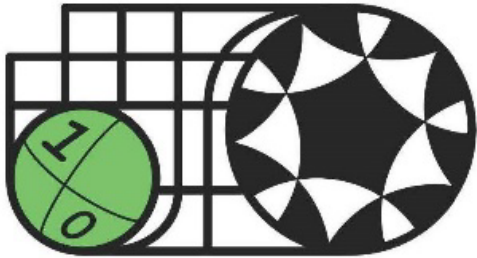


Research Highlights in ExU Collaborations

Tadashi Takayanagi (Head Investigator)
Yukawa Institute for Theoretical Physics, Kyoto University



Grant-in-Aid for Transformative Research Areas A

Extreme Universe

MEXT -KAKENHI- Grant-in-Aid for Transformative
Research Areas (A)

“The Natural Laws of Extreme Universe--
A New Paradigm for Spacetime and Matter from Quantum
Information”



科研費
KAKENHI



Our Target: Three problems of Extreme Universe

① Limit of Space

[Quantum Black hole (B)]

If a black hole evaporates, does the information inside disappear?

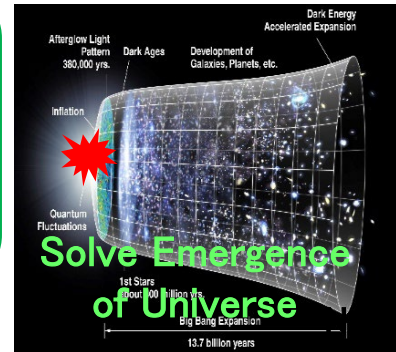


Quantum Gravity

② Limit of Time

[Quantum Cosmology (C)]

What is the ultimate law that explains the creation of the universe?

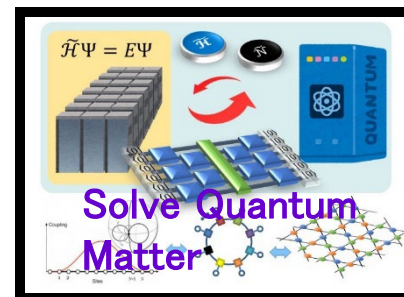


Holography

③ Limit of Matter

[Dynamics of Quantum Matter (D)]

How can the dynamics of quantum matter be solved efficiently?



Quantum Communication

Quantum Error Correction

Solve these Problems in the light of quantum information

Quantum Entanglement

Computational Complexity

Quantum Computing

Quantum Chaos

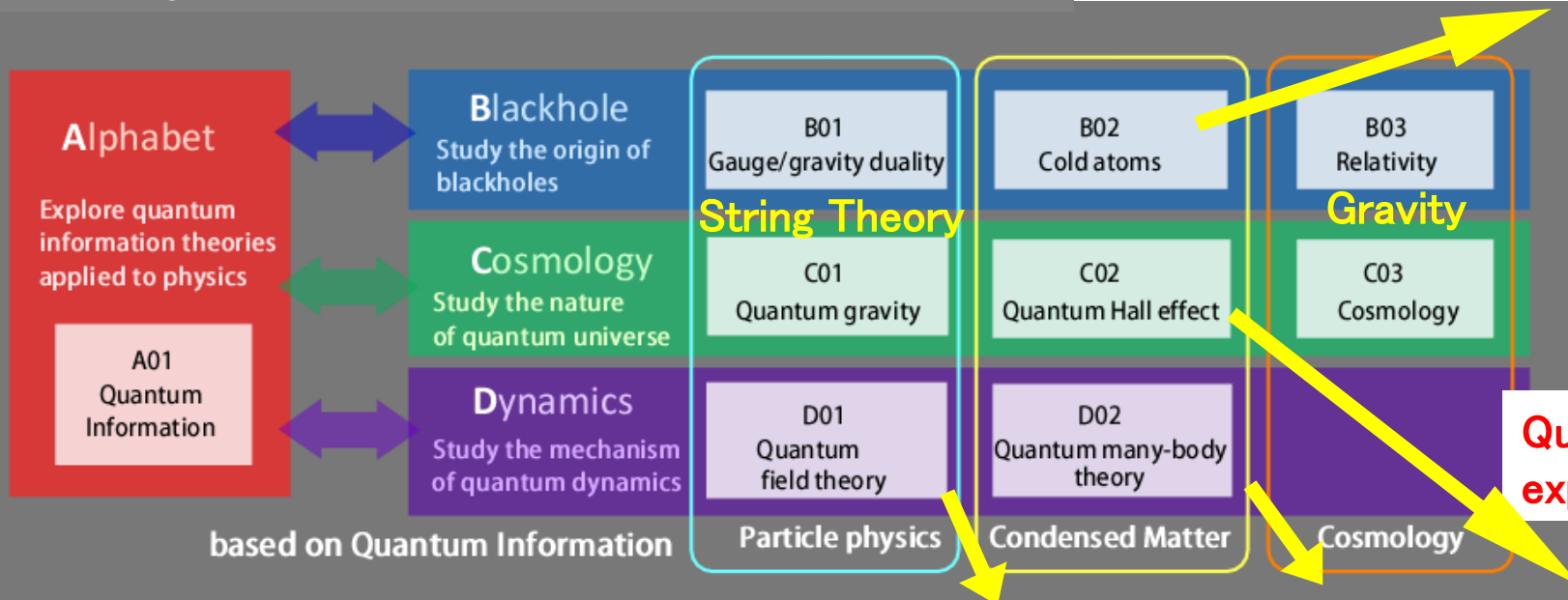
Research Organization of ExU Collaboration

PIs+Cols
+collaborators
≈200 researchers

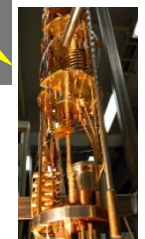
Planned Research

[Totally 42 members = 9 PIs + 33 CoIs,]

Cold atom
experiment

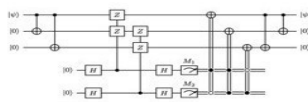


Quantum Hall
experiment



Publicly Offered Research
E01 (Quantum Information)
E02, E03 (Physics)
[Totally 22 members]

Quantum
Computer

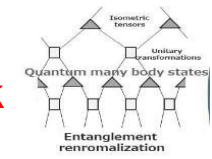


Quantum computation

Super
Computer



Tensor
Network



Entanglement renormalization



Grant-in-Aid for Transformative Research Areas (A)

Extreme Universe

A01group Research Highlight

Tomoyuki Morimae

collaborators:

Yoshifumi Nakata YITP

Koji Azuma NTT

Francesco Buscemi Nagoya University

Ryu Hayakawa YITP

Goal

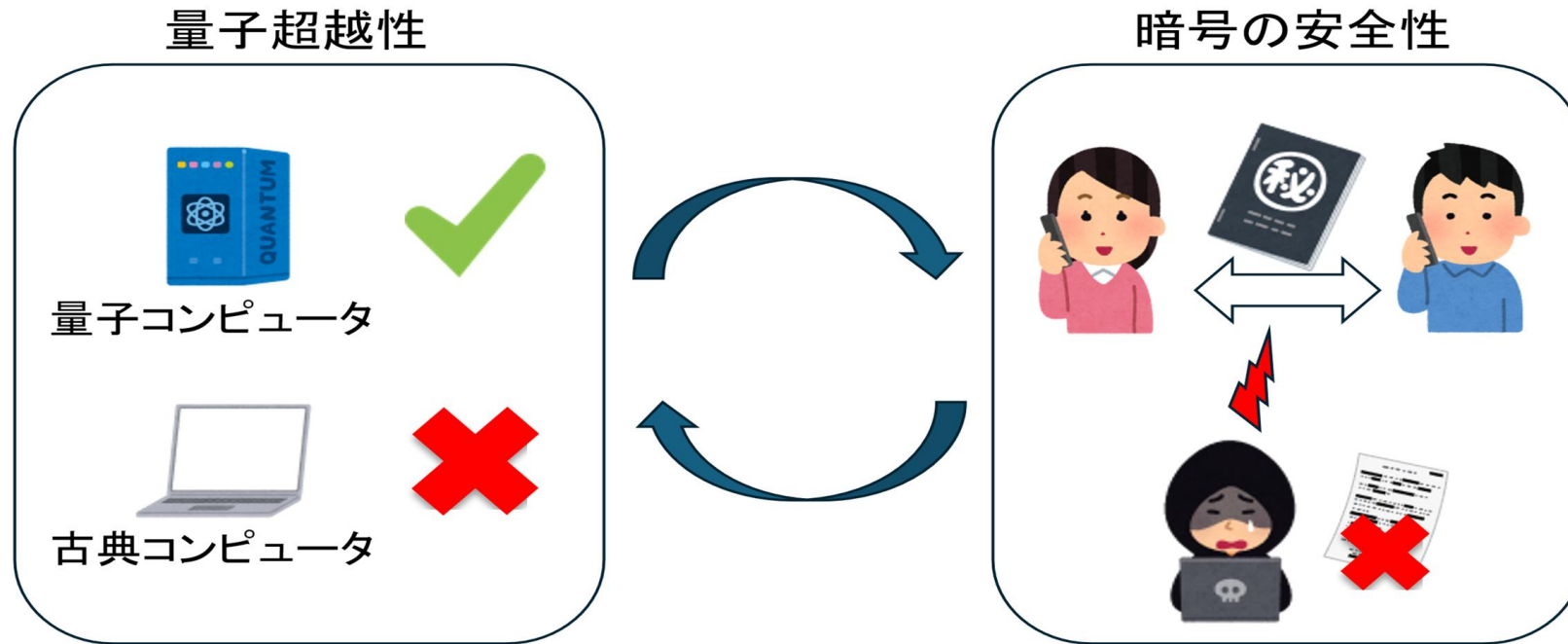
Quantum Information for Extreme Universe

Plan and summary

Study quantum information as a language to understand extreme universe

- (1) Quantum cryptography without one-way functions [Crypto]
- (2) Equivalence between quantum advantage and quantum cryptography [STOC]
- (3) Derivation of a consistent rule for quantum inference from the principle of minimum change [PRL, selected as one of the 2025 Breakthroughs of the Year by the National University of Singapore]
- (4) Quantum advantage of topological data analysis
- (5) Complexity and quantum advantage of estimating Berry phase
- (6) Advancing the understanding of the black hole information problem through quantum information theory [Invited talks at many interdisciplinary conferences]

Equivalence between quantum advantage and quantum crypto



Morimae, Yamakawa,
and Shirakawa,
STOC2025

Theoretical importance of showing two different concepts

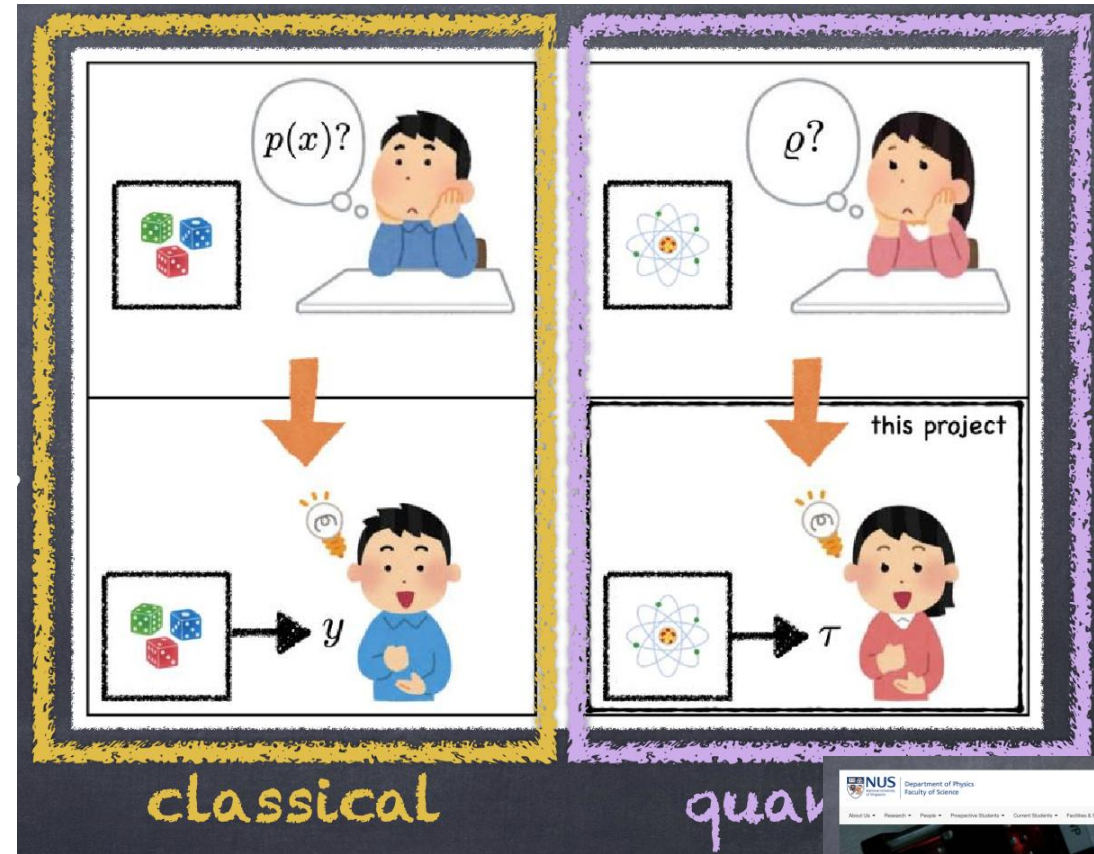
Important consequence: if there is no quantum advantage, then there is no crypto

Rule for Bayesian quantum inference

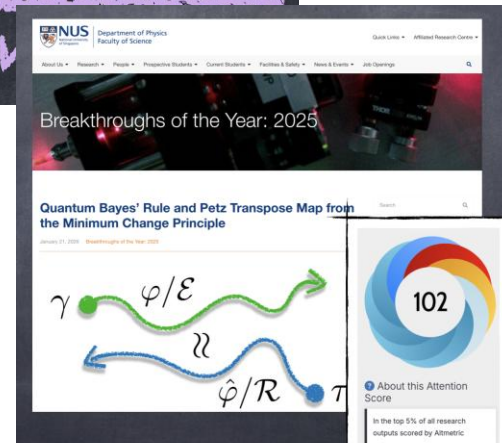
A reformulation of quantum inference as a learning principle that unifies otherwise disparate theories

Key conclusion: even in the quantum world, there exists a universal principle of rational belief updating (serving as a foundation for future quantum technologies, AI, and scientific reasoning!)

