial_t \phi_i}{\alpha}\ ,\ U_i \equiv f(u)\left[h_{ui} - \frac{\partial_u \phi_i}{\alpha u^2}\right]\ ,\ B_i \equiv b_i - \frac{\phi_i}{\alpha}$$

gauge invariant variables

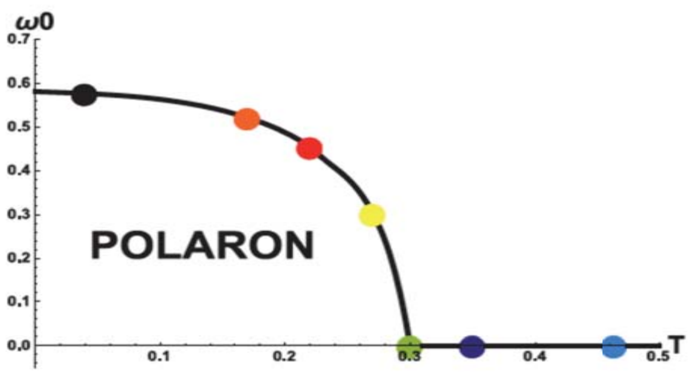
$$\bar{m}^2(u) = \alpha^2 m^2 V'(\alpha^2 u^2)$$

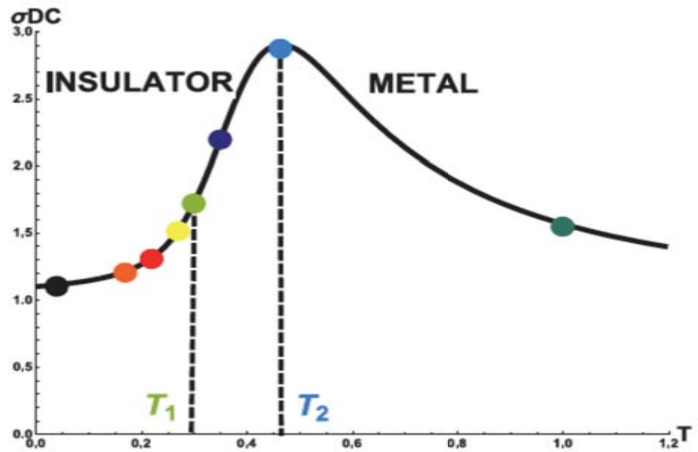
Metal-Insulator transitions

i)



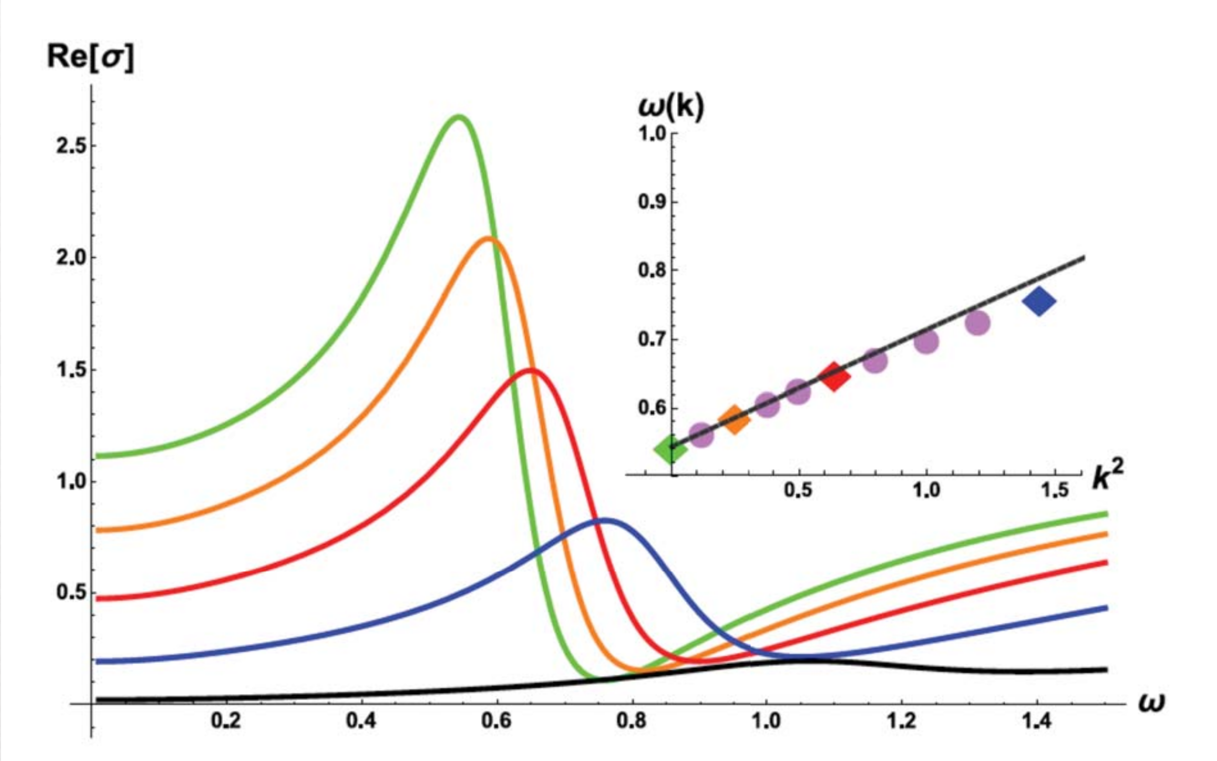
electrons trapped by large lattice deformations → m_* huge





