Many-body Quantum Score: A scalable benchmark for digital and analog QPUs and first results on a Pasqal device

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Collaborators



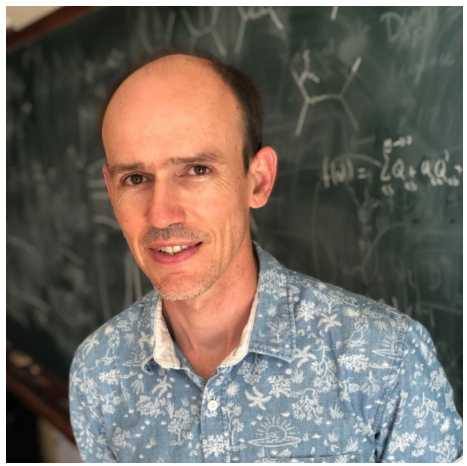
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Outline: 1. Motivations

Motivations

Benchmark protocol

Benchmark for neutral-atom QPU

Analytical results

Conclusion

Why benchmarking?

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4. standardization
   - better interoperability
   - set and follow industry standards
   - more efficient decision-making

Properties of a good benchmark

1. Relevance: should measure important features
2. Representativeness: metrics should be broadly accepted by industry and academia
3. Equity: all systems should be fairly compared, and metrics specialized to a technology only if not relevant for others
4. Repeatability: results should be unambiguous and verifiable
5. Cost-effectiveness: tests should be resource-efficient
6. Scalability: metrics should be computable for systems of different sizes
7. Transparency: metrics should be readily understandable and easy to compare, and informative for non-experts

Inspired from [1907.03626, Dai-Berleant] (see also [2407.08828, Proctor et al., 2406.03905, Mesman et al.])

Benchmark or characterization

- characterization: model device behavior, in particular, the sources of noises and errors
  $\rightarrow$ interpretability
- benchmark: assess device performance using a single or multiple metrics under standardized conditions
  $\rightarrow$ scalability and comparative evaluation

Some reviews: [2503.04905, Lorenz et al.; 2502.06717, Lall et al.; 2408.12064, Hashim et al.; 2407.08828, Proctor et al.; DIN SPEC 91480; etc.]

Levels of characterization

1. component-level
   - physical qubits
   - single- and multi-qubit gates / operations
2. system-level
   - circuit
   - logical qubits (error correction. . .)
   - architecture design (firmware. . .)
3. application-level
   - algorithmic (subroutines)
   - end-user cases
   - test suites
   - frameworks

Analog- and digital-compatible benchmark

Objective [2601.03461, CEA-IPHT/Bull]

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Challenges for analog QPU

- not universal $\Rightarrow$ less abstraction and more technology-dependent
- continuous process instead of discrete operations
- many-body effective models (spins, bosonic, fermionic...)

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- many-body effective models (spins, bosonic, fermionic...)

$\Rightarrow$ application benchmark based on many-body dynamics

- applications in condensed matter and quantum chemistry
- one of the best place to look for exponential advantage

Here: motivate protocol using neutral-atom QPU

Outline

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Outline: 2. Benchmark protocol

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Rydberg spin model

- L spins $1/2$ on a $2d$ lattice
- Effective Hamiltonian in Ising mode

$$H_{\mathrm{R}} \sim \underbrace{\sum_{i<j} \frac{C_6}{\boldsymbol{r}_{ij}^6}\, n_i n_j}_{\text{spin interaction}} + \underbrace{\frac{\hbar\Omega(t)}{2} \sum_i \sigma_i^x}_{\substack{\text{transversal} \\ \text{magnetic field}}} - \underbrace{\hbar\delta(t) \sum_i n_i}_{\substack{\text{longitudinal} \\ \text{magnetic field}}}$$

$$n_i = (\sigma_i^z + 1)/2$$

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$$\approx J \sum_{\langle i,j \rangle} \sigma_i^z \sigma_j^z - Jg \sum_i \sigma_i^x$$

$n_i = (\sigma_i^z + 1)/2, \quad \langle i,j \rangle \rightarrow$ sum over nearest neighors

- recover (approximately) transverse-field Ising model (TFIM)

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3. Stop the evolution at a time t_*, perform measurements on state $|\psi_{\text{exp}}\rangle$ and compare with the theoretical result $|\psi_{\text{target}}\rangle$:
   - theory side: easy to compute correlation functions and other properties for $|\psi_{\text{target}}\rangle$
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4. Setup a score based on agreement precision between the properties of both states.

Many-body quantum score (1)

$\texttt{MBQS}_\psi$ test protocol

1. Setup a spin chain with L spin-$\frac{1}{2}$ equally spaced on a $1d$ ring.
2. Initialize the register with the state $|\psi\rangle$.
3. Evolve the system (quench) with the Ising Hamiltonian at the critical point $g = 1$ for a duration $t_*(L)$ ("surge time").
4. Perform measurements $\{\sigma_i^z\}$ and compute the connected 2-point functions

$$g_\ell^{(2)}(t) := \langle \sigma_1^z \sigma_\ell^z \rangle_c := \langle \sigma_1^z \sigma_\ell^z \rangle - \langle \sigma_1^z \rangle \langle \sigma_\ell^z \rangle$$

5. Compute the score function (average relative error with respect to the theoretical values in Ising model)

$$P_2(L) := \frac{1}{\lfloor L/2 \rfloor - 1} \sum_{\ell=2}^{\lfloor L/2 \rfloor} \left| \frac{g_\ell^{(2)\mathrm{exp}}(t_*) - g_\ell^{(2)\mathrm{th}}(t_*)}{g_\ell^{(2)\mathrm{th}}(t_*)} \right|$$

Many-body quantum score (2)

[2601.03461, CEA-IPHT/Bull]

$\mathtt{MBQS}_{\psi}(\epsilon)$

The score S associated with the initial state $|\psi\rangle$ corresponds to the largest problem size L reached before failing the test with a threshold ϵ, but excluding system sizes below some cut-off:

$$S = L \quad \Longrightarrow \quad \forall L' \leq L : \quad P_2(L') \leq \epsilon.$$

Notes

- typical initial states: $|\psi\rangle = |+\cdots+\rangle\,, |\downarrow\cdots\downarrow\rangle\,, |\downarrow\uparrow\cdots\downarrow\uparrow\rangle \ldots$
- allow for error mitigation if procedure is documented

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- Ising model
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- Periodic boundary conditions
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  - harder for tensor network simulations (MPS...)
- Critical point $g_c = 1$: non-trivial many-body dynamics
  - competition between different terms in Hamiltonian
  - interatomic distance $\approx$ Rydberg blockade radius
  - sensitive to positional noise

Motivations (2)

- Initial states
  - $\texttt{MBQS}_{+}$: $|+\cdots+\rangle$
    - test state preparation (in particular, for neutral-atom QPUs)
    - simpler theoretically since $\langle\sigma^z_\ell(t)\rangle = 0$
  - $\texttt{MBQS}_{\downarrow}$: $|\downarrow\cdots\downarrow\rangle$
    - natural on neutral-atom QPUs
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- Surge time $t_*(L)$
  - physical meaning ($\sim$ time needed for signal to propagate to antipodal point)
  - all spins become highly correlated
  - highly entangled state, $S_{\text{vN}} = O(L)$ (volume law)
    $\Rightarrow$ target is non-trivial quantum state
  - increases with $L \Rightarrow$ non-constant difficulty
    (probe sensitivity to decoherence)
  - increases with interatomic distance

