Impurity Driven Metal-Insulator Transitions in Holography

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Based on the arXiv:2302.07539 with Kyung Kiu Kim,
Sang-Jin Sin, Keun-Young Kim and Yongjun Ahn

Introduction

Introduction

■ Metal

- Freely moving electrons
- Described by Drude model: conventional metal
- Bad metal : $\rho \sim T$
- Resistivity increases as temperature increased

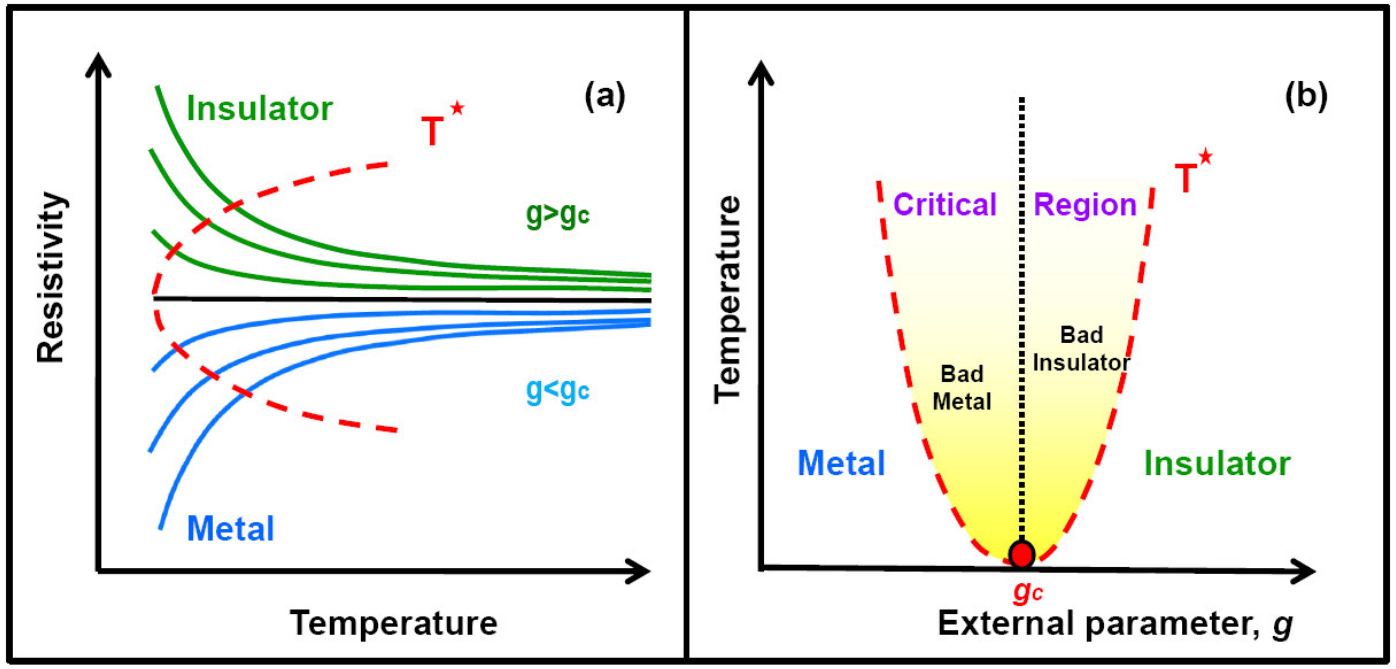
Introduction

- Insulator
  - No freely moving electrons
  - Strong electron-electron interaction: Mott
  - Strong electron-disorder interaction: Anderson
  - Resistivity decreases as temperature increased

Introduction

■ Metal-Insulator Transition(MIT)

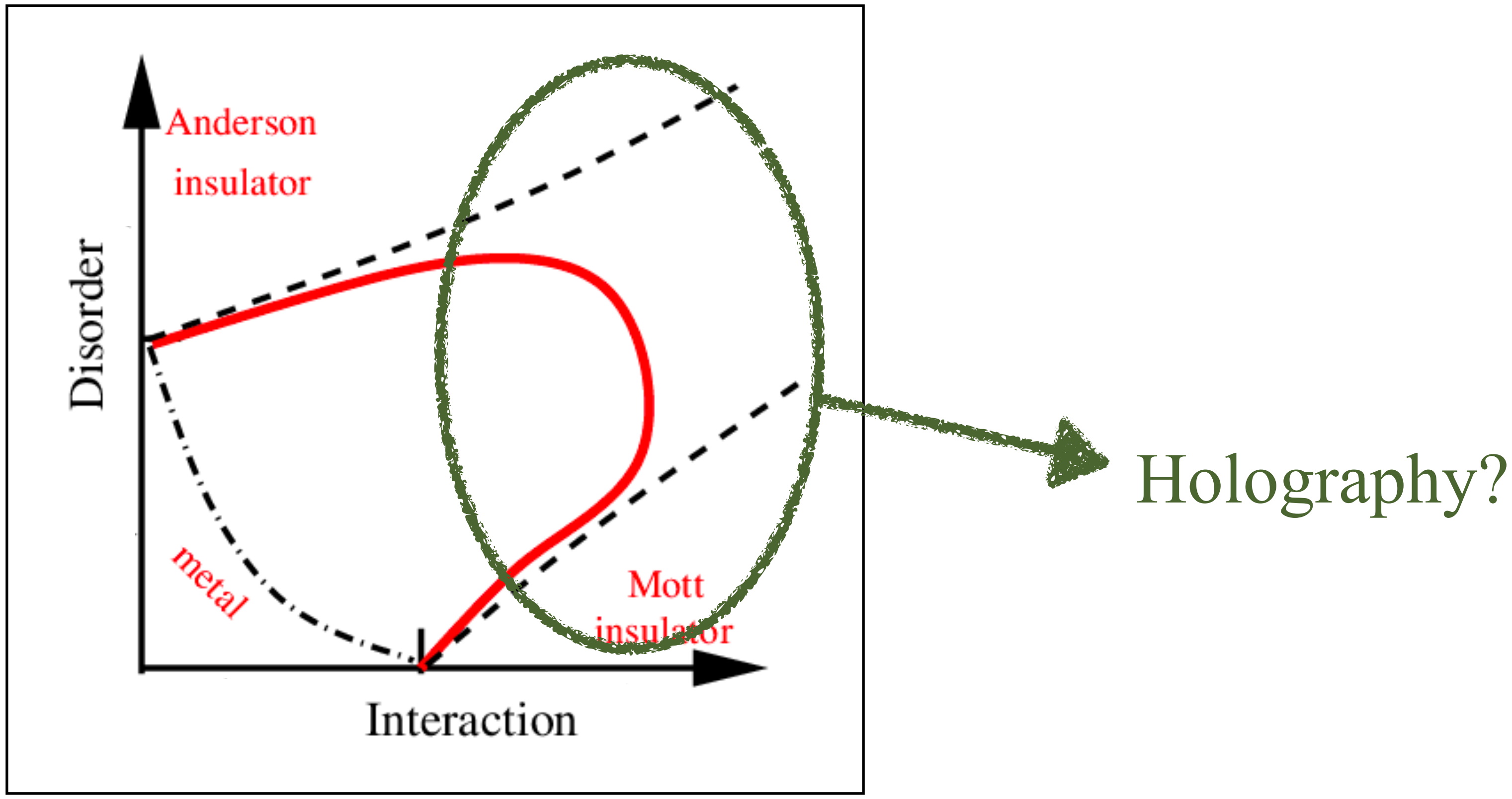
- The MIT is one of the oldest, not yet understood well in condensed matter physics
- MIT can capture properties of quantum critical point
- It is very hart to describe different excitations in one model



1112.6166: Dovrosavljevic

Introduction

■ Insulating mechanism
- Interaction induced insulator: Mott insulator
- Impurity(or disorder) induced insulator: Anderson insulator



Byczuk et al, IJMPB(2010)

Introduction

■ Holography(gauge/gravity duality)

- AdS/CFT: Strongly interacting gauge theory in d-dimension can be described by weakly interacting gravity theory in d+1-dimension
- Boundary system ↔ Bulk gravity
- Strongly interacting electron ↔ background geometry
- Temperature ↔ Hawking temperature of black hole
- Conserved charge ↔ U(1) gauge field
- Momentum relaxation ↔ linear axion field
- Operator $\mathcal{O}_\Delta$ ↔ field ϕ_m
- …

Introduction

- Holography(gauge/gravity duality)
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  - …

- MIT in holography
  - Helical lattice(Donos, Hartnoll: Nature, 2013)
  - Scalar potential(Refford, Horowitz: PRD, 2014)
  - In massive gravity(Baggioli: PRL, 2015)
  - …

Background Geometry

■ Action in 3+1 dim.

$$S_{tot} = S_0 + S_{int} + S_{bd},$$

$$S_0 = \int d^4x\sqrt{-g}\left(R - 2\Lambda - \frac{1}{2}(\partial\chi)^2 - \frac{1}{4}F^2 - \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2\right)$$

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Electron interactions

Background Geometry

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Momentum relaxation

E.O.M: $\nabla^2\chi = 0$

Solution: $(\chi_1, \chi_2) = (\beta x, \beta y)$

Ward identities:

$\nabla^\nu < T_{\mu\nu} > = < \mathcal{O}_I > \nabla_\mu \chi_I^{(0)} + F_{\mu\nu}^{(0)} < J^\nu >$

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Finite density

E.O.M: $\nabla_\mu F^{\mu\nu} = 0$

Conserved charge: $\sqrt{-g}F^{rt} = \mathcal{Q}$

Chemical potential:

$$A_t \sim \mu + \frac{\mathcal{Q}}{r} + \cdots$$

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Order parameter

Asymptotic expansion: $\phi \sim \frac{C_1}{r^{\Delta_+}} + \frac{C_2}{r^{\Delta_-}} + \cdots$

Pure AdS_{d+1}: $\Delta_\pm = \frac{3}{2} \pm \sqrt{m^2 + \frac{d^2}{4}}$

Breitenlohner-Freedman (BF) bound: $m_{BF}^2 \geq \frac{d^2}{4}$

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$\boxed{\text{Order parameter}}$

$$m^2 = -2$$

BF bound

$$\boxed{m^2 > -\frac{d^2}{4L^2} \quad \text{in } AdS_{d+1}}$$

AdS_4 $\quad m_{BF} = -\frac{9}{4}$

AdS_2 $\quad m_{BF} = -\frac{1}{4}$

$r = \infty$ $\qquad$ $r = r_H$

Background Geometry

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$$S_{int} = \boxed{-\int \sqrt{-g}\frac{\gamma_2}{4}\phi^2 F^2.}$$

$\gamma_2 = -0.2 < 0$

Background Geometry

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■ Equations of motion

$$R_{MN} - \frac{1}{2}g_{MN}\mathcal{L} - \frac{1}{2}\partial_M\phi\partial_N\phi - \frac{1}{2}\partial_M\chi\partial_N\chi - \frac{1}{2}\left(1+\gamma_2\phi^2\right)F_{MP}F^P_M = 0$$
$$\nabla^2\phi - \left(m^2 + \frac{1}{2}\gamma_2F^2\right)\phi = 0$$
$$\nabla_M\left(1+\gamma_2\phi^2\right)F^{MN} = 0,$$

■ Ansaz

$$ds^2 = -U(r)e^{2W(r)-2W(\infty)}dt^2 + \frac{dr^2}{U(r)} + r^2(dx^2+dy^2)$$
$$\chi^I = (\beta x, \beta y), \qquad \phi = \phi(r), \qquad A = A_t(r)dt.$$

Background Geometry

■ Thermodynamic variables

$$
\begin{aligned}
&\text{Temperature}: \ T = \frac{U'(r_h)}{4\pi} \\
&\text{Entropy density}: \ s = 4\pi r_h^2 \\
&\text{Charge density}: \ Q = (1+\gamma_2\phi^2)F^{rt} \\
&\text{Chemical poential}: \ \mu = A_t(\infty)
\end{aligned}
$$

