Spectroscopy of Ising Mesons on a Noisy Quantum Simulator

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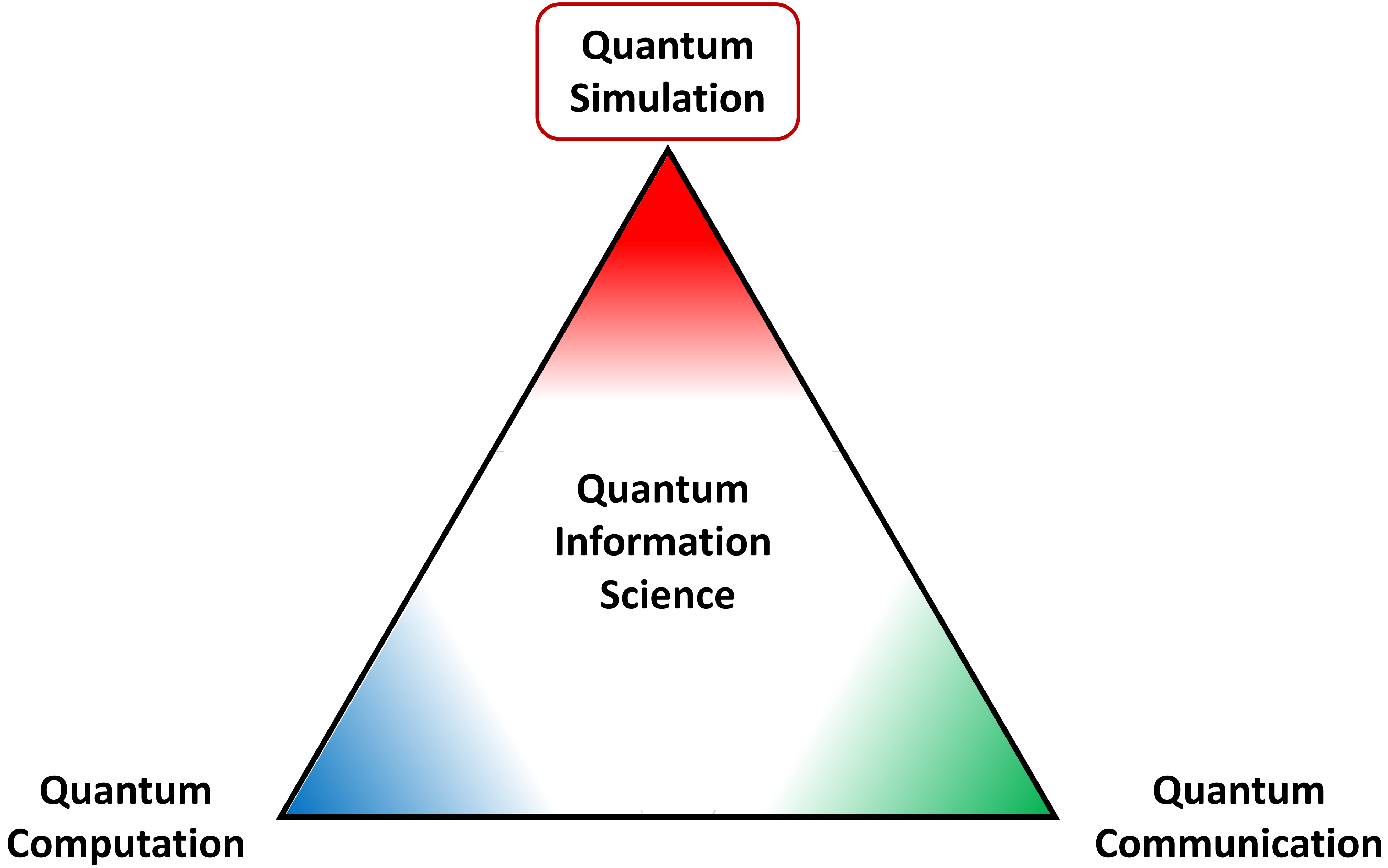
Rutgers University

Ref: arXiv:2303.03311

APS Topical Group on Hadronic Physics Workshop
April 14, 2023



Quantum
Simulation

Quantum
Information
Science

Quantum
Computation

Quantum
Communication

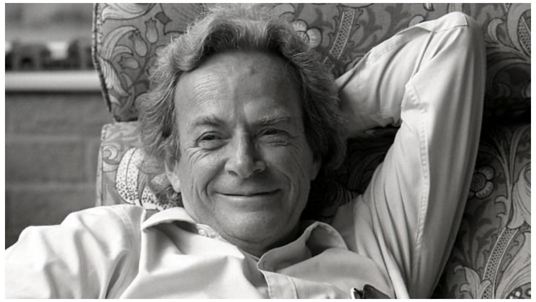


Image: BBC UK

What kind of computer are we going to use to simulate physics?

… you can simulate this with a quantum system, with quantum computer elements. It's not a Turing machine, but a machine of a different kind.

Feynman (1982)

Quantum Simulation

Digital

Analog

A universal quantum computer is also a universal digital quantum simulator

Lloyd (1996)

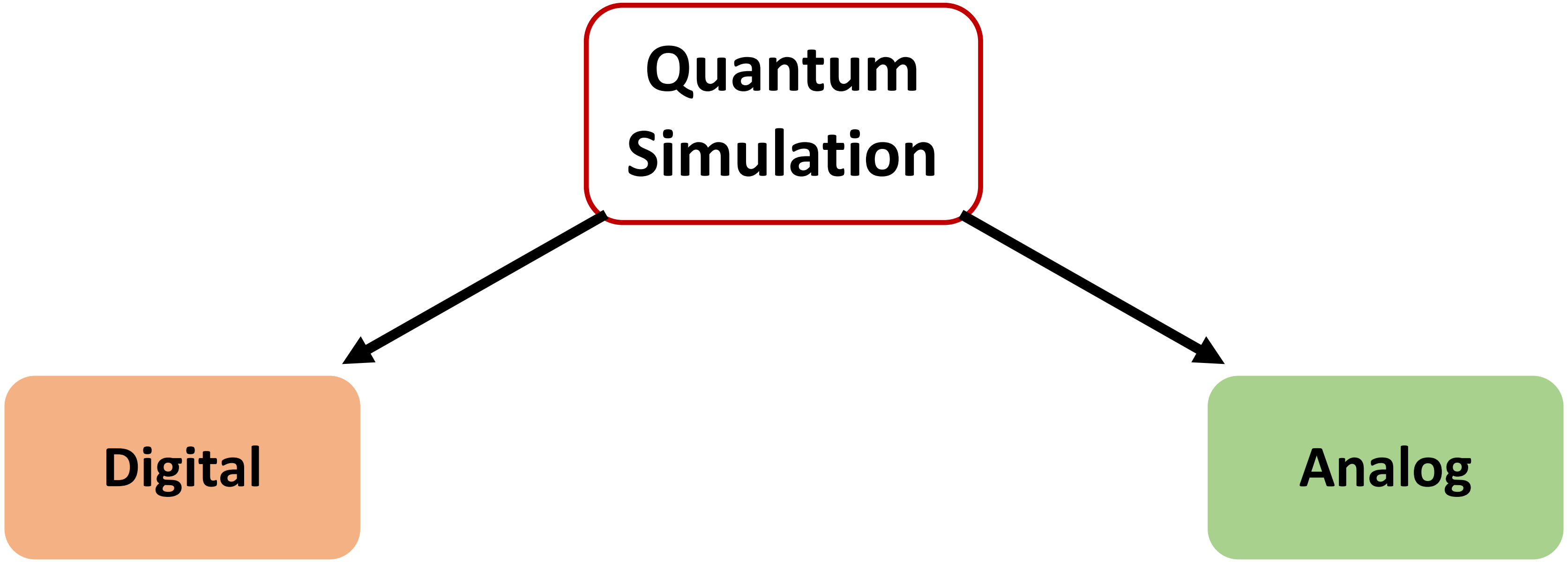
Needs to be error-correcting, fault-tolerant

