Holographic Metal-Insulator Transitions

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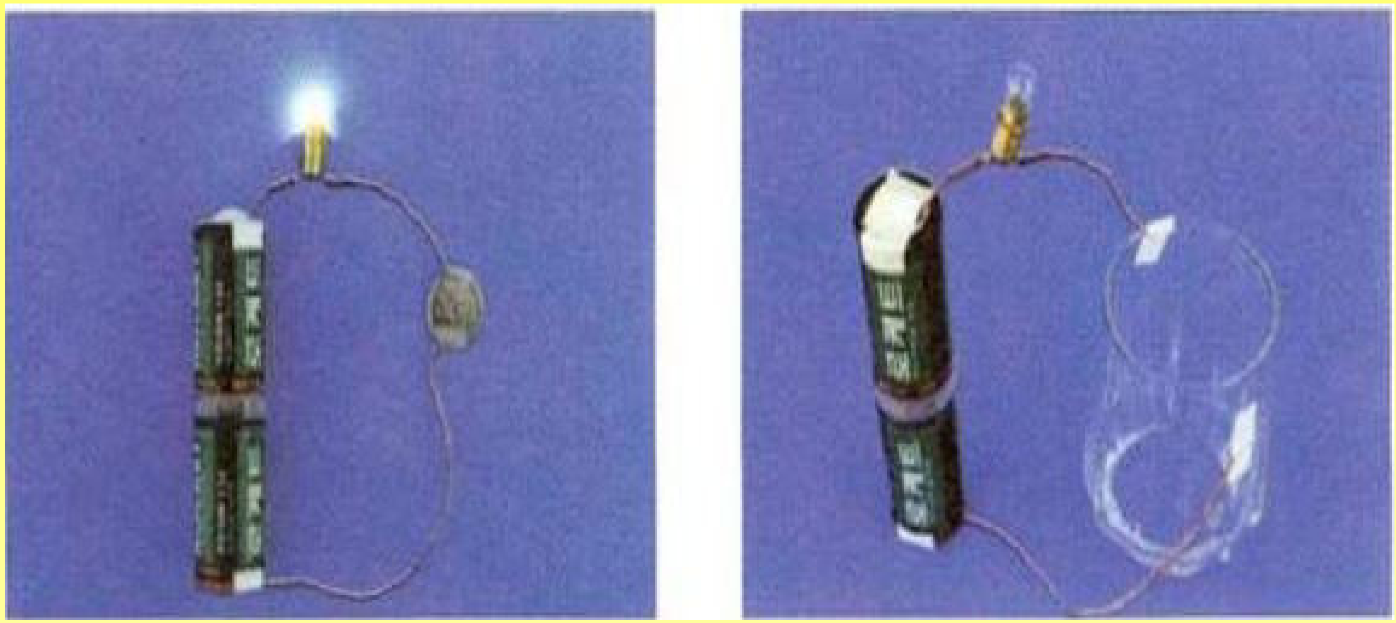
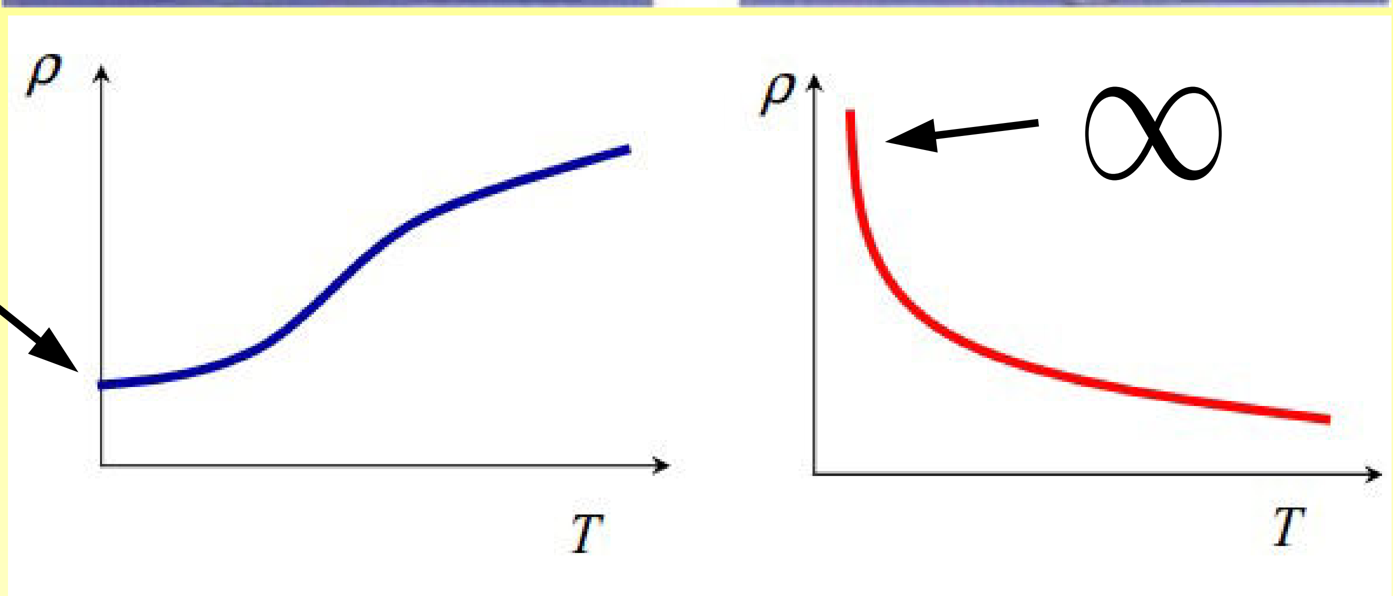
Metal vs Insulator : Experiments



