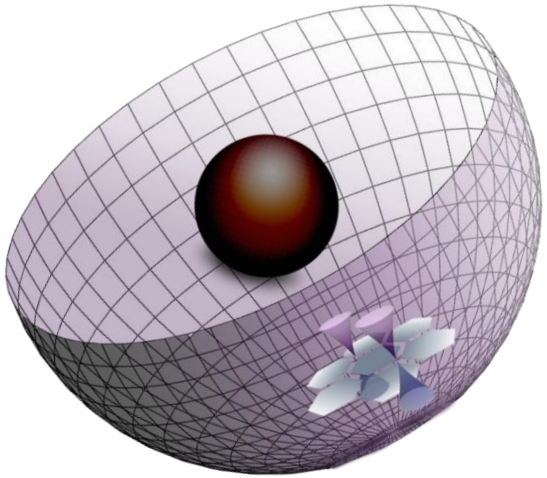
Holography

String inside holographic particles

Entanglement String

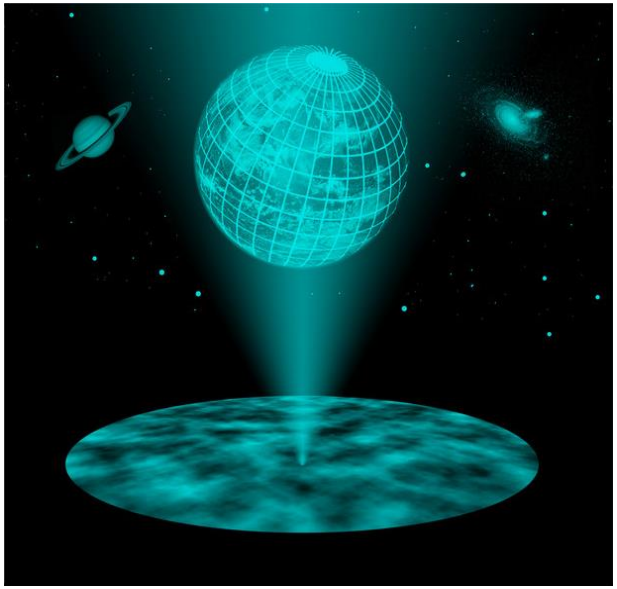
Sang-Jin Sin
(Hanyang)



2018.11@KIAS.east-asian

ES. Oh +SJS :To appear

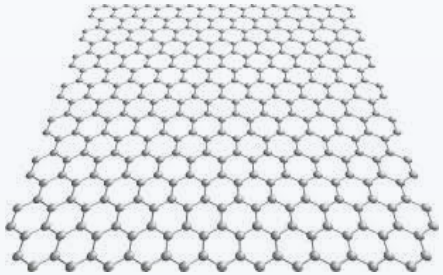
Theme : Use of Holography to real material



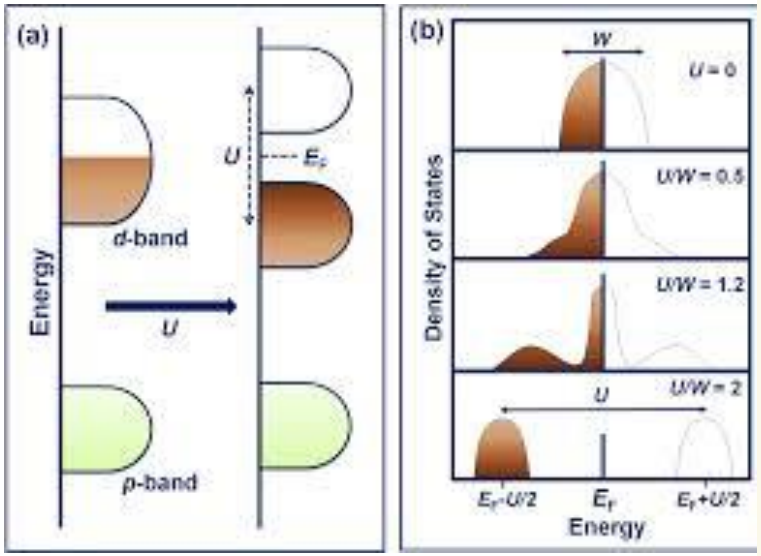
3 dim.
Classical
BH

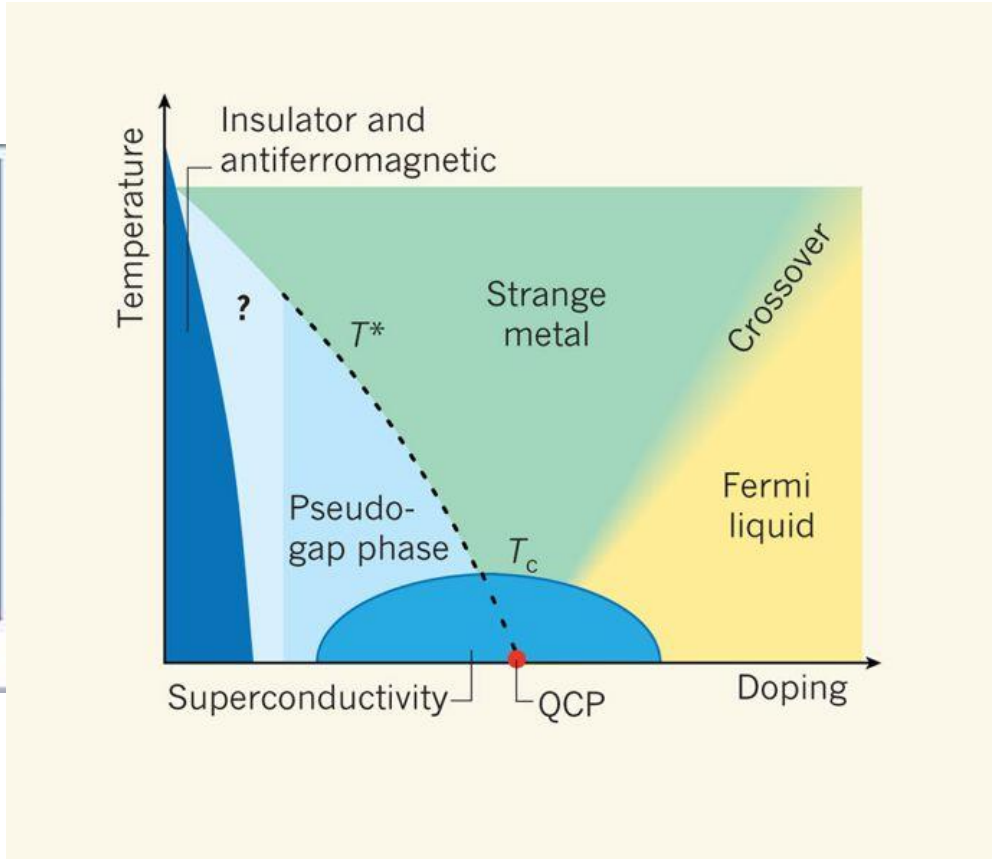


2 dim.
Quantum
Matter



There Exist giant Motivation : Mott Transition , High Tc SC





However, is there any feasibility of being real ?

Some success story in fitting real data is necessary before any serious attempt.