Shor (1995), Steane (1996)

Trade-off universality for near-term achievability

Does not need Quantum Error Correction

Wide range of platforms available



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→

Quantum code candidates:

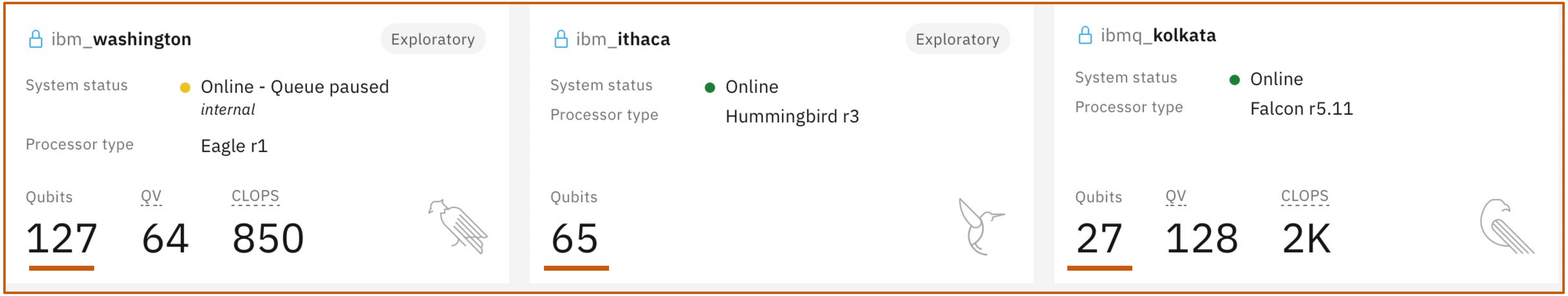
1. Shor code (1 logical = 9 data + 8 ancilla)
2. Surface-17 (1 logical = 9 data + 8 ancilla)

Shor (1995), Dennis *et al* (2001), O'Brien *et al* (2017)

Examples of Current Digital Quantum Machines

IBM Quantum Simulators

source: quantum-computing.ibm.com



ibm_**washington** Exploratory
System status ● Online - Queue paused
internal
Processor type Eagle r1
Qubits 127
QV 64
CLOPS 850

ibm_**ithaca** Exploratory
System status ● Online
Processor type Hummingbird r3
Qubits 65

ibmq_**kolkata**
System status ● Online
Processor type Falcon r5.11
Qubits 27
QV 128
CLOPS 2K

Similar Quantum Simulators available from AWS, Rigetti, Microsoft, Google, …, similar number of qubits, decoherence times $\sim 100\mu s$

Effective number of <u>logical</u> qubits $\simeq \frac{100}{17} \sim 6$

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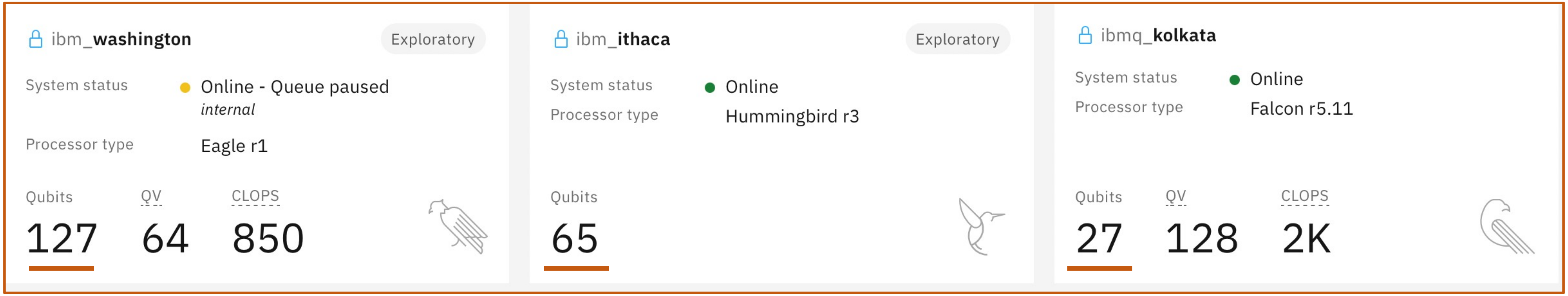

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System status ● Online - Queue paused *internal*

Processor type Eagle r1

Qubits	QV	CLOPS
127	64	850

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Qubits	QV	CLOPS
27	128	2K

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What can we do with these quantum machines of the NISQ era?

Effective number of logical qubits $\simeq \frac{100}{17} \sim 6$

NISQ = Noisy Intermediate-Scale Quantum

What kind of quantum field theories can be simulated on the NISQ machines?

Early works on scattering in massless real scalar field (Klein-Gordon, …)

Jordan *et al* (2012), Klco and Savage (2019), …

A more minimalistic approach: spin-chains which can be mapped to qubits with minimal overhead

Smith *et al* (2019), Vovrosh and Knolle (2020), …

Abandon error-correction – leads to new question about how quantum field theories respond to noise and dissipation

Look for a model with a `small correlation length’

This talk: the Ising model with transverse and longitudinal field

McCoy and Wu (1978), Rutkevich (2005, 2008), Fonseca and Zamolodchikov (2001, 2006)

Ising model with transverse and longitudinal field

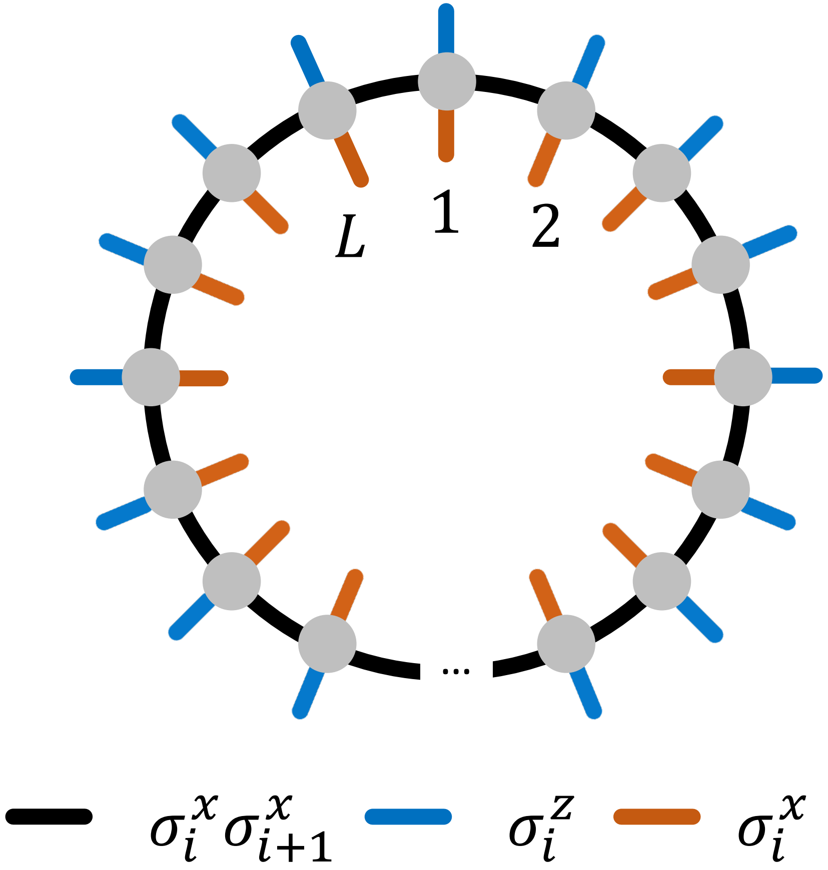
Hamiltonian (periodic boundary conditions):