We derive a quantum version of a learning rule corresponding to Bayes' rule, and show that consistent inference remains possible even in the presence of measurement disturbance and non-commutativity



Bai, Buscemi, Scarani;
Physical Review
Letters 2025



Quantum advantage of TDA



Analysis of higher topology



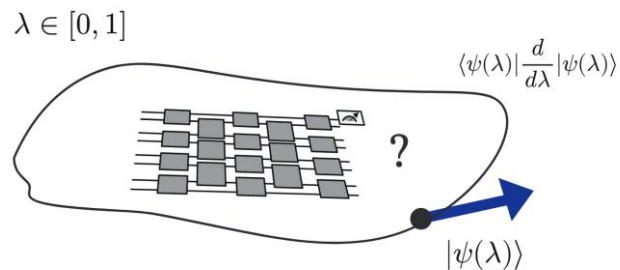
TDA: Promising application of quantum computing

Proof of quantum advantage in TDA based on complexity theory

C. Gyurik, A. Schmidhuber, R. King, V. Dunjko, and R. Hayakawa
arXiv:2410.21258, Highlighted talk in QTML2025



Estimation of Berry phase



Berry phase : characterizing topological matter

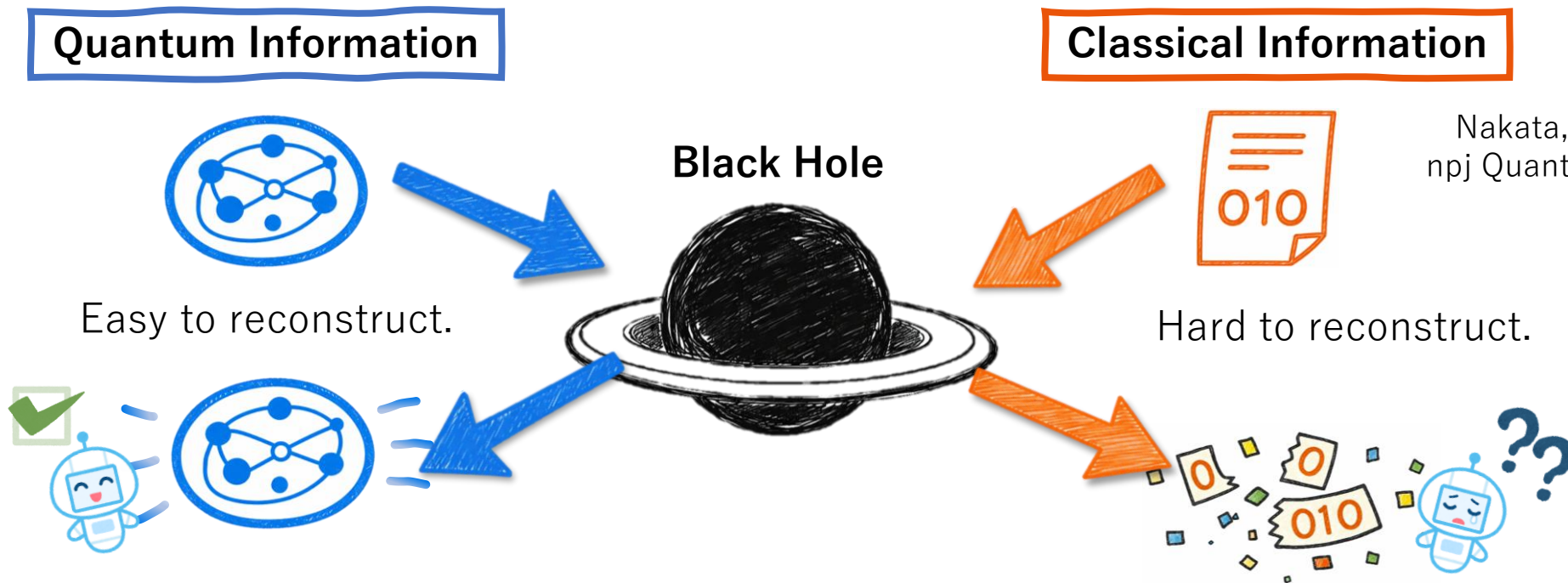
Proof of quantum advantage in estimating Berry phase

R. Hayakawa, K. Sakamoto, and C. Kiumi, arXiv:2509.13423

Black hole information problem: Quantum vs Classical

Is it possible to reconstruct quantum information inside a black hole from Hawking radiation?
What about classical information?

→ Quantum information is scrambled in a way that allows for its recovery, whereas classical information becomes over-scrambled and is difficult to recover.



Nakata, Matsuura, Koashi,
npj Quantum Information 2025

In addition, if the black holes conserves, e.g., energy, the reconstruction is delayed.

Nakata, Wakakuwa, Koashi, Quantum 2023



Grant-in-Aid for Transformative Research Areas (A)

Extreme Universe

B01 Research Highlights

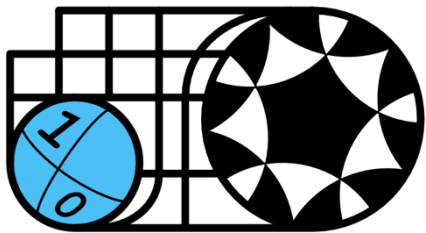
PI: Norihiro Iizuka (NTHU/YITP)

CoIs: Toshifumi Noumi (Tokyo U. Komaba)

Masaki Shigemori (Nagoya U.)

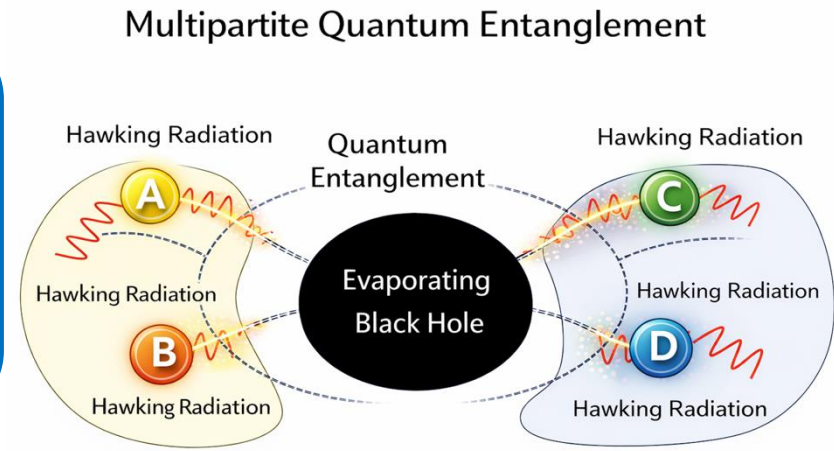
Seiji Terashima (YITP Kyoto U.)

Tomonori Ugajin (Rikkyo U.)



Research Goal

To understand the black hole interior and the information problem using quantum information and gauge/gravity duality



Research Plans and Achievements

We developed new perspectives based on quantum information, multipartite entanglement, and gauge/gravity duality

[1] Research Result 1: Constructed a measure of genuine multipartite entanglement for arbitrary q -party system

→ In black hole evaporation, bipartite entanglement alone is not sufficient

→ Multipartite entanglement is localized near the junction

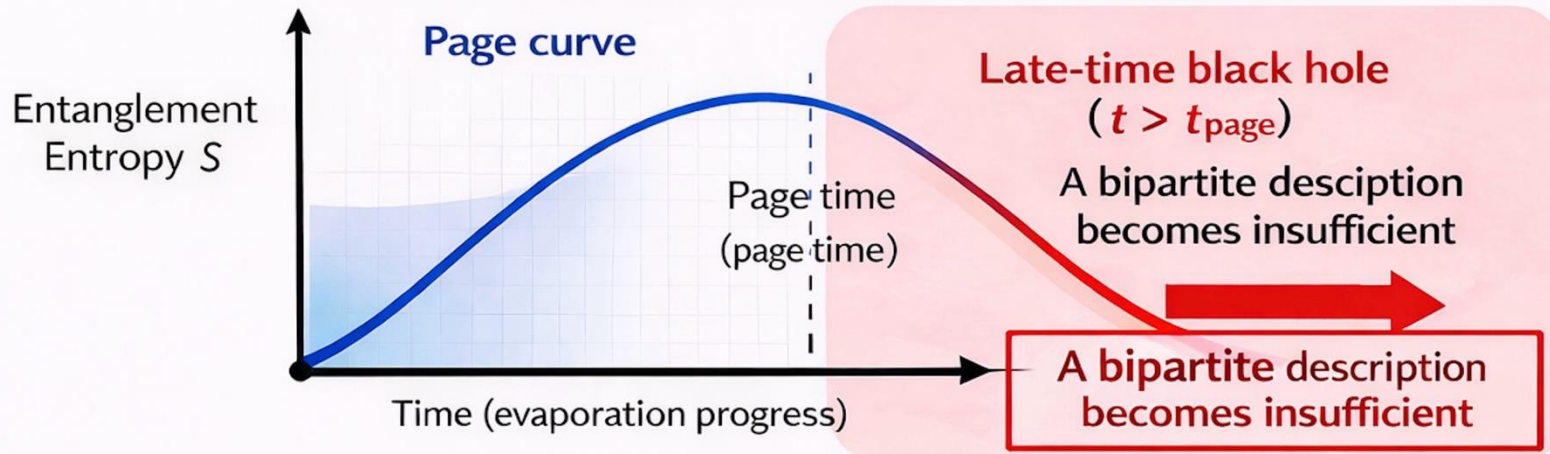
[2] Research Result 2: Multifaceted approaches to black holes

→ Scrambling, information recovery, exact solutions, and symmetry

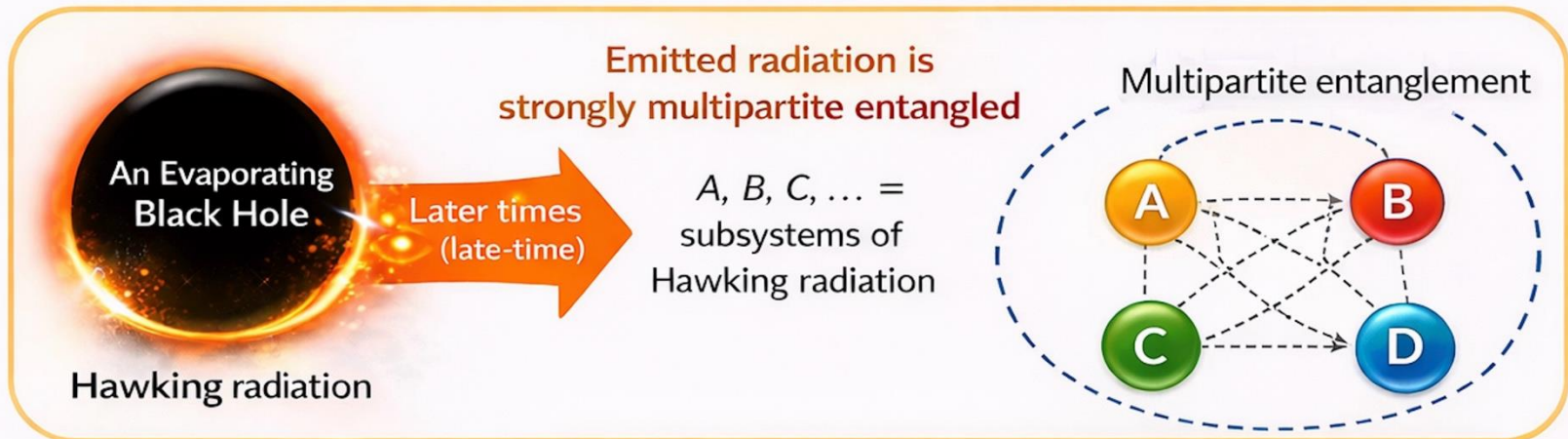
Research Result 1: Construction of Genuine Multi-Entropy

- Constructed a measure of genuinely multipartite entanglement for an arbitrary q -partite system
- Clarified when and where multipartite effects become important in black hole evaporation and gauge/gravity duality
- **Important consequence: In black hole evaporation and gauge/gravity duality, there are regimes where bipartite entanglement alone is insufficient**

Multipartite entanglement effects cannot be ignored in late-time black holes



arXiv:2502.07995, Phys. Rev. D 112, 026011 (2025)



After a black hole evaporates a lot, multipartite entanglement becomes essential.

