UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

INFN Istituto Nazionale di Fisica Nucleare

NQSTI National Quantum Science and Technology Institute

ICSC Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

UNIVERSITÀ DI PAVIA
Department of Physics

Exponential optimization of adiabatic quantum-state preparation

Davide Cugini

D. Nigro, M. Bruno, D.Gerace

INFN Quantum Computing, 30 October 2024

Simulations of physical systems

Observation of the phenomenon

Simulations of physical systems

Observation of the phenomenon

Mathematical model

$$H = \ldots\ldots$$

Simulations of physical systems

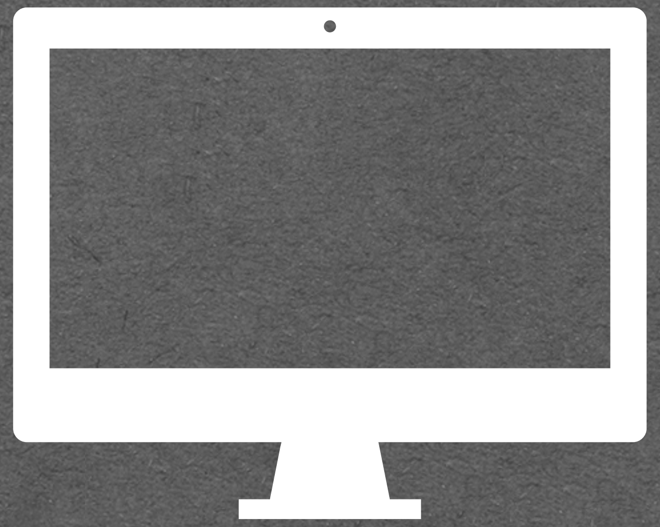
Observation of the phenomenon

Mathematical model

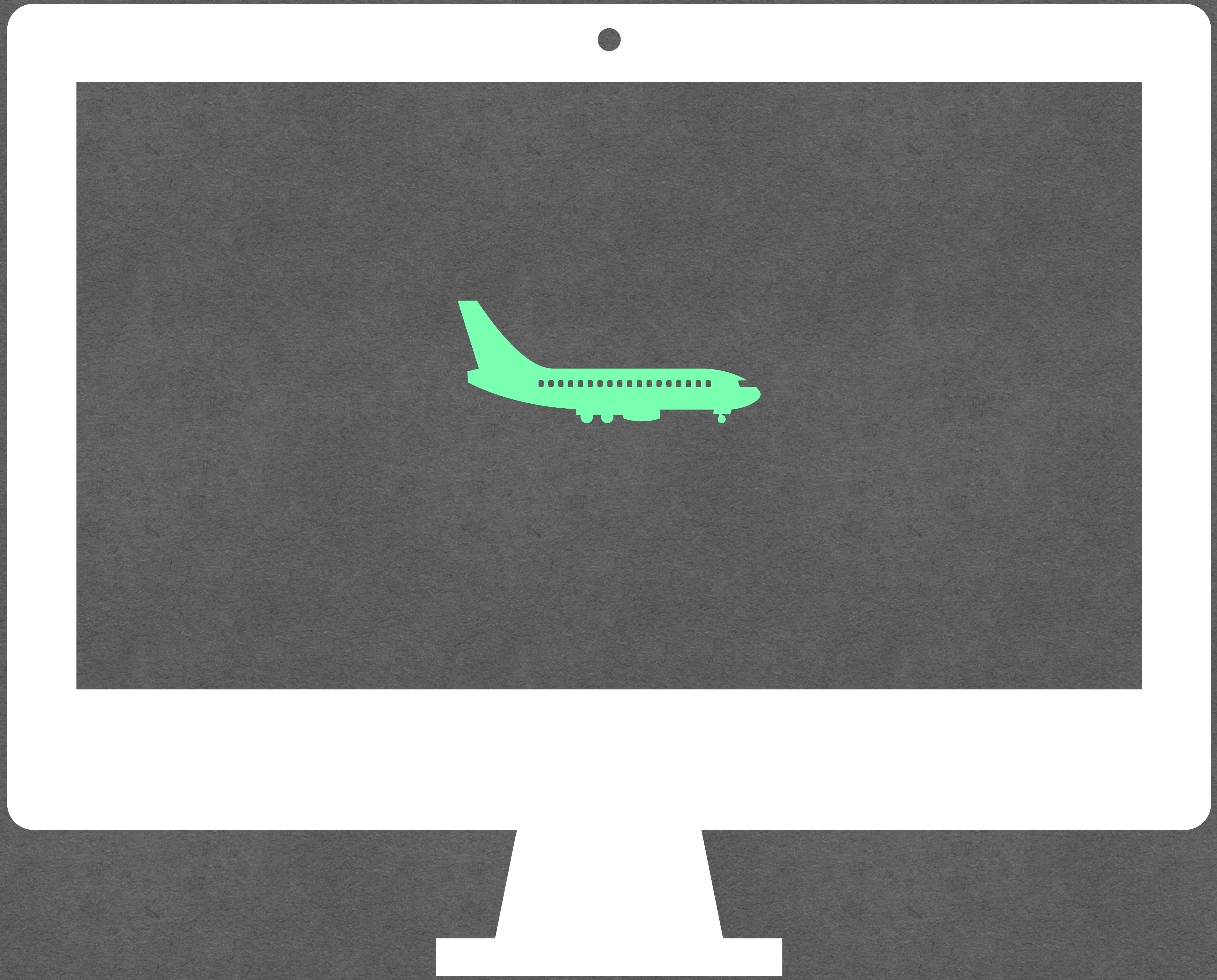
$$H = \ldots\ldots$$

Analytical calculation

Numerical Calculus

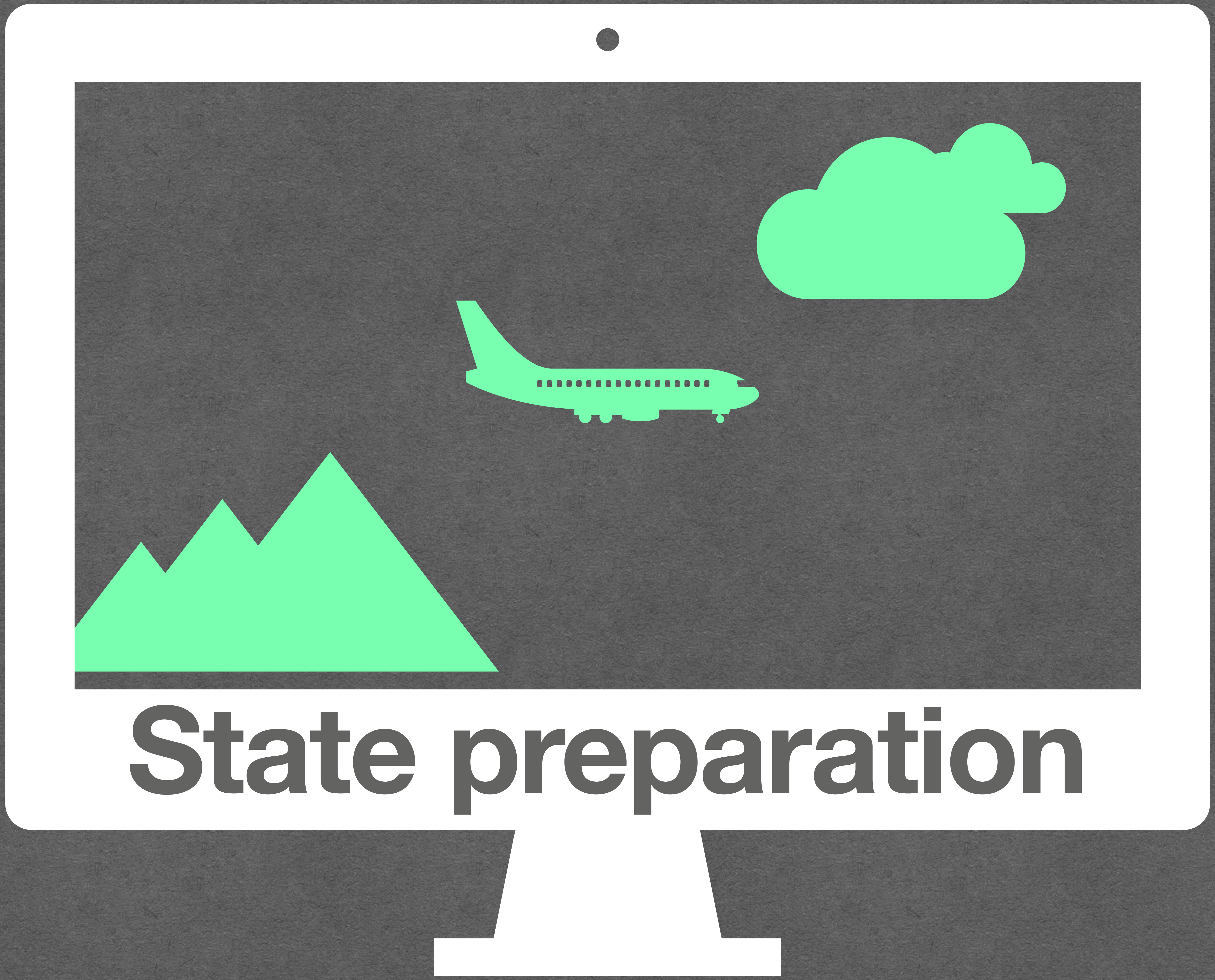


Simulations of physical systems



Simulations of physical systems

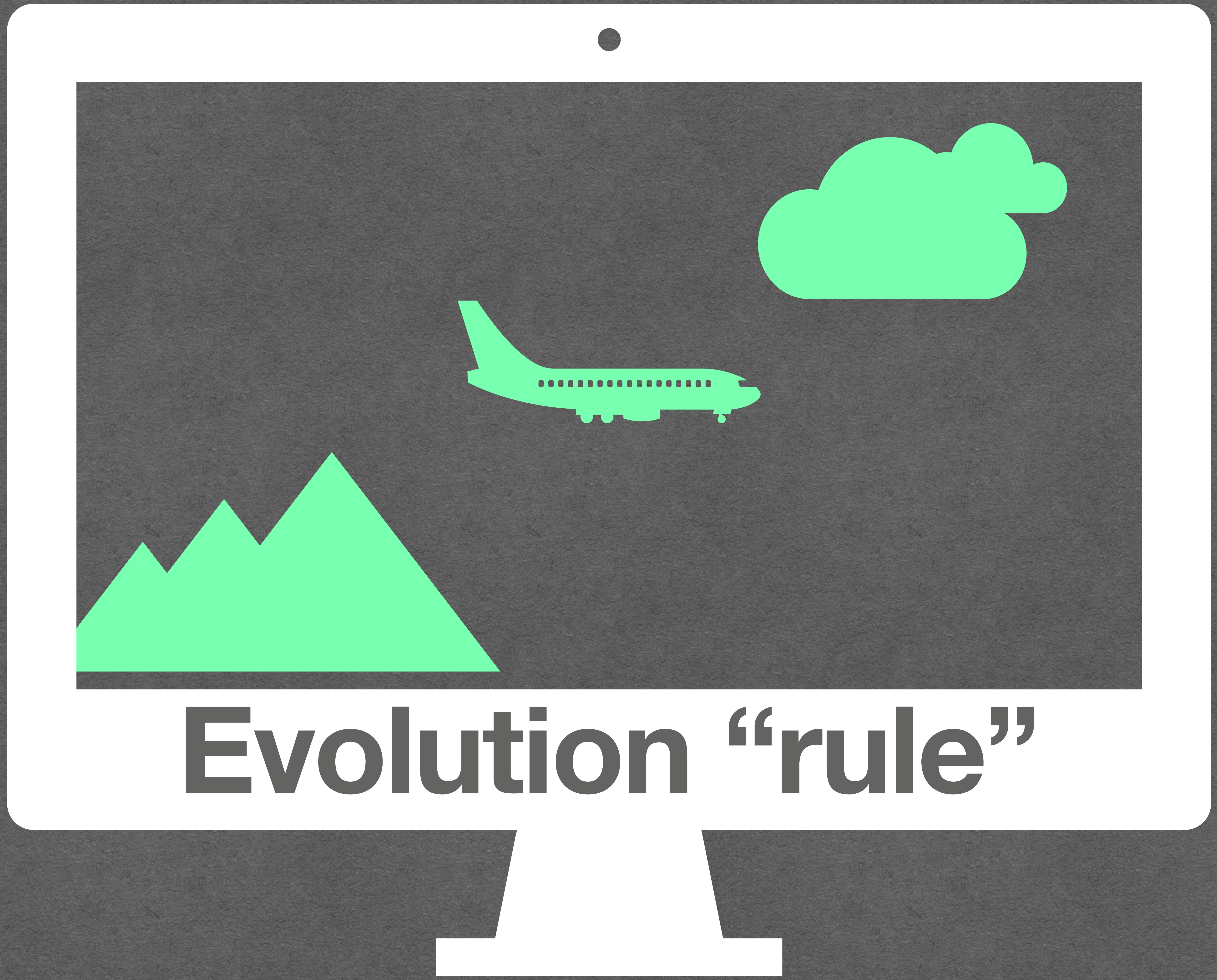
#1



State preparation

Simulations of physical systems

#2



Simulations of physical systems

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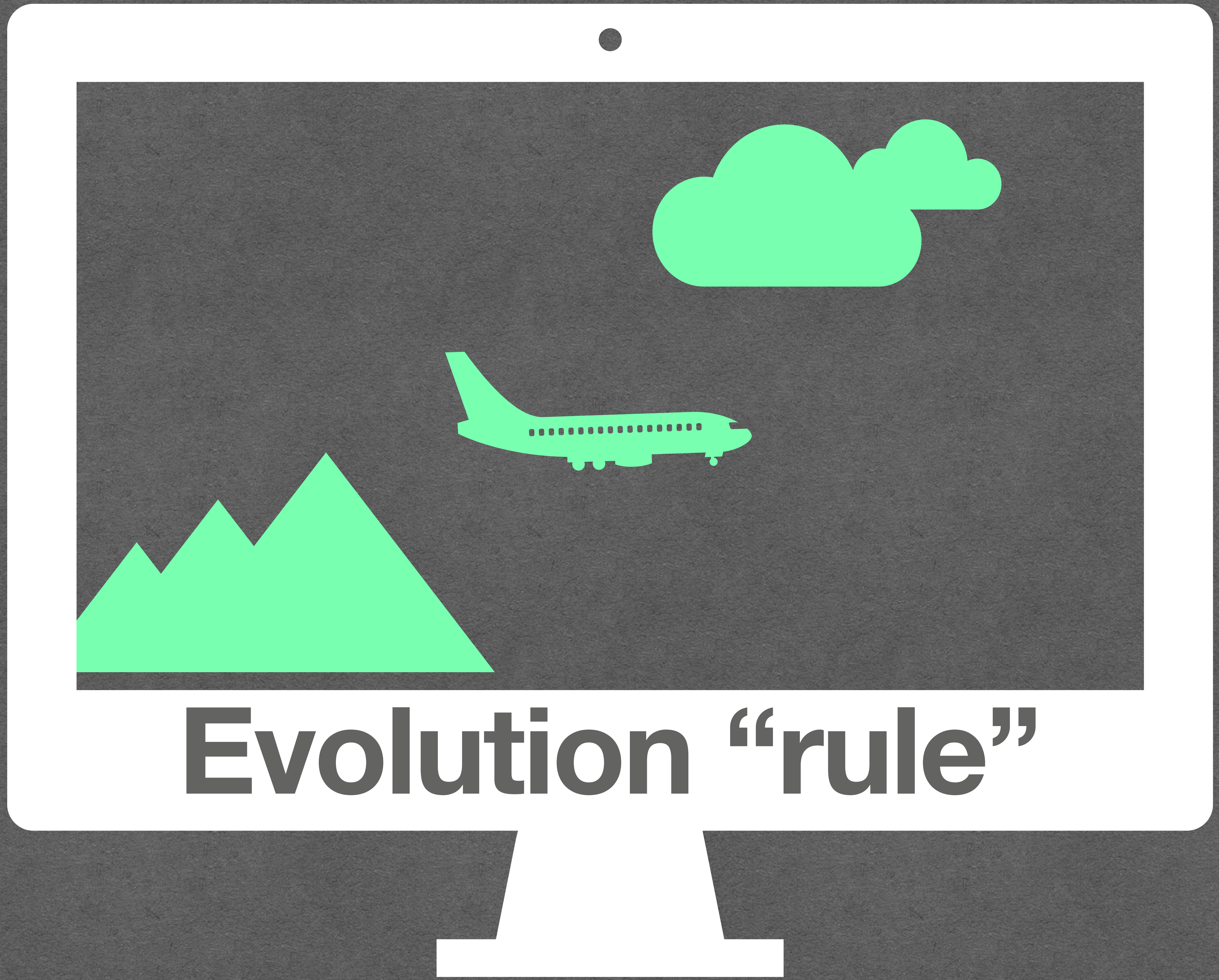

Simulations of physical systems

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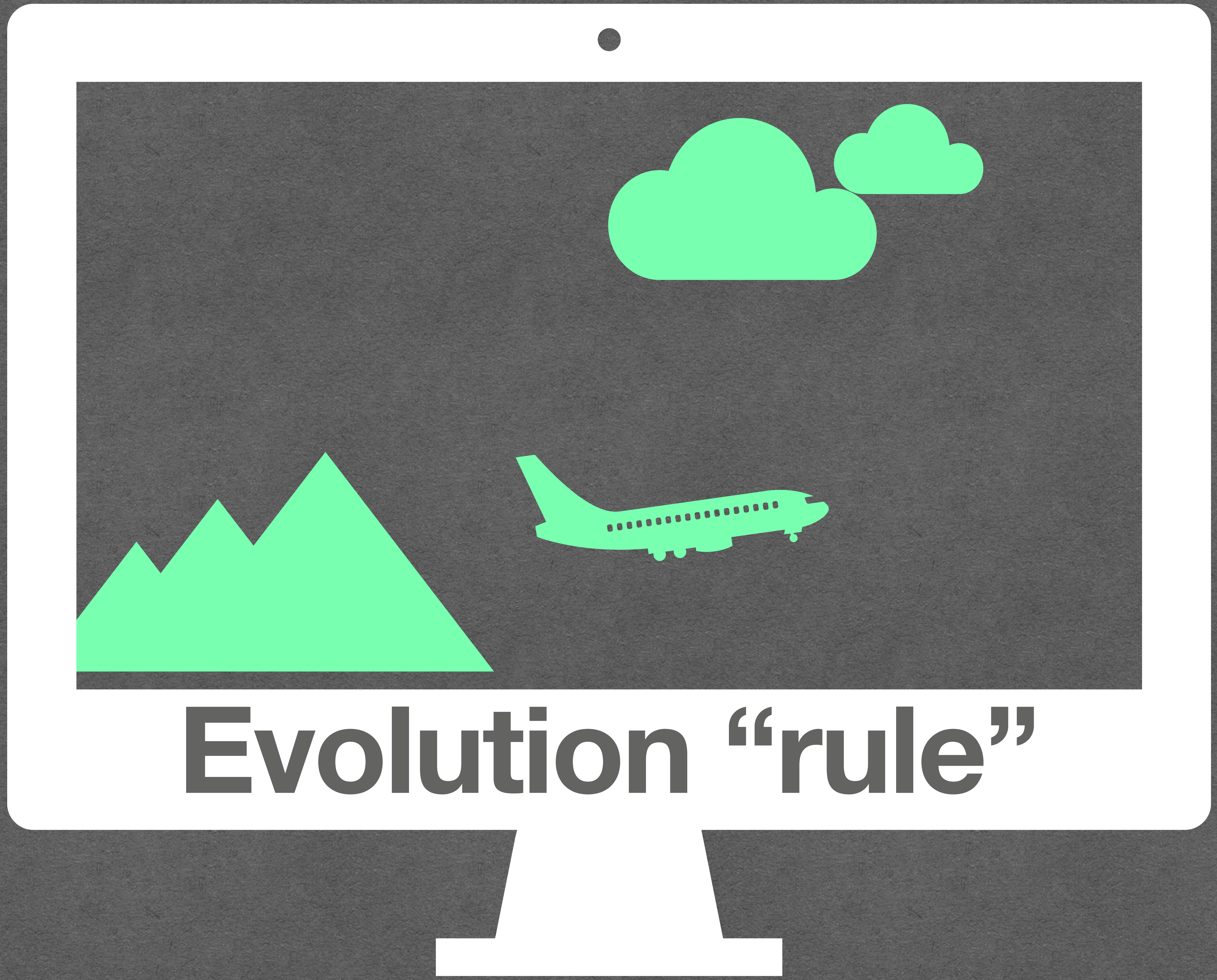

Simulations of physical systems

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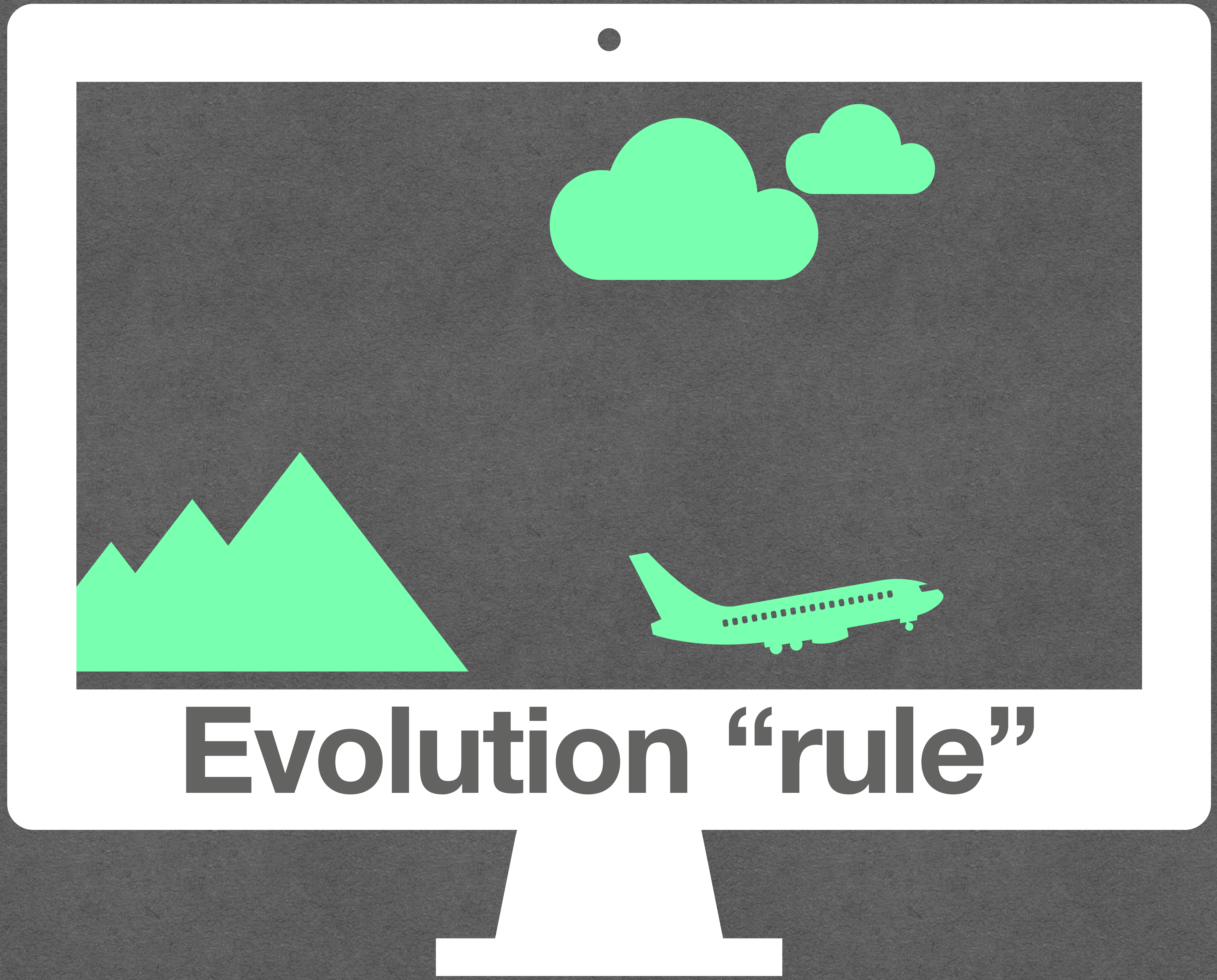
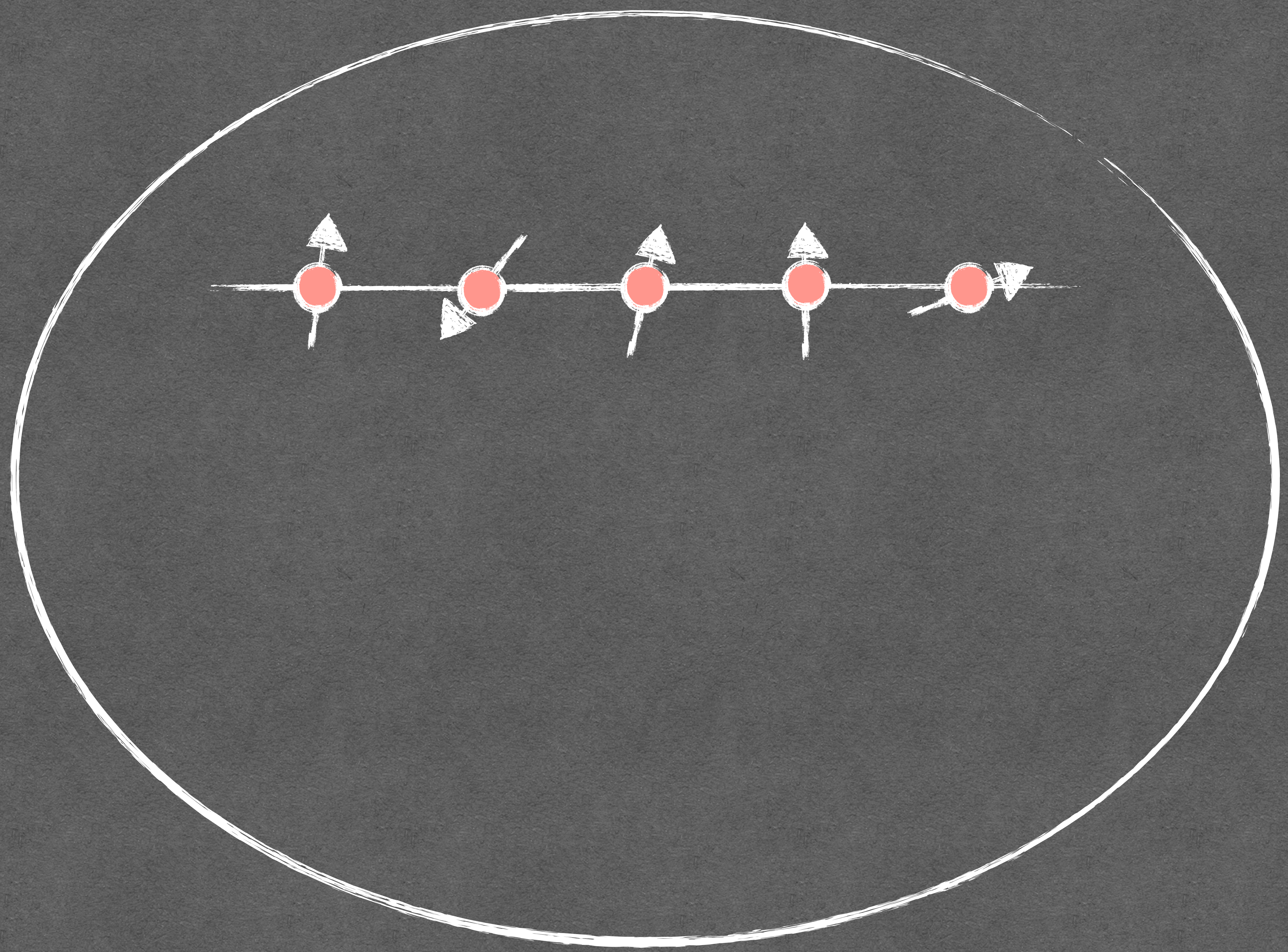


Quantum systems



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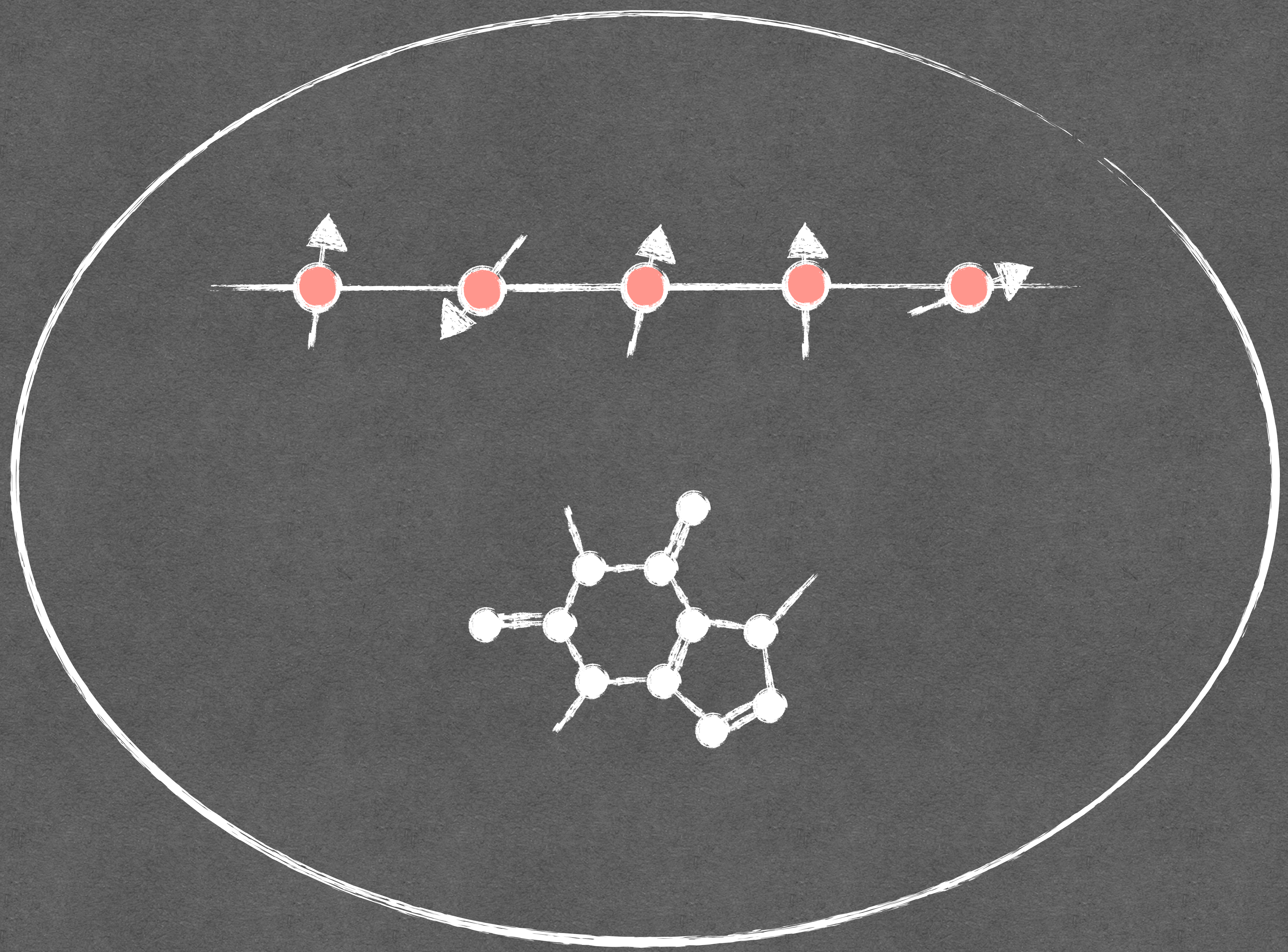
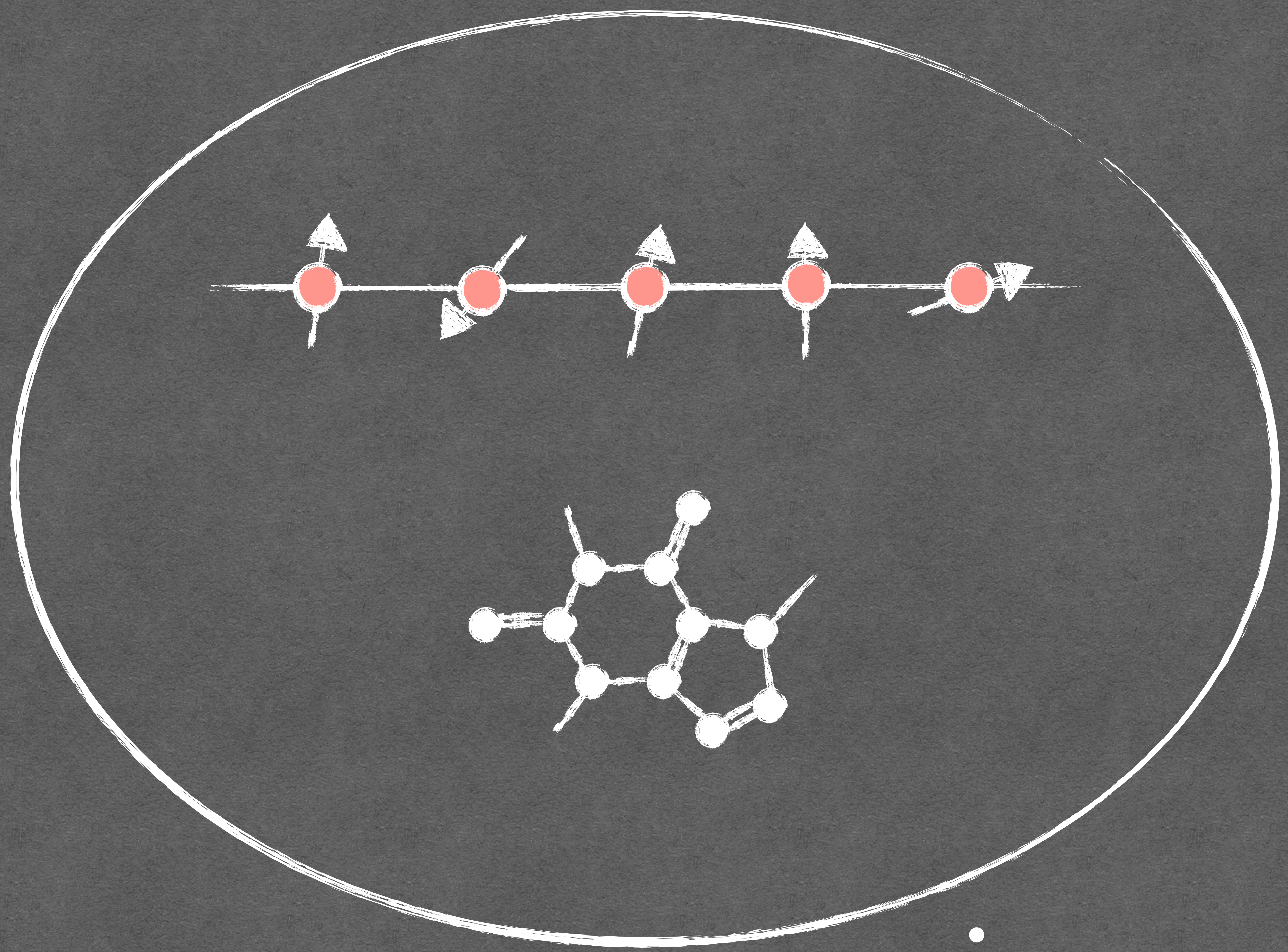
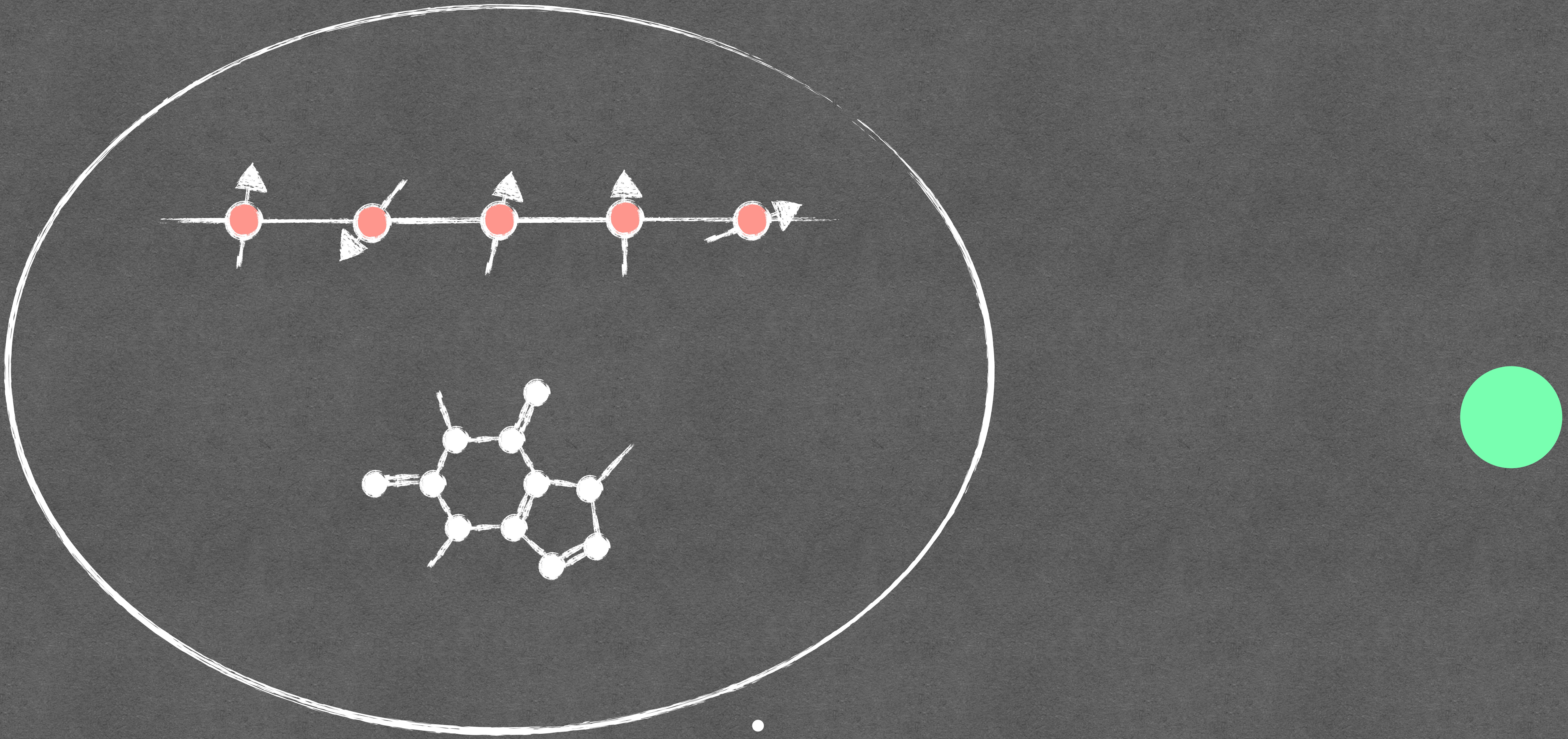