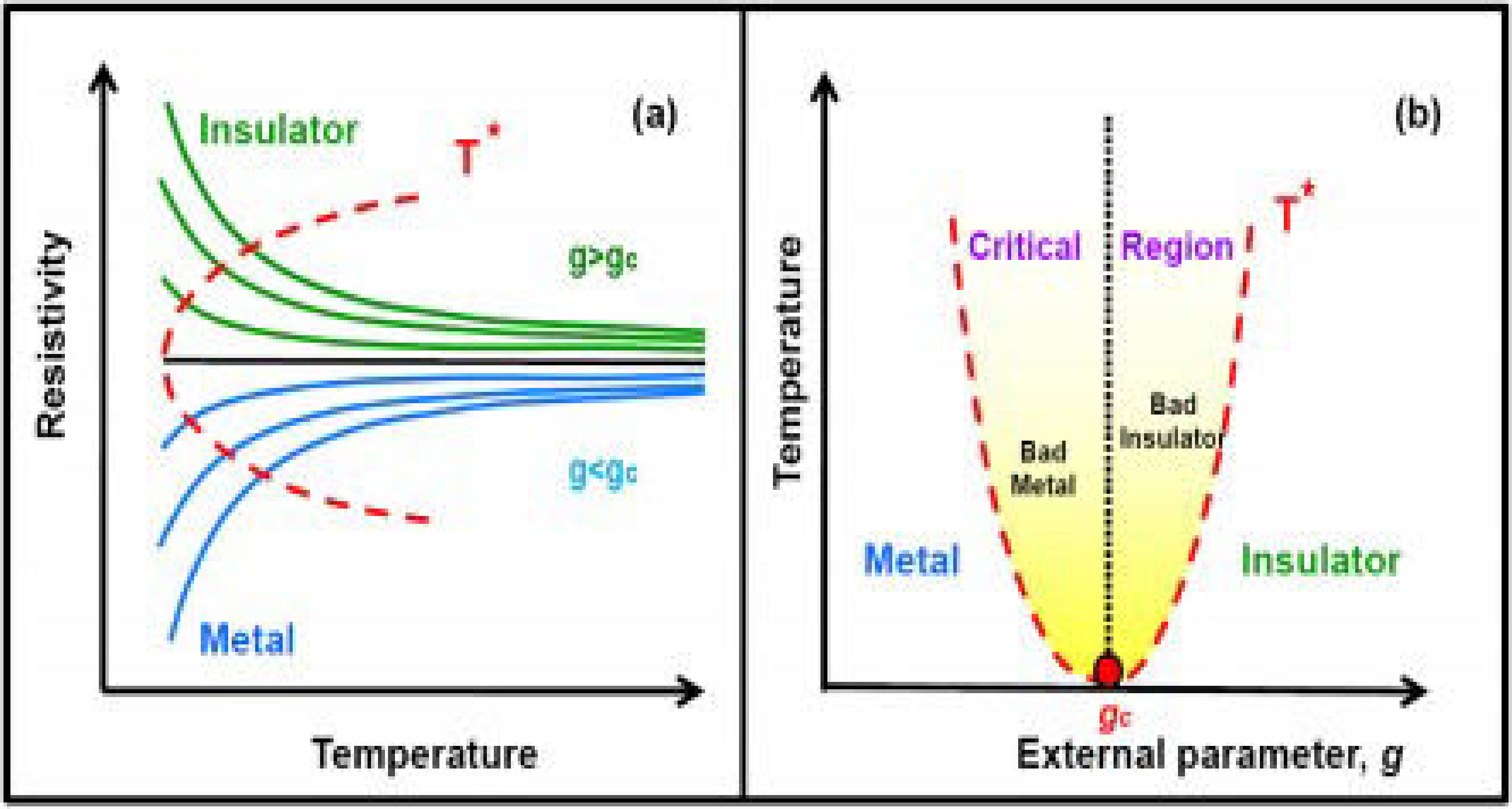


FINITE

Increasing with T

Decreasing with T

WANTED Metal-Insulator transition



QUANTUM PHASE TRANSITION (T=0)

Why a so difficult problem?

- **The two limits, that of a good metal and that of a good insulator,**

  are very different physical systems, which can be characterized by

  very different elementary excitations.

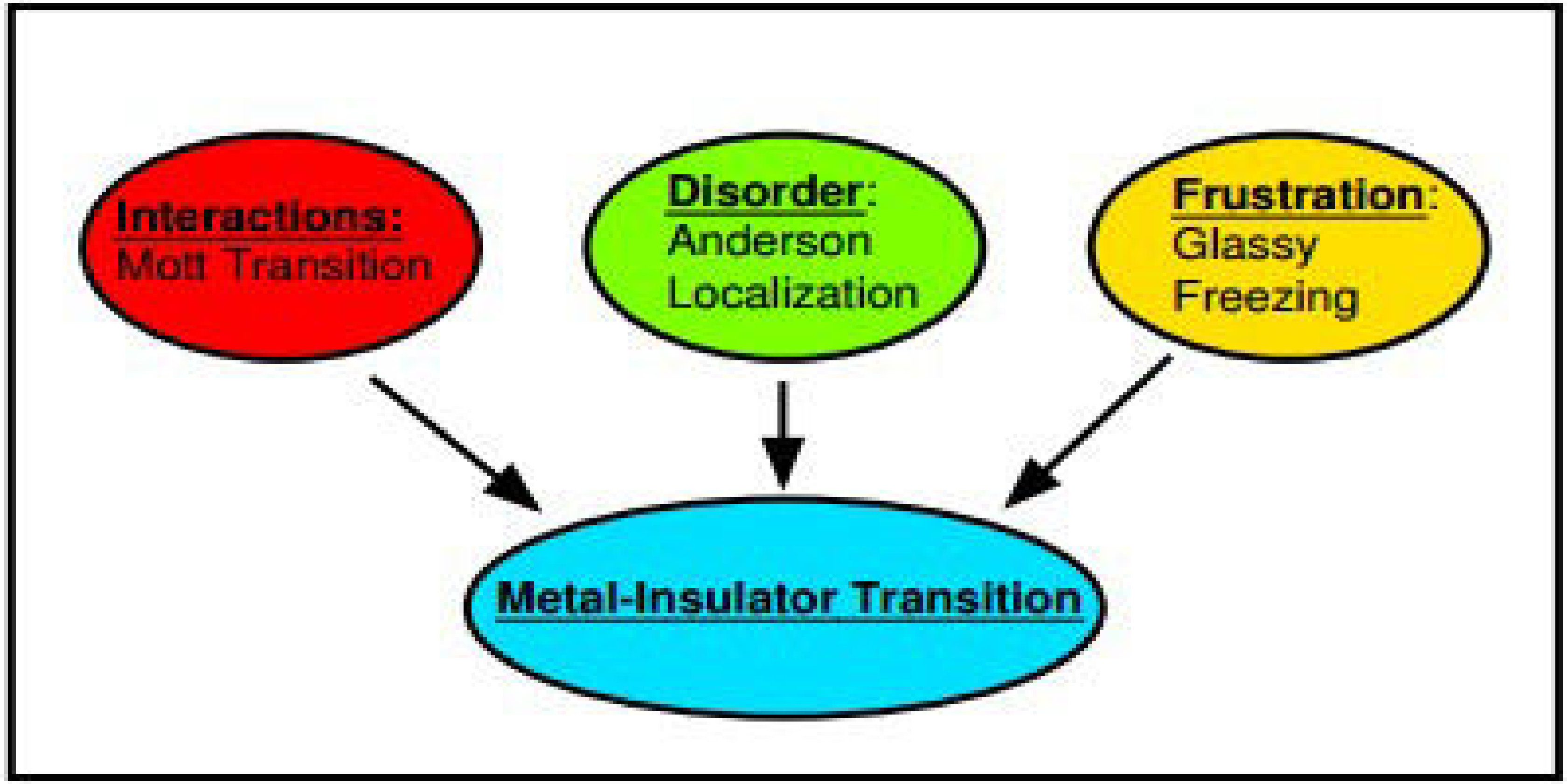
- **No simmetry breaking**

  An obvious order parameter theory is not available.

- **Strongly correlated-coupled situations**

  No perturbative control

Wide landscape...



1. Interactions : electron-electron

2. Disorder

“Standard” Fails

STRONG CORRELATION → **LOSS OF INDIVIDUALITY**

Description in terms of single almost free “electrons” breaks down

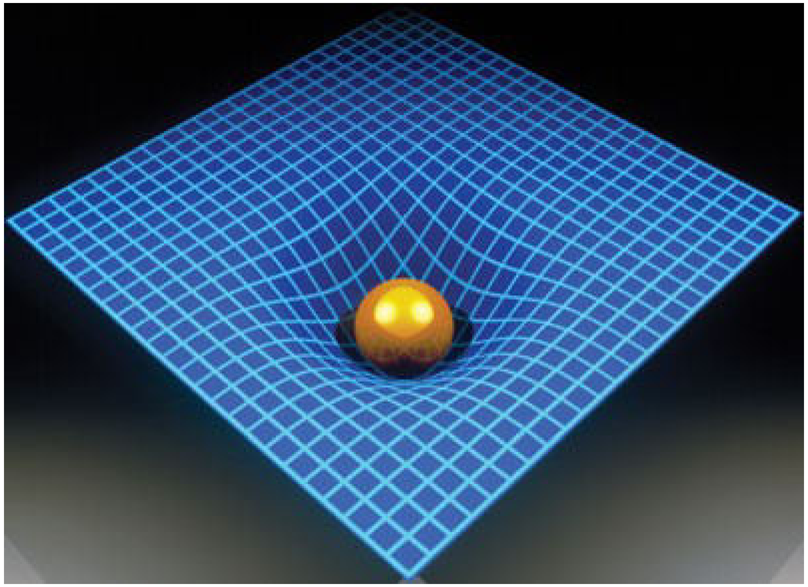
Quantum strongly correlated soup

New mechanisms...

We need new description

which goes beyond single particle logic !!

