Rethinking Quantum Information in Gravity and Field

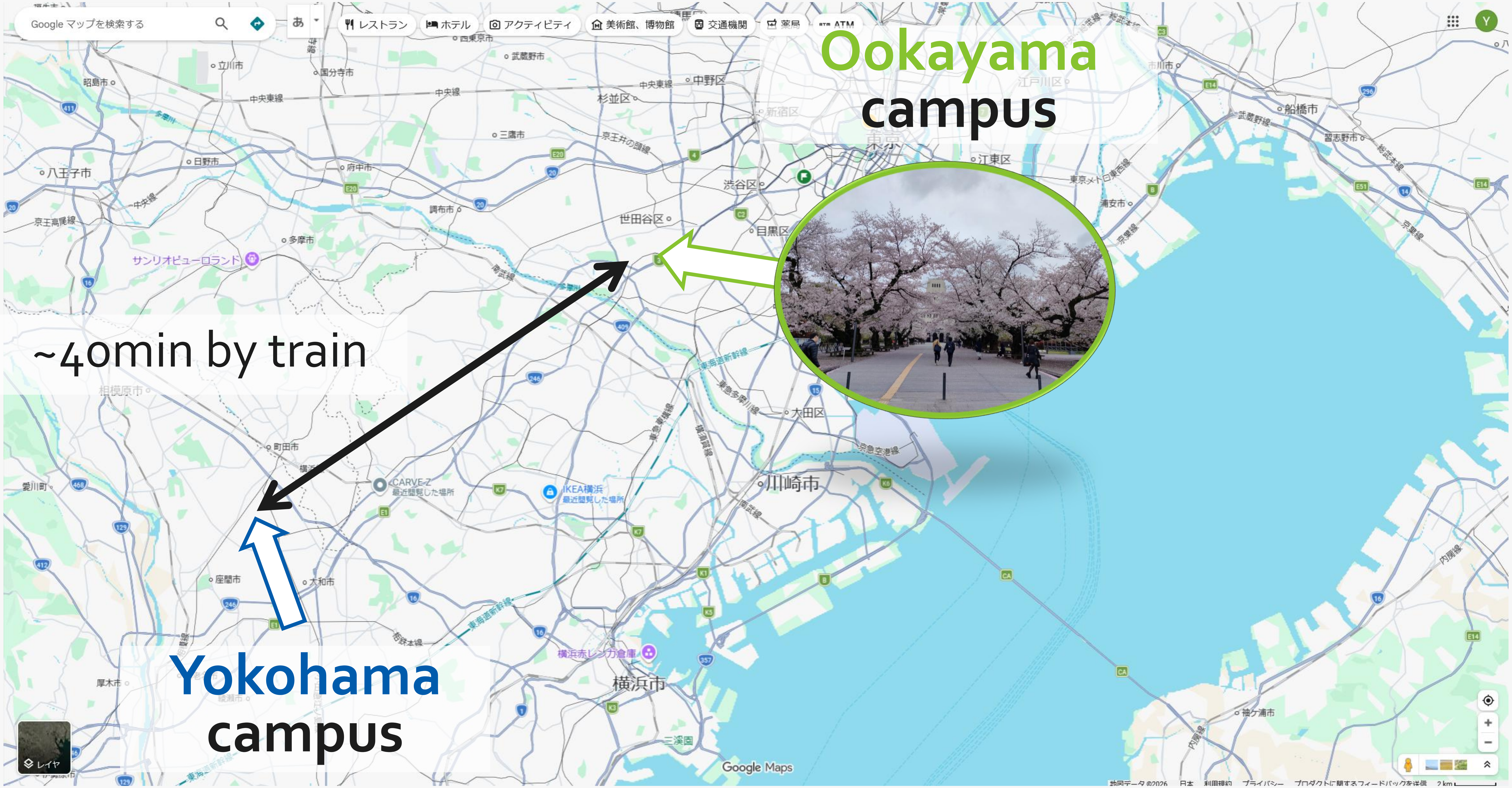
Section 4. Quantum Error Correction

Yoshifumi Nakata

Institute of Science Tokyo

arXiv:2606.30853

QI Group launched at Science Tokyo.



QI Group launched at Science Tokyo.

- A green, family-friendly campus — easy on the eyes and a great place to work.
  - If you are nearby, please feel free to visit.
  - Interested in QI? Happy to host you by, e.g., JSPS postdoc fellowship program.

View from my office.

Rethinking Q.info. in gravity and fields

1 Section 4. Quantum Error Correction

2 Hayden-Preskill-type thought experiment

3 Chaos and Error Correction

Gravity and Quantum Error Correction

Six questions at the gravity-QEC interface

arXiv

High Energy Physics - Theory

[Submitted on 29 Jun 2026]

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Kanato Goto, Yuta Hamada, Kohtaro Kato, Takato Mori, Yoshifumi Nakata, Masataka Watanabe, Hayata Yamasaki, Masahito Yamazaki, Takuya Yoda

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Main writers:

Y. Hamada (KEK) and YN (Science Tokyo)

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How can one refine the Hayden–Preskill toy model to incorporate more realistic black hole physics?

Problem 4.2

What properties of many-body Hamiltonian dynamics are necessary and sufficient for near-Haar quantum encoding?

Problem 4.3

Can black hole dynamics be learned from Hawking radiation?