■ Boundary behavior of scalar field

$$\phi(r)|_{r\to\infty} \sim \phi_\infty + \frac{<\mathcal{O}>}{r} + \cdots$$

Background Geometry

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■ Boundary behavior of scalar field

$$\phi(r)\,|_{r\to\infty} \sim \cancel{\phi_\infty} + \frac{<\mathcal{O}>}{r} + \cdots$$

Spontaneous symmetry breaking

Background Geometry

- Equations of motion

$$R_{MN}-\frac{1}{2}g_{MN}\mathcal{L}-\frac{1}{2}\partial_M\phi\partial_N\phi-\frac{1}{2}\partial_M\chi\partial_N\chi-\frac{1}{2}\left(1+\gamma_2\phi^2\right)F_{MP}F^P_M=0$$
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$$ds^2=-U(r)e^{2W(r)-2W(\infty)}dt^2+\frac{dr^2}{U(r)}+r^2(dx^2+dy^2)$$
$$\chi^I=(\beta x,\beta y),\qquad \phi=\phi(r),\qquad A=A_t(r)dt.$$

- Conserved charge

$$\mathcal{Q}\equiv\frac{\sqrt{-g}}{L}(1+\gamma_2\phi^2)F^{tr}$$

Background Geometry

- Equations of motion

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$$\mathcal{Q}\equiv\frac{\sqrt{-g}}{L}(1+\gamma_2\phi^2)F^{tr}$$

- Independent equations

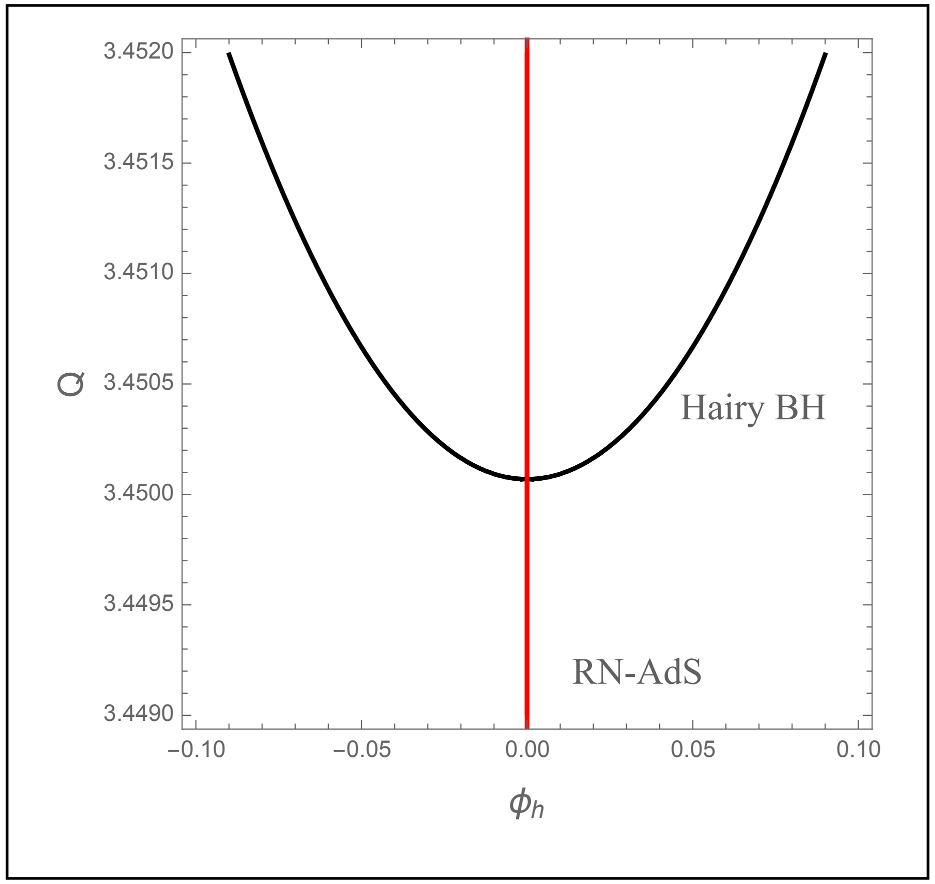
$$w'-\frac{1}{4}r\varphi'^2=0$$
$$\varphi''+\left(\frac{1}{r}-\frac{2\beta^2r^2+\frac{\mathcal{Q}^2}{\gamma_2\varphi^2+1}-2\left(\varphi^2+6\right)r^4}{4U\,r^3}\right)\varphi'+\frac{\gamma_2\mathcal{Q}^2\varphi}{U\,r^4\left(\gamma_2\varphi^2+1\right)^2}+\frac{2\varphi}{U}=0$$
$$U'+\frac{1}{4}U\,r\varphi'^2+\frac{\beta^2+2U-\left(\varphi^2+6\right)r^2}{2r}+\frac{\mathcal{Q}^2}{4r^3\left(\gamma_2\varphi^2+1\right)}=0.$$

$$U'(1)=\frac{6+\varphi(1)^2-\beta^2}{2}-\frac{\mathcal{Q}^2}{4\left(1+\gamma_2\varphi(1)^2\right)}\qquad \varphi'(1)=\frac{4\varphi(1)\left(\gamma_2\mathcal{Q}^2+2(\gamma_2\varphi(1)^2+1)^2\right)}{(\gamma_2\varphi(1)^2+1)(\mathcal{Q}^2+2(\beta^2-\varphi(1)^2-6)(\gamma_2\varphi(1)^2+1))}.$$

Background Geometry

■ Background Solution

- Without scalar condensation($\phi = 0$): RN-AdS black hole
- With a scalar condensation($\phi \neq 0$): Hairy black hole



Source free condition

Background Geometry

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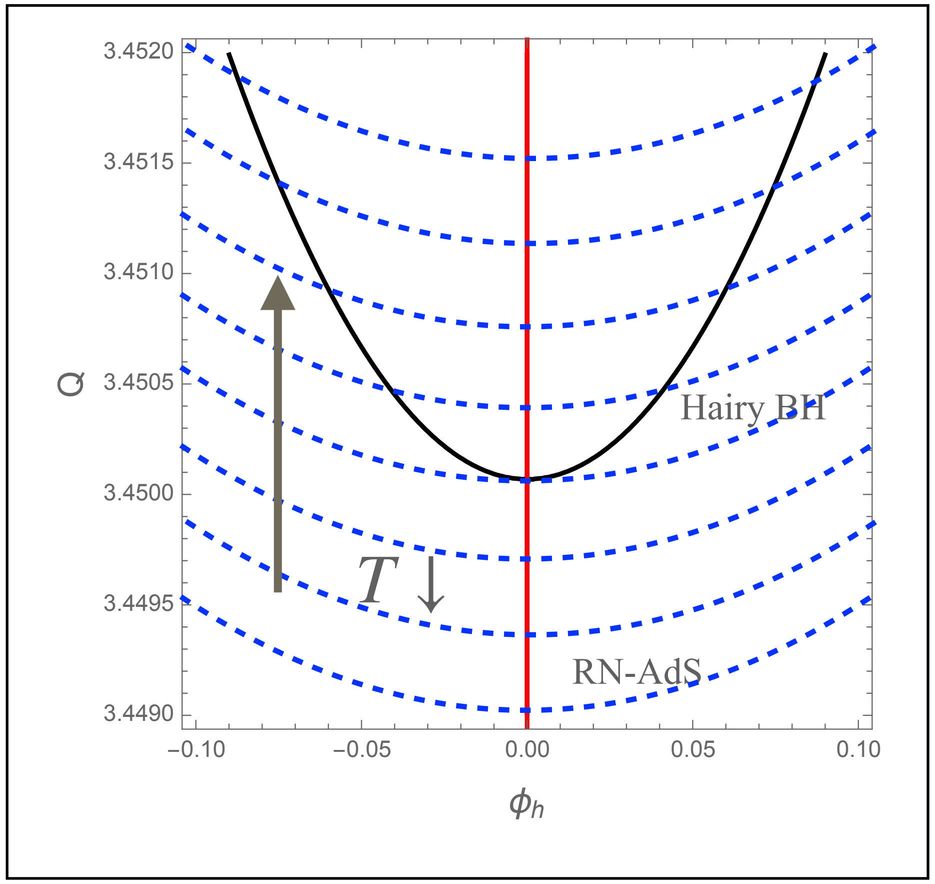

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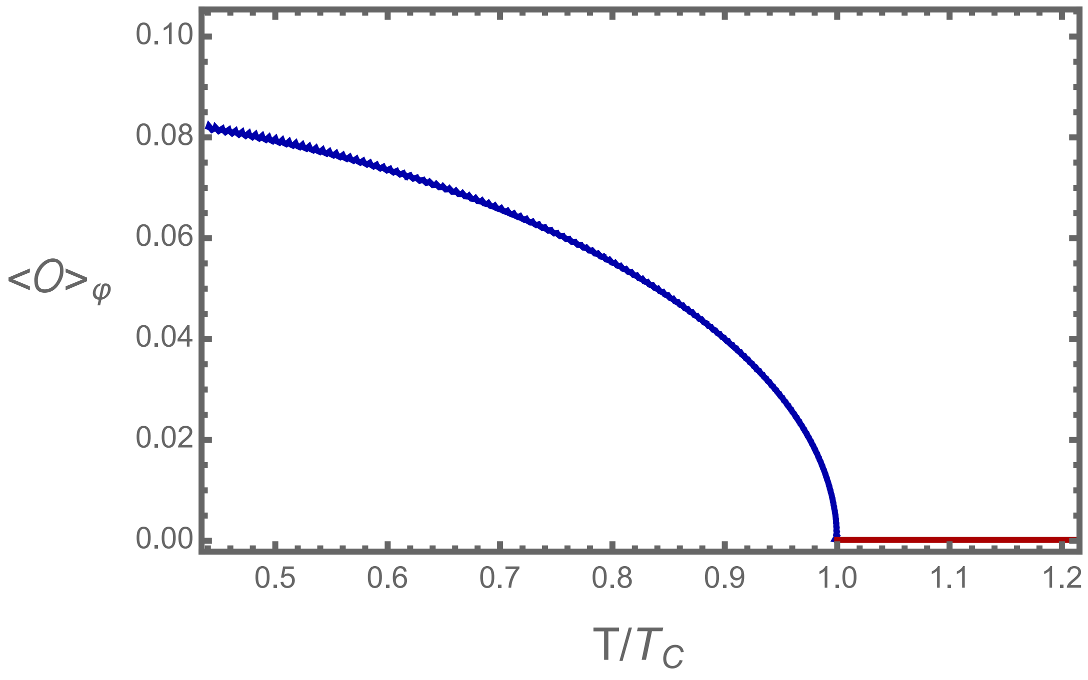
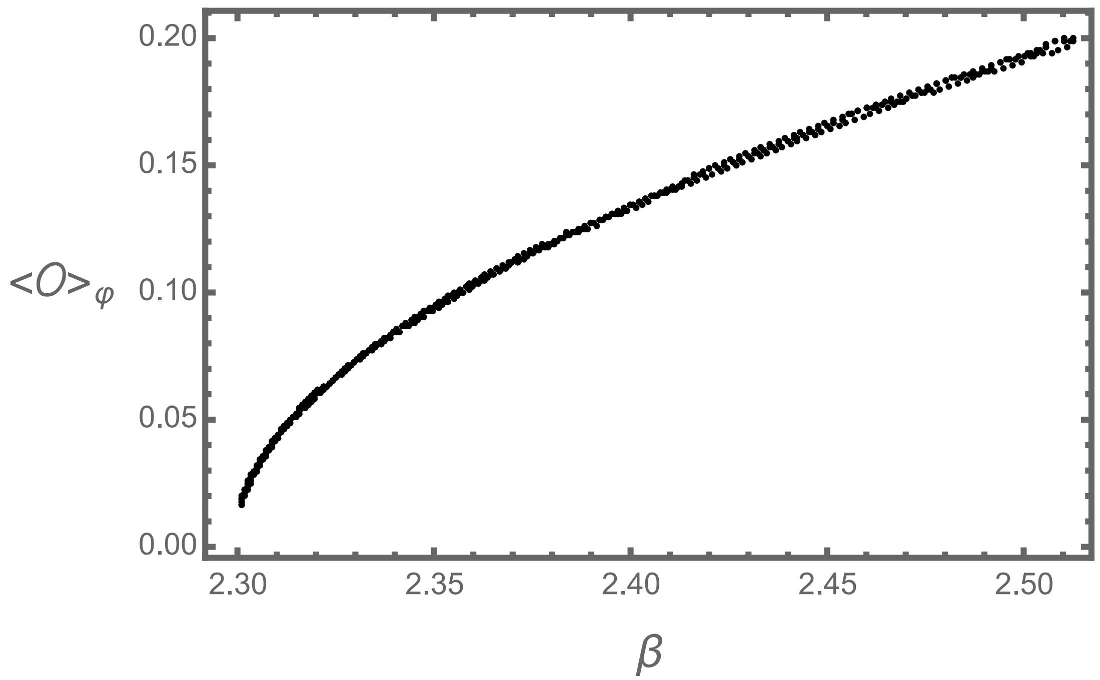


