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January 30, 2026

Improving quantum communication rates with permutation-invariant codes

arXiv:2508.09978

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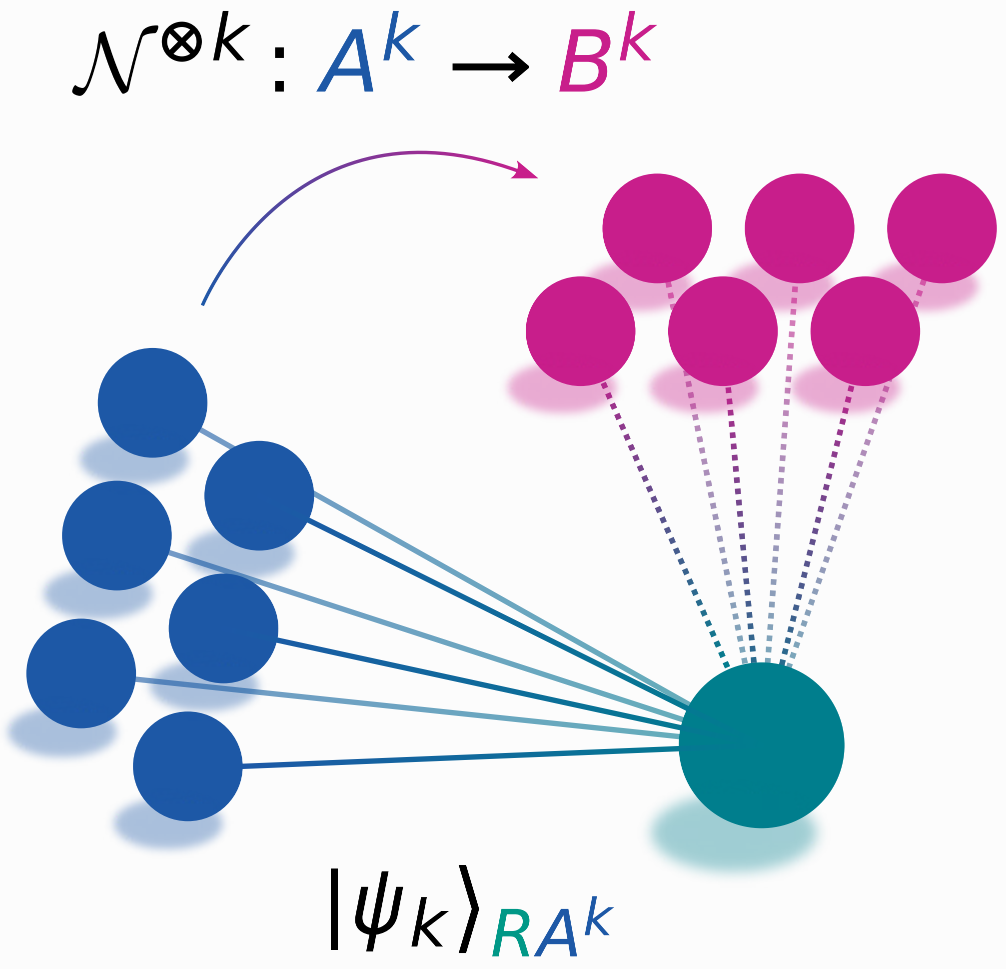

Joint work with my student
Sujeet Bhalerao (UIUC Math)

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

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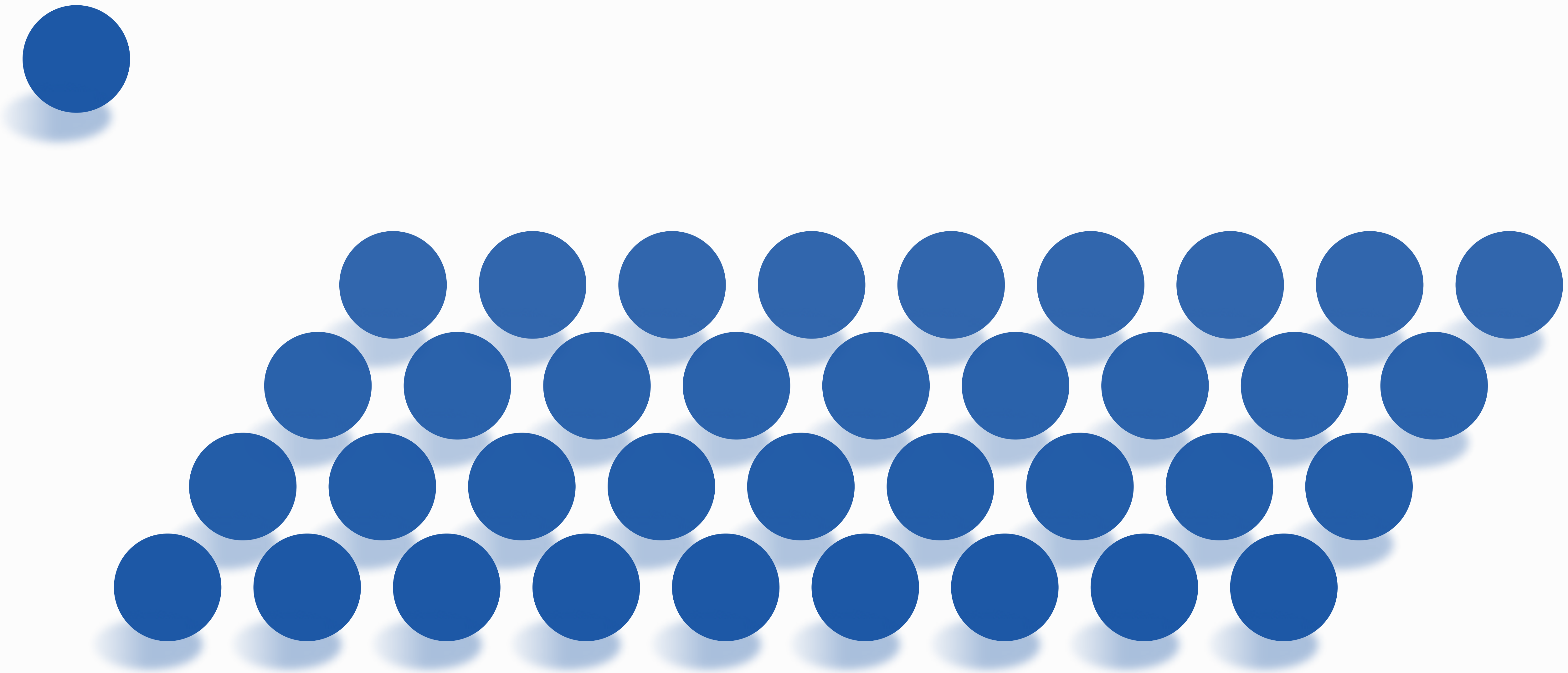
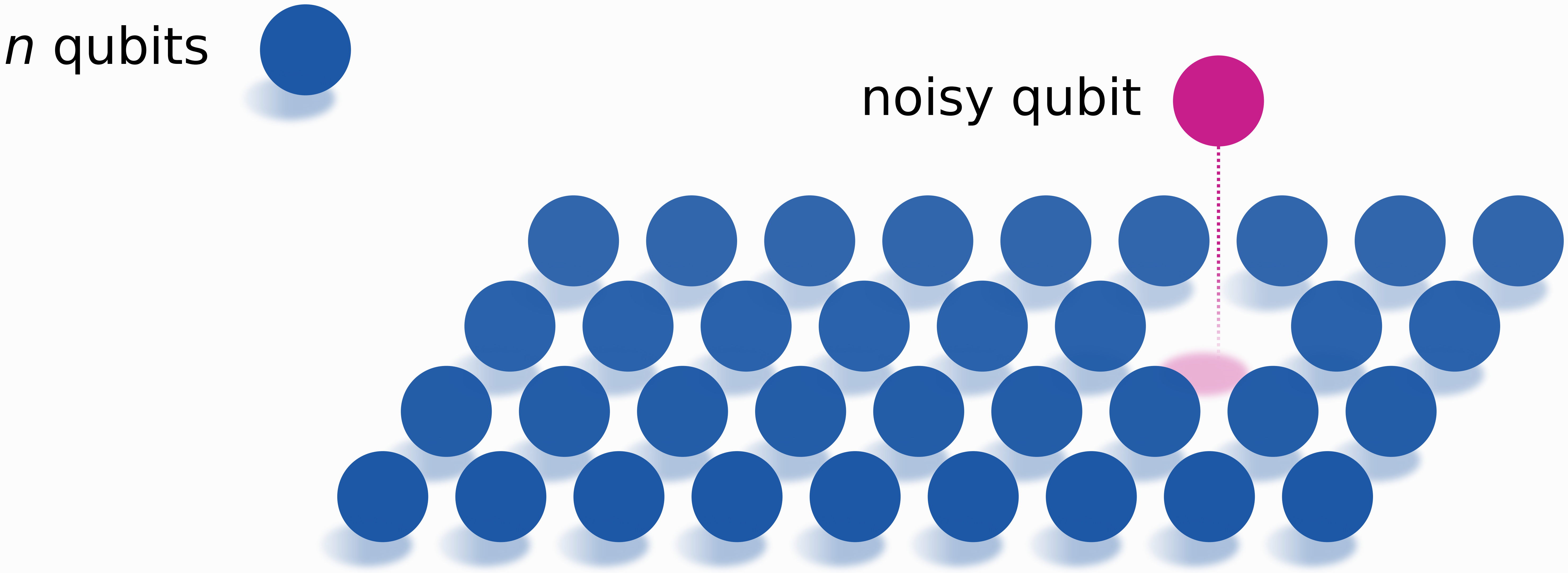
Noise in quantum devices

n qubits



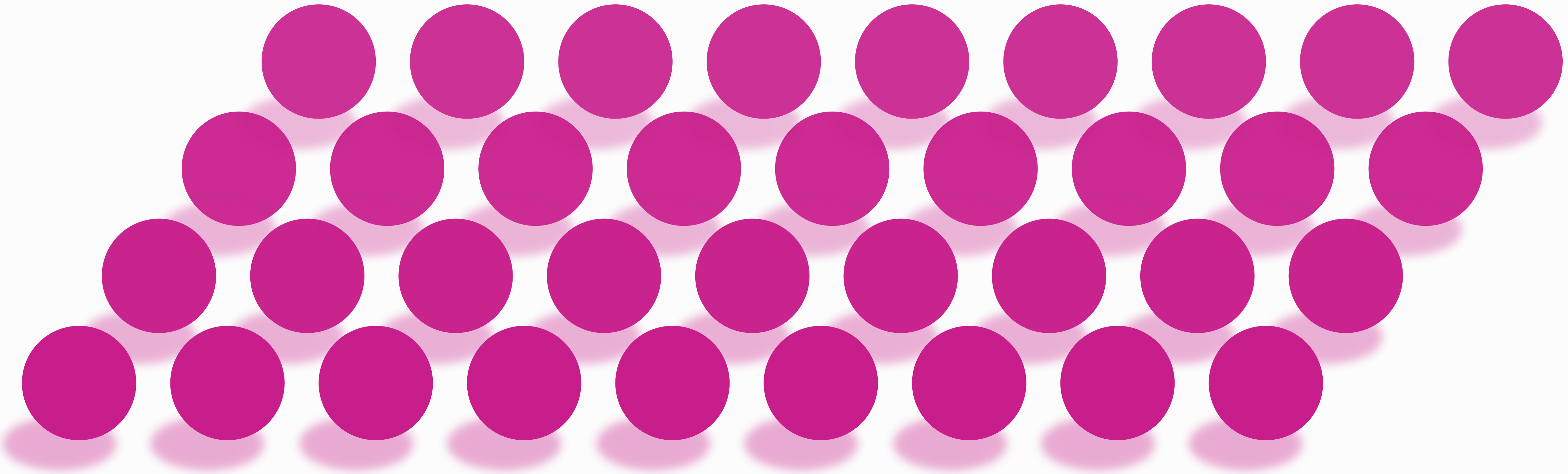
Noise in quantum devices



$$\bullet = \mathcal{N}(\bullet) = (1-p)\,\bullet + p\left[q_1\, X \bullet X + q_2\, Y \bullet Y + q_3\, Z \bullet Z\right]$$

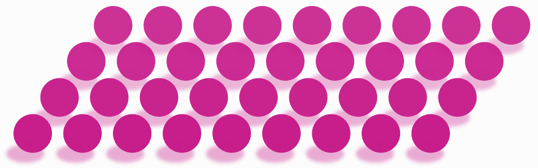
Noise in quantum devices

n noisy qubits $\bullet = \mathcal{N}(\bullet) = (1-p)\bullet + p\left[q_1 X \bullet X + q_2 Y \bullet Y + q_3 Z \bullet Z\right]$



Independent and identically distributed (i.i.d.) noise model $\mathcal{N}^{\otimes n}$

Noise in quantum devices

How much quantum information can be stored in a device  ?

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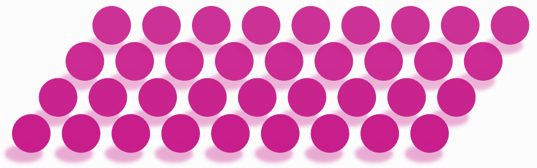
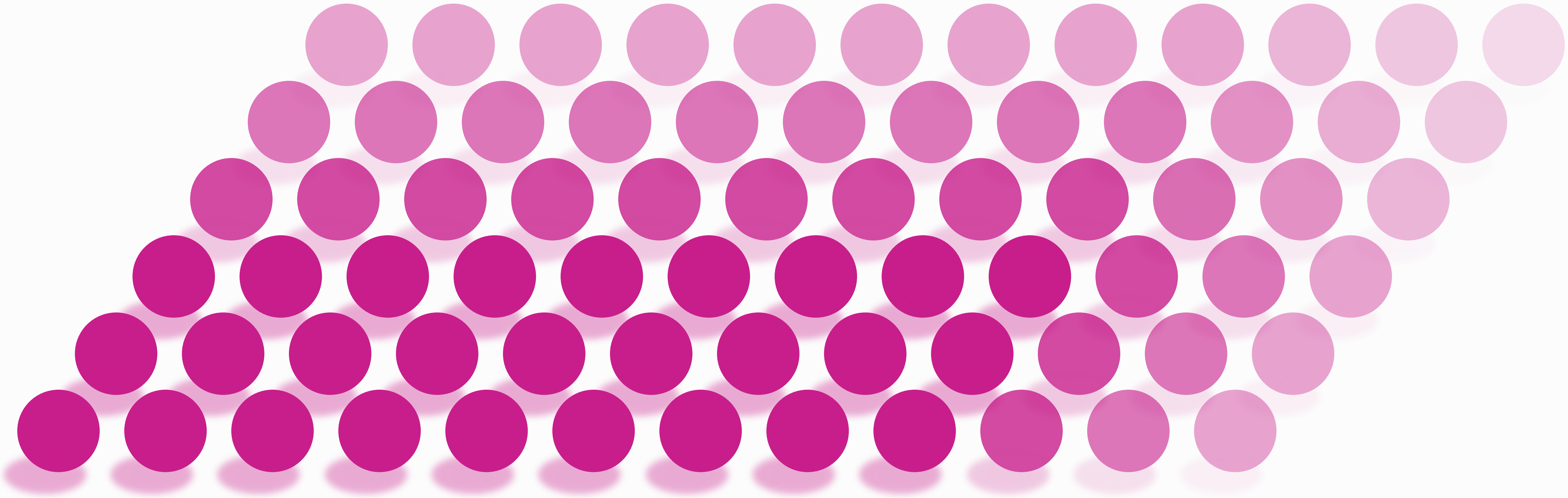
How much quantum information can be stored in a device  ?

Step 1: Extend n-qubit system infinitely ($n \to \infty$).



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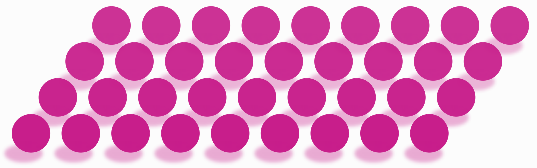
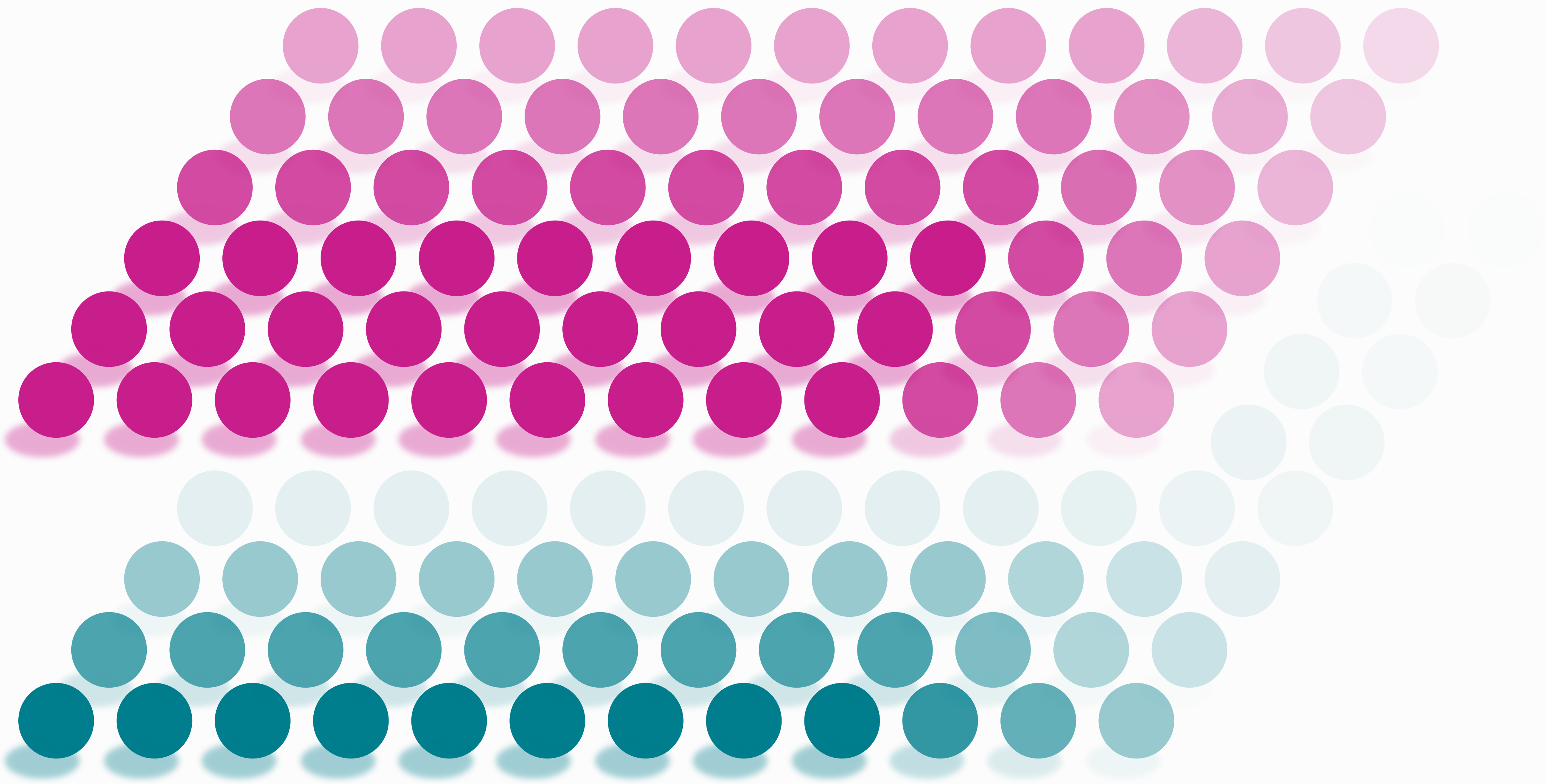
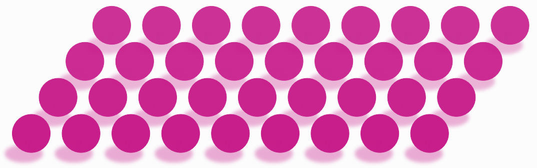
How much quantum information can be stored in a device  ?

