Solid applications of Massive Gravity

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Based on arXiv:1411.1003 (PRL) with Oriol Pujolàs
+ work in progress with L.Alberte, A.Khmelnitsky, D.Musso, A.Amoretti, A.Braggio, N.Magnoli

Sestri Levante, September 2015

IFAE

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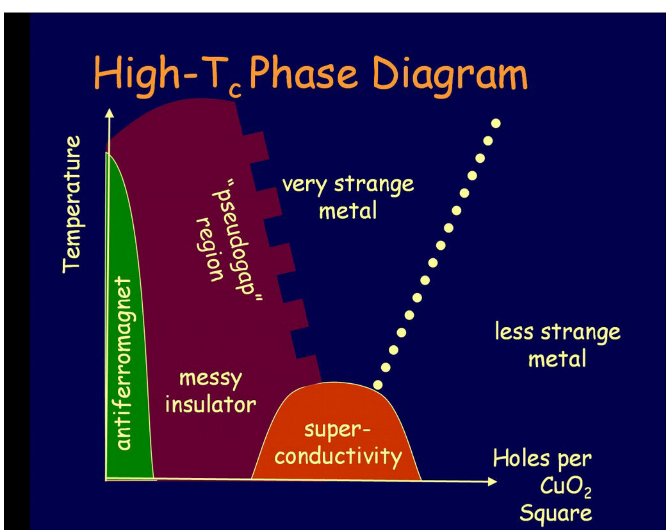
Motivations

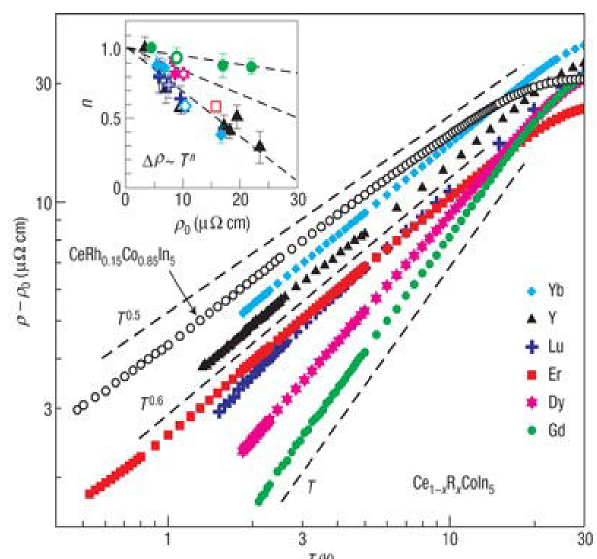
CONDENSED MATTER → **# OF PUZZLES**

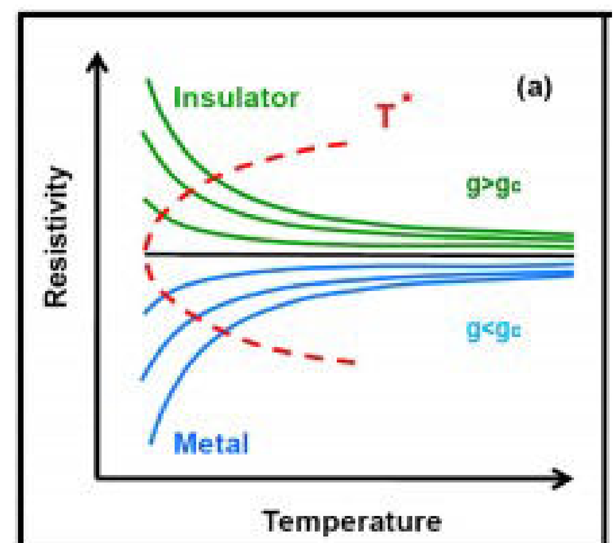
Finite density + Strong coupling →

HARD PROBLEM

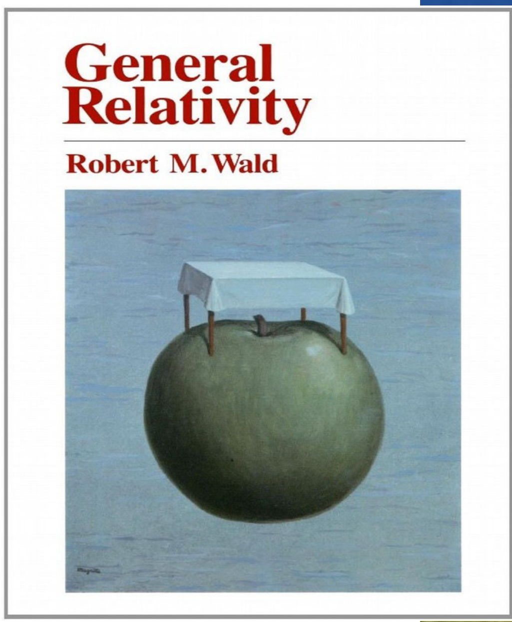
HTSCs , Strange Metals, Mott-Anderson Insulators & MIT

