Title: The SYK model and matter without quasiparticle

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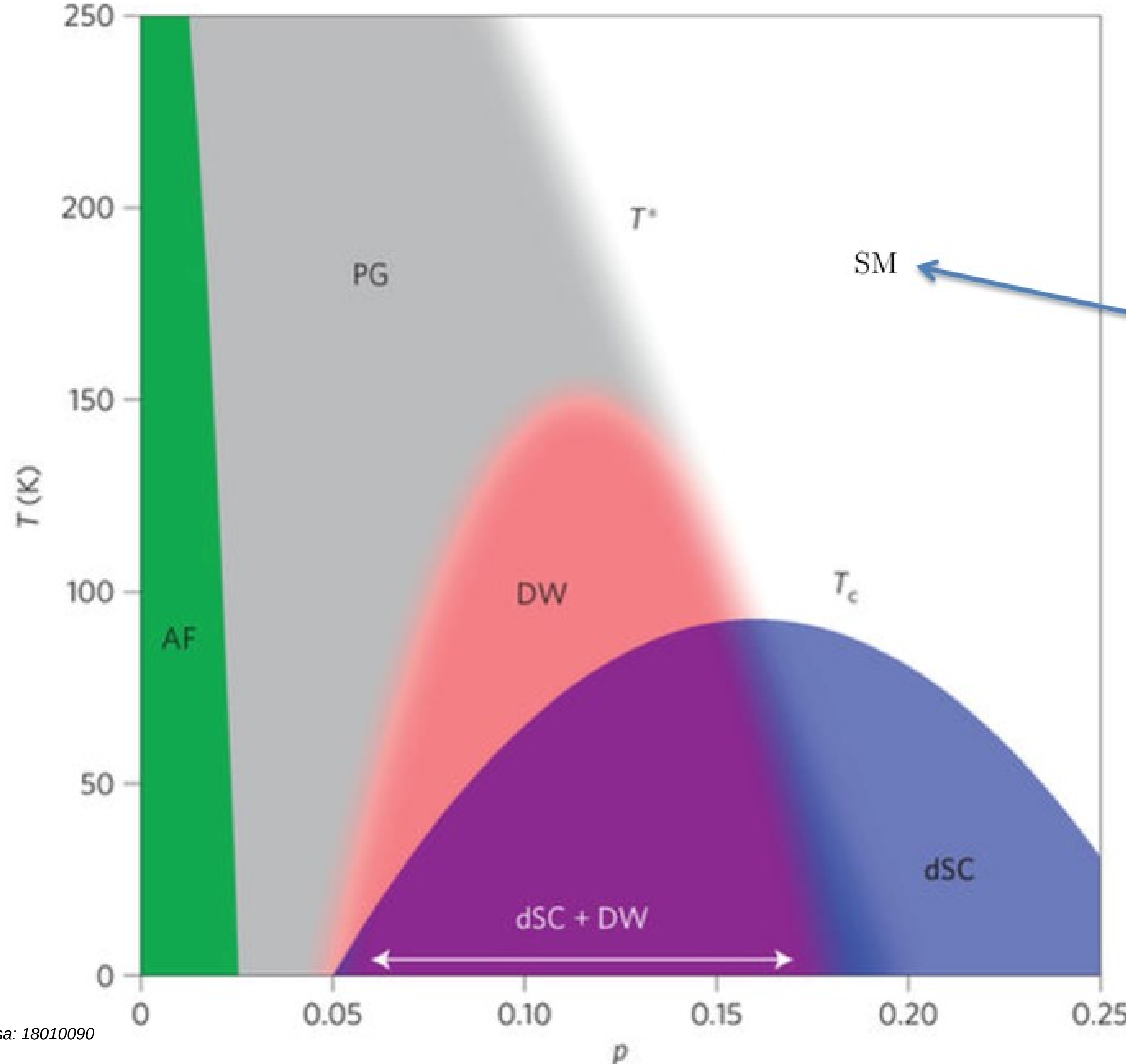
Abstract: <p>Many strongly-correlated systems like high Tc cuprates and heavy fermions have interesting features going beyond quasi-particle description. While Sachdev-Ye-Kitaev(SYK) models are exactly solvable models that can provide a platform to study these physics. In this talk, I will discuss interesting features about the SYK models, including extensive zero temperature entropy and maximally chaos. I will also show some generalization of the SYK models and discuss physical insights from them.</p>

The SYK models and matter without quasiparticle

Wenbo Fu

Harvard University

01/23/2018 PI



Strange Metal:
A metallic phase which does not have a quasiparticle description

$YBa_2Cu_3O_{6+a}$

K. Fujita et al, Nature Physics 12, 150–156 (2016)

Strange Metal

- Linear T resistivity
- Linear H magnetoresistance
- Tlog(T) heat capacity
- Instability towards other order

Strange Metal

- Linear T resistivity

  "A strongly correlated metal built from SYK models" X-Y Song et al 2017

- Linear H magnetoresistance

  "Magnetotransport in a model of a disordered strange metal" A. A. Patel et al 2017

- Tlog(T) heat capacity

  "Translationally invariant non-Fermi liquid metals with critical Fermi-surfaces:Solvable models" D. Chowdhury et al 2018

- Instability towards other order

  "Instability of the non-fermi liquid state of the sachdev-Ye-Kitaev model" Z. Bi et al 2017

Motivation

- The SYK models are solvable non Fermi liquid models which provide a platform to study the strange metal physics

- NCFT1/NAdS2 holography, maximal chaos, relation to random matrix ensemble and black hole physics

My adventures with SYK

- Numerical study with exact diagonalization

  Spectrum, thermal entropy, entanglement entropy

  W. Fu. and S. Sachdev, PRB 94, 035135 (2016)

- Supersymmetric SYK models

  Different origins of zero temperature entropy in N=1 and N=2 theories

  W. Fu, D. Gaiotto, J. Maldacena, and S. Sachdev, PRD 95, 026009(2017)

- Lattice construction of complex SYK model

  Zero temperature entropy with different charge density, effective action, charge/energy diffusion