Motivations (3)

- Interatomic distance a
  - determines coupling J = timescale $\propto a^{-6}$
  - no canonical value of J (or a) for a given machine
  - optimal value = tradeoff between different effects
    - L (number of atoms fitting in the chamber)
    - positional noise (increases when a decreases)
    - dephasing noise (increases when a increases)

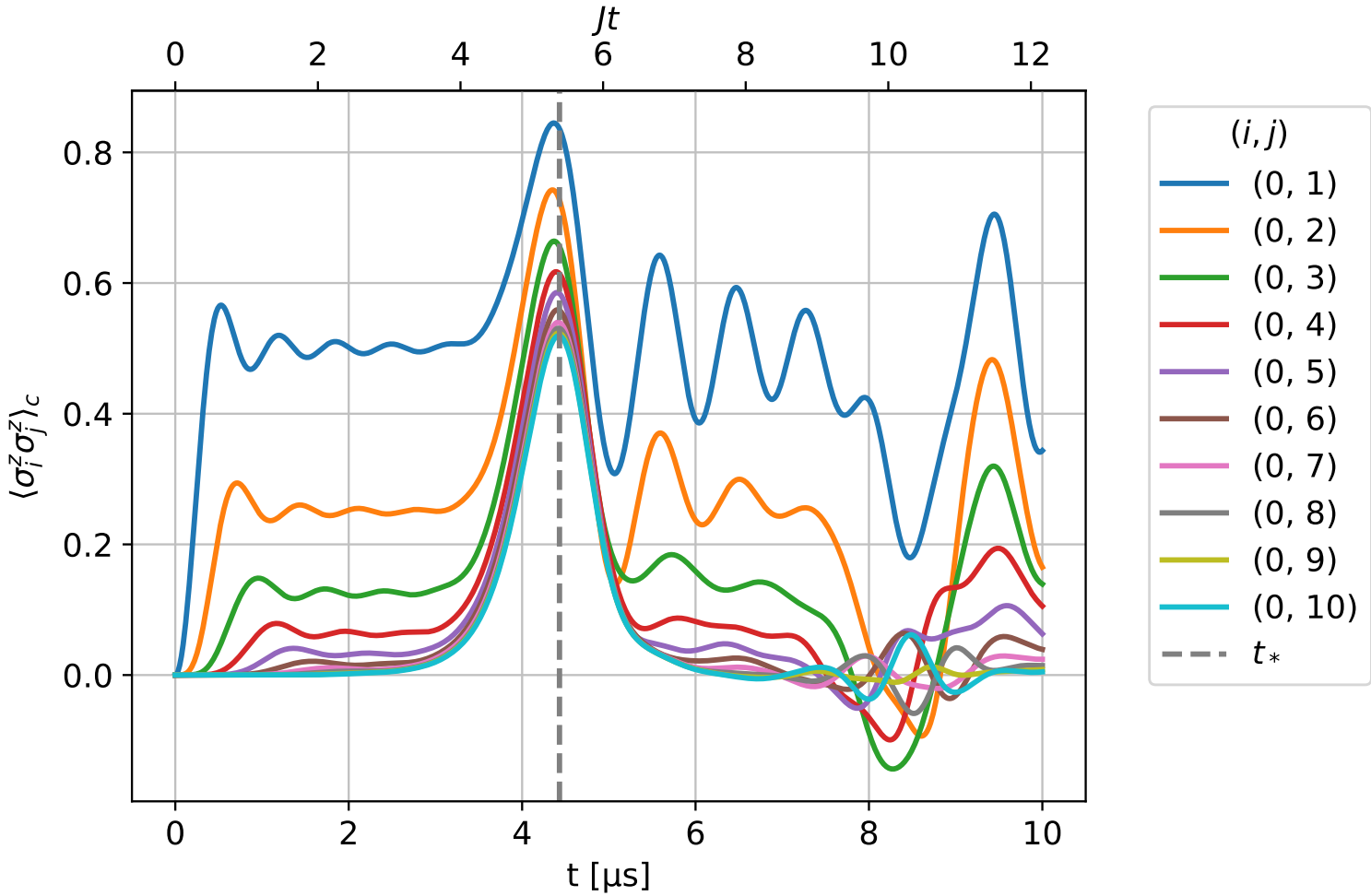
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    - L (number of atoms fitting in the chamber)
    - positional noise (increases when a decreases)
    - dephasing noise (increases when a increases)
- Several extensions are possible
  - check values for several peaks (second and later more sensitive to dephasing)
  - check values for higher n-point correlation functions
  - combine results for different ψ

Caveats

- "hard problem" for classical simulations (brute-force, MPS), not in the sense of complexity theory
- cannot certify that a quantum device has been used
- $g_\ell^{(2)}(t_*; L) = O(\mathrm{e}^{-L})$: weak signal when L increases
  $\rightarrow$ need higher number of shots (test repetition rate)