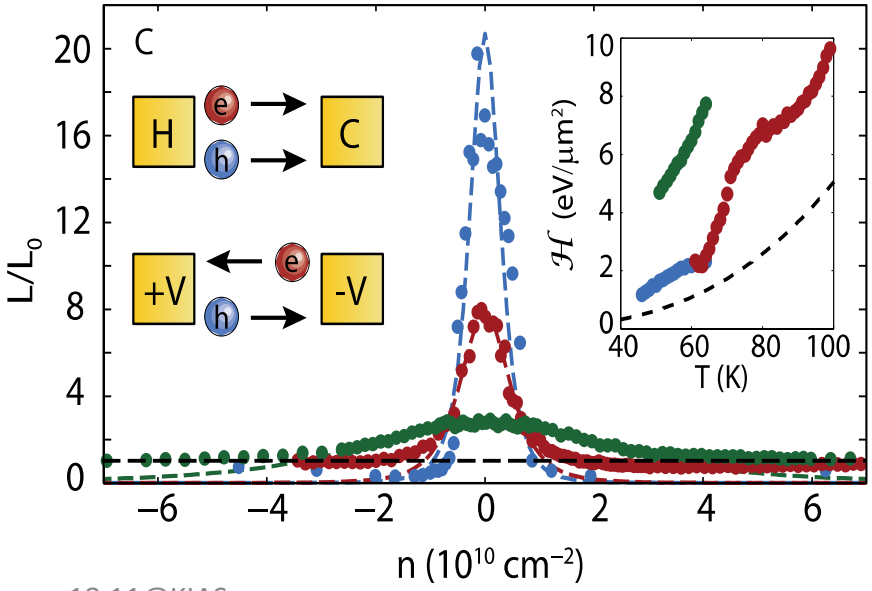
First data

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

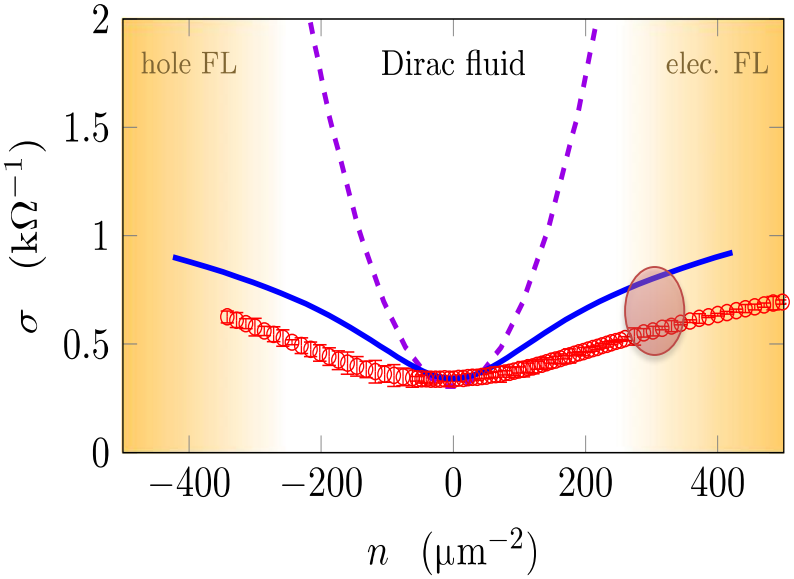
Jesse Crossno,[1,2] Jing K. Shi,[1] Ke Wang,[1] Xiaomeng Liu,[1] Achim Harzheim,[1] Andrew Lucas,[1] Subir Sachdev,[1,3] Philip Kim,[1,2]* Takashi Taniguchi,[4] Kenji Watanabe,[4] Thomas A. Ohki,[5] Kin Chung Fong[5]*

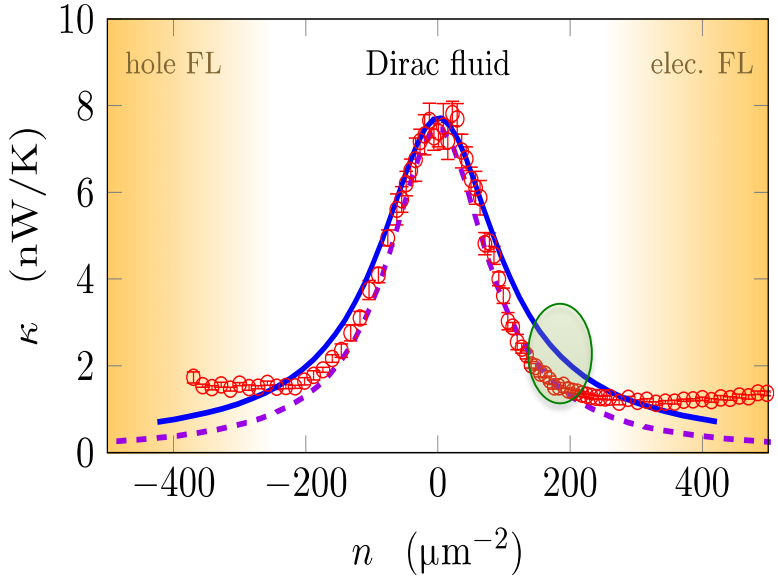
4 March 2016

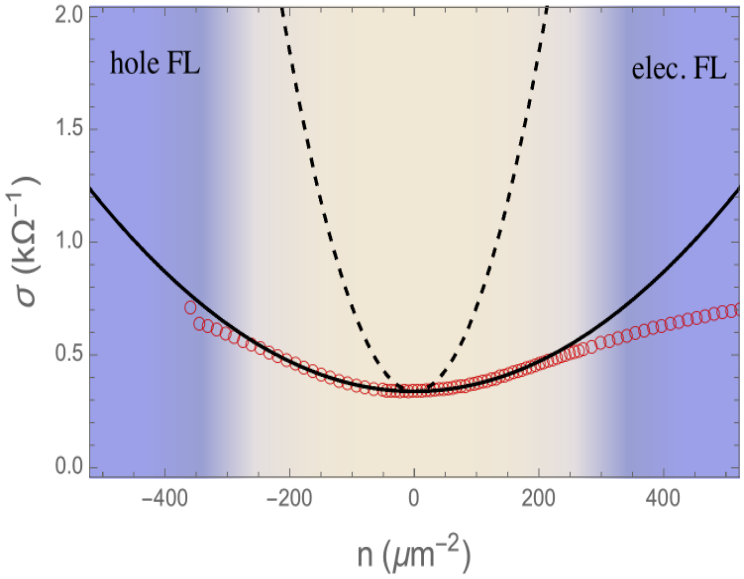
Science AAAS

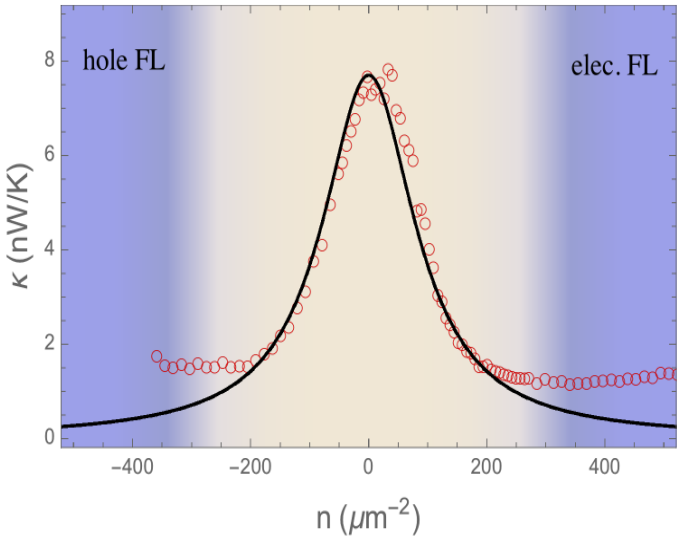


Anomalous transport in Graphene : holography of two current model









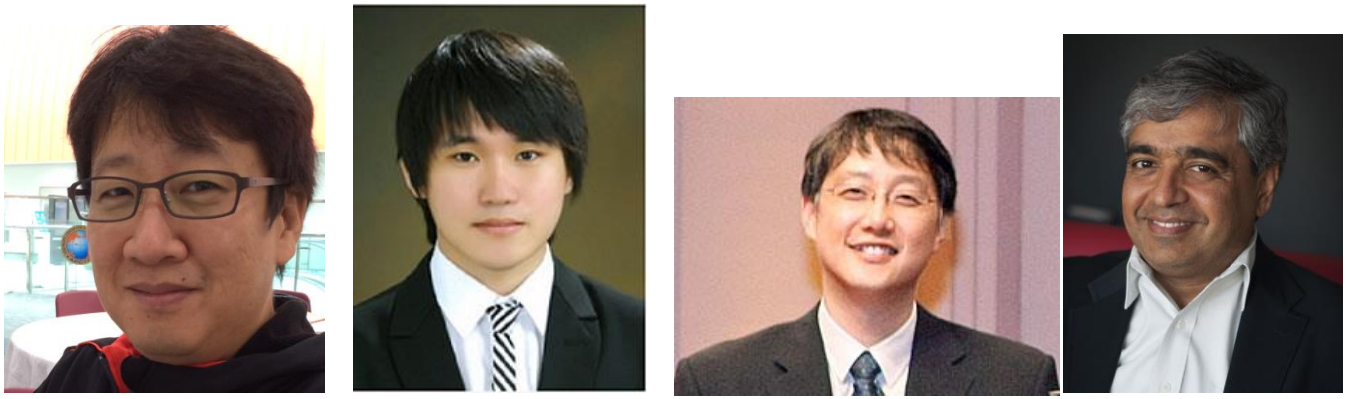
(b)

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]
[1]*Department of Physics, Hanyang University, Seoul 133-791, Korea*
[2]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*