  R. Davison, **W. Fu**, A. Georges, Y. Gu, K. Jensen and S. Sachdev, PRB 95, 155131(2017)

- SYK boson/fermion model

  Tunable Lyapunov exponent

  W. Fu, C-M. Jian, Z Bi and C. Xu, in progress

- Quantum transitions of fractionalized SYK model

  Quasi-Higgs to de-confinement transition

  W. Fu, Y. Gu, G. Tarnopolsky and S. Sachdev, in progress

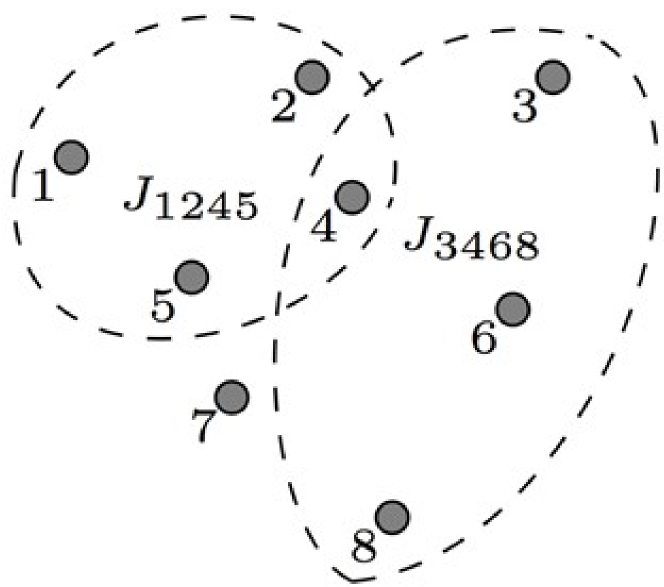
The SYK models

Complex fermion version

$$H = \frac{1}{(4/2)!} \sum_{j,k;l,m}^{N} J_{jk;lm} c_j^\dagger c_k^\dagger c_l c_m - \sum_i^N \mu c_i^\dagger c_i \qquad \overline{J_{jk;lm}} = 0 \qquad \overline{|J_{jk;lm}|^2} = \frac{2\mathcal{J}^2}{4N^3}$$

Majorana fermion version

$$H = \frac{1}{4!} \sum_{jklm} J_{jklm} \chi_j \chi_k \chi_l \chi_m \qquad \overline{J_{jklm}} = 0 \qquad \overline{J_{jklm}^2} = \frac{3!}{N^3} \mathcal{J}^2 \qquad N\text{: site number}$$



$N = 8$

General q-body interaction

Complex fermion version

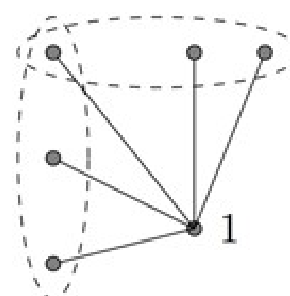
$$H = \frac{1}{(q/2)!} \sum_{j_1,\cdots,j_{q/2};k_1,\cdots,k_{q/2}}^{N} J_\star c_{j_1}^\dagger \cdots c_{k_{q/2}}^\dagger c_{k_1} \cdots c_{j_{q/2}} - \sum_i^N \mu c_i^\dagger c_i \qquad \overline{J_\star} = 0 \qquad \overline{|J_\star|^2} = \frac{2\mathcal{J}^2}{qN^{q-1}}$$

Majorana fermion version

$$H = \frac{1}{q!} \sum_{j_1,\cdots,j_q}^{N} J_\star \chi_{j_1} \cdots \chi_{j_q} \qquad \overline{J_\star} = 0 \qquad \overline{J_\star^2} = \frac{q!}{N^{q-1}} \mathcal{J}^2$$

The model as fermion coupled to heat bath field:

$$c_1^\dagger \mathcal{B}_1 + h.c. \quad , \quad \mathcal{B}_1 = \frac{1}{(q/2-1)!} \sum J_\star c_{j_1}^\dagger \cdots c_{j_{q/2-1}}^\dagger c_{k_1} \cdots c_{k_{q/2}}$$



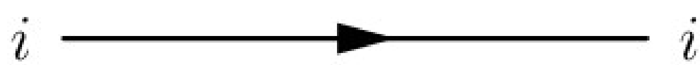
$$\langle \mathcal{B}_1 \mathcal{B}_1^\dagger \rangle \sim \mathcal{J}^2$$

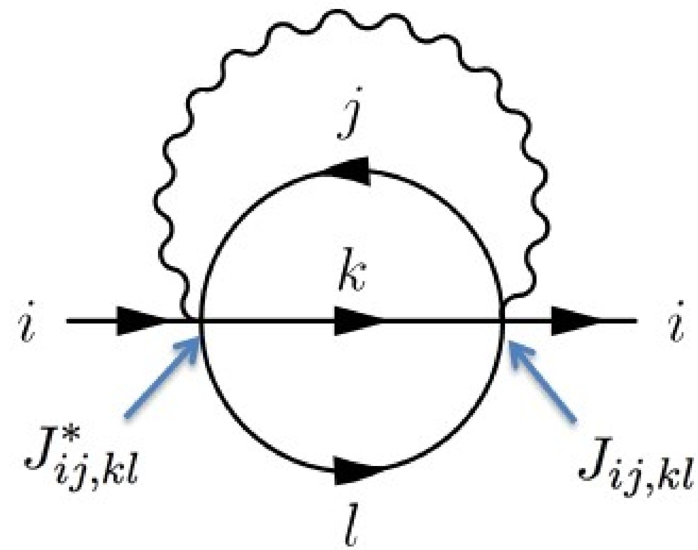
$$\mathcal{B}_1 \sim \sum_{k,l,m} J_{1k;lm} c_k^\dagger c_l c_m$$

Solve the model

- Diagrammatics:

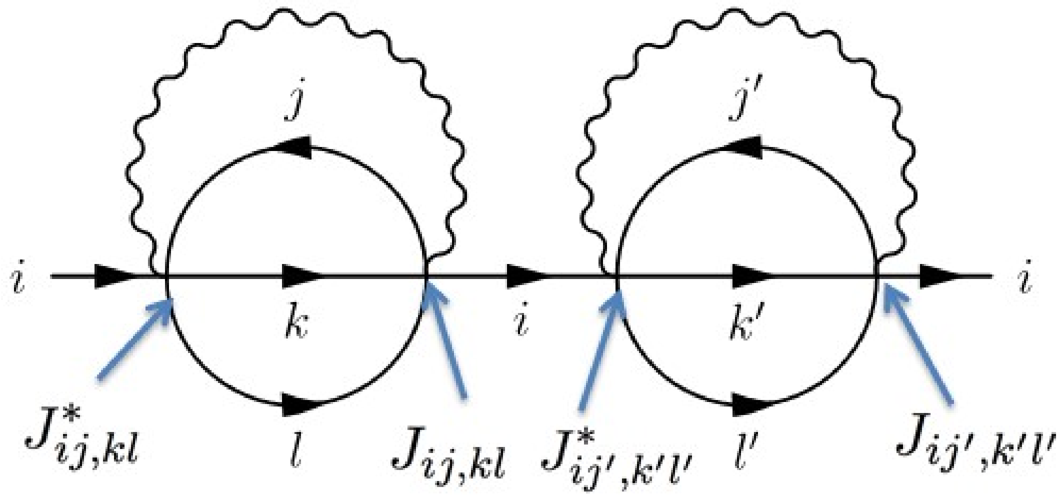
Two point function: $G(\tau_1, \tau_2) = -\langle T_\tau c(\tau_1) c^\dagger(\tau_2) \rangle$