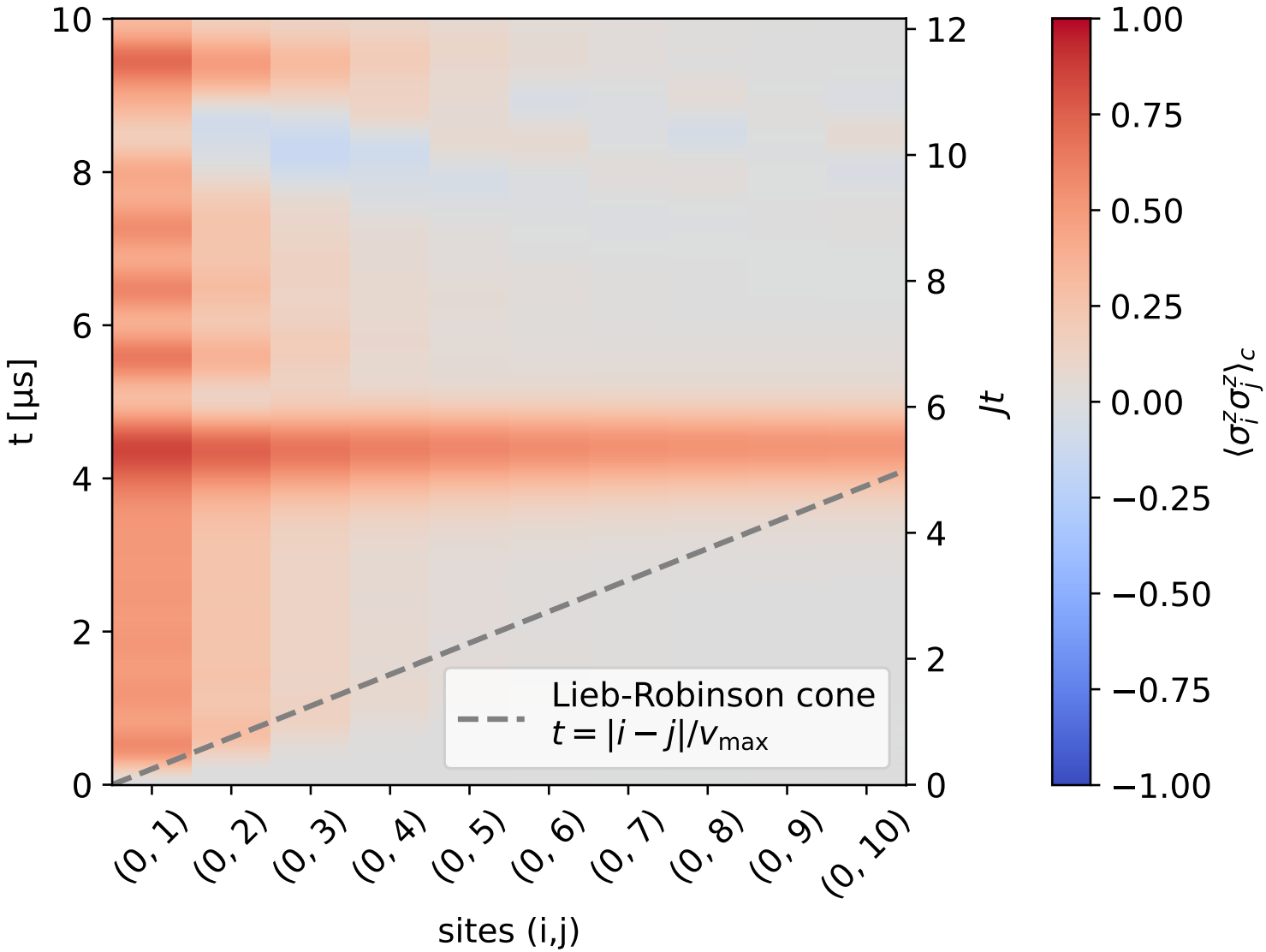
Global correlation surge



$$\langle \sigma_1^z \sigma_\ell^z \rangle_c := \langle \sigma_1^z \sigma_\ell^z \rangle - \langle \sigma_1^z \rangle \langle \sigma_\ell^z \rangle$$

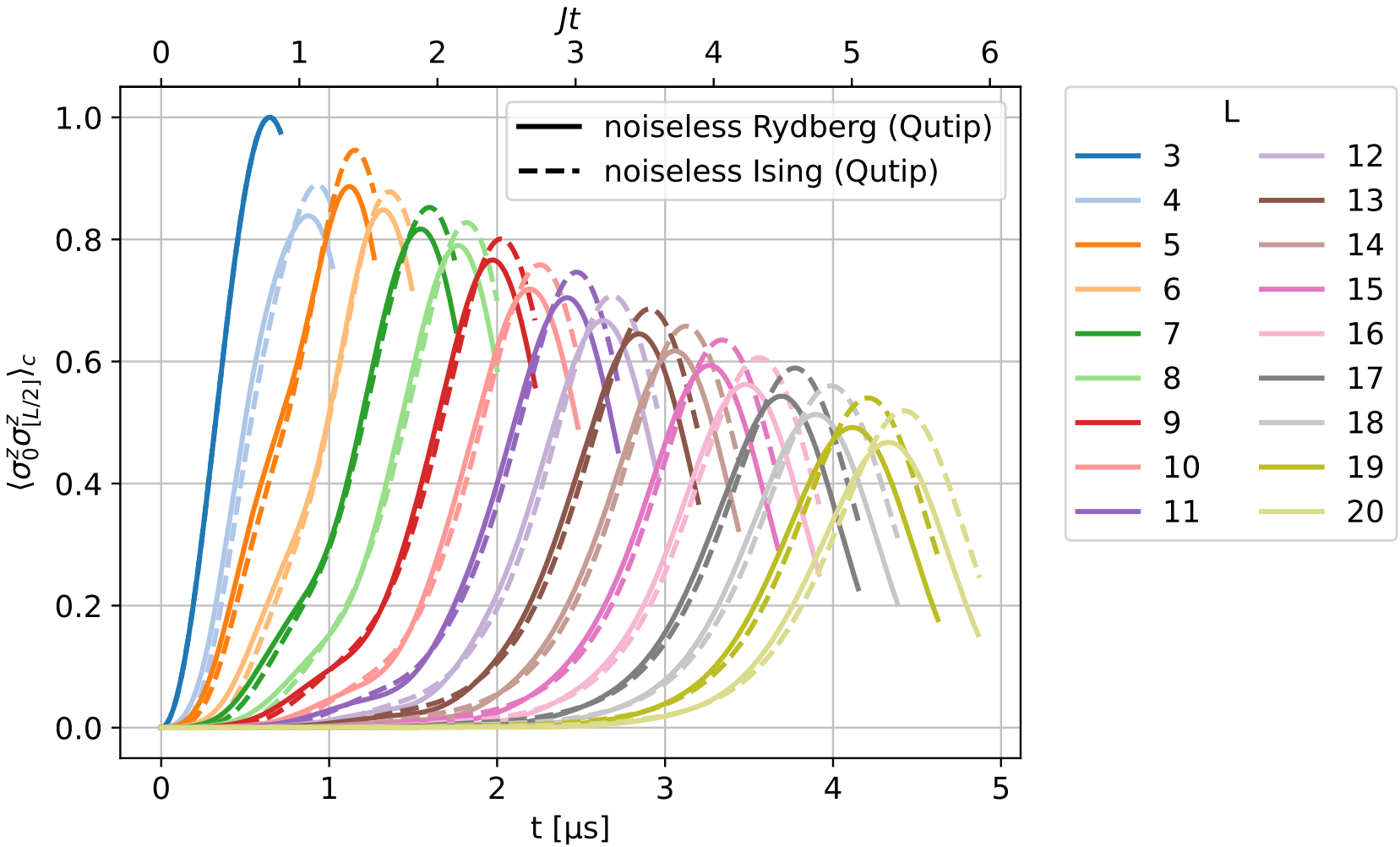
Model: Ising, $R = 7.5\,\mu\text{m}$ ($J \approx 1.22$), $|\psi_{\text{ini}}\rangle = |+\cdots+\rangle$, $L = 20$