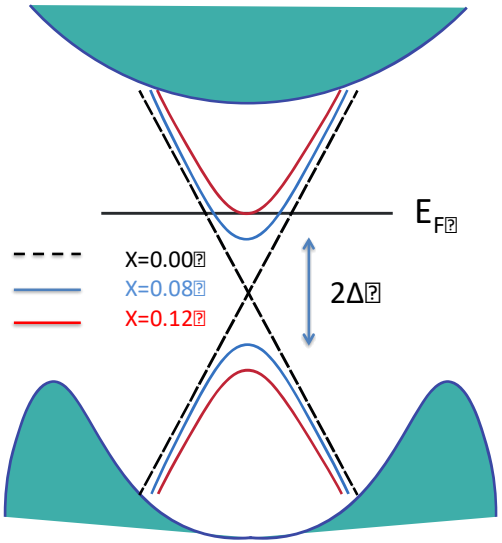
Phys.Rev.Lett. 118 (2017) no.3, 036601

Editors' Suggestion

Surface states of TI

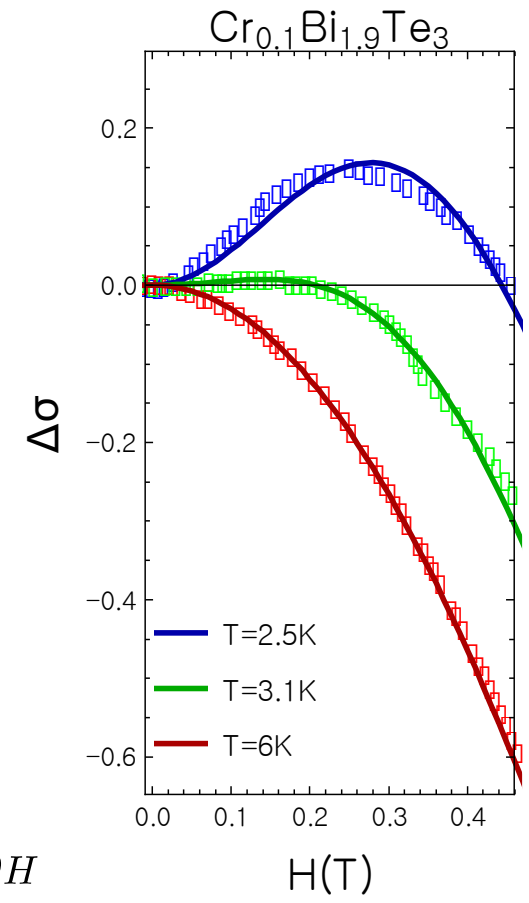
[1703.07361, prB, rapid comm, Seo,Song,Sin]

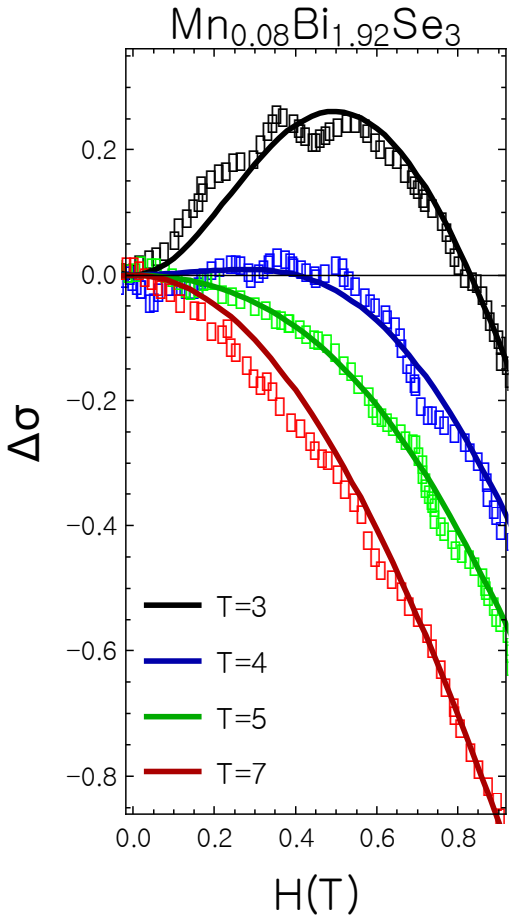
Theory fits
not only for Cr doped Bi_2Te_3 but also Mn doped Bi_2Se_3



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

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





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)





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

+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

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

More recently: Holographic Fermion with Pauli

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

First studied by Philips et.al (PRL 106, 091602 (2011) without m

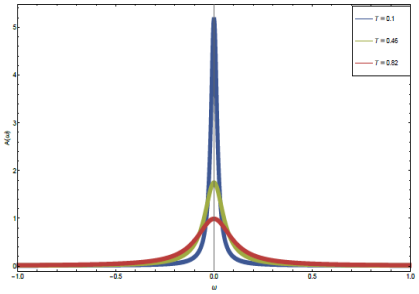
Two parameters : m, p

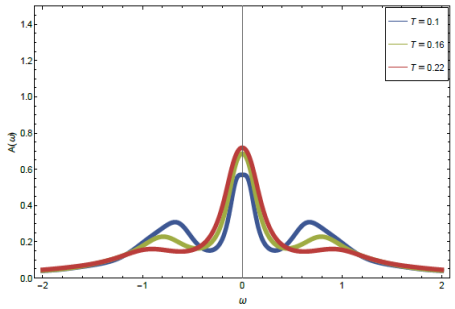


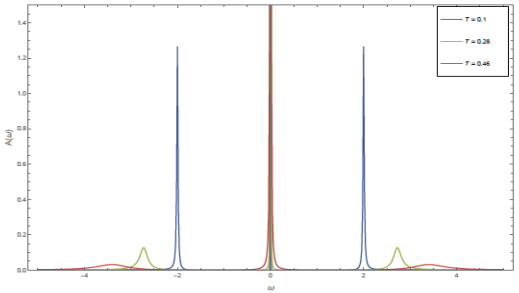


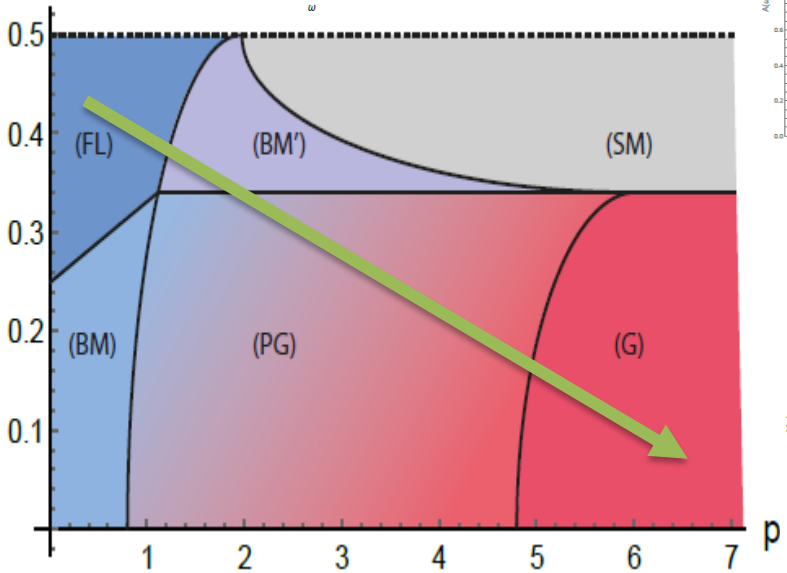
Mott transition with Holographic Spectral function
Yunseok Seo, Geunho Song, Yong-Hui Qi, Sang-Jin Sin
JHEP 1808 (2018) 077, 1803.01864

