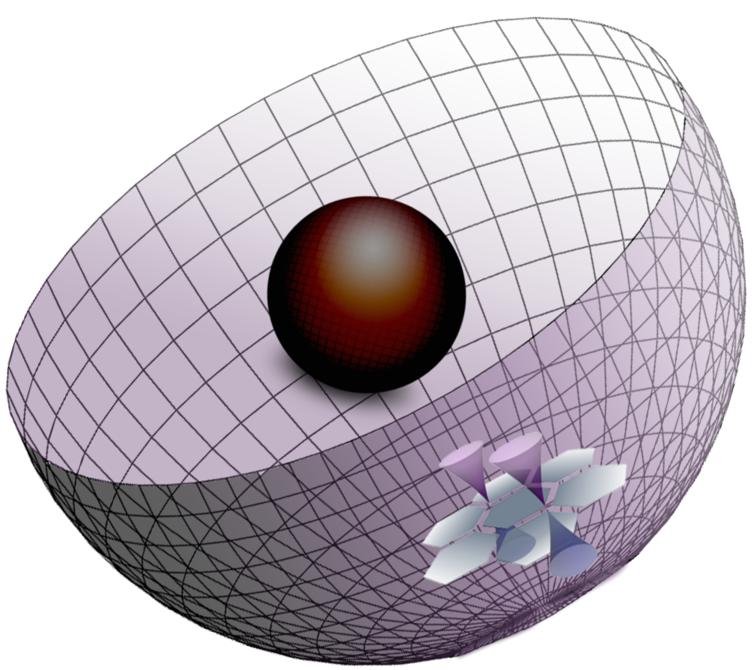
Holography and
A new quantum ground state with Kondo condensation



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Based on

https://doi.org/10.1038/s41567-022-01930-3

Nature Physics (2023)

Late Prof. Rim, Chaiho

- ICTP 1991(31years ago) : Rome, Veneccia, …

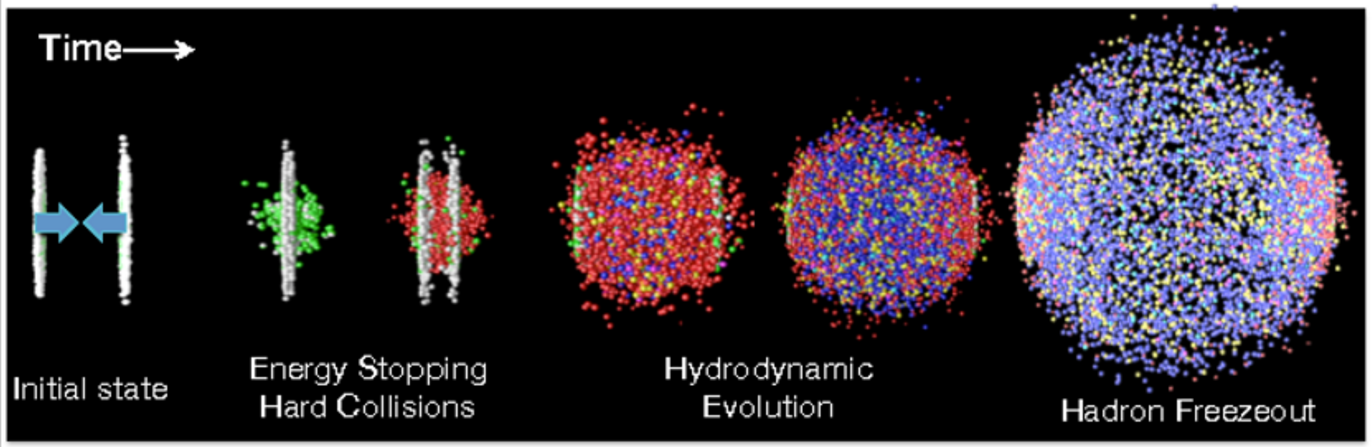
A few example of evidence of the AdS/CMT

I. Graphene
II. Topological stability of Fermi-liquid
III. Random Kondo problem*

Character of strong coupling:

i. Loss of Quasi particle=> make hard
ii. Non-causal correlation=> make easy

Heavy ion collision



No time to equilibrate with causal contacts.

==>

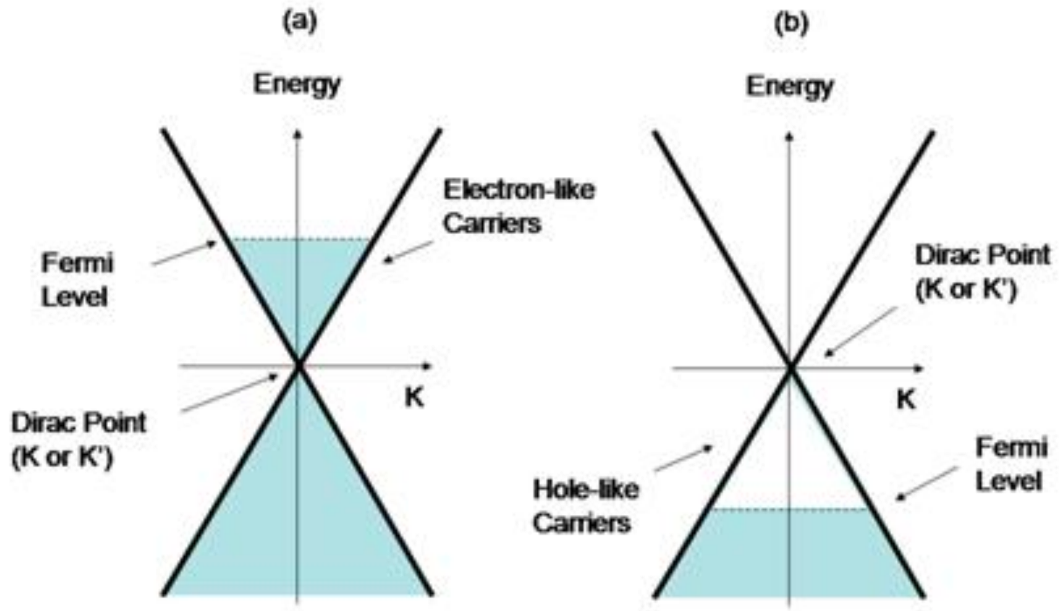
I. $\eta/s =$ shear vis./(entropy d.) $= \dfrac{\hbar}{4\pi k_B}$ ~ universal,

cf: $\eta/s \sim 1/g^2$, in $g\phi^4$ theory.

II. Plankian Dissipation. $\rho \sim T$

I. Graphene

- Relativistic fermion in the Graphene.



- Why strong coupling in graphene?

Small FS—> less screening Strong coupling.

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

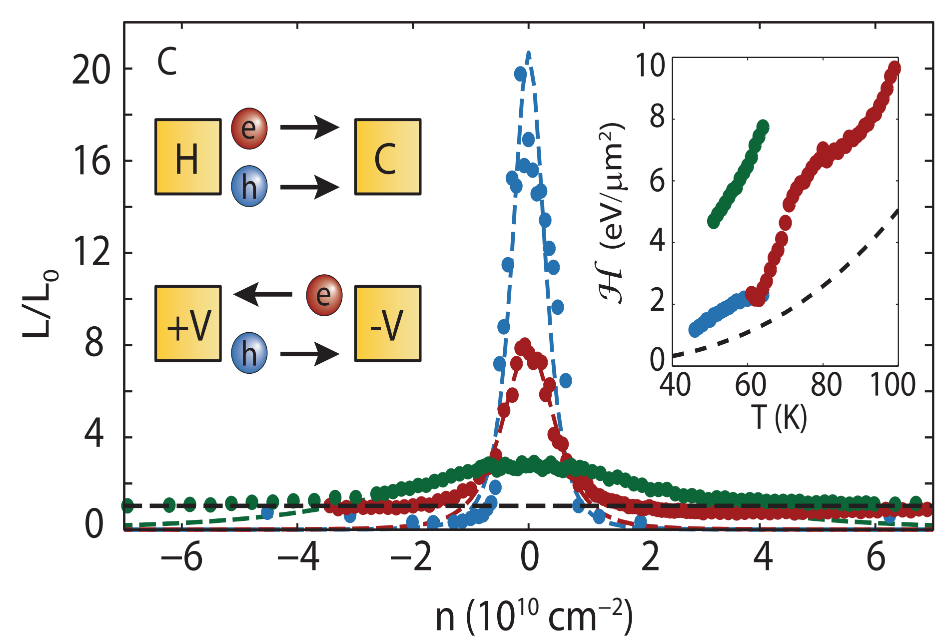
clean Graphene=Strong Coulomb

Wiedermann-Franz Law violation

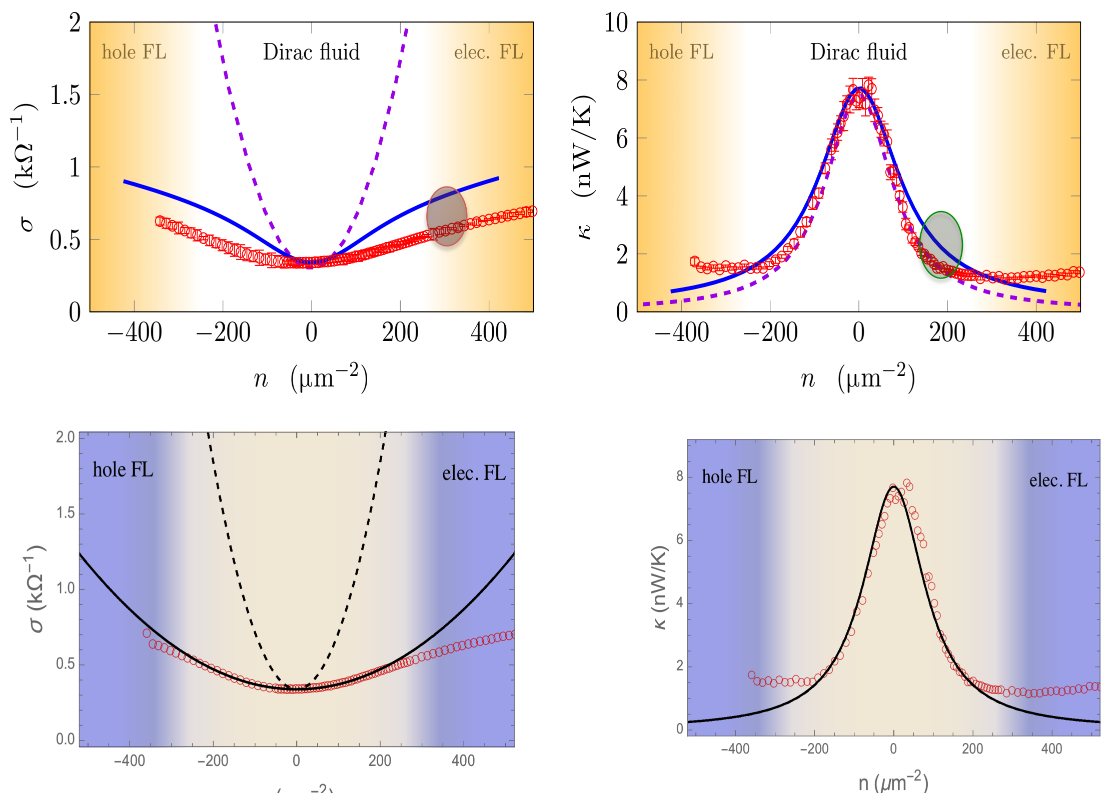
Observation of the Dirac fluid and the breakdown of the Wiedemann-Franz law in graphene

