領域３，１，８，11共催

学術変革A 「極限宇宙」共催

Grant-in-Aid for Transformative Research Areas A

Extreme Universe

量子多体系におけるダイナミクス研究の進展
～極限宇宙の物理法則を探る

Dynamics in quantum many-body systems

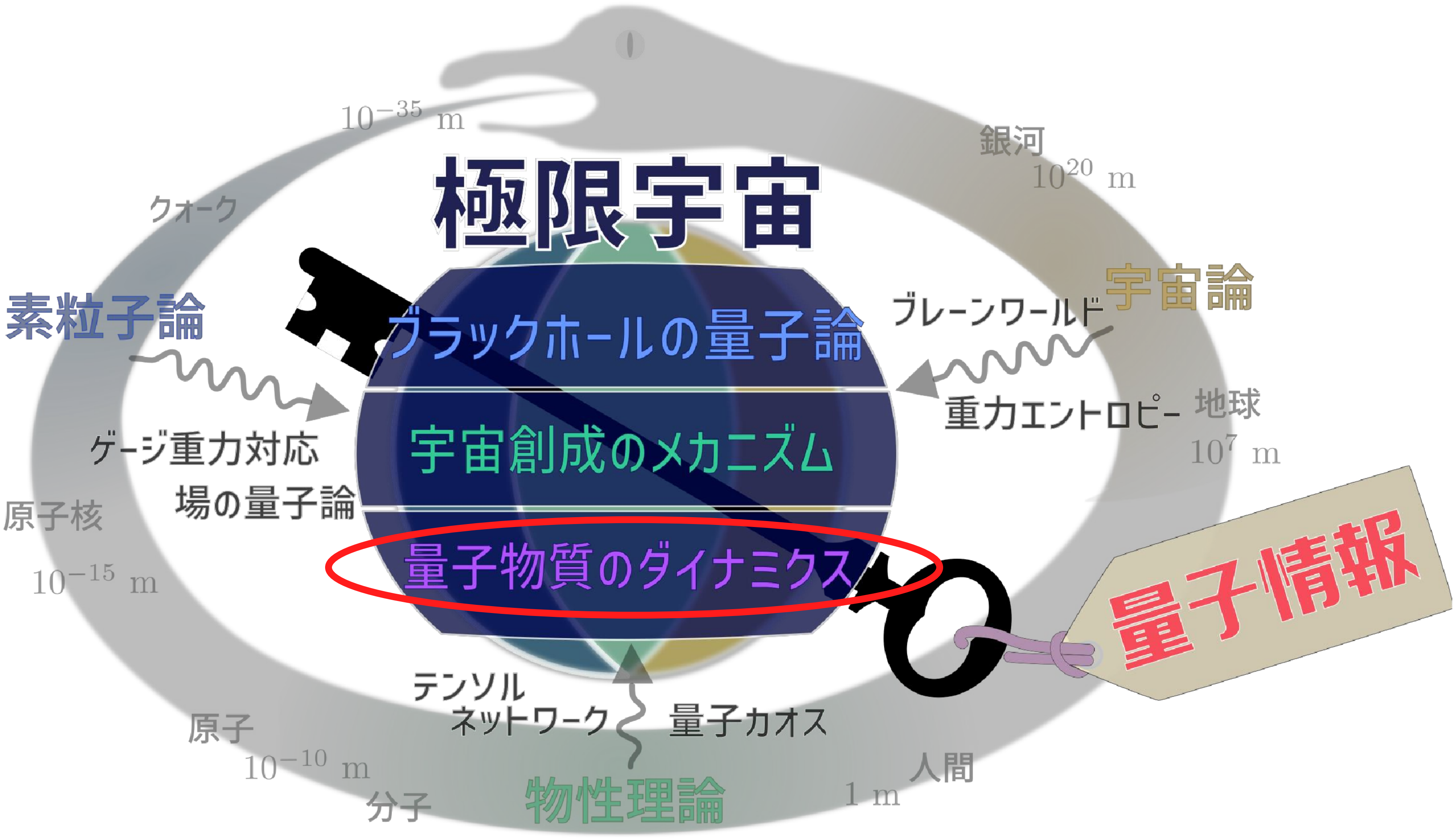
はじめに(趣旨説明)