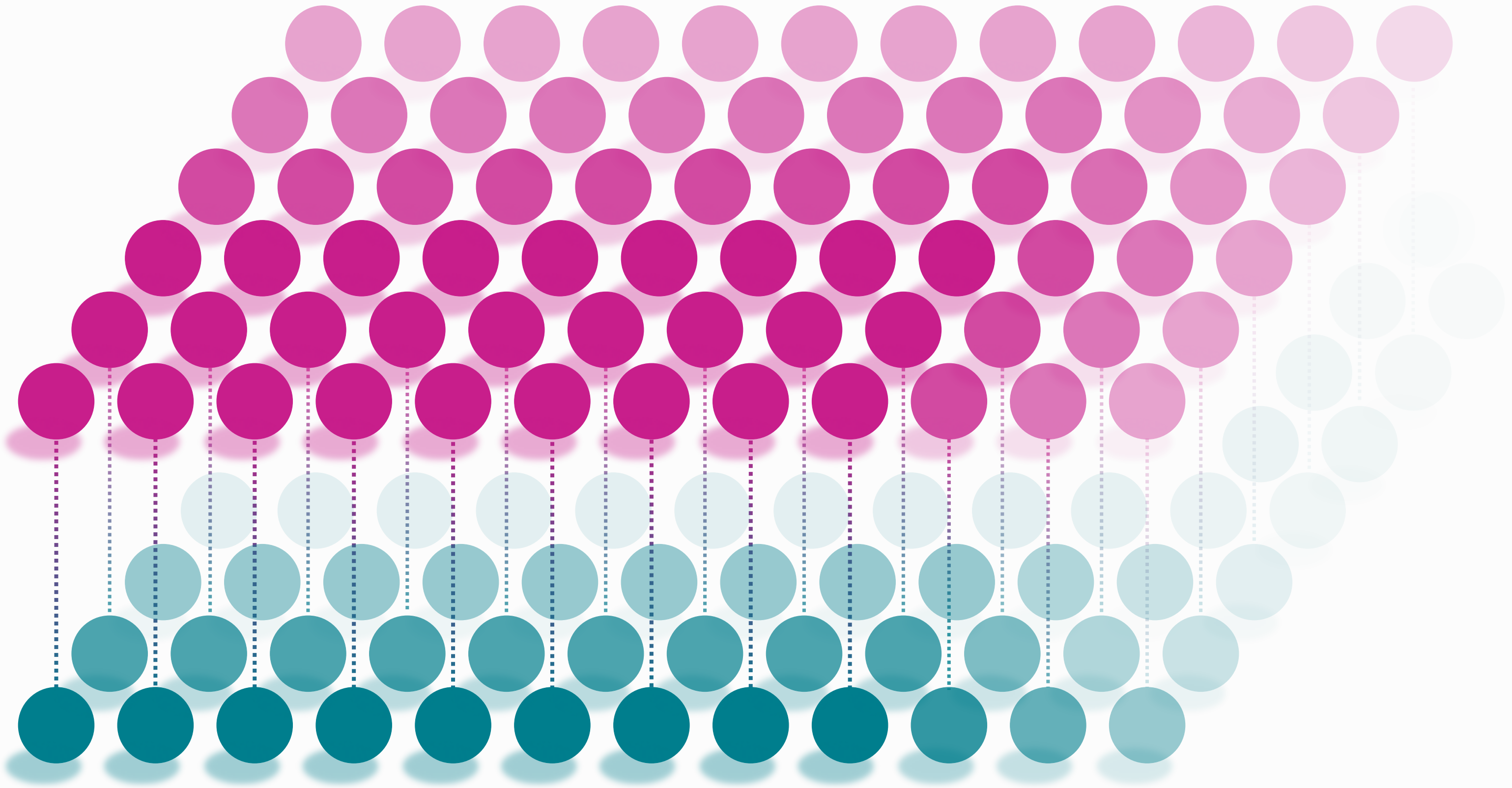
Step 2: Consider a **reference qubit** for each **system qubit**.

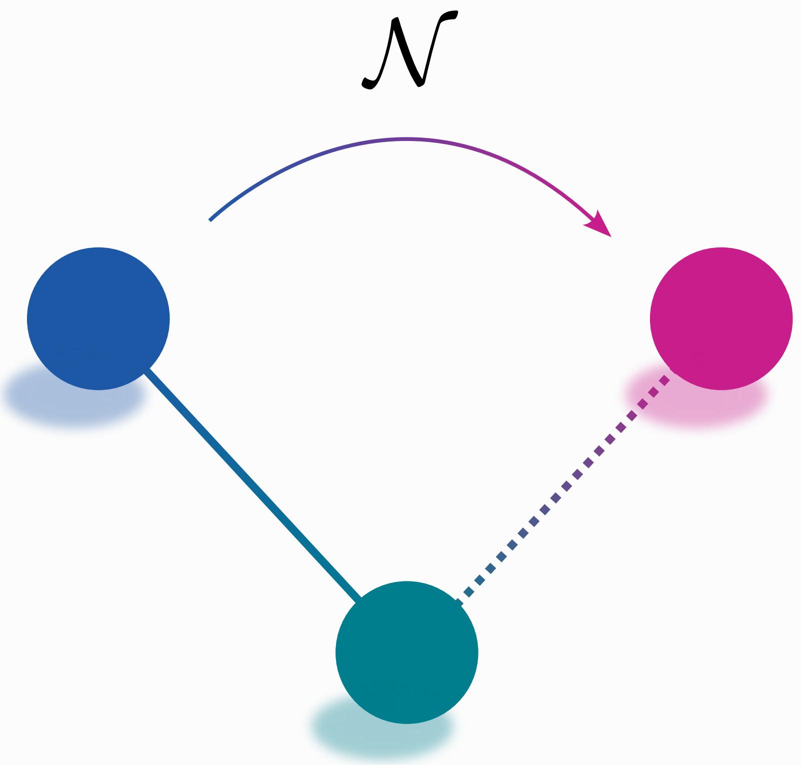


Noise in quantum devices

How much quantum information can be stored in a device  ?

Step 3: Quantify how much initial correlation between **system** and **reference qubits** survives the noise.





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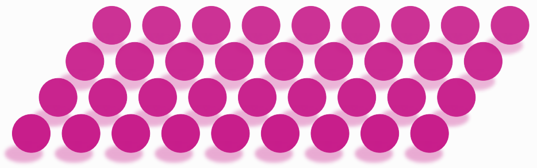
How much quantum information can be stored in a device  ?

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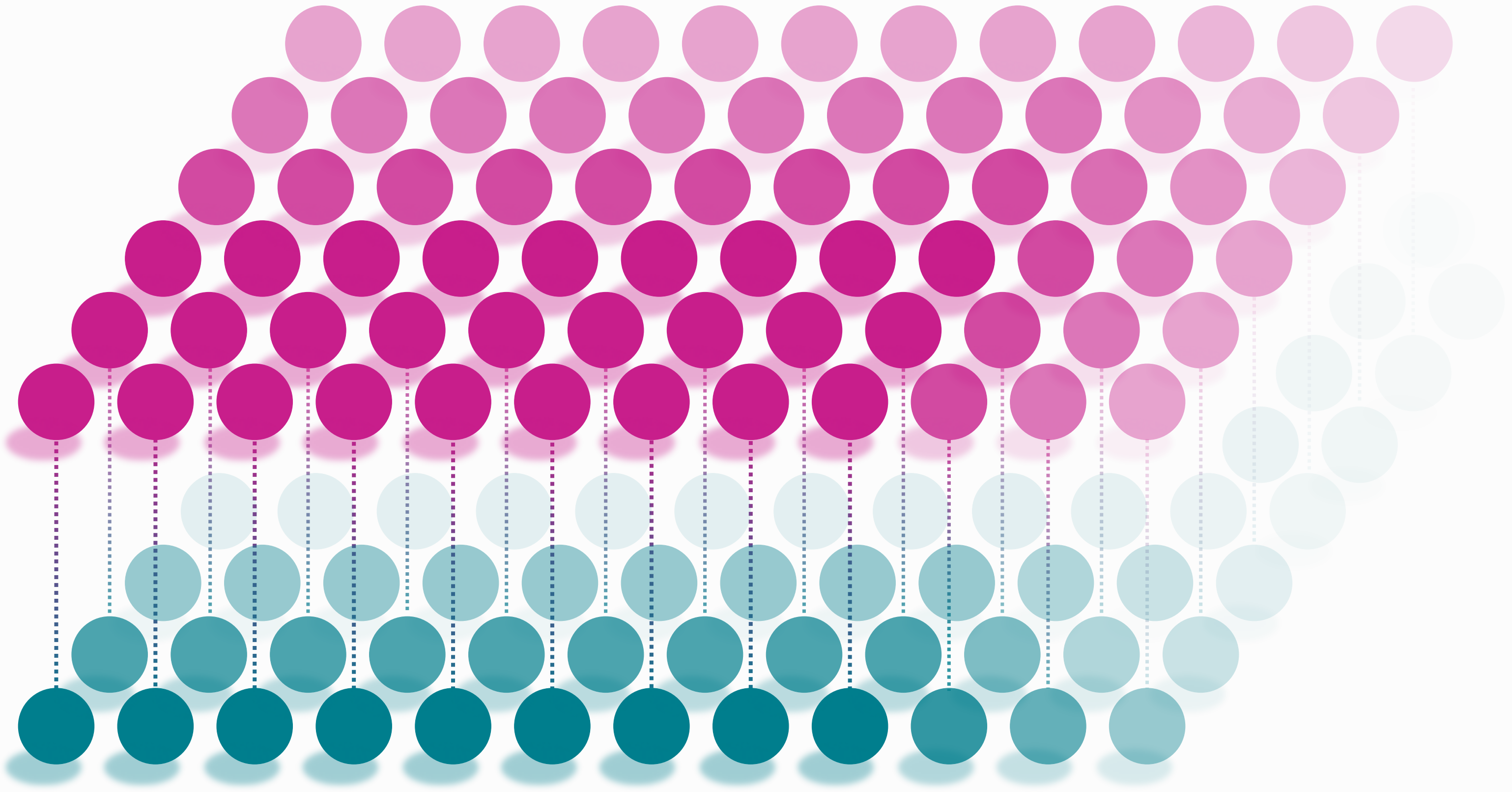
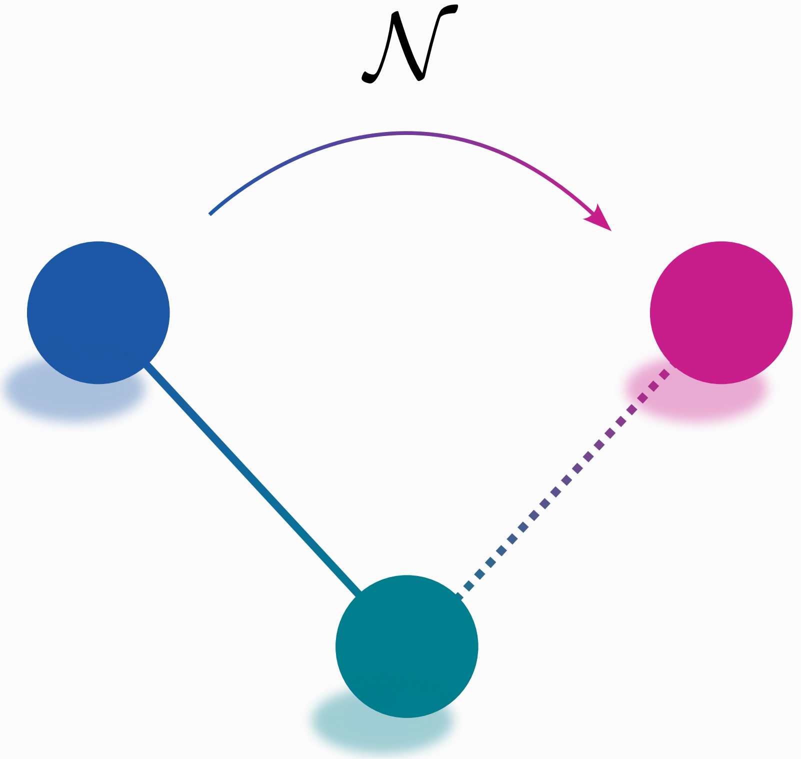
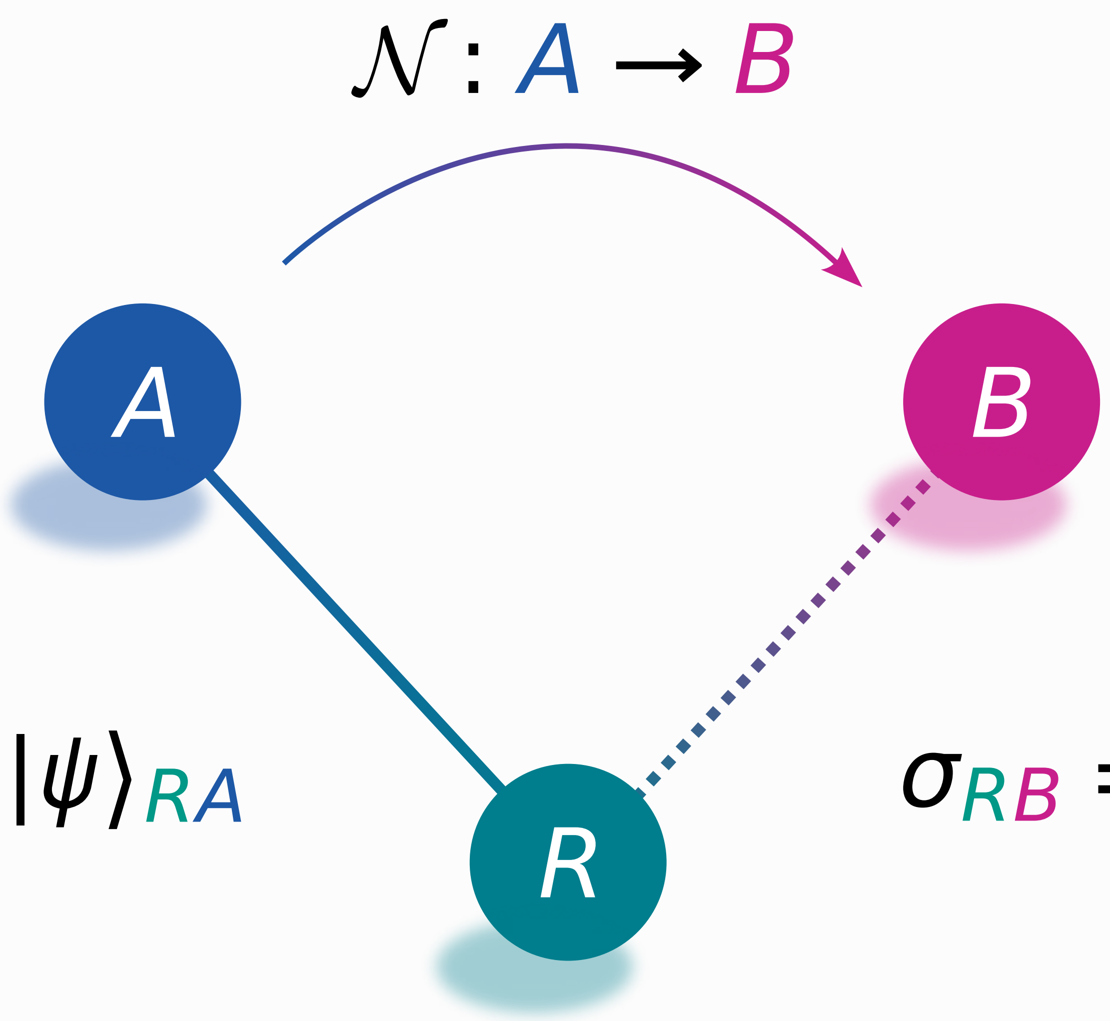




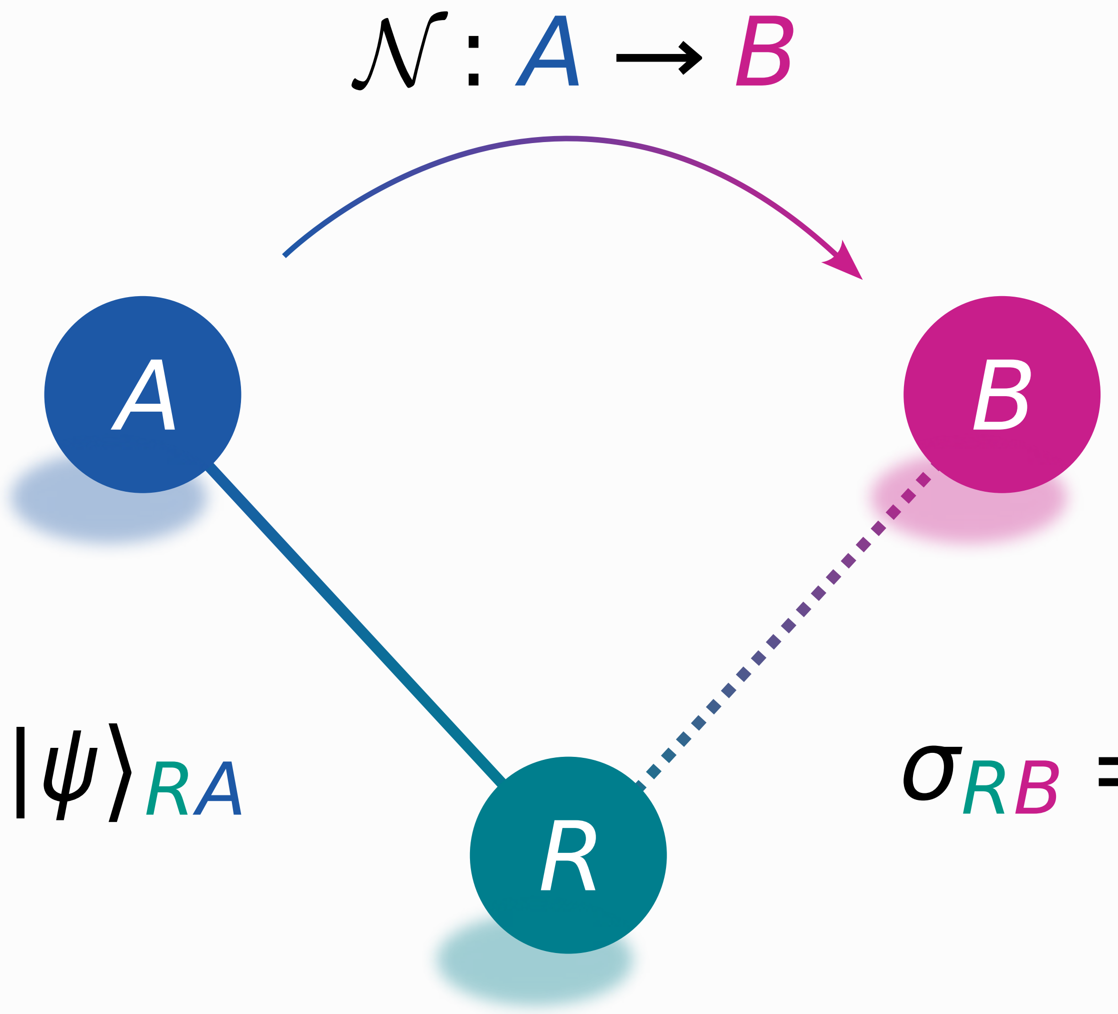
How to quantify correlations?