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



Transport anomaly in pure graphene



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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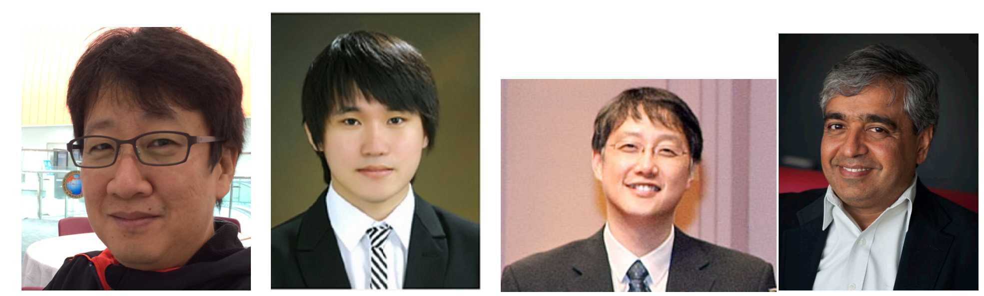


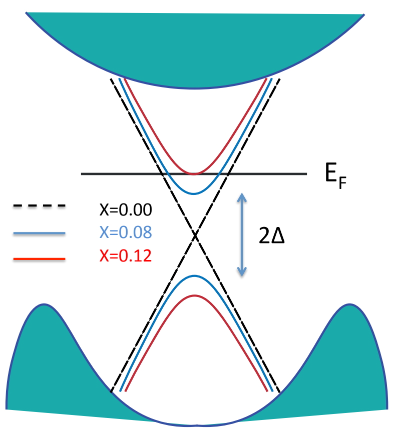
Phys.Rev.Lett. 118 (2017) no.3, 036601
Editors' Suggestion

Dirac material is a class of material with $\omega = k$

Surface of Topological Insulators

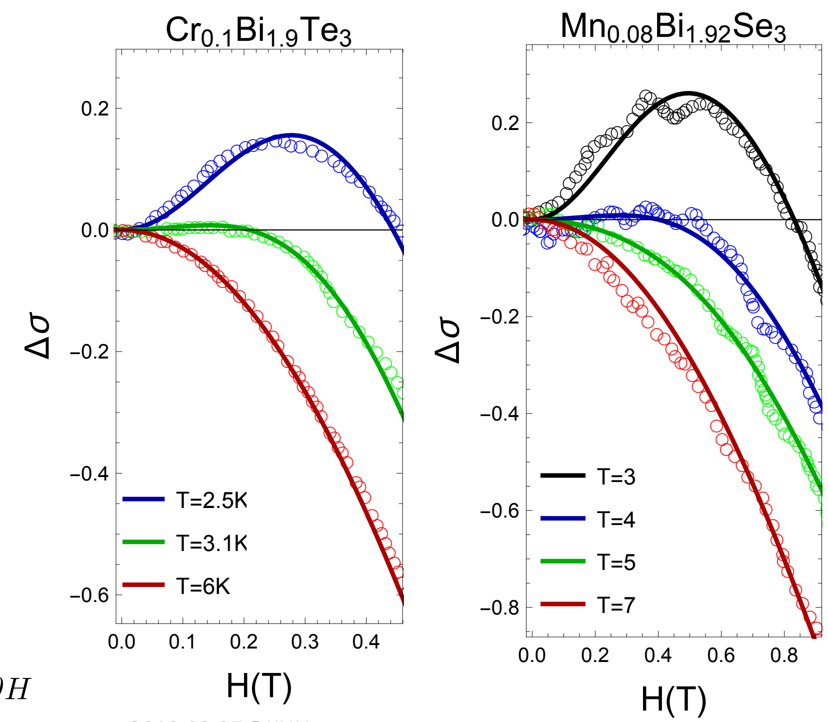
[1703.07361, prB, rapid comm 서윤석,송근호,SJS

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



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

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



2019.03.27@KHU

Strong Correlation Effects on Surfaces of Topological Insulators via Holography

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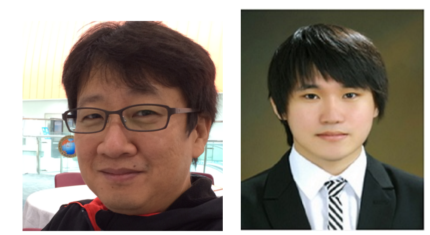
Department of Physics, Hanyang University, Seoul 04763, Korea.

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

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

II. Topological Stability of FL

- In metal, $V_{ee} \sim E_F$, $g_{eff} \sim V_{ee}/E_K > 1$: strong interaction not weak at all.
- Why such strongly interacting system behave like a free electron system?
- Here we want to understand it as a topological stability just as the edge mode of TI.

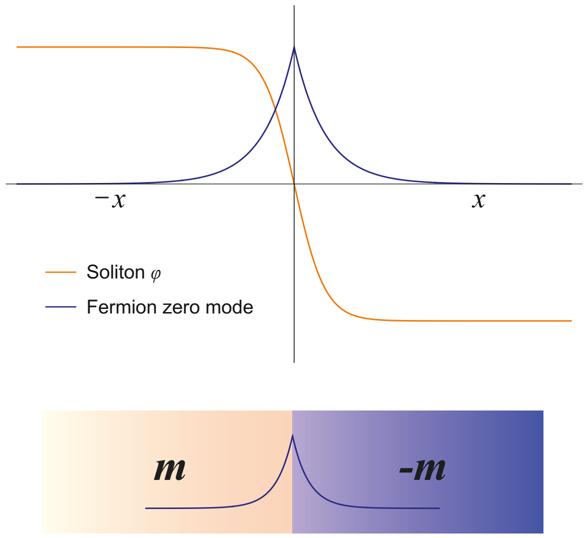
Jackiw-Rebbi and Topology

- Jackiw-Rebbi: in the presence of bosonic soliton,
  there is a Fermionic zero mode localized at the boundary

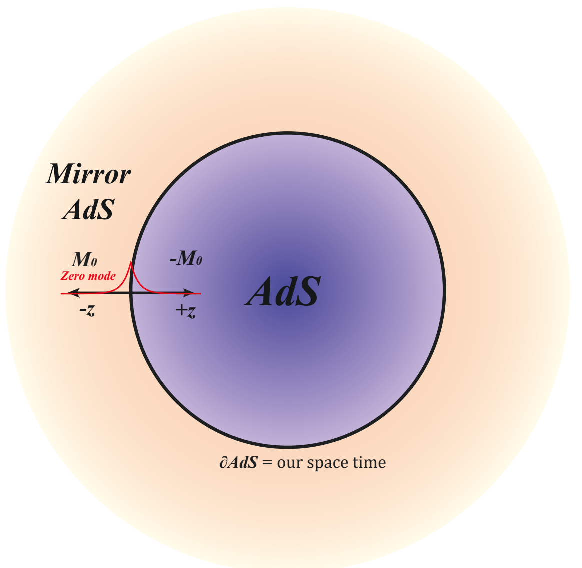
$$(\gamma^\mu D_\mu - \phi)\psi = 0$$

- TI : fermion zero mode localized at the boundary.

- sign change of m is equivalent to impose a boundary condition m(0)=0 and



(a) Jackiw-Rebbi mode



(b) JR mode in AdS

A holographic model

$$S = S_\Phi + S_\psi + S_{bdy},$$

$$S_\Phi = \int d^{d+1}x\sqrt{-g}\left(D_\mu\Phi_I^2 - m_\Phi^2\Phi^2\right),$$

$$m_\Phi^2 = -2$$

$$\Phi = M_0 z + M_1 z^2$$

$$S_\psi = \int d^{d+1}\sqrt{-g}x\; i\bar{\psi}\left(\Gamma^\mu\mathcal{D}_\mu - (m + g\Phi)\right)\psi,$$

$$S_{bdy} = i\int_{\partial M} d^d x\sqrt{-h}\bar{\psi}\psi,$$

$$ds^2 = -\frac{f(z)}{z^2}dt^2 + \frac{1}{z^2 f(z)}dz^2 + \frac{1}{z^2}\sum_{i=1}^{d-2} dx_i^2$$

$f(r) = 1-(z/z_H)^{d-1}$ for AdS_{d+1} and z_H i
temperature by $z_H = (d-1)/4\pi T$.

The Jackiw-Rebbi solution in AdS

- $\left[\partial_z + \left(iK_\mu\Gamma^\mu + \frac{m+\Phi}{z}\right)\Gamma^z\right]\phi = 0$, with $K_\mu = (-\omega, k_x, k_y)$,
- $$\Phi = M_0 z + M z^2 .$$
- $\left[\Gamma^z\partial_z - iK_\mu\Gamma^\mu + M_0 + Mz\right]\phi = 0$, cf: in flat space $(\gamma^\mu D_\mu \mp m)\psi = 0$,

$$\phi_{0\pm}(z,x) = z^{\mp m}\exp(\mp g\int_0^z dz'\varphi(z'))\chi_{0+},$$

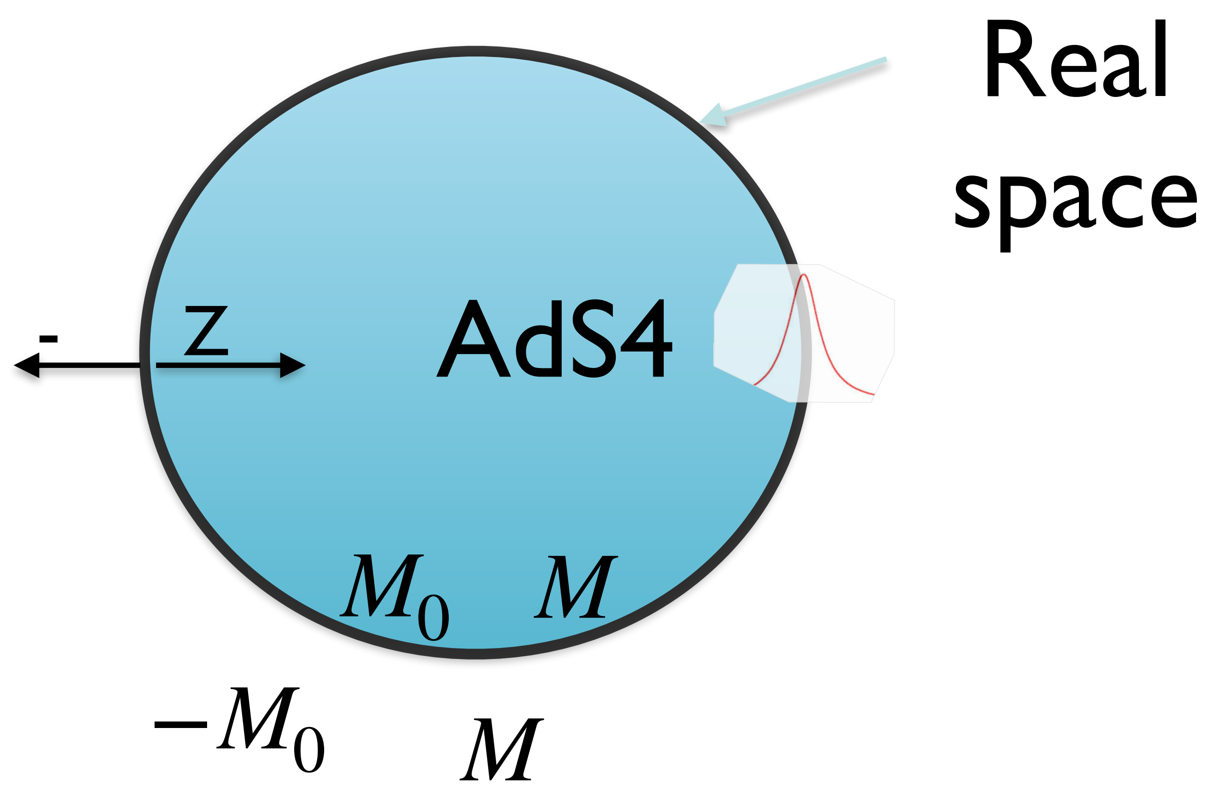
where $\varphi = \Phi/z$ for $z > 0$.

