BH/QCP Duality and quantum matters.

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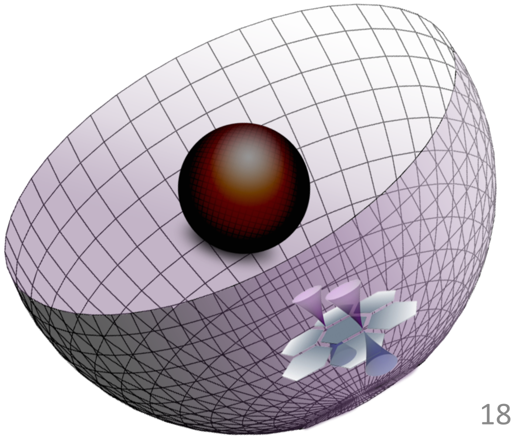
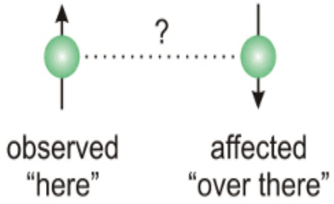


Introduction: unification

- Physics= Simplification by (unification,reduction,symmetry)

- Unification= Identify different objects
  → reduces the # of axioms



$$\psi = \frac{|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle}{\sqrt{2}}$$

Example : Electricity+ Magnetism → Electromagnetism
particle+wave →Quantum Physics
space+time Special relativity
spacetime+gravity→ General relativity
spacetime geometry+ force+dulaity ➔string theory

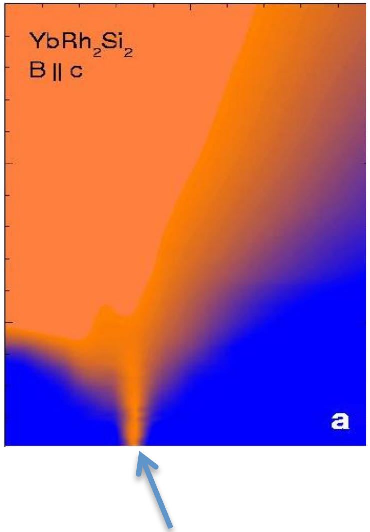
- Issue of today:

  Quantum matter + spacetime geometry

Theme

- Similarity of Quantum Critical point and black hole

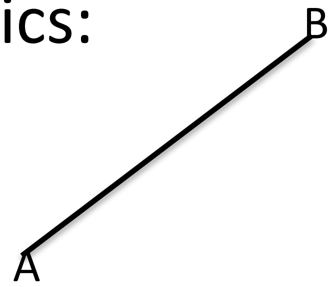
  → New field theory for strongly int. system

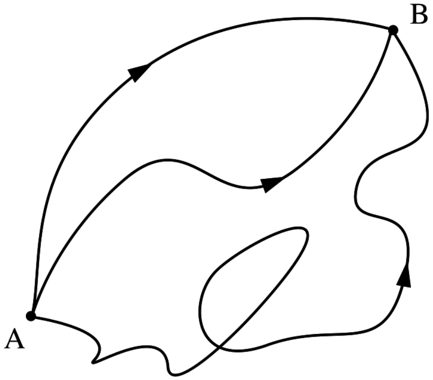


QCP

Quantum matter = large quantum fluctuation

- Classical vs quantum mechanics:





- One configuration dominant → no fluctuation

  sum over many configuration → big fluctuation .

- Quantum matter = matter with large quantum fluctuation

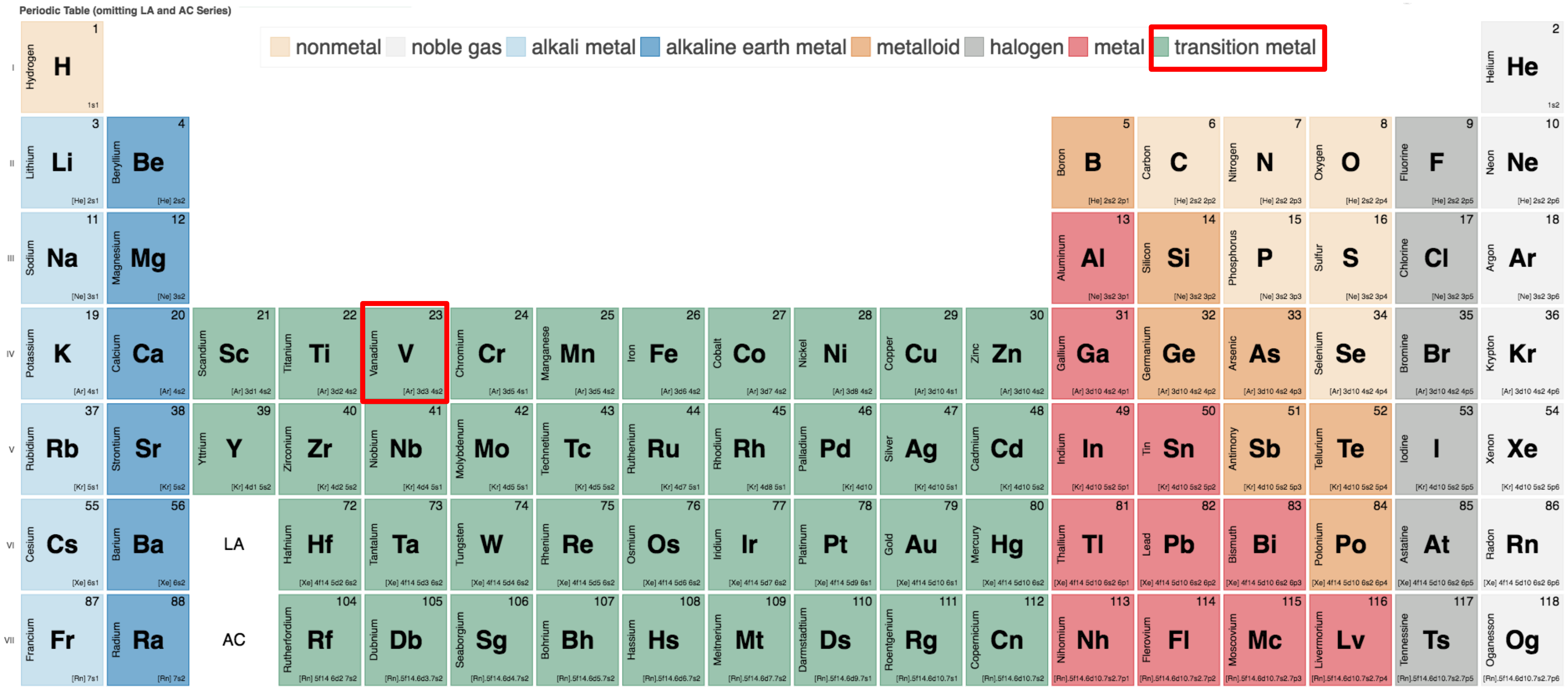
When Quantum fluctuation is large?

1. Strong interaction→ Large fluctuation
2. g ~ V/K
3. Slow elctron: large g → large fluctuation
4. Quantum matter→ slow electrons

Material with slow electrons

3d Transition metal Oxide,

Hi Tc SC

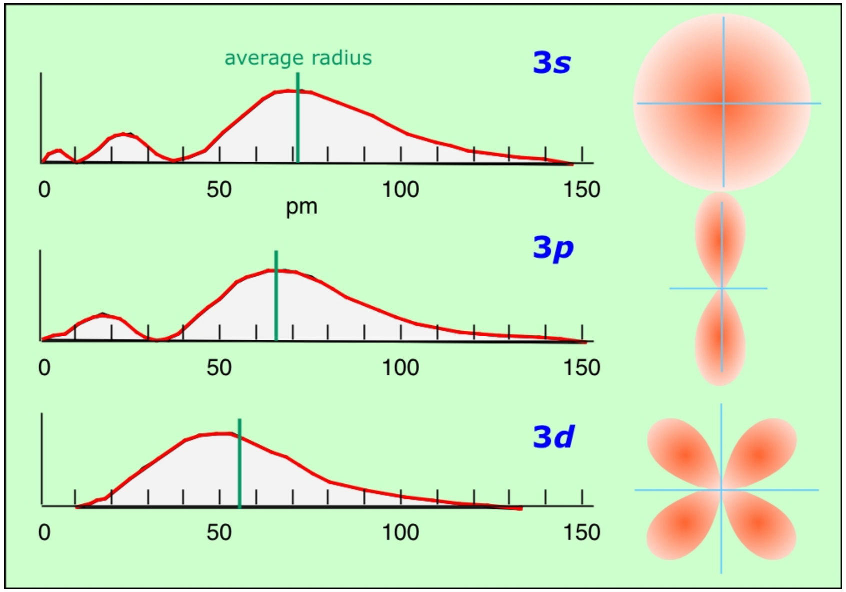


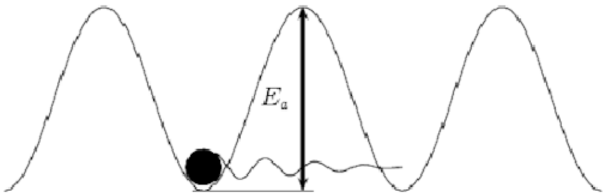
Periodic Table (omitting LA and AC Series)

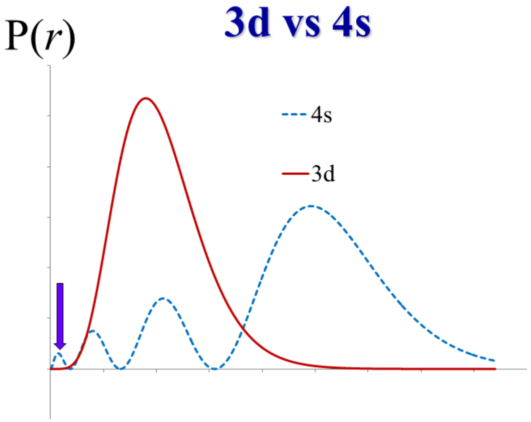
🟧 nonmetal ⬜ noble gas 🟦 alkali metal 🟦 alkaline earth metal 🟧 metalloid ⬜ halogen 🟥 metal 🟩 transition metal

I	1 H Hydrogen 1s1																	2 He Helium 1s2
II	3 Li Lithium [He] 2s1	4 Be Beryllium [He] 2s2											5 B Boron [He] 2s2 2p1	6 C Carbon [He] 2s2 2p2	7 N Nitrogen [He] 2s2 2p3	8 O Oxygen [He] 2s2 2p4	9 F Fluorine [He] 2s2 2p5	10 Ne Neon [He] 2s2 2p6
III	11 Na Sodium [Ne] 3s1	12 Mg Magnesium [Ne] 3s2											13 Al Aluminum [Ne] 3s2 3p1	14 Si Silicon [Ne] 3s2 3p2	15 P Phosphorus [Ne] 3s2 3p3	16 S Sulfur [Ne] 3s2 3p4	17 Cl Chlorine [Ne] 3s2 3p5	18 Ar Argon [Ne] 3s2 3p6
IV	19 K Potassium [Ar] 4s1	20 Ca Calcium [Ar] 4s2	21 Sc Scandium [Ar] 3d1 4s2	22 Ti Titanium [Ar] 3d2 4s2	23 V Vanadium [Ar] 3d3 4s2	24 Cr Chromium [Ar] 3d5 4s1	25 Mn Manganese [Ar] 3d5 4s2	26 Fe Iron [Ar] 3d6 4s2	27 Co Cobalt [Ar] 3d7 4s2	28 Ni Nickel [Ar] 3d8 4s2	29 Cu Copper [Ar] 3d10 4s1	30 Zn Zinc [Ar] 3d10 4s2	31 Ga Gallium [Ar] 3d10 4s2 4p1	32 Ge Germanium [Ar] 3d10 4s2 4p2	33 As Arsenic [Ar] 3d10 4s2 4p3	34 Se Selenium [Ar] 3d10 4s2 4p4	35 Br Bromine [Ar] 3d10 4s2 4p5	36 Kr Krypton [Ar] 3d10 4s2 4p6
V	37 Rb Rubidium [Kr] 5s1	38 Sr Strontium [Kr] 5s2	39 Y Yttrium [Kr] 4d1 5s2	40 Zr Zirconium [Kr] 4d2 5s2	41 Nb Niobium [Kr] 4d4 5s1	42 Mo Molybdenum [Kr] 4d5 5s1	43 Tc Technetium [Kr] 4d5 5s2	44 Ru Ruthenium [Kr] 4d7 5s1	45 Rh Rhodium [Kr] 4d8 5s1	46 Pd Palladium [Kr] 4d10	47 Ag Silver [Kr] 4d10 5s1	48 Cd Cadmium [Kr] 4d10 5s2	49 In Indium [Kr] 4d10 5s2 5p1	50 Sn Tin [Kr] 4d10 5s2 5p2	51 Sb Antimony [Kr] 4d10 5s2 5p3	52 Te Tellurium [Kr] 4d10 5s2 5p4	53 I Iodine [Kr] 4d10 5s2 5p5	54 Xe Xenon [Kr] 4d10 5s2 5p6
VI	55 Cs Cesium [Xe] 6s1	56 Ba Barium [Xe] 6s2	LA	72 Hf Hafnium [Xe] 4f14 5d2 6s2	73 Ta Tantalum [Xe] 4f14 5d3 6s2	74 W Tungsten [Xe] 4f14 5d4 6s2	75 Re Rhenium [Xe] 4f14 5d5 6s2	76 Os Osmium [Xe] 4f14 5d6 6s2	77 Ir Iridium [Xe] 4f14 5d7 6s2	78 Pt Platinum [Xe] 4f14 5d9 6s1	79 Au Gold [Xe] 4f14 5d10 6s1	80 Hg Mercury [Xe] 4f14 5d10 6s2	81 Tl Thallium [Xe] 4f14 5d10 6s2 6p1	82 Pb Lead [Xe] 4f14 5d10 6s2 6p2	83 Bi Bismuth [Xe] 4f14 5d10 6s2 6p3	84 Po Polonium [Xe] 4f14 5d10 6s2 6p4	85 At Astatine [Xe] 4f14 5d10 6s2 6p5	86 Rn Radon [Xe] 4f14 5d10 6s2 6p6
VII	87 Fr Francium [Rn] 7s1	88 Ra Radium [Rn] 7s2	AC	104 Rf Rutherfordium [Rn] 5f14 6d2 7s2	105 Db Dubnium [Rn].5f14.6d3.7s2	106 Sg Seaborgium [Rn].5f14.6d4.7s2	107 Bh Bohrium [Rn].5f14.6d5.7s2	108 Hs Hassium [Rn].5f14.6d6.7s2	109 Mt Meitnerium [Rn].5f14.6d7.7s2	110 Ds Darmstadtium [Rn].5f14.6d9.7s1	111 Rg Roentgenium [Rn].5f14.6d10.7s1	112 Cn Copernicium [Rn].5f14.6d10.7s2	113 Nh Nihomium [Rn].5f14.6d10.7s2.7p1	114 Fl Flerovium [Rn].5f14.6d10.7s2.7p2	115 Mc Moscovium [Rn].5f14.6d10.7s2.7p3	116 Lv Livermorium [Rn].5f14.6d10.7s2.7p4	117 Ts Tennessine [Rn].5f14.6d10.7s2.7p5	118 Og Oganesson [Rn].5f14.6d10.7s2.7p6

Why 3d? why Oxide?



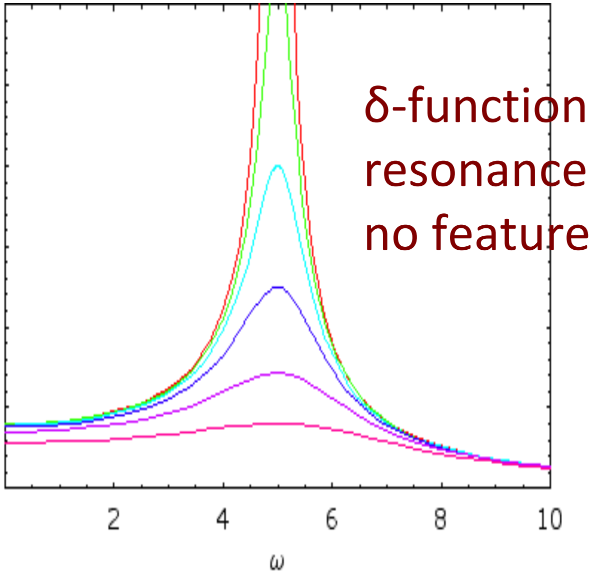




Transition metal oxide 3d $^{1\text{-}10}$ 4s$^{1\text{-}}$ O

Effect of strong Interaction i)

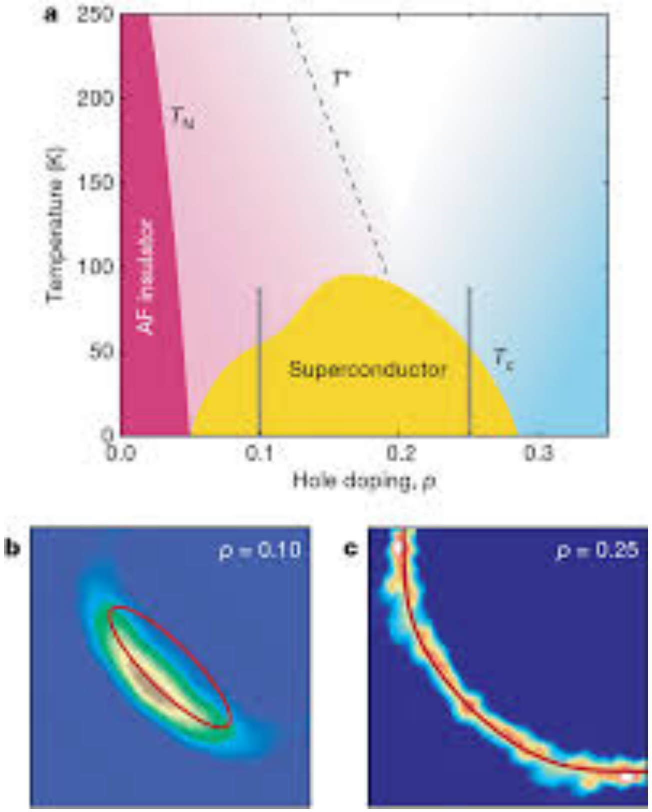
1. Loss of particle → Loss of calculability:



δ-function=Particle

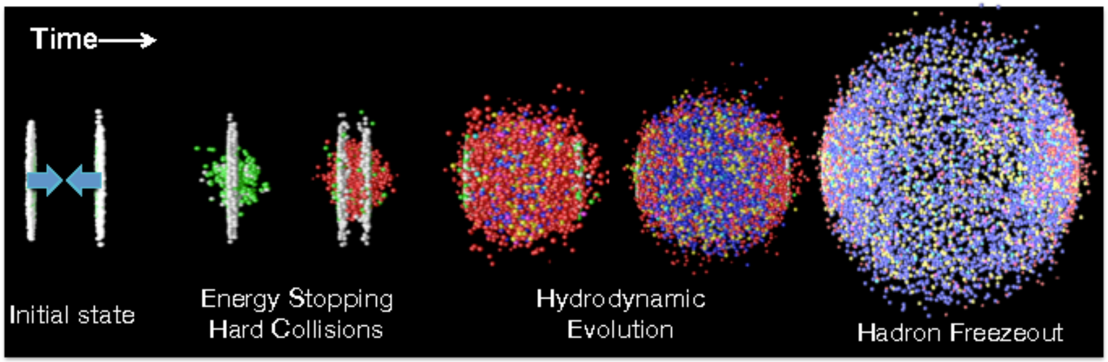
resonance=quasi-particle

no feature=non-particle



Effect of strong Interaction (ii)

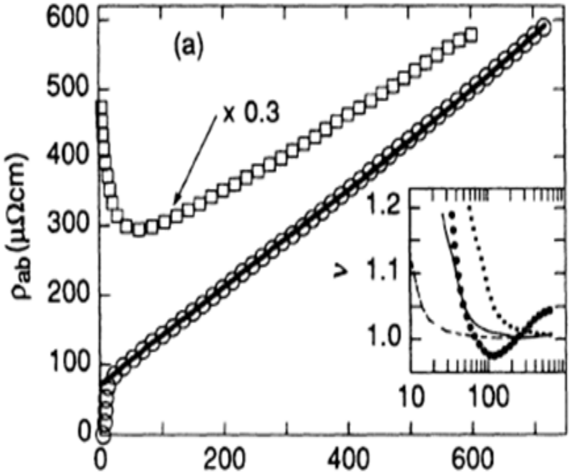
2. Abnormally Rapid Thermalization → Hydro-dynamic description



Plankian Dissipation: Arriving at universality instantly.

$$\tau = \tau_{\hbar} \approx \frac{\hbar}{k_B T}$$

$$\rho \propto \frac{1}{\tau_{\hbar}} \propto k_B T$$

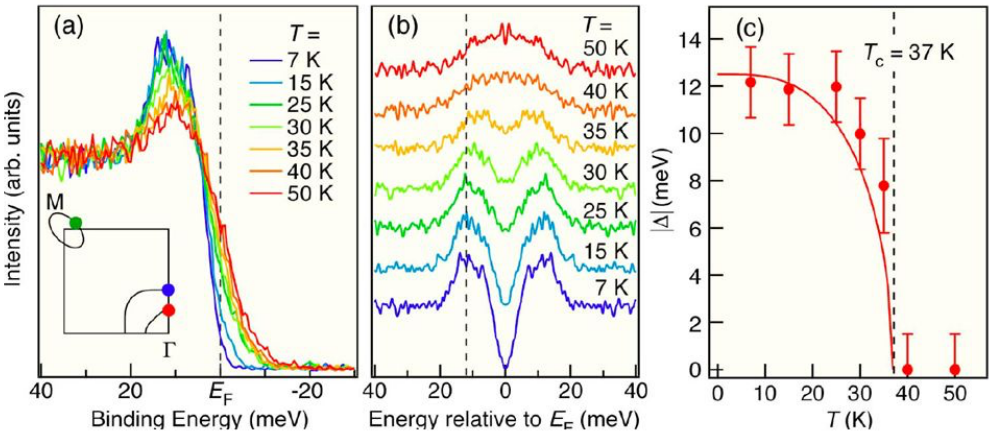


Linear Registivity in Strange Metal

Other Effect of strong Interaction

Pseudo Gap

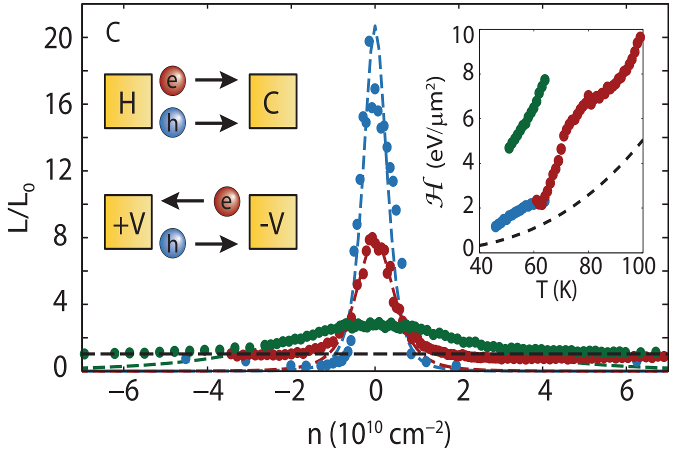
ARPES observation of superconducting gap



$2\Delta/T_c \sim 7$

H. Ding *et al.*, EPL 83, 47001 (2008)

Violation of Wiedemann-Franz law



Problem

1. SIS
2. QFT=calculation method for many body system

3. 20C QFT=pertubation theory
   g=U/t (or t/U), $A= 1+ a\,g^2+b\,g^3+c\,g^4+d\,g^5+\cdots$
4. g>1 → the more you calculate the wronger you beocome.

5. No calculation method for such matter.
   → No theory for new material, high Tc.
   Recognized from 1930, Famous after 1986.

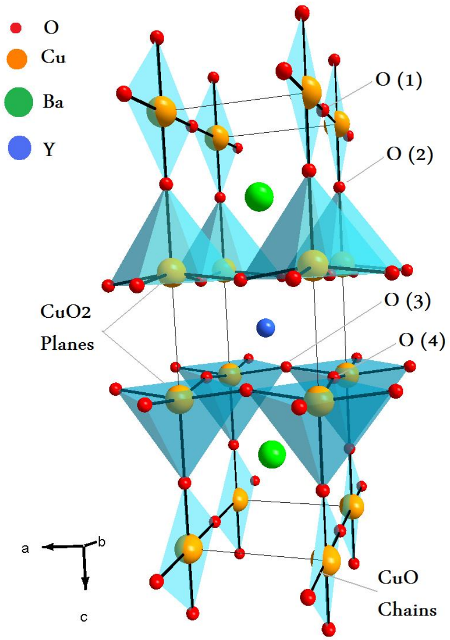
Implications

Condensed matter theory

= Structure in UV scale → functionality in IR scale

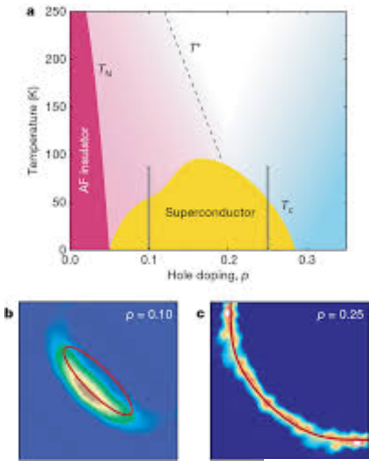
physics with reductionism.

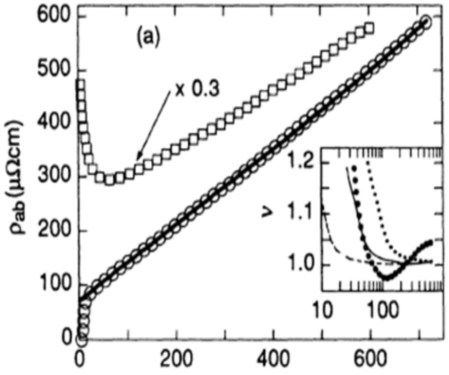
Not applicable to SIS.



keV

meV

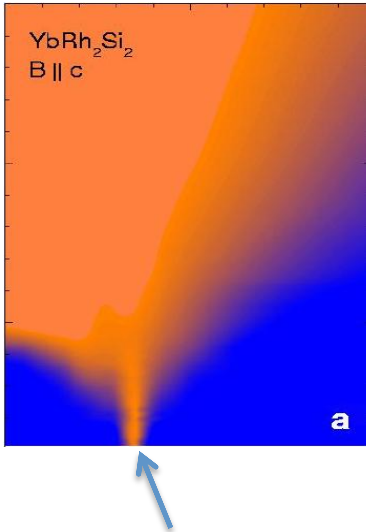




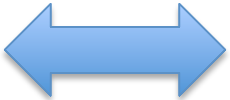
New idea?

- Similarity of Quantum Critical point and black hole

  → New field theory for strongly int. system



QCP

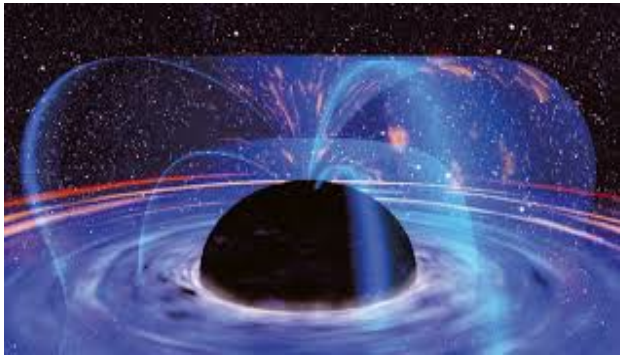


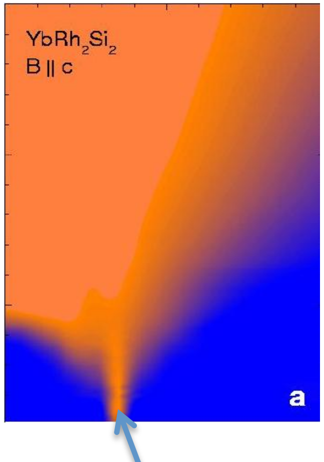
Quantum critical point

1. Critical point→ Fluctuation of all size .
2. inconsistency→ divegence:
   vapor-water critical point: density =0 as water.
   Density=infinity as vapor 0 or infinity
3. For divergence L→infinity
4. Quantum critical= lcutuation in time.
   Size of time=1/Temp=β→infinity ➔ T=0.

* divergence of a order parameter means not a good parameter for the system
appearance of massless d.o.f $\omega = k^z$

Similarity of BH and QCP





Quantum Critical point

Black Hole has

i) Universality /no hair / information loss

ii) Thermodynamics (1st law ←→Einstein eq.)

iii) Transport

So is the QCP.

one for all.

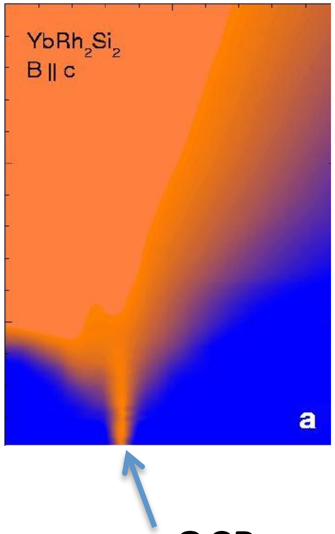
Good Observables for the new theory?

Most universal quantity: spectral function and Transport near QCP

Absence of scale→absence of structural dependence → Universality

Classifying QCP : dynamical exponent

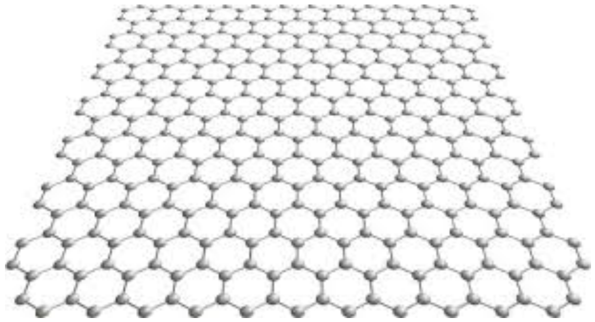
Z, θ: $\omega = k^z$, $[s] = D - \theta$

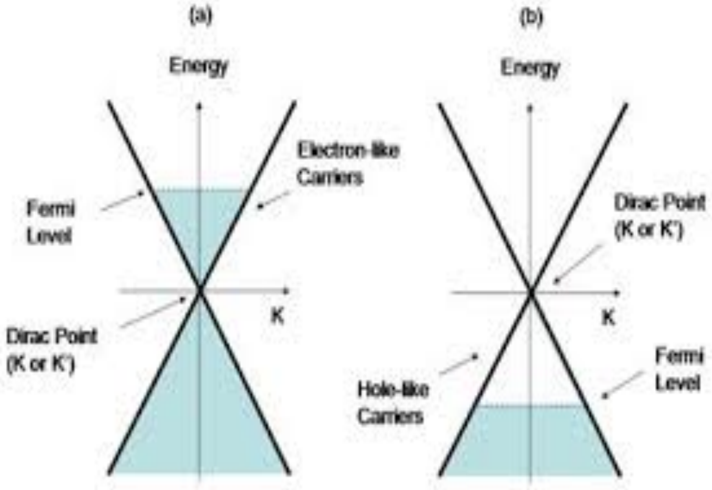


QCP

holography meets the experiment

Simplest QCP is z=1 : graphene





Q: strong coupling? …. 10 years of speculation

1. $$g^2 = \frac{e^2 \cdot c}{4\pi\epsilon\hbar c \cdot v_F} \sim 1$$

2. near Dirac Point : Tiny FS → No (insufficient) screening

experimental evidence

Observation of the Dirac fluid and the breakdown of the Wiedemann-Franz law in graphene

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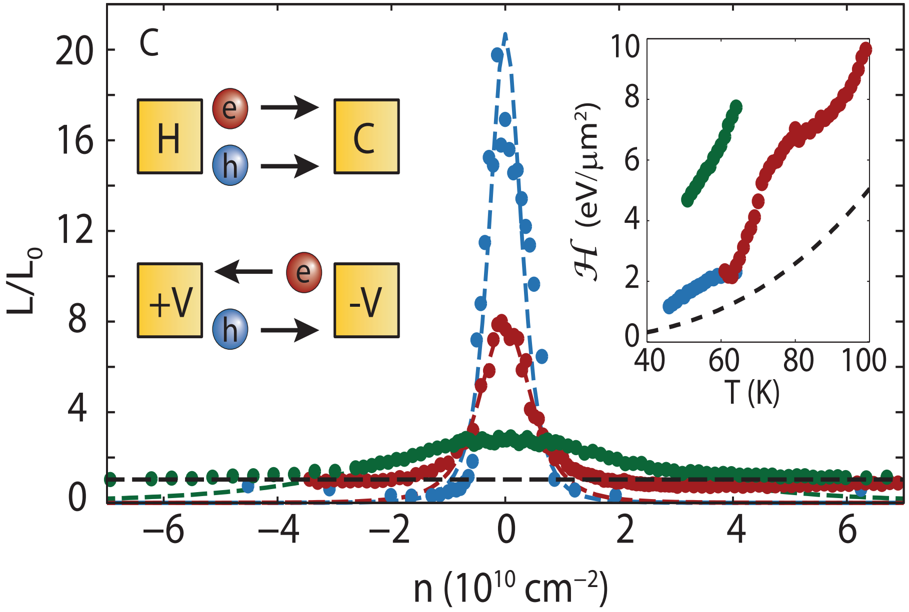
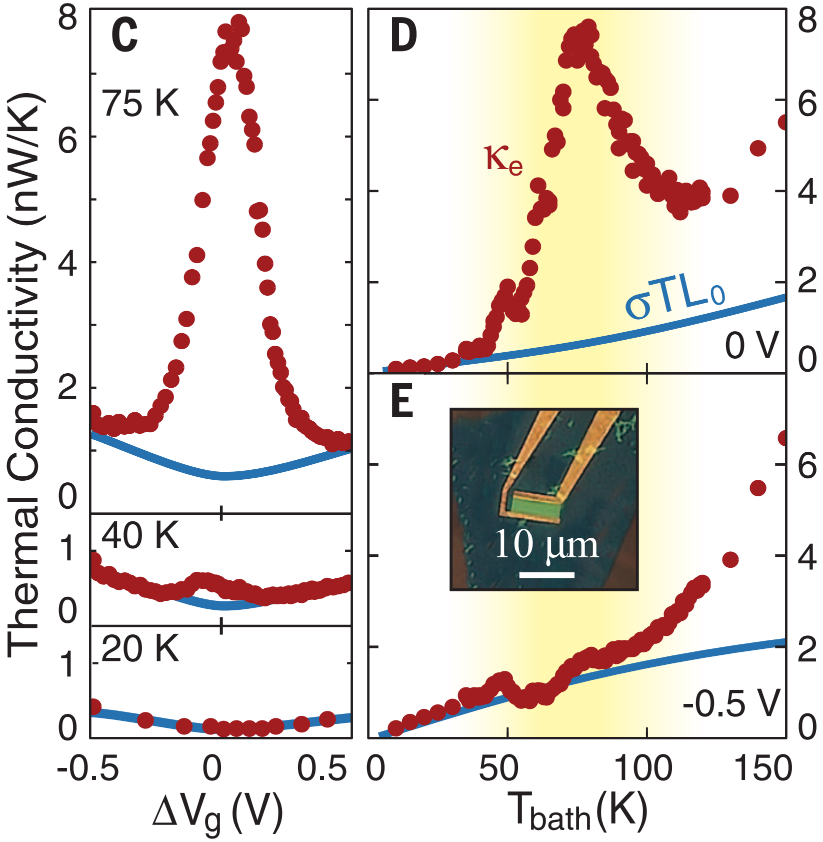
Andrew Lucas,[1] Subir Sachdev,[1,3] Philip Kim,[1,2]* Takashi Taniguchi,[4] Kenji Wa
Thomas A. Ohki,[5] Kin Chung Fong[5]*

4 March 2016 Science





Simple → Pure → Hard !

holographic model

Idea : neutral current → Enhance the heat conductivity

$$S=\int d^4x\sqrt{-g}\left[R-\frac{1}{2}\left[(\partial\phi)^2+\Phi_1(\phi)(\partial\chi_1)^2+\Phi_2(\phi)(\partial\chi_2)^2\right]-V(\phi)-\frac{Z(\phi)}{4}F^2-\frac{W(\phi)}{4}G^2\right]$$

$$\sigma=\sigma_0(1+(Q/Q_0)^2),$$

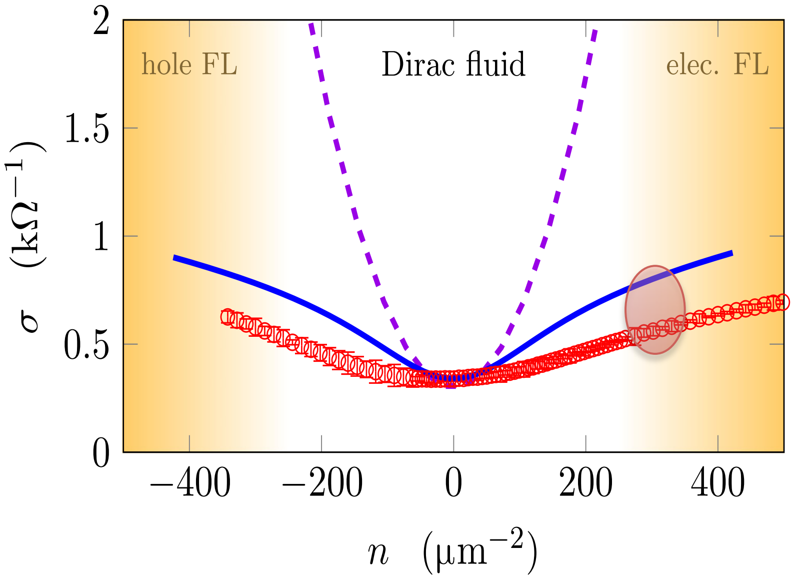
$$\kappa=\frac{\bar{\kappa}}{1+(1+g_n^2)(Q/Q_0)^2}$$

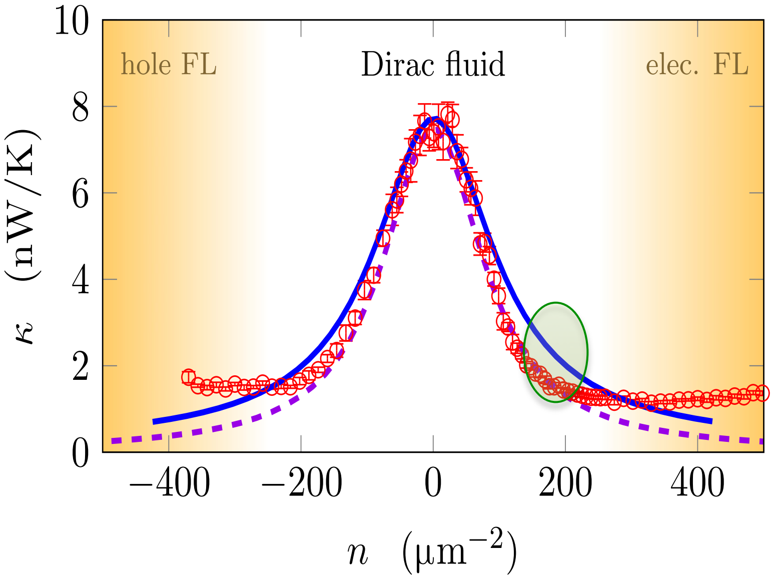
4 basic parameters.