Quantifying quantum correlations



$$\sigma_{RB} = (\mathrm{id}_R \otimes \mathcal{N}_{A\to B})(\psi_{RA})$$

Quantifying quantum correlations



$$\sigma_{RB} = (\mathrm{id}_R \otimes \mathcal{N}_{A\to B})(\psi_{RA})$$

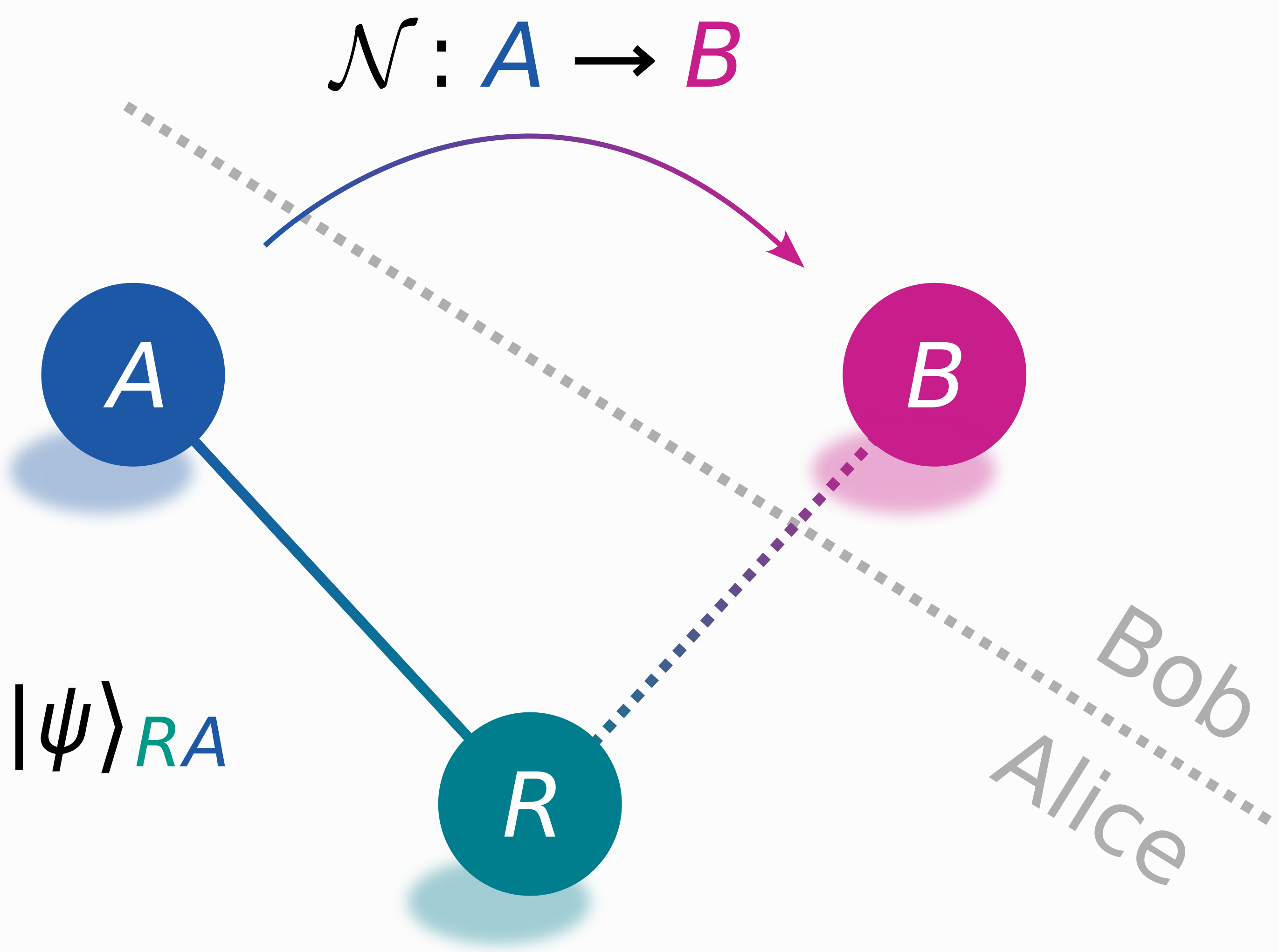
Coherent information

$$I_c(\mathcal{N}, \psi) = S(B)_\sigma - S(RB)_\sigma$$

$$S(Q)_\sigma = -\mathrm{tr}\left(\sigma_Q \log \sigma_Q\right)$$

Quantifying quantum correlations

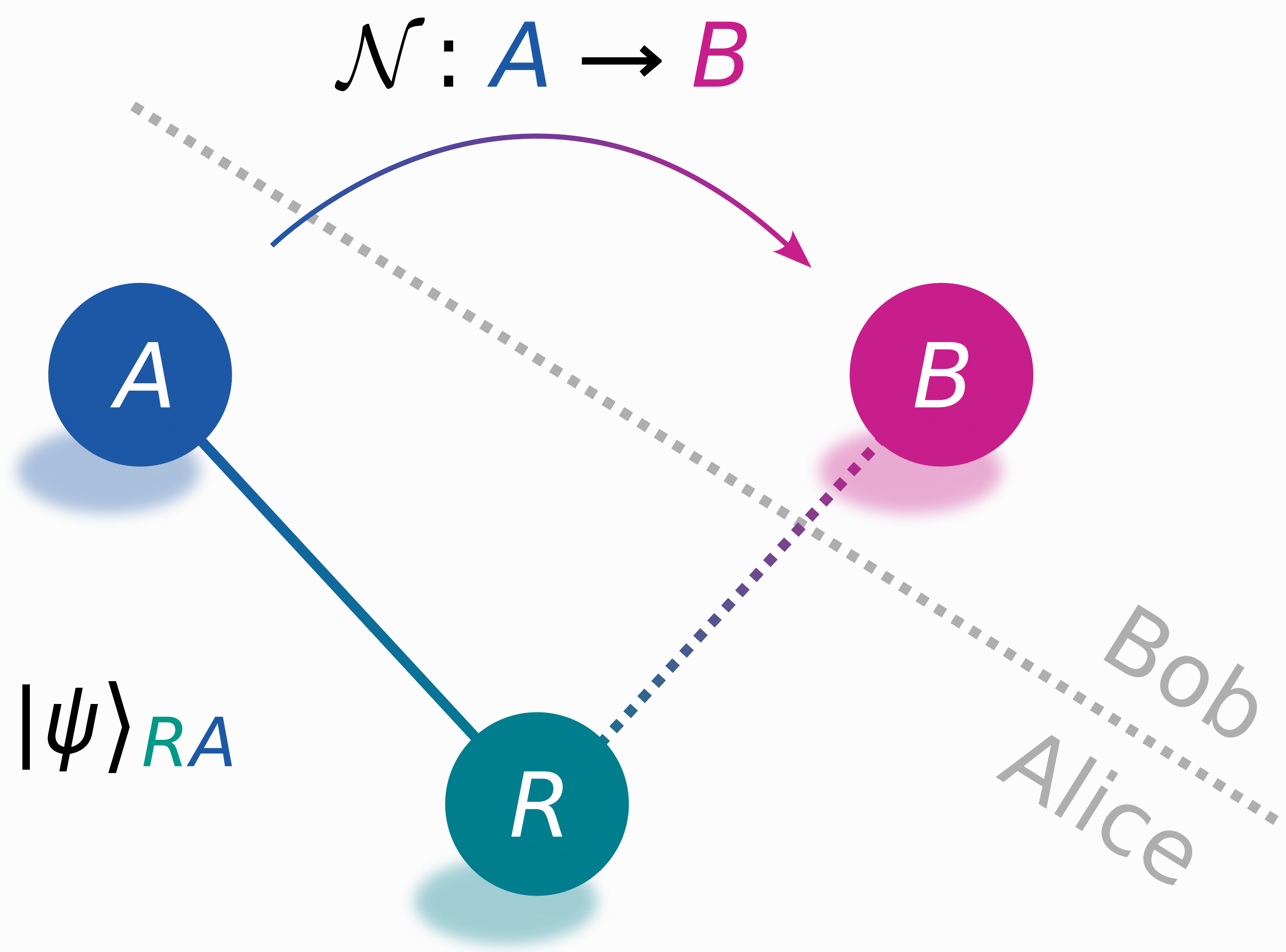
Coherent information $I_c(\mathcal{N}, \psi) = S(B)_\sigma - S(RB)_\sigma$



Interpretation of $I_c(\mathcal{N}, \psi)$:

Correlations established between **Alice** and **Bob** that survived the noisy channel action.

Quantifying quantum correlations



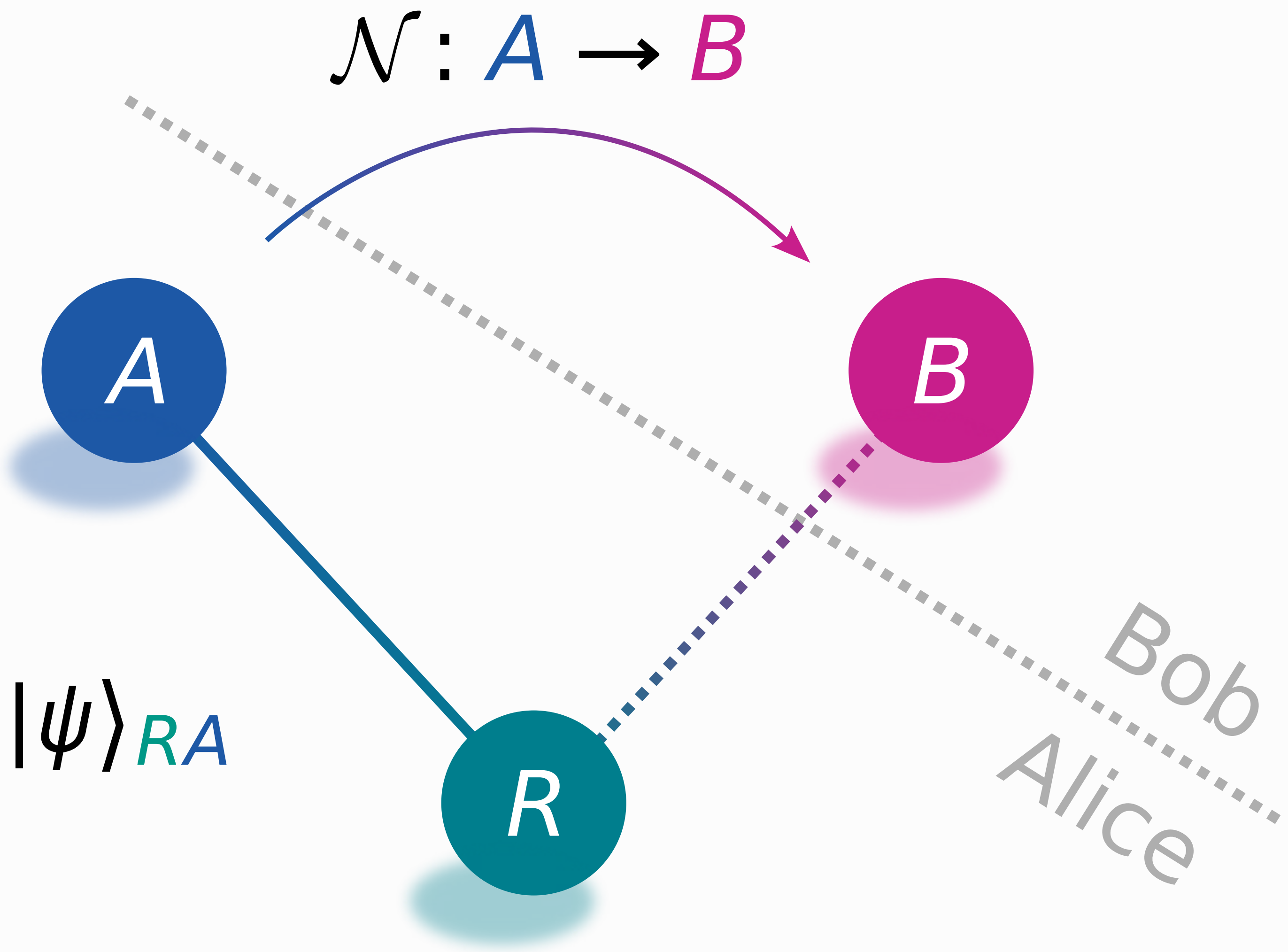
Channel coherent information

Choose best initial state ψ_{RA} between **reference** and **channel** qubit:

$$I_c(\mathcal{N}) = \max_{\psi} I_c(\mathcal{N}, \psi)$$

Quantifying quantum correlations

Channel coherent information $I_c(\mathcal{N}) = \max_{\psi} I_c(\mathcal{N}, \psi)$



Quantum capacity theorem:

$I_c(\mathcal{N})$ many ebits per channel use can be recovered with fidelity ≈ 1 in the limit $n \to \infty$.

Lloyd '97, Shor '02, Devetak '05

Quantifying quantum correlations

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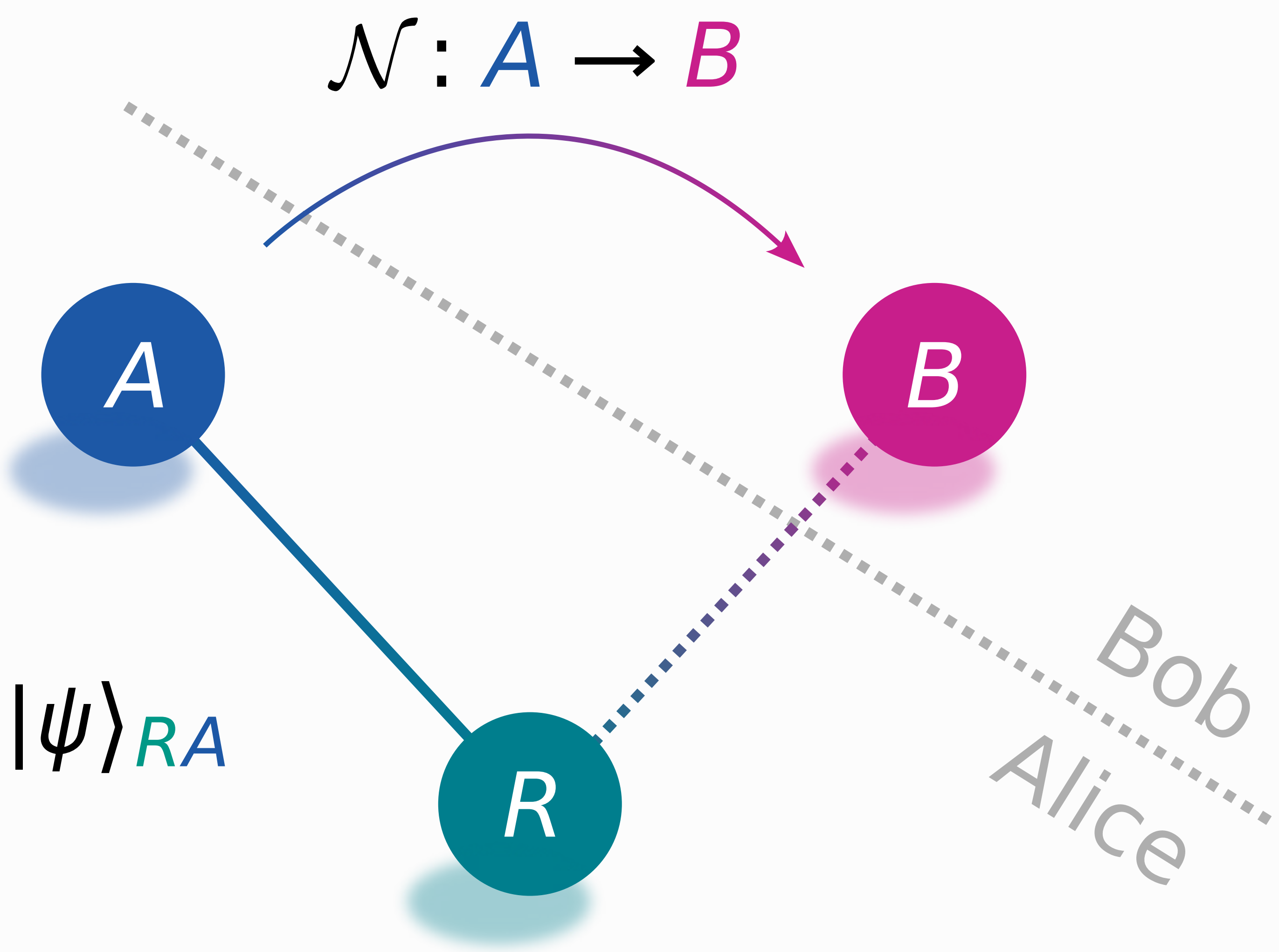

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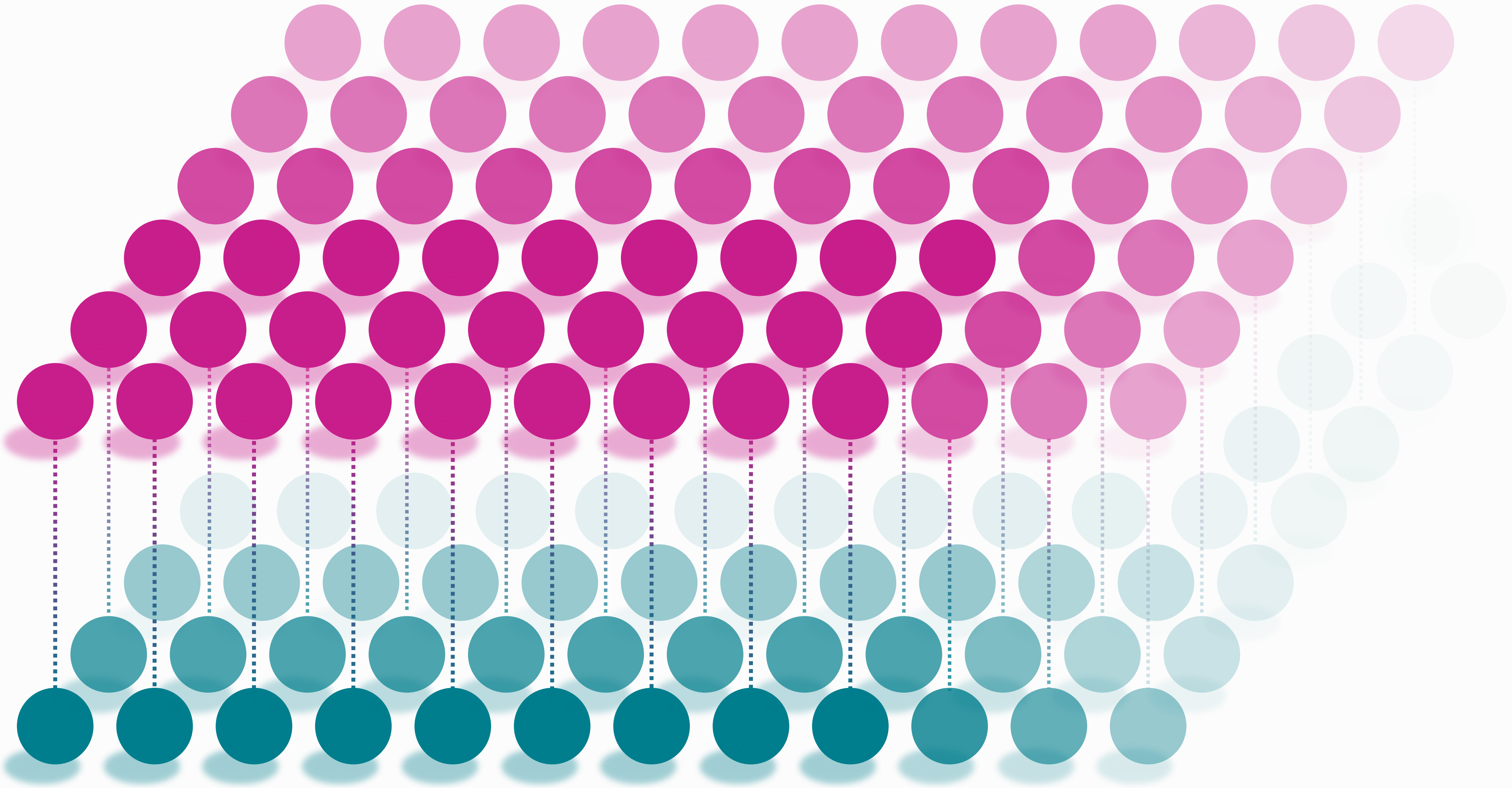
Clearest proof:

Hayden et al., quant-ph/0702005

Lloyd '97, Shor '02, Devetak '05

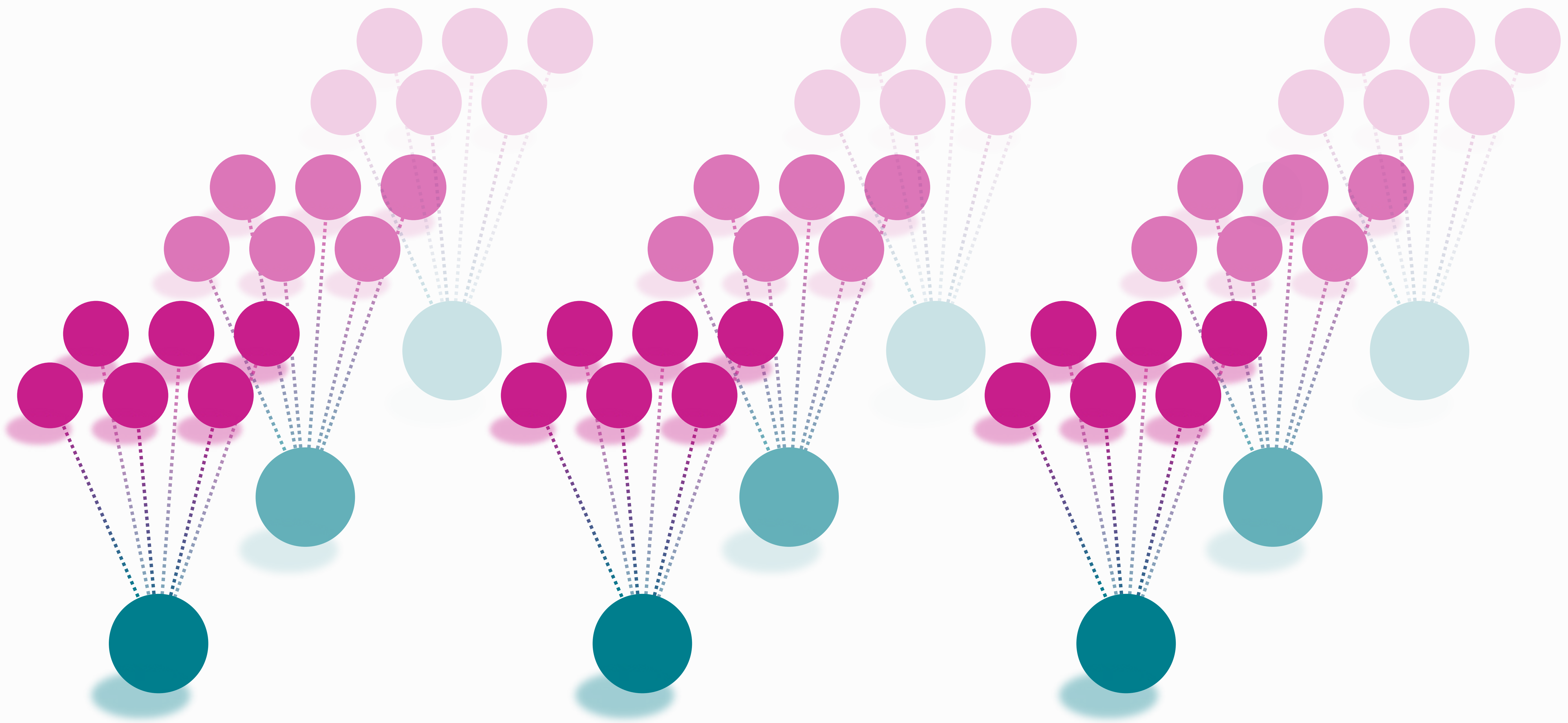
Superadditivity of coherent information

Recall: We aim to quantify surviving correlations to a reference system.