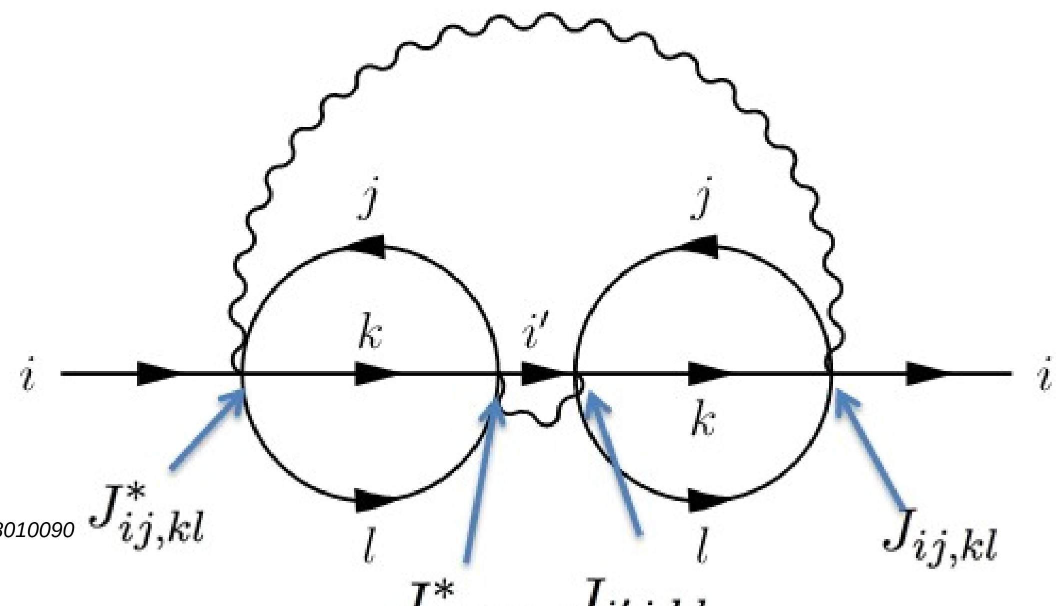


$$|J_{ij,kl}|^2 N^3 \sim \frac{\mathcal{J}^2}{N^3} N^3 \sim \mathcal{J}^2$$

Two point function: $G(\tau_1, \tau_2) = -\langle T_\tau c(\tau_1) c^\dagger(\tau_2) \rangle$

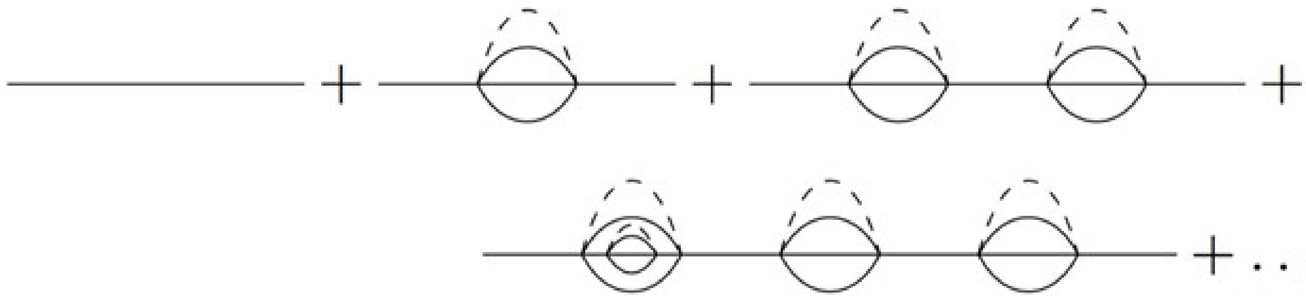


$$(\frac{\mathcal{J}^2}{N^3})^2 N^6 \sim \mathcal{J}^4$$



$$(\frac{\mathcal{J}^2}{N^3})^2 N^4 \sim \frac{\mathcal{J}^4}{N^2}$$

Large N limit:

$G =$ 

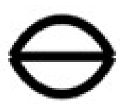
Schwinger-Dyson equation:

$G_0 =$

$G =$ 

$$G(i\omega_n) = \frac{1}{i\omega_n + \mu - \Sigma(i\omega_n)}$$

$$\Sigma(\tau) = -J^2 G^2(\tau) G(-\tau)$$

$\Sigma =$ 

Solved numerically for any coupling;

analytically in the strong coupling limit $\beta J \gg 1$

Solve the model

- Effective action:

$$H = \frac{1}{(q/2)!} \sum_{j_1,\cdots,j_{q/2};k_1,\cdots,k_{q/2}}^{N} J_\star c^\dagger_{j_1} \cdots c^\dagger_{k_{q/2}} c_{k_1} \cdots c_{j_{q/2}} - \sum_i^N \mu c_i^\dagger c_i \qquad \overline{J_\star} = 0 \qquad \overline{|J_\star|^2} = \frac{2\mathcal{J}^2}{qN^{q-1}}$$

Introduce replicas: $\log Z = \lim_{M\to 0} \frac{Z^M}{M}$

Integrate out disorder J field:

$$S_{eff}\left[c, c^\dagger\right] = \int d\tau \sum_\alpha c^\dagger_{i\alpha}(\tau)(\partial_\tau - \mu) c_{i\alpha}(\tau) - (-)^{q/2} \frac{\mathcal{J}^2}{qN^{q-1}} \int d\tau_1 d\tau_2 \sum_{\alpha,\beta} |c^\dagger_{i\alpha}(\tau_1) c_{i\beta}(\tau_2)|^q$$

Introduce Bi-local field G and Σ: Σ is the Lagrangian multiplier that enforces

$$G_{\alpha\beta}(\tau_1, \tau_2) = -\frac{1}{N} \sum_i c_{i\alpha}(\tau_1) c^\dagger_{i\beta}(\tau_2)$$

Then the effective action : $S_{eff}(c, G, \Sigma) \sim c^\dagger(\partial_\tau - \mu)c + \Sigma(G - c^\dagger c) + |G|^q$

Integrate out fermion field:

$$S_{eff}(G,\Sigma) = N\left\{-\sum_n \log\left[-i\omega_n - \mu + \Sigma(i\omega_n)\right] - \int d\tau_1 d\tau_2 \left[\Sigma(\tau_1,\tau_2) G(\tau_2,\tau_1) + (-)^{q/2} \frac{N\mathcal{J}^2}{q} |G(\tau_2,\tau_1)|^q\right]\right\}$$

Solve the model

Saddle point approximation:

$$G(i\omega_n) = \frac{1}{i\omega_n + \mu - \Sigma(i\omega_n)}$$

$$\Sigma(\tau) = -(-)^{q/2}\mathcal{J}^2 G^{q/2}(\tau) G^{q/2-1}(-\tau)$$

In the low energy scaling limit: $\omega, T \ll J \quad i\omega_n + \mu - \Sigma(i\omega_n = 0)$ irrelevant

$$\int d\tau_2 G(\tau_1, \tau_2)\Sigma(\tau_2, \tau_3) = -\delta(\tau_1 - \tau_3)$$

$$\Sigma(\tau_1, \tau_2) = -(-)^{q/2}\mathcal{J}^2 G^{q/2}(\tau_1, \tau_2) G^{q/2-1}(\tau_2, \tau_1)$$

Reparameterization symmetry and U(1) symmetry:

$$\begin{aligned} \tau &= f(\sigma) \\ G(\tau_1, \tau_2) &= [f'(\sigma_1) f'(\sigma_2)]^{-1/q} \frac{g(\sigma_1)}{g(\sigma_2)} \widetilde{G}(\sigma_1, \sigma_2) \\ \Sigma(\tau_1, \tau_2) &= [f'(\sigma_1) f'(\sigma_2)]^{1-1/q} \frac{g(\sigma_1)}{g(\sigma_2)} \widetilde{\Sigma}(\sigma_1, \sigma_2) \end{aligned}$$

If $G(\tau_1, \tau_2), \Sigma(\tau_1, \tau_2)$ is the solution, $\widetilde{G}(\sigma_1, \sigma_2), \widetilde{\Sigma}(\sigma_1, \sigma_2)$ is also the solution.

