양자 홀로그래피로 본 강상관계
(Quantum matter with Holography)

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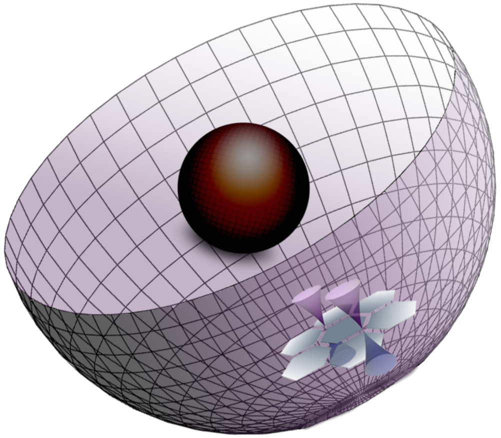
2018.10.10@SNU



들어가기

- 물리학 = 자연에 대한 수학적 이해

  (반복 측정이 가능한 양들 사이의 정량적 관계성)

$N_A \rightarrow O(1)$: 단순화 (환원,대칭,통일)

- 통일= 서로 다른 것을 동일시 하는것

  전기//자기 → 전자기학

  시간//공간 → 특수상대론

  시공//중력 → 일반상대론

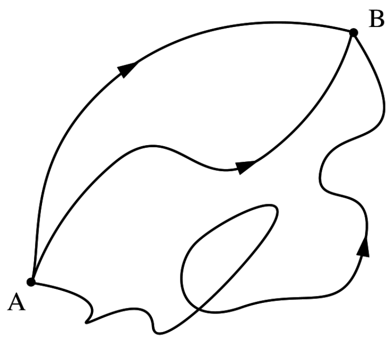
  입자//파동 → 양자역학

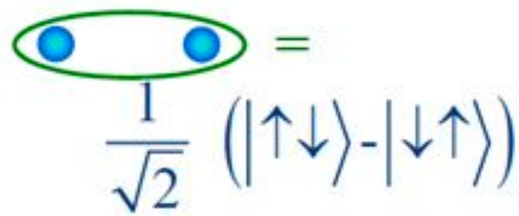
- 오늘의 주제 : 양자물질 + 시공간의 통일

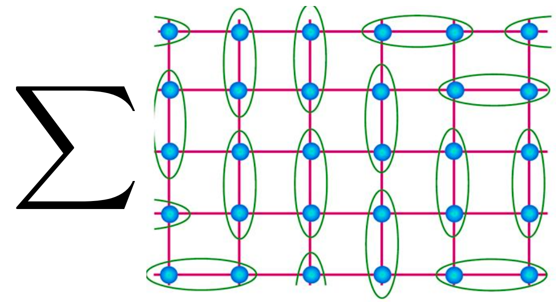
양자임계점// 블랙홀 → 강상관계의 새로운 이론

양자물질의 정의

- 양자물질 = 전자계의 양자 요동/얽힘이 큰 물질







(그림: 요동과 얽힘)

- 요동: 한 상태가 여러상태의 중첩일때
- 얽힘: 두입자 이상의 상태가 각개 입자상태의 곱의 중첩일때.

- 상호작용이 크면 양자요동과 얽힘이 크다.

  양자물질 = 강상호작용계=강상관 계

물질이 강상관계가 되는 세가지 방법

- 상호작용의 세기 = 퍼텐셜에너지/운동에너지

$$g_{eff}^2 = \frac{e^2}{\hbar c}\frac{1}{v_F}\frac{1}{\epsilon}$$

- 유전상수가 작은계 → Class I

  예) 그래핀, 토폴로지물질, Dirac materials

- 느린 전자계 → Class II

  예) 전이금속 산화물 (고온 초전도체),
  Heavy Fermion, 전통적 강상물질

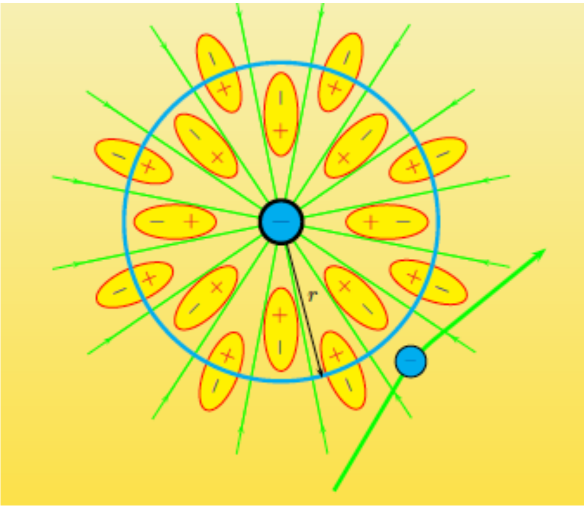
- 원천 커플링이 센 계 → Class 0

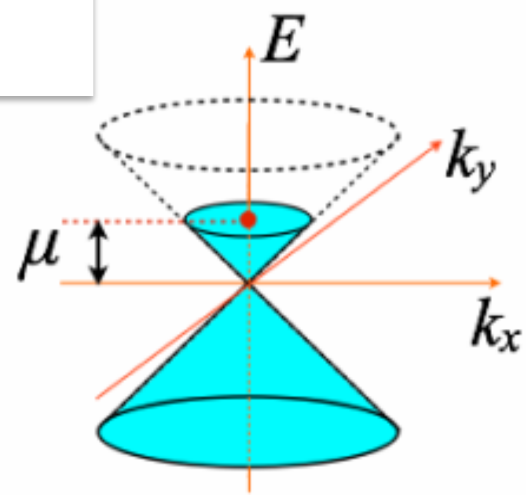
  예) 핵물질 (not Today)

Class I) 작은 유전상수 = 작은 페르미면을 가진계

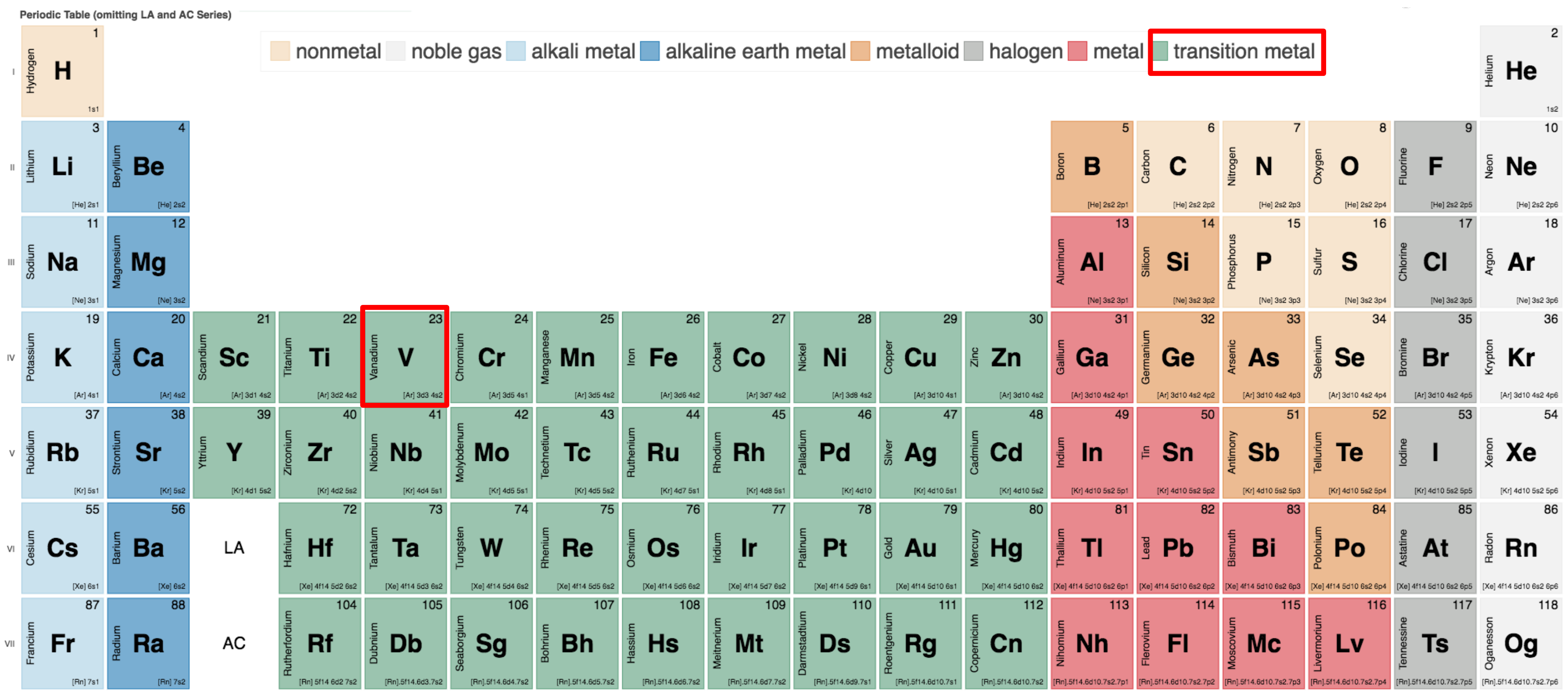
$$g_{eff}^2 = \frac{e^2}{\hbar c}\frac{1}{v_F}\boxed{\frac{1}{\epsilon}}$$

Class I = 유전상수가 작다 ← Small FS
예) Dirac materials,
Graphene, Weyl SM, Surface of TI ....





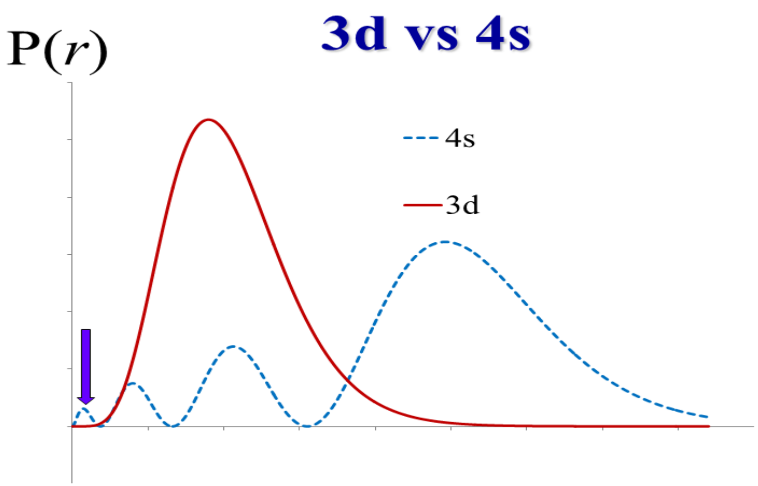
전이금속 산화물


Periodic Table (omitting LA and AC Series)
nonmetal
noble gas
alkali metal
alkaline earth metal
metalloid
halogen
metal
transition metal
I
II
III
IV
V
VI
VII
H He
Li Be B C N O F Ne
Na Mg Al Si P S Cl Ar
K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe
Cs Ba LA Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
Fr Ra AC Rf Db Sg Bh Hs Mt Ds Rg Cn Nh Fl Mc Lv Ts Og

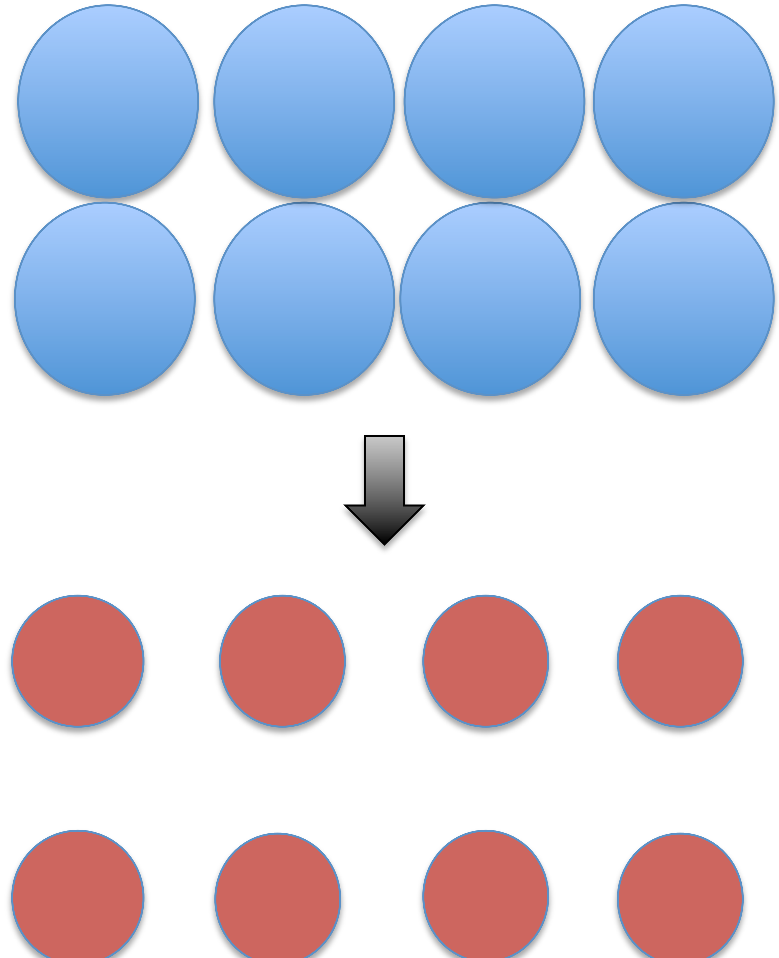
Class II) 느린 전자를 가진 물질들: flat band

전이금속 3d $^{1\text{-}10}$ 4s$^{1\text{-}2}$

전이금속 산화물 3d $^{1\text{-}10}$



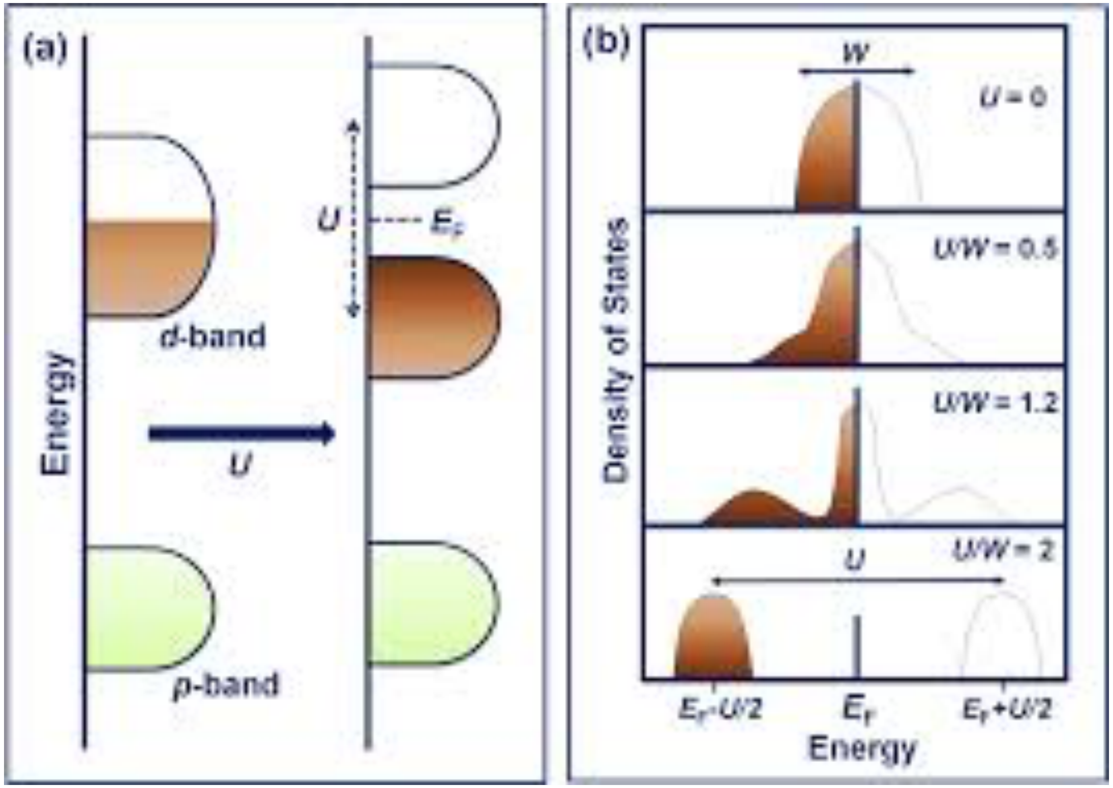
$$g_{eff}^2 = \frac{e^2}{\hbar c}\left[\frac{1}{v_F}\right]\frac{1}{\epsilon}$$