$$H = -\sum_{i=1}^{L} \sigma_i^x \sigma_{i+1}^x - g \sum_{i=1}^{L} \sigma_i^z - h \sum_{i=1}^{L} \sigma_i^x$$

ferromagnetic coupling

transverse field

longitudinal field



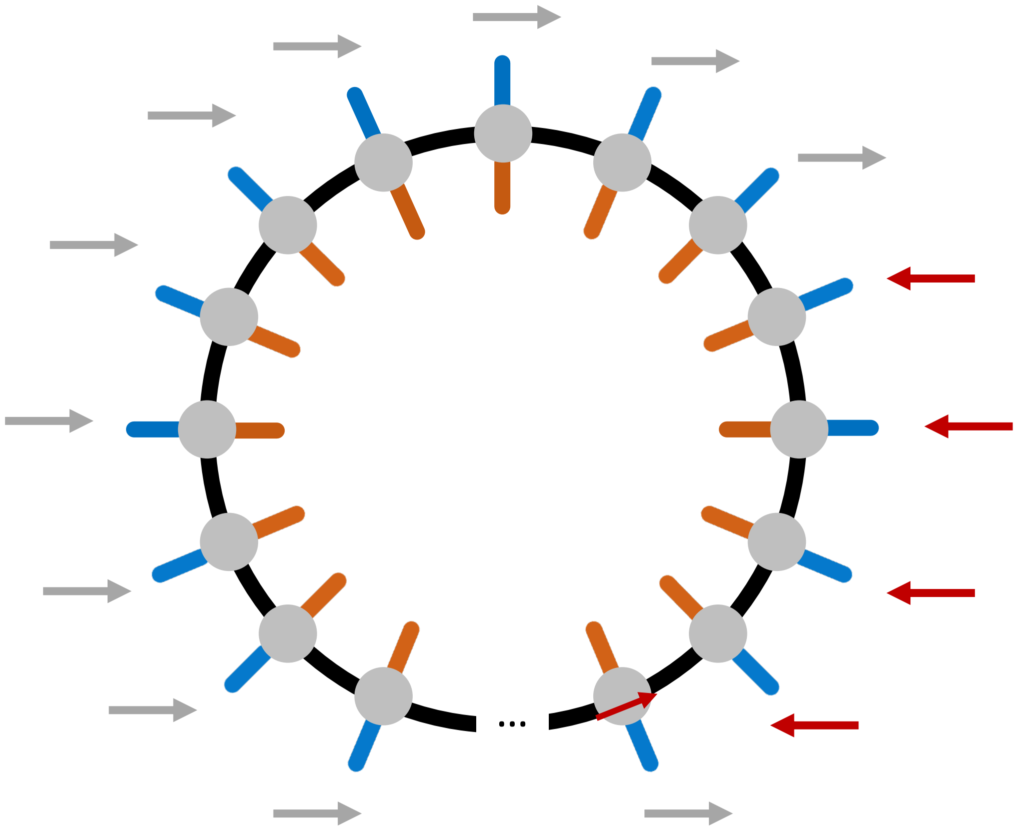
Important solvable cases:

1. Free fermion: $h = 0$ (Onsager, 1944)
2. E_8 model: $g = 1, h \ll 1$ (Zamolodchikov, 1989)

No known exact solution for arbitrary g, h

Formation of Mesonic Bound States in the model

Ferromagnetic phase, excitations are *free*, domain walls
$h = 0, g < 1$

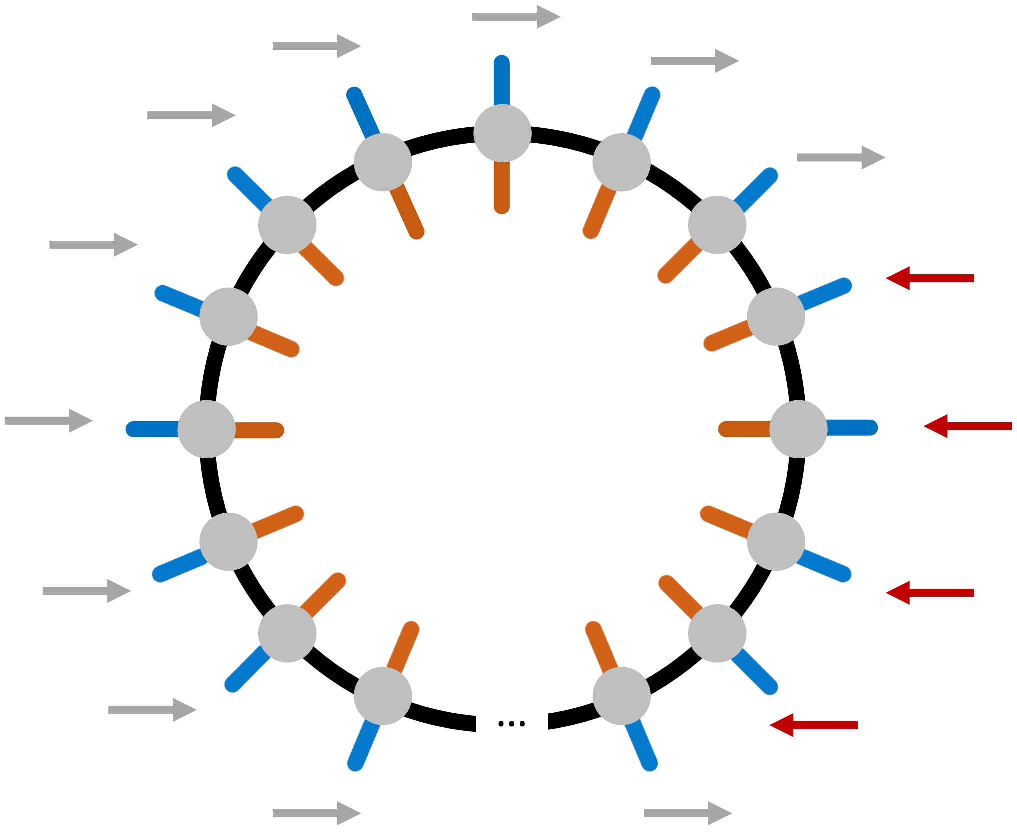


▬ $\sigma_i^x \sigma_{i+1}^x$

▬ σ_i^z

▬ σ_i^x

Ferromagnetic phase, domain walls *confined* into mesons
$h > 0, g < 1$



McCoy and Wu (1978), Rutkevich (2005, 2008), Fonseca and Zamolodchikov (2001, 2006)

