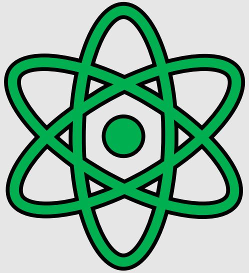
University of Exeter

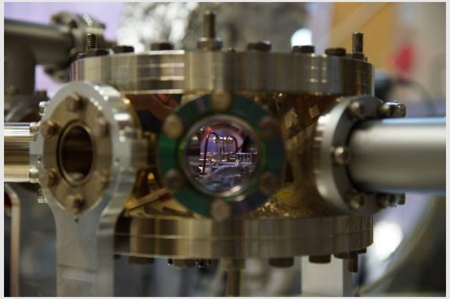
Simplifying quantum simulations

Many others and Luca Dellantonio
QuantHEP, London, 20/07/2026

What?

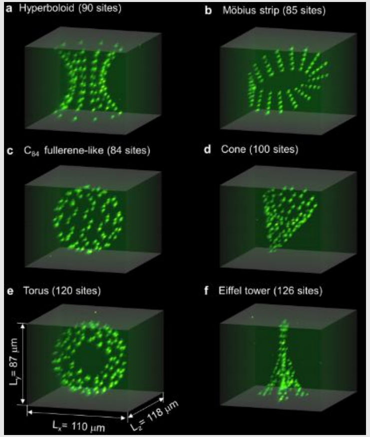


Hardware

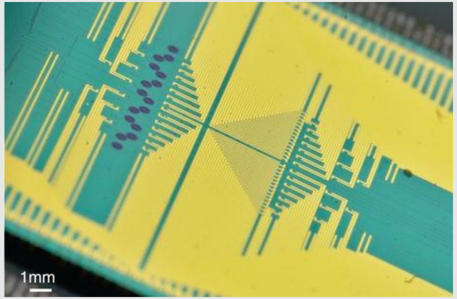


University of Innsbruck,
IonQ, ***Quantinuum***...

IBM, Fujitsu,
NPL, Google, Righetti,
Intel, Alibaba...

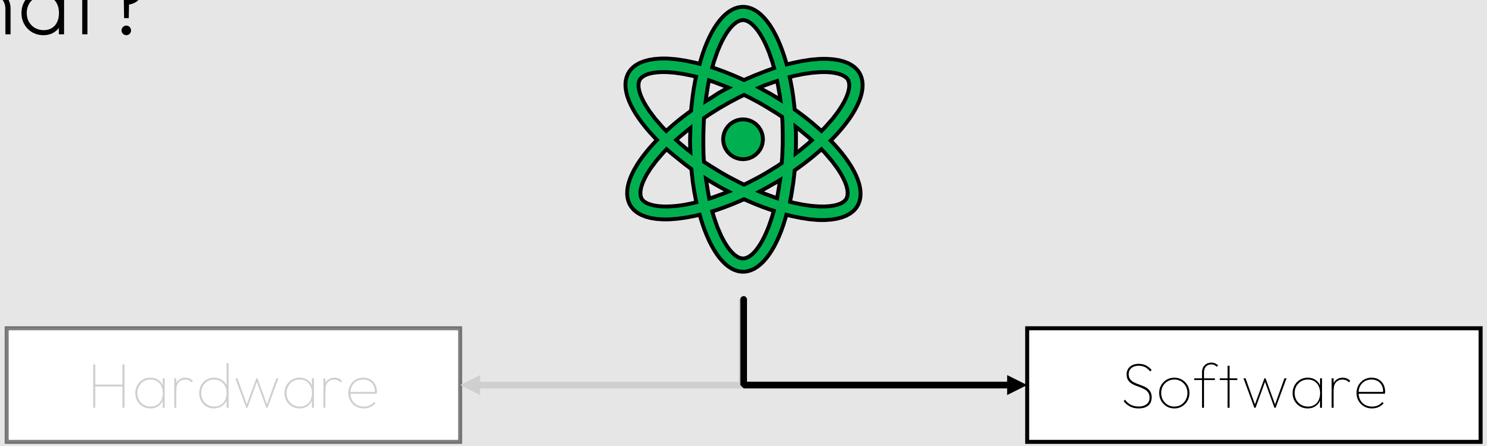


Pasqal, QuERA, ...



University of Bristol,
PsiQuantum, Orca,
Niels Bohr Institute...

What?



- Encoding a problem onto a q. comp [1, 2, 3, 4]
- Develop better languages [5, 6]
- Efficient measurement of q. observables [7, 8, 9]

[1] L. Gunderman, A. Jena, LD, Phys. Rev. A 109, 022618, (2024)
[2] C. Nation, R. Simon, S. Banerjee, F. Martini, A. Ricottone, F. Cerisola, LD, arXiv:2605.18966 (2026)
[3] C. Nation, R. Simon, S. Banerjee, F. Martini, A. Ricottone, F. Cerisola, LD, arXiv:2605.30428 (2026)
[4] S. Banerjee, V. Muthu, C. Nation, R. Simon, F. Martini, A. Ricottone, F. Cerisola, LD, arXiv:2605.30429 (2026)
[5] R. R. Ferguson, LD, A. A. Balushi, K. Jansen, W. Dür and C. Muschik, ***PRL,*** 126, 22, (2021)
[6] A. Chan, Z. Shi, L. Dellantonio, W. Duer, C. Muschik, ***PRL,*** 132, 240601, (2024)
[7] A. J. Jena, A., Schlosberg P. Mukhopadhyay, J. F. Haase, F. Leditzky and LD, Quantum 7, 903, (2023)
[8] R. Simon, Z. Shi, C. Nation, A. Jena, LD, arXiv:2509.01482 (2025)
[9] R. Simon, M. Meth, F. Martini, P. Tirler, A. Jena, M. Ringbauer, LD, arXiv:2605.00682 (2026)

Software

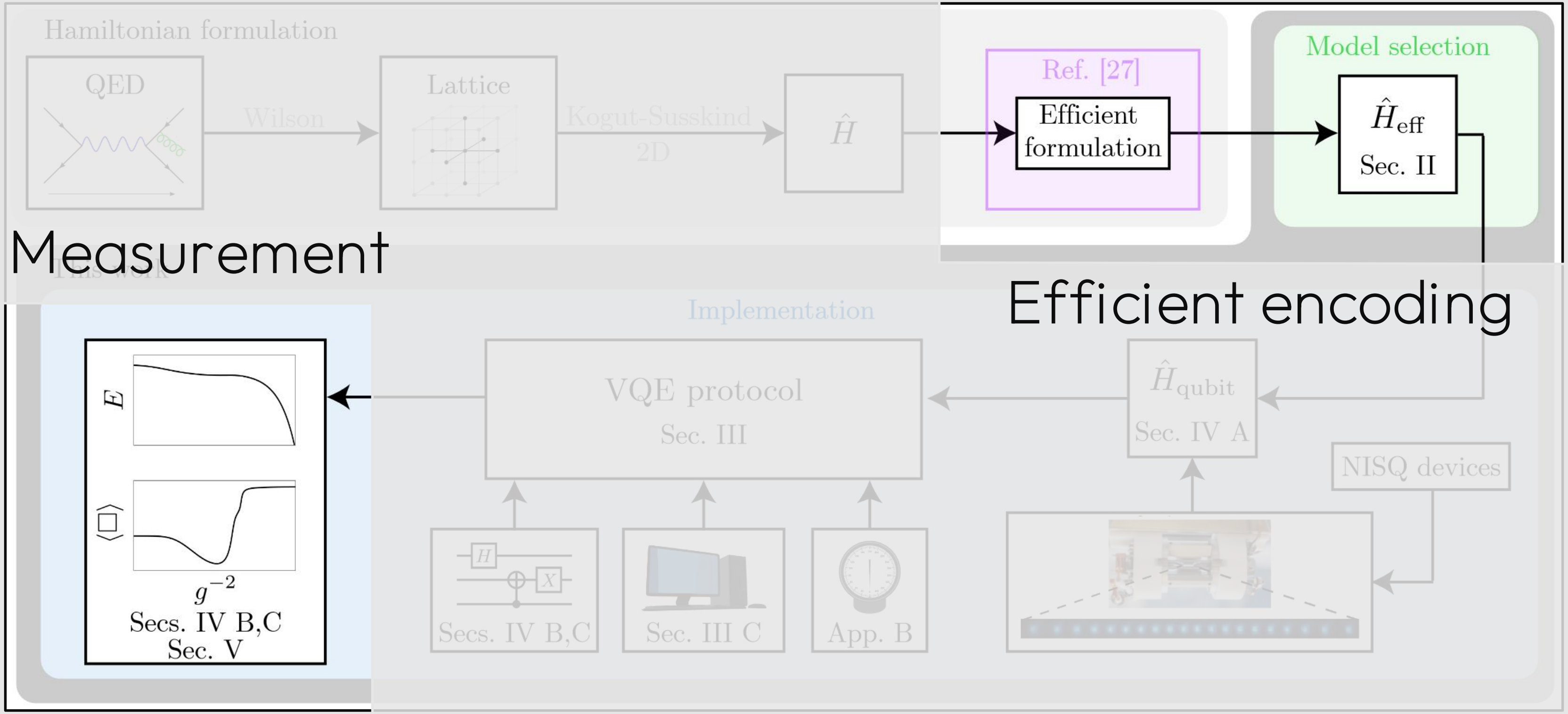


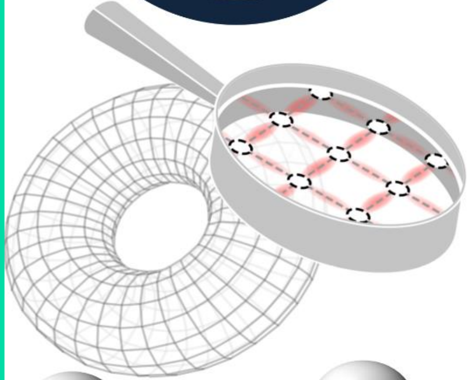
Image from D. Paulson*, LD*, J. F. Haase*, A. Celi*, A. Kan, A. Jena, C. Kokail, R. v. Bijnen, K. Jansen, P. Zoller and C. A. Muschik, ***PRX Quantum, 2***, 030334, 2021

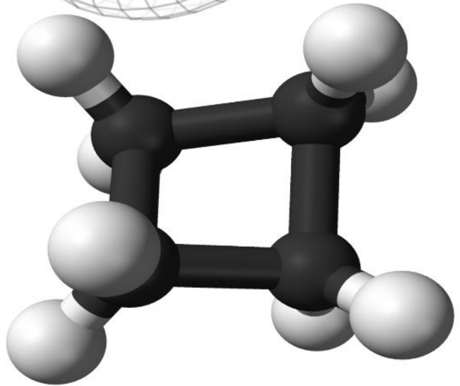
Efficient Encoding

More computational power

More symmetries needed

Too hard for HPC or Quantum





S. Bravyi et al., arXiv:1701.08213, (2017)
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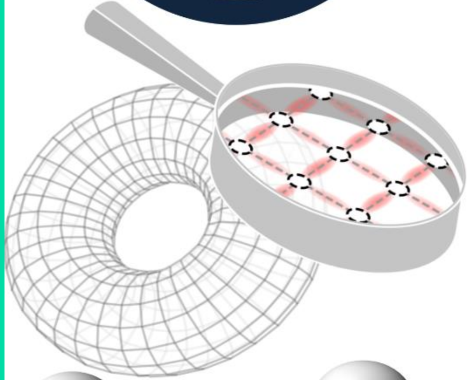
C. Nation et al., arXiv:2605.18966 (2026)
C. Nation et al., arXiv:2605.30428 (2026)
S. Banerjee et al., arXiv:2605.30429 (2026)