Quantum systems



$$\mathscr{H} \sim 2^{\text{size}}$$

Quantum systems



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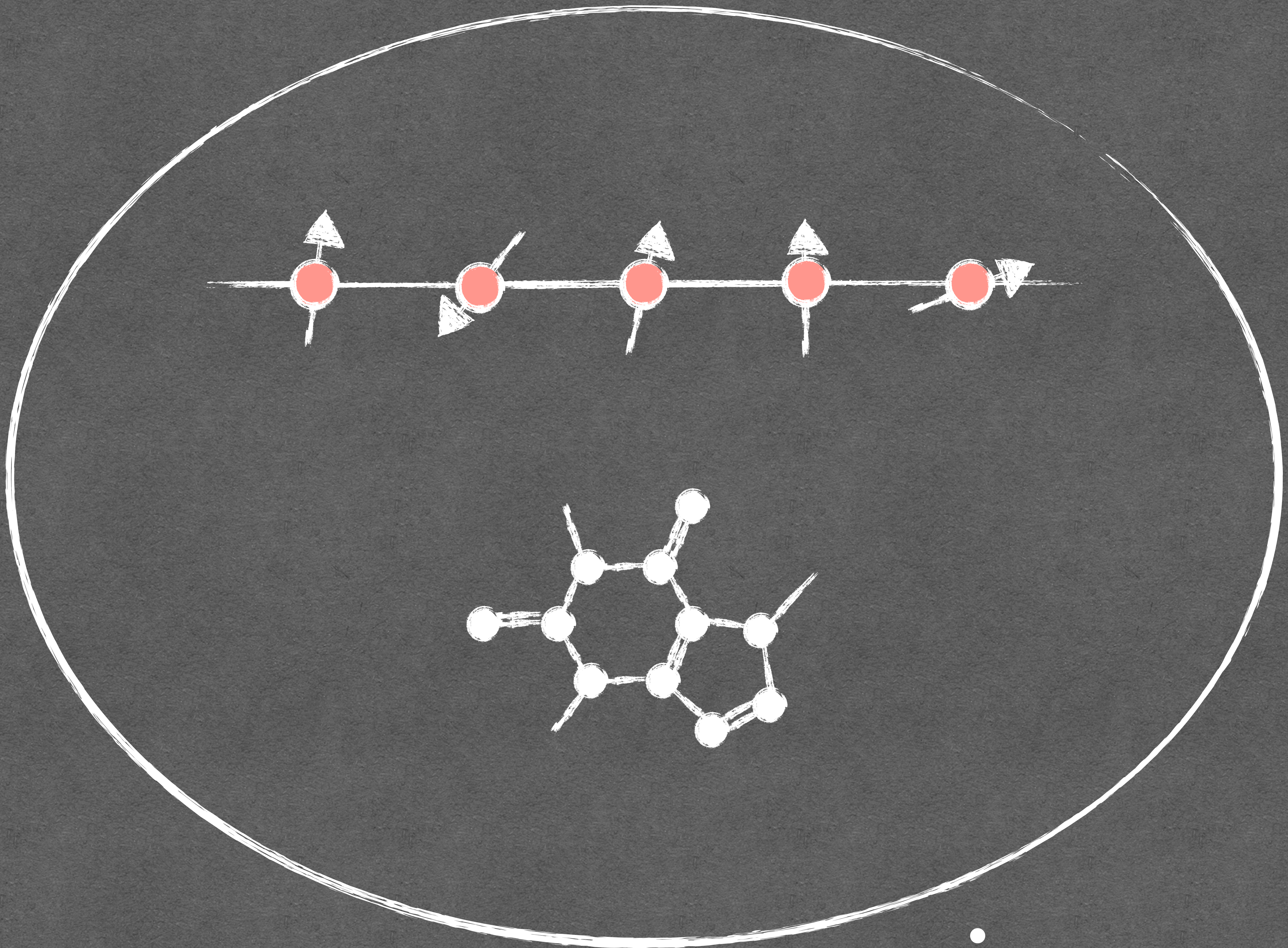
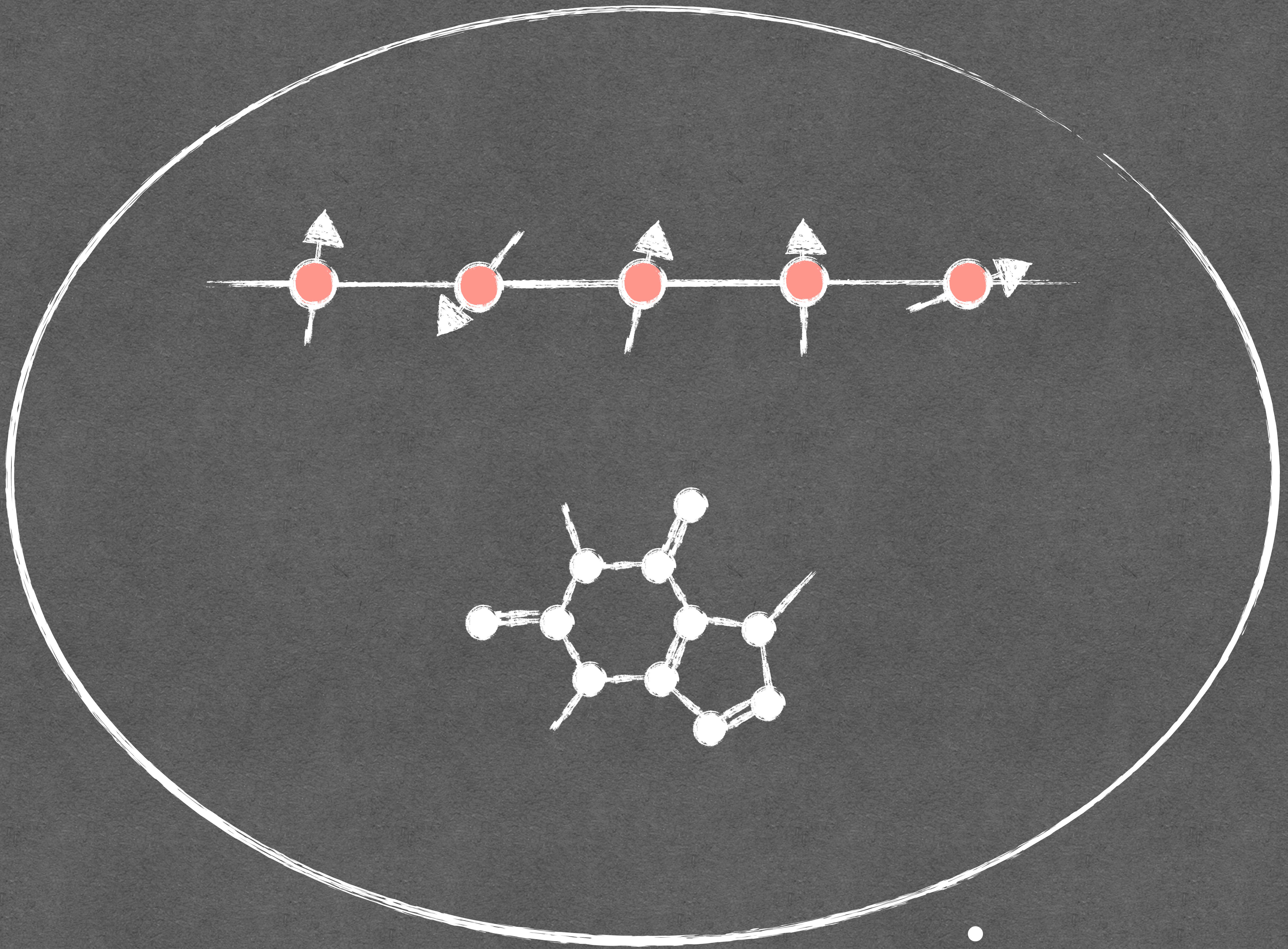


$$\mathscr{H} \sim 2^{\text{size}}$$

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

Quantum systems



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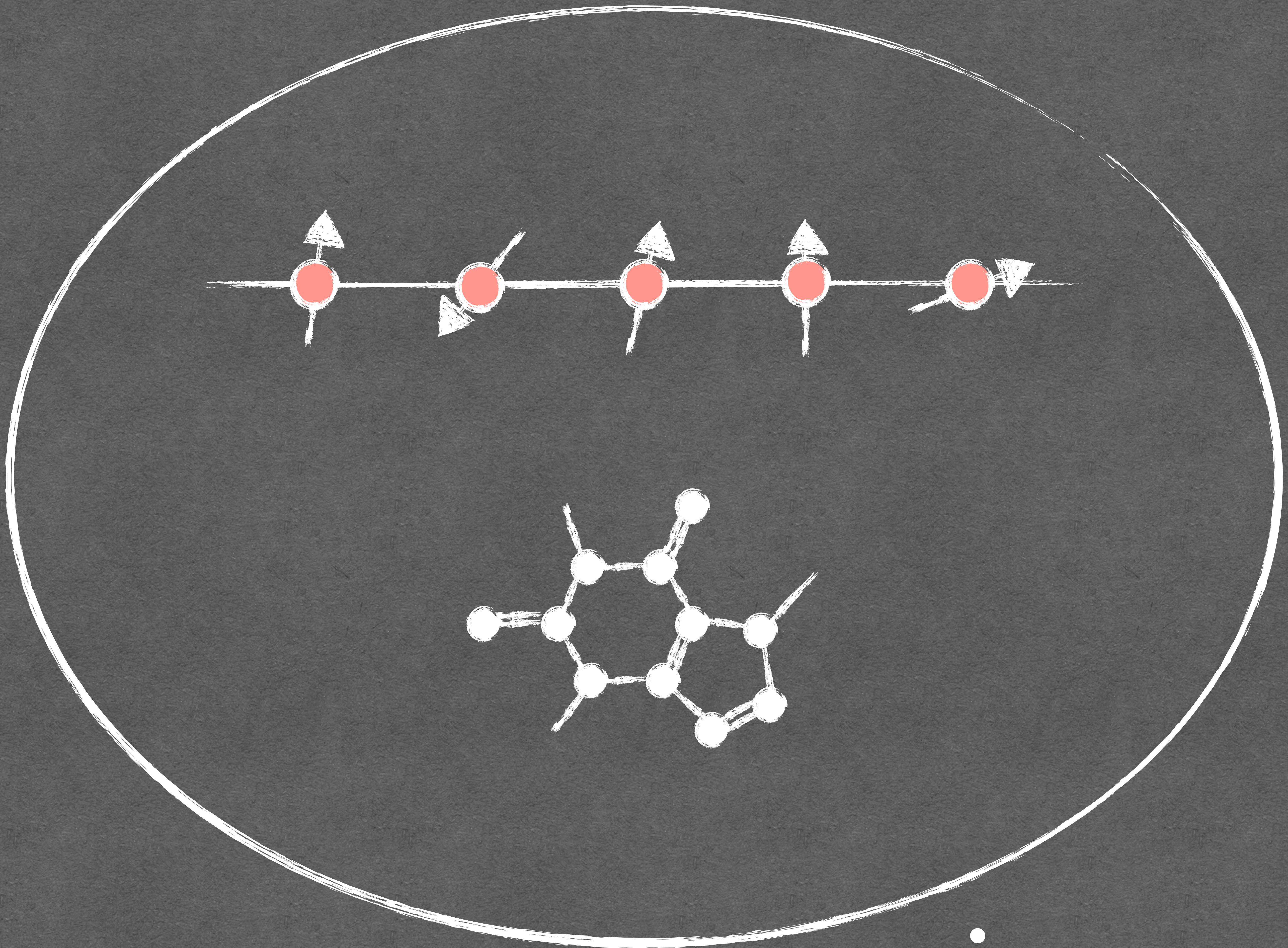

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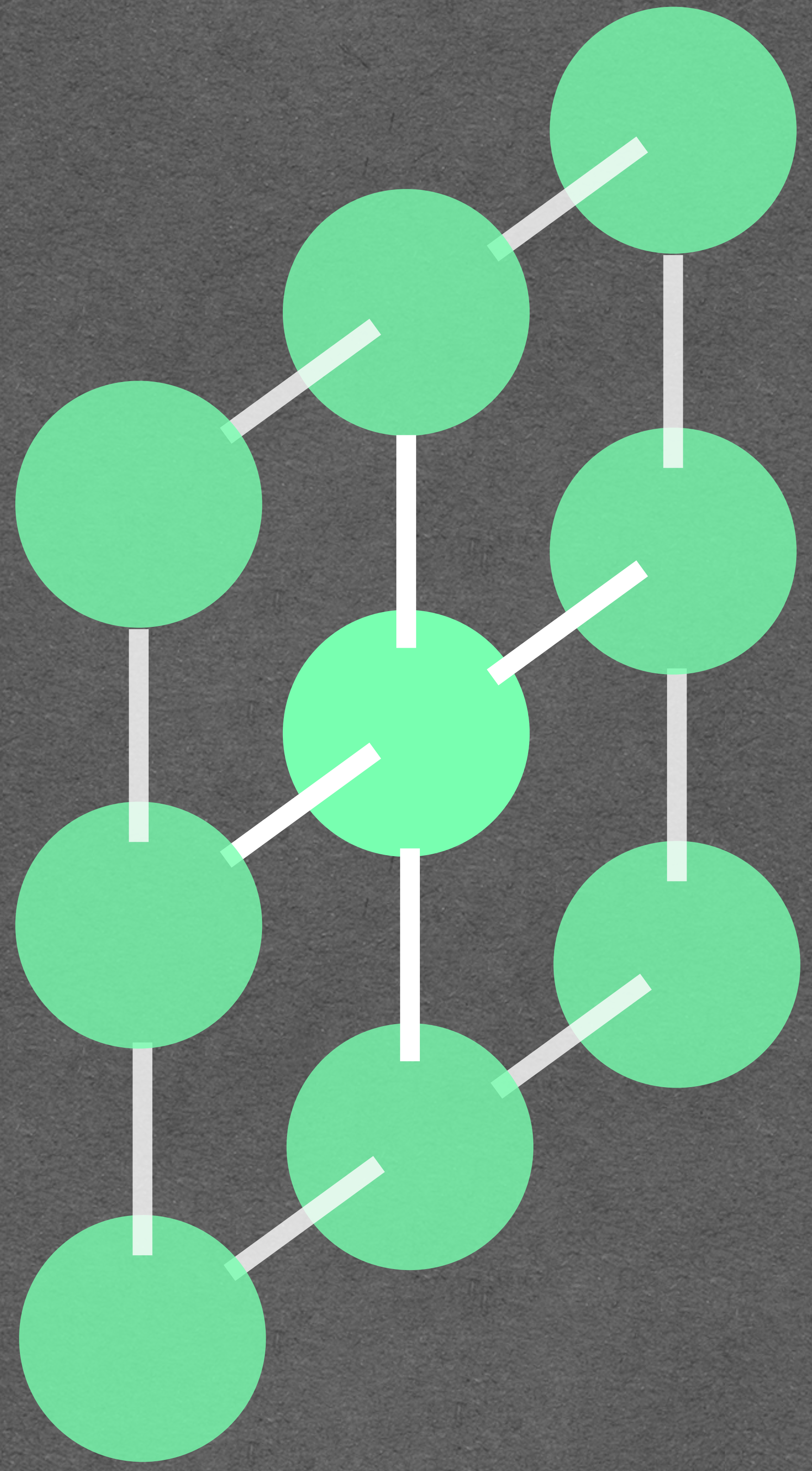

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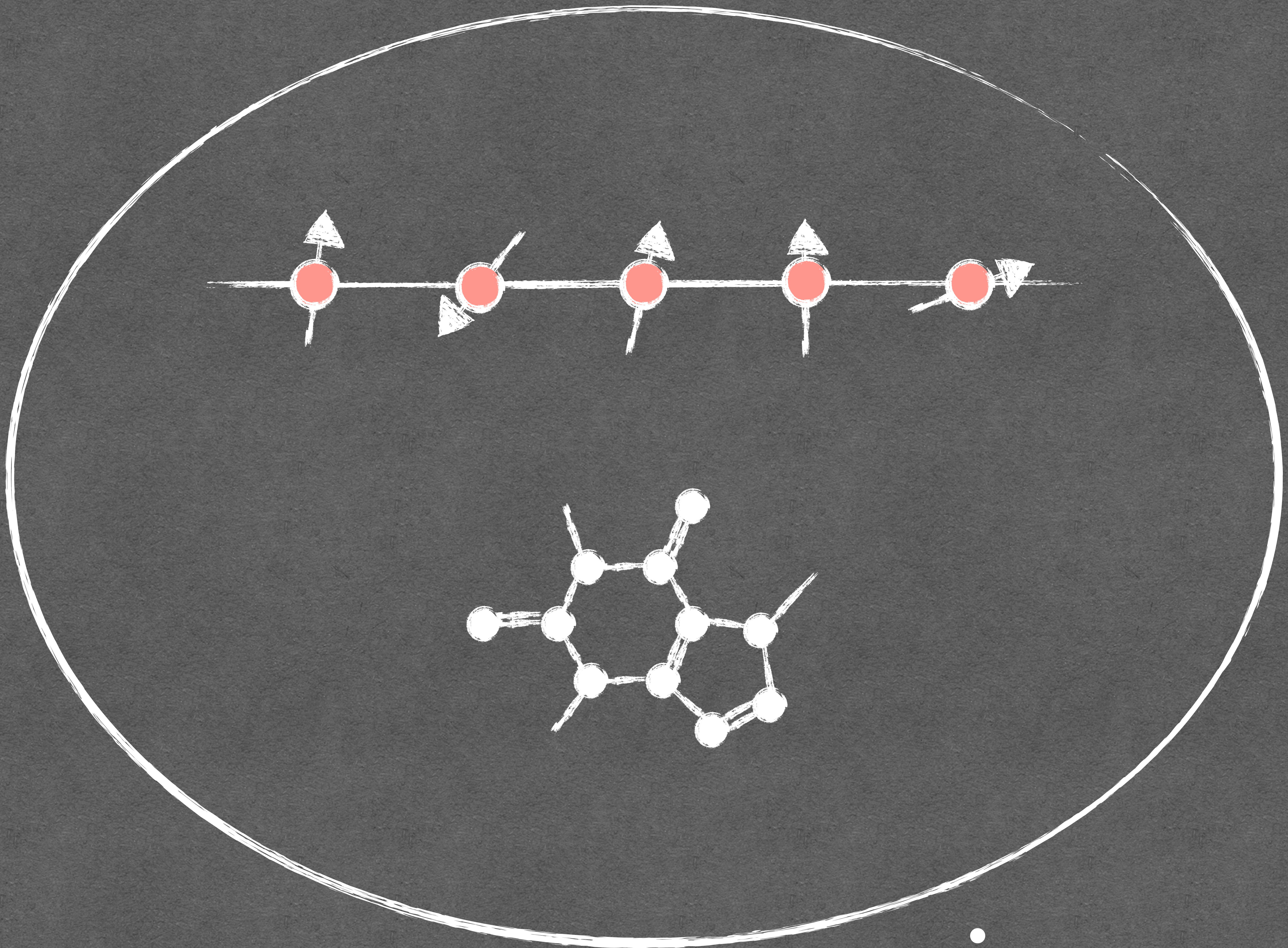

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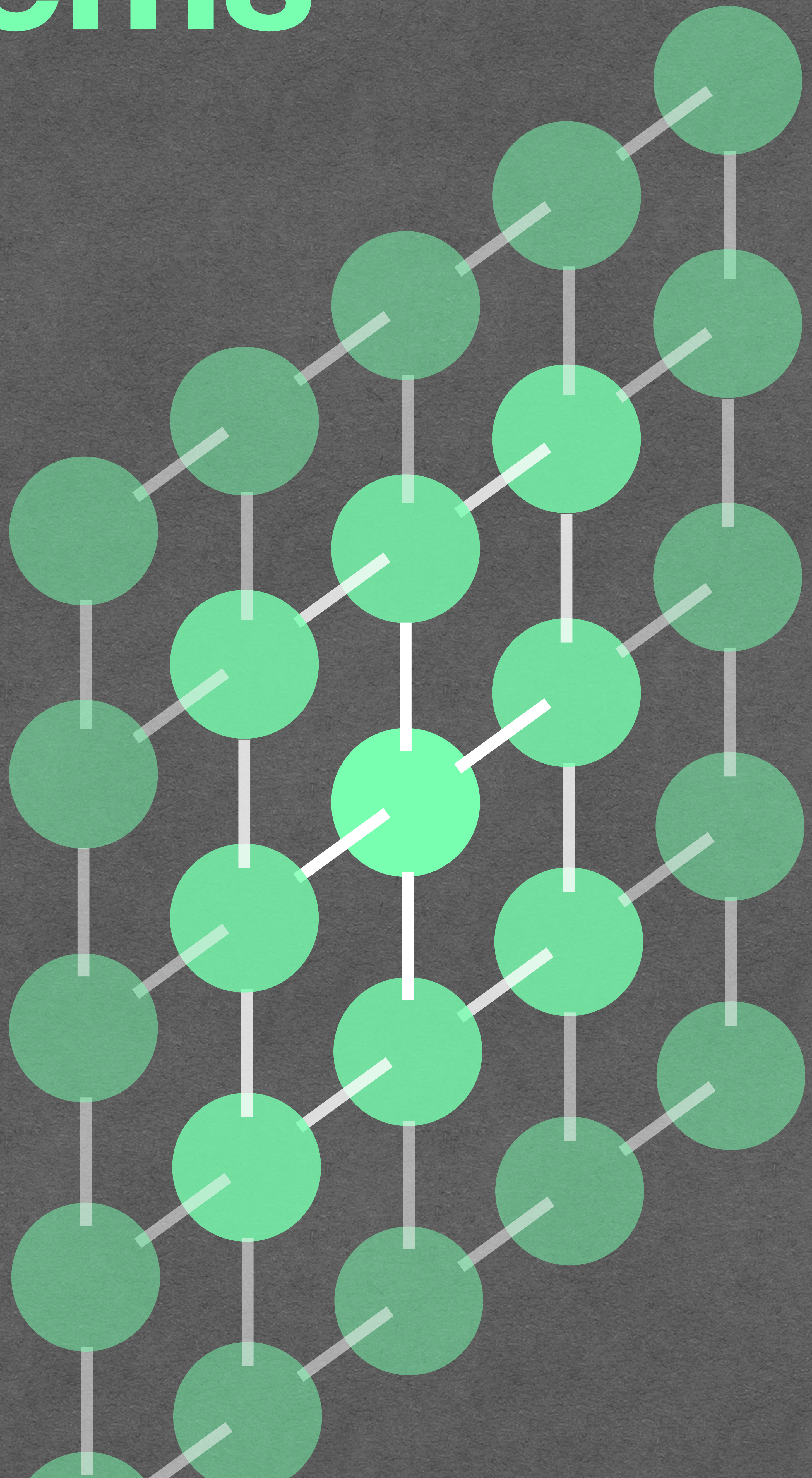

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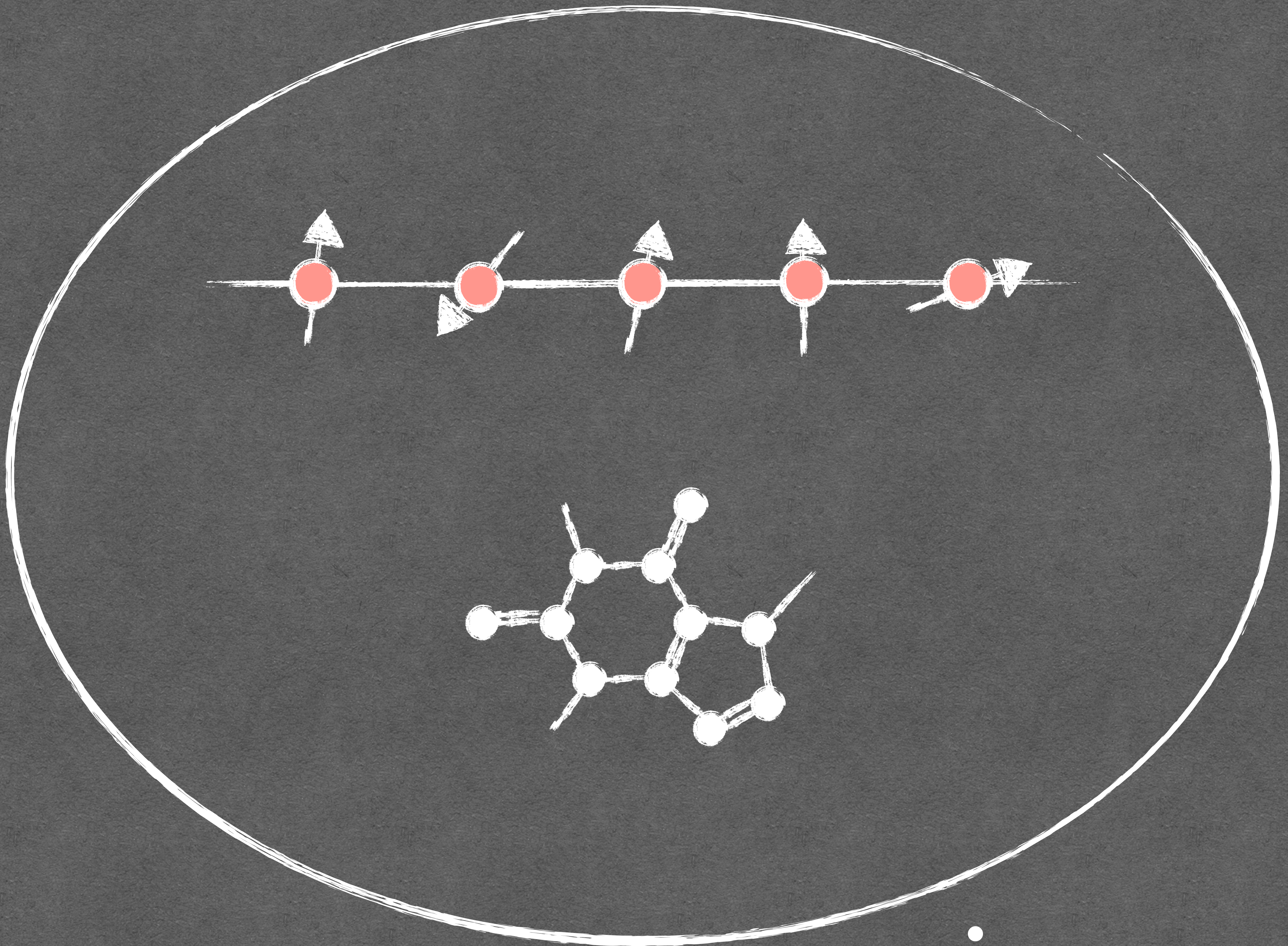

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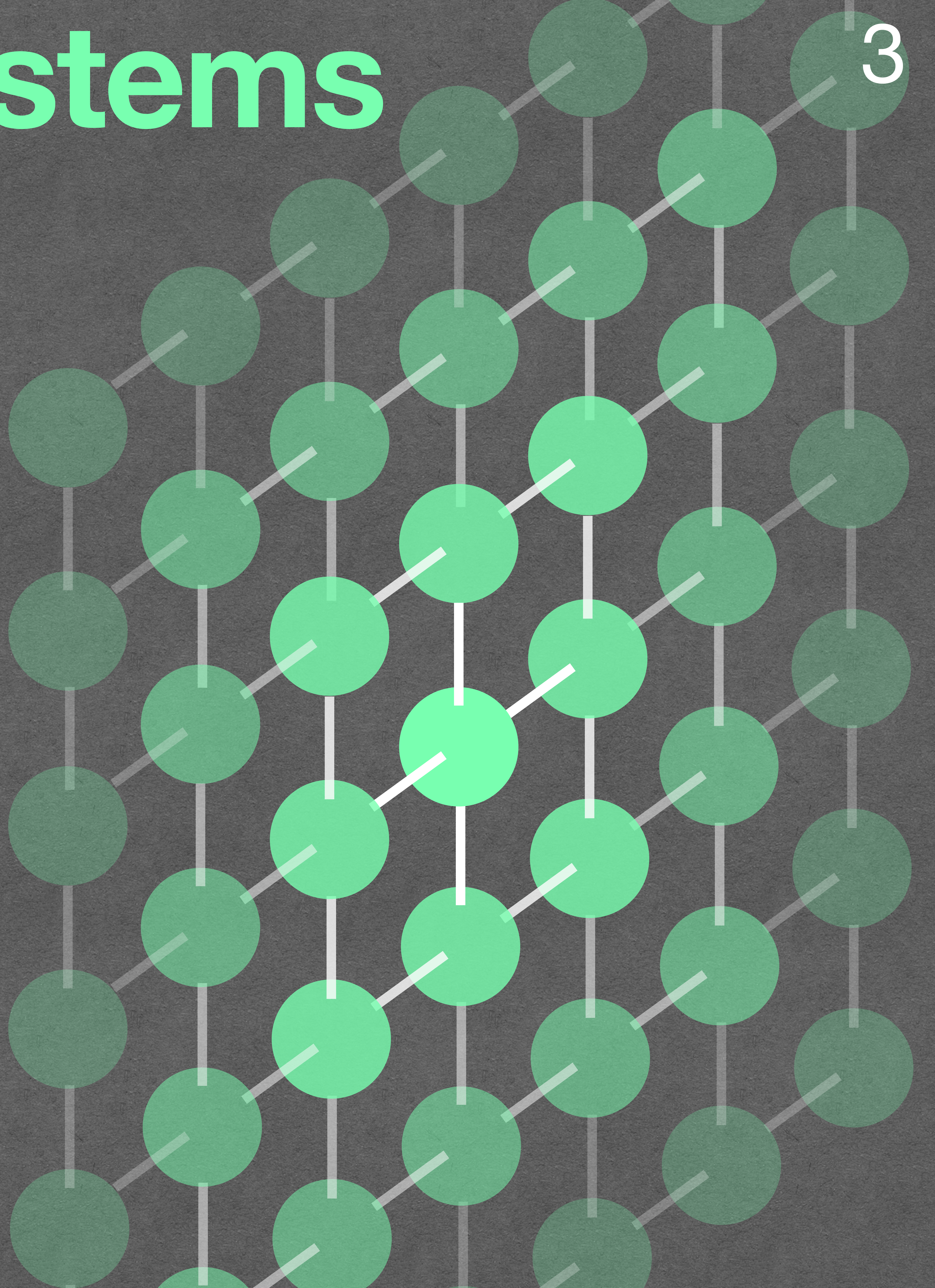
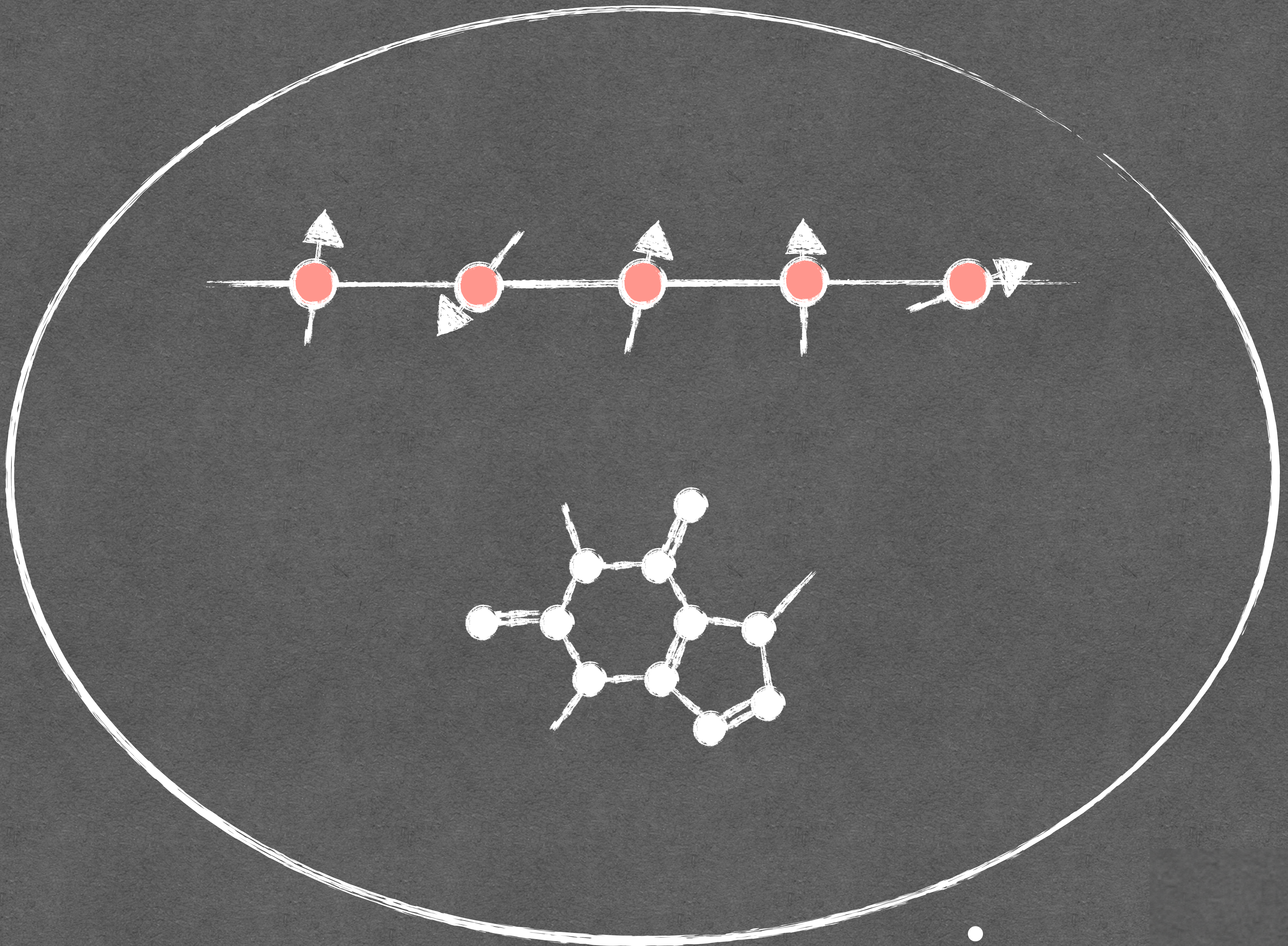
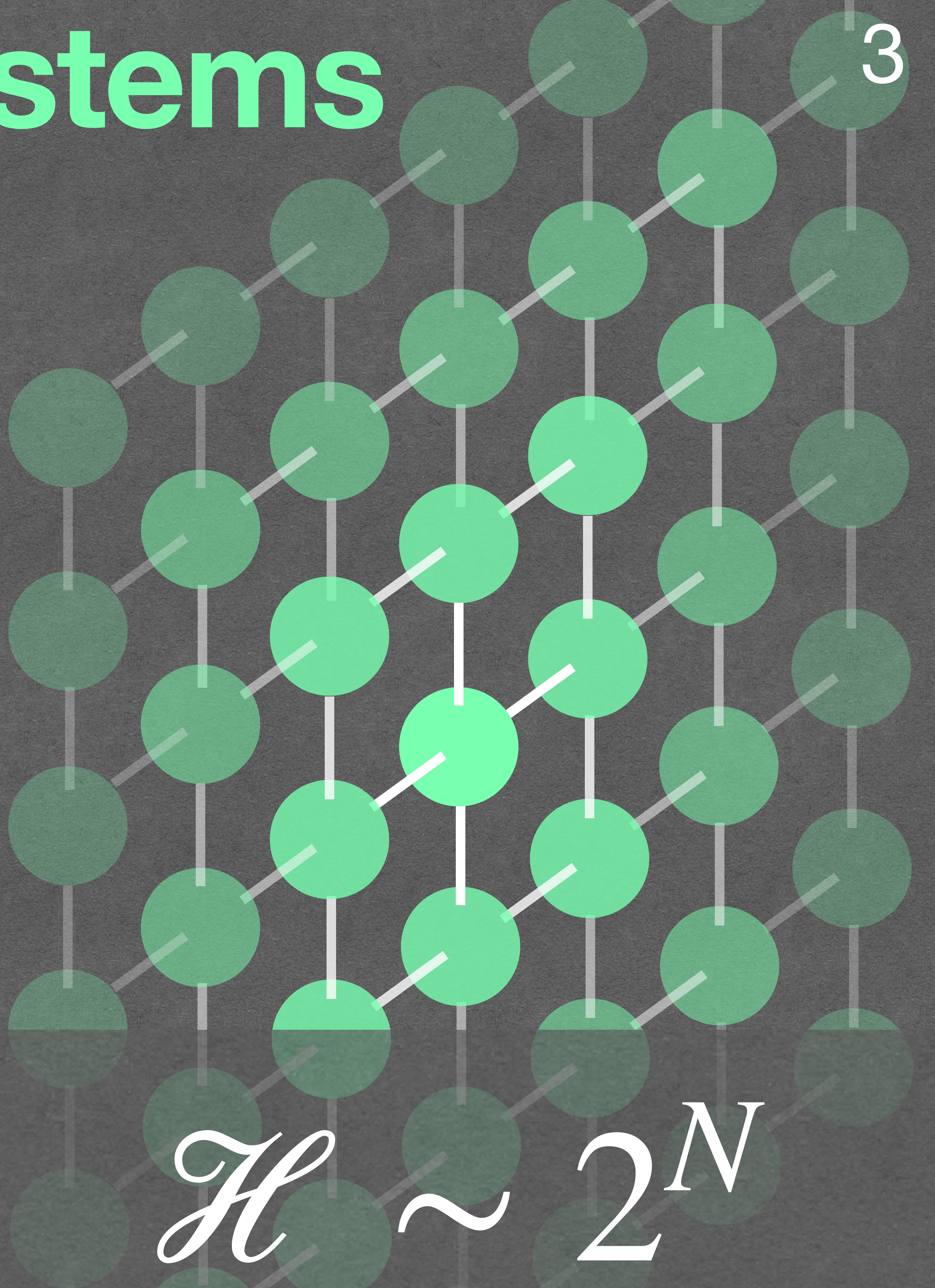


Quantum systems

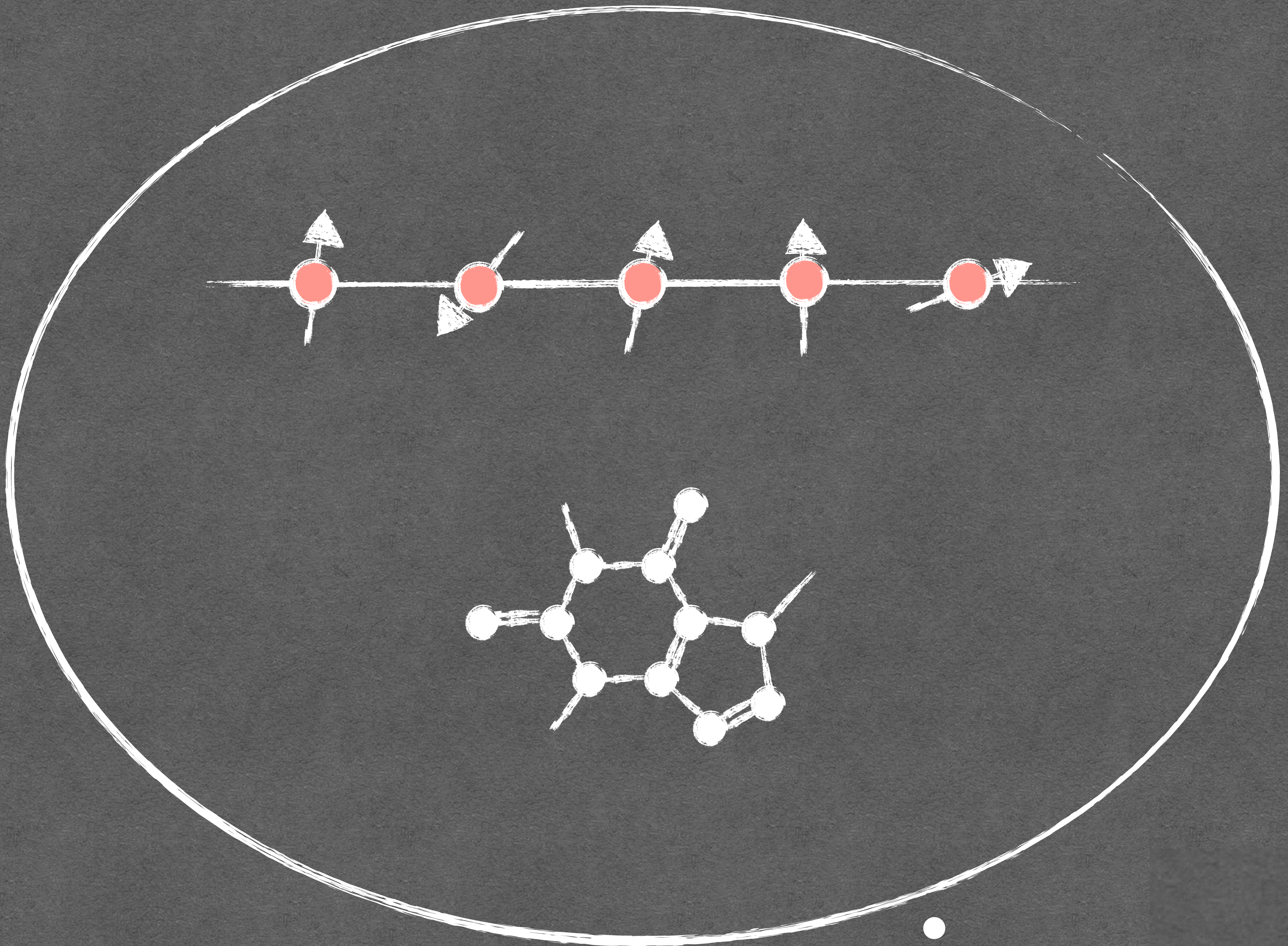


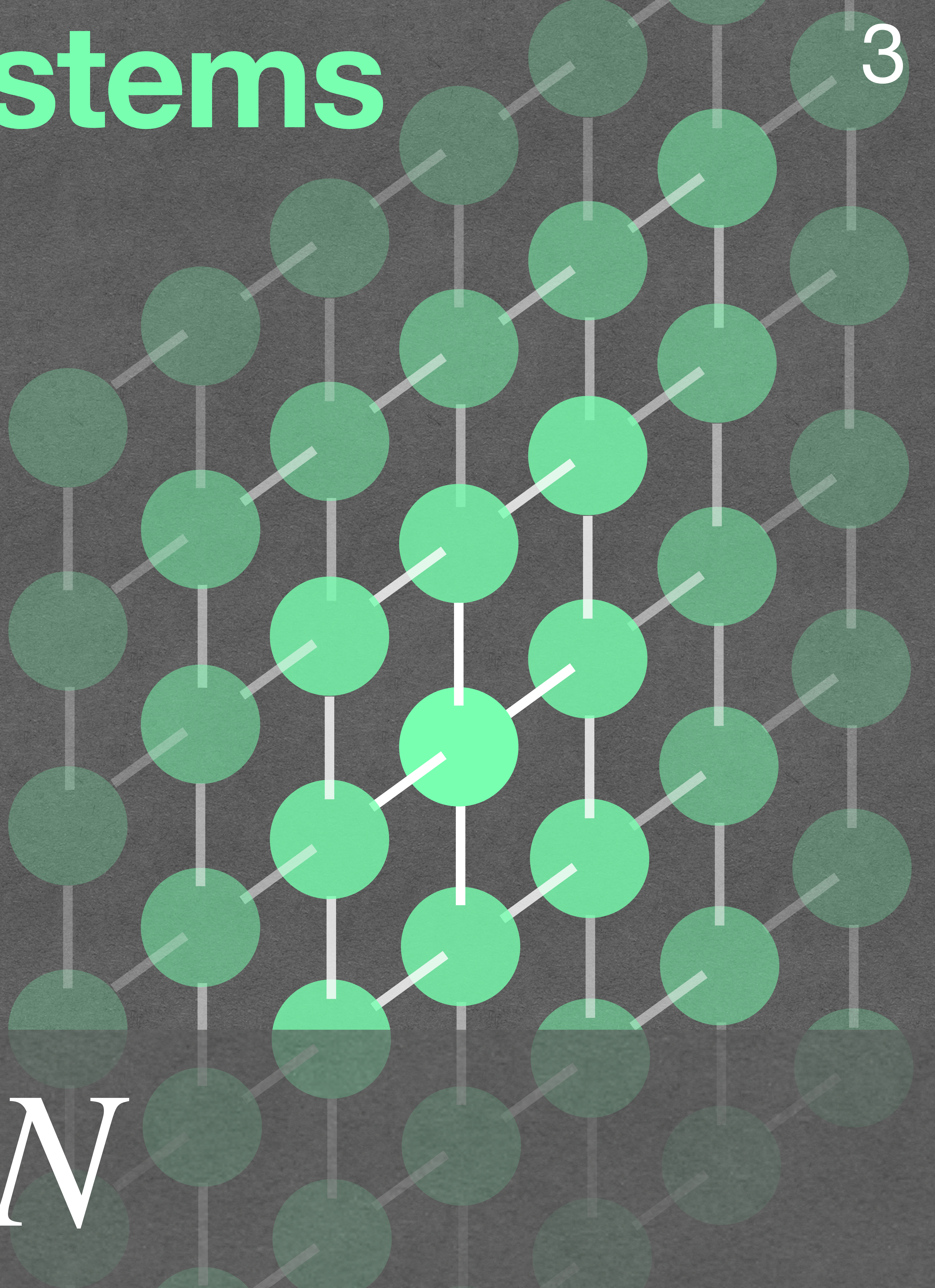


$\mathscr{H} \sim 2^{\mathrm{size}}$

$\mathscr{H} \sim 2^{N}$

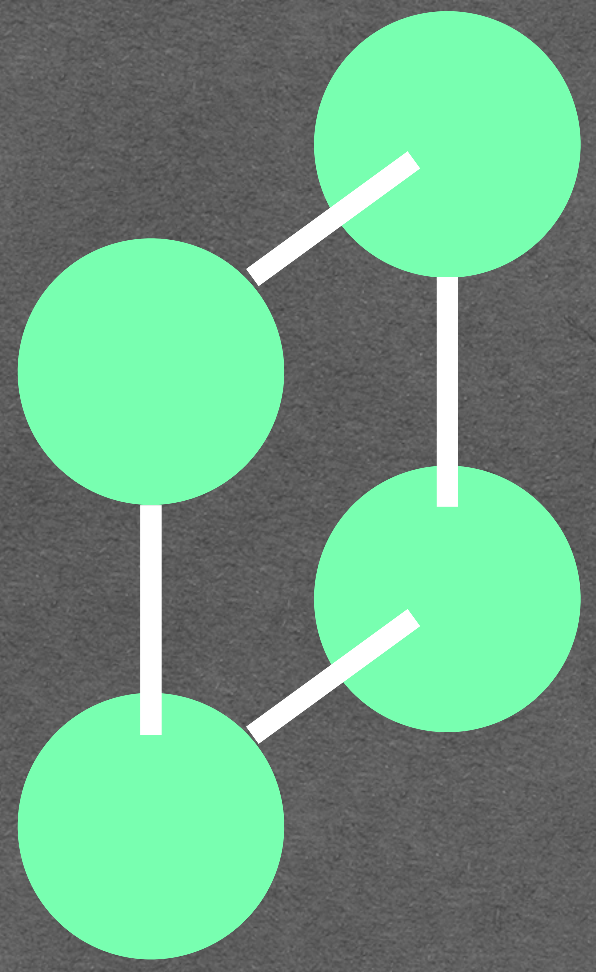
Quantum systems





size $\sim N$

Quantum-state preparation



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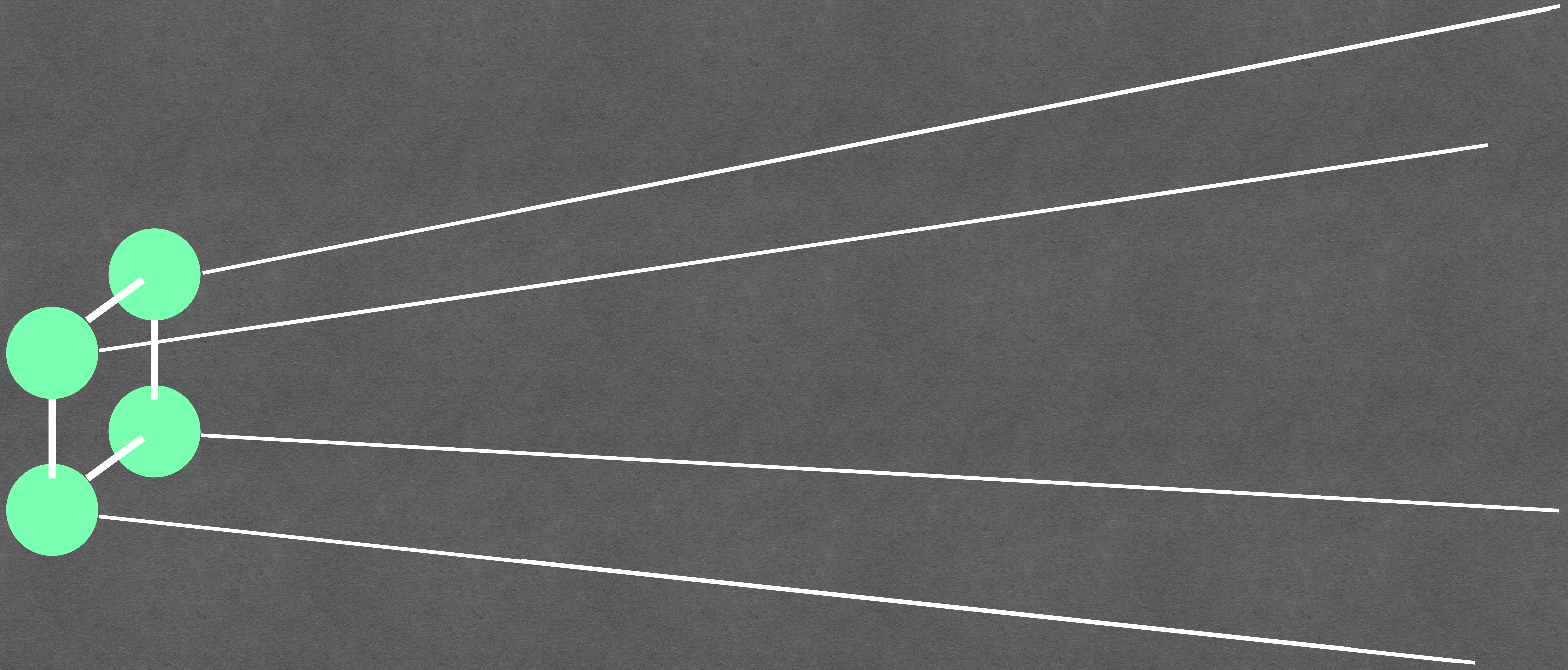