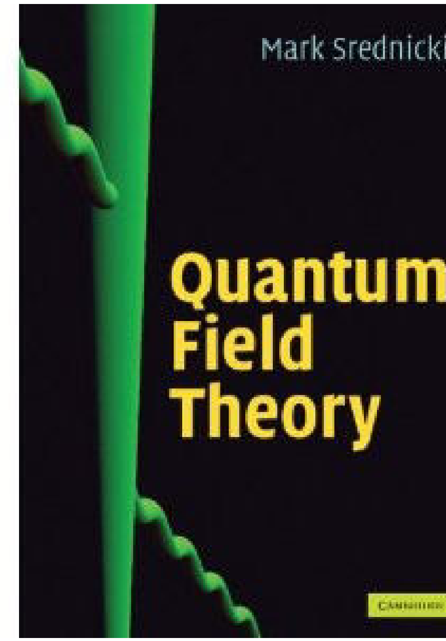






Tools



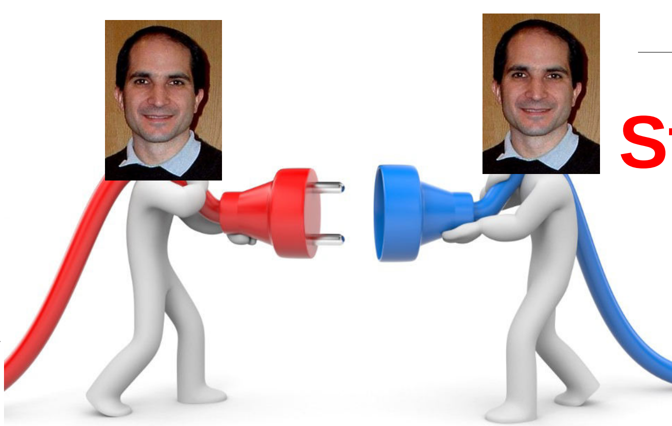


AdS-CFT

Weakly coupled

Classical

General Relativity



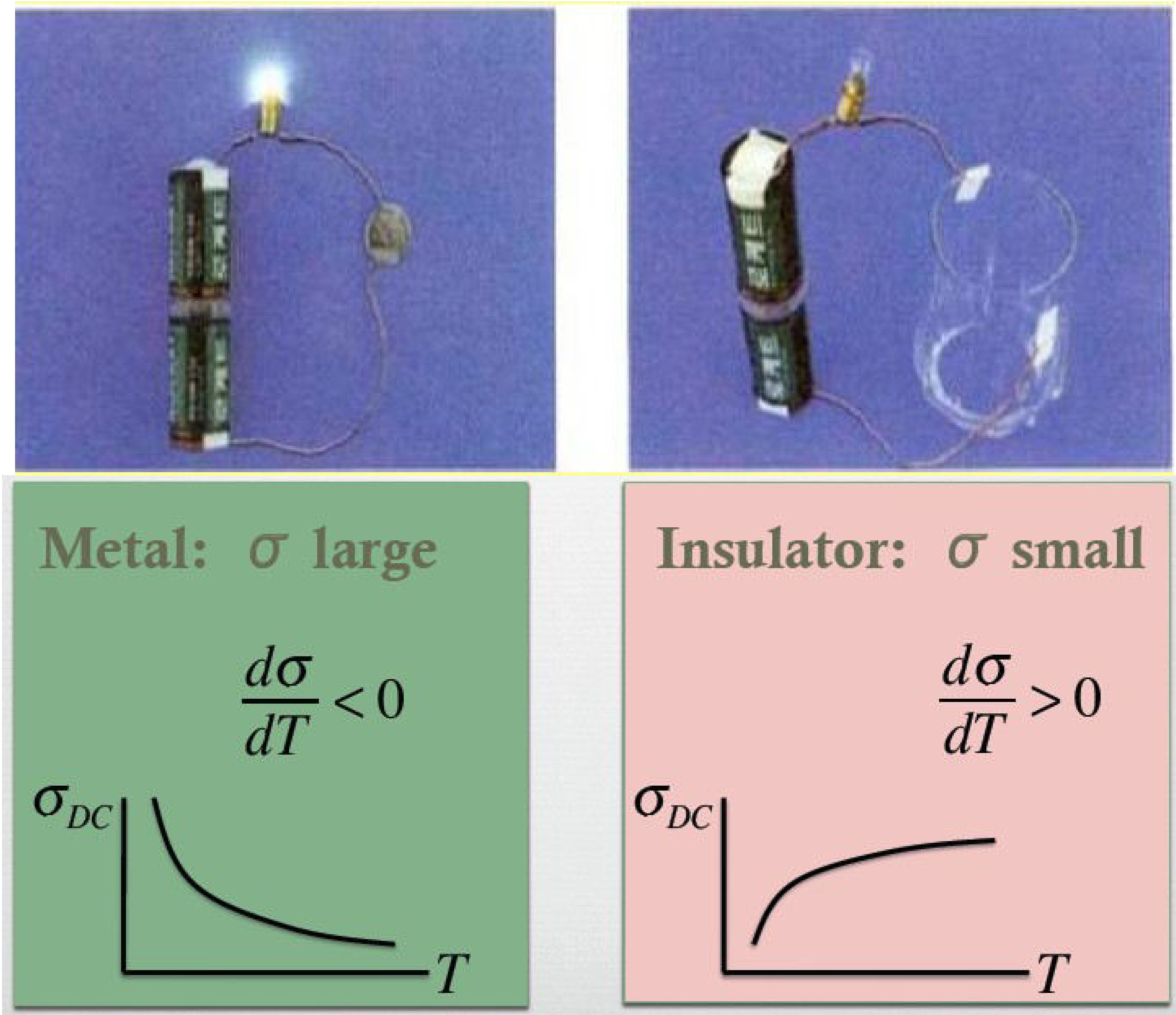
Strongly coupled

Quantum

Field theory

Metal or Insulator - and why?

ELECTRIC RESPONSE



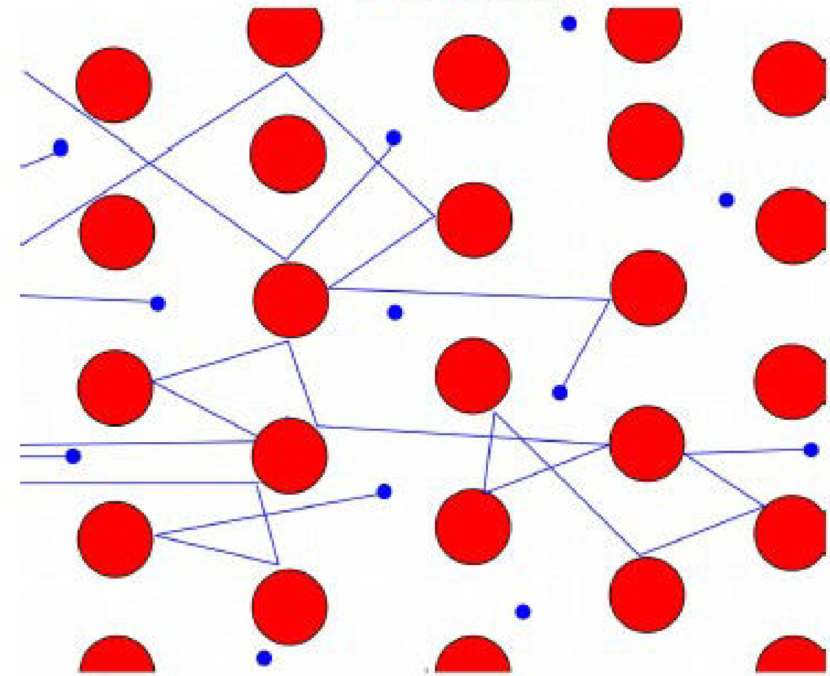
Electric Response à la Drude

Drude Model (1900)

$$\frac{d}{dt}p(t) = q\,E - \frac{p(t)}{\tau}$$

$$\sigma_{DC} = \frac{n\,q^2\,\tau}{m}$$

Weakly coupled logic:
“Pinball”



A lot of simplifications but a very good phenomenological model

τ
- → COLLISION TIME , RATE OF MOMENTUM DISSIPATION
- → IONS, IMPURITIES, DISORDER
- → BREAKING OF TRANSLATIONAL INVARIANCE

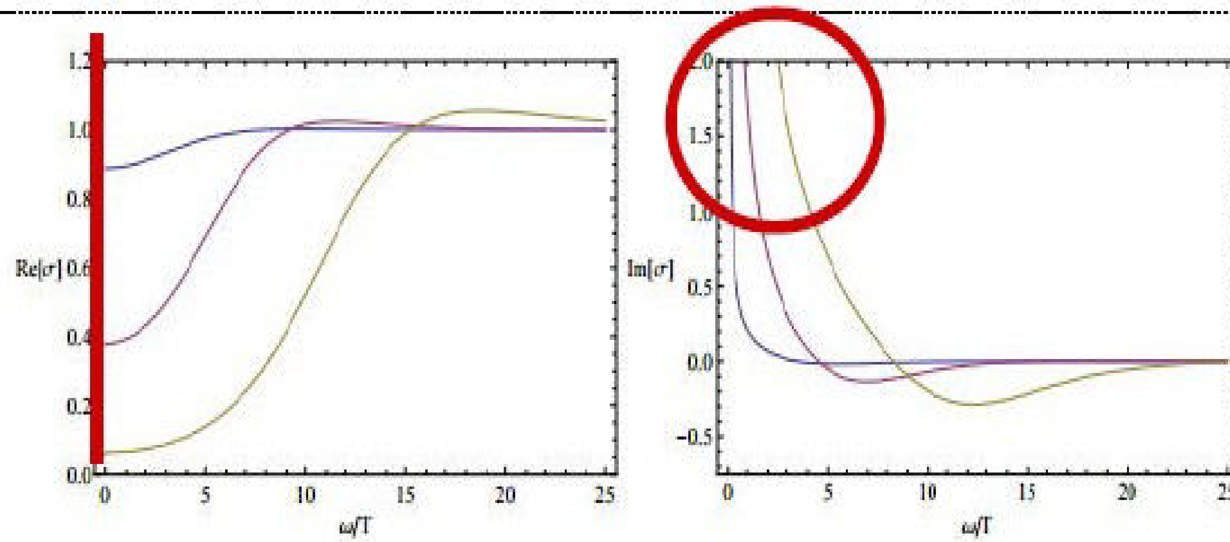
Unrealistic AdS-CMT

Reissner Nordstrom Black Hole

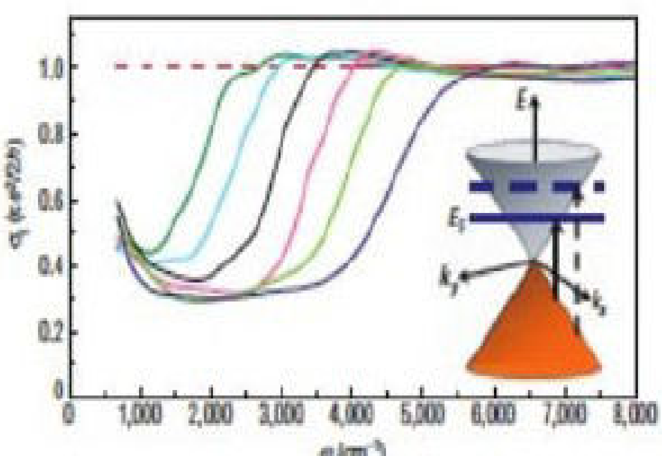
$$S = \int d^{d+1}x\sqrt{-g}\left[\frac{1}{2\kappa^2}\left(R + \frac{d(d-1)}{L^2}\right) - \frac{1}{4g^2}F^2\right].$$

- **Temperature**
- **Charge density**
- **Translational invariance**

Holography:



Graphene:



There is an infinite DC Conductivity!