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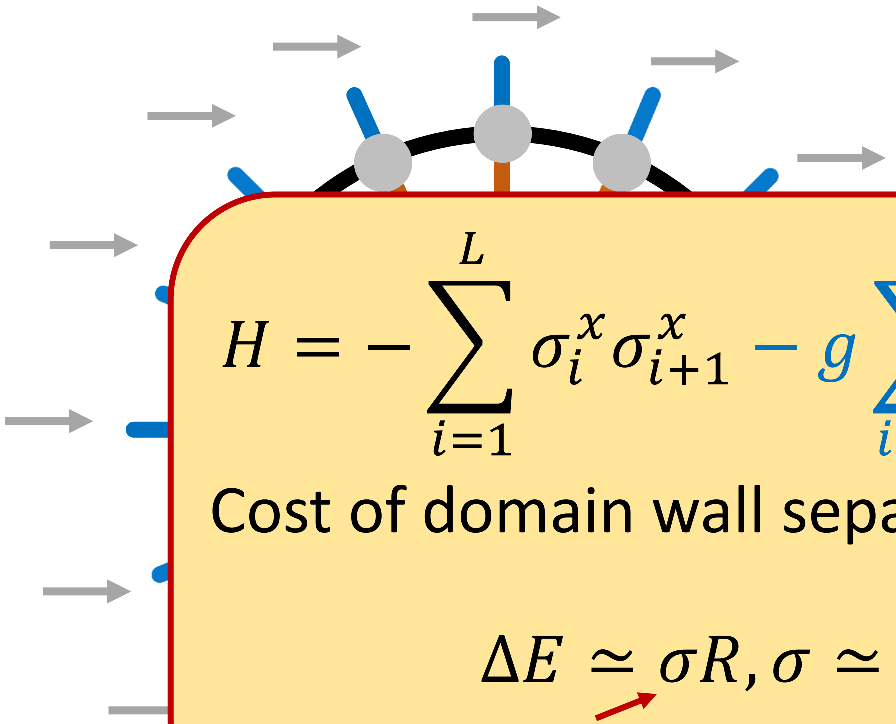

▬ $\sigma_i^x \sigma_{i+1}^x$

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▬ σ_i^x

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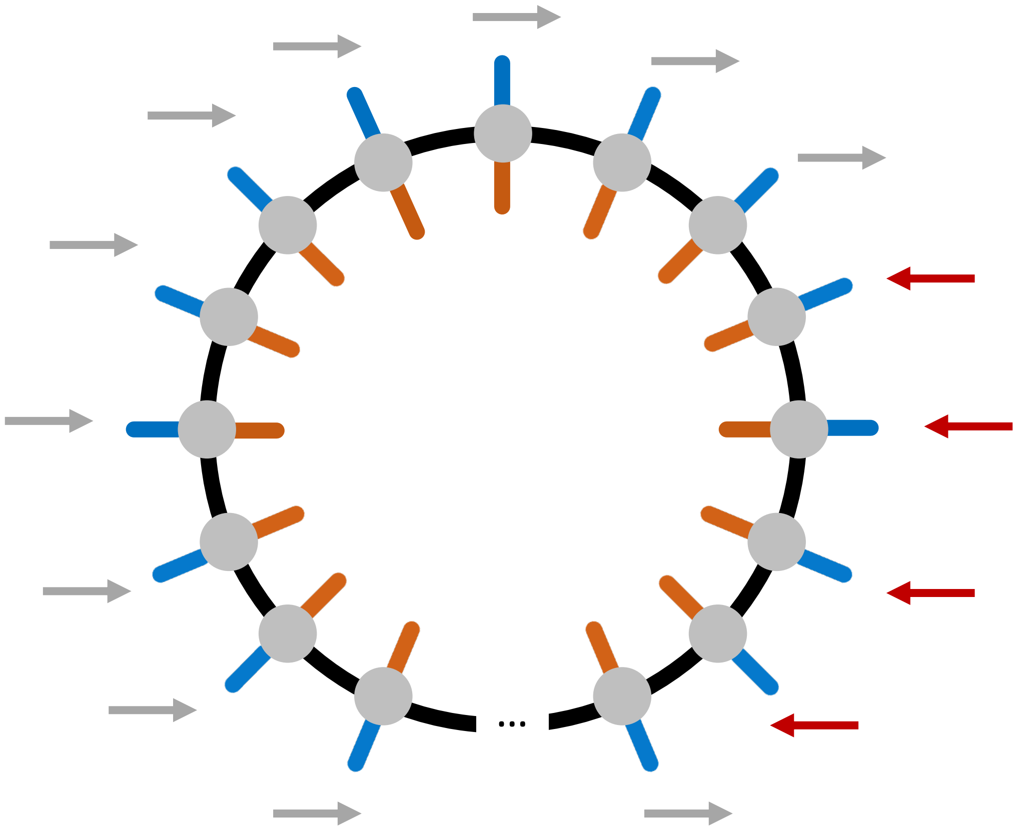


$$H = -\sum_{i=1}^{L} \sigma_i^x \sigma_{i+1}^x - g \sum_{i=1}^{L} \sigma_i^z - h \sum_{i=1}^{L} \sigma_i^x$$

Cost of domain wall separation (R):

$$\Delta E \simeq \sigma R, \sigma \simeq 2\langle \sigma^x \rangle h$$

string tension

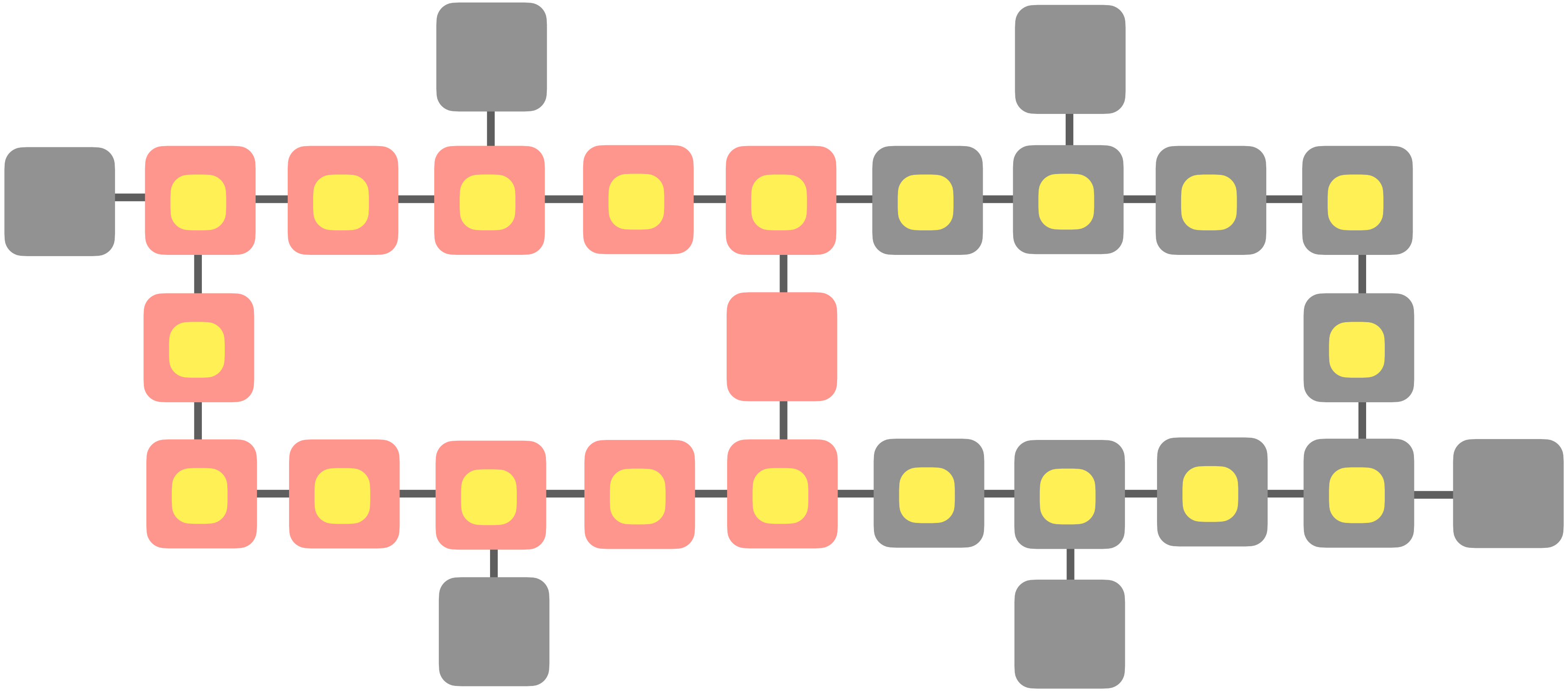
McCoy and Wu (1978), Rutkevich (2005, 2008), Fonseca and Zamolodchikov (2001, 2006)

