Title: Dissipative State Preparation and the Dissipative Quantum Eigensolver

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Abstract: Finding ground states of quantum many-body systems is one of the most important---and one of the most notoriously difficult---problems in physics, both in scientific research and in practical applications. Indeed, we know from a complexity-theoretic perspective that all methods (quantum or classical) must necessarily fail to find the ground state efficiently in general. The ground state energy problem is already NP-hard even for classical, frustration-free, local Hamiltonians with constant spectral gap. For general quantum Hamiltonians, the problem becomes QMA-hard.

Nonetheless, as ground state problems are of such importance, and classical algorithms are often successful despite the theoretical exponential worst-case complexity, a number of quantum algorithms for the ground state problem have been proposed and studied. From quantum phase estimation-based methods, to adiabatic state preparation, to dissipative state engineering, to the variation quantum eigensolver (VQE), to quantum/probabilistic imaginary-time evolution (QITE/PITE).

Dissipative state engineering was first introduced in 2009 by Verstraete, Cirac and Wolf and by Kraus et al. However, it only works for the restricted class of frustration-free Hamiltonians.

In this talk, I will show how to construct a dissipative state preparation dynamics that provably produces the correct ground state for arbitrary Hamiltonians, including frustrated ones. This leads to a new quantum algorithm for preparing ground states: the Dissipative Quantum Eigensolver (DQE). DQE has a number of interesting advantages over previous ground state preparation algorithms:

o The entire algorithm consists simply of iterating the same set of simple local measurements repeatedly.
o The expected overlap with the ground state increases monotonically with the length of time this process is allowed to run.
o It converges to the ground state subspace unconditionally, without any assumptions on or prior information about the Hamiltonian (such as spectral gap or ground state energy bound).
o The algorithm does not require any variational optimisation over parameters.
o It is often able to find the ground state in low circuit depth in practice.
o It has a simple implementation on certain types of quantum hardware, in particular photonic quantum computers.
o It is immune to errors in the initial state.
o It is inherently fault-resilient, without incurring any fault-tolerance overhead. I.e.\ not only is it resilient to errors on the quantum state, but also to faulty implementations of the algorithm itself; the overlap of the output with the ground state subspace degrades smoothly with the error rate, independent of the total run-time.

I give a mathematically rigorous analysis of the DQE algorithm and proofs of all the above properties, using non-commutative generalisations of methods from classical probability theory.

Zoom link https://pitp.zoom.us/j/96022753460?pwd=SWlUVkVta1RyY3dsWUJWckRqOHdNdz09

PHASECRAFT

Dissipative Ground State Preparation & the Dissipative Quantum Eigensolver

Toby Cubitt

[arXiv: 2303.11962]

THE QUANTUM ALGORITHMS COMPANY

UCL

PHASECRAFT

Ashley Montanaro

John Morton

Toby Cubitt

- Intro & Background
- AGSPs
- Conditionally stopped process
- Epsilon schedules
- Fault-resilience

main

- Resampling strategies
- Optimal stopping
- Fixed-point process

bonus

- Conclusions & Outlook

Ground State Problem

<u>Input:</u>

(Description of) k-local Hamiltonian

$$H = \sum_{i=1}^{m} h_i \qquad h_i \text{ k-local}$$

<u>Output:</u>

$$H|\psi_0\rangle = \lambda_{min}|\psi_0\rangle$$

$$|\tilde{\psi}\rangle \quad \text{s.t.} \quad \| |\tilde{\psi}\rangle - |\psi_0\rangle \| \leq \varepsilon$$

Ground State Problem

Input:

(Description of) k-local Hamiltonian

$$H = \sum_{i=1}^{m} h_i \qquad h_i \text{ k-local}$$

Output:

$$H \Pi_0 = \lambda_{min} \Pi_0$$

$$\tilde{\rho} \quad \text{s.t.} \quad \mathrm{tr}(\Pi_0 \tilde{\rho}) \geq 1 - \varepsilon$$

Ground State Problem

QMA - hard $\longrightarrow$ exponential time even on quantum computer

Physical assumptions on H do <u>not</u> make ground state problem easy:

- Frustration-free
- Constant spectral gap
- Commuting local terms
- Polynomial density of states

$\longrightarrow$ still NP-hard.

Algorithm	Adiabatic	QPE	i-time	VQE
No conditions on H				✓
Provably succeeds		✓	✓	
Low-depth in practice				✓
No parameter optimisation	✓	✓	✓	
Efficient to generate multiple copies				✓
Convenient implementation				✓
Insensitive to initial state				
Noise- and fault-resilient				

Algorithm	Adiabatic	QPE	i-time	VQE	Dissipative
No conditions on H				✓	
Provably succeeds		✓	✓		✓
Low-depth in practice				✓	
No parameter optimisation	✓	✓	✓		✓
Efficient to generate multiple copies				✓	
Convenient implementation				✓	✓
Insensitive to initial state					✓
Noise- and fault-resilient					✓[1]

Dissipative state engineering & quantum computation

Dissipative...

- ground state engineering
- MPS / PEPS / stabilizer state engineering
- Quantum computation

[VWC '09]

Dissipative state engineering & quantum computation

Dissipative...