東大総合文化　堀田知佐

謝辞：手塚真樹（京大）
山本大輔（日大）

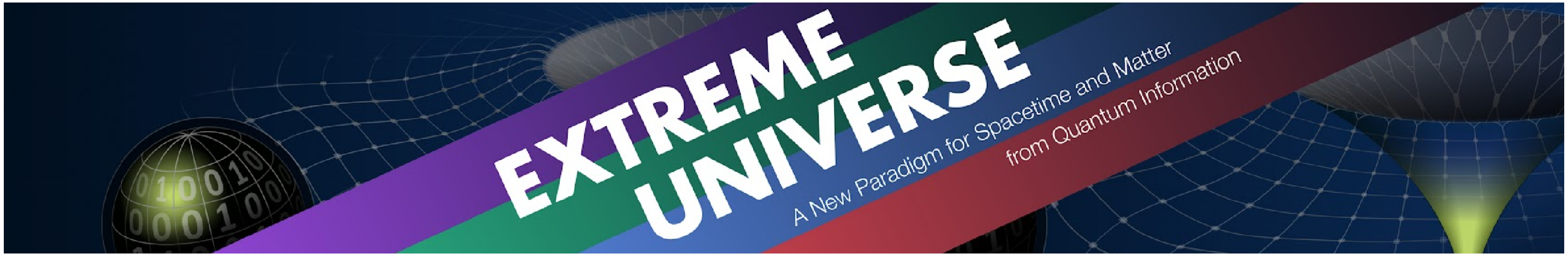
学術変革領域研究A「極限宇宙(Extreme Universe)」

https://www2.yukawa.kyoto-u.ac.jp/~extremeuniverse/



素粒子、宇宙論、物性論の基礎的な問題を量子情報の様々な考え方、ツールを用いて解き明かせるか？

YouTube　Extreme Universe　作成



極限宇宙の物理法則を創る --Extreme Universe Collaboration--

@extremeuniverse4346　78 本の動画

文部科学省科学研究費補助金　学術変革領域研究（A）「極限宇宙の物理法則を創る－量子情報で拓く時空と物 ...さらに表示

知的資産の蓄積

物性（量子系の計算、ダイナミクス、その他）、宇宙論、素粒子論が順番に定期的にオンライン（英語）でセミナー講演を実施．研究の最前線の話題、チュートリアルなどもあり

- **領域コロキウム （国内外 各分野の専門家がオンライン講演）**
- **circular meeting 月1回程度： C02, D02班は物性、統計に沿った内容**
- **市民講演会（一般向け）：日本語**
- **スクール**

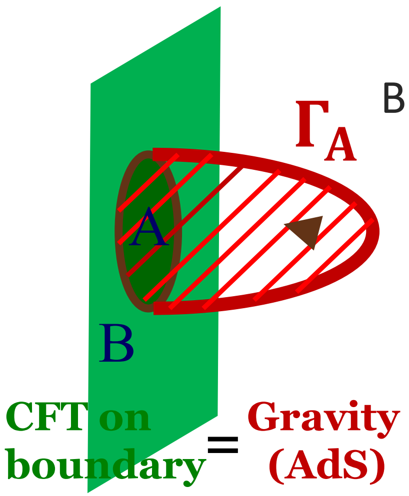
領域のWEBページからお知らせがくるよう登録できます！

素粒子宇宙論:

量子重力理論の構築

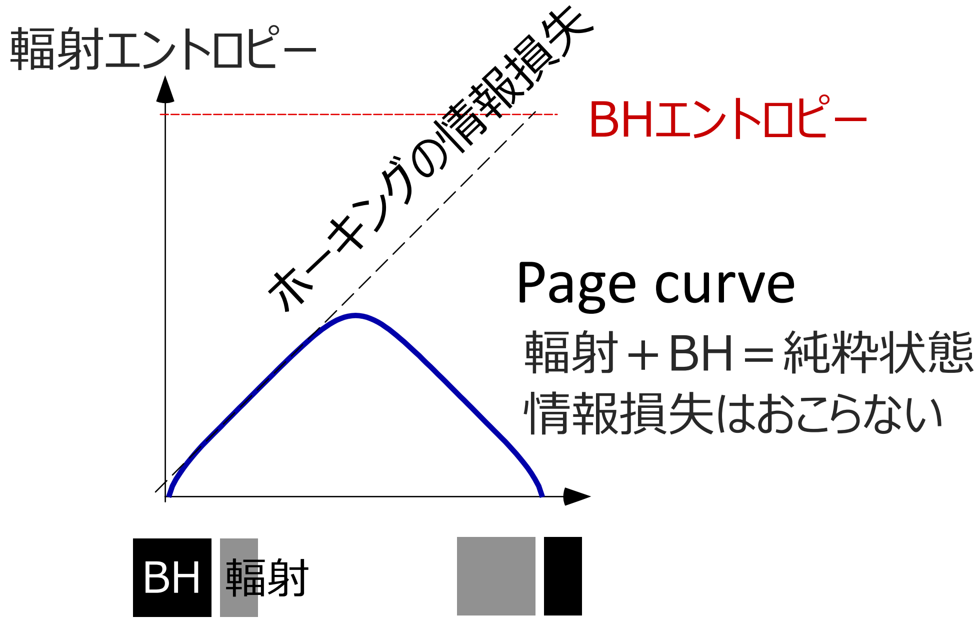
BH 情報損失問題

dS(正の宇宙定数）に対応するCFTは?



Black hole のエントロピー：Area law

$$S_A = \min_{\Gamma_A} \left[\frac{\mathrm{Area}(\Gamma_A)}{4G_N} \right]$$



量子エンタングルメントを使って
量子系の物理をどう理解するか？

量子多体物性論

量子多体系の基底状態

Area law entanglement

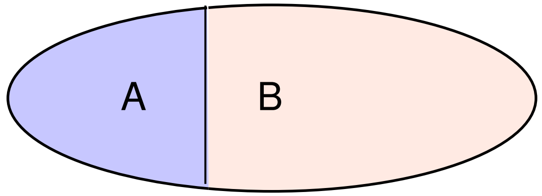
熱的純粋状態とGibbs状態

Quantum entanglement

Quantum state

Schmidt decomposition

$$|\Psi\rangle = \sum_m \sum_n \Psi_{mn} |\psi_m^A\rangle |\psi_n^B\rangle = \sum_i \lambda_i |\alpha_i\rangle |\beta_i\rangle$$