Quantum Simulation Protocol

1. Initialize in ferromagnetic state: $| \rightarrow, \rightarrow, \ldots, \rightarrow \rangle$
2. Trotterized time-evolution in terms of single and two qubit gates
3. Measure $\langle \sigma_i^x \rangle$

Lamb, Davis, Tang, AR, arXiv:2303.03311

IBM Mumbai Quantum Simulator



Median life-times: $\sim 100\mu s$

Gate and readout errors: $\sim 1\%$

Ref: https://quantum-computing.ibm.com

Mapping to IBM's Mumbai Quantum Simulator

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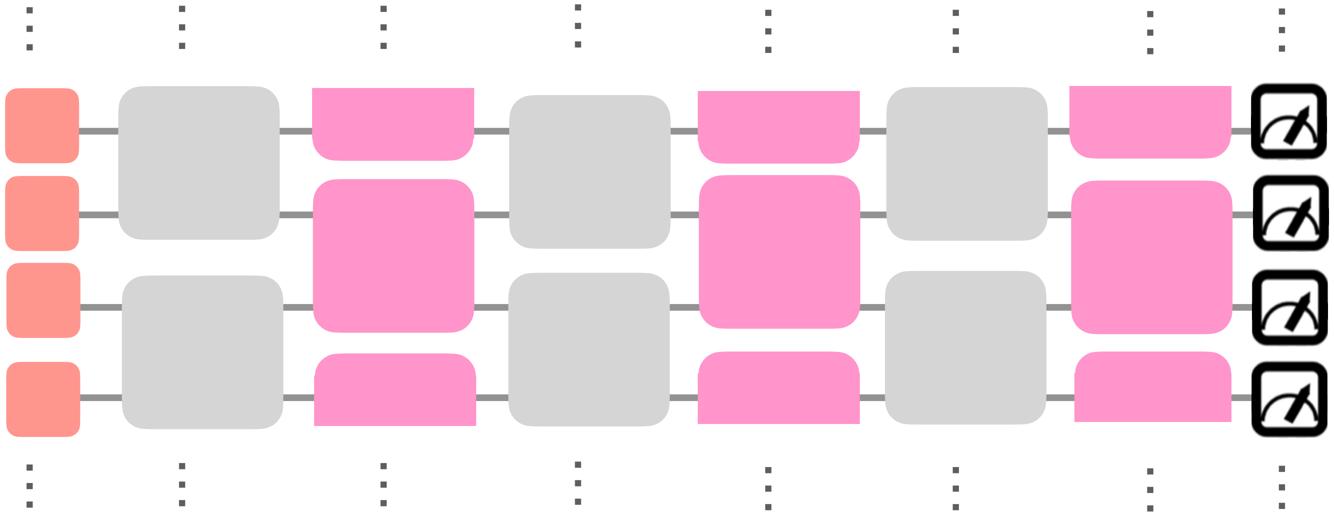
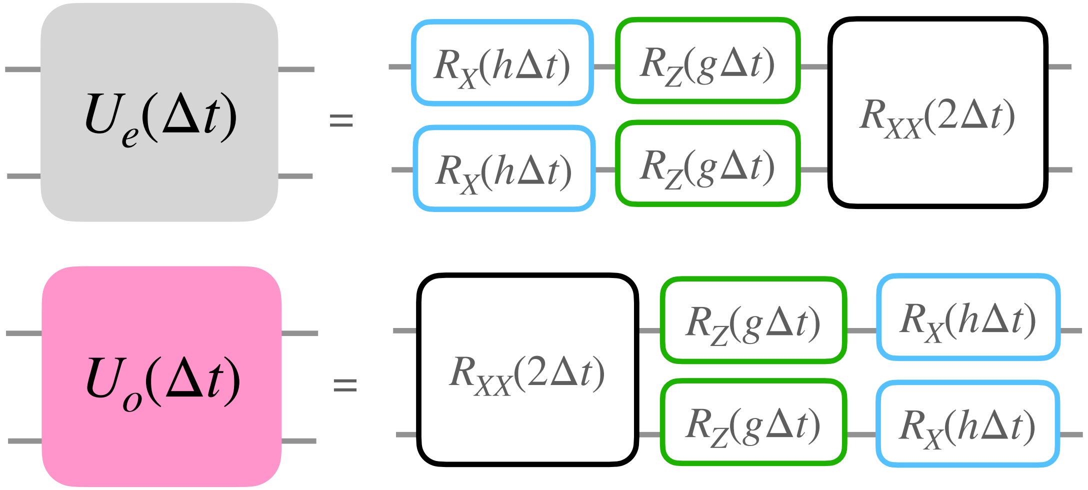
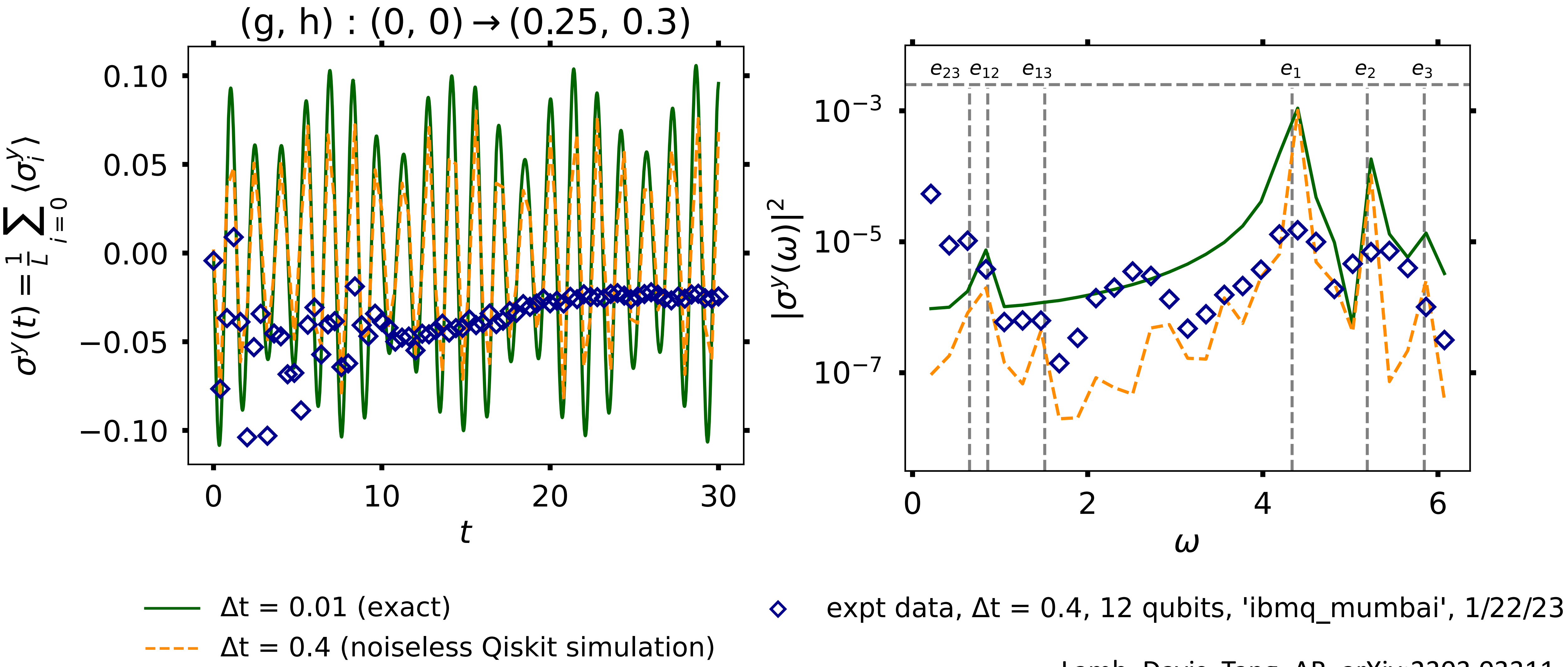