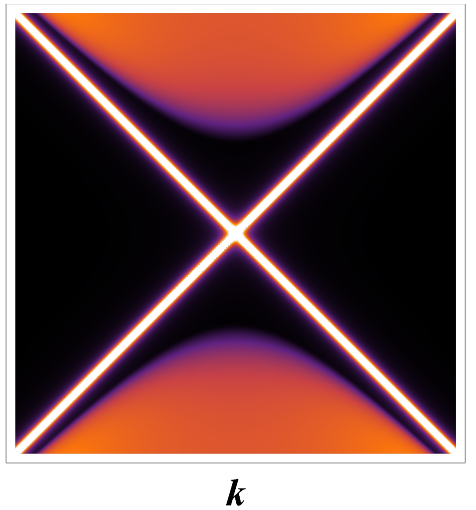
$$= M_0\,\mathrm{sign}(z) + M_1 z.$$

$$\psi_{0-}^{(M_0)} = |z|^m e^{-M_0|z|}\chi_{0-}, \quad \psi_{0-}^{(M)} = |z|^m e^{-\frac{1}{2}M_1 z^2}\chi_{0-},$$

Fermion zero mode Localized at the boundary

Because AdS bdy=our real space,
we suggest this edge mode as the Fermi liquid.





(c)$g\Phi < 0$, Gapless

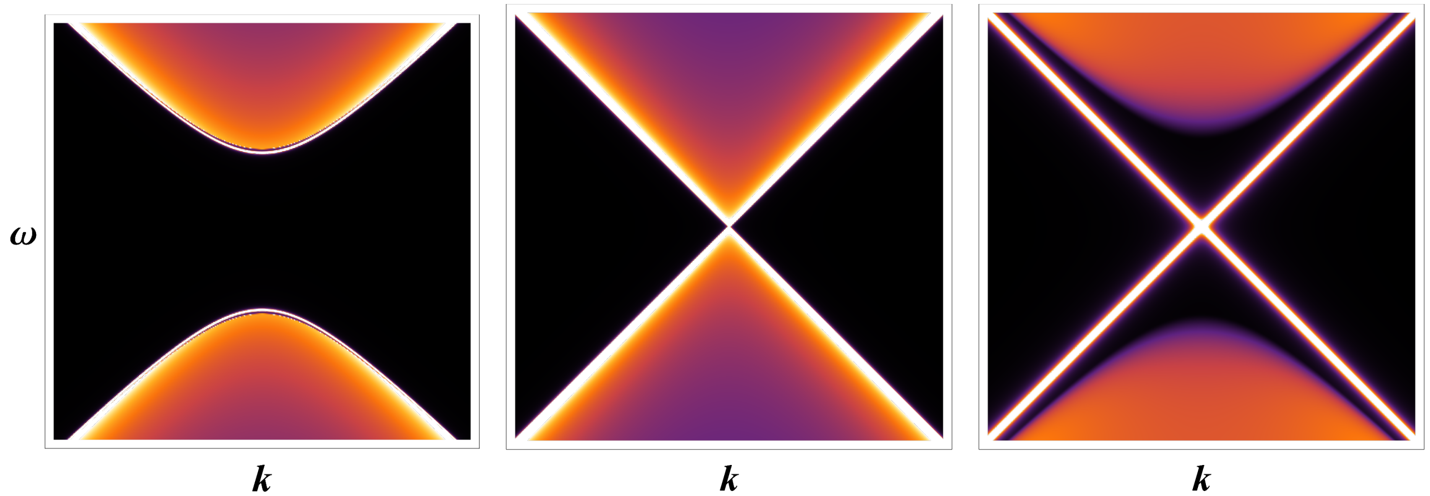
Character of Spectrum

$$\left(\Gamma^\mu \mathcal{D}_\mu - m - g\Phi\right)\psi = 0$$

$$\mathcal{D}_\mu = \partial_\mu + \tfrac{1}{4}\omega_{\mu ab}\Gamma^{ab}$$

Exact solution, though not simple is available.

1. Metal-Insulator Transition by the sign change of the coupling.
2. Fermion zero mode in the presence of the scalar order.
3. Pole type Green fct —> δ-function spectrum: characteristic!



(a)$g\Phi > 0$, Gap (b)$g\Phi = 0$, QCP (c)$g\Phi < 0$, Gapless

Singularity types:
(a,b): branch cut
(c) : simple Pole

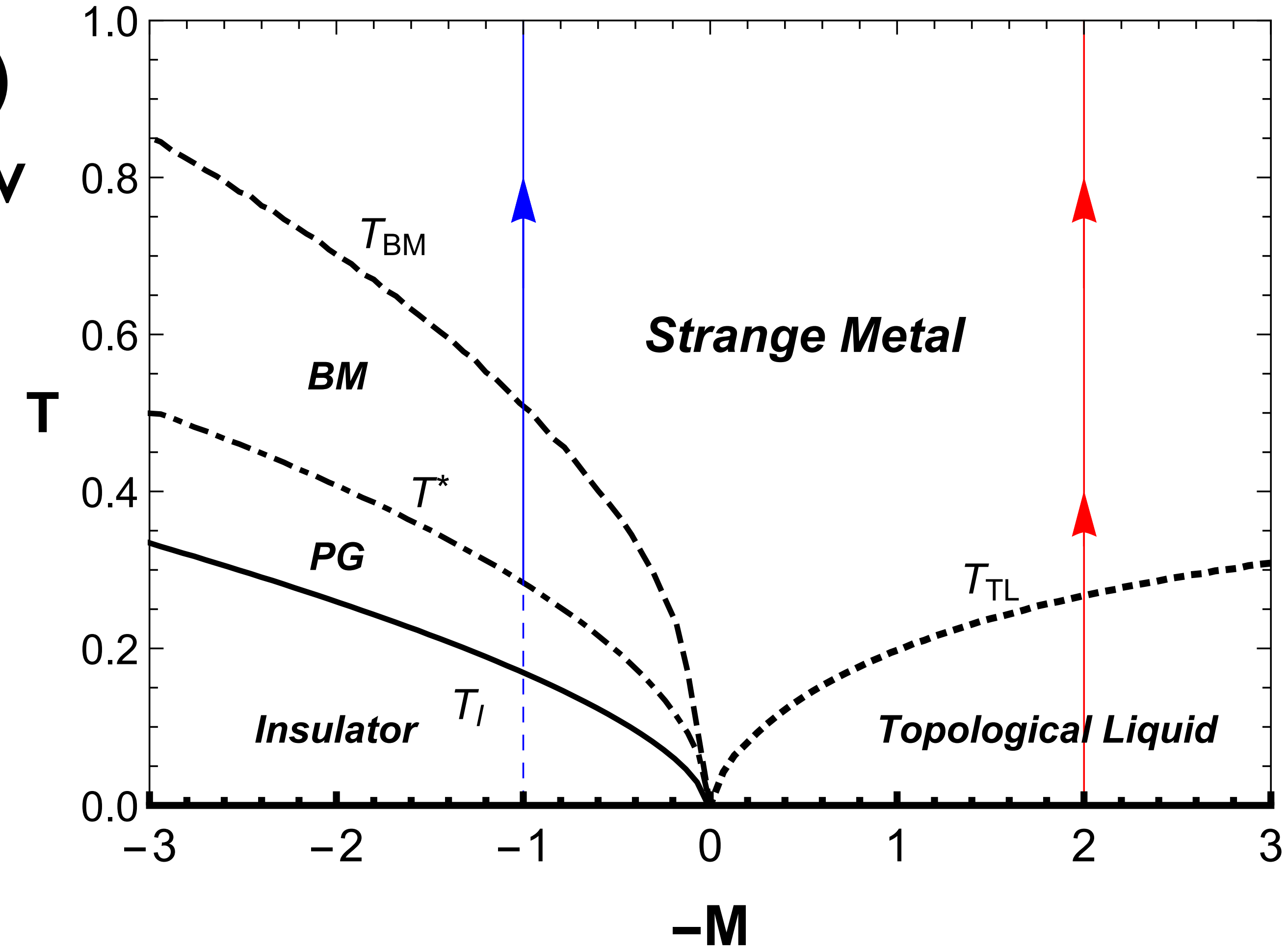
$$\frac{1}{x - i0^+} = \frac{1}{x} + i\pi\delta(x)$$

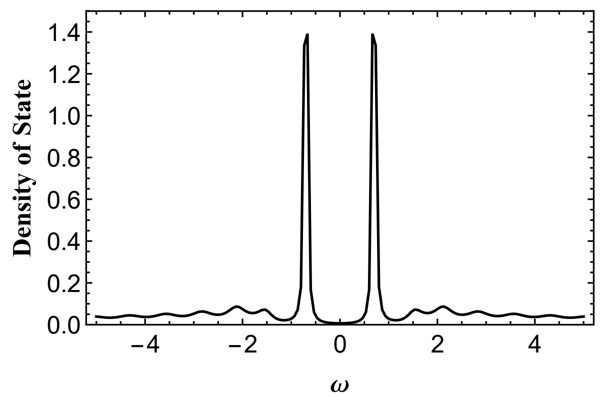
This is impossible in the flat spacetime.

Spectrum and Phases

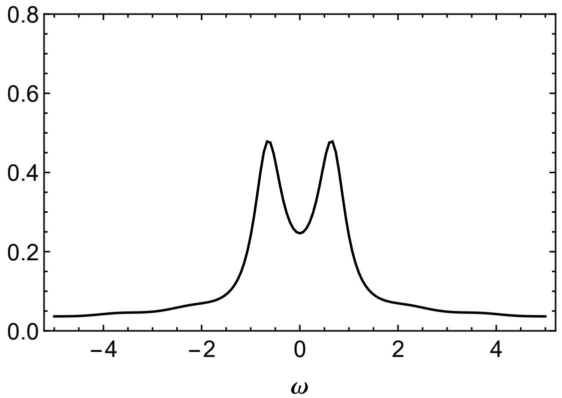
Draw DOS at each point (T, M)
And classify the shapes to a few categories