Research Result 2: Multifaceted Approaches to Black Holes

- **Toshifumi Noumi:** Analyzed the Page curve in black hole evaporation incorporating the effects of symmetry
[arXiv:2206.09633] JHEP 10 (2022) 015
- **Masaki Shigemori:** Constructed new exact solutions for microscopic spacetimes toward clarifying the microstates of black holes in string theory
[arXiv:2212.13388] JHEP 02 (2023) 099

Research Result 2: Multifaceted Approaches to Black Holes

- **Seiji Terashima:** Analyzed boundary dynamics in the AdS/BCFT correspondence and clarified the consistency conditions

[arXiv:2205.10600] JHEP 09 (2022) 103

- **Tomonori Ugajin:** Showed that in scrambled quantum systems, the information recovery map becomes drastically simplified

[arXiv:2310.18991] PTEP 2023 (2023) 123B04



Grant-in-Aid for Transformative Research Areas (A)

Extreme Universe

B02 Research Highlights

PI: Masaki Tezuka (Kyoto)

CoIs: Shuta Nakajima (Osaka)

Eriko Kaminishi (Keio)

Takashi Mori (Keio)

Daisuke Yamamoto (Nihon)

Research Goal

Using cold atoms as highly controllable artificial quantum matter, understand their nonequilibrium dynamics experimentally → Approach the essence of black holes from study of many-body quantum systems without gravity via gauge-gravity correspondence

Understand (I) effects of dissipation and (II) scrambling in quantum many-body systems

Research Plans and Achievements

Construction of cold lithium atom systems in optical lattices & Theory

- (I) Towards observation of measurement-induced quantum phase transition, develop quantum state tomography and theory of open quantum many-body systems
- (II) Hamiltonian engineering towards measuring out-of-time ordered correlators; spin chain/2+1-d gravity correspondence (with B03); simplified SYK-like models; quantitative evaluation of scrambling (with A01)

Theoretical Result I. Quantum state tomography

“Measuring Entanglement Without Local Addressing in Quantum Many-Body Simulators via Spiral Quantum State Tomography”

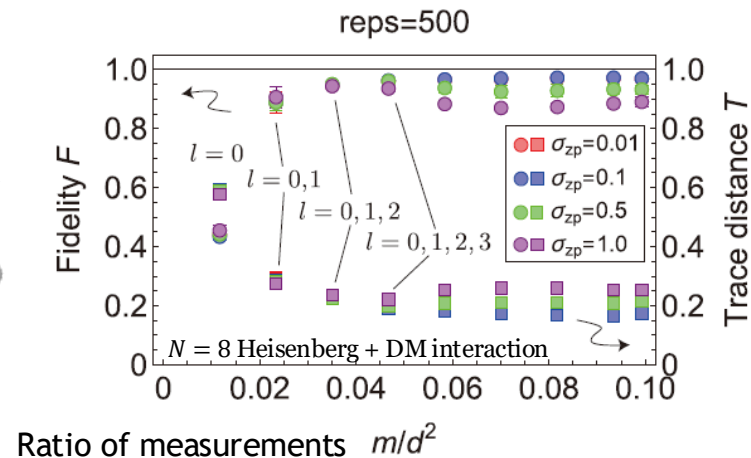
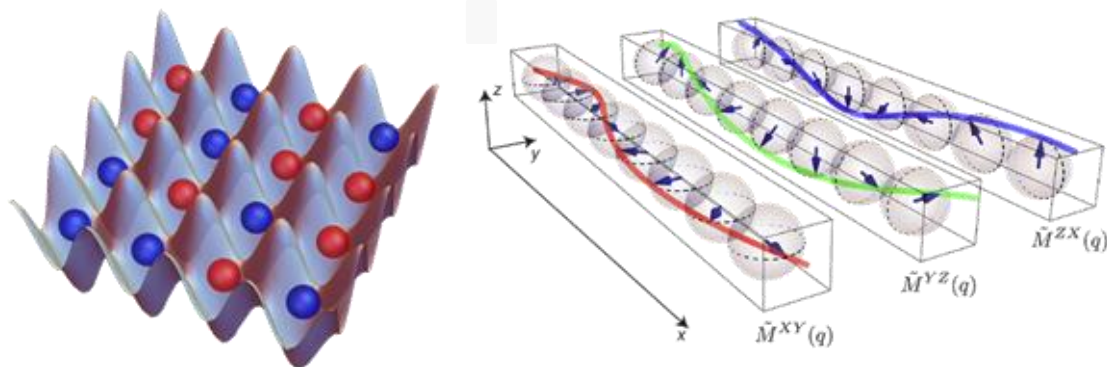
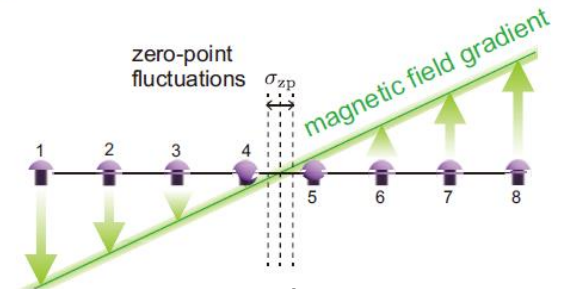
Giacomo Marmorini (B02 ExU-PD), Takeshi Fukuhara (RIKEN & Waseda; ExU School lecturer), and Daisuke Yamamoto (B02 Co-I)
PRX Quantum **7**, 010355 (18 Mar 2026) (arXiv:2411.16603)

Quantum-gas microscope (QGM) in optical lattices: single-site measurement of particle occupancy

Spin- $1/2$ system: QGM after blowing away a spin component \rightarrow n -point correlation by multiple shots

\Leftrightarrow $d(=2^N)$ -dimensional density matrix requires $\sim 4^N$ values with nontrivial quantization axis alignments!

- Measure after spiral quantization axis rotation
 - Field gradient + global pulse
- Complement by compressed sensing (assume low rank)
- Direct recovery of reduced density matrix (\rightarrow entanglement entropy)

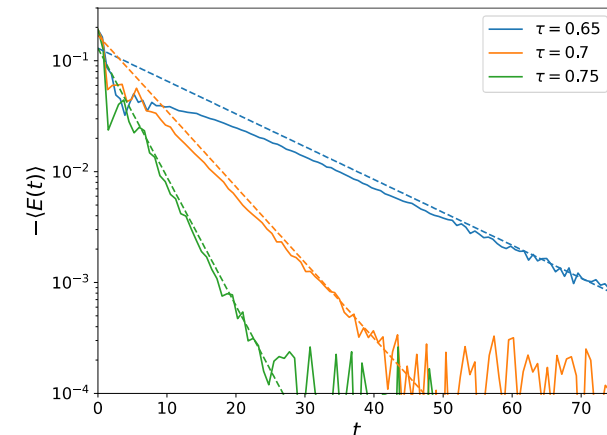
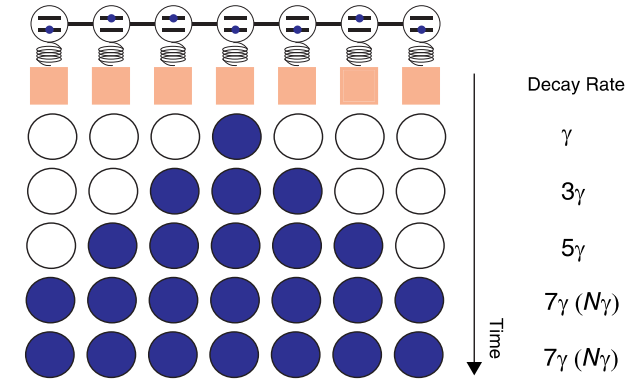


Theoretical Result II. Slow relaxation and accelerated dissipation in open quantum many-body systems

Tatsuhiko Shirai and Takashi Mori, Phys. Rev. Lett. **133**, 040201 (2024)

Takashi Mori, Phys. Rev. B **109**, 064311 (2024)

- Lindbladian description of open quantum systems:
Eigenvalues $0 = \lambda_0 > \text{Re } \lambda_1 \geq \dots$
 - Smallest decay rate $g = |\text{Re } \lambda_1|$: Liouvillian gap
- Bulk dissipation: operator growth accelerates dissipation
- Relaxation is slowed by local conserved quantities: $\tau_{\text{rel}} \gg 1/g$
 - Small overlaps between left and right eigenvectors [Mori and Shirai, PRL 2020]
- $\bar{g} := \lim_{\gamma \rightarrow +0} \lim_{L \rightarrow \infty} g \neq \lim_{L \rightarrow \infty} \lim_{\gamma \rightarrow +0} g = 0$
 - Related to thermalization of isolated ($\gamma = 0$) systems
- Extracts hidden exponential decay in unitary time evolution
 - Quantum analogue of Ruelle-Pollicott resonance in classical chaos

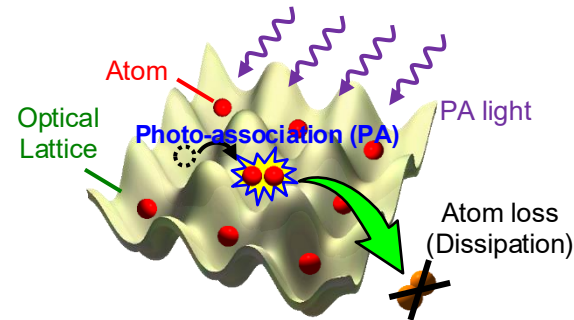


Experimental Result I. Construction of ultracold Li atomic systems in an optical lattice

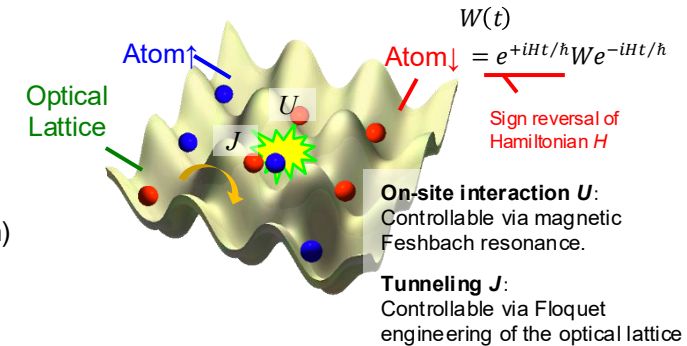
B02 group “Understanding quantum black holes through the study of artificial quantum matter”

- Objective:** Aiming to observe and measure
- ✓ **Measurement-Induced Transition (MIT)** and
 - ✓ **Out-of-Time-Ordered Correlators (OTOC)**
- using **cold atomic systems** with high controllability.

Measurement-Induced Transition

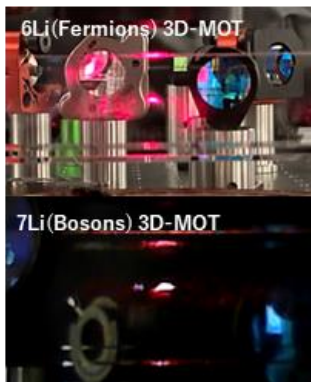


Measurement of OTOC

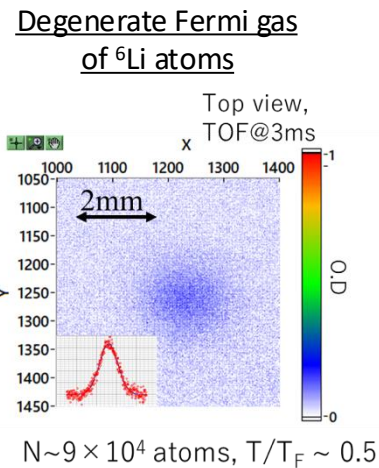
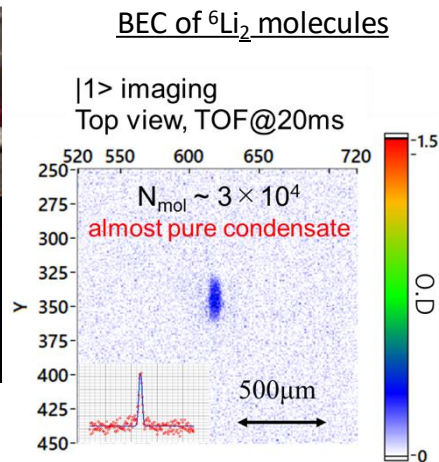


Research Highlights I: Construction of ultracold lithium (Li) atomic systems in an optical lattice (FY2021-FY2023)

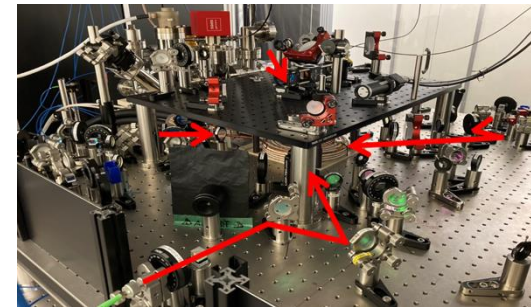
✓ Laser cooling of ${}^6\text{Li}$ & ${}^7\text{Li}$ atoms



✓ Evaporative cooling of atoms to a quantum degenerate regime



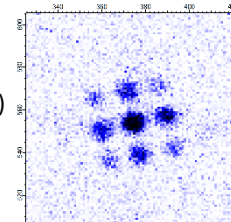
✓ Construction of a 2D optical lattice with a 1.5 μm laser



1560 nm optical lattice, $2w_0=200$ mm, $U_{\text{max}} \sim 35 E_{\text{Lat}}$

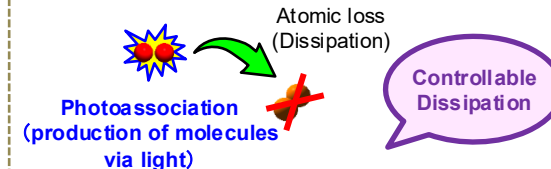
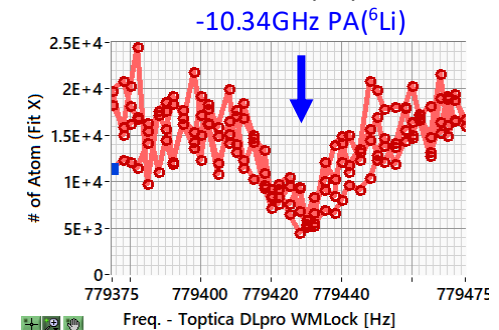
Diffracted atom pattern with pulsed lattice \rightarrow (degenerate Fermi gas of ${}^6\text{Li}$ atoms)

TOF@1.2ms
Pulse length@2.5 μs



Toward the measurement of MIT...