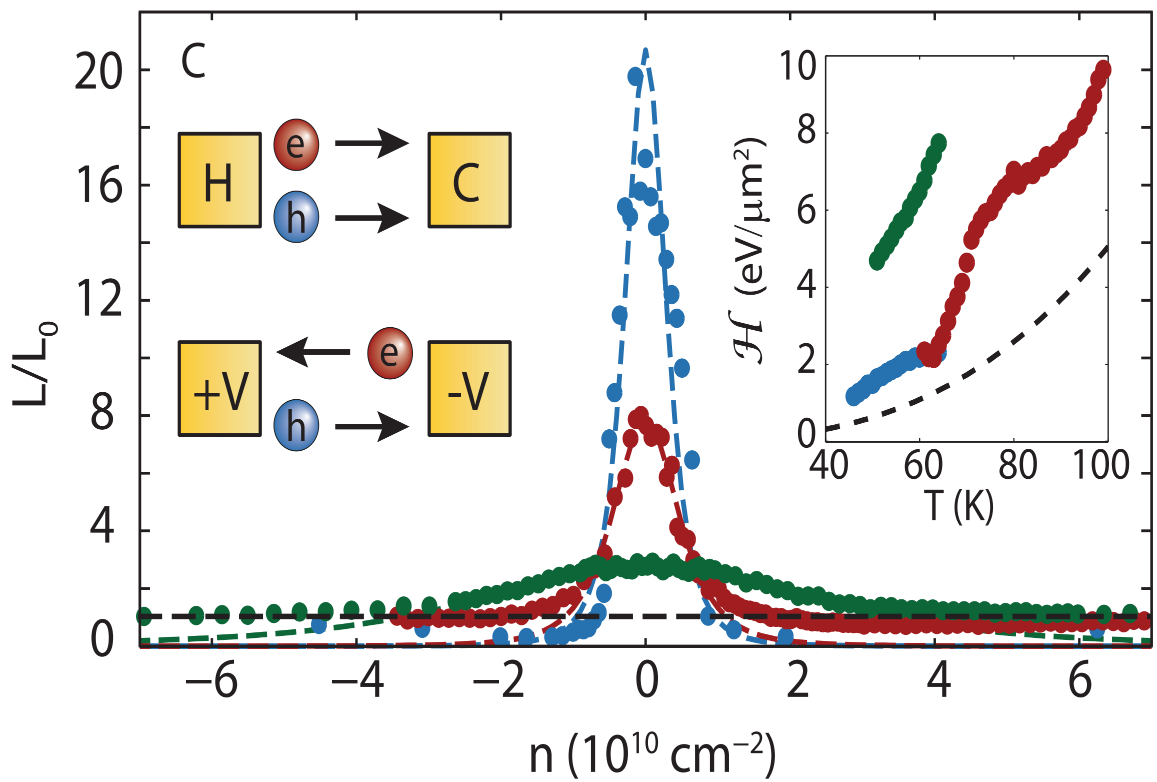
Brittle !

- 어떤 흥미로운 일이 생기는가?

- 예상밖의 부도체성 (Mott 1935)

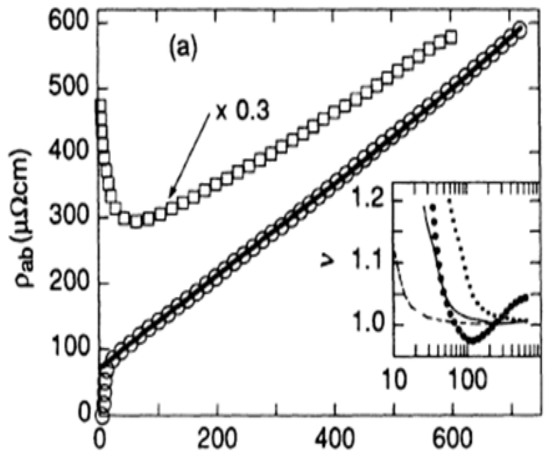


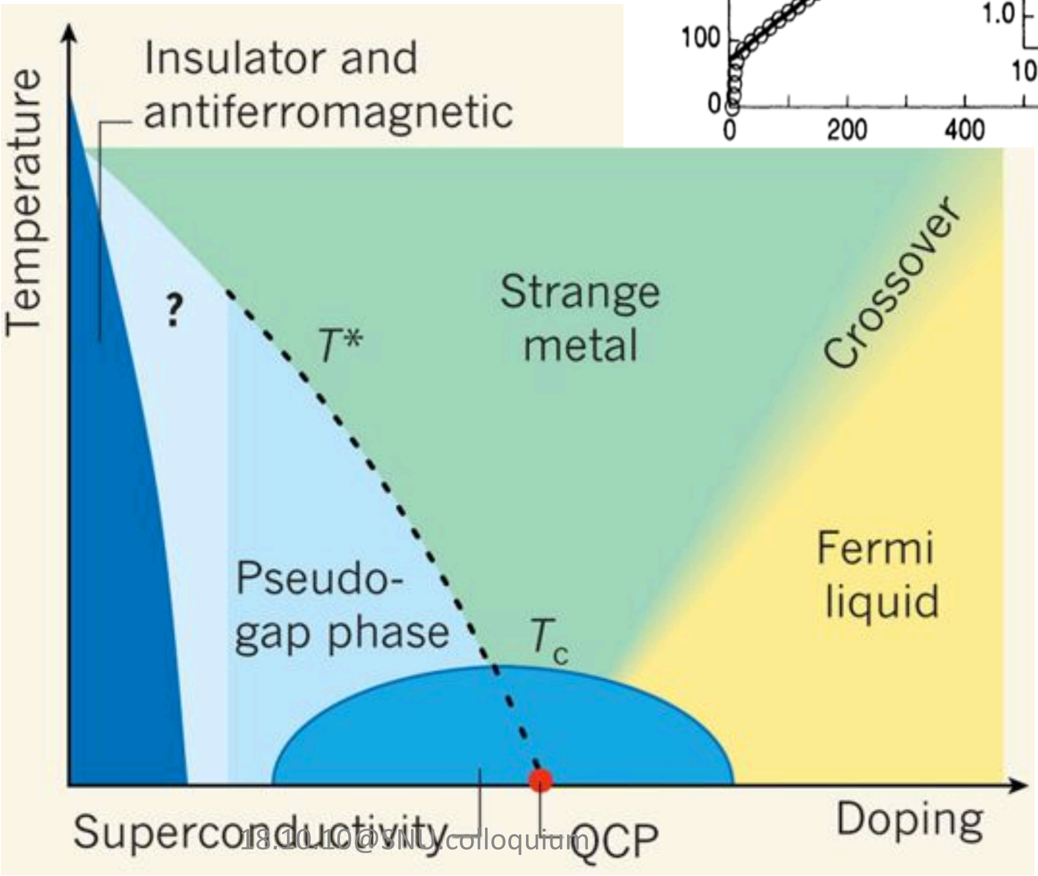
Violation of Wiedemann-Franz law

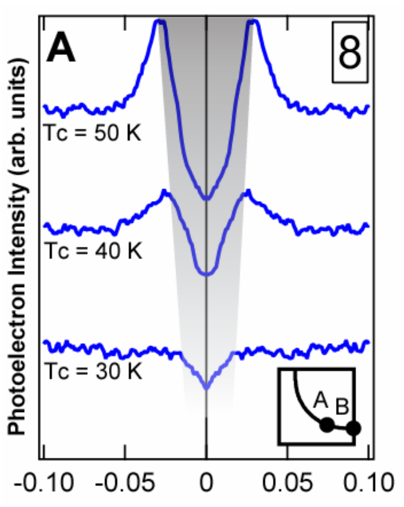


양자물질의 현상: Phenomena of strong Interaction 0)

- 높은 초전도 임계 온도(1987)

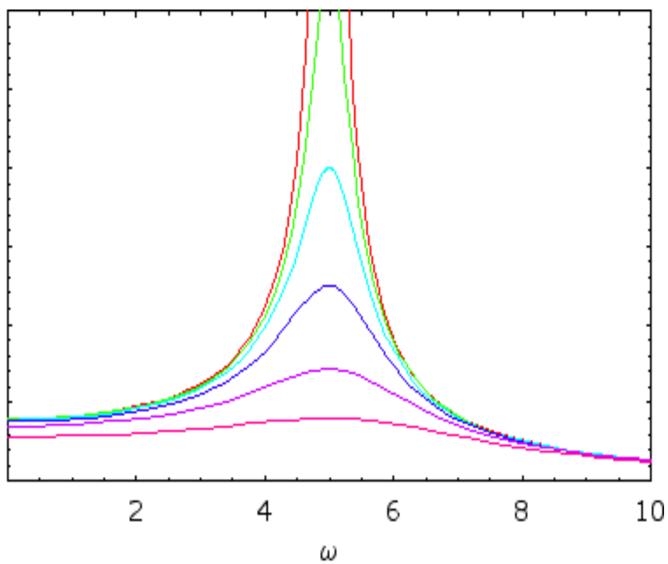






- 강상관계를 특징짓는 현상은 무엇인가?

1. (quasi-) Particle Lost !



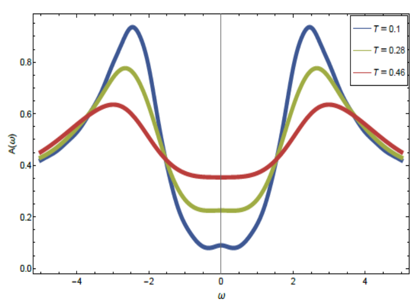
δ-function=Particle

resonance=quasi-particle

…….

…….

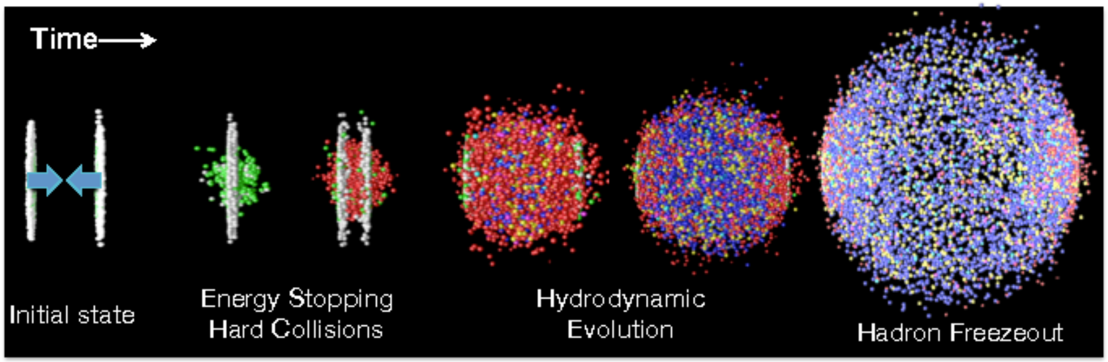
Split→Mott insulator

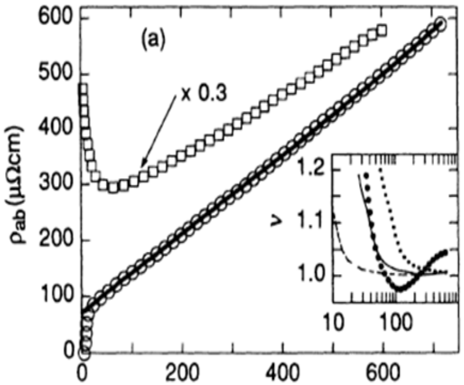


$$Im[\frac{1}{\pi}\frac{-1}{\omega - E_k + i\epsilon}] = \delta(\omega - E_k),$$

Interaction : E→E-iΓ/2

2. Abnormally Rapid Thermalization
→ Hydro-dynamic description





$$absence\ of\ \frac{E_F}{k_B T}$$

Plankian Dissipation:

Quantum Entanglement →QCP

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

아이디어:

얽힘의 비국소성 + 양자중첩도 일종의 평균

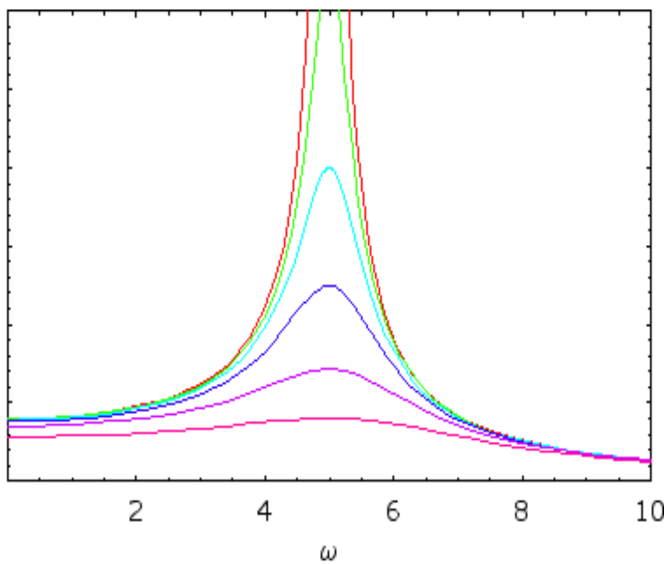
$$\rho \propto \frac{1}{\tau_\hbar} \propto k_B T$$

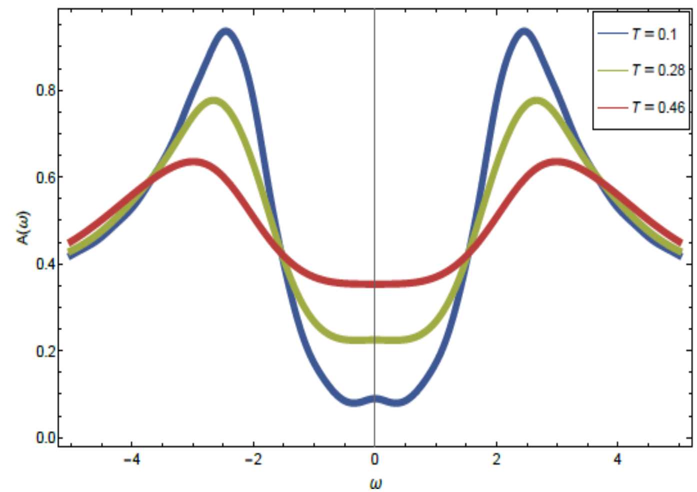
- 무엇이 문제인가?