Solve the model

- Analytical solution:

In the low energy scaling limit: $\omega, T \ll J \quad i\omega_n + \mu - \Sigma(i\omega_n = 0)$ irrelevant

$$G(i\omega_n) = -\Sigma(i\omega_n)^{-1}$$

$$\Sigma(\tau) = -(-)^{q/2}\mathcal{J}^2 G^{q/2}(\tau) G^{q/2-1}(-\tau)$$

$$\longrightarrow \quad G(\tau) \sim \begin{cases} -|\tau|^{-2\Delta}, & \tau > 0, \\ e^{-2\pi\mathcal{E}}|\tau|^{-2\Delta}, & \tau < 0, \end{cases} \qquad \Delta = \frac{1}{q}$$

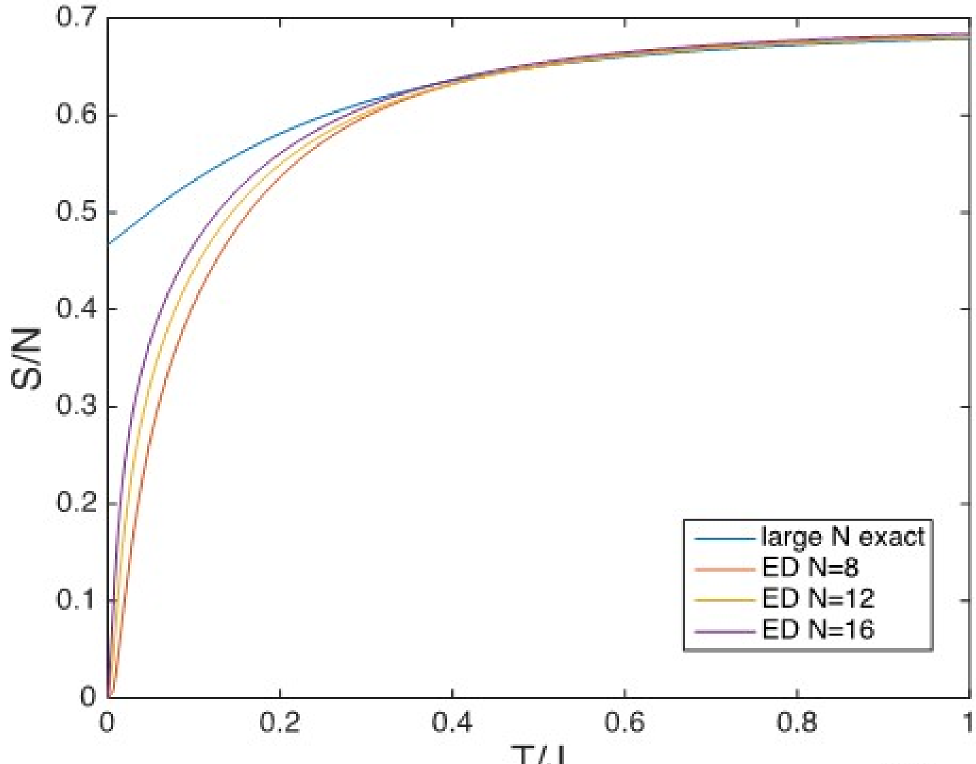
Finite temperature $\xrightarrow{\tau = \frac{1}{\pi T}\tan(\pi T \sigma)}$ $G(\sigma) \sim e^{-2\pi\mathcal{E}\sigma/\beta}\left[\frac{\pi}{\beta \sin\frac{\pi\sigma}{\beta}}\right]^{2\Delta}$

0T entropy

- Numerical solution:

$$\frac{\mathcal{F}}{N} = T\sum_n \ln\left(-\beta G(i\omega_n)\right) - \int_0^\beta d\tau \frac{3}{4}\Sigma(\tau)G(-\tau)$$

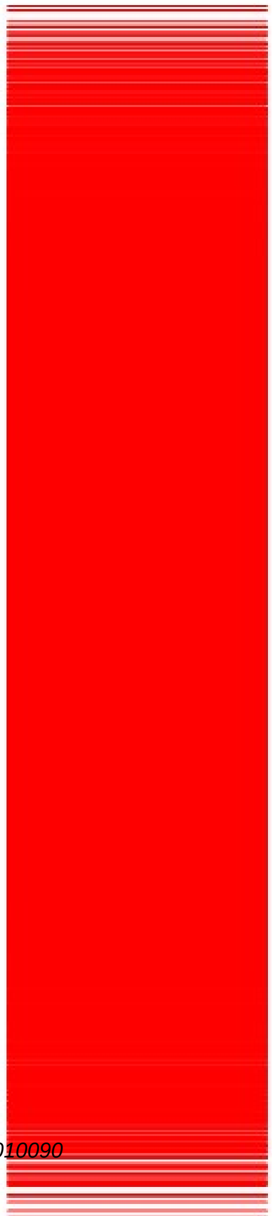
$$\frac{S}{N} = -\frac{1}{N}\frac{\partial \mathcal{F}}{\partial T}$$



0T entropy

W. Fu and S. Sachdev, PRB 94, 035135 (2016)
J. Maldacena and D. Stanford , PRB 94, 106002(2016)

SYK:



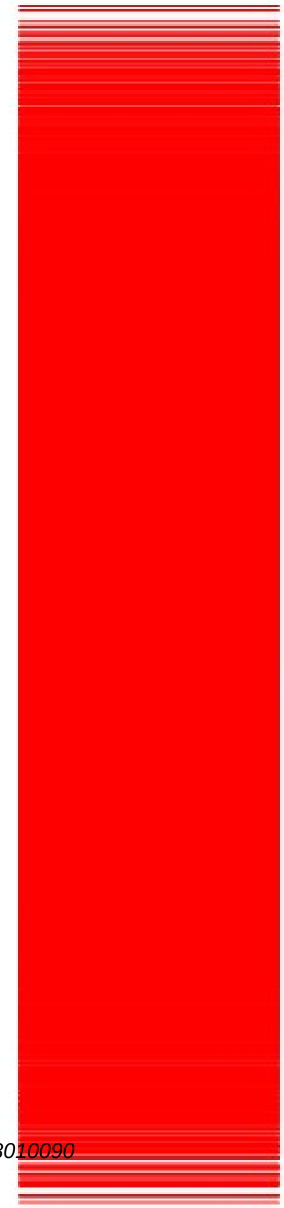
Random hopping:

$$\Delta E \sim e^{-N \ln 2}$$

$$\Delta E \sim e^{-S_0}$$

$$\Delta E \sim \frac{1}{N}$$

0T entropy



$$\Delta E \sim e^{-N \ln 2}$$

$$\Delta E \sim e^{-S_0}$$

There is a finite zero temperature entropy maximally at half -filling:

$$\frac{S_0}{N} = \frac{\text{Catalan}}{\pi} + \frac{\log 2}{4} \approx 0.4648$$

A. Georges, O. Parcollet, and S. Sachdev Phys. Rev. B 63, 134406 (2001)

The low energy sector cannot be described by polynomial in N number of parameters:

$$E\left[\{n_\alpha\}\right] = \sum n_\alpha \epsilon_\alpha + \sum F_{\alpha\beta} n_\alpha n_\beta + \cdots$$