τ **Is infinite !**

Targets & Open questions

REALISTIC AdS-CMT → **MOMENTUM DISSIPATION**

Mechanisms :

- **Umklapp and electron- phonon interactions**
- **Impurities & Disorder**
- **Electron- Electron interactions**

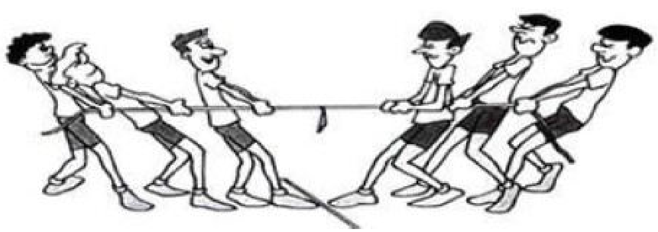
Phenomenology & Puzzles :

- **1st : Finite DC conductivity**

- **Strongly Correlated Insulators**

- **Metal- Insulator transitions**

Mott Insulators



Anderson Insulators

(More) Realistic AdS-CMT

MASSIVE GRAVITY

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

$t \to \tilde{t}(t,x)$

~~$x^i \to \tilde{x}^i(t,x)$~~

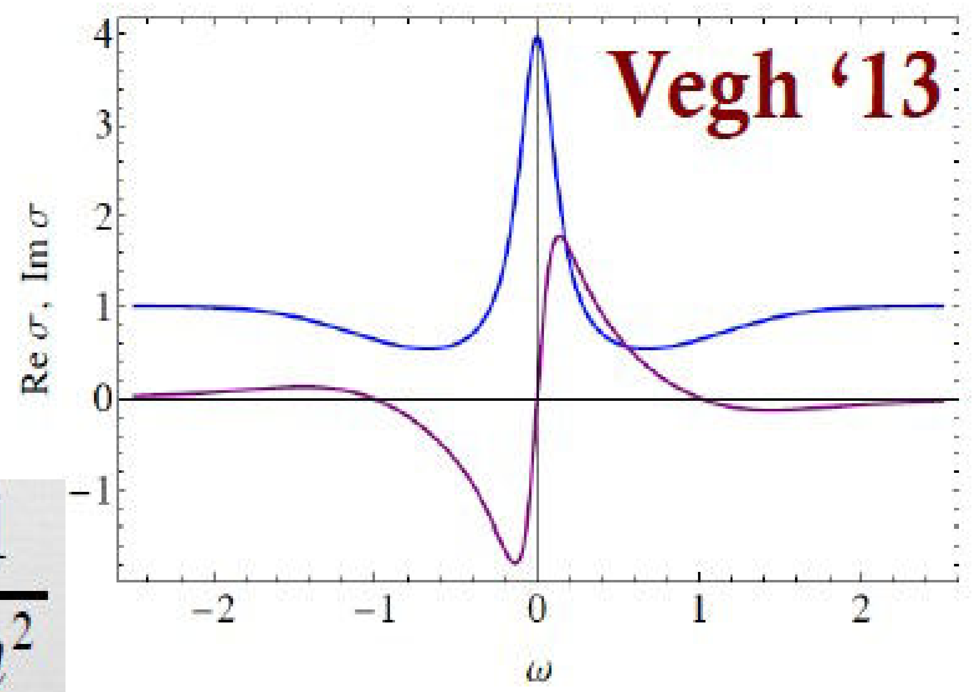
→ **Broken diffeos** → **Broken CFT Transl INV** → **Momentum Dissipation**

Conductivity:

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

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

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



EFT for Solids and Massive Gravity

Comoving coordinates of the volume elements: $\Phi^I(\vec{x}, t)$

EFT for Phonons (Goldstone bosons of SB-translations)

equilibrium

$$\Phi^i = x^i + \phi^i$$

Leutwyler '93

Classification in *Nicolis Penco Rosen '14 & Nicolis Penco Piazza Rattazzi '15*

SOLIDS =
Internal Shift simmetry : $L_{eff} \simeq \partial\phi^i \partial\phi^i + (\vec{\partial}\cdot\vec{\phi})^2$ → **Elastic response**

EFT of fluids/solids ⇔ LV Massive Gravity

Gauging SSB of translations → graviton 'eats up' phonons

SOLIDS:

$$L = V(X, Y)$$

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

$$\langle \Phi^I \rangle = \delta^I_i x^i$$

$$Y \equiv \partial_\mu \Phi^J \partial^\mu \Phi^K \partial_\nu \Phi^J \partial^\nu \Phi^K$$

(More^2) Realistic AdS-CMT

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

Massive Gravity in Stuckelbergs form; healthy theory

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

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

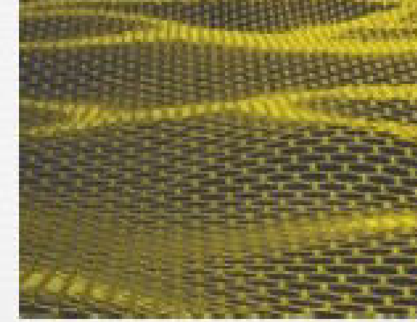
$V'(X) > 0 \quad XV''(X) + V'(X) > 0$

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

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

→ **Quite generic T dependence**
Of the Drude-Like part
+
Gapped phonons & Polaron formation

Strongly coupled solids



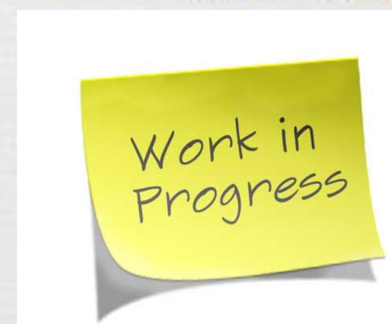
$\langle \Phi^I \rangle = \delta^I_i x^i$ realizes **spontaneous** and **explicit breaking**

$\delta\Phi^I$ contains a **phonon pole** for $m\ell \ll 1$

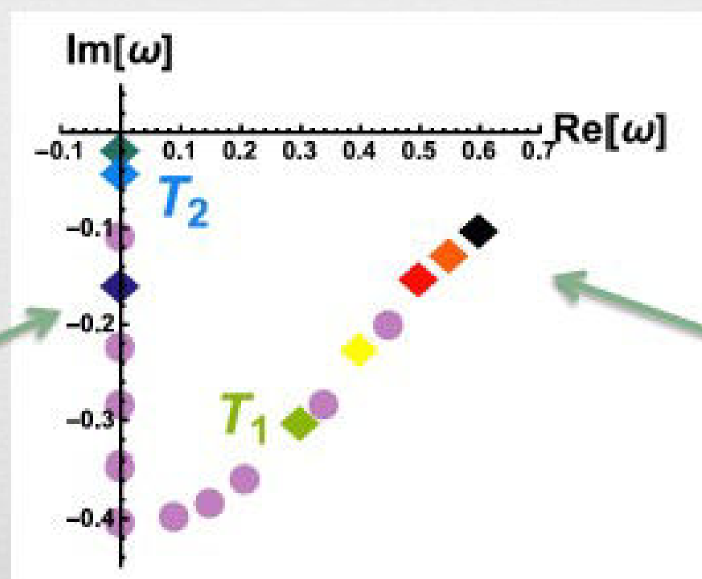
$$w(k) \simeq w_0 - i\,\Gamma_0 + c_S\,k$$

disorder (expl breaking)

elastic moduli (w.i.p.)