$$\Phi = M_0 z + M_1 z^2$$

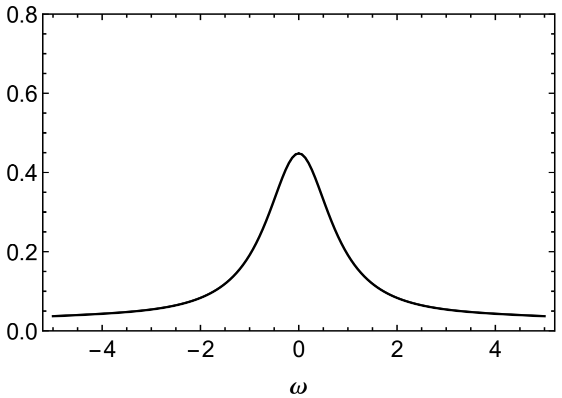




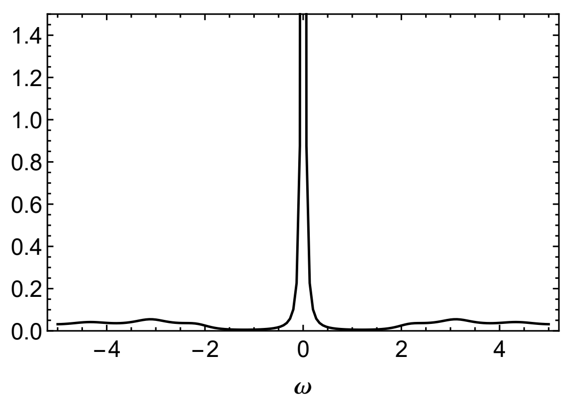
(a) Insulator



(b) Pseudogap



(c) Strange Metal

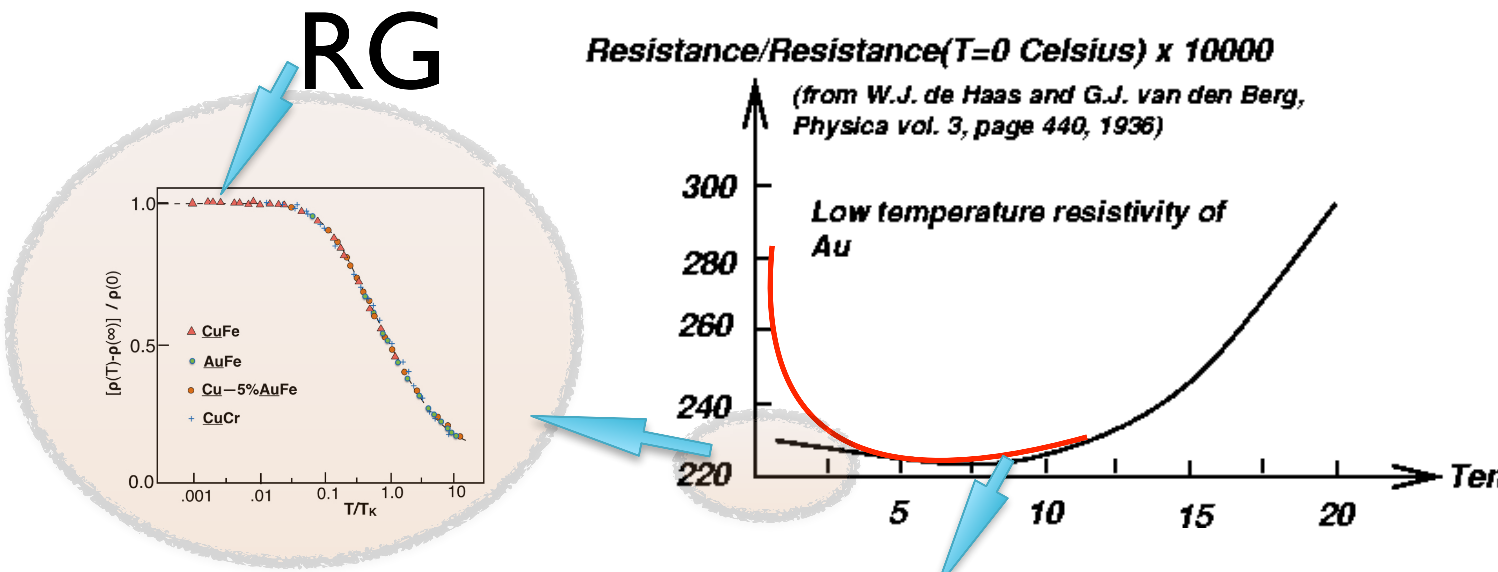


(d) Topological Liquid

III. Random Kondo

Main theme of talk : Random Kondo physics

1. Single Kondo : Feynman diagram + Wilson RG



$$\rho(T) = \rho_0 + aT^2 + bT^5 + c_m \ln \frac{\mu}{T},$$

Saturation of ρ in $T \to 0$

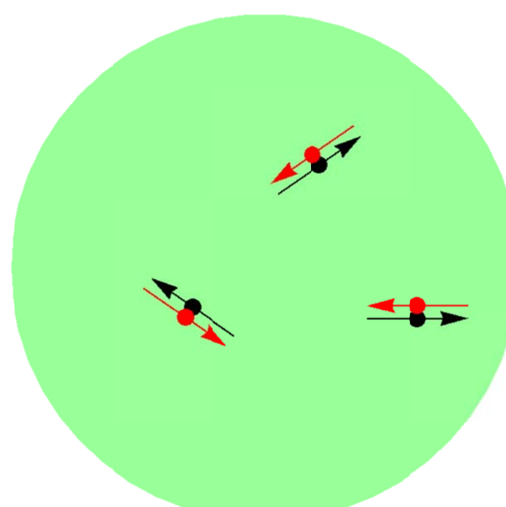
RG: imp-itinerant e coupling goes strong in IR: complete screening

$$H = \sum_{k\sigma} \epsilon_k c^\dagger{}_{k\sigma} c_{k\sigma} + \overbrace{g\psi^\dagger(0)\vec{\sigma}\psi(0)\cdot\vec{S}_f}^{\Delta H}$$

$$\frac{dg}{d\ln\mathcal{D}} = \beta(g) = -2g^2$$

$$g(D') = \frac{g_0}{1 + 2g_0 \ln(D_0/D')}$$

$$T_K = D_0 e^{-1/2g_0} = D_0 e^{-1/\rho_0 J}$$



2. Multi Kondo : ??? : coupling strong, impurity random,

Perhaps, Holography !

Collaborators

Exp.

Hyunsik Im

Eunkyu Kim

. . . . . .

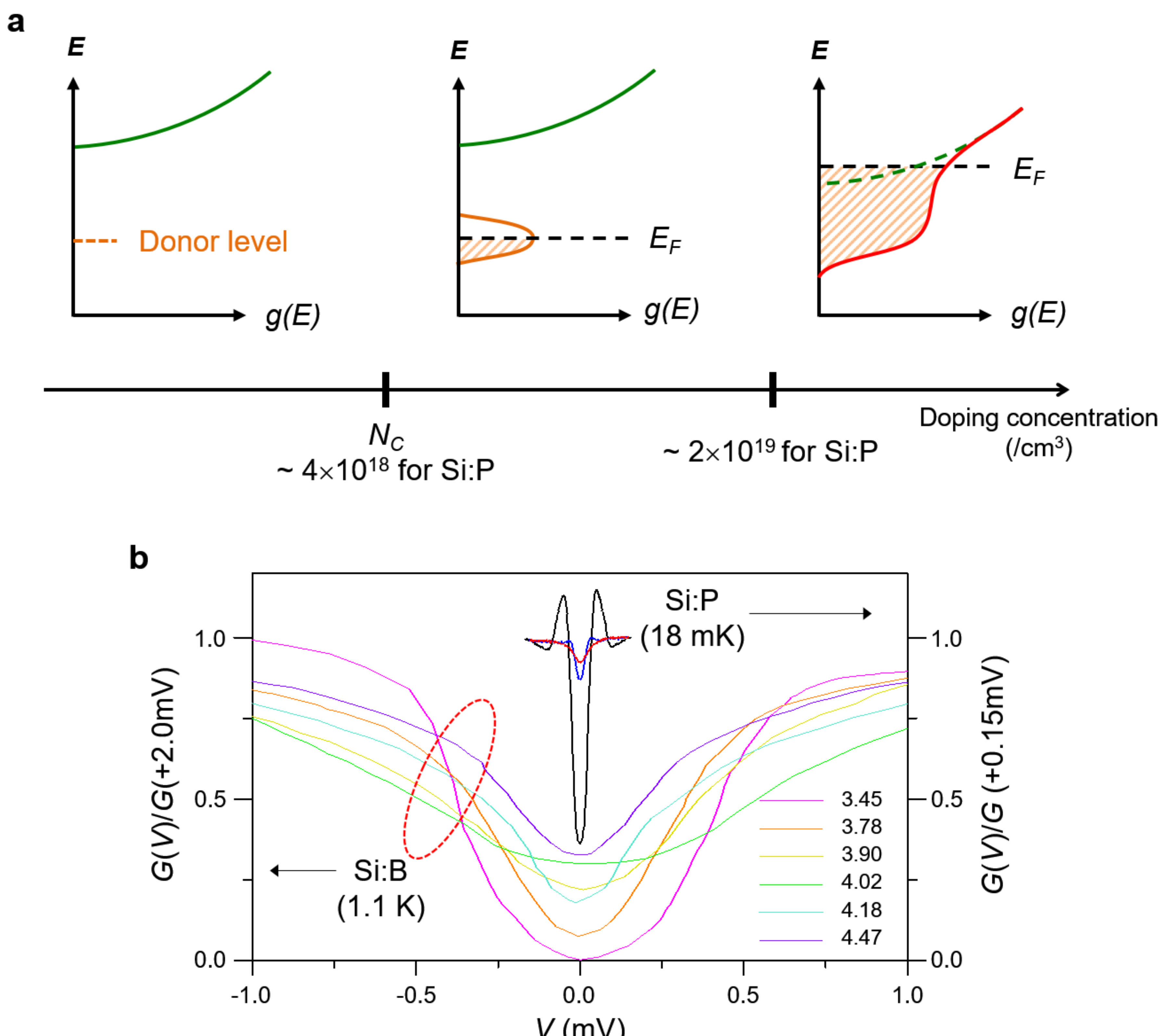
Found a coherence
in a disordered semiconductor.

Th.