Superadditivity of coherent information

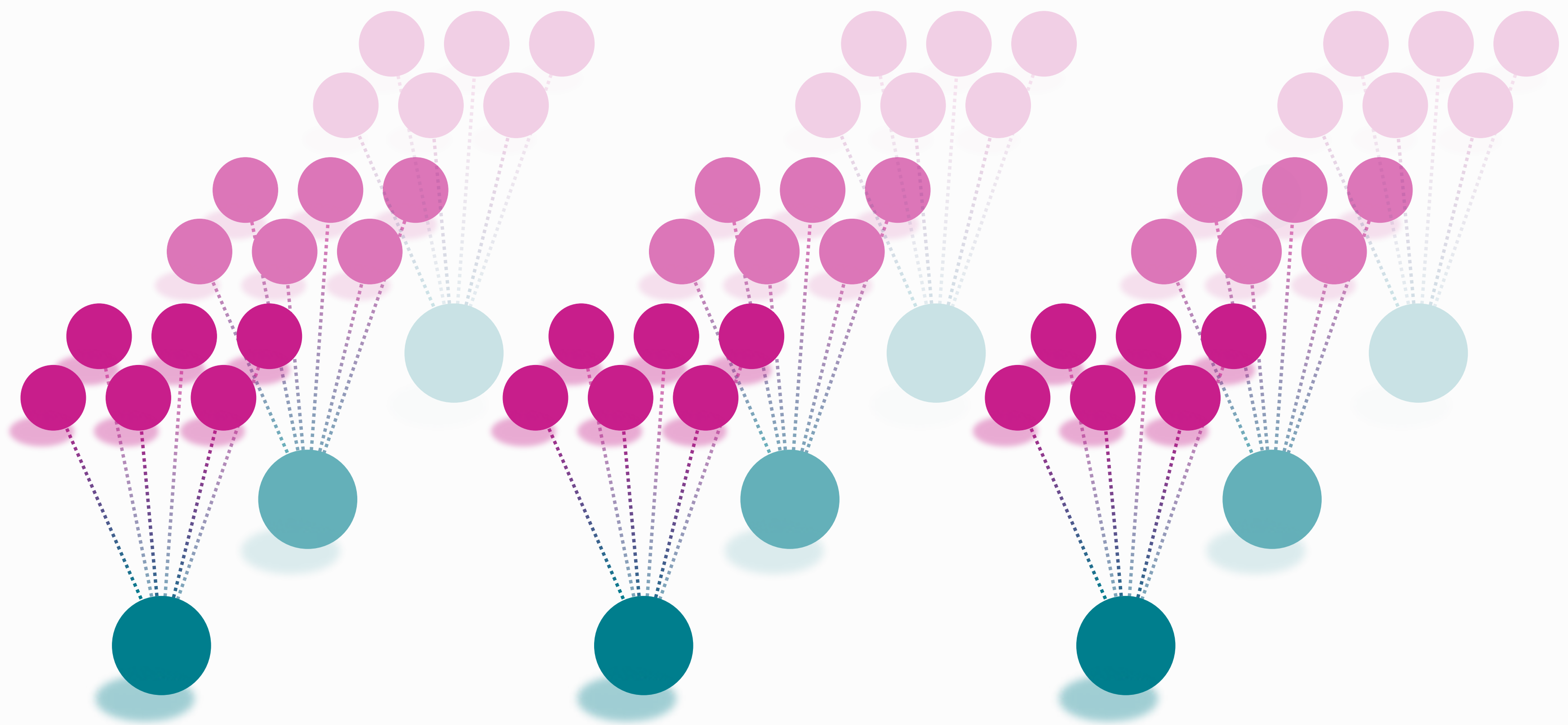
Idea: Use code blocks consisting of *k* entangled qubits.



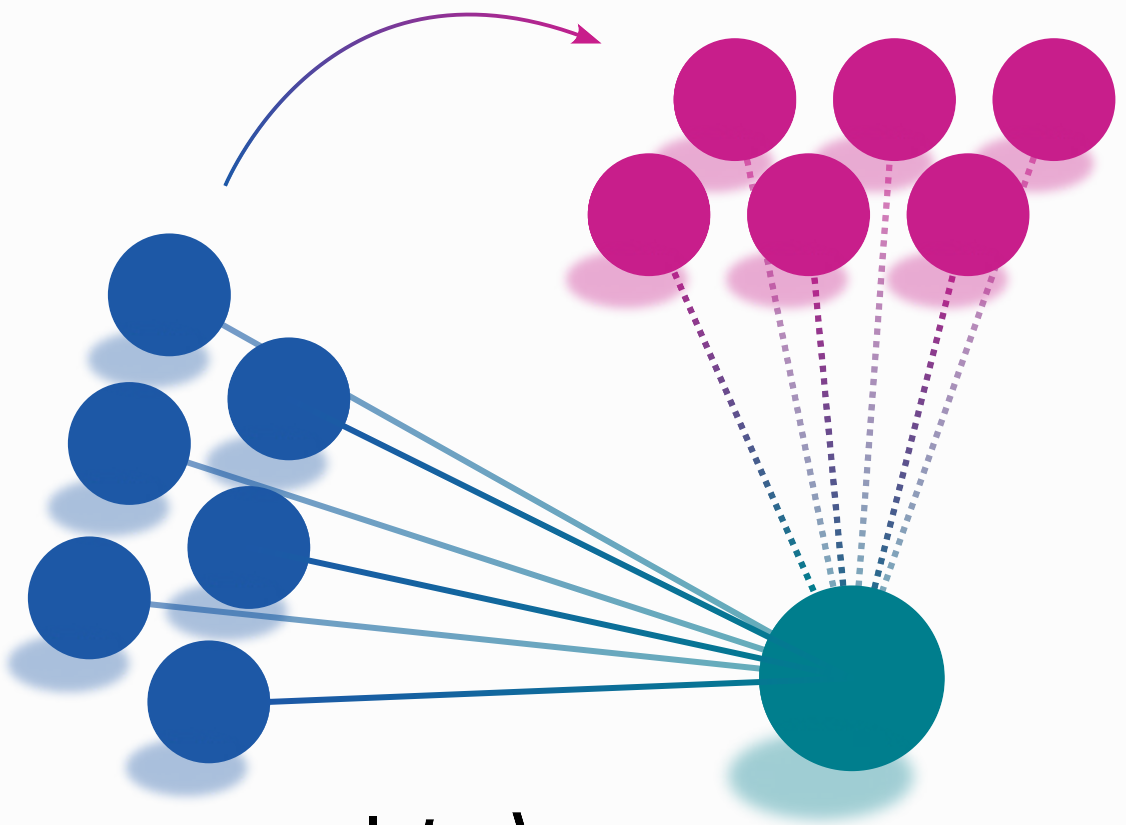
Superadditivity of coherent information

This creates blocks of k qubits in a state $|\psi_k\rangle_{RA^k}$

with coherent information $\frac{1}{k} I_c(\mathcal{N}^{\otimes k}, \psi_k)$.



$\mathcal{N}^{\otimes k} : A^k \to B^k$



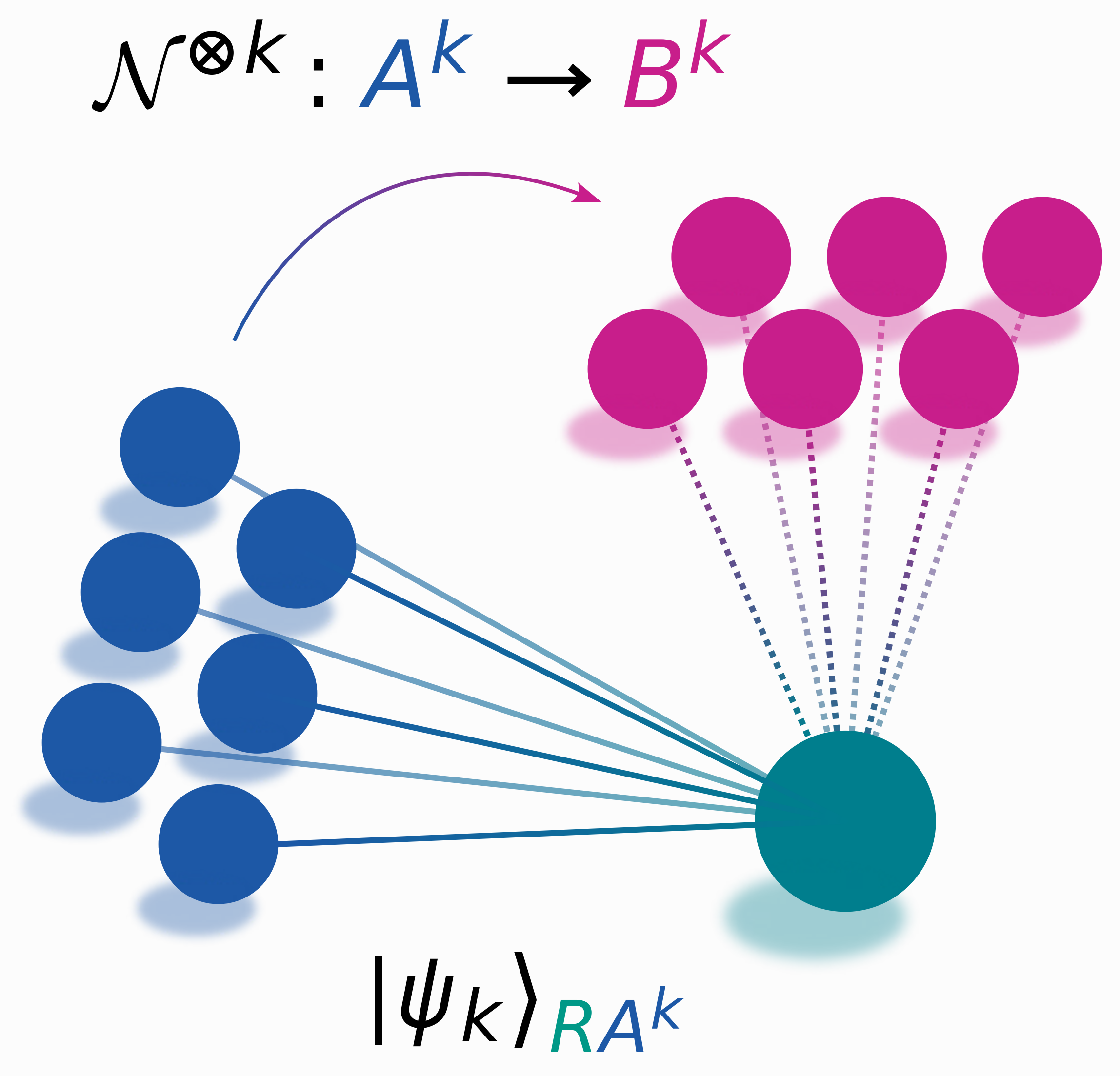
$|\psi_k\rangle_{RA^k}$

Superadditivity of coherent information

With $n = m \cdot k$ system qubits and taking $m \to \infty$,

we can recover $\frac{1}{k} I_c(\mathcal{N}^{\otimes k})$ ebits per channel use

with fidelity ≈ 1.



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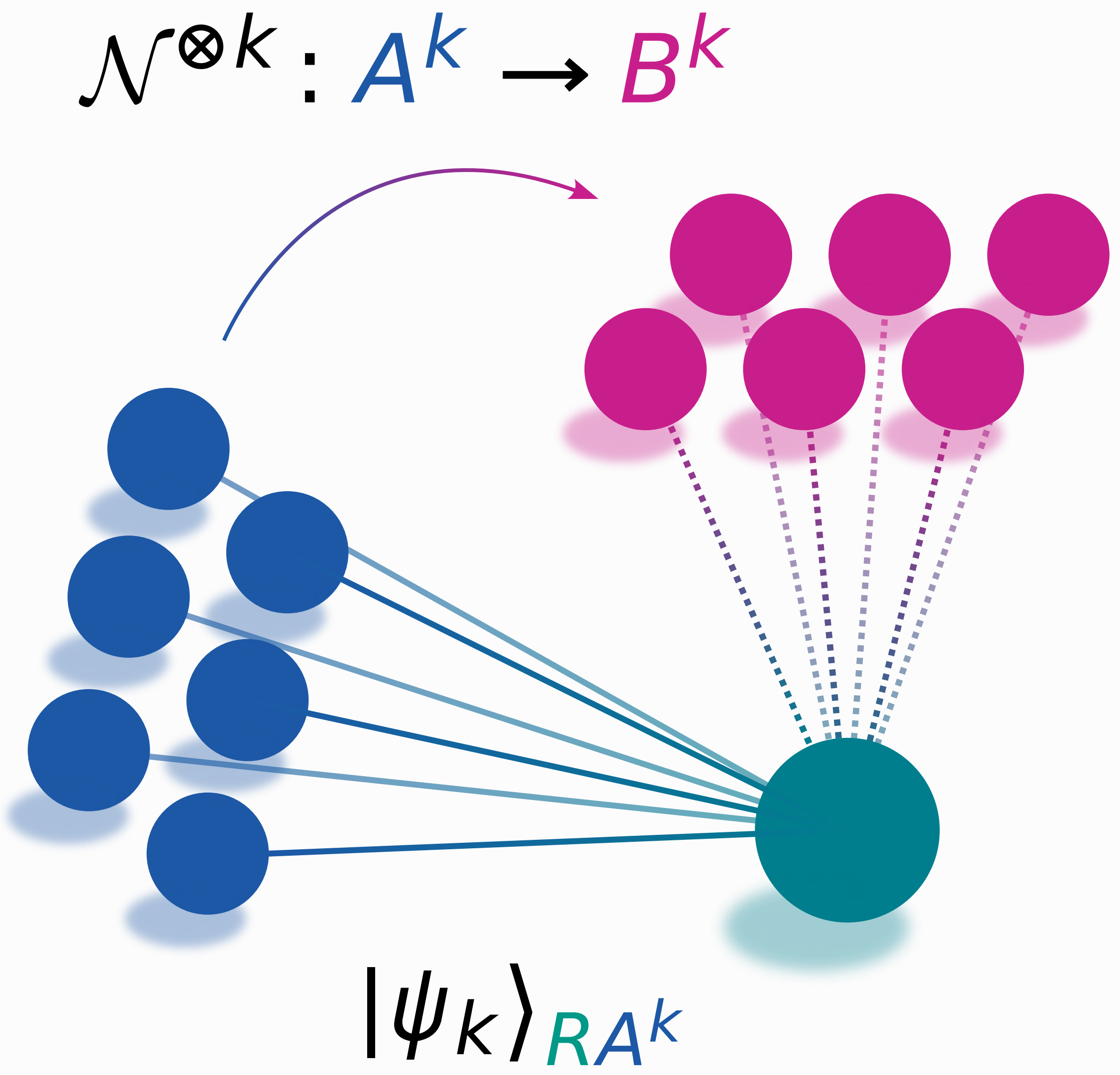
Advantage:

Possible superadditivity of

coherent information,

$$\frac{1}{k} I_c(\mathcal{N}^{\otimes k}) > I_c(\mathcal{N}).$$



Shor & Smolin '96, DiVincenzo et al. '98, Smith & Smolin '07,...

Quantum capacity

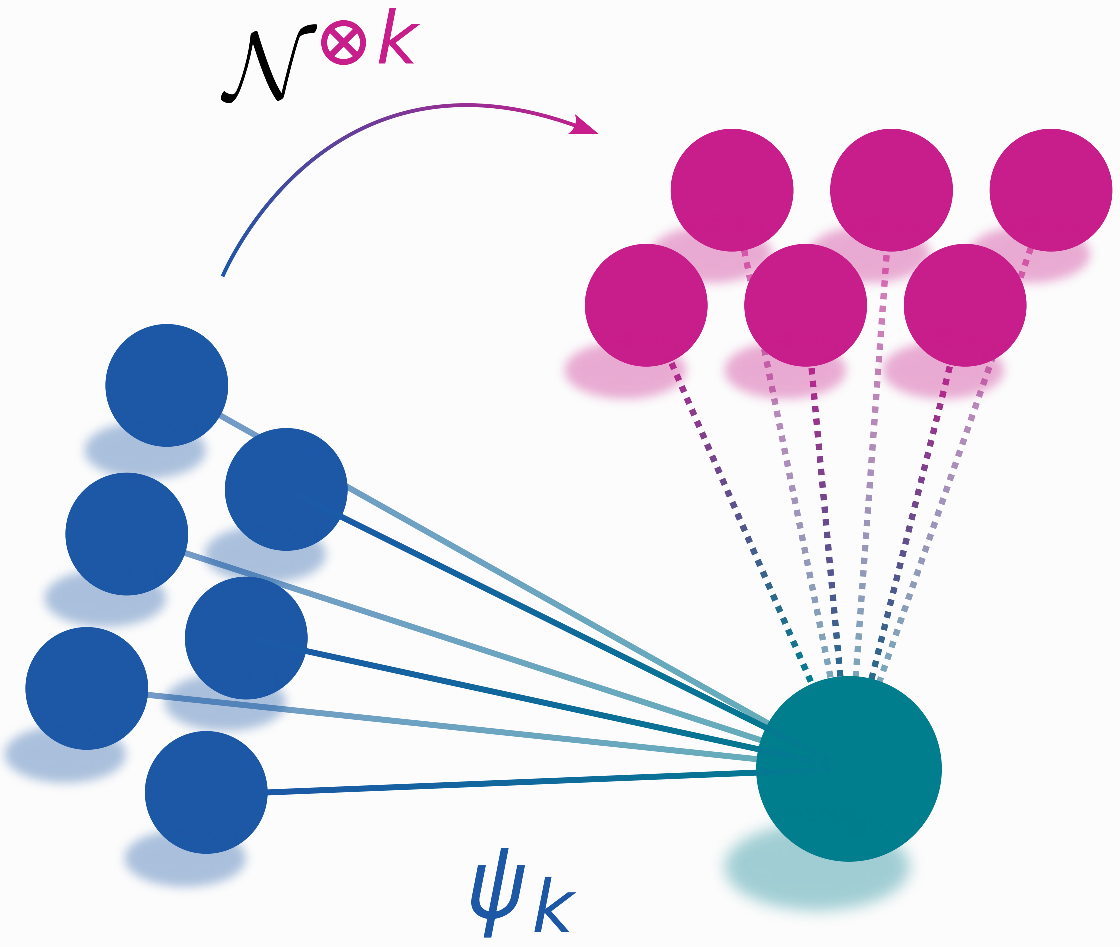
Quantum capacity $Q(\mathcal{N})$: Maximum rate at which ebits can be recovered.

Entropic formula: $$Q(\mathcal{N}) = \sup_{k\in\mathbb{N}} \frac{1}{k} I_c(\mathcal{N}^{\otimes k})$$

Schumacher, Nielsen, Barnum, Knill, Lloyd, Shor, Devetak 1996-2005

Quantum capacity

Entropic formula: $$Q(\mathcal{N}) = \sup_{k\in\mathbb{N}} \max_{\psi_k} \frac{1}{k} I_c(\mathcal{N}^{\otimes k}, \psi_k)$$



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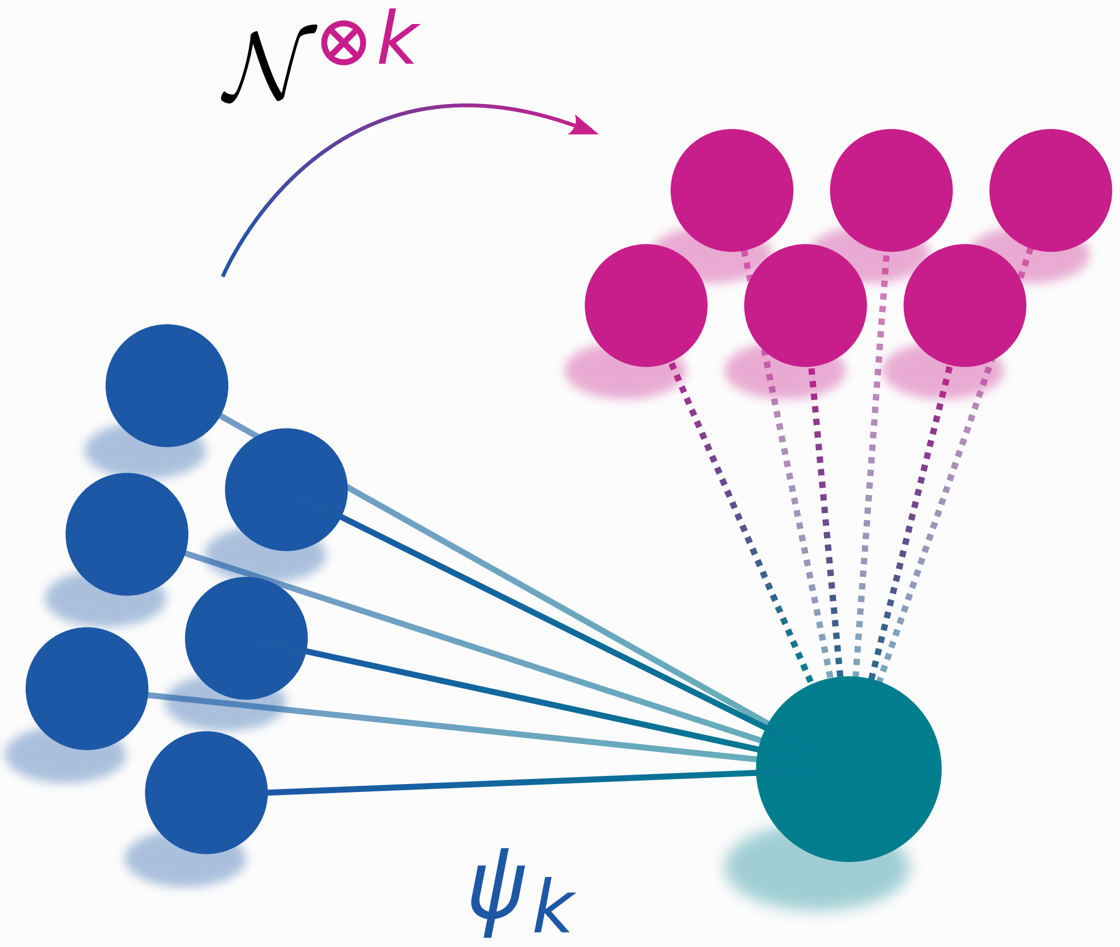