- ground state engineering

  → exp-time

[VWC '09]

Dissipative state engineering

Def. Frustration-free

$$H = \sum_i h_i \qquad H|\psi_0\rangle = \lambda_{min}(H)\,|\psi_0\rangle$$

$$h_i|\psi_0\rangle = \lambda_{min}(h_i)\,|\psi_0\rangle$$

For H frustration-free:

$$H = \sum_i h_i \longrightarrow H = \sum_i \Pi_i \quad \text{w.l.o.g.}$$

Dissipative state engineering

$$H = \sum_{i=1}^{m} \Pi_i \qquad n \text{ qubits}, \quad \dim = 2^n =: D$$

$$\mathcal{E}(\rho) = \frac{1}{m} \sum_{i=1}^{m} \left(\Pi_i \rho \Pi_i + (1 - \mathrm{tr}(\Pi_i \rho)) \, \mathbb{1}/D \right)$$

1. Pick random $i \in \{1, \ldots, m\}$
2. Measure $\{\Pi_i, \Pi_i^{\perp}\}$
3. On $\Pi_i^{\perp}$ outcome, replace state with maximally-mixed state

Dissipative state engineering

$$H = \sum_{i=1}^{m} \Pi_i \qquad n \text{ qubits}, \quad \dim = 2^n =: D$$

$$\mathcal{E}(\rho) = \frac{1}{m} \sum_{i=1}^{m} \left(\Pi_i \rho \Pi_i + (1 - \mathrm{tr}(\Pi_i \rho)) \mathbb{1}/D \right)$$

1. Pick random $i \in \{1, \dots, m\}$
2. Measure $\{\Pi_i, \Pi_i^\perp\}$ $\longrightarrow \mathrm{tr}(\mathcal{E}^\infty(\rho)\Pi_0) = 1$
3. On $\Pi_i^\perp$ outcome, replace state with maximally-mixed state

Dissipative state engineering

Advantages:

- Simple, local procedure
- Succeeds independent of initial state
- Succeeds even if state hit by errors during computation (but only proven for error rate = 0)

Dissipative state engineering

Advantages:

- Simple, local procedure
- Succeeds independent of initial state
- Succeeds even if state hit by errors during computation (but only proven for error rate $= 0$)

Disadvantages:

- Only works for frustration-free H
- (Exp-time)

Algorithm	Adiabatic	QPE	i-time	VQE	Dissipative	DQE
No conditions on H				✓		✓
Provably succeeds		✓	✓		✓	✓
Low-depth in practice				✓		✓
No parameter optimisation	✓	✓	✓		✓	✓
Efficient to generate multiple copies				✓		
Convenient implementation				✓	✓	✓
Insensitive to initial state					✓	✓
Noise- and fault-resilient					✓[1]	✓

Dissipative Quantum Eigensolver

Advantages:

- Simple, local procedure
- Works for <u>any</u> H
- Does not require knowledge of properties of H
- Fault-resilient (without any overhead)

Disadvantages:

- (Exp-time)

Dissipative Quantum Eigensolver

Two new ingredients:

1. Use weak measurements rather than projective.

2. Make use of information from measurement outcomes.

- Intro & Background
- AGSPs
- Conditionally stopped process
- Epsilon schedules
- Fault-resilience

main

- Resampling strategies
- Optimal stopping
- Fixed-point process

bonus

- Conclusions & Outlook

Approximate Ground State Projectors

Def. AGSP

K Hermitian is $(\Delta, \Gamma, \varepsilon)$-AGSP for Π_0 if

(i) $[K, \Pi] = 0$

(ii) $K\Pi \geq \sqrt{\Gamma}\,\Pi$

(iii) $K\Pi^{\perp} \leq \sqrt{\Delta}\,\Pi$

(iv) $\| \Pi - \Pi_0 \| \leq \varepsilon$

(cf. [AKLV '13])

Approximate Ground State Projectors

$$H = \sum_{i=1}^{m} h_i \quad , \qquad H\,\Pi_0 = \lambda_{min}\,\Pi_0$$

<u>Lem.</u>

$$K = \prod_{i=1}^{m} \left((1-\varepsilon)\mathbb{1} + \varepsilon \kappa_i k_i \right) \prod_{i=m}^{1} \left((1-\varepsilon)\mathbb{1} + \varepsilon \kappa_i k_i \right)$$

is a $(\Gamma, \Delta, O(\varepsilon^2))$ - AGSP for Π_0, where

$$k_i = \tfrac{1}{2}\left(\mathbb{1} - h_i / \|h_i\|\right) \ , \quad \kappa = \sum_i \|h_i\| \ , \quad \kappa_i = \|h_i\| / \kappa$$

$$\Gamma = (1-\varepsilon)^{2m-1}\left(1 - \varepsilon\lambda_1/\kappa\right) + O(\varepsilon^2)$$

$$\Delta = (1-\varepsilon)^{2m-1}\left(1 - \varepsilon\lambda_0/\kappa\right) - O(\varepsilon^2)$$

Approximate Ground State Projectors

AGSP K can be implemented by local measurements.