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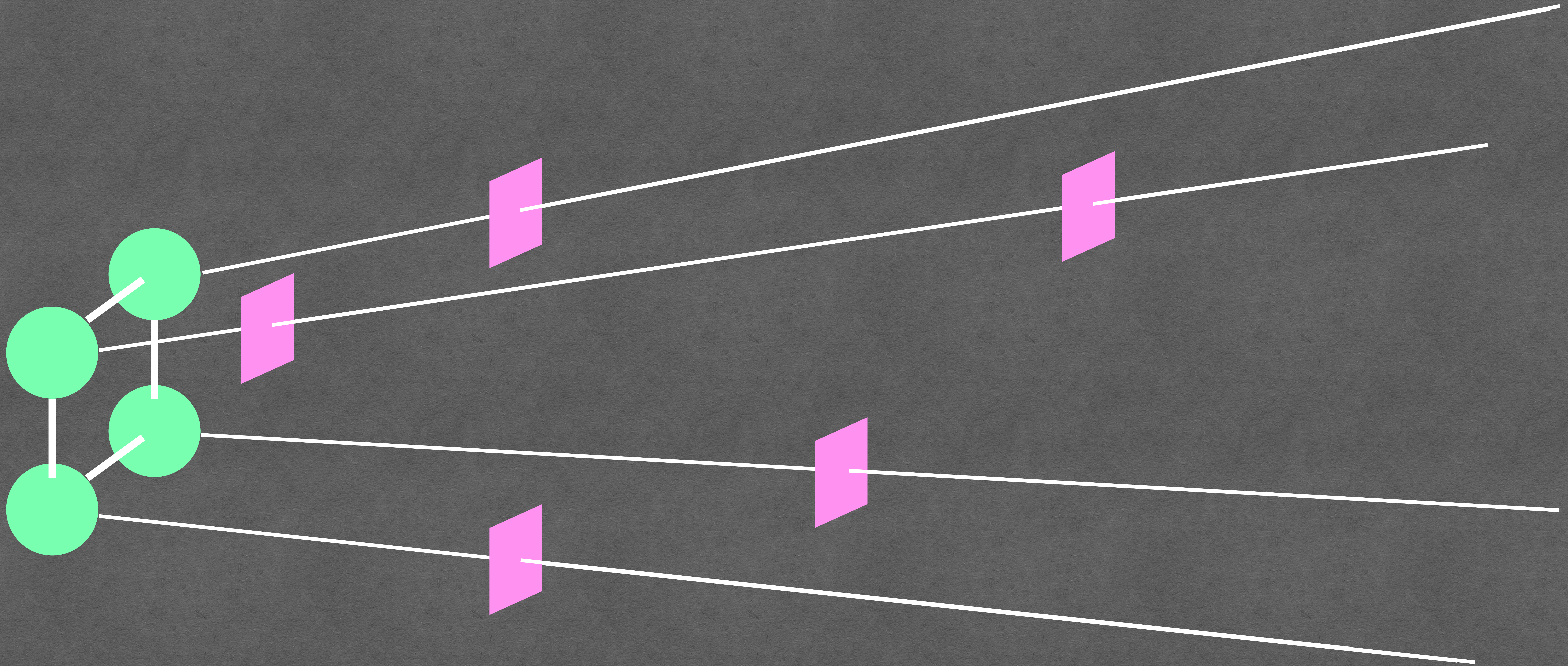

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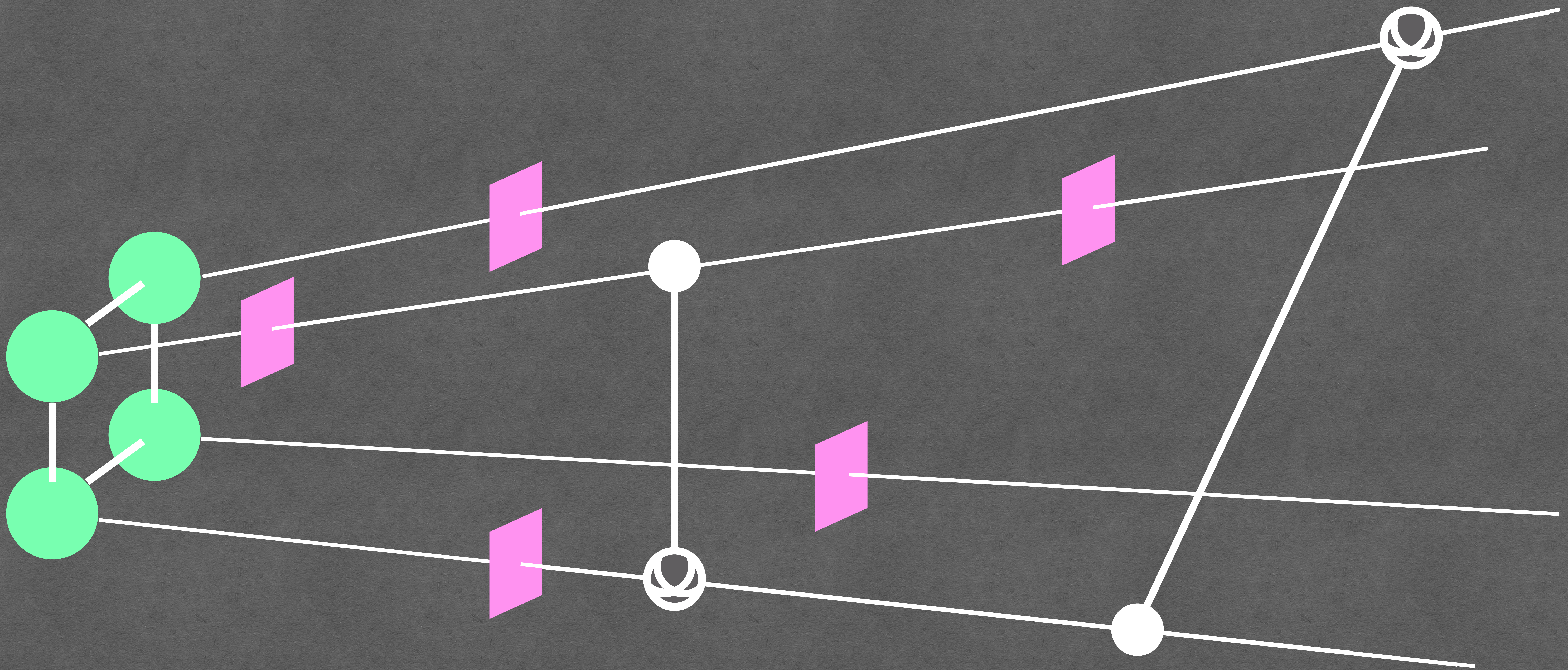
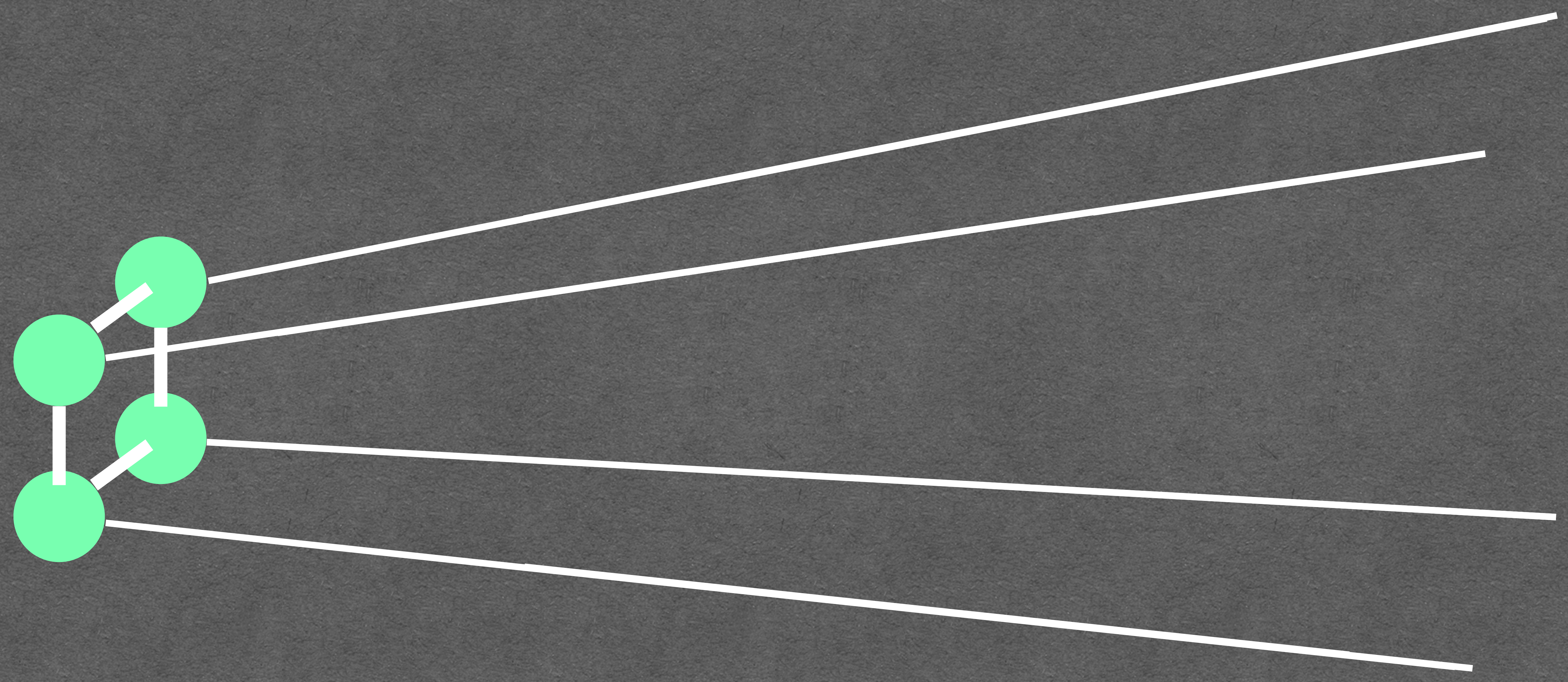


State preparation challenge

Default state

$|0\rangle^{\otimes N}$



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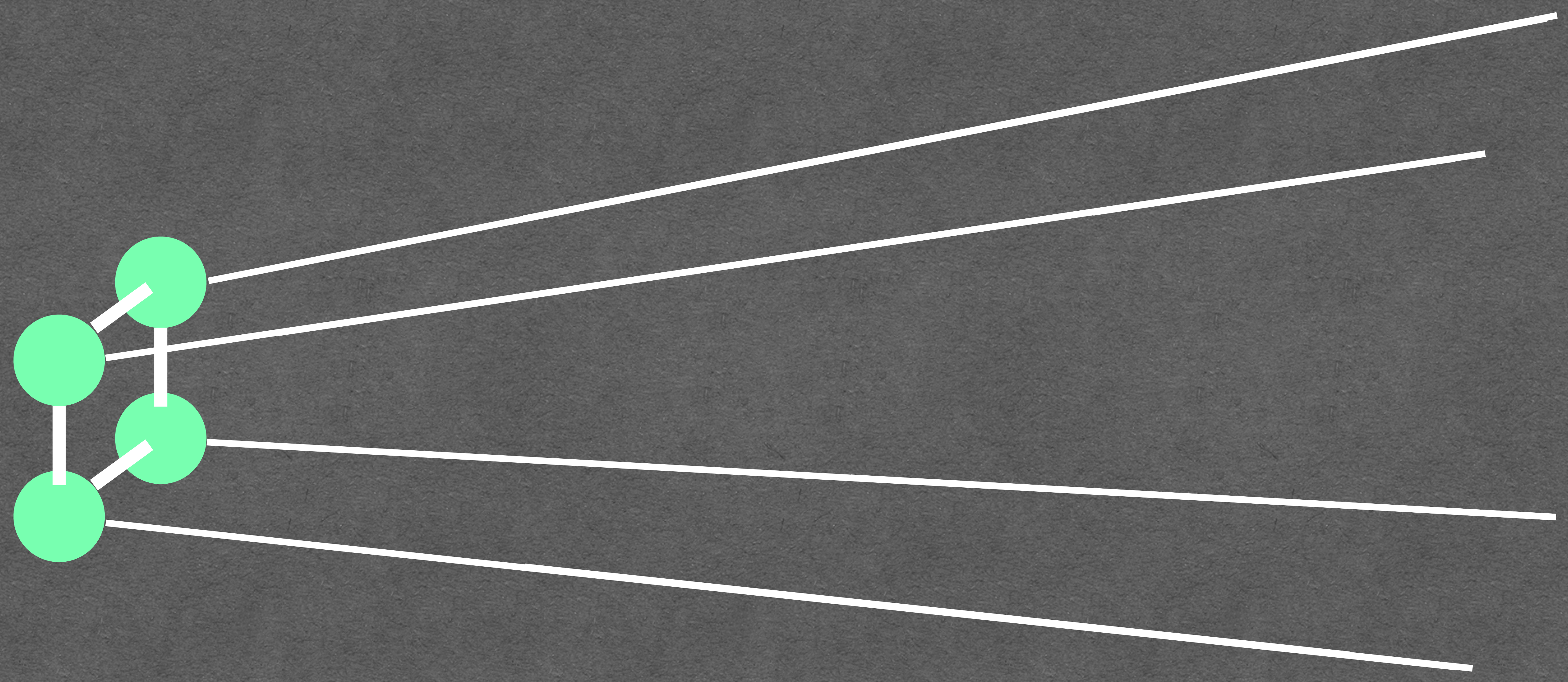


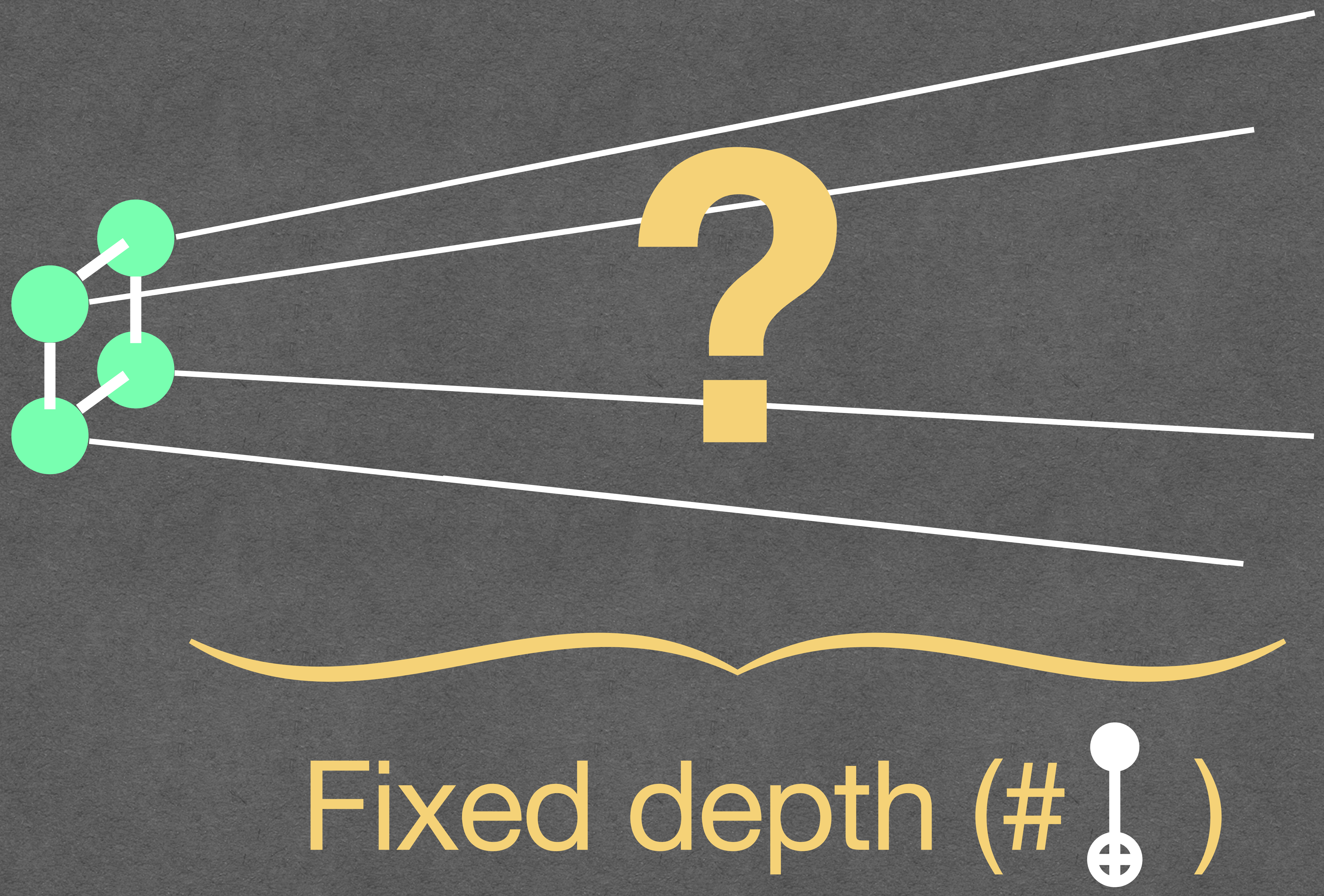
Target state

$$|\Psi\rangle$$

State preparation challenge

Default state

$|0\rangle^{\otimes N}$



Target state

$|\Psi\rangle$

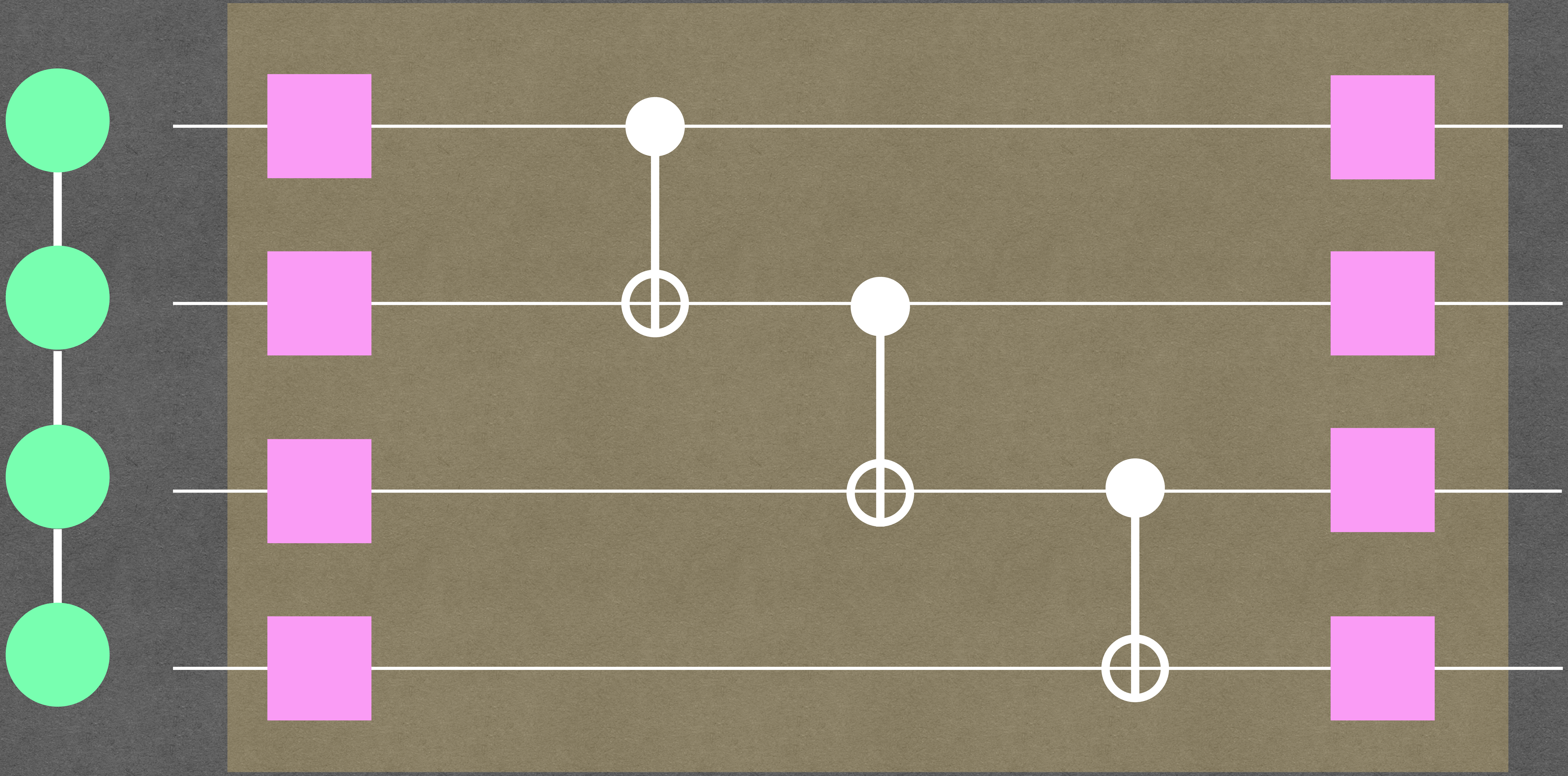
Fixed depth (#

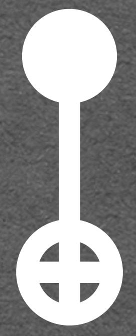
ALGORITHMS

H_1**: Hamiltonian of the problem**

$|\Psi_n\rangle$**: n-th eigenstate (target)**

Variational Quantum Eigensolvers (VQE)



Fixed depth (# )

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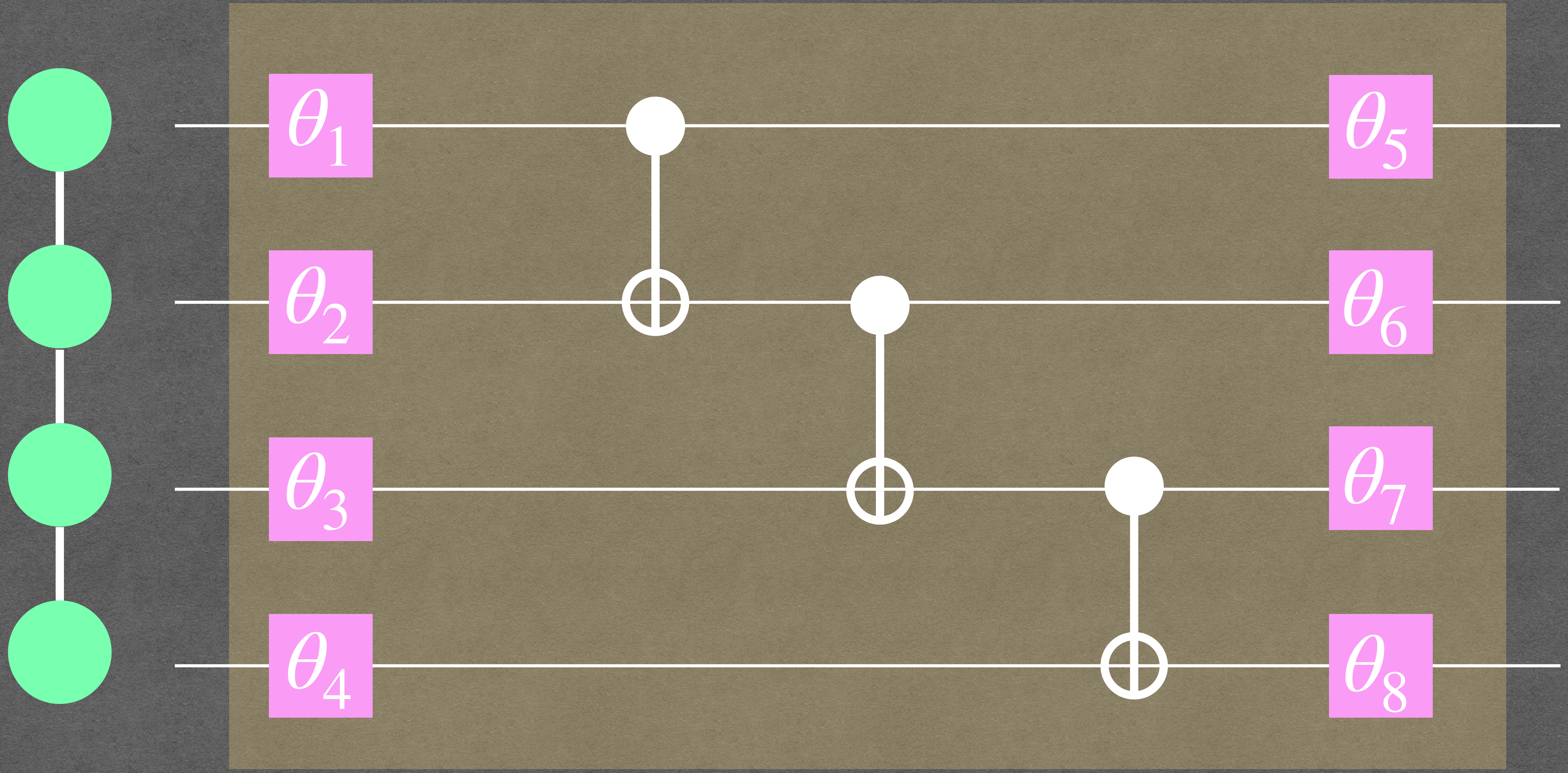
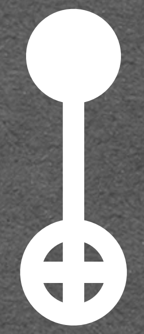


Fixed depth (# )