Difficulty in calculation in standard formalism.

$$Im[\frac{1}{\pi}\frac{-1}{\omega - E_k + i\epsilon}] = \delta(\omega - E_k),$$

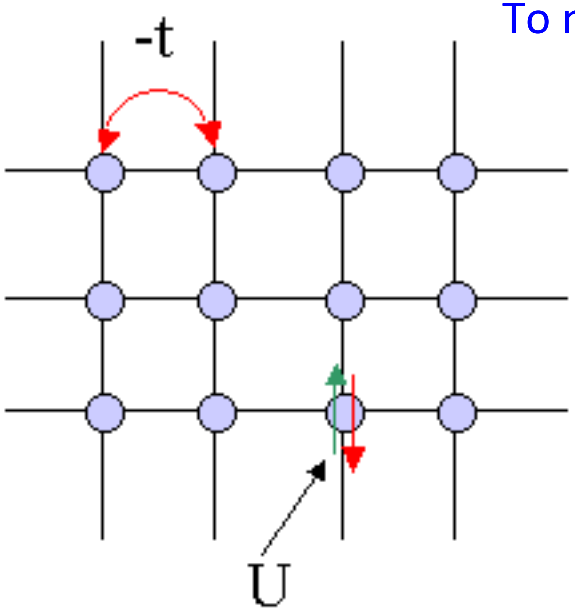
Interaction : E→E-iΓ/2

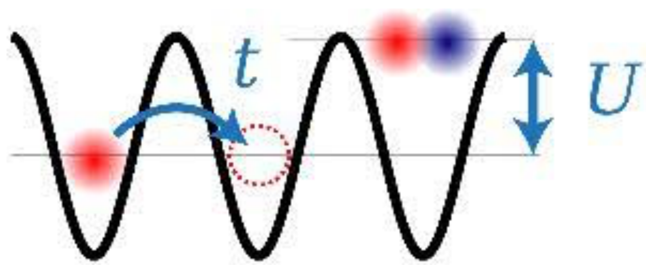




Hubbard Model: 가느냐 마느냐 그것이 문제로다…? No!

To move or not to move, that is the problem!





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

Coupling = U/t (대부분의 실험은 t 를 조절)

2차원이상은 80년이상 풀리지 않았다.

강상호작용계의 문제 : 일반적 계산방법의 부재

커플링의 관점

1. 다체의 양자역학적 계산법 = 장론
2. 일반장론의 구조 : (자유입자+상호작용 g) → 섭동론

   $g=U/t$ (or t/U), $A= 1+ a\,g^2+b\,g^3 +c\,g^4 + \cdots$

   $g>=1$ → ?

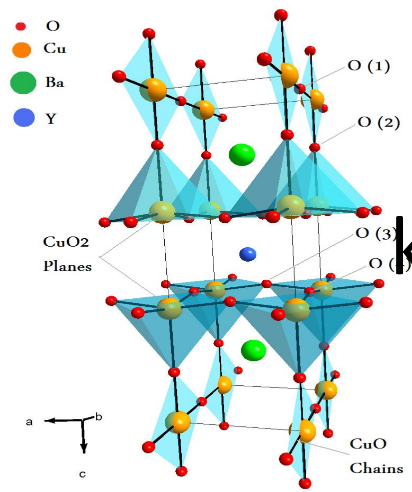
얽힘의 관점

1. 약상관관계: 셀 몇개만 계산하면 된다.
2. 강상관관계: macroscopic 입자 갯수가 서로 얽혀있다.

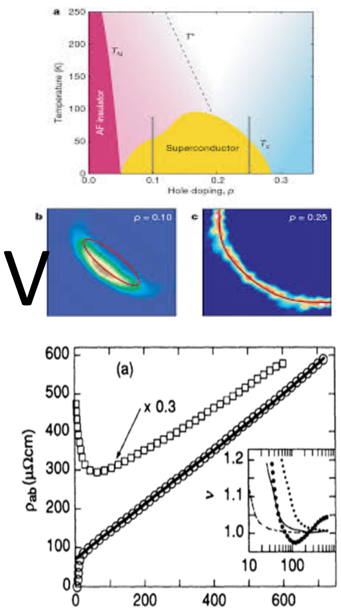
문제의 의미: 환원론이 작동하지 않는다

물리학: 구조→기능 (쿼→양성자)

응집물리학: X-ray data → 수송계수



keV → meV



강상관계에서는 UV scale 구조→IR scale 기능 이 성립하지 않는다.

Contents

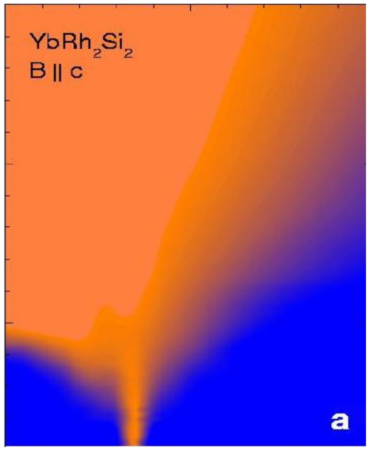
- Part I: 문제 제기 Question
- Part II: 해결의 아이디어 Idea to the solutions
- Part III: 새 이론의 결과

  -Transport in Dirac metal,

  -Spectral density of V_2O_3

idea?

- 거시 스케일 양자얽힘이 중요 → 양자임계점이 중요
- 양자임계점과 블랙홀의 유사성



QCP

양자임계점

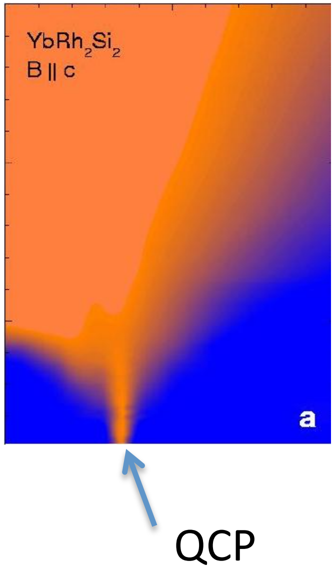
1. macroscopic 갯수의 입자가 연결
   → 모든 크기의 에너지 요동이 생성
   → 양자임계점근처의 동역학
   T=0 (시간박스의 크기=1/T →∞)

2. 임계점에서의 발산:
   i)임계점=질서변수의 부적절성의 시발점
   물리량 = 0 or ∞ (예: 물-기체의 임계점)
   ii)스케일이 없는 자유도의 출현 ($\omega=k^z$)

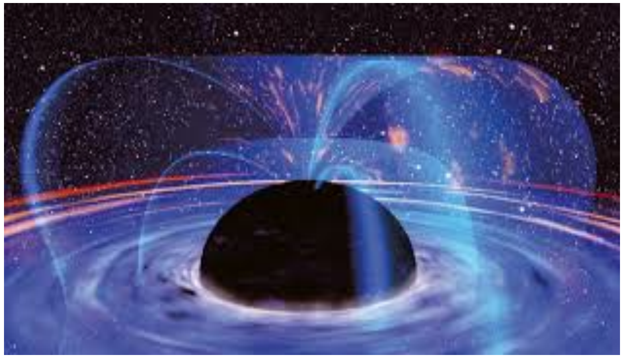
QCP 분류: dynamical exponent z, θ: $\omega=k^z$, [s]=D-θ

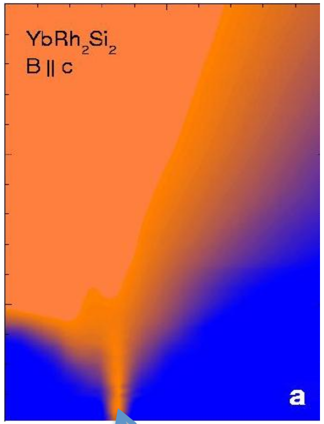
양자임계점: Scale invariance와 보편성의 출현

스케일 부재
→ 대칭성을 제외한 격자구조가 무시. vast simplification
→Information Loss
→ Universality → data scaling의 출현의 이유



블랙홀과 정보소실 → 양자상전이점과의 유사성





Quantum Critical point

Black Hole has

i) 정보상실/ 보편성/ 대머리.

ii) 열역학. (1법칙←→중력장방정식)

So is the QCP

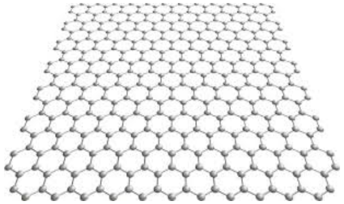
블랙홀과 홀로그래피

Black hole : 열역학 0,1,2,3 법칙

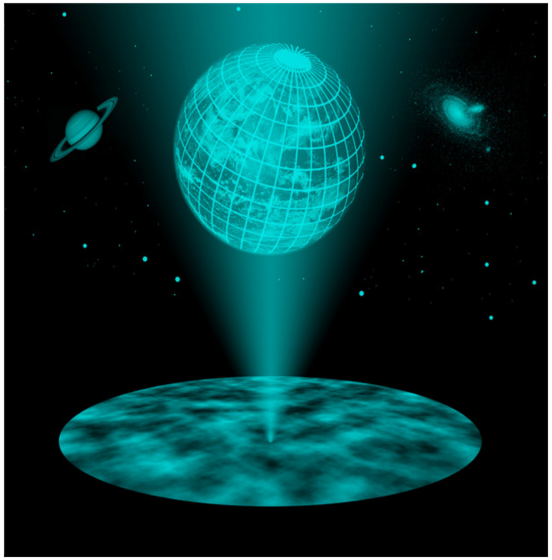
- Bekenstein: $$S_{BH} = \frac{Area}{4G}$$

부피가 아니라 면적 ← Principle of equivalence

→ 3차원 블랙홀의 짝 양자상전이계는 2차원의 계 !

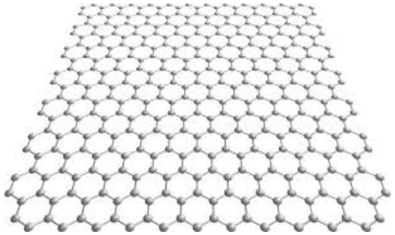


블랙홀과 양자상전이간의 쌍대성



3 dim.
Classical
BH

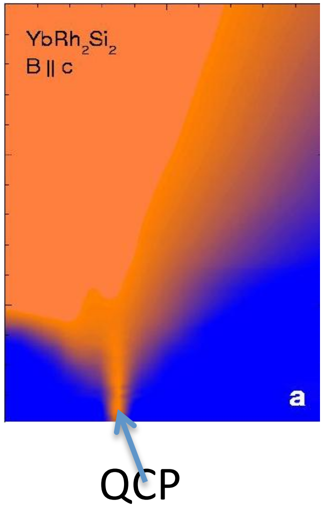
2 dim.
Quantum
Matter



2차원 강상관계의 홀로그램 = 3차원 블랙홀

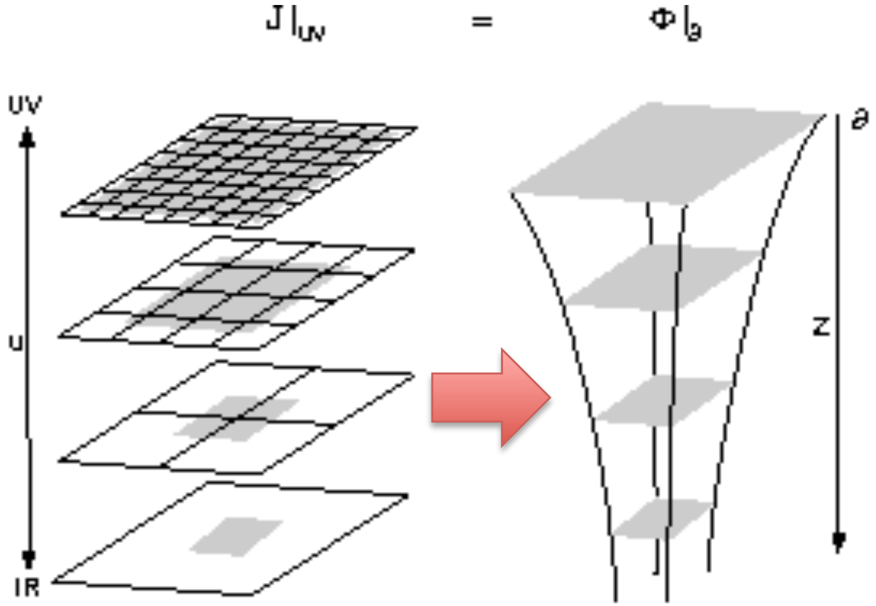
→ (양자) 홀로그래피

양자임계점관점에서의 홀로그래피



모든 스케일의 자유도들이 서로 관련 k. Wilson : RG

→에너지 스케일이 하나의 차원으로 등장
→각각의 단면이 Quantuam Entanglement
에 의해 연결되어 한차원 높은 공간을 형성
→Holography=RG



둘 사이의 관계가 정확히 수립되는 계의 존재 : J. Maldacena

N=4 Supersymmetric gauge theory = Gravity in AdS5 x S5

정식화 : Ed. Witten, Gubser+Klebanov+Polyakov

홀로그래피=계산의 방법론

→ 쌍대성의 SHO//H-atom 를 수립 (1998)

→ 계산의 정식화: 모든 쌍대성에 확장

현실적 물리계에의 적용을 통한 체계의 수립?

Large N? SUSY?

.... 진행중.