Background Geometry

- Impurity effect on the scalar condensation
  - Impurity enhances scalar condensation through gravity(electron interaction)



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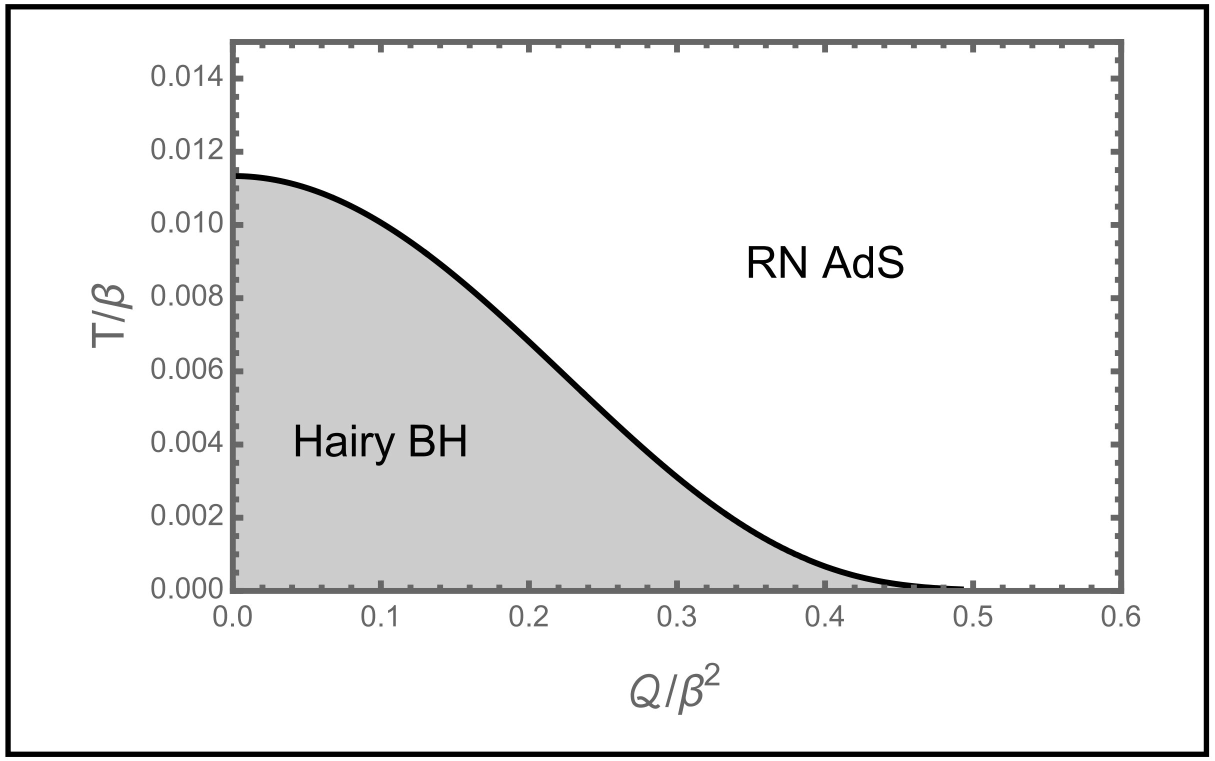
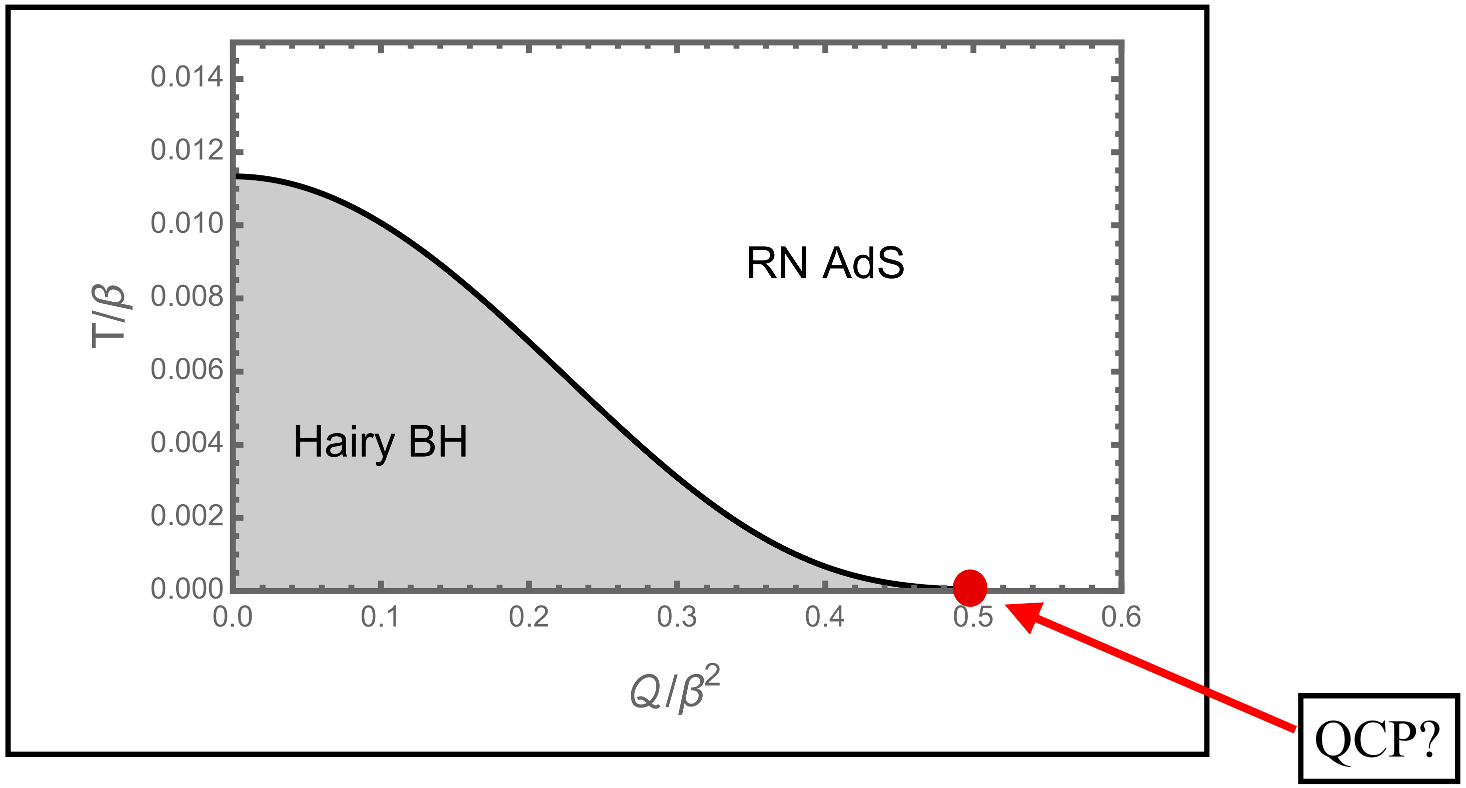
Background Geometry