✓ Observation of atomic loss via Photoassociation (PA)



Experimental Result II. Hamiltonian engineering towards OTOC measurement

Research Highlights II: Reconstruction of setups and Hamiltonian engineering for OTOC Measurement (FY2024-FY2025)

Cold atoms in an optical lattice (Fermi-Hubbard model)

$$H = -t \sum_{\langle ij \rangle} c_i^\dagger c_j + U \sum_i n_{i\uparrow} n_{i\downarrow} + V \sum_i r_i^2 n_i$$

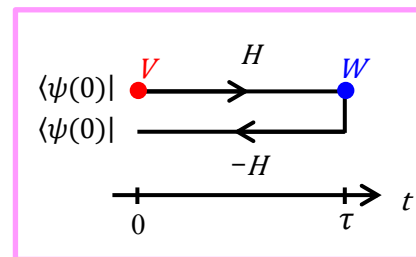
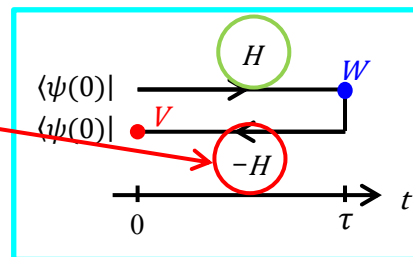
$-H$ $-t$ $-U$

The Hubbard model is a system capable of sign reversal of the Hamiltonian for OTOC measurements
 B. Swingle *et al.*, PRA **94**, 040302 (2016)

Out-of-Time-Ordered correlator (OTOC)

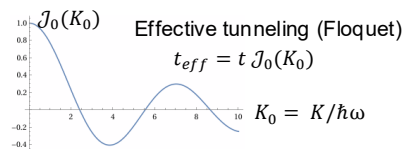
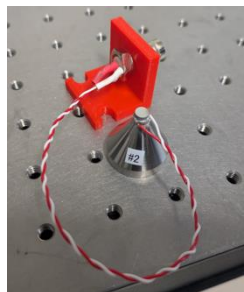
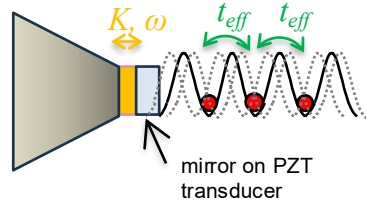
$$C(\tau) = \langle W^\dagger(\tau) V^\dagger(0) W(\tau) V(0) \rangle$$

W, V : operation
 $W(t) = e^{iHt} W e^{-iHt}$



① Sign reversal of the tunneling t

Achieved through lattice modulation



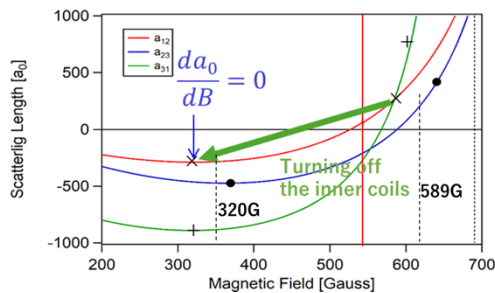
← Evaluate the mechanical response of PZT mirror using a Michelson interferometer:

amplitude variation <math>< 2\%</math> at <math>< 50</math> kHz, phase delay <math>< -\pi/9</math> rad

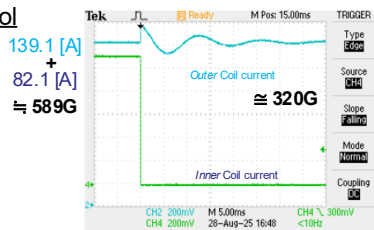
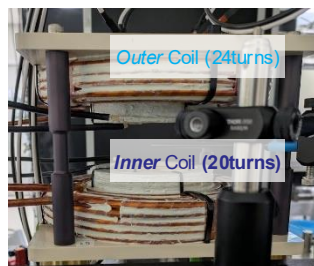
→ OK

② Sign reversal of the on-site interaction U

Achieved through magnetic Feshbach resonance with high-speed B-field switching.



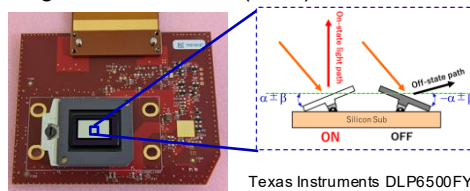
Implementation of dual Helmholtz coils for high-speed B-field control



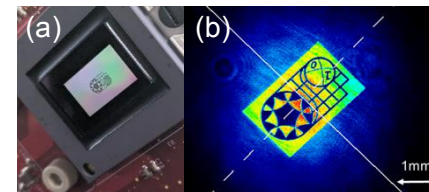
The scattering length a_{12} is tuned from $+290a_0$ to $-290a_0$ by varying the bias field.

③ Sign reversal of the confinement potential V

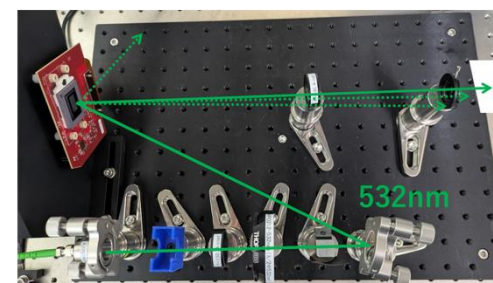
Digital-Mirror Device (DMD)



(a) DMD pattern. (b) Reflected image.



Test setup for arbitrary beam shaping using DMD-SLM



← Example of beam profile at the Fourier plane. (generating "こんにちは")

Enables generation of arbitrary optical potentials, including inversion of confinement potential V .



Grant-in-Aid for Transformative Research Areas (A)

Extreme Universe

B03 Research Highlights

Akihiro Ishibashi (Nagoya U.)

CoIs: Kengo Maeda (Shibaura Inst. Of Tech)
Keiju Murata (Nihon U.)

Research Goal

Understand fundamental nature of quantum black holes from quantum information

Research Plans and Achievements

1. Quantum Energy Conditions and Dynamics of Causal Boundaries
Semiclassical Einstein equations from Holography
2. Quantum Black Holes and Observables
Spin systems and Quantum field theories in curved spacetimes

Highlight 1: Semiclassical Einstein equations from holography

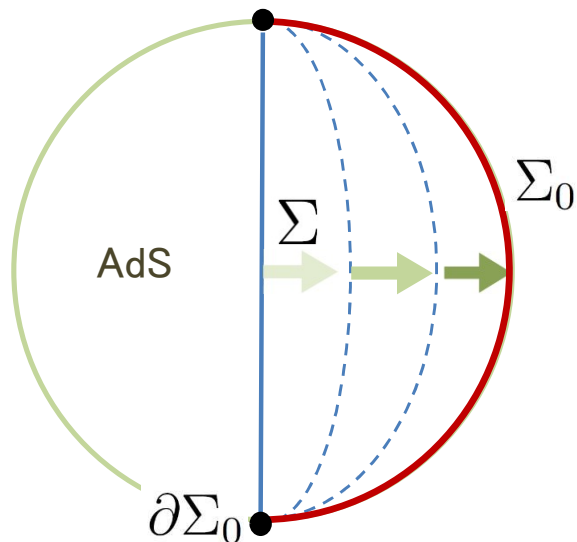
A. Ishibashi, K. Maeda, T. Okamura
2512.00503 [hep-th], JHEP 04 (2025) 167,
JHEP 02 (2024) 146, JHEP 05 (2023) 212

Quantum effects on spacetime dynamics: Semiclassical Einstein equations



It is in general difficult to compute the quantum stress energy tensor $\langle \mathcal{T}^{\mu\nu} \rangle$

➔ So, why not use Holographic method (gauge/gravity duality) ?



However, the boundary metric $\mathcal{G}_{\mu\nu}$
stays fixed and remains non-dynamical

$$\mathcal{S}_{\text{eff}} = \frac{1}{16 \pi G_d} \int_{\Sigma_0} \sqrt{-\mathcal{G}} (\mathcal{R} - 2 \Lambda_d)$$

Changing boundary conditions and adding self-action term allows the metric $\mathcal{G}_{\mu\nu}$ to become dynamical

$$+ \frac{1}{16 \pi G_{d+1}} \int_M \sqrt{-G} (R[G] - 2 \Lambda_{d+1}) + S_{\text{GH}} + S_{\text{ct}}$$



$$\mathcal{R}^{\mu\nu} - \frac{\mathcal{R}}{2} \mathcal{G}^{\mu\nu} + \Lambda_d \mathcal{G}^{\mu\nu} = 8 \pi G_d \langle \mathcal{T}^{\mu\nu} \rangle$$

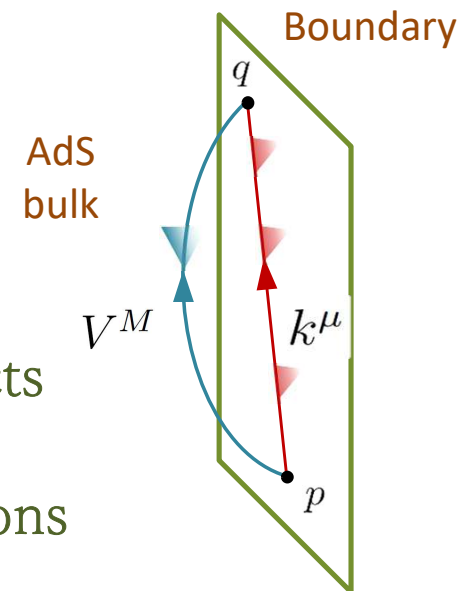
Holographic semiclassical Einstein equations

$$\gamma_d := \frac{G_d L}{\pi G_{d+1}} \left(\frac{L}{\ell} \right)^{d-2}$$

Quantum effects in terms of geometric parameters

A new instability due to strong quantum backreaction effects

A new approach to self-consistent quantum energy conditions



Highlight 2: Spin Systems and Quantum Fields in Curved Spacetimes

S.Kinoshita, K.Murata, D.Yamamoto and R.Yoshii

arXiv: 2602.17935, Phys. Rev. Res. 7 (2025) 043135,

Phys. Rev. Res. 7 (2025) 023197

Let us compare Quantum field theory and Spin system.

Quantum field theory (Majorana fermions)

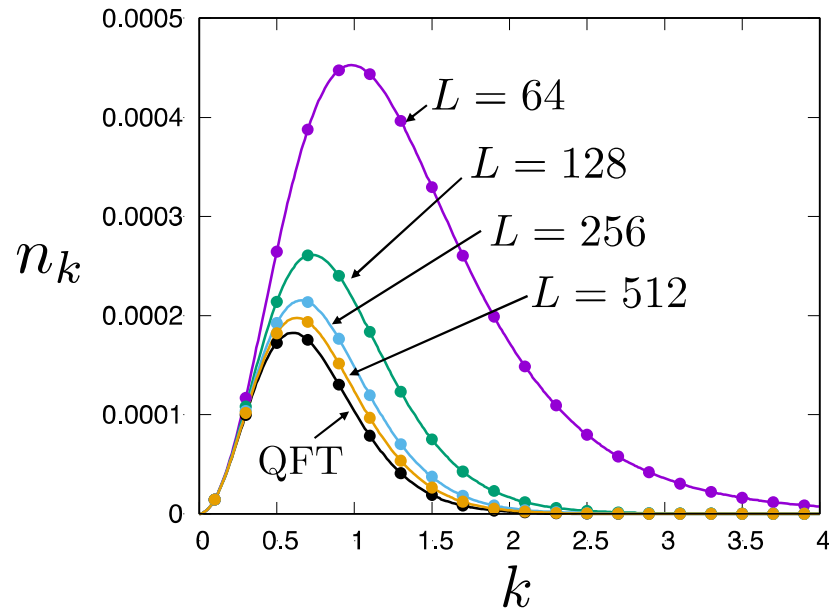
$$H = - \int_{-\pi\ell}^{\pi\ell} dx \left[\frac{\alpha}{2\gamma} (\Psi^\dagger \partial_x \Psi^\dagger - \Psi \partial_x \Psi) + \frac{i\beta}{2} (\Psi^\dagger \partial_x \Psi + \Psi \partial_x \Psi^\dagger) + m\alpha \Psi^\dagger \Psi \right].$$

Continuum limit of spin system

$$H = - \int_{-\pi\ell}^{\pi\ell} dx \left[\frac{v(t, x)}{2} (\Psi^\dagger \partial_x \Psi^\dagger - \Psi \partial_x \Psi) + \frac{iw(t, x)}{2} (\Psi^\dagger \partial_x \Psi^\dagger + \Psi \partial_x \Psi) \right. \\ \left. + \frac{i}{2} \rho(t, x) \{ \Psi^\dagger \partial_x \Psi + \Psi \partial_x \Psi^\dagger \} + \left\{ \mu(t, x) - \frac{1}{2} \partial_x \lambda(t, x) \right\} \Psi^\dagger \Psi \right]$$

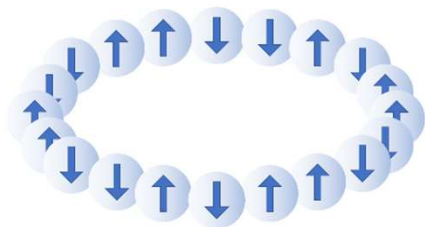
Equivalence between the two theories !