Results

- Part I: 문제 제기
- Part II: 아이디어
- Part III: 새 이론의 결과

-Anomalous Transport in Dirac metal,

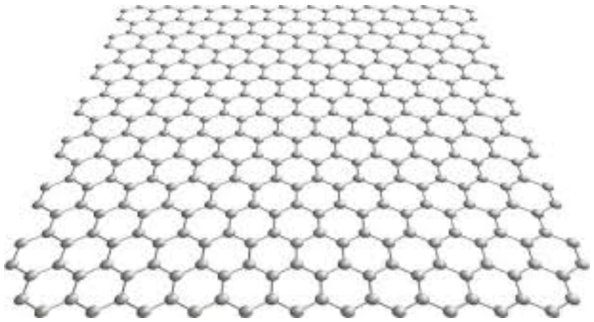
-Mott transition, Spectral density of V_2O_3

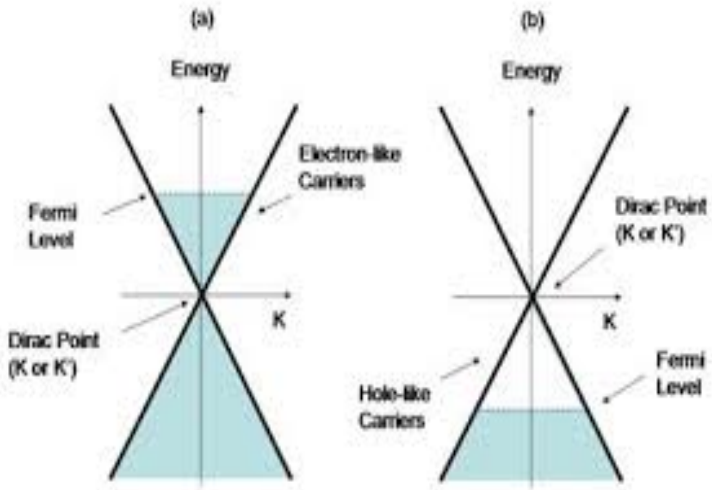
Type i : Dirac Materials

1. Graphene and anomalous transport

2. Topological insulator and magnetotransport

Simplest QCP with z=1





Q: 강상관계? Yes : Tiny FS → small screening → Type II 양자물질

$$g_{eff}^2 = \frac{e^2}{\hbar c}\frac{1}{v_F}\frac{1}{\epsilon}$$

Charge from Dirty Substrate → FS not small.

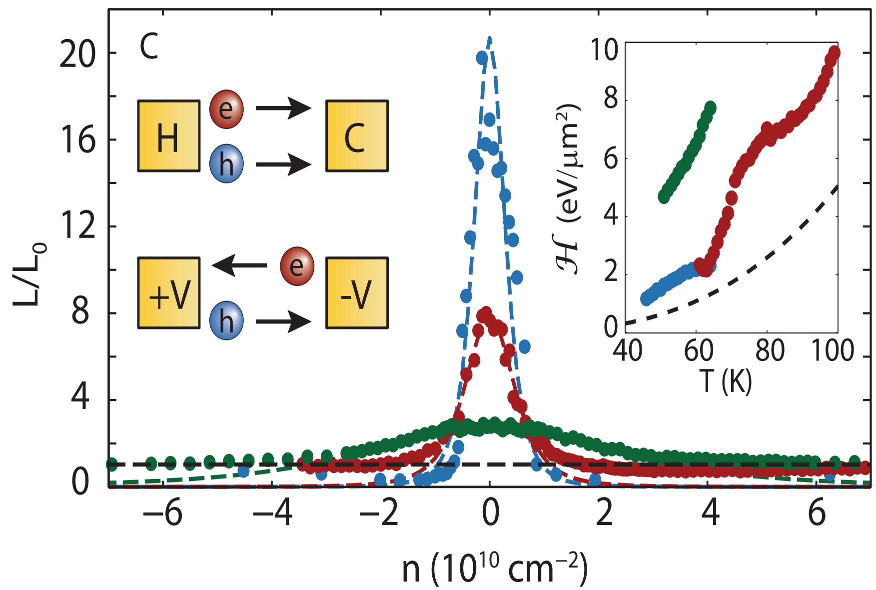
Key: BN substrate → 10 years of delay

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

Jesse Crossno,[1,2] Jing K. Shi,[1] Ke Wang,[1] Xiaomeng Liu,[1] Achim Harzheim,[1] Andrew Lucas,[1] Subir Sachdev,[1,3] Philip Kim,[1,2*] Takashi Taniguchi,[4] Kenji Watanabe,[4] Thomas A. Ohki,[5] Kin Chung Fong[5*]

4 March 2016

Science AAAS



홀로그래피 계산의 모델

Idea : neutral current → Enhance the heat conductivity

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

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

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

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

4 basic parameters.

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

Remark: all analytical result

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

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

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

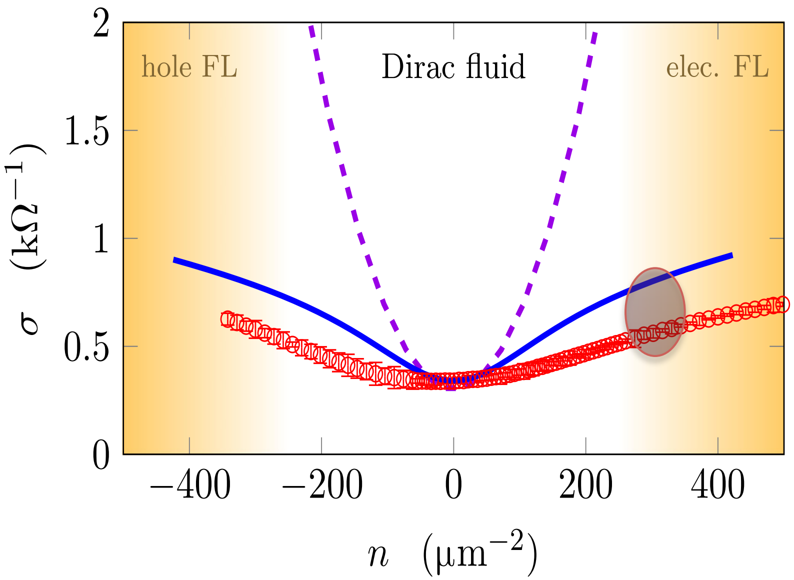
where $Q = \sum_i Q_i$ and $Z = \sum_i Z_i$, showing the additivity

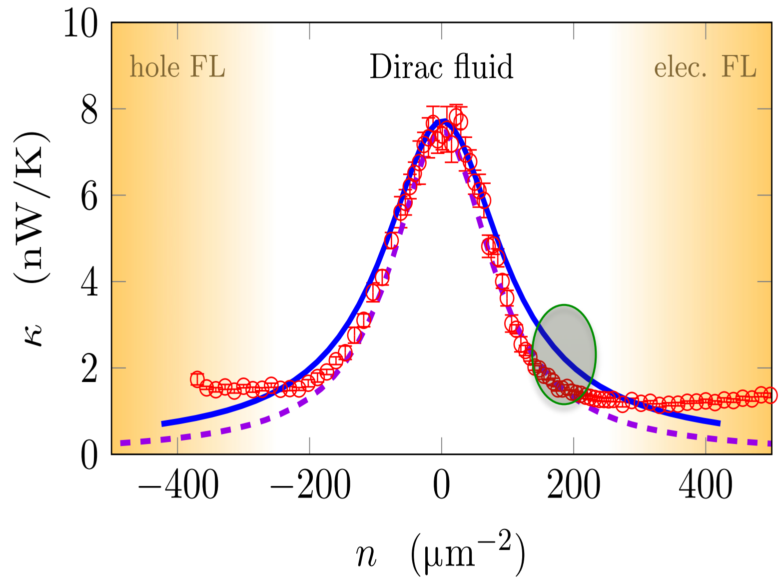
$$D[1/\kappa] = \sum_i D[1/\kappa_i], \qquad \bar{D}[\sigma] = \sum_i \bar{D}[\sigma_i],$$

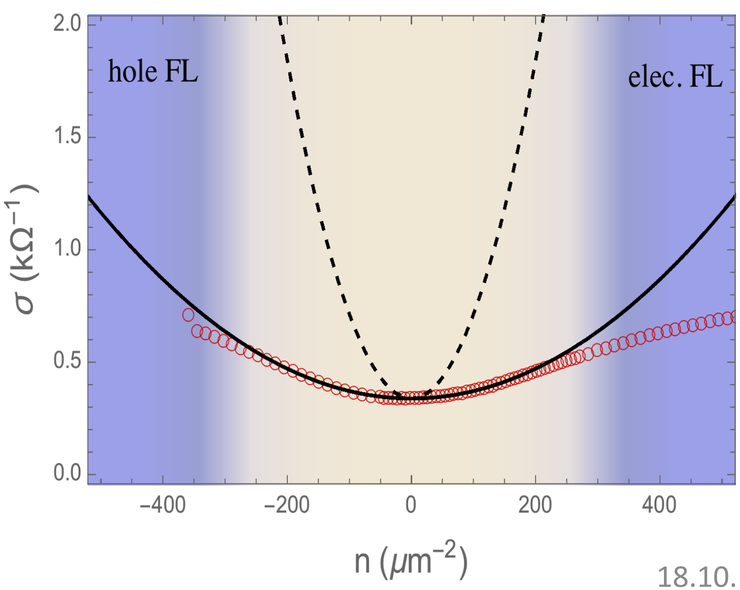
$$\kappa = \frac{\bar{\kappa}}{1 + \sum_i 4\pi Q_i^2 / s k^2 Z_i}, \qquad 1/\kappa_i = 1/\bar{\kappa} + Q_i^2 / Z_i s^2 T,$$

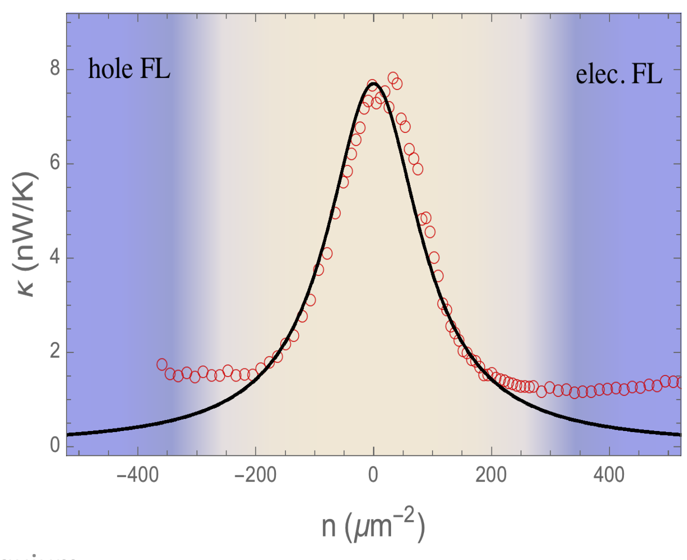
where $D[f], \bar{D}[f]$ denote the density dependent and in-
dependent part of f, respectively.

Hydrodynamics vs quantum Holography in data fitting









(b)

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

Yunseok Seo,[1] Geunho Song,[1] Philip Kim,[2,3] Subir Sachdev,[2,4] and Sang-Jin Sin[1]

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[2]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*

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

Editors' Suggestion

Other z=1 material ?

Dirac material is a class (1405.5774): 예측: all of them have anomalous transports.

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			

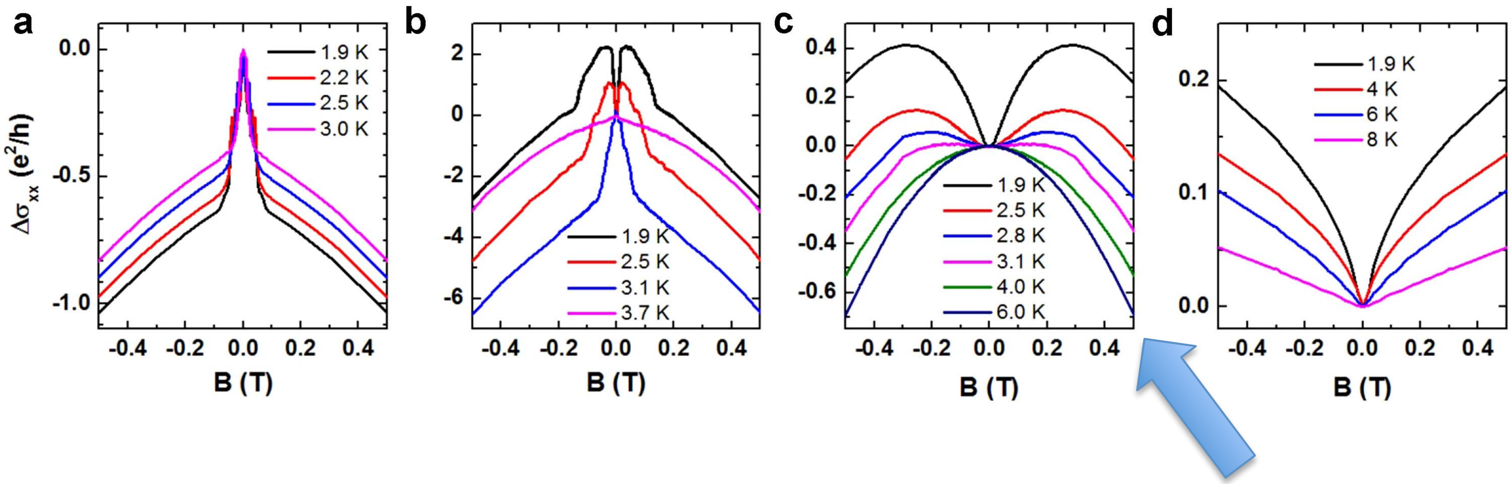
Table 1. Table of Dirac materials indicated by material family, pseudospin realization in the Dirac Hamiltonian, and the energy scale for which the Dirac spectrum is present without any other states.