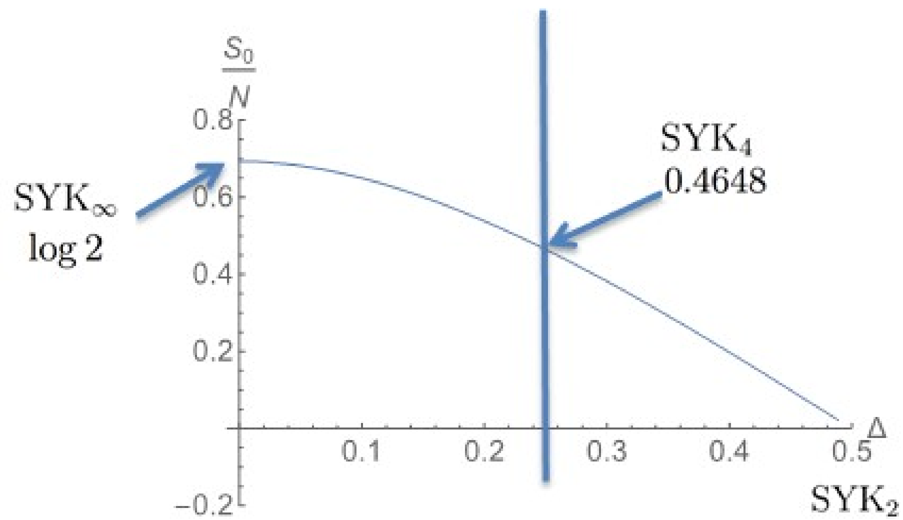
No quasiparticle description

0T entropy

Plug in the conformal solution into free energy: $G(\sigma) \sim e^{-2\pi\mathcal{E}\sigma/\beta}\left[\frac{\pi}{\beta\sin\left(\frac{\pi\sigma}{\beta}\right)}\right]^{2\Delta}$

$$\partial_q \frac{\log Z}{N} = \beta \int d\sigma \mathcal{J}^2 G(\sigma)^{q-1} \log G(\sigma) = \beta(\text{constant}) + q\pi(q-2)\tan\left(\frac{\pi}{q}\right)$$

$$\frac{1}{N}\frac{\partial S_0}{\partial \Delta} = -\pi(1-2\Delta)\tan(\Delta\pi)$$



A. Kitaev talks at KITP (2015)

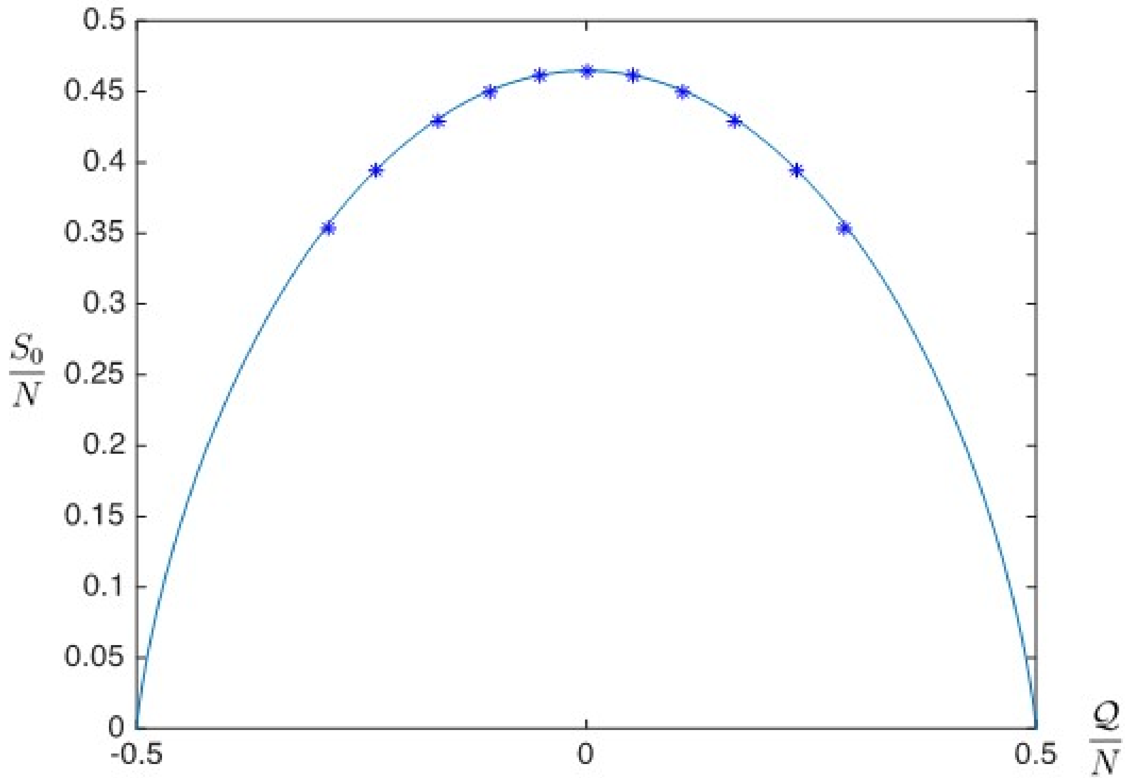
0T entropy

In general, particle-hole asymmetric case:

$$\left(\frac{S_0(\mathcal{E})}{N}, \frac{\mathcal{Q}(\mathcal{E})}{N}\right)$$

A. Georges, O. Parcollet, and S. Sachdev PRB 63, 134406 (2001)

S. Sachdev, PRX 5, 041025 (2015)



R. Davison, **W. Fu**, A. Georges, Y. Gu, K. Jensen and S. Sachdev, PRB 95, 155131(2017)

Another aspect of the SYK models

Another aspect of the SYK models

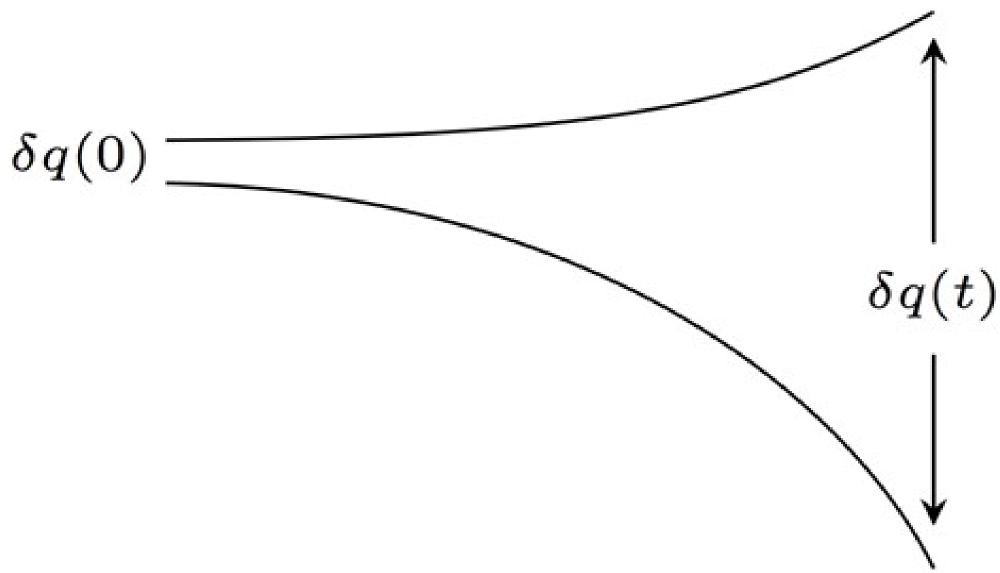
Chaos!

fast information scrambling

How to characterize chaos

Classical chaos $\{q(t), p(0)\} = \frac{\partial q(t)}{\partial q(0)} \sim e^{\lambda_L t}$

Lyapunov exponent: λ_L



Quantum analogy $\{q(t), p(0)\} \to \frac{i}{\hbar}\left[\widehat{q}(t), \widehat{p}(0)\right]$

Quantum chaos: growth of $C_{AB}(t) = \langle | \left[\widehat{A}(t), \widehat{B}(0)\right] |^2 \rangle_\beta$

Out of time ordered correlator

Normal order terms

$$C_{AB}(t) = \langle |\, [A(t), B(0)]\, |^2 \rangle_\beta$$
$$= \langle A(t)B(0)B^\dagger(0)A^\dagger(t)\rangle_\beta + \langle B(0)A(t)A^\dagger(t)B^\dagger(0)\rangle_\beta$$
$$-\langle A(t)B(0)A^\dagger(t)B^\dagger(0)\rangle_\beta - \langle B(0)A(t)B^\dagger(0)A^\dagger(t)\rangle_\beta$$

Out of time ordered correlators(OTOC)

Early time exponential deviation in OTOC causes exponential growth in C(t)

Normalized OTOC $\mathrm{OTOC} \approx 1 - \# e^{\lambda_L t}$

A bound on chaos: $\lambda_L \leq \frac{2\pi}{\beta}$ J. Maldacena, S. H. Shenker and D. Stanford JHEP 08, 106 (2016)

SYK (all to all and q-local): C grows exponentially:

And saturates the bound at low temperature!

A quick recap

Symmetry of the action: Reparameterization and U(1)

$$
\begin{aligned}
\tau &= f(\sigma) \\
G(\tau_1,\tau_2) &= [f'(\sigma_1)f'(\sigma_2)]^{-1/q}\frac{g(\sigma_1)}{g(\sigma_2)}\widetilde{G}(\sigma_1,\sigma_2) \\
\Sigma(\tau_1,\tau_2) &= [f'(\sigma_1)f'(\sigma_2)]^{1-1/q}\frac{g(\sigma_1)}{g(\sigma_2)}\widetilde{\Sigma}(\sigma_1,\sigma_2)
\end{aligned}
$$

Conformal Green's function:

$$G(\sigma) \sim e^{-2\pi\mathcal{E}\sigma/\beta}\left[\frac{\pi}{\beta\sin\left(\frac{\pi\sigma}{\beta}\right)}\right]^{2\Delta}$$

Residue symmetry of conformal solutions PSL(2,R) semiproduce U(1):

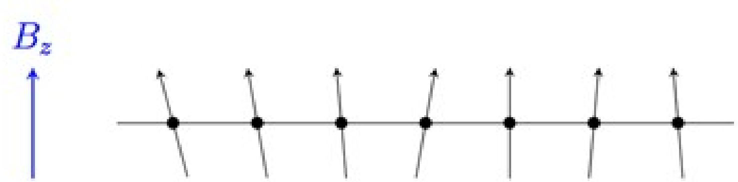
$$G(\tau_1,\tau_2) = [f'(\tau_1)f'(\tau_2)]^{\Delta}\,G_c(f(\tau_1),f(\tau_2))e^{i\phi(\tau_1)-i\phi(\tau_2)}$$

$$\frac{1}{\pi T}\tan(\pi T f(\tau)) = \frac{a\tan(\pi T\tau)+b\pi T}{c\tan(\pi T\tau)+d\pi T}$$

$$-i\phi(\tau) = 2\pi\mathcal{E}T(\tau - f(\tau)) = -2\pi\mathcal{E}T\epsilon(\tau)$$

Infinite many goldstone mode: including UV iw term, become soft mode

Analogy with ferromagnetic chain:



Out of time ordered correlator

Treat OTOC as two point function of bilocal fields:

$$F \sim \int DGD\Sigma G(t_1, t_2)G(t_3, t_4)e^{-S_{eff}}$$

After including UV terms, the Goldstone modes become pseudo Goldstone modes and produces Schwarzian action that gives maximal chaos:

$$F_{\text{big}}(t) \sim -e^{\frac{2\pi t}{\beta}}$$

Other sub-leading modes make much smaller contribution effectively reduce the Lyapunov exponent for a bit:

$$F(t) \sim -e^{\frac{2\pi t}{\beta}(1-\delta\lambda_L)} \quad , \quad \delta\lambda_L \sim \frac{1}{\beta\mathcal{J}}$$

J. Maldacena and D. Stanford , PRB 94, 106002(2016)
A. Kitaev and S J. Suh, arXiv:1711.08467

A generalization: SUSY SYK model

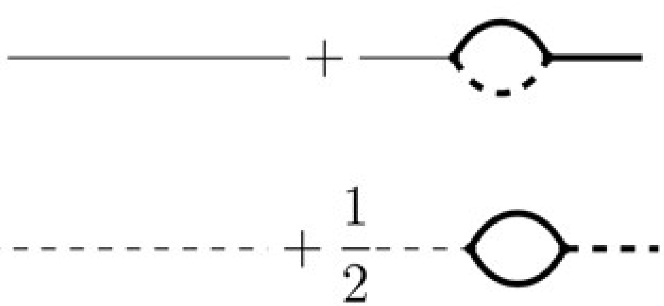
$$Q = i \sum_{1 \leqslant i<j<k \leqslant N} C_{ijk} \psi^i \psi^j \psi^k \qquad \overline{C_{ijk}} = 0 \quad , \quad \overline{C_{ijk}^2} = \frac{4J}{N^2}$$

$$\mathcal{H} = Q^2 = E_0 + \sum_{1 \leqslant i<j<k<l \leqslant N} J_{ijkl}\, \psi^i \psi^j \psi^k \psi^l \qquad J_{ijkl} = -\frac{1}{8} \sum_a C_{a[ij} C_{kl]a}$$