Information propagation



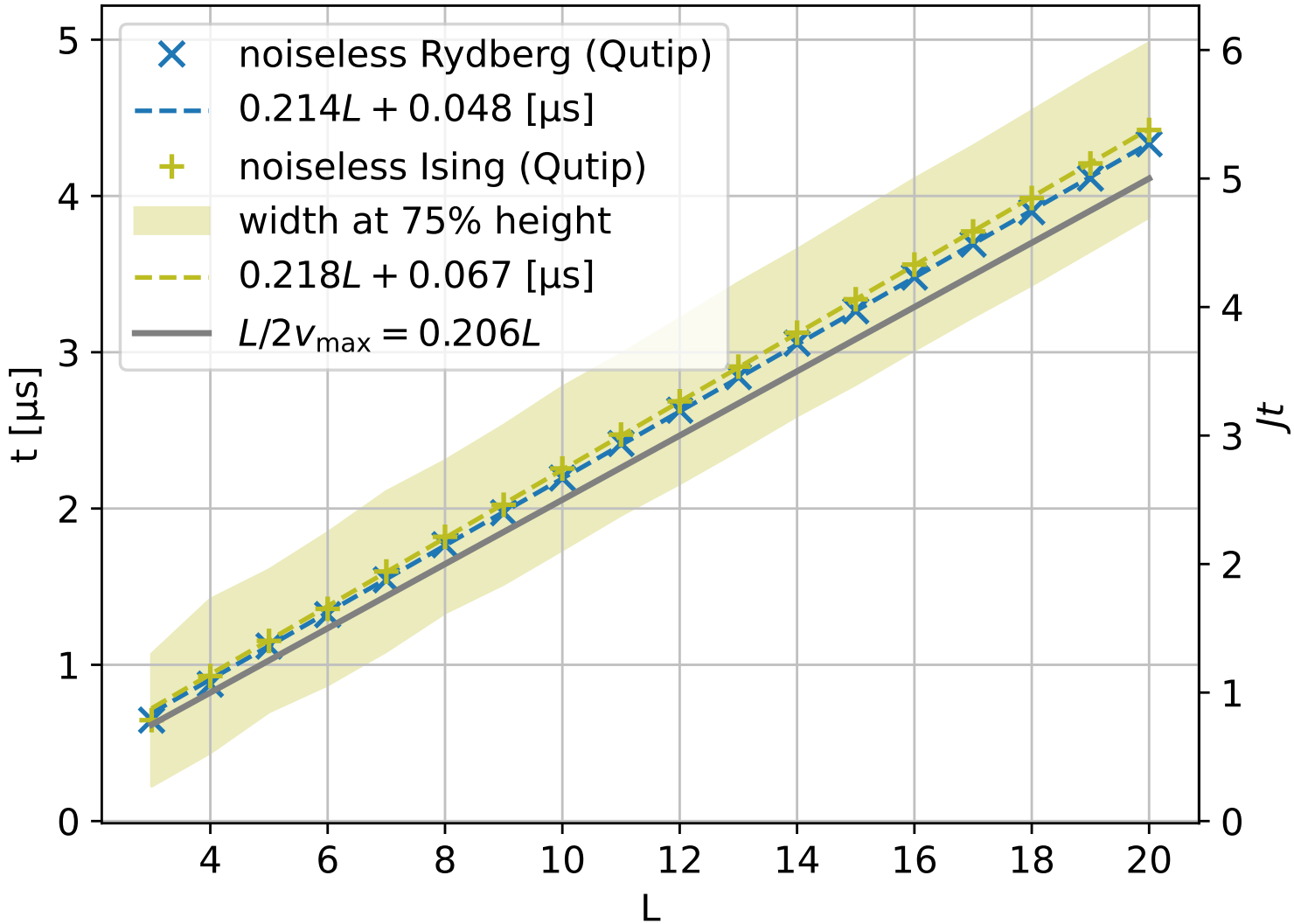
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Antipodal correlations



$R = 7.5\,\mu\text{m}$ ($J \approx 1.22$), $|\psi_{\text{ini}}\rangle = |+\cdots+\rangle$, $L = 20$

surge time prediction with linear regression



- $R^2 = 0.995$, RMSE $= 0.016$
- linear behavior $\rightarrow$ ballistic propagation

Outline: 3. Benchmark for neutral-atom QPU

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- Target: $\mathtt{MBQS}_{\downarrow}$
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  - $\texttt{MBQS}_{+}$ is too challenging for current QPU
  - Ising is still a good reference (difference with Rydberg $\sim 1\,\%$)
- Pulse sequence
  - constant Ω to reach critical point $g = 1$
  - constant δ to remove longitudinal field

  $\rightarrow$ match Ising model up to small corrections
- Implementation at TGCC
  - emulation with Bull's QLM40
  - Pasqal's Ruby QPU (Orion Beta)

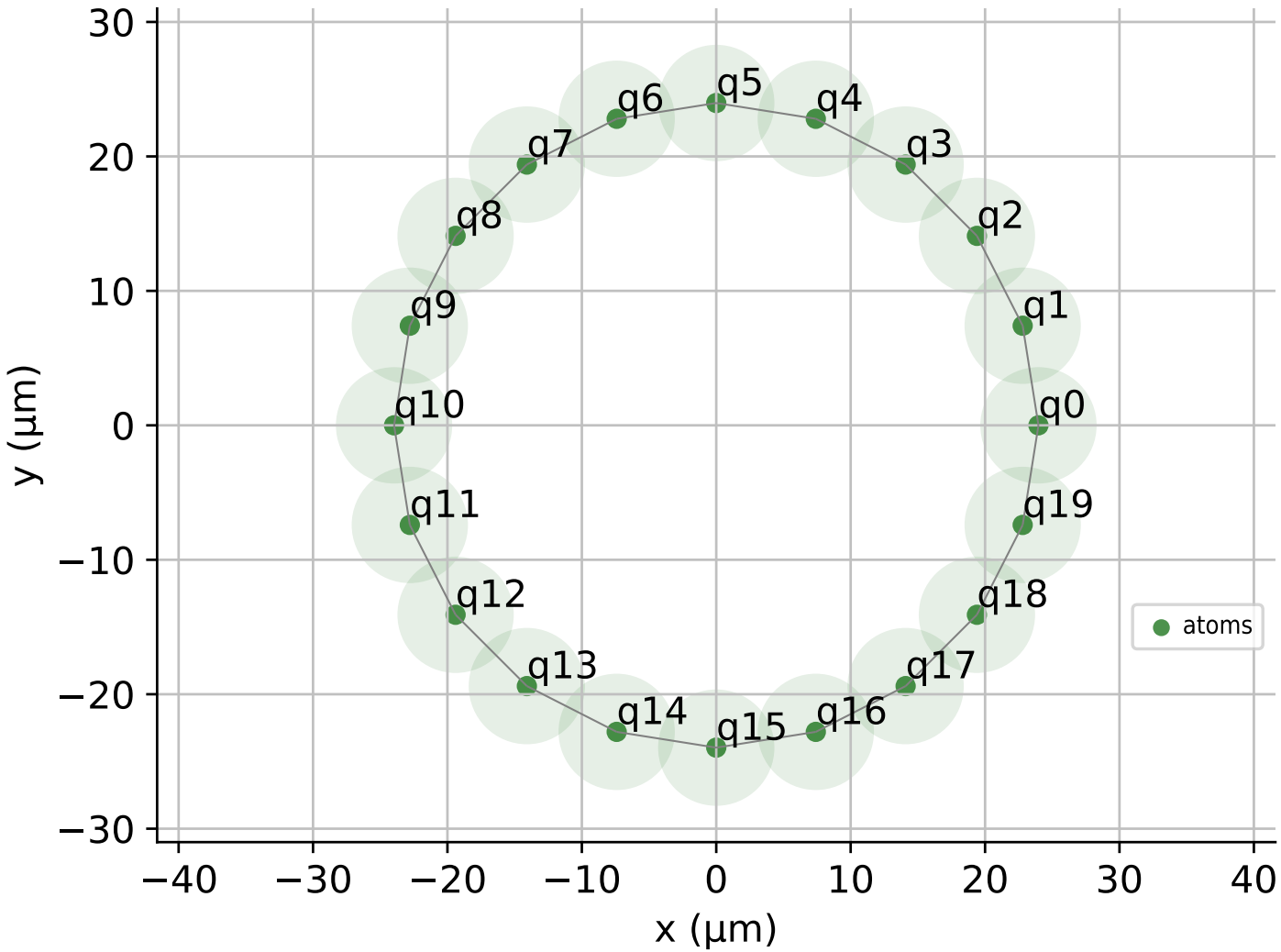
$\rightarrow$ First application in the world on a commercial neutral-atom device!