Metal-Insulator transitions

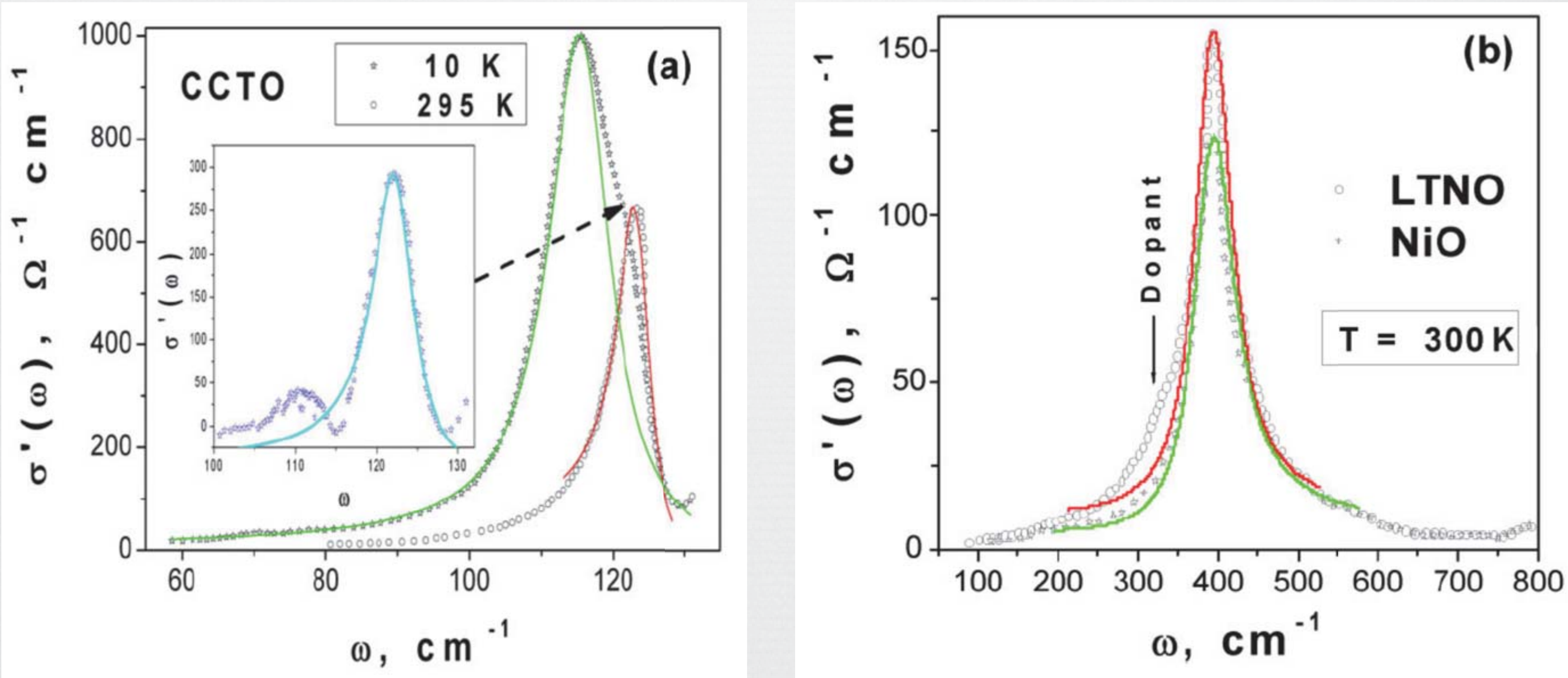
i)