Taewon Yuk

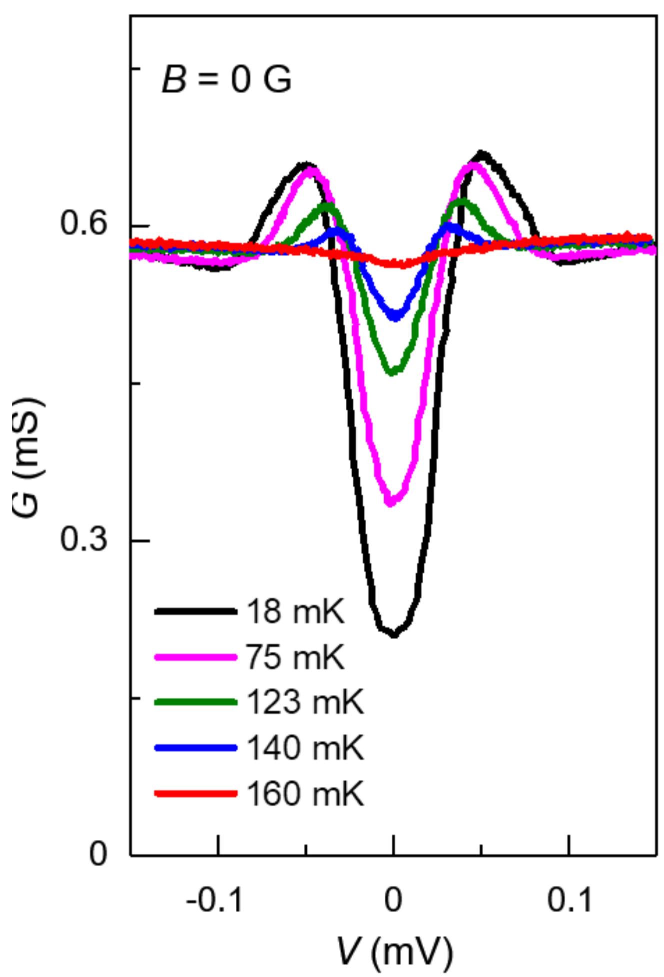
Soonjae Moon

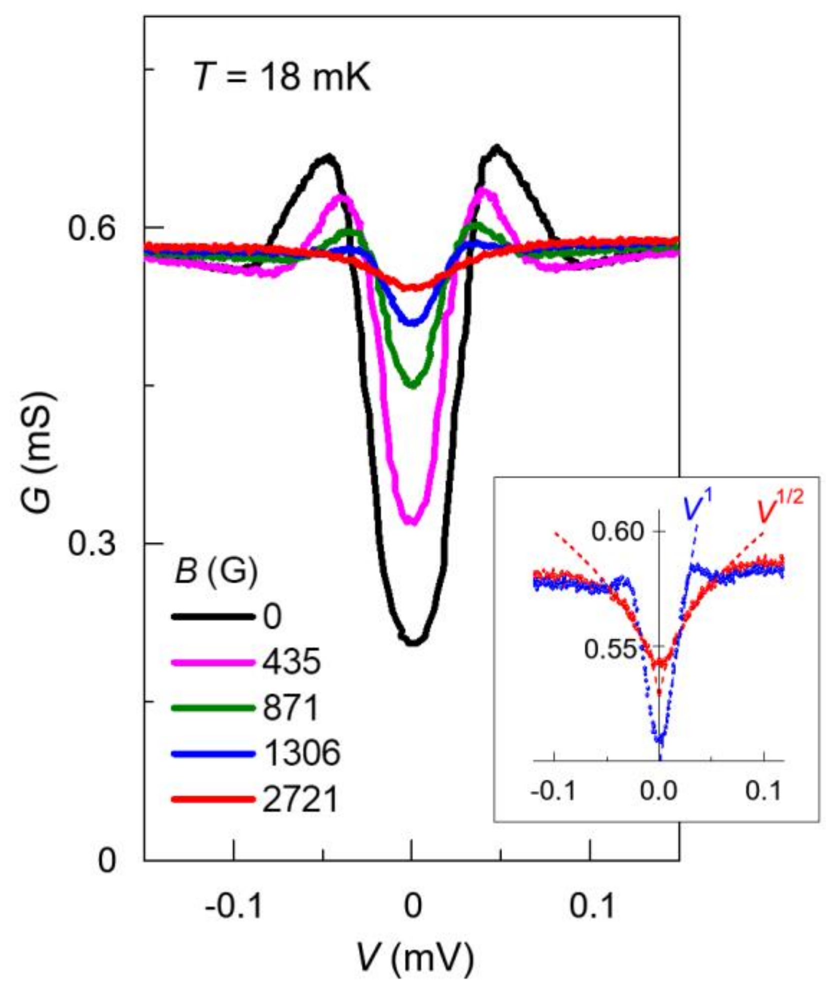
Doped Si, the material of our civilization !
About 10 years ago, my exp. colleages discovered a puzzle.



Observation of the pseudo gap and its Character

- The gap's shoulder looks like that of SC gap, but no evidence for SC !
- The gap disappear in high B, T

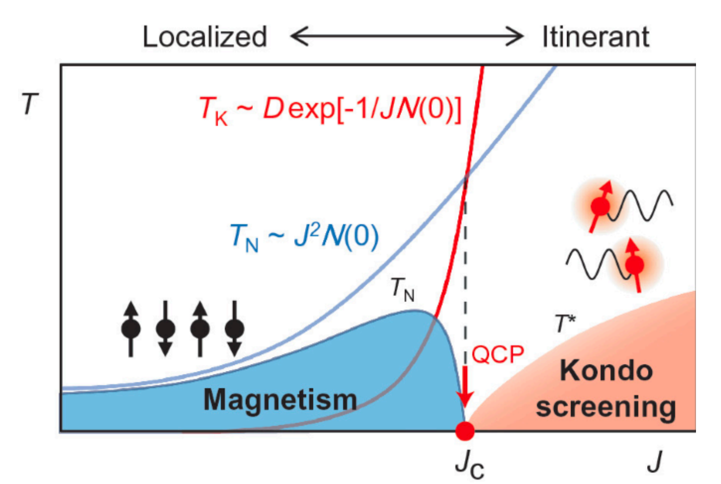




Hint from the previous study

- It Has long been Known :
  Si:P has magnetic moments, although none of Si or P is magnetic material. (P.W. Anderson, Patrick Lee, Bhatt)
- Then, Kondo physics, many impurity one!
- At first sight, Presence of gap -> Order -> RKKY domination ?
- However,
  i) below 100mK,

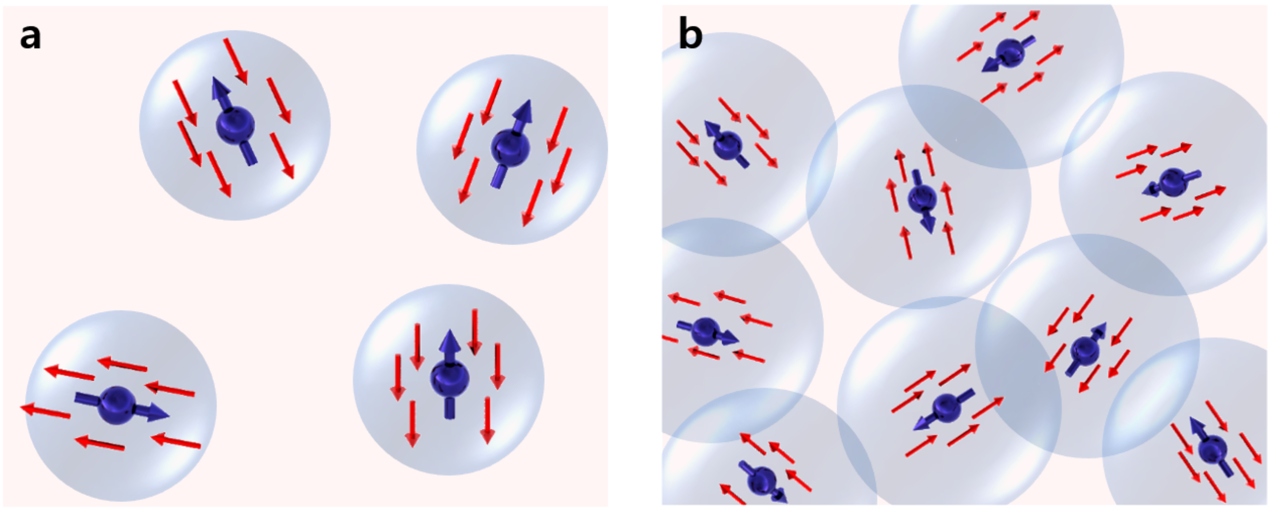
  $$g_{Kondo} > g_{RKKY}$$



  ii) random impurity would lead to spin glass without gap.

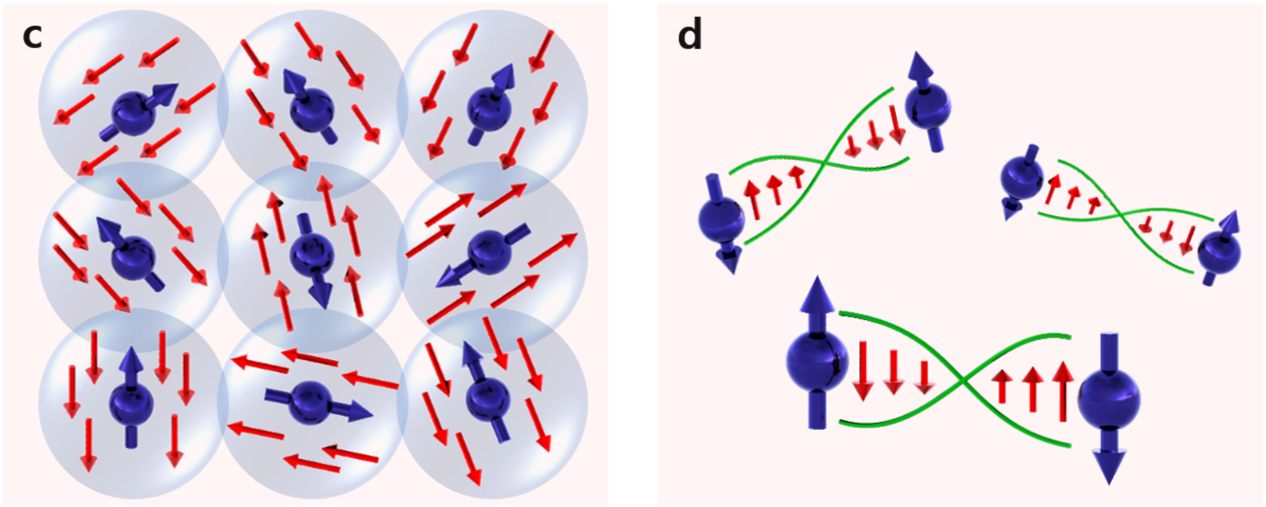
Many Kondo physics

single Kondo



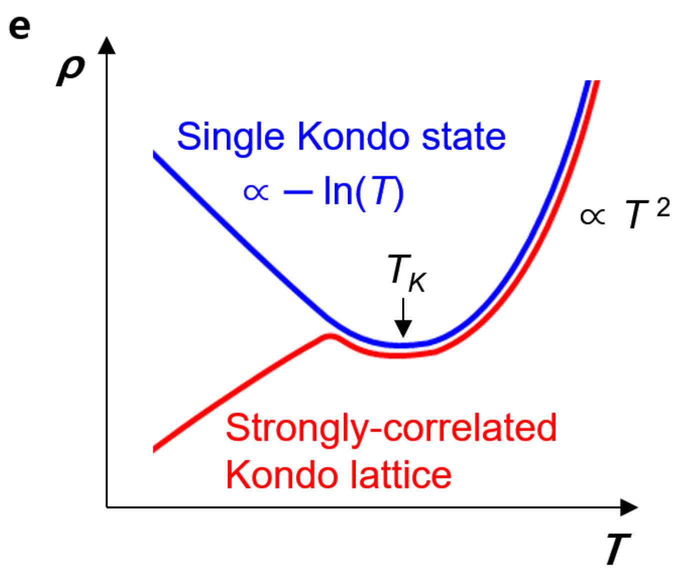
?

Kondo Lattice
heavy fermion/
Kondo insulator



RKKY
weak coupling

below 100mK,
$g_{Kondo} > g_{RKKY}$

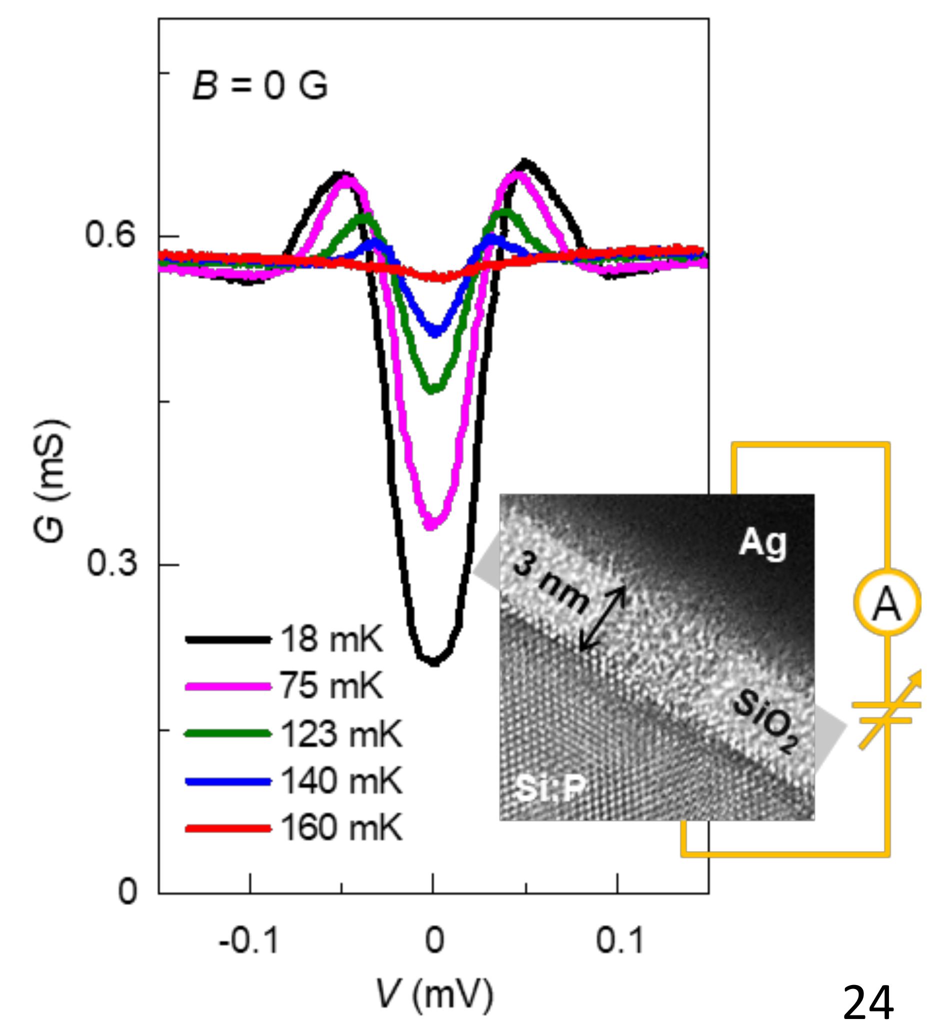


Difficulty of our system as Kondo lattice

- If no periodicity—> No momentum !
  No band.
  The whole picture of Kondo-lattice break down.