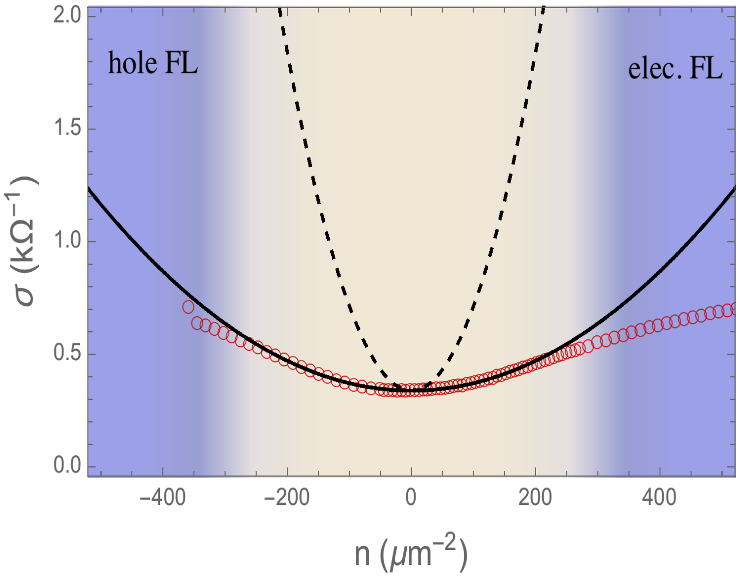
at 75K, $\sigma_0=0.338/k\Omega$, $\bar{\kappa}=7.7nW/K$, $Q_0=e\cdot 320/(\mu m)^2$,

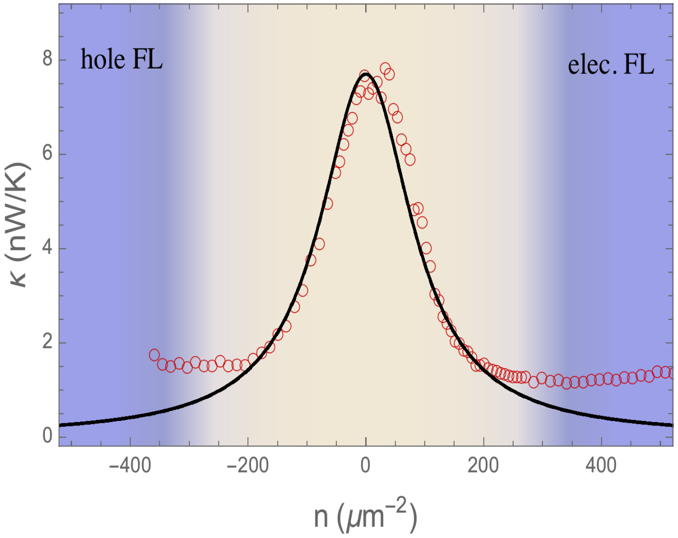
$$\sigma_0=\frac{e^2}{\hbar}2Z_0,\quad \bar{\kappa}=\frac{4\pi k_B}{\hbar}\frac{sT}{k^2},\quad Q_0^2=\frac{\hbar\sigma_0}{4\pi k_B}sk^2.$$

Hydrodynamics vs quantum Holography in data fitting



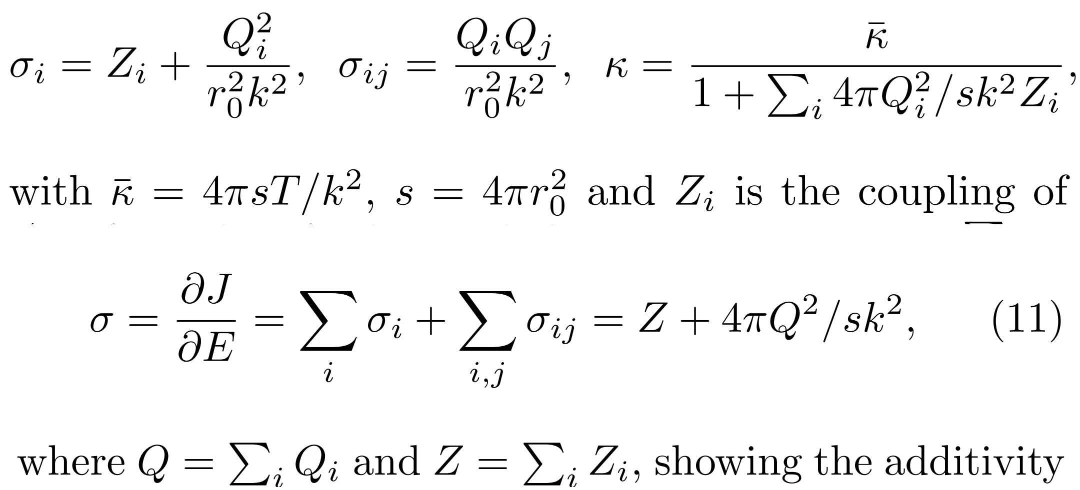






(b)

Remark: all analytical

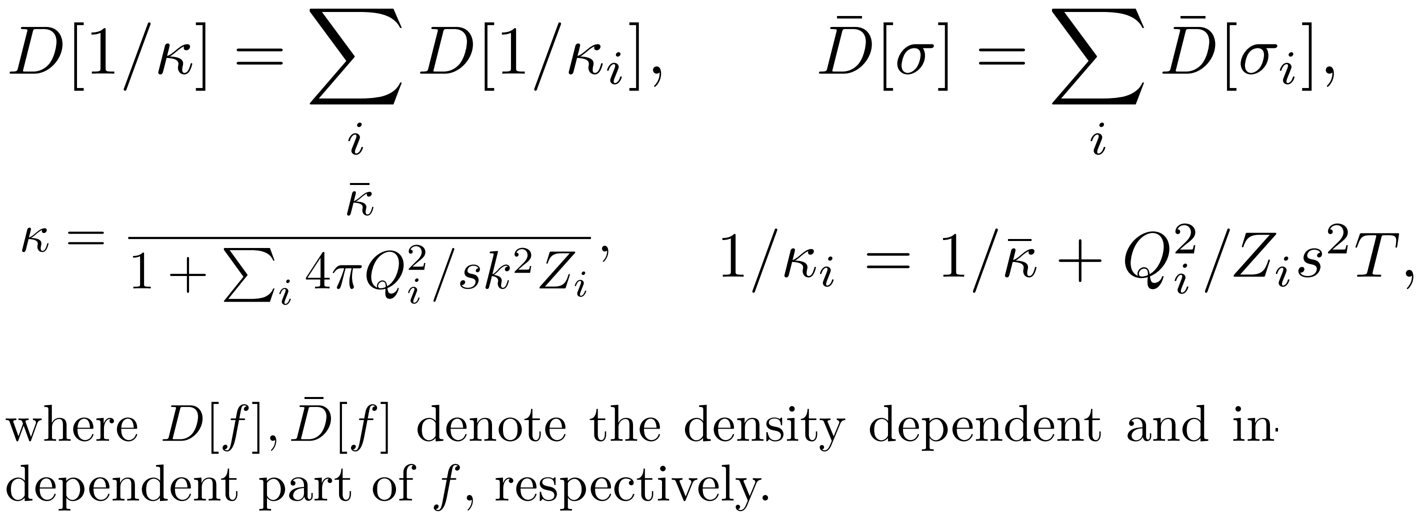


$$\sigma_i = Z_i + \frac{Q_i^2}{r_0^2 k^2}, \quad \sigma_{ij} = \frac{Q_i Q_j}{r_0^2 k^2}, \quad \kappa = \frac{\bar{\kappa}}{1 + \sum_i 4\pi Q_i^2 / s k^2 Z_i},$$

with $\bar{\kappa} = 4\pi s T / k^2$, $s = 4\pi r_0^2$ and Z_i is the coupling of

$$\sigma = \frac{\partial J}{\partial E} = \sum_i \sigma_i + \sum_{i,j} \sigma_{ij} = Z + 4\pi Q^2 / s k^2, \qquad (11)$$

where $Q = \sum_i Q_i$ and $Z = \sum_i Z_i$, showing the additivity

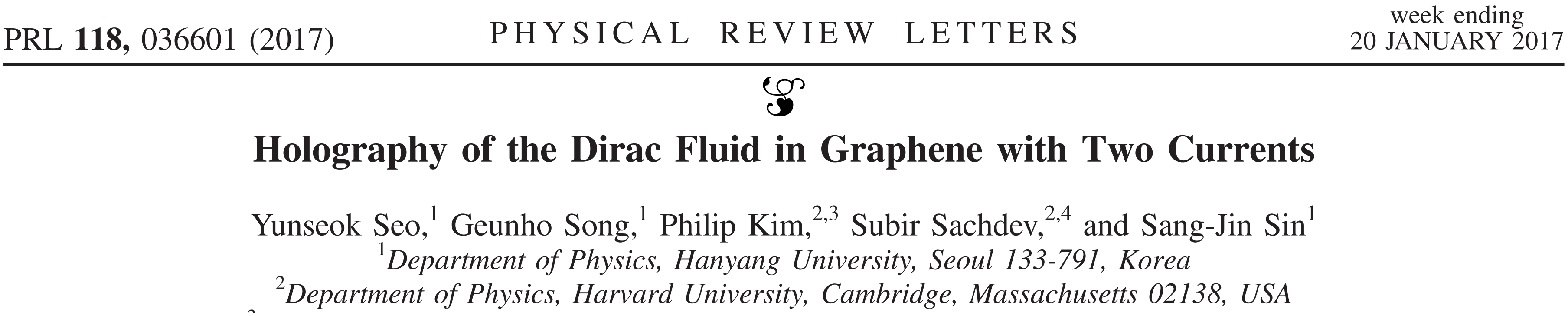


$$D[1/\kappa] = \sum_i D[1/\kappa_i], \qquad \bar{D}[\sigma] = \sum_i \bar{D}[\sigma_i],$$

$$\kappa = \frac{\bar{\kappa}}{1 + \sum_i 4\pi Q_i^2 / s k^2 Z_i}, \qquad 1/\kappa_i = 1/\bar{\kappa} + Q_i^2 / Z_i s^2 T,$$

where $D[f], \bar{D}[f]$ denote the density dependent and independent part of f, respectively.

The story was published as



PRL **118,** 036601 (2017) PHYSICAL REVIEW LETTERS week ending 20 JANUARY 2017

Holography of the Dirac Fluid in Graphene with Two Currents

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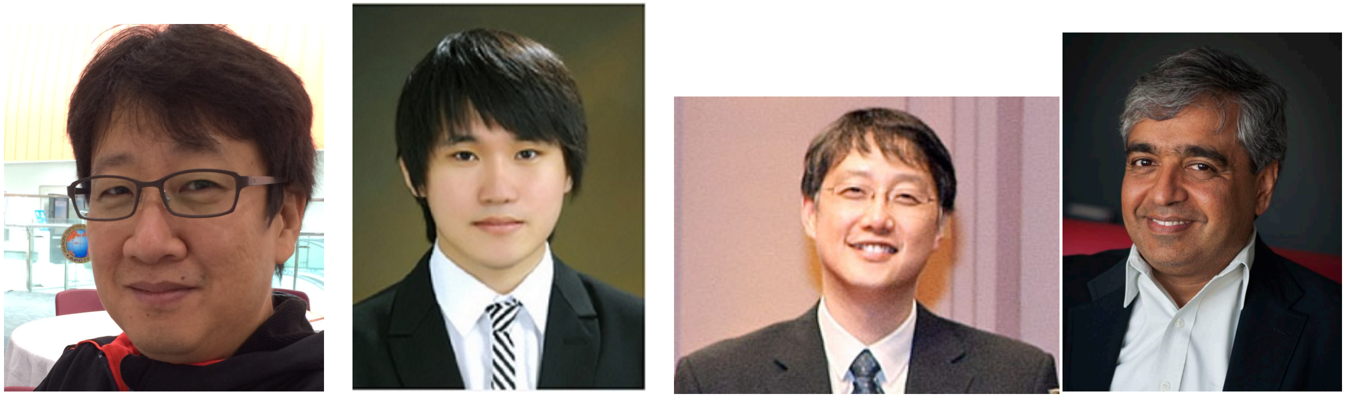
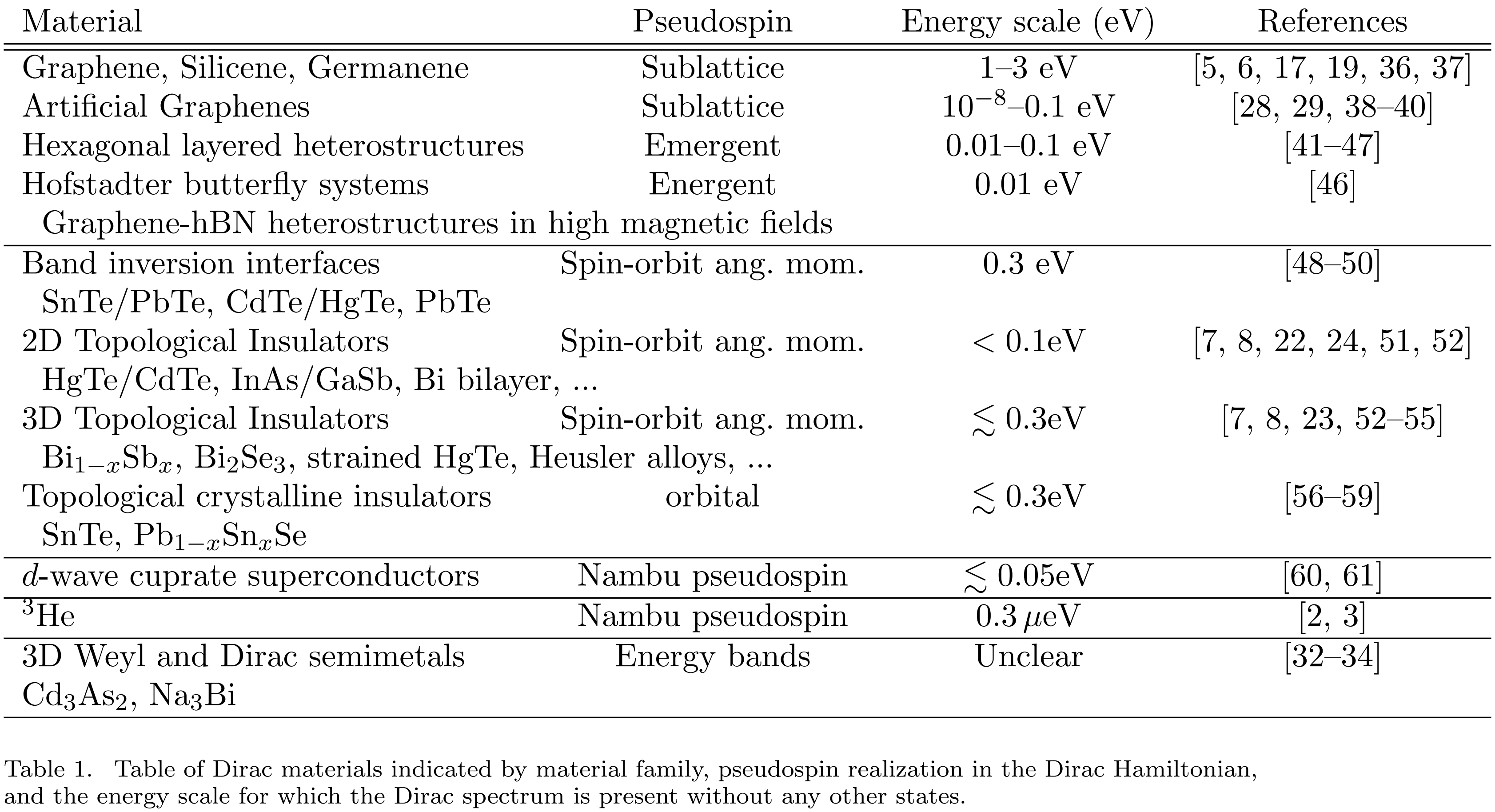


Phys.Rev.Lett. 118 (2017) no.3, 036601

Editors' Suggestion

Other z=1 material ?