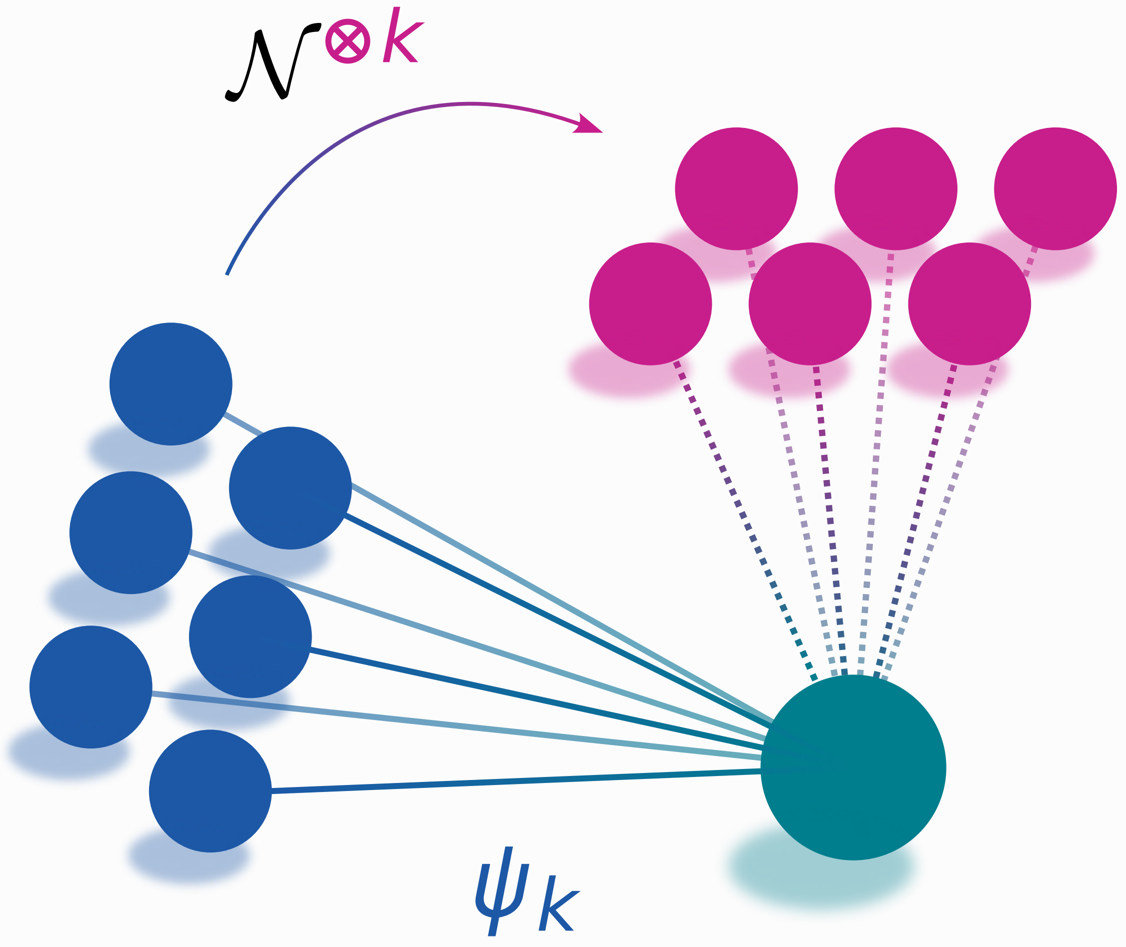
Many problems:

Unboundedness, non-convexity, multipartite entanglement, ...

Lower bounds on quantum capacity

$$Q(\mathcal{N}) = \sup_{k \in \mathbb{N}} \max_{\psi_k} \frac{1}{k} I_c(\mathcal{N}^{\otimes k}, \psi_k)$$

This work: Focus on lower bounds



Lower bounds on quantum capacity

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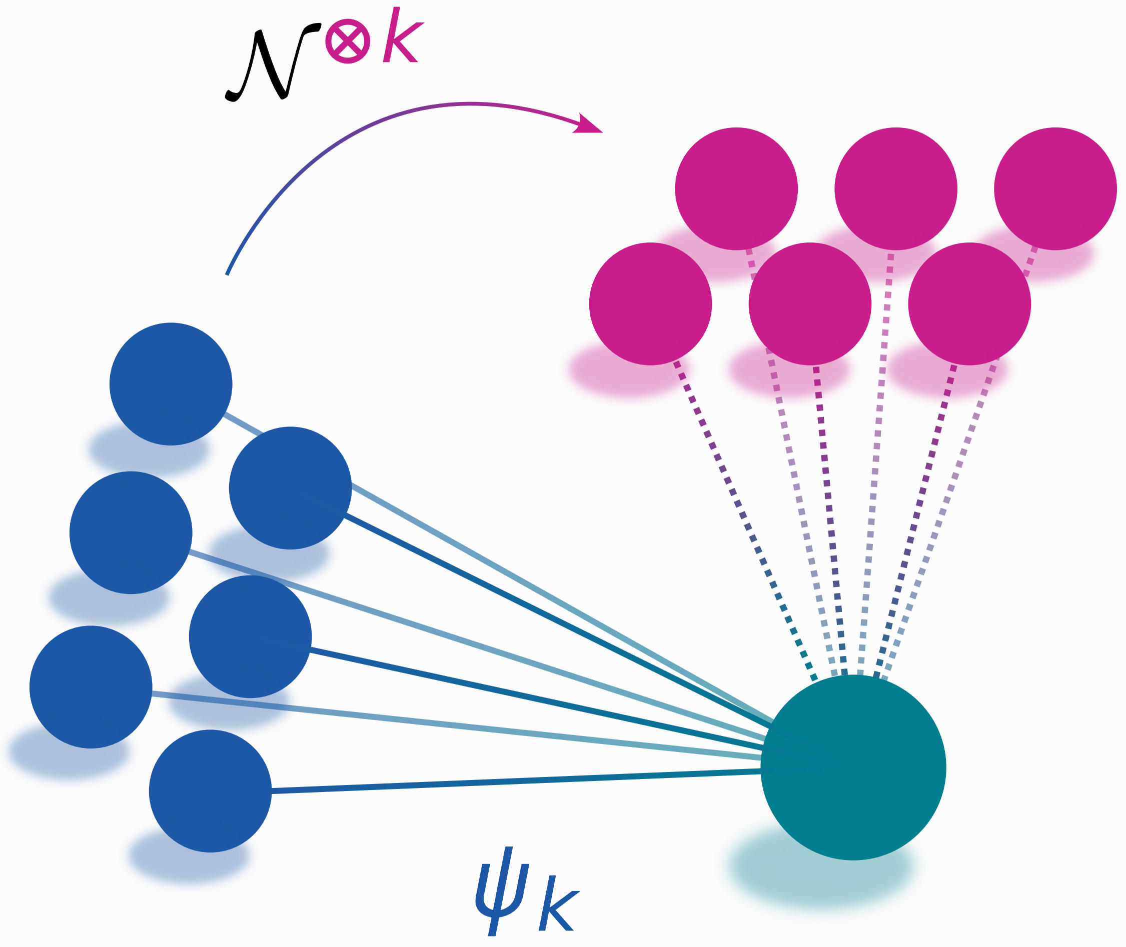
This work: Focus on lower bounds

Fix $k = \#$channel qubits and find ψ_k such that

$$Q(\mathcal{N}) \geq \frac{1}{k} I_c(\mathcal{N}^{\otimes k}, \psi_k) > I_c(\mathcal{N}).$$



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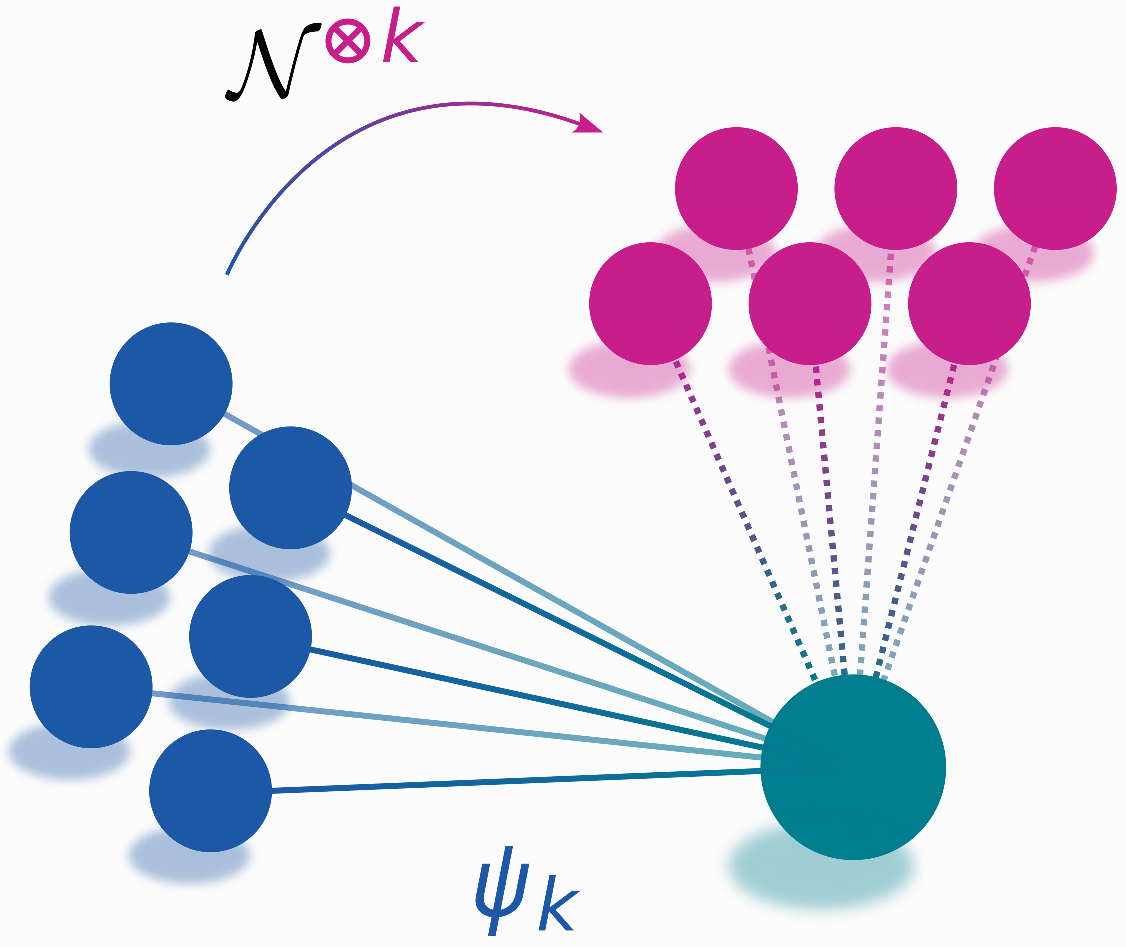

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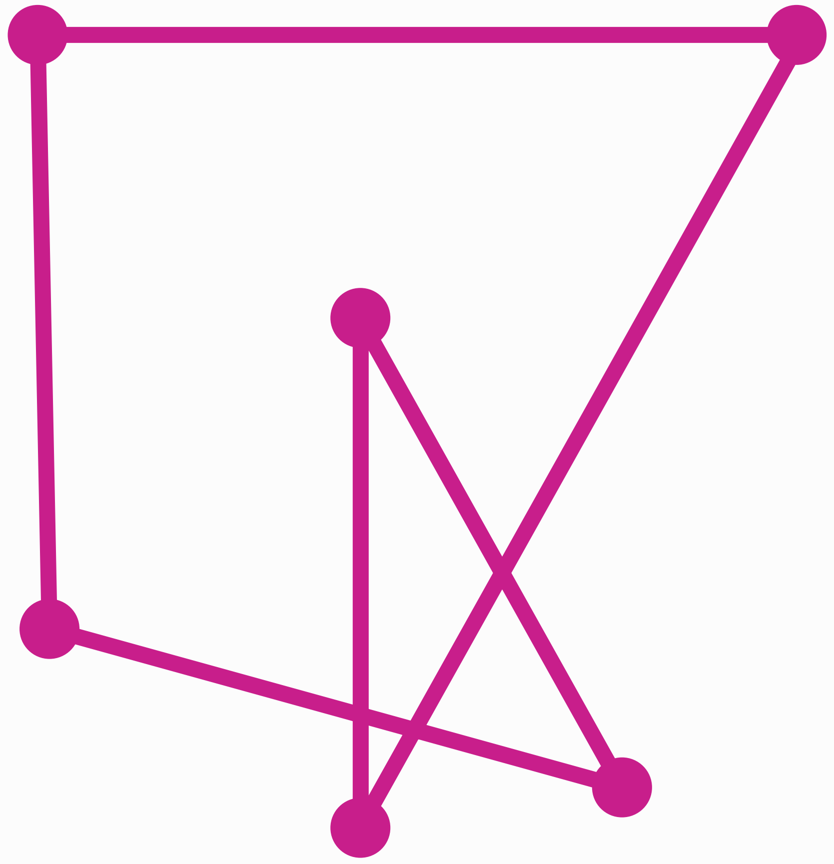
How to efficiently compute coherent information for larger k?

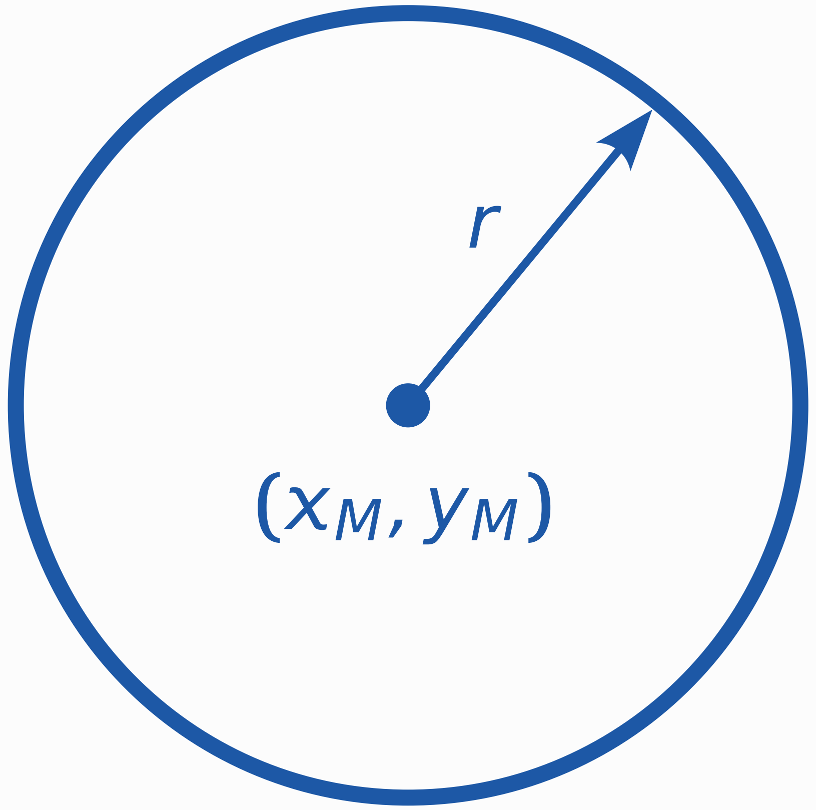
Symmetries in mathematical physics

Symmetry eliminates free parameters:

"Do something and nothing happens."



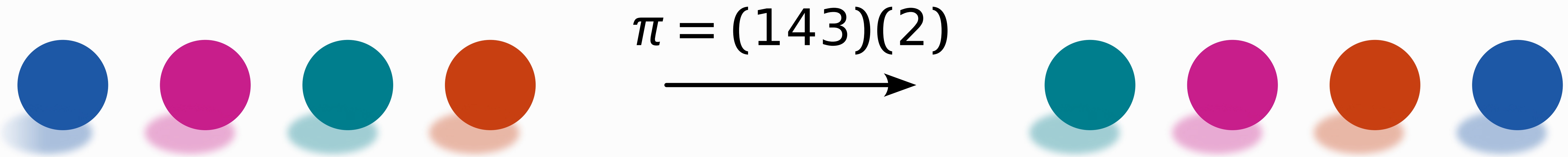
no symmetries,
complicated description



rotational symmetry,
described by three parameters

Symmetries in quantum information

Permuting k qudits



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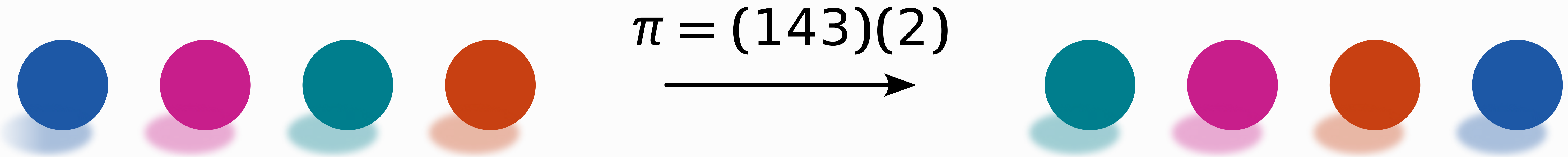
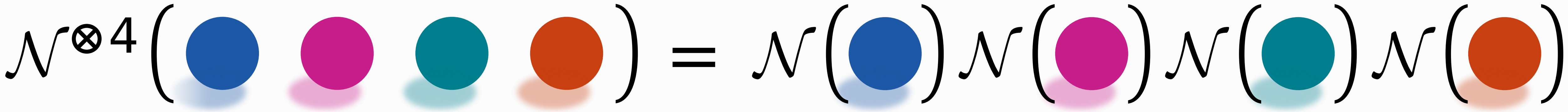


This action commutes with an i.i.d. channel $\mathcal{N}^{\otimes k}$:



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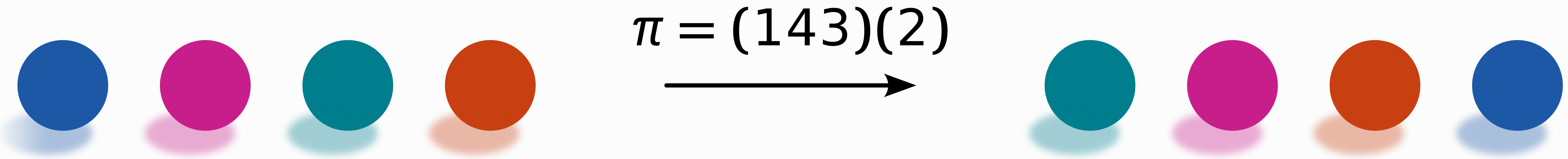

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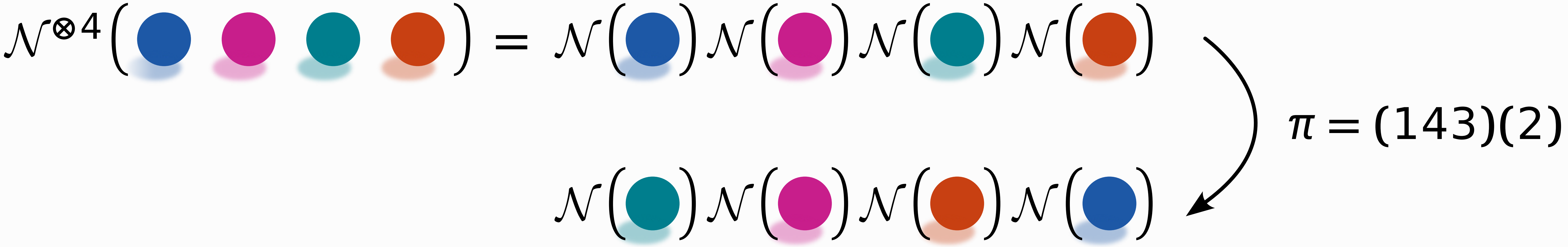


Decomposing representations

Permuting qudits is a **representation** of the symmetric group S_k on the Hilbert space $(\mathbb{C}^d)^{\otimes k}$.

Decomposing representations

Permuting qudits is a **representation** of the symmetric group S_k on the Hilbert space $(\mathbb{C}^d)^{\otimes k}$.