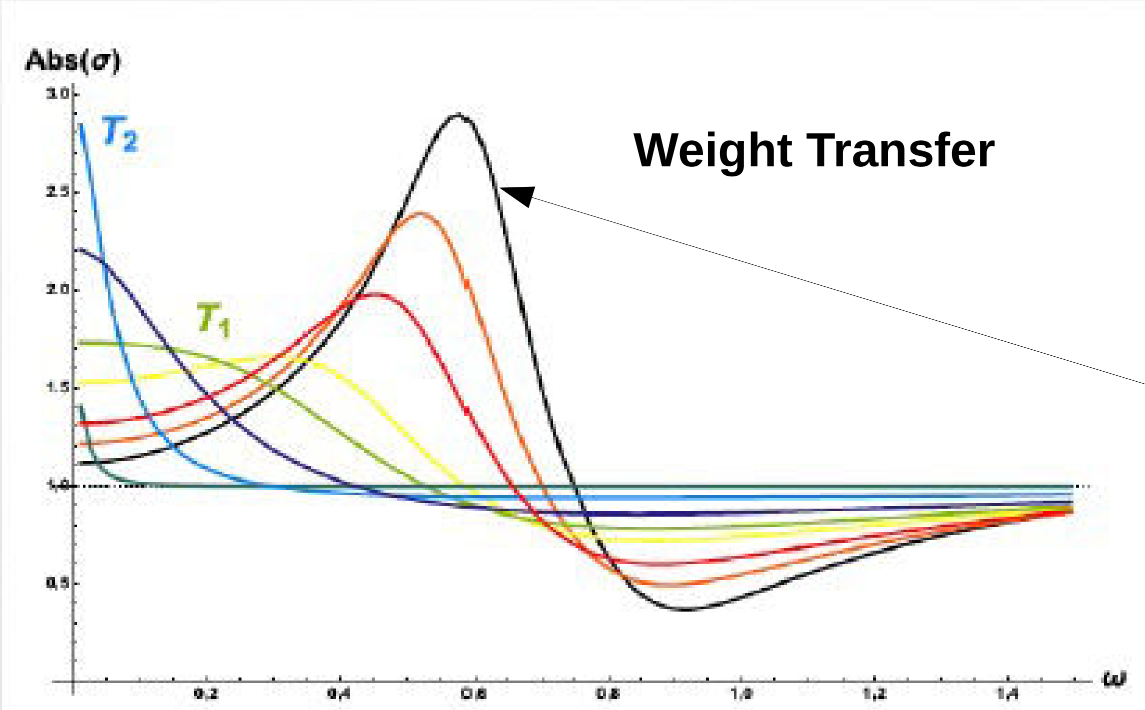


over-damped



under-damped
energy gap

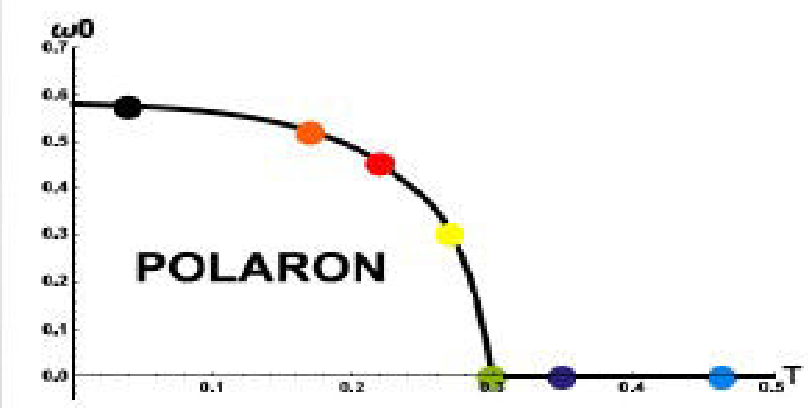
Metal – Insulator transition

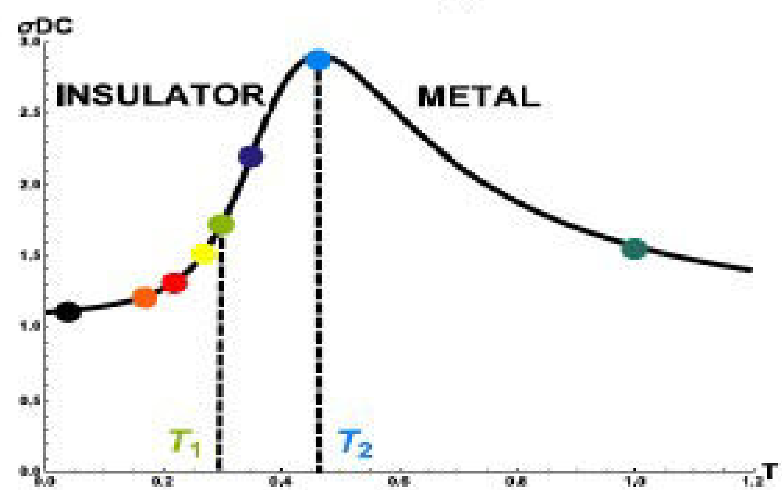


phonons gapped

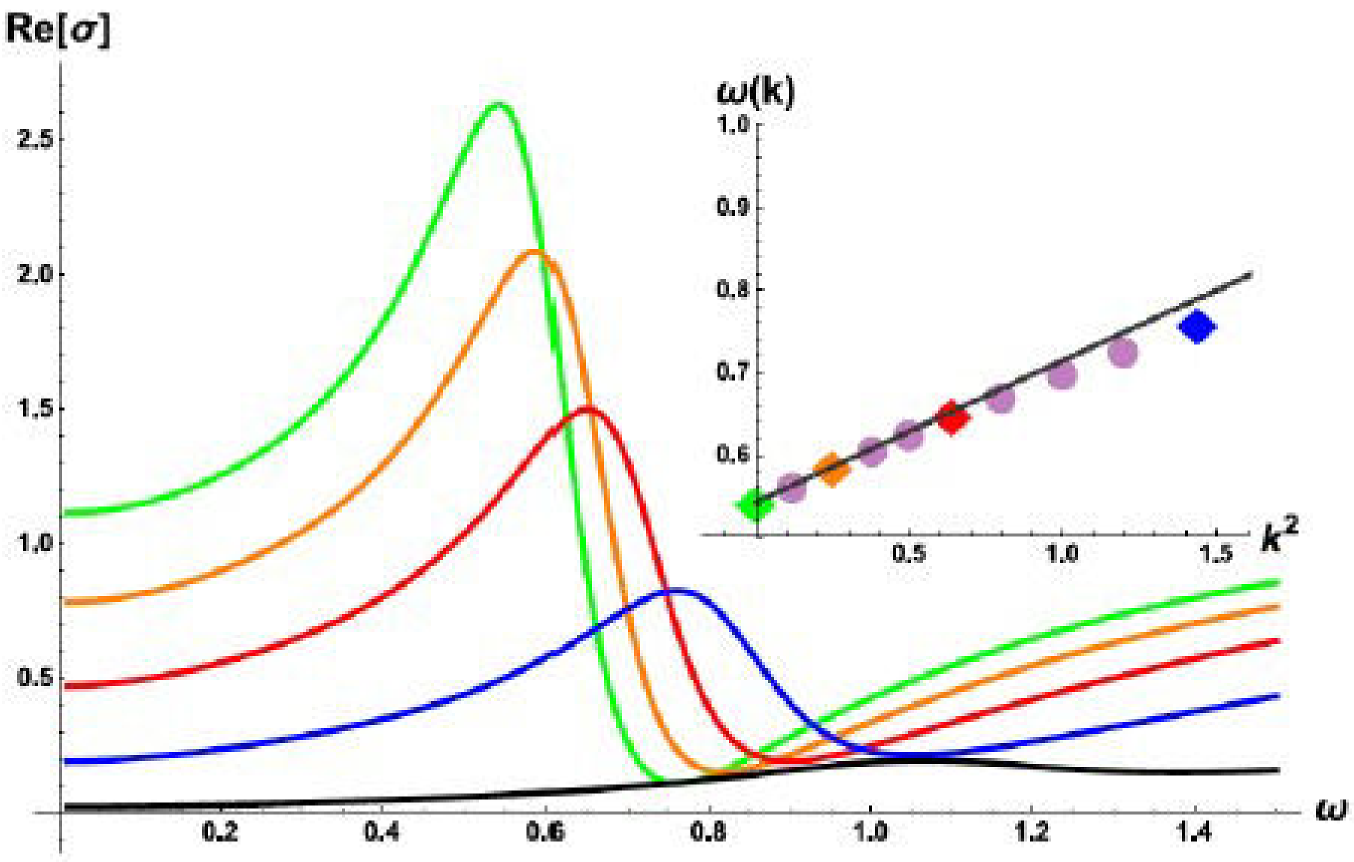
electrons trapped into **polarons** with large m_*

$$m_*^2 = m^2 V'(z_h^2)$$





Emergent Polaron-like dofs



POLARON

There is a localized and propagating excitation with well defined mass, width and dispersion relation...

Disorder Driven Metal-Insulator transition from holography

$$S_{bulk} = \int d^4x\sqrt{-g}\left(R - 2\Lambda - \frac{F^2}{4e^2} + \mathcal{D}(\phi^I,\dots)\right) \longrightarrow \sigma_{DC} = \frac{1}{e^2}\left(1 + \dots\right)$$

There is a lower bound on the DC conductivity → $\sigma_{DC} \geq \frac{1}{e^2}$

Coupling Massive Gravity to Charged Sector

$$S = \int d^4x\sqrt{-g}\left[R - 2\Lambda - \frac{1}{2e^2}Y(X)F^2 - 2\,m^2V(X)\right].$$