선택: Surface of Topological Insulator (내부=부도체, 표면=도체)

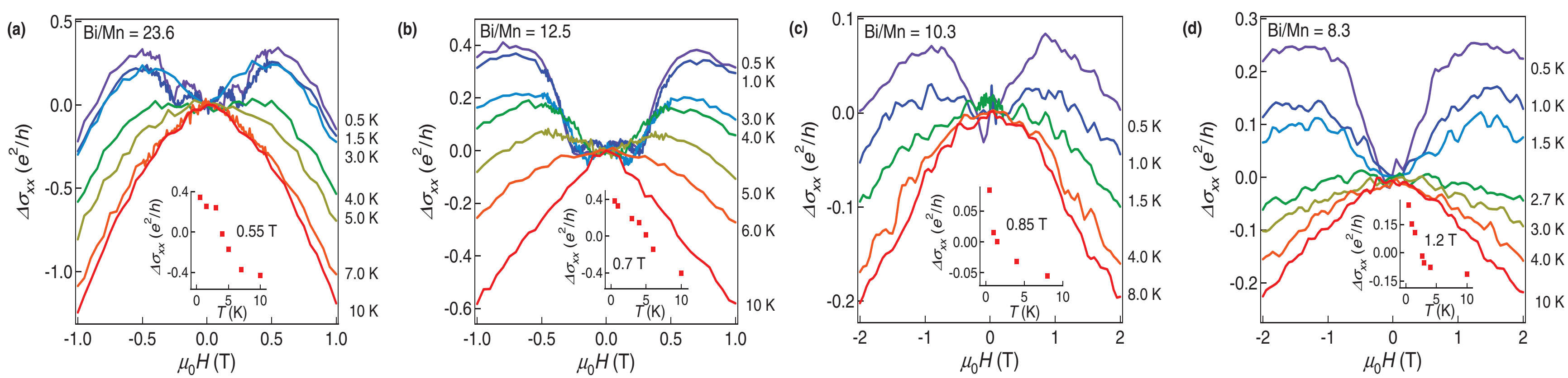
Similar, but differ by strong spin-orbit interaction

Surface phenomena of TI : WAL → WL transition

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



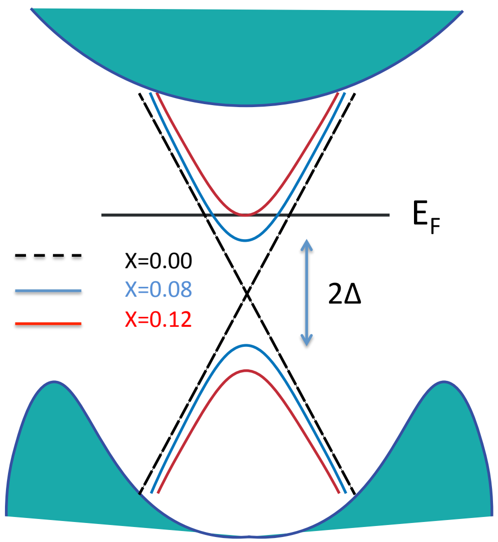
2. . Bi_2Se_3 with Mn doping : Zhang et.al, prB86,205127(2012)



Surface states of TI

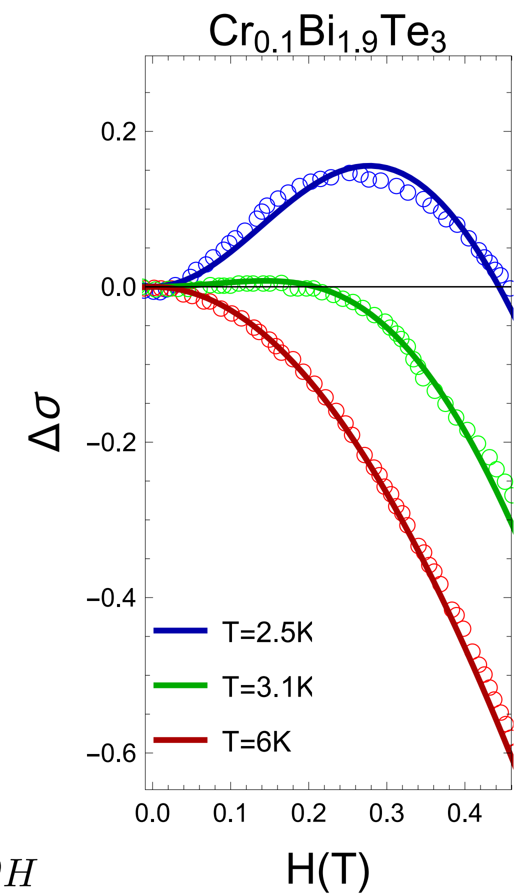
[1703.07361, prB, rapid comm 서윤석,송근호,SJS]

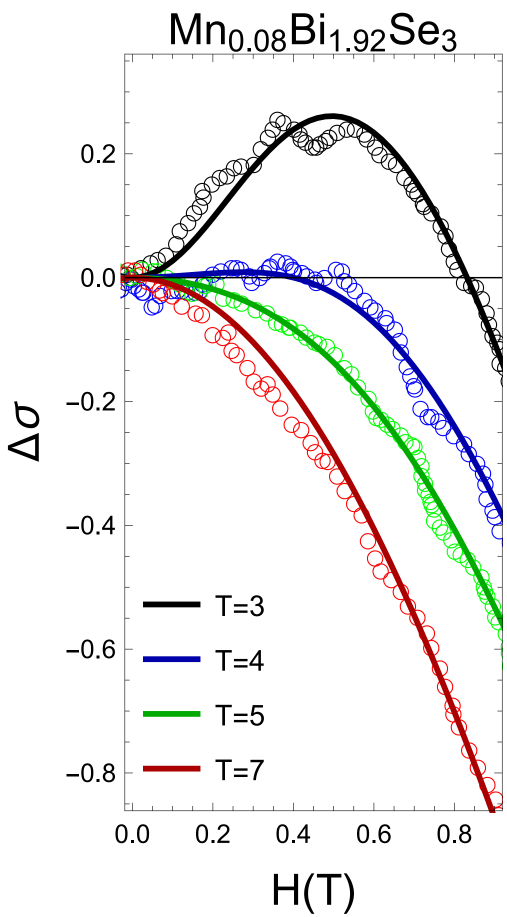
Theory fits
not only for Cr doped Bi_2Te_3 but also Mn doped Bi_2Se_3



$$\sigma_{xx} = \frac{(\mathcal{F}+\mathcal{G}^2)(\mathcal{F}-H^2)}{\mathcal{F}^2+H^2\mathcal{G}^2}$$

$$\mathcal{F} = r_0^2(\alpha^2+\lambda^2)+(1+\theta^2)H^2 - q\,\theta H$$
$$\mathcal{G} = q-\theta H.$$





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

$$\sigma_{ij}(B, T, n_{imp})$$

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

$$\kappa_{ij}(B, T, n_{imp})$$

Now, Type II

Type I and II Unified in Holography

Type I: z=1, Dirac cone

Type II: z>1 … ∞ (more) Flat band

In leading order, there are only quantitative difference.

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

Dual?

QCP(z,θ)

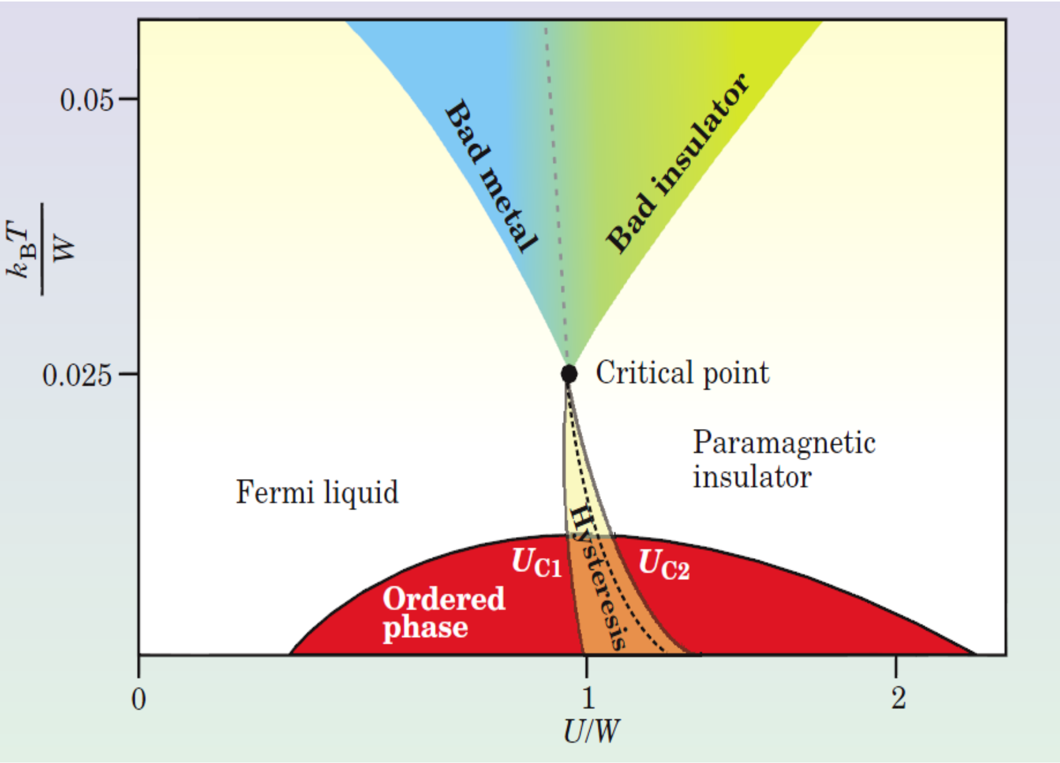
Geometry (z,θ)

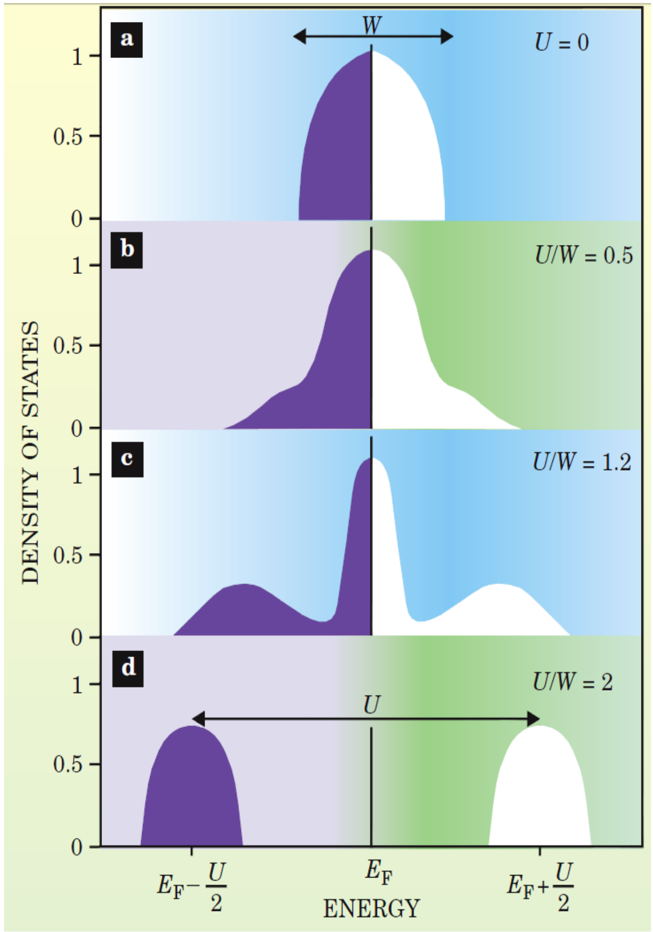
Exp. data

Make a unique rule

Transport coefficients

Mott Transition





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

Theme

1. Hubbard model in d>1 → Not solvable
2. finding its gravity dual is V. difficult. → title
3. Can we replace the Hubbard Model by a holographic-model?
4. Try a Holographic Fermion Model
   with free fermion like behavior and gap generation.

Spectral function

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

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

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

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

Calculating the spectral function is already standard.

SS. Lee, H. Liu, Iqbal, T. Faulkner, J. Mcgreevy, Vegh, Cubrovic, K. Schalm, J. Zaanen, ……

Phase Diagram

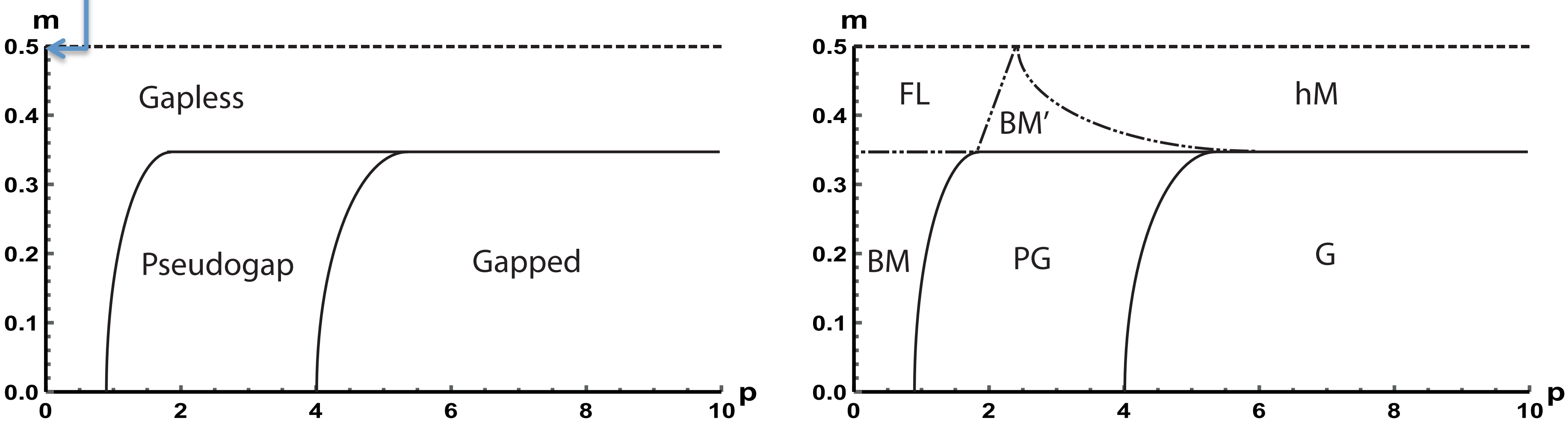
$$S_\psi = \int d^4x\sqrt{-g}\, i\bar{\psi}(\not{D} - m - ip\not{F})\psi + S_{bdy}$$

Known to Gap generating
Phillips et.al

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

m=1/2 is Free fermionic.

Free fermion



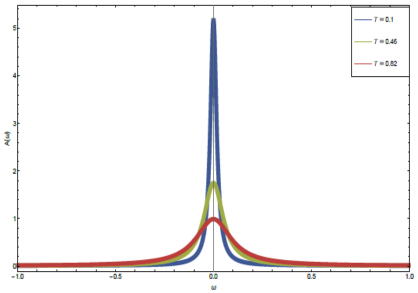
(a) Phase diagram

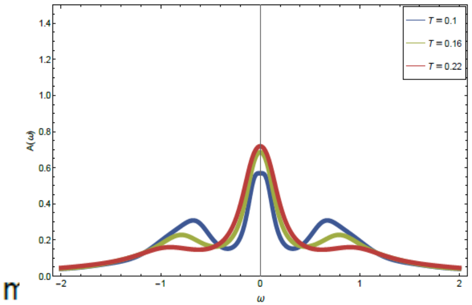
(b) Substructure in gapless phase

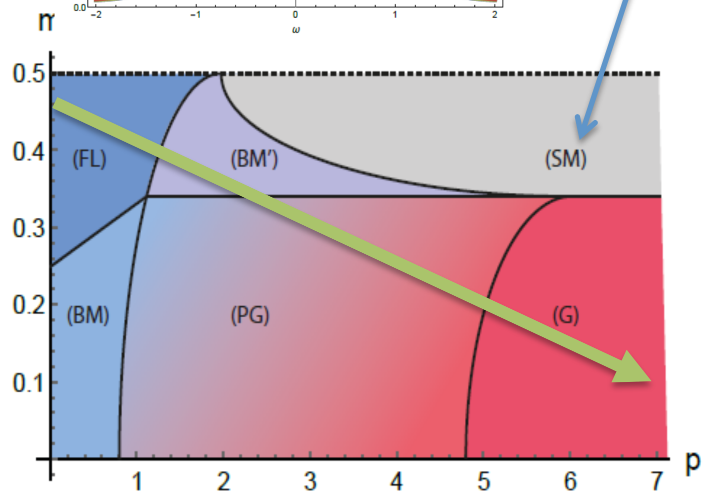
“Transition” is smooth everywhere.