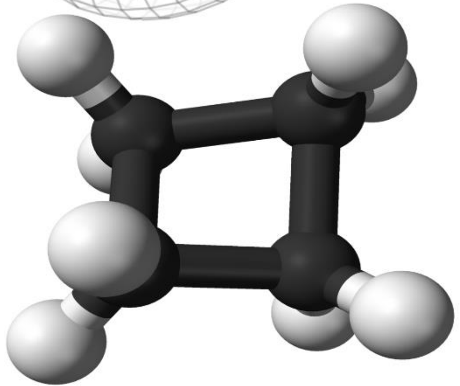
Efficient Encoding

More computational power

More symmetries ***exploited***

Solved with HPC or Quantum





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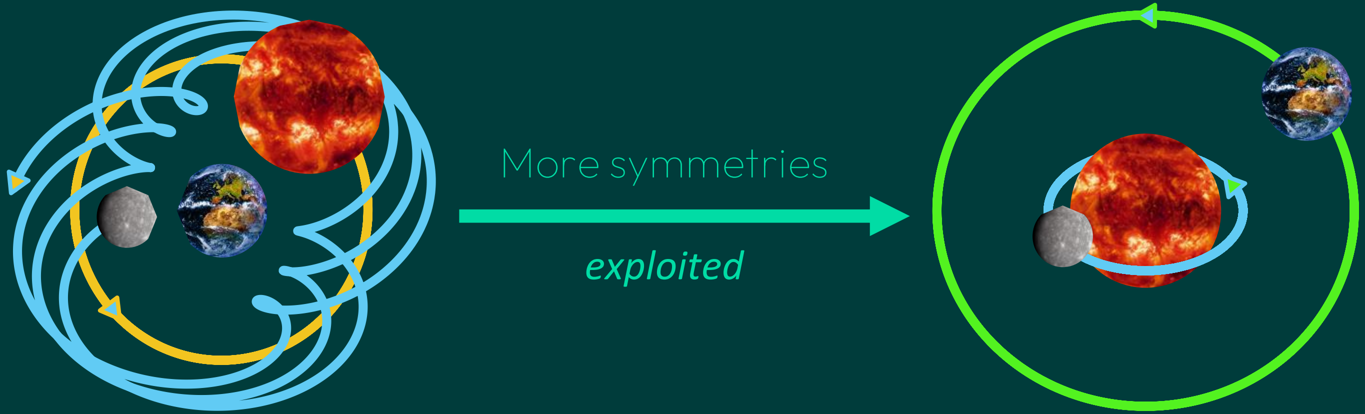
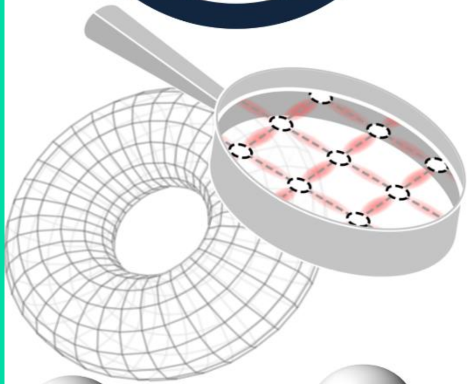
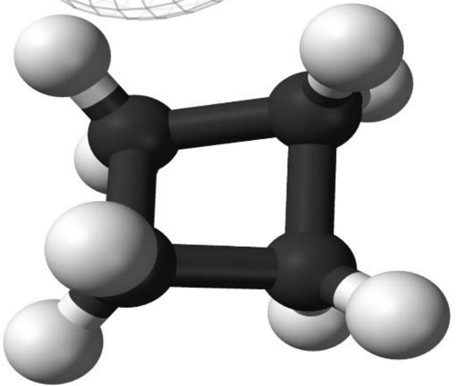
Efficient Encoding



- Quantum Inspired, Classically Efficient
- For Quantum and Classical Simulations
- Solidifies Quantum Advantage





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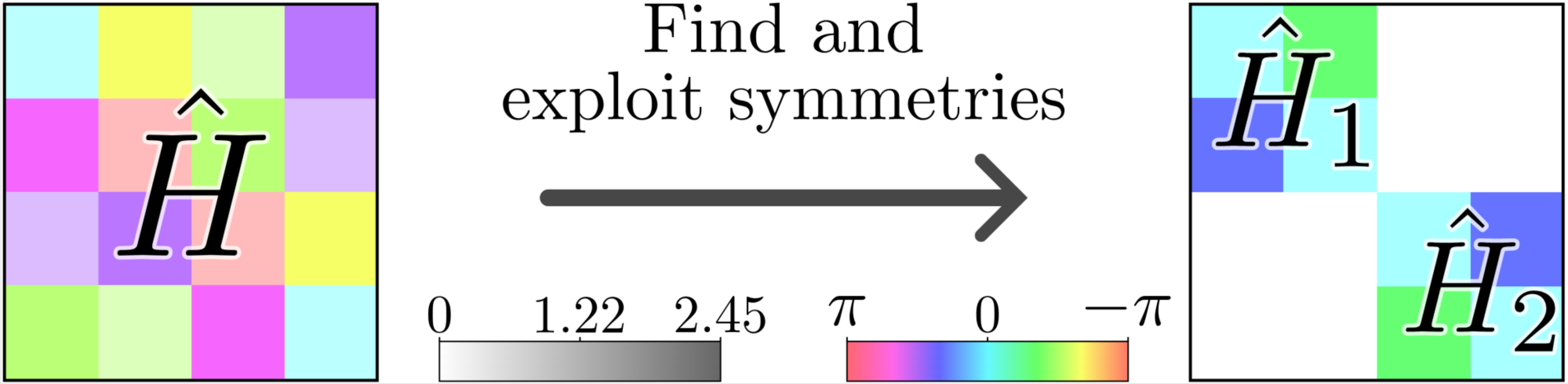

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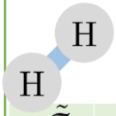
[4] S. Banerjee, V. Muthu, C. Nation, R. Simon, F. Martini, A. Ricottone, F. Cerisola, LD, arXiv:2605.30429 (2026)

Efficient Encoding

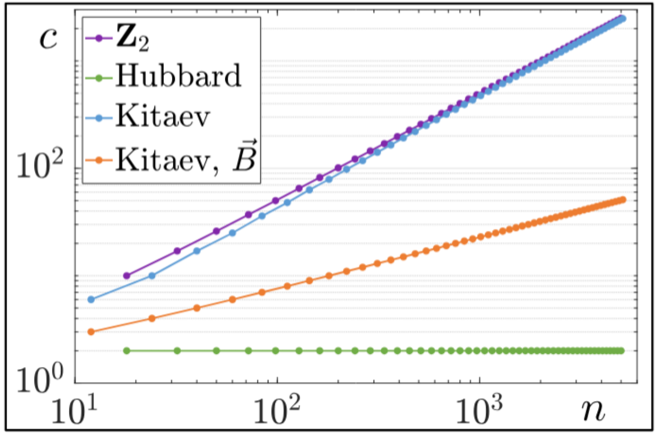
Pauli symmetries

Molecule	n	c
H_2	4	3
H_2	8	3
LiH	12	4
BeH_2	14	5
CH_4	18	3
C_2H_2	24	4
C_2H_4	28	5
C_2H_6	32	4

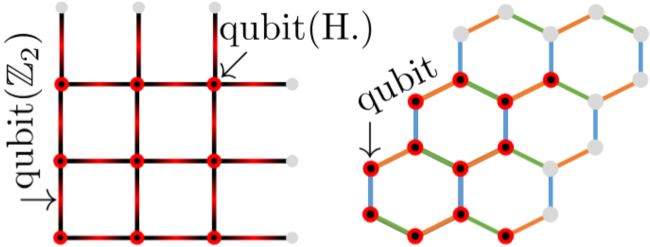


H_2, 6-31G
JW encoding

$\tilde{Z}_1$	$ZZZZIIII$
$\tilde{Z}_2$	$IIIIZZZZ$
$\tilde{Z}_3$	$IZIZIZIZ$



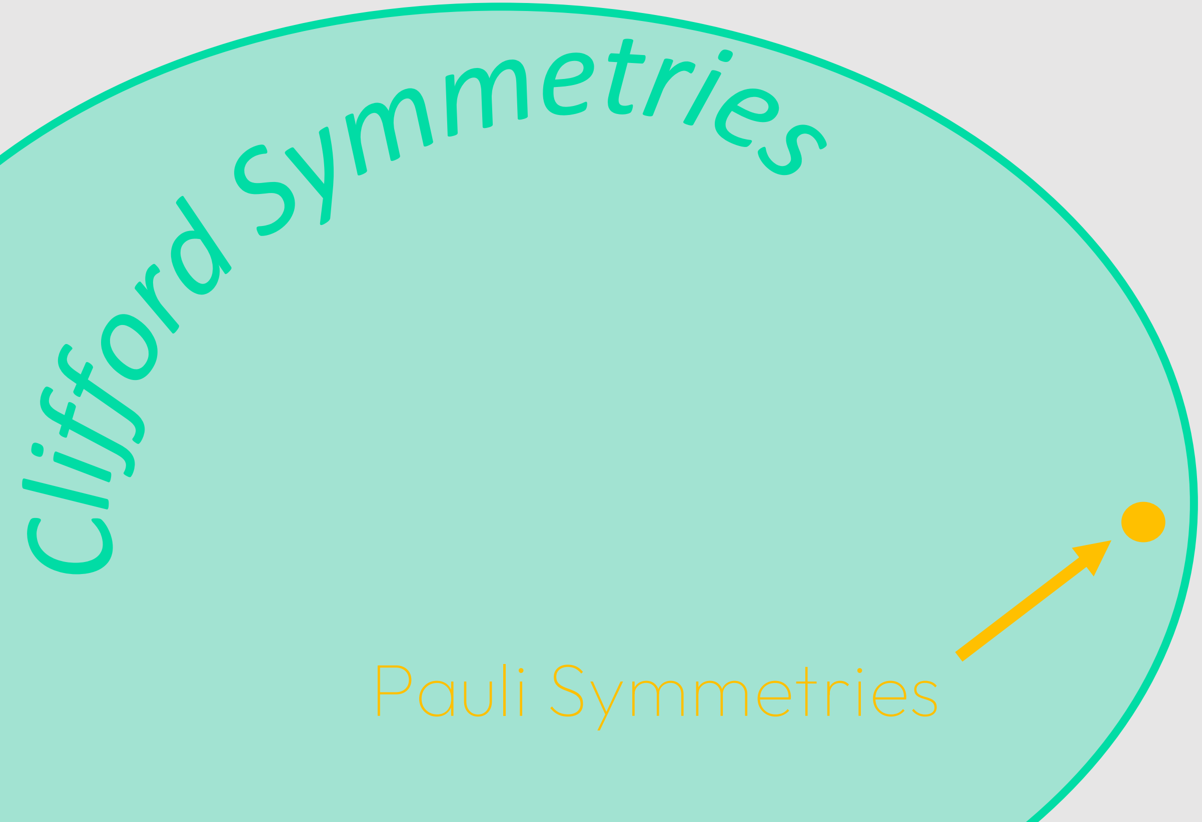
$\mathbb{Z}_2$ & Hubbard   Kitaev



- 5000+ qubits ✓
- Generalised to **quDits** ✓
- **Any** input Hamiltonian ✓
- **Exponential** advantage ✓
- (still exponentially hard)

[1] S. Bravyi, J. M. Gambetta, A. Mezzacapo, and K. Temme, arXiv:1701.08213, 2017
[2] Image from L. Gunderman, A. Jena, LD, and Phys. Rev. A 109, 022618, 2024

Efficient Encoding



- Permutations are Clifford
- Reflections are Clifford
- Rotations are Clifford
- $|GHZ\rangle$ «are Clifford»
- …