[Special thanks to people from Pasqal and TGCC]

[Pasqal/Genci]



Atom register and pulses

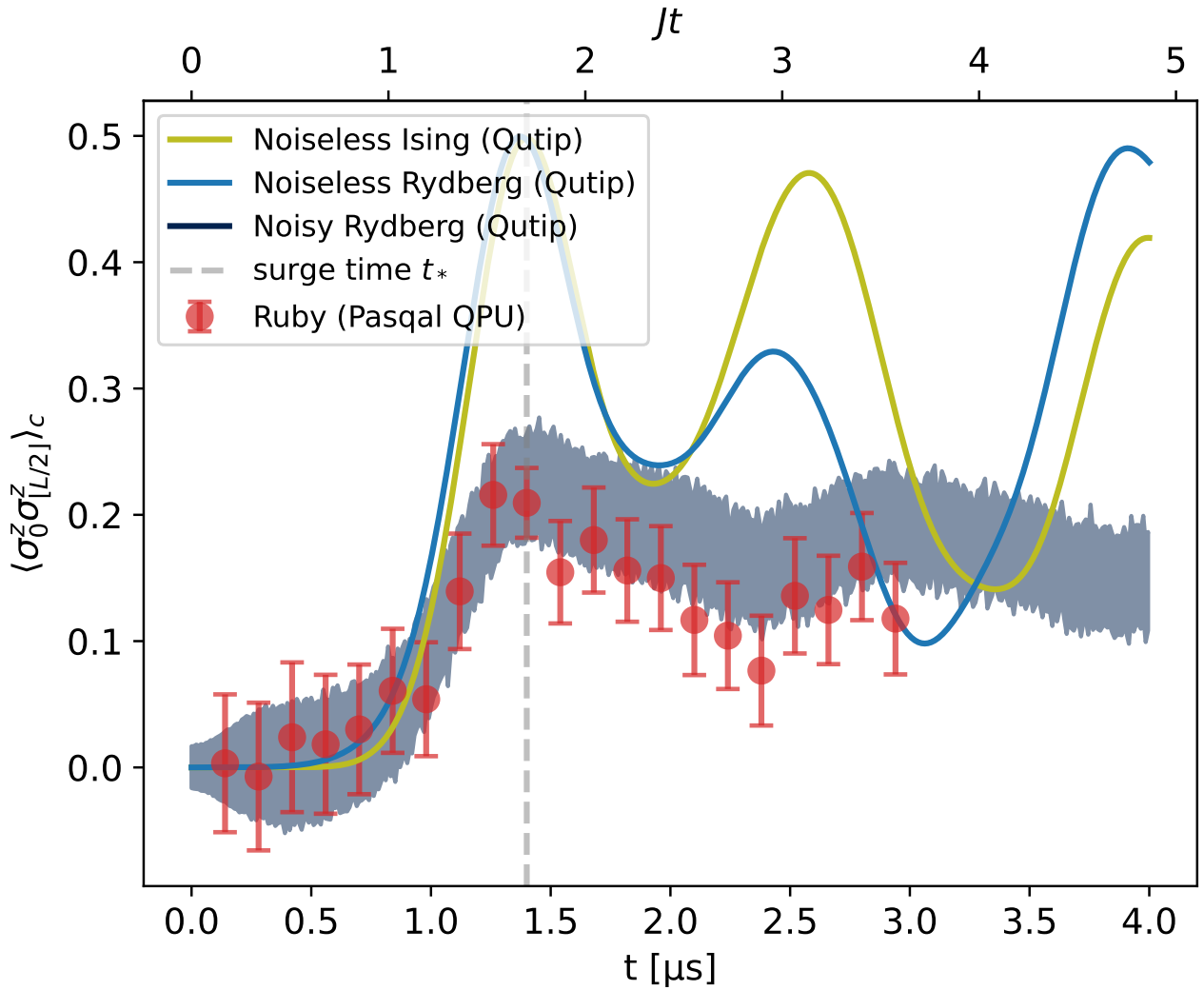


green area: half of Rydberg blockade radius

Noise sources

- dissipation due to quantum decoherence:
  - relaxation time: $T_1 = 100\,\mu s$
  - dephasing time: $T_2 = 20\,\mu s$
- register noise (atom position fluctutations between shots)
  $\sigma_r^{x,y} \approx 0.2\,\mu m$, $\sigma_r^z \approx 0.7\,\mu m$, controlled by:
  - temperature $T = 20\,\mu K$
  - trap depth $U_{trap} = 150\,\mu K$
  - trap waist $w = 1\,\mu m$
  - wavelength $\lambda = 0.85\,\mu m$
- SPAM errors (state preparation and measure)
  - preparation error: $p_{prep} = 0.01$
  - false negative readout: $p_{fn} = 0.07$
  - false positive readout: $p_{fp} = 0.02$
- Doppler noise from thermal motion
- laser noises
  - amplitude fluctuation between shots: $\sigma_\Omega = 0.02$
  - finite resolution of the laser beam: $w_\Omega = 175\,\mu m$
  - detuning fluctuation between shots: $\sigma_\delta = 2\pi \times 0.05\,rad/\mu s$
  - detuning high-frequency noise (PSD): confidential
- pulse shaping (sequence modulation) + shot noise