Problem 4.4

Can we identify specific features of QEC that are needed to describe QG?

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Later

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- Is **full QEC** necessary for quantum gravity, or is protecting only **macroscopic / limited information** sufficient?
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What is the holographic counterpart of the classical–quantum correspondence of QEC?

Using **classical-quantum correspondence of QEC**, can we build Q holography from **two "classical" holographic models**? (idea)

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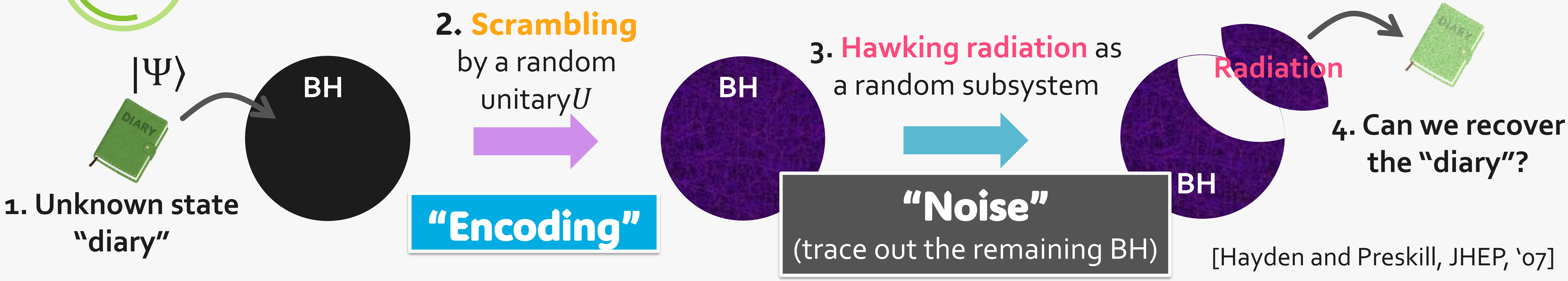
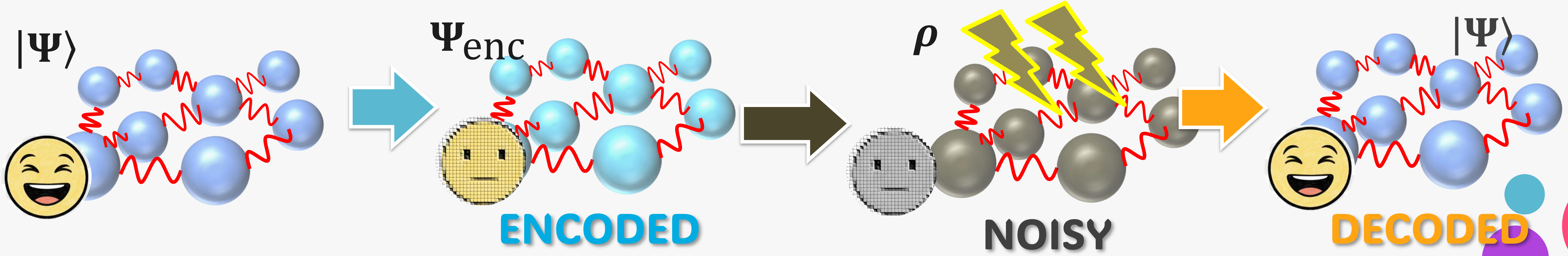
Hayden-Preskill setting

Information recovery from Hawking radiation



[Hayden and Preskill, JHEP, '07]

- This can be viewed as **Quantum Error Correction** against erasure of the remaining BH.



Hayden-Preskill setting

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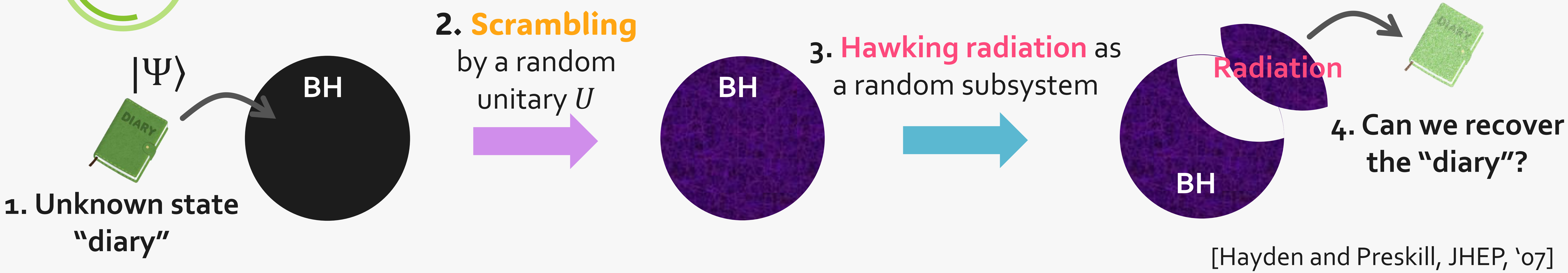

[Hayden and Preskill, JHEP, '07]

- ☐ This setting is based on various (probably unphysical) assumptions
  1. Hawking radiation as a subsystem? ➔ No clear tensor-product factorization $\mathcal{H}_{\mathrm{BH}} = \mathcal{H}_{\mathrm{remain}} \otimes \mathcal{H}_{\mathrm{radiation}}$
  2. We know which subsystem has been radiated. ➔ Not accessible as the emission is quantum process.
  3. Haar-random unitary in 2 ➔ How close can realistic Hamiltonian dynamics get?