[2] C. Nation, R. Simon, S. Banerjee, F. Martini, A. Ricottone, F. Cerisola, LD, arXiv:2605.18966 (2026)
[3] C. Nation, R. Simon, S. Banerjee, F. Martini, A. Ricottone, F. Cerisola, LD, arXiv:2605.30428 (2026)
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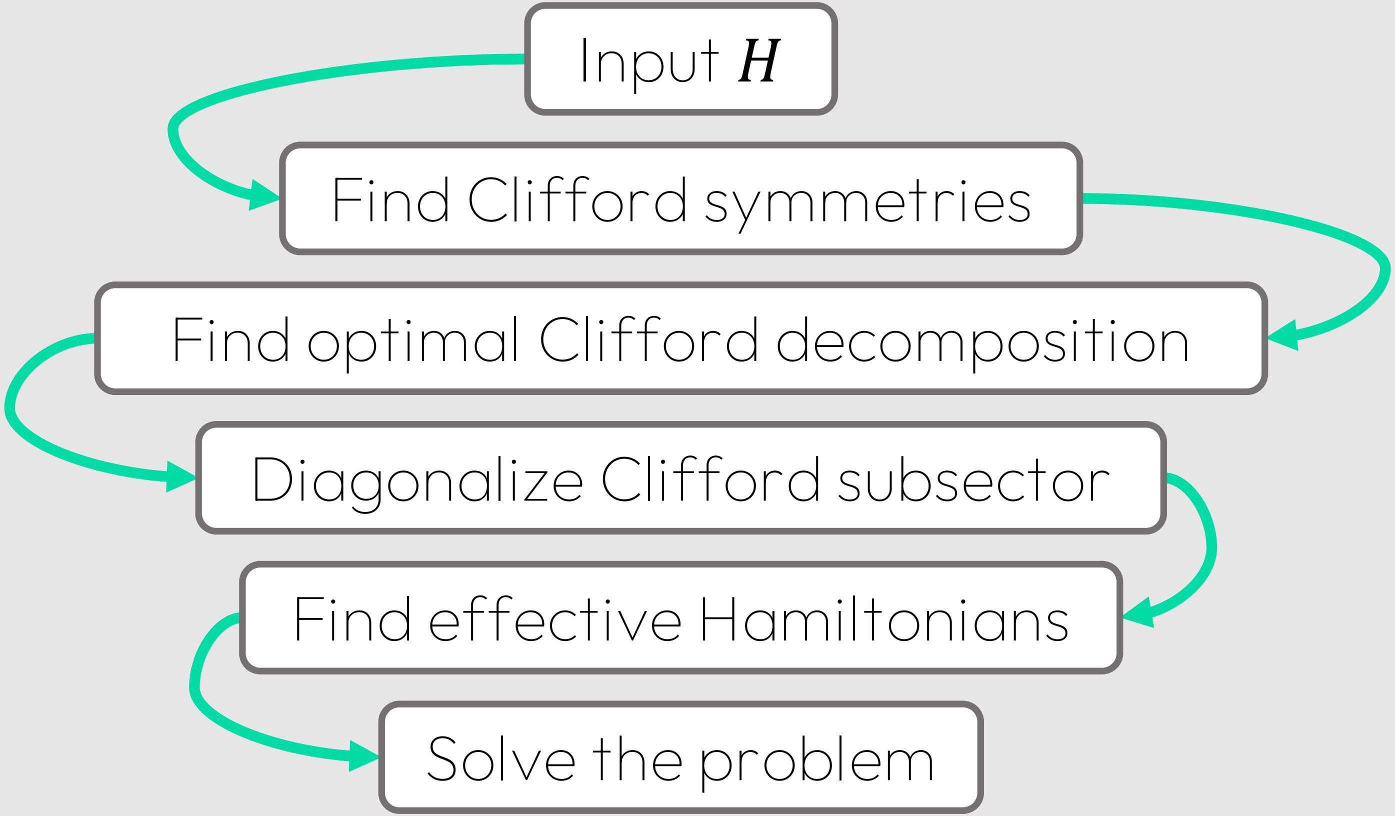

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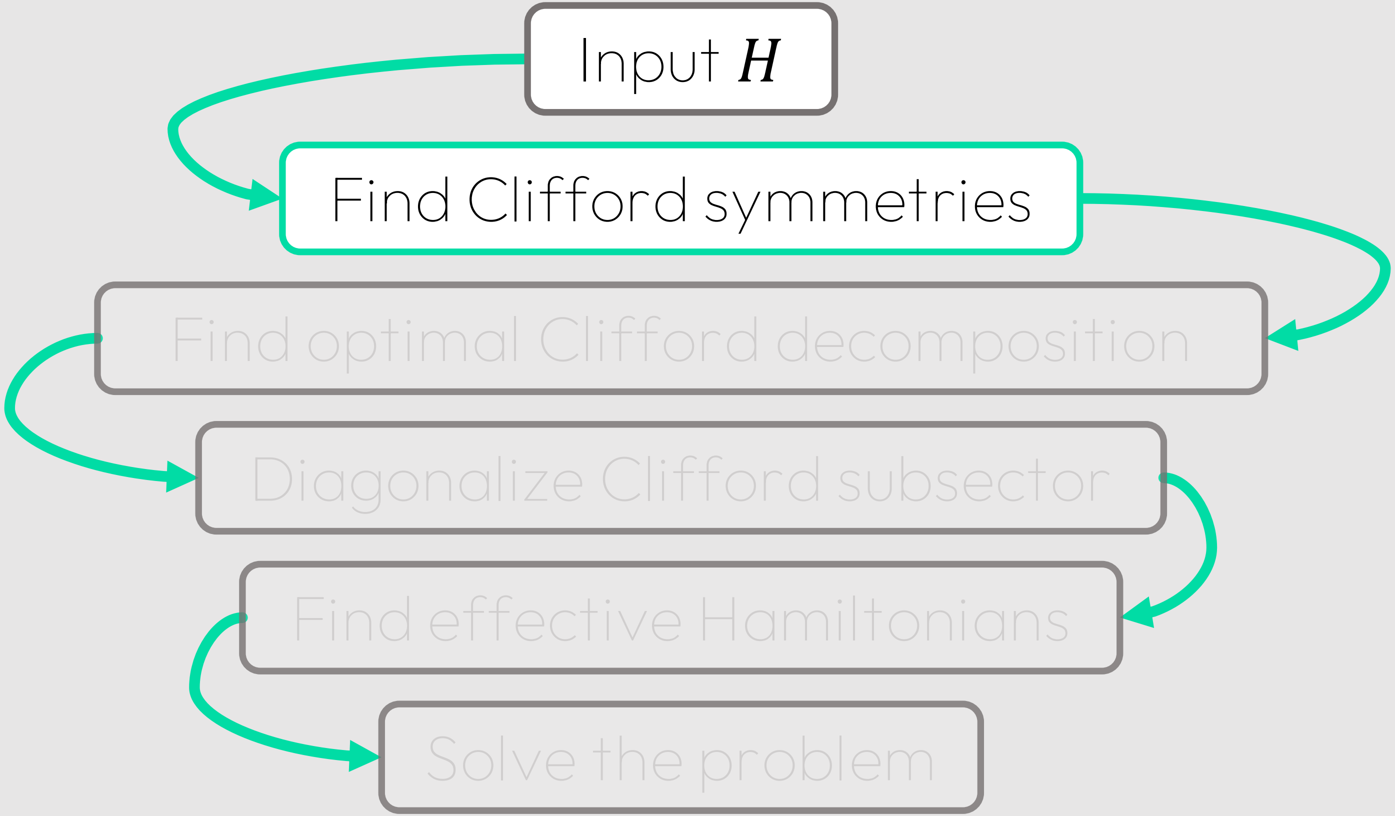
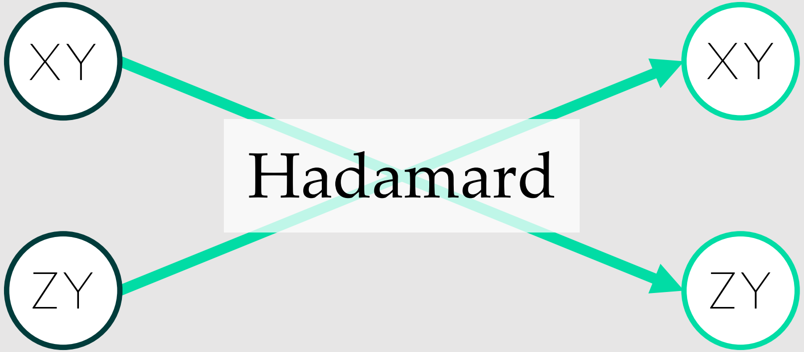
Efficient Encoding



[2] C. Nation et al., arXiv:2605.18966 (2026)
[3] C. Nation et al., arXiv:2605.30428 (2026)

Efficient Encoding

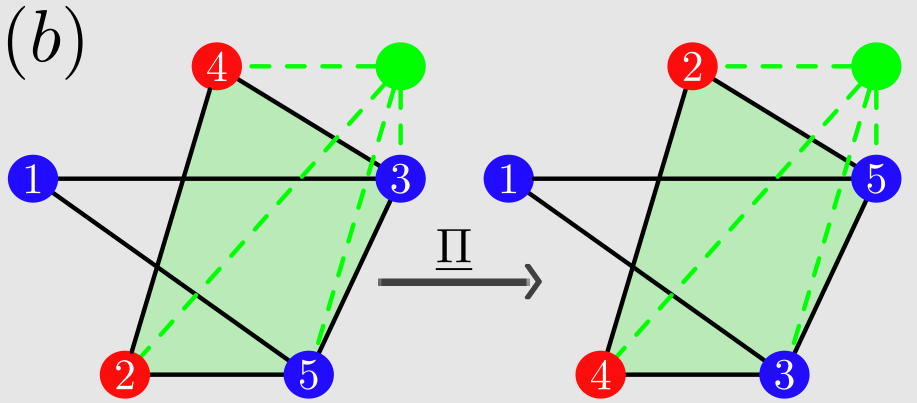
$$H = XY + ZY$$



[2] C. Nation et al., arXiv:2605.18966 (2026)
[3] C. Nation et al., arXiv:2605.30428 (2026)

Efficient Encoding

$$\hat{H} = c_1(\overset{1}{\hat{Y}_1\hat{Z}_2} + \overset{3}{\hat{Z}_1\hat{Z}_2} - \overset{5}{\hat{X}_2}) - c_2(\overset{2}{\hat{X}_1\hat{Y}_2} - \overset{4}{\hat{Y}_1})$$



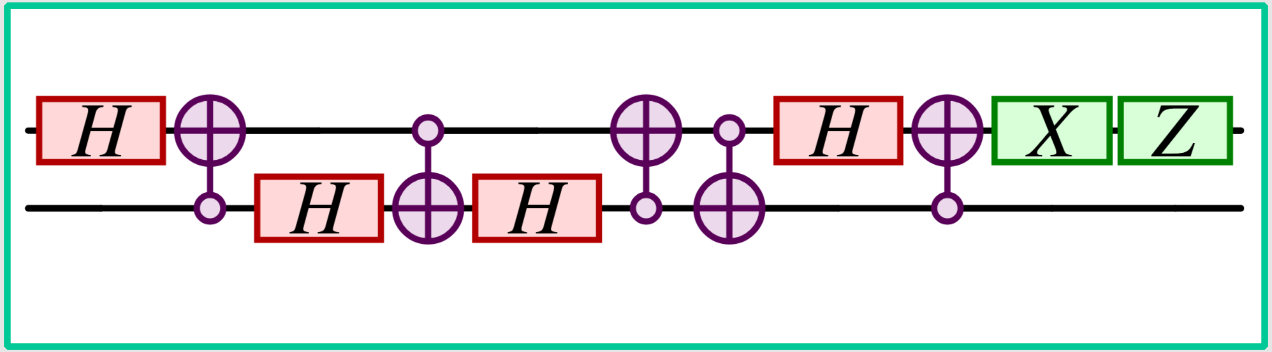
$$\underline{\Pi} : (2 \leftrightarrow 4),\ (3 \leftrightarrow 5)$$

Find a mapping that corresponds to a Clifford and preserves the input Hamiltonian... Is np-hard (in the **worst** case)!