Our methods



Classical Gravity

General Relativity

Black Hole Physics

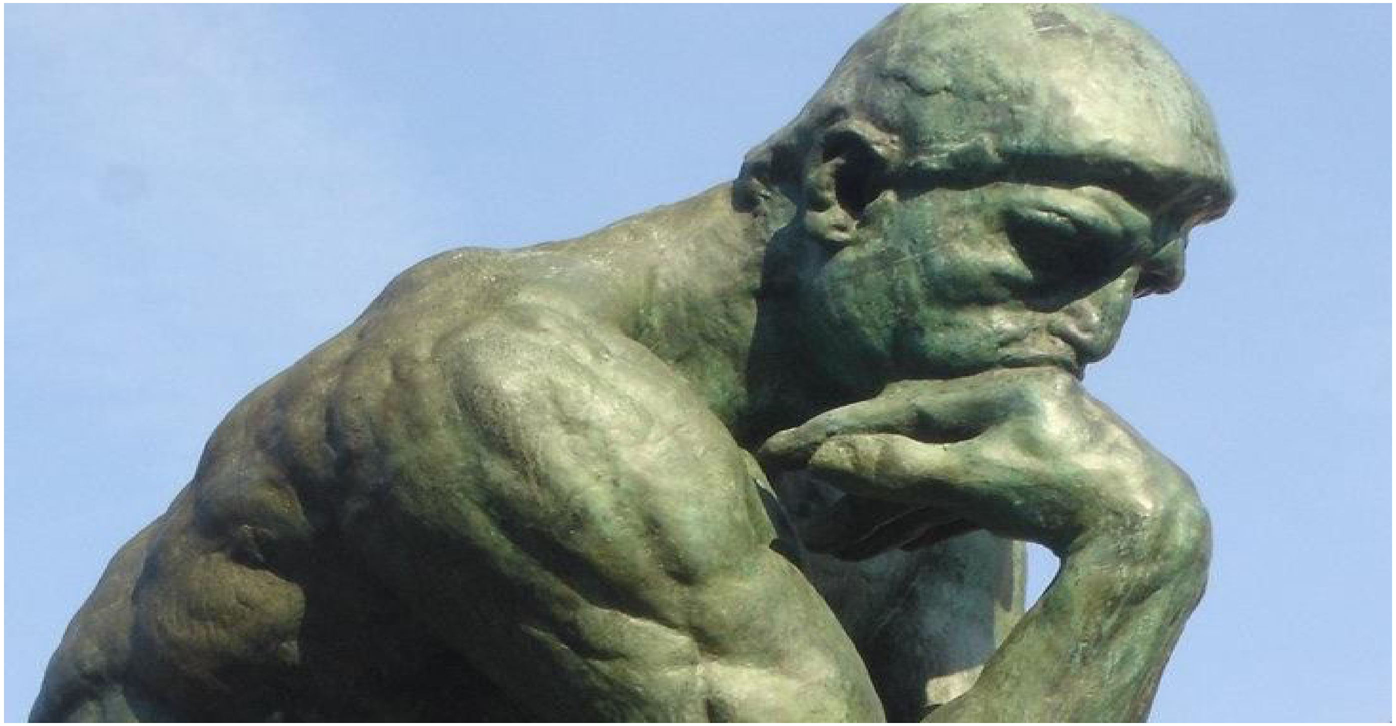
GAUGE GRAVITY DUALITY

Our question(s):

1) How to produce an insulator within this framework ?

2) How to produce a Metal-Insulator transition ?

3) Can we have different types as in Nature ?

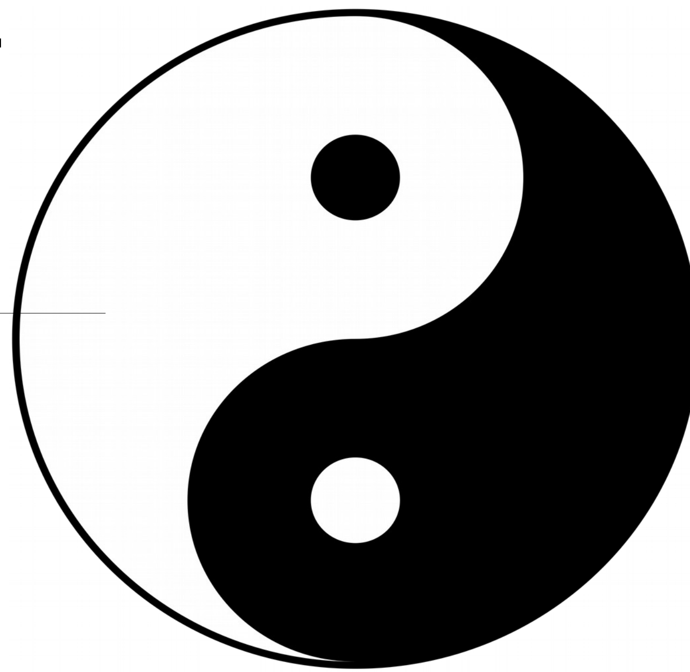


What is the plan...

1) **How to speak about Condensed Matter through Black Holes …**

Metals and Insulators in Holography...

2) **Getting serious...**



Holographic Mott Transitions

Driven by interactions Electron-Electron

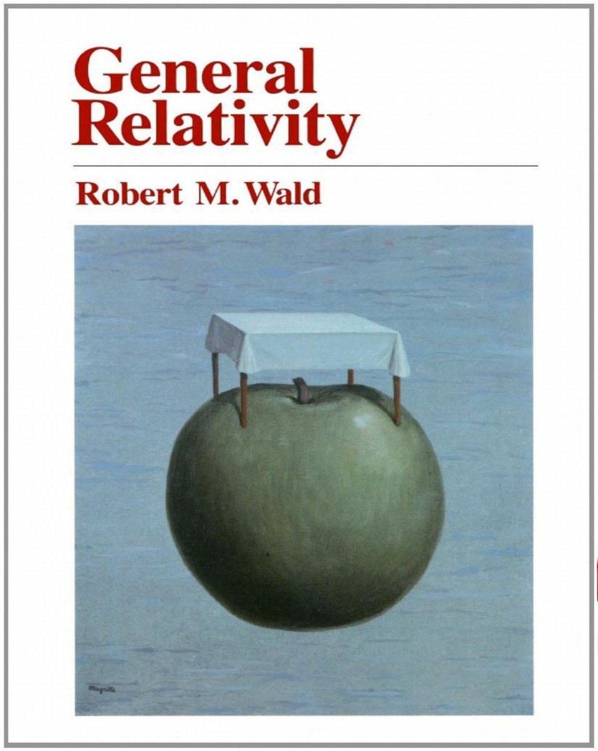
Non Linear Electrodynamics

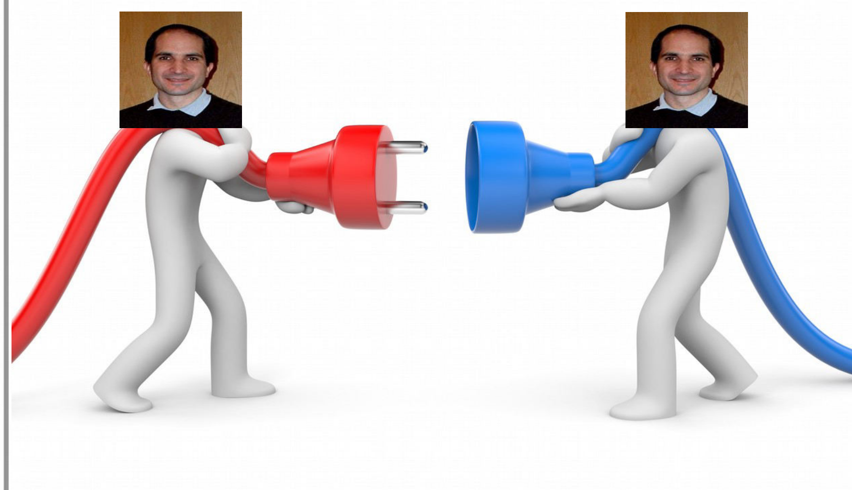
Holographic Anderson Transitions

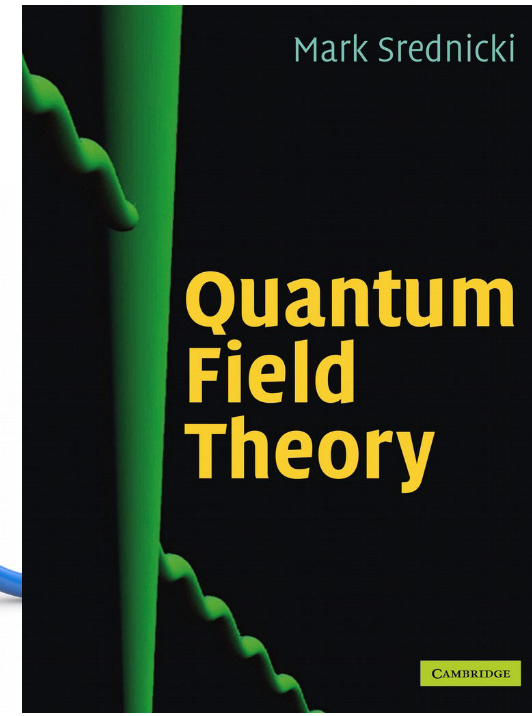
Driven by disorder

Massive Gravity

Just few words...