- Phase diagram



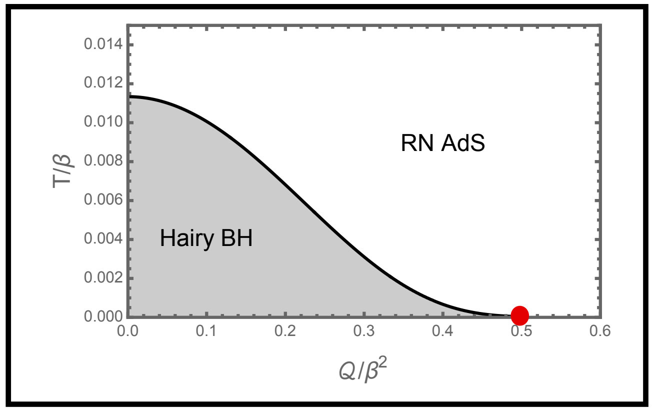
Background Geometry

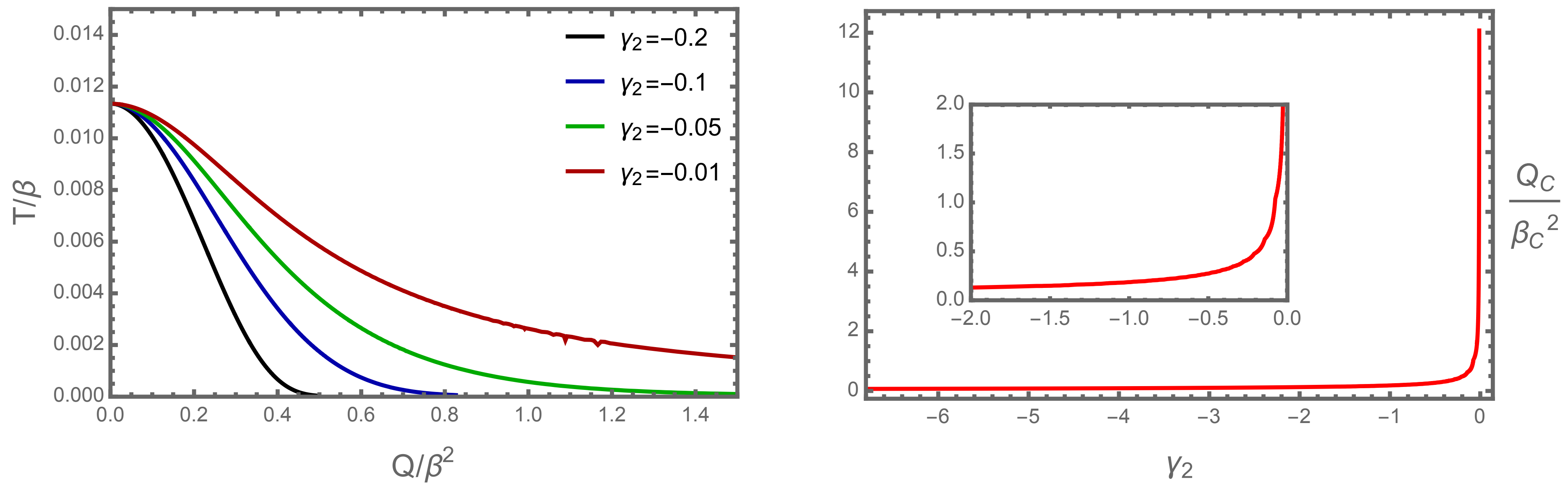
■ Phase diagram



Background Geometry

■ γ_2 dependence of Quantum critical point

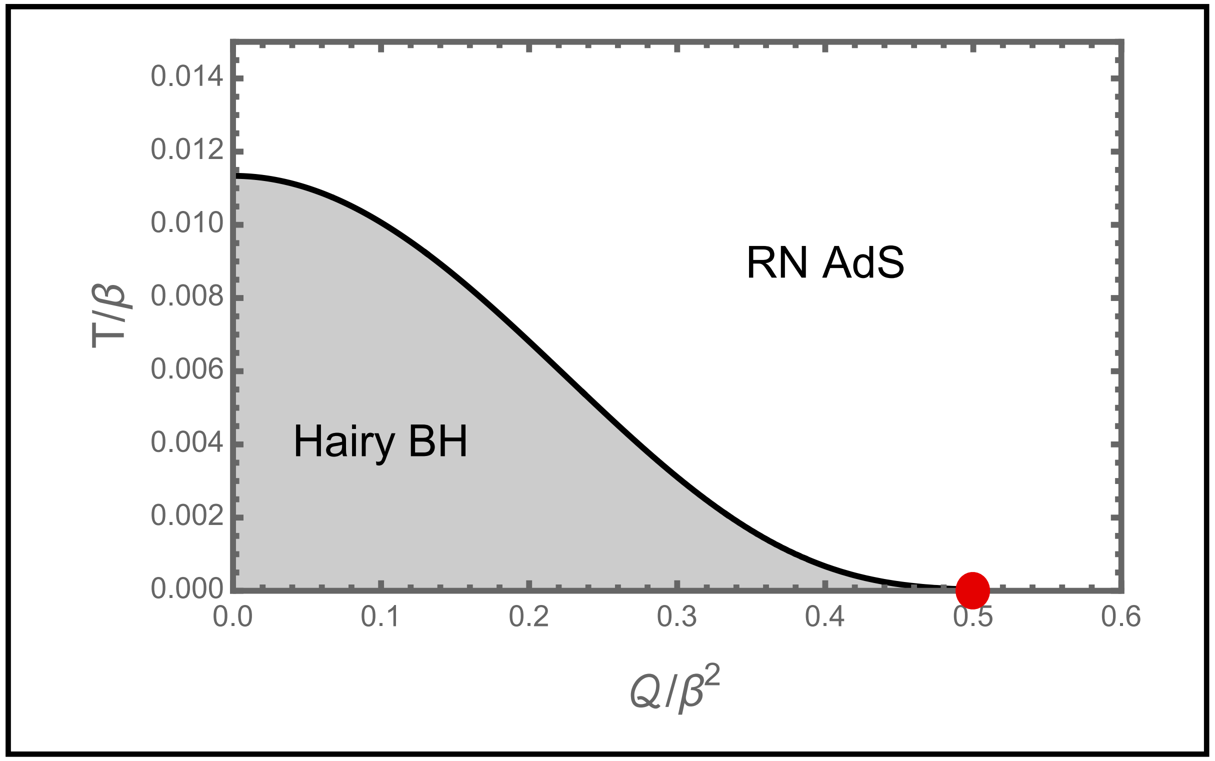




(a) (b)

Background Geometry

■ Quantum phase transition



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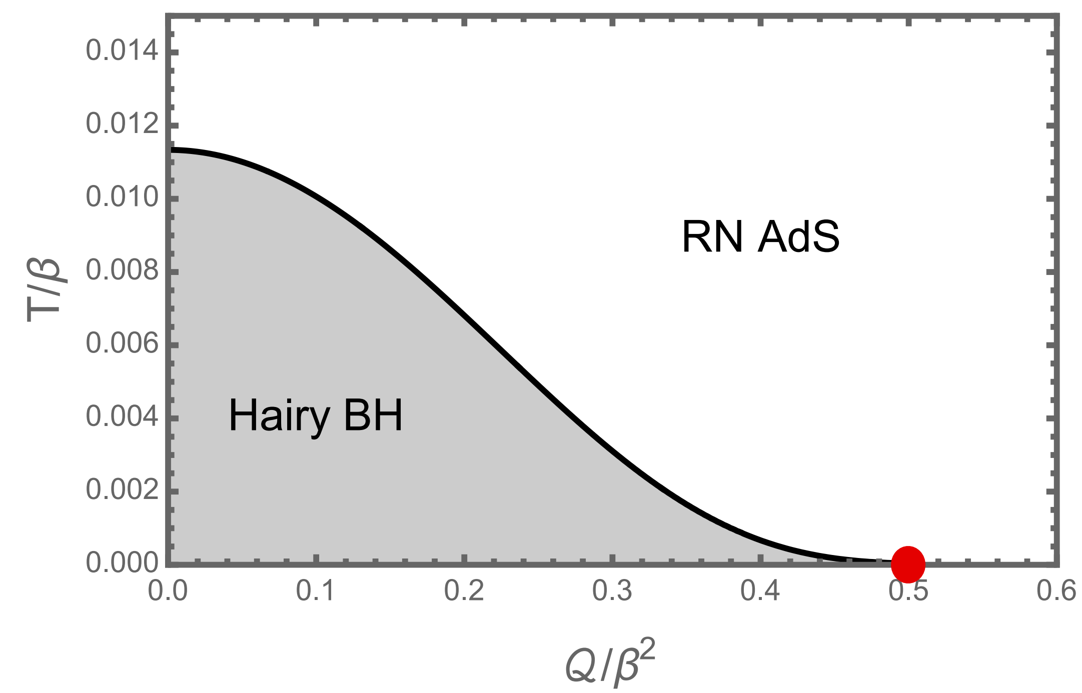
Background Geometry

■ Quantum phase transition



$$m_{\text{eff}}^2 = \left(m^2 + \frac{1}{2}\gamma_2 F^2\right)\Bigg|_{r=r_h} = m^2 - \gamma_2 \frac{\mathcal{Q}^2 L^6}{r_h^4}$$

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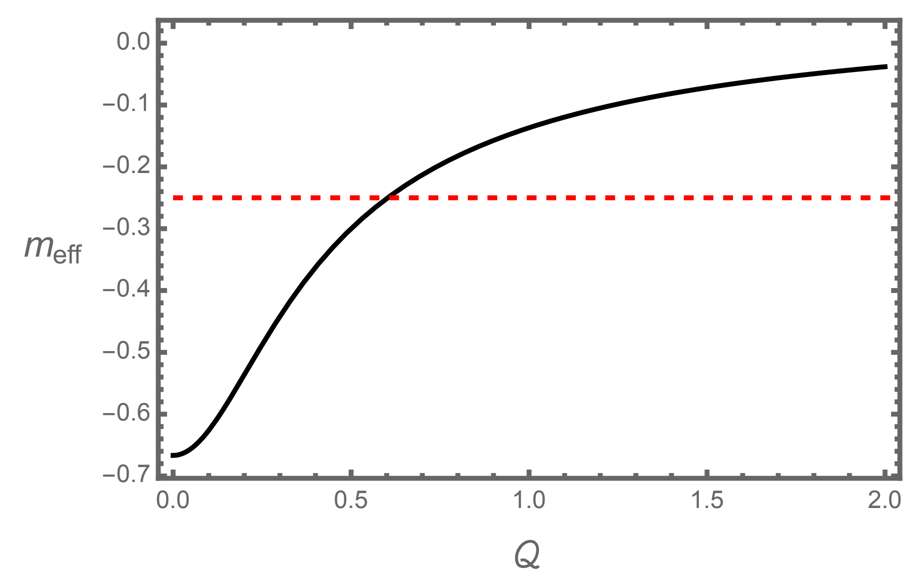

DC Conductivity

- Fluctuation around background solution

$$
\begin{aligned}
\delta G_{ti} &= -t\,U(r)\zeta_i + \delta g_{ti}(r) \\
\delta G_{ri} &= r^2 \delta g_{ri} \\
\delta A_i &= t(-E_i + \zeta_i a(r)) + \delta a_i(r)
\end{aligned}
$$

$$\delta A_i(r) \sim -E_i\, t + \frac{J^i}{r} + \cdots$$

- Regularity condition on the horizon:

$$
\begin{aligned}
&\delta g_{ti}(r) \sim \delta g_{ti}^0 + \cdots\,, \qquad \delta h_{ti}(r) \sim \frac{1}{r^2 U(r)} \delta g_{ti}^0 + \cdots\,, \\
&\delta A_i(r) \sim -\frac{E_i}{4\pi T} \log(r - r_h) + \cdots\,, \qquad \delta\chi^{\mathcal{I}} \sim \delta\chi_0^{\mathcal{I}} + \cdots\,.
\end{aligned}
$$

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■ Fluctuation around background solution

$$\boxed{\begin{aligned} \delta G_{ti} &= -t\,U(r)\zeta_i + \delta g_{ti}(r) \\ \delta G_{ri} &= r^2 \delta g_{ri} \\ \delta A_i &= t(-E_i + \zeta_i a(r)) + \delta a_i(r) \end{aligned}}$$

$$\delta A_i(r) \sim -E_i\,t + \frac{J^i}{r} + \cdots$$

■ Boundary current

$$\boxed{\begin{aligned} \mathcal{J}^i &= \sqrt{-g}(1+\gamma_2\phi^2)F^{ir} \\ &= -U(r)(1+\gamma_2\phi(r)^2)\delta a_i'(r) - a_t'(r)\delta g_{ti}(r) \end{aligned}}$$

$$\sim (1+\cancel{\gamma_2\phi(\infty)})J^i$$

■ Fluctuation equation + Regularity condition on the horizon: DC conductivity

$$\boxed{\sigma_{DC} = \left(1+\gamma_2\phi_h^2\right) + \frac{Q^2}{r_h^2\beta^2}}$$

DC Conductivity

- Two contributions to DC conductivity

$$\boxed{\begin{aligned}\sigma_{DC} &= \left(1+\gamma_2\phi_h^2\right)+\frac{Q^2}{r_h^2\beta^2}\\ &= \sigma_{ccs}+\sigma_{diss}\end{aligned}}$$

2015: Blake, Donos

DC Conductivity

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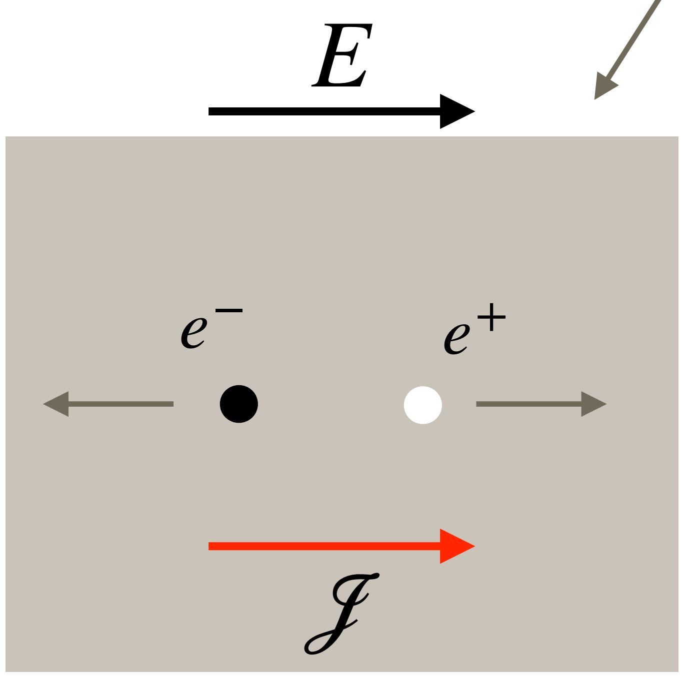

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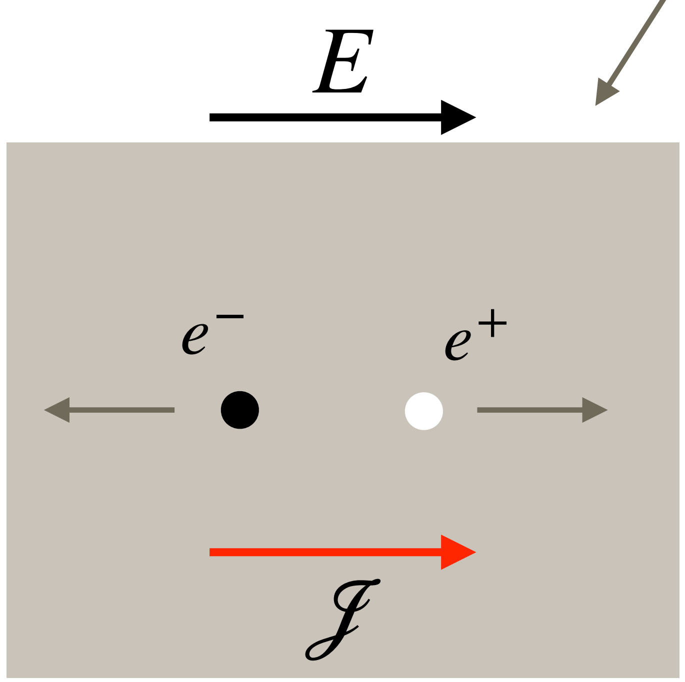