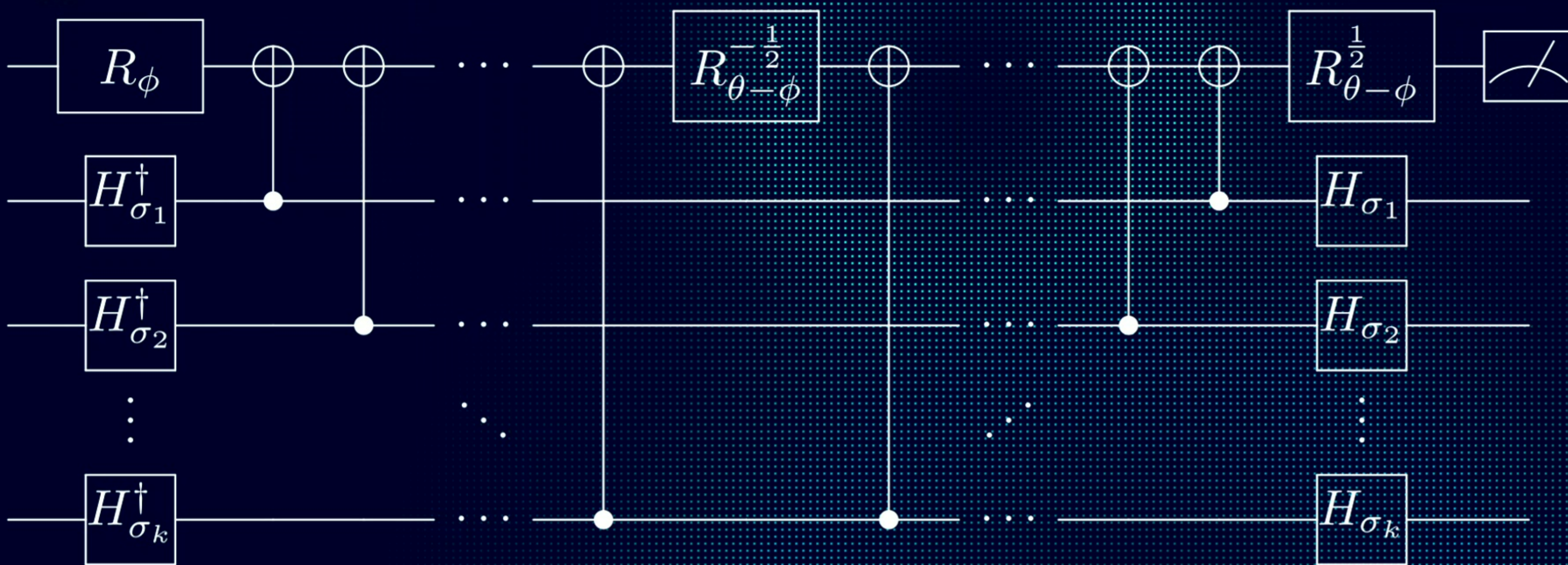
$$K = \prod_{i=1}^{m} \left((1-\varepsilon)\mathbb{1} + \varepsilon k_i k_i \right) \prod_{i=m}^{1} \big(\underbrace{(1-\varepsilon)\mathbb{1} + \varepsilon k_i k_i}_{K_i} \big)$$

$$= \prod_{i=1}^{m} K_i \prod_{i=m}^{1} K_i$$

Weak-measure each (suitably normalised) local term in Hamiltonian in turn

$\longrightarrow K$ if obtain all "$(1-\varepsilon)\mathbb{1} + \varepsilon k_i k_i$" outcomes.

Approximate Ground State Projectors



Weak-measurement of $h_i = \sigma_1 \otimes \sigma_2 \otimes \cdots \otimes \sigma_k$

$\theta = \cos^{-1}(1-\varepsilon)$, $\phi = \cos^{-1}(1-\varepsilon(1-k_i))$

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Conditionally stopped process

Quantum instrument $\{ \mathcal{E}_0, \mathcal{E}_1 \}$

$$\mathcal{E}_0(\rho) = K \rho K^\dagger, \qquad \mathcal{E}_1(\rho) = \left(1 - \mathrm{tr}(K\rho K^\dagger)\right) \mathbb{1}/D$$

Iterate instrument starting from $\rho = \mathbb{1}/D$ until obtain n "0"s $\longrightarrow \rho_n$.

Thm.

$$\mathrm{tr}(\Pi_0 \rho_n) \geq 1 - \varepsilon - \frac{D}{N}\left(\frac{\Delta}{\Gamma}\right)^n$$

$D :=$ total dim., $N := \mathrm{tr}\, \Pi_0 =$ g.s. degeneracy

Conditionally stopped process

Thm.

$$\mathrm{tr}(\Pi_0 \rho_n) \geq 1 - \varepsilon - \frac{D}{N}\left(\frac{\Delta}{\Gamma}\right)^n$$

Pf.

Recall $[K, \Pi] = 0$, $\|\Pi - \Pi_0\| \leq \varepsilon$ (Def. AGSP)

$$\mathrm{tr}(\Pi K^n \rho K^n) = \mathrm{tr}((K\Pi)^n \rho (K\Pi)^n) \geq \Gamma^n \mathrm{tr}\, \Pi\rho.$$

Similarly, $\mathrm{tr}(\Pi^\perp K^n \rho K^n) \leq \Delta^n (1 - \mathrm{tr}\, \Pi\rho)$.

Conditionally stopped process

$$\rho_n = \frac{\mathcal{E}_0^n(\rho)}{\operatorname{tr} \mathcal{E}_0^n(\rho)} = \frac{K^n \rho K^n}{\operatorname{tr}(K^n \rho K^n)}$$

$$\operatorname{tr}(\Pi \rho_n) = \frac{\operatorname{tr}(\Pi K^n \rho K^n)}{\operatorname{tr}(K^n \rho K^n)}$$

$$= 1 - \frac{\operatorname{tr}(\Pi^\perp K^n \rho K^n)}{\operatorname{tr}(\Pi K^n \rho K^n) + \operatorname{tr}(\Pi^\perp K^n \rho K^n)}$$

$$\geq 1 - \frac{\Delta^n (1 - \operatorname{tr} \Pi \rho)}{\Gamma^n \operatorname{tr} \Pi \rho}$$