WE CAN SPEAK ABOUT

STRONGLY COUPLED QUANTUM FIELD THEORIES

USING WEAKLY COUPLED CLASSICAL GRAVITY

How to get it from a black hole...

1. Take a black hole and put charge into

2. Shake it

3. Analyze its response

4. Use Kubo Formulas

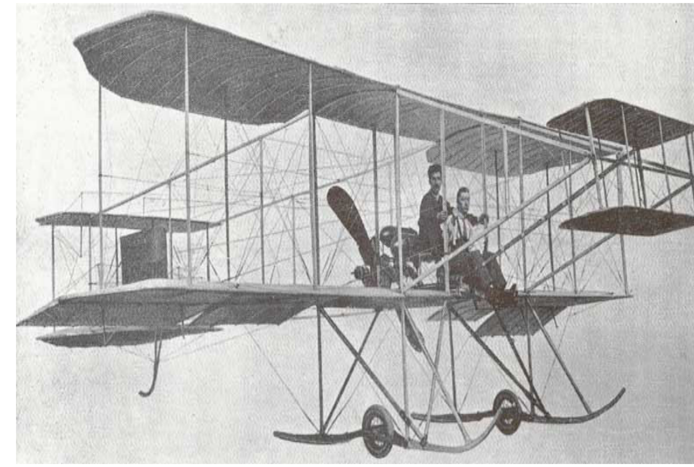
5. Read conductivity

Ingredients:

Gravity (+ negative cosmological constant)

U(1) vector field = ELECTRIC CHARGE

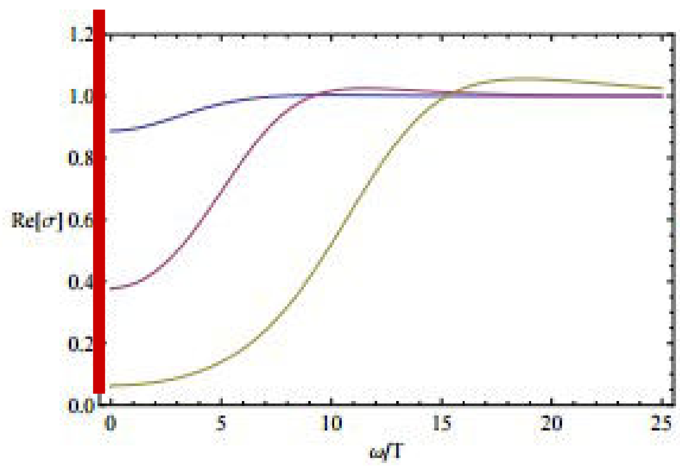
1st Attempt

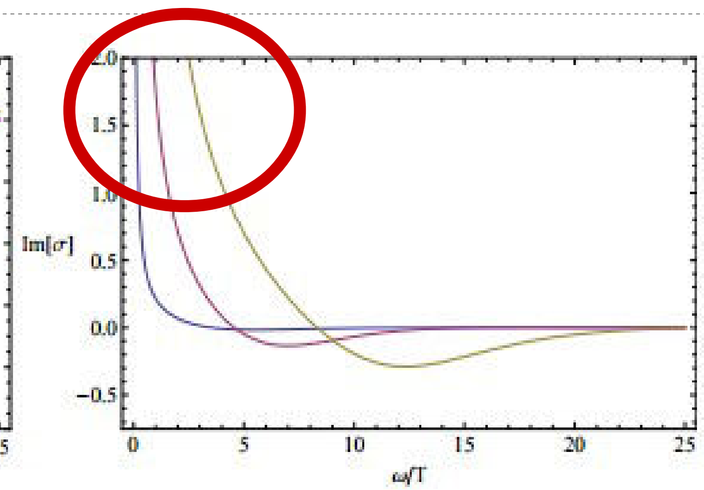


Reissner Nordstrom Black Hole

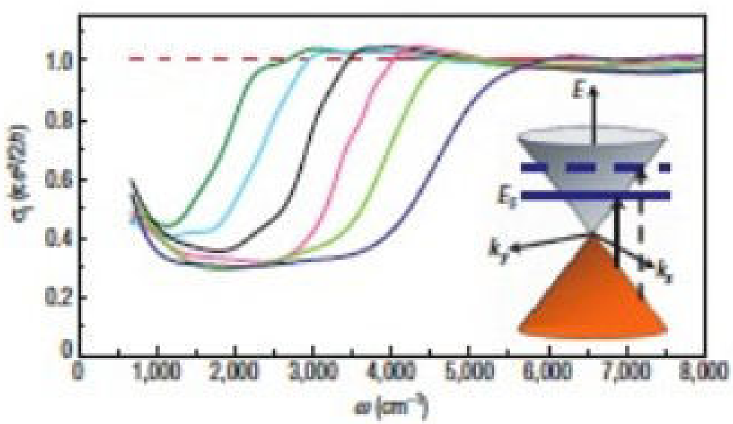
$$S = \int d^{d+1}x\sqrt{-g}\left[\frac{1}{2\kappa^2}\left(R+\frac{d(d-1)}{L^2}\right)-\frac{1}{4g^2}F^2\right].$$

Holography:





Graphene:



There is an infinite DC Conductivity!

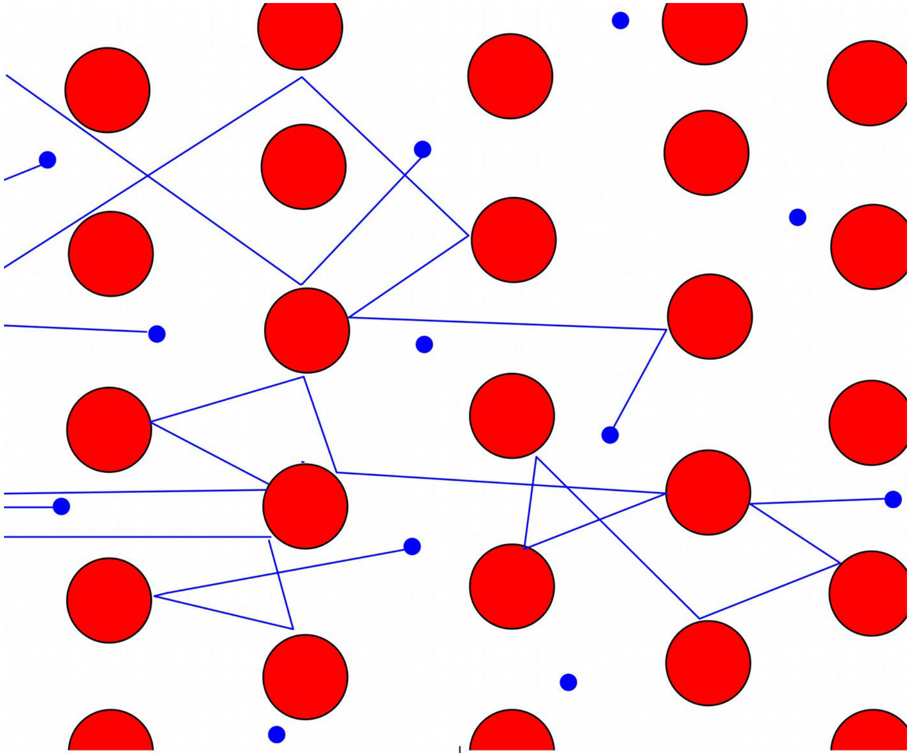
What's wrong?