Main Problems of VQE

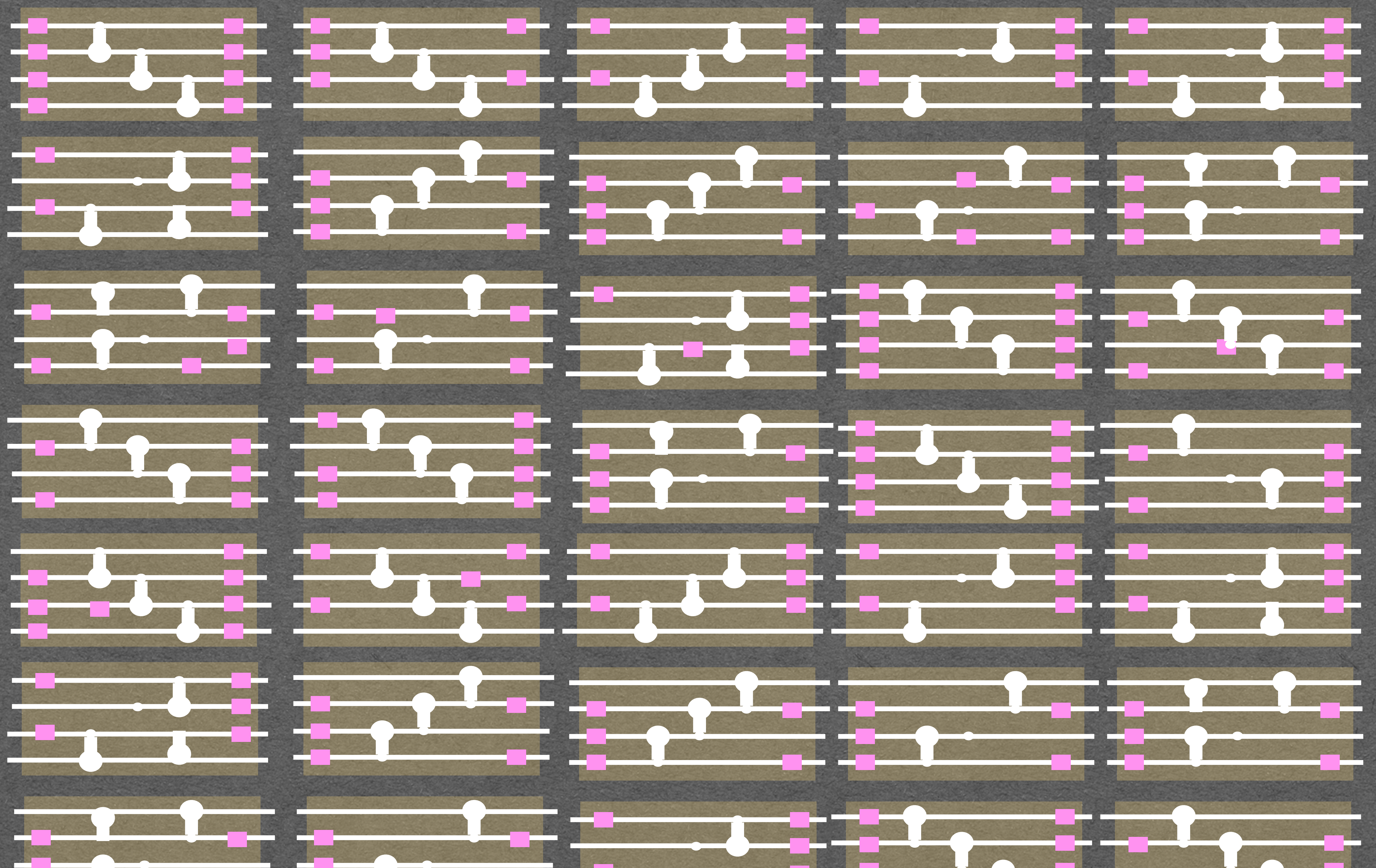
Shallow circuit

Main Problems of VQE

Shallow circuit

↓

Ansatz choice

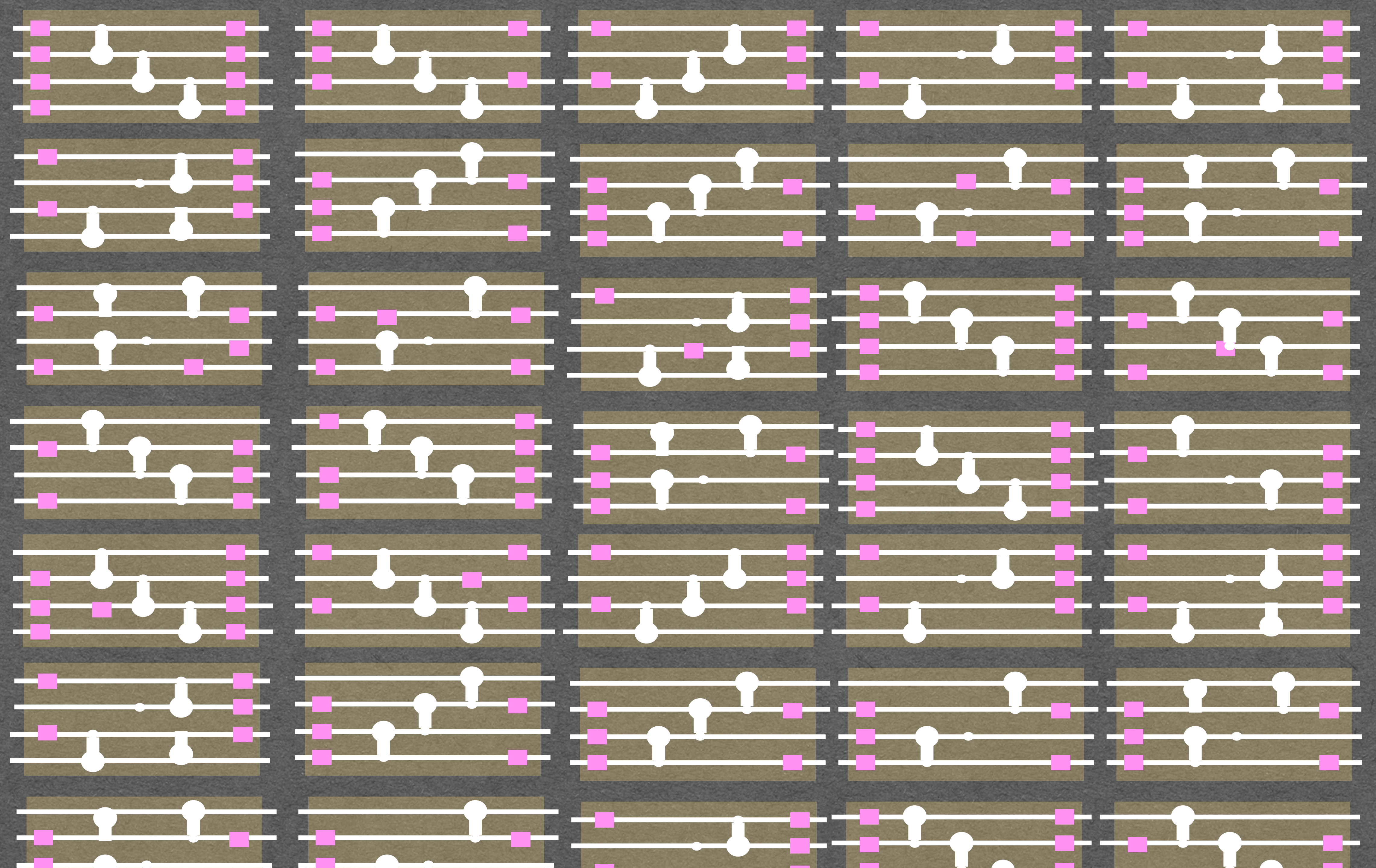


Main Problems of VQE

Shallow circuit

↓

Ansatz choice



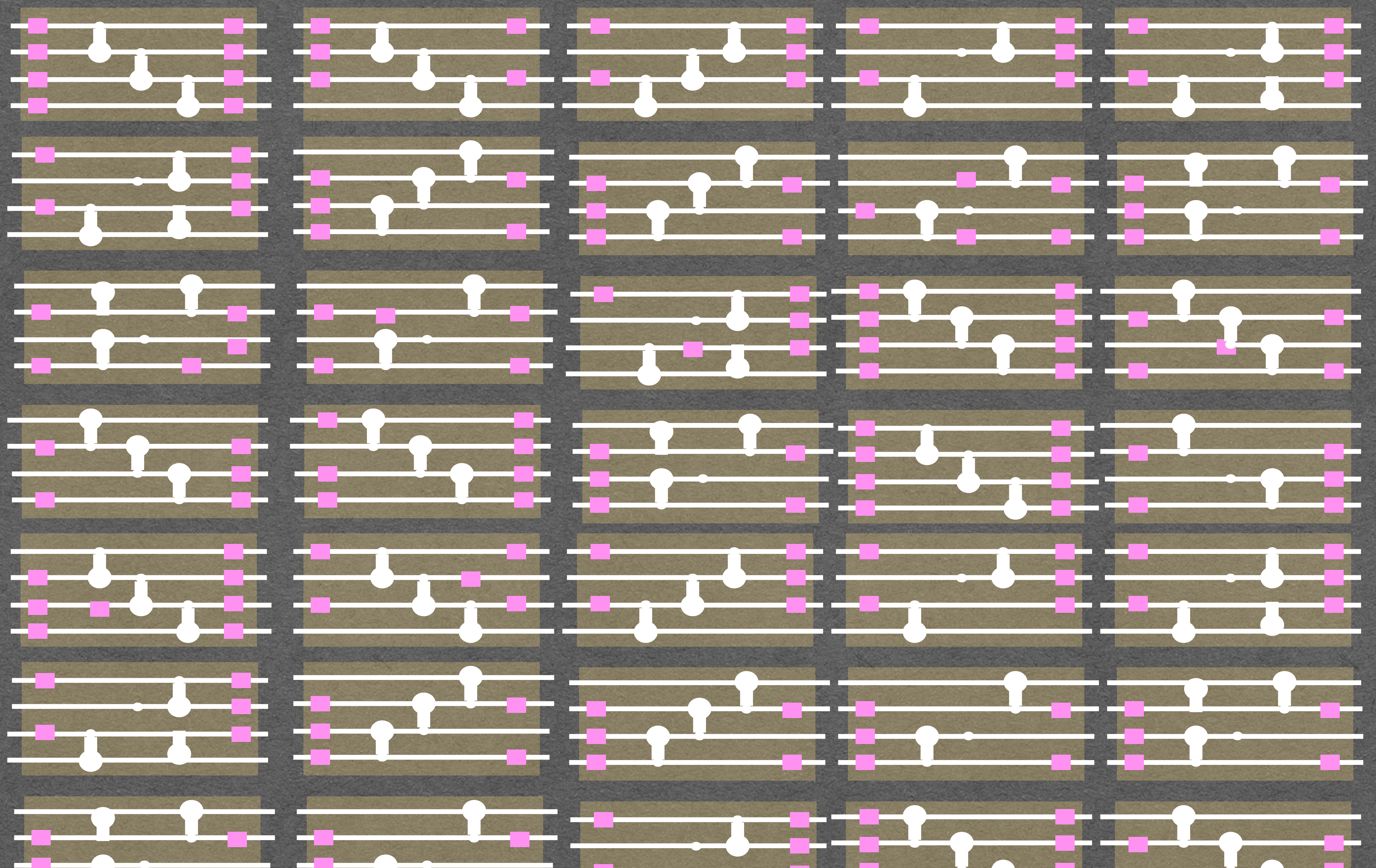
Large Hilbert spaces

Main Problems of VQE

Shallow circuit

↓

Ansatz choice

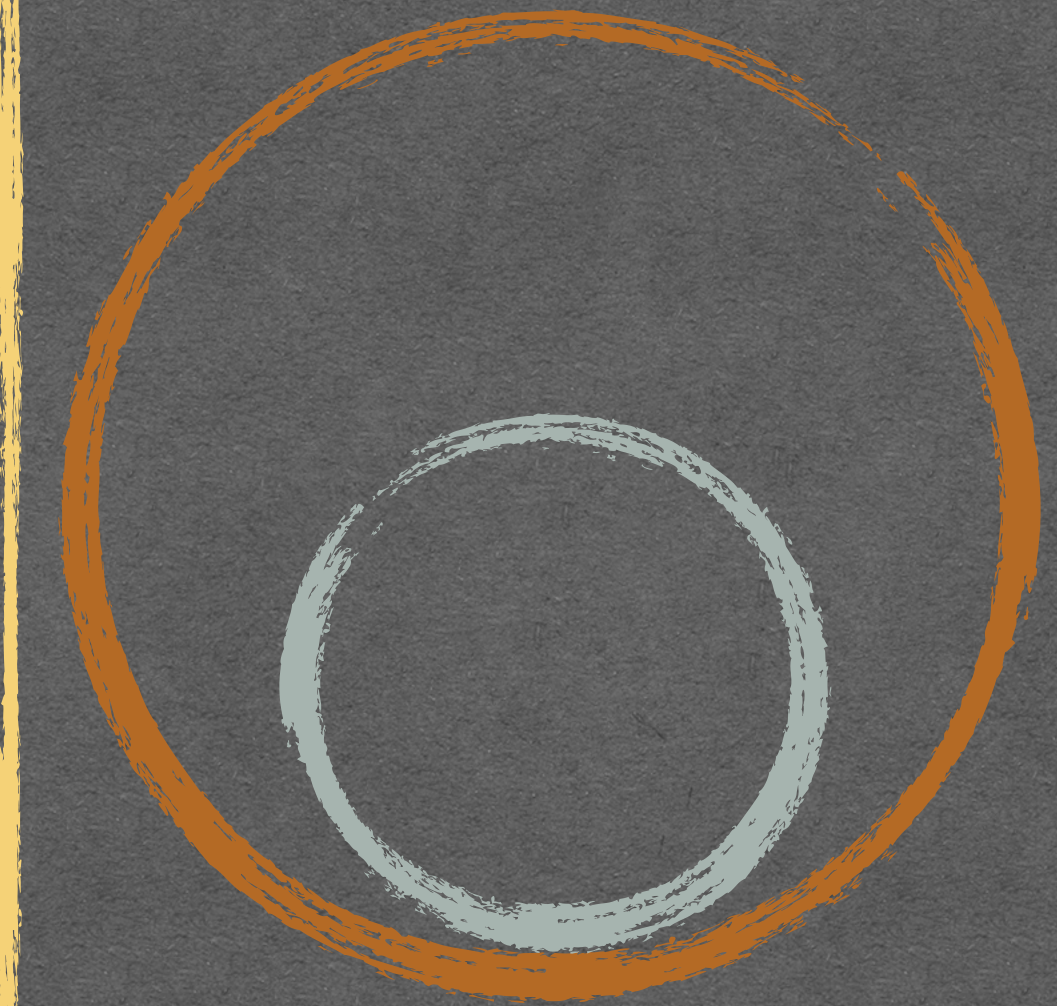


Large Hilbert spaces

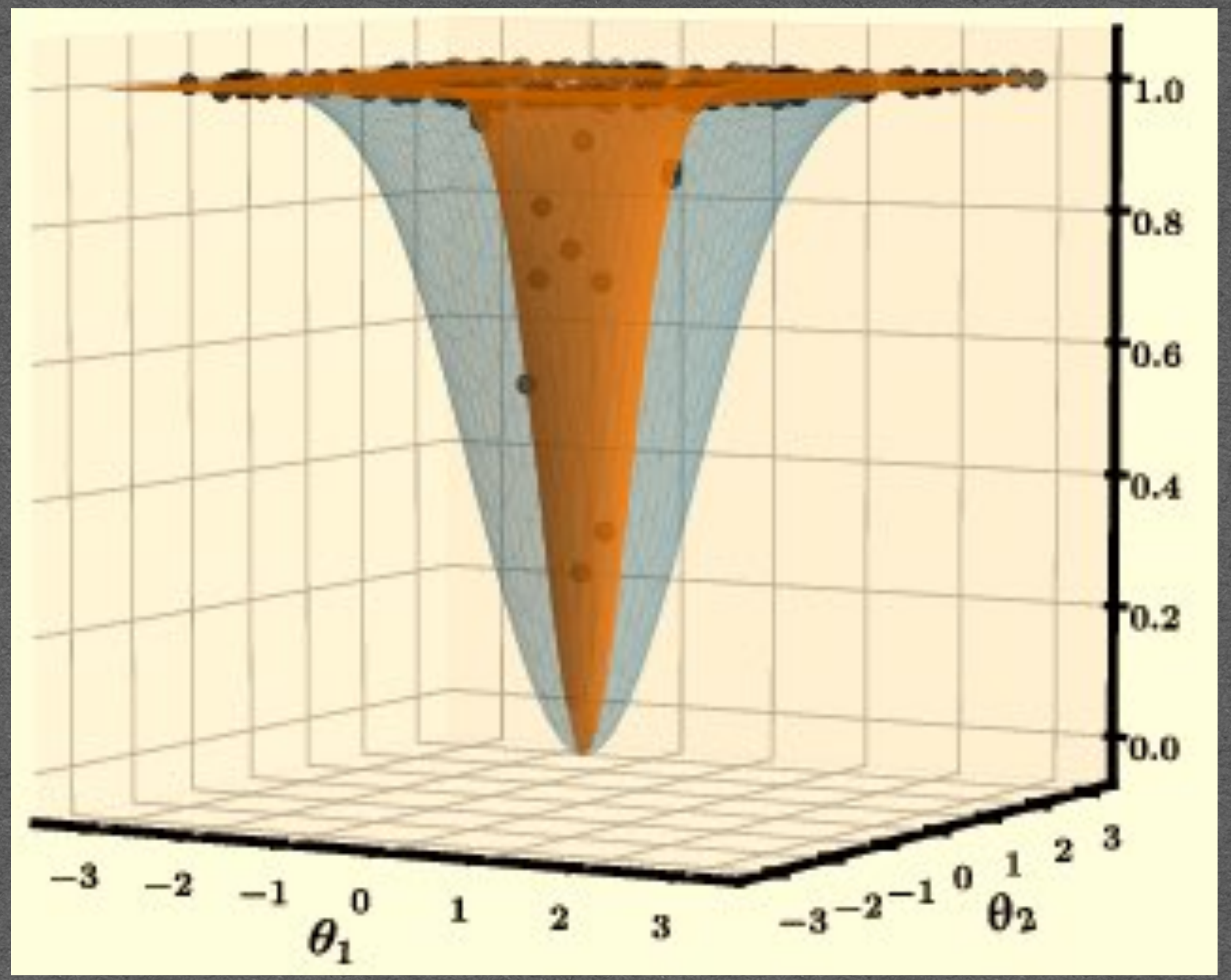
↓

Barren Plateaus

$\mathscr{H} \sim 2^N$



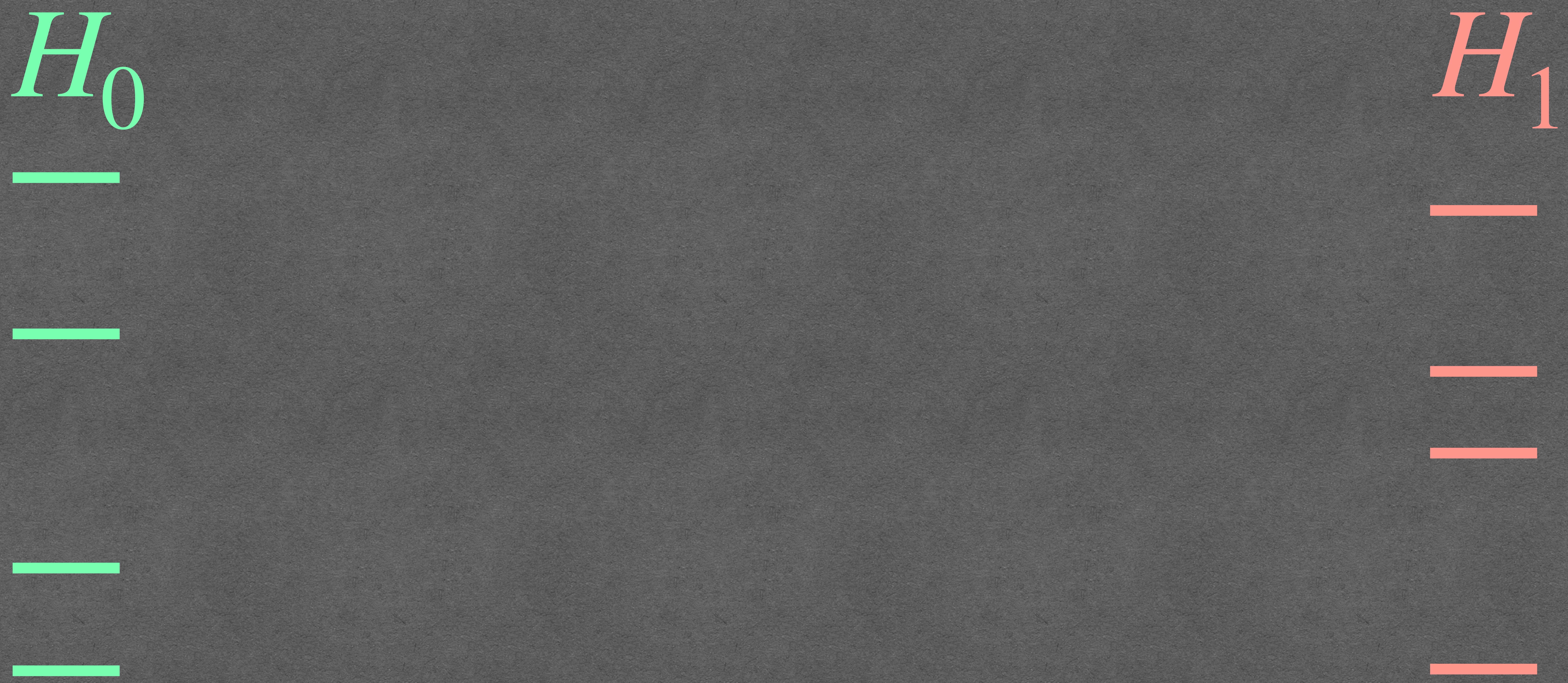
Loss function



Adiabatic Preparation AP

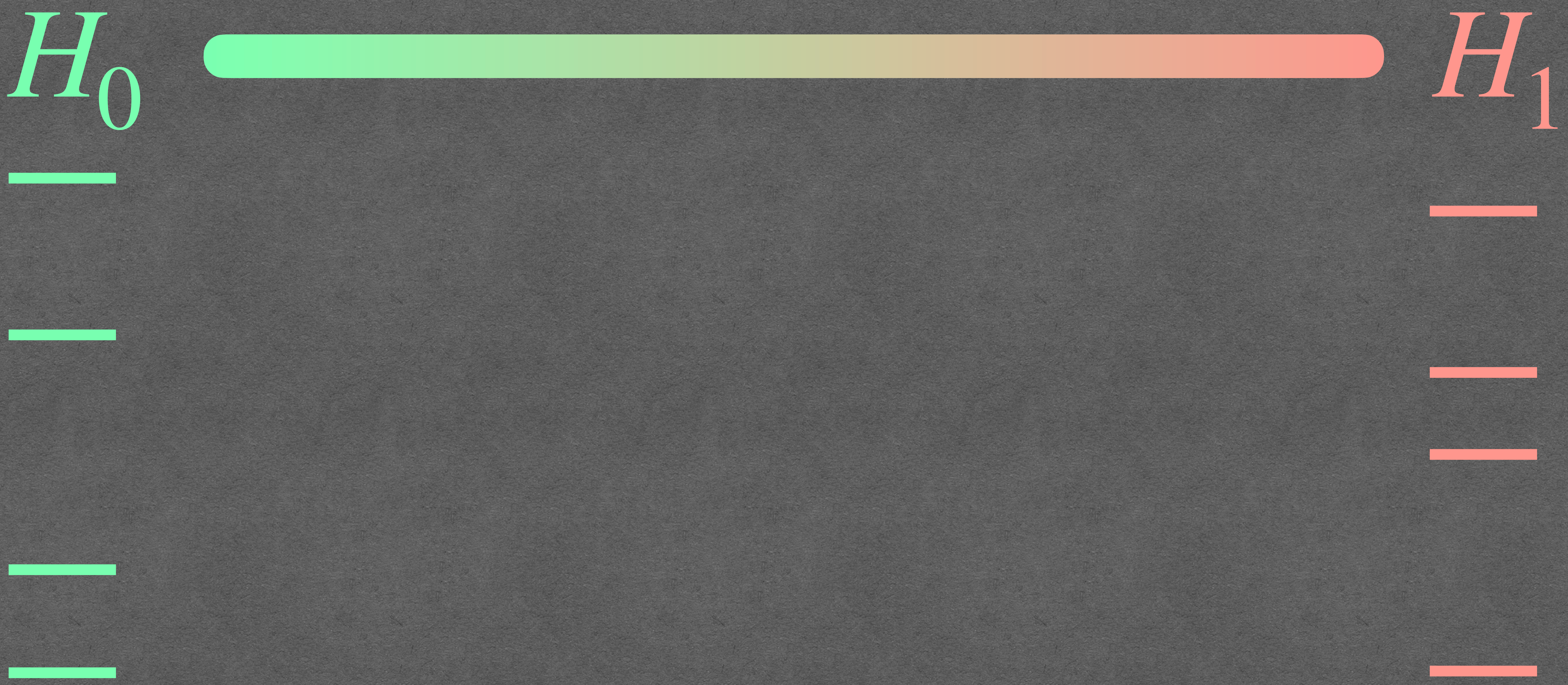
H_1

Adiabatic Preparation AP



Adiabatic Preparation AP

$$H(s) = H_0 + f(s)[H_1 - H_0]$$



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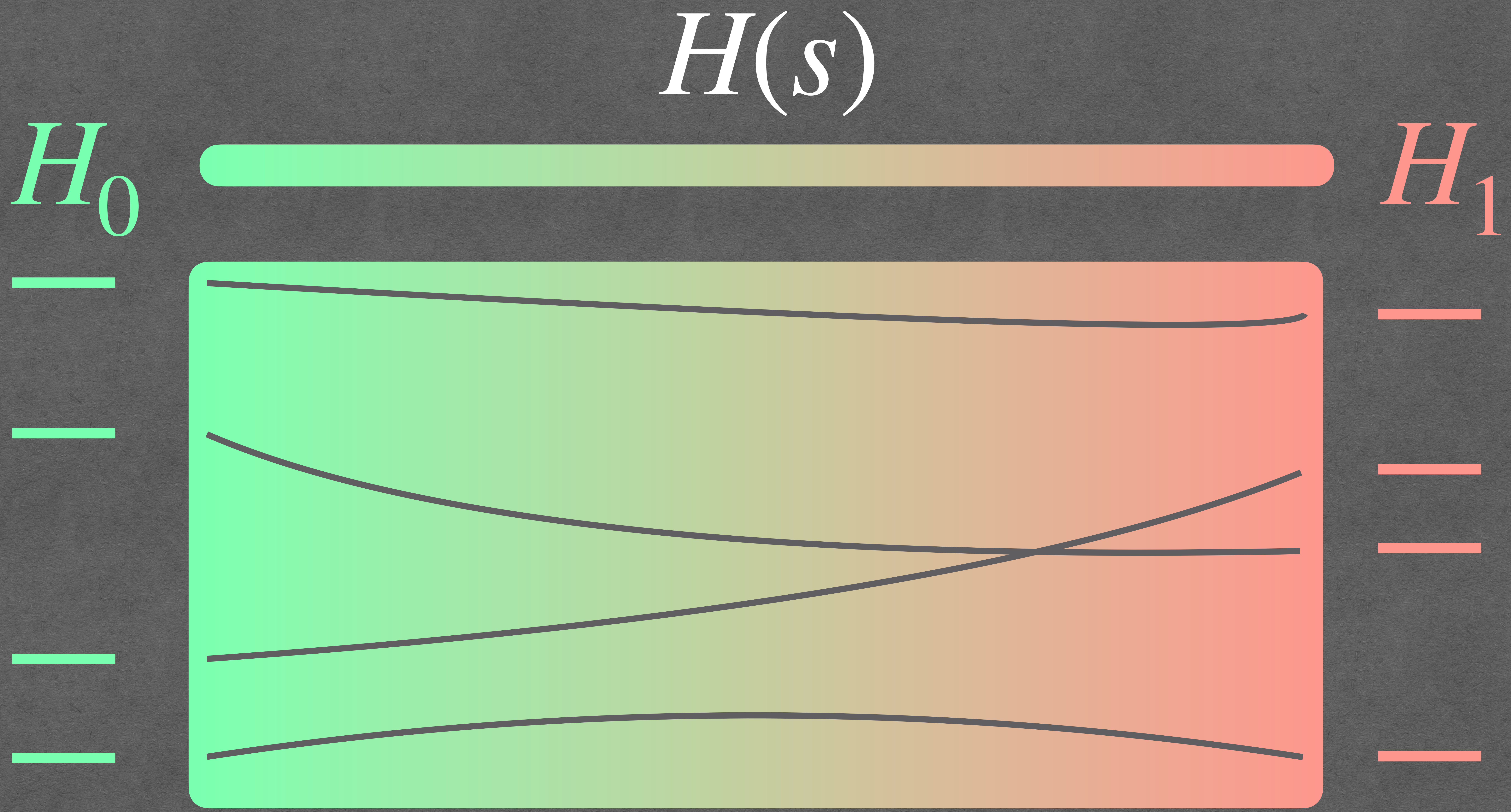

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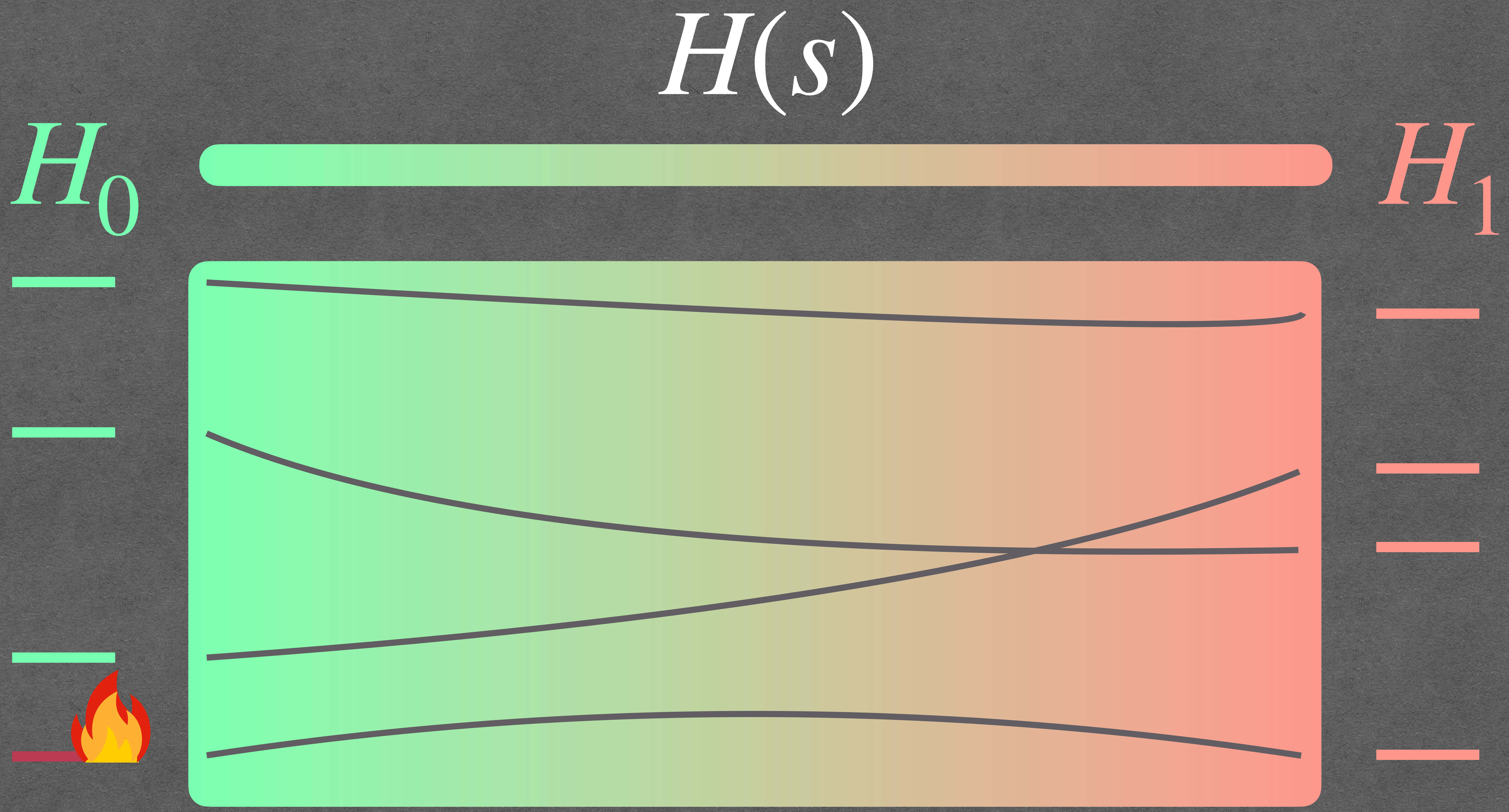

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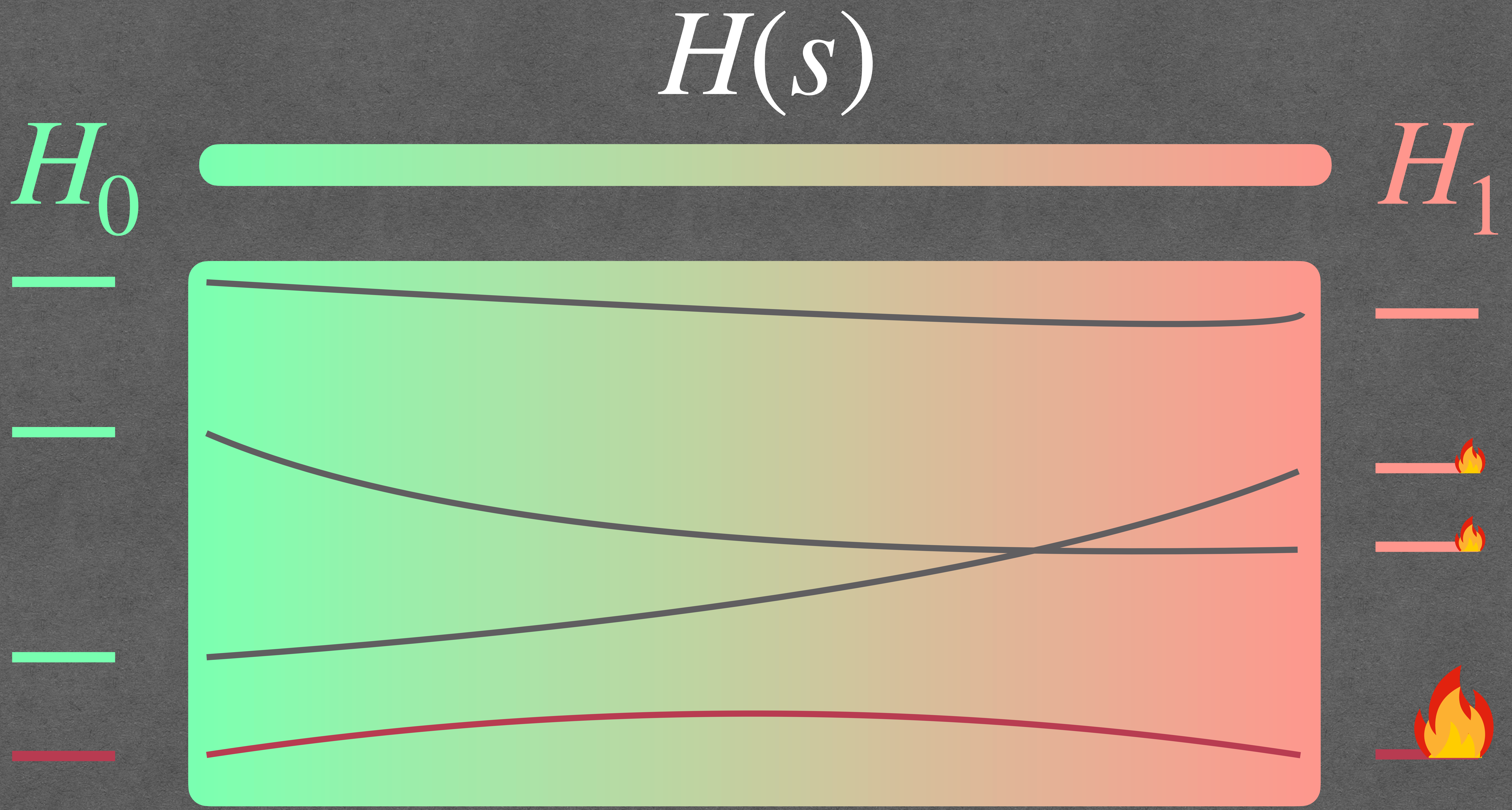

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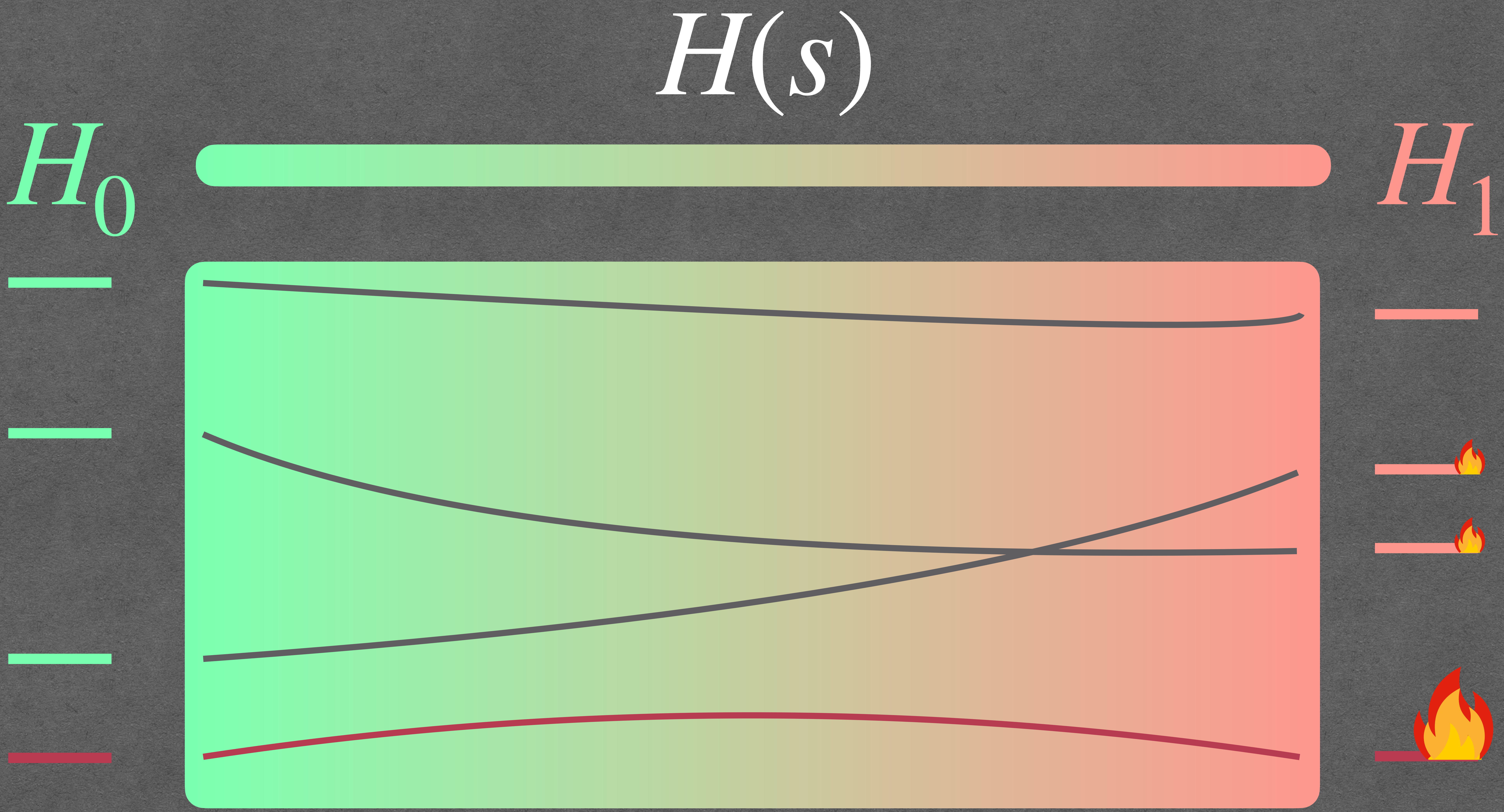

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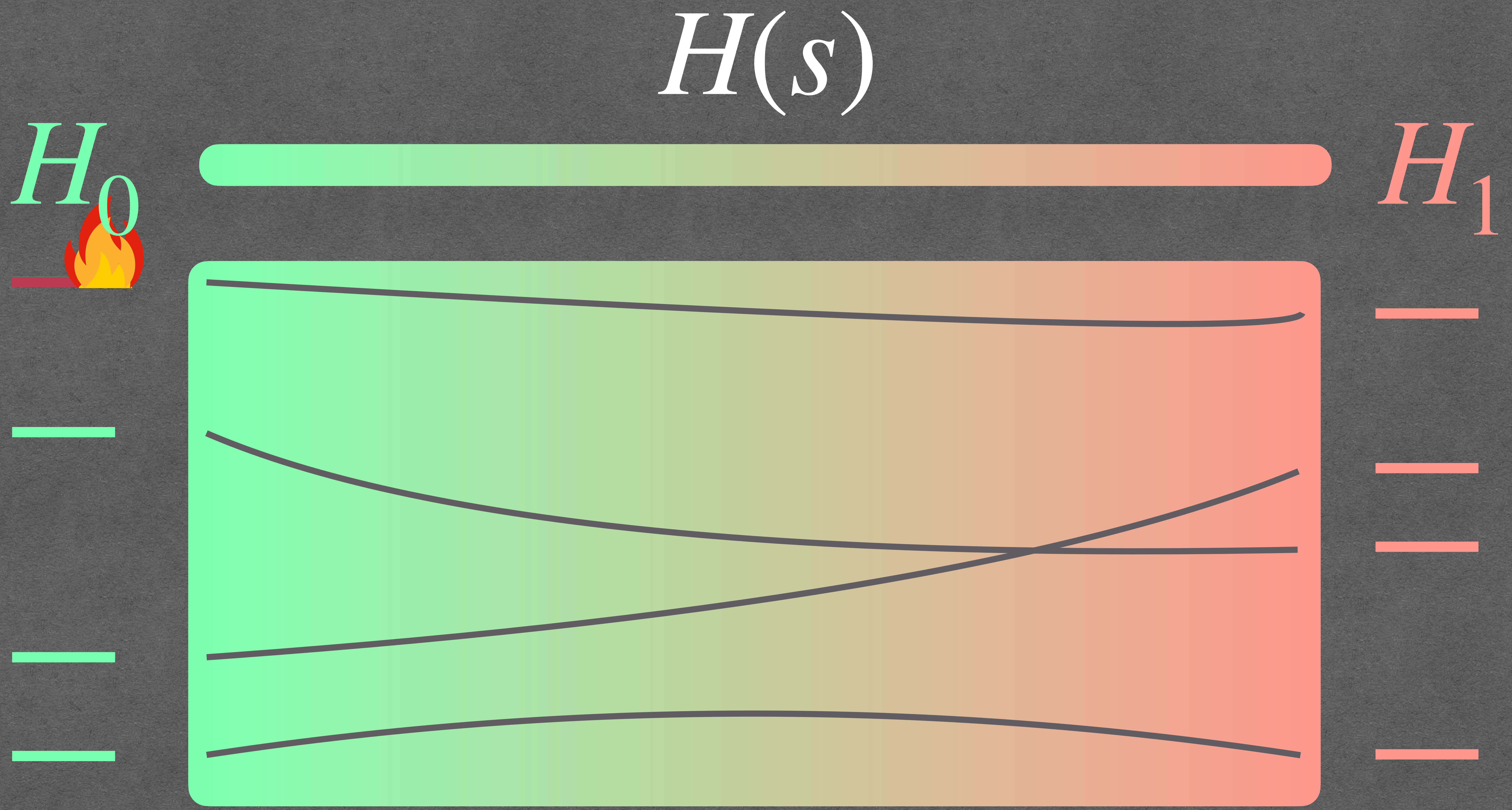

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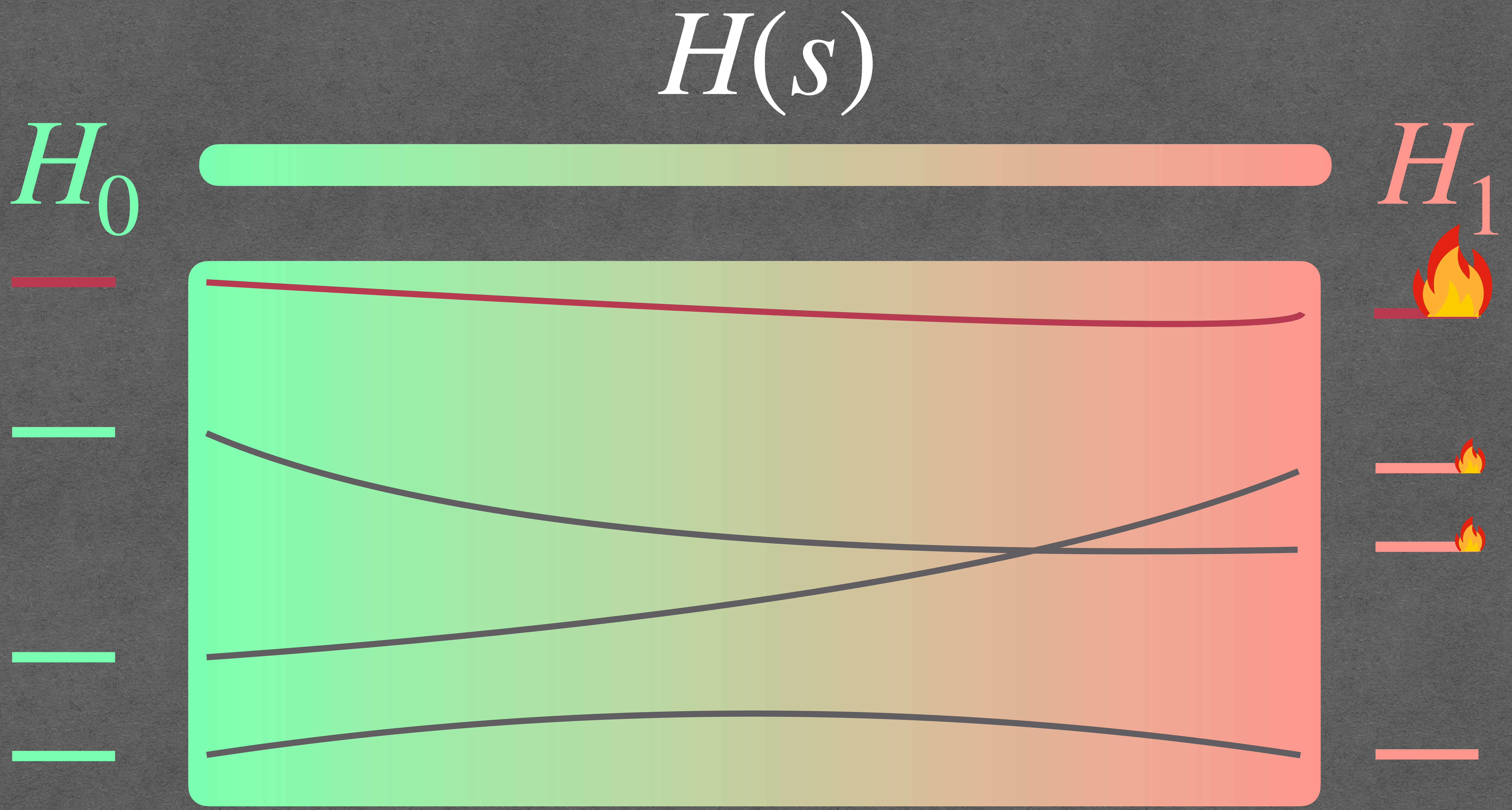

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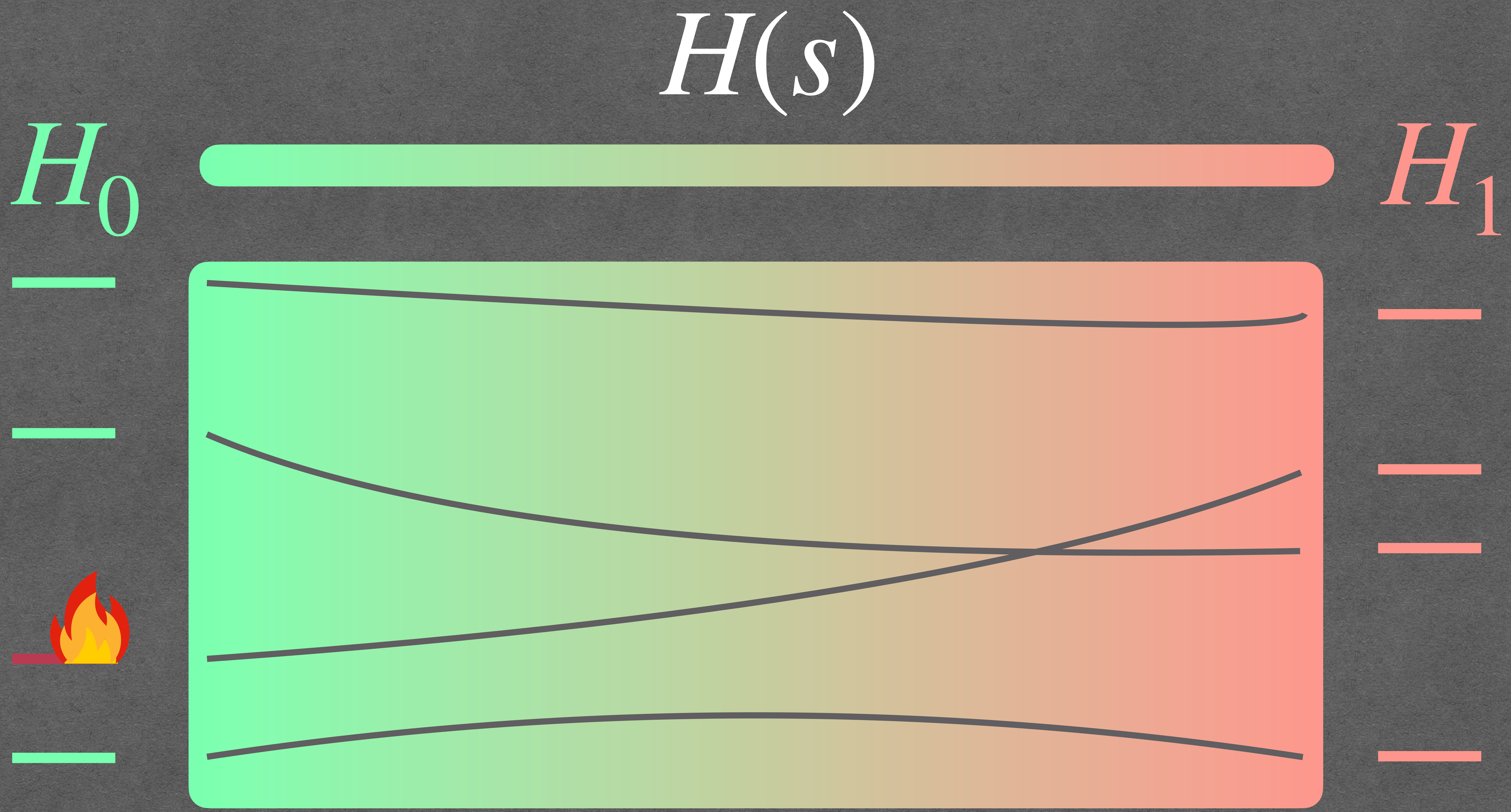

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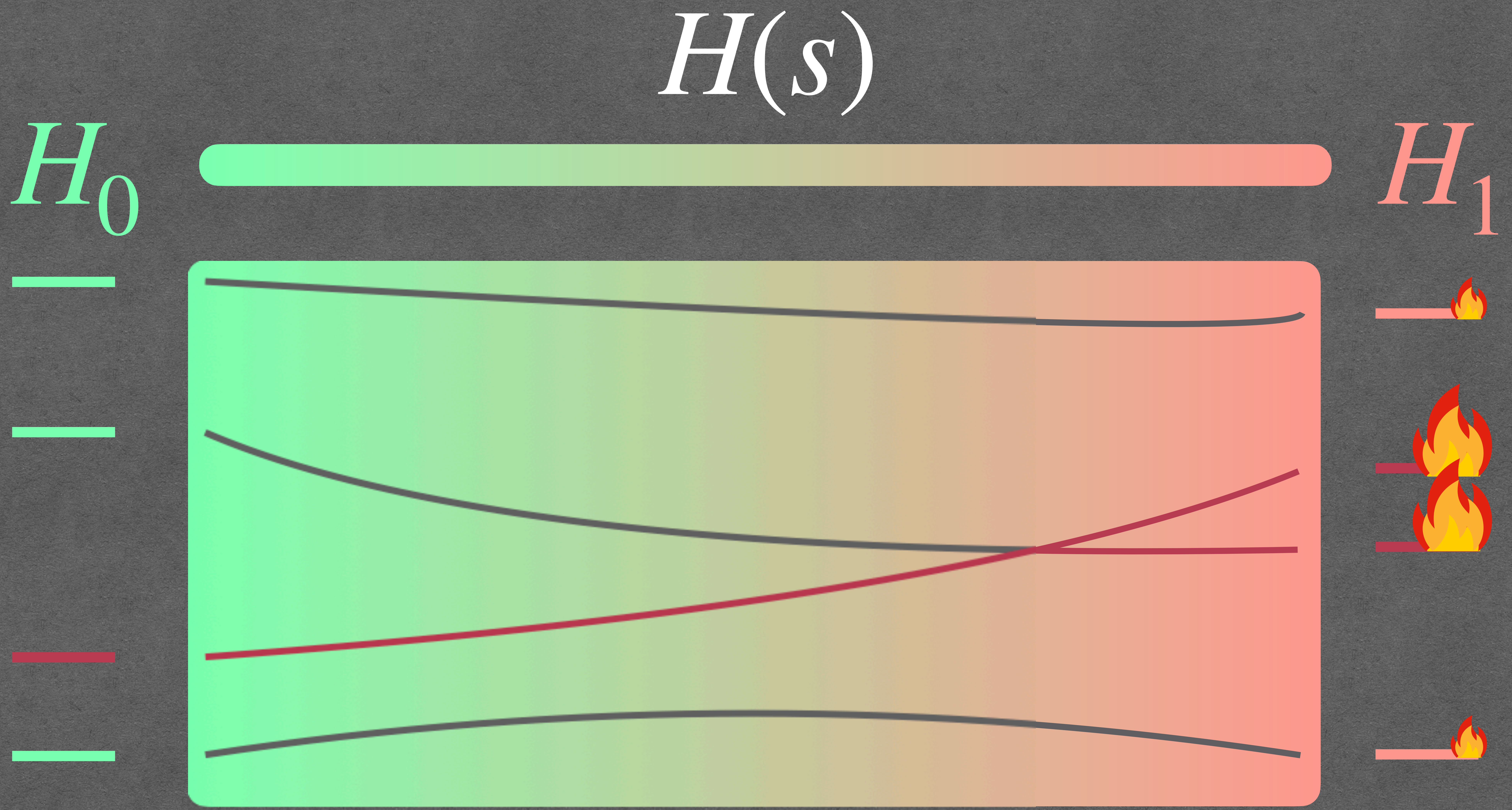