Our proposal: **Refine these assumptions to better understand information recovery from Hawking radiation.**

Hayden-Preskill setting

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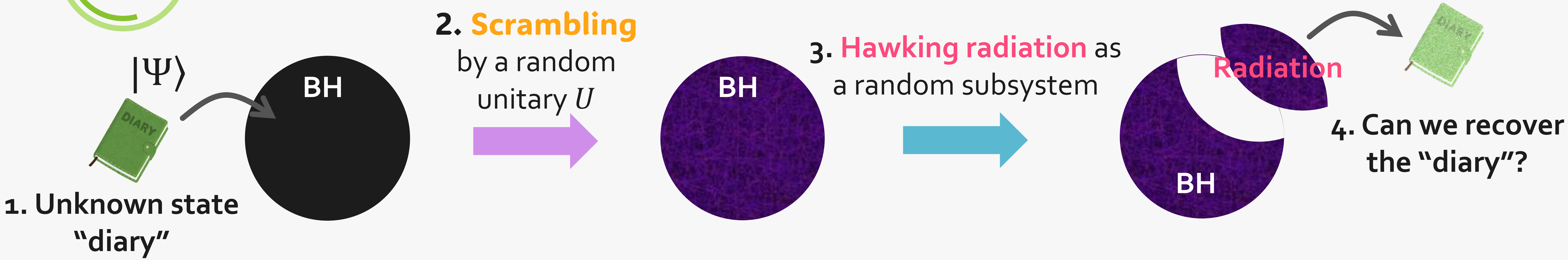

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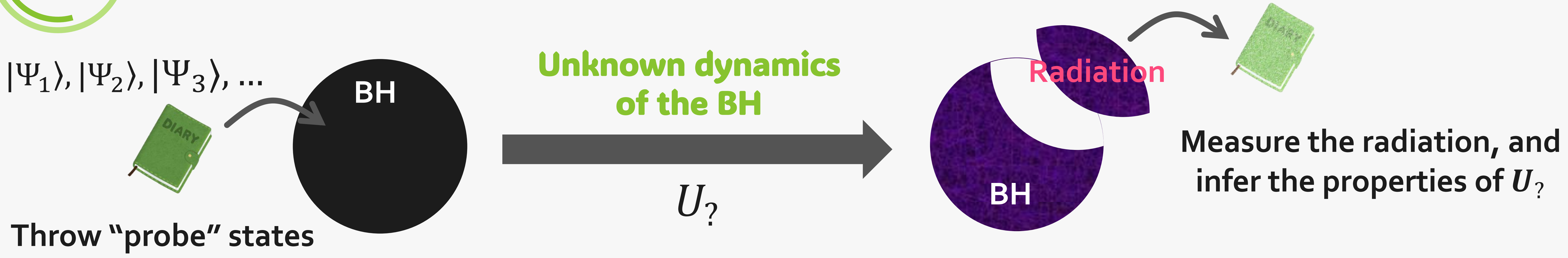
Can black hole dynamics be learned from Hawking radiation?

Hayden-Preskill setting

Information recovery from Hawking radiation



Problem 4.3

Can black hole dynamics be learned from Hawking radiation?

- This can be viewed as process tomography or quantum process learning.
  1. How many probe states are needed?
  2. How should we choose the probe states?
  3. What properties of $U_?$ are actually learnable under the BH-specific constraints?

Gravity and Quantum Error Correction

Six questions at the gravity-QEC interface

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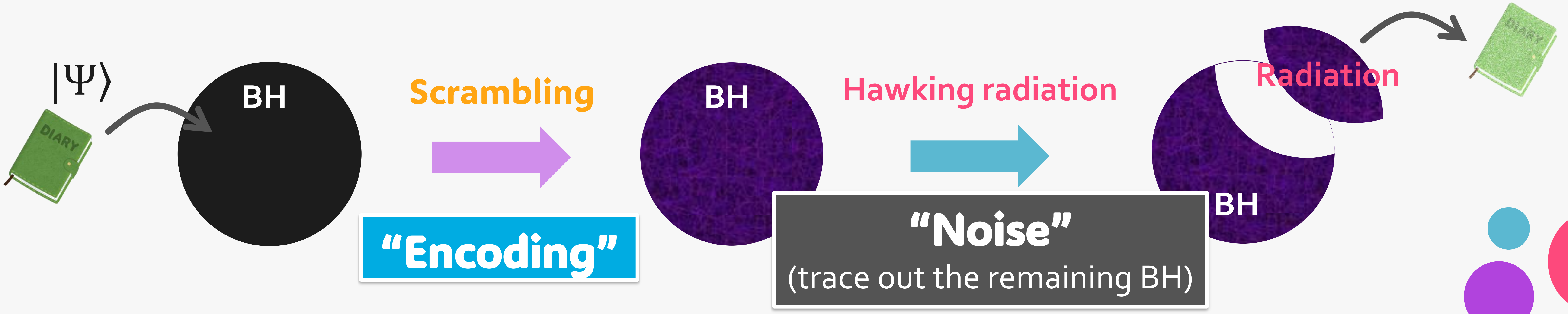
Chaos and QEC in Gravity?