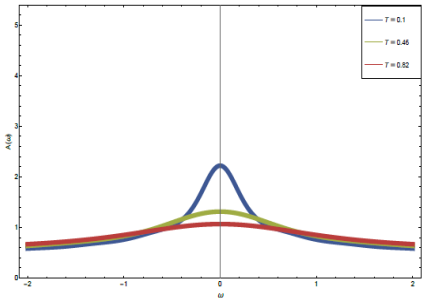
6-phases

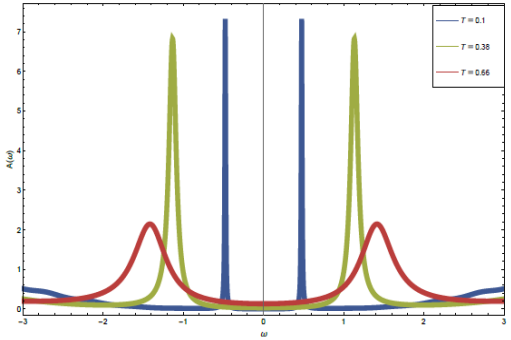


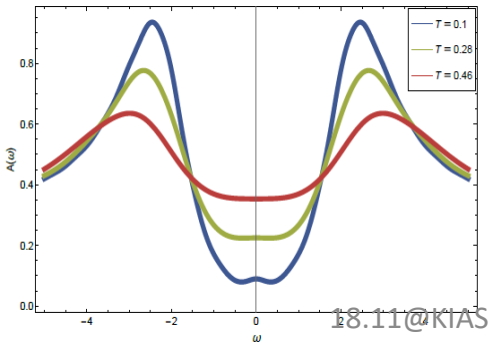






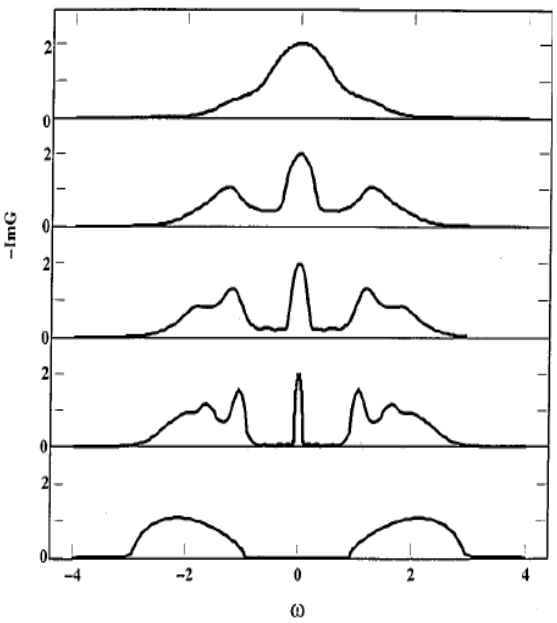




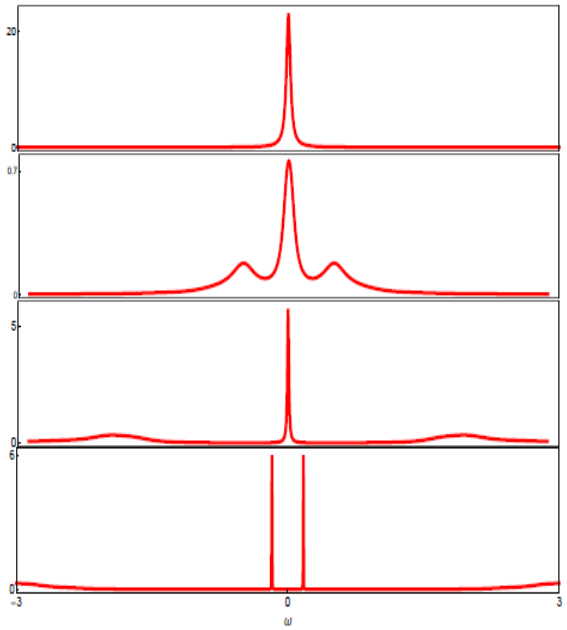


We can replace Hubbard model

Comparision with DMFT results



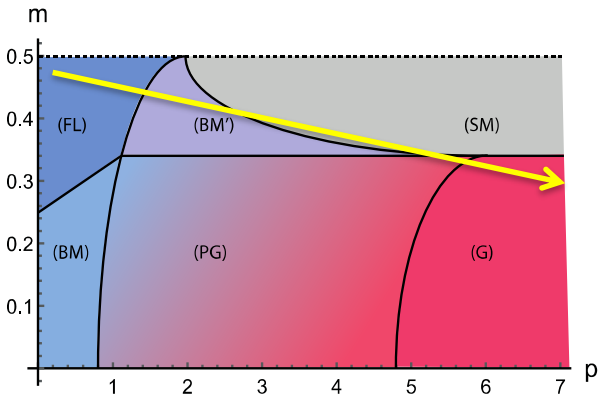
Single-site DMFT result



Holography with embedding

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

Depending on the path, evolution is different.



Holography

Message is that it is very encouraging to apply holography to real physics.

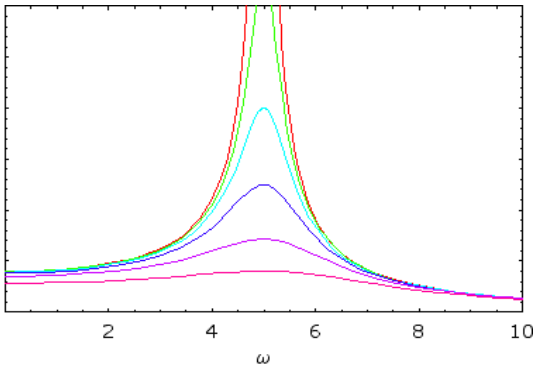
Let's think about why it works and how we can do it more systematically.



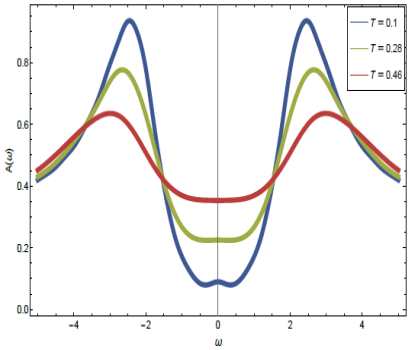
Work based on archive: 1811.xxxxx
with Enseok Oh + SJS

Character of strong Interaction i)

1. Particle Lost !



Split → Mott insulator

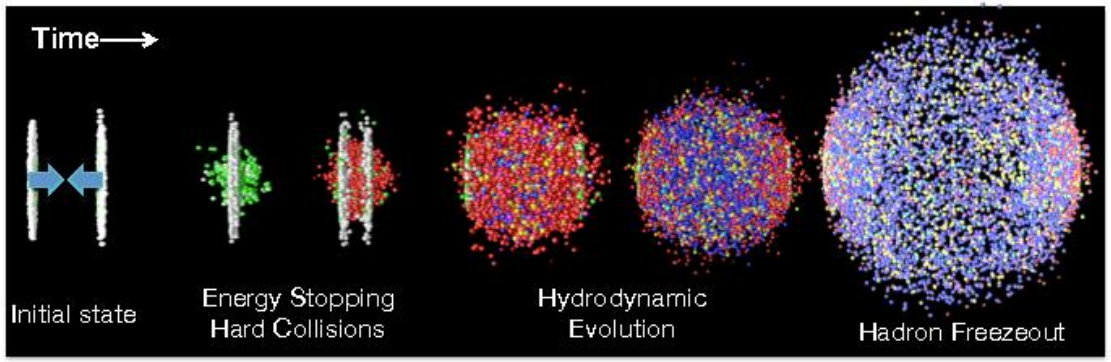


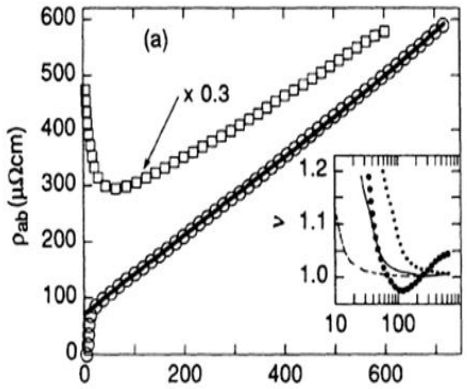
$$Spec = Im[\frac{1}{\pi}\frac{-1}{\omega - E_k + i\epsilon}] = \delta(\omega - E_k),$$

Interaction : E→E-iΓ/2

Also some times Completely different basic excitation emerges. Ex. Qcd string

2. Abnormally Rapid Thermalization





Plankian Dissipationin Strange metal
Non-local /non-causal.

→Quantum Entanglement is involved!

HOW?

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

$$t = t_{!} \gg \frac{!}{k_B T}$$

$$r\ \mu\ \frac{1}{t_{!}}\ \mu\ k_B T$$

reduction of degree if freedom

Strong interaction→ Strong Entanglement
Then, Reducing Material to basic elements is not a blessing.

Manybody physics has to handle Macroscopic d.o.f

How to reduce the dof ?

Look at QCP → loss of scales → Loss of information
→ achieving Universality

Very similar to BH or gravity by
Diffeomorphism inv (equiv. prin.)



Problem of Holography

Black Hole itself : too much Universality.

How can we encode some system specific information?

Add matter field.

No good intuition about Composite field.

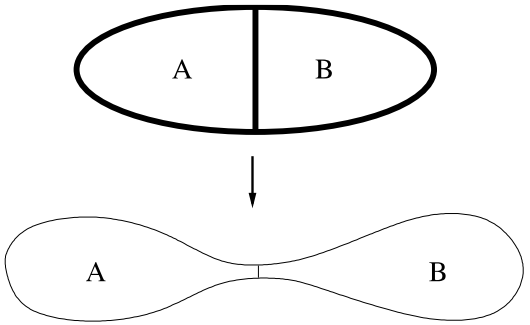
Therefore the key is using Fermion

The bulk fermion ψ is dual to the fermion χ in the boundary.

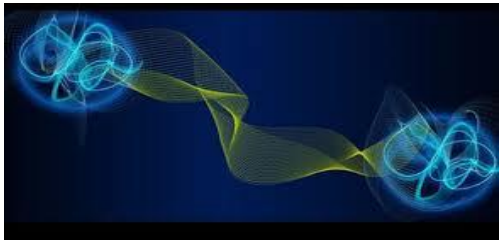
Quantum entanglement

Two mind boggling ideas in recent days about entanglement

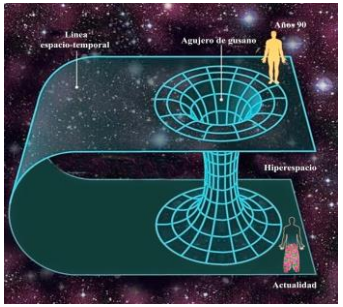
1. Quantuam Entanglement glue spacetime (Raamsdonk)
2. EPR=ER (Suuskind, Maldacena)



Both are developed in the context of Holography.