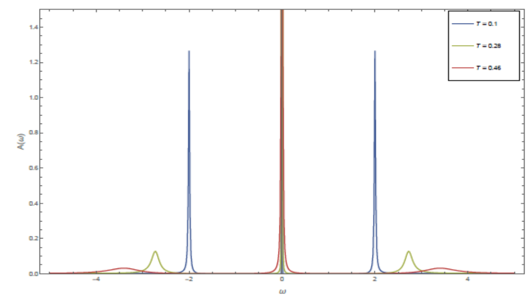
6 phases : with symmetrized spectral function

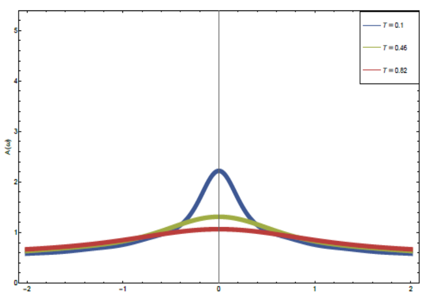
SM/hM phase : 상호작용있는 topological matter

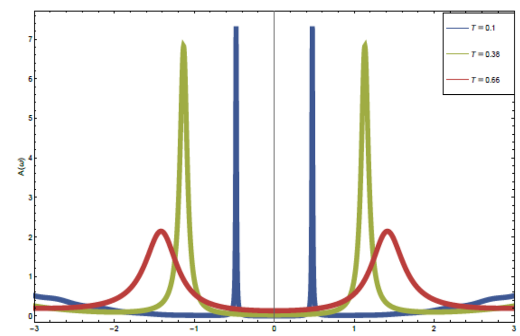


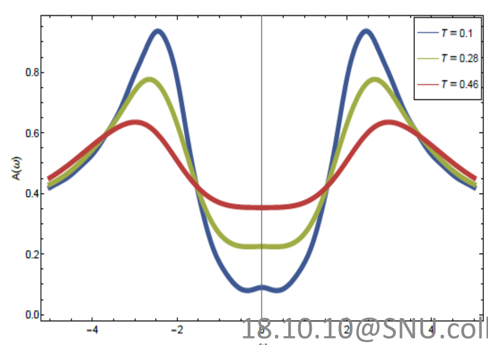






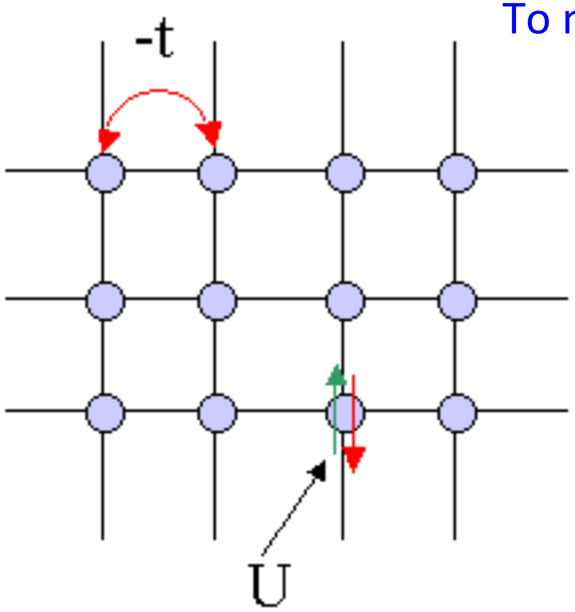


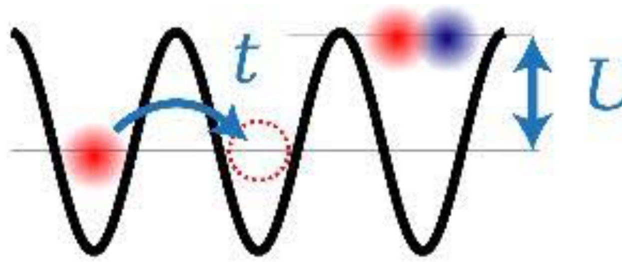




Hubbard Model: from free fermion to strongly repulsive int.

To move or not to move, that is the problem!



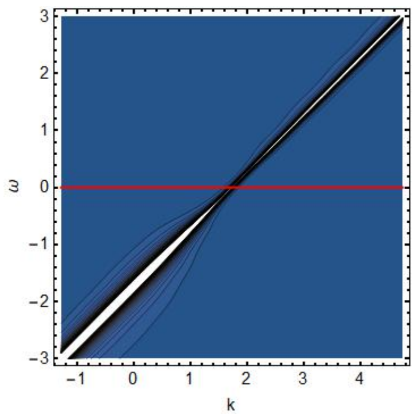


$$H = -t \sum_{\langle i,j\rangle,\sigma} \left(c^\dagger_{i,\sigma} c_{j,\sigma} + c^\dagger_{j,\sigma} c_{i,\sigma}\right) + U \sum_{i=1}^{N} n_{i\uparrow} n_{i\downarrow},$$