From chaos to scrambling to QEC

- The Hayden-Preskill setting might suggest some connection b/t chaos and QEC.
  - **Intuition**: strongly chaotic dynamics should be scrambling!?

Folklore

Strongly chaotic dynamics scrambles quantum information, encoding it into highly non-local degrees of freedom, and thereby achieving QEC.



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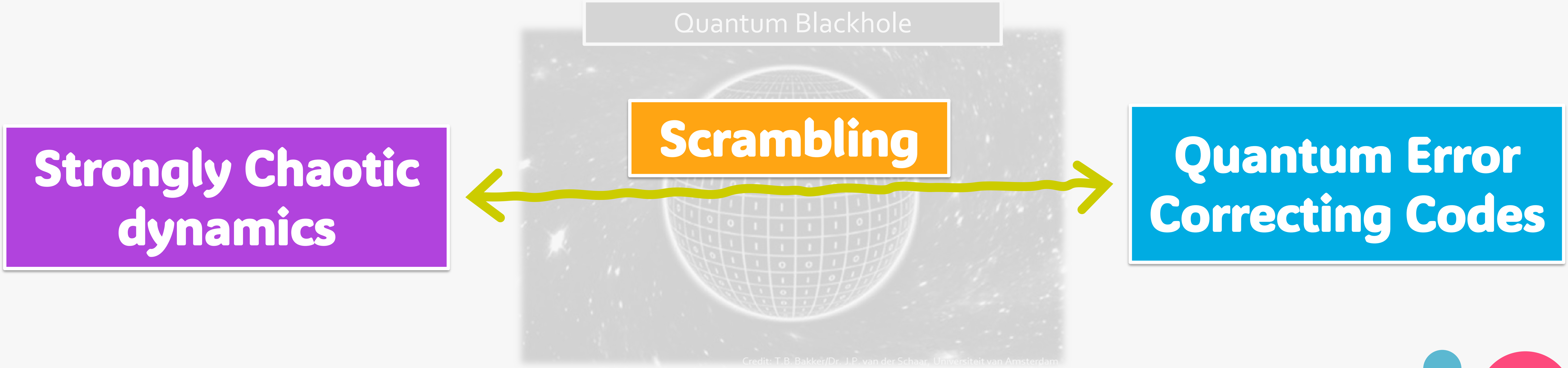
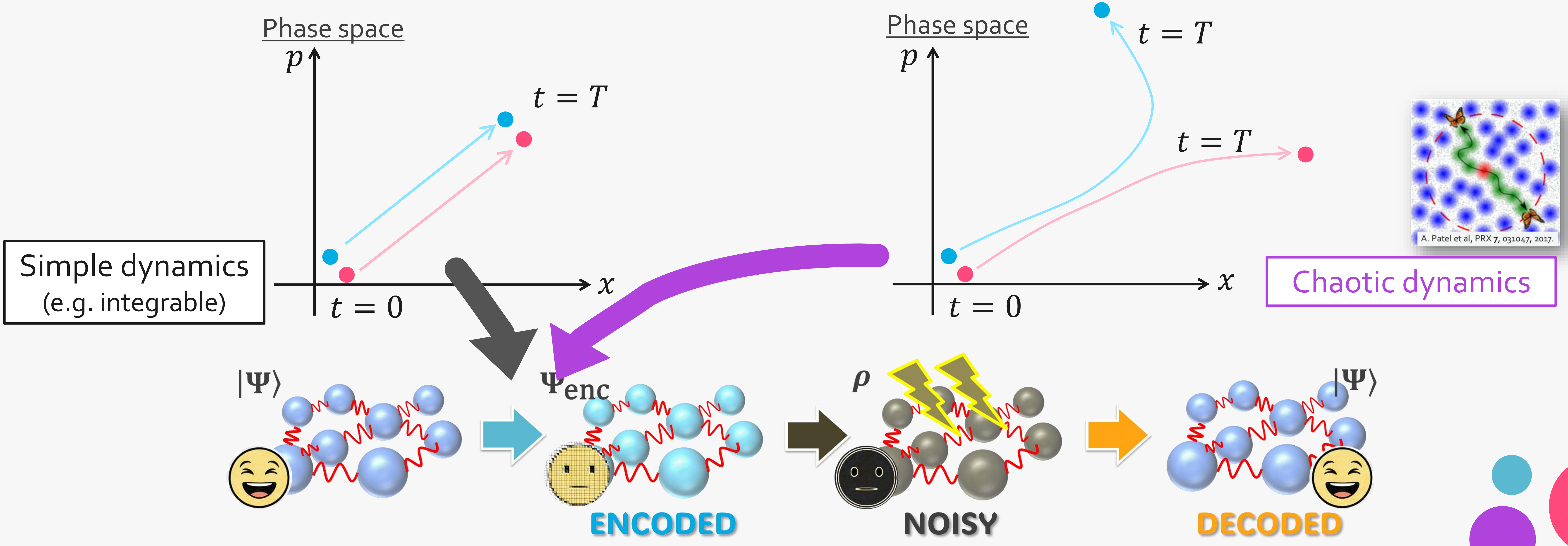


Chaos and QEC in Gravity?