No Momentum Dissipation

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

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

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

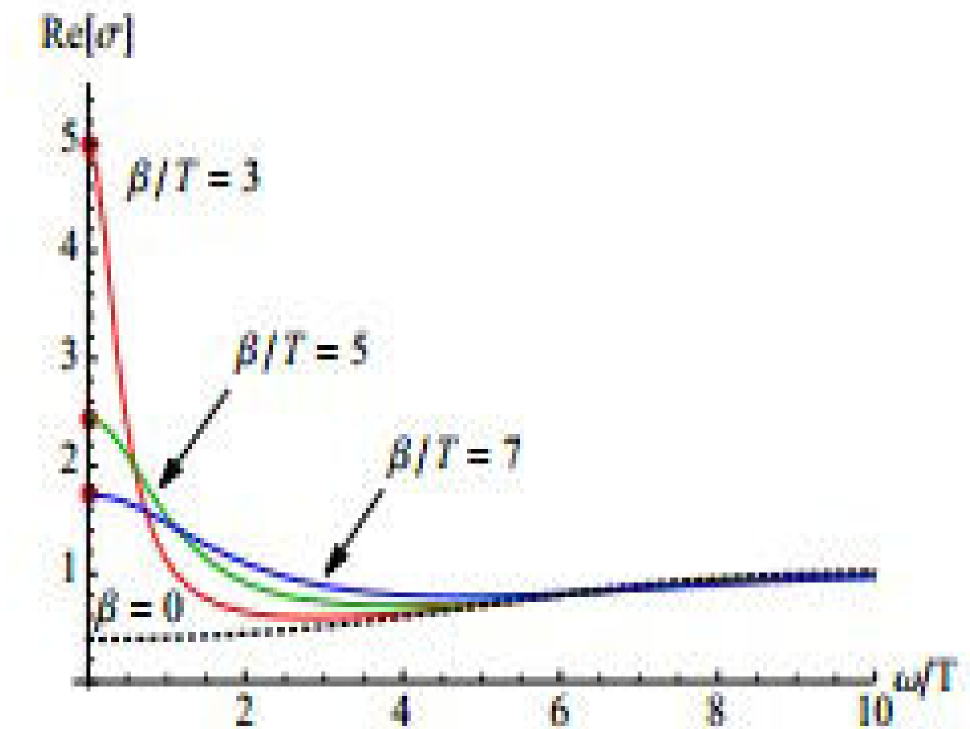
2^{nd} Attempt

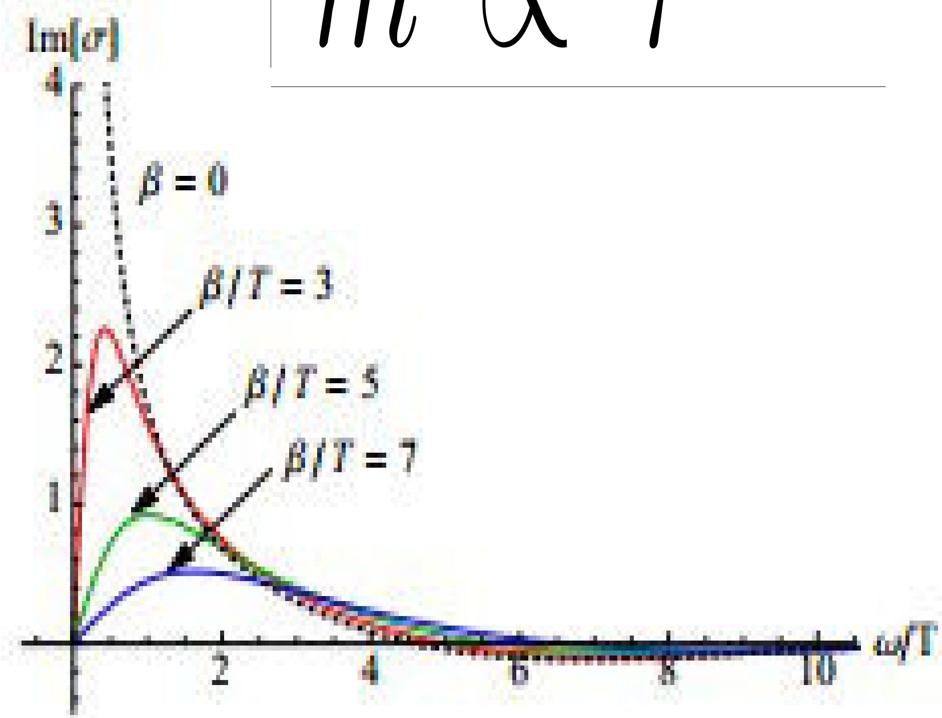
$$S_{bulk} = \int d^4x\sqrt{-g}\left(\mathcal{R} - 2\Lambda - \frac{F^2}{4e^2} + \underline{\mathcal{D}(\phi^I,\dots)}\right)$$

Translational Sym. Breaking : Dissipative Sector → Momentum Gets dissipated

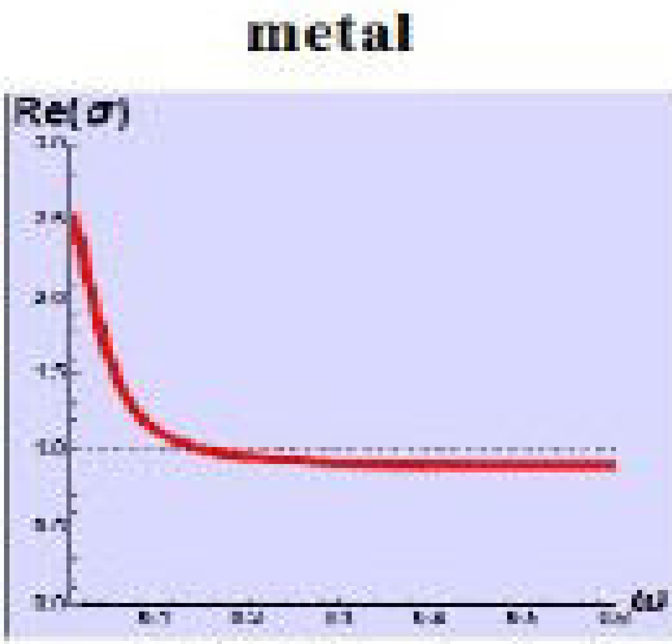
Easiest way: **MASSIVE GRAVITY**

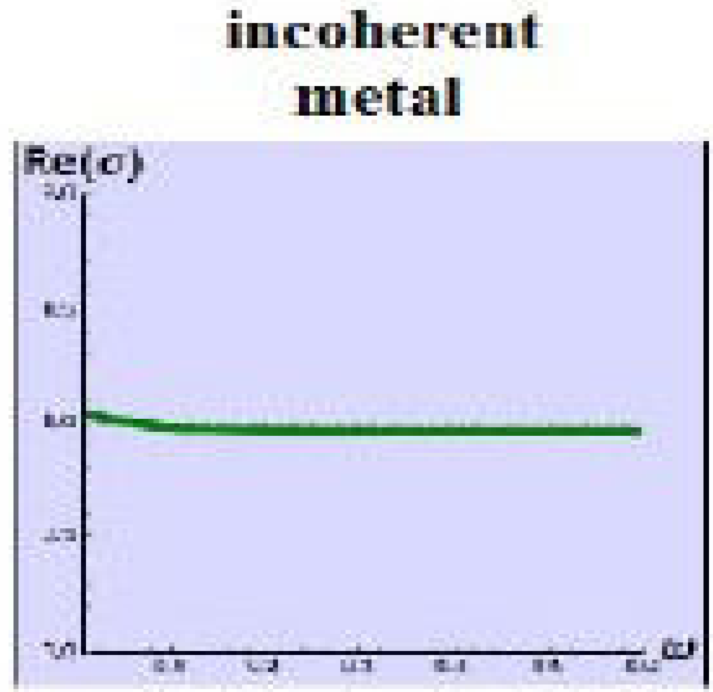
$$m \propto \tau^{-1}$$





What do we get ?





Nice, but what about an Insulator ?

Why we dont get it ?

Incomplete phenomenology !

Why not?

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

This statement Can be formalized rigorously

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

Dissipative Contribution (à la Drude)

Ex. Massive Gravity $\sigma_{DC} = \frac{1}{e^2}\left(1 + \frac{\mu^2}{m^2}\right)$

This means there is a bound which prevents to get insulators

How to overcome it?

Way(s) of proceeding...