the polaron is an emergent particle degree of freedom with a well defined dispersion relation, mass, width, … (we started from a CFT)

Polarons in the real world

i)

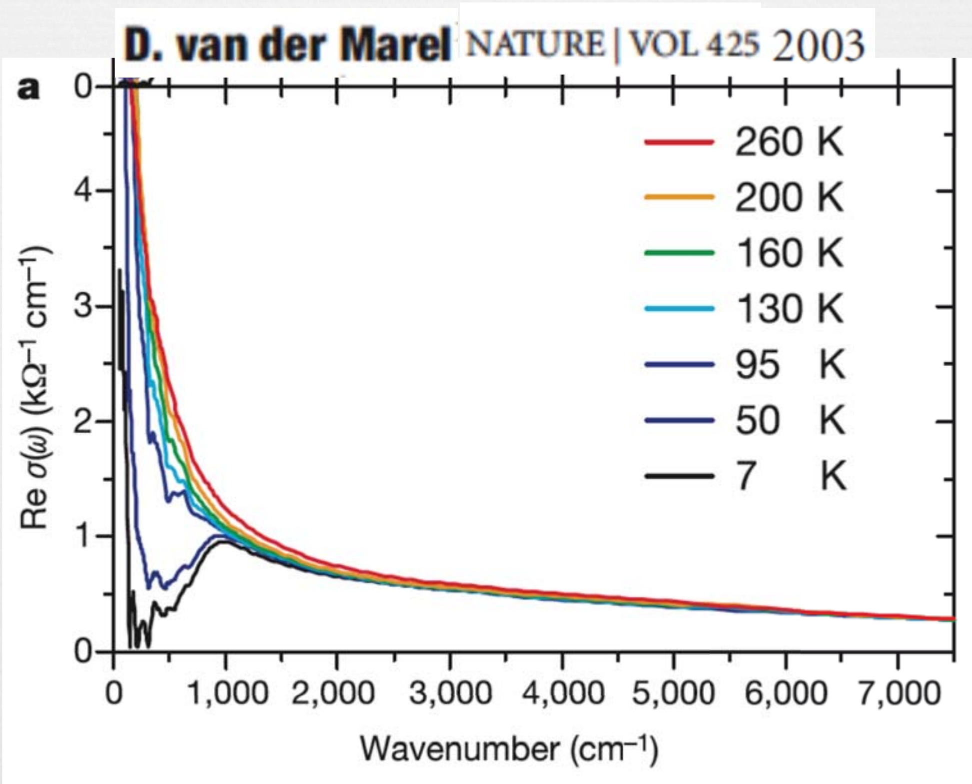


Phys. Status Solidi B **251**, No. 3, 569–592 (2014)