Chaotic dynamics for encoding -intuition-

- Chaotic dynamics is sensitive to initial conditions (at least in classical case).



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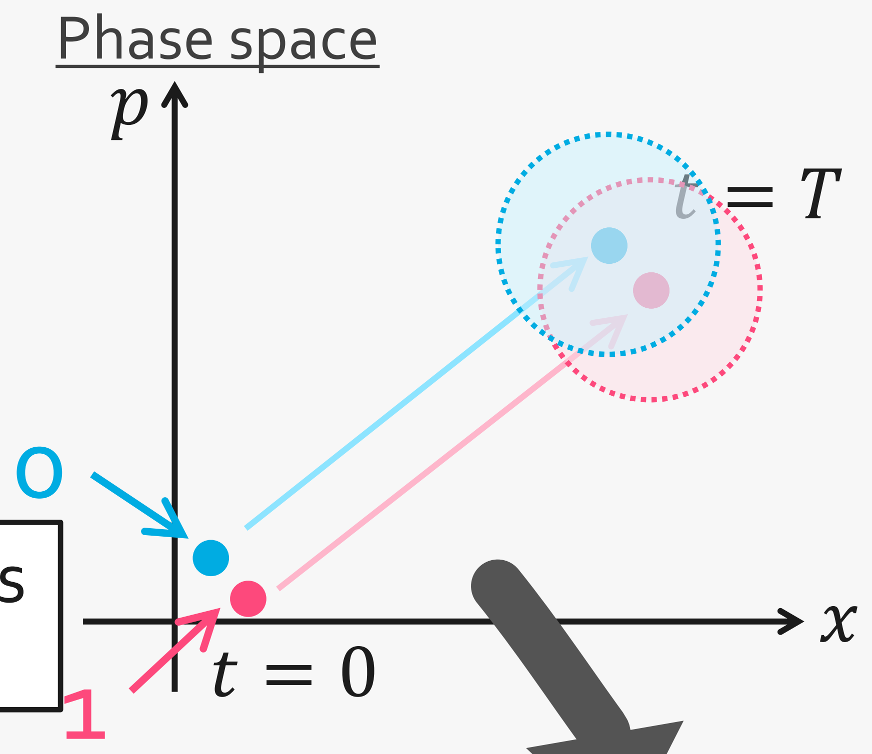
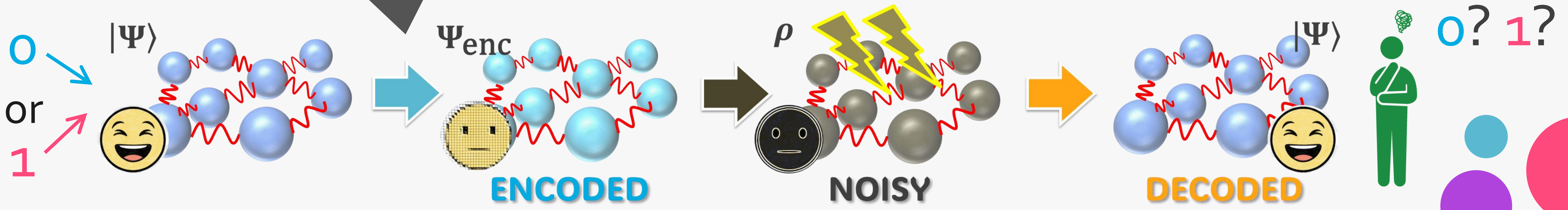


Simple dynamics
(e.g. integrable)

1. Encode 0 or 1 into an initial condition.
2. It undergoes the time evolution.
3. It is "***distorted***" by the **noise**.
4. Huge overlap!! No way to distinguish the *distorted* 0 or 1.

→ Decoding will **NOT** be possible.