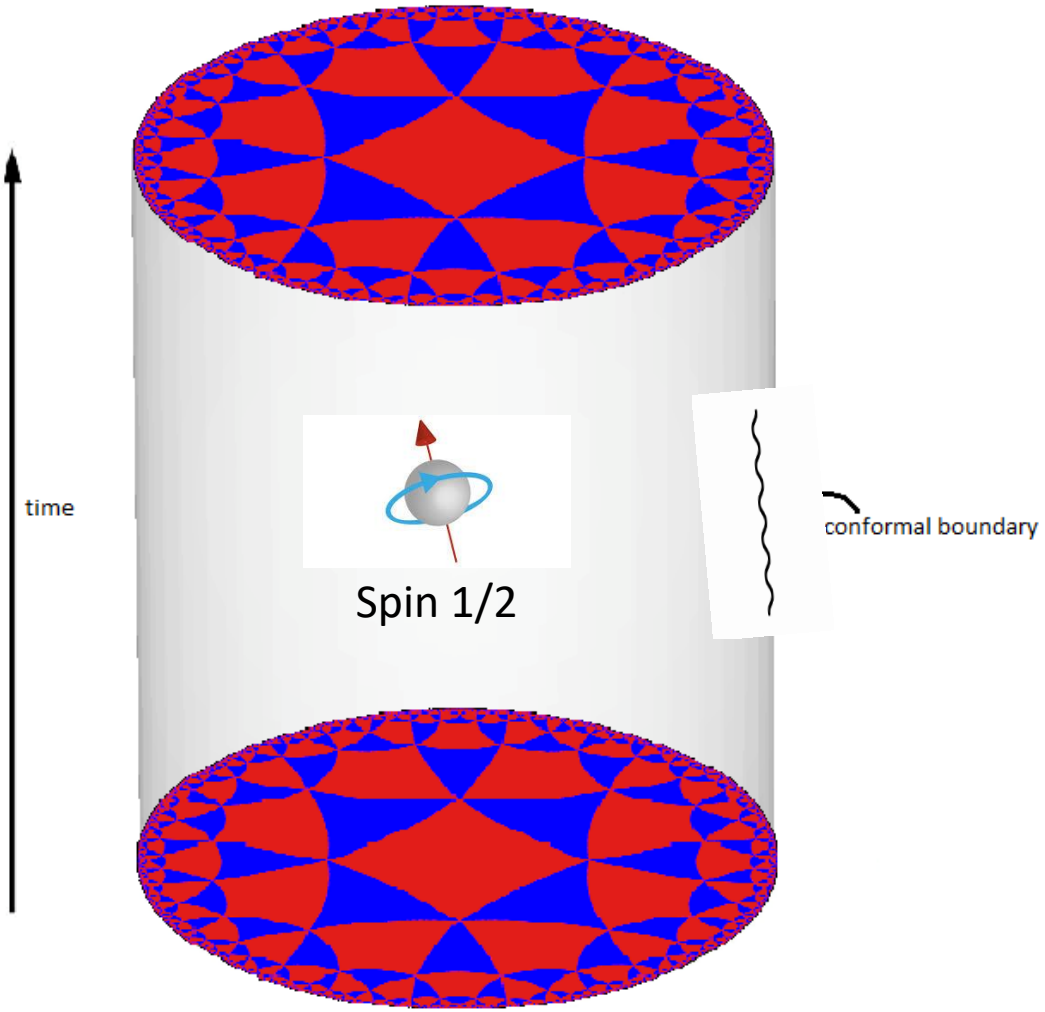


=



Q1. A simple mathematical realization?
Q2. Experimental proof?
Seek more insight from holography !

Will show : weakly coupled particle in ads =strongly coupled string at Bdry

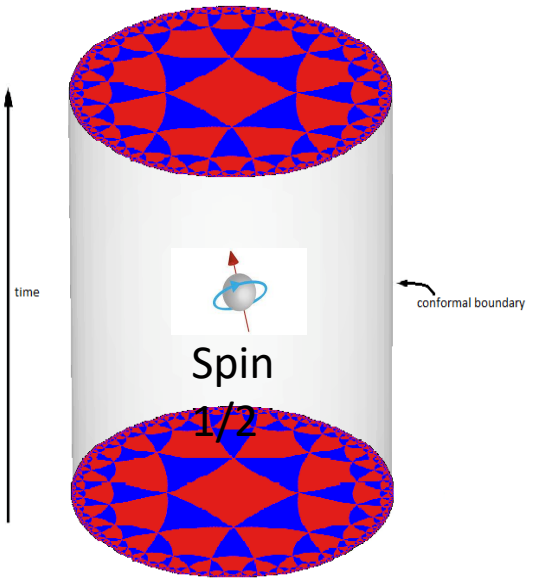


Simplest Holographic model

$$S_D = i\int d^dx\sqrt{-g}\bar{\psi}(\Gamma^M\mathcal{D}_M - m - \Phi)\psi + S_{bd},$$

$$m_\Phi^2 L^2 = \Delta(\Delta-3) = -2$$

$$\Phi(x,r) = \frac{\Phi^{(0)}}{r} + \frac{M}{r^2} + \cdots . \qquad \Phi^{(0)} = 0.$$



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

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

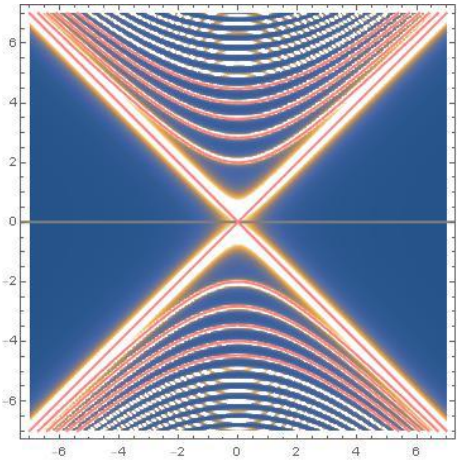
$$r^2\partial_r\xi_- + (2mr + 2\frac{M}{r})\xi_- + (k_1 - w)\xi_-^2 - k_1 - w = 0.$$

$$G_R = \lim_{r\to\infty} r^{2m}\mathrm{diag}(\xi_+, \xi_-),$$

Stringy spectrum

$$G_{22} = \frac{M^{-\frac{1}{2}+m}(k_1+w)\Gamma(\frac{1}{2}-m)\Gamma(m+\frac{1}{2}+\frac{k_1^2-w^2}{4M})}{2\Gamma(\frac{1}{2}+m)\Gamma(1+\frac{k_1^2-w^2}{4M})},$$

$$\frac{k^2-\omega^2}{4M} + m + \frac{1}{2} = -n, \quad \text{for} \quad n \in \mathbf{Z},$$

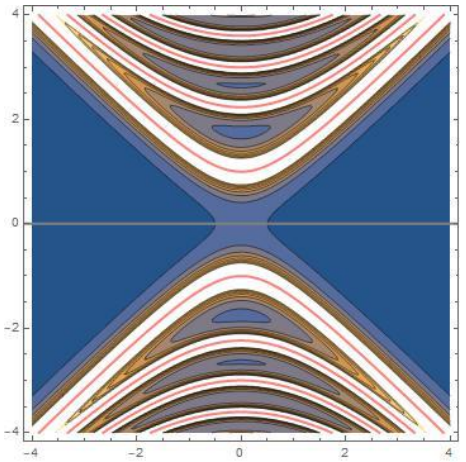


(a) gapless $m = -\frac{1}{2}, M = 1$

→ Open string with tension

$$T = 1/(2\pi\alpha') \text{ with } \alpha' = \frac{1}{4M}, \text{ if } M \neq 0.$$

→ Zero tension in zero condensation



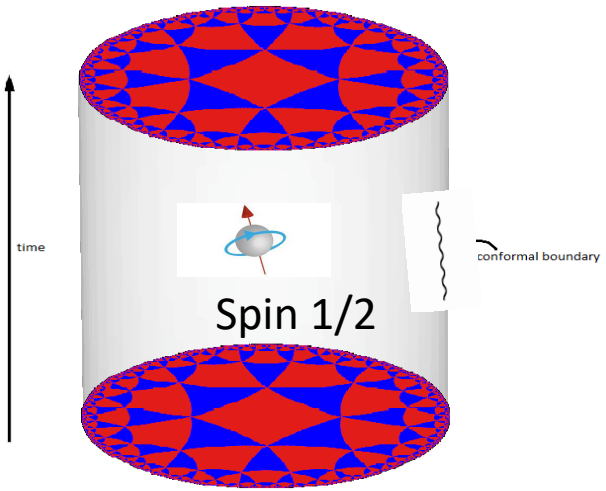
(b) gaped $m = -\frac{1}{4}, M = 1$

Remarks

String is in Boundary not in the bulk

Because the two point fct is that of boundary.