Lamb, Davis, Tang, AR, arXiv:2303.03311

Quantum Simulation Experimental Data



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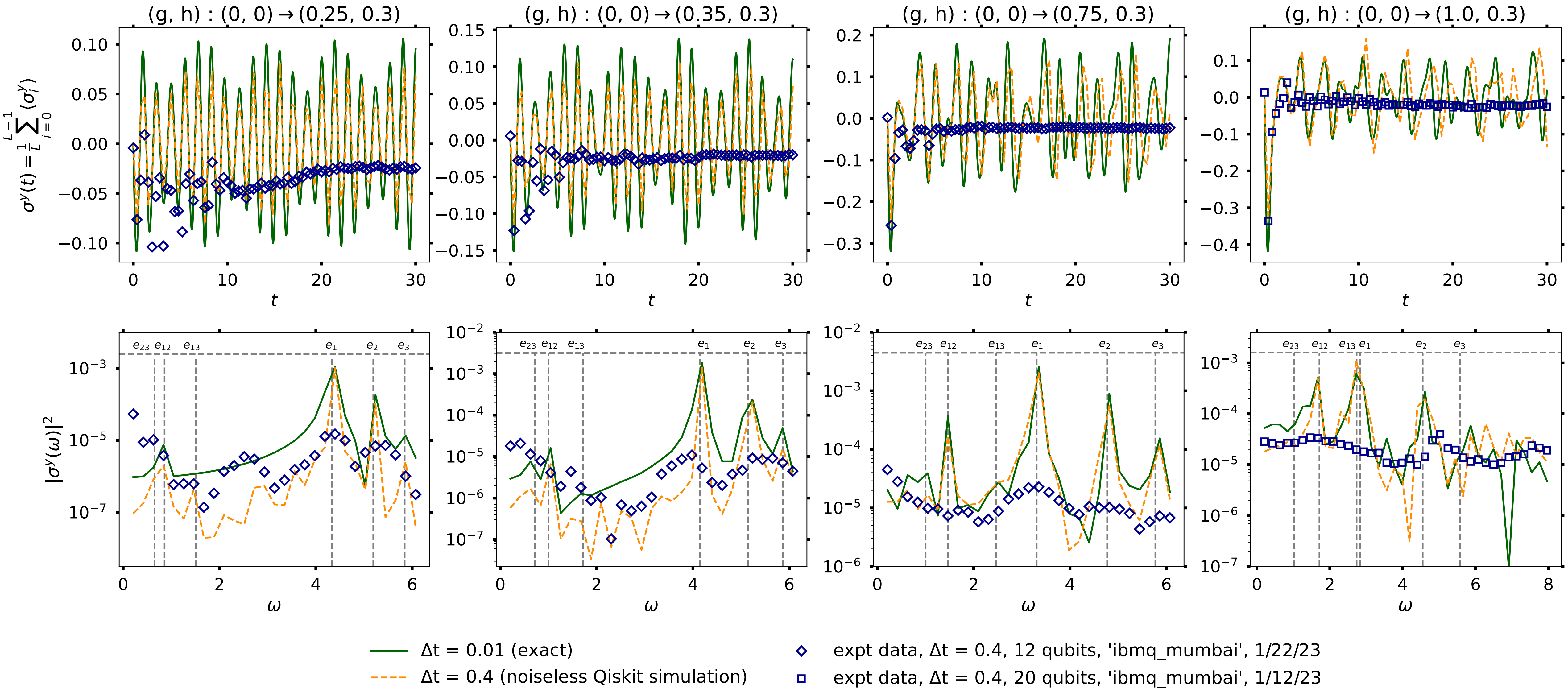
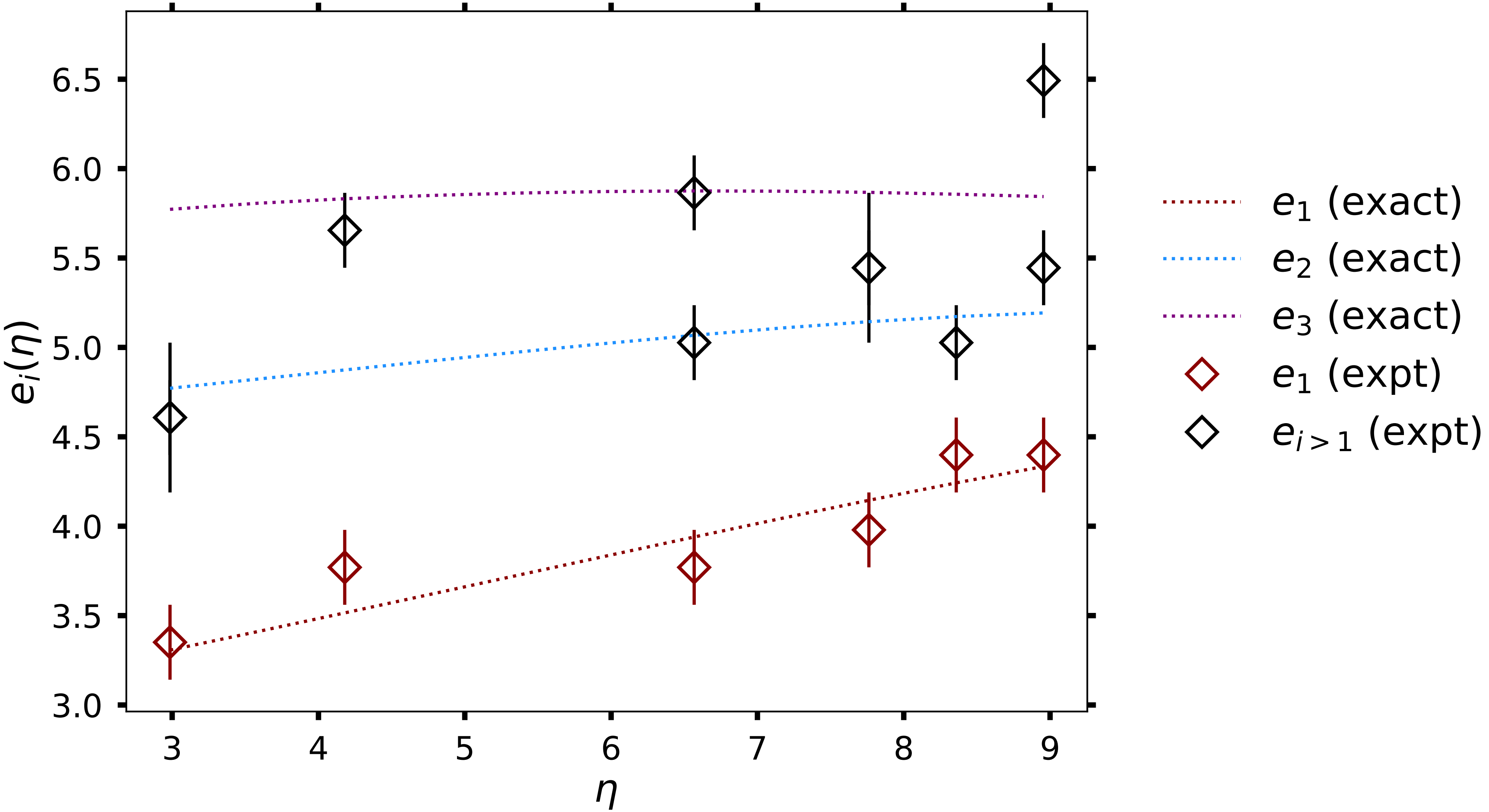