Quantum Field Theory of Majorana fermion in Curved Spacetimes is equivalent to Continuum limit of Spin systems

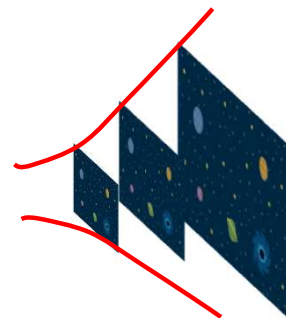


Example: Particle creation in expanding universe and Ising model with time-dependent magnetic field

This provides an experimentally viable system for probing various phenomena in QFT in curved spacetimes, while also opening the door to uncovering nontrivial phenomena in spin systems inspired by curved spacetime physics

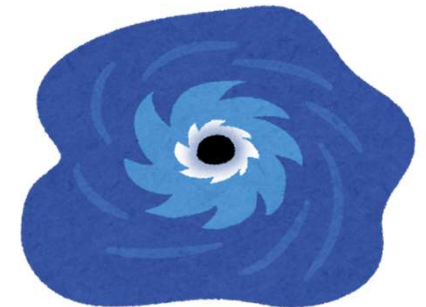


Ising model



Expanding universe

or



Black holes



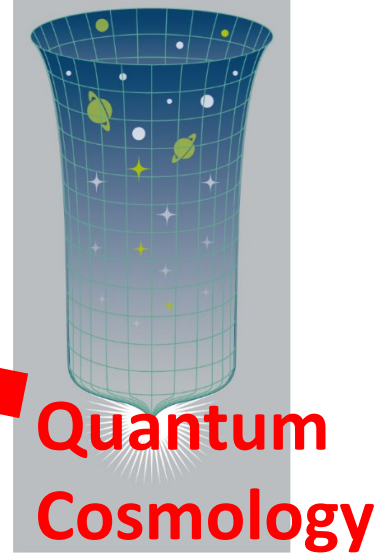
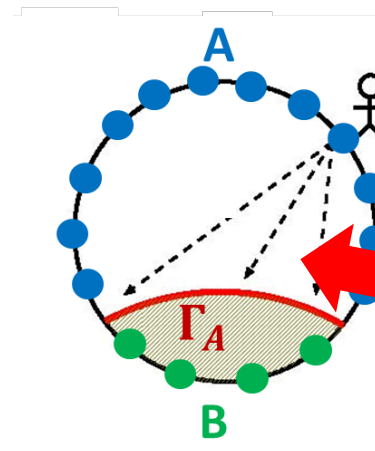
C01 Research Highlights

Tadashi Takayanagi (YITP, Kyoto)

CoIs: Yasuaki Hikida (YITP, Kyoto U.)
Kazumi Okuyama (Shinshu U.)
Yasuhiro Sekino (Takushoku U.)
Shigeki Sugimoto (YITP, Kyoto U.)

Research Goal

Understand quantum cosmology using holography and quantum information



Research Plans and Achievements

- [1] Understand AdS/CFT duality from Quantum Information
→ Introducing the idea of “time-like entanglement” and finding mechanism of emergent time
- [2] Construction of holographic duality for general spacetimes
→ Discovery of an explicit example of holography for three dimensional de Sitter spaces

Highlight 1 : Time-like Entanglement and Emergent Time

K. Doi, J. Harper, A. Mollabashi, T. Takayanagi and Y. Taki, PRL 130 (2023) 3,031601

JHEP 05 (2023) 052

Simple Idea

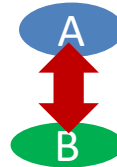
We know:



Quantum correlation in spatially separated systems → Quantum entanglement

Why don't you consider:

Quantum correlation in temporally separated systems → **Time-like entanglement ?**



~ Strength of influence ?

Motivation from Holography

Entanglement entropy = Area of minimal surface in Universe

→ Space coordinates emerge from quantum entanglement !

Q. Can the time coordinate emerge from some sort of quantum information ?

→ **Time-like Entanglement Entropy = Area of time-like surface in Universe**

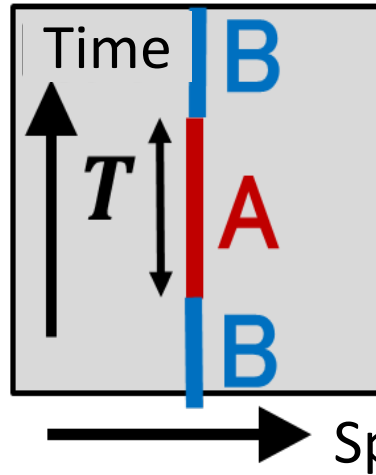
Time-like entanglement in two dimensional CFTs and Holography

Time-like entanglement entropy
in a two dimensional CFT

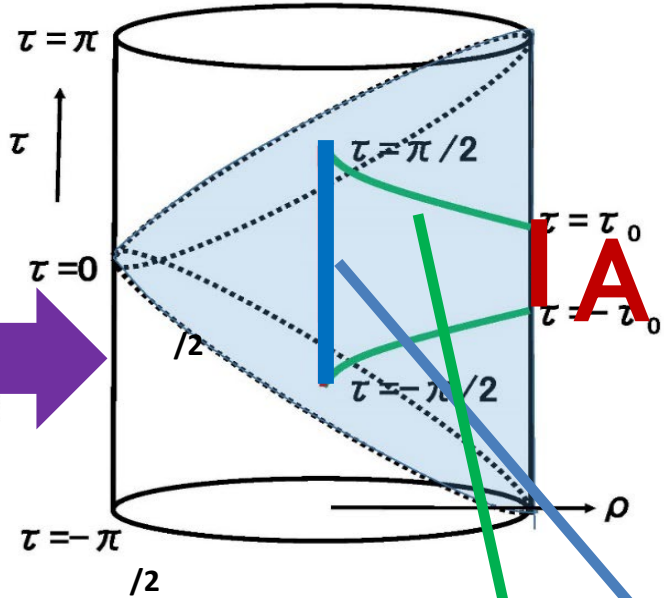
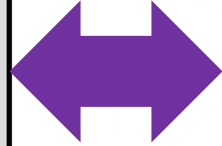
Geodesics in three dimensional
anti de-Sitter space

Wick-rotate subsystems.
Extend density matrices
into non-Hermitian ones.

$$\rho_A^\dagger \neq \rho_A \Leftrightarrow \text{Causal influence}$$



AdS/CFT duality



$$S_A = \frac{C}{3} \log \left[\frac{T}{\epsilon} \right] + \frac{\pi}{6} iC = [\text{Length of space-like geodesic}] + i \times [\text{Length of time-like one}].$$



The time coordinate emerges from the imaginary part of time-like entanglement entropy.

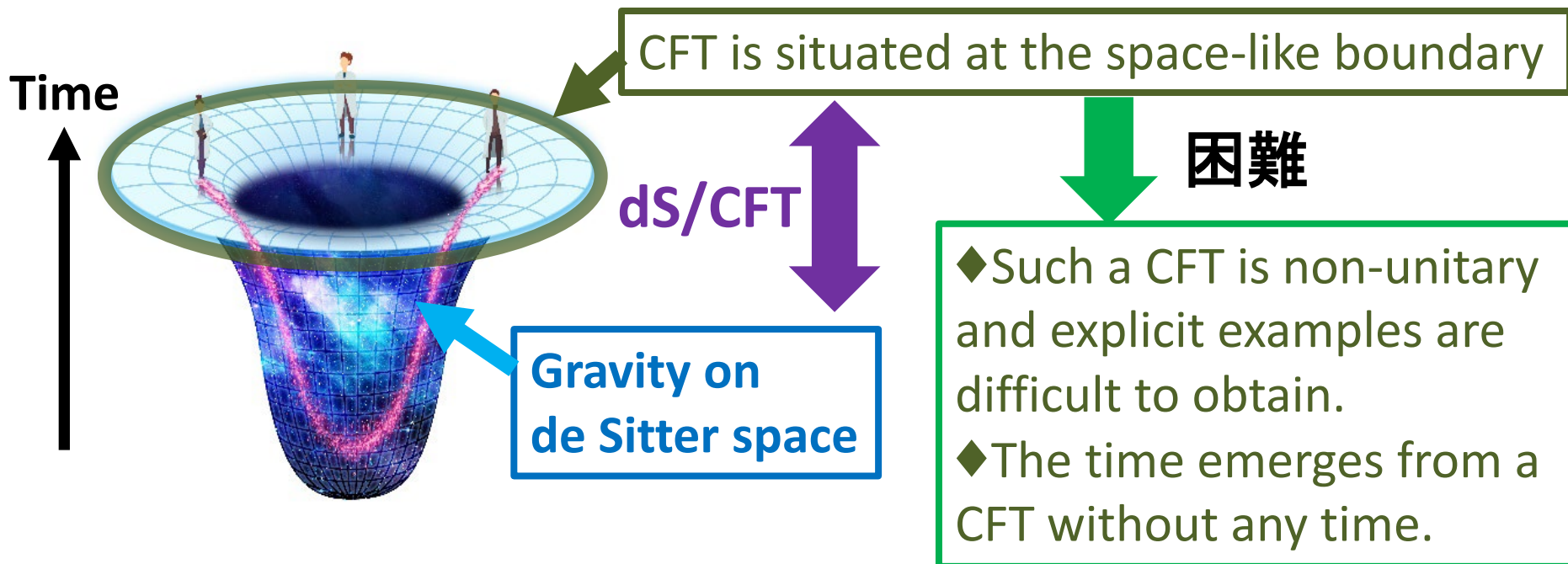
Highlight2 : Holography for three dim. de Sitter Space

Y. Hikida, T. Nishioka (D01), T. Takayanagi and Y. Taki,

PRL 129 (2022)4,041601 [Editor's suggestion, Viewpoint in APS "Physics"]

JHEP 05 (2022)129

Difficulty of Holography for de Sitter Space (dS/CFT)



➔ We find the first example of holography for three dim. de Sitter space.
The time in de Sitter space emerges from time-like entanglement.

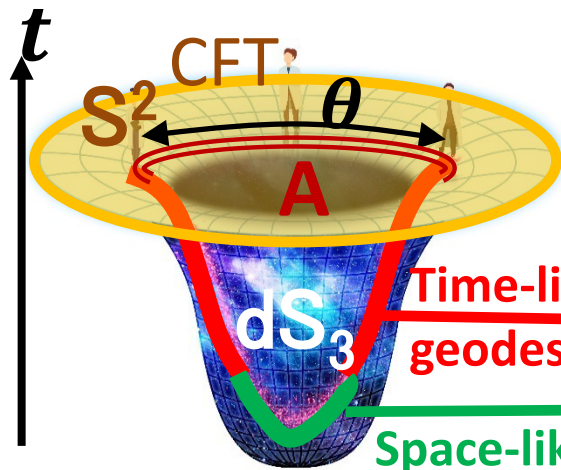
Our CFT example dual to three dimensional de Sitter Space

◆ It is a non-unitary CFT obtained from SU(2) WZW model at level $k \approx -2 + \frac{4iG_N}{L_{ds}}$.

→ Its central charge: $c = \frac{3k}{k+2} \approx i \frac{3L_{ds}}{2G_N}$.

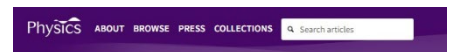
This reproduces de Sitter partition function:

$$Z_{CFT} \approx e^{\frac{\pi L_{ds}}{2G_N} \sqrt{1-8G_N E}} = Z_{ds}$$



Again the imaginary part of entropy leads to the emergence of time.

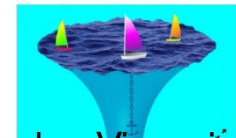
$$S_A = i \frac{C_{ds}}{3} \log \left(\frac{2}{\epsilon} \sin \frac{\theta}{2} \right) + \frac{C_{ds}}{6} \pi.$$



VIEWPOINT
Steps toward Quantum Gravity in a Realistic Cosmos

Jordan Cotler
Society of Fellows, Harvard University, Cambridge, MA, USA
July 18, 2022 - Physics 15, 107

Theorists have modeled an expanding spacetime—akin to our Universe—by taking inspiration from a string theory framework in which spacetime is emergent.



[Introduced as Viewpoint in APS magazine “Physics” (July, 2022)]

◆ Recently, we derived the dS Einstein equation from the first law of the entropy

→ K.Fujiki, M.Kohara, K.Shinmyo, Y.k.Suzuki and T.Takayanagi, to appear in JHEP

◆ Studies of dS/CFT via Double Scaled SYK model have also been successful.