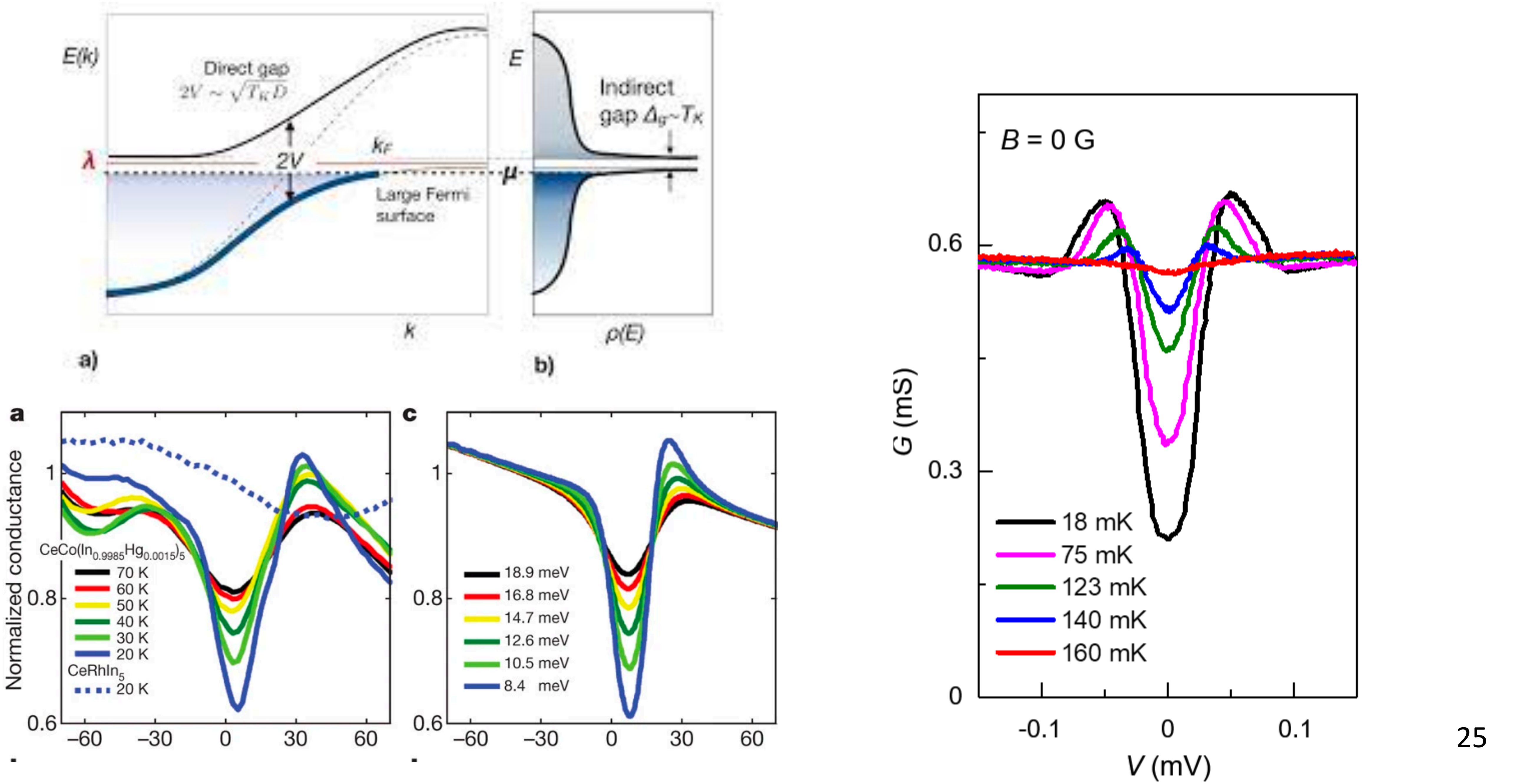
  random singlet picture —> No gap!

- However, ……
  A gap is found in random impurity



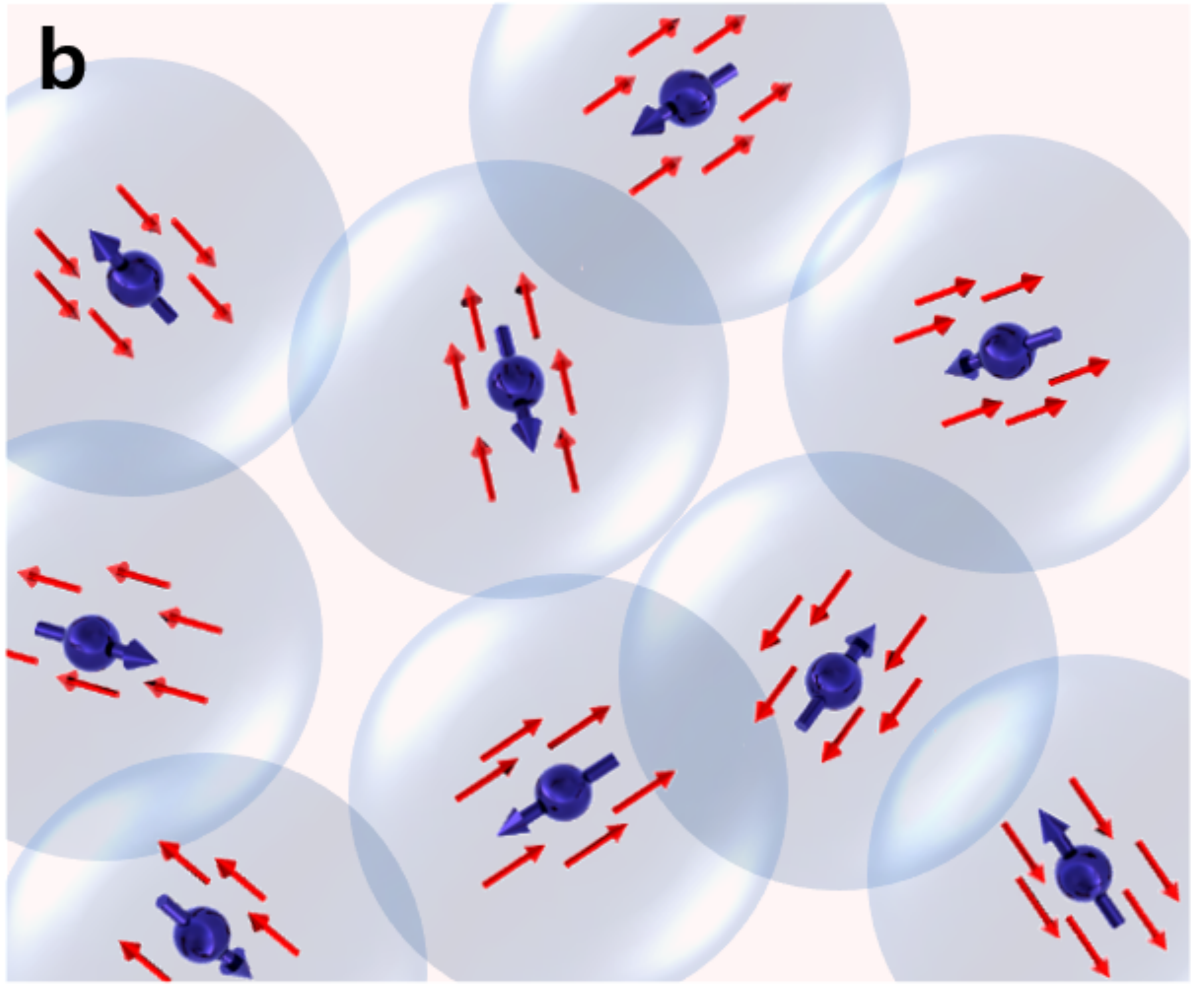
Difficulty of our system as Kondo lattice II

- Kondo lattice has characteristic asymmetry in G(V)



Our proposal: dense Random multi-Kondo
Overlapping Kondo cloud => Kondo condensation :

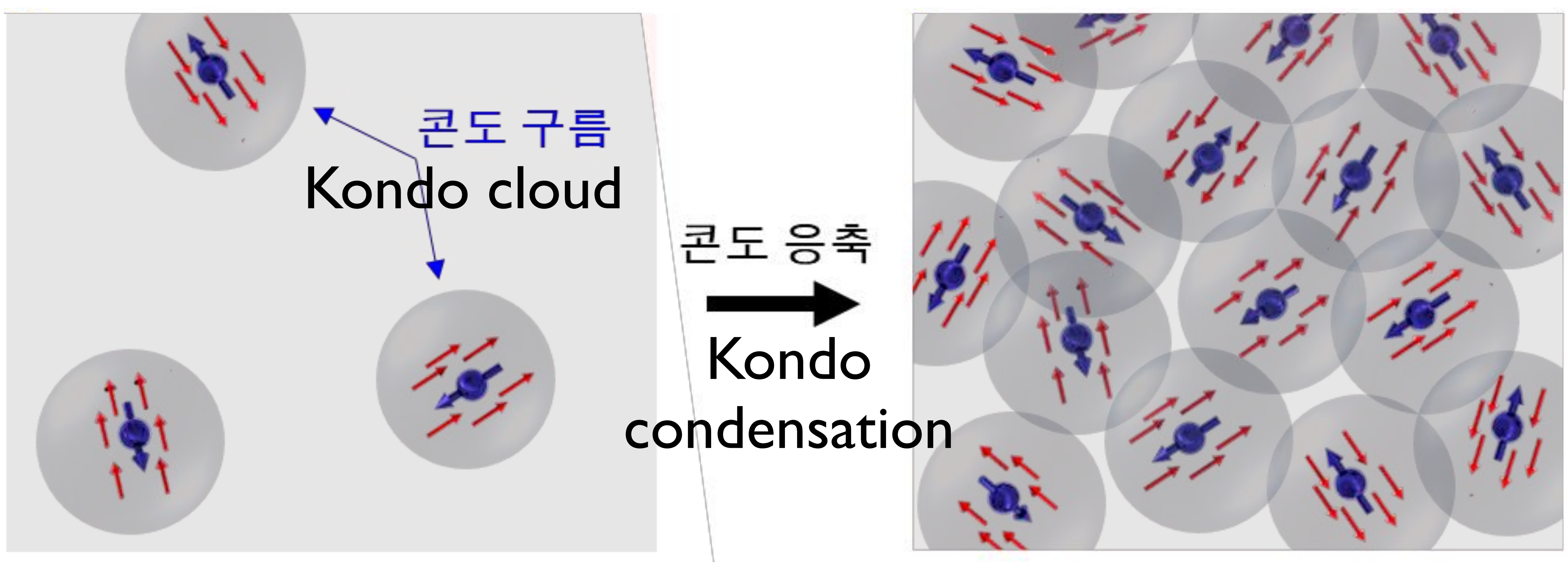
A key: size of Kondo cloud is ~ 1μ, large!