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

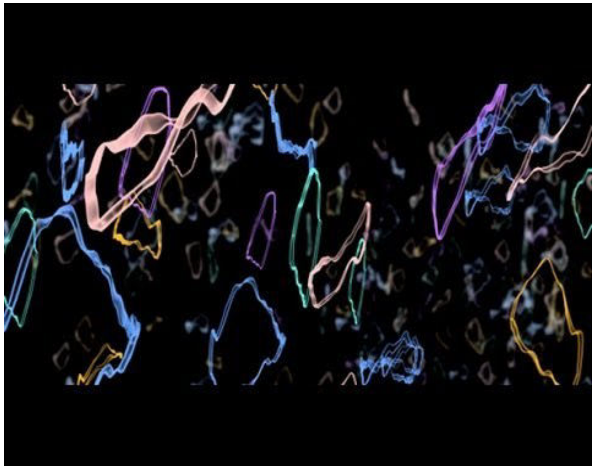
We need to modify the Maxwell term in the action

And we can do it in several ways

$$\sigma_{DC} = \frac{1}{e^2}\,(1 + \ldots)$$

$$\sigma_{DC} = \frac{1}{e^2}\,(◀▶ + \ldots)$$

The dilatonic (known) case



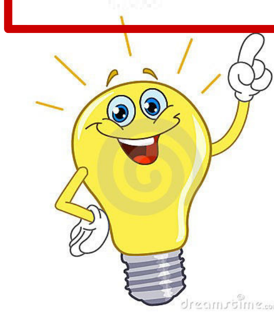
String theory inspired (embedding known)

Adding a new (running) scalar degree of freedom

$$S = \int d^4x \sqrt{-g}\left(R - \underbrace{\frac{1}{2}(\partial\phi)^2 - V(\phi)}_{\text{new dof}} \boxed{- \frac{Z(\phi)}{4e^2}F^2} + \underbrace{\mathcal{L}_m(\phi,\psi^I,\ldots)}_{\text{Dissipative sector}} \right)$$

new dof

Dissipative sector



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

→ **Rich phenomenology**

<u>**Habemus Insulators**</u>

An additional gain

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

Famous and robust LINEAR T RESISTIVITY

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

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

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

2 other (new) options

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

1) Non Linear Electrodynamics

$$-\frac{1}{4e^2}F^2 \to -\frac{1}{4e^2}\mathcal{K}\left(F^2\right)$$

2) Coupling the dissipative sector with the gauge field

$$-\frac{1}{4e^2}F^2 \to -\frac{1}{4e^2}Y\left(\phi^I,\ldots\right)F^2$$

What do they mean?

1) Non Linear Electrodynamics

Self Interactions between " charge carriers "

→ **"Electron – Electron" interactions**

Mott Physics

2) Coupling dissipative sector with gauge field

Interactions between "disorder-impurities" and the "charge carriers"

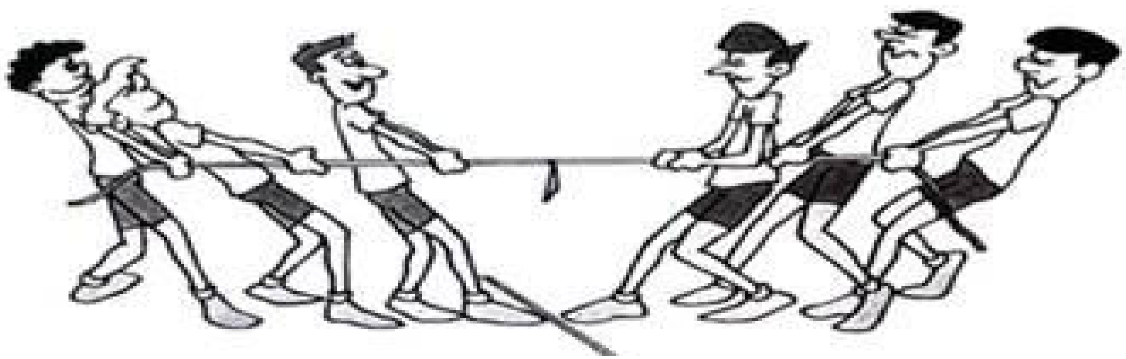
→ **Disordered physics**

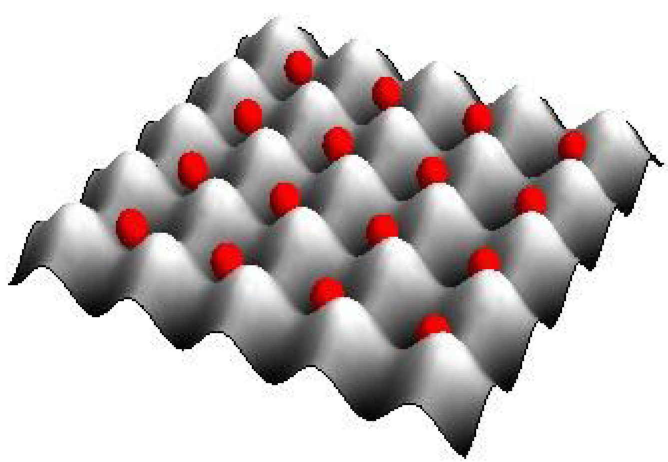
Mott Insulators Primer

Materials which should be metallic (following band theory)