We can decompose this representation into "building blocks" called **irreducible representations** (irreps) S_λ:

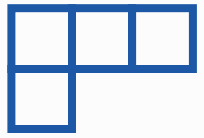
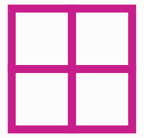
$$(\mathbb{C}^d)^{\otimes k} \cong \bigoplus_\lambda S_\lambda \oplus \cdots \oplus S_\lambda$$

$$\cong \bigoplus_\lambda S_\lambda \otimes M_\lambda$$

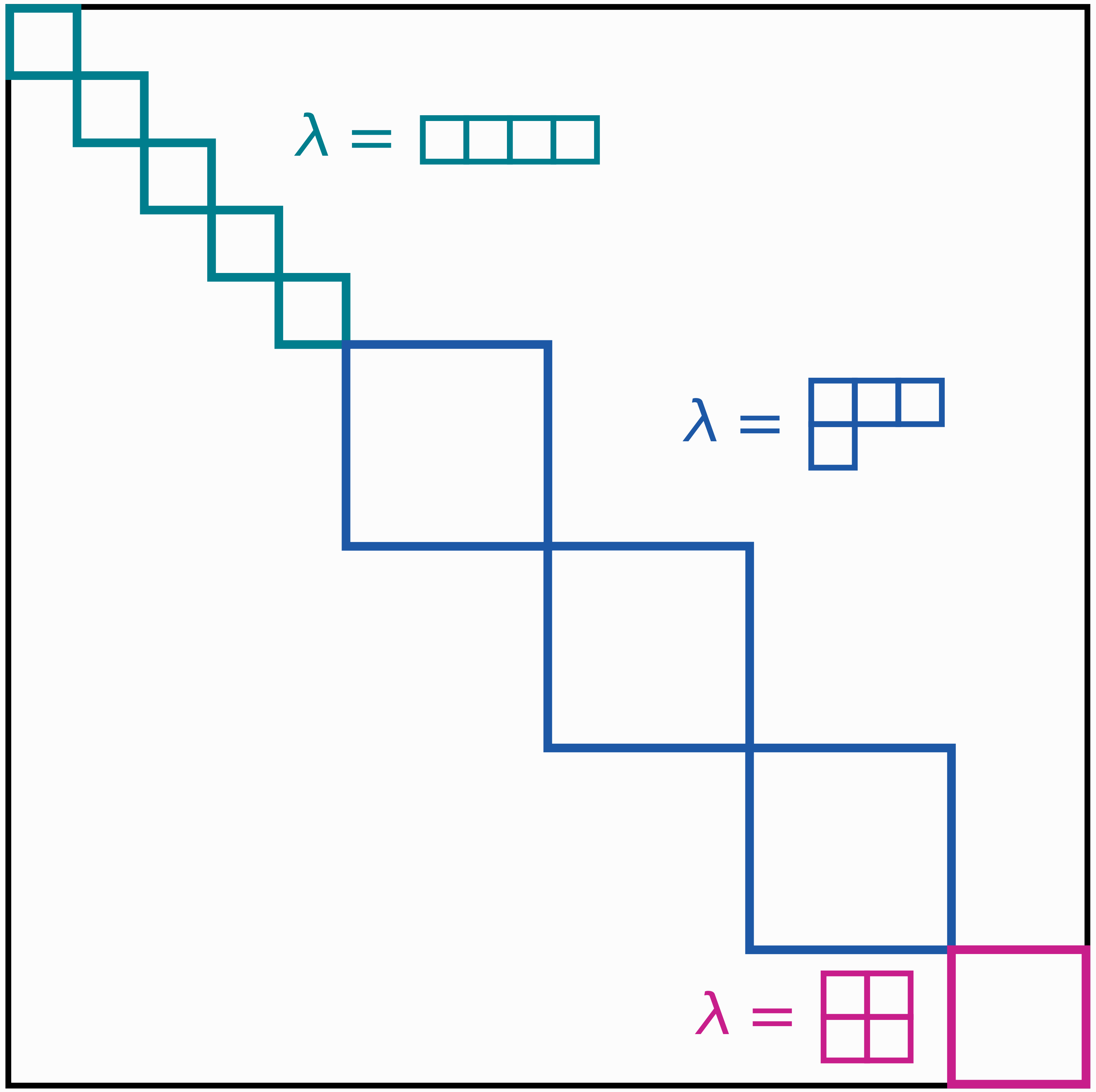
λ labels inequivalent **irreps** S_λ, and M_λ is a **multiplicity space**.

Decomposing representations

$$(\mathbb{C}^d)^{\otimes k} \cong \bigoplus_{\lambda} S_\lambda \otimes M_\lambda$$

λ			
$\dim S_\lambda$	1	3	2
$\dim M_\lambda$	5	3	1

Example: $d = 2, k = 4$



Decomposing representations

$$(\mathbb{C}^d)^{\otimes k} \cong \bigoplus_{\lambda} S_\lambda \otimes M_\lambda$$

λ	(4)	$(3,1)$	$(2,2)$
$\dim S_\lambda$	1	3	2
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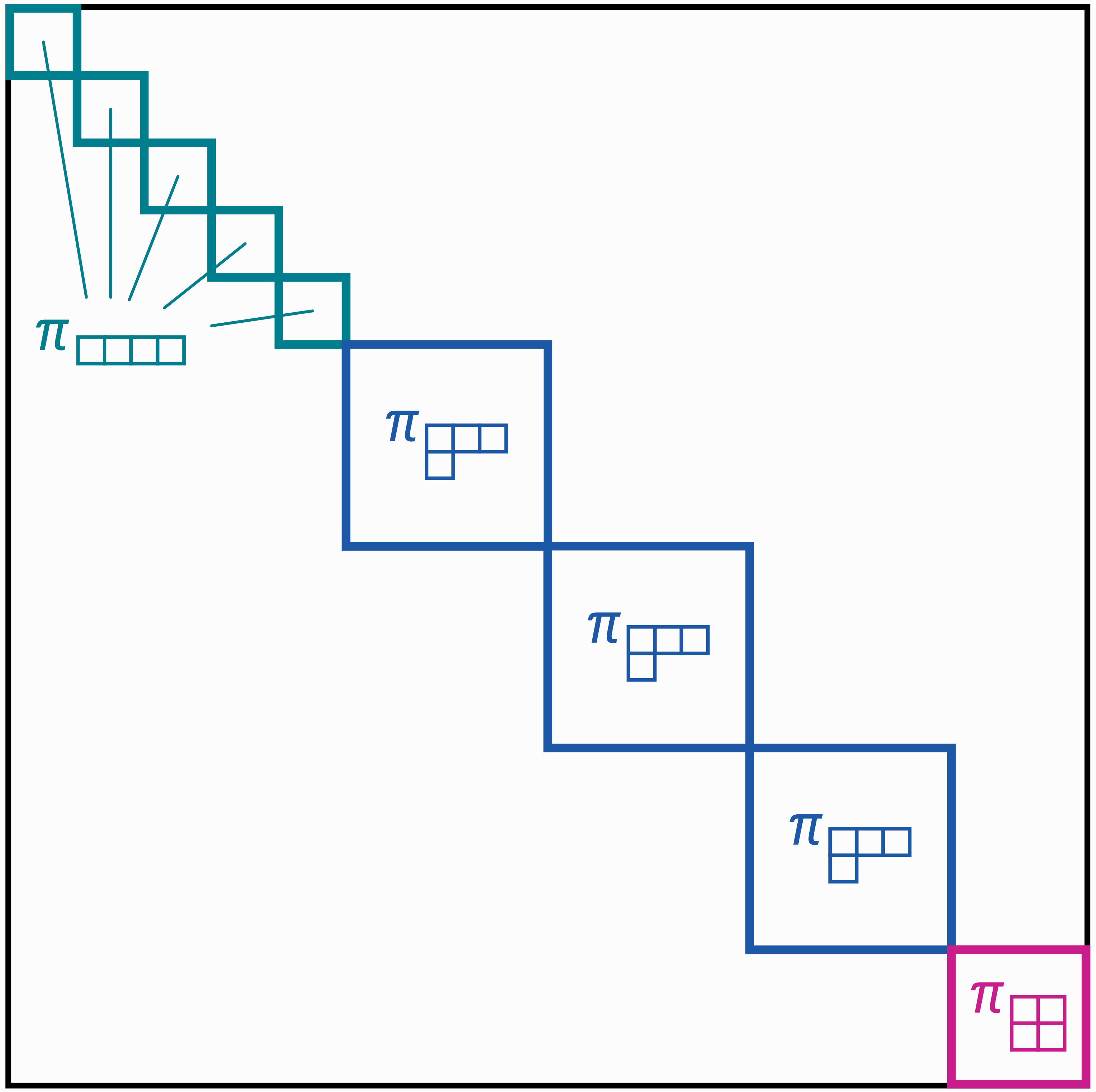
Example: $d = 2, k = 4$

Permutations only act on the S_λ:

$$\pi \cong \bigoplus_{\lambda} \pi_\lambda \otimes \mathbb{1}_{M_\lambda}$$



Invariant states

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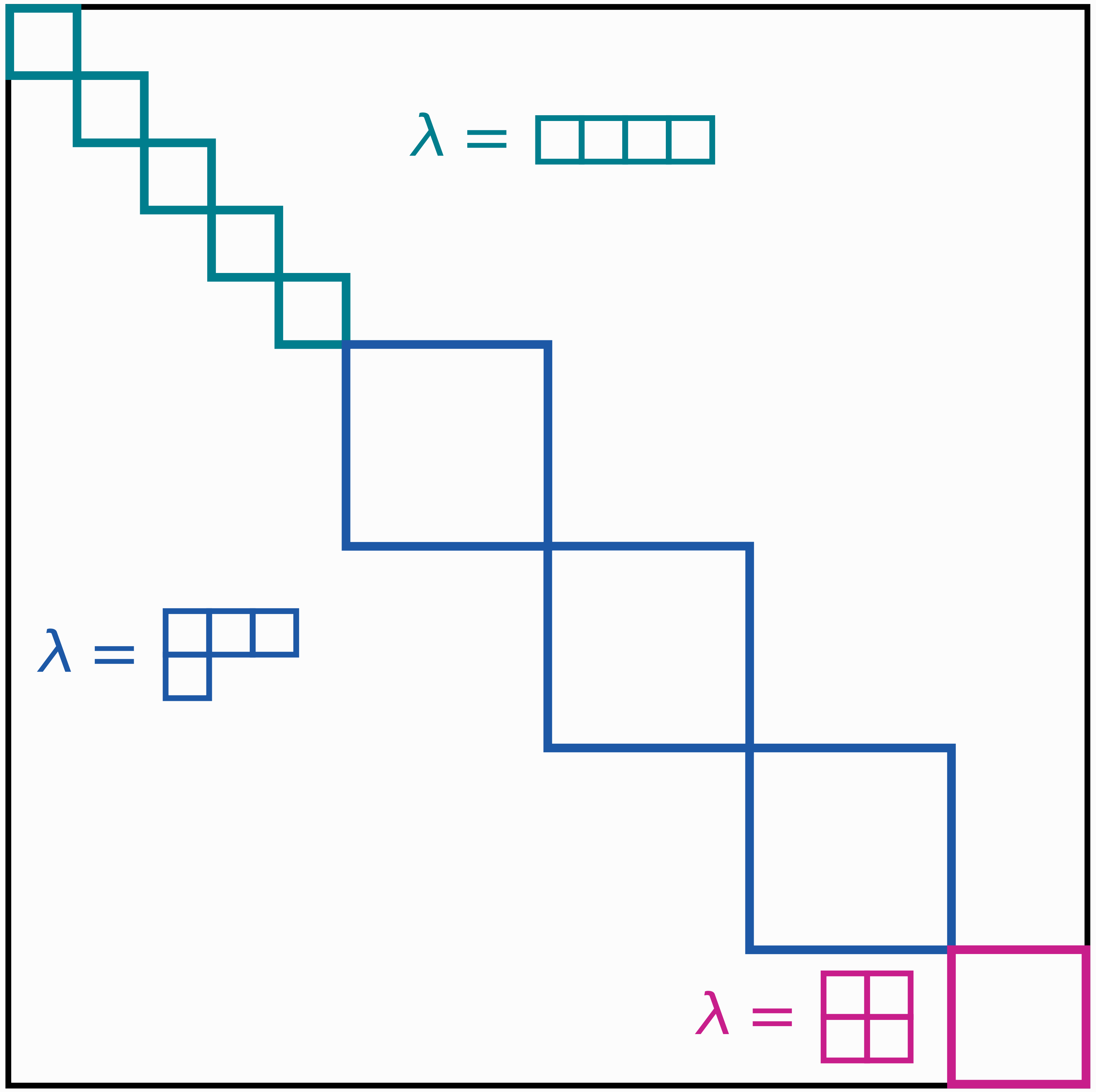

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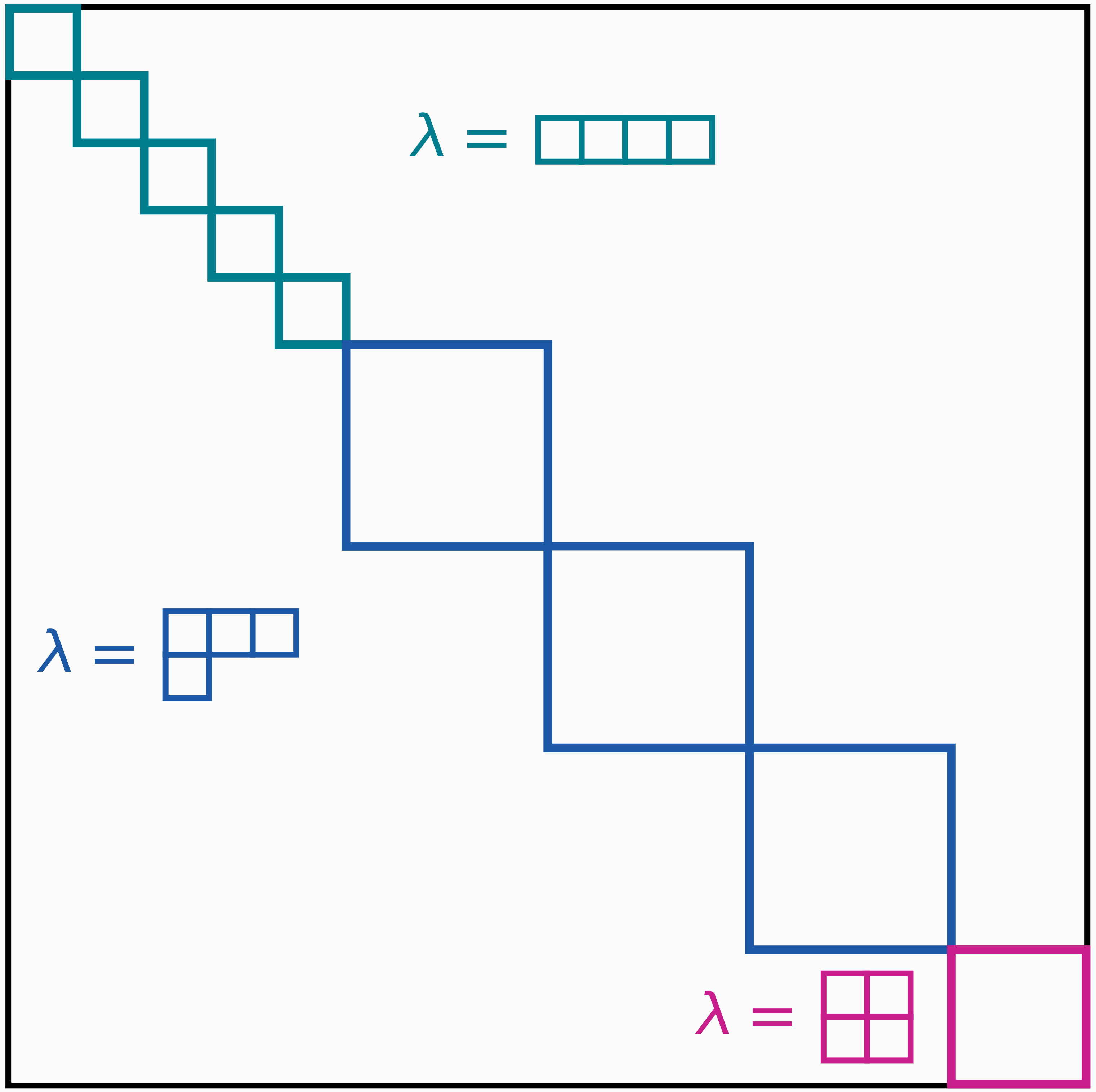
If a state ρ is permutation-invariant,

$$[\rho, \pi] = 0 \text{ for all } \pi \in S_k,$$



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then Schur's Lemma ensures that

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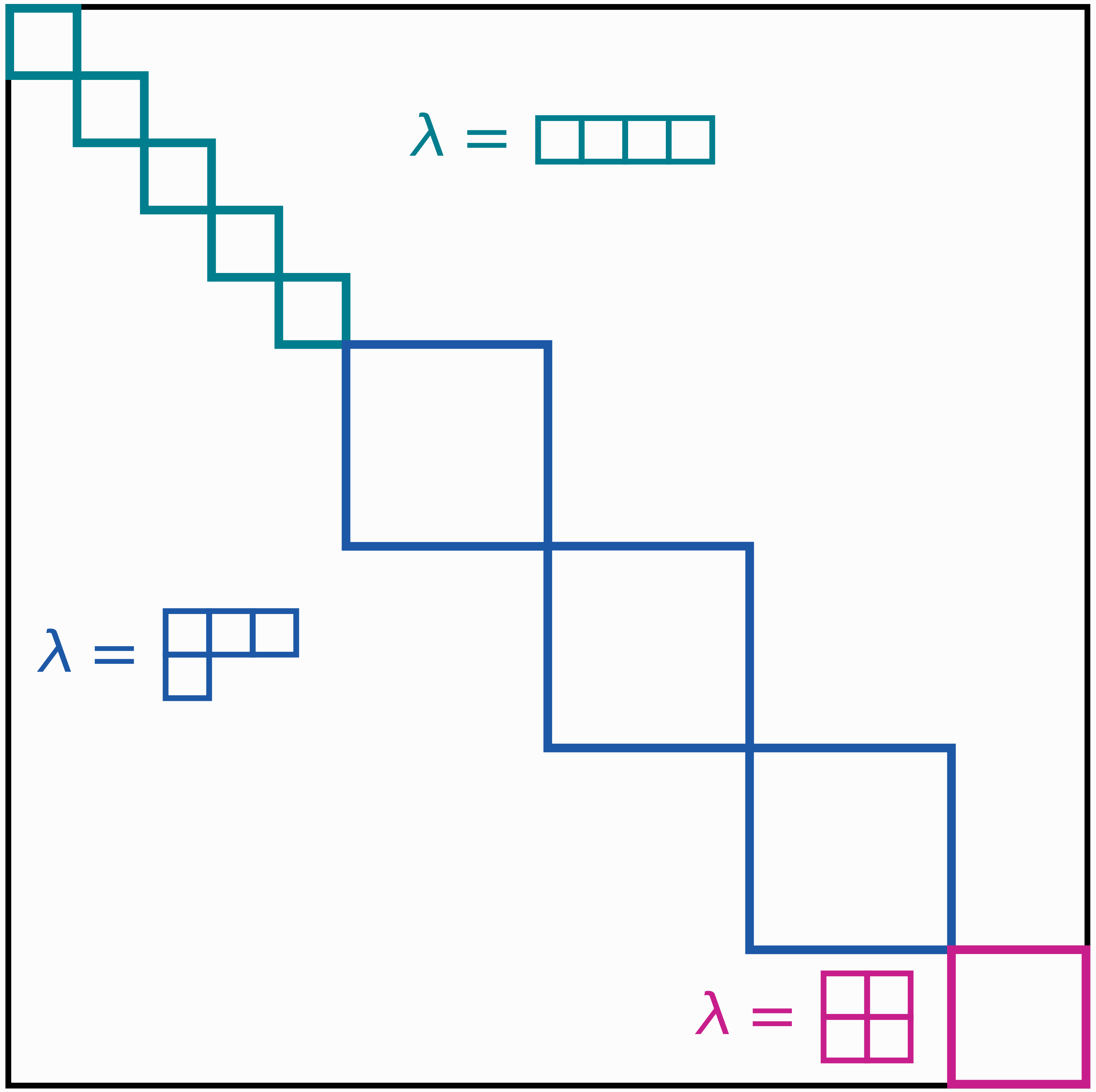