[Okuyama JHEP 08 (2025) 181]

[Sekino-Susskind JHEP 10 (2025) 137,

Miyashita-Sekino-Susskind JHEP 11 (2025) 107]

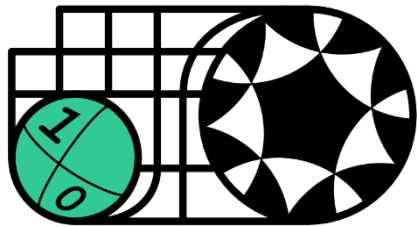


Grant-in-Aid for Transformative Research Areas (A)

Extreme Universe

C02 Research Highlights

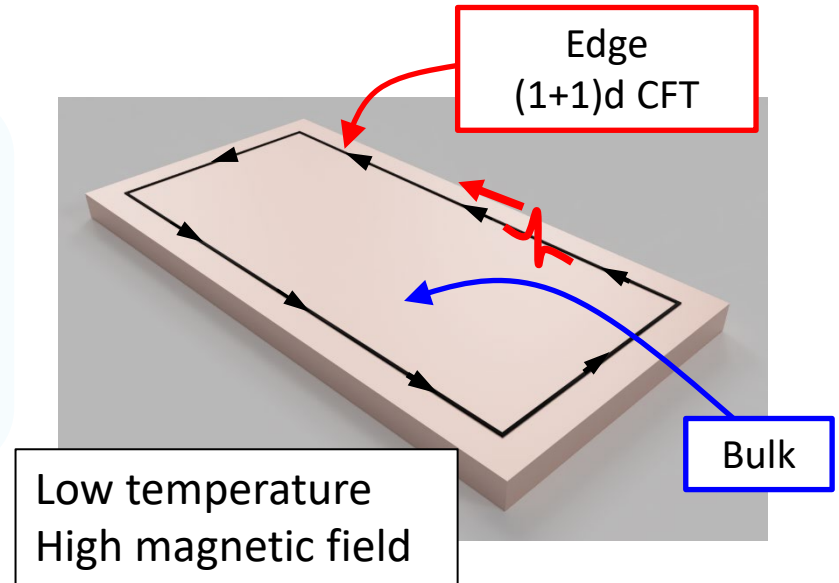
Go Yusa (Tohoku)



CoIs: Masahiro Hotta (Tohoku)
Naokazu Shibata (Tohoku)
Kazuya Yonekura (Tohoku)

Research Goal

Realization of toy models of a quantum universe in quantum Hall systems through experiment and theory



Research Plans and Achievements

[1] Establish experimental techniques, including advanced quantum measurement methods, and perform experiments on quantum Hall edges.

→ Understanding the dynamics of edge excitations, including their coupling to bulk excitations

[2] Examine the quantum universe realized on edges from the perspectives of high-energy theory, mathematical physics, condensed matter theory, quantum information, and cosmology.

→ Theoretical development of edge-based toy models

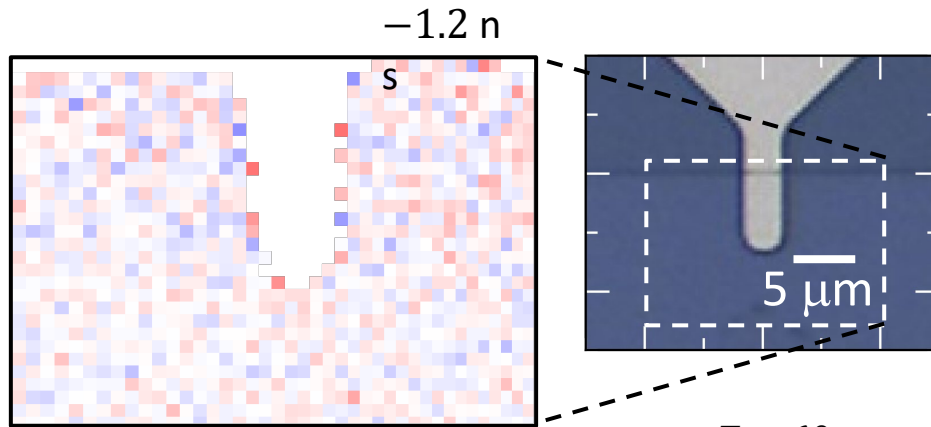
Highlight 1: Spatiotemporal imaging of edge excitations and their dynamics

Q. France et al., Phys. Rev. Lett. (2025).

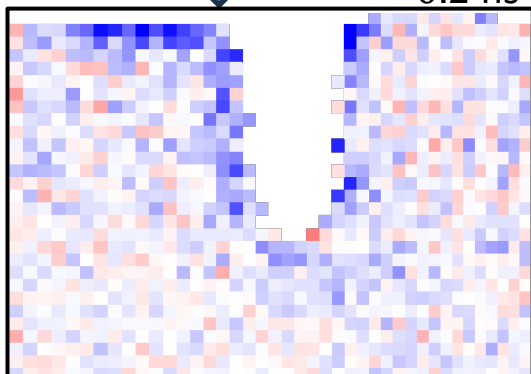
A. Kamiyama, et al., Phys. Rev. Research (2022).

Appl. Phys. Lett. (2023).

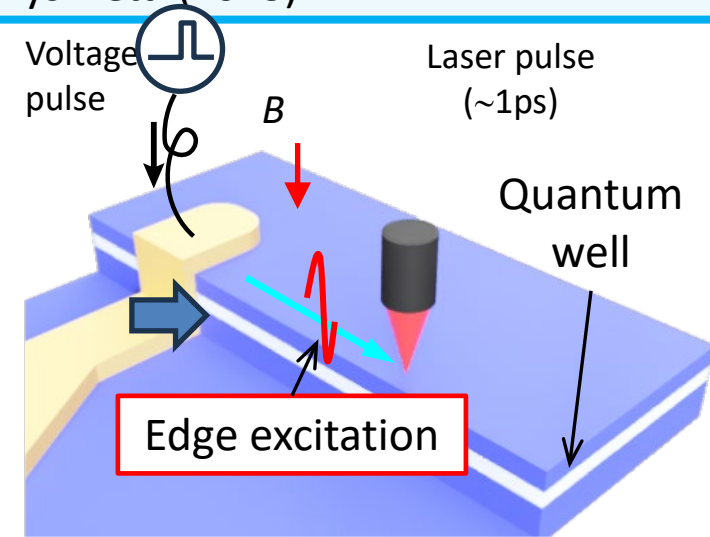
Development of an ultrafast spectroscopic microscope operable under ultralow temperatures and high magnetic fields → Successful time-resolved imaging of edge excitations



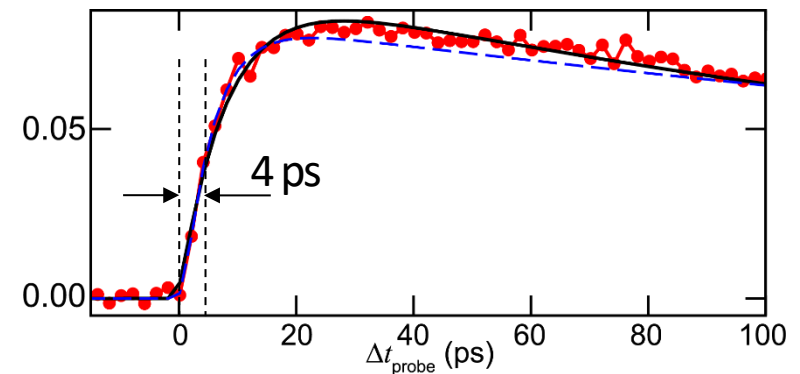
After \downarrow 1 ns



$T = 60$ mK,
 $B = 11.5$ T



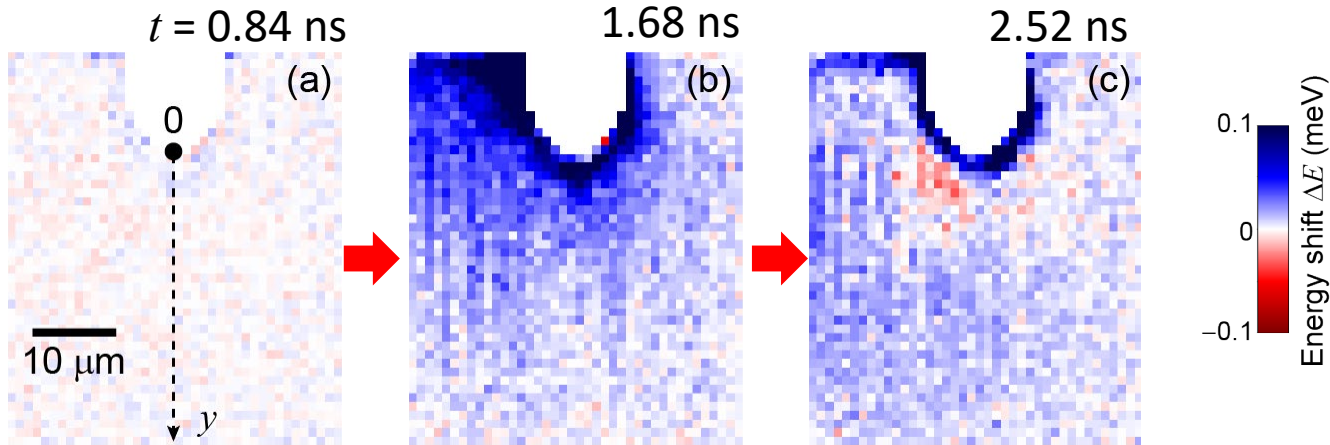
Achieved a two-orders-of-magnitude improvement in time resolution, from ~ 300 ps to a few picoseconds



Edge and bulk excitations

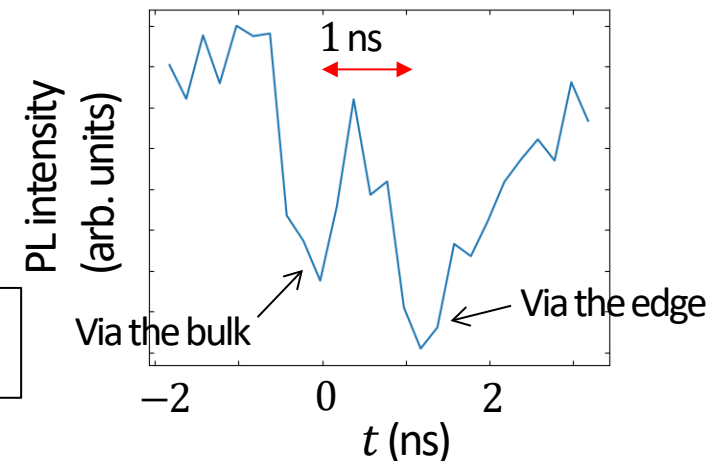
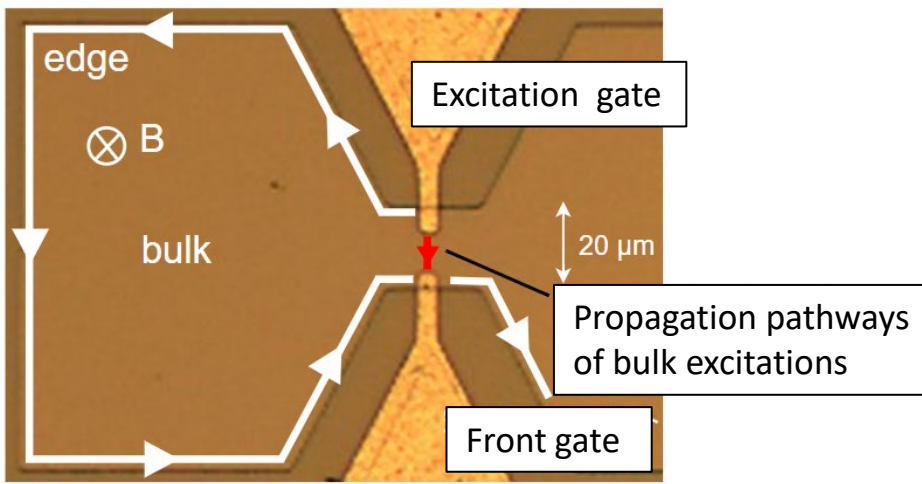
$\nu = 2/3$

Successful visualization of bulk excitations



Quentin et al., Phys. Rev. Lett. **135** 066203 (2025).

Use of bulk excitations as a platform technology for analogue wormhole experiments (**In collaboration with Takayanagi, Group C01**; presented at the Physical Society of Japan Meeting in March 2026; manuscript in preparation)



Highlight 2: Expanding edges in quantum Hall systems and their control

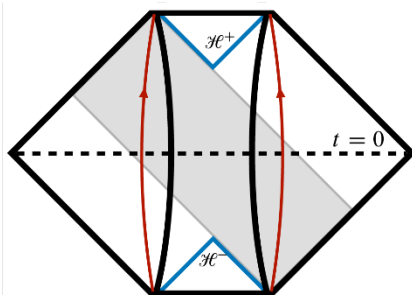
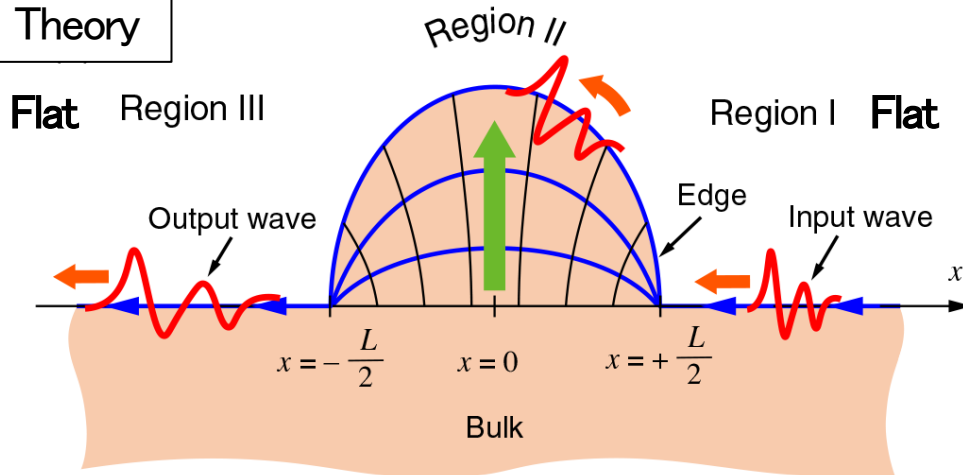
M. Hotta et al., Phys. Rev. D (2022).