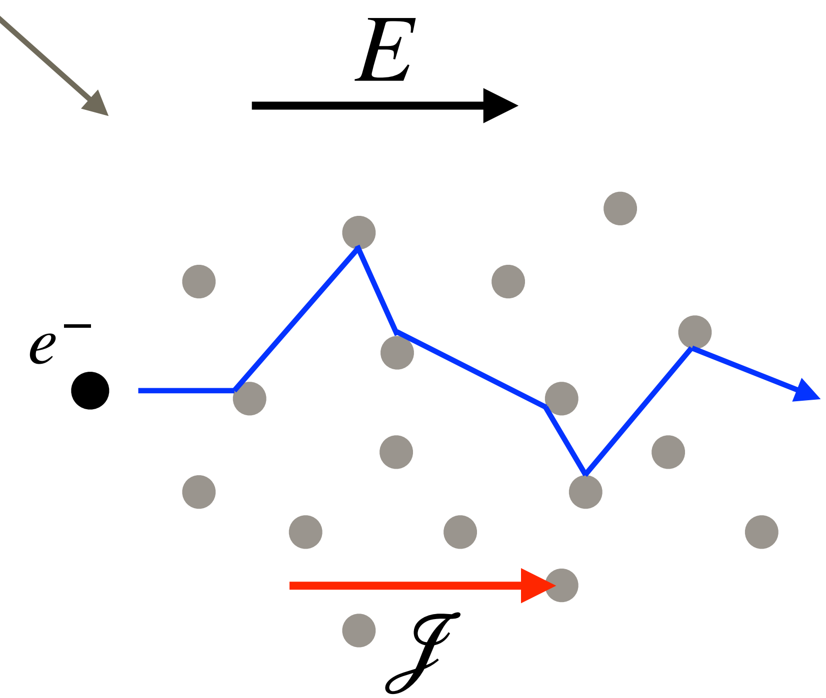

DC Conductivity

■ DC conductivity without charge carrier($Q = 0$)

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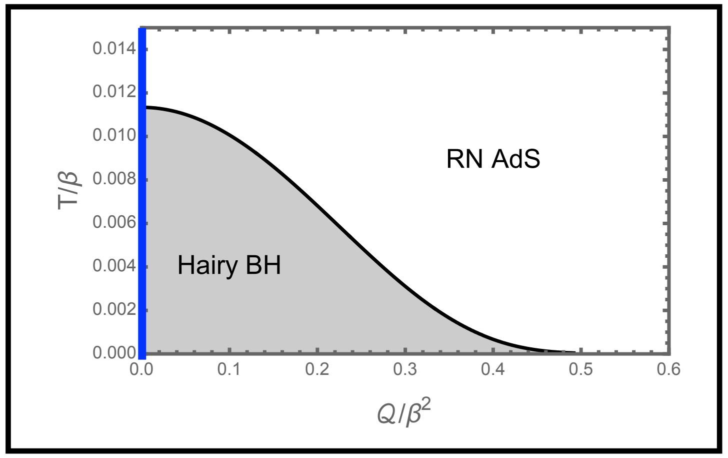
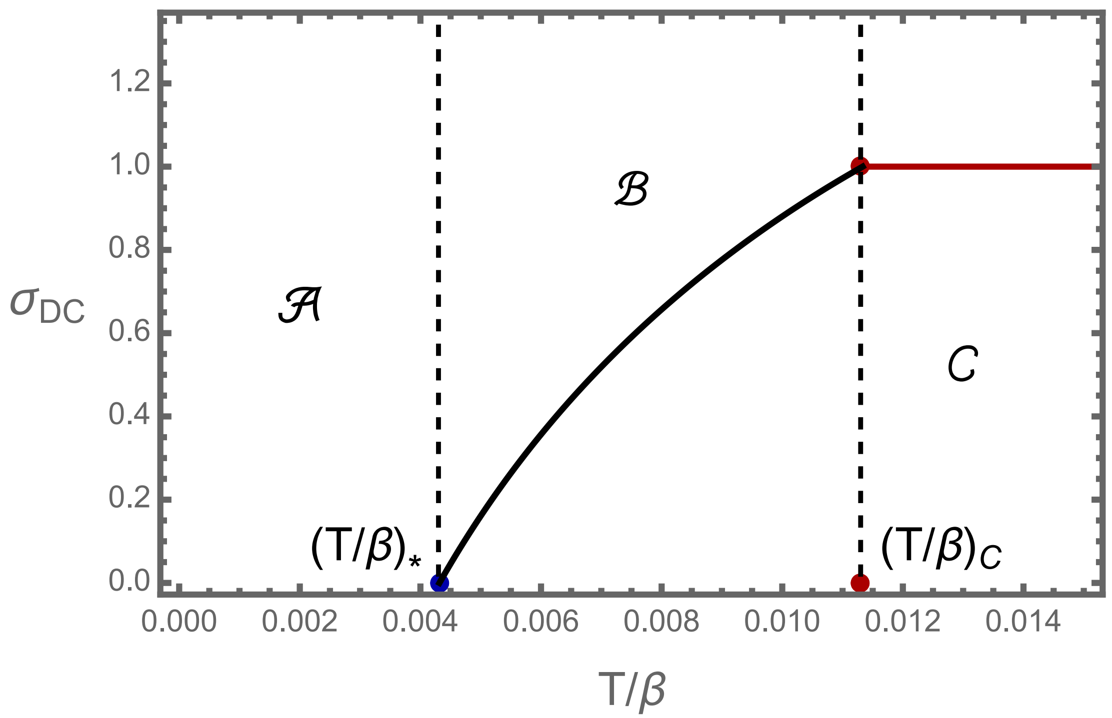


○ Temperature dependence of DC conductivity



DC Conductivity

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$$\sigma_{DC} = (1 + \gamma_2 \phi_h^2) + \cancel{\frac{Q^2}{r_h^2 \beta^2}}$$
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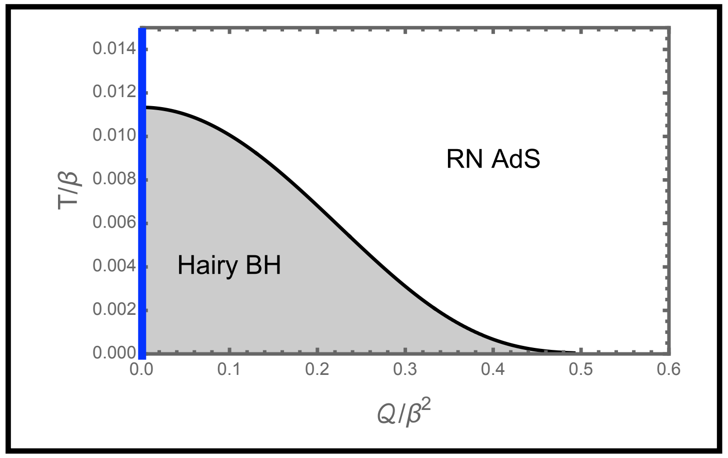

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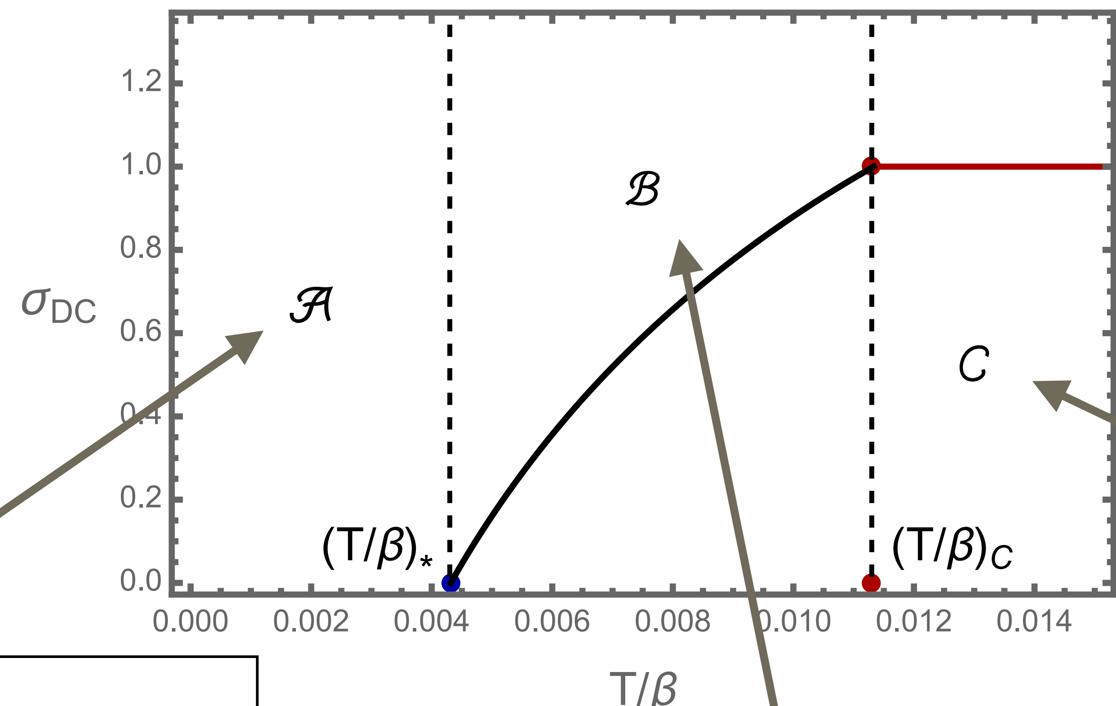


$$1 + \gamma_2 \phi_h^2 < 0$$

Instability of gauge field fluctuation

$$\frac{\partial \rho}{\partial T} < 0$$

Insulating behavior

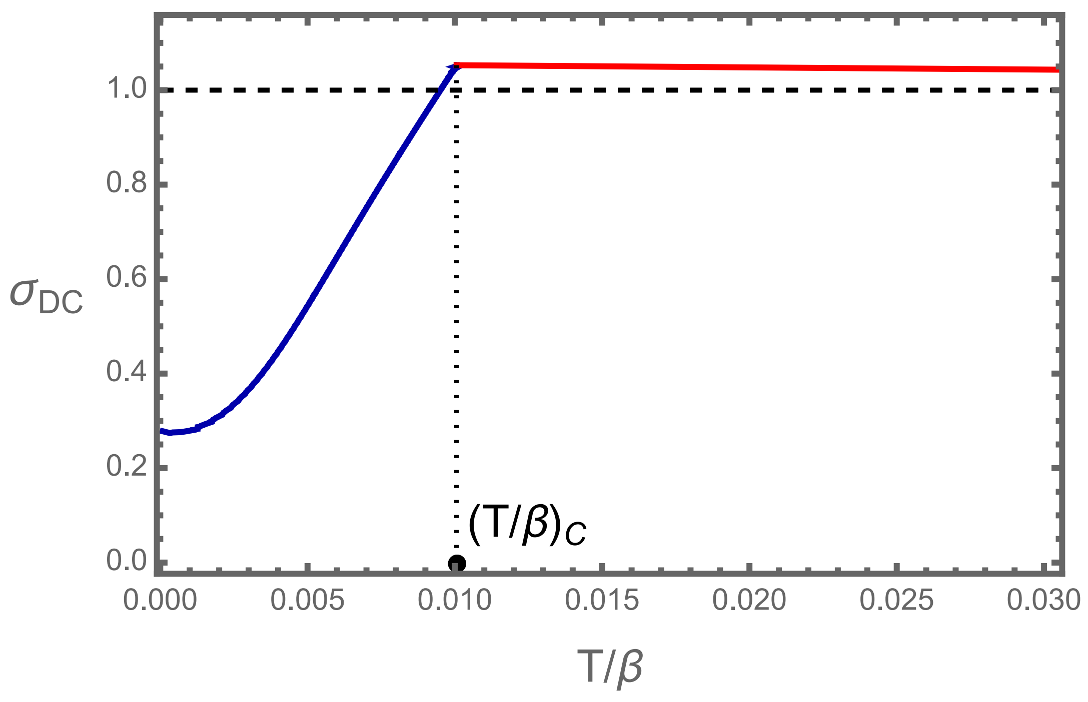
$$\frac{\partial \rho}{\partial T} = 0$$

Pure ccs.