by ineqs. shown before

Conditionally stopped process

$$\mathrm{tr}\, \Pi \rho_0 = \mathrm{tr}\, \Pi \, \mathbb{1}/D = N/D$$

$$\mathrm{tr}\, \Pi \rho_n \geq 1 - \frac{1 - \mathrm{tr}\, \Pi \rho_0}{\mathrm{tr}\, \Pi \rho_0} \left(\frac{\Delta}{\Gamma} \right)^n \geq 1 - \frac{D}{N} \left(\frac{\Delta}{\Gamma} \right)^n$$

$$\mathrm{tr}\, \Pi_0 \rho_n \geq \mathrm{tr}\, \Pi \rho - \varepsilon$$

$\| \Pi - \Pi_0 \| \leq \varepsilon$

Def. AGSP

$$= 1 - \varepsilon - \frac{D}{N} \left(\frac{\Delta}{\Gamma} \right)^n \quad \square$$

Conditionally stopped process

$$\mathcal{E}_0(\rho) = K\rho K^\dagger, \qquad \mathcal{E}_1(\rho) = (1-\mathrm{tr}(K\rho K^\dagger))\, \mathbb{1}/D$$

$\rho_0 = \mathbb{1}/D$, iterate until n "0"s.

Thm.

$\tau_n :=$ stopping time $=$ # iterations until run of n zeros

Expected stopping time:

$$\mathbb{E}(\tau_n) = \frac{1}{\mathrm{tr}(K^{2n})}\, \mathrm{tr}\left(\frac{1-K^{2n}}{1-K^2}\right) \leq \frac{1}{\Gamma^n}\left(n + \frac{1-\Delta^n}{1-\Delta}\left(\frac{D}{N}-1\right)\right)$$

Conditionally stopped process

<u>Pf.</u>

Imagine betting on sequence of 0/1 outcomes according to following strategy:

- At time step t, bet all winnings so far + additional £t on "0", at fair odds.
- Outcome "0" $\longrightarrow$ get back stake × odds.
- Outcome "1" $\longrightarrow$ lose entire stake.

Conditionally stopped process

Random vars $X_t :=$ t'th 0/1 outcome

$M_t :=$ net winnings at time t

$$M_0 = 0$$

$$M_t = \begin{cases} (M_{t-1} + t) \times \dfrac{1}{Pr(X_t = 0 \mid X_{t-1} X_{t-2} \cdots X_1)} & X_t = 0 \\ -t & X_t = 1 \end{cases}$$

Conditionally stopped process

Random vars $X_t :=$ t'th 0/1 outcome

$M_t :=$ net winnings at time t

$M_0 = 0$

$$M_t = \begin{cases} (M_{t-1} + t) \times \dfrac{1}{\Pr(X_t = 0 \mid X_{t-1} X_{t-2} \cdots X_1)} & X_t = 0 \\ -t & X_t = 1 \end{cases}$$

fair odds

Conditionally stopped process

$$\mathbb{E}(M_t \mid X_{t-1} \cdots X_1)$$

$$= Pr(0 \mid X_{t-1} \cdots X_1) \cdot \left(\frac{M_{t-1} + t}{Pr(0 \mid X_{t-1} \cdots X_1)} - t \right)$$

$$- Pr(1 \mid X_{t-1} \cdots X_1) \cdot t \qquad (\text{Def. } M_t)$$

$$= M_{t-1}$$

$\Rightarrow$ M_t is a Martingale wrt X_t. (fair odds)

$\Rightarrow$ $\mathbb{E}(M_{\tau_n})$ is also a Martingale (Doob's optional stopping Thm.)

Conditionally stopped process

$$\mathbb{E}(M_t \mid X_{t-1} \cdots X_1)$$

$$= \Pr(0 \mid X_{t-1} \cdots X_1) \cdot \left(\frac{M_{t-1} + t}{\Pr(0 \mid X_{t-1} \cdots X_1)} - t \right)$$

$$- \Pr(1 \mid X_{t-1} \cdots X_1) \cdot t \qquad (\text{Def. } M_t)$$

$$= M_{t-1}$$

$\Rightarrow$ M_t is a Martingale wrt X_t. (fair odds)

$\Rightarrow$ $\mathbb{E}(M_{\tau_n})$ is also a Martingale (Doob's optional stopping Thm.)

$\Rightarrow$ $\mathbb{E}(M_{\tau_n}) = \mathbb{E}(M_0)$

Conditionally stopped process

Reset state to $\mathbb{1}/D$ after a "1"

$\Rightarrow$ state at run of k "0"s is

$$\rho_k = \frac{K^k \, \mathbb{1}/D \, K^k}{\mathrm{tr}(\text{———})} = \frac{K^{2k}}{\mathrm{tr}(K^{2k})}$$

Conditionally stopped process

Reset state to $\mathbb{1}/D$ after a "1"

$\Rightarrow$ state at run of k "0"s is

$$\rho_k = \frac{K^k \, \mathbb{1}/D \, K^k}{\mathrm{tr}(\text{———})} = \frac{K^{2k}}{\mathrm{tr}(K^{2k})}$$

$$\Pr(0 \mid 0^k 1 \cdots) = \frac{\mathrm{tr}(K \rho_k K)}{\mathrm{tr}(K^{2k})}$$

Conditionally stopped process

$$M_{\tau_n - n} = -\tau_n + n$$

Just had run of n "0"s since last "1".

$$M_{\tau_n - k} = \frac{1}{Pr(010^{n-1}1\cdots)} \left(M_{\tau_n - k - 1} + \tau_n - k \right) - \tau_n + k$$