So, Particle in AdS = String in the boundary.

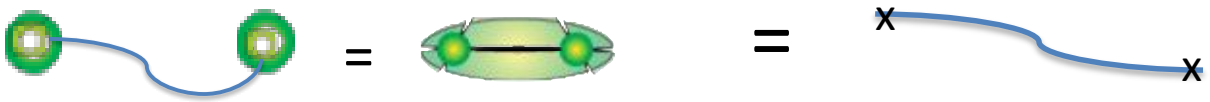


Entanglement String

Open string ends at two fermions

spin singlet = string+Entangled_N_vanished Fermions

= a dimer



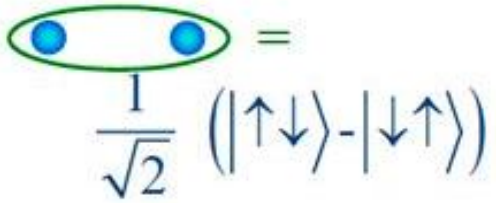
The above dumb-bell picture is slightly misleading: F-disappeared String= in weakly (non) interacting bulk picture while fermions are in strongly interacting and gone.

Emerging picture : open string = dimer (without fermion pair)

Overall charge neutrality → can be a Majorana pair.

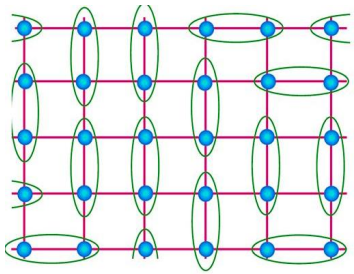
Scalar condensation

Scalar condensation = Dimerization

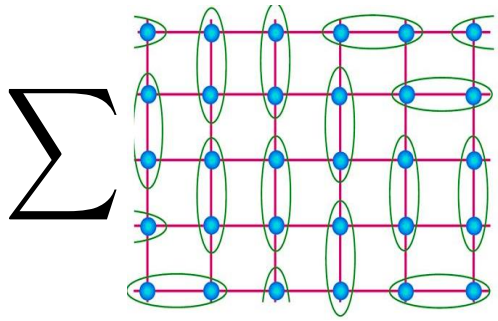


Spin Solid

Spin Liquid



or



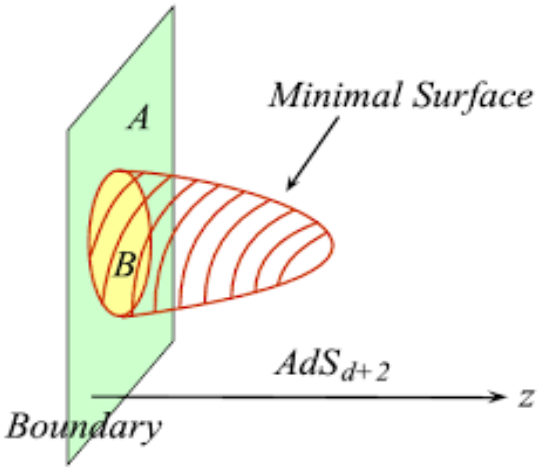
Difference : Entanglement Entropy

Entanglement String

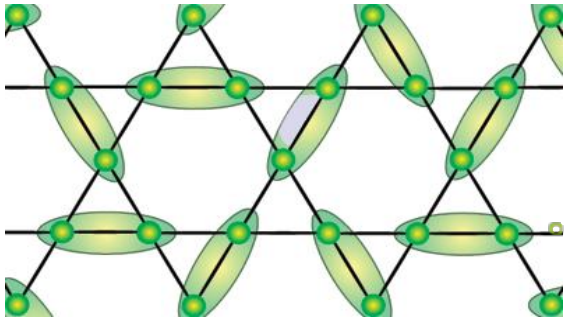
Divergently large Entanglement entropy

$$S_{EE} = \frac{1}{4G_N}\frac{A}{\epsilon^{d-2}} + \dots \qquad 1/\epsilon \text{ is the probe energy scale}$$

→ Spin Liquid rather than valence solid





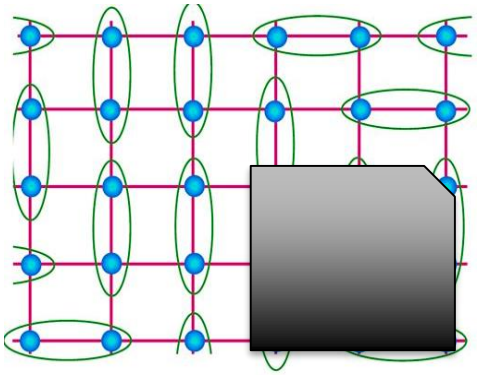


$$S_{EE} = \frac{1}{4G_N}\frac{A}{\epsilon^{d-2}} + \dots$$

Q: Topological order Z_2

- Degrees of dimerization need to be quantified
  Not a topological problem

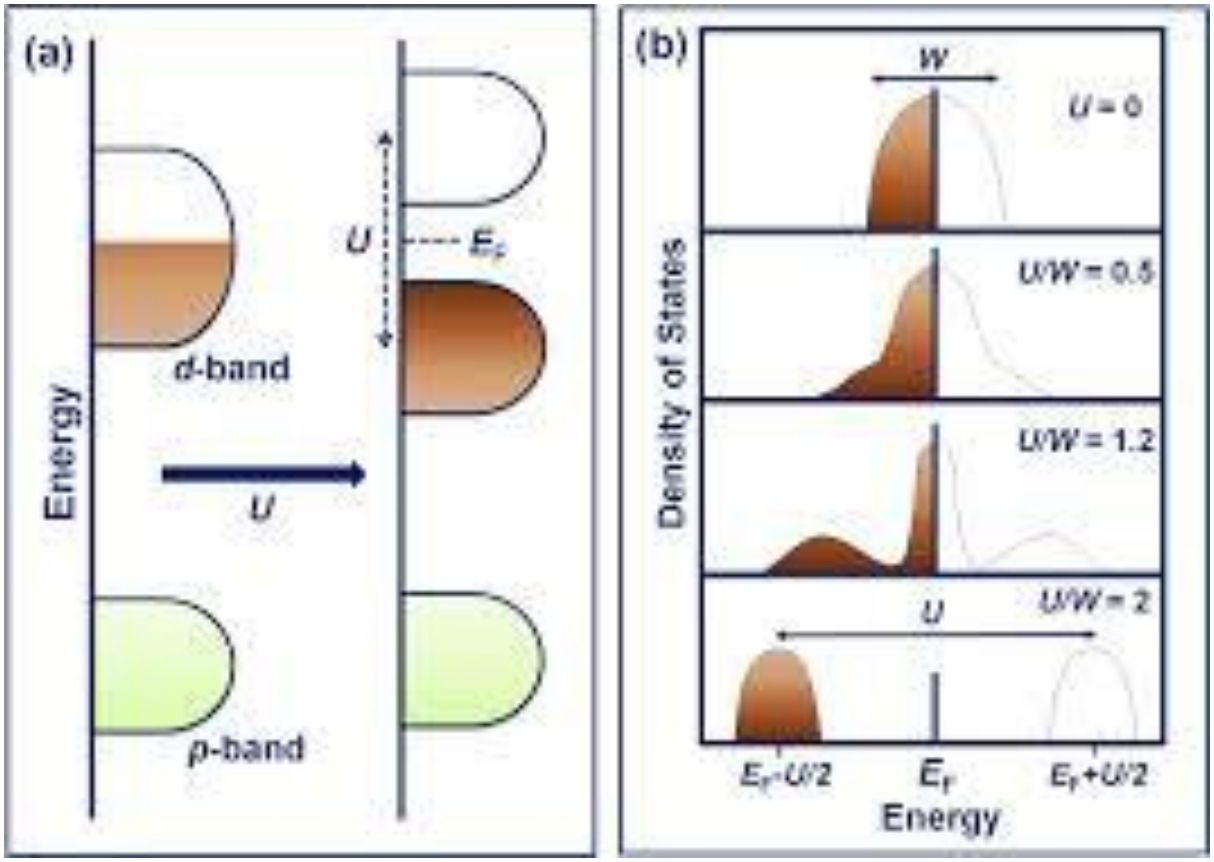
$$\sum$$



- Real scalar condensation make sense.