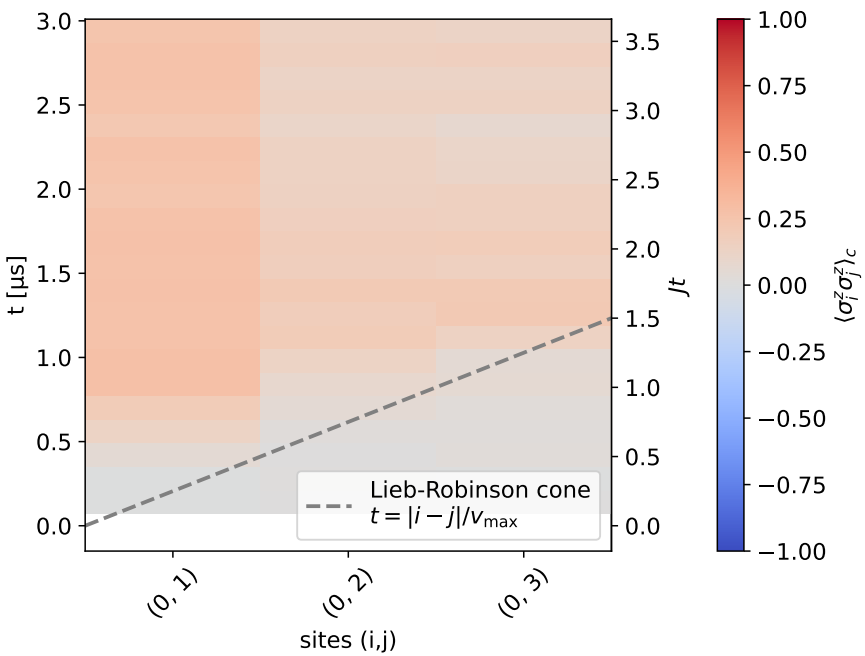
2-point correlation functions: $L = 6$



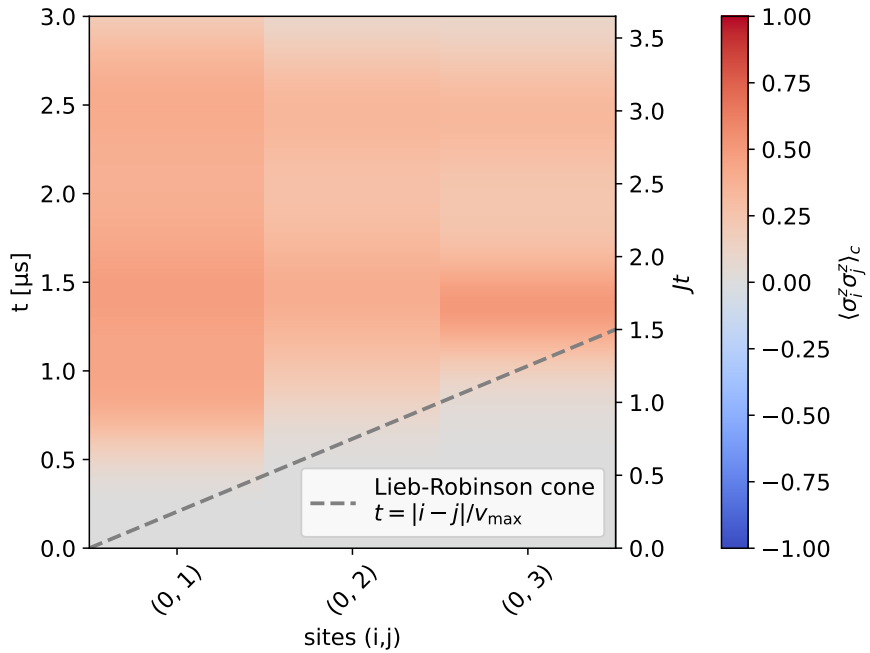
$\Rightarrow$ non-trivial correlations measured, quantitative agreement with the noise model