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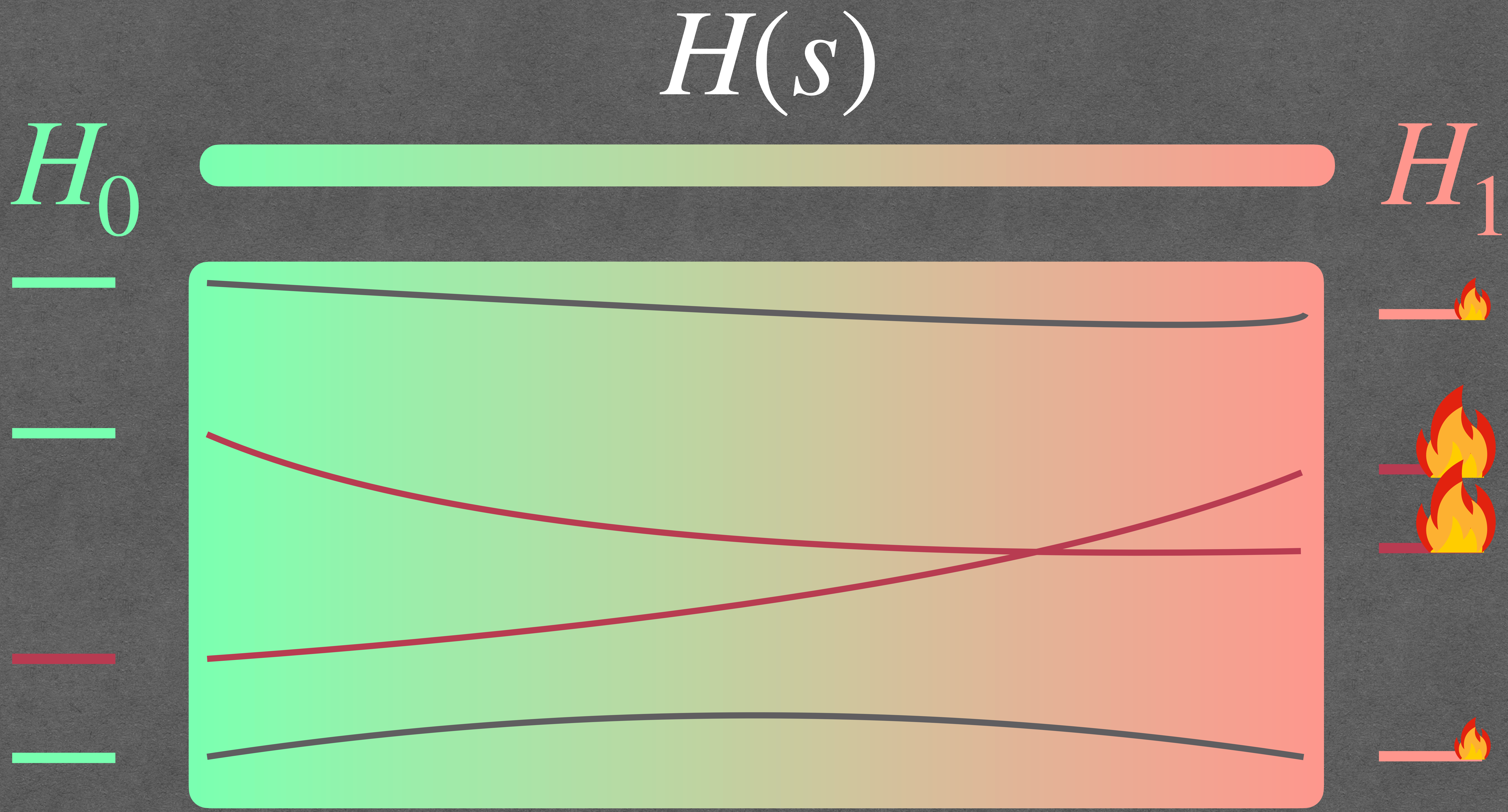

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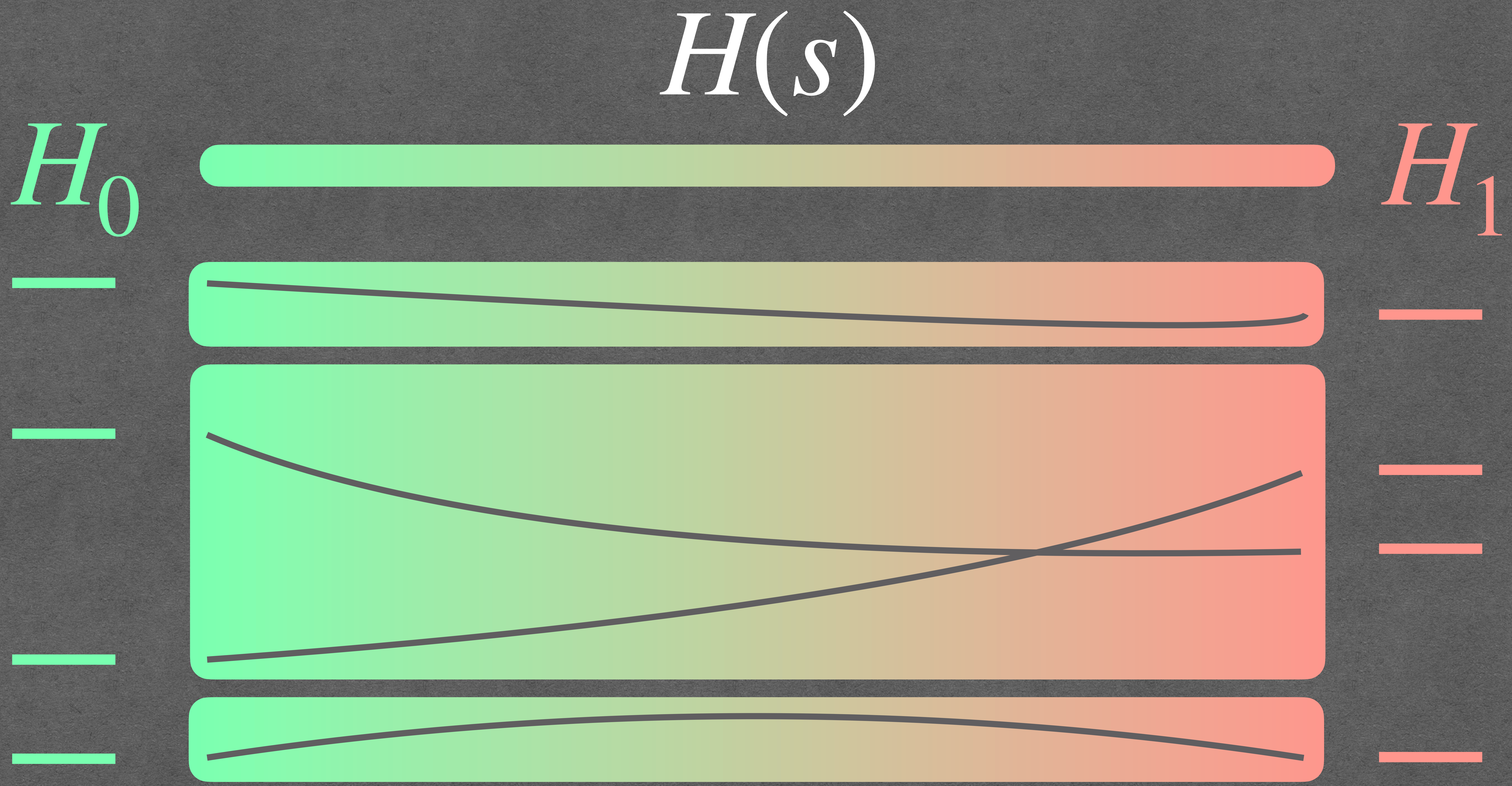
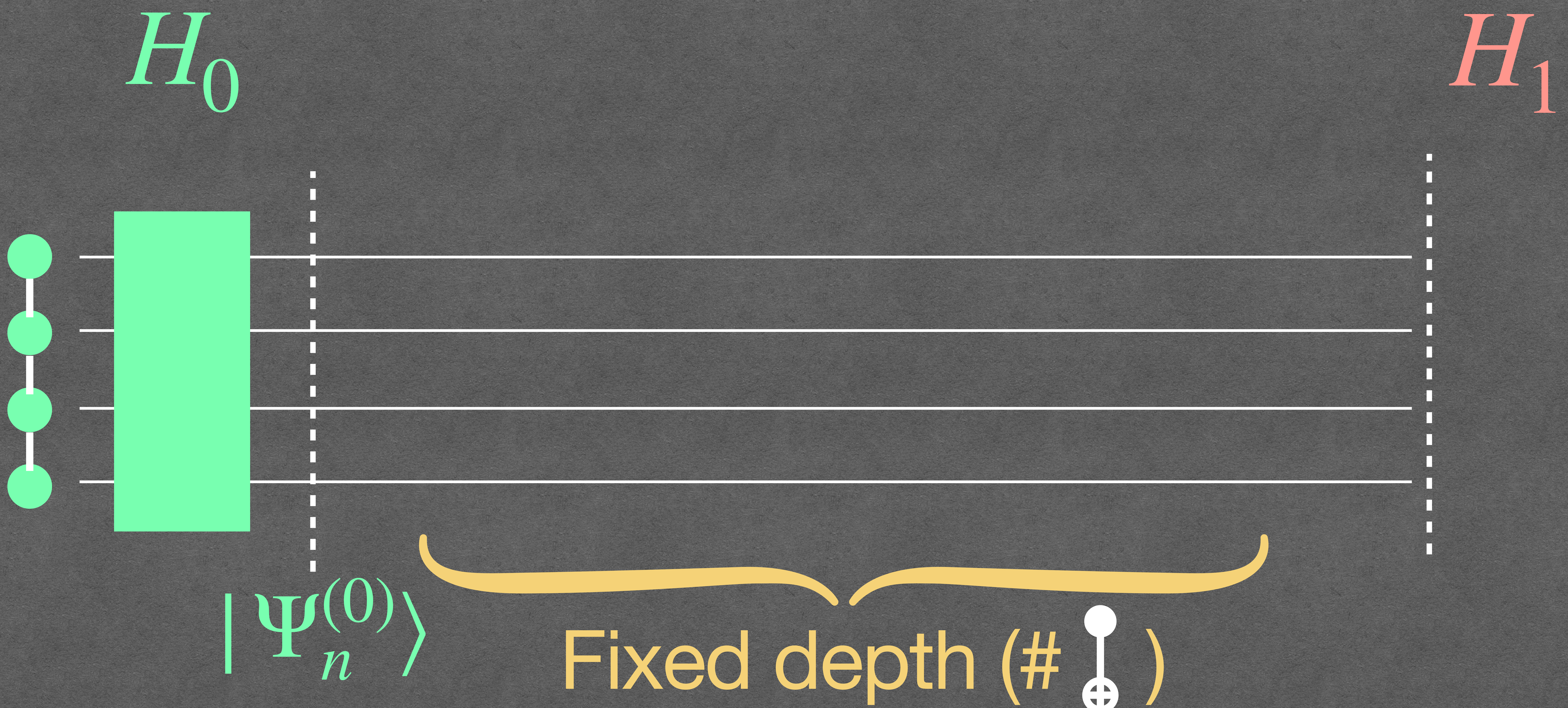


AP on quantum computers



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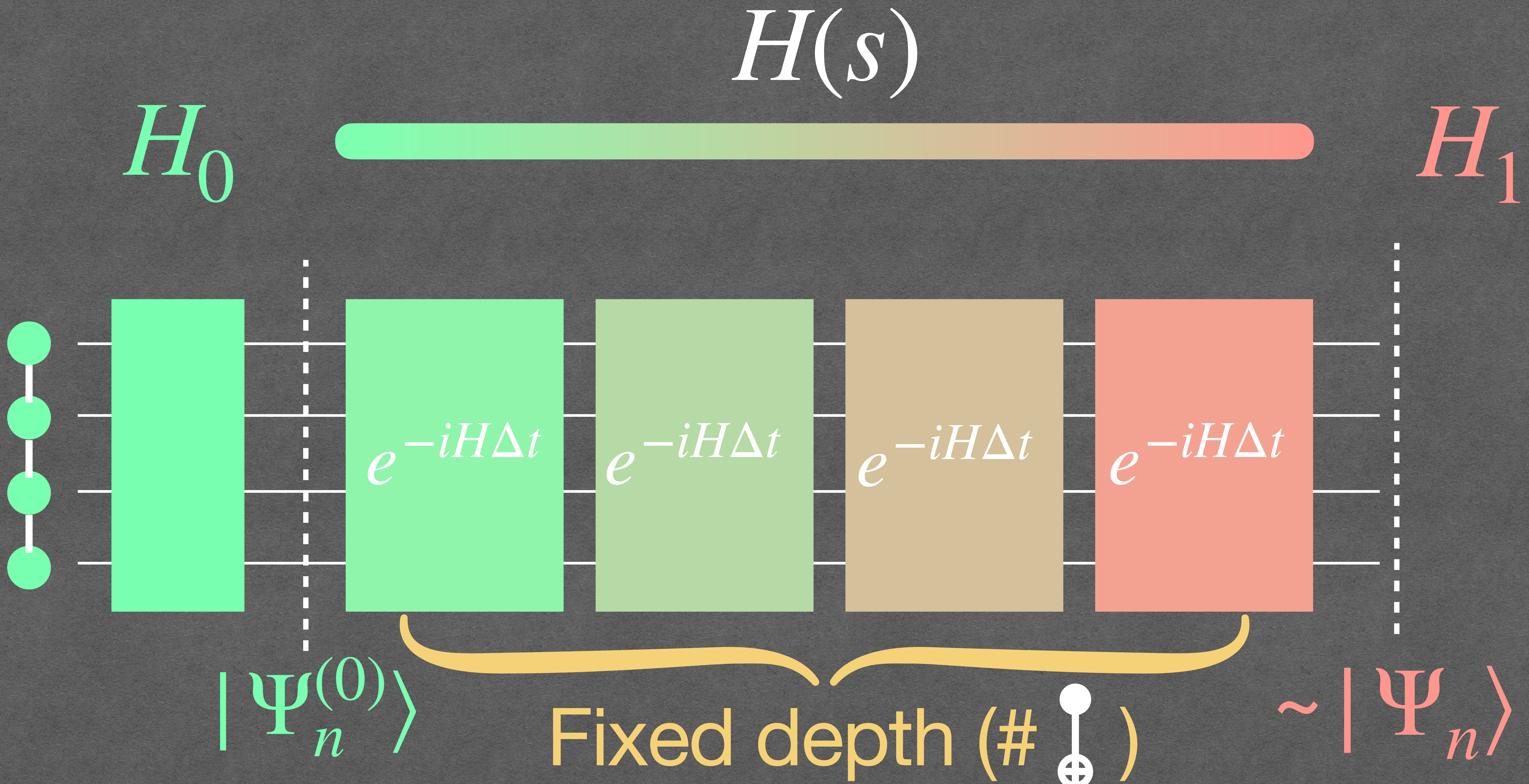


Losses bound for AP

Linear Adiabatic Theory. Exponential Estimates

G. Nenciu

Losses bound for AP

Linear Adiabatic Theory. Exponential Estimates

G. Nenciu

$\exists C, \tilde{g} > 0$ such that

$$\left|\left|1 - |\Psi_n\rangle\langle\Psi_n|\right|\right| \leq C \exp\left[-\tau/\tilde{g}\right]$$

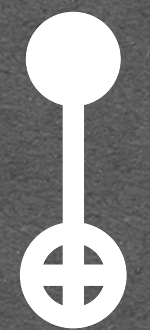
τ : Duration of the adiabatic process

Losses bound for AP

Linear Adiabatic Theory. Exponential Estimates

G. Nenciu

$\exists\, C, \tilde{g} > 0$ such that

🔥🔥🔥🔥🔥 $\leq C \exp\left[-(\#$  $)/\tilde{g}\right]$

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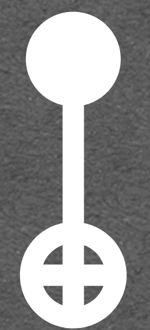
🔥🔥🔥🔥🔥 $\leq C \exp\big[-($**#**  $)/\tilde{g}\big]$

Fixed by the hardware

CAN WE REDUCE $\tilde{g}$?

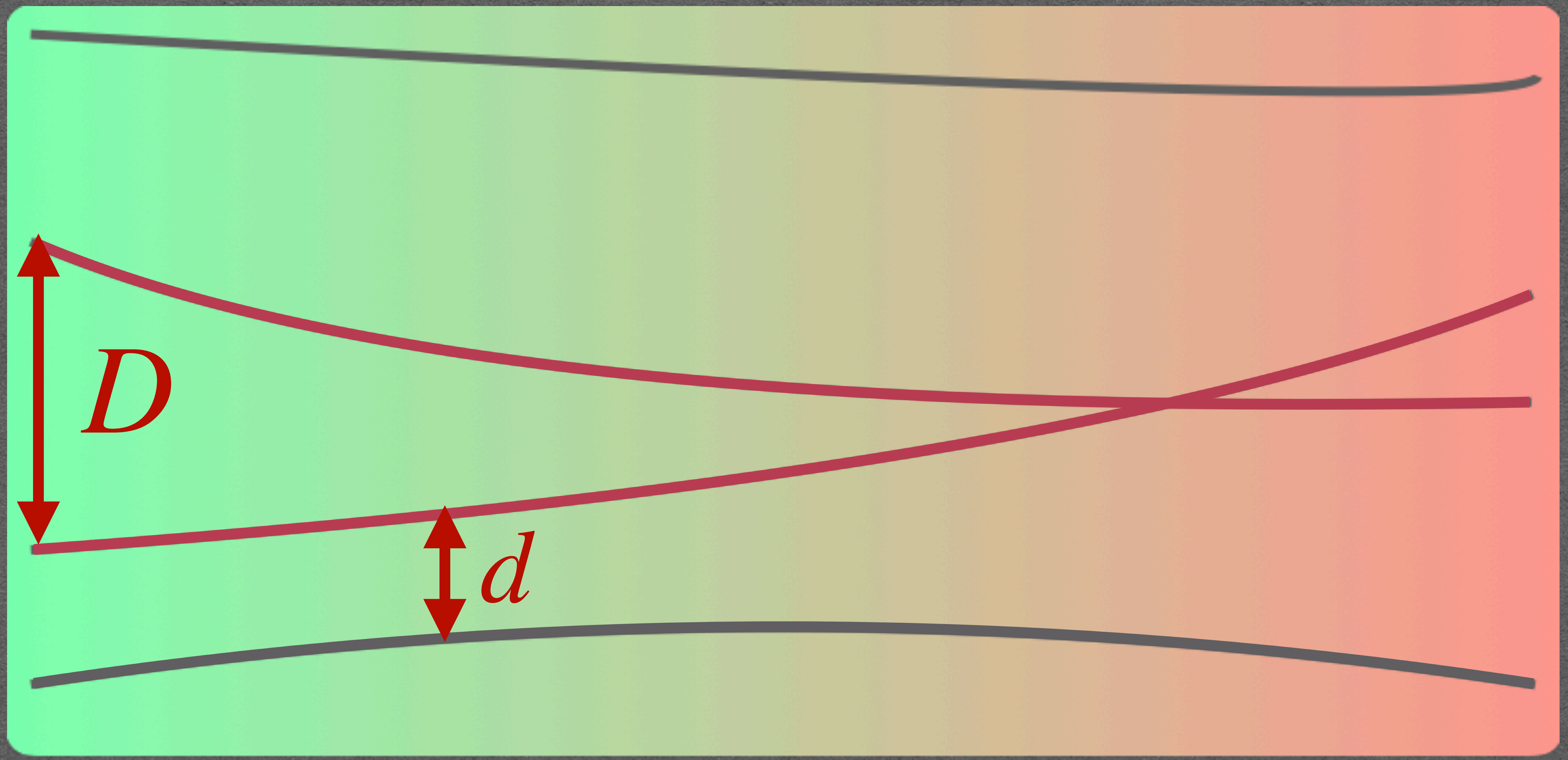
Exponential optimization of quantum state preparation via adiabatic thermalization

Davide Cugini,[1] Davide Nigro,[1] Mattia Bruno,[2] and Dario Gerace[1]
[1] Dipartimento di Fisica, Università di Pavia, via Bassi 6, 27100, Pavia, Italy
[2] Dipartimento di Fisica, Università di Milano–Bicocca, and INFN, sezione di Milano–Bicocca, Piazza della Scienza 3, I-20126 Milano, Italy

$$\tilde{g} = \tilde{g}(||H_1 - H_0||, D, d)$$

Increasing function in terms of

$$||\Delta|| = ||H_1 - H_0||, \quad D, \quad d^{-1}$$



arXiv preprint arXiv:2405.03656

Exponential optimization of quantum state preparation via adiabatic thermalization

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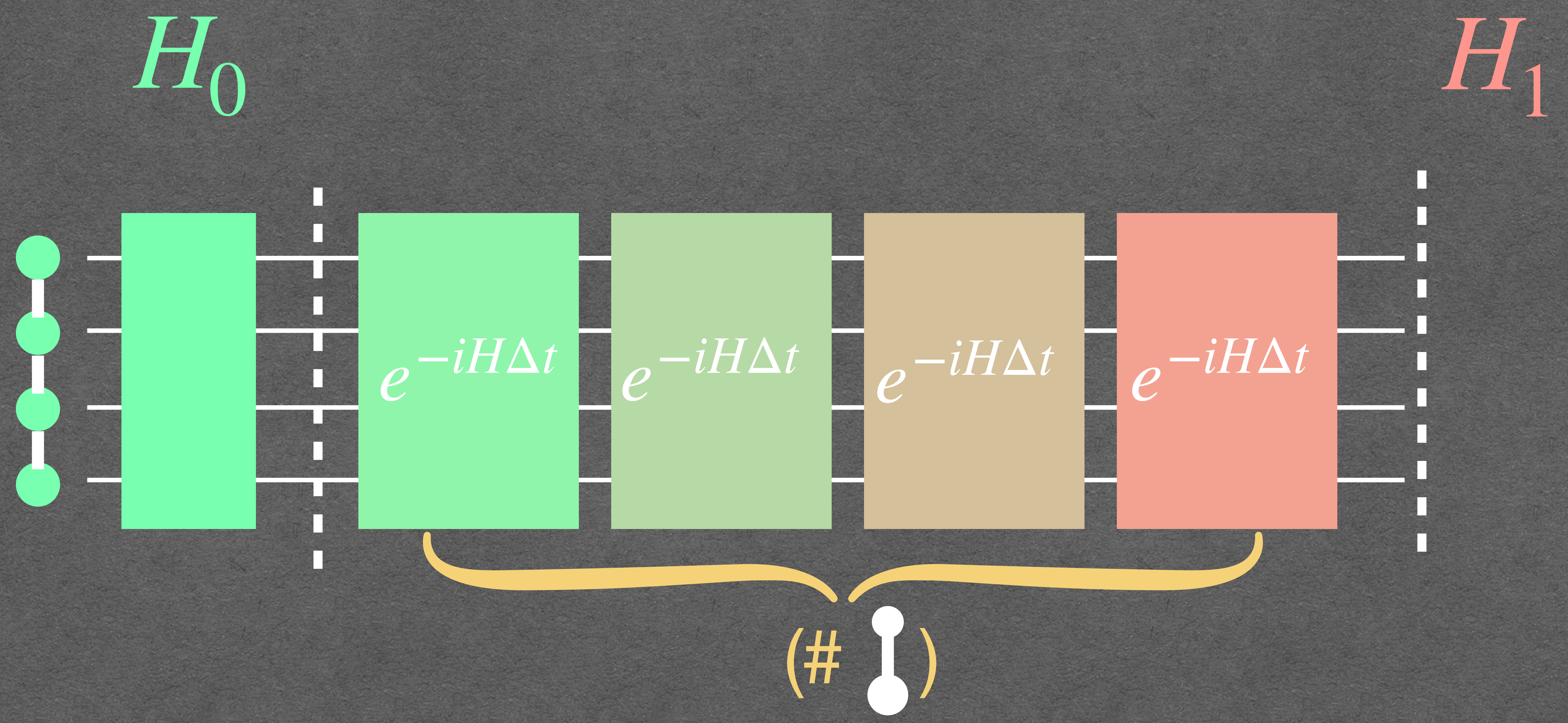

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$$H_0 = \text{diag}(H_1)$$

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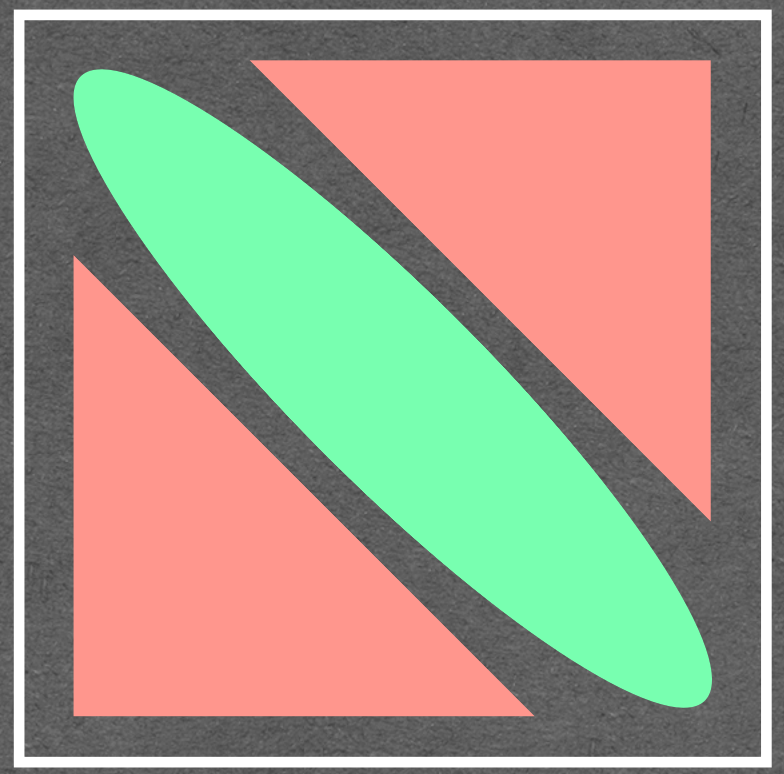
Increasing function in terms of

$$||\Delta|| = ||H_1 - H_0||, \quad D, \quad d^{-1}$$

$$H_0 = \mathrm{diag}(H_1) + M(\alpha)$$

Exponential optimisation of AP

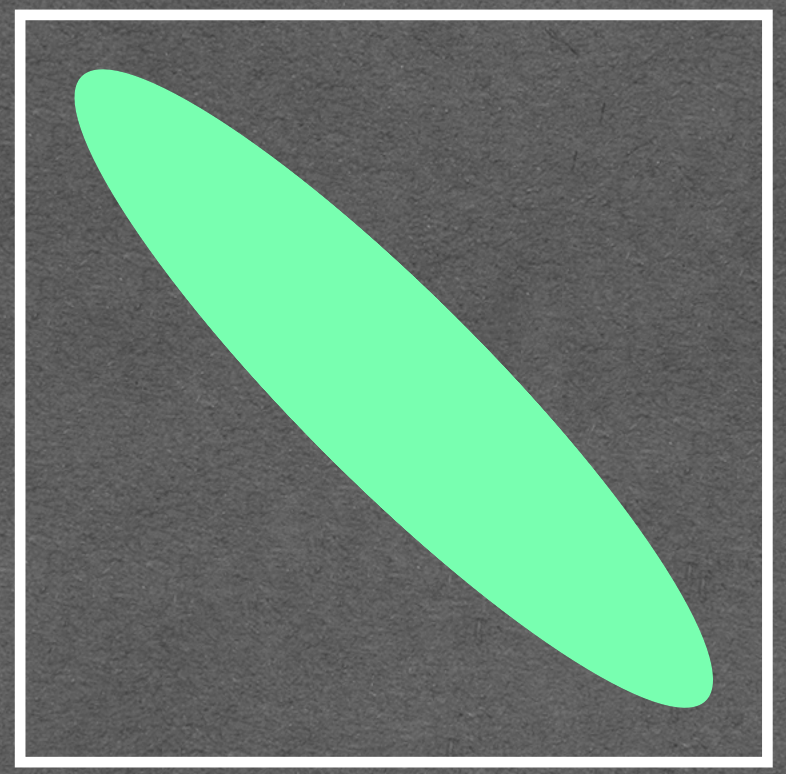
H_1

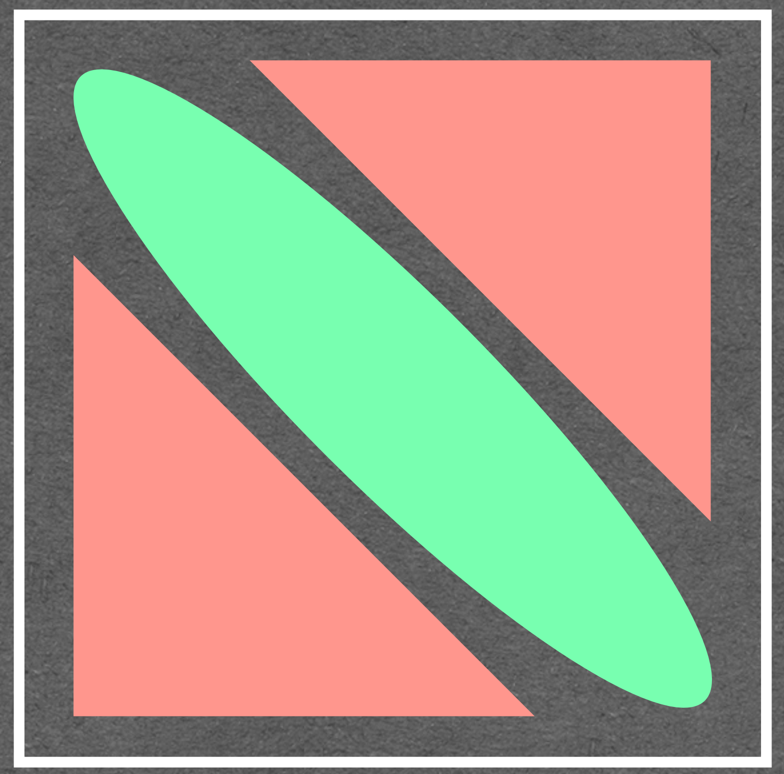


Exponential optimisation of AP

$H_0 = \mathrm{diag}(\mathrm{H}_1)$

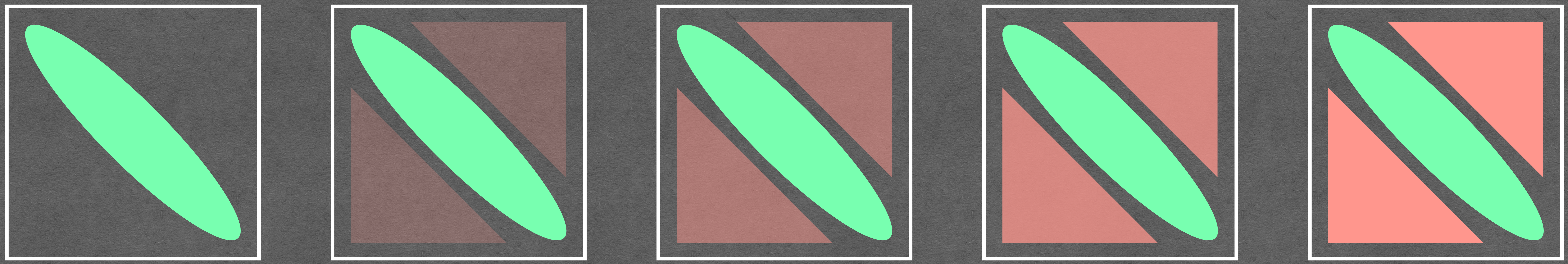
H_1



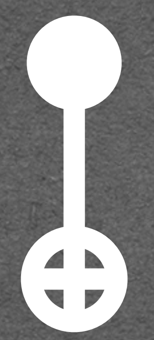


Exponential optimisation of AP

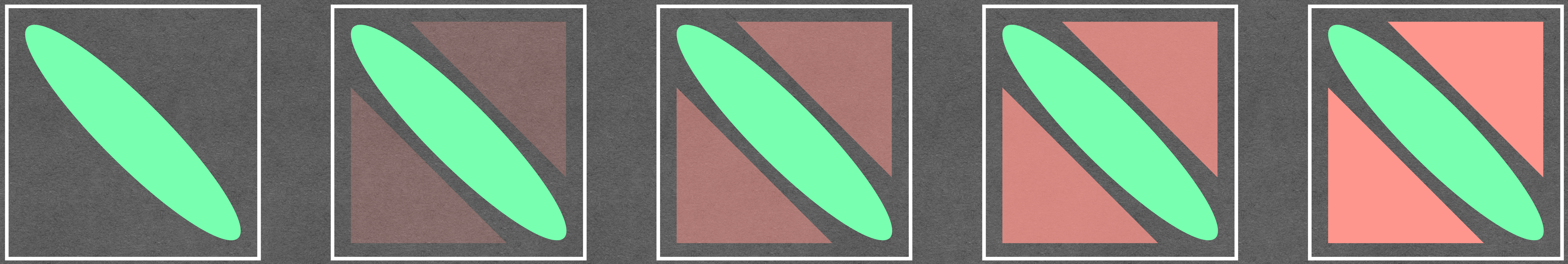
$H_0 = \mathrm{diag}(\mathrm{H}_1)$ H_1



Exponential optimisation of AP

🔥🔥🔥🔥🔥 $\leq C \exp\Big[-(\#$  $)/\tilde{g}\Big]$

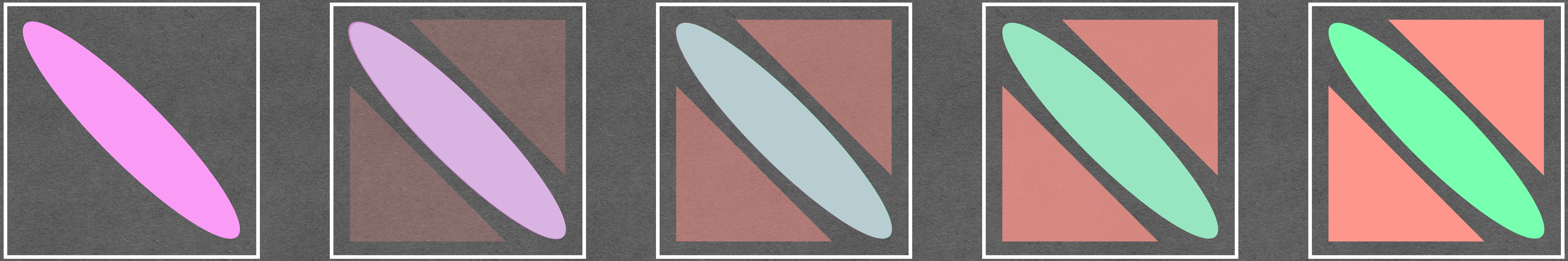
$H_0 = \mathrm{diag}(\mathrm{H}_1)$ $\qquad\qquad$ H_1



Exponential optimisation of AP

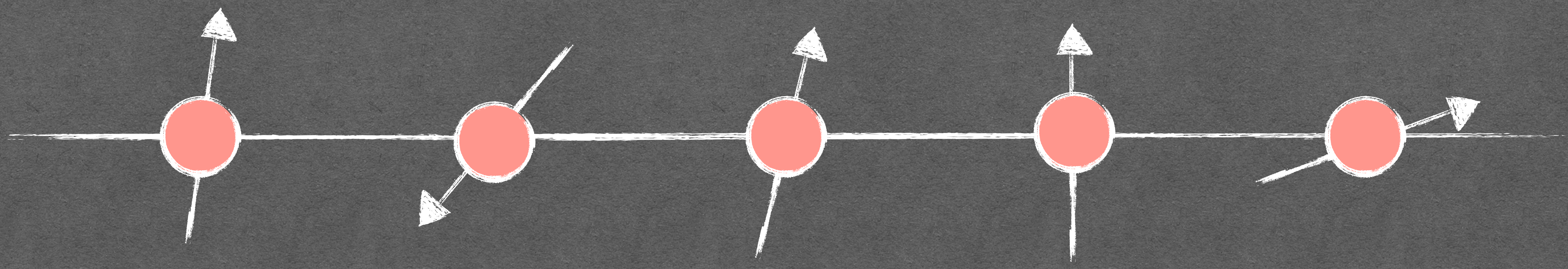
🔥🔥🔥🔥🔥 $\leq C \exp\left[-(\#\ \bullet\!-\!\oplus)/\tilde{g}\right]$

$$H_0 = \mathrm{diag}(\mathrm{H}_1) + M(\alpha) \qquad H_1$$



Numerical tests

XZ Heisenberg model



$$H_1 = -\frac{1}{2}\Sigma_{\langle i,j\rangle}\left(J^z Z_i Z_j + J^x X_i X_j\right)$$

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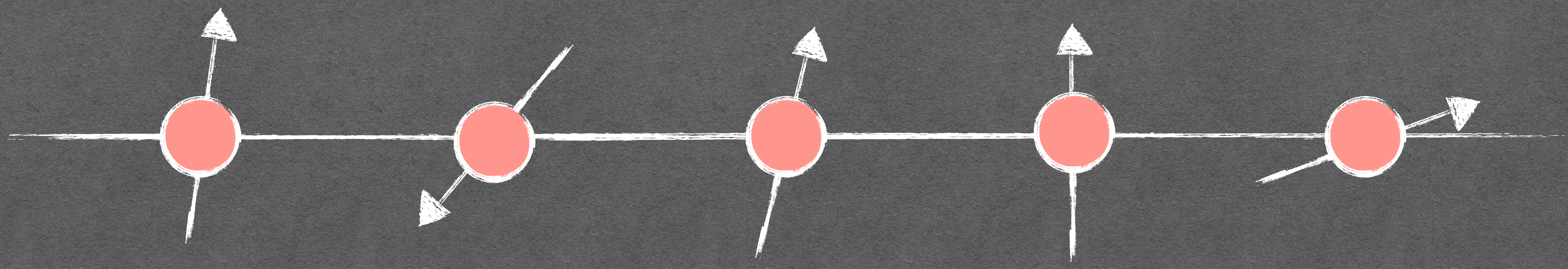

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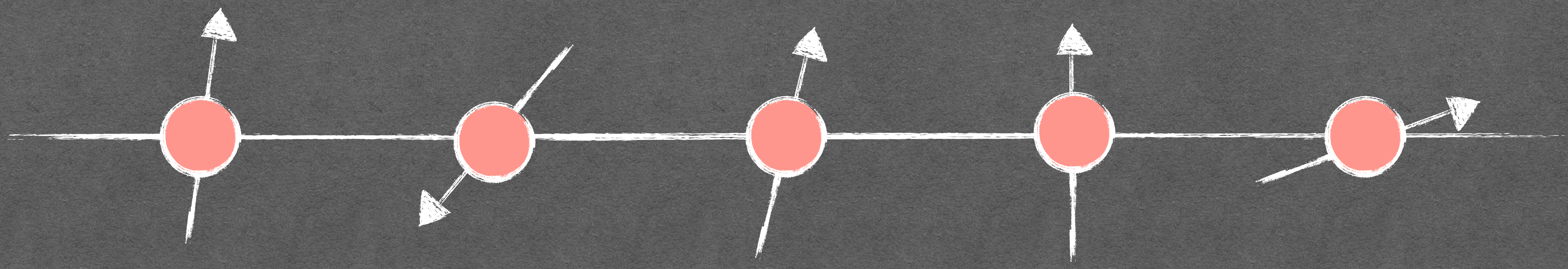
XZ Heisenberg model