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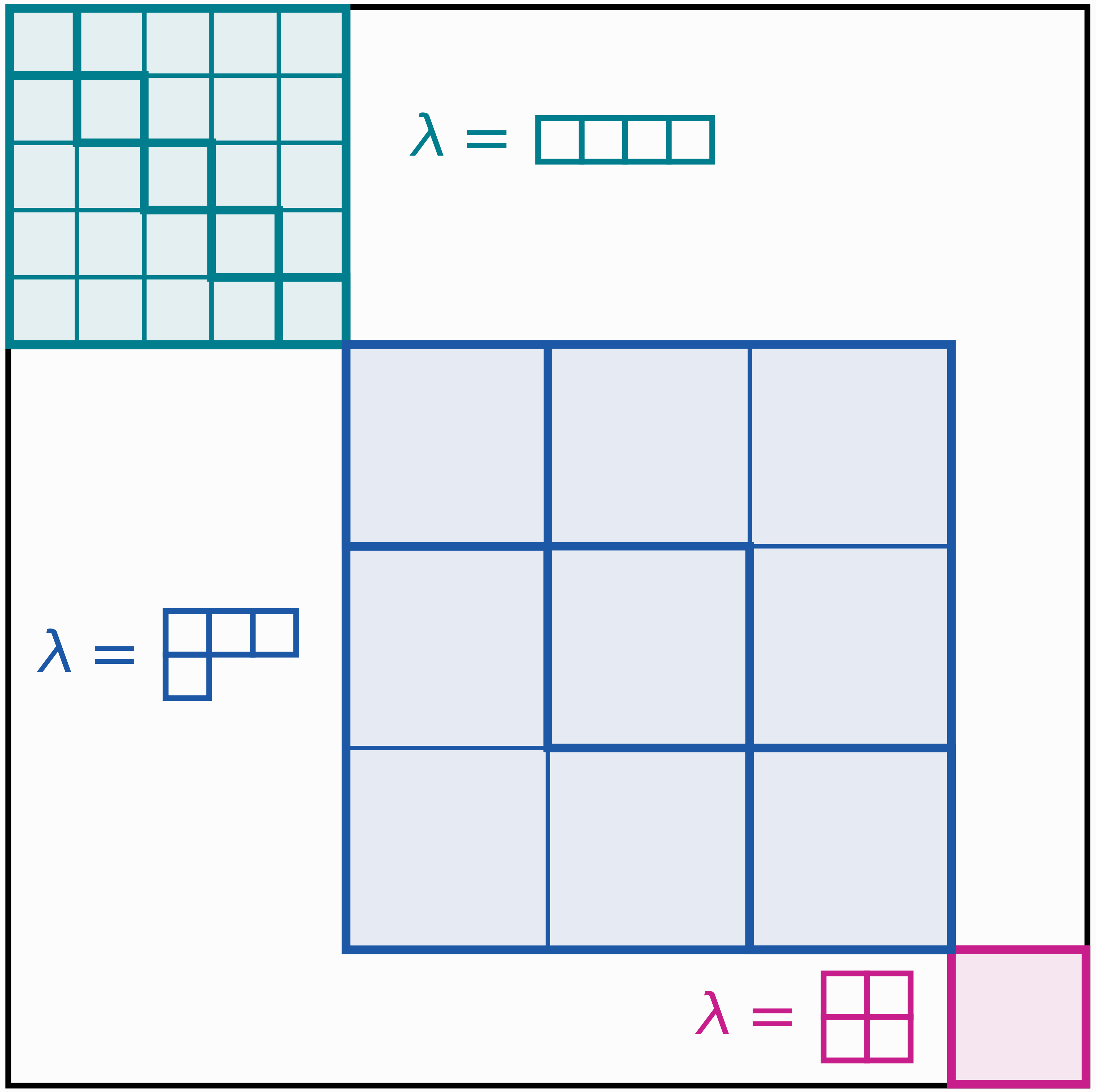

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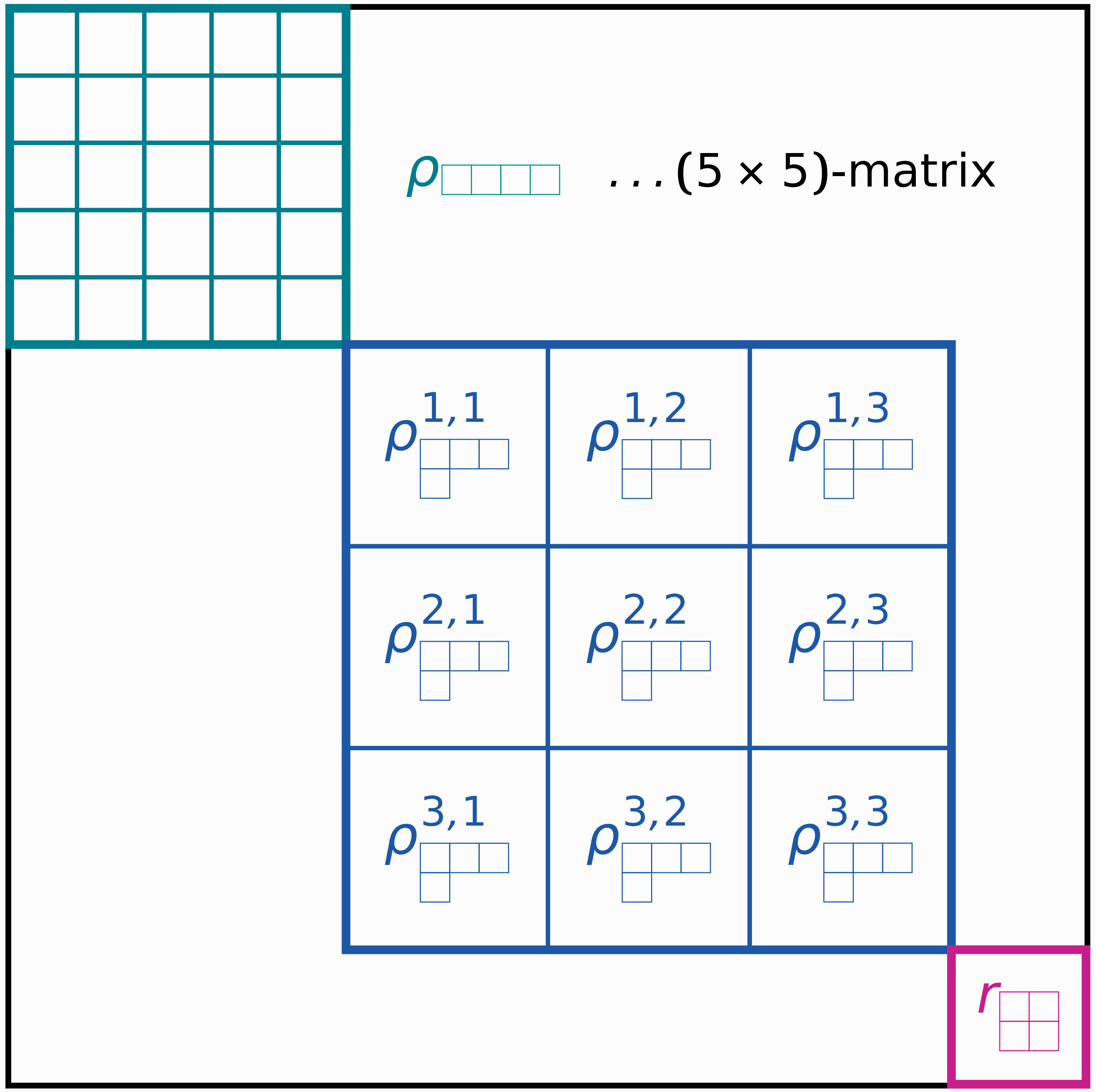

Invariant states

$$\rho \cong \bigoplus_{\lambda} \mathbb{1}_{S_\lambda} \otimes \rho_\lambda .$$

How can we determine the effective states ρ_λ?

Invariant states

$\rho \cong \bigoplus_{\lambda} \mathbb{1}_{S_\lambda} \otimes \rho_\lambda.$ How can we determine the effective states ρ_λ?

Schur-Weyl duality

The multiplicity spaces M_λ in the decomposition

$$(\mathbb{C}^d)^{\otimes k} \cong \bigoplus_{\lambda} S_\lambda \otimes M_\lambda$$

are actually the irreps of the representation $\mathrm{GL}(d) \ni g \mapsto g^{\otimes k}$
of the general linear group $\mathrm{GL}(d)$.

Invariant states

Recall: $$(\mathbb{C}^d)^{\otimes k} \cong \bigoplus_\lambda S_\lambda \otimes M_\lambda$$

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Molev '06

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Well-known example: Repetition code

$$\rho_{(k)} = \frac{1}{2}\left(|0\rangle\langle 0|^{\otimes k} + |1\rangle\langle 1|^{\otimes k}\right)$$

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This code gives **superadditive coherent information** for Pauli channels

$$\rho \longmapsto (1-p)\rho + p\left[q_1 X\rho X + q_2 Y\rho Y + q_3 Z\rho Z\right]$$

Shor & Smolin '96; Smith & Smolin '07; Bausch & **FL** '21

Main theoretical result

For states of the form $\rho_{(k)} = \sum_i x_i \rho_i^{\otimes k} \cong \bigoplus_\lambda \mathbb{1}_{S_\lambda} \otimes \sum_i x_i \rho_i^{(\lambda)}$,

the coherent information $I_c(\mathcal{N}^{\otimes k}, \rho_{(k)})$ assumes the form

$$I_c(\mathcal{N}^{\otimes k}, \rho_{(k)}) = \sum_\lambda f\left(\mathcal{N}, \sum_i x_i \rho_i^{(\lambda)}\right).$$

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Since $|\{\lambda\}|, \dim M_\lambda = O(\text{poly}(n))$, this formula is **efficiently computable**

for up to $n \approx 100$ for qubit channels!

Numerical studies

Goal: Find lower bounds on the quantum capacity of channels such as

$$\mathcal{N}_p : \sigma \longmapsto (1-p)\sigma + p\,[\,q_1 X\sigma X + q_2 Y\sigma Y + q_3 Z\sigma Z\,]$$

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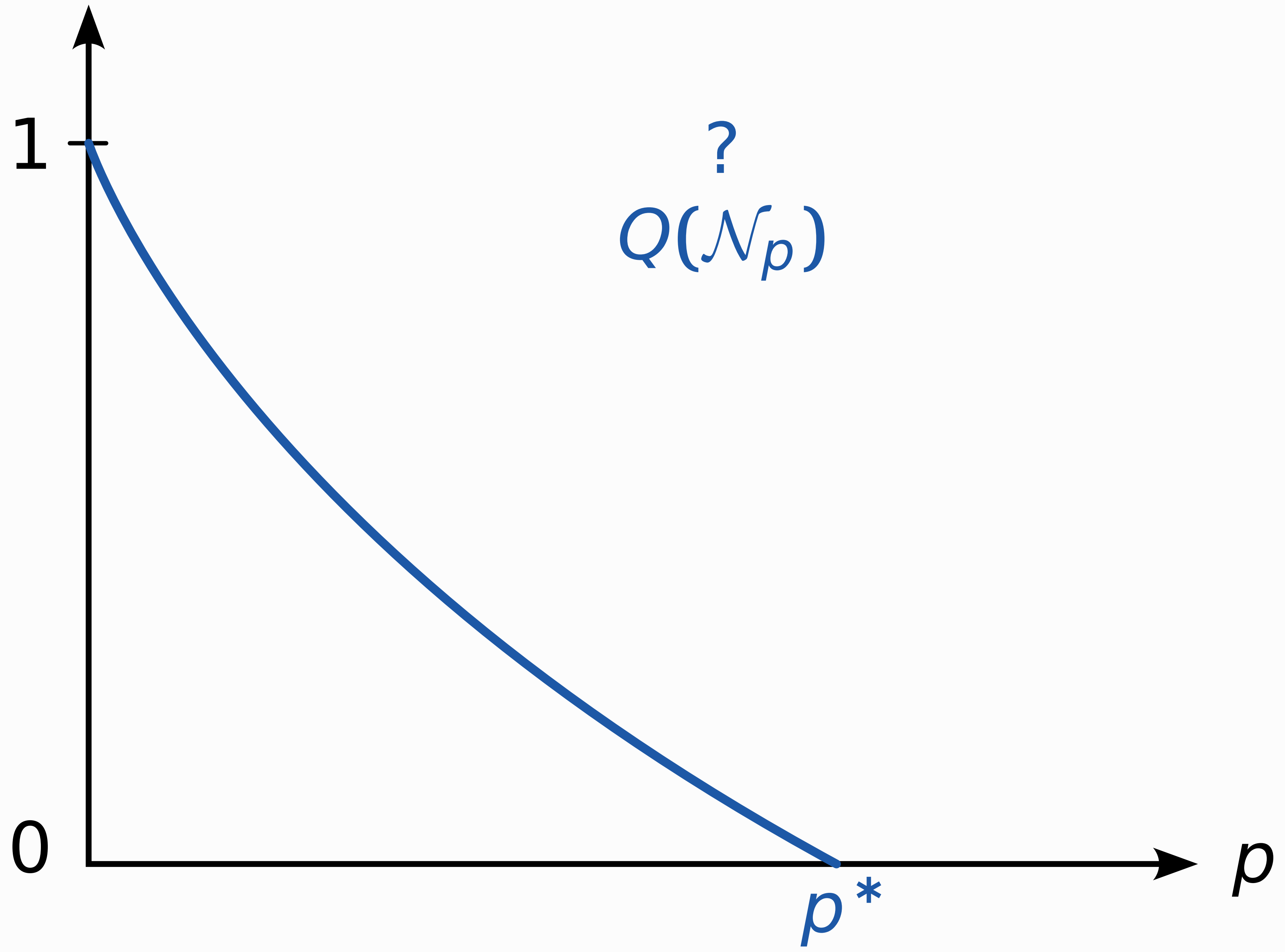
Quantum capacity threshold:

$$p^* = \sup\{p : Q(\mathcal{N}_p) > 0\}$$



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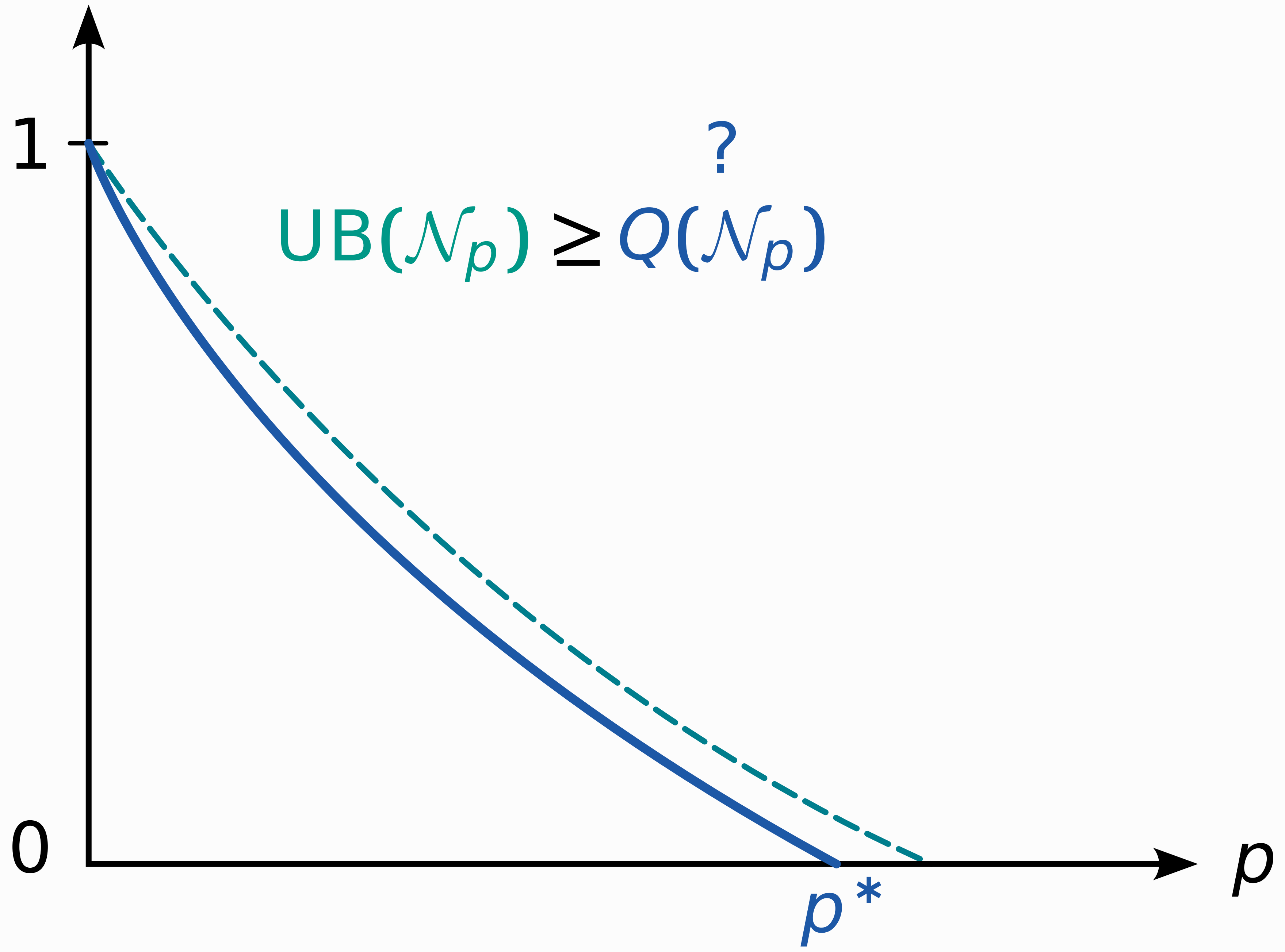

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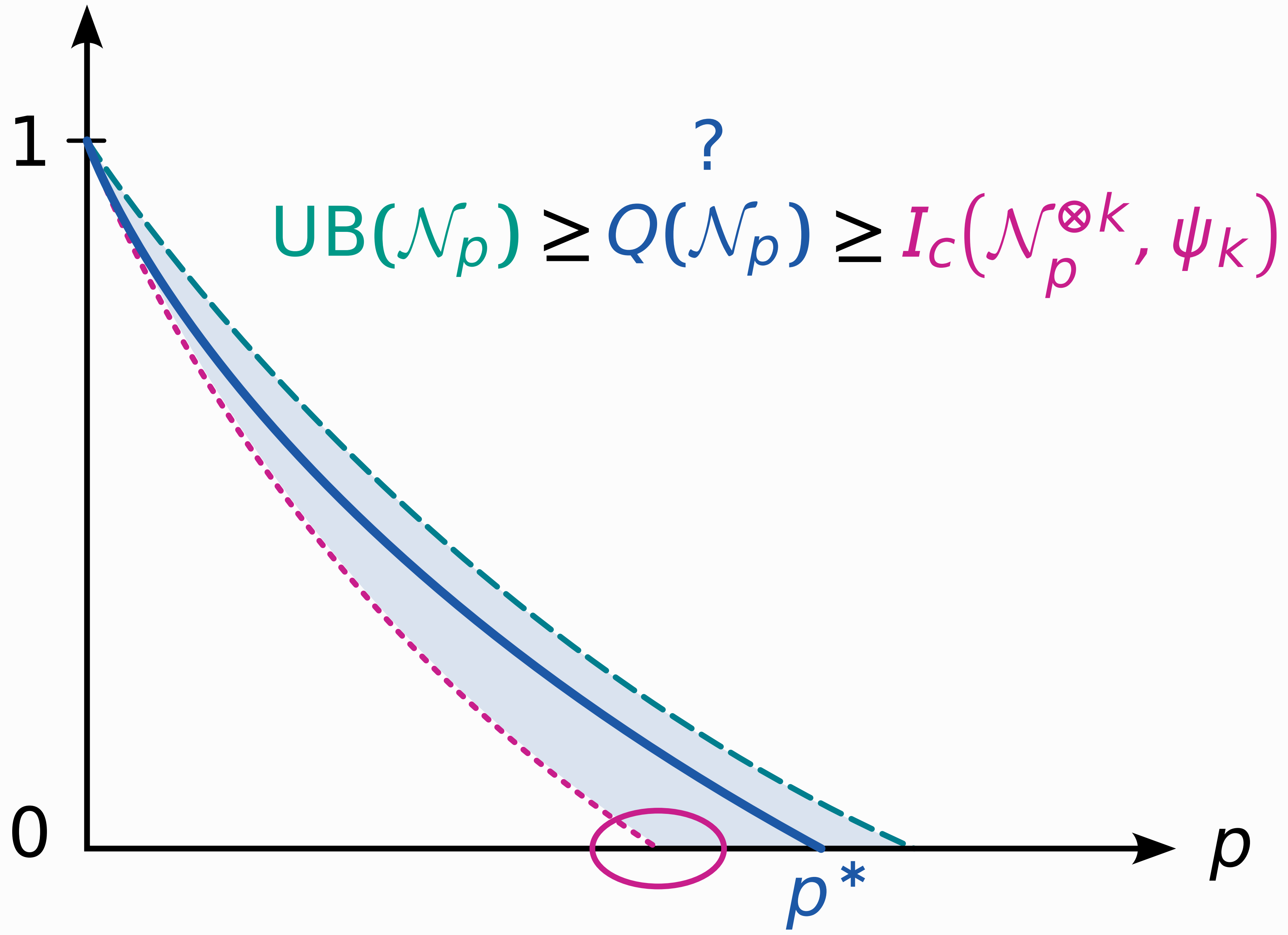

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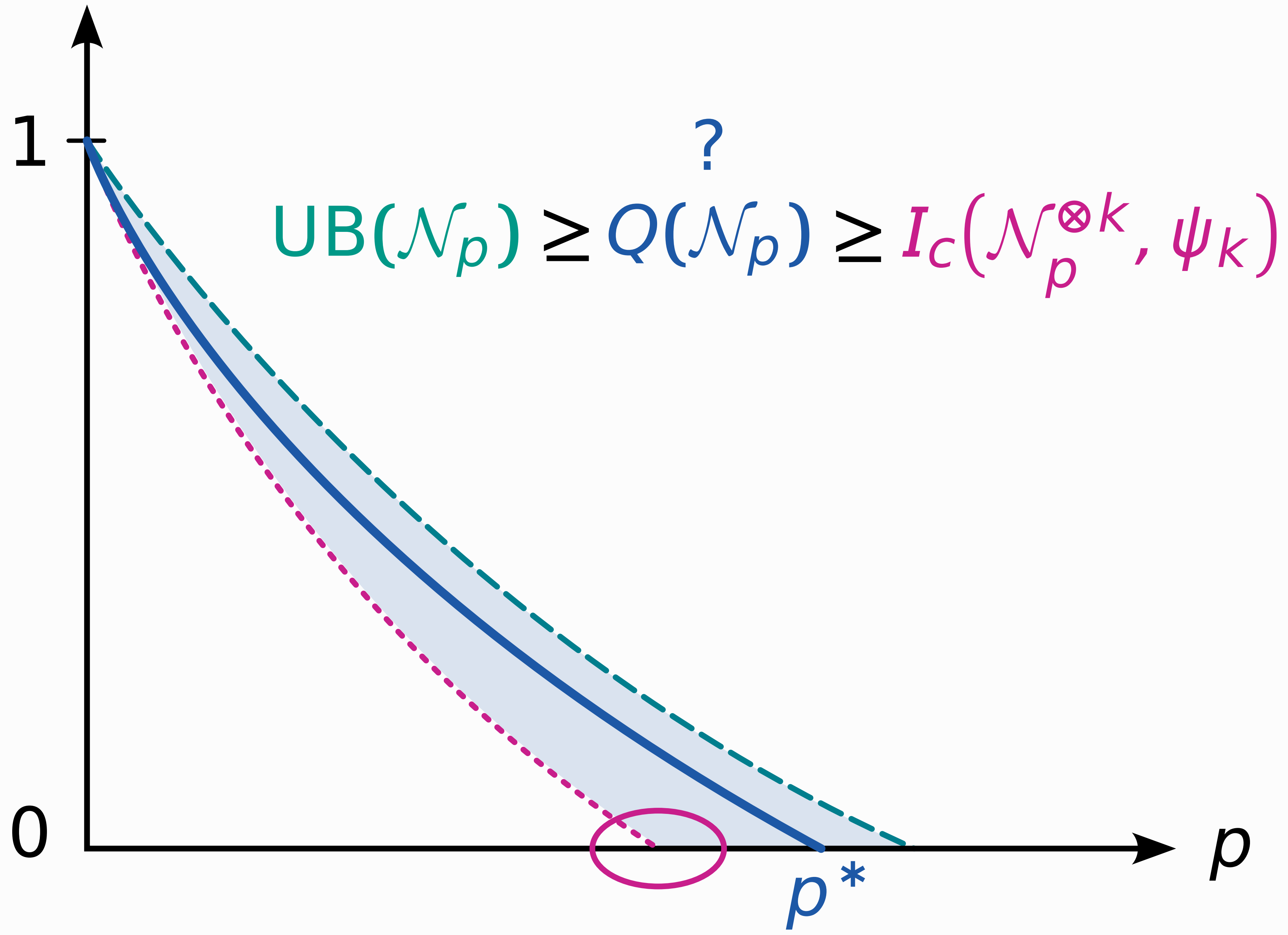
$$\Longrightarrow p^* \geq p_0$$



Two-Pauli channel

$$\mathcal{N}_p : \sigma \longmapsto (1-p)\sigma + \frac{p}{2}(X\sigma X + Z\sigma Z)$$

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No-cloning bound: $p^* \leq 1/3$

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Hashing bound: $p^* \geq 0.227 = \sup\{p : I_c(\mathcal{N}_p) > 0\}$

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Fern, Whaley '08: $p^* \geq 0.228$ (over 10^9 channel qubits needed!)