Interaction linearized by introducing N bosons:

$$\mathcal{L} = \sum_i \left[\frac{1}{2} \psi^i \partial_\tau \psi^i - \frac{1}{2} b^i b^i + i \sum_{1 \leqslant j<k \leqslant N} C_{ijk} b^i \psi^j \psi^k \right]$$

$G_f =$, $G_b =$ ... $+ \frac{1}{2}$



$$\Delta_f = \frac{1}{6} \quad , \quad \Delta_b = \frac{2}{3}$$

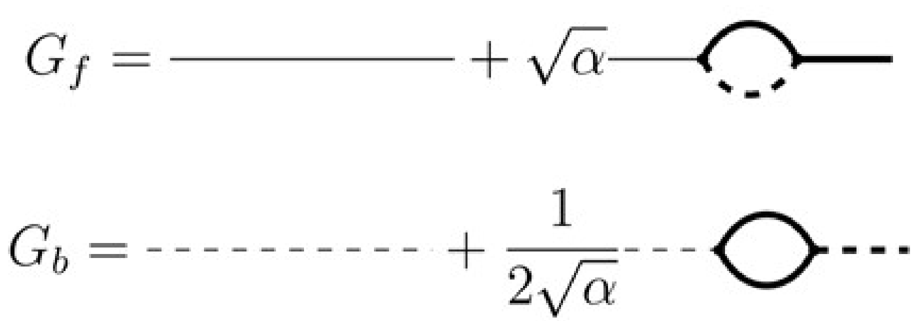
W. Fu, D. Gaiotto, J. Maldacena, and S. Sachdev, PRD 95, 026009(2017)

A further generalization:

$$H = (i)^2 \sum_{a=1}^{M} \sum_{i,j,k,l}^{N} C_{ij}^{a} C_{kl}^{a} \psi^i \psi^j \psi^k \psi^l$$

Interaction linearized by introducing M bosons:

$$\mathcal{L} = \sum_{i}^{N} \frac{1}{2} \psi^i \partial_\tau \psi^i - \sum_{a}^{M} \frac{1}{2} b^a b^a + i \sum C_{jk}^{a} b^a \psi^j \psi^k$$



$$\alpha = \frac{M}{N}$$

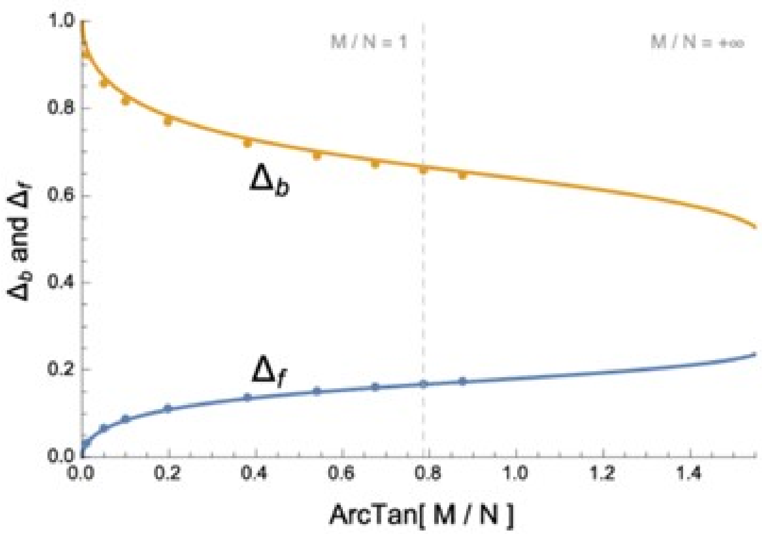
Z. Bi, C-M. Jian, Y-Z. You, K.A. Pawlak and C. Xu, PRB 95, 205105(2017)

A further generalization:

$$H = (i)^2 \sum_{a=1}^{M} \sum_{i,j,k,l}^{N} C^a_{ij} C^a_{kl} \psi^i \psi^j \psi^k \psi^l$$

Interaction linearized by introducing bosons:

$$\mathcal{L} = \sum_i^N \frac{1}{2} \psi^i \partial_\tau \psi^i - \sum_a^M \frac{1}{2} b^a b^a + i \sum C^a_{jk} b^a \psi^j \psi^k$$



$$\alpha = \frac{M}{N}$$

At small α: $\Delta_f = \frac{\sqrt{\alpha}}{\pi}$

Z. Bi, C-M. Jian, Y-Z. You, K.A. Pawlak and C. Xu, PRB 95, 205105(2017)

A further generalization:

$$H = (i)^2 \sum_{a=1}^{M} \sum_{i,j,k,l}^{N} C_{ij}^{a} C_{kl}^{a} \psi^i \psi^j \psi^k \psi^l$$

At small α, comparing with the free case, the anomalous dimension:

$$\Delta_f = \frac{\sqrt{\alpha}}{\pi} \to 0$$

What about the chaos behavior?

λ_L becomes smaller?

A further generalization:

Define OTOC:

$$\langle\langle \psi^i(t)\psi^j(0)\psi^i(t)\psi^j(0)\rangle\rangle_\beta = F(t)$$

Contribution from pseudo-Goldstone mode:

$$F_{\rm big}(t) \sim -\frac{\Delta_f^2 \beta J}{4\pi(\alpha_f^S + \alpha_b^S)} e^{\frac{2\pi t}{\beta}}$$

Contribution from sub-leading modes

$$F_{\rm sub}(t) \sim \frac{3}{2\pi k_R'(-1)} \frac{2\pi t}{\beta} e^{\frac{2\pi t}{\beta}}$$