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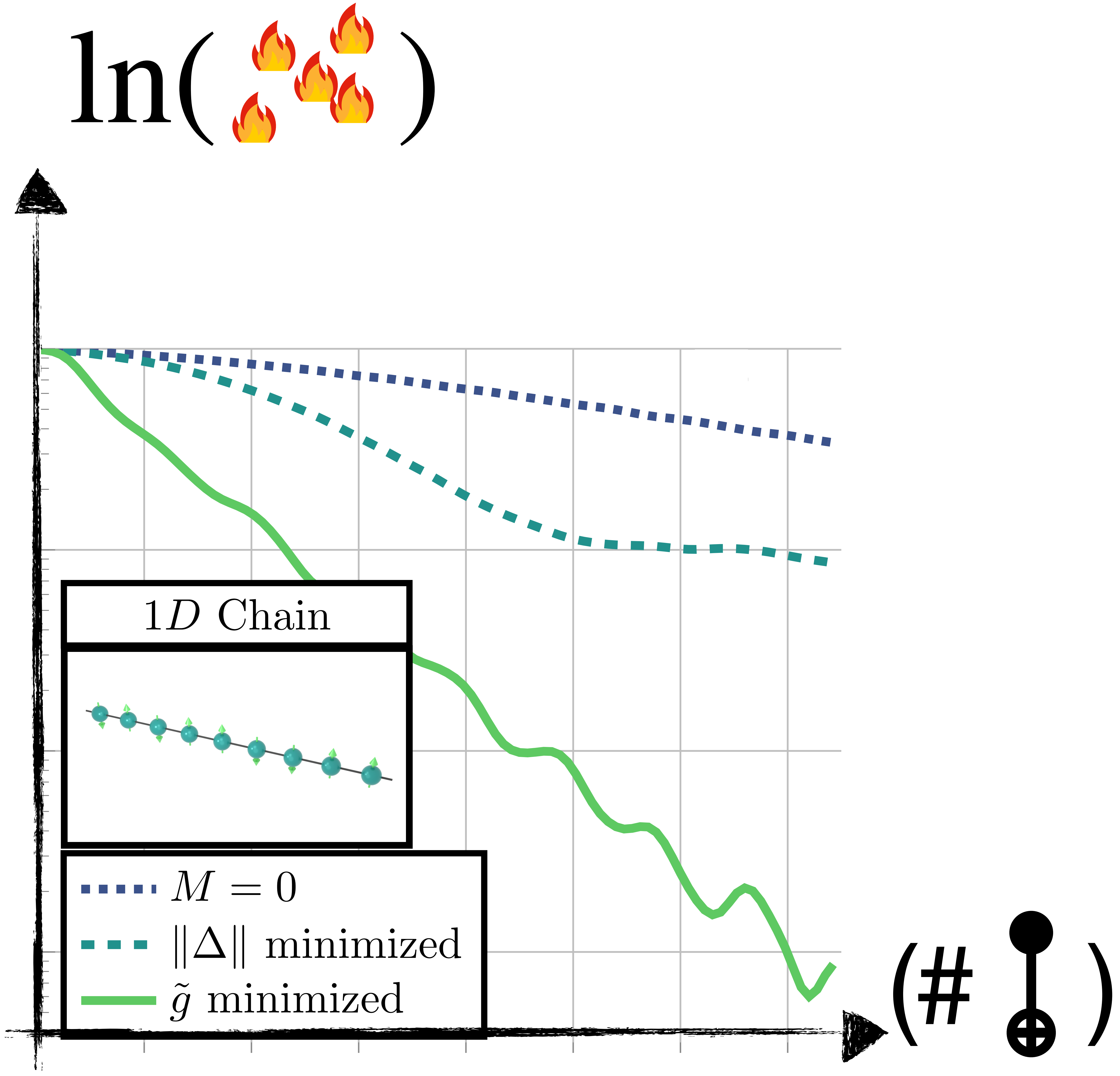
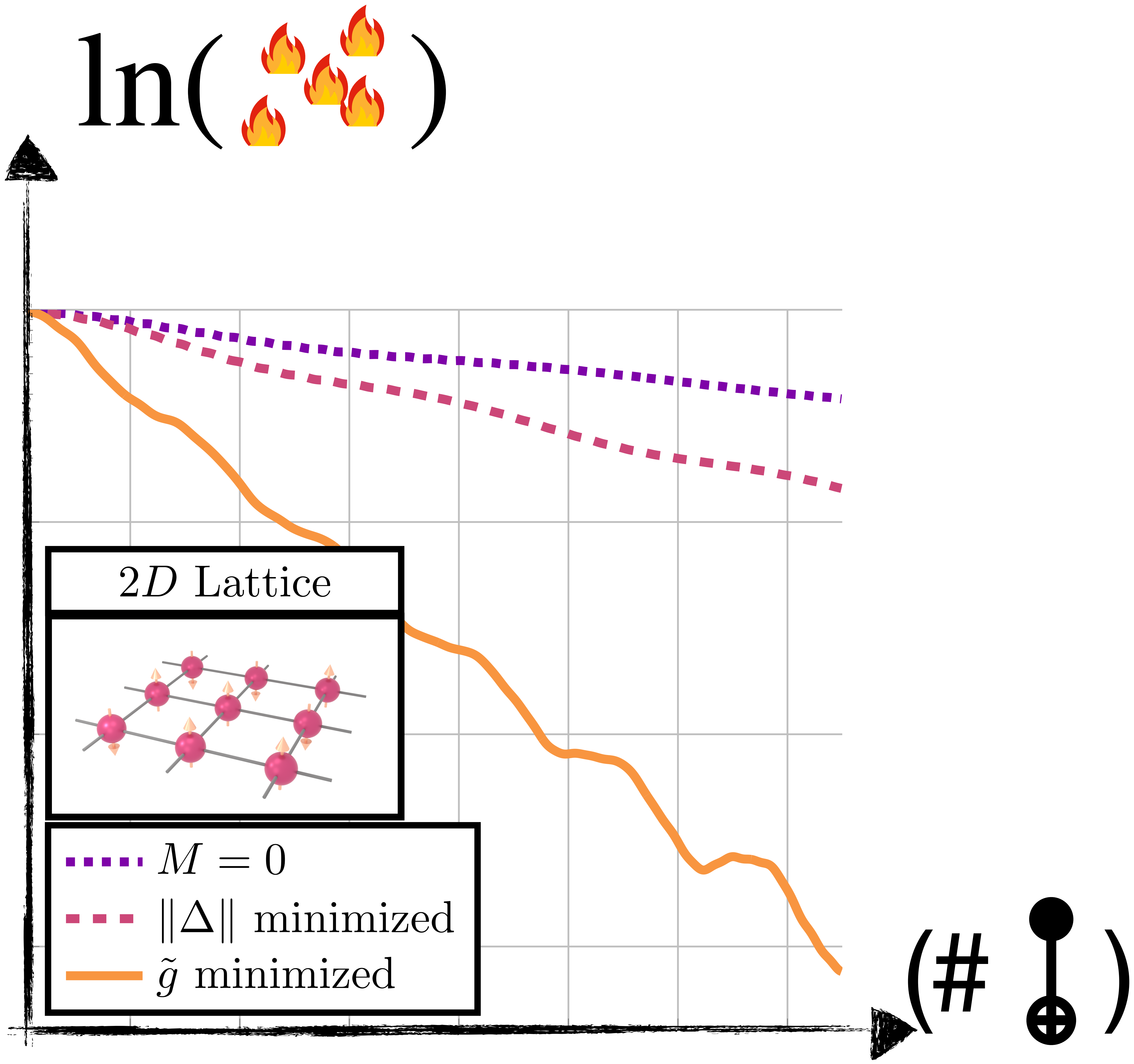
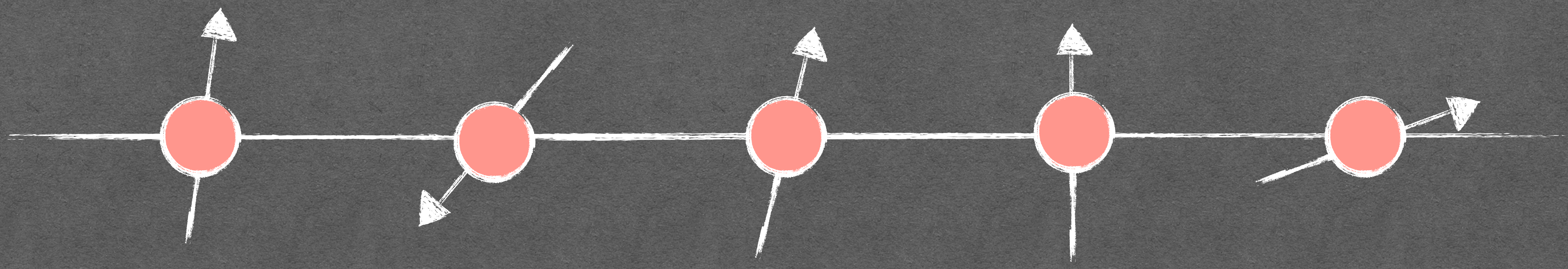
COSTLESS

$J^x = 5J^z$


ln( )
1D Chain
M = 0
‖Δ‖ minimized
g̃ minimized
(#)


ln( )
2D Lattice
M = 0
‖Δ‖ minimized
g̃ minimized
(#)

Ising model in a magnetic field



$$H_1 = -\frac{h}{2}\sum_i Z_i - \frac{J^x}{2}\Sigma_{\langle i,j\rangle}\left(X_i X_j\right)$$

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(#)

- State preparation with **shallow circuits**
- AP error is **exponentially** bounded
- **Explicit formula** for the **characteristic time**
- Numerical tests for spin-systems GS preparation

QR code to the paper:

arXiv preprint arXiv:2405.03656

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

INFN Istituto Nazionale di Fisica Nucleare

NQSTI National Quantum Science and Technology Institute

ICSC Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

UNIVERSITÀ DI PAVIA
Department of Physics

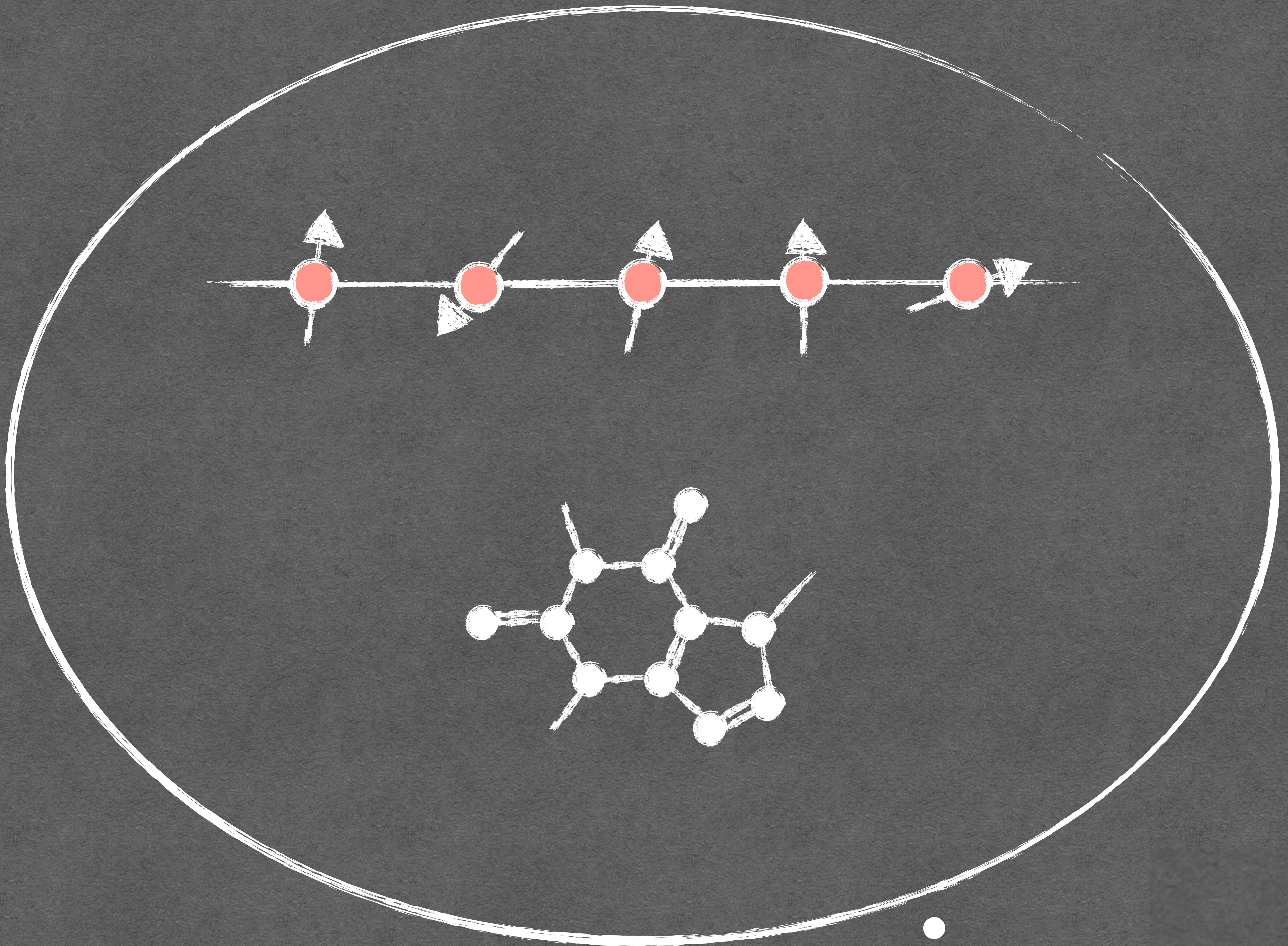
Exponential optimization of adiabatic quantum-state preparation

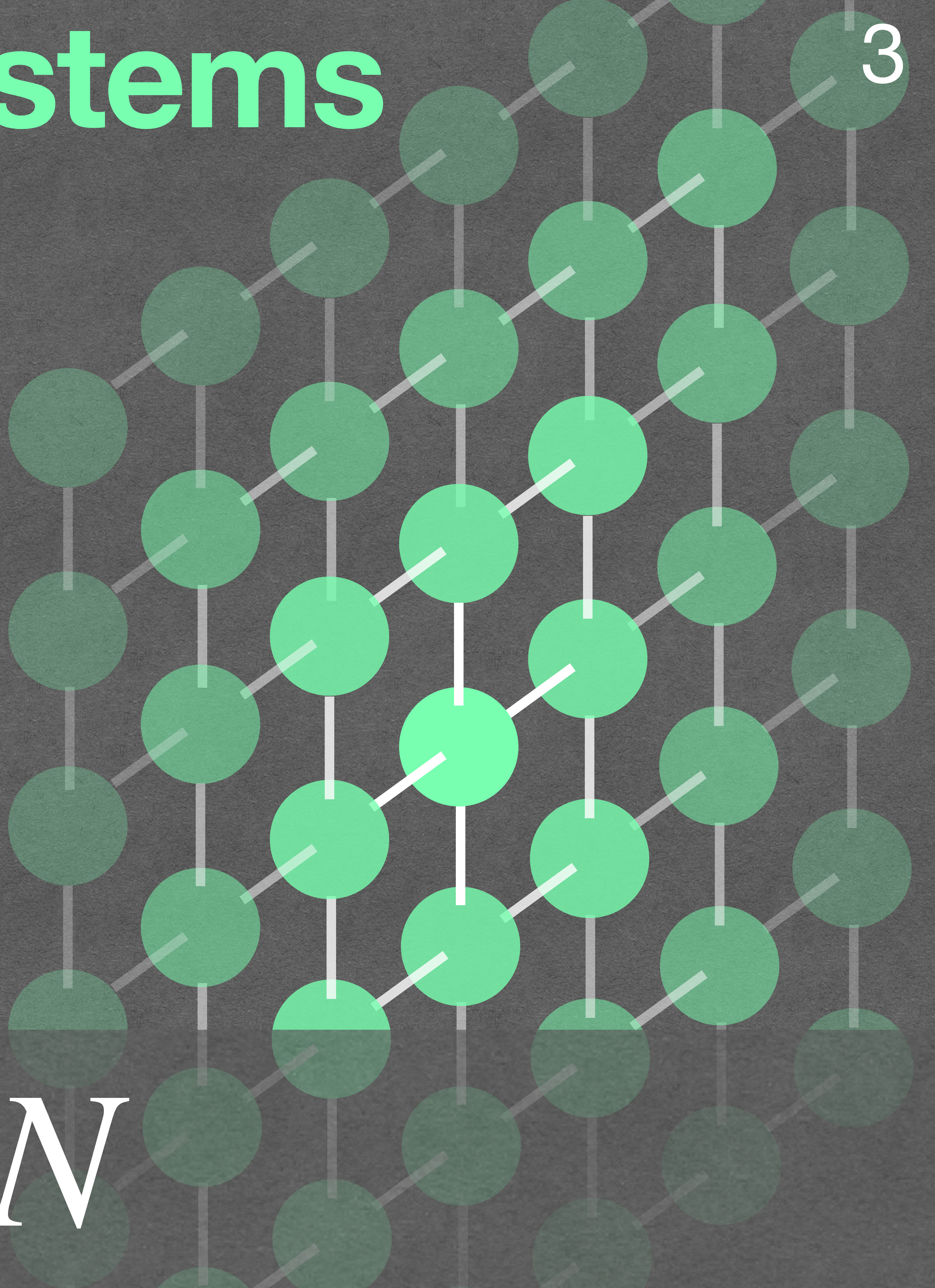
Davide Cugini

D. Nigro, M. Bruno, D.Gerace

INFN Quantum Computing, 30 October 2024

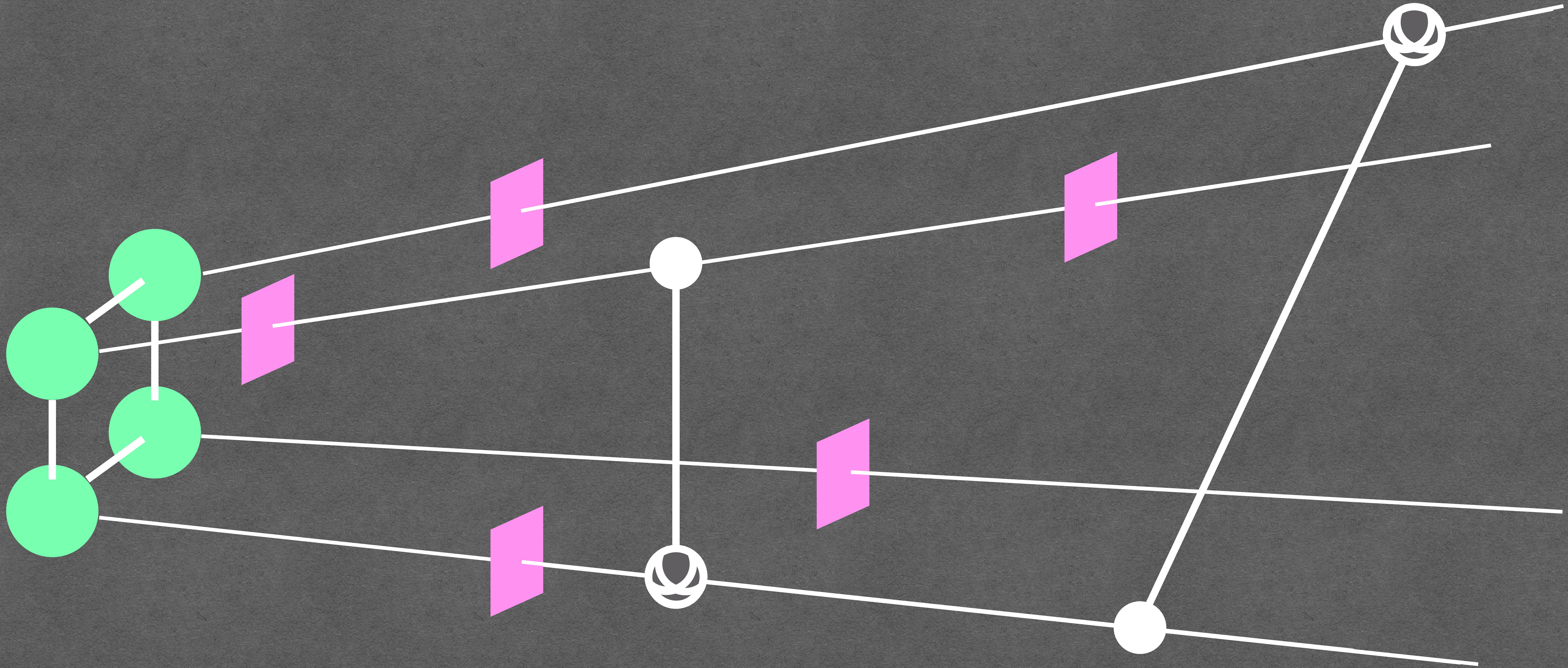
Quantum systems





$$\text{size} \sim N$$

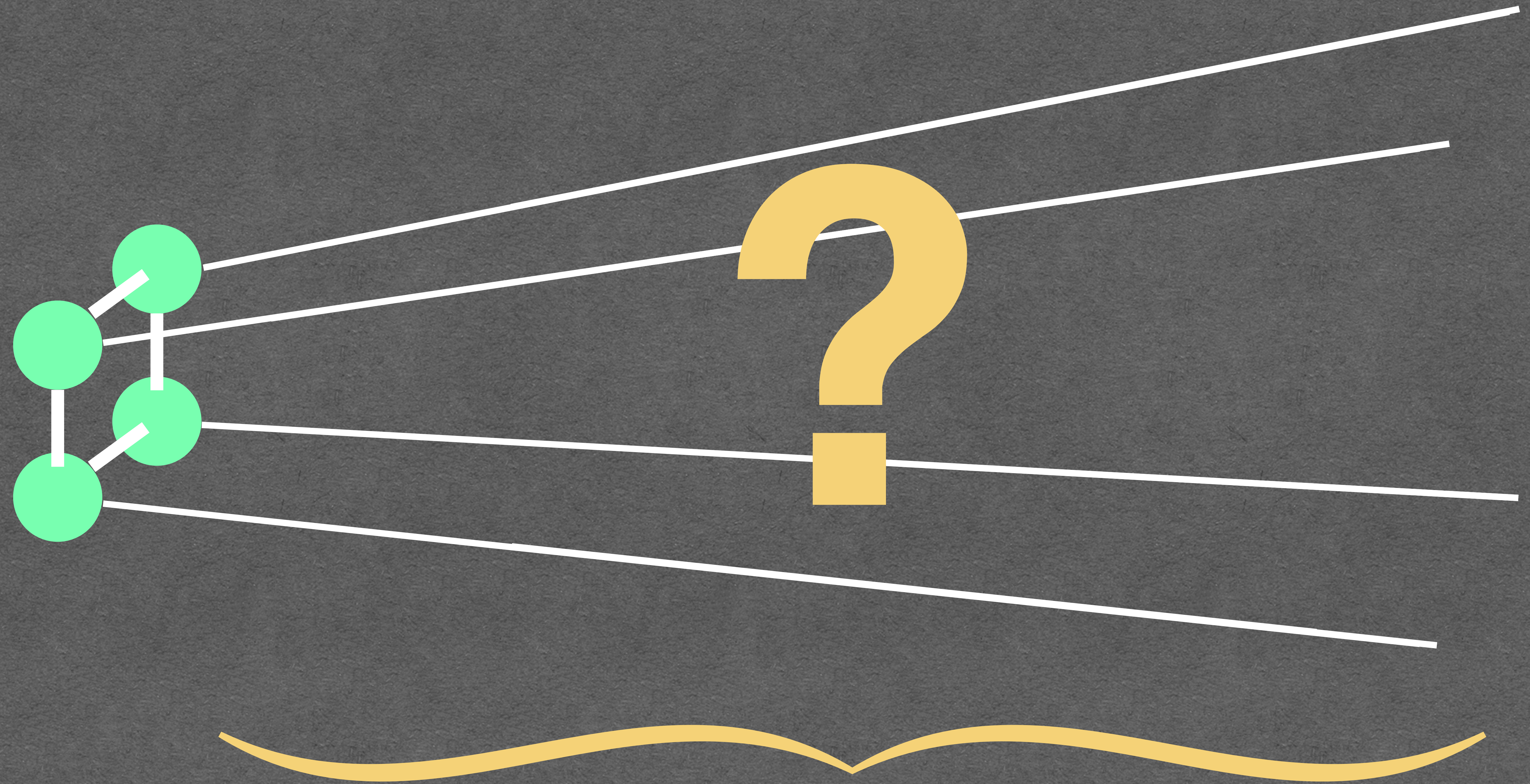
Quantum-state preparation



State preparation challenge

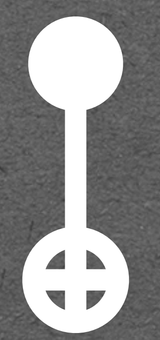
Default state

$|0\rangle^{\otimes N}$



Target state

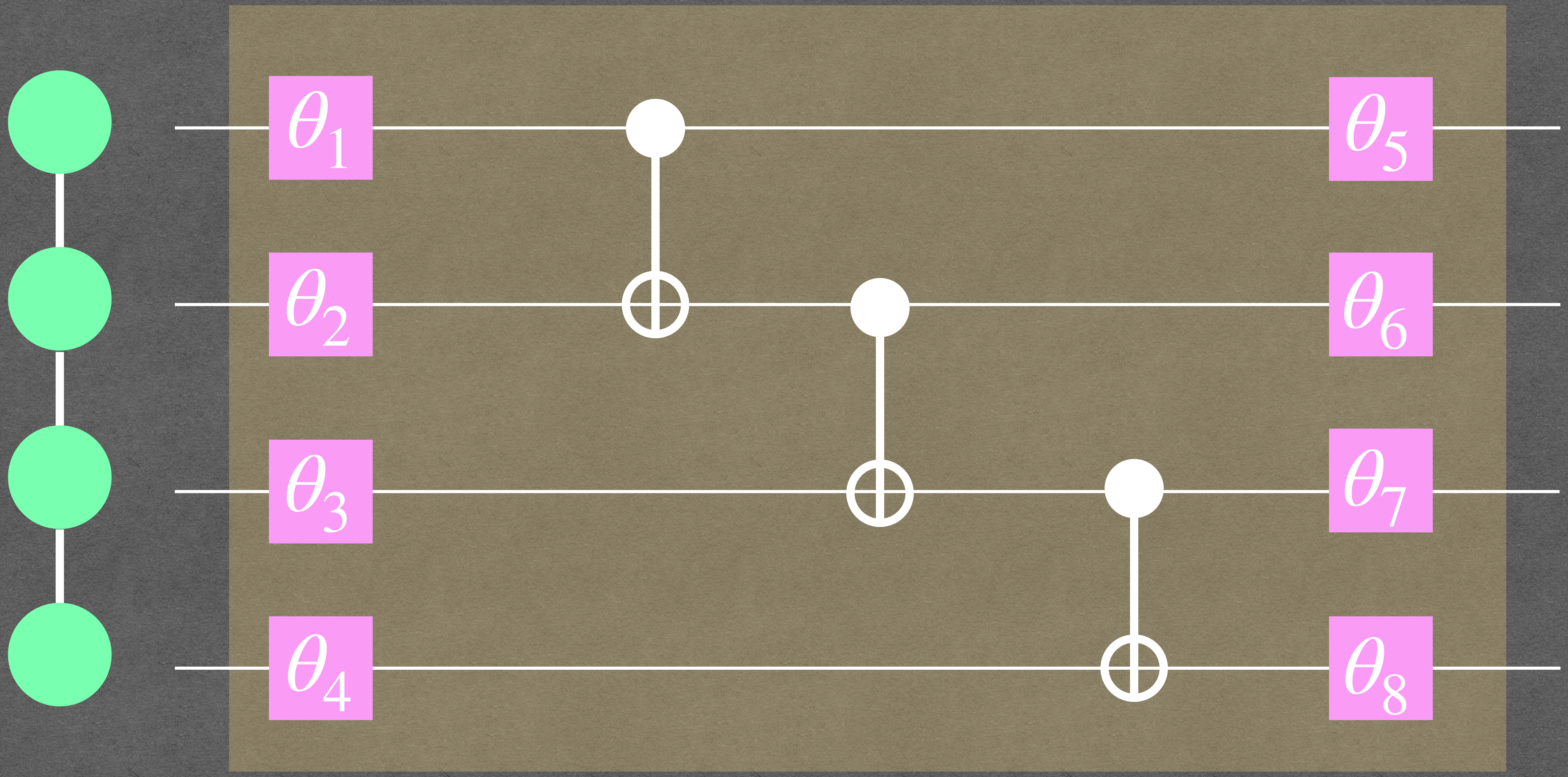
$|\Psi\rangle$

Fixed depth (# )

H_1: **Hamiltonian of the problem**

$|\Psi_n\rangle$: **n-th eigenstate (target)**

Variational Quantum Eigensolvers (VQE)



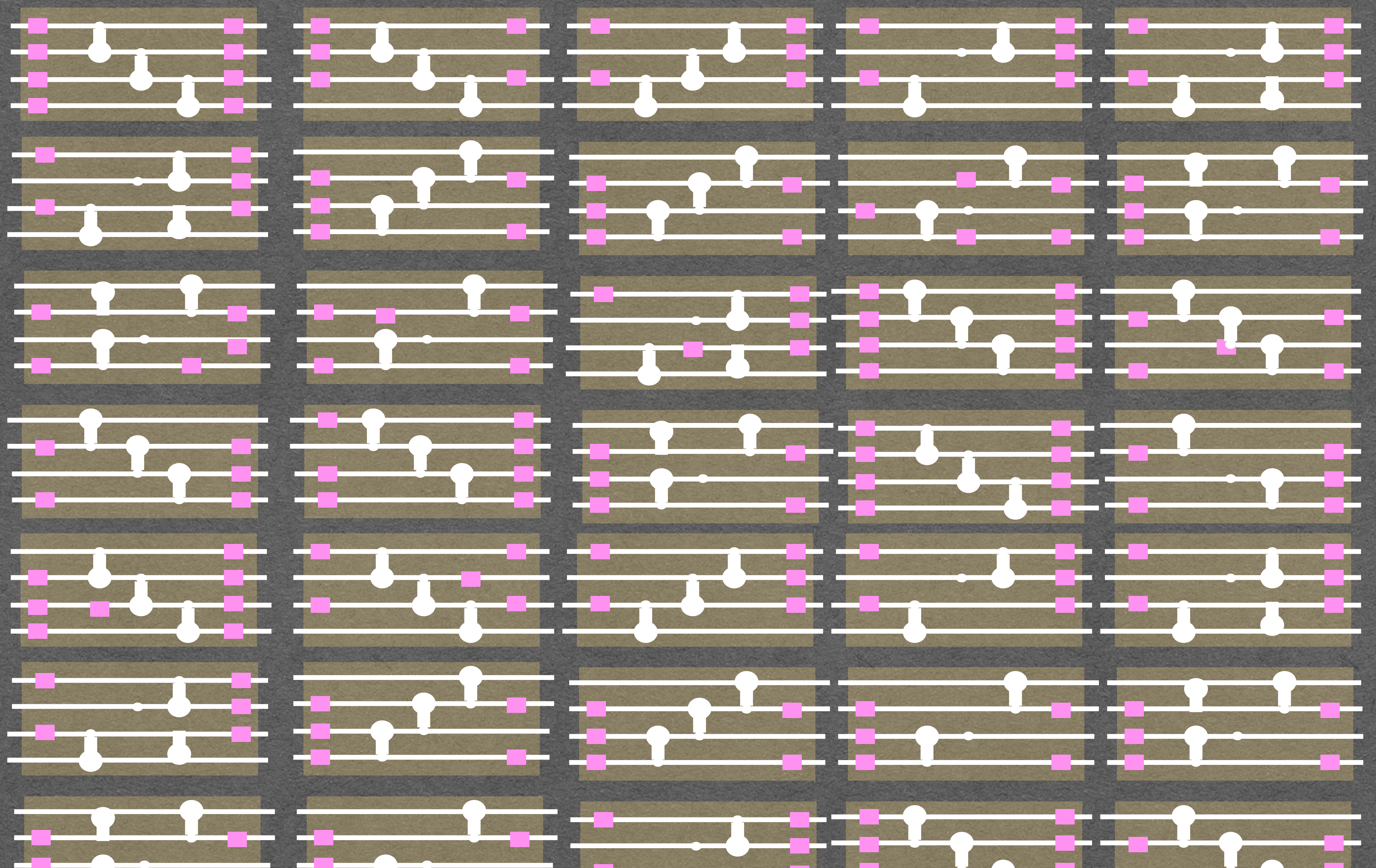
Fixed depth (#)

Main Problems of VQE

Shallow circuit

↓

Ansatz choice

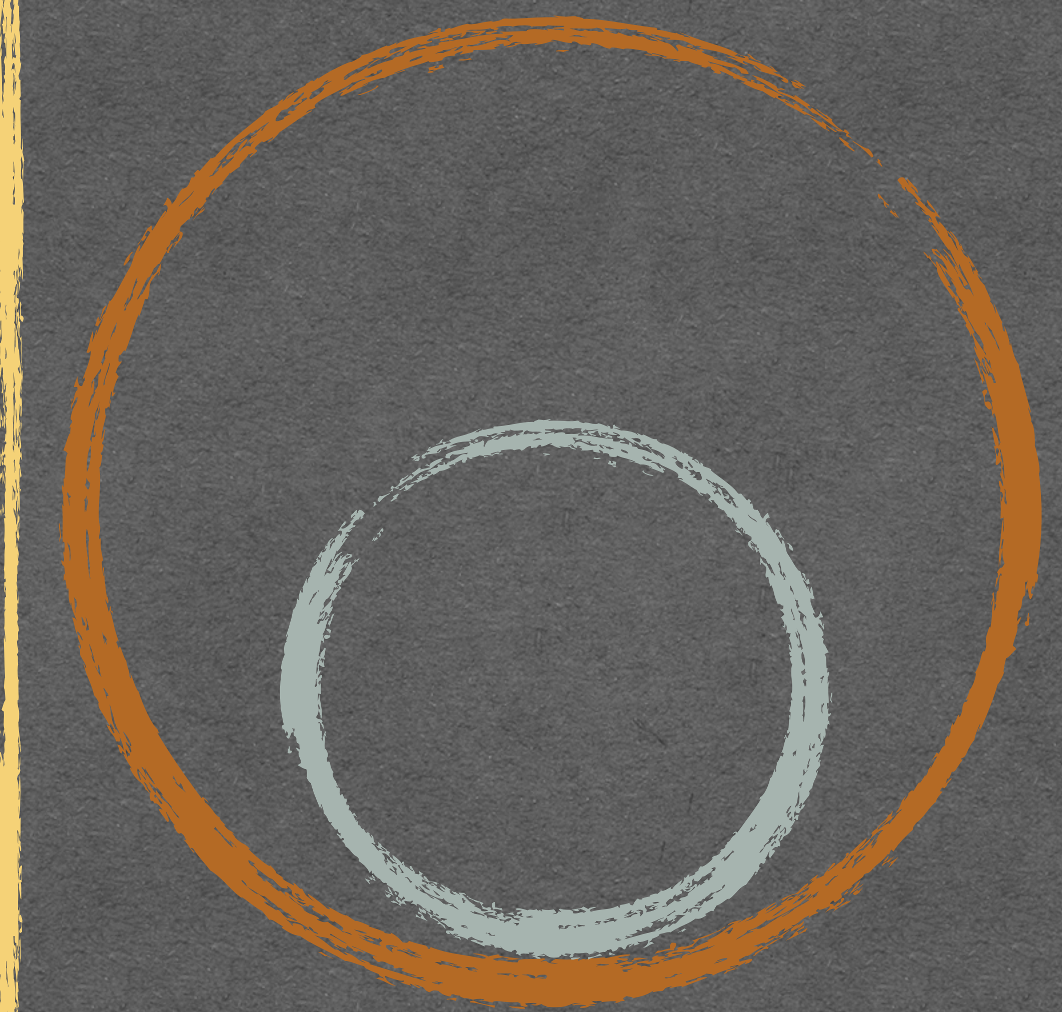


Large Hilbert spaces

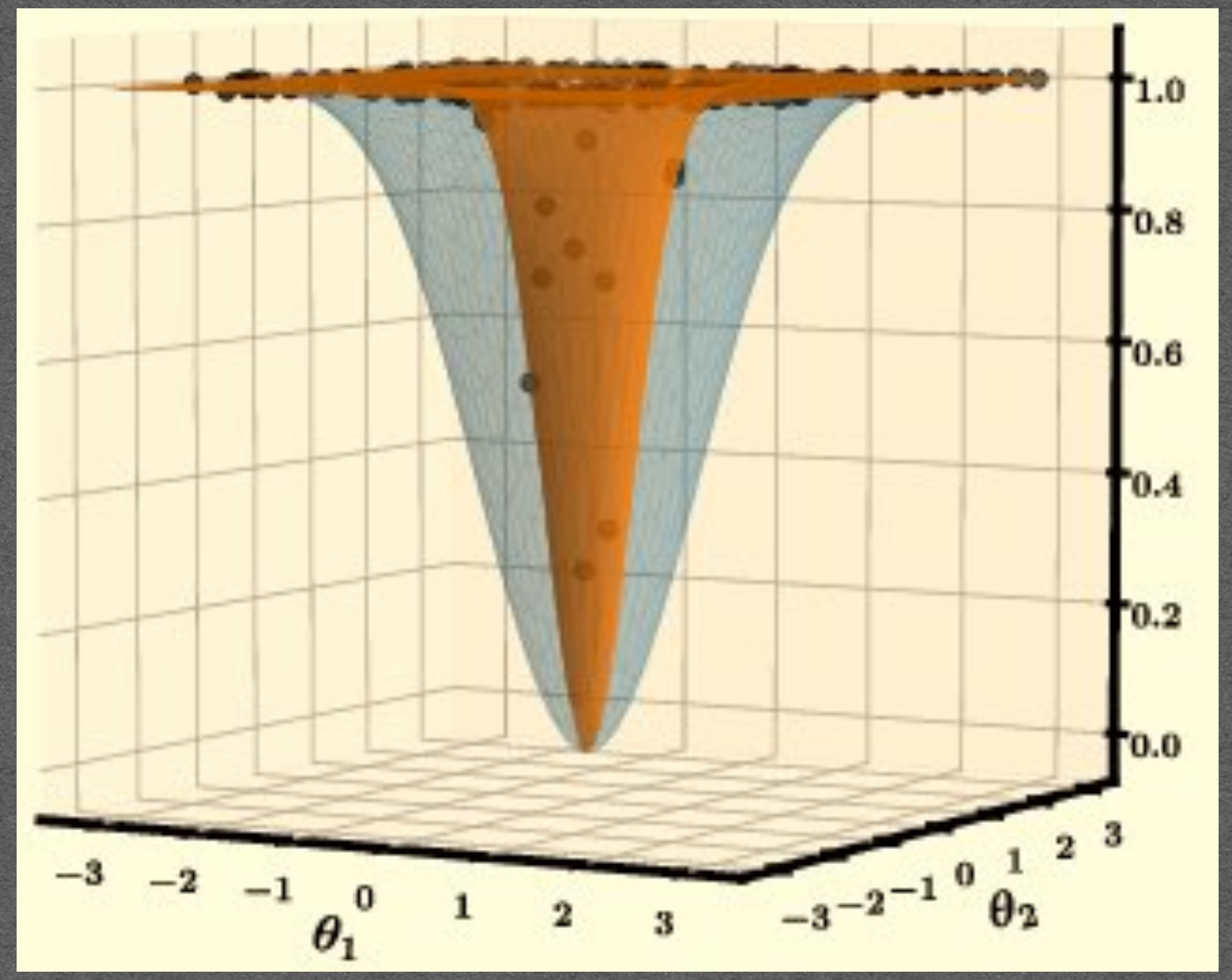
↓

Barren Plateaus

$\mathscr{H} \sim 2^N$



Loss function



Eigenstates superposition

$$|SGS(i,j)\rangle \equiv \frac{1}{\sqrt{2}}\Big(|\Psi_i\rangle + |\Psi_j\rangle\Big)$$

Spectral Gap Superposition States

Davide Cugini,[1,*] Francesco Ghisoni,[1,†] Angela Rosy Morgillo,[1,‡] and Francesco Scala[1,§]

[1] *Dipartimento di Fisica, Università degli Studi di Pavia, via A. Bassi 6, 27100 Pavia (Italy)*

(Dated: February 28, 2024)

Eigenstates superposition

$$|SGS(i,j)\rangle \equiv \frac{1}{\sqrt{2}}\Big(|\Psi_i\rangle + |\Psi_j\rangle \Big)$$

$$\langle O(t)\rangle = \frac{1}{2}\Big(\langle\Omega_i|O|\Omega_i\rangle + \langle\Omega_j|O|\Omega_j\rangle \Big) + \rho\cos\Big(\Delta E_{ji}t + \theta\Big)$$

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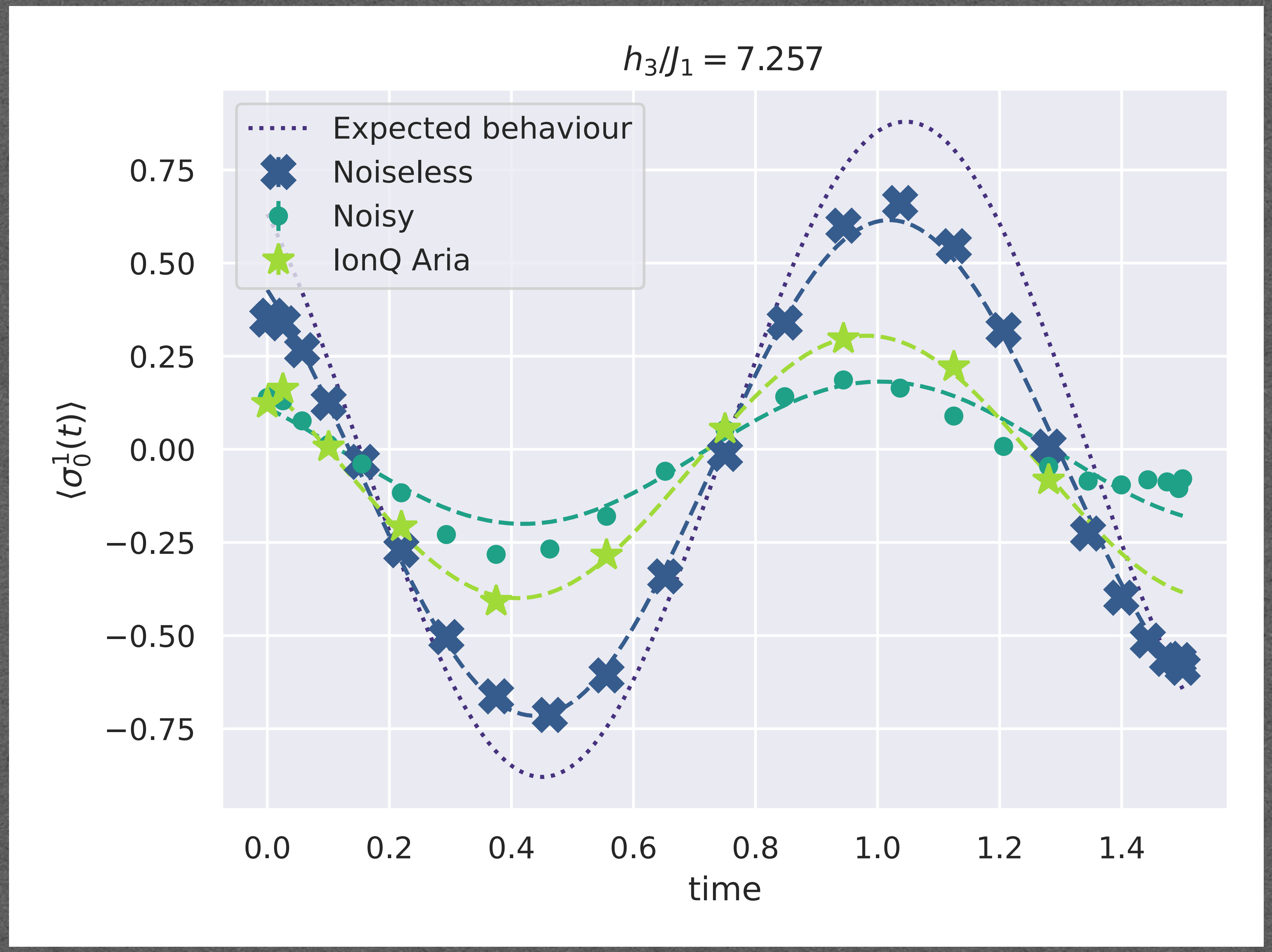