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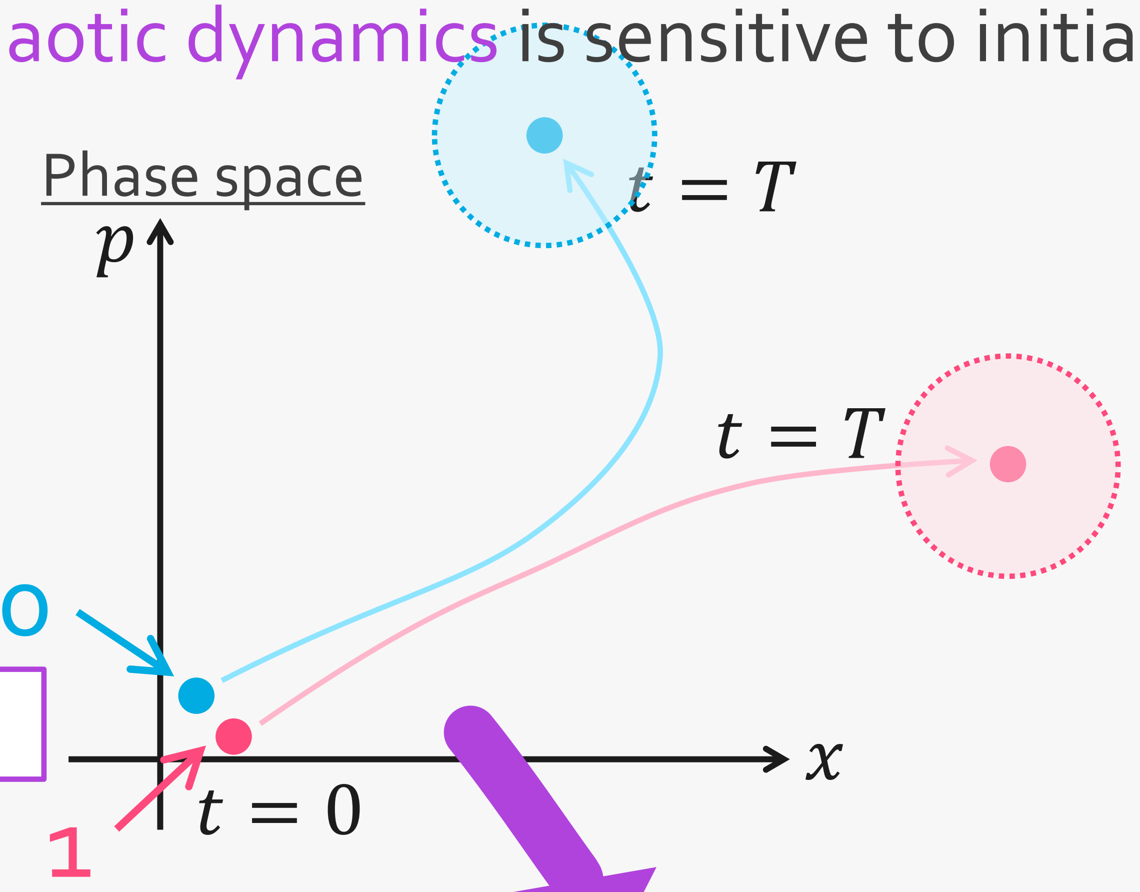
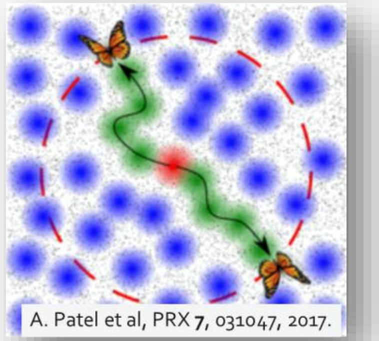
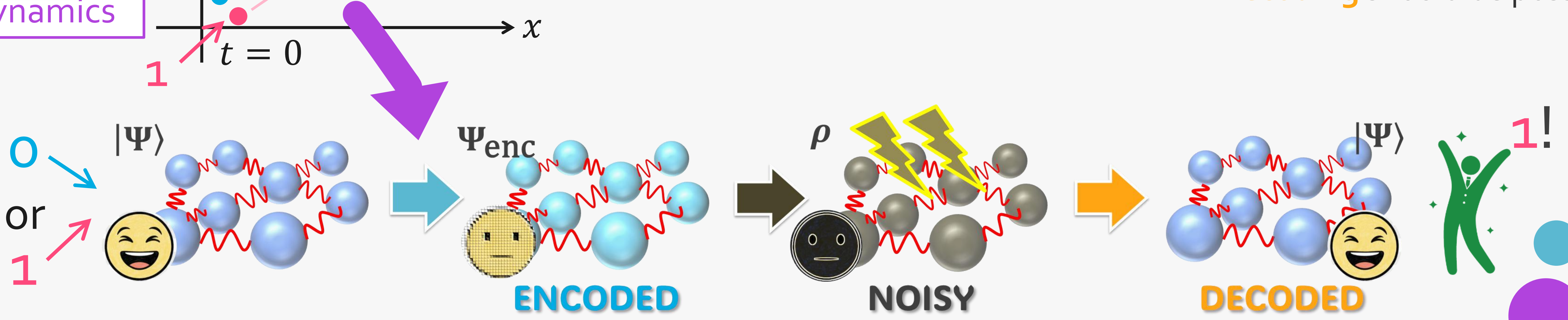




Chaotic dynamics

1. Encode 0 or 1 into an initial condition.
2. It undergoes the **chaotic** time evolution.
3. It is "*distorted*" by the **noise**.
4. **No overlap** between the *distorted* 0 or 1.

→ Decoding should be possible.