Dirac material is a class (1405.5774): 우리 예측: so is the anomalous transport.



Material	Pseudospin	Energy scale (eV)	References
Graphene, Silicene, Germanene	Sublattice	1–3 eV	[5, 6, 17, 19, 36, 37]
Artificial Graphenes	Sublattice	10^{-8}–0.1 eV	[28, 29, 38–40]
Hexagonal layered heterostructures	Emergent	0.01–0.1 eV	[41–47]
Hofstadter butterfly systems	Energent	0.01 eV	[46]
Graphene-hBN heterostructures in high magnetic fields			
Band inversion interfaces	Spin-orbit ang. mom.	0.3 eV	[48–50]
SnTe/PbTe, CdTe/HgTe, PbTe			
2D Topological Insulators	Spin-orbit ang. mom.	< 0.1eV	[7, 8, 22, 24, 51, 52]
HgTe/CdTe, InAs/GaSb, Bi bilayer, ...			
3D Topological Insulators	Spin-orbit ang. mom.	$\lesssim 0.3$eV	[7, 8, 23, 52–55]
$Bi_{1-x}Sb_x$, Bi_2Se_3, strained HgTe, Heusler alloys, ...			
Topological crystalline insulators	orbital	$\lesssim 0.3$eV	[56–59]
SnTe, $Pb_{1-x}Sn_xSe$			
d-wave cuprate superconductors	Nambu pseudospin	$\lesssim 0.05$eV	[60, 61]
^{3}He	Nambu pseudospin	0.3 μeV	[2, 3]
3D Weyl and Dirac semimetals	Energy bands	Unclear	[32–34]
Cd_3As_2, Na_3Bi			

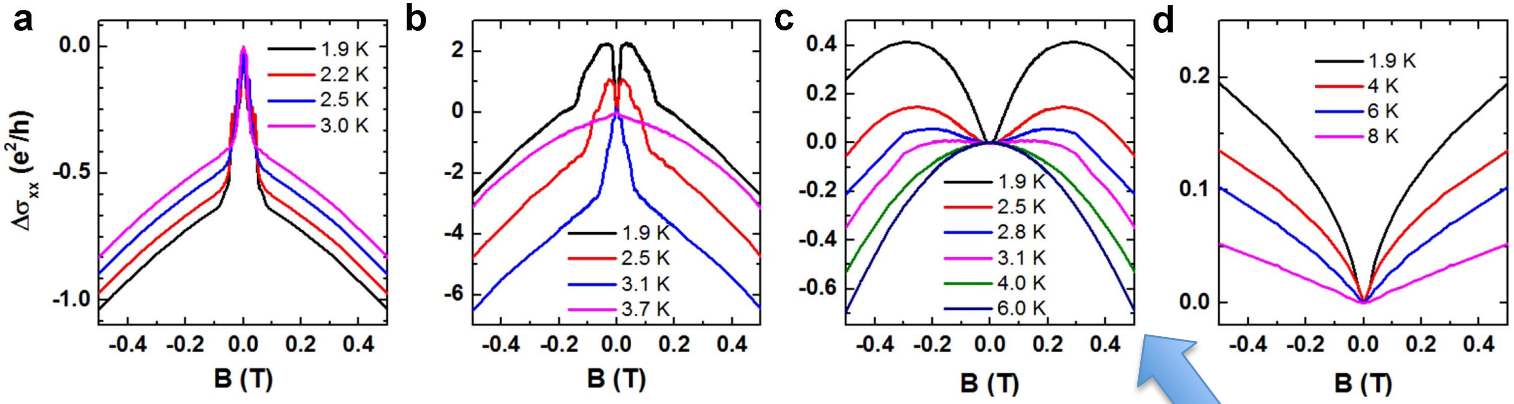
Table 1. Table of Dirac materials indicated by material family, pseudospin realization in the Dirac Hamiltonian, and the energy scale for which the Dirac spectrum is present without any other states.

Surface of TI

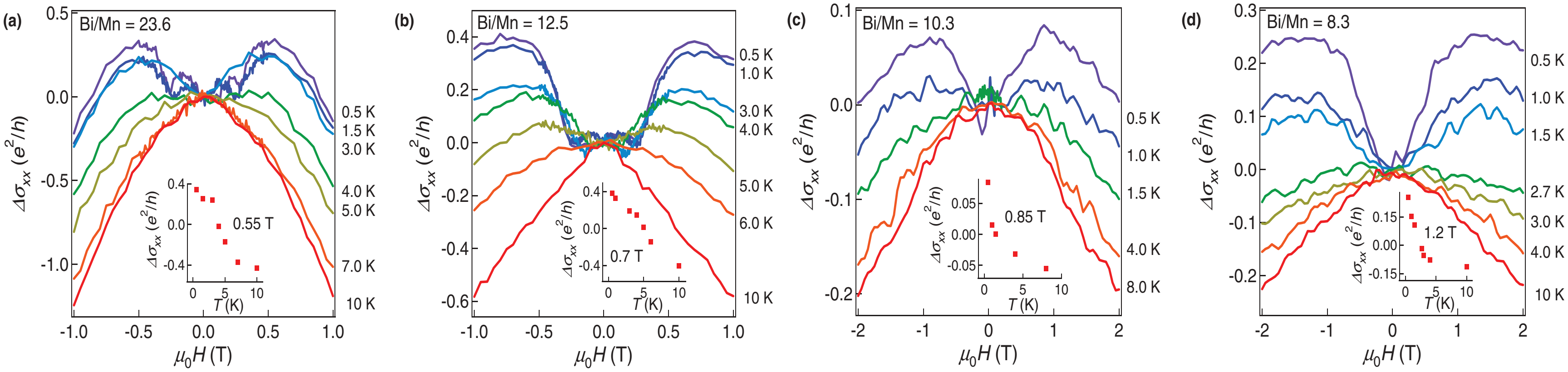
Similar, but differ by strong spin-orbit interaction

Surface phenomena of TI : WAL → WL transition

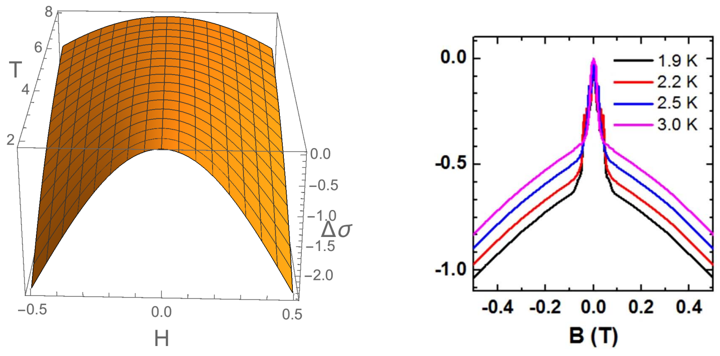
1. Bi_2Te_3 with Cr doping: Bao et.al, SREP02391



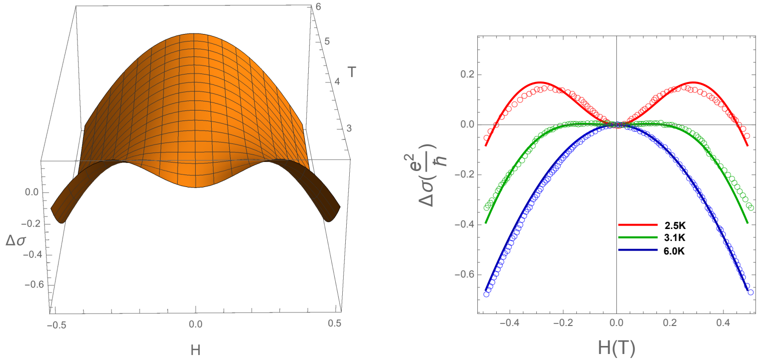
2. . Bi_2Se_3 with Mn doping : Zhang et.al, prB86,205127(2012)



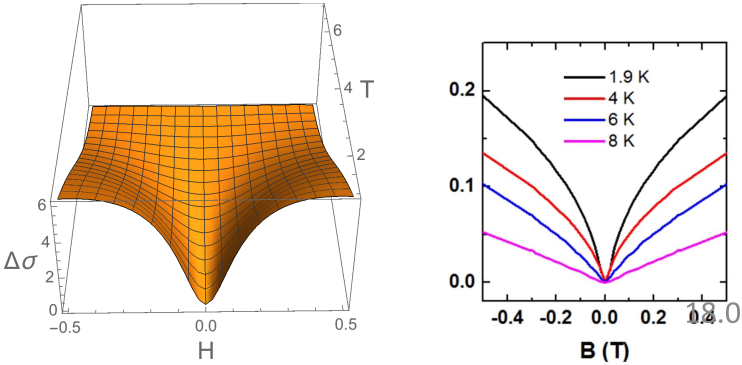
Surface states of TI [1703.07361]

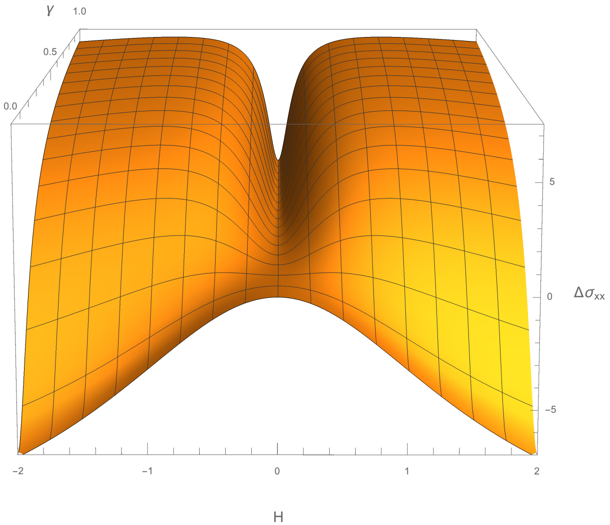


(a) (b)

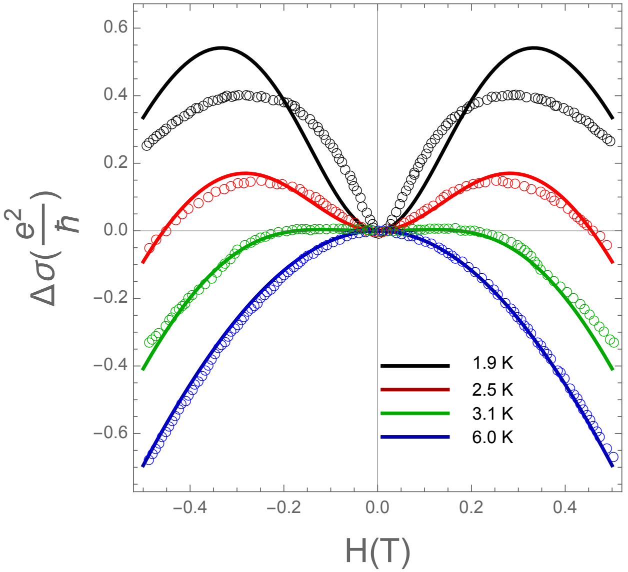


(c) (d)





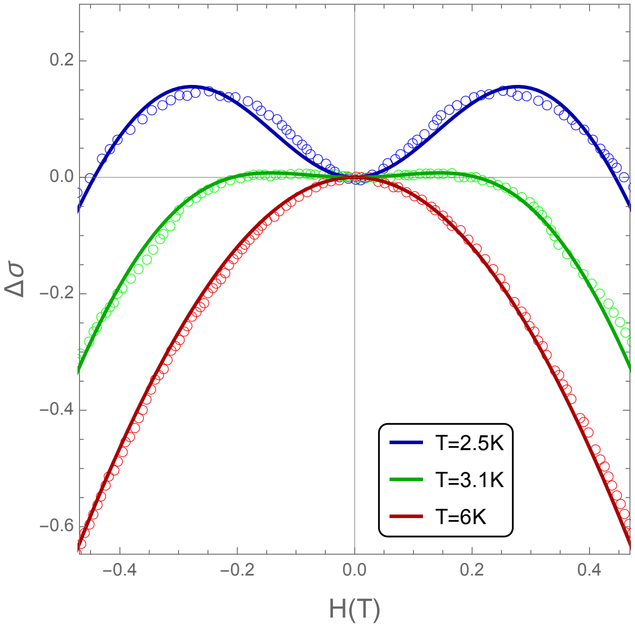
Evolution of MC curve from WAL to WL

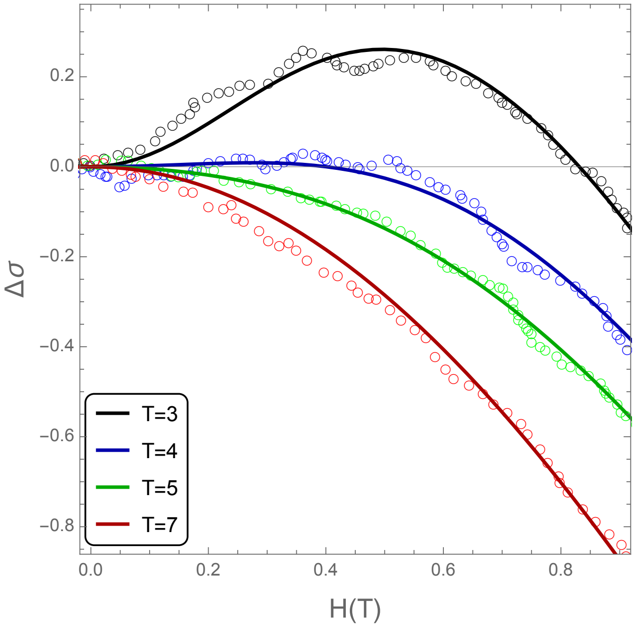


Universality in transition due to surface gap

Theory fits

not only for Cr doped Bi_2Te_3 but also Mn doped Bi_2Se_3



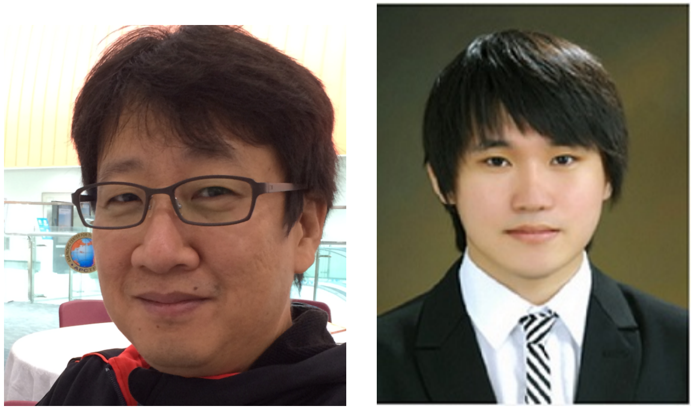


results

Strong Correlation Effects on Surfaces of Topological Insulators via Holography

Yunseok Seo, Geunho Song and Sang-Jin Sin
Department of Physics, Hanyang University, Seoul 04763, Korea.

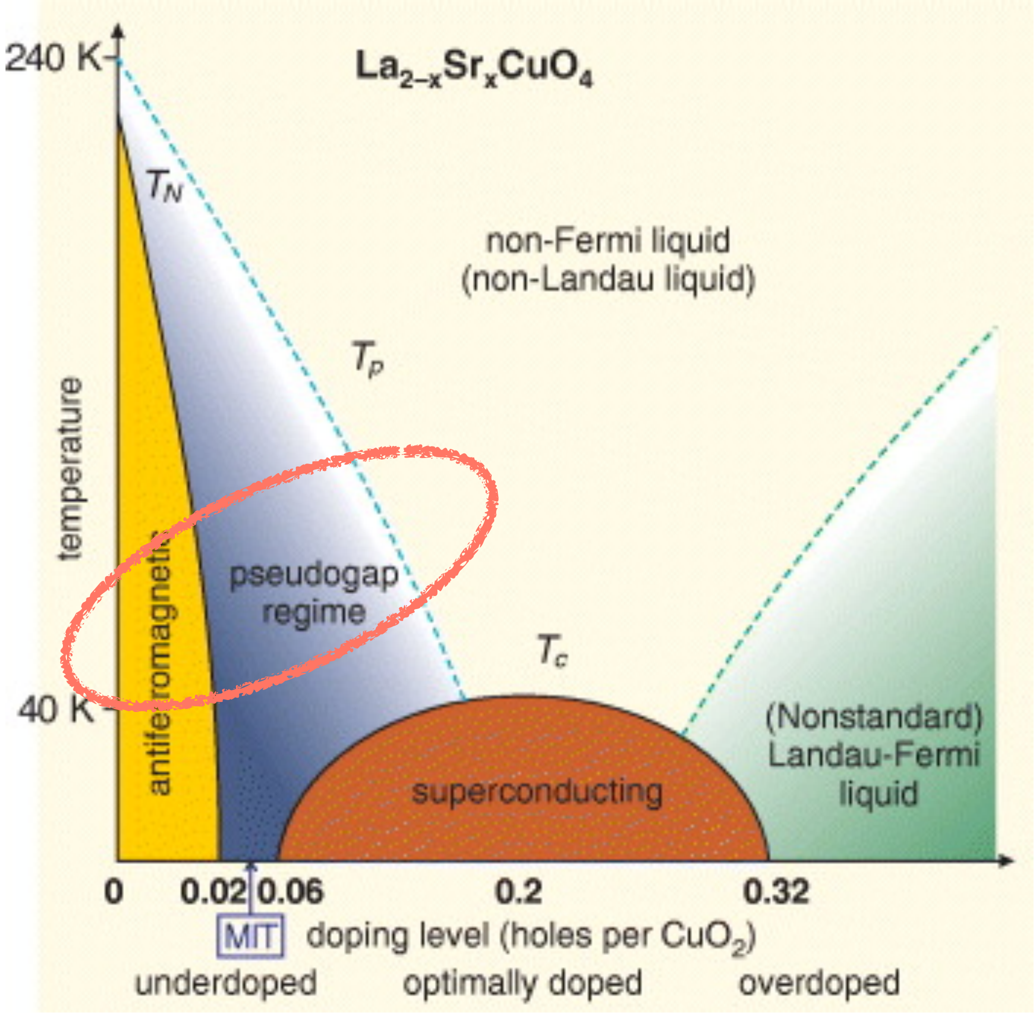
Published in Phys.Rev. B96 (2017) no.4, 041104 (rapid communications)



+SJS

Small Fermi Surfaces and Strong Correlation Effects in Dirac Materials with Holography
Y. Seo, G. Song, C. Park + SJS
Published in JHEP 1710 (2017) 204

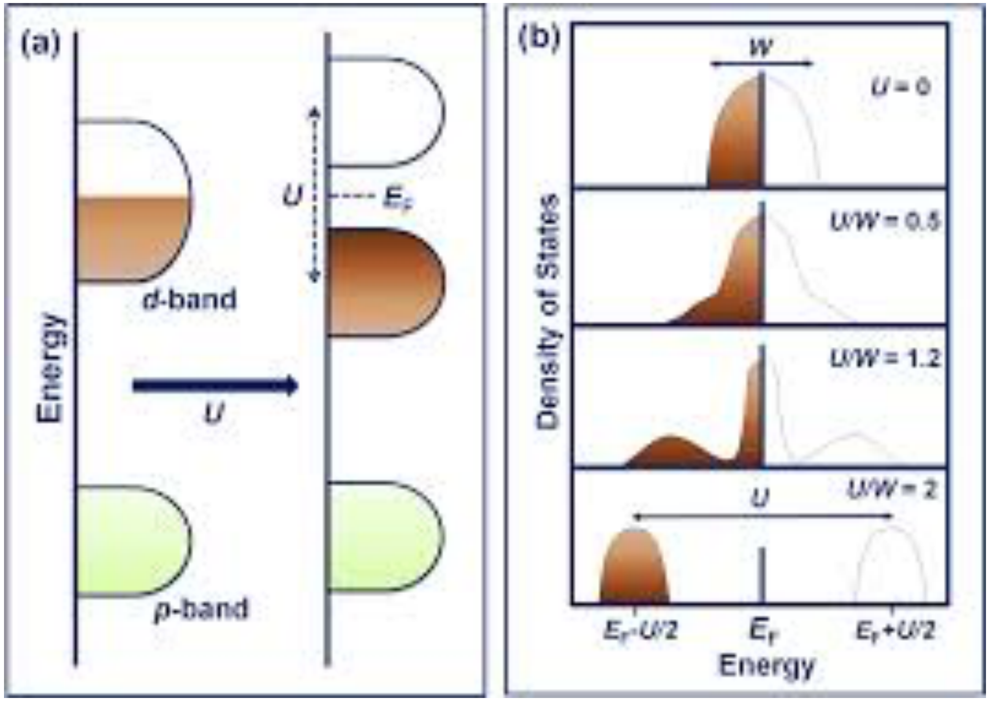
So far, transport,   What about spectrum?