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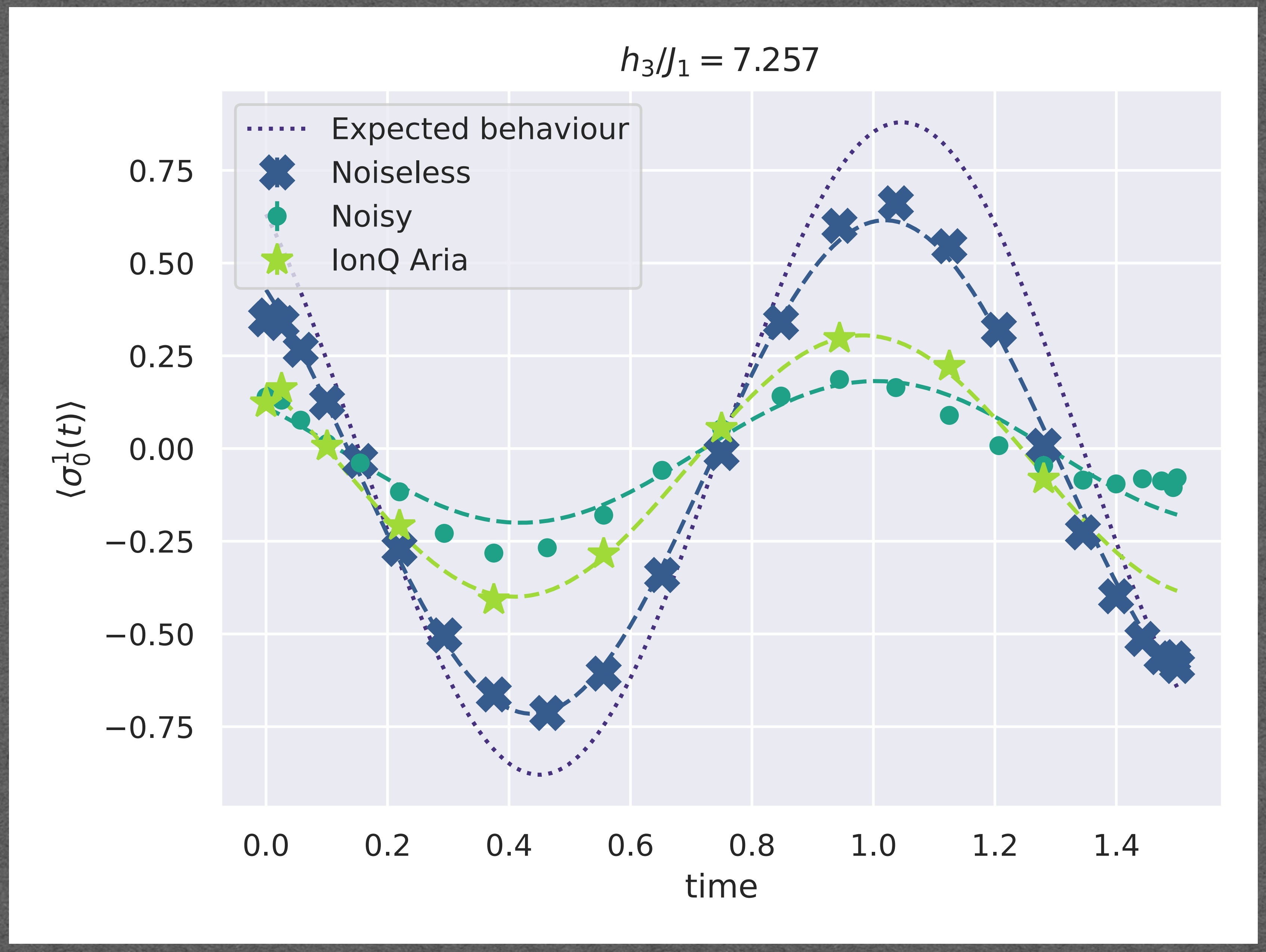
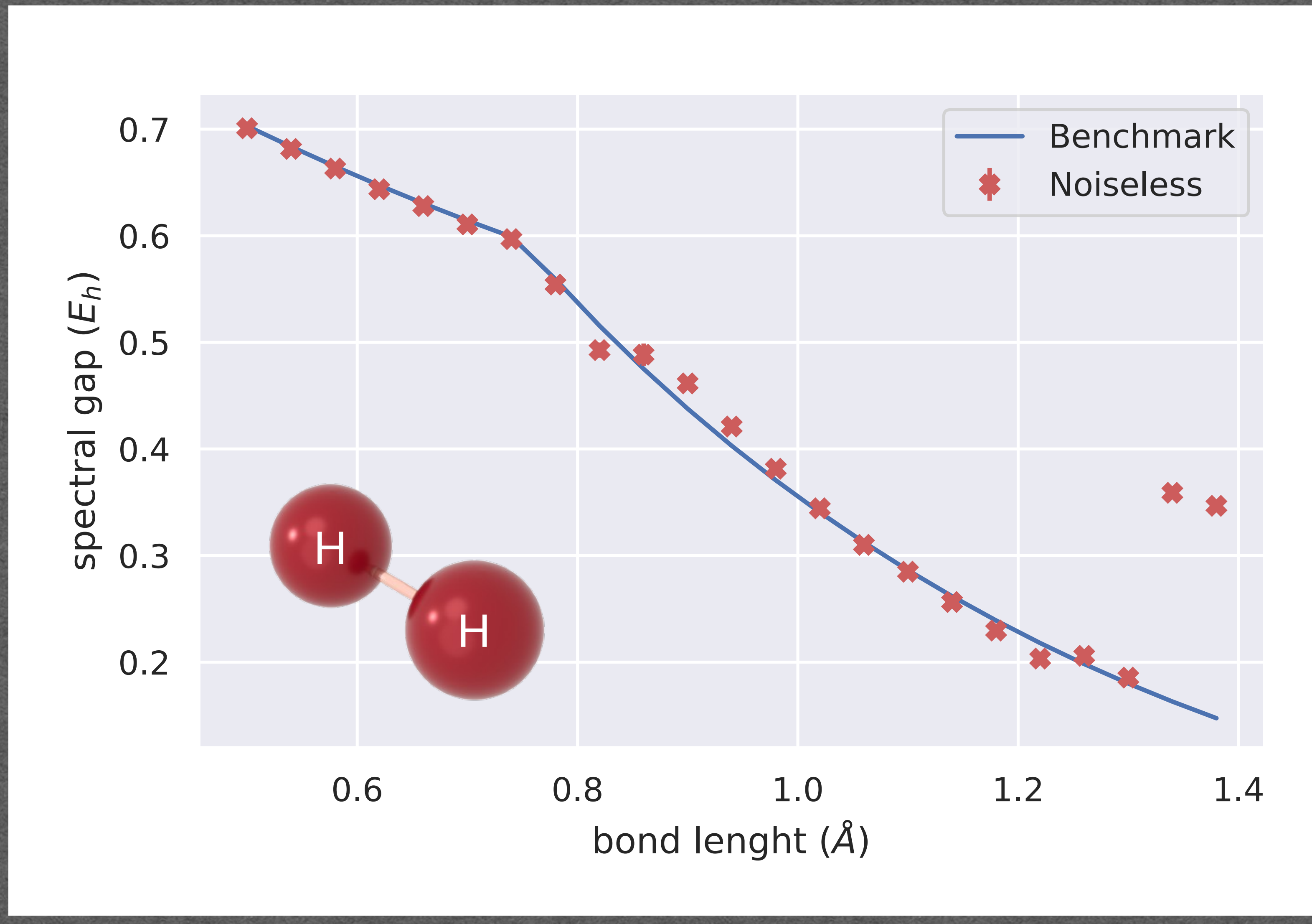
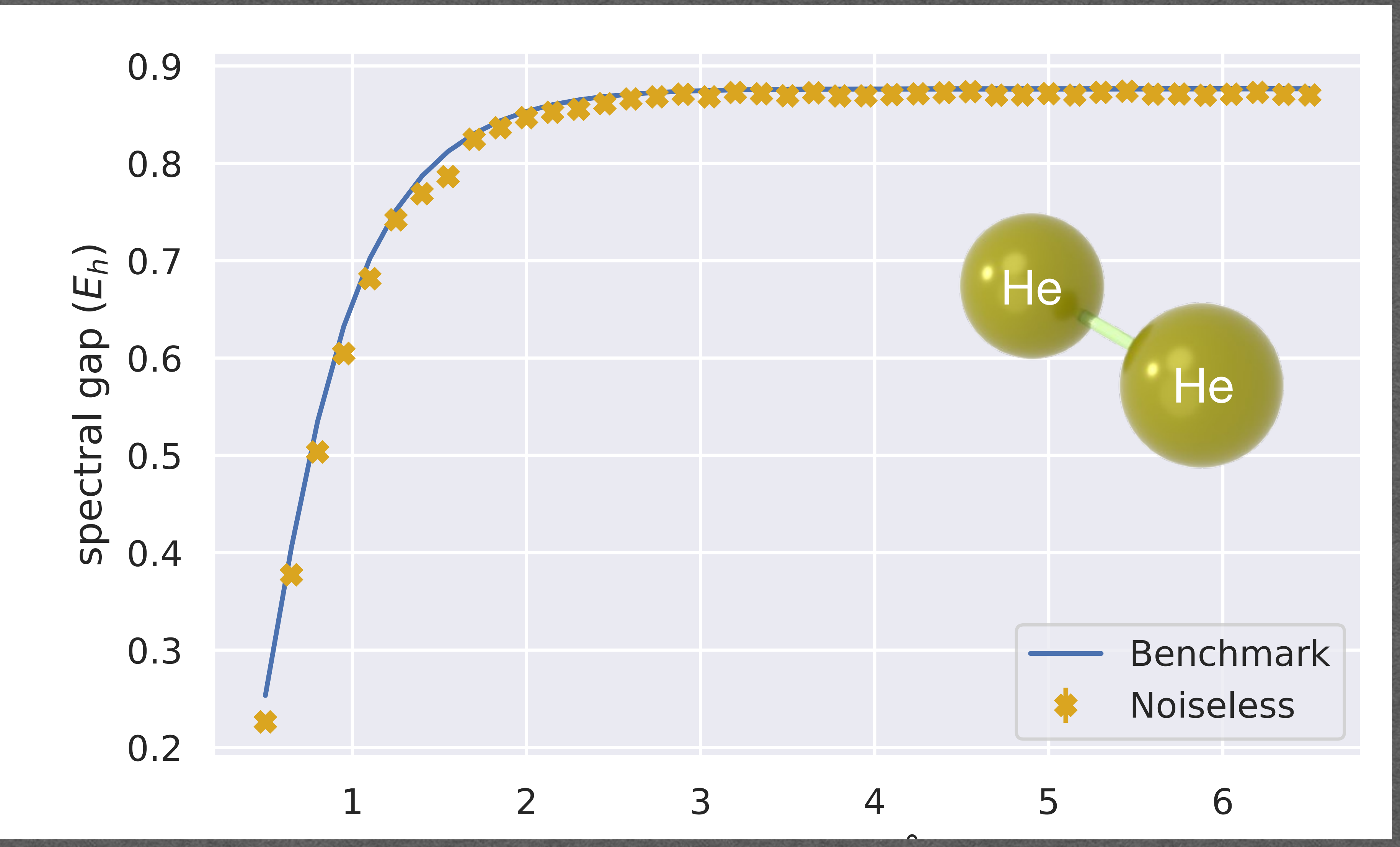
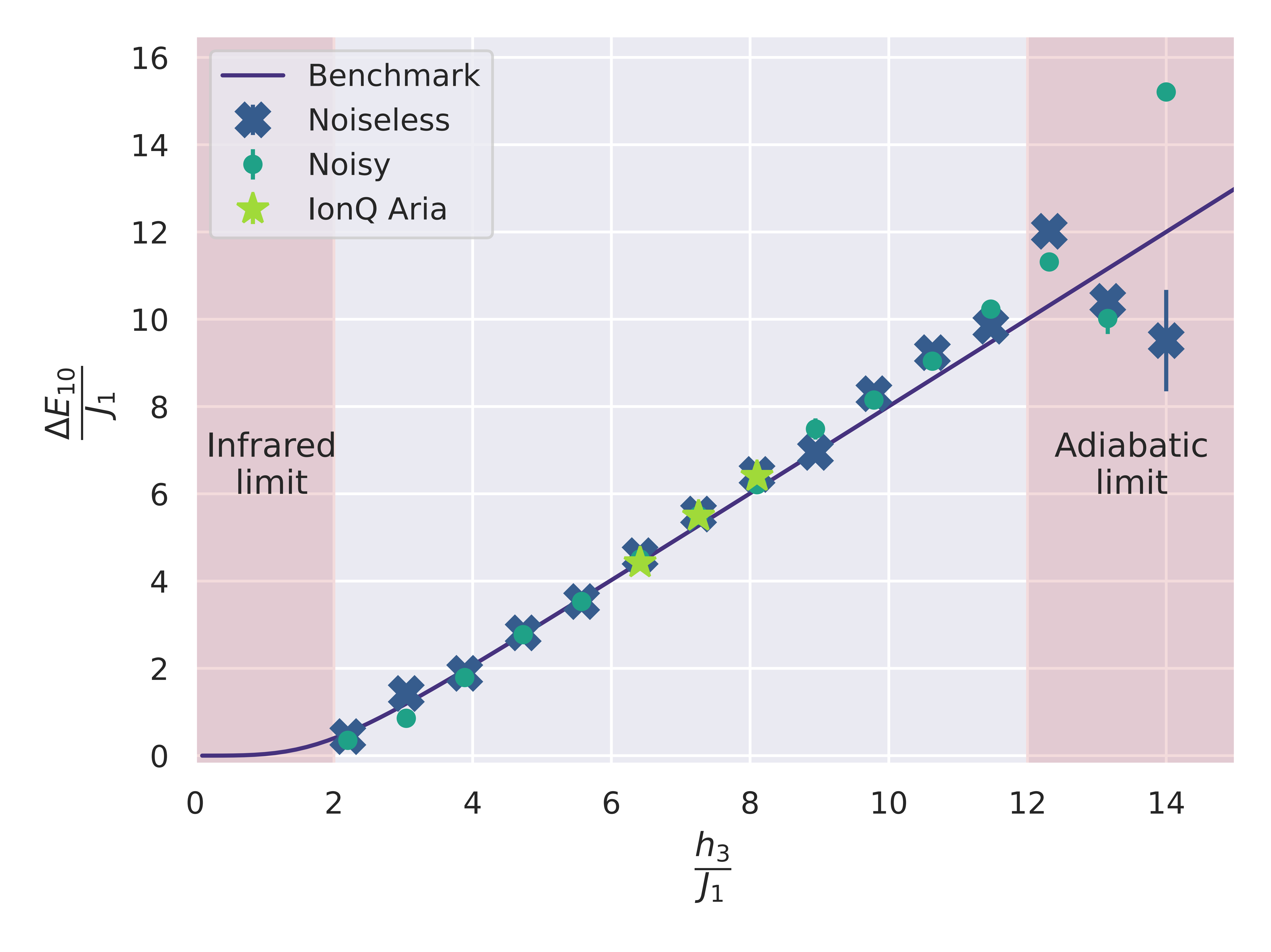




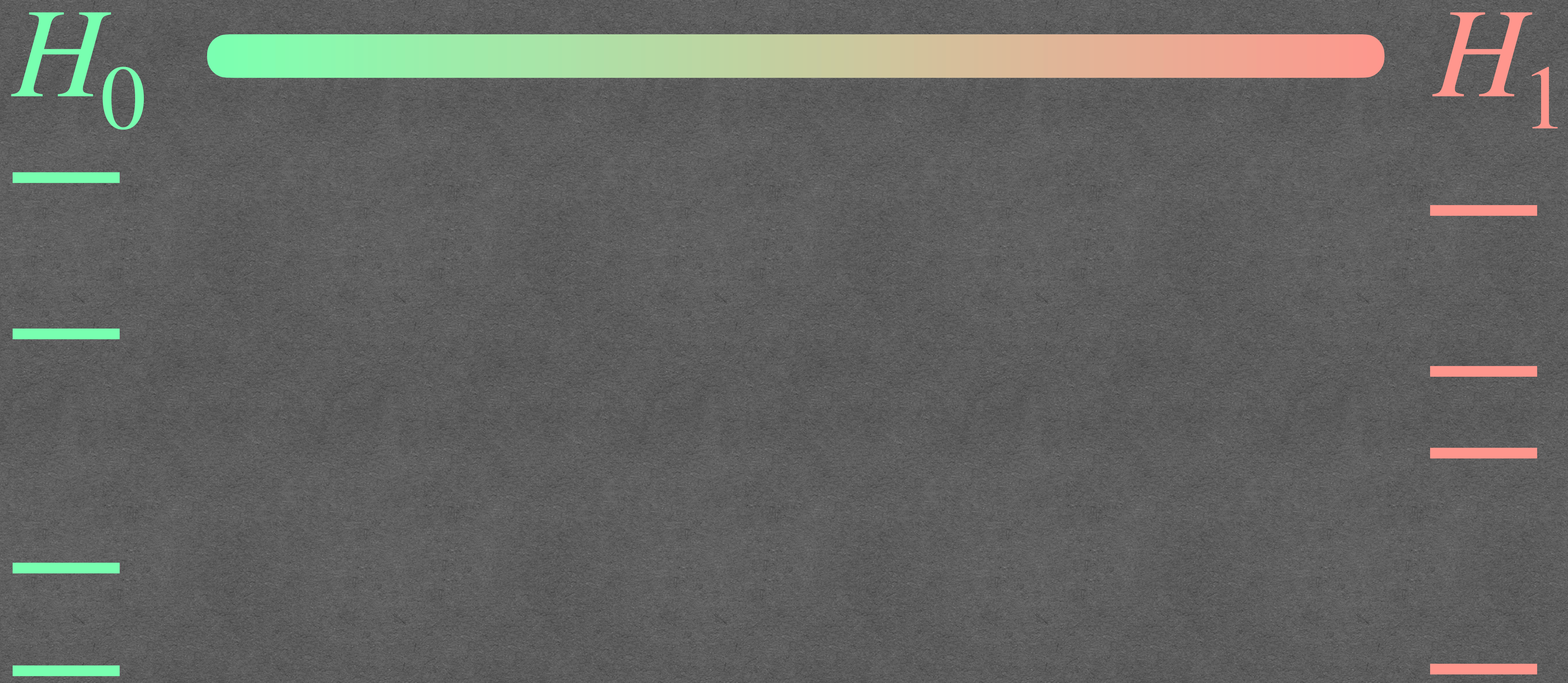


Eigenstates superposition: Ising model

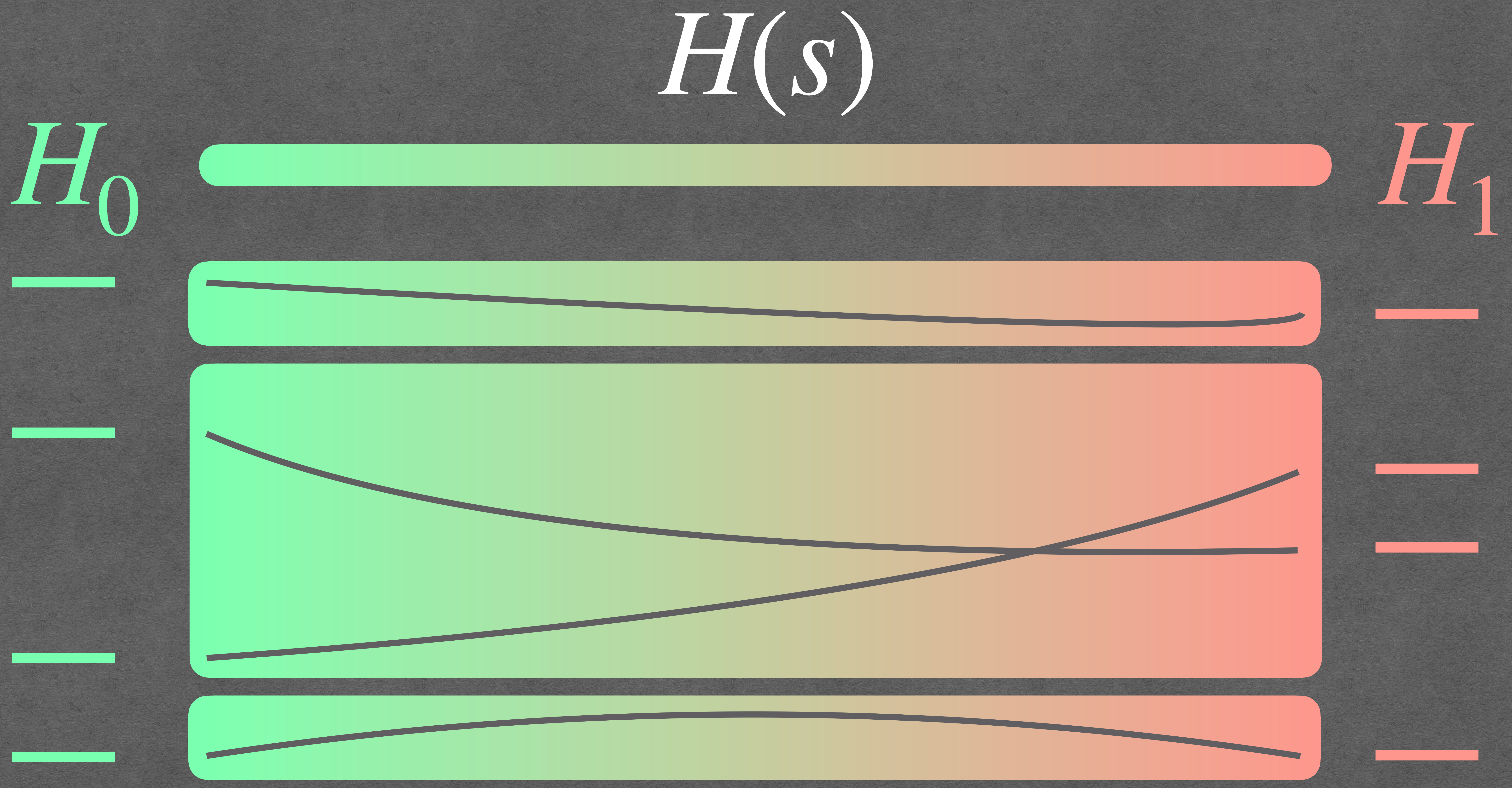


Adiabatic Preparation AP

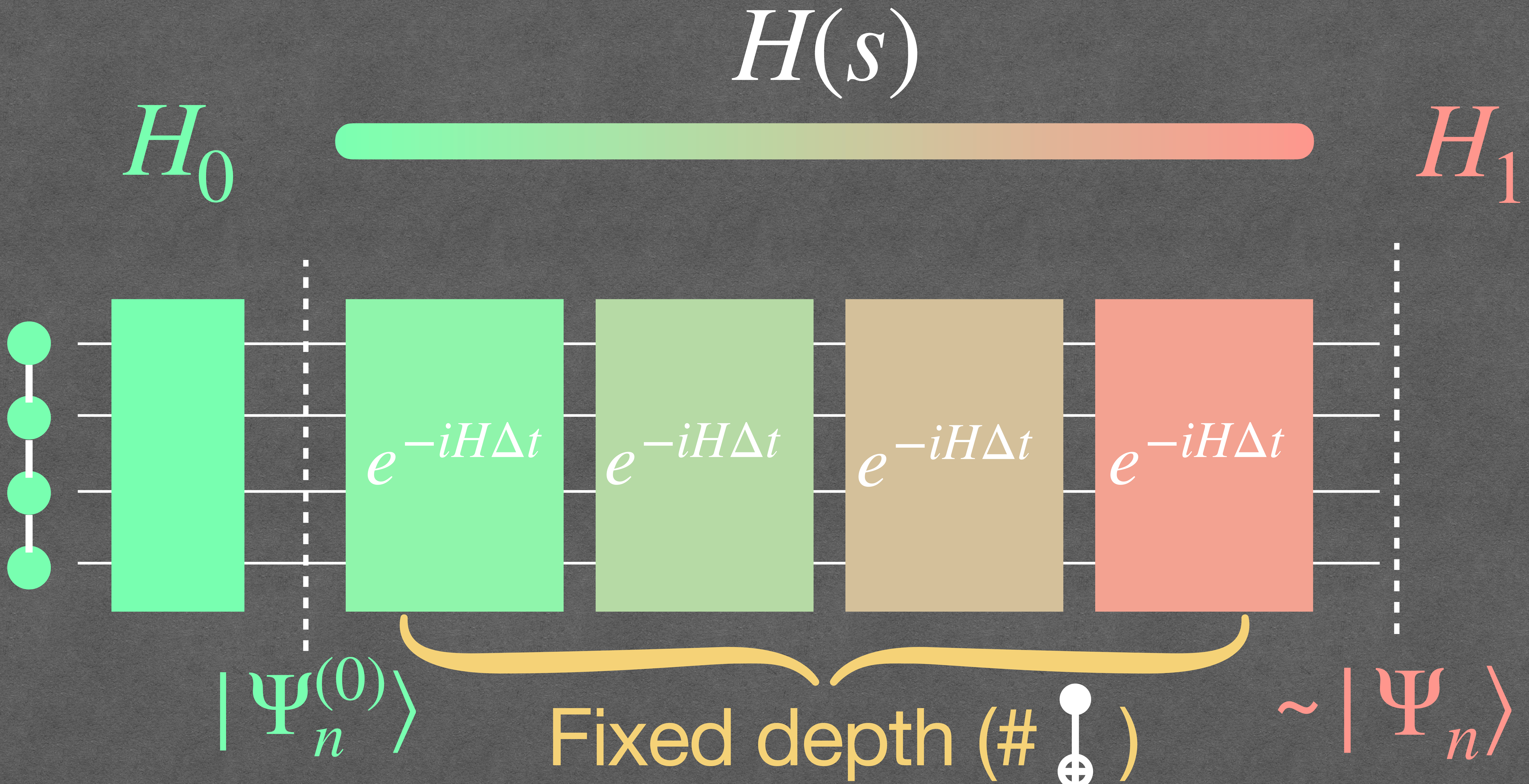
$$H(s) = H_0 + f(s)[H_1 - H_0]$$



Adiabatic Preparation AP



AP on quantum computers



Losses bound for AP

Linear Adiabatic Theory. Exponential Estimates

G. Nenciu

$\exists C, \tilde{g} > 0$ such that

$$\left|\left|1 - |\Psi_n\rangle\langle\Psi_n|\right|\right| \leq C \exp\left[-\tau/\tilde{g}\right]$$

τ : Duration of the adiabatic process

Losses bound for AP

Linear Adiabatic Theory. Exponential Estimates

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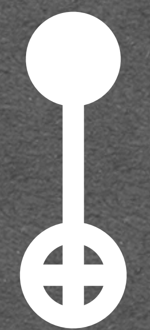
🔥🔥🔥🔥🔥 $\leq C \exp\Big[-($**#**  $)/\tilde{g}\Big]$

Fixed by the hardware

CAN WE REDUCE $\tilde{g}$?

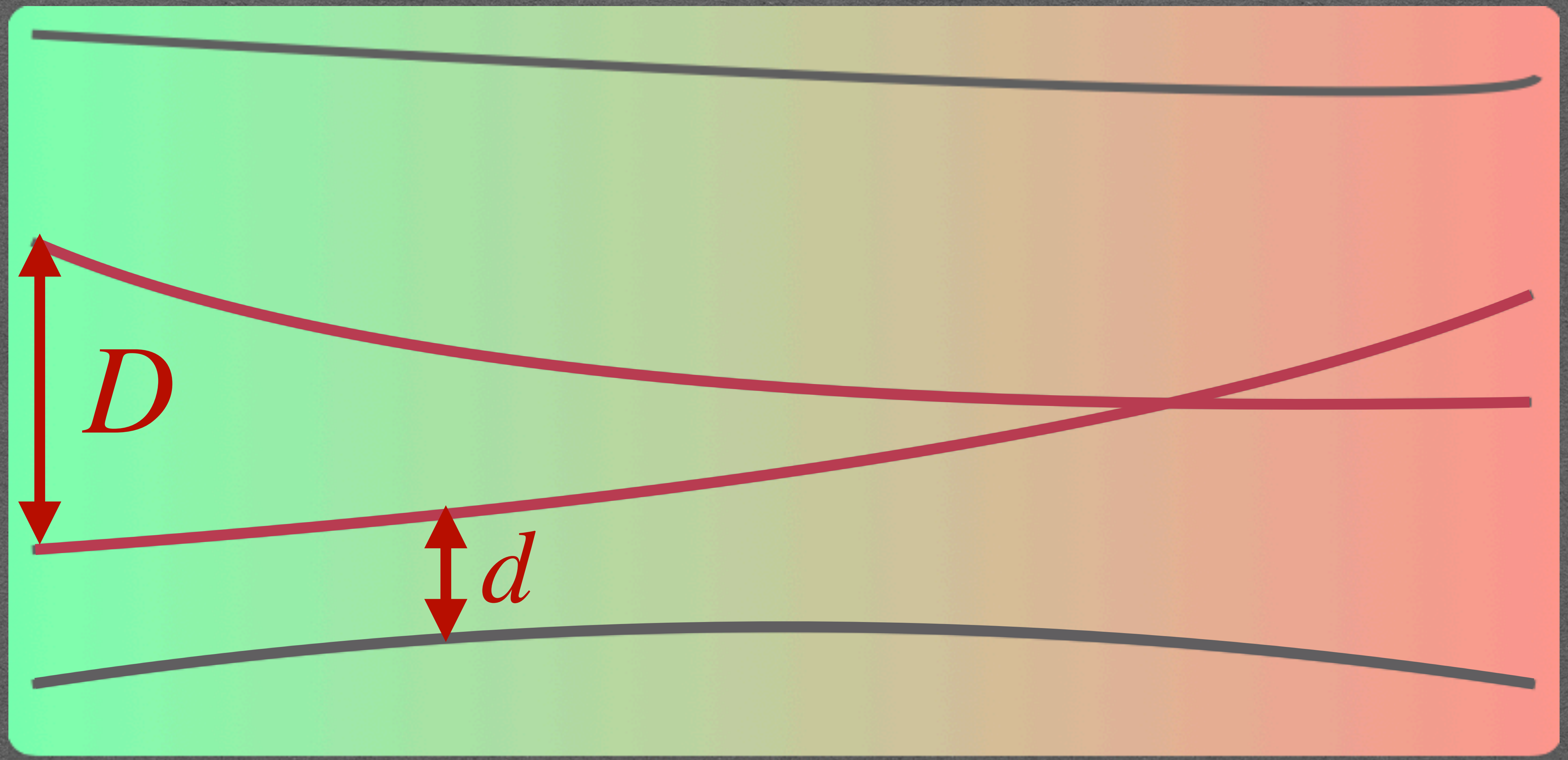
Exponential optimization of quantum state preparation via adiabatic thermalization

Davide Cugini,[1] Davide Nigro,[1] Mattia Bruno,[2] and Dario Gerace[1]
[1] *Dipartimento di Fisica, Università di Pavia, via Bassi 6, 27100, Pavia, Italy*
[2] *Dipartimento di Fisica, Università di Milano–Bicocca, and INFN, sezione di Milano–Bicocca, Piazza della Scienza 3, I-20126 Milano, Italy*

$$\tilde{g} = \tilde{g}(||H_1 - H_0||, D, d)$$

Increasing function in terms of

$$||\Delta|| = ||H_1 - H_0||, \quad D, \quad d^{-1}$$



arXiv preprint arXiv:2405.03656

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$$\tilde{g} = 4\frac{W(D,d)}{\rho(||\Delta||,d)}$$

$$W(d,D) = \left[2^8\left(1+2\frac{D}{\pi d}\right)^2\left(\frac{\pi^2}{3}+\frac{4}{d}\right)\right]^{7/3}$$

$$\rho\left(\frac{d}{||\Delta||}\right) = \inf_{s\in[0,1]}\sup_{\rho\in C}\left[|\rho| : \left|f(s+\rho)-f(s)\right| < \frac{d}{4||\Delta||}\right]$$

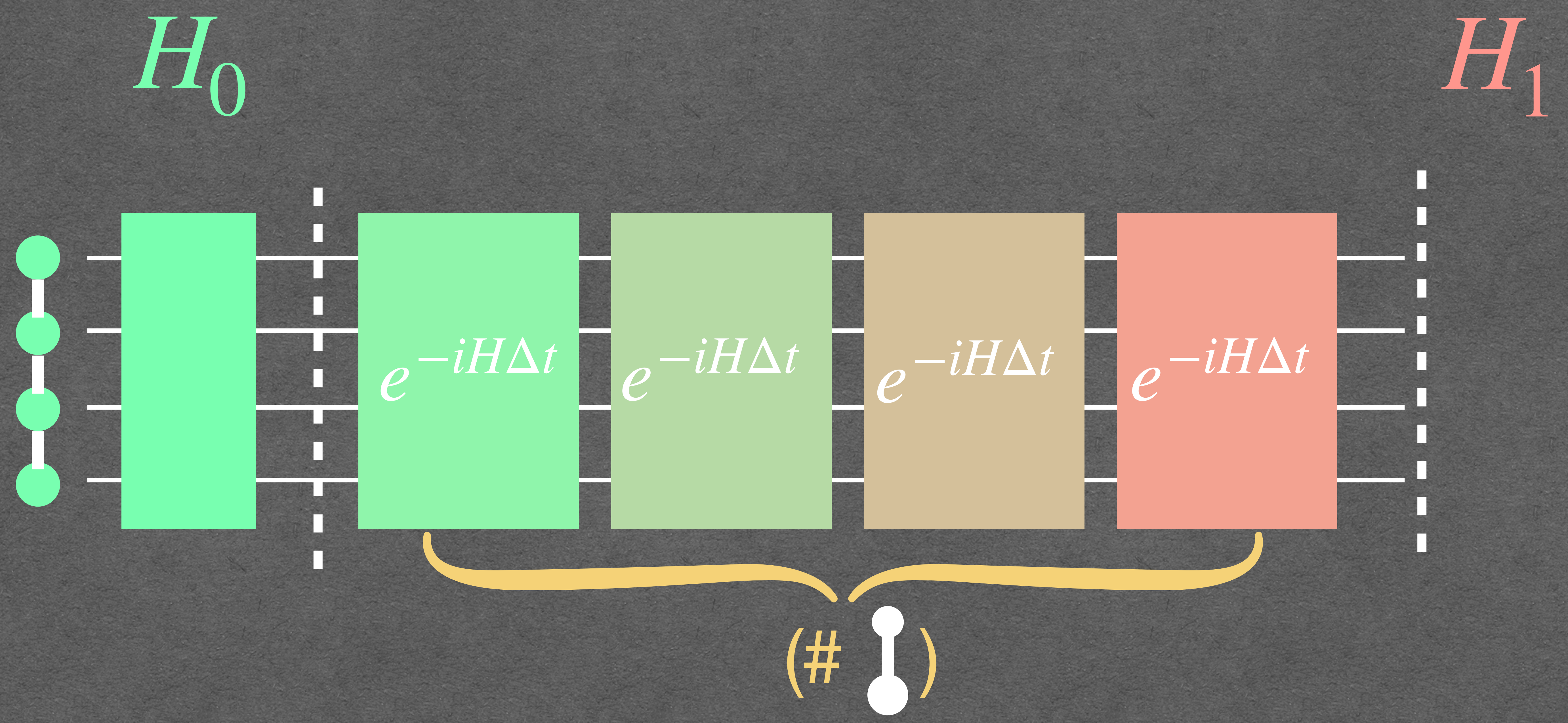
Linear case

$$\rho\left(\frac{d}{||\Delta||}\right) = \frac{d}{4||\Delta||}$$

$$\tilde{g} = \tilde{g}(||H_1 - H_0||, D, d)$$

Increasing function in terms of

$$||\Delta|| = ||H_1 - H_0||, \quad D, \quad d^{-1}$$



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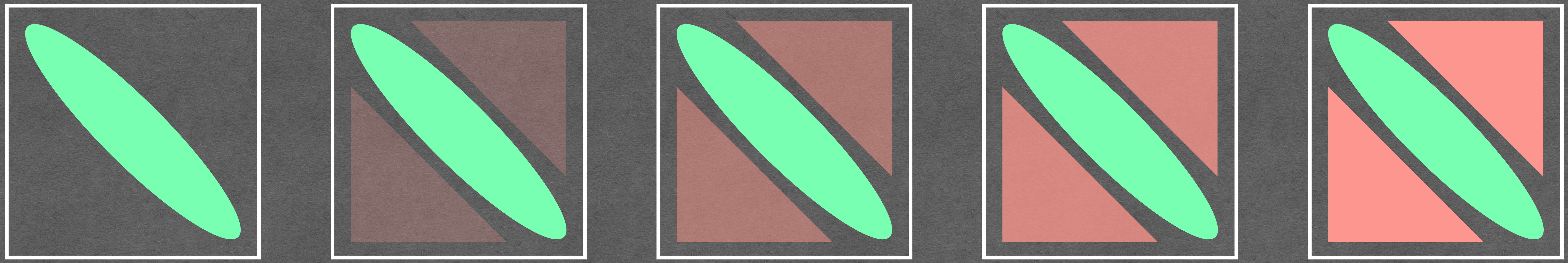
$$H_0 = \mathrm{diag}(H_1) + M(\alpha)$$

Exponential optimisation of AP

$$H_0 = \mathrm{diag}(\mathrm{H}_1)$$

$$H_1$$



Exponential optimisation of AP

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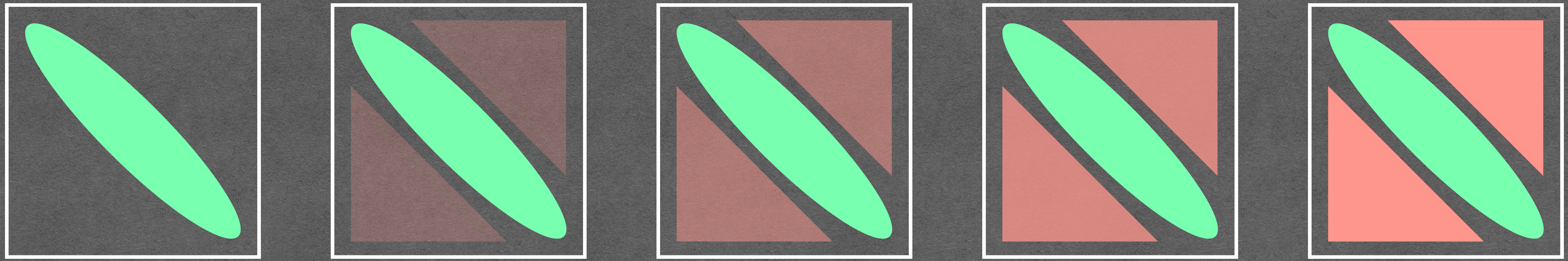

Exponential optimisation of AP

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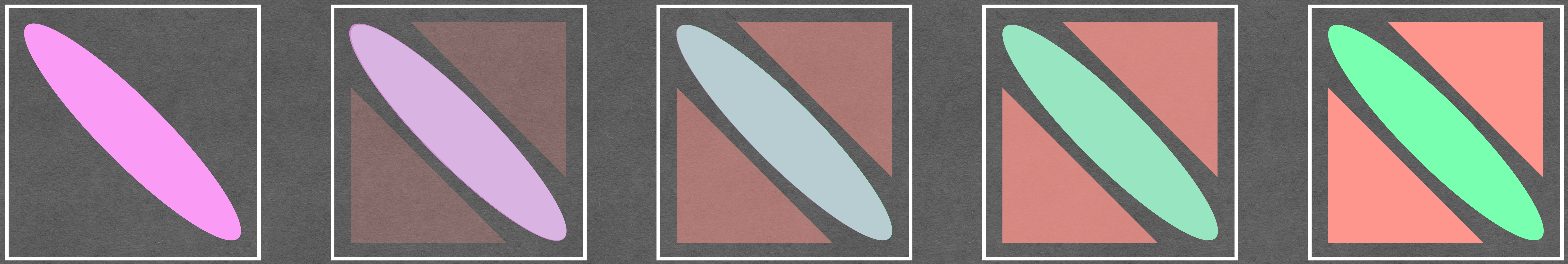

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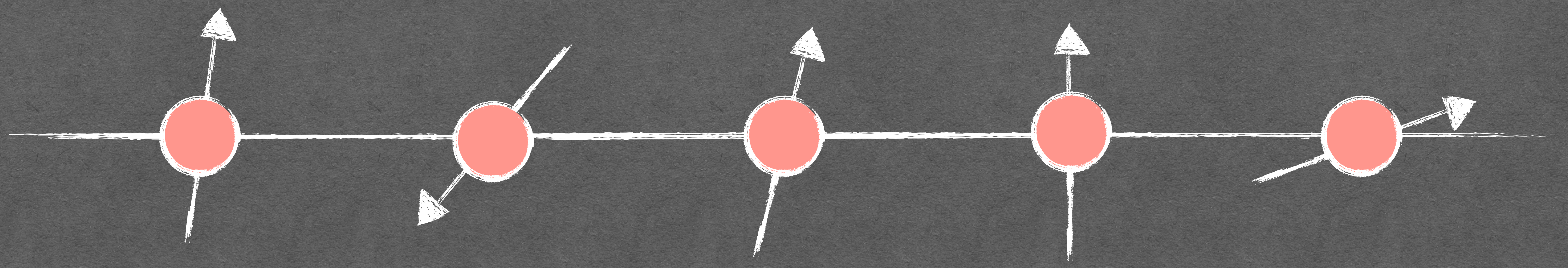