(Def. M_t)

$$Pr(010^k1\cdots) = \frac{tr(K^{2k+2})}{tr(K^{2k})}$$

(from previously)

Solve recurrence:

$$\Rightarrow M_{\tau_n} = \frac{1}{tr(K^{2n})} tr\left(\frac{1-K^{2n}}{1-K^2}\right) - \tau_n$$

Conditionally stopped process

$$\cancel{\mathbb{E}(M_{\tau_n})} = \frac{1}{\mathrm{tr}(K^{2n})}\,\mathrm{tr}\left(\frac{1-K^{2n}}{1-K^2}\right) - \mathbb{E}(\tau_n)$$

$\cancel{\mathbb{E}(M_{\tau_n})} = 0$ from previously

Conditionally stopped process

$$0 = \frac{1}{\mathrm{tr}(K^{2n})} \mathrm{tr}\left(\frac{1-K^{2n}}{1-K^2}\right) - \mathbb{E}(\tau_n)$$

Rearranging:

$$\mathbb{E}(\tau_n) = \frac{1}{\mathrm{tr}(K^{2n})} \mathrm{tr}\left(\frac{1-K^{2n}}{1-K^2}\right)$$

Conditionally stopped process

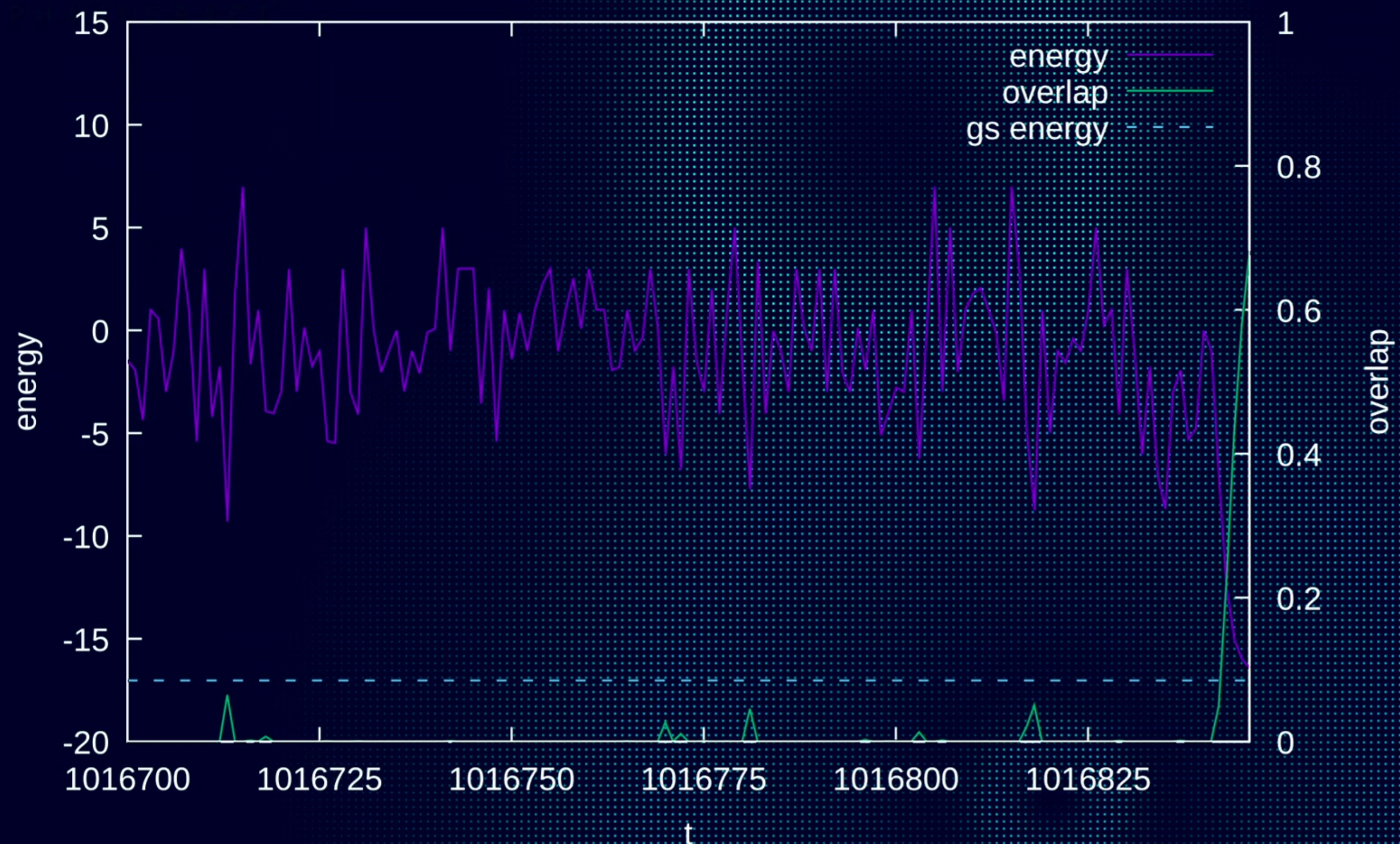
$$0 = \frac{1}{\mathrm{tr}(K^{2n})} \mathrm{tr}\left(\frac{1-K^{2n}}{1-K^2}\right) - \mathbb{E}(\tau_n)$$