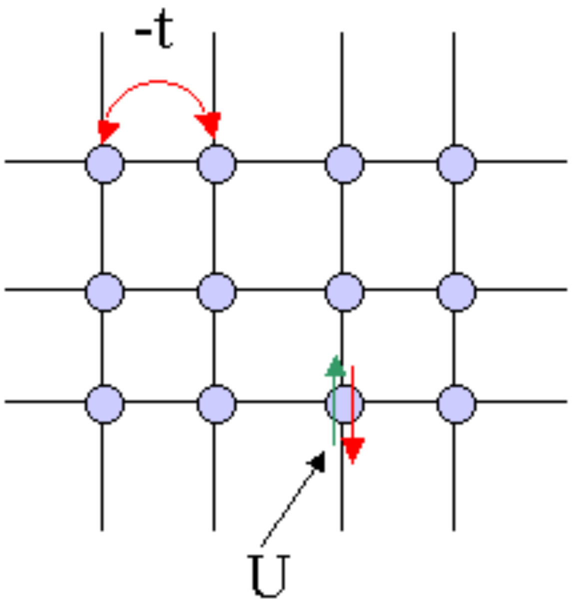
Spectral data-ARPES

- It comes from fundamental fermion’s two point function .
- Mott transition is first candidate to understand
- DMFT is successful to an extend so we can compare

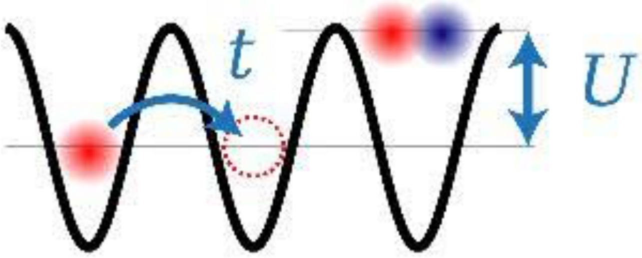
Mott Transition



Hubbard model



Coupling = U/t



대부분의 실험은 t 를 조절한다.

$$H = -t \sum_{\langle i,j\rangle,\sigma} \left(c^\dagger_{i,\sigma} c_{j,\sigma} + c^\dagger_{j,\sigma} c_{i,\sigma}\right) + U \sum_{i=1}^{N} n_{i\uparrow} n_{i\downarrow},$$

e: To move or not to, that is the problem

Real problem to human : unsolvable!

Theme

Hubbard model (HM) → Not solvable

Holography is effective tool.

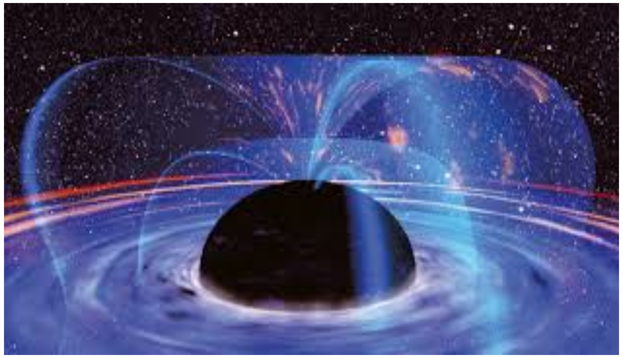
Can we replace the Hubbard Model by a calculable h-model?

Spectral function

$$ds^2 = -\frac{r^2 f(r)}{L^2}dt^2 + \frac{L^2}{r^2 f(r)}dr^2 + \frac{r^2}{L^2}d\vec{x}^2$$

$$f(r) = 1 + \frac{Q^2}{r^4} - \frac{M}{r^3}, \qquad A = \mu\left(1 - \frac{r_0}{r}\right),$$

$$Q = r_0\,\mu, M = r_0(r_0^2 + \mu^2).$$



$$S_D = \int d^4x\sqrt{-g}i\bar{\psi}\left(\Gamma^M \mathcal{D}_M - m - ip\,\Gamma^{MN}F_{MN}\right)\psi + S_{\rm bd},$$

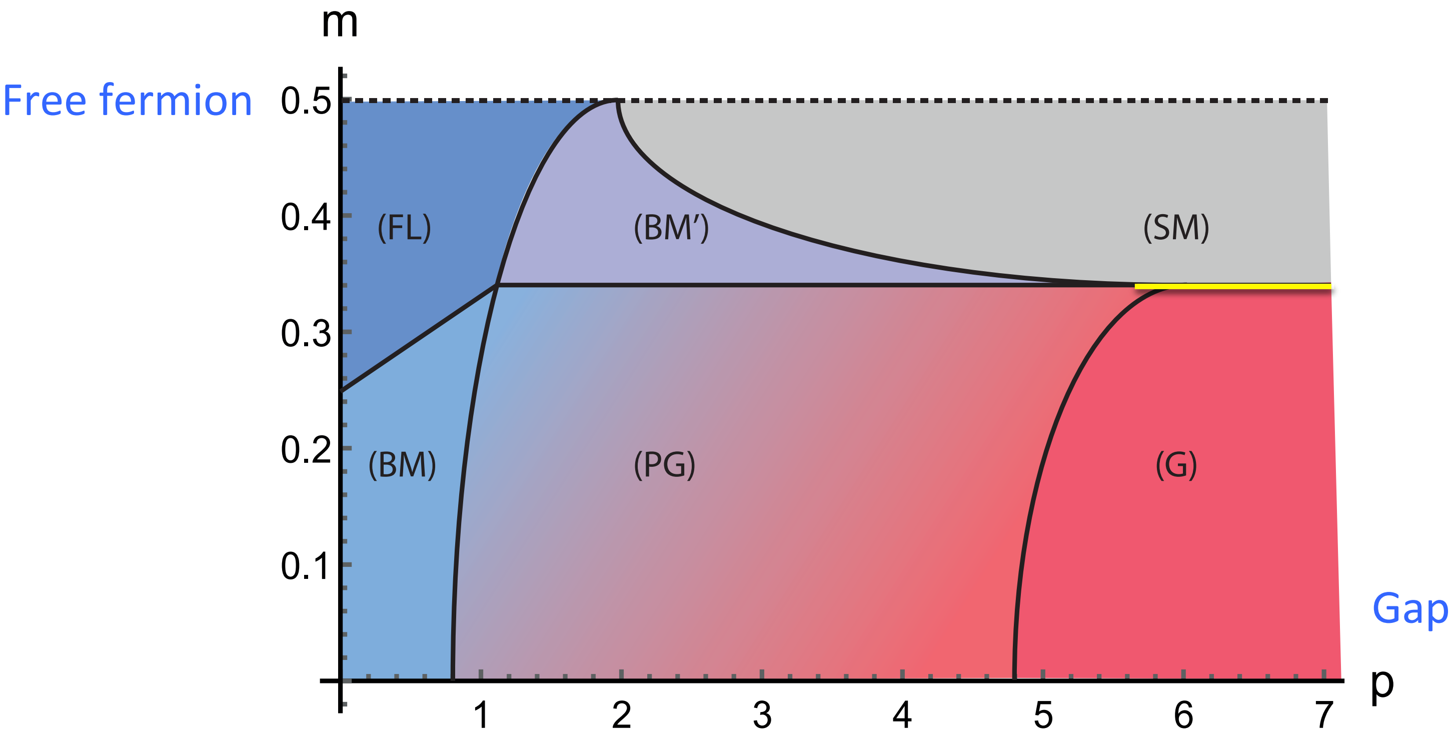
$$\mathcal{D}_M = \partial_M + \frac{1}{4}\omega_{abM}\Gamma^{ab} - iqA_M.$$

$$S_{\rm bd} = \frac{\pm 1}{2}\int d^3x\sqrt{h}\bar{\psi}\psi = \frac{\pm 1}{2}\int d^3x\sqrt{h}(\bar{\psi}_-\psi_+ + \bar{\psi}_+\psi_-),$$

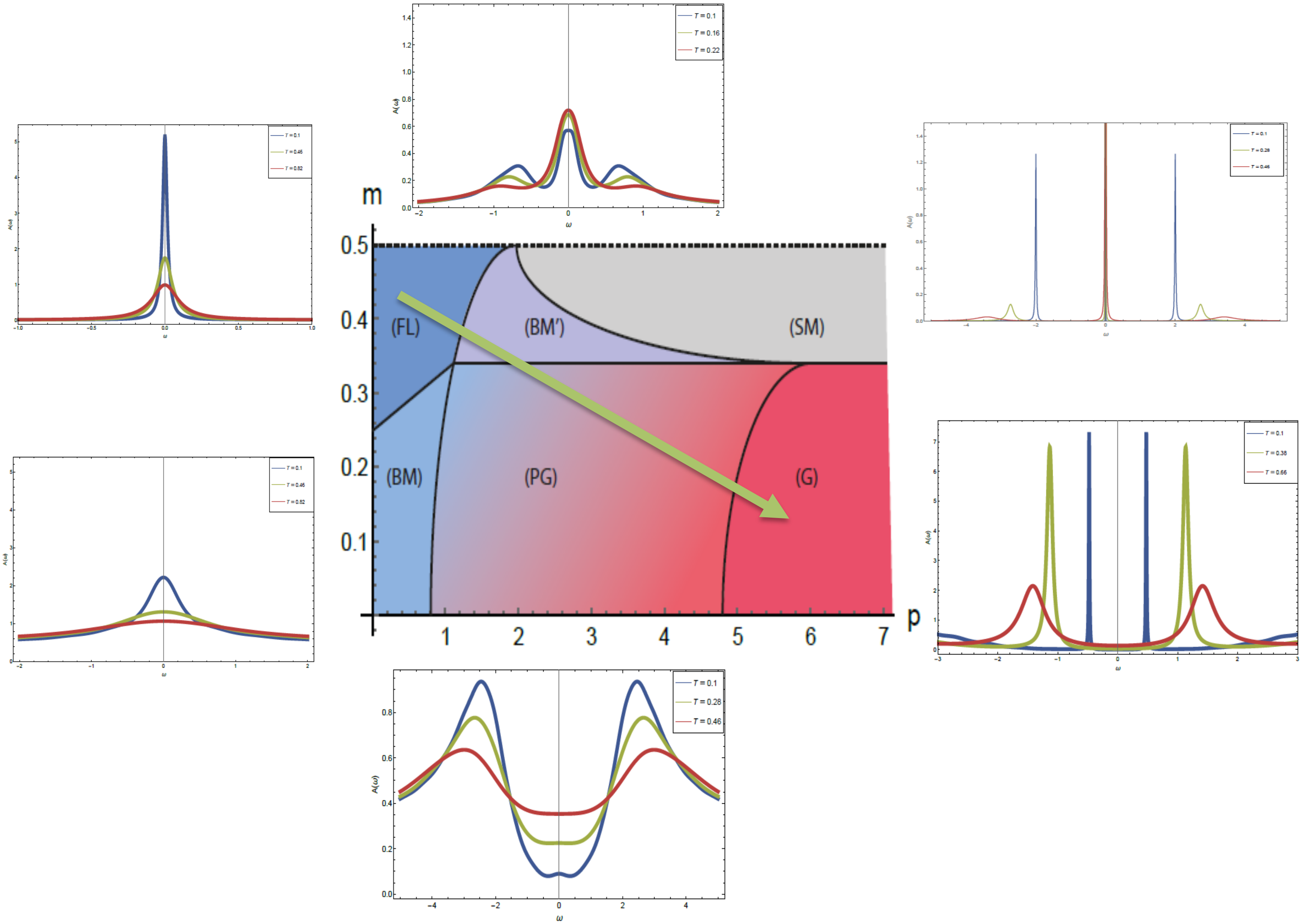
$h = -gg^{rr}$, $\psi_\pm$ are the spin-up and down

Phase Diagram has 6 phases

$$S_\psi = \int d^4x\sqrt{-g}\,i\bar{\psi}(\not{D} - m - ip\not{F})\psi + S_{bdy}$$



6 phases

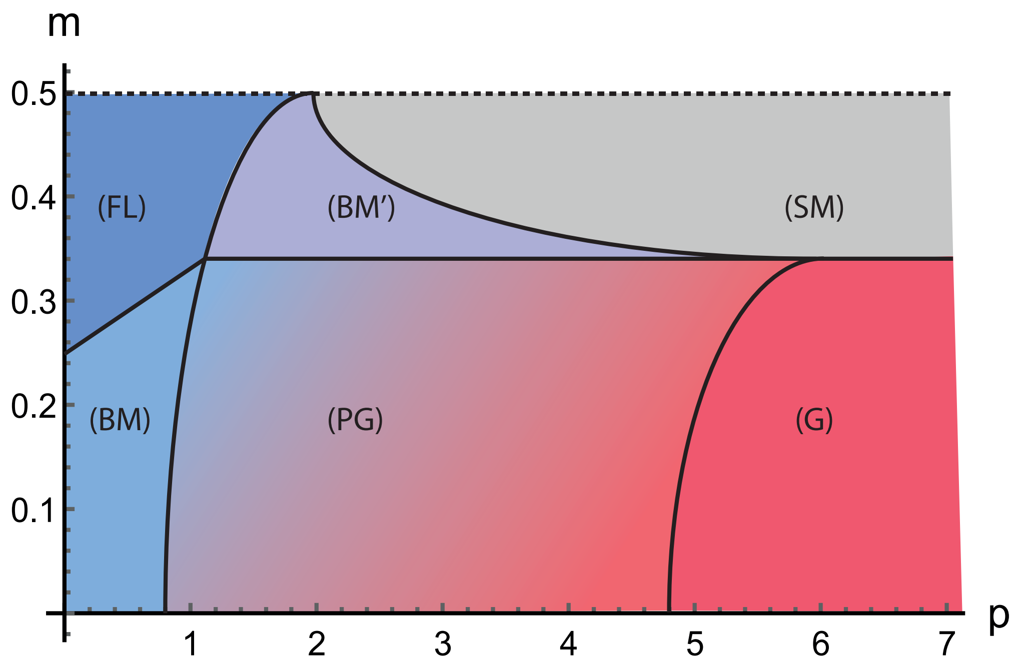

m
p
0.5
0.4
0.3
0.2
0.1
1
2
3
4
5
6
7
(FL)
(BM′)
(SM)
(BM)
(PG)
(G)
A(ω)
ω
T = 0.1
T = 0.16
T = 0.22
T = 0.1
T = 0.46
T = 0.82
T = 0.1
T = 0.46
T = 0.82
T = 0.1
T = 0.28
T = 0.46
T = 0.1
T = 0.38
T = 0.66
T = 0.1
T = 0.28
T = 0.46

understanding phase diagram

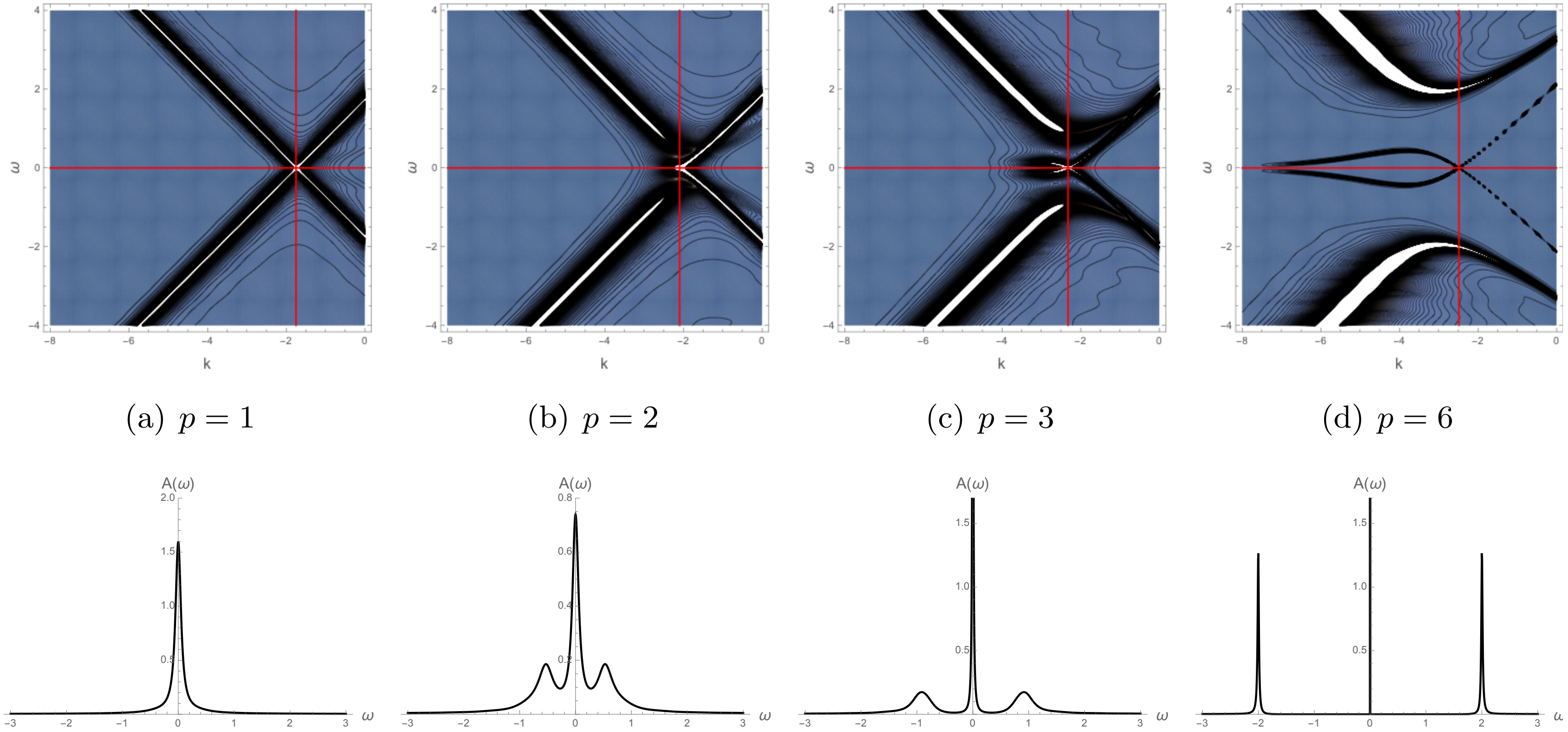
$$\Delta = d/2 - m$$

$$\Delta_{FF} = (d-1)/2$$

m=1/2 is the Free fermionic regardless of dim.