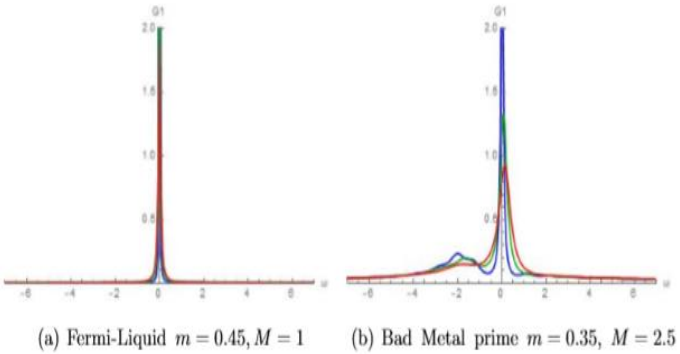
- Real scalar condensation
- Z_2 symmetry: $\pm\phi$
- → Gauge symmetry in the AdS bulk
- a topological order ? Not clear !

Check point: Spin Liquid is Mott insulator



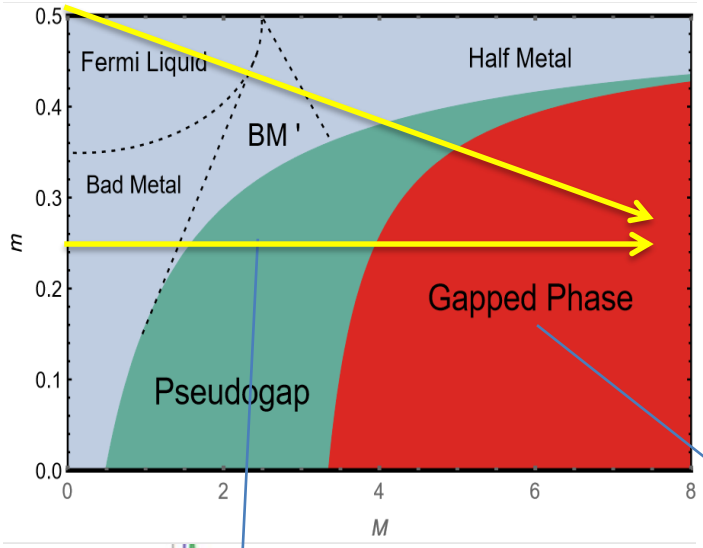
Check point: Spin Liquid is Mott insulator

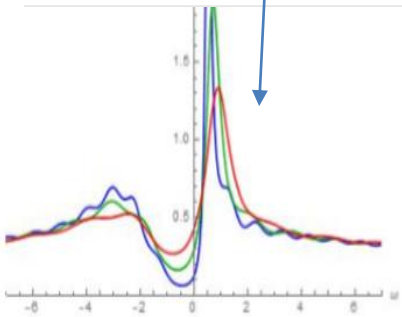
Gap is generated for all valie of m, M

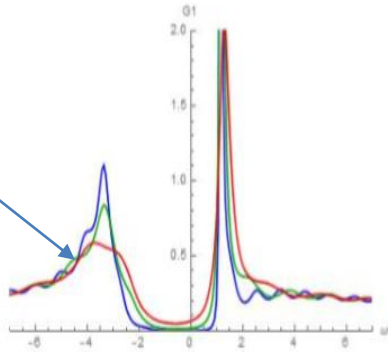


(a) Fermi-Liquid $m = 0.45, M = 1$ (b) Bad Metal prime $m = 0.35,\ M = 2.5$

(c) Bad Metal $m = 0.25,\ M = 1$ (d) half Metal $m = 0.45,\ M = 6$





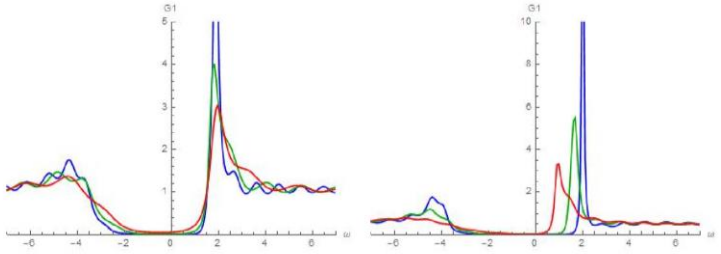


Pseudo Gap phase

Gapped phase

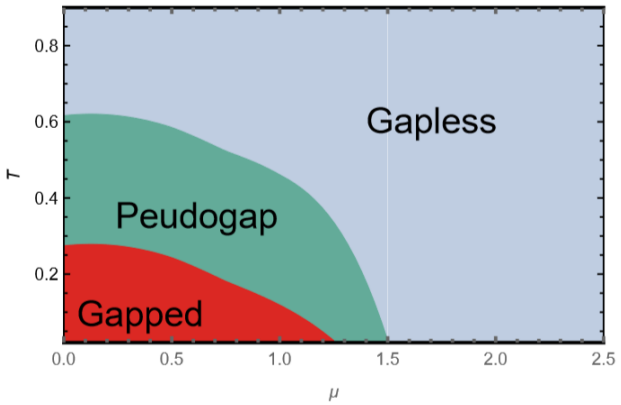
Effects of μ and T and μ -T Phase Diagram

Raising μ and T cause declining effects of gap size.

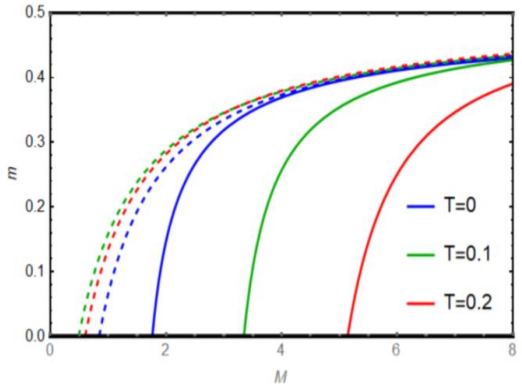


(a) T-evolution $m = 0$ $M = 6$ (b) $m = 0.1$ $M = 8$ μ-evolution

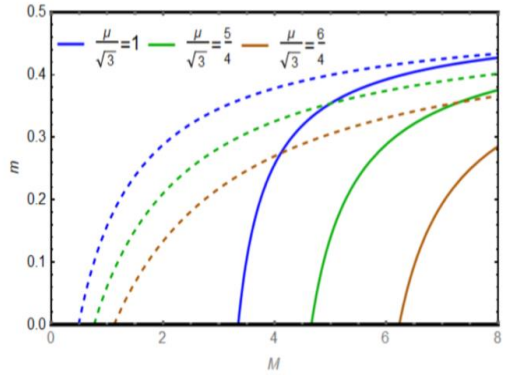
With finite temperature and chemical potential, phase diagrams are the following.



Mu-T phase diagram



(a) m-M Phase Diagram for various T

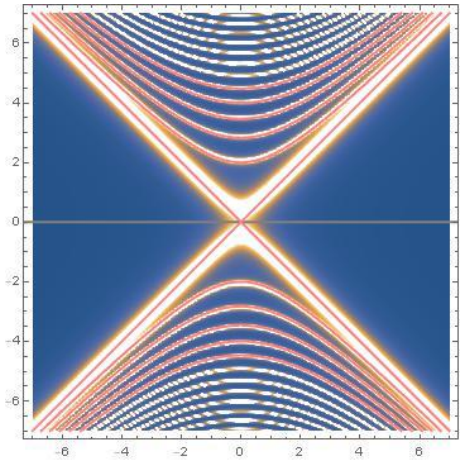


(b) m-M Phase Diagram for various μ

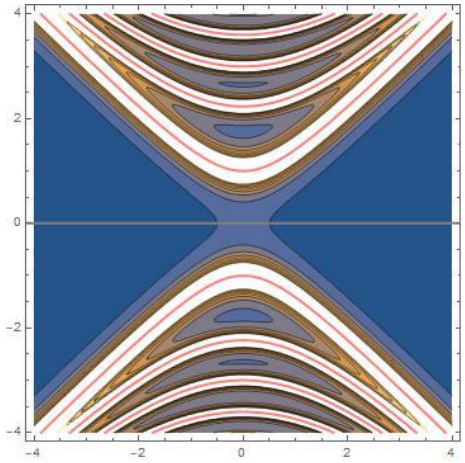
The mechanism of gap generation came from r→0 (IR behavior).