Y. Nambu and M. Hotta, Phys. Rev. D (2023).

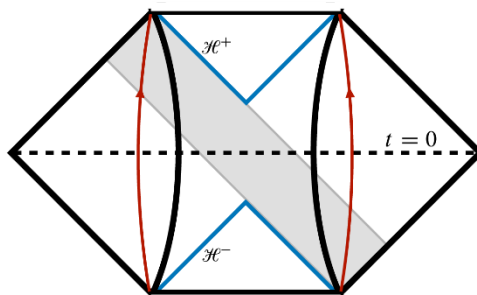
(In collaboration with Nambu and Yamamoto, Group E02)

A cosmological formulation of expanding edges \rightarrow Hawking radiation emerging from edge modes

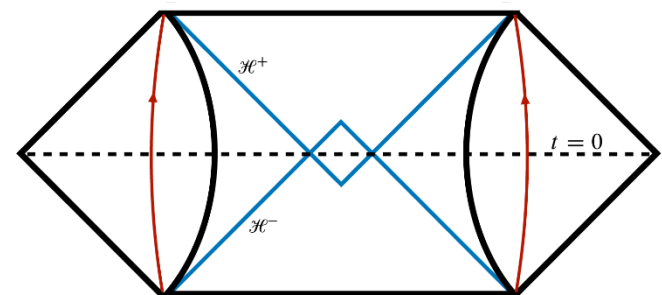
Theory



$$0 < LH < \frac{\pi}{4}$$



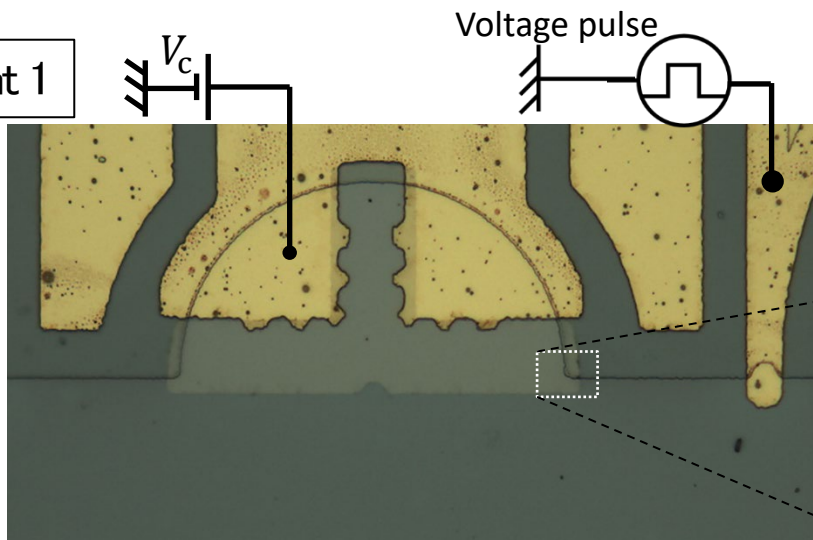
$$\frac{\pi}{4} < LH < \frac{\pi}{2}$$



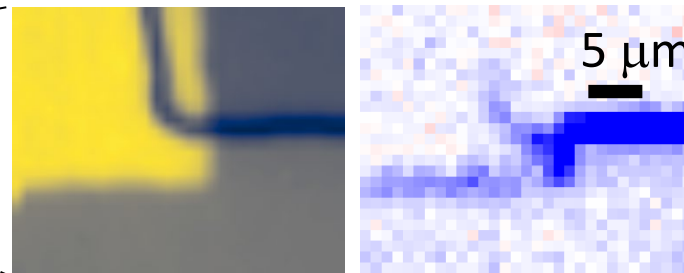
$$\frac{\pi}{2} < LH$$

Experimental studies toward expanding edges in QH systems

Experiment 1



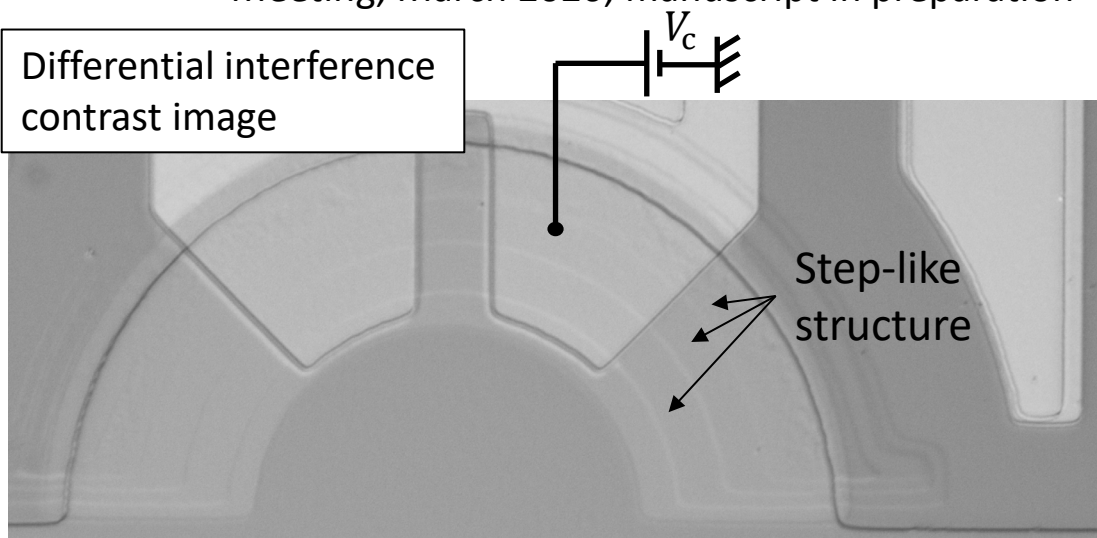
Control and visualization of nonlocal multipath propagation of edge excitations, together with near-field observation of edge excitations
 (Manuscript under submission; collaborative work with Numasawa in Group E02)



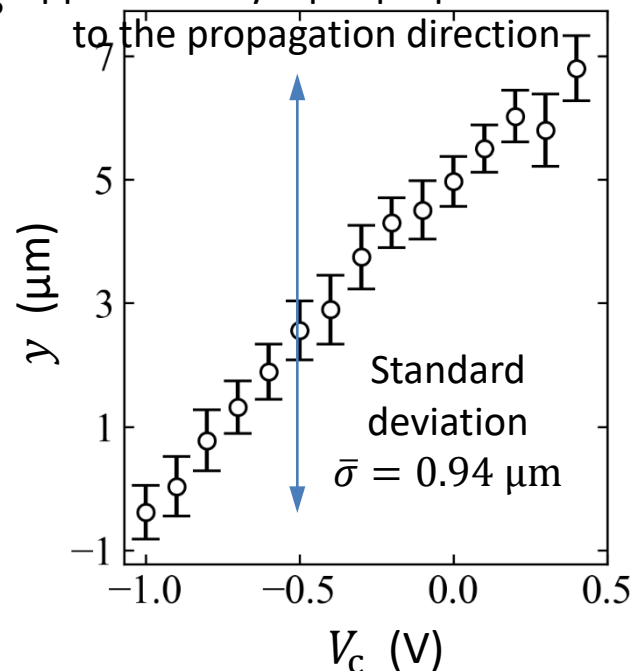
Long-range deformation of localized edge (approximately ten times larger than in previous studies) Presented at the Physical Society of Japan Meeting, March 2026; manuscript in preparation

Experiment 2

Differential interference contrast image



Approximately 5 μm perpendicular to the propagation direction





Grant-in-Aid for Transformative Research Areas (A)

Extreme Universe

C03 Research Highlights

PI: Tetsuya Shiromizu(Nagoya U.)

CoIs: Keisuke Izumi (Nagoya U.)

Tsutomu Kobayashi (Rikkyo U.)

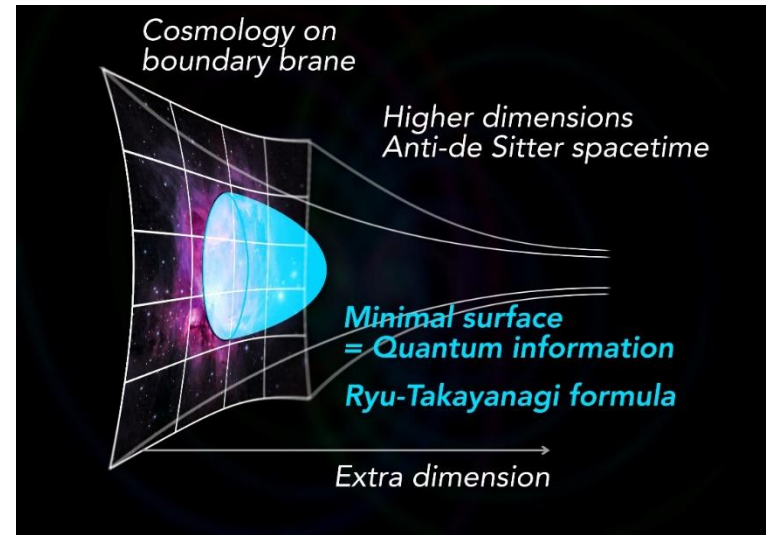
Norihiro Tanahashi (Kyoto U.)

Masato Nozawa (Osaka I. T.)

Hiroataka Yoshino (Osaka Metro.U.)

Research Goal

Clarification of quantum cosmology through Ryu-Takayanagi formula



Research Plans and Achievements

A. Clarification of the mathematical structure of braneworld models

Gravitational perturbation in “new braneworld” scenarios associated with AdS/BCFT in higher dimensions

B. Investigation of the mathematical structure of quantum cosmology with observational perspectives

Dynamics of axion clouds around black holes

Research Highlight 1

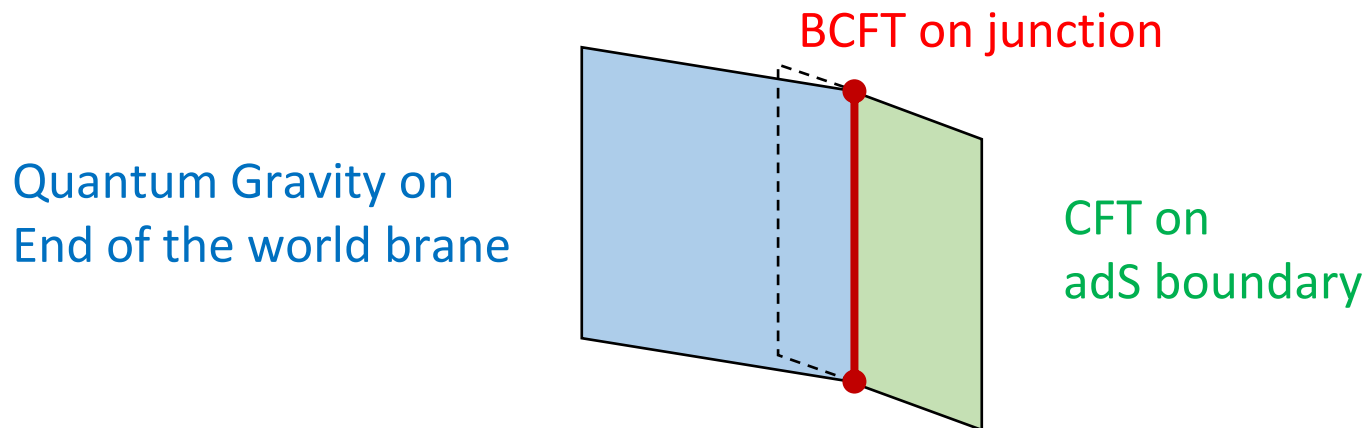
C01–C03 Joint Research

“Brane Dynamics of Holographic BCFTs”

K. Izumi, T. Shiromizu, K. Suzuki, T. Takayanagi, N. Tanahashi

JHEP 10, 050 (2022) [Citations: 46]

Braneworld associated with AdS/BCFT \approx a model for quantum gravity



Analysis of gravitational perturbation in **higher dimensions**

- confirmed that **matter on the junction boundary (BCFT)** behaves consistently
- strong support for the validity of the model

Research Highlight 2 Collaboration with T. Tanaka (2nd-phase project)

“Impact of multiple modes on the evolution of self-interacting axion condensate around rotating black holes”

H. Omiya, T. Takahashi, T. Tanaka, H. Yoshino, JCAP 06, 016 (2023) [[Citations: 48](#)]

“Deci-Hz gravitational waves from the self-interacting axion cloud around a rotating stellar-mass black hole”

H. Omiya, T. Takahashi, T. Tanaka, H. Yoshino, PRD 110, 044002 (2024) [[Citations: 21](#)]

Axion Cloud Dynamics Around Black Holes

Axions: a candidate for (light) dark matter

- [Numerical study of long-term evolution](#) of axion clouds around black holes
- showed that the [expected explosive phenomena \(e.g., bosonova\)](#) do not occur due to dissipation caused by mode interactions
- provided [concrete predictions for gravitational waves](#)

D01 Research Highlights

Tatsuma Nishioka
(UOsaka)

Cols

Etsuko Ito (YITP)

Masazumi Honda (iTHEMS, RIKEN)

Yutaka Matsuo (UTokyo)

Takuya Okuda (UTokyo)



Research Goals

To elucidate the dynamics of quantum field theories using the mathematical structure of quantum information theory and quantum computation.