Lamb, Davis, Tang, AR, arXiv:2303.03311

Ising meson energies: experimental vs exact results



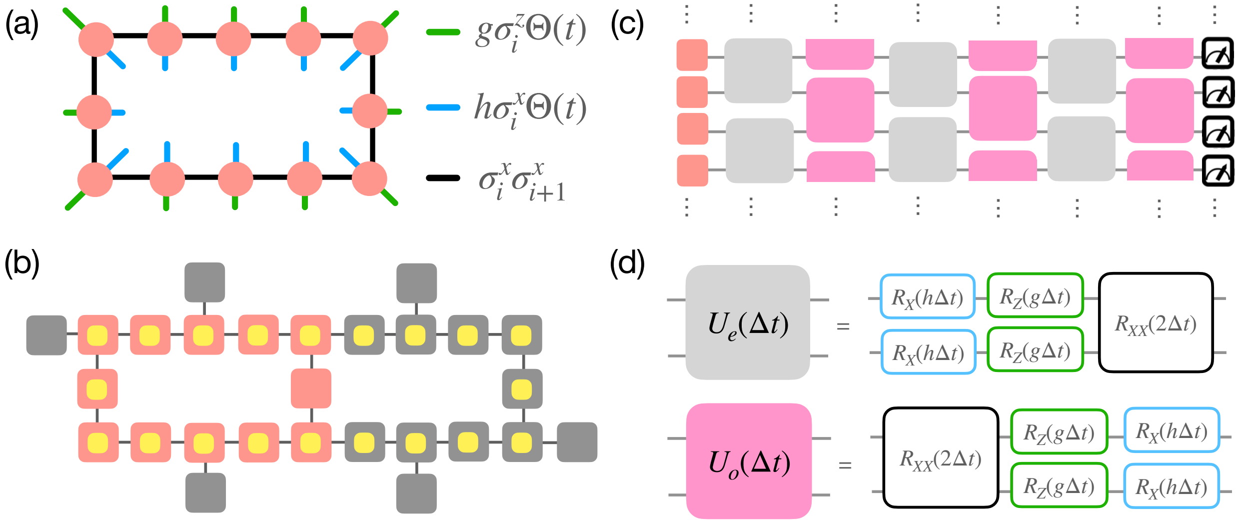
$$\eta = \frac{2\pi(1-g)}{h^{8/15}}$$

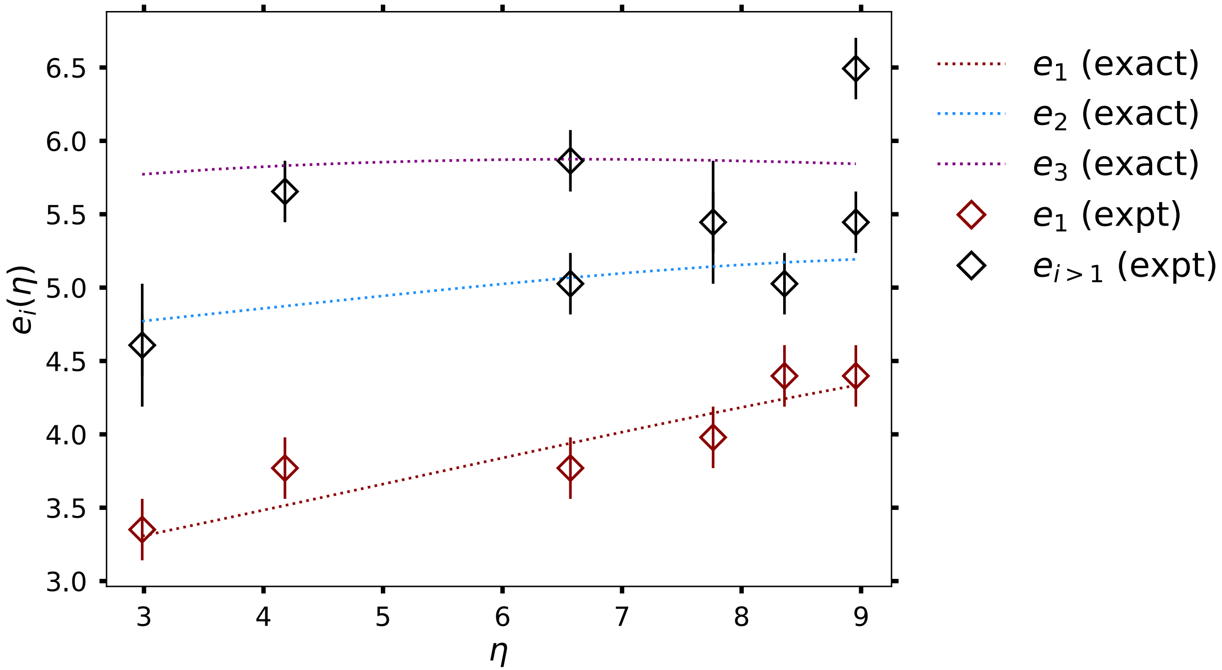
Lamb, Davis, Tang, AR, arXiv:2303.03311

Summary

Noisy Intermediate Scale Quantum can simulate low-dimensional QFTs

-- example: Ising field theory



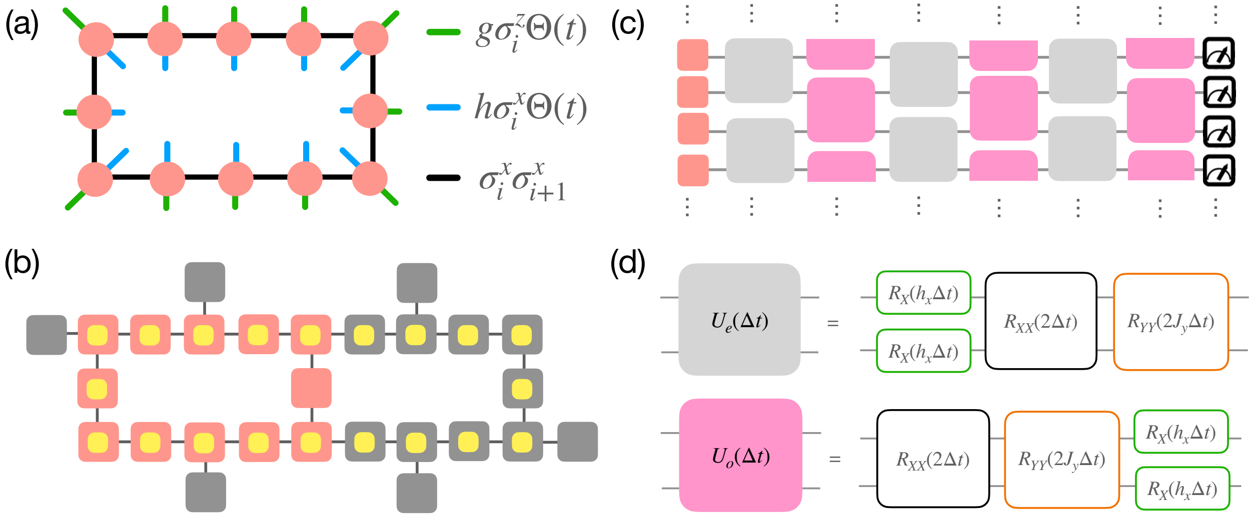


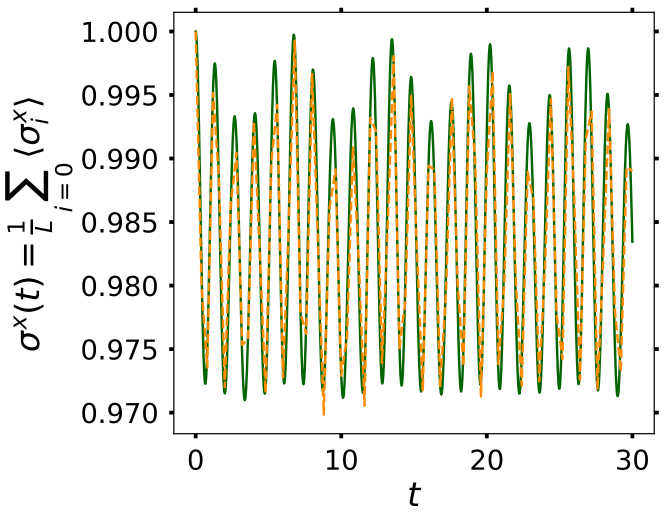
Summary

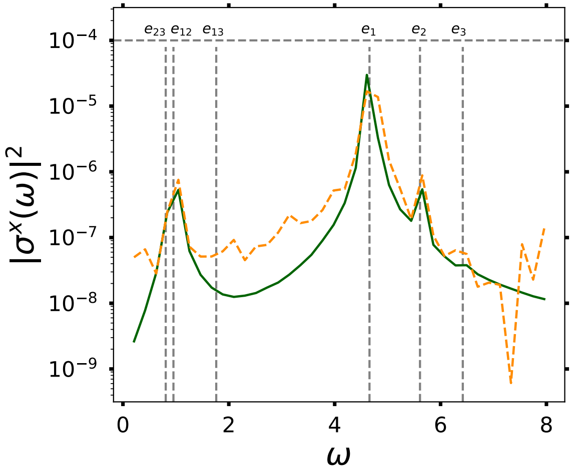
Noisy Intermediate Scale Quantum can simulate low-dimensional QFTs