Information propagation: $L = 6$

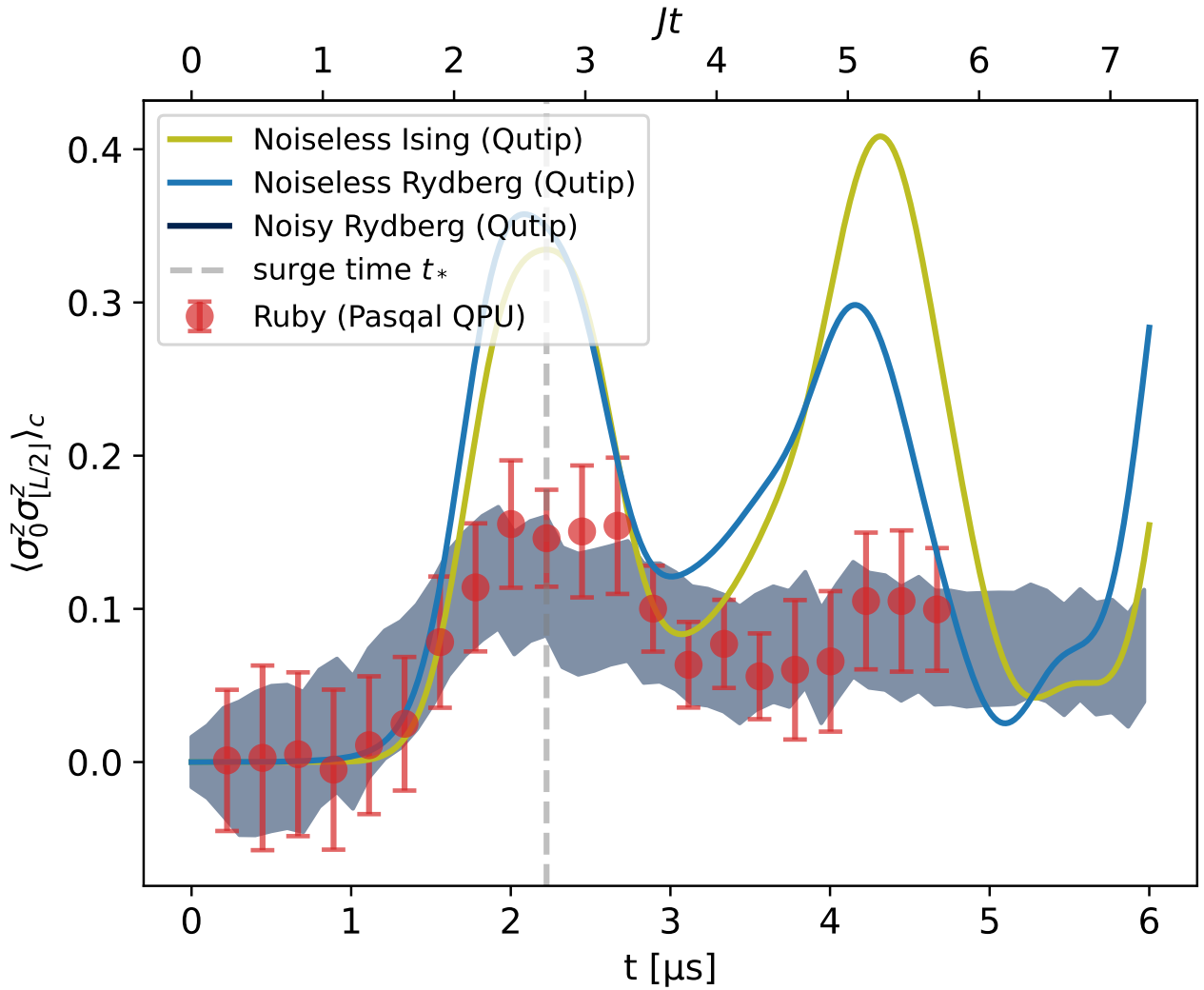
Ruby



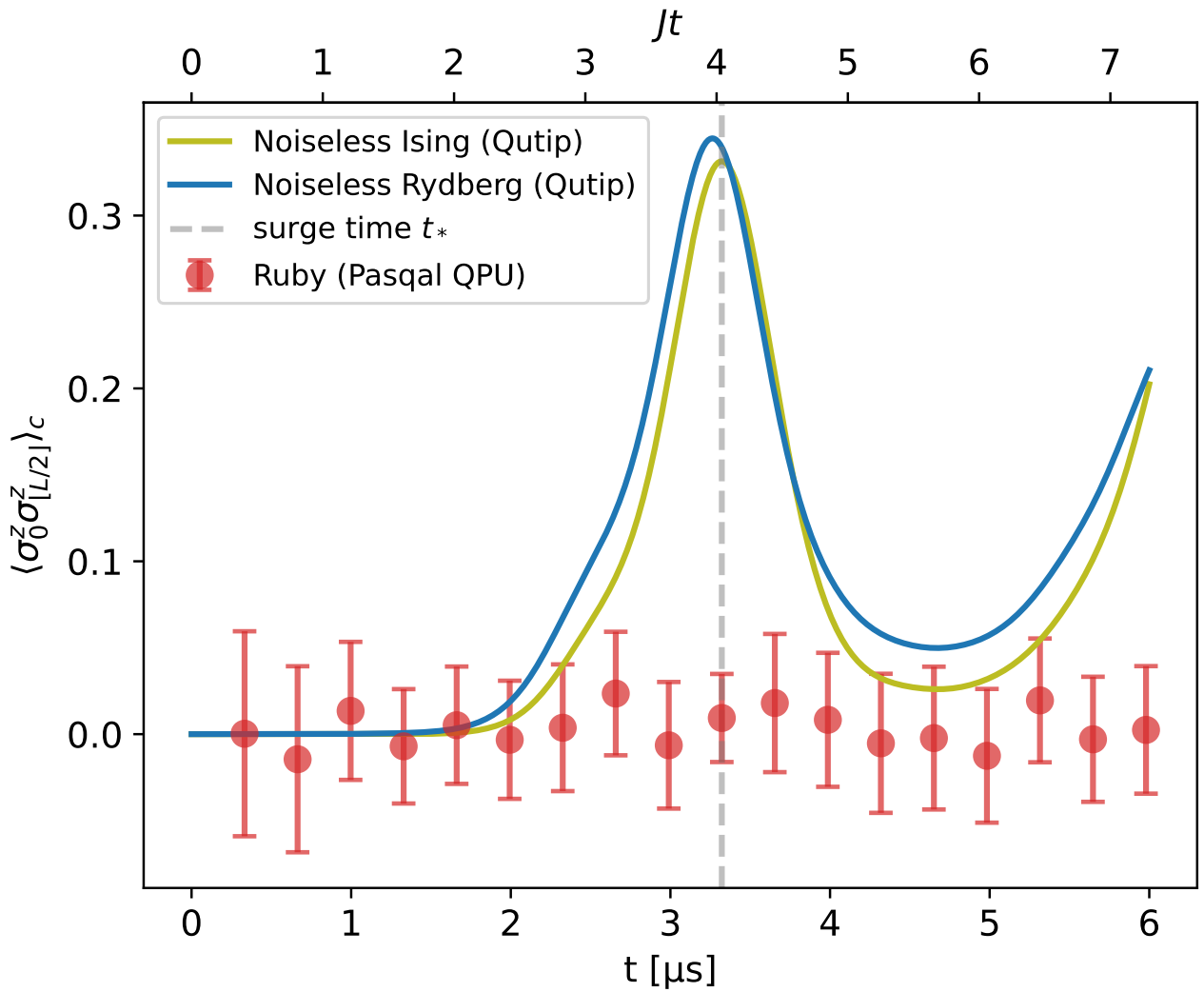
Simulation



2-point correlation functions: $L = 10$

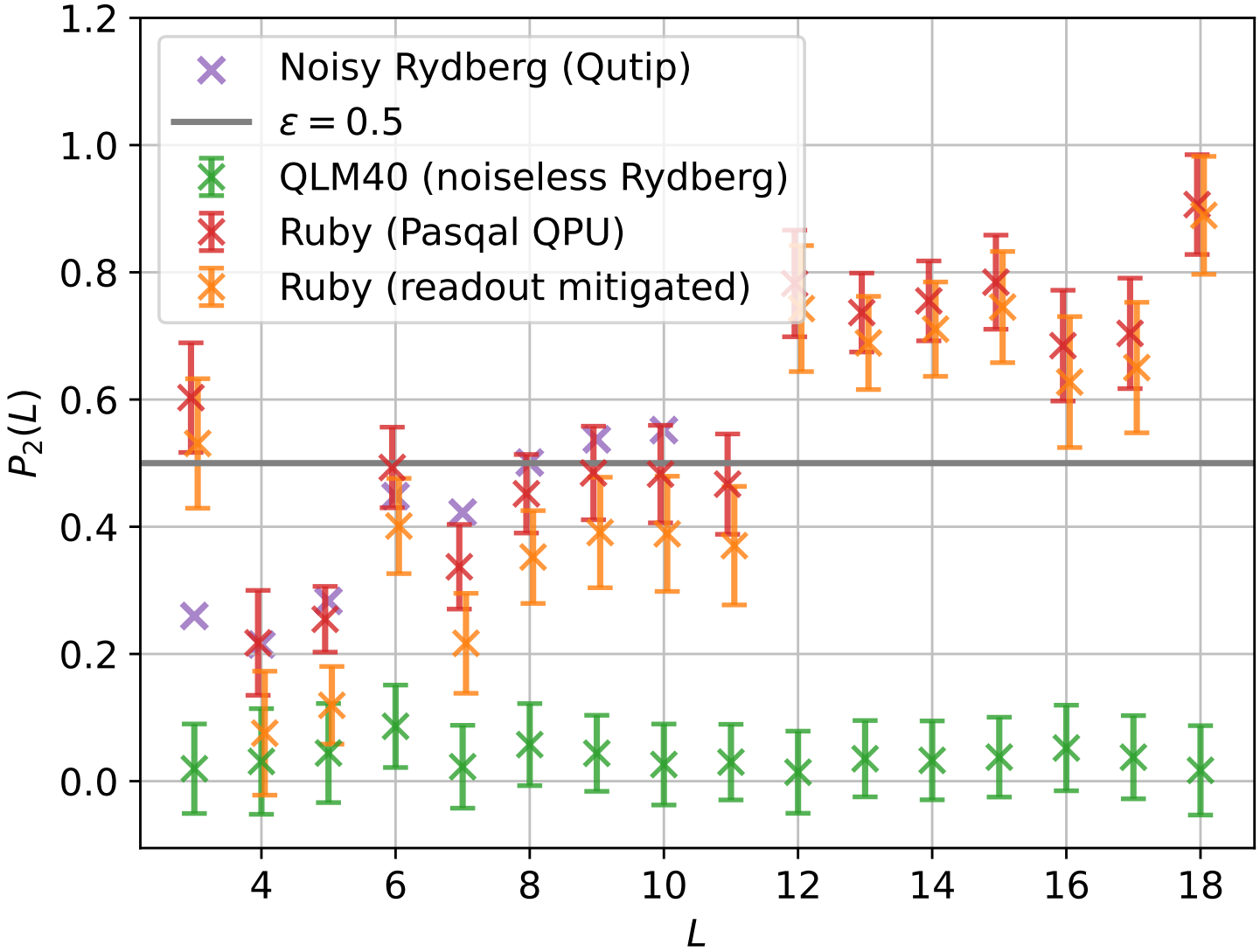


2-point correlation functions: $L = 15$



$\Rightarrow$ low correlations in measurements, test failed

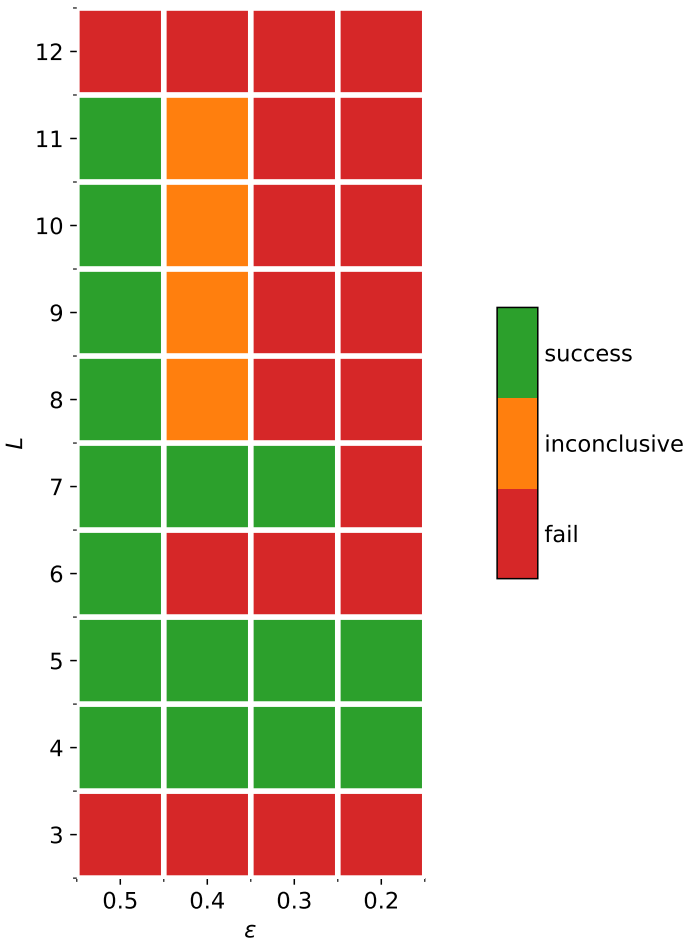
2-point correlation errors



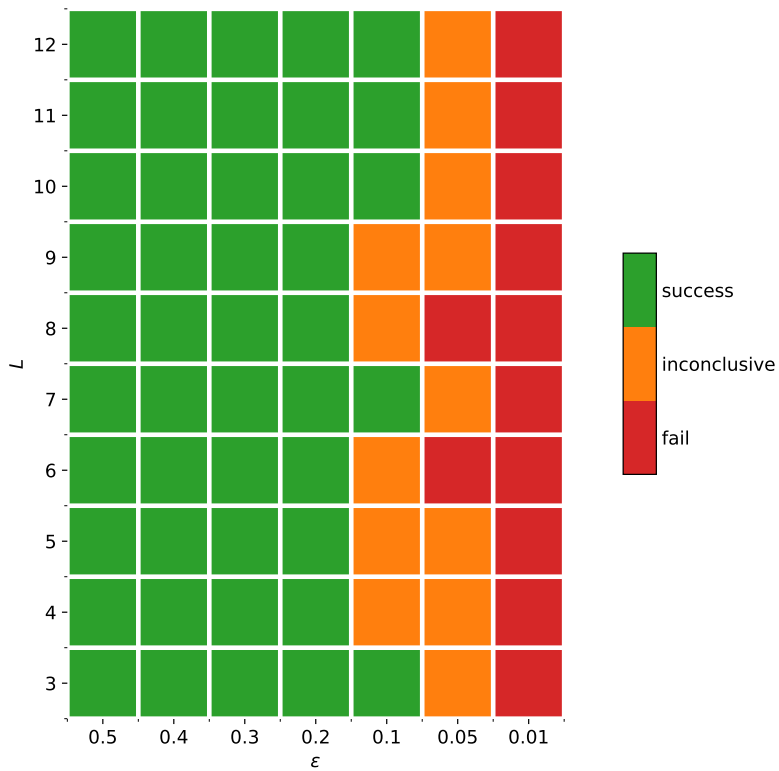
$|\psi_{\text{ini}}\rangle = |\downarrow \cdots \downarrow\rangle$, $R = 7.5\,\mu\text{m}$

Volumetric success plot

Ruby



QLM (noiseless Rydberg)



$$\Rightarrow \texttt{MBQS}_{\downarrow}(0.5) = 11$$

Outline: 4. Analytical results

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Effective Hamiltonian (1)

- consider L qubits on a $2d$ lattice located at $\boldsymbol{r}_i$ $(i = 1, \ldots, L)$
- natural basis:

$$\sigma_i^z \left|\downarrow\right\rangle_i = -\left|\downarrow\right\rangle_i, \qquad \sigma_i^z \left|\uparrow\right\rangle_i = +\left|\uparrow\right\rangle_i$$

- Hamiltonian (Pasqal)

$$H_{\mathrm{RI}} = \sum_{i<j} \frac{C_6}{r_{ij}^6} n_i n_j + \frac{\hbar\Omega(t)}{2} \sum_i \sigma_i^x - \hbar\delta(t) \sum_i n_i,$$

  first term: van der Waals interaction

- number operator and distance