[2] C. Nation et al., arXiv:2605.18966 (2026)
[3] C. Nation et al., arXiv:2605.30428 (2026)

Efficient Encoding

$$\hat{H} = c_1(\overset{1}{\hat{Y}_1\hat{Z}_2} + \overset{3}{\hat{Z}_1\hat{Z}_2} - \overset{5}{\hat{X}_2}) - c_2(\overset{2}{\hat{X}_1\hat{Y}_2} - \overset{4}{\hat{Y}_1})$$



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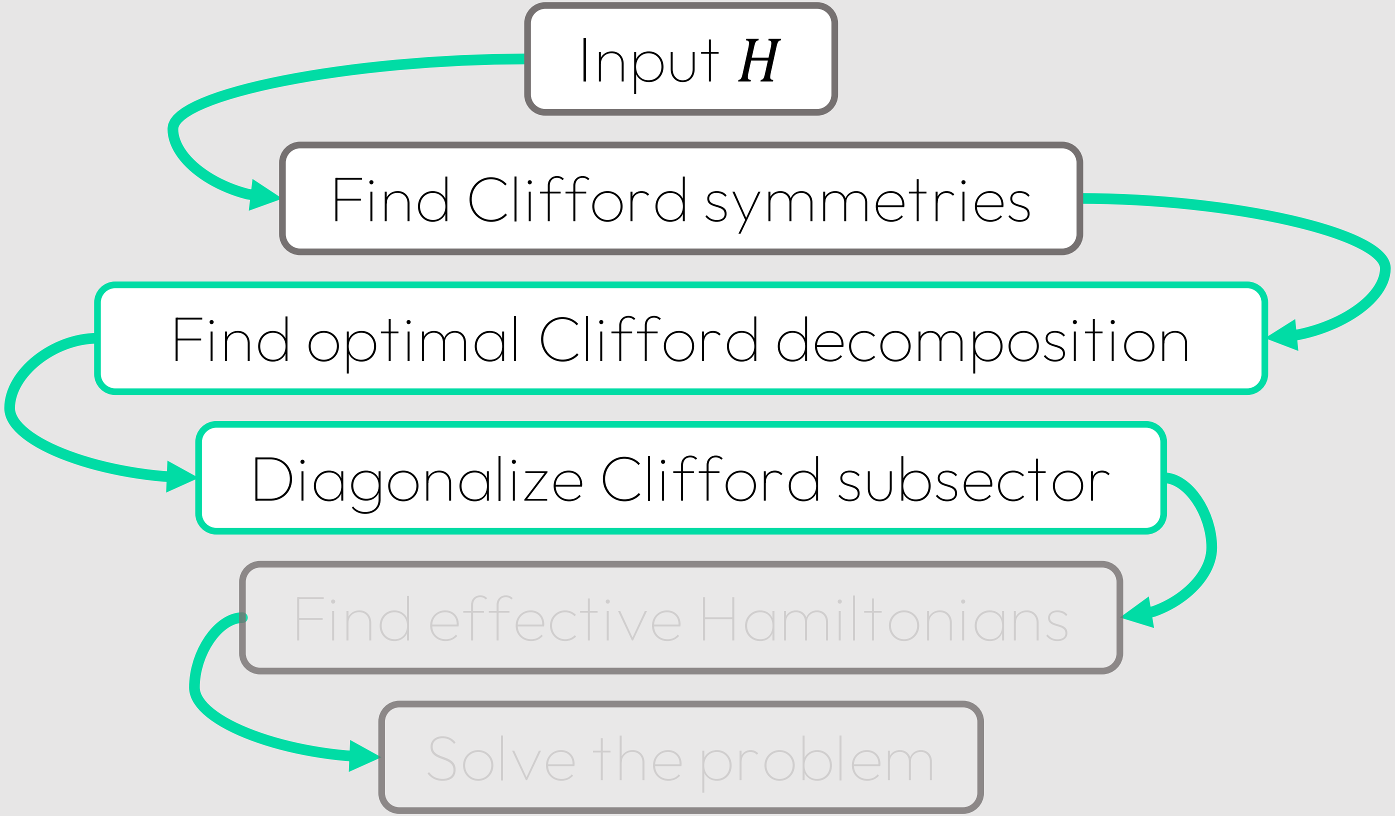

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Efficient Encoding

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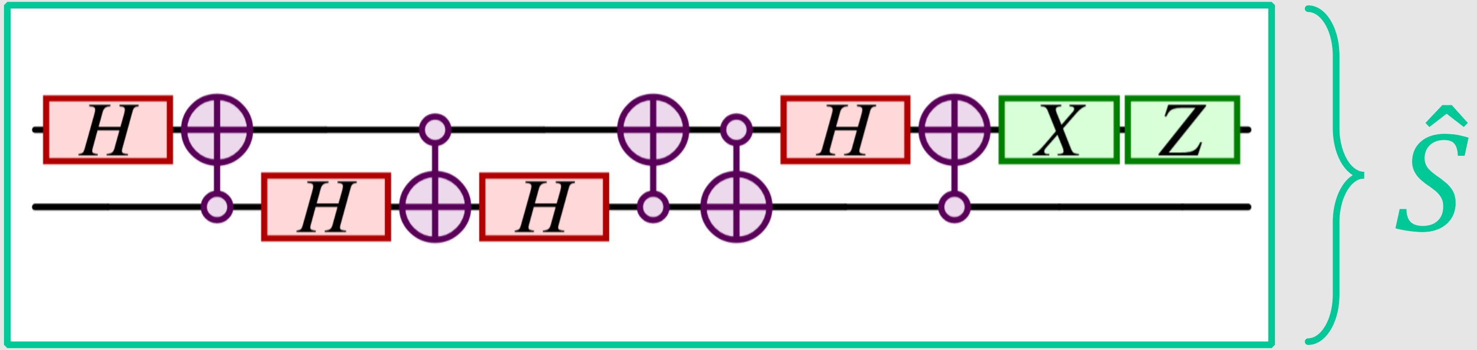


Diagonalizing a Clifford... Is np-hard!

[2] C. Nation et al., arXiv:2605.18966 (2026)
[3] C. Nation et al., arXiv:2605.30428 (2026)

Efficient Encoding

$$\hat{H} = c_1(\overset{1}{\hat{Y}_1\hat{Z}_2} + \overset{3}{\hat{Z}_1\hat{Z}_2} - \overset{5}{\hat{X}_2}) - c_2(\overset{2}{\hat{X}_1\hat{Y}_2} - \overset{4}{\hat{Y}_1})$$

$$\hat{S} = \hat{B}\hat{S}_{min}\hat{B}^{\dagger}$$

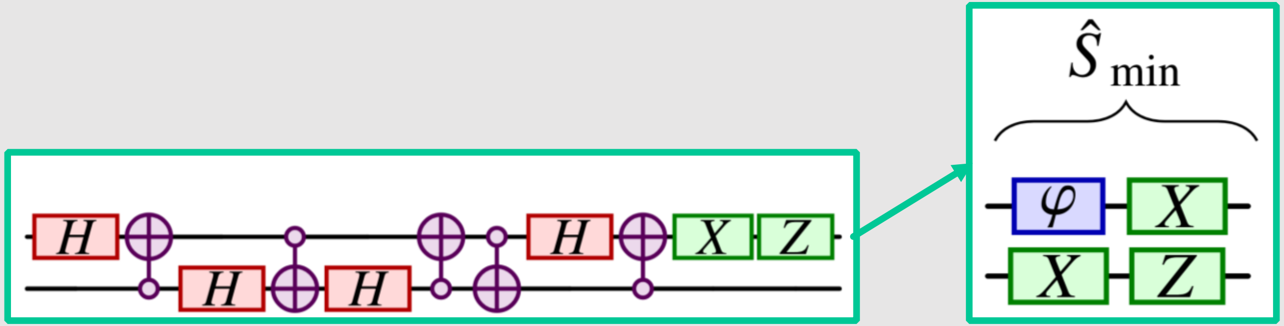
($\hat{H}_{sym} = \hat{B}\hat{H}\hat{B}^{\dagger} \rightarrow$ classically efficient)

Efficiently find minimal block decomposition $\hat{S}_{min}$

[2] C. Nation et al., arXiv:2605.18966 (2026)
[3] C. Nation et al., arXiv:2605.30428 (2026)

Efficient Encoding

$$\hat{H} = c_1(\overset{1}{\hat{Y}_1\hat{Z}_2} + \overset{3}{\hat{Z}_1\hat{Z}_2} - \overset{5}{\hat{X}_2}) - c_2(\overset{2}{\hat{X}_1\hat{Y}_2} - \overset{4}{\hat{Y}_1})$$



Qubit cost is minimized:

$2 \rightarrow 1$

(no entangling gate)

Efficiently find minimal block decomposition $\hat{S}_{min}$

[2] C. Nation et al., arXiv:2605.18966 (2026)
[3] C. Nation et al., arXiv:2605.30428 (2026)

Efficient Encoding

Input H

Find Clifford symmetries

Find optimal Clifford decomposition

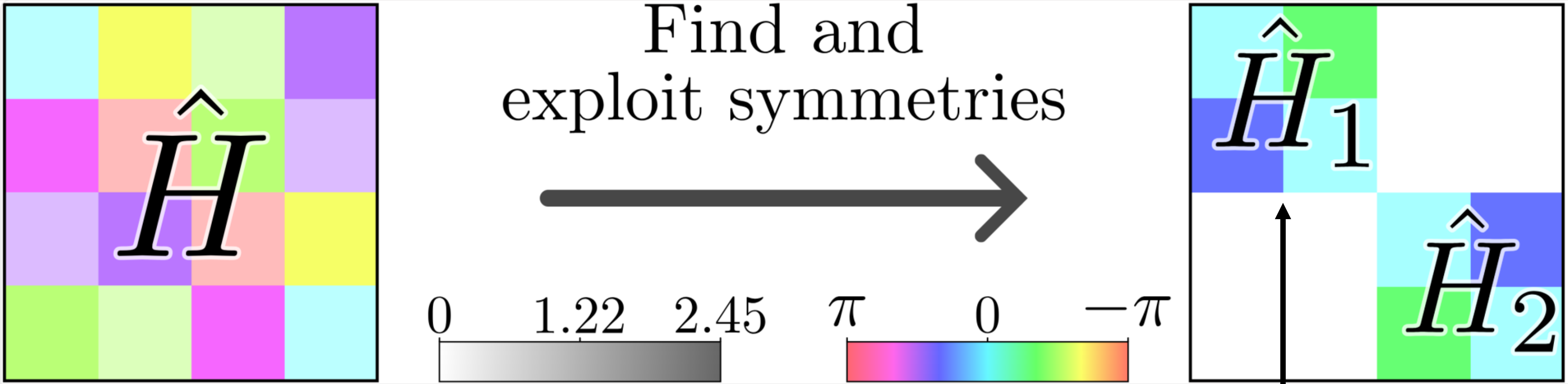
Diagonalize Clifford subsector

Find effective Hamiltonians

Solve the problem

[2] C. Nation et al., arXiv:2605.18966 (2026)
[3] C. Nation et al., arXiv:2605.30428 (2026)

Efficient Encoding



$$\hat{H} = \hat{Y}\hat{Z} + \hat{Z}\hat{Z} - \hat{1}\hat{X} - 2\hat{X}\hat{Y} + 2\hat{Y}\hat{1}$$

$$\hat{H}_1 = \sqrt{2}(\hat{1} + \hat{X}) + 2\hat{Y}$$

$$\hat{H}_2 = \sqrt{2}(\hat{1} + \hat{X}) - 2\hat{Y}$$

[2] C. Nation et al., arXiv:2605.18966 (2026)
[3] C. Nation et al., arXiv:2605.30428 (2026)

Efficient Encoding

Cost?

- Diagonalization of $\hat{S}_{min}$ (minimal with our method)
- Degeneracy of the eigenvalues of $\hat{S}_{min}$

Finding all effective Hamiltonians… Is np-hard, but yields exponential advantage, and if know the right subsector you WIN!