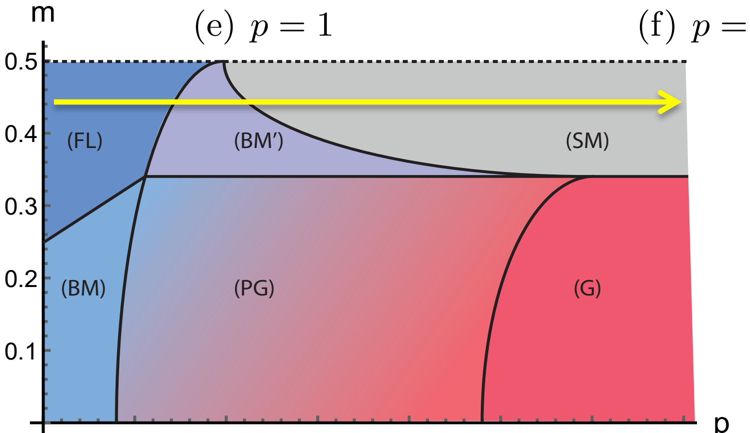


Role of p in BM' and SM creation



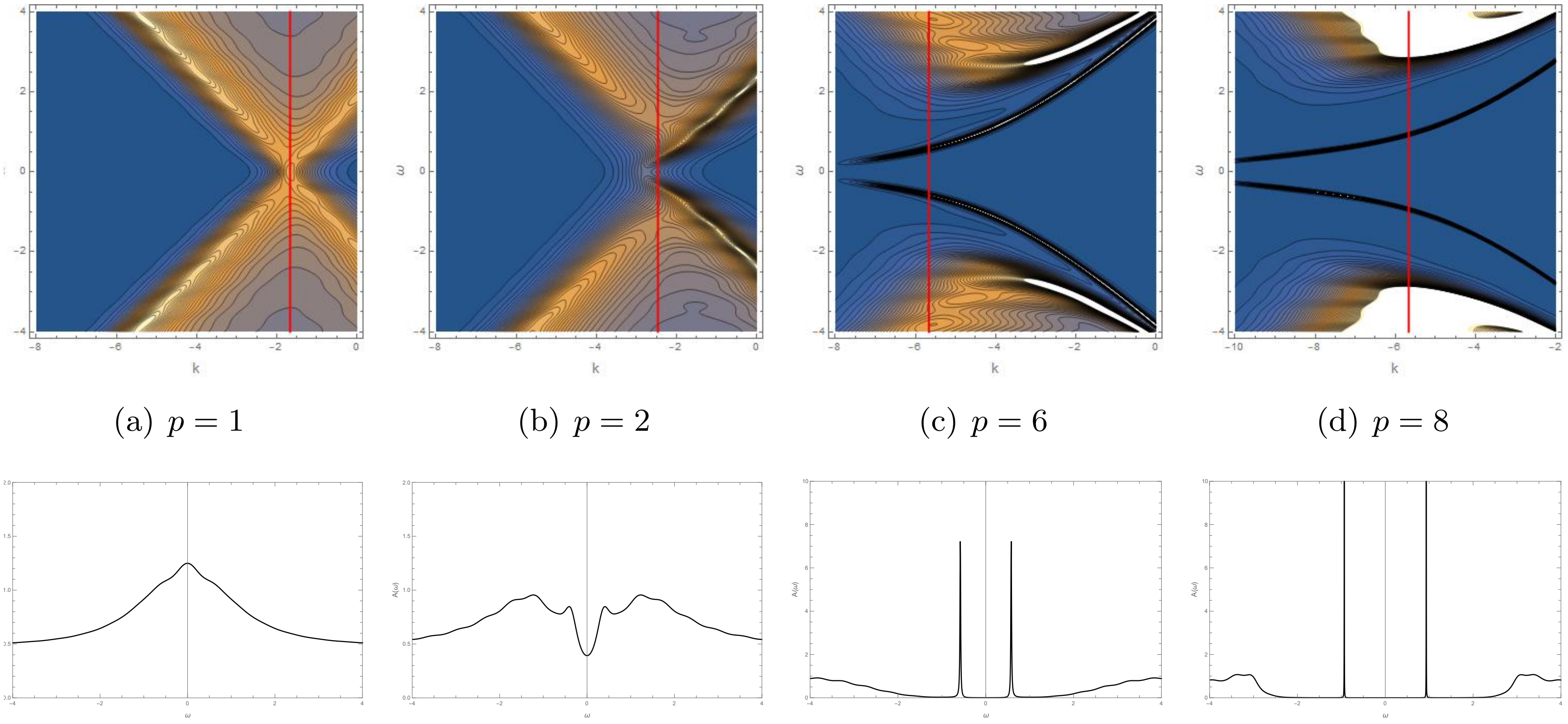
(a) $p = 1$ (b) $p = 2$ (c) $p = 3$ (d) $p = 6$

(e) $p = 1$ (f) $p = 2$ (g) $p = 3$ (h) $p = 6$



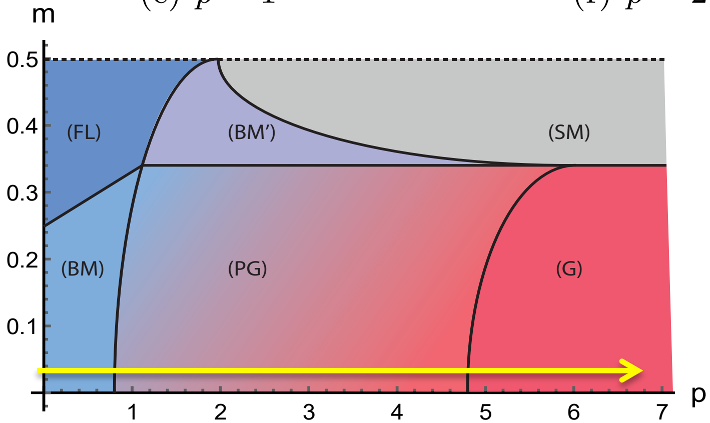
18.04@KPS

Role of p in PG and Gap creation

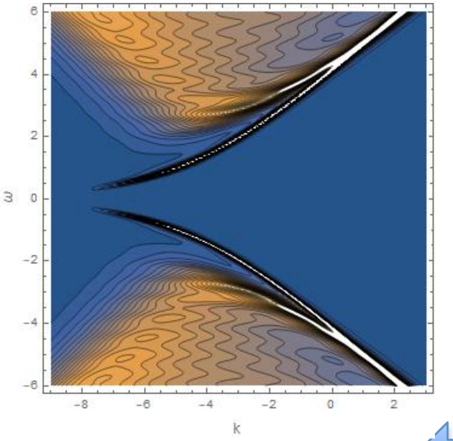


(a) $p = 1$ (b) $p = 2$ (c) $p = 6$ (d) $p = 8$

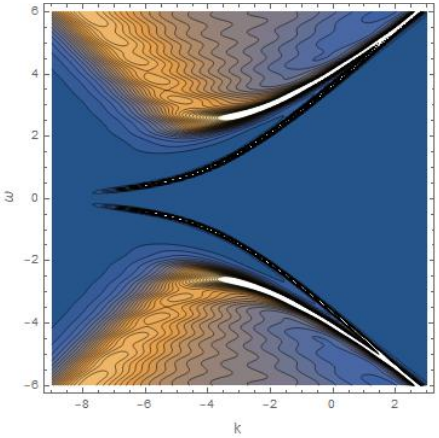
(e) $p = 1$ (f) $p = 2$ (g) $p = 6$ (h) $p = 8$



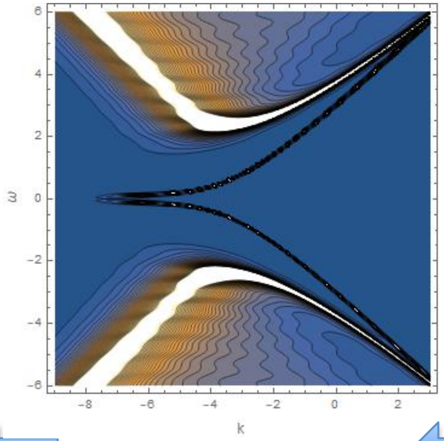
Role of bulk mass in Gap creation



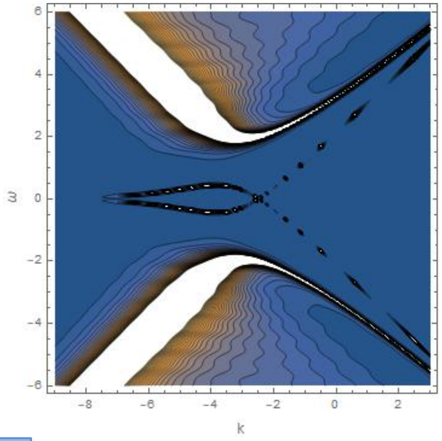
(i) $m = 0$ $p = 6$



(j) $m = 0.15$ $p = 6$

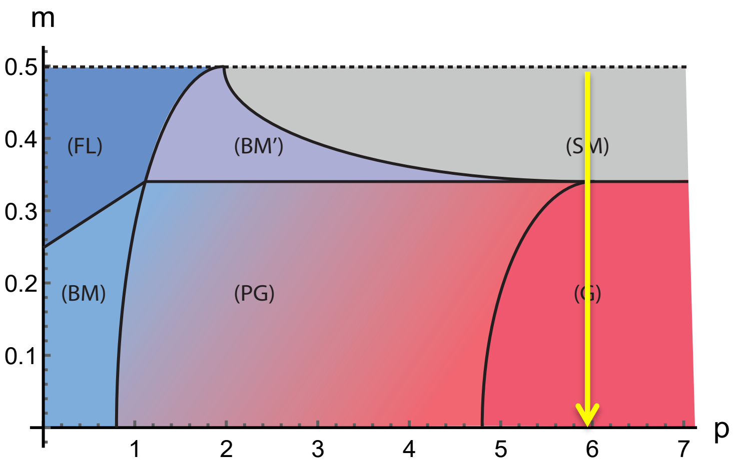


(k) $m = 0.3$ $p = 6$

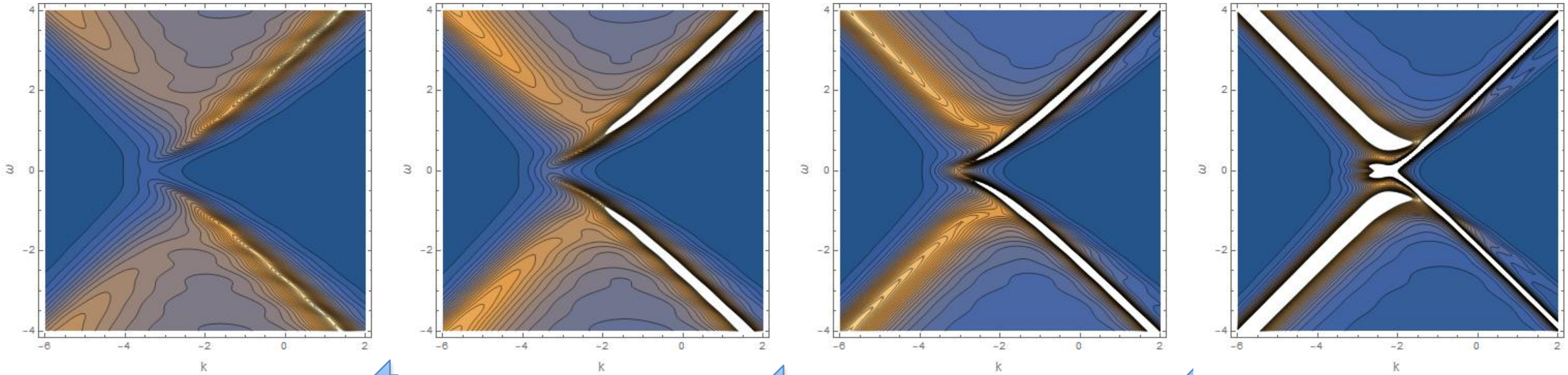


(l) $m = 0.45$ $p = 6$

Now as we decreases m further, the lower one goes down upper one goes up → gap creation, i.e, As (½-m) increases, gap is created.



Role of bulk mass in psuedo-Gap creation

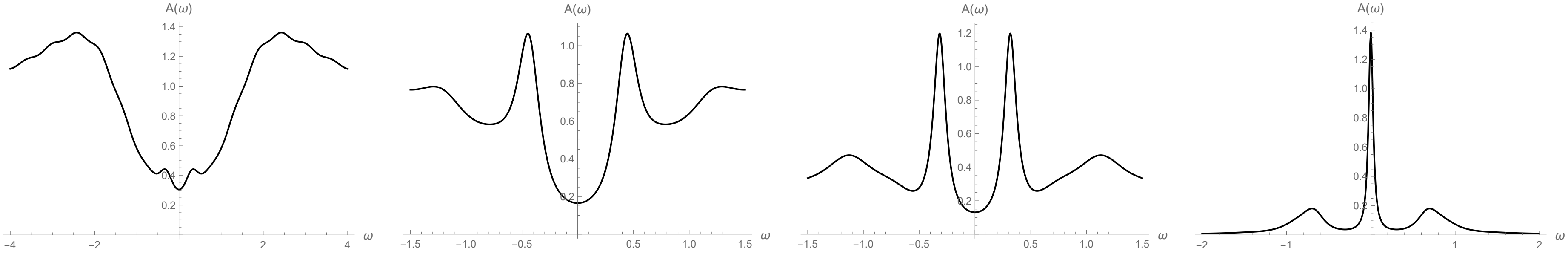


(a) $m = 0$ $p = 2.5$

(b) $m = 0.15$ $p = 2.5$

(c) $m = 0.3$ $p = 2.5$

(d) $m = 0.45$ $p = 2.5$

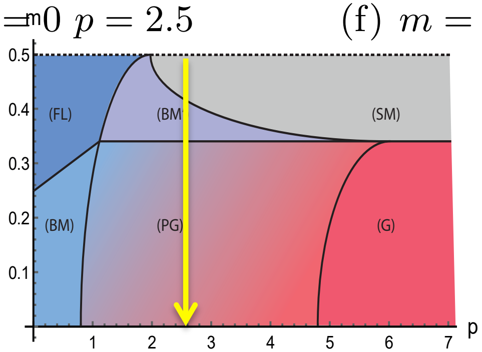


(e) $m = 0$ $p = 2.5$

(f) $m = 0.15$ $p = 2.5$

(g) $m = 0.3$ $p = 2.5$

(h) $m = 0.45$ $p = 2.5$



Comparing with Hubbard Model by Embedding

Hubbard model

Competition of t and U.

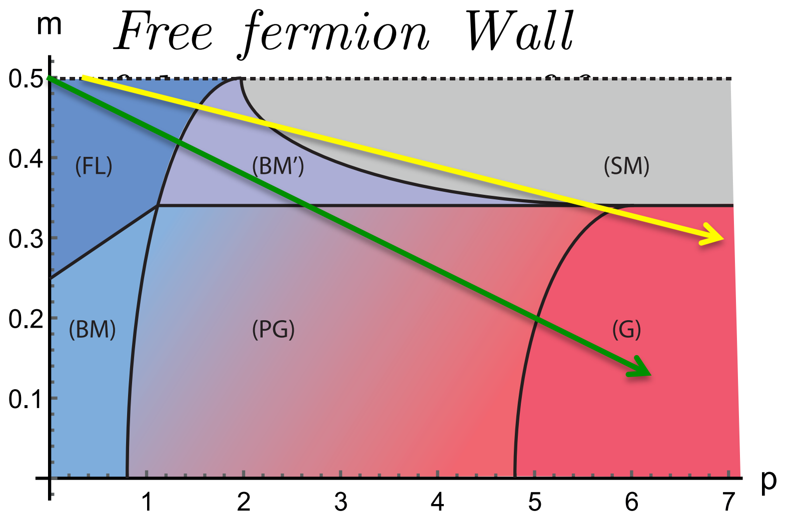
$$H = -t(\sum c^\dagger_{i\sigma} c_{j\sigma} + H.c.) + U \sum n_{i\sigma} n_{i\text{-}\sigma}$$
$$+V \sum_{<ij>} n_i n_j + V_2 + V_3 +$$

P, m play the role of U, V.