Rearranging:

$$\mathbb{E}(\tau_n) = \frac{1}{\mathrm{tr}(K^{2n})} \mathrm{tr}\left(\frac{1-K^{2n}}{1-K^2}\right)$$

$$\leq \frac{1}{\Gamma^n}\left(n + \frac{1-\Delta^n}{1-\Delta}\left(\frac{D}{N}-1\right)\right) \quad \square$$

1D Heisenberg chain Length 10, n = 4



- Intro & Background
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main

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bonus

- Conclusions & Outlook

Epsilon Schedules

Thm.

$$\mathrm{tr}(\Pi_0 \rho_n) \geq 1 - \epsilon - \frac{D}{N}\left(\frac{\Delta}{\Gamma}\right)^n$$

$$\Gamma = (1-\epsilon)^{2m-1}\left(1 - \epsilon\lambda_1/k\right) + O(\epsilon^2)$$

$$\Delta = (1-\epsilon)^{2m-1}\left(1 - \epsilon\lambda_0/k\right) - O(\epsilon^2)$$

Epsilon Schedules

Solution: choose ϵ_t decreasing with t.

<u>Thm.</u>

$\{\mathcal{E}_0, \mathcal{E}_1\}$, stop after n "0"s

$$\epsilon_t = \frac{\epsilon_0}{t - t_1} \quad \text{where} \quad t_1 = \text{time of last "1"}$$

ρ_n = stopping state

$$\lim_{n \to \infty} \mathrm{tr}(\Pi_0 \rho_n) = 1.$$

Epsilon Schedules

Thm. $\lim_{n\to\infty} \mathrm{tr}(\Pi_0 \rho_n) = 1.$

harmonic series
is divergent
$\Rightarrow$ product convergen

Pf. (intuition)

- Once $\epsilon_t \ll \lambda_1 - \lambda_0 \longrightarrow$ convergence $\sim \prod_t \left(1-\frac{c}{t}\right) \to 0$

- Error accumulated up to that point

$$\sim \sum_t \frac{1}{t^2} \prod_{s=1}^{t} \left(1-\frac{c}{s}\right)^{-1} \leq e^{2c}\,\zeta(2(1-c)) = O(1).$$

Epsilon Schedules

Thm. $\lim_{n \to \infty} \mathrm{tr}(\Pi_0 \rho_n) = 1.$

harmonic series
is divergent
$\Rightarrow$ product convergent

Pf. (intuition)

- Once $\epsilon_t \ll \lambda_1 - \lambda_0 \longrightarrow$ convergence $\sim \prod_t \left(1 - \frac{c}{t}\right) \longrightarrow 0$

$(r, \Delta, O(\epsilon^2))$-AGSP

- Error accumulated up to that point

$$\sim \sum_t \frac{1}{t^2} \prod_{s=1}^{t} \left(1 - \frac{c}{s}\right)^{-1} \leq e^{2c}\, \zeta(2(1-c)) = O(1).$$

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Fault-Resilience

- What if errors occur during the process?
- What if the process itself is implemented using faulty operations?

Both possibilities encompassed by:

$$\{\mathcal{E}_0, \mathcal{E}_1\} \longrightarrow \{\mathcal{E}_0', \mathcal{E}_1'\}$$

$$\|\mathcal{E}_0' - \mathcal{E}_0\|_1, \|\mathcal{E}_1' - \mathcal{E}_1\|_1 \leq \delta$$

Fault - Resilience

Thm.

$\{\mathcal{E}_0', \mathcal{E}_1'\}$ s.t. $\|\mathcal{E}_0' - \mathcal{E}_0\| \leq \delta$

Iterate $\{\mathcal{E}_0', \mathcal{E}_1'\}$ until run of n "0"s.

ρ_n = stopping state.

$$\lim_{n\to\infty} \mathrm{tr}(\Pi_0 \rho_n) = 1 - O(\epsilon) + O(\delta)$$

Fault-Resilience

<u>Thm.</u> $\lim_{n\to\infty} \mathrm{tr}(\Pi_0 \rho_n) = 1 - O(\epsilon) + O(\delta)$

<u>Pf.</u> (hint)