[2] C. Nation et al., arXiv:2605.18966 (2026)
[3] C. Nation et al., arXiv:2605.30428 (2026)

Efficient Encoding

Input $\boldsymbol{H}$

Find Clifford symmetries

Find optimal Clifford decomposition

Diagonalize Clifford subsector

Find effective Hamiltonians

Solve the problem – go ahead ☺

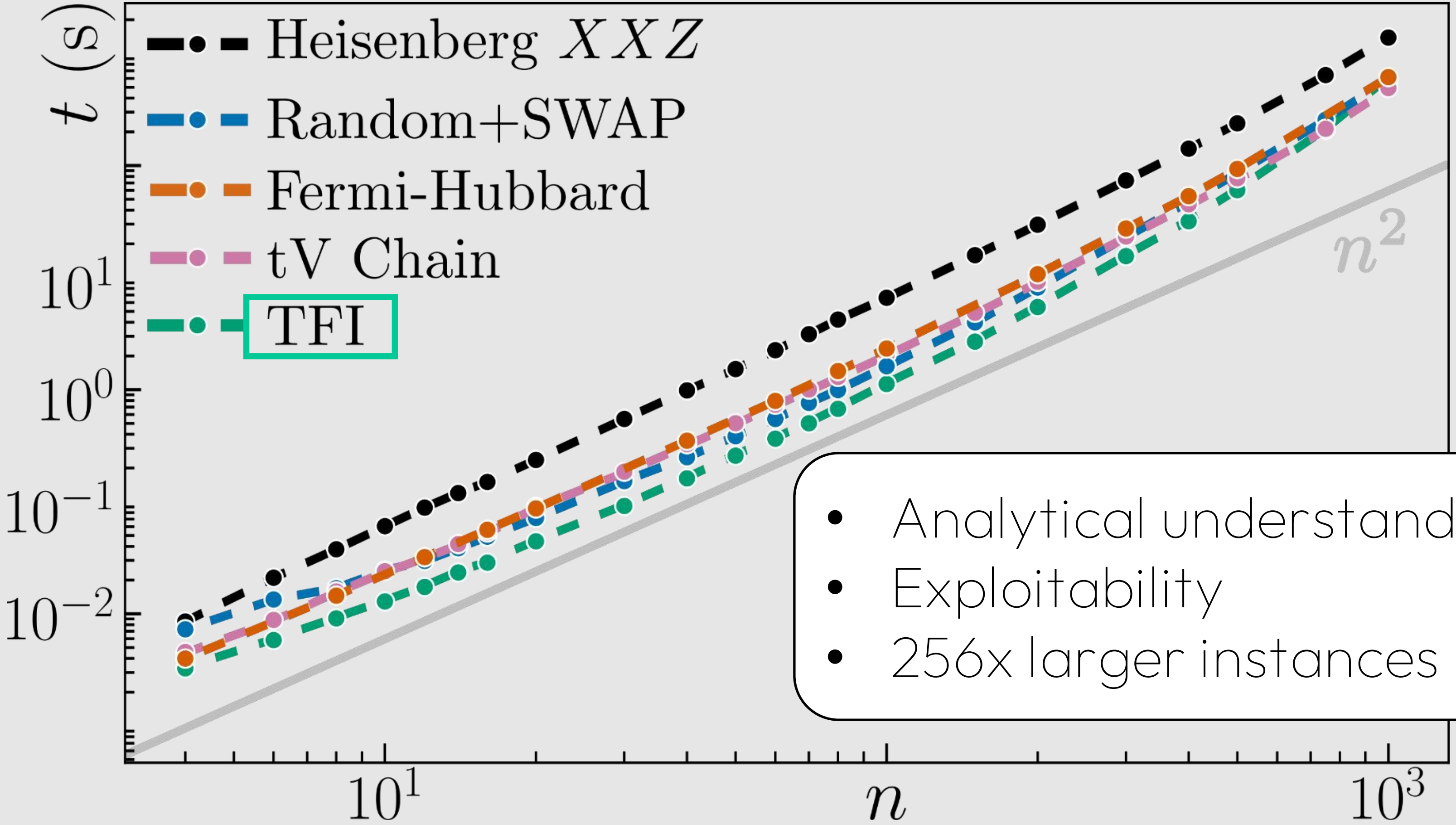
[2] C. Nation et al., arXiv:2605.18966 (2026)
[3] C. Nation et al., arXiv:2605.30428 (2026)

Efficient Encoding

Does it work?

[2] C. Nation et al., arXiv:2605.18966 (2026)
[3] C. Nation et al., arXiv:2605.30428 (2026)

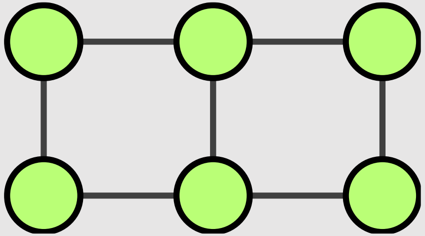
Efficient Encoding



- Analytical understanding
- Exploitability
- 256x larger instances

Efficient Encoding

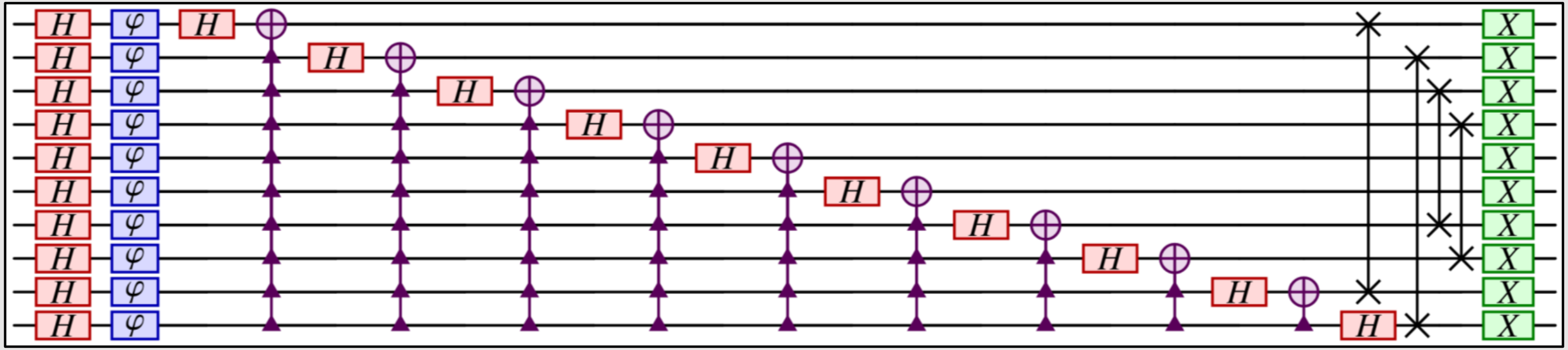
TFI (Transverse-Field Ising model)

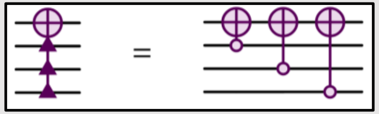


$$\hat{H}_{\mathrm{TFI}} = J_{\mathrm{TFI}} \sum_{\langle i,j \rangle}^{n-1} \hat{Z}_i \hat{Z}_j + h_{\mathrm{TFI}} \sum_{i=1}^{n} \hat{X}_i$$

Efficient Encoding

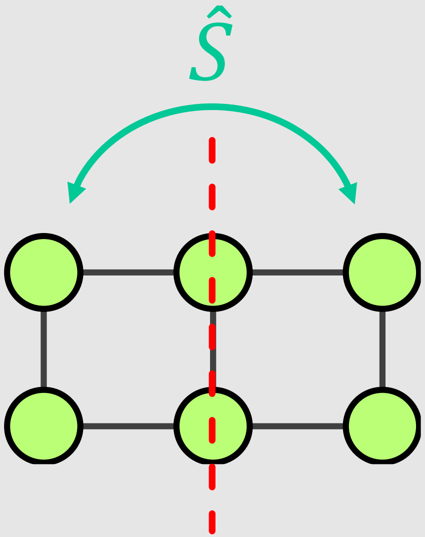
TFI (Transverse-Field Ising model)

$\hat{S} =$ 



Efficient Encoding

TFI (Transverse-Field Ising model)

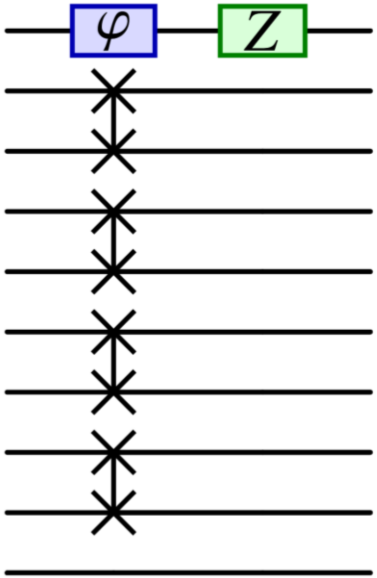


Exploitability?

Efficient Encoding

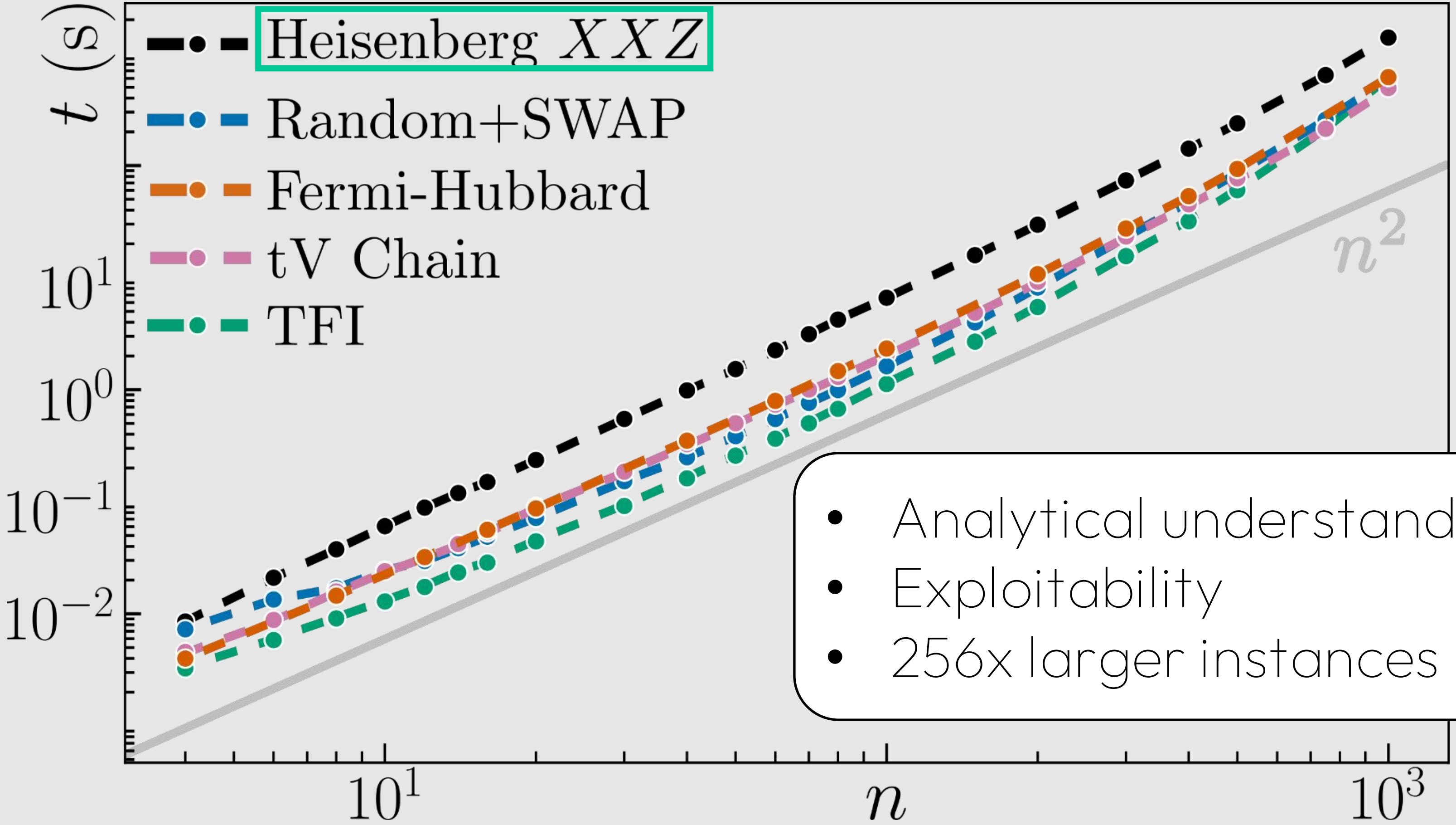
TFI (Transverse-Field Ising model)

$$\hat{S}_{\min} = \hat{B}^{\dagger}\hat{S}_{\mathrm{TFI}}\hat{B} =$$



- Symmetry found+diagonalized
- “Qubit cost” is 2 for ***all*** sizes!
- Best reference frame