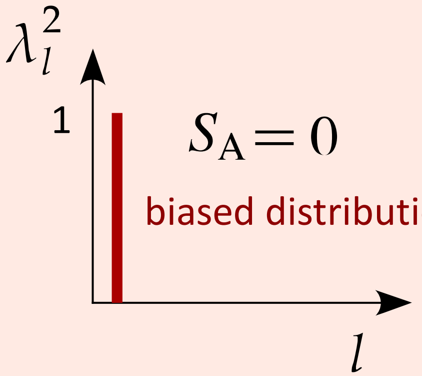


Aの状態空間 x Bの状態空間

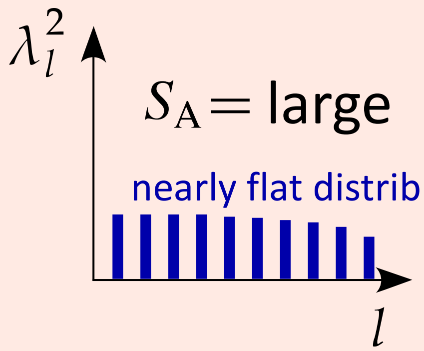
多：多の組み合わせ

１：１の組み合わせ

Entanglement entropy $$S_A = -\sum_l \lambda_l^2 \ln \lambda_l^2$$



classical product state:
no entanglement



large entanglement

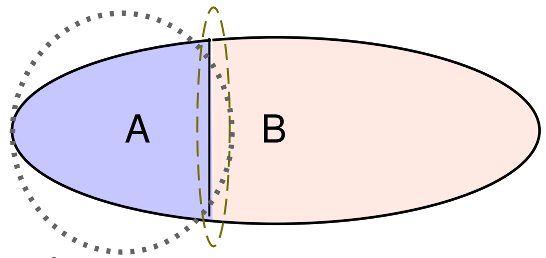
For larger S_A, it is far more difficult to describe the quantum state.

Quantum entanglement

Quantum state

$$|\Psi\rangle = \sum_m \sum_n \Psi_{mn} |\psi_m^{\mathrm{A}}\rangle |\psi_n^{\mathrm{B}}\rangle = \sum_i \lambda_i |\alpha_i\rangle |\beta_i\rangle$$

Schmidt decomposition



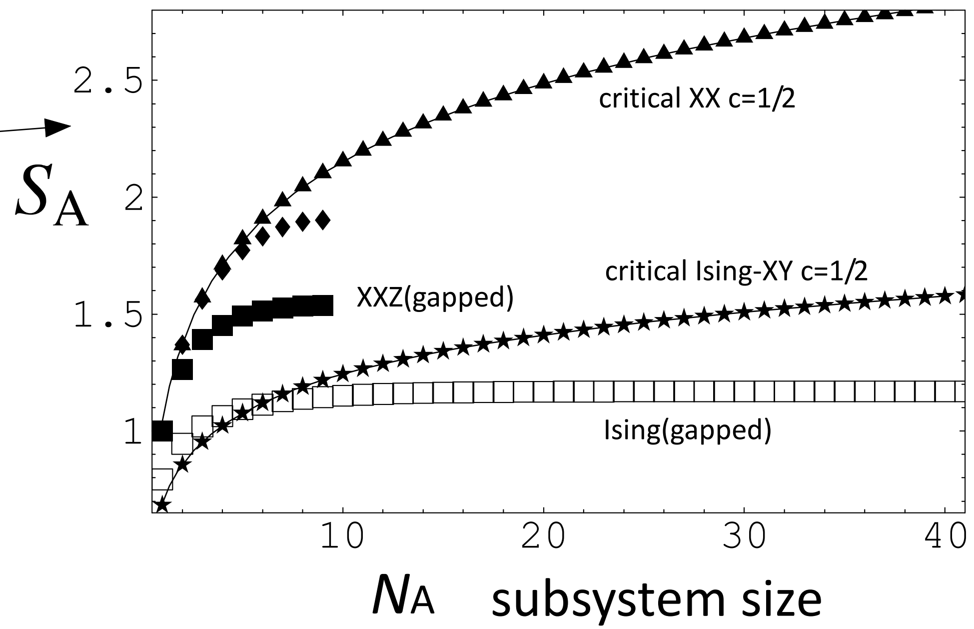
Entanglement entropy $$S_{\mathrm{A}} = -\sum_l \lambda_l^2 \ln \lambda_l^2$$

Area law:

$S_{\mathrm{A}} \propto$ (Area of a bipartition)

ground state of 1D systems

Calabrese, Cardy J. Stat. Mech. 06002 (2004)



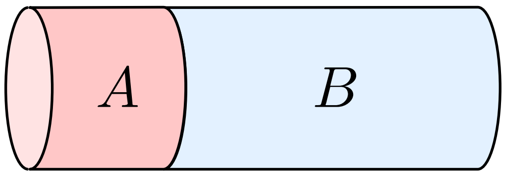
Volume law:

$S_{\mathrm{A}} \propto$ (Volume of A)

excited states, thermal states

At finite *T*,

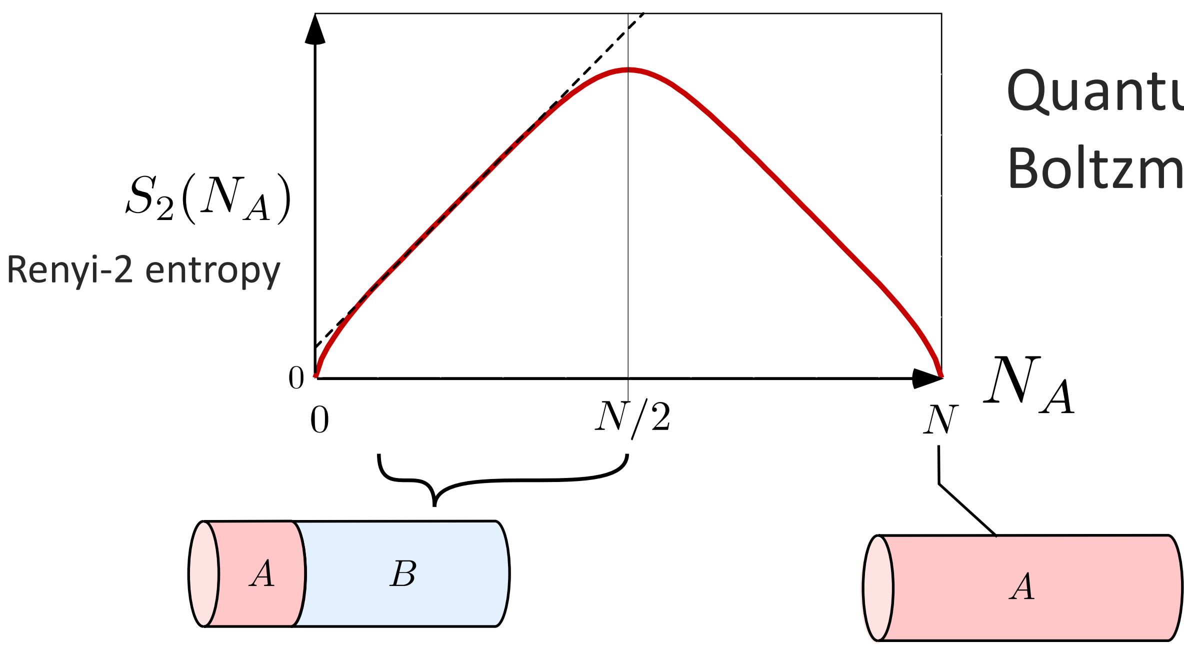
entanglement entropy ~ thermal entropy



$$\langle \Psi_{AB} | O_A | \Psi_{AB} \rangle = \sum_{\alpha=1}^{\chi} \lambda_\alpha^2 \langle \alpha | O_A | \alpha \rangle_A$$

$$\lambda_\alpha^2 = \frac{e^{-\beta E_\alpha}}{Z_A(\beta)}$$

volume law



Quantum contribution from B converted to Boltzmann weight (classical contribution).

$$S_A(N_A) = S_{\mathrm{th}} = N s_{\mathrm{th}}$$

岩木、堀田　「熱的量子状態をどう理解するか？」　固体物理 解説（年内に出る?!）

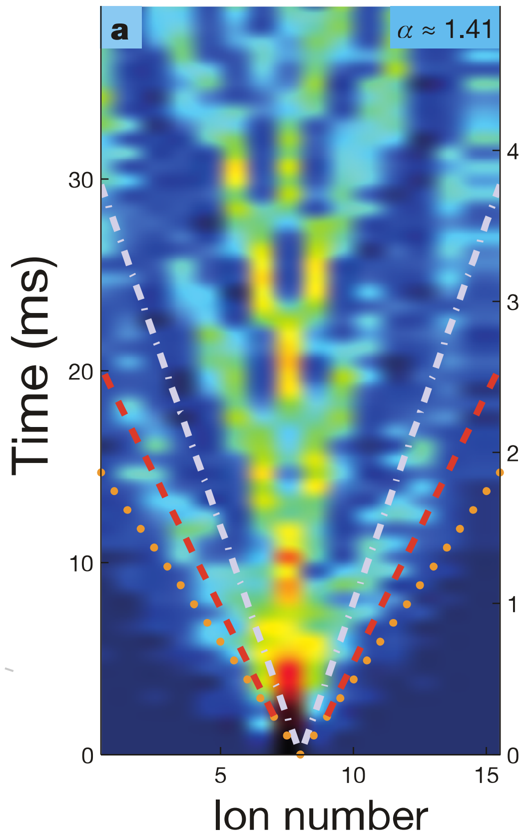
Why is quantum dynamics difficult to treat?