Def. Of Kondo condensation
cf Superconductivity

$$H = \sum_{i\sigma} \varepsilon_i^f f_{i\sigma}^\dagger f_{i\sigma} + U n_{i\uparrow} n_{i\downarrow} + \sum_{\vec{k}\sigma} \varepsilon_{\vec{k}\sigma} c^\dagger_{\vec{k}\sigma} c_{\vec{k}\sigma} + \sum_{i,\vec{k},\sigma} V_k \left(e^{i\vec{k}\vec{R}_i} f^\dagger_{i\sigma} c_{\vec{k}\sigma} + e^{-i\vec{k}\vec{R}_i} c^\dagger_{\vec{k}\sigma} f_{i\sigma} \right)$$

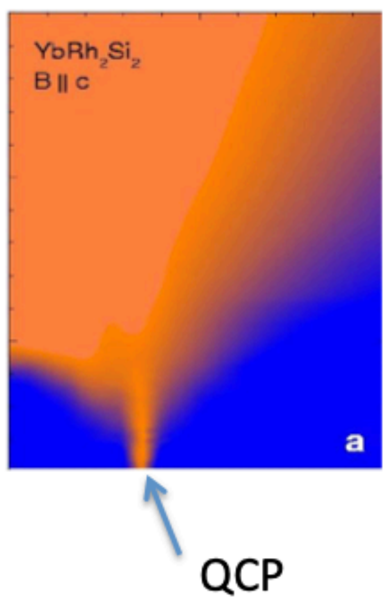
- Cooper pair=cc : $< cc > \neq 0 \rightarrow$ superconductivity
- Kondo pair = $f^\dagger c$: $< f^\dagger c > \neq 0 \rightarrow$ Kondo condensation

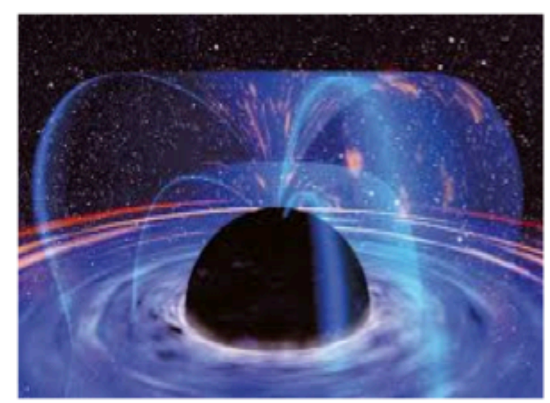


- Yamamoto et. al.
  "Observation of the Kondo screening cloud"
  Nature 2020

How to calculate KC in the presence of randomness?
Holography!

Why ads/cft help for randomness + strong coupling?
Why it works? Universality





- Key point: Near QCP of a strongly correlated system, ordered and disordered systems are not much different by the universality.

Our Holographic Model and its result

$$S_D = \int d^{d+1}x\sqrt{-g}\bar{\psi}(\Gamma^M D_M - m - \Phi)\psi + \int d^{d+1}x\sqrt{-g}\left(|\partial_\mu \Phi|^2 - m^2\Phi^2\right)$$

$$\Phi \sim f^\dagger c$$

$$D_M = \partial_M + \frac{1}{4}\omega_{abM}\Gamma^{ab} - iqA_M,$$

$$ds^2 = -r^2 f(r)dt^2 + \frac{1}{r^2 f(r)}dr^2 + r^2 d\vec{x}^2$$

$$\Phi = \frac{\Phi^{(0)}}{r} + \frac{\Phi^{(1)}}{r^2} + \cdots$$

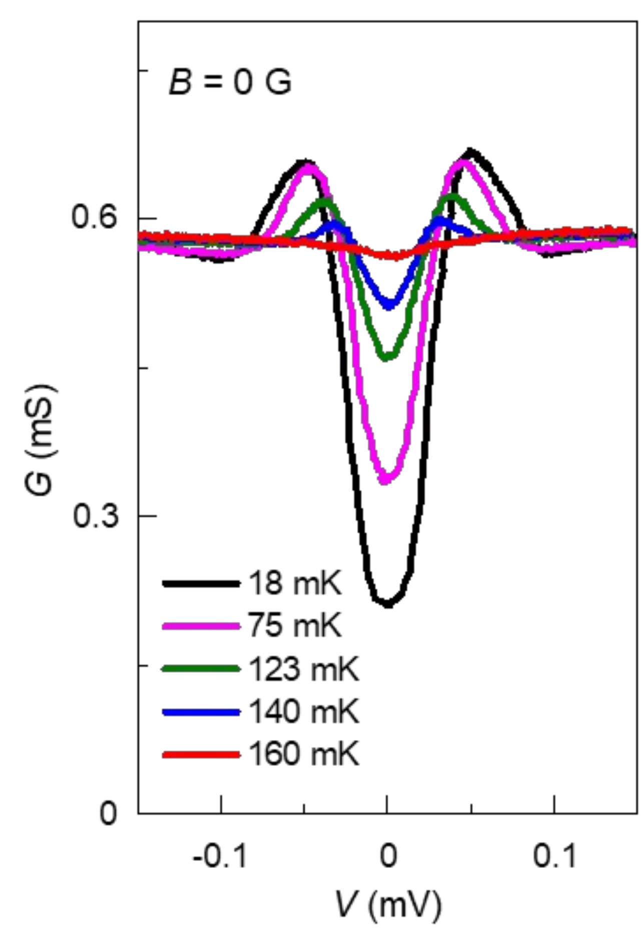
$$f(r) = 1 - \frac{{r_0}^3}{r^3} - \frac{r_0\mu^2}{r^3} + \frac{{r_0}^2\mu^2}{r^4} \; .$$

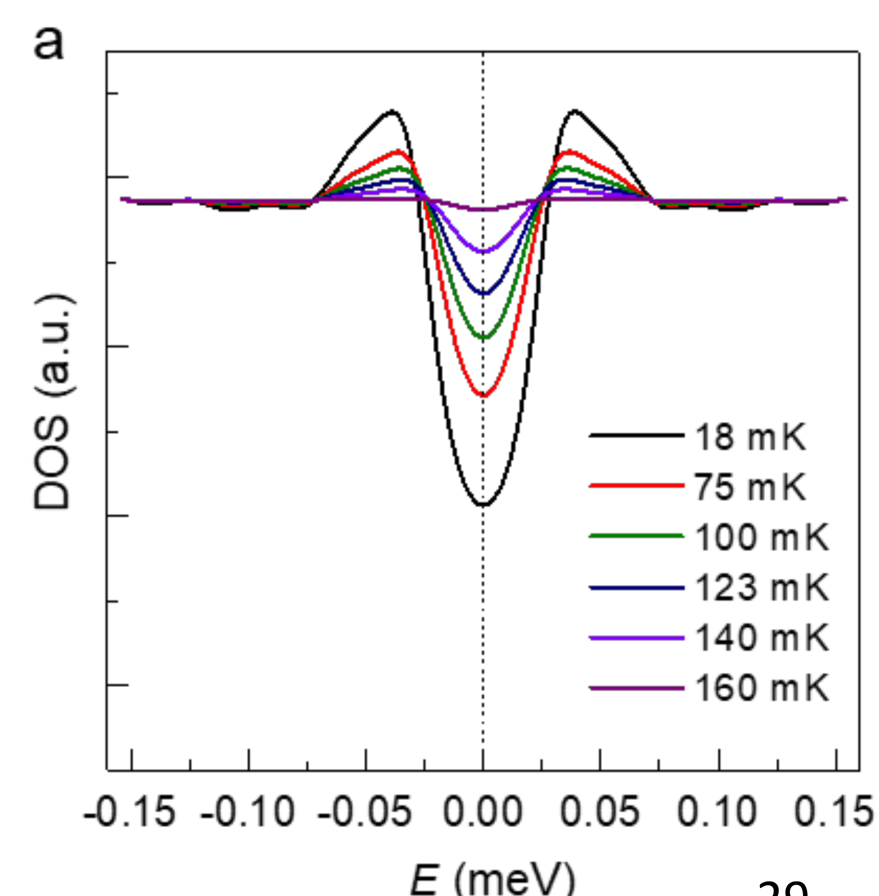
$$\Phi^{(0)} = 0, \quad \Phi^{(1)} = M_0\sqrt{1 - T/T^*}$$

$$T \to \frac{k_B T}{\hbar v_F} L = \frac{\hat{T}}{Kelvin}\frac{L}{2.3\times10^6 nm}$$

$$B \to \frac{e}{\hbar} B L^2 = \frac{\hat{B}}{Tesla}\frac{L^2}{(25.7nm)^2}$$

$$M_0 \to \frac{M_0}{(\hbar v_F)^2} L^2 = \frac{9v_0^2}{4v_F^2}\frac{L^2}{(nm)^2}\frac{M}{(eV)^2}$$





Holographic Kondo Lattice

YoungKwon Han

$$S_{\text{tot}} = S_{\text{background}} + S_{\text{bulk}} + S_{\text{int}} + S_{\text{bdy}},$$

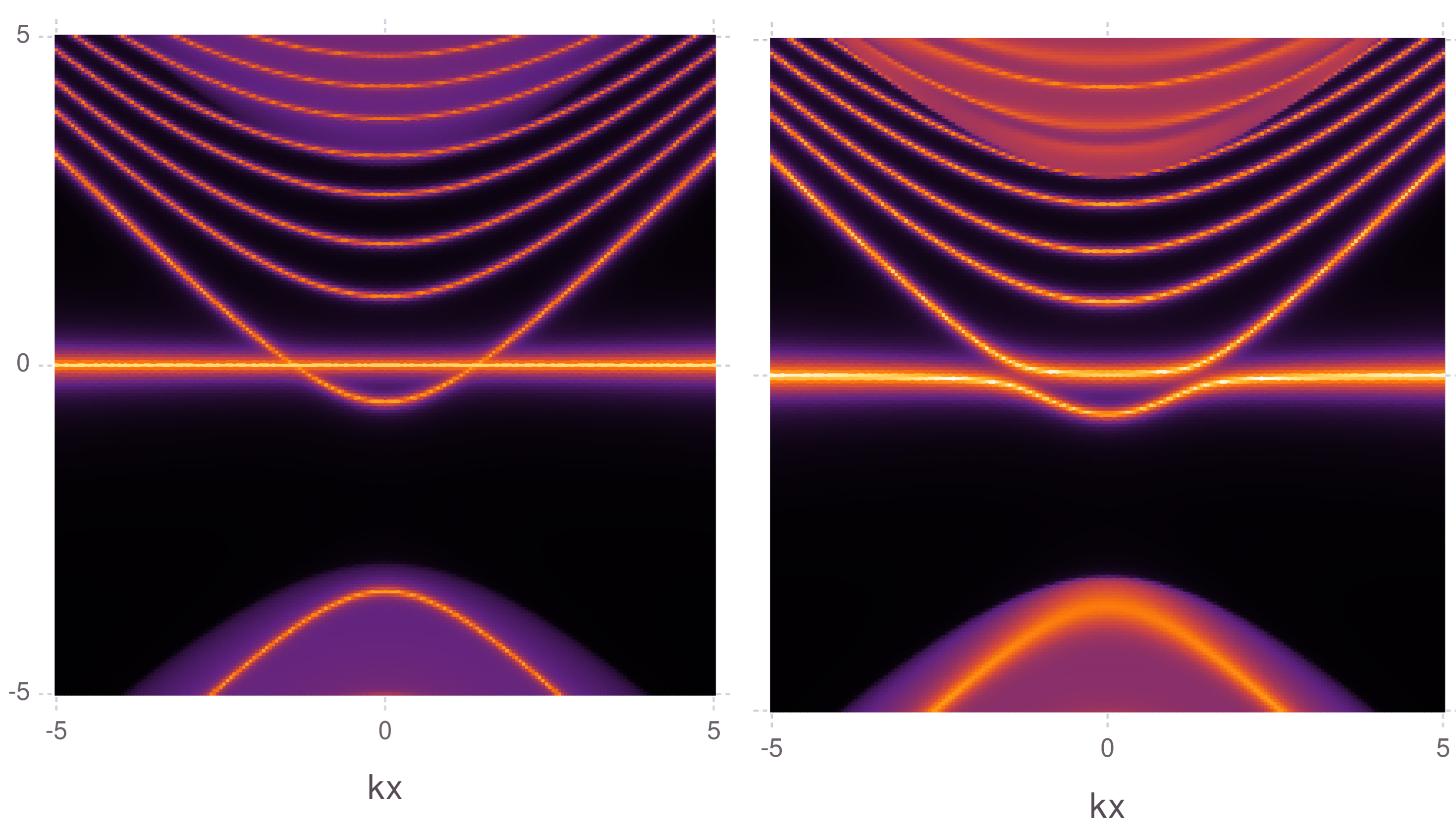
$$S_{\text{bulk}} = \sum_{j=1}^{2} \int d^4x \sqrt{-g}\, i\bar{\psi}^{(j)} \left[\frac{1}{2}(\overrightarrow{\not{D}} - \overleftarrow{\not{D}}) - m\right] \psi^{(j)}$$