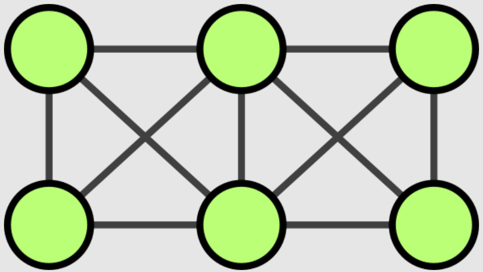
Efficient Encoding



- Analytical understanding
- Exploitability
- 256x larger instances

Efficient Encoding

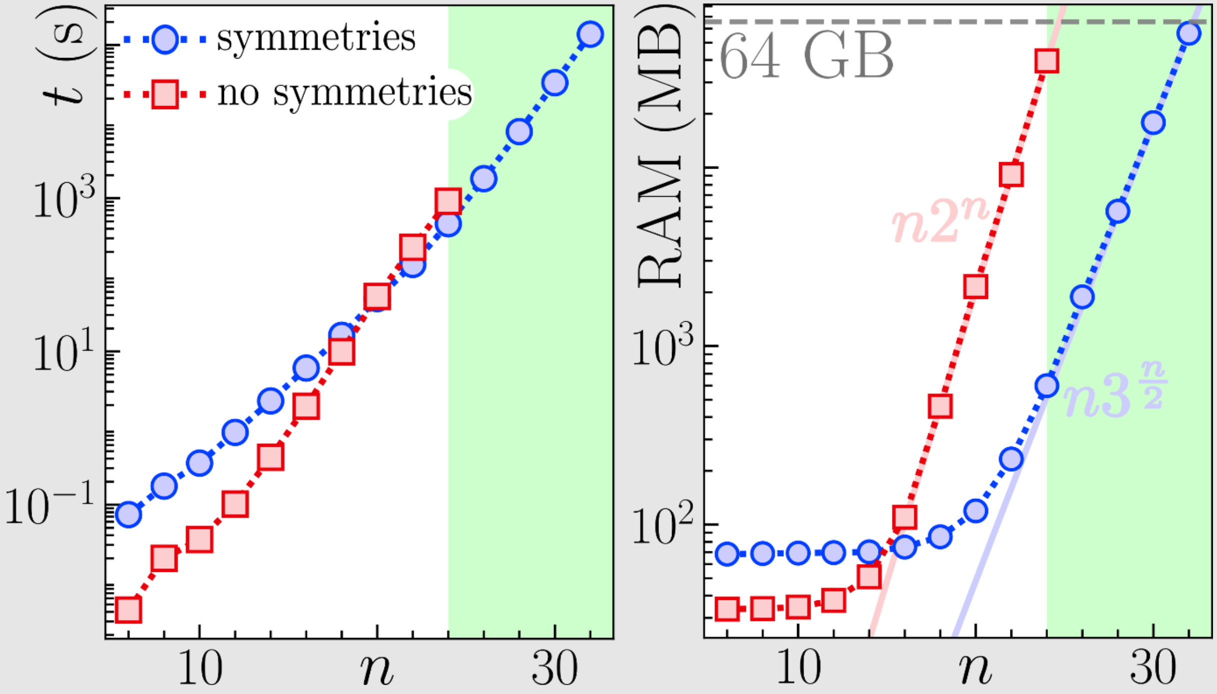
Heisenberg XXZ



$$\hat{H}_{XXZ} = \sum_{1 \leq i < j \leq n} J_{ij} \left(\hat{X}_i \hat{X}_j + \hat{Y}_i \hat{Y}_j + \Delta \hat{Z}_i \hat{Z}_j \right) + \sum_{i=1}^{n} h_i \hat{Z}_i$$

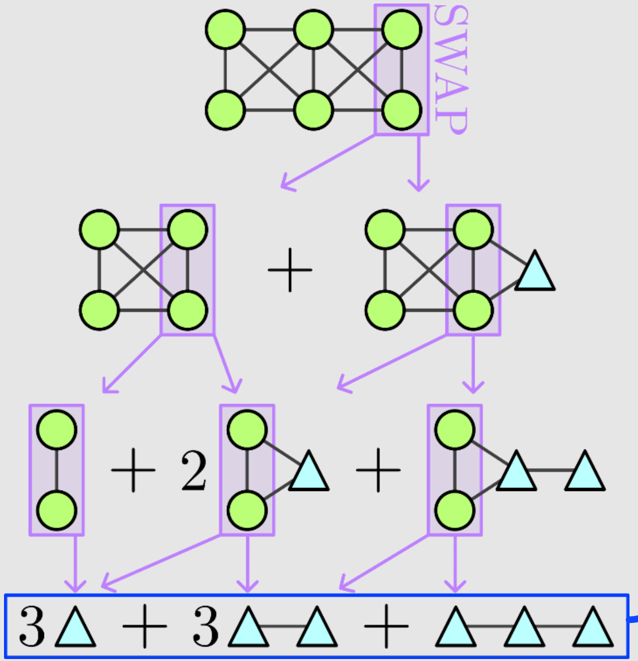
Efficient Encoding

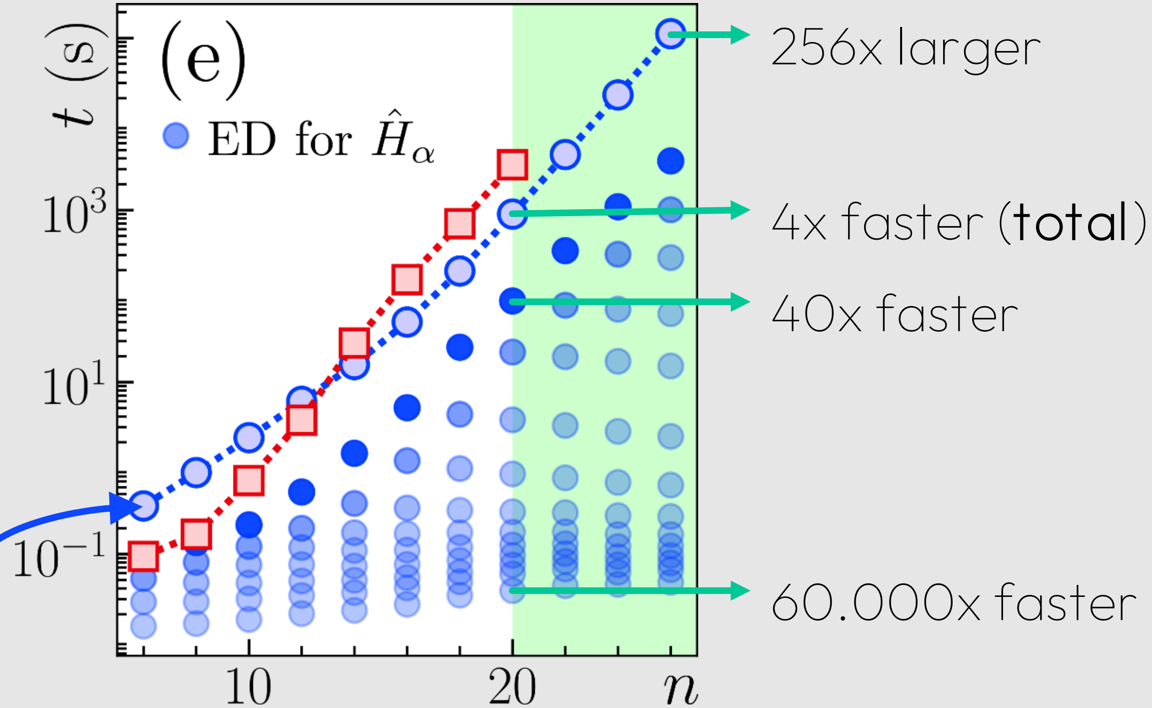
Heisenberg XXZ



Efficient Encoding

Heisenberg XXZ





Efficient Encoding

Does it work?

- Efficiently finds all Clifford symmetries of any model
- Diagonalizes the symmetry optimally by minimizing their qubit cost
- Even if the symmetry is known, we exploit it finding effective Hamiltonians
- Crucial to develop understanding the model
- 256x larger models solved up to 60.000 times faster for 20 qubits (ED)

[2] C. Nation et al., arXiv:2605.18966 (2026)
[3] C. Nation et al., arXiv:2605.30428 (2026)

Efficient Encoding

Can we bypass complexity with a **quantum computer**?

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Efficient Encoding

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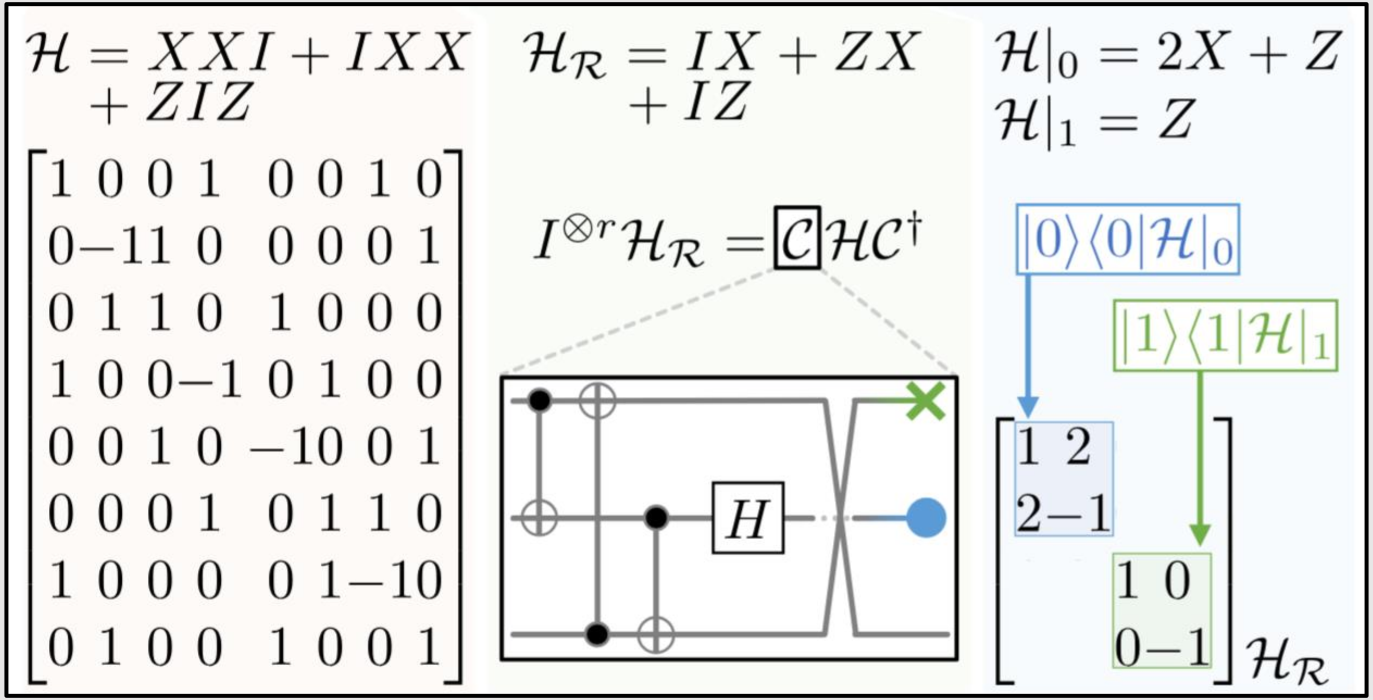

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Efficient Encoding

Can we bypass complexity with a **quantum computer**?