DC Conductivity

- DC conductivity with charge carrier($Q \neq 0$)

$$\begin{aligned} \sigma_{DC} &= (1+\gamma_2\varphi_h^2) + \frac{e^{W(\infty)}\mathcal{Q}^2}{r_h^2\beta^2} && \text{for hairy BH} \\ \sigma_{DC} &= 1 + \frac{\mathcal{Q}^2}{r_h^2\beta^2} && \text{for RN AdS BH.} \end{aligned}$$



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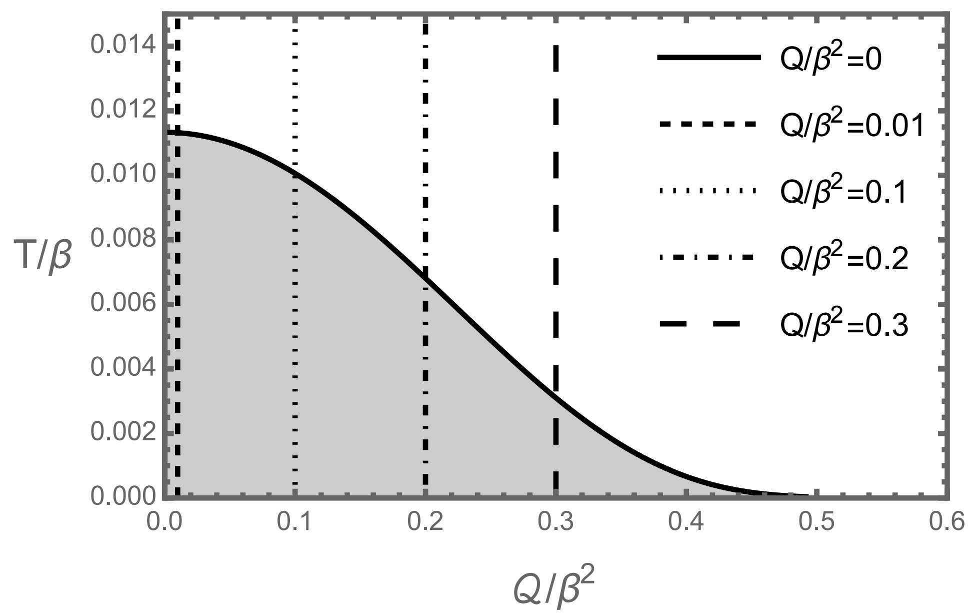
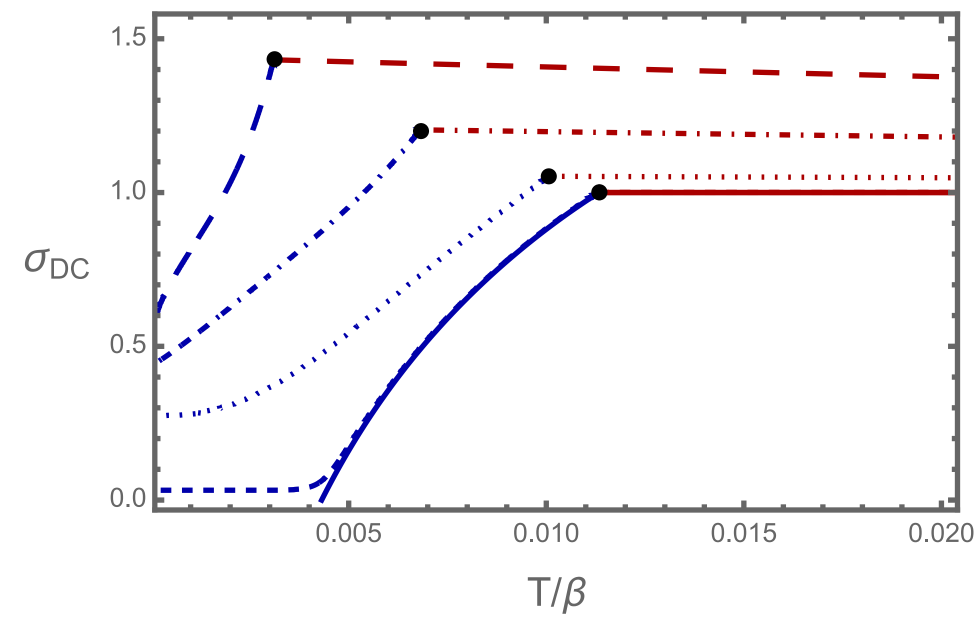
$$\sigma_{DC} = (1 + \gamma_2 \varphi_h^2) + \frac{e^{W(\infty)} \mathcal{Q}^2}{r_h^2 \beta^2} \quad \text{for hairy BH}$$
$$\sigma_{DC} = 1 + \frac{\mathcal{Q}^2}{r_h^2 \beta^2} \quad \text{for RN AdS BH.}$$



(a)

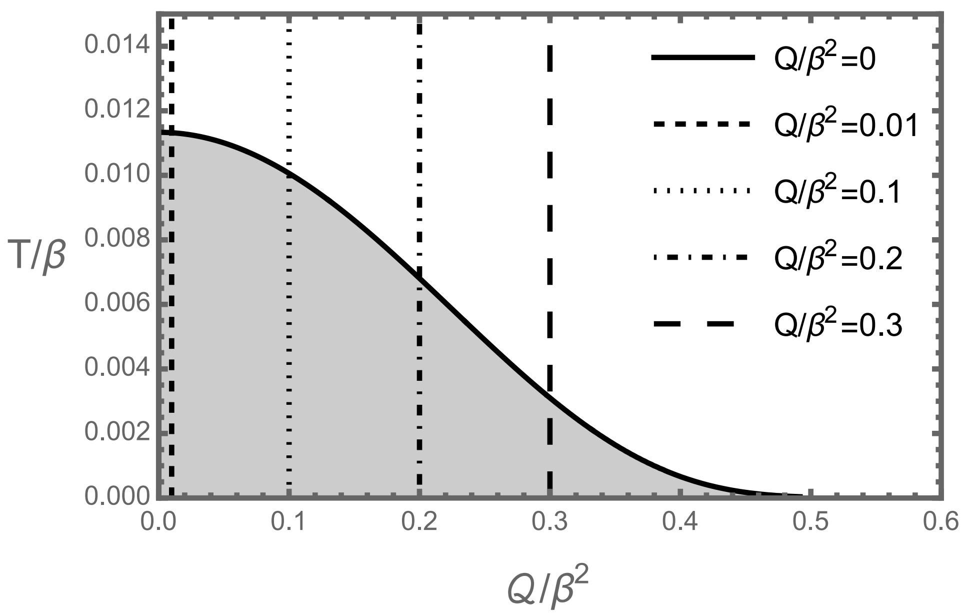


(b)

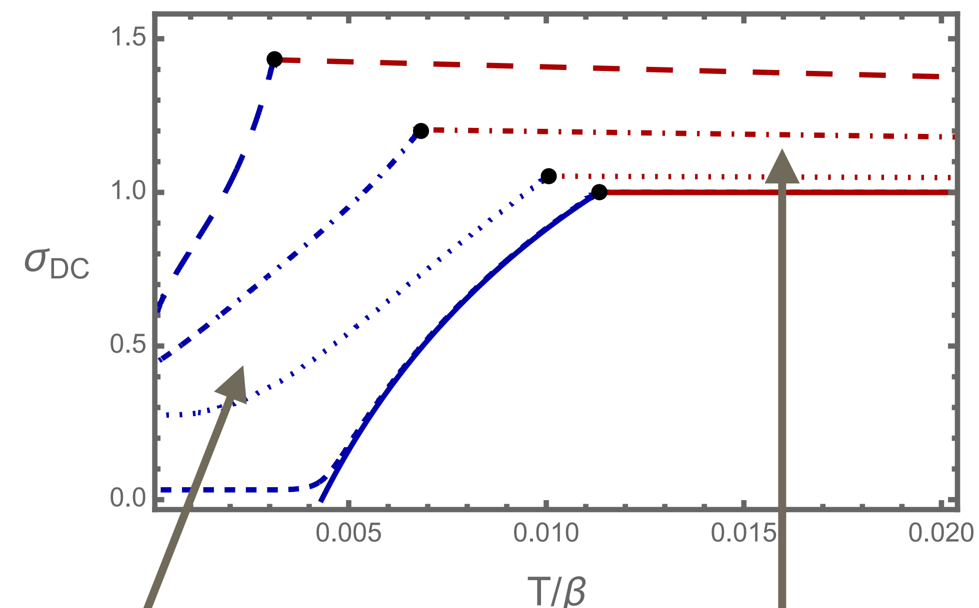
DC Conductivity

- DC conductivity with charge carrier($Q \neq 0$)

$$
\begin{aligned}
\sigma_{DC} &= (1 + \gamma_2 \varphi_h^2) + \frac{e^{W(\infty)} \mathcal{Q}^2}{r_h^2 \beta^2} && \text{for hairy BH} \\
\sigma_{DC} &= 1 + \frac{\mathcal{Q}^2}{r_h^2 \beta^2} && \text{for RN AdS BH.}
\end{aligned}
$$



(a)



(b)