$$S_{\text{int}} = \sum_{j,k=1}^{2} \int d^4x \sqrt{-g}\, \bar{\psi}^{(j)} (\text{int})^{(jk)} \psi^{(k)}$$

$\left\{ \begin{array}{l} (\text{int})^{(11)} : \text{shifted parabolic band} \\ (\text{int})^{(12),(21)} : \text{hybridization} \end{array} \right\}$

$$S_{\text{bdy}} = \frac{1}{2} \int d^3x \sqrt{-h} [\bar{\psi}^{(1)} i\mathbb{I}_4 \psi^{(1)} + \bar{\psi}^{(2)} \Gamma^{xy} \psi^{(2)}]$$

$\left\{ \begin{array}{l} i\mathbb{I}_4 : \text{standard quantization} \\ \Gamma^{xy} : \text{mixed quantization} \Rightarrow \text{flat band} \end{array} \right\}$

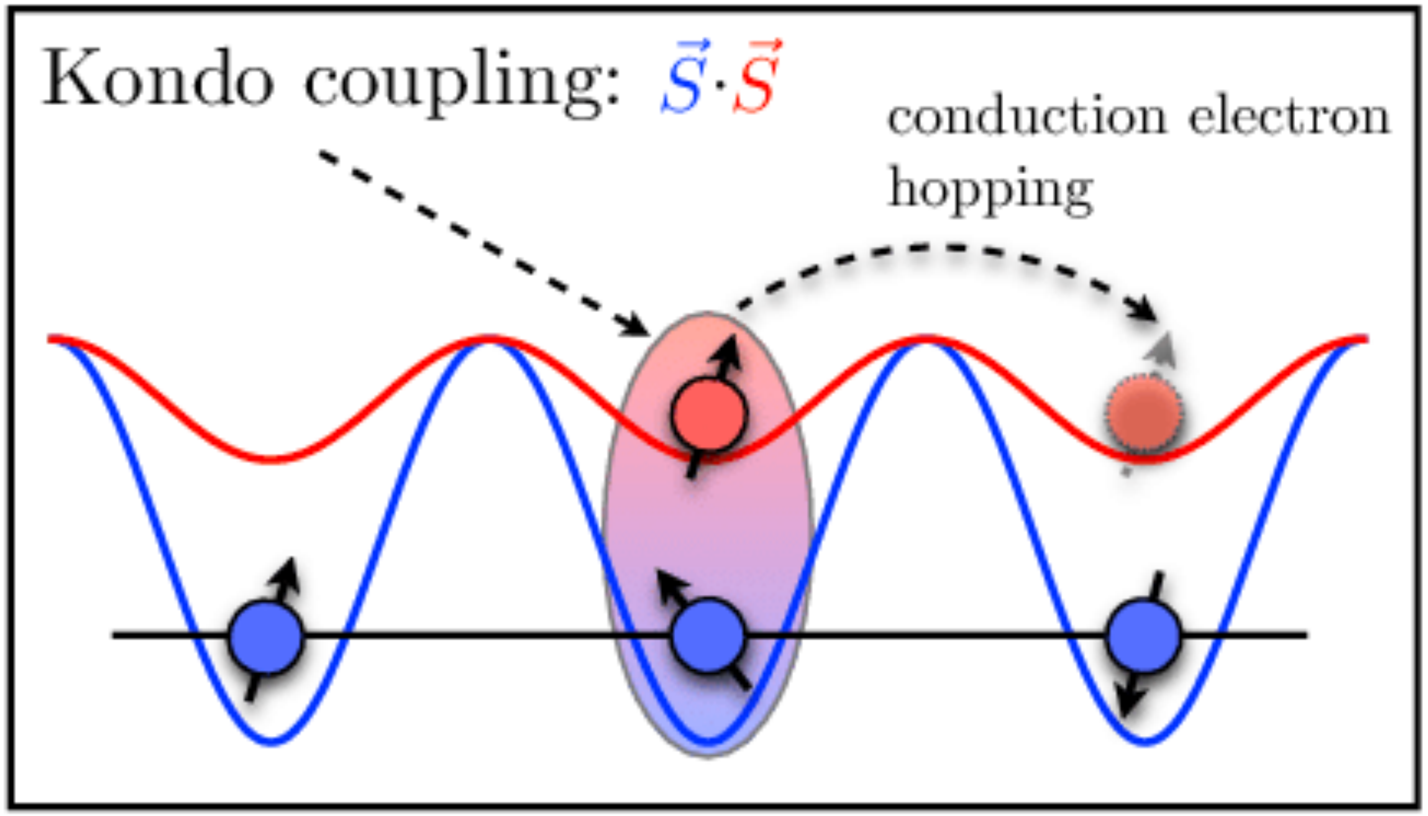


Conclusion

- We introduce Kondo condensation a dense random Kondo system where Kondo cloud overlaps.
- It forms a new state of quantum matter
- It can be treated by the holography, a mean field theory for strongly coupled system.

Thank you

Kondo lattice



Essence of the Kondo Lattice physics:

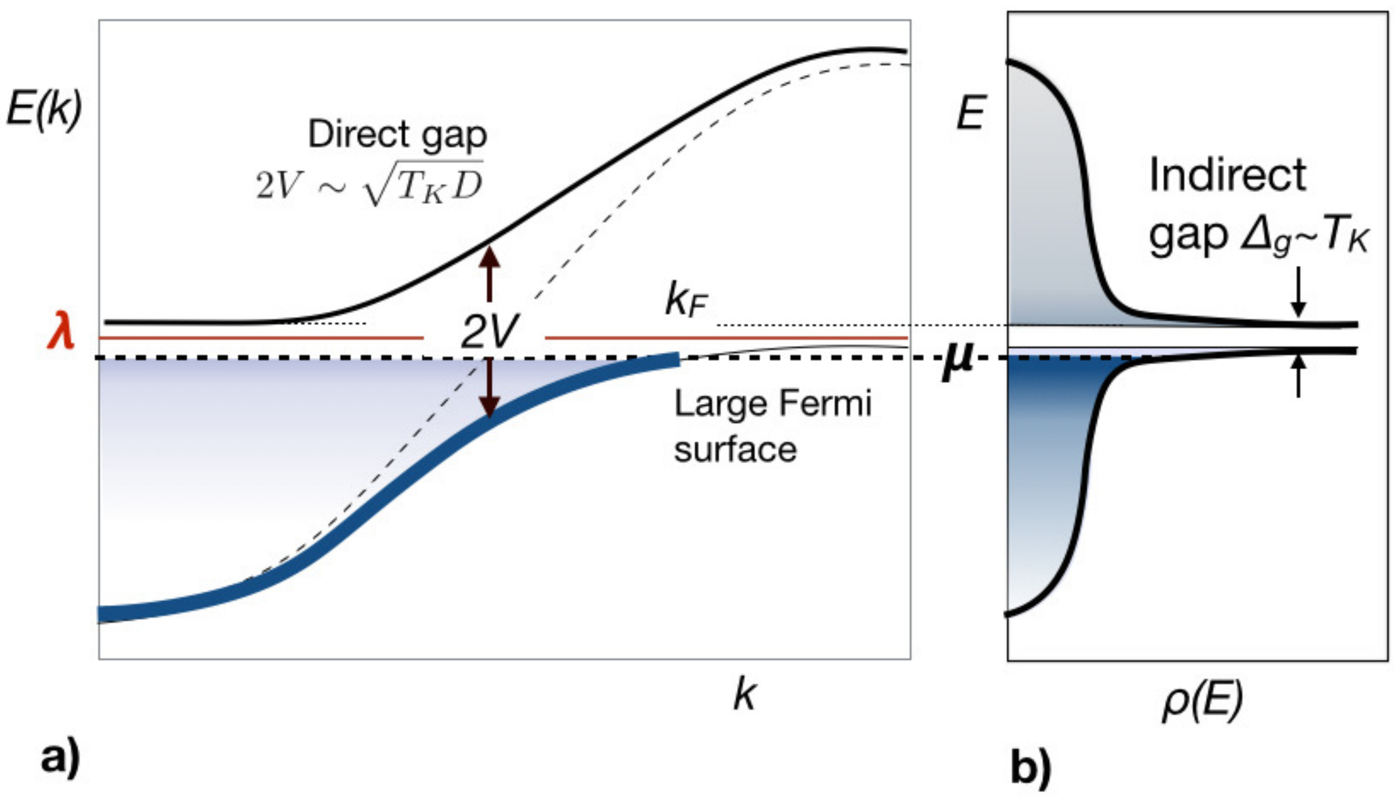
Electron trapped and propagate rarely from site to site.

On a larger length scale, a very slow coherent motion
= a quasi-particle with a large effective mass.

Kondo lattice (mean field theory)

$$H_{MFT} = \sum_{\mathbf{k}\sigma} \left(c^{\dagger}{}_{\mathbf{k}\sigma}, f^{\dagger}{}_{\mathbf{k}\sigma}\right) \begin{pmatrix} \epsilon_{\mathbf{k}} & V \\ \bar{V} & \lambda \end{pmatrix} \begin{pmatrix} c_{\mathbf{k}\sigma} \\ f_{\mathbf{k}\sigma} \end{pmatrix} + N\mathcal{N}_s \left(\frac{|V|^2}{J} - \lambda q \right)$$

- mean field theory



$$E^{\pm} = \frac{\mp D + \lambda}{2} \pm \sqrt{\left(\frac{\mp D - \lambda}{2}\right)^2 + V^2} \approx \lambda \pm \frac{V^2}{D},$$

$$T_K \sim V^2/D : \;\; 1 - Kondo\ Temp\,.$$

FS in gap-> K insulator,
otherwise
Heavy Fermion w/ larger FS