$$X = g^{\mu\nu}\partial_\mu\phi^I\partial_\nu\phi^I$$

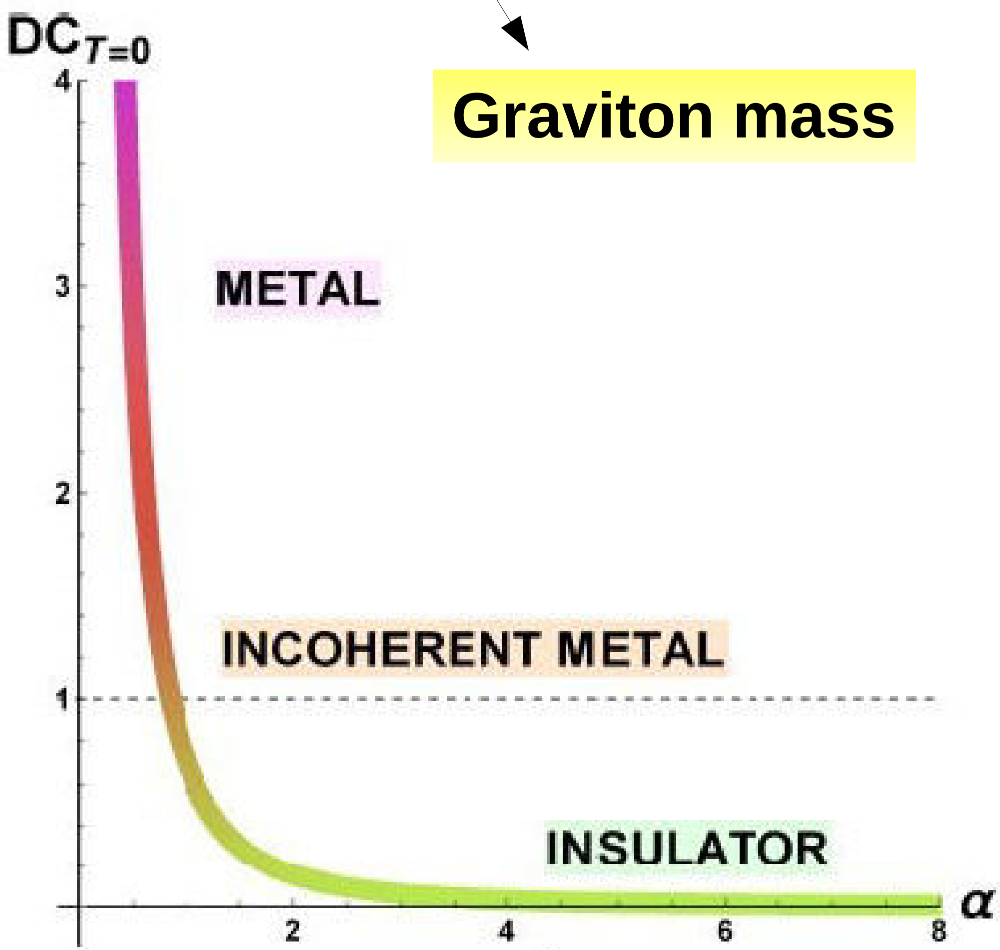
$$\phi^I = \alpha\,\delta^I_i x^i$$

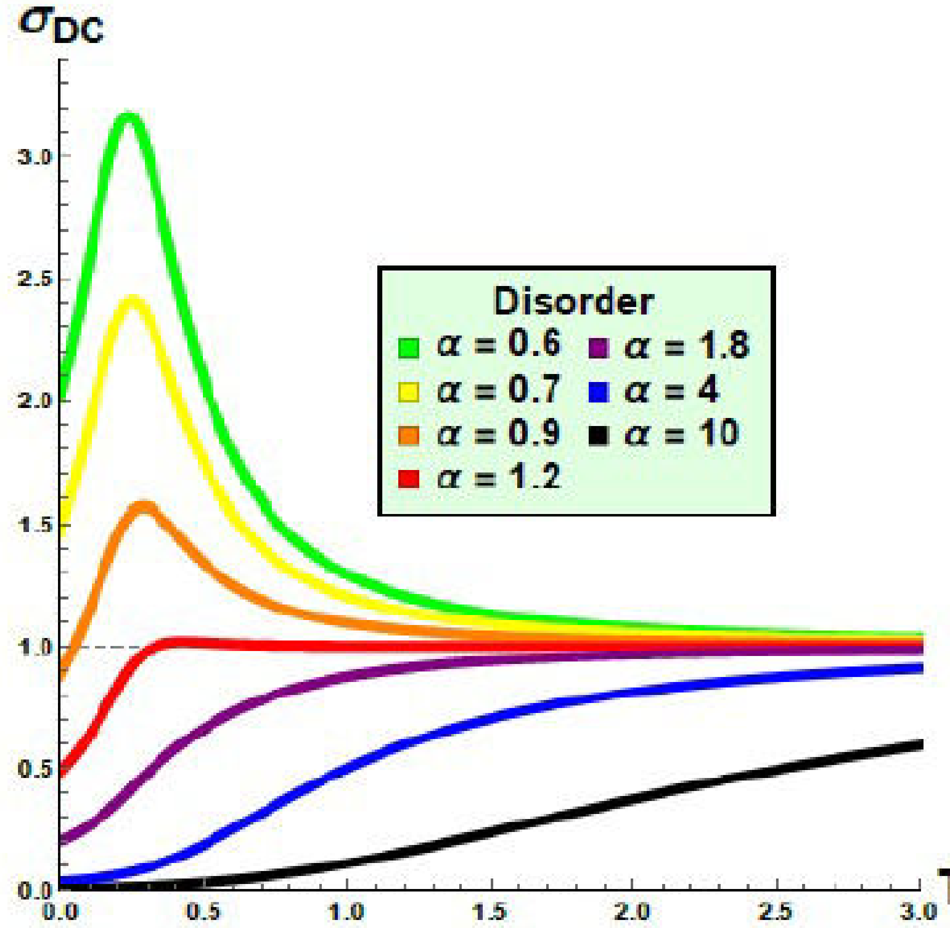
Electrons- Disorder Interactions

$$\sigma_{DC} = Y\left(\bar{X}_h\right) + \dots$$

COMING SOON

Disorder Driven Scenario Results





Disorder Driven Insulator

Disorder Driven
Metal-Insulator Transition

Conclusions

- **MASSIVE GRAVITY has REAL WORLD applications (CM)**
- **There are many USEFUL phases of NR MASSIVE GRAVITY**
- **MASSIVE GRAVITY encodes PHONONS dynamics**
- **MASSIVE GRAVITY can model DISORDER DRIVEN MIT**
- **AdS – CMT PREDICTABILITY ?**

  Several candicate correlations & observables...

Work in progress

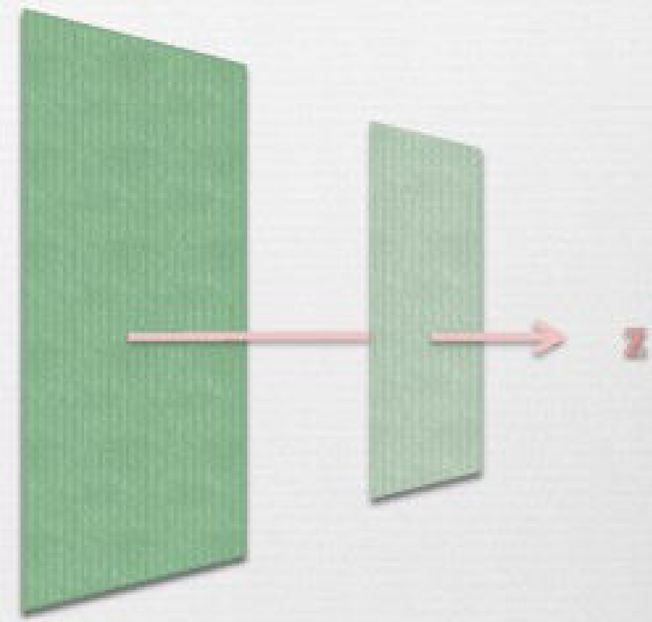
- Phases of Non Relativistic Massive gravity
- (with L. Alberte, O. Pujolàs, A. Khmelnitsky)
- Thermoelectric Response and Coherent-Incoherent contributions
- (with A. Amoretti, D. Musso)
- Towards Holographic Mott Insulators
- (with O. Pujolàs)
- Bounds, scalings and phenomenology
- (with N. Magnoli, A. Braggio)

& much more...


AND THANKS FOR
YOUR
"ATTENTION"

AdS/CFT

$z \sim \frac{1}{\mu}$ (RG-scale)



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

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

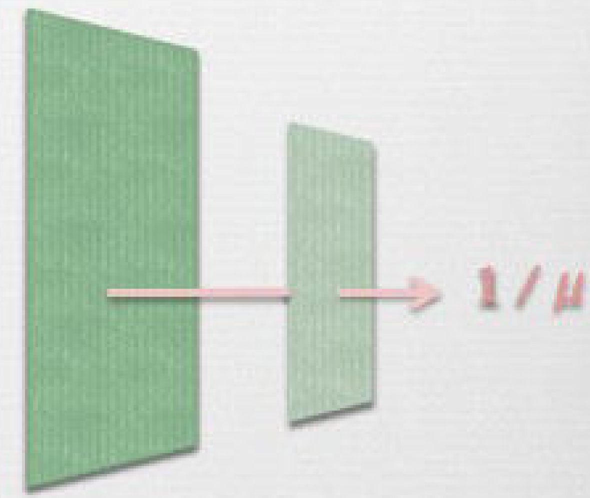
$$S_{on-shell} = \int d^d x \sqrt{h}\left(\Phi_- \Phi_+ + \dots\right) \quad = \log\left[Z(J)\right]$$