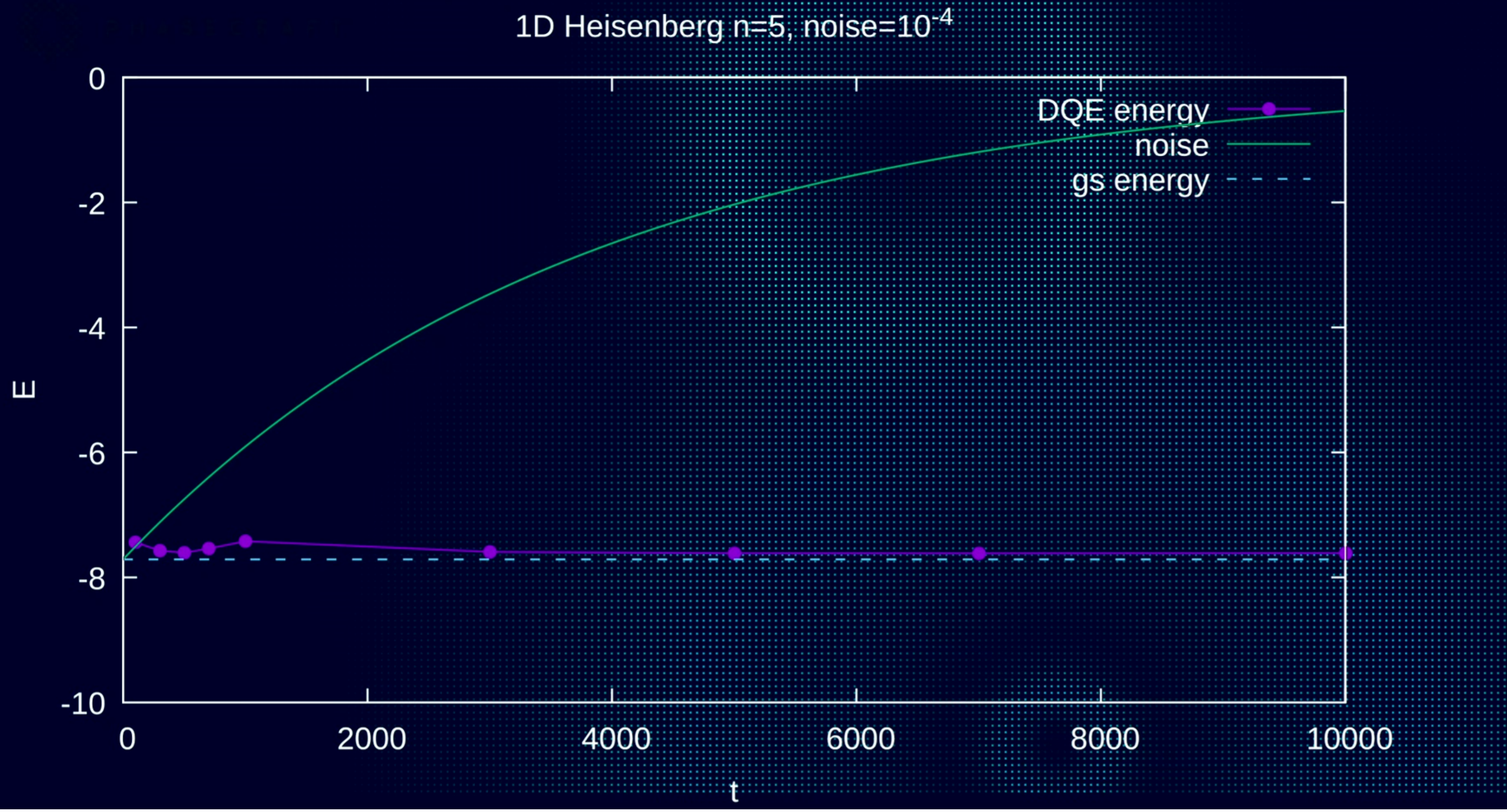
$\mathcal{E}_0^n(\rho) \equiv E_0^n |\rho\rangle\rangle$

Non-commutative Perron-Frobenius theory

+ Schur structure of transfer matrix

+ eigenspace perturbation theory

Fault - Resilience



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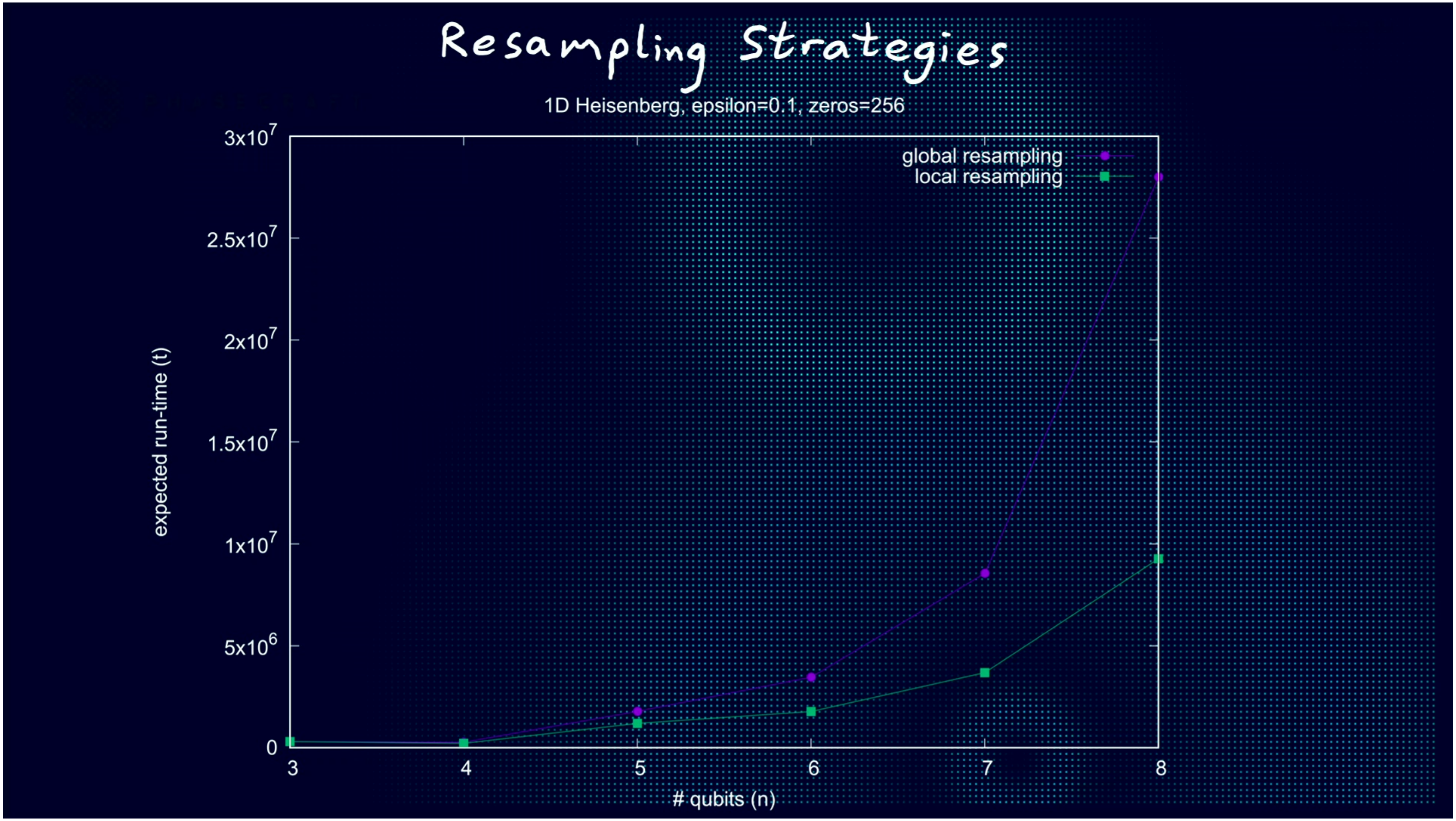
Resampling Strategies
1D Heisenberg, epsilon=0.1, zeros=256
global resampling
local resampling
expected run-time (t)
qubits (n)
3x10^7
2.5x10^7
2x10^7
1.5x10^7
1x10^7
5x10^6
0
3
4
5
6
7
8