How fast does the correlation spread? It is rather local.

Lieb-Robinson bound (1972)

$$\| [A, B(t)] \| \leq c\, e^{-d_{AB} - v|t|}$$

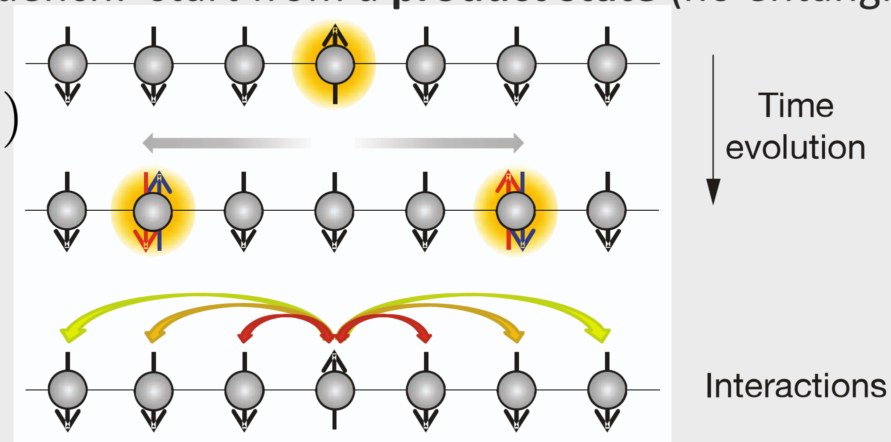
$^{40}Ca^{+}$



P. Jurcevic, et.al. Nature 511, 202 (2014)

Quench: start from a **product state** (no entanglement)

(1)



For these simplest cases:

Area law of entanglement entropy (dynamical)

but ... grow very fast in time.

$$S_A \leq c_0 + c_1 |t|$$

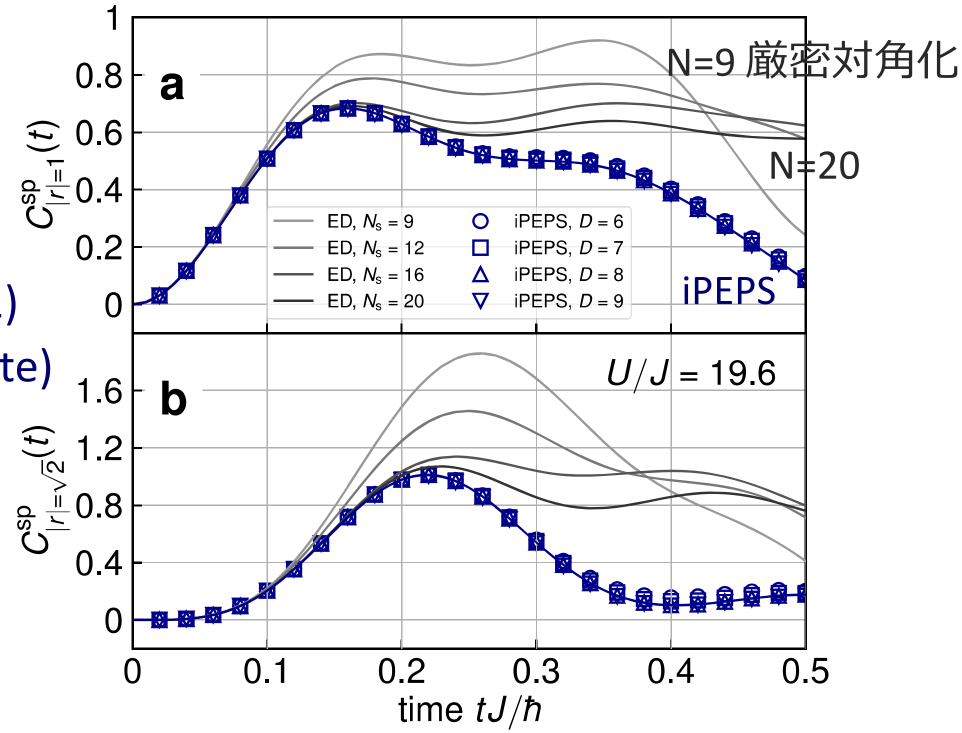
Eisert & Osborne PRL (2006)