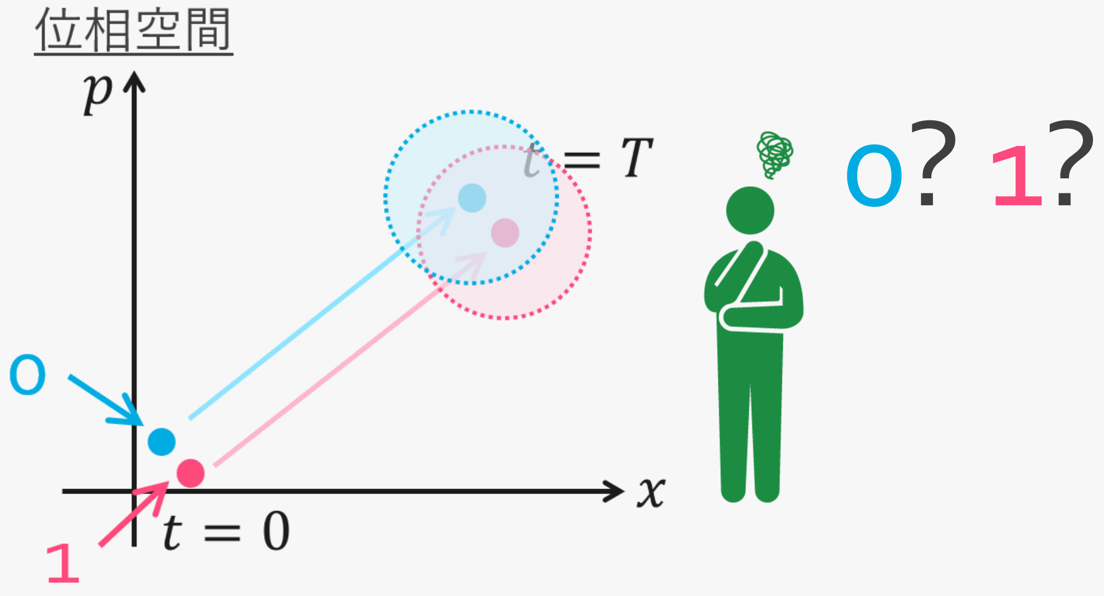


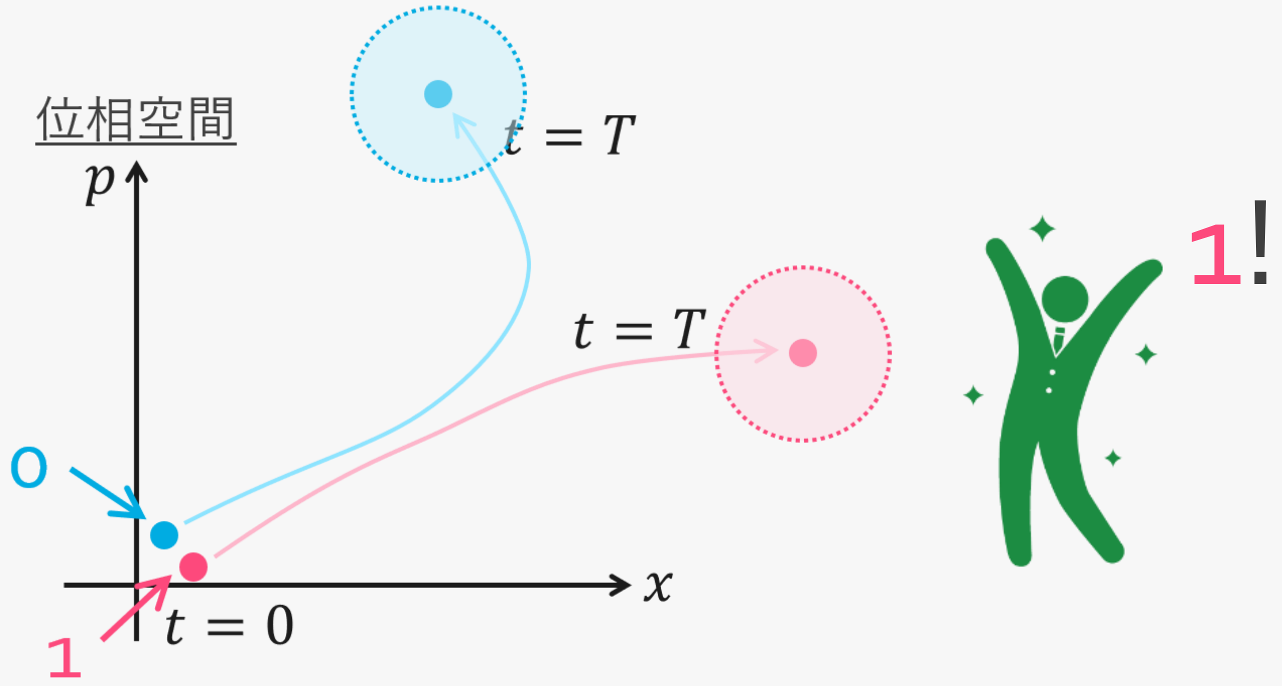
Chaos and QEC in Gravity?

Chaotic dynamics for encoding -intuition-

- Chaotic dynamics is sensitive to initial conditions (at least in classical case).
  - The sensitivity would be useful for protecting the initial information.
  - NOTE: precise control of the system is needed, to keep track of the information.

Chaos is hard to tame, but once controlled,
it may offer powerful encoding methods/capabilities.