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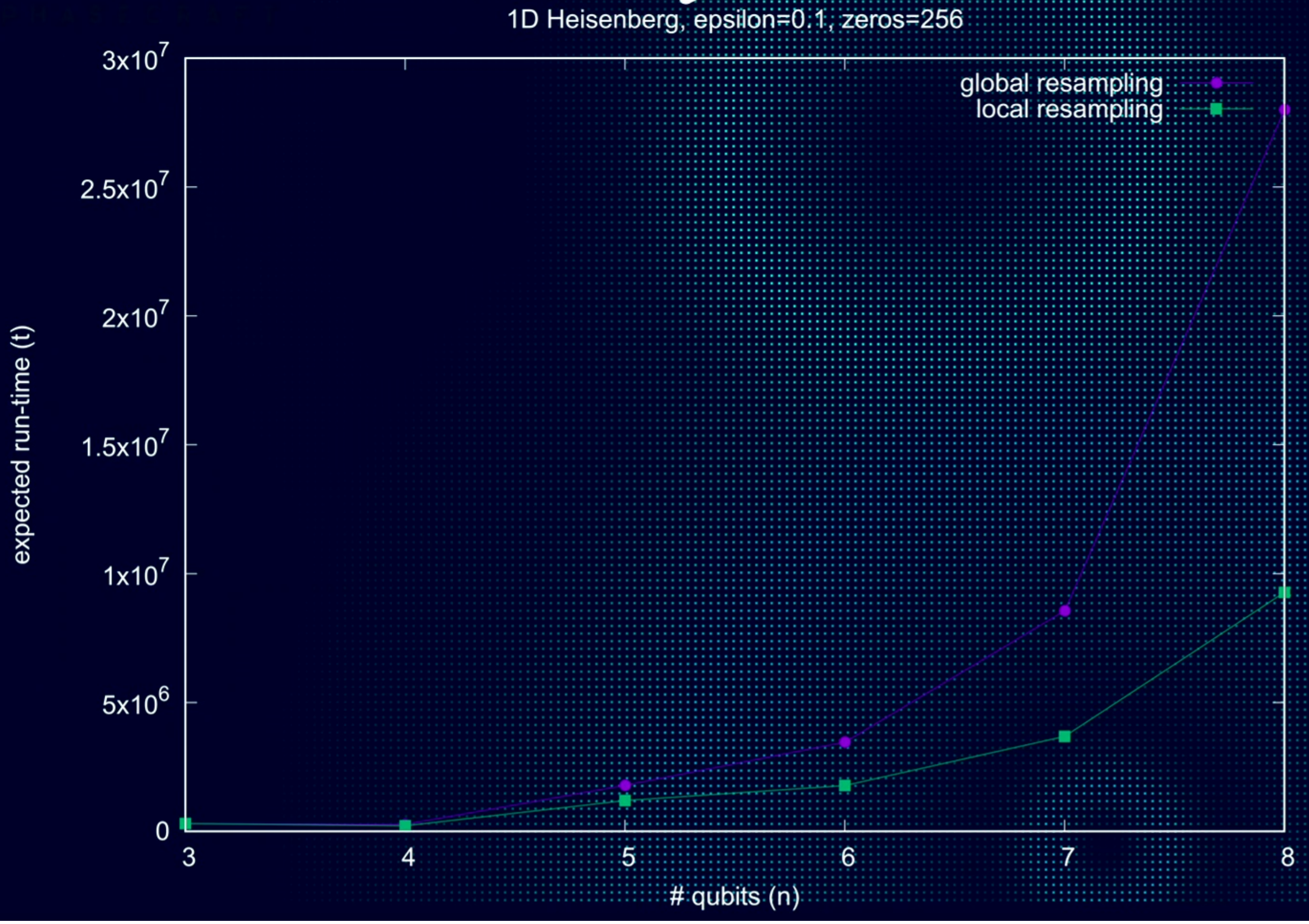
Resampling Strategies



Dissipative Gibbs Sampling

- Similar benefits to DQE : simple local procedure, fault-resilience, no complex q. subroutines required (no H. simulation, phase estimation, qubitization, etc.)

- Exact analytic expressions for run-time, no hard-to-analyse quanties (e.g. mixing times).

- Optimal(?) run-time scaling with precision.