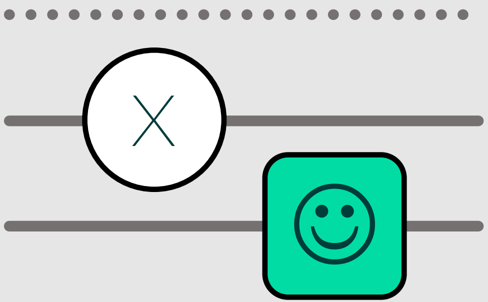
$\mathcal{H} = XXI + IXX + ZIZ$

$\mathcal{H}_{\mathcal{R}} = IX + ZX + IZ$

$\mathcal{H}|_0 \quad + Z$

$\mathcal{H}|_1$

No need to find effective H



gone

One X rotation

Residual complexity

[2] C. Nation et al., arXiv:2605.18966 (2026)
[3] C. Nation et al., arXiv:2605.30428 (2026)

Efficient Encoding

- Symmetries have huge **untapped** potential
- They can push the limits of **classical** simulations
- They can push the limits of **quantum** simulations
- They will shed light on **real quantum advantage**

[2] C. Nation, R. Simon, S. Banerjee, F. Martini, A. Ricottone, F. Cerisola, LD, arXiv:2605.18966 (2026)
[3] C. Nation, R. Simon, S. Banerjee, F. Martini, A. Ricottone, F. Cerisola, LD, arXiv:2605.30428 (2026)
[4] S. Banerjee, V. Muthu, C. Nation, R. Simon, F. Martini, A. Ricottone, F. Cerisola, LD, arXiv:2605.30429 (2026)

Software

Measurement

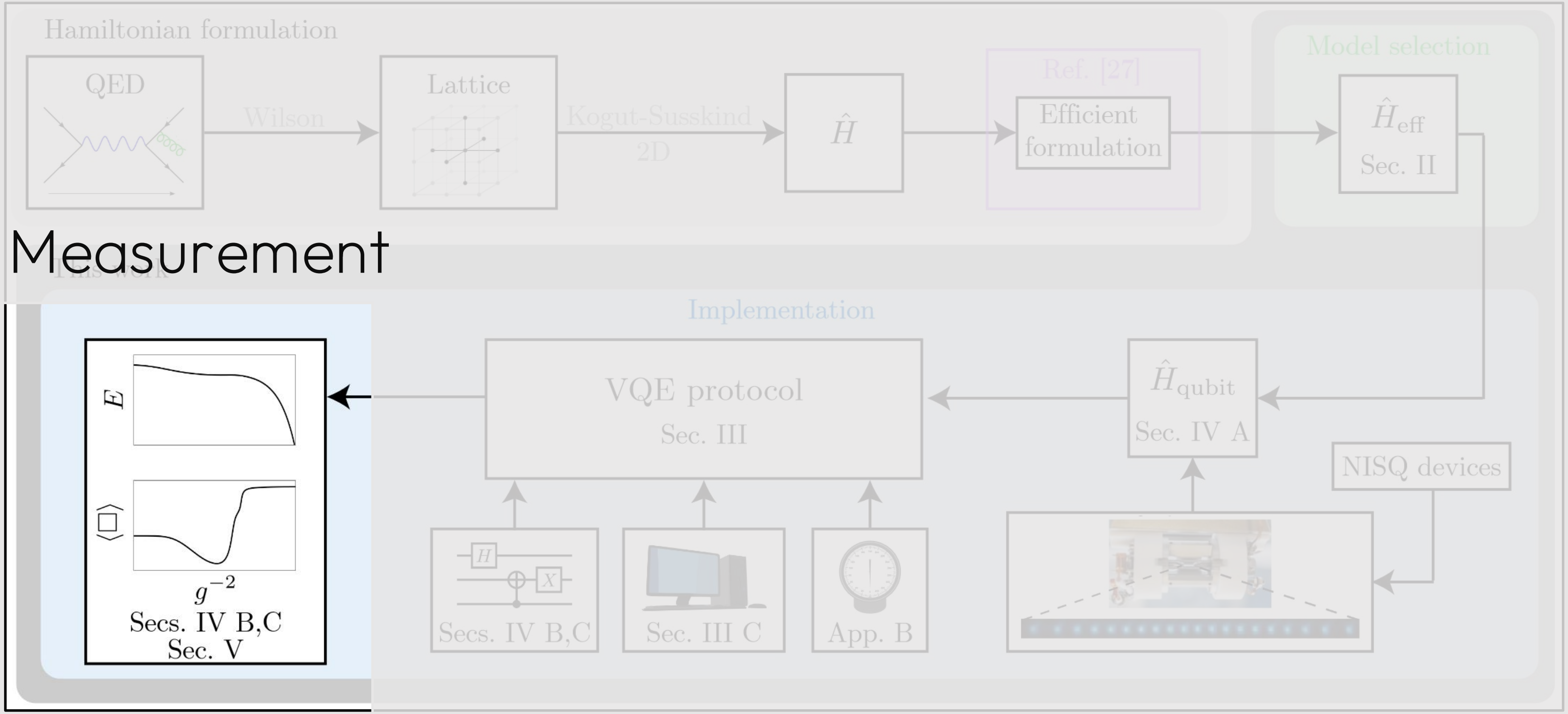


Image from D. Paulson*, LD*, J. F. Haase*, A. Celi*, A. Kan, A. Jena, C. Kokail, R. v. Bijnen, K. Jansen, P. Zoller and C. A. Muschik, ***PRX Quantum, 2***, 030334, 2021

Measurement

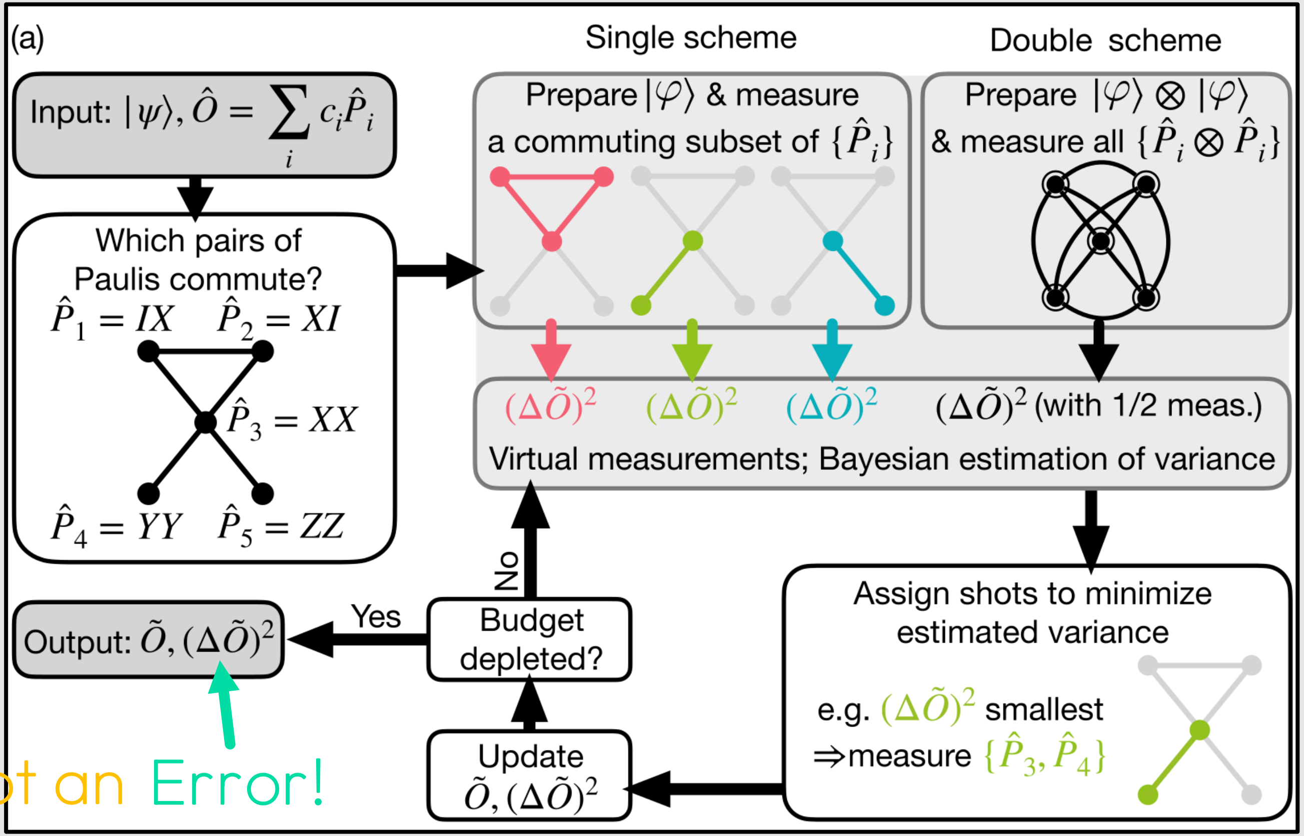
Protocol	Overlap	1/M scaling	Non-bitwise	Single-shot error	Adaptive	Doubling	Noise	qudit
LDF [1]	NO	YES	YES	YES (trivial)	NO	NO	NO	NO
Classical shadow [2]	YES	NO (exp. worse)	NO	NO	NO	NO	NO	NO
APS [3]	YES	NO	NO	NO	NO	NO	NO	NO
Derand [4]	YES	YES	NO	NO	NO	NO	NO	NO
OGM [5]	YES	YES	NO	NO	NO	NO	NO	NO
AEQuO [1]	YES	YES	YES	YES	YES	NO	NO	NO
CBS [6]	YES	YES	YES	NO	NO	NO	NO	NO
AQuIRE [7,8]	YES	YES	YES	YES	YES	YES	YES	YES

[1]: A. J. Jena, A., Schlosberg P. Mukhopadhyay, J. F. Haase, F. Leditzky and LD, Quantum 7, 903, 2023
[2]: H. Y. Huang, R. Kueng, J. Preskill, ***Nat. Physics***, 16, 1050-1057, 2020
[3]: C. Hadfield, S. Bravy, R. Raymond, A. Mezzacapo, arXiv:2006.15788, 2020
[4]: H. Y. Huang, R. Kueng, J. Preskill, ***PRL,*** 127, 030503, 2021
[5]: B. Wu, J. Sun, Q. Huang, X. Yuan, arXiv:2105.13091, 2021
[6]: M. Kohda, R. Imai, K. Kanno, K. Mitarai, W. Mizukami, Y. O. Nakagawa, arXiv:2112.07416, 2022
[7] R. Simon, Z. Shi, C. Nation, A. Jena, LD, arXiv:2509.01482 (2025)
[8] R. Simon, M. Meth, F. Martini, P. Tirler, A. Jena, M. Ringbauer, LD, arXiv:2605.00682 (2026)

Measurement

Qudit ready

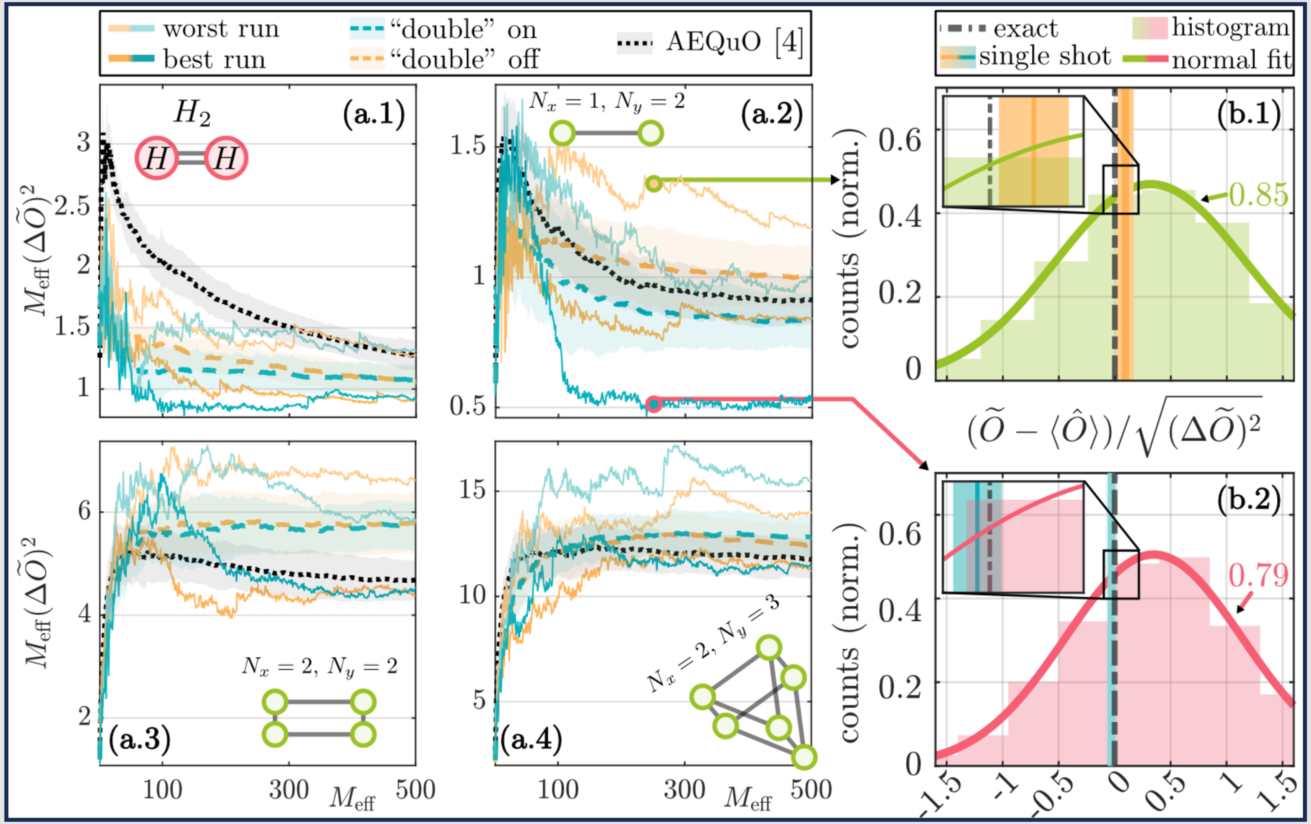
Hardware noise awareness



Not an Error!