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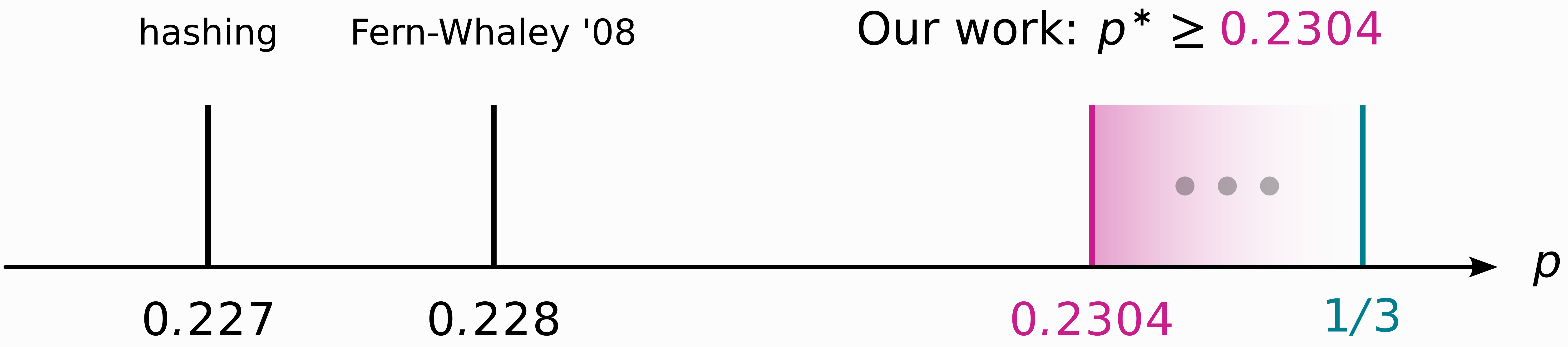

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Our work: Significantly improved lower bound $p^* \geq 0.2304$.

Strategy:

Optimize over states

$$\rho_{(n)} = \sum_i x_i \rho_i^{\otimes n}$$

and use rep-th. formula

to compute $I_c\left(\mathcal{N}_p^{\otimes n}, \rho_{(n)}\right)$.

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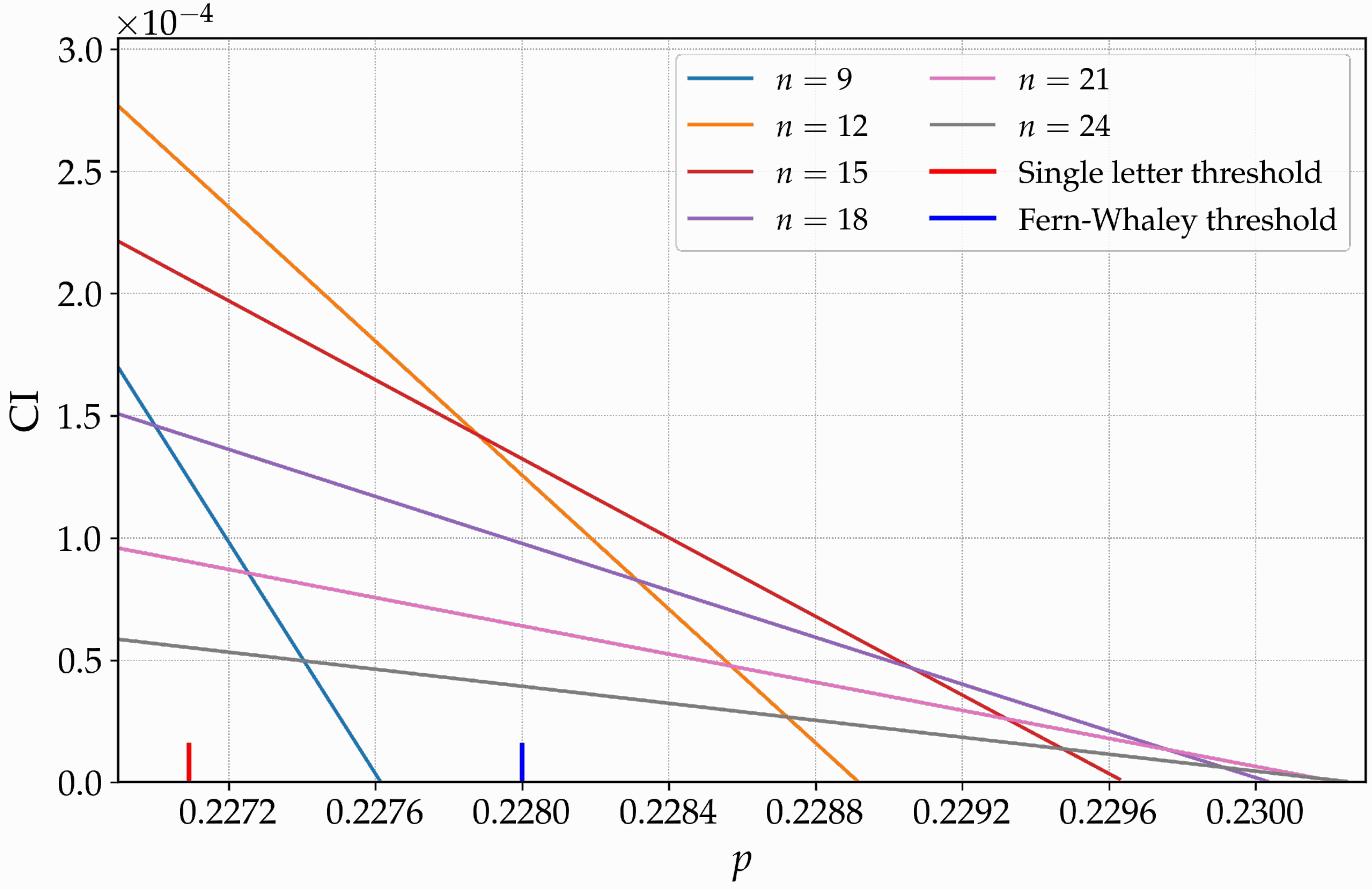
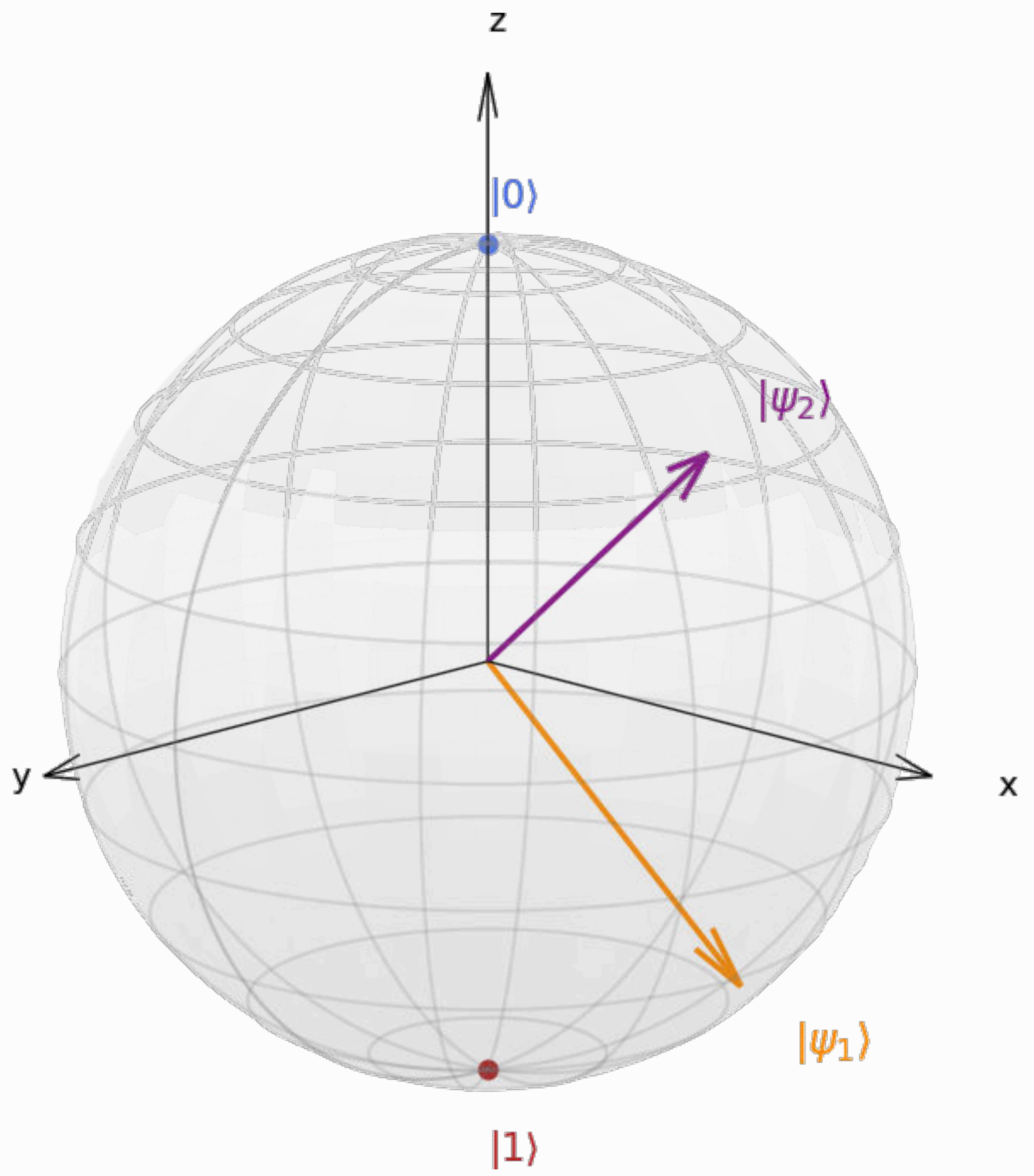


Two-Pauli channel

Optimal code: "non-orthogonal repetition code"



$$\rho_{(n)} = \frac{1}{2}\left(\psi_1^{\otimes n} + \psi_2^{\otimes n}\right) \quad \text{with} \quad |\langle \psi_1 | \psi_2 \rangle| = 0.7645.$$

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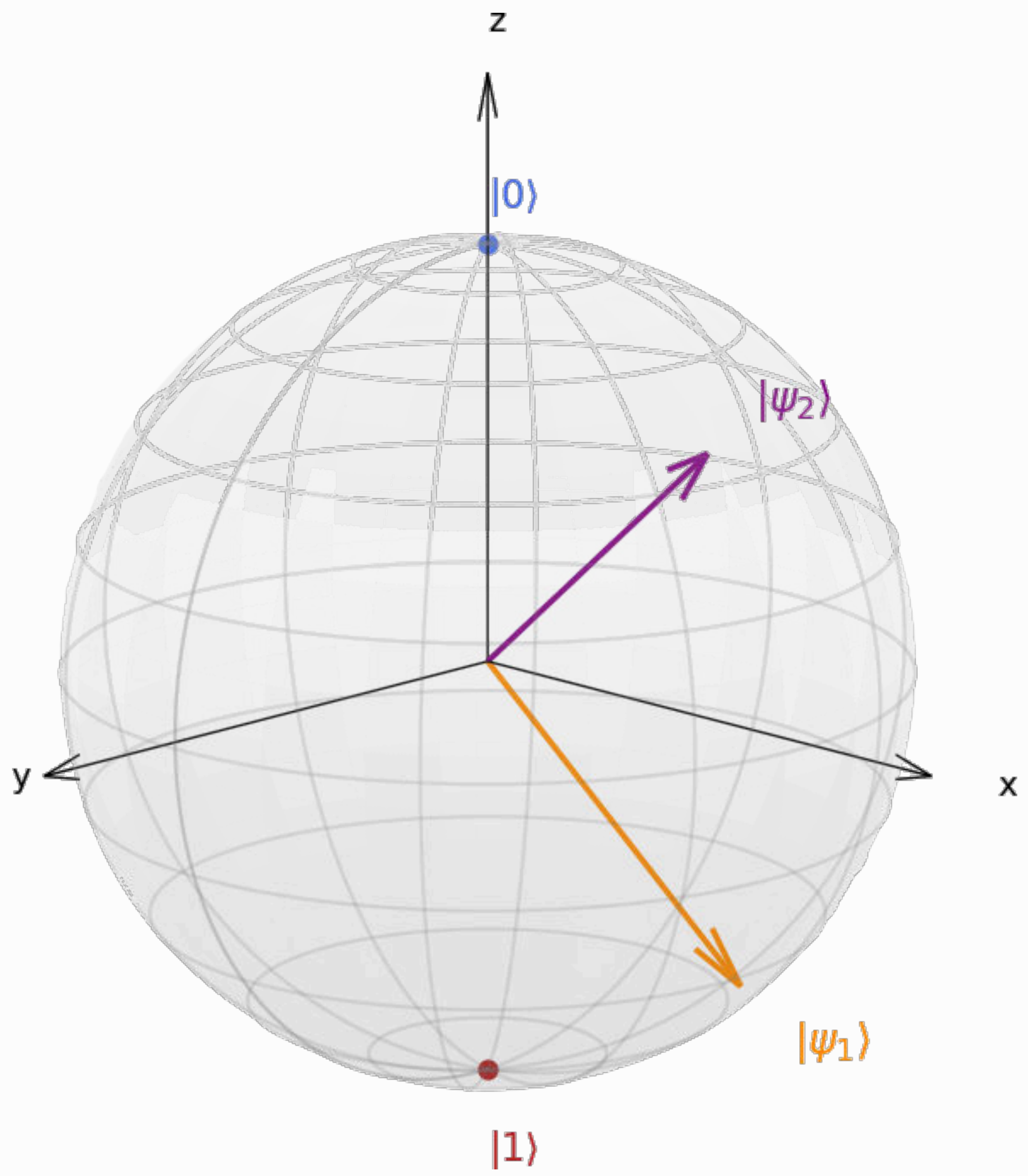

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Usual orthogonal repetition codes with $\langle\psi_1|\psi_2\rangle = 0$ do not even beat the single-letter threshold!

Smith & Smolin '07; Fern & Whaley '08; Bausch & **FL** '21

Two-Pauli channel

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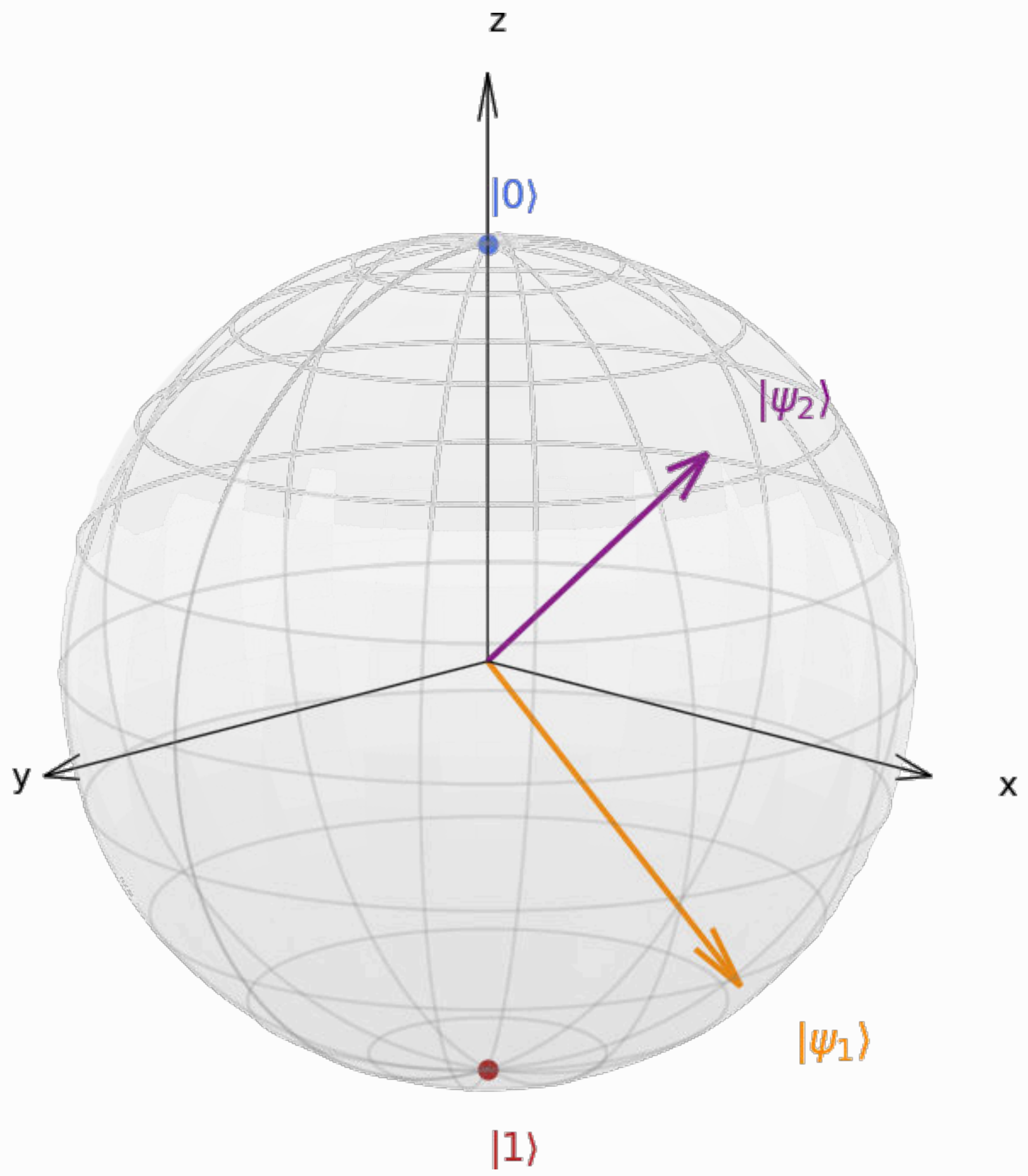

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Other Pauli channels (e.g., BB84 channel)

also benefit from non-orthogonal rep codes.

Representation-theoretic analysis in paper!

Conclusion

We use a permutation-invariant ansatz for quantum codes and tools from representation theory to improve achievable communication rates for many channels of interest:

- Pauli channels (e.g., two-Pauli, BB84)
- Generalized amplitude damping channel
- Dephrasure channel
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Future work: Handle more general symmetry group to make code ansatz more flexible and tailored to specific noise models.

Links to paper and code

Paper

Code on GitHub

Thanks for your attention!