-- example: Ising field theory

Approach readily generalizable to a wide-family of quantum spin-chains







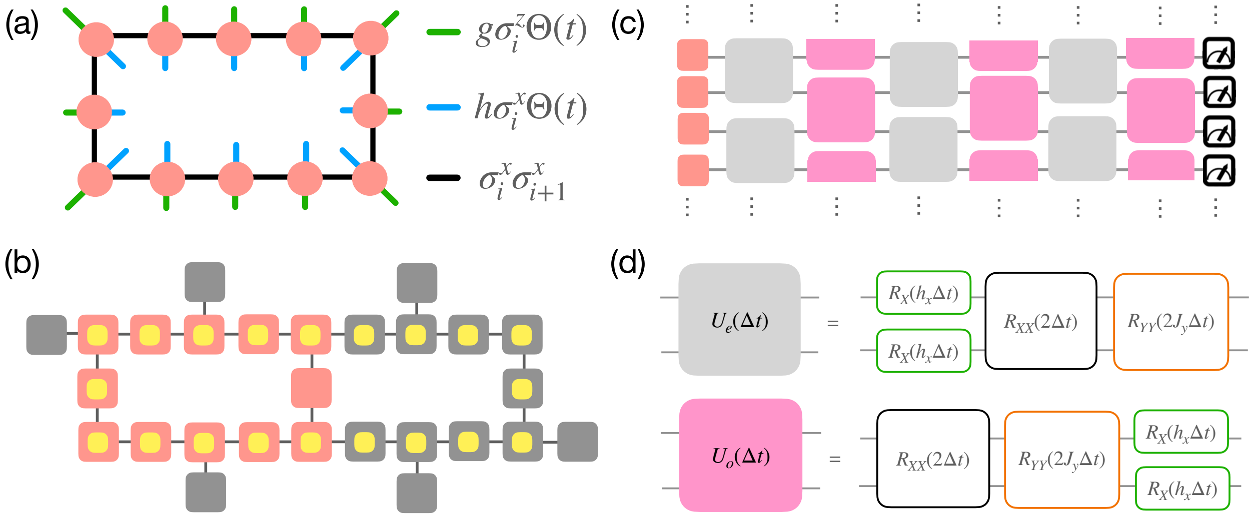
Ongoing work on the quantum sine-Gordon model

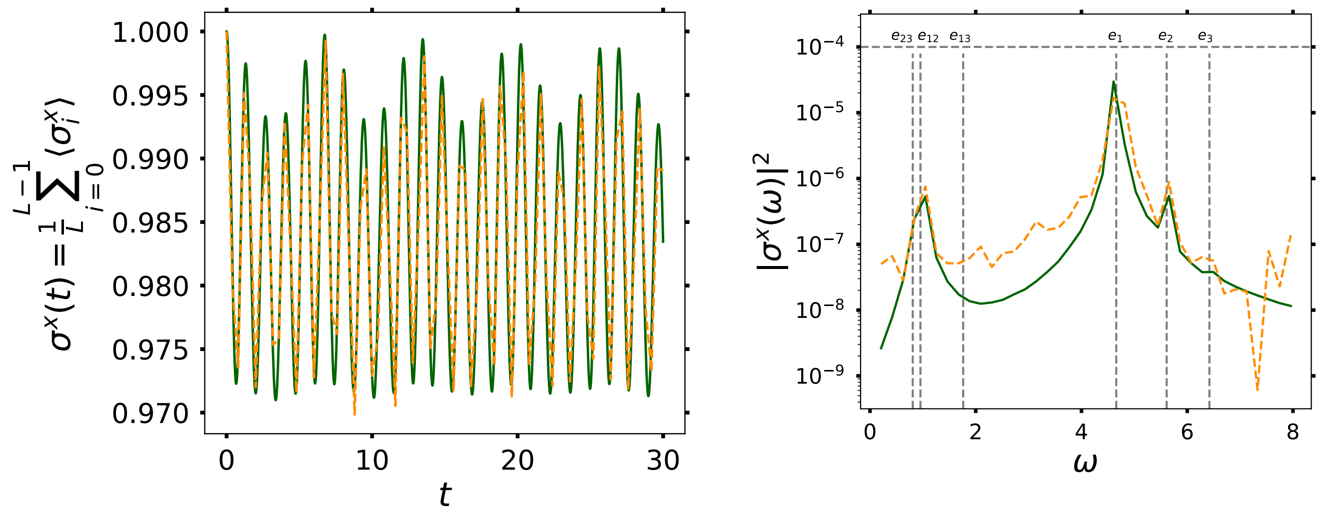
Outlook

Measurement of scattering matrix amplitudes

Improve resilience to noise – `a bit' of error-correction

Towards problems which cannot be solved with classical computers

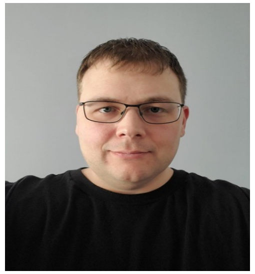




Ongoing work on the quantum sine-Gordon model

Thank You!

Chris Lamb



Rob Davis

Yicheng Tang

More details in arXiv:2303.03311