[7] R. Simon, Z. Shi, C. Nation, A. Jena, LD, arXiv:2509.01482 (2025)
[8] R. Simon, M. Meth, F. Martini, P. Tirler, A. Jena, M. Ringbauer, LD, arXiv:2605.00682 (2026)

Measurement – double scheme

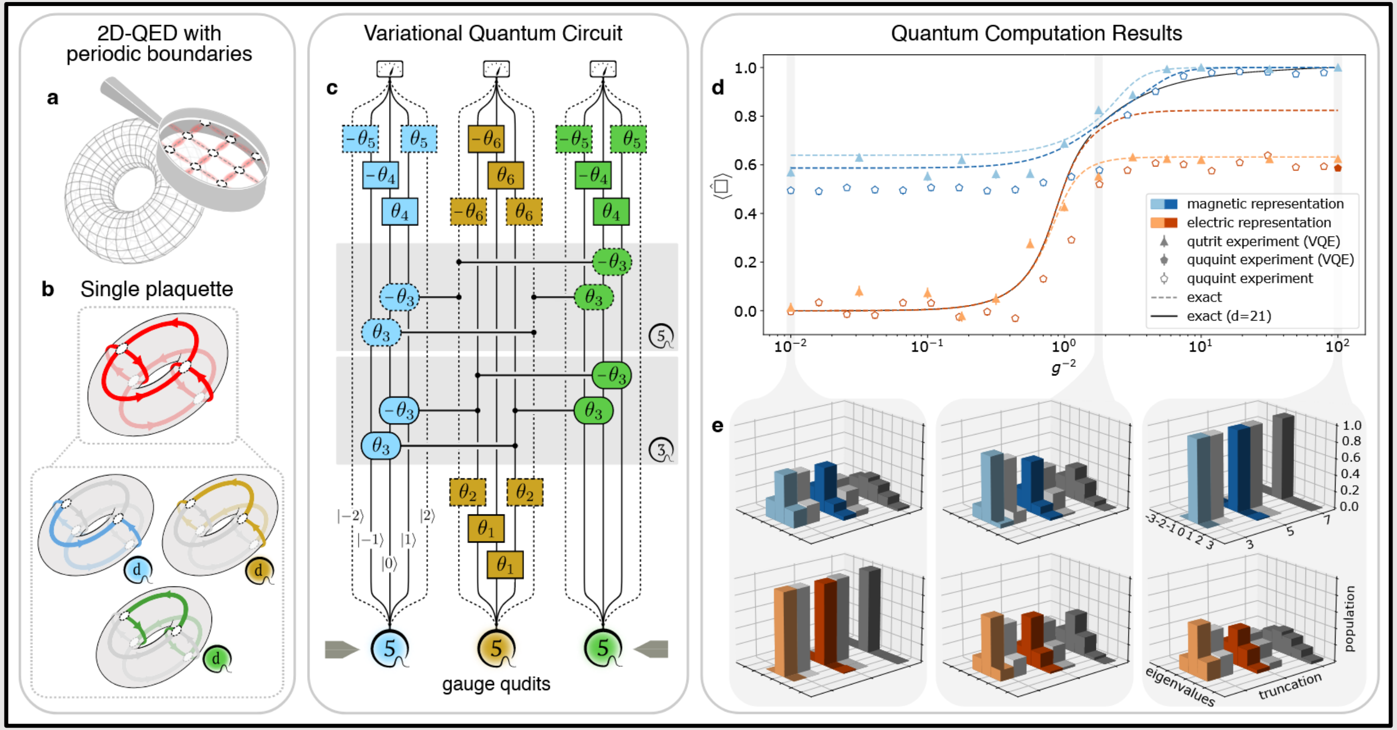


[7] Image from R. Simon, Z. Shi, C. Nation, A. Jena, LD, arXiv:2509.01482 (2025)
[8] R. Simon, M. Meth, F. Martini, P. Tirler, A. Jena, M. Ringbauer, LD, arXiv:2605.00682 (2026)

Measurement – qudit observables

Particles → ‘easy’ for q. computer

Gauge fields → hard and expensive for q. computer… Much better if qudit ready!



M. Meth et many al., Nature Physics 21, 570-576 (2025)

Measurement – qudit observables

$$\hat{O} = \sum_{i=1}^{p} c_i \hat{P}_i \quad \text{with} \quad \hat{P}_i = \bigotimes_{j=1}^{q} \hat{X}_{d_j}^{r_j} \hat{Z}_{d_j}^{s_j},$$

Spin Hamiltonian

Classically efficient

Pauli Hamiltonian

$$\hat{S}_\alpha = \sum_{r,s} c_\alpha^{r,s} \hat{X}_{d_S}^{r} \hat{Z}_{d_S}^{s} \quad \text{with} \quad \alpha = x, y, z$$

is obtained from the coefficients

$$c_x^{r,s} = \frac{1}{d_S} \sum_{\mu=0}^{d_S-2} \sigma_\mu \left(\frac{\delta(r-1)}{\omega^{s\mu}} + \frac{\delta(r+1-d)}{\omega^{s(\mu+1)}} \right),$$

$$c_y^{r,s} = \frac{\mathrm{i}}{d_S} \sum_{\mu=0}^{d_S-2} \sigma_\mu \left(\frac{\delta(r-1)}{\omega^{s\mu}} - \frac{\delta(r+1-d)}{\omega^{s(\mu+1)}} \right),$$

$$c_z^{r,s} = \frac{2}{d_S} \sum_{\mu=0}^{d_S-1} \left(\frac{d_S-1}{2} - \mu \right) \omega^{-s\mu} \delta(r),$$

[7] R. Simon, Z. Shi, C. Nation, A. Jena, LD, arXiv:2509.01482 (2025)
[8] R. Simon, M. Meth, F. Martini, P. Tirler, A. Jena, M. Ringbauer, LD, arXiv:2605.00682 (2026)

Measurement – error awareness

$$(\widetilde{\Delta O_{\mathrm{e}}})^2 = (\widetilde{\Delta O})^2 + (\tilde{O}_{\mathrm{e}} - \tilde{O})^2,$$

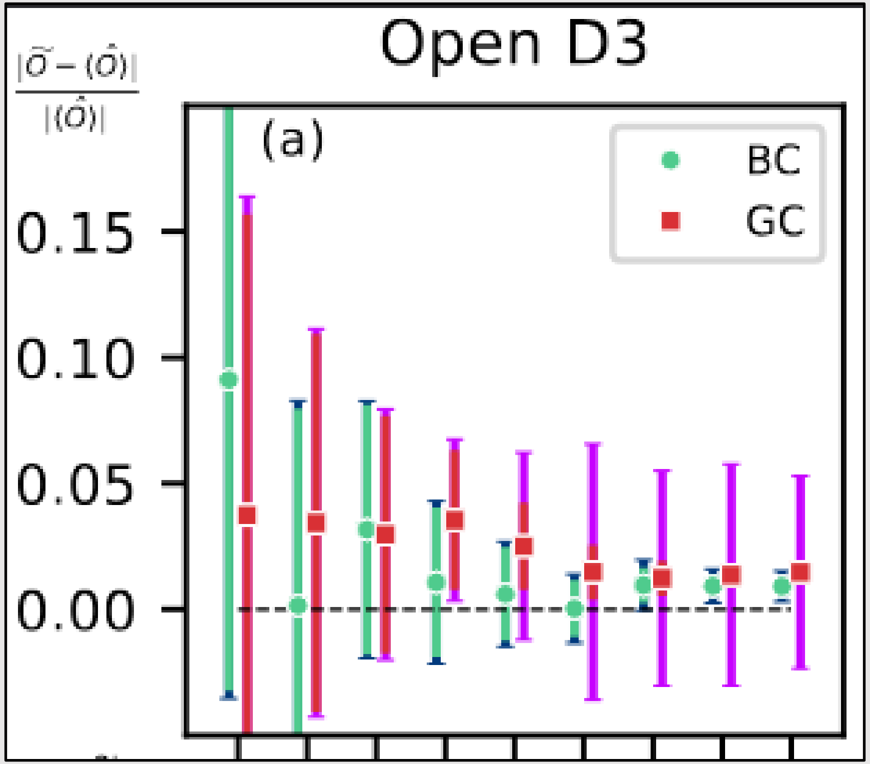
$$\tilde{O}_{\mathrm{e}} - \tilde{O} \simeq \sum_i c_i \tilde{\xi}_i \sum_\mu \left(\tilde{\theta}_{i\mu} - \frac{1}{d_P} \right) \omega^\mu_{d_P}.$$

Cheap

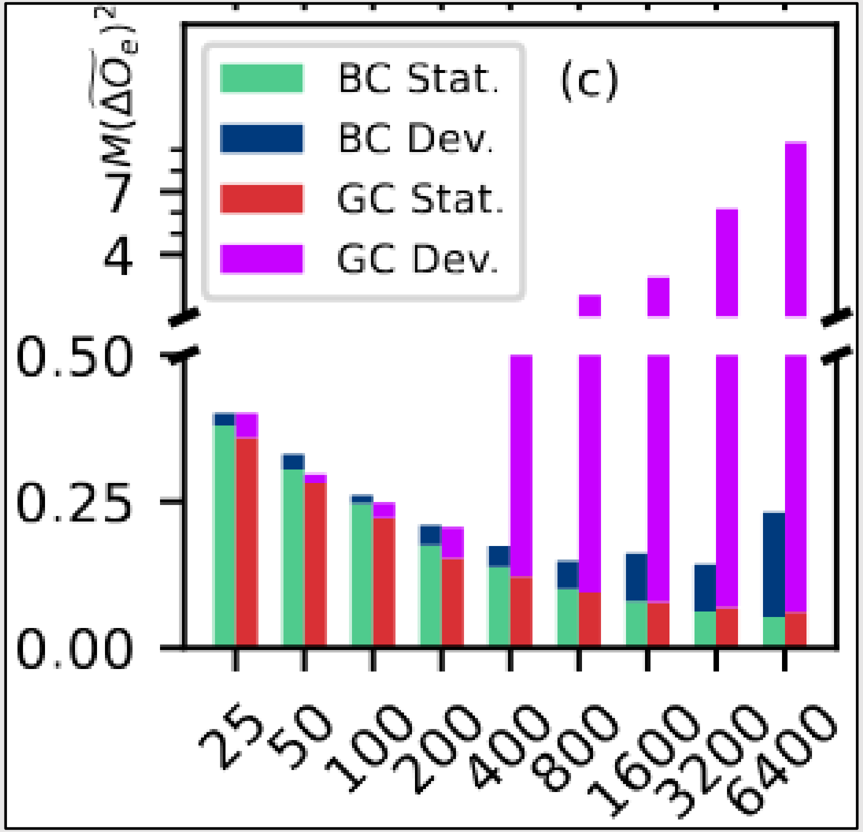
Impact on the specific experiment

[7] R. Simon, Z. Shi, C. Nation, A. Jena, LD, arXiv:2509.01482 (2025)
[8] R. Simon, M. Meth, F. Martini, P. Tirler, A. Jena, M. Ringbauer, LD, arXiv:2605.00682 (2026)

Measurement



shots



shots

[7] R. Simon, Z. Shi, C. Nation, A. Jena, LD, arXiv:2509.01482 (2025)
[8] Image from R. Simon, M. Meth, A. Jena, F. Martini, M. Ringbauer, LD, in preparation

Conclusions and Outlook

- Classically efficient approach for symmetry finding
- **Measurement protocol that will not let you down**

sympleq

- Error mitigation within AQuIRE
- Beyond Clifford symmetries and “almost” symmetries

Acknowledgements