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

AdS/CFT

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

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



$$T_{\mu\nu}^{CFT} \subset g_{\mu\nu}$$
$$J_{\mu}^{CFT} \subset A_{\mu}$$

- **Many non-trivial QFT effects:**

nonperturbative RG flows, collective effects, emergent symmetries & DOFs, unparticles, QFT plasmas, dissipation in QFT

Metal-Insulator transitions

Debye / plasma mass term

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

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

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

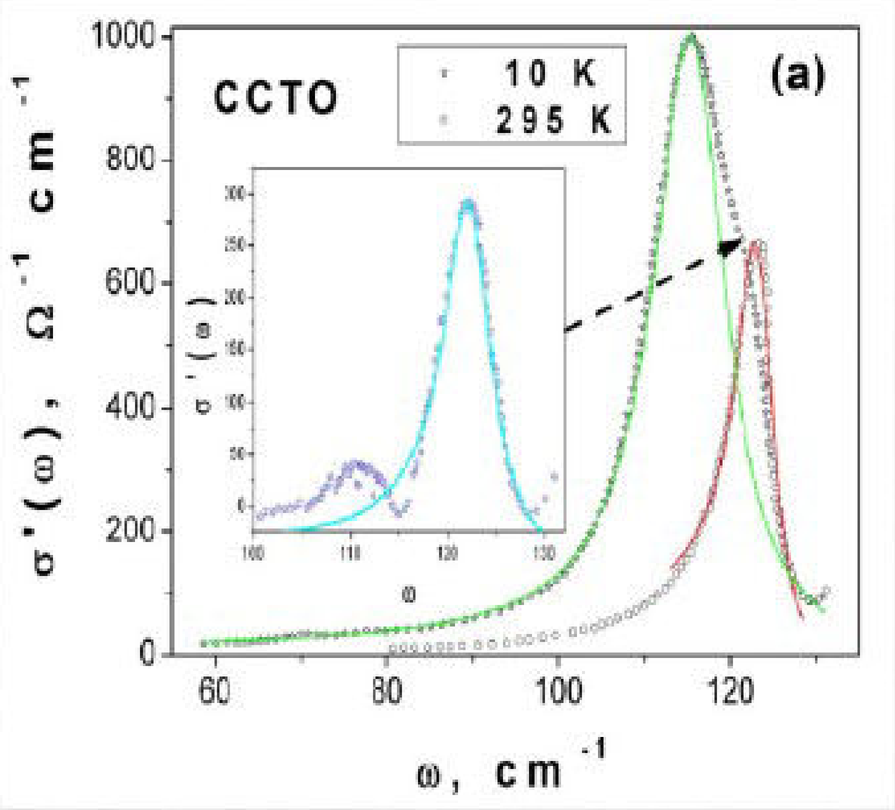
bulk liearized equations for vector modes

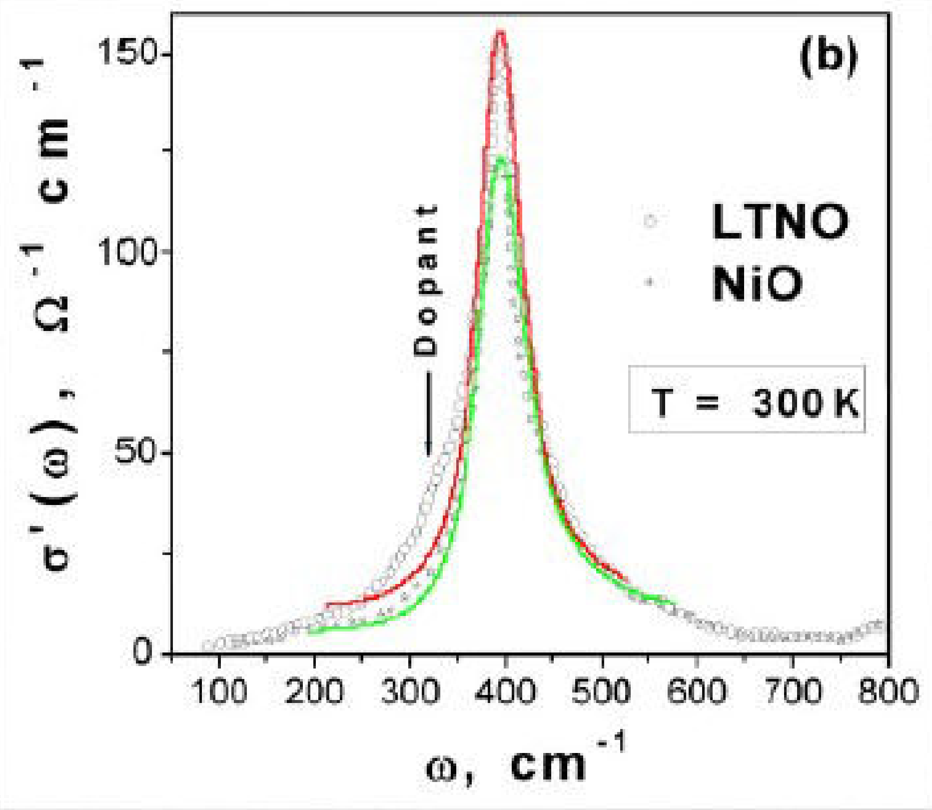
gauge invariant variables $U_i \equiv f(u)\left[h_{ui} - \frac{\partial_u \phi_i}{\alpha u^2}\right],\ B_i \equiv b_i - \frac{\phi_i}{\alpha}$

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

Polarons in the real world

ii)





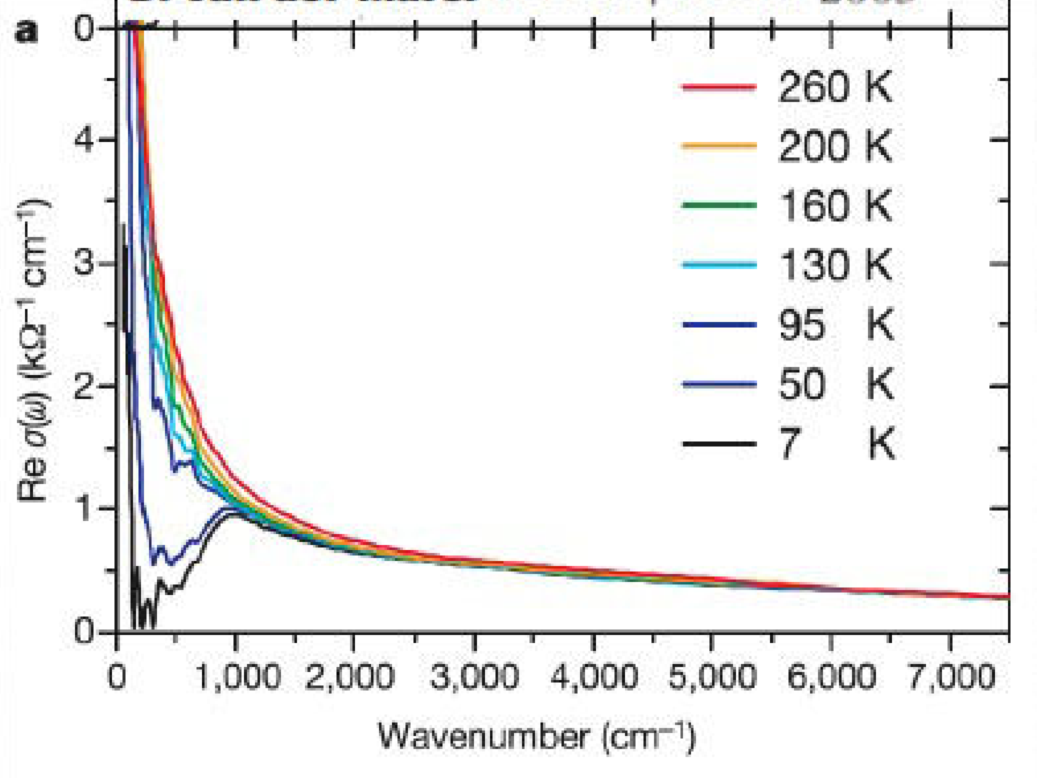
Phys. Status Solidi B **251**, No. 3, 569–592 (2014)

Valeri Ligatchev

Polarons in the real world

ii)