None of constant m or p line has Mott transition

U/t into (m,p) → Embed Hubbard into Holography

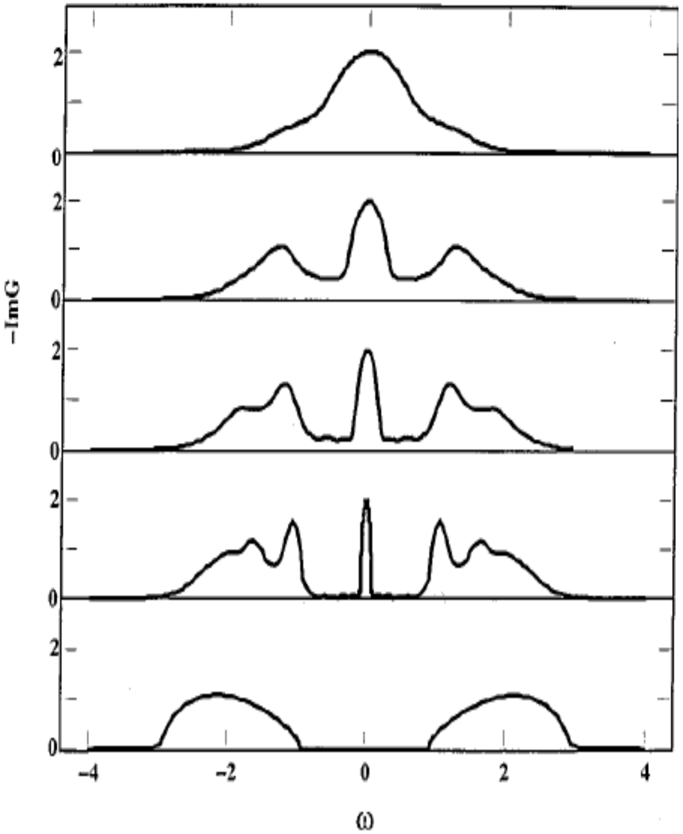
$$p = U/t. \quad V/t = (1/2 - m) \qquad V = \alpha U$$



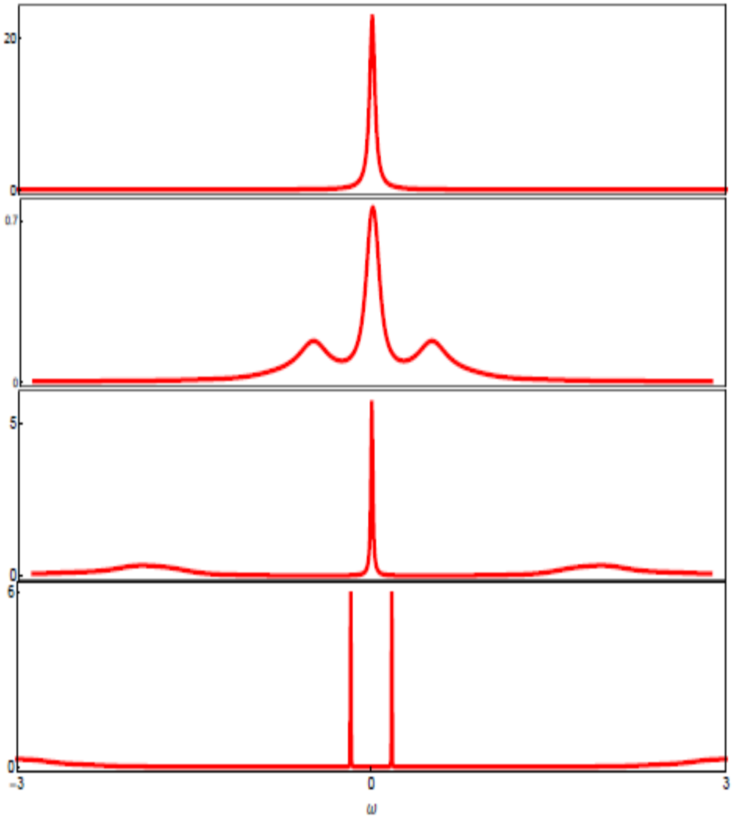
$$m + \alpha p = 1/2,$$

One Embedding (alpha) defines one Holographic Hubbard model.

Comparision with DMFT results

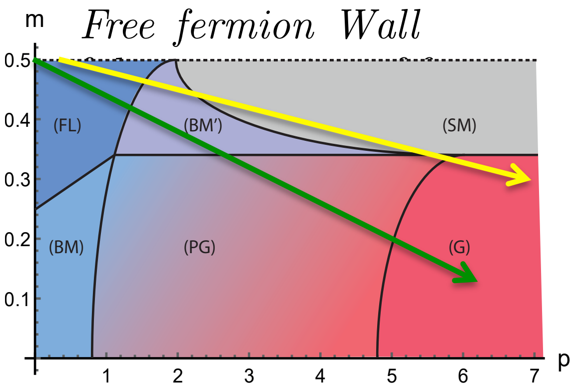


Single-site DMFT result

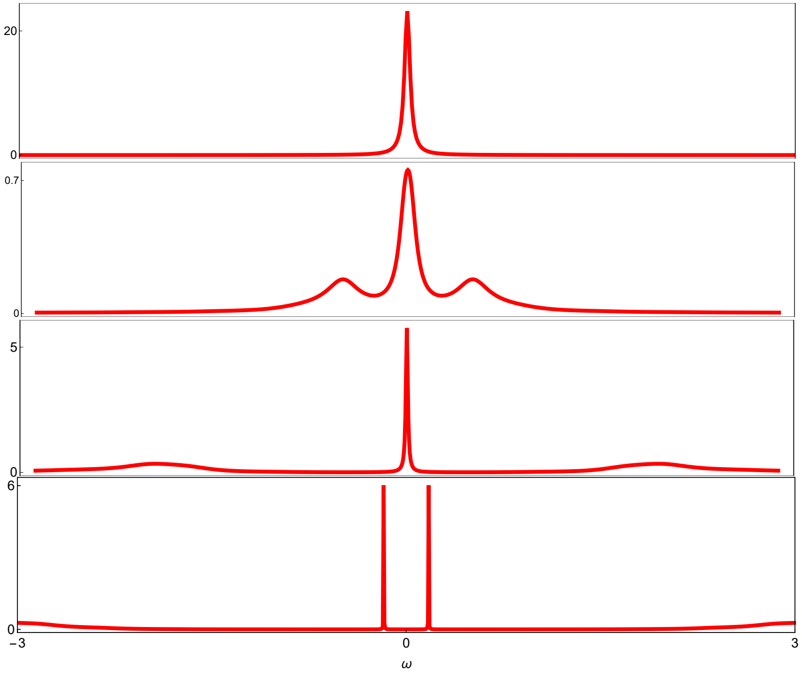


Holography with embedding Yellow

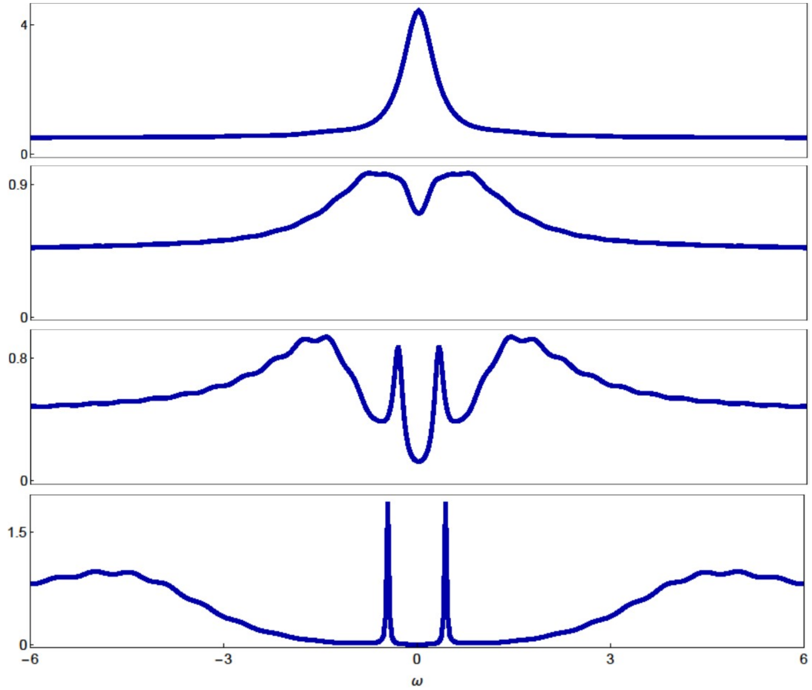
Comparision with DMFT results ii



~single site DMFT

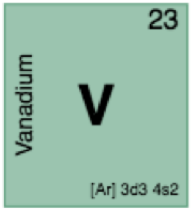


~Clustre DMFT



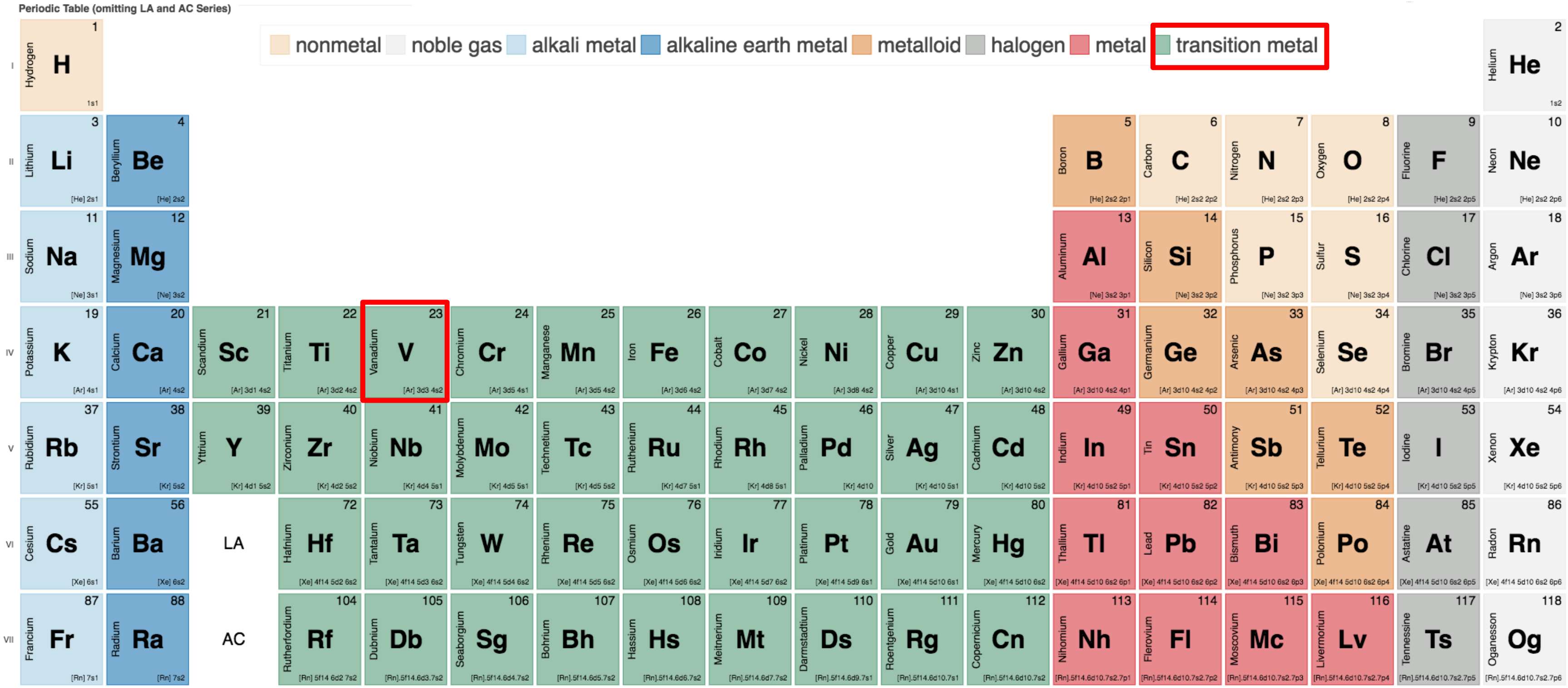
Data for Transition Metal Oxide

O^{2-}: anion



23
V
Vanadium
[Ar] 3d3 4s2

V^{3+}: V_2O_3, d^2
V^{4+}: VO_2, d^1



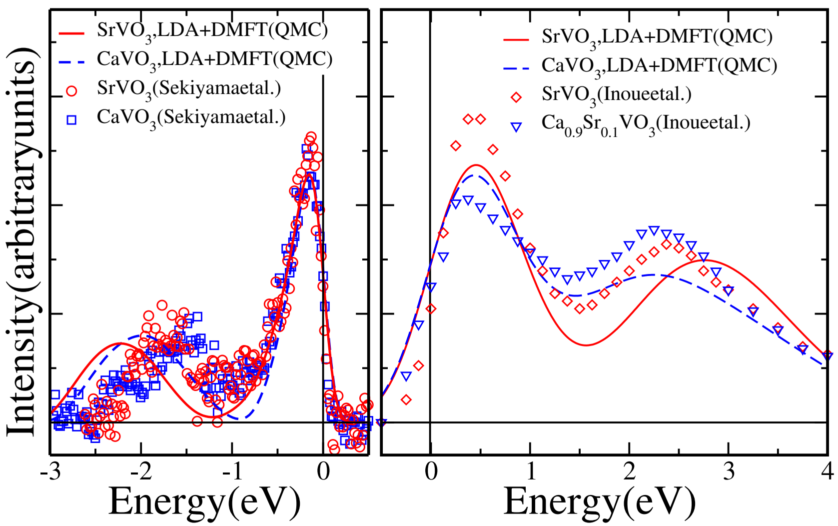
Periodic Table (omitting LA and AC Series)

■ nonmetal ■ noble gas ■ alkali metal ■ alkaline earth metal ■ metalloid ■ halogen ■ metal ■ transition metal

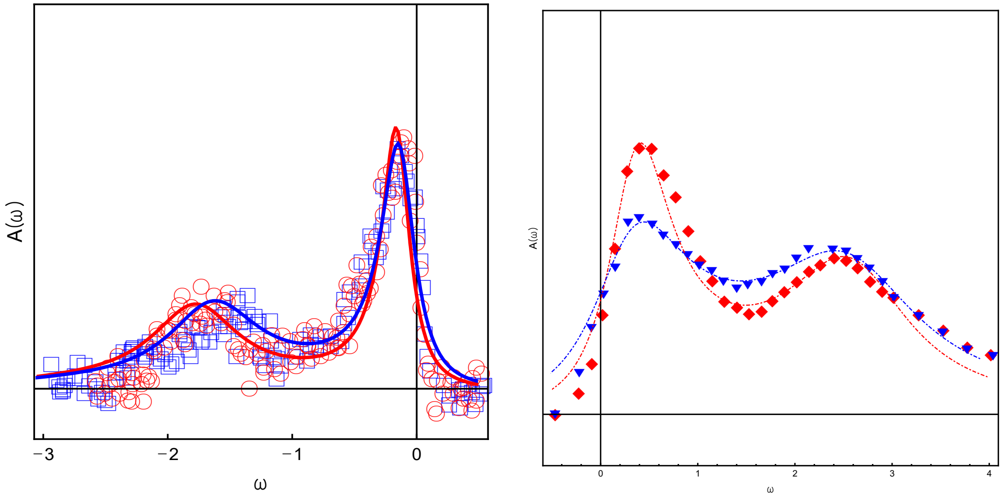
I	1 **H** Hydrogen 1s1																	2 **He** Helium 1s2
II	3 **Li** Lithium [He] 2s1	4 **Be** Beryllium [He] 2s2											5 **B** Boron [He] 2s2 2p1	6 **C** Carbon [He] 2s2 2p2	7 **N** Nitrogen [He] 2s2 2p3	8 **O** Oxygen [He] 2s2 2p4	9 **F** Fluorine [He] 2s2 2p5	10 **Ne** Neon [He] 2s2 2p6
III	11 **Na** Sodium [Ne] 3s1	12 **Mg** Magnesium [Ne] 3s2											13 **Al** Aluminum [Ne] 3s2 3p1	14 **Si** Silicon [Ne] 3s2 3p2	15 **P** Phosphorus [Ne] 3s2 3p3	16 **S** Sulfur [Ne] 3s2 3p4	17 **Cl** Chlorine [Ne] 3s2 3p5	18 **Ar** Argon [Ne] 3s2 3p6
IV	19 **K** Potassium [Ar] 4s1	20 **Ca** Calcium [Ar] 4s2	21 **Sc** Scandium [Ar] 3d1 4s2	22 **Ti** Titanium [Ar] 3d2 4s2	23 **V** Vanadium [Ar] 3d3 4s2	24 **Cr** Chromium [Ar] 3d5 4s1	25 **Mn** Manganese [Ar] 3d5 4s2	26 **Fe** Iron [Ar] 3d6 4s2	27 **Co** Cobalt [Ar] 3d7 4s2	28 **Ni** Nickel [Ar] 3d8 4s2	29 **Cu** Copper [Ar] 3d10 4s1	30 **Zn** Zinc [Ar] 3d10 4s2	31 **Ga** Gallium [Ar] 3d10 4s2 4p1	32 **Ge** Germanium [Ar] 3d10 4s2 4p2	33 **As** Arsenic [Ar] 3d10 4s2 4p3	34 **Se** Selenium [Ar] 3d10 4s2 4p4	35 **Br** Bromine [Ar] 3d10 4s2 4p5	36 **Kr** Krypton [Ar] 3d10 4s2 4p6
V	37 **Rb** Rubidium [Kr] 5s1	38 **Sr** Strontium [Kr] 5s2	39 **Y** Yttrium [Kr] 4d1 5s2	40 **Zr** Zirconium [Kr] 4d2 5s2	41 **Nb** Niobium [Kr] 4d4 5s1	42 **Mo** Molybdenum [Kr] 4d5 5s1	43 **Tc** Technetium [Kr] 4d5 5s2	44 **Ru** Ruthenium [Kr] 4d7 5s1	45 **Rh** Rhodium [Kr] 4d8 5s1	46 **Pd** Palladium [Kr] 4d10	47 **Ag** Silver [Kr] 4d10 5s1	48 **Cd** Cadmium [Kr] 4d10 5s2	49 **In** Indium [Kr] 4d10 5s2 5p1	50 **Sn** Tin [Kr] 4d10 5s2 5p2	51 **Sb** Antimony [Kr] 4d10 5s2 5p3	52 **Te** Tellurium [Kr] 4d10 5s2 5p4	53 **I** Iodine [Kr] 4d10 5s2 5p5	54 **Xe** Xenon [Kr] 4d10 5s2 5p6
VI	55 **Cs** Cesium [Xe] 6s1	56 **Ba** Barium [Xe] 6s2	LA	72 **Hf** Hafnium [Xe] 4f14 5d2 6s2	73 **Ta** Tantalum [Xe] 4f14 5d3 6s2	74 **W** Tungsten [Xe] 4f14 5d4 6s2	75 **Re** Rhenium [Xe] 4f14 5d5 6s2	76 **Os** Osmium [Xe] 4f14 5d6 6s2	77 **Ir** Iridium [Xe] 4f14 5d7 6s2	78 **Pt** Platinum [Xe] 4f14 5d9 6s1	79 **Au** Gold [Xe] 4f14 5d10 6s1	80 **Hg** Mercury [Xe] 4f14 5d10 6s2	81 **Tl** Thallium [Xe] 4f14 5d10 6s2 6p1	82 **Pb** Lead [Xe] 4f14 5d10 6s2 6p2	83 **Bi** Bismuth [Xe] 4f14 5d10 6s2 6p3	84 **Po** Polonium [Xe] 4f14 5d10 6s2 6p4	85 **At** Astatine [Xe] 4f14 5d10 6s2 6p5	86 **Rn** Radon [Xe] 4f14 5d10 6s2 6p6
VII	87 **Fr** Francium [Rn] 7s1	88 **Ra** Radium [Rn] 7s2	AC	104 **Rf** Rutherfordium [Rn] 5f14 6d2 7s2	105 **Db** Dubnium [Rn].5f14.6d3.7s2	106 **Sg** Seaborgium [Rn].5f14.6d4.7s2	107 **Bh** Bohrium [Rn].5f14.6d5.7s2	108 **Hs** Hassium [Rn].5f14.6d6.7s2	109 **Mt** Meitnerium [Rn].5f14.6d7.7s2	110 **Ds** Darmstadtium [Rn].5f14.6d9.7s1	111 **Rg** Roentgenium [Rn].5f14.6d10.7s1	112 **Cn** Copernicium [Rn].5f14.6d10.7s2	113 **Nh** Nihonium [Rn].5f14.6d10.7s2.7p1	114 **Fl** Flerovium [Rn].5f14.6d10.7s2.7p2	115 **Mc** Moscovium [Rn].5f14.6d10.7s2.7p3	116 **Lv** Livermorium [Rn].5f14.6d10.7s2.7p4	117 **Ts** Tennessine [Rn].5f14.6d10.7s2.7p5	118 **Og** Oganesson [Rn].5f14.6d10.7s2.7p6