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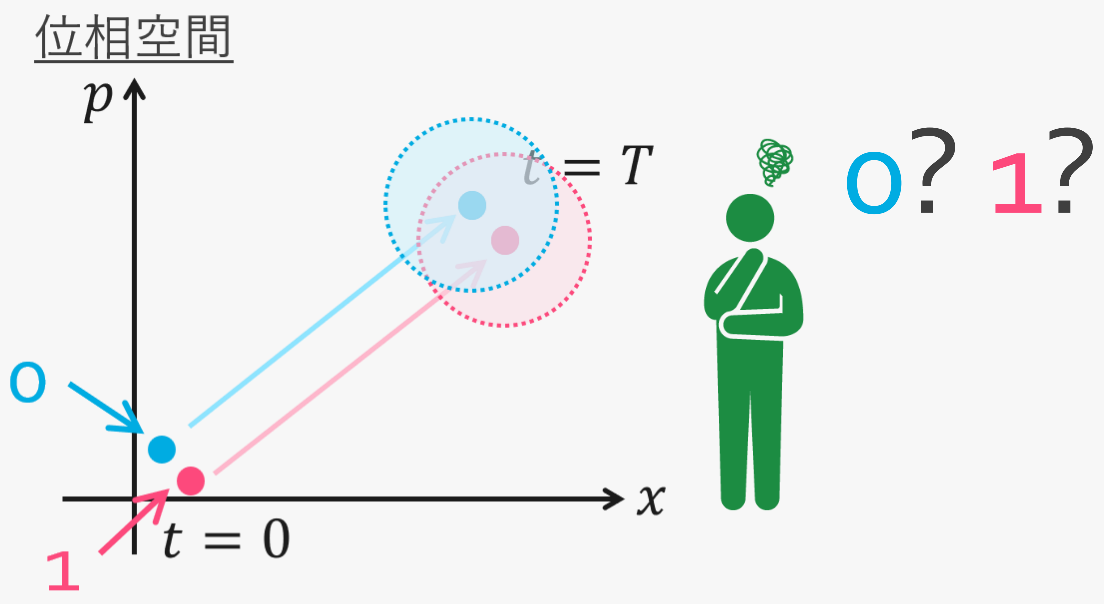
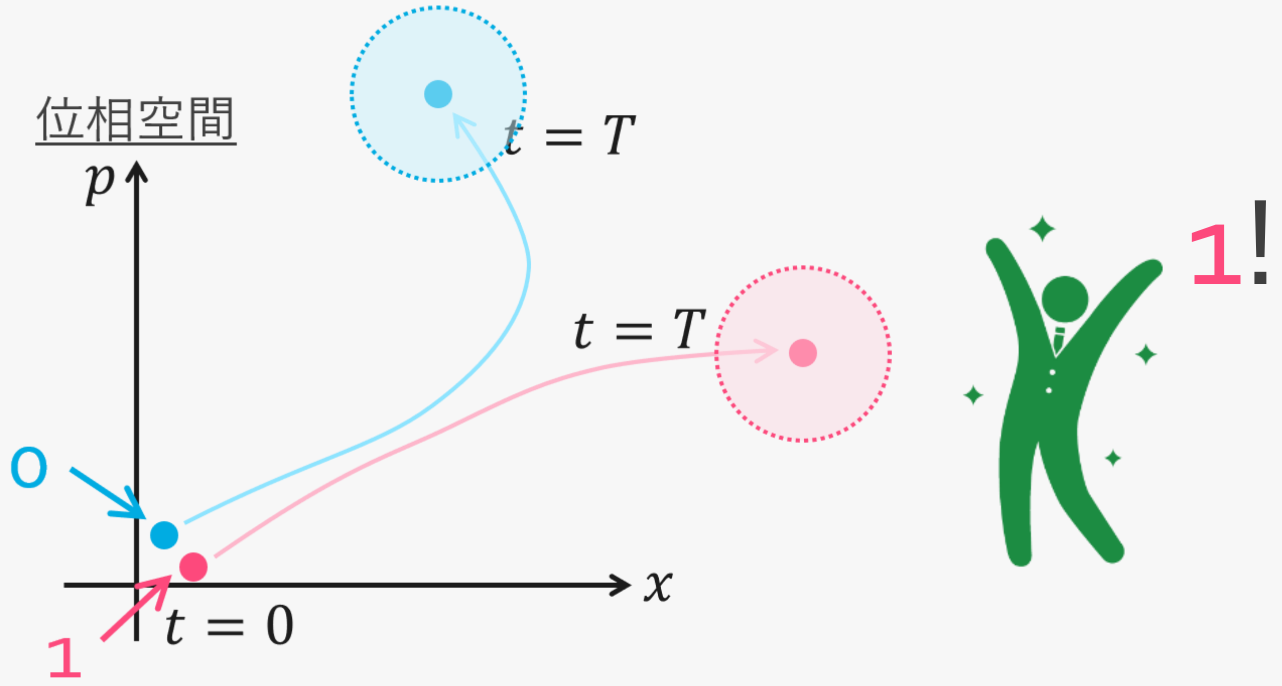
- In **the quantum realm**, things are not as clear as in the classical case.
  - **Superposition:** information can be encoded as $\alpha|0\rangle + \beta|1\rangle$
  - **Unitarity:** unitary preserves the distance, $\| U|\varphi_0\rangle - U|\varphi_1\rangle \| = \| |\varphi_0\rangle - |\varphi_1\rangle \|$





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Classical-Quantum correspondence of QEC:

Quantum recovery ⇔ classical recovery in two different bases

e.g., If one can recover both "position" and "momentum" information, one can recover the entire quantum state — and hence any observable.

$\mathbf{Q} = \mathbf{C}^{\times 2}$

[Renes, PRA 2016] [YN, Matsuura and Koashi, npj QI 2025] [Utsumi, YN, et al., in prep]

$t = 0$

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Chaos and QEC in Gravity?

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- ☐ Quantum holography could be viewed as a Quantum Error Correcting Code (QECC).
  - ➢ C-Q correspondence implies that "a QECC = two copies of Classical Error Correcting Codes".
    - ➢ This is true even if it's not a stabilizer code.
  - ➢ **Can quantum holography be built from two "classical holographies"?**

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So, is there a "classical holography"?

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Thank you

for your attention