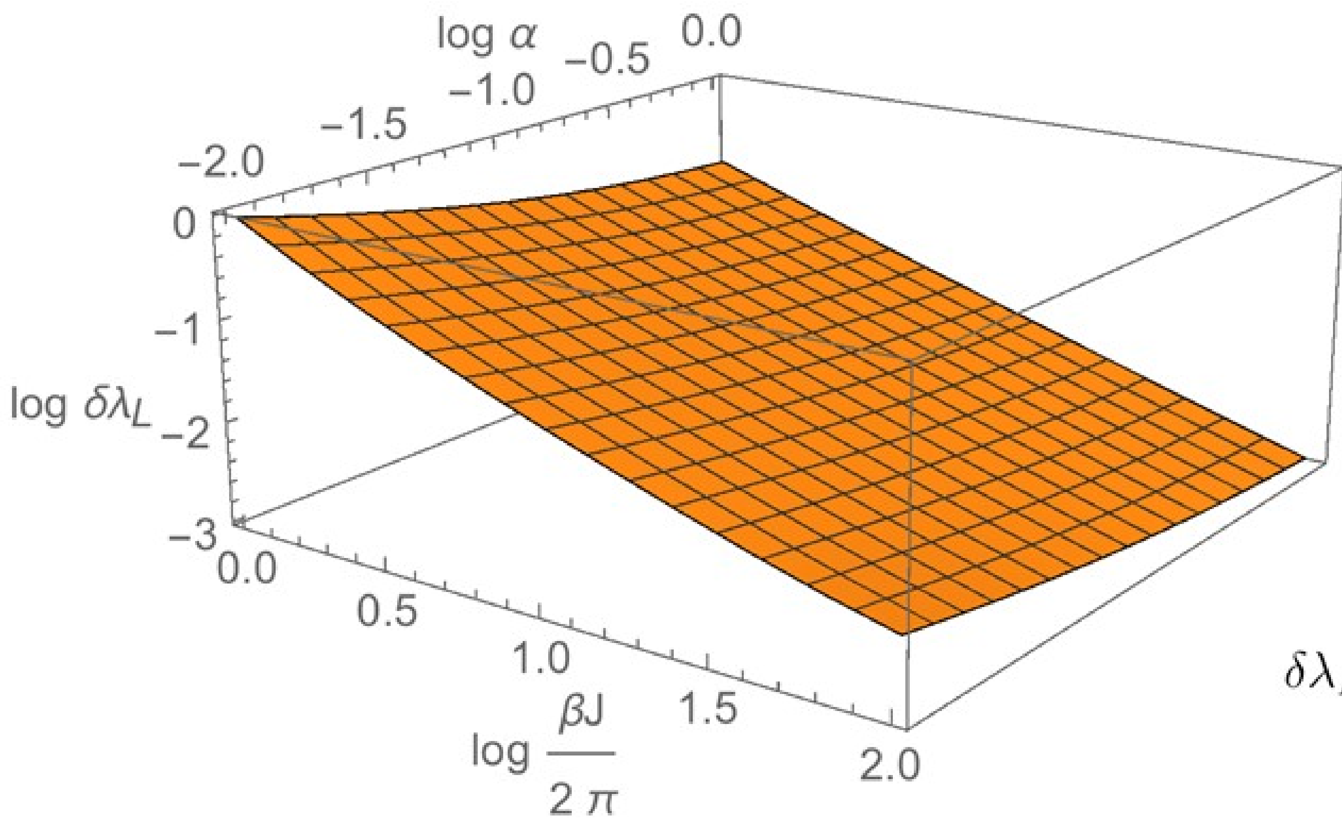
Assume the full expression $F(t) \sim -\frac{\Delta_f^2 \beta J}{4\pi(\alpha_f^S + \alpha_b^S)} e^{\frac{2\pi t}{\beta}(1-\delta\lambda_L)}$

W. Fu, C-M. Jian, Z Bi and C. Xu, in progress

A further generalization:

Define OTOC:

$$\langle\langle \psi^i(t)\psi^j(0)\psi^i(t)\psi^j(0)\rangle\rangle_\beta = F(t)$$



$$\delta\lambda_L \sim \frac{1}{\beta J \Delta_f}$$

W. Fu, C-M. Jian, Z Bi and C. Xu, in progress

Discussion

- Less chaotic towards free fermion limit
- How Lyapunov time is related to decoherence time?

$\delta\lambda_L$ ⟺ Decoherence factor ⟺ Branching time

A. Kitaev talk at IAS (2017)

- Does this have a thermal dynamical interpretation?

Quantum transition of SYK models

Fractionalize electrons:

$$c_{i\alpha} = f_{i\alpha}\,\sigma_i^z \quad \Longrightarrow \quad c_{i\alpha p} = f_{i\alpha}\phi_{ip}$$

$$\sum_{p=1}^{M} \phi_{ip}^2 = M\,.$$

Fractionalized particles carry Z2 charge

$$\mathcal{L} \;=\; \frac{1}{2g}\sum_{i,p}(\partial_\tau \phi_{ip})^2 + \sum_{i,\alpha} f_{i\alpha}^\dagger \left(\frac{\partial}{\partial\tau} - \mu\right) f_{i\alpha} + \frac{1}{\sqrt{NM}}\sum_{i,j,p,\alpha} t_{ij}\phi_{ip}\phi_{jp} f_{i\alpha}^\dagger f_{j\alpha} + \frac{1}{\sqrt{NM}}\sum_{i>j,\alpha\beta} J_{ij} f_{i\alpha}^\dagger f_{i\beta} f_{j\beta}^\dagger f_{j\alpha}\,.$$

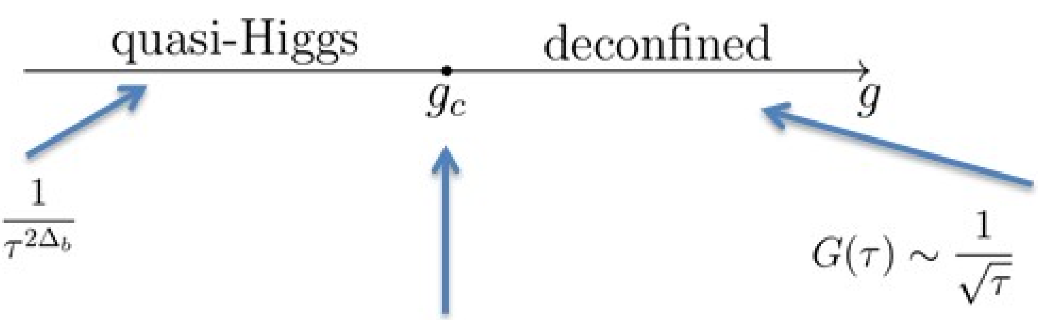
Quantum transition of SYK models

SYK type Schwinger-Dyson equations:

$$G(\omega_n) = \frac{1}{i\omega_n + \mu - \Sigma(\omega_n)} \quad , \quad \Sigma(\tau) = -J^2 G^2(\tau) G(-\tau) + \alpha \widetilde{t}^2 G(\tau) \chi^2(\tau)$$

$$\chi(\omega_n) = \frac{1}{\omega_n^2 + \Delta_0^2 - P(\omega_n)} \quad , \quad P(\tau) = -2\widetilde{t}^2 G(\tau) G(-\tau) \chi(\tau)$$

$$\frac{1}{\beta} \sum_{\omega_n} \chi(\omega_n) = \frac{1}{g}$$



$$G(\tau) \sim \frac{1}{\tau^{2\Delta_f}} \quad , \quad \chi(\tau) \sim \frac{1}{\tau^{2\Delta_b}}$$

$$G(\tau) \sim \frac{1}{\sqrt{\tau}} \quad , \quad \chi(\tau) \sim \frac{e^{-\Delta\tau}}{\sqrt{\tau}}$$

$$G(\tau) \sim \frac{1}{\sqrt{\tau}} \quad , \quad \chi(\tau) \sim \frac{1}{\sqrt{\tau}}$$

Summary

- SYK models are matter without quasiparticle, it can reproduces strange metal properties and also has a close relation to gravity
  - Extensive 0T entropy
  - Chaotic behavior
  - Quantum transitions
- Other generalizations
  - Lattice model: transport properties
  - Witten-Gurau models

Outlook

- Relate chaos with decoherence
- Entanglement and information dynamics
- Time dependent SYK models

- My other interest: TQFT, duality…

Thank you!