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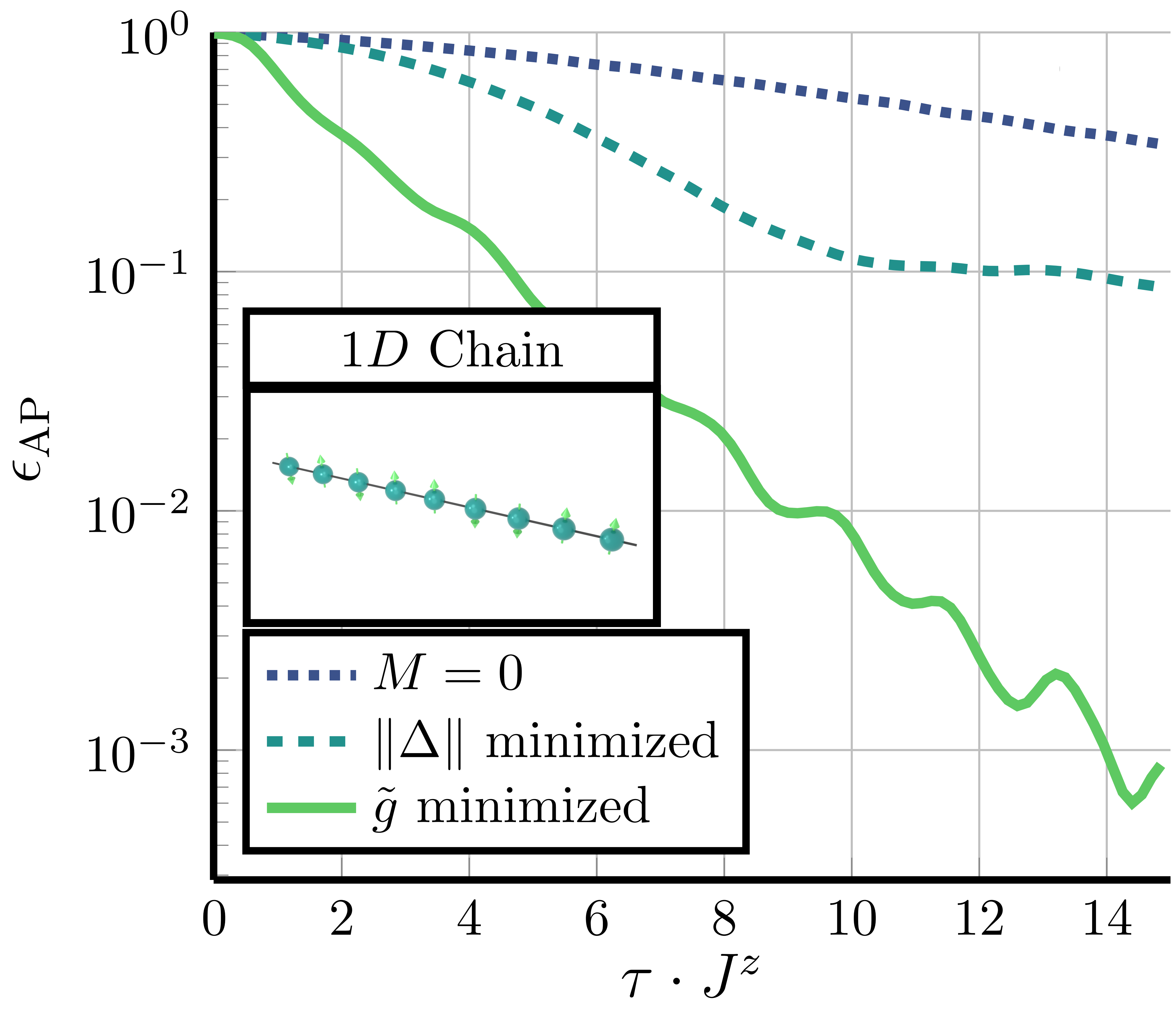
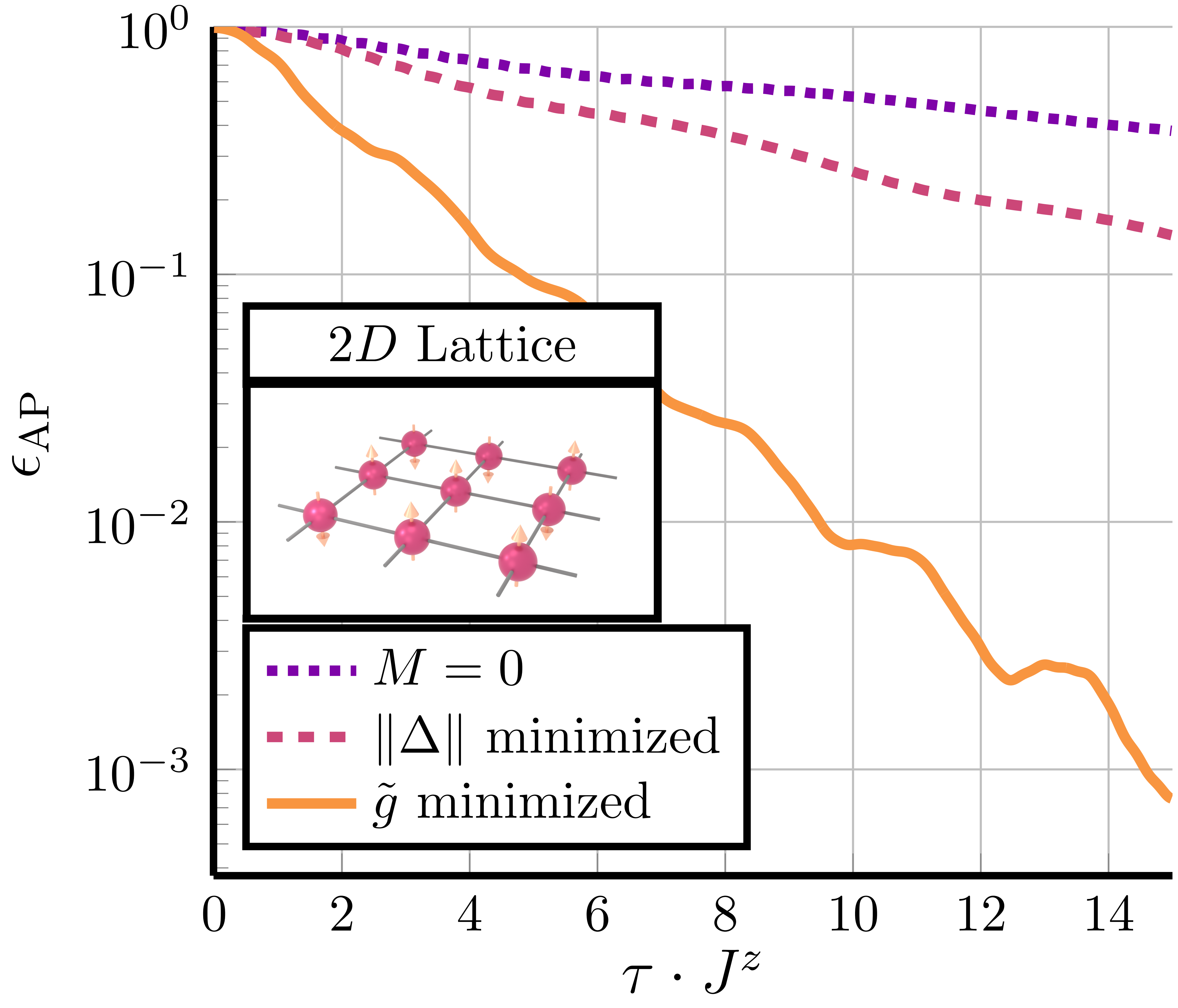
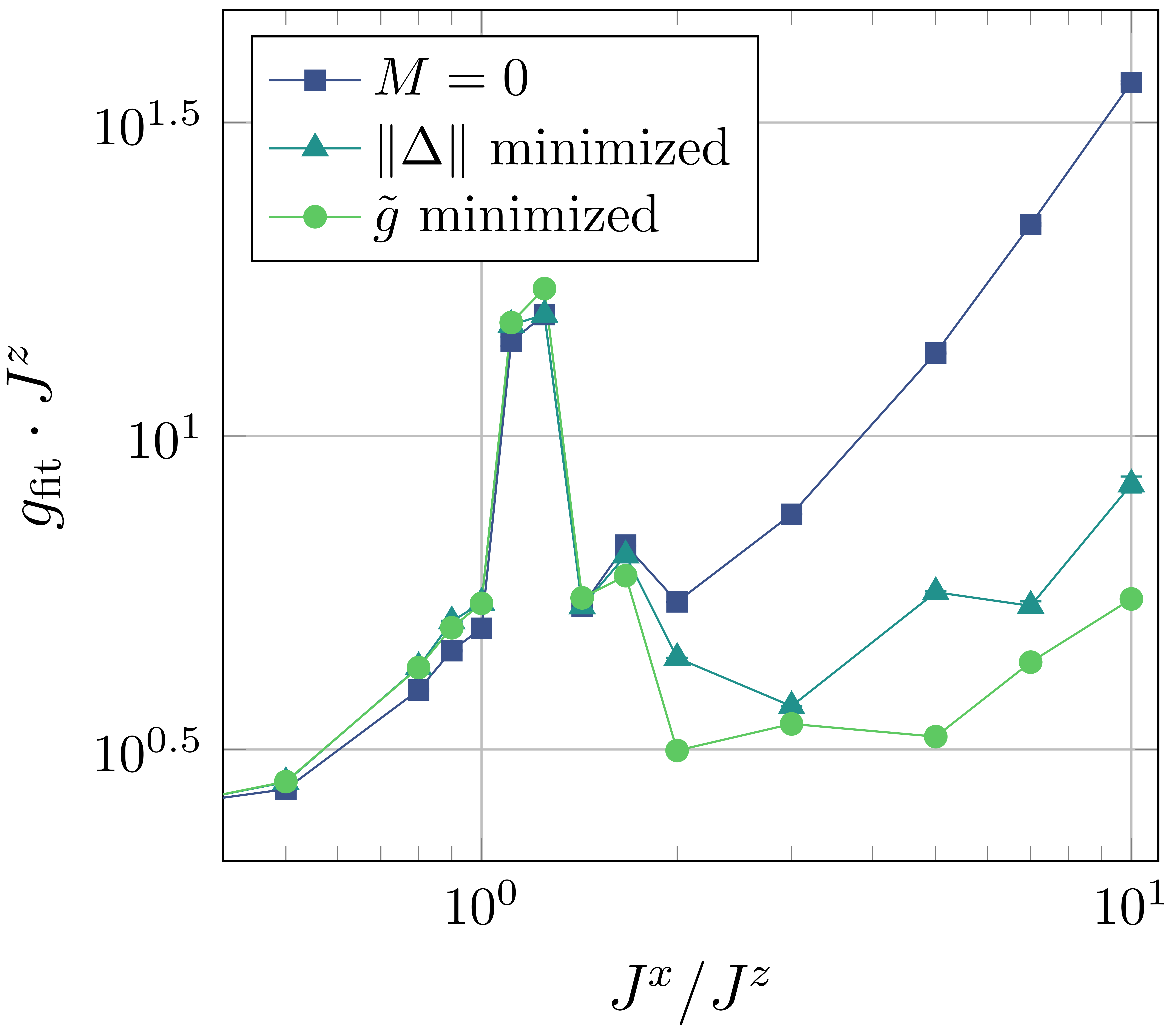


10^0
10^{-1}
10^{-2}
10^{-3}
ϵ_{AP}
$1D$ Chain
$M = 0$
$\|\Delta\|$ minimized
$\tilde{g}$ minimized
0
2
4
6
8
10
12
14
$\tau \cdot J^z$

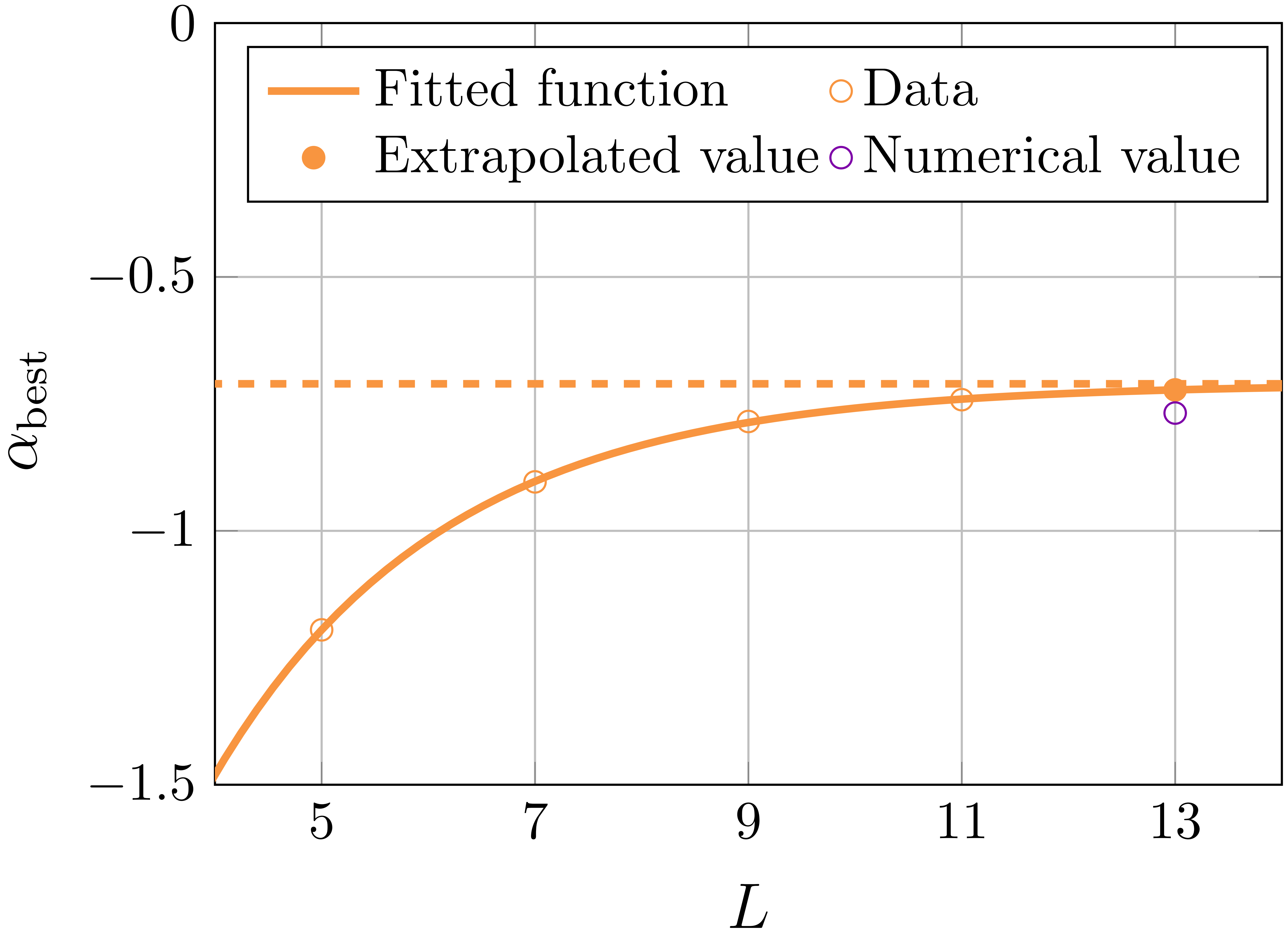


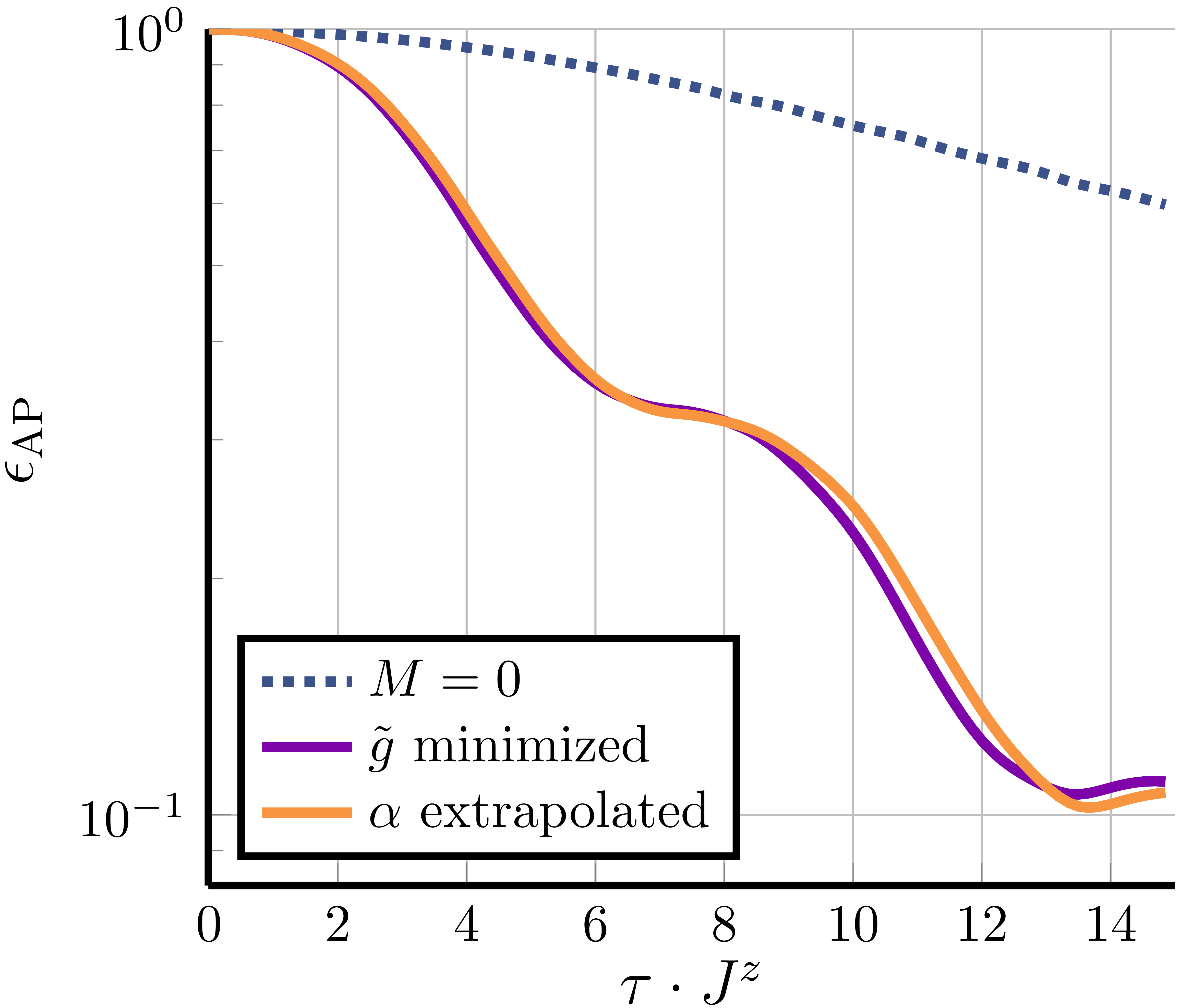
10^0
10^{-1}
10^{-2}
10^{-3}
ϵ_{AP}
$2D$ Lattice
$M = 0$
$\|\Delta\|$ minimized
$\tilde{g}$ minimized
0
2
4
6
8
10
12
14
$\tau \cdot J^z$



$M = 0$
$\|\Delta\|$ minimized
$\tilde{g}$ minimized
$10^{1.5}$
10^{1}
$10^{0.5}$
10^{0}
10^{1}
$g_{\text{fit}} \cdot J^z$
J^x / J^z

A possible approach: extrapolation





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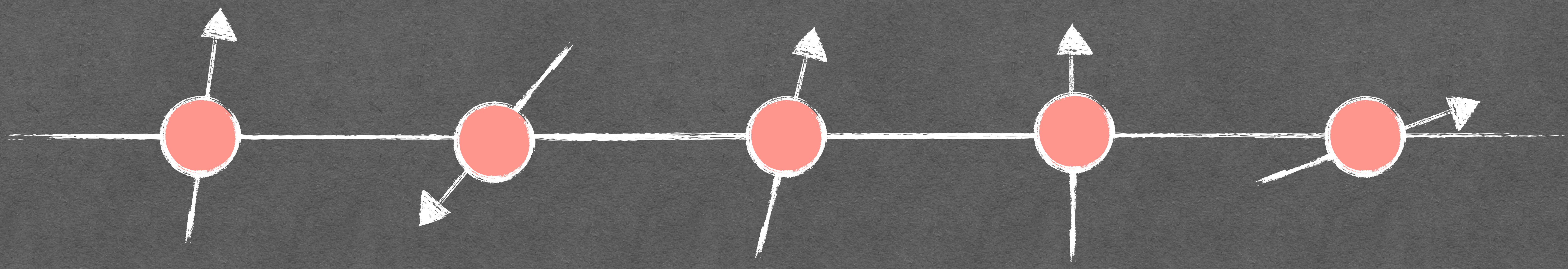

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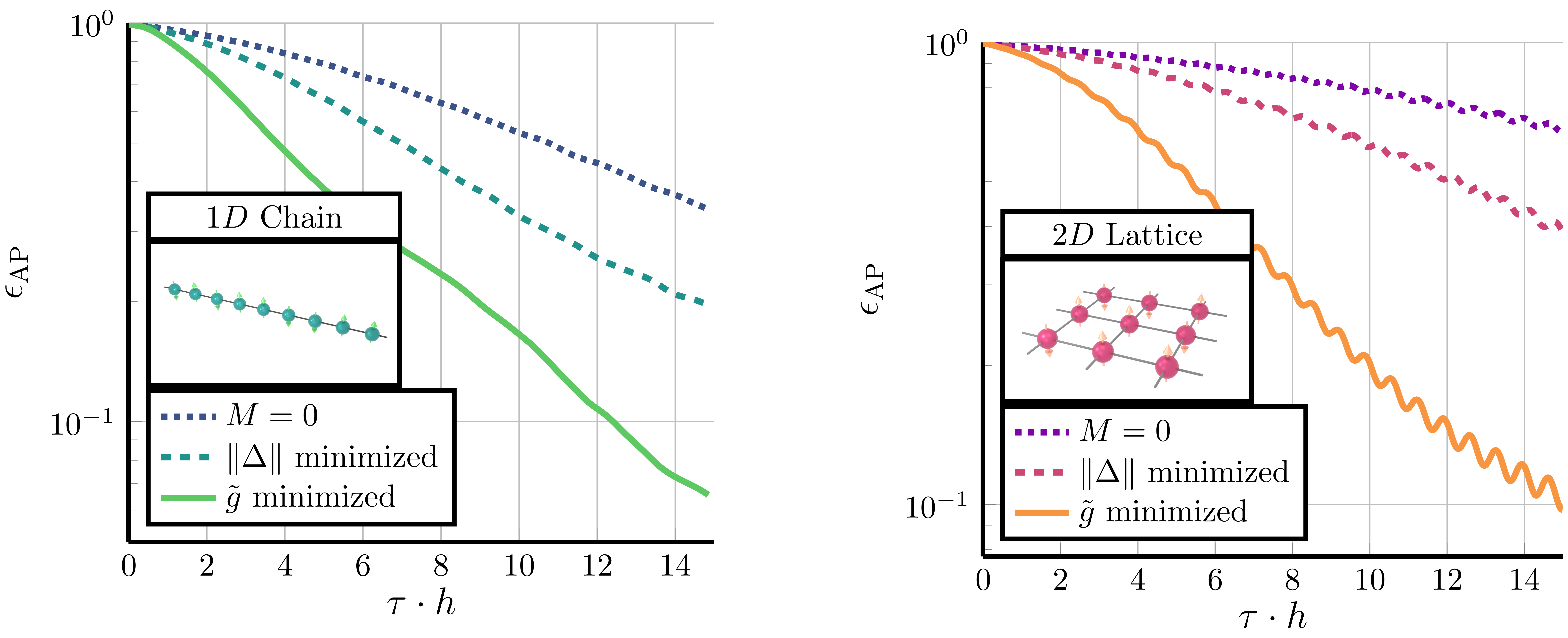
$$H_0 = -\frac{h}{2}\sum_i Z_i + \alpha\Sigma_i\left(Z_i\right)$$

$J^x = 5h$



10^0
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1D Chain
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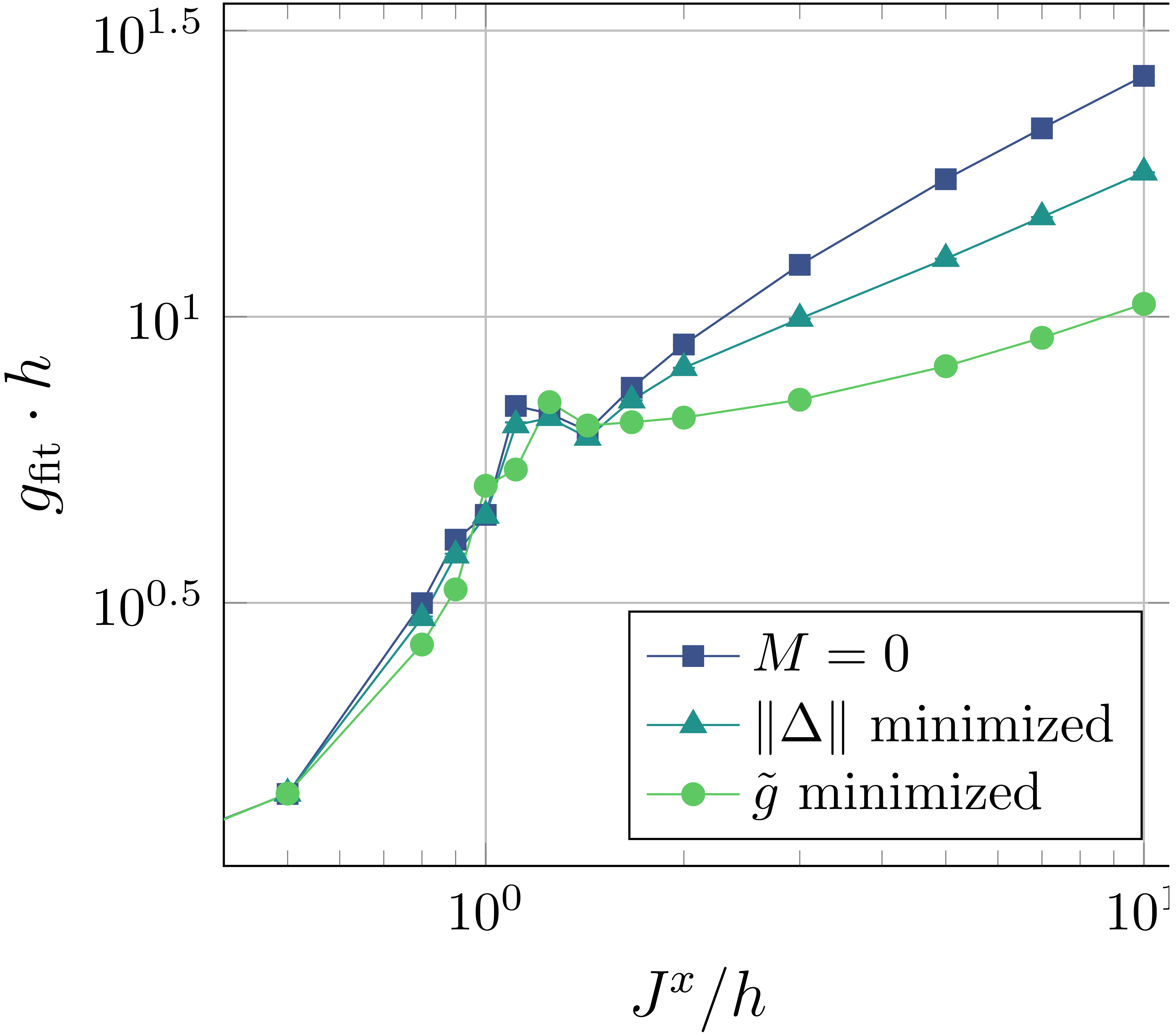
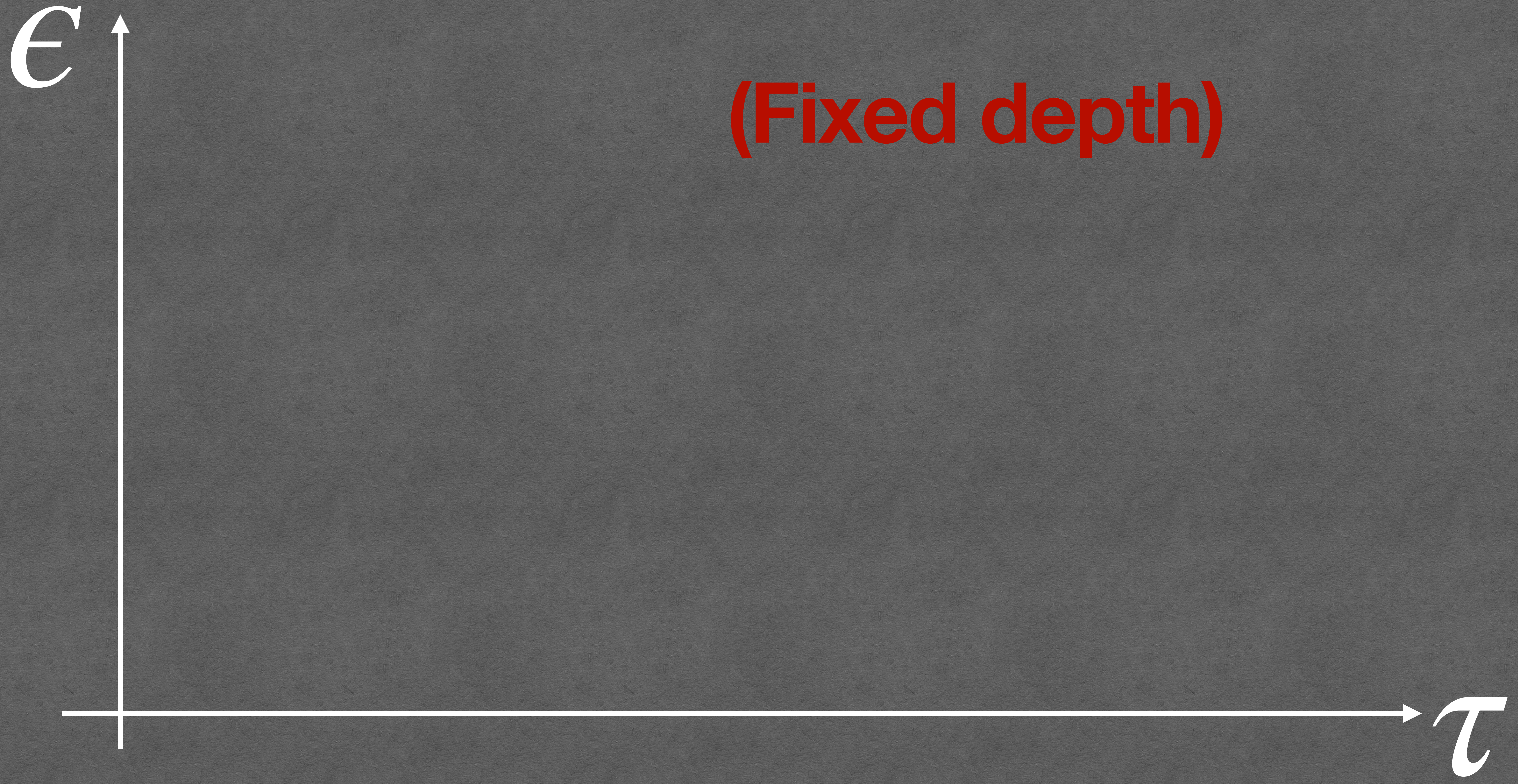
$\|\Delta\|$ minimized
$\tilde{g}$ minimized
0 2 4 6 8 10 12 14
$\tau \cdot h$
10^0
10^{-1}
ϵ_{AP}
2D Lattice
$M = 0$
$\|\Delta\|$ minimized
$\tilde{g}$ minimized
0 2 4 6 8 10 12 14
$\tau \cdot h$

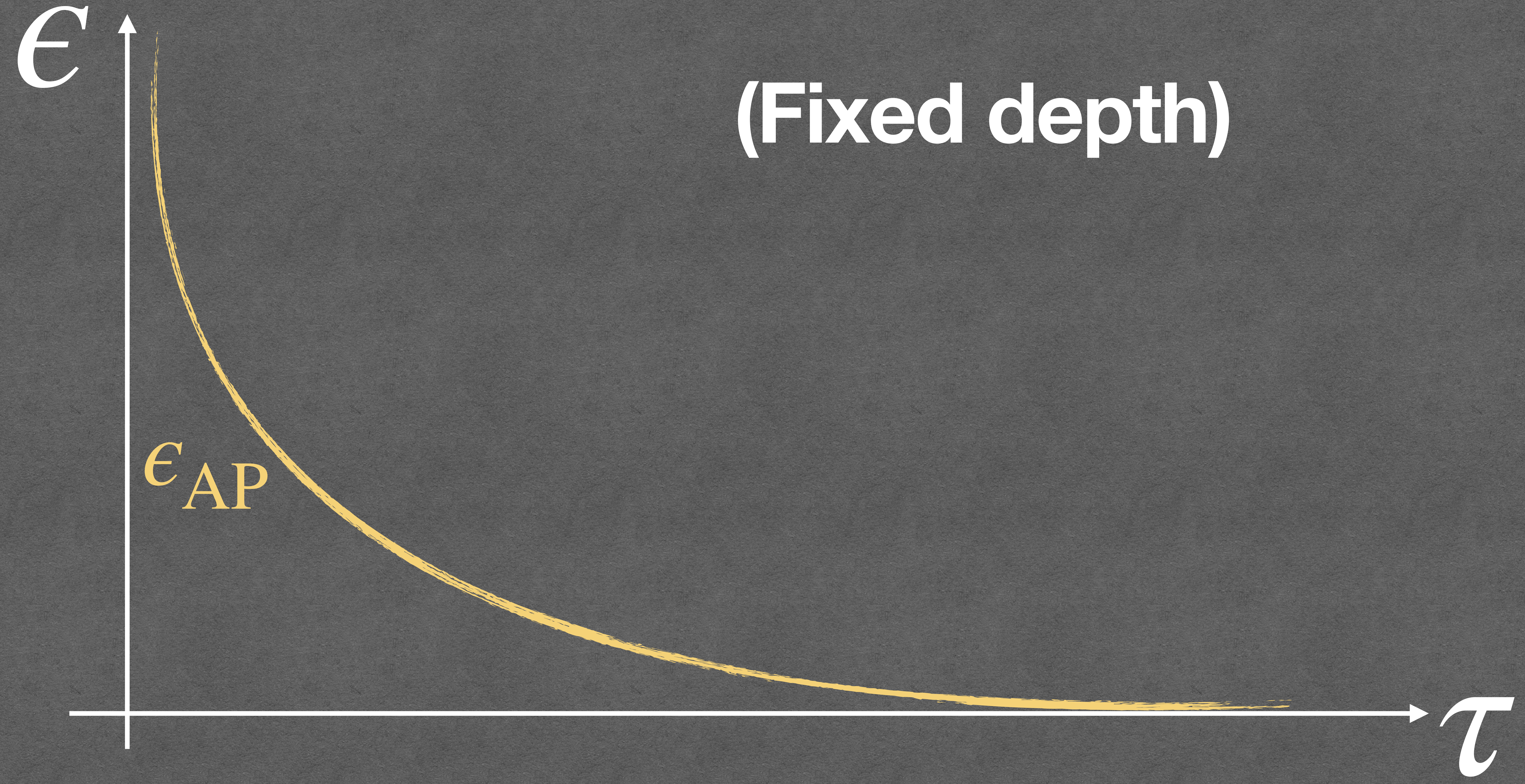


$10^{1.5}$
10^{1}
$10^{0.5}$
$g_{\text{fit}} \cdot h$
10^{0}
10^{1}
J^x/h
$M = 0$
$\|\Delta\|$ minimized
$\tilde{g}$ minimized

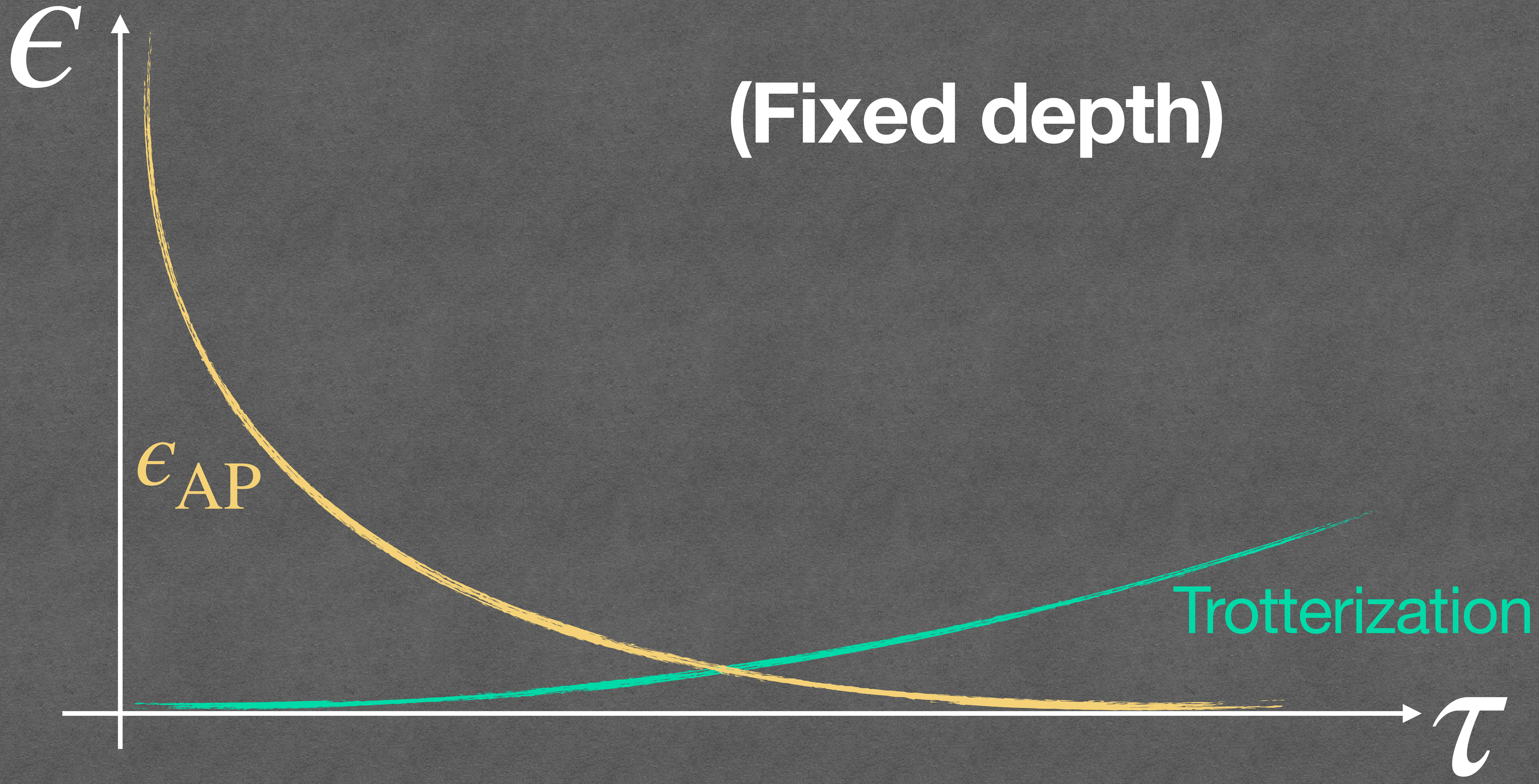
Adiabatic Preparation Error



Adiabatic Preparation Error

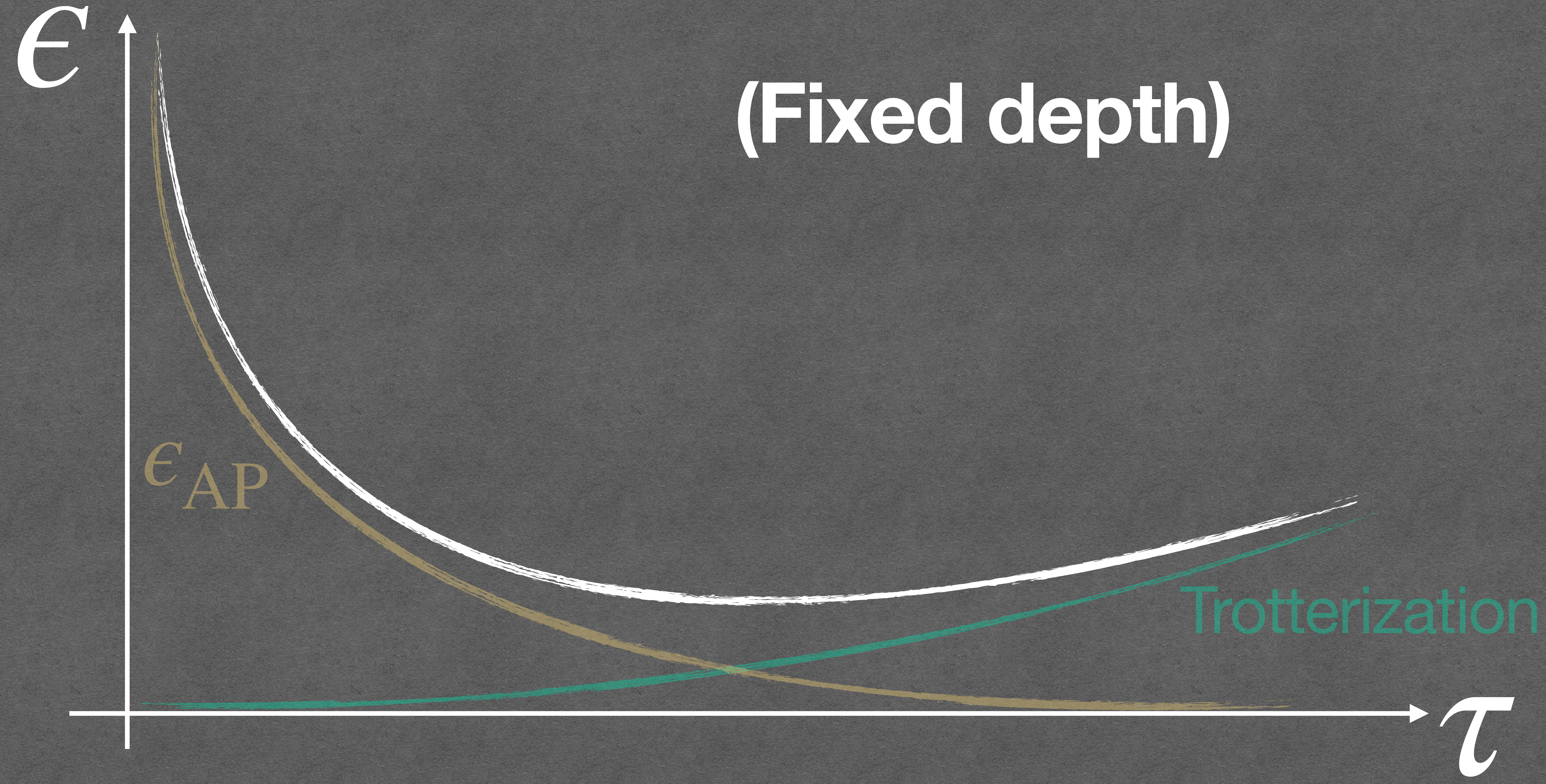


Adiabatic Preparation Error



Adiabatic Preparation Error

(Fixed depth)



Adiabatic Preparation Error