$$\frac{\partial \rho}{\partial T} < 0$$

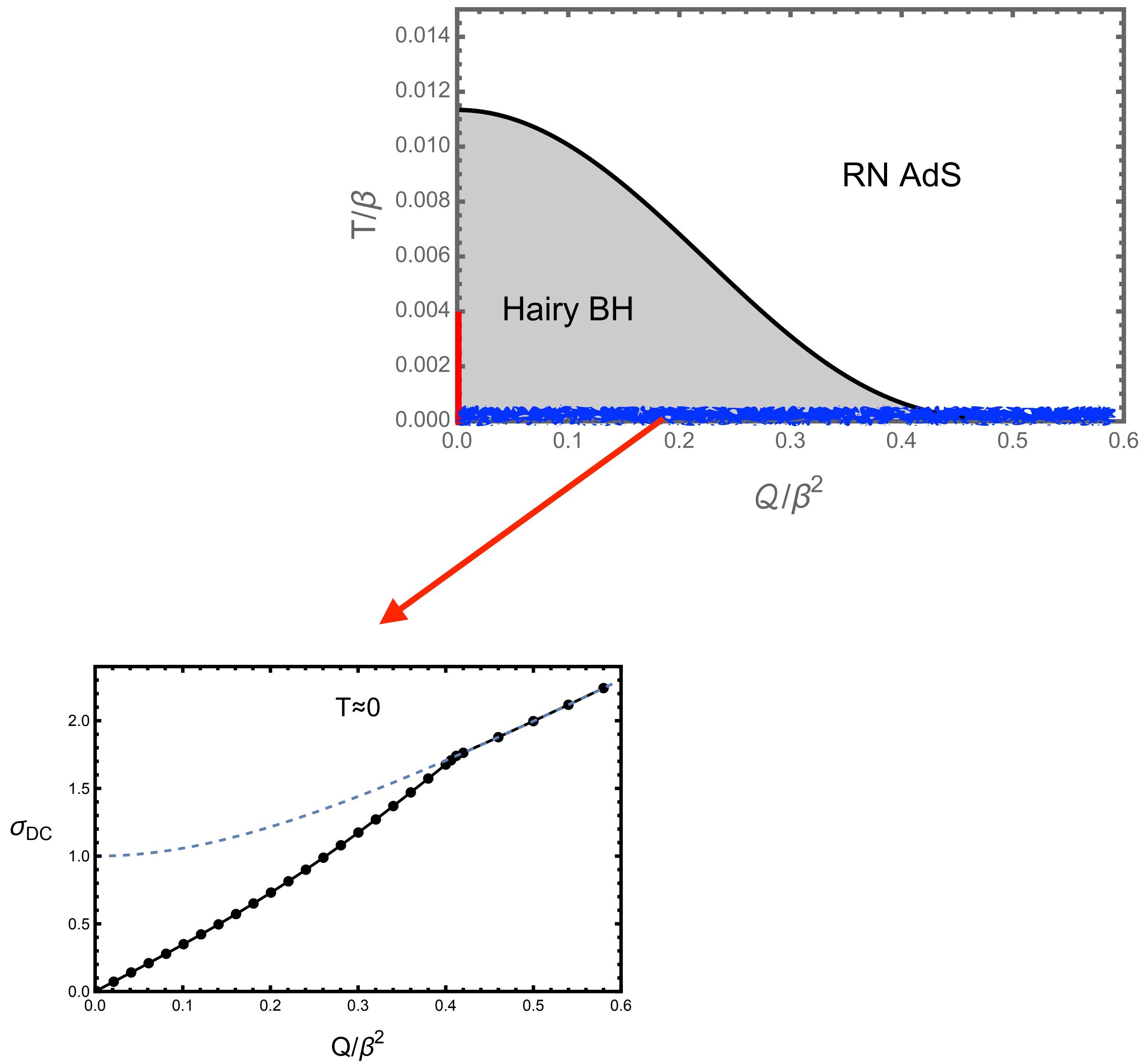
Insulating behavior

$$\frac{\partial \rho}{\partial T} > 0$$

Metallic behavior

Metal-Insulator Transition

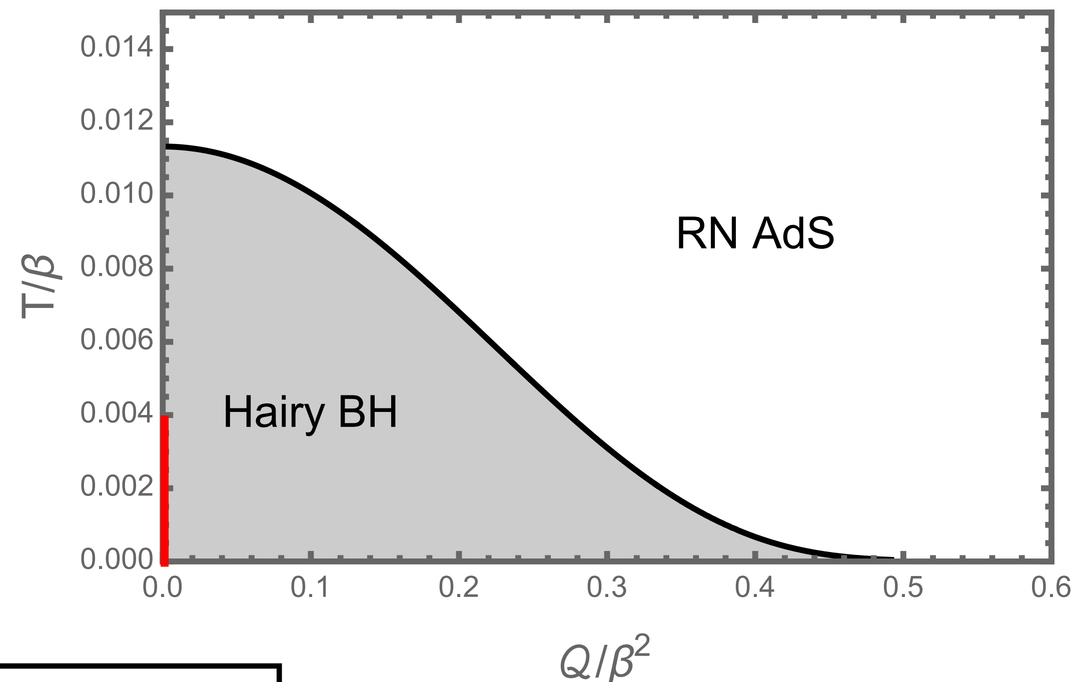
■ Phase diagram



$$\sigma_{DC} = \left(1 + \gamma_2 \phi_h^2\right) + \frac{Q^2}{r_h^2 \beta^2}$$
$$= \sigma_{ccs} + \sigma_{diss}$$

Metal-Insulator Transition

■ Phase diagram



$$\sigma_{DC} = \left(1 + \gamma_2 \phi_h^2\right) + \frac{Q^2}{r_h^2 \beta^2}$$
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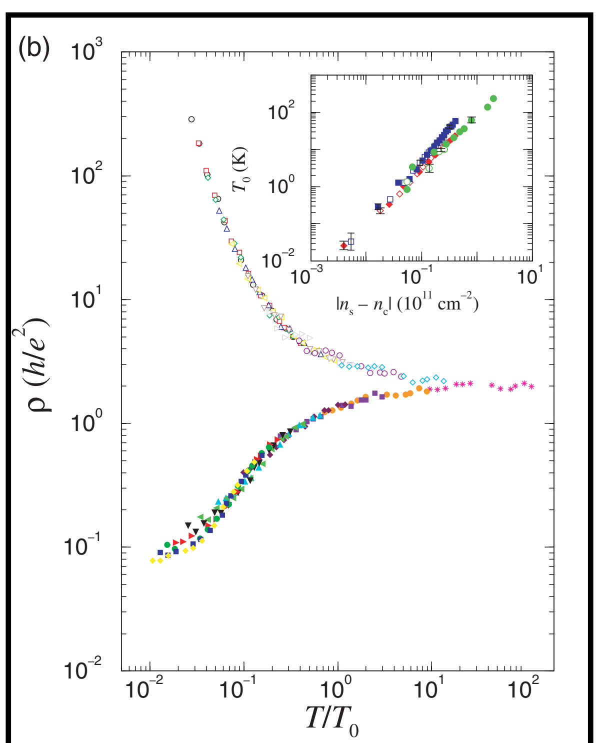
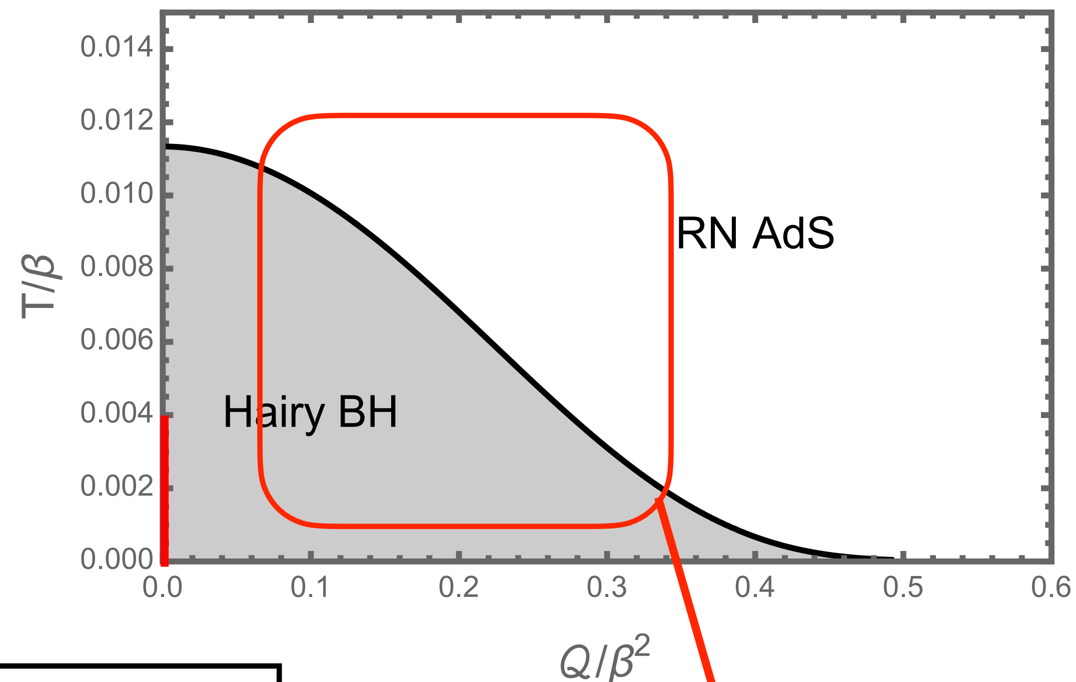


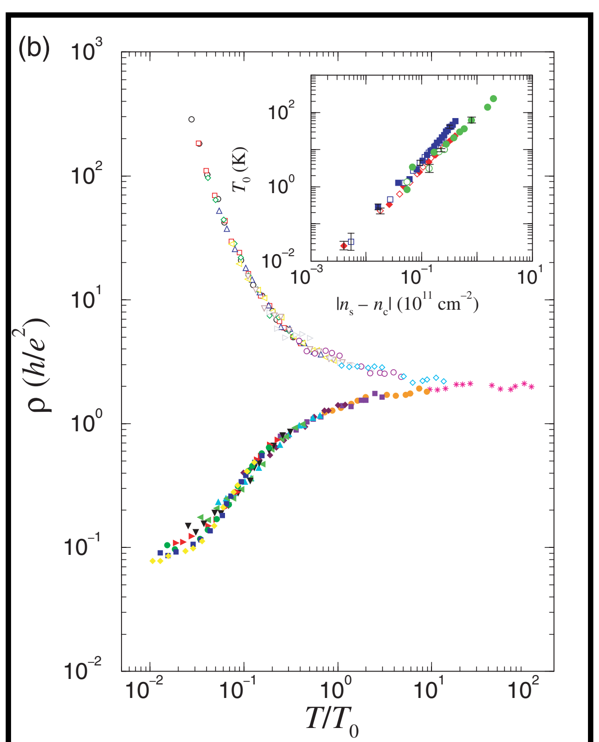
Kravchenko et al (1995)

Metal-Insulator Transition

■ Phase diagram

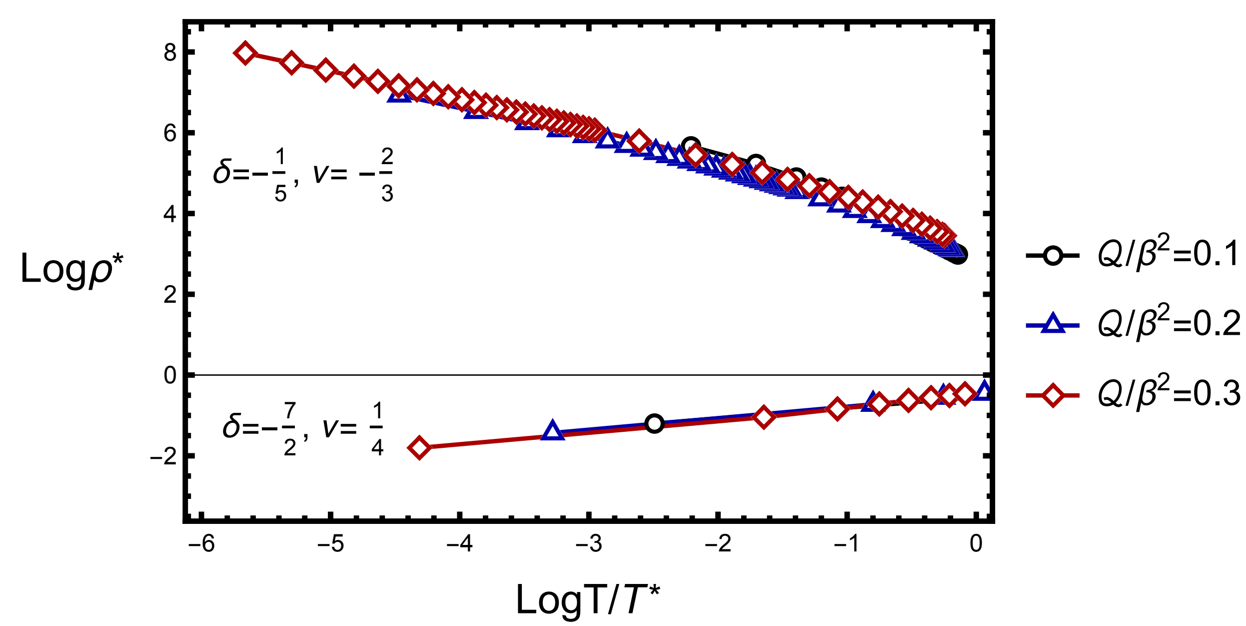


$$\sigma_{DC} = (1+\gamma_2\phi_h^2) + \frac{Q^2}{r_h^2\beta^2} = \sigma_{ccs} + \sigma_{diss}$$