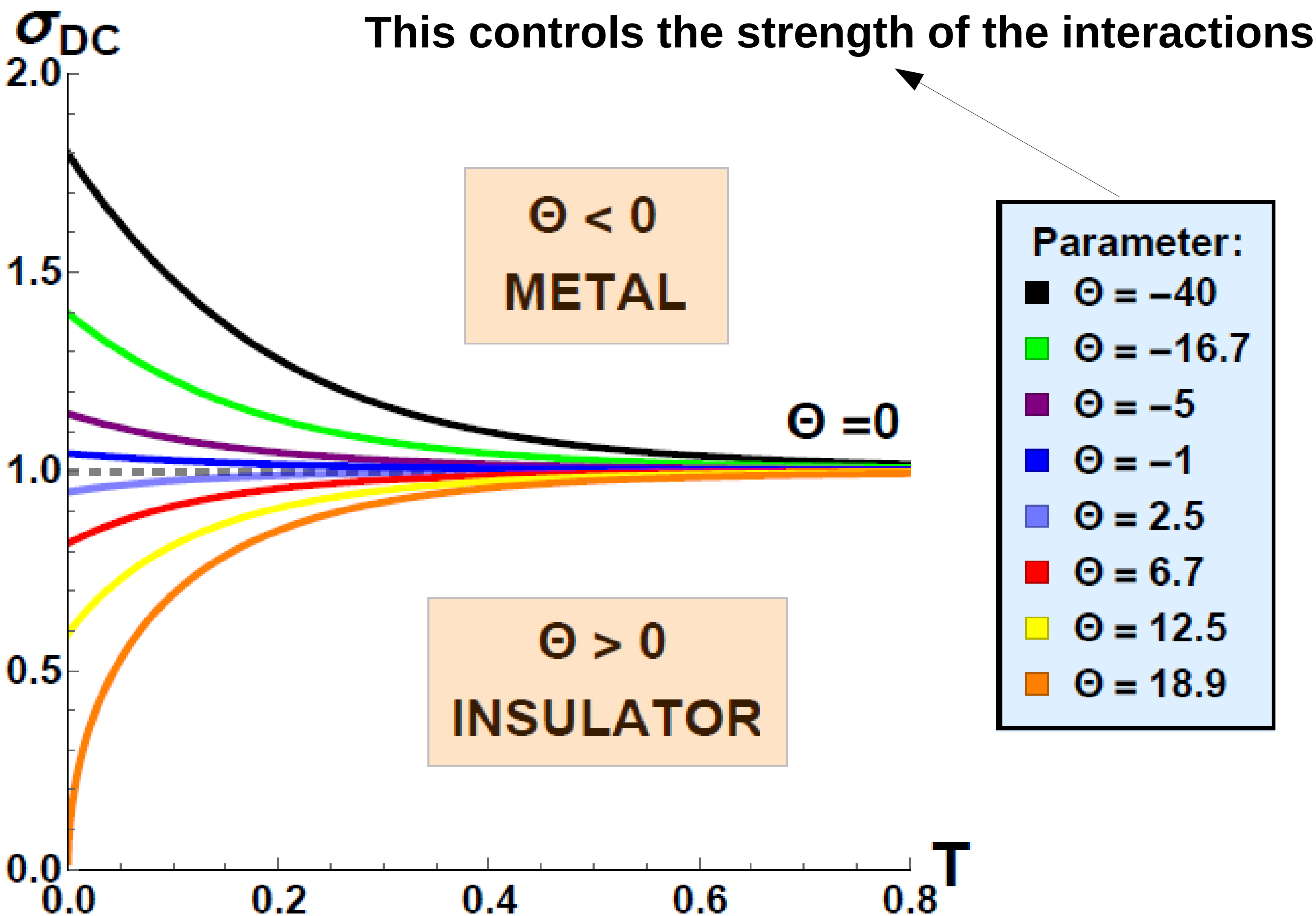
But once measured they are insulators

WHY? Strong electron - electron self interactions
Localization



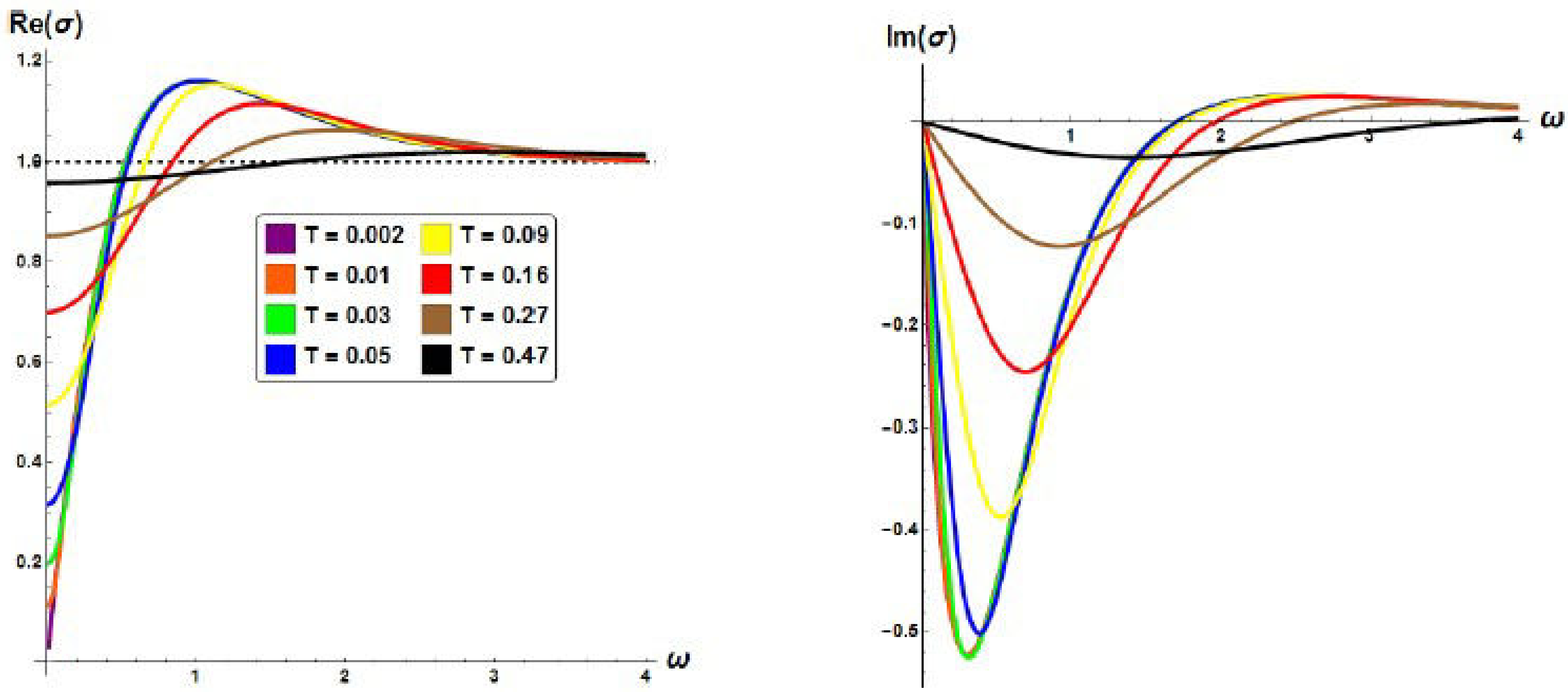


Non Linear Electrodynamics Results



METAL- INSULATOR TRANSITION à LA MOTT

Non Linear Electrodynamics Results



Optical conductivity in the insulating phase

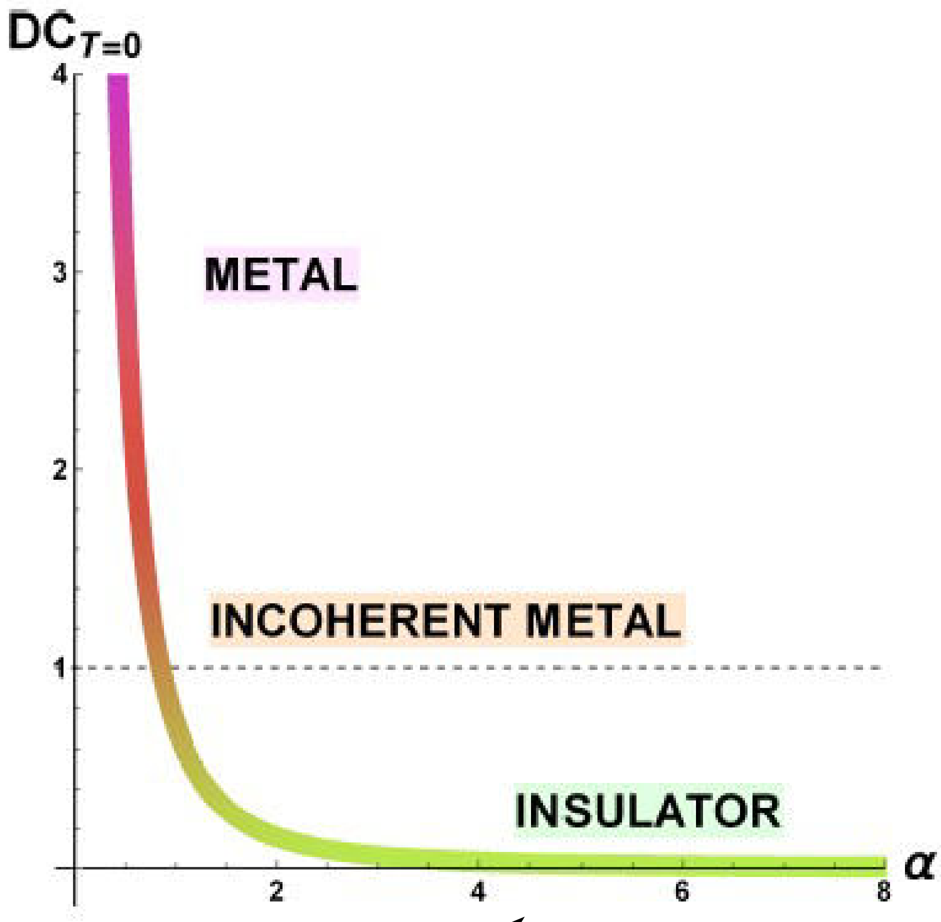
Disorder & Insulators Primer

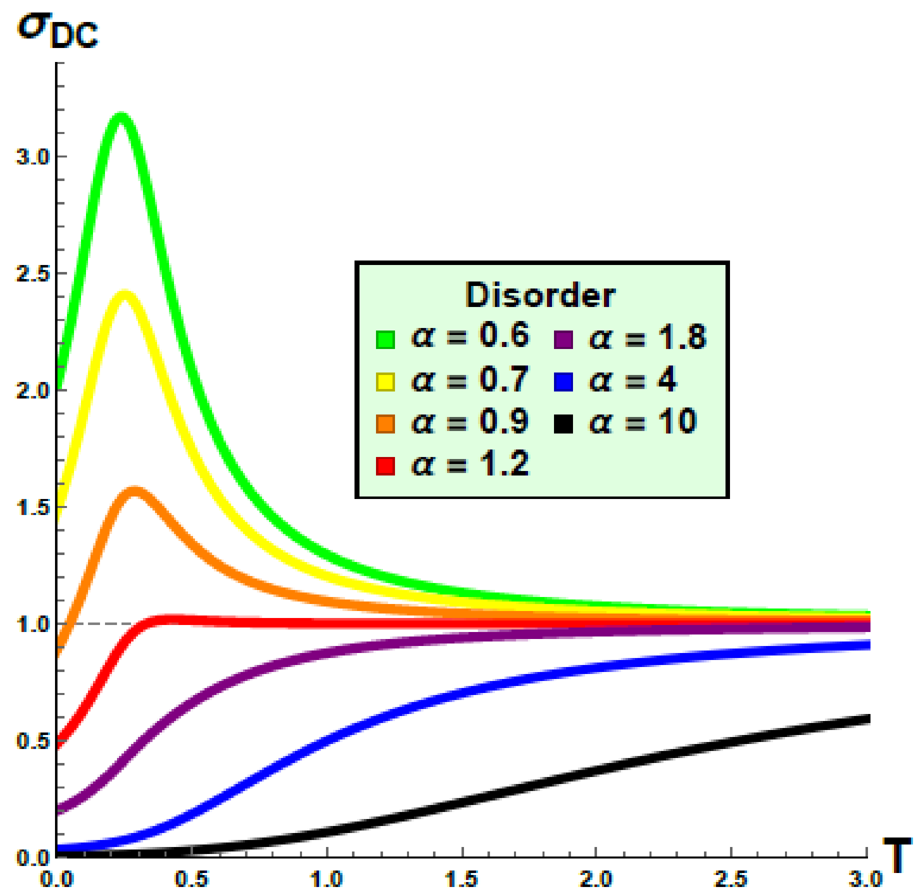
Interactions between charge carriers (electrons)

And disorder produce insulating behaviours

Note: for the reason of before a disorder driven insulator has not been found yet in holography !