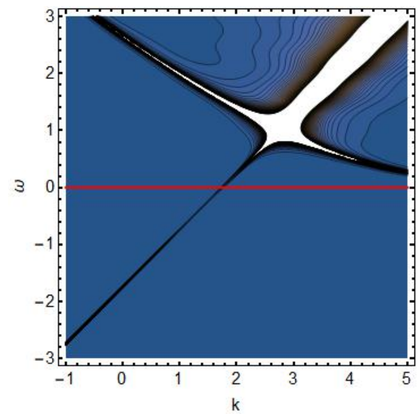
U=0 → U=infinity

Understanding the Gap creation

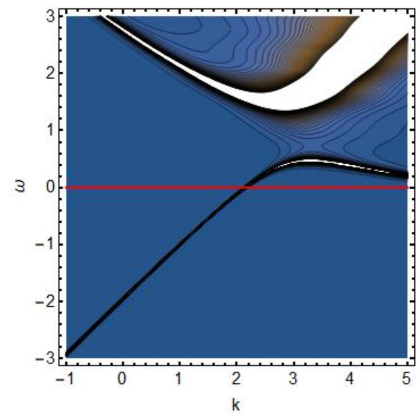
New Band creation →



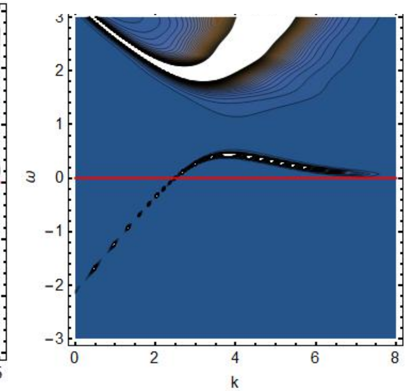
(a) $m = 0.5, p = 0$



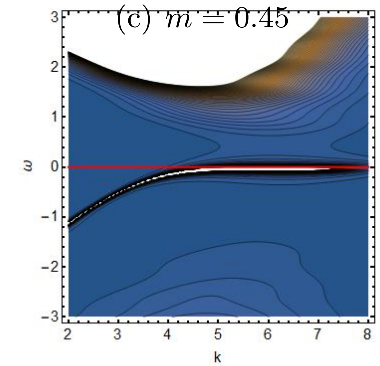
(b) $m = 0.5, p = 5$

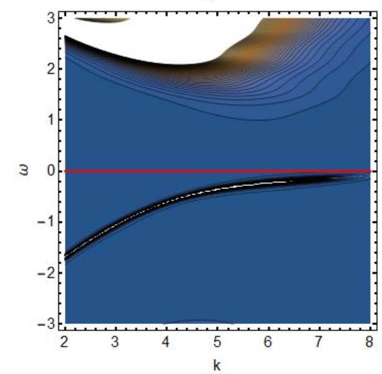


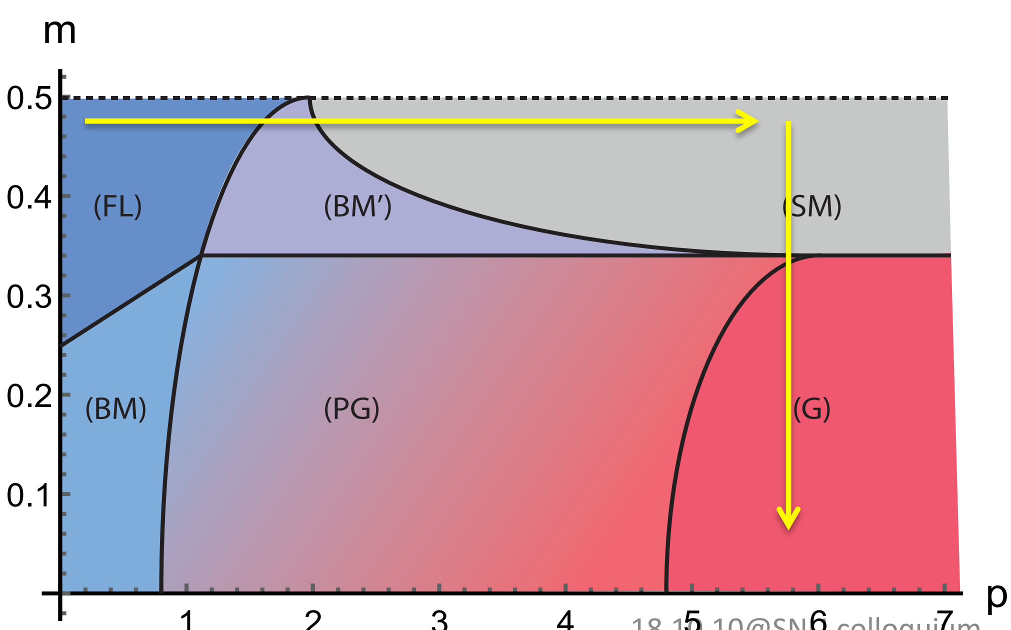
(c) $m = 0.47, p = 5$



(c) $m = 0.45$

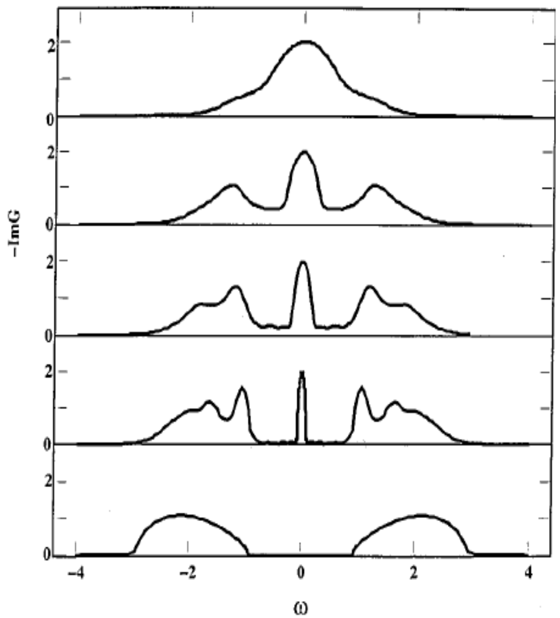






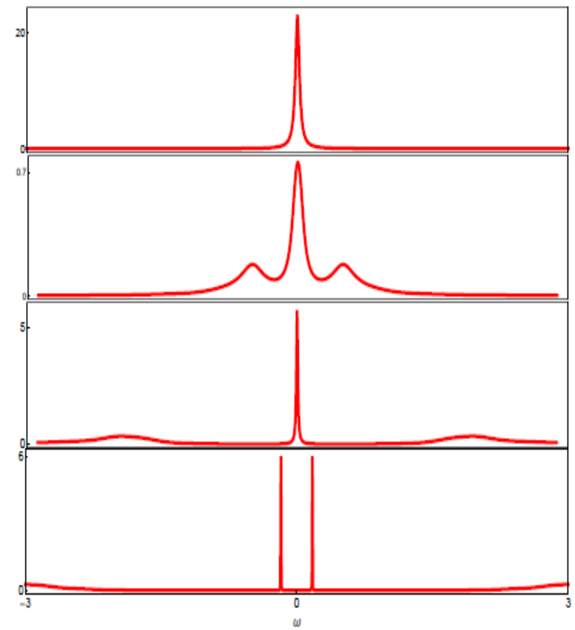
Gap Creation

Comparision with DMFT results

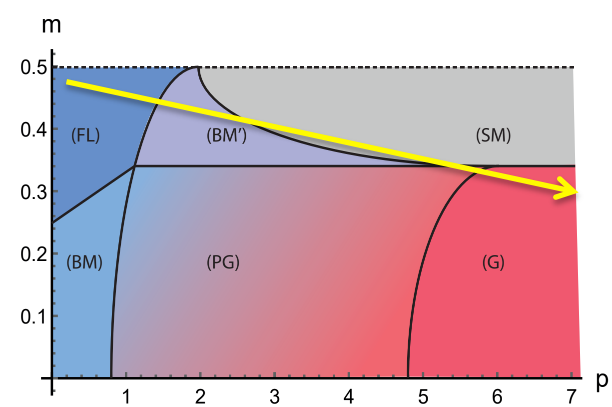


Single-site DMFT result

A. Georges, et.al Rev. Mod. Phys. 68 (Jan, 1996) 13–125.



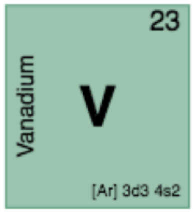
Holography with embedding



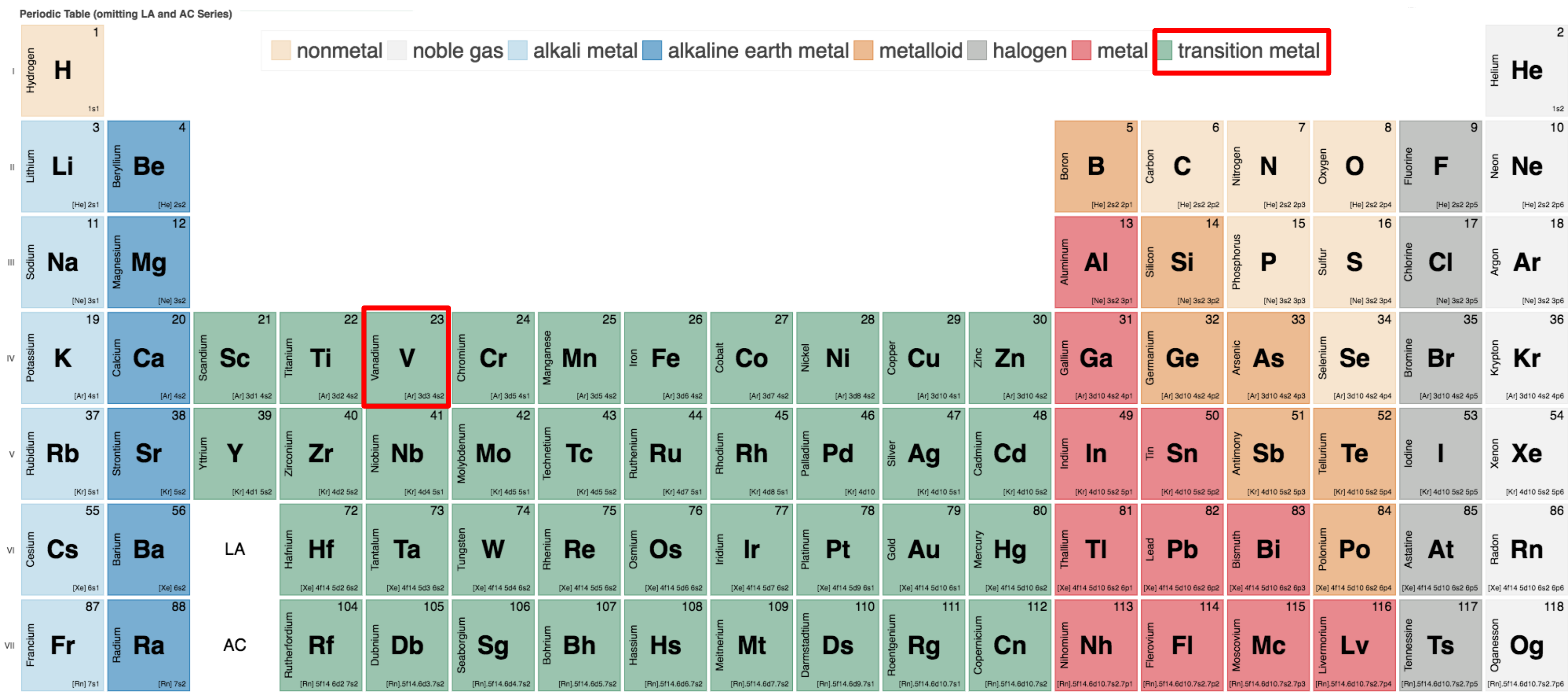
Depending on the path, evolution is different.

Data for Transition Metal Oxide

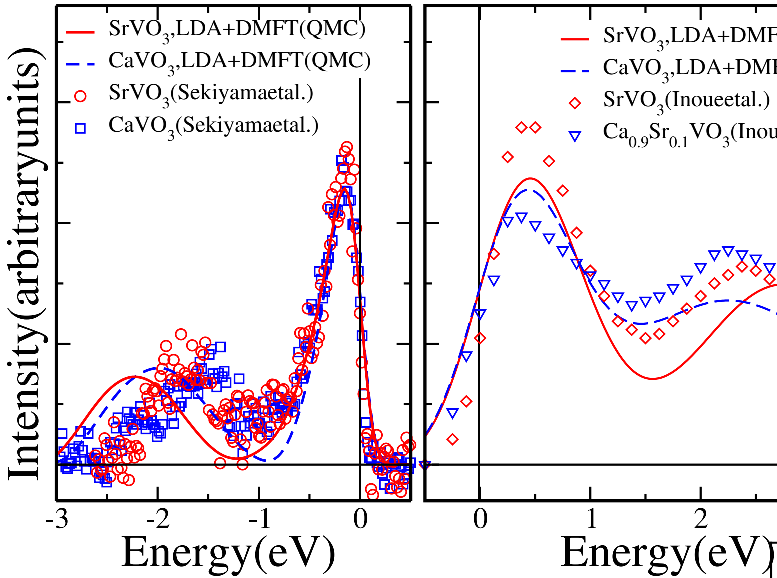
O^{2-}: anion



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

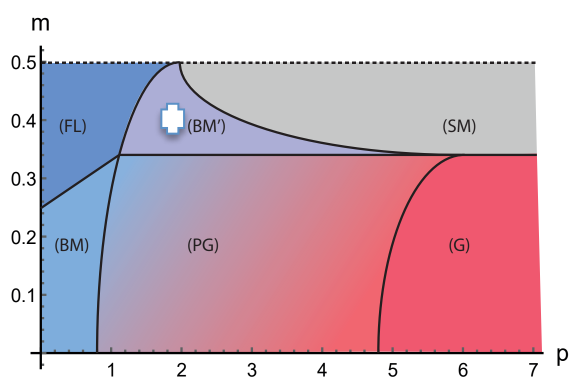


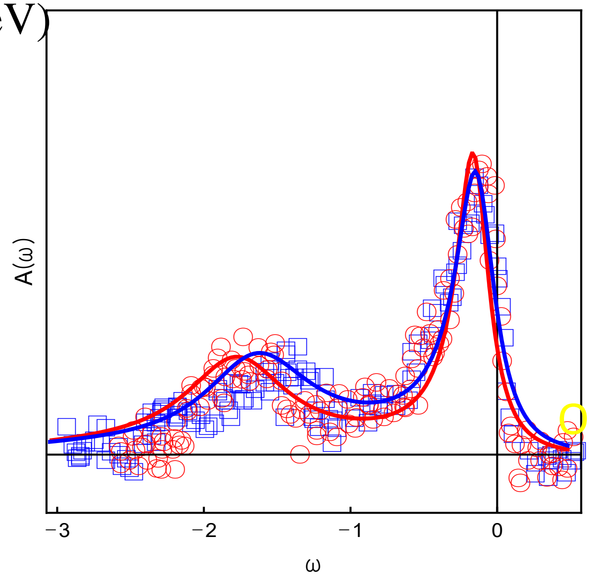
DMFT vs Experiment // Holography vs Exp



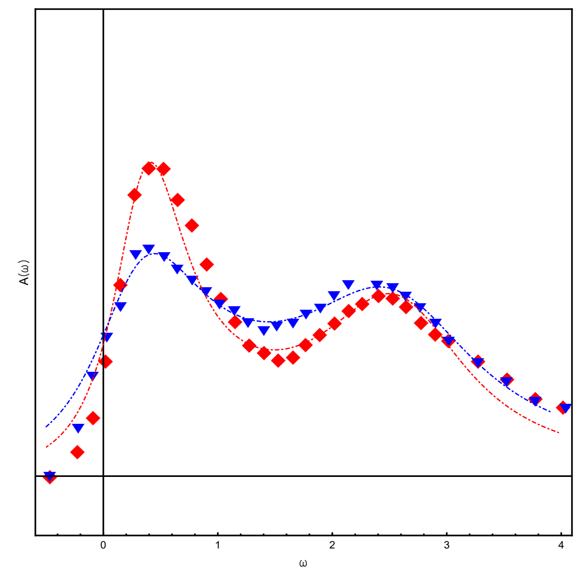
← DMFT school (2011) Dieter Vollhardt

Holography





(a)PES data vs theory



(b)XAS data vs theory

Future results

- Mott gap in type 1 (z>1), spin Liquid
- asymmetry, magnetism, backreaction.
- instability, d-wave condensation.
- other gap generation mechanism

$$S=\int\sqrt{-g}i\bar{\psi}\left(\not{D}-m-ig_vB_\mu\Gamma^\mu-ig_aB^{(5)}_\mu\Gamma^{5\mu}-ig_TM_{\mu\nu}\Gamma^{\mu\nu}\right)\psi-\int\sqrt{-g}i\bar{\psi}\left(g_0M_0+ig_5M_5\Gamma^5\right)\psi,$$

$$B_t=p\left[1-\left(\frac{r_0}{r}\right)^\alpha\right]$$
$$B_i=p\,r^{-\alpha}$$
$$M_{\mu\nu}=p\,r^{-\alpha},$$

α	0	1	2	3
M_s	·	○	○	○

M_s	0	○	○	○

α	0	1	2	3
$B_t\gamma^t$	·	●	●	●
$B_x\gamma^x$	●	○	○	○
$B_y\gamma^y$	○	○	○	○

Table 1: $g_v\neq 0$, ●: Gapless, ○: Gapped

α	0	1	2	3
$B^{(5)}_t\gamma^{5t}$	·	●	●	●
$B^{(5)}_x\gamma^{5x}$	●′	○	○	○
$B^{(5)}_y\gamma^{5y}$	○	○	○	○

α	0	1	2	3
$M_{tr}\gamma^{tr}$	0	●	○	○
$M_{tx}\gamma^{tx}$	●	●	●	●
$M_{ty}\gamma^{ty}$	●	●	●	●
$M_{rx}\gamma^{rx}$	●	●	●	●
$M_{ry}\gamma^{ry}$	●	●	●	●
$M_{xy}\gamma^{xy}$	○	○	○	○

Why rapid Thermalization?

Thermalization ←→
Black hole formation

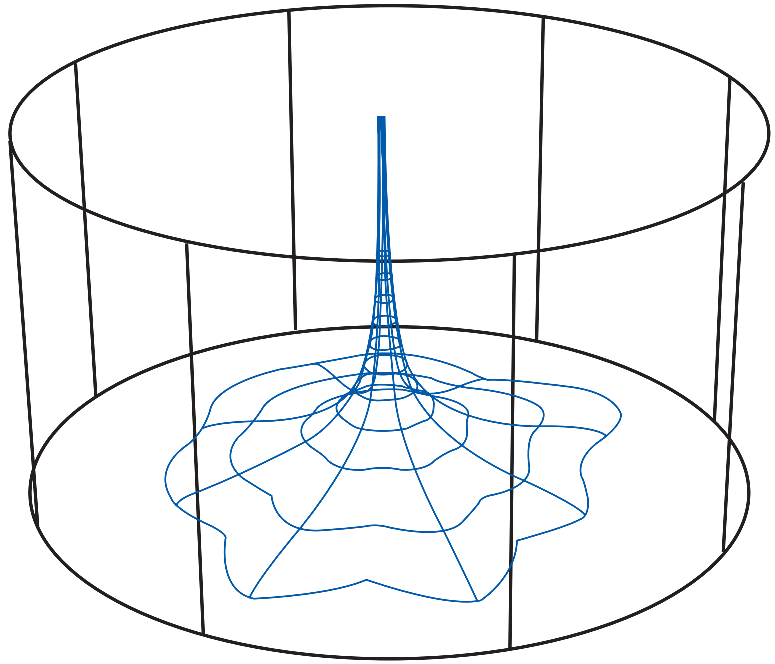


FIG. 3 Any shape of shell falls to form a black hole in one dynamical time. This special dynamics in AdS is the mechanism for easy thermalization for strong coupling [17].

[17] Eunseok Oh, Sang-Jin Sin, "Non-spherical collapse in AdS and Early Thermalization in RHIC" Phys. Lett. B **726** (2013) 456-460, arXiv:1302.1277 [hep-th];
Sang-Jin Sin, The physical mechanism of AdS instability and Holographic Thermalization, arXiv: 1310.7179.

Near Future subject

- Mott gap in class 2 (z>1),
- Moire Pattern and Flat Band
- spin Liquid, Fractionization
- CDW, instability, other gap generation mechanism
- d-wave condensation.
- Strange metal
- Pairing
- magnetism, backreaction.

Conclusion

- 중력 → 강상관계를 위한 새로운 물리학으로 역할
- 전이금속 산화물, 디랙물질을 통일적으로 기술
- 21세기 장론/응집물리학의 새 방향

감사합니다.

How to formulate fermion

For conductivity : need <JJ> : (J,A) → extend A into AdS

F^2 in the bulk

For spectrum: need <χχ> : (ψ,χ) → extend ψ into AdS

ψ(D-m)ψ +bulk interaction.

What interaction?

pψ F.Γ ψ. → Gap (Phillips et.al)

comment: Gravity already accounted

e-e long range repulsion in the absence of the lattice.

So p describe the onsite repulsion.

Spectral function

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

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

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

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

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

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

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

Green Function

$$\psi_\pm = (-gg^{rr})^{-\frac{1}{4}}\phi_\pm, \quad \phi_\pm = \begin{pmatrix} y_\pm \\ z_\pm \end{pmatrix}$$

Introducing the $\xi_\pm$ by

$$\xi_+ = i\frac{y_-}{z_+}, \text{ and } \quad \xi_- = -i\frac{z_-}{y_+}, \tag{11}$$

the equations of motion Eqs.(8) can be recast into two independent equations for $\xi_\pm$:

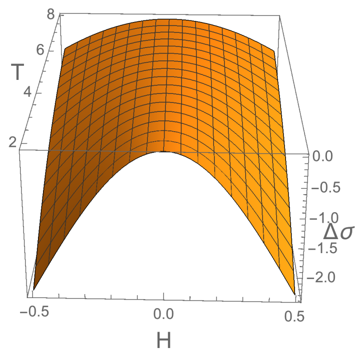
$$u(r) = \sqrt{\frac{g_{xx}}{-g_{tt}}}(\omega + qA_t(r)).$$

$$\sqrt{\frac{g_{xx}}{g_{rr}}}\xi'_\pm = -2m\sqrt{g_{xx}}\xi_\pm + [u(r) + p\sqrt{g_{xx}}A'_t(r) \mp k] + [u(r) - p\sqrt{g_{xx}}A'_t(r) \pm k]\xi^2_\pm.$$

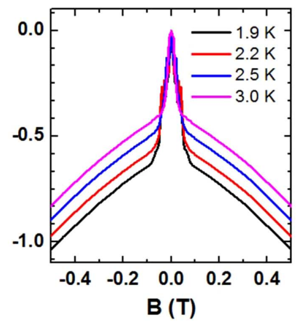
and the Green functions for $m < 1/2$ can be written as

$$G^R_\pm(\omega, k) = \lim_{r\to\infty} r^{2m}\xi_\pm(r, \omega, k). \tag{12}$$

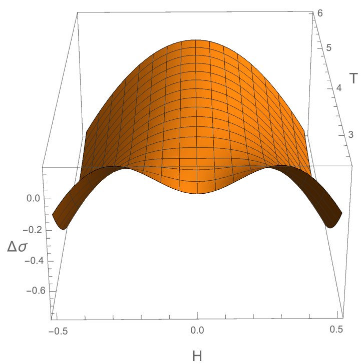
Surface states of TI [1703.07361, 서,송,신]



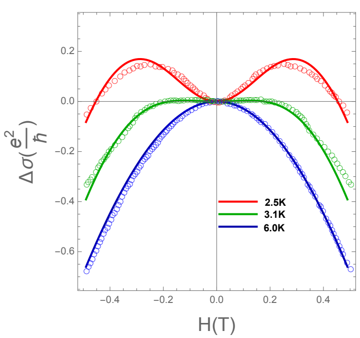
(a)