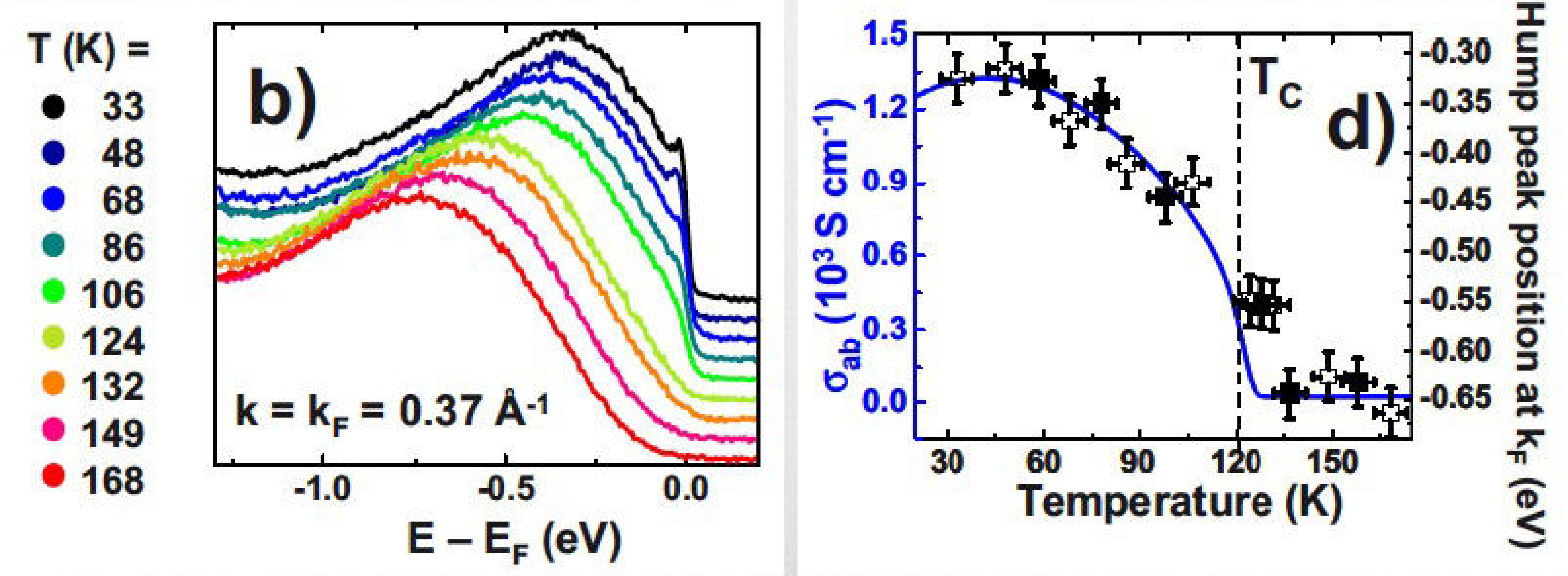
D. van der Marel NATURE | VOL 425 2003



Polarons in the real world

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

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



Mott-Wigner localization

iii) $e^- - e^-$ interactions

Natural expectation:
nonlinear electrodynamics

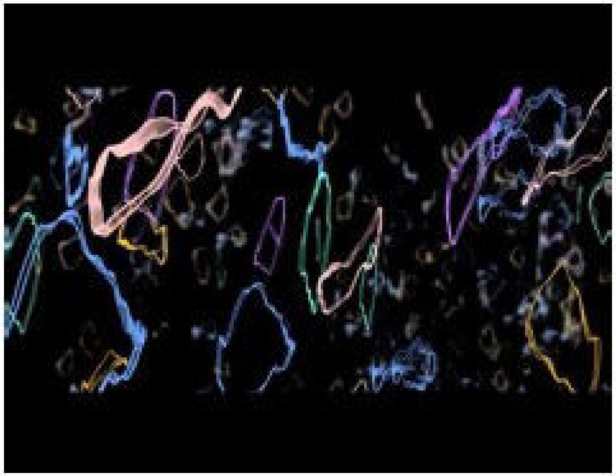
$$S = \int \sqrt{-g} \left\{ R - 2\Lambda - K\left(F_{\mu\nu}^2\right) + m^2 V(X) \right\}$$

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

- smoother transition
- also forms quasiparticles

→ Heavy Fermions ??

The dilatonic (known) case



String theory inspired (embedding known)

Adding a new (running) scalar degree of freedom

$$\mathcal{S} = \int d^4x\sqrt{-g}\left(R - \frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{Z(\phi)}{4e^2}F^2 + \mathcal{D}_m(\phi, \psi^I, \dots)\right)$$

new dof

Dissipative sector

$$\sigma_{DC} = \frac{1}{e^2}\left(Z(\phi)_{horizon} + \dots\right)$$

→ Rich phenomenology

Habemus Insulators

An additional gain

STRANGE METALS : $\sigma \propto \dfrac{1}{T}$ $\quad \Theta_H \propto \dfrac{1}{T^2}$

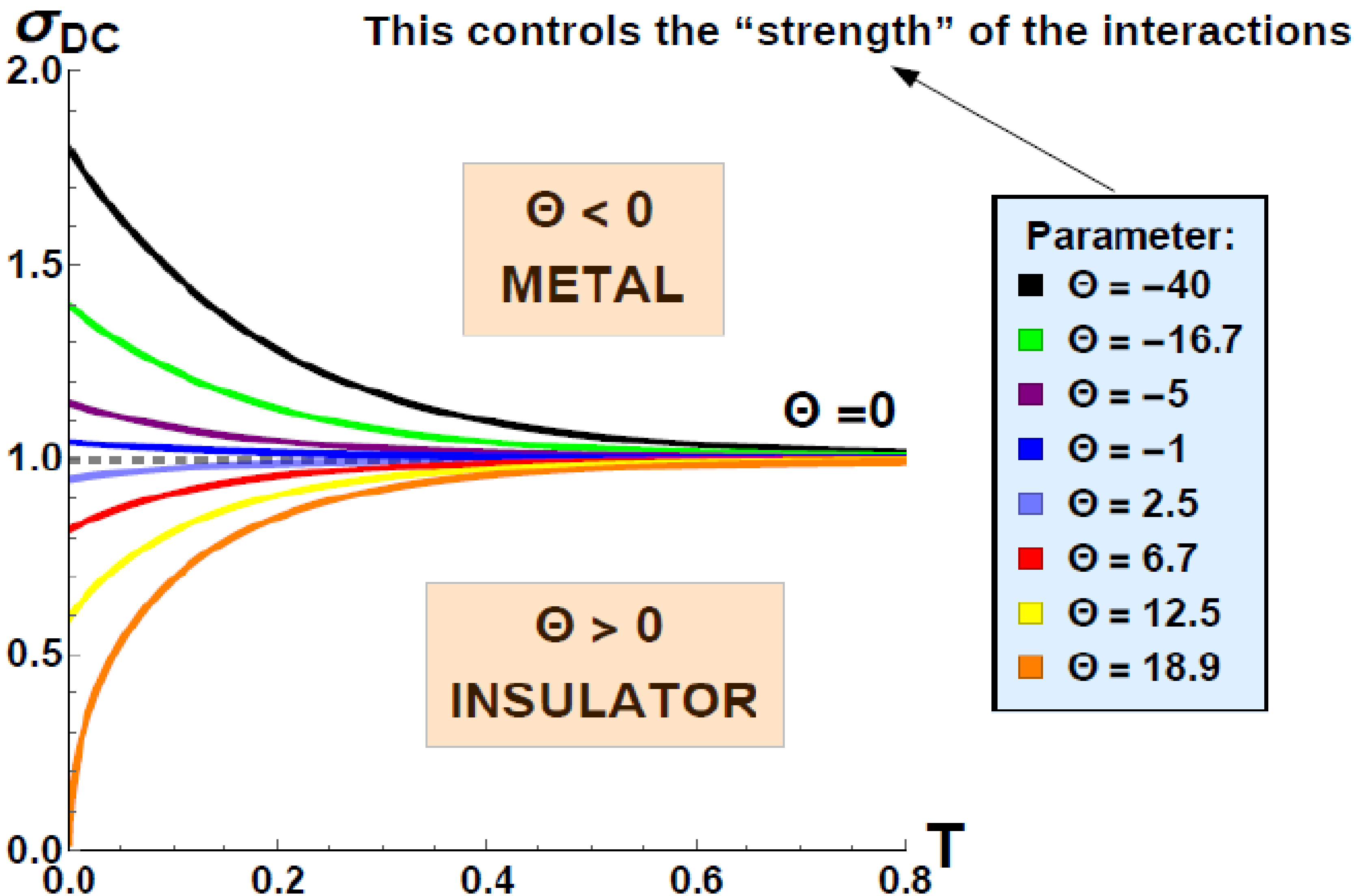
Famous and robust LINEAR T RESISTIVITY

From holography: $\sigma \propto \sigma_{ccs} + \sigma_{diss}$ $\quad \Theta_H \propto \dfrac{B}{Q}\sigma_{diss}$