Disorder Driven Scenario Results

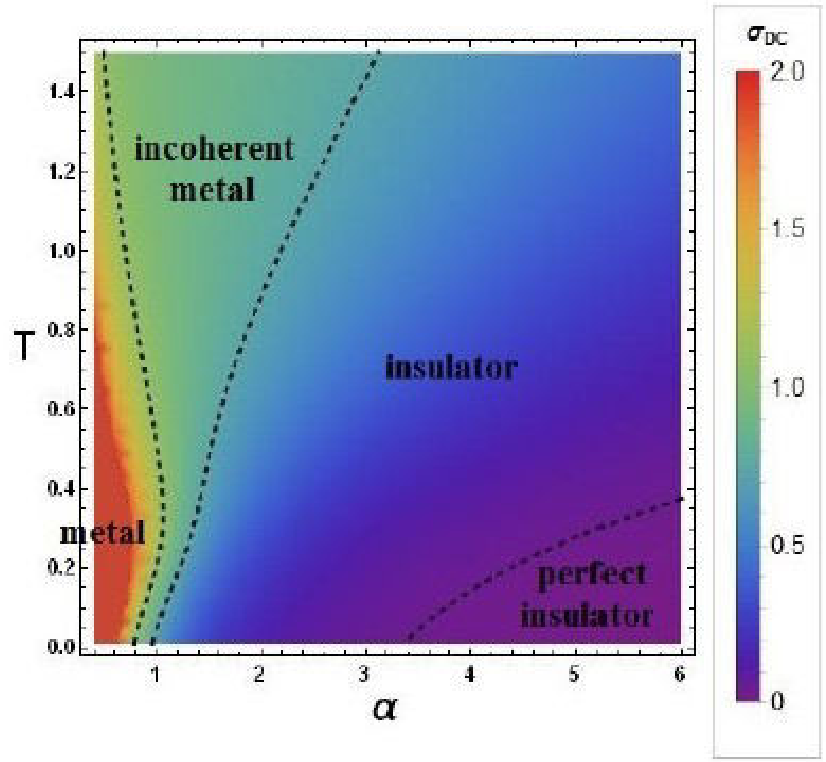


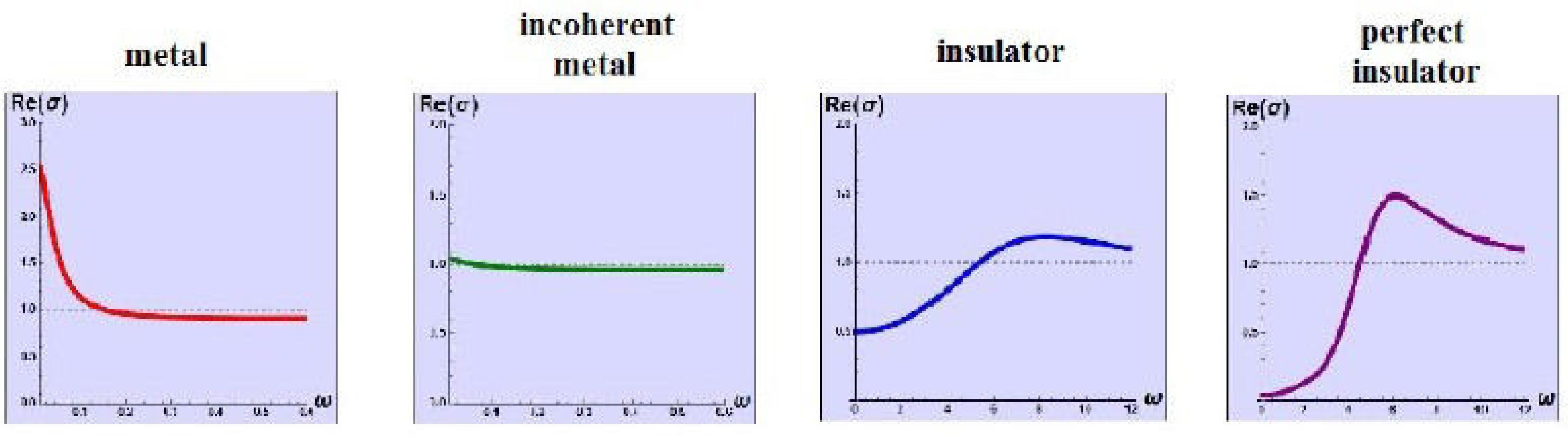


Disorder Driven Insulator

Disorder Driven
Metal-Insulator Transition

Disorder Driven Scenario Results





Old results...

New results...

Take home 1st message

To capture a more complete condensed matter phenomenology we have to go beyond:

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

There are several ways

Doing so we can get insulators and metal-insulator transitions

Conclusions

Non Linear Electrodynamics → **Mott Insulators**
Mott Transitions

Coupling dissipative sector (massive gravity)
To Maxwell

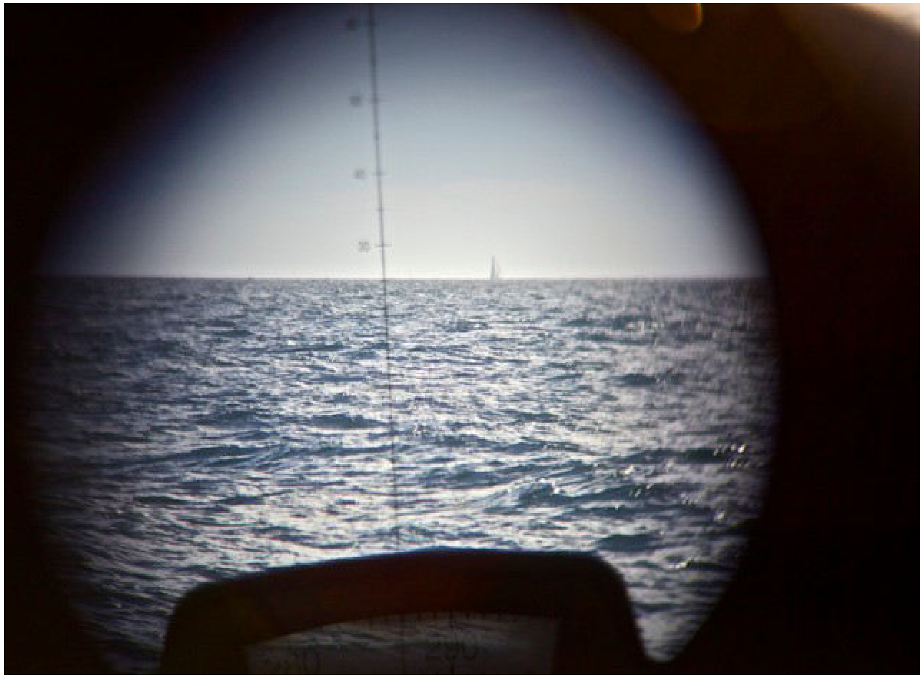
↓

Disordered Insulators and disorder driven MIT

Close future

- Holographic insulator(s)
- Effective field theory for condensed matter
- Hard Gapped Insulators
- Scalings
- Magnetic field
- Disorder instabilities

Far Future...



Phenomenology and comparison with real experiments

ORA LO SAI ANCHE TU!