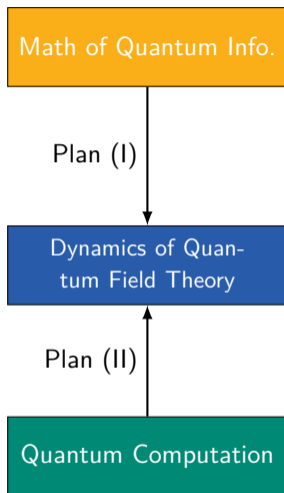
Research Plan and Results

(I) Analysis of quantum field theories using the mathematical structure of quantum information

⇒ Construction of conformal field theories from quantum error-correcting codes

(II) Elucidation of the dynamics of quantum field theories via quantum computation

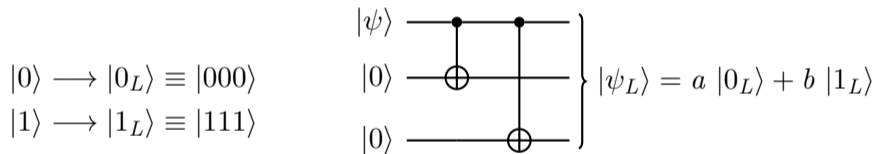
⇒ Quantum simulation of systems with the sign problem



Results of Plan (I): Construction of CFTs from QEC Codes

- Quantum Error-Correcting (QEC) codes: A crucial theory for realizing fault-tolerant quantum computers.

By distributing (quantum) information across multiple locations, the original information can be recovered even if errors occur.



- QEC has a structure analogous to “gauge symmetry” in quantum field theory.

Symmetry \longleftrightarrow Distribution of information
?

- Do quantum field theories with the structure of quantum error-correcting codes exist?

Results of Plan (I): Construction of CFTs from QEC Codes

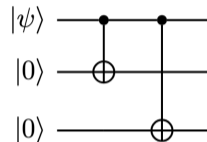
- Develop a new method to systematically construct (1+1)-dimensional conformal field theories from quantum error-correcting codes

[Kawabata-Nishioka-Okuda, SciPost Phys. Core 6 (2023) 035, JHEP 12 (2023) 127]

- Apply this method to discover and classify conformal field theories with supersymmetry

[Kawabata-Nishioka-Okuda, PRD 108 (2023) 8, L081901, w/ Yahagi, JHEP 05 (2025) 105]

Quantum Error-Correcting Codes



Conformal Field Theories

Quantum state $|\psi\rangle \implies$ Operator \mathcal{O}_ψ

Results of Plan (II): Quantum Simulation of Systems with the Sign Problem

- Challenges in numerical computation of quantum field theories

Sign Problem: When the action is complex, computational complexity becomes enormous, making numerical simulations difficult.

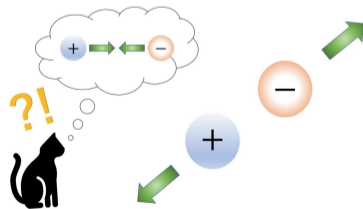
Examples: Finite temperature systems, topological terms, etc.

- Avoid the sign problem using quantum computation

- Quantum simulation of finite temperature systems using quantum imaginary time evolution

[Petersen-Itou-Sun-Yunoki, PoS LATTICE2023 (2024) 220]

- Realization of a situation where a repulsive force acts between particles with opposite charges via quantum computation [Honda-Itou-Kikuchi-Tanizaki, PTEP (2022) 033B01]





Grant-in-Aid for Transformative Research Areas (A)

Extreme Universe

D02 Research Highlights

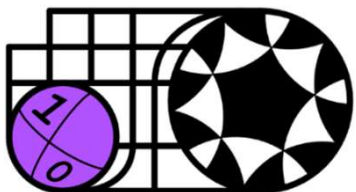
Kouichi Okunishi (Osaka Metropolitan U)

CoIs: Hiroshi Ueda (Osaka U QIQB)

Kenji Harada (Kyoto U)

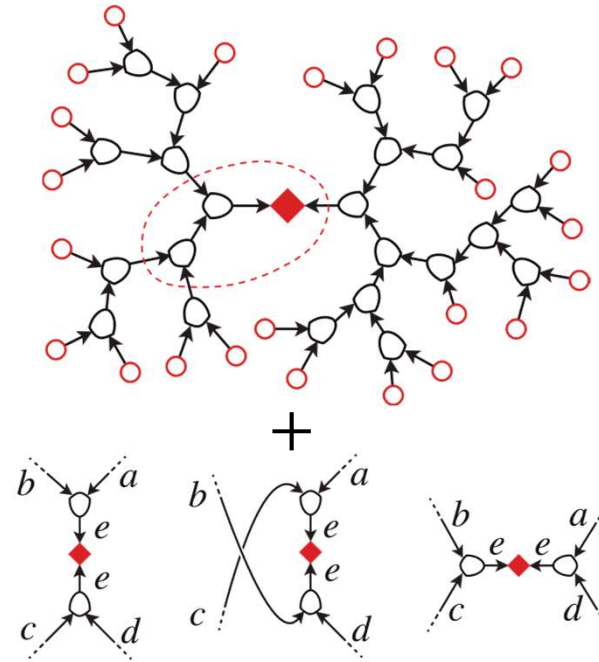
Hosho Katsura (U Tokyo)

Chisa Hotta (U Tokyo)



Research Goal

to develop tensor networks based on quantum information perspectives and to elucidate quantum many-body dynamics on their basis.



Research Plans and Achievements

- I. to clarify systematic control mechanisms for quantum states via tensor networks and to develop its innovative algorithms.



Structural optimization of tree tensor networks

From quantum many-body entanglement control through network optimization to interdisciplinary studies of quantum many-body physics.

- II. to develop a precise theoretical understanding of quantum many-body dynamics based on underlying mathematical structures with a quantum information perspective. **Systematic algebraic construction of quantum scar states**



Mathematical foundations of anomalous quantum dynamics evading thermalization.

I Structural optimization of Tree Tensor Networks

Tensor Network(TN): Quantum simulation for quantum many-body systems based on entanglement controlling
Decomposing quantum many-body systems into small parts (tensors) and reconstructing them as a network

- + Developed in condensed matter field \Rightarrow Universal and flexible theoretical framework across various physics fields
- + Leading method in quantum simulation free from such a known problem as the negative sign problem
- + Similarities to the Ryu-Takayanagi formula in holography \Rightarrow Connection to quantum gravity
- + Compatible with quantum circuits and quantum algorithms \Rightarrow Essential for verifying quantum computation

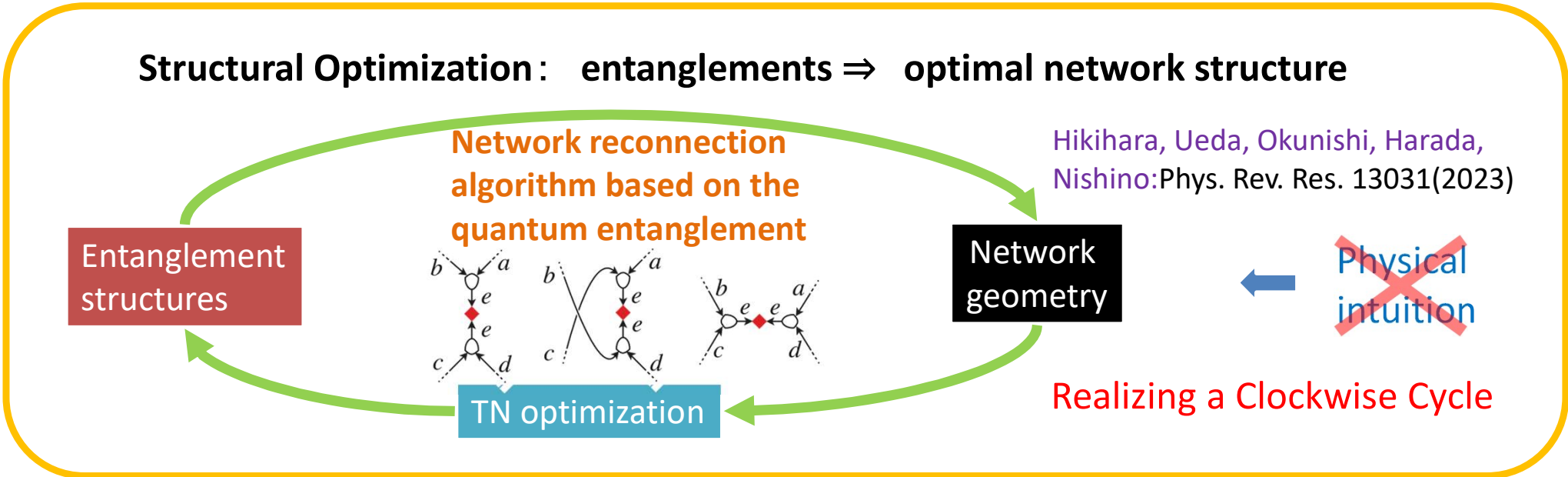
Common Keyword in the extreme universe project

Problem: Inherent difficulties in handling complex entanglement structures and higher dimensions.

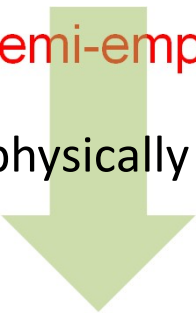
Known typical TNs (MPS, block spin transformations, PEPS, MERA)

\uparrow originating from semi-empirical construction based on intuition

Barriers to the next step

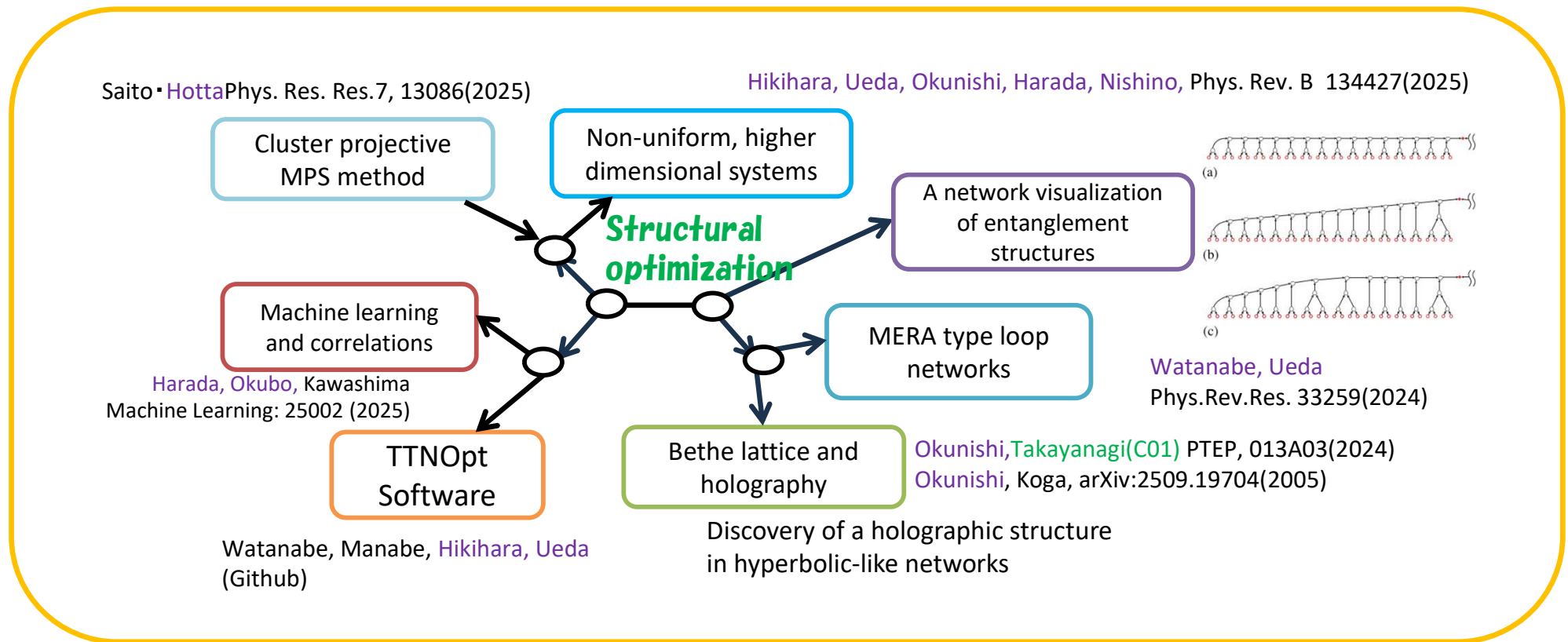


beyond conventional, semi-empirical tree-type TN constructions



The network structure realizing the physically important quantum entanglement structure.

Towards new practical developments of the quantum many-body theory based on optimal network structures.



A starting point for multifaceted, interdisciplinary research developments focusing on the network structure of TNs associated with the ExU project.

Despite algorithm papers typically not gaining many citations, this one already has 40 citations.

II Systematic construction of quantum scar states

Quantum scar states: peculiar quantum states exhibiting non-thermalizing dynamics

- + A new mechanism for evading thermalization \Rightarrow A crucial challenge to quantum statistical mechanics based on ETH
- + Neither fully integrable nor fully chaotic \Rightarrow What are the mathematical backgrounds of such intermediate behaviors?
- + Analysis of various models \Rightarrow Is there an underlying mechanism?
- + Observed in cold-atom systems, etc. \Rightarrow A new research field with synergistic interplay between theory and experiment

A key concept for elucidating quantum many-body dynamics

Are scar states
mere exception?

**Towards a systematic understanding of the underlying
mechanism beyond individual model analyses.**



**A mathematical foundation for the emergence of
quantum scar states needs to be established**

**We demonstrated that quantum scar states can be systematically and exactly
constructed from algebraic structures embedded in non-integrable systems.**

Quantum scar states are low-entanglement states
at high energy \Rightarrow Natural connection to TNs



Phys. Rev. B 108, 155102 (2023)
Phys. Rev. A 110, 043312 (2024)
Phys. Rev. Research 6, 043259 (2024)
arXiv:2411.01270
Phys. Rev. Res. 7, 043107 (2025)

By developing a mathematical framework for anomalous quantum dynamics, we
pave a pathway toward a general theory of quantum scar states that bridges
quantum information and experimental studies.