Experimental prediction 1

- String spectrum in Dirac material

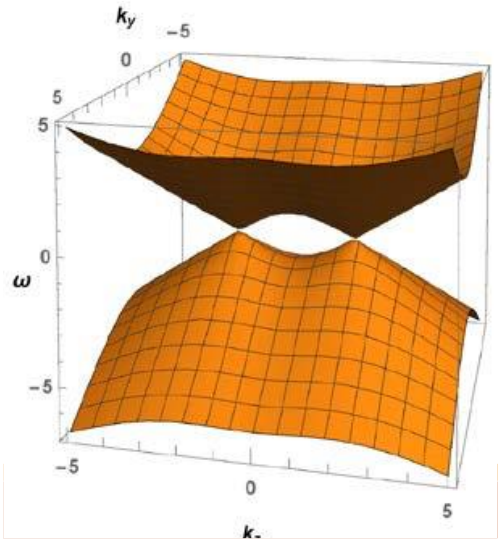


(a) gapless $m = -\frac{1}{2}, M = 1$



(b) gaped $m = -\frac{1}{4}, M = 1$

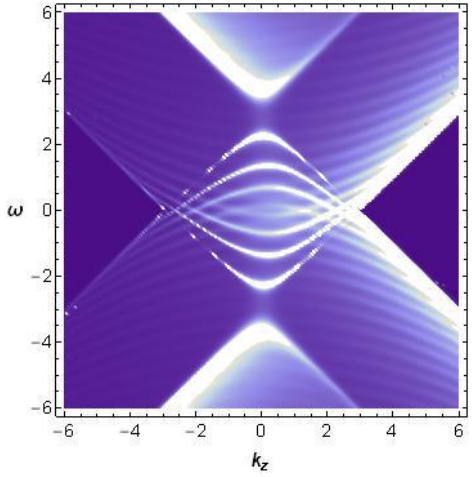
Experimental prediction 2 : SI- Weyl metal



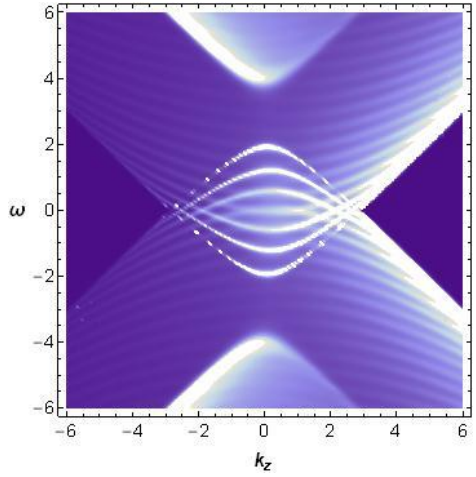
G. Song, Y. Seo, J. Rong SJS : to appear

← Non-interacting

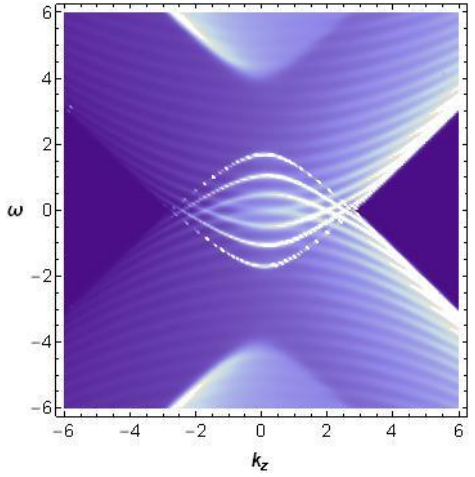
↓ Interacting



$m = 0.5$

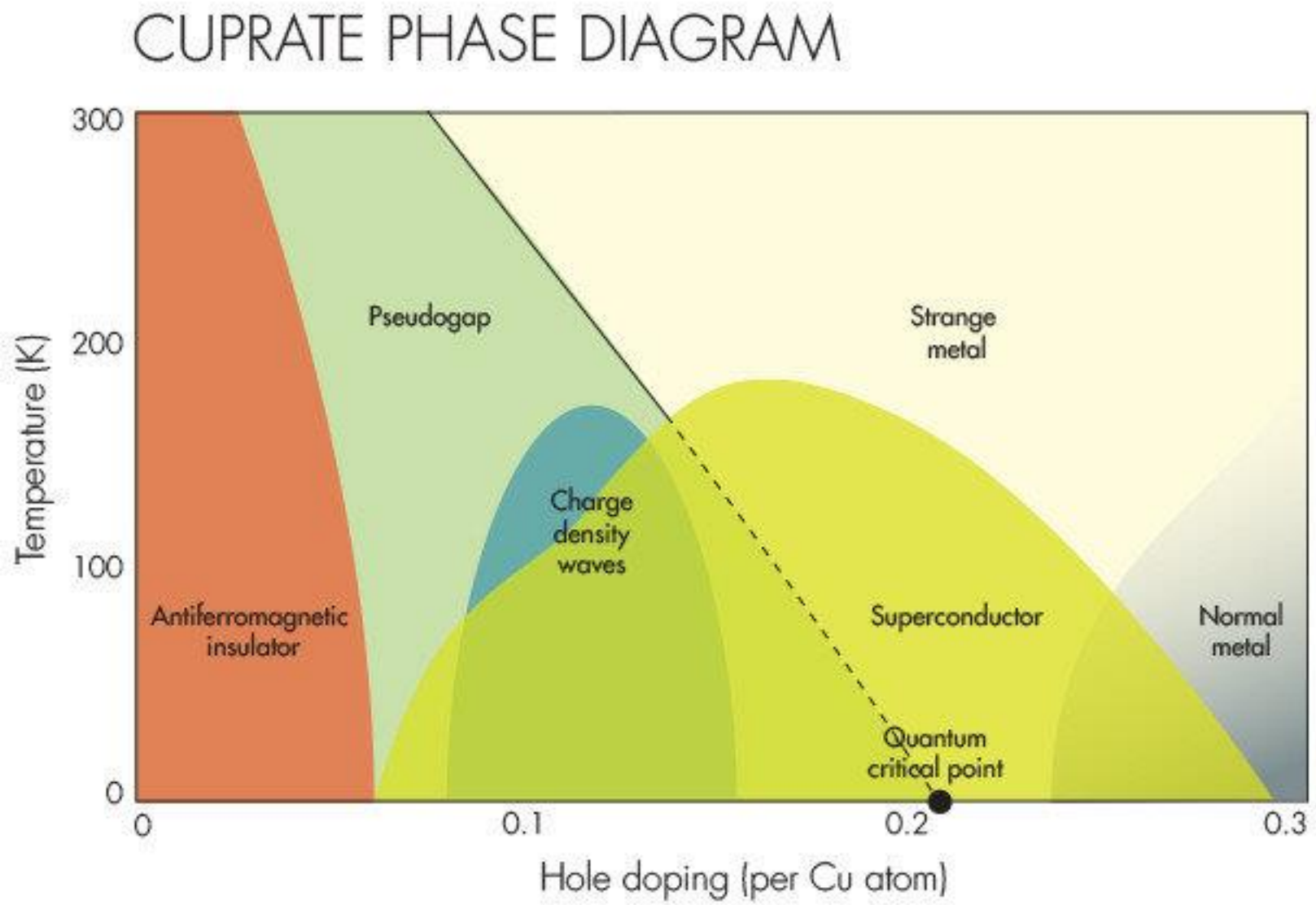


$m = 0.3$



$m = 0.1$

Competing orders



Variety of gap generation

Order ←→ gap generation

any gap has pseudo gap regime.

Coexistence of many order

←→ Variety of gap generation

$$S = \int \sqrt{-g} i\bar{\psi} \left(\not{D} - m - i g_v B_\mu \Gamma^\mu - i g_a B_\mu^{(5)} \Gamma^{5\mu} - i g_T M_{\mu\nu} \Gamma^{\mu\nu} \right) \psi$$

$$- \int \sqrt{-g} i\bar{\psi} \left(g_0 M_0 + i g_5 M_5 \Gamma^5 \right) \psi,$$

gap mechanisms

$$S = \int \sqrt{-g} i\bar{\psi} \left(\not{D} - m - i g_v B_\mu \Gamma^\mu - i g_a B^{(5)}_\mu \Gamma^{5\mu} - i g_T M_{\mu\nu} \Gamma^{\mu\nu} \right) \psi \; - \int \sqrt{-g} i\bar{\psi} \left(g_0 M_0 + i g_5 M_5 \Gamma^5 \right) \psi$$

α	0	1	2	3
M_s	·	○	○	○

α	0	1	2	3
M_a	0	○	○	○

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

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

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

●: Gapless, ○: Gapped, ●′: gapless only $m = 0$

Pseudo scalar, Vector, pseudo vector, tensor

- All spatial components of the
- S, pS, V, pV, Frt, Txy can generate gap.
- What are the physical identification of these orders?
- S scalar gap: Spin Liqiuid
- Frt : CDW
- Others? Future project

Summary : New words in dictionary

1. Entanglement string = Dimer

2. H-Fermion+ the scalar condensation
   = spin liquid model

3. Different gap generation
   =Different order

4. Simultaneous condensation of different fermion biliear
   =Competing orders

감사합니다

Holography from QCP point of view:

The first one can be recasted to say how the holography arize!

Quantuam Entanglement glue spacetime →

It combine DOF at different scales into higher dimensional system.