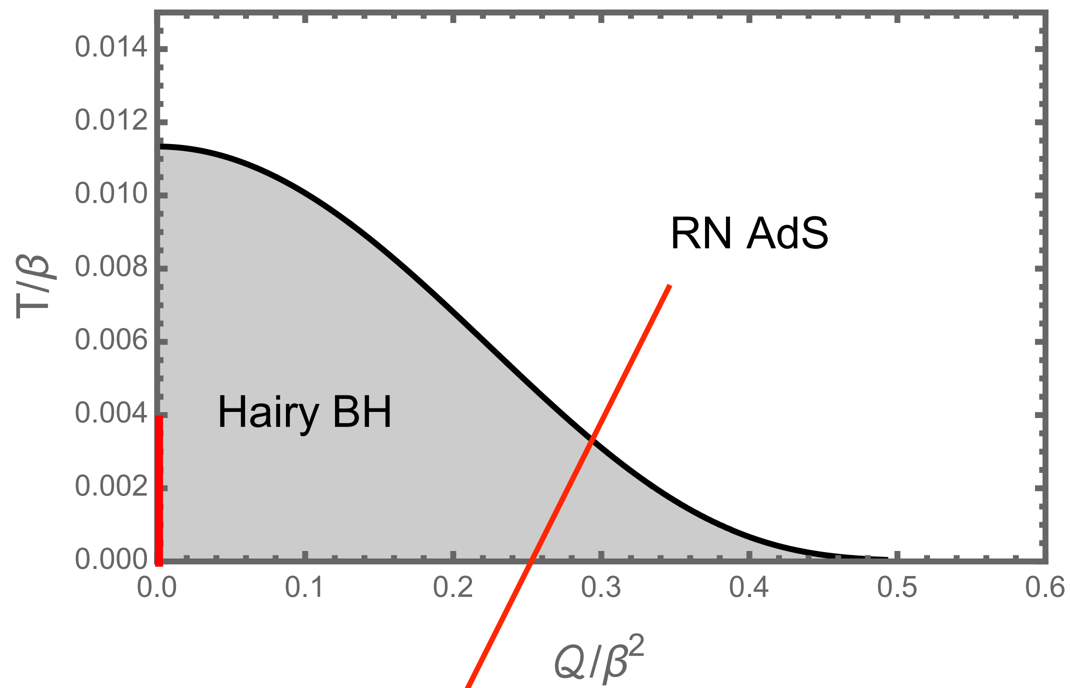
Kravchenko et al (1995)

$$T^* = T_C|Q-Q_C|^{\delta}, \quad \rho^* = \rho T^{\nu}$$



Metal-Insulator Transition

■ Phase diagram

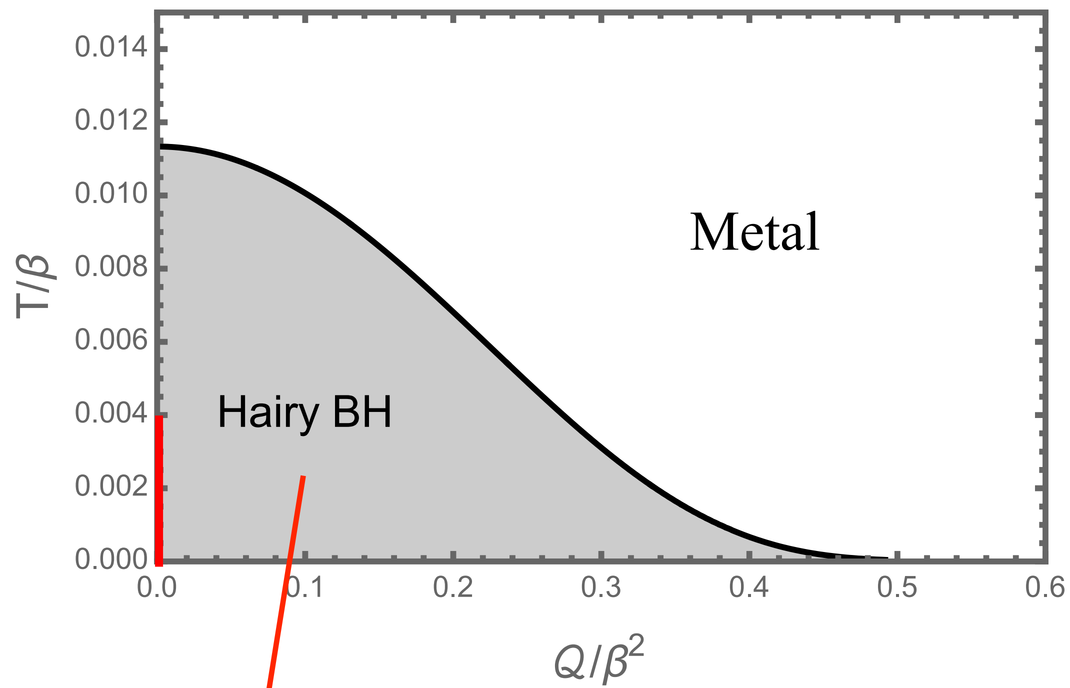


$$\sigma_{DC} = (1 + \gamma_2 \phi_h^2) + \frac{Q^2}{r_h^2 \beta^2}$$
$$= \sigma_{ccs} + \sigma_{diss}$$

- σ_{diss} dominant
- Drude like behavior
- Resistivity is increasing to T
- Metallic phase

Metal-Insulator Transition

■ Phase diagram

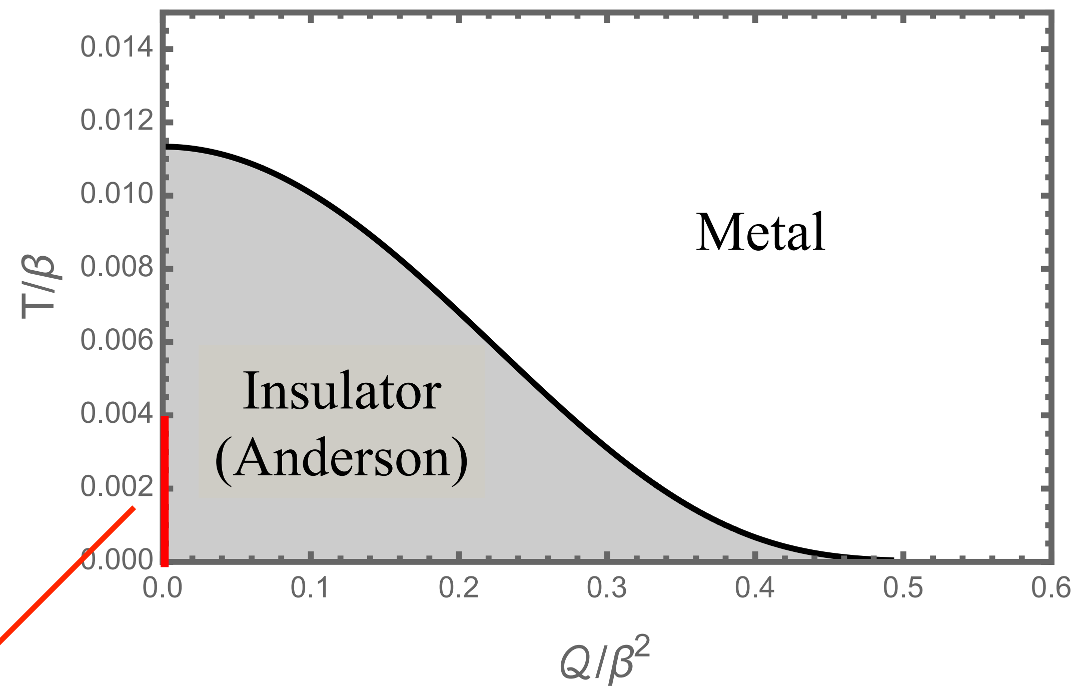


$$\sigma_{DC} = (1 + \gamma_2 \phi_h^2) + \frac{Q^2}{r_h^2 \beta^2} = \sigma_{ccs} + \sigma_{diss}$$

- σ_{ccs} suppression dominant
- Resistivity is decreasing to T
- Impurity induced insulating phase
- 'Anderson insulator'

Metal-Insulator Transition

- Phase diagram

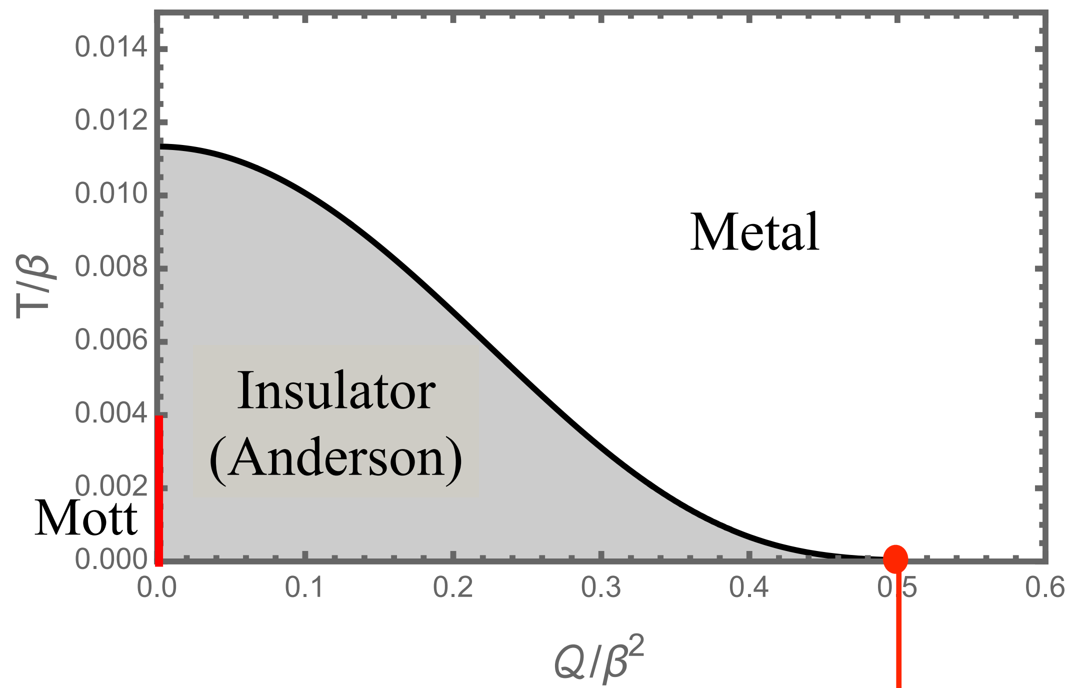


$$\sigma_{DC} = (1+\gamma_2\phi_h^2) + \frac{Q^2}{r_h^2\beta^2}$$
$$= \sigma_{ccs} + \sigma_{diss}$$

- No black hole solution
- Hawking-Page transition(geometric transition)
- Solitonic(or singular) solution
- Insulating phase
- ‘Mott insulator’

Metal-Insulator Transition

■ Phase diagram



$$\sigma_{DC} = (1+\gamma_2\phi_h^2) + \frac{Q^2}{r_h^2\beta^2}$$
$$= \sigma_{ccs} + \sigma_{diss}$$

- Zero temperature phase transition(quantum)
- IR effect
- Change of scaling dimension of order parameter in IR region

Discussion and Future direction

- We construct a gravity system with scalar-gauge field interaction
  - We find a phase transition between RN AdS black hole and a hairy black hole
  - We find quantum phase transition at zero temperature from density effect in IR
  - Impurity enhances scalar condensation: “Order parameter enhanced by disorder”
  - Scalar condensation leads to the insulating phase
  - The insulating phase comes from the localization of electron-hole pair creation
  - We realize ‘Anderson insulator’-metal transition in holography

- Physical meaning of the order parameter : AFM order?
- Calculation of AC conductivity: gap or pseudo-gap creating mechanism
- Couple to the complex scalar field: Superconducting dorm?

Thank you !!