.ppt from Ara Go

Cf: DMFT vs Experiment // Holography vs Exp



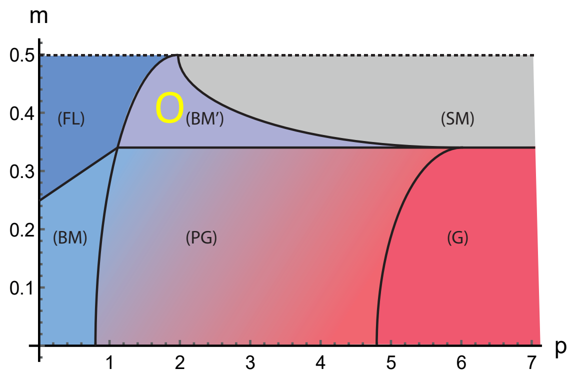
DMFT school (2011) Dieter Vollhardt



(a)PES data vs theory

(b)XAS data vs theory

FIG. 5. Experimenal data vs holographic theory: (a) PES data, (b) XAS data ; In both case (color red) is for SrVO$_3$ and (color blue) is for CaVO$_3$. The data for SrVO$_3$ is from [26], and that for CaVO$_3$ is from [25].

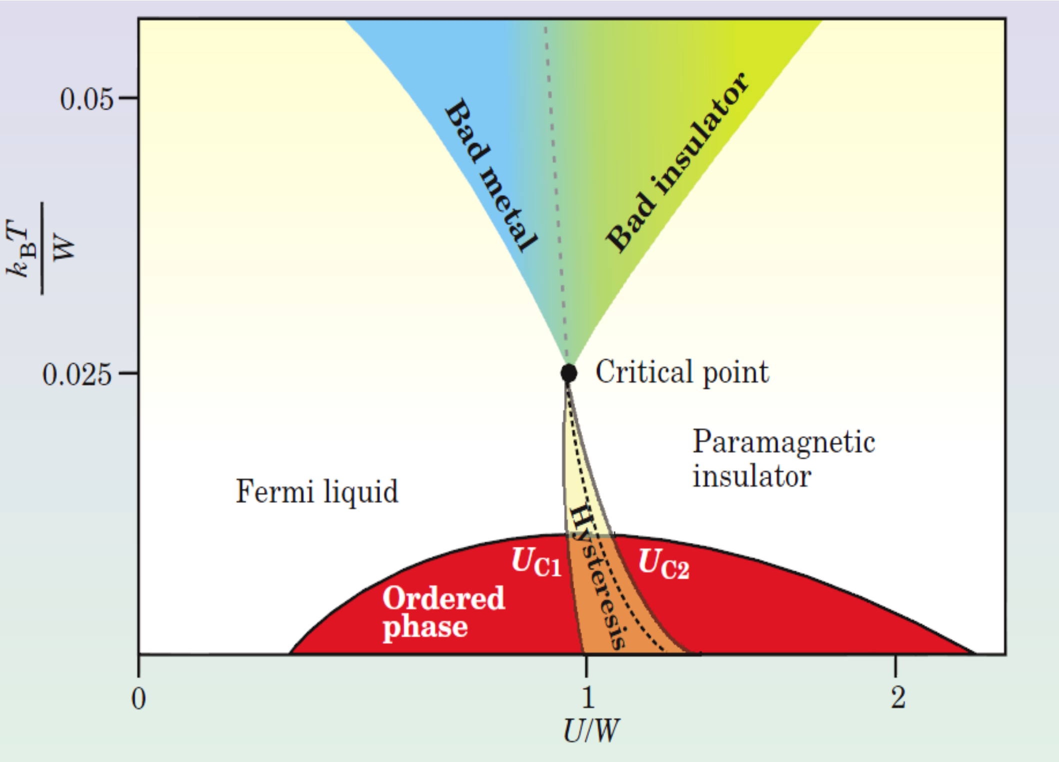


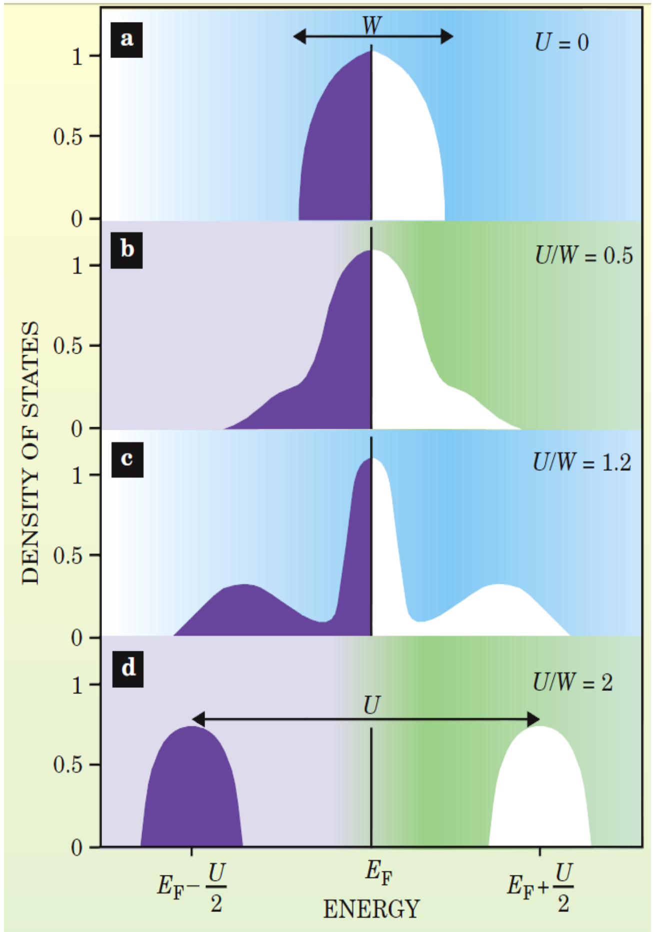
Conclusion

- New field theory based on holography
- Applied to Dirac material, Transition metal
- 21 century physics=highly interesting theory with exp.

Thanks you.

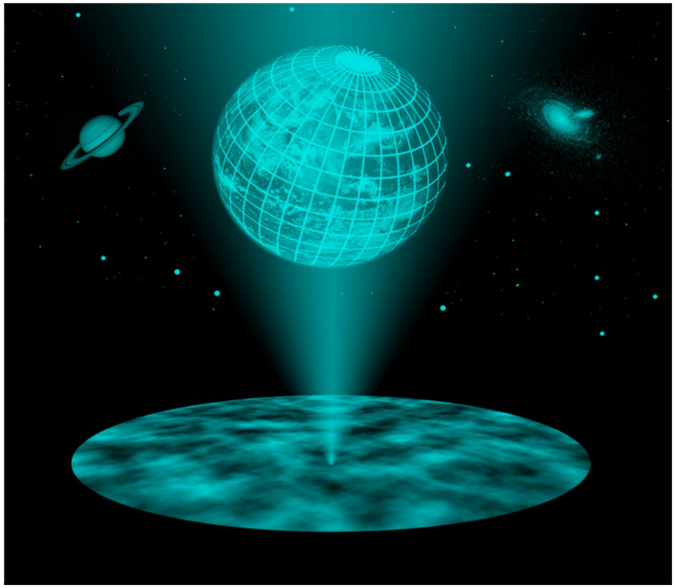
Mott Transition First order?



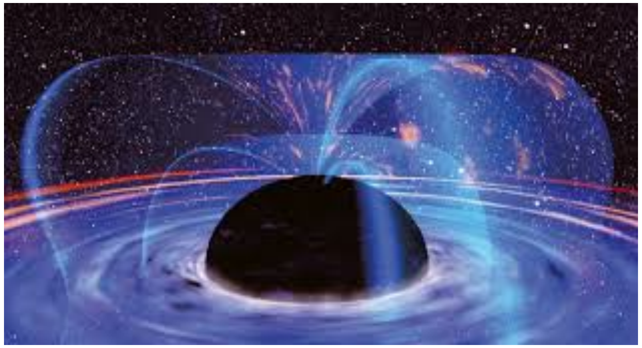


G Kotliar and D Vollhardt, Physics Today **57**, 53 (2004).

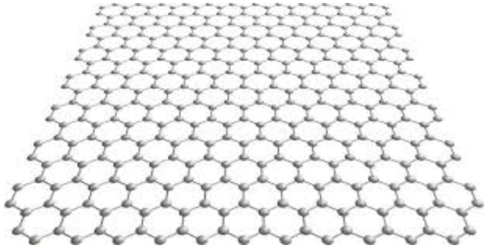
Method : quantum holography



3 dim.
Classical
BH



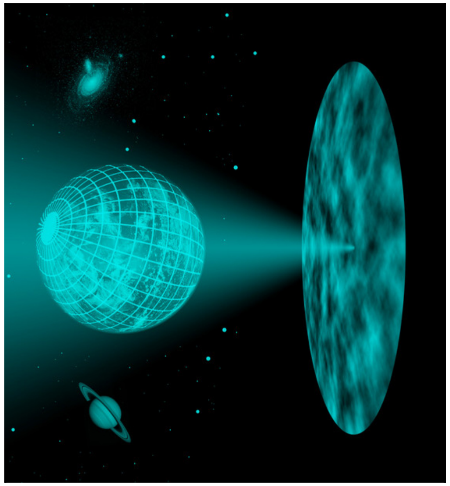
2 dim.
Quantum
Matter



2d SIS (near QCP) hologram = 3dim Black hole

→ quantum black hole

quantum holography



QCP : dynamical exponent

But

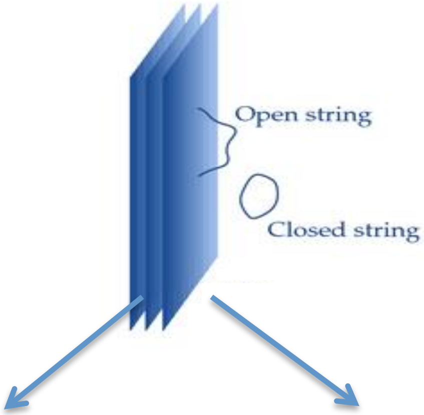
BH :

←→ equilibrium, fluid dynamic behavior

←→ transport(transport is input in traditional fluid dynamics)

method

Supersymmetric D-brane



Susy gauge theory

Susy AdS gravity

Theory of Quantum Matter ⟷ Classical Geometry

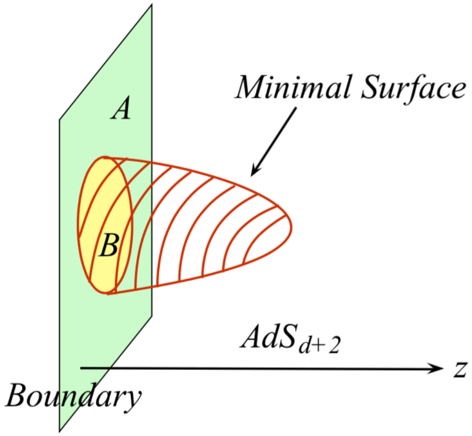
General case without SUSY

i. Find example outside string theory.
ii. Asume→ caculate → compare with exp..

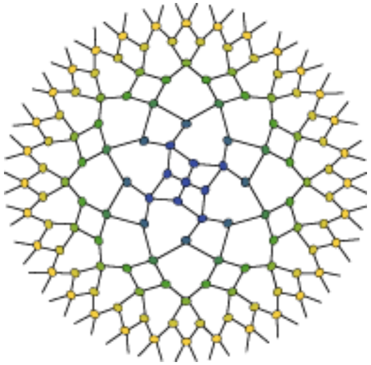
i) Evidence outside string theory

1. entanglement entropy calculation in 2d

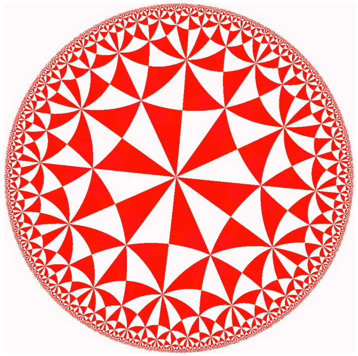
Ryu & Takayanagi (2006)



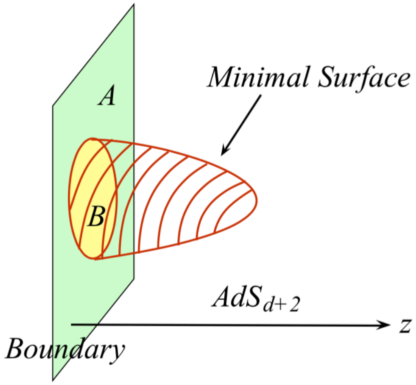
2. Tensor network : (Multiscale Entanglement Renormalization Ansatz)



[Swingle]



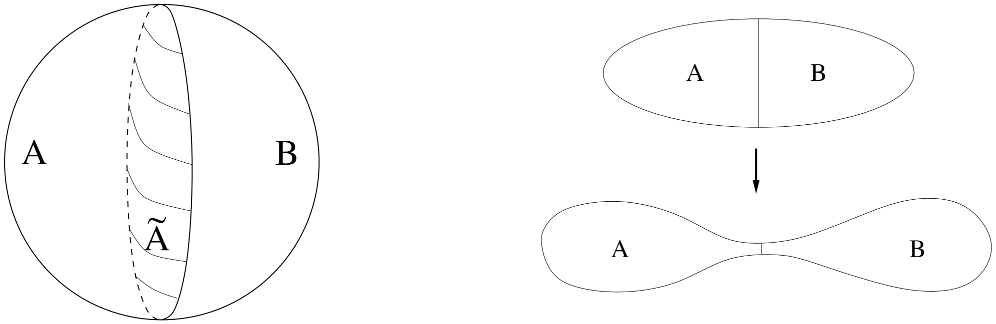
Comment : Entanglement and Holography



Ryu & Takayanagi (2006) by product.

Presence of dual space time=
presence of high entanglement

Raamsdonk : classical .
Space is sewn by entanglement.
Entanglement first law → Linearized gravity equation.



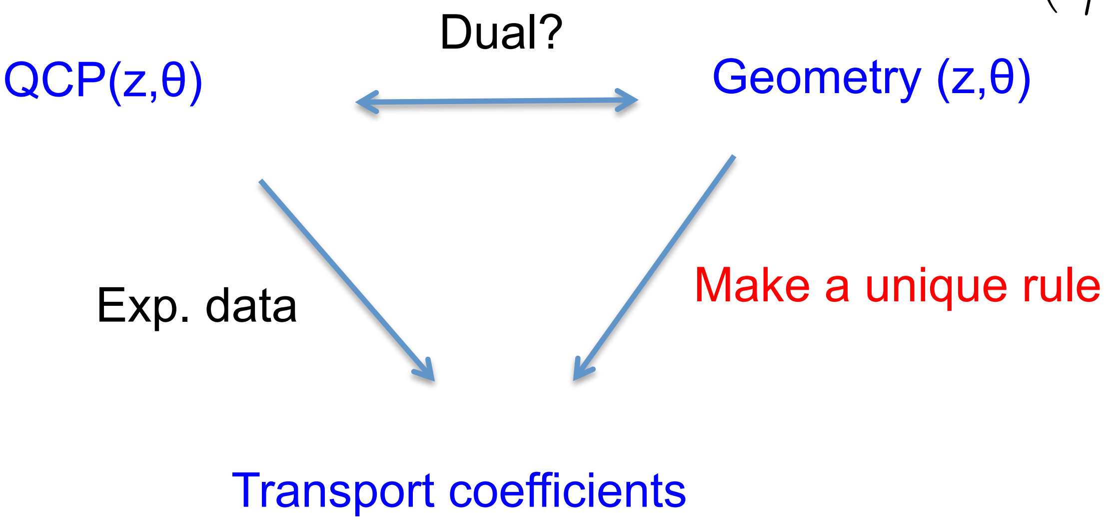
Complete Einstein equation from the generalized First Law of Entanglement
Eunseok Oh (Hanyang U.), I.Y. Park (Philander Smith Coll.), Sang-Jin Sin (Hanyang U.):
arXiv:1709.05752 [hep-th] | PDF

Def. of AdS/CMT

AdS/CFT : an exact duality where dictionary is given

Hydrogen atom of Holographic Duality

$$ds^2_{D+2} = r^{\frac{2\theta}{D}}\left(\frac{-dt^2}{r^{2z}} + \frac{dr^2}{r^2} + \frac{1}{r^2}\sum_{i=1}^{D} dx_i^2\right)$$



Dual?

QCP(z,θ)

Geometry (z,θ)

Exp. data

Make a unique rule

Transport coefficients