$$c_1 \propto |t|$$

More complicated case: quantum scrambling

Why is quantum dynamics difficult to treat?

Approximations cannot follow the growth of entanglement.

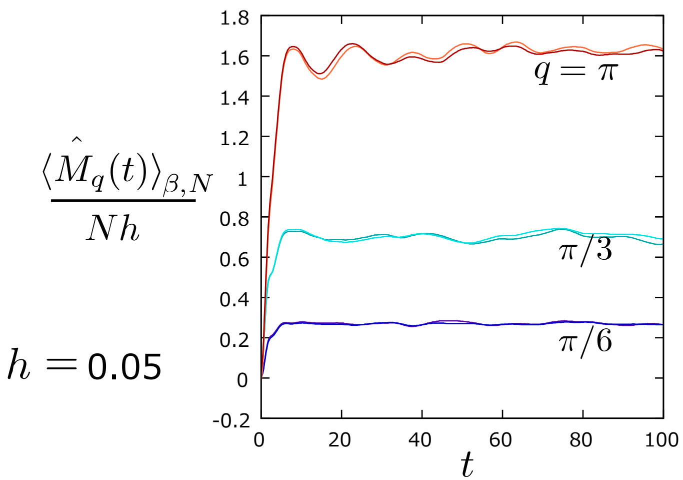


Kaneko, Danshita, Comm.Phys.(2022)

2D bose Hubbard by iPEPS (N=infinite)

We are living in a finite temperature world.

Most of the states will thermalize toward the "volume-law" state in the end.

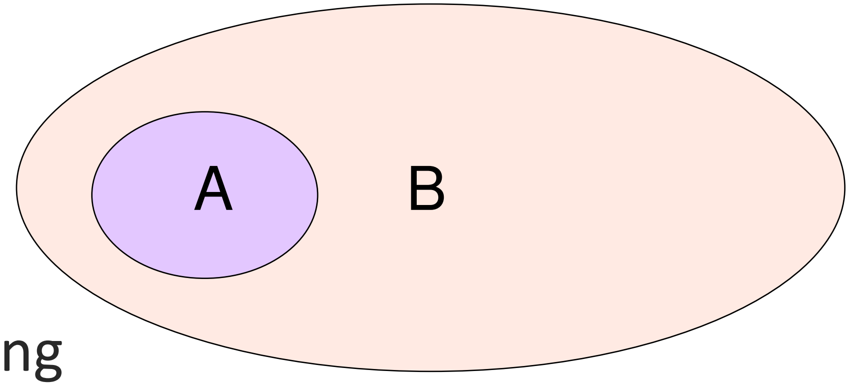


Linear response in 2D kagome spin 1/2 Heisenberg model N=27.

We can almost exactly track finite *T* finite-time evolution.

Endo, Hotta, Shimizu PRL(2018)

Questions in dynamics



- How does the information spread ?

(2) Motome: Quantum reservoir probing

- When/how the system thermalizes ?

(3) Mori : Timescale of thermalization

- How to properly calculate quantum dynamics ?

(4) Harada : Quantum Glauber dynamics

(5) Kaneko : Long-time dynamics by mode coupling

- Observing particular features in dynamics

(6) Tamura : Bose gas in optical box

- Recovering information of quantum states (entanglement)

(7,8) Yamamoto & Ozawa : Tomography