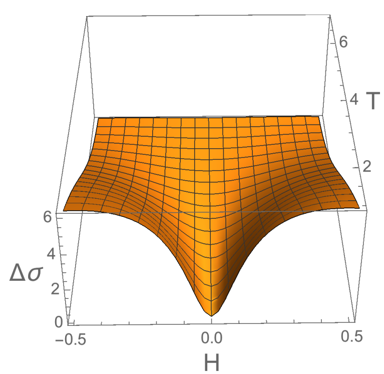
(b)

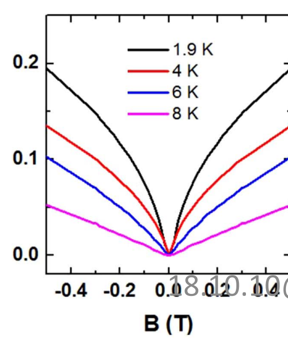


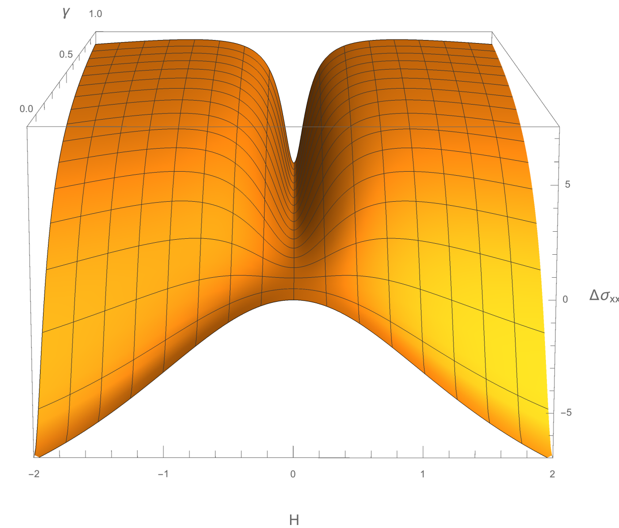
(c)



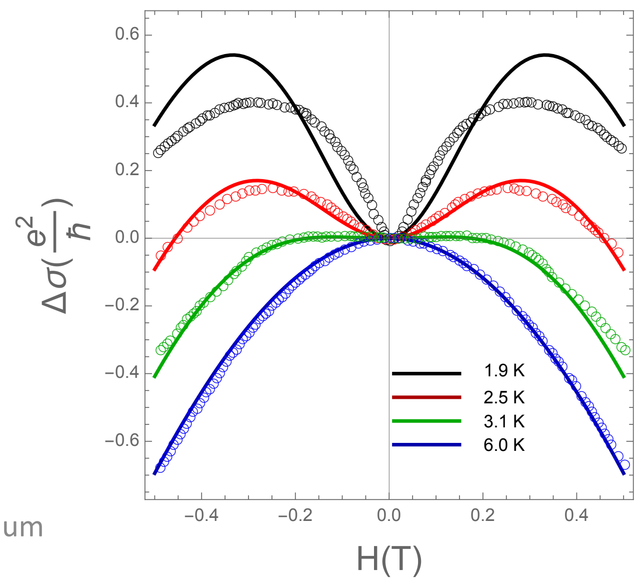
(d)







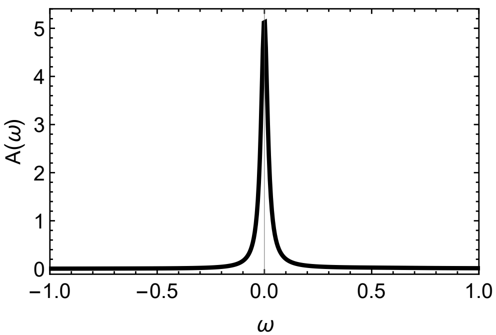
Evolution of MC curve from WAL to WL



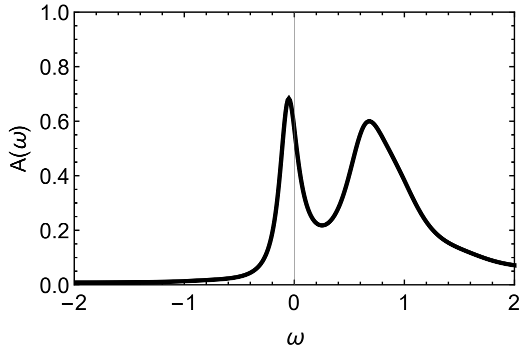
Spectral data-ARPES

- 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

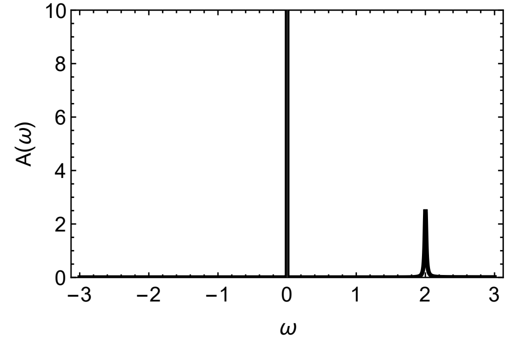
spectral function



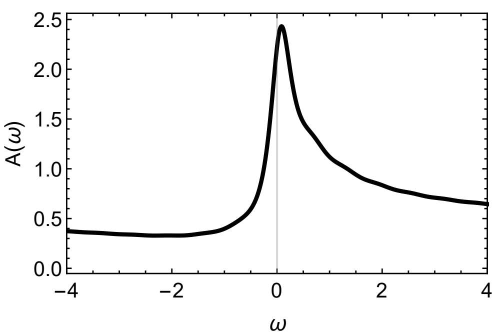
(a) Fermi liquid like (FL)



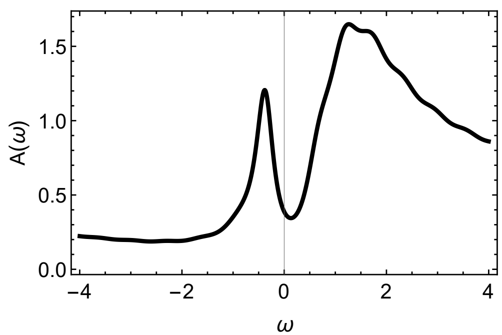
(b) bad metal prime (BM')



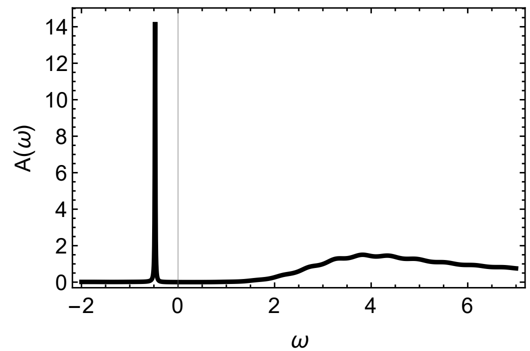
(c) half-metal (hM)



(d) bad metal (BM)

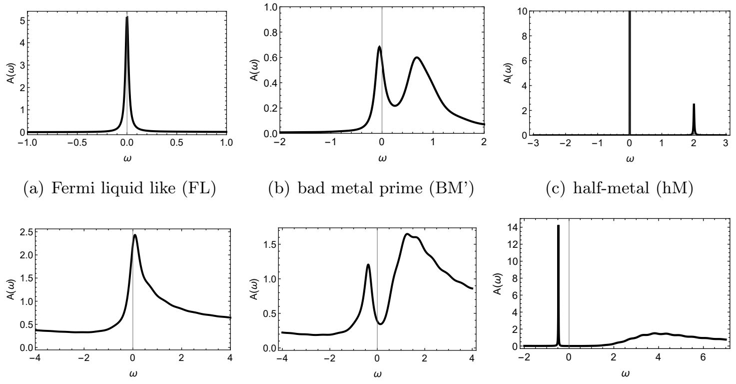


(e) pseudogap (PG)



(f) gapped (G)

Diagnosis



(a) Fermi liquid like (FL) (b) bad metal prime (BM') (c) half-metal (hM)

(d) bad metal (BM) (e) pseudogap (PG) (f) gapped (G)

1. Problem: Spectral function gives too much asymmetry.
   This is the evidence of Pauli principle is working partially.

2. Reason: Hole degree of freedom is not encoded.
   (Positive and Negative energy spectrum have the same charge)

3. Spectral function of hole = Spectral function of particle (q→-q)

How to add hole spectrum?

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

p → p Sign[q]

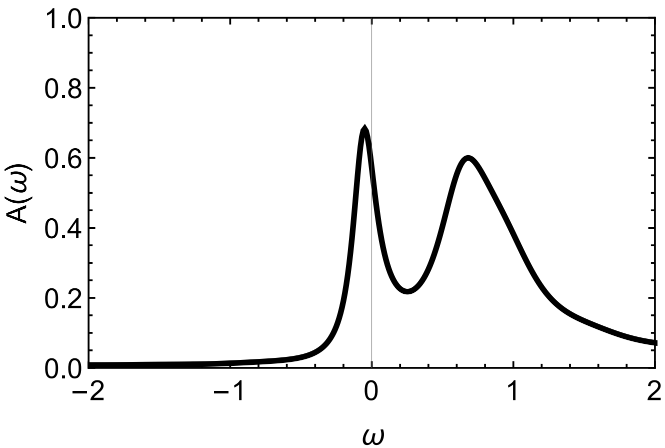
Minimal interaction contains qA_t

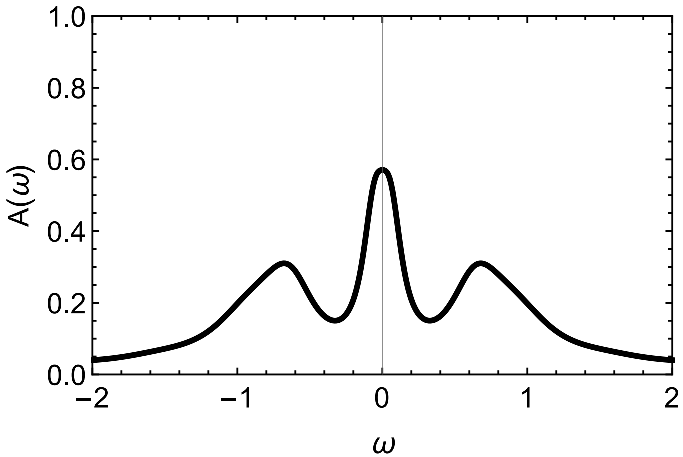
1. We change Lagrangian → L[q] +L[-q]

2. Consequence:
   equivalent to Spectral function is Symmetrized.
   due to the relation
   G[w, k, q] =-G*[-w,-k,-q]

   A[w, k,q]+A[w,k,-q]=A[w, k,q]+A[-w,-k,q]

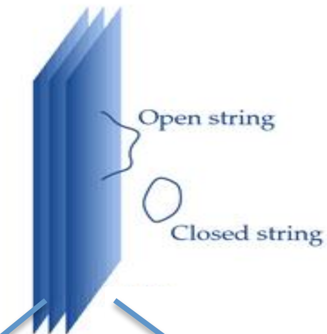
Consequece of adding hole spectrum





끈이론의 양자 홀로그래피 (exact)

D-brane



(초대칭 등각대칭) 게이지이론,

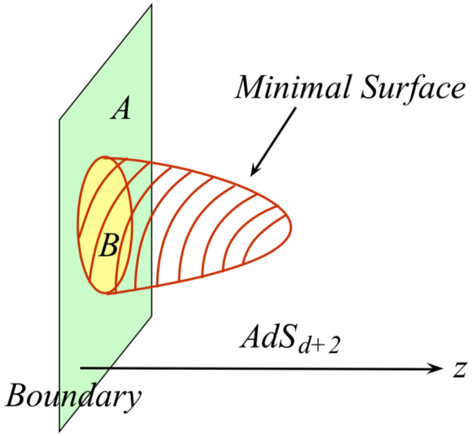
AdS 중력이론 (초대칭)

Theory of
Quantum
Matter

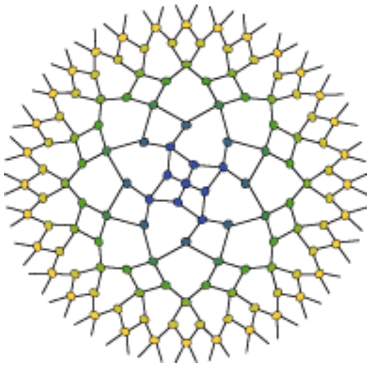
Classical
Geometry

1. 등각장론에서의 얽힘 엔트로피

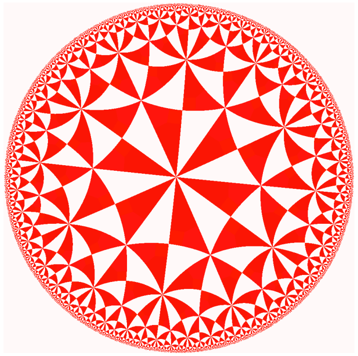
Ryu & Takayanagi (2006)



2. 텐서그물망 : (Multiscale Entanglement Renormalization Ansatz)

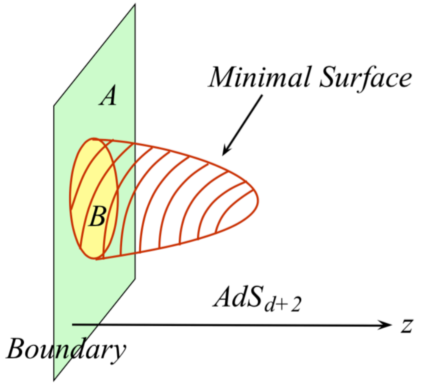


[Swingle]

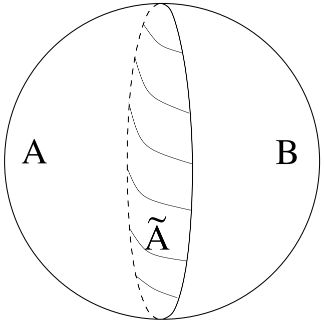


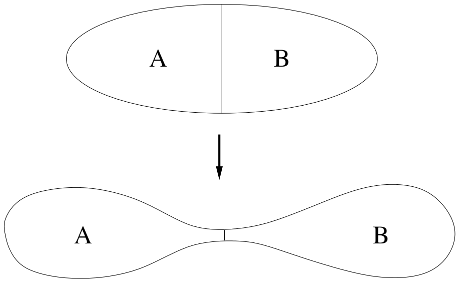
Comment : Entanglement and Holography

Ryu & Takayanagi (2006) 의 가정은 심오한 결과를 파생
홀로그래픽 듀얼공간의 존재와
계에 높은 양자얽힘이 있다는 것은 동치임



Raamsdonk : classical (듀얼) 공간의 존재는 그 공간안에 정의된 물질의 엔탱글먼트에 의존한다. 공간은 얽힘으로 바느질된 보자기와 같다.
Entanglement first law → Linearized gravity equation.





Complete Einstein equation from the generalized First Law of Entanglement
ES. Oh , IY. Park +sjs
arXiv:1709.05752 [hep-th] | PDF