If $\sigma_{ccs} = \dfrac{1}{e^2}$ like with standard maxwell term →

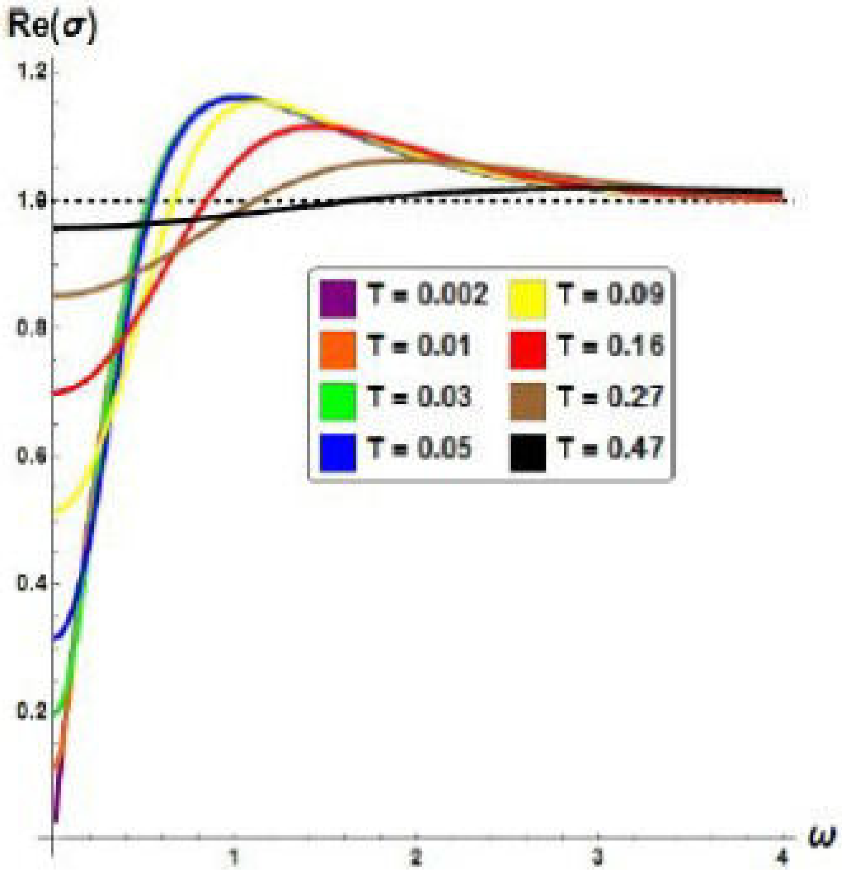
Otherwise we can achieve having two different scales
And reproducing the right phenomenology (scalings) →

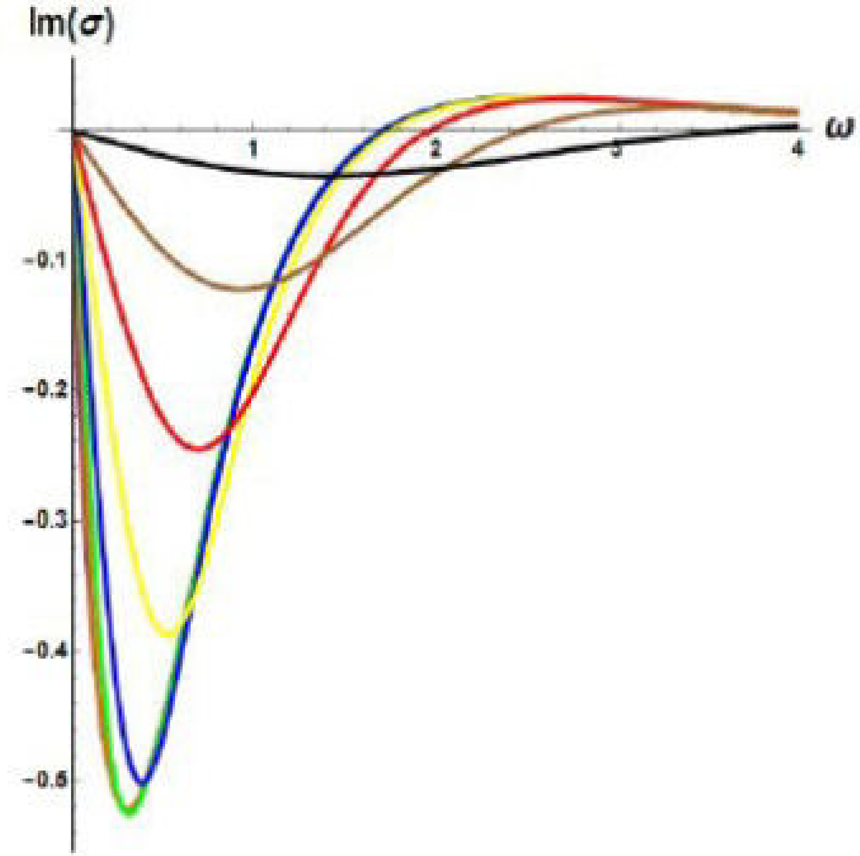
Non Linear Electrodynamics Results



METAL- INSULATOR TRANSITION à LA MOTT

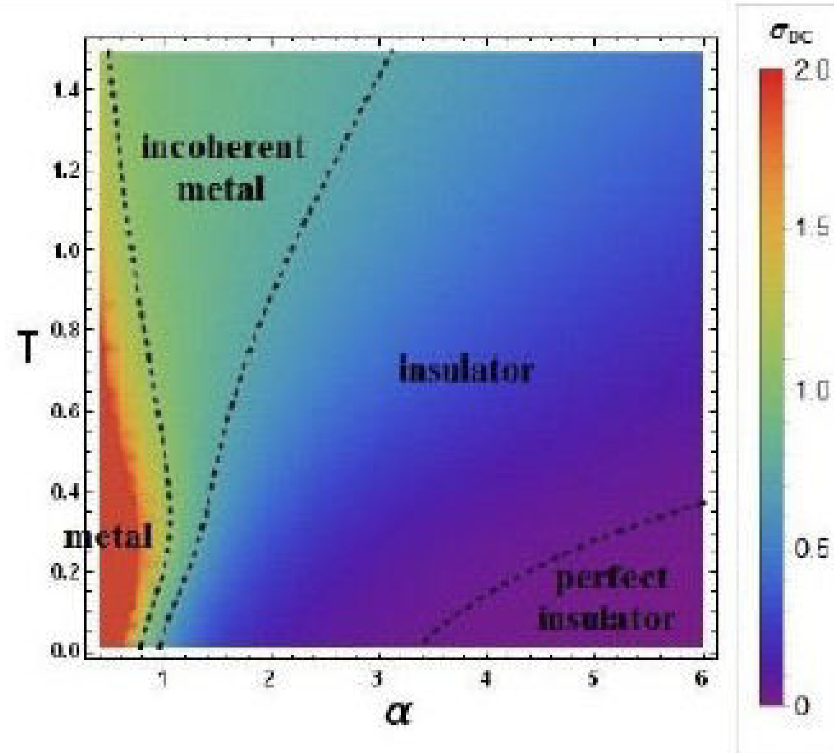
Non Linear Electrodynamics Results



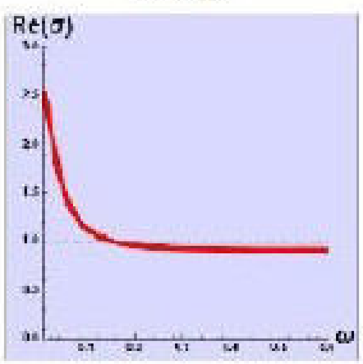


Optical conductivity in the insulating phase

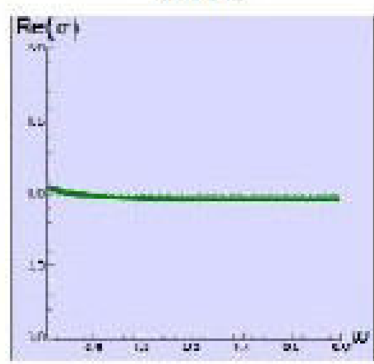
Disorder Driven Scenario Results



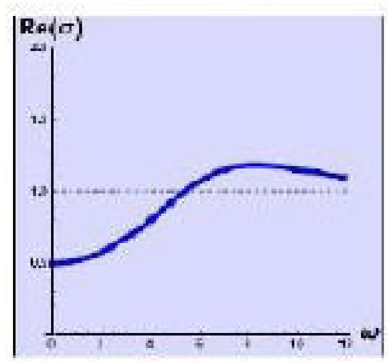
metal



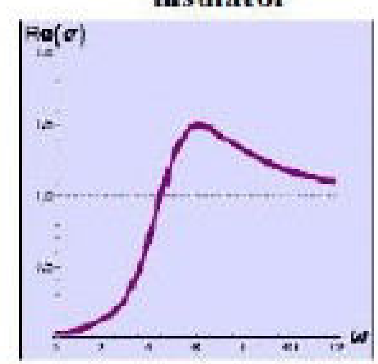
incoherent metal



insulator



perfect insulator



Old results...

New results...