Valeri Ligatchev

Polarons in the real world

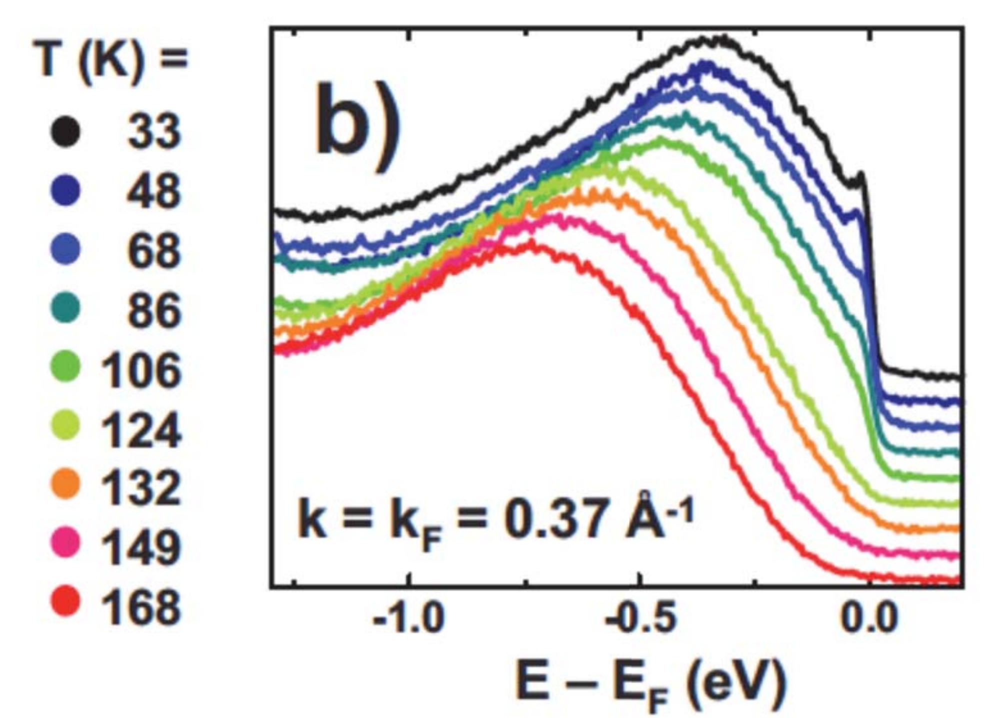
i)

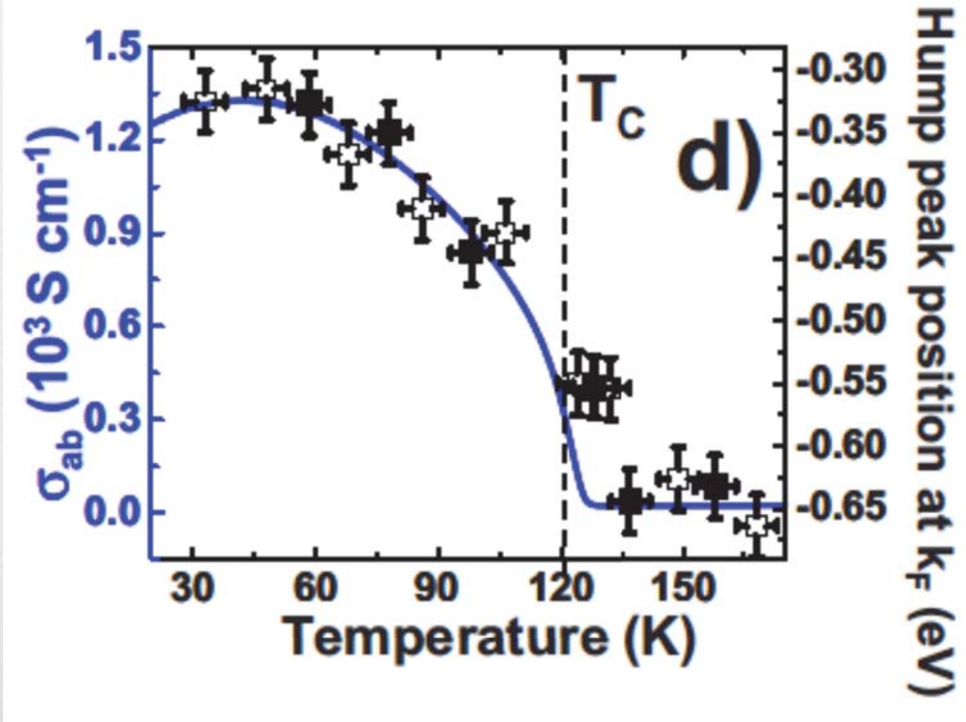


Polarons in the real world

i) **Polaron coherence condensation as the mechanism for colossal magnetoresistance in layered manganites**

N. Mannella, PHYSICAL REVIEW B **76**, 233102 (2007)





Conclusions

- Massive Gravity has a real-world application !
- Charged MG AdS BHs know about CM !
- Many consistent phases of LV MG out there
- Phases of MG -> phases of Holography?
- AdS/CMT predictability

  → identify robust correlations (in progress)

Thanks!