$$n_i = \frac{\sigma_i^z + 1}{2}, \qquad r_{ij} := |\boldsymbol{r}_i - \boldsymbol{r}_j|$$

- $\Omega(t)$ and $\delta(t)$: external laser amplitude and detuning

Effective Hamiltonian (2)

- Hamiltonian in terms of Pauli matrices

$$H_{\mathrm{RI}} = J \sum_{i<j} \frac{\sigma_i^z \sigma_j^z}{(r_{ij}/a)^6} + h(t) \sum_i \sigma_i^x + \sum_i m_i(t)\, \sigma_i^z + C_L(t)$$

- parameters

$$J := \frac{C_6}{4a^6}, \qquad C_L(t) := J \sum_{i<j} \frac{1}{(r_{ij}/a)^6} - \frac{\hbar \delta(t) L}{2}$$

$$h(t) := \frac{\hbar \Omega(t)}{2}, \qquad m_i(t) := \hat{m}_i - \frac{\hbar \delta(t)}{2},$$

$$\hat{m}_i := J \sum_{j \neq i} \frac{1}{(r_{ij}/a)^6}.$$

a length scale (typically, interatomic distance)

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- note: for QuEra, $\delta(t) \to \delta_i(t) := \Delta_i \delta(t)$, $\Delta_i \in [0, 1]$

1d spin chains (1)

- $1d$ Hamiltonian:

$$H_{\mathrm{RI}} = J \sum_{i=1}^{N-\alpha} \sum_{\ell=1}^{N-i} \frac{\sigma_i^z \sigma_{i+\ell}^z}{\ell^6} + h(t) \sum_i \sigma_i^x + \sum_i m_i(t) \sigma_i^z + C_L(t)$$

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- atoms on a line (open boundary conditions, $\alpha = 1$)

$$\hat{m}_i := J\big(H_{i-1,6} + H_{L-i,6}\big), \qquad H_{n,m} := \sum_{k=1}^{n} \frac{1}{k^m}$$

$$\sum_{i=2}^{L-1} \hat{m}_i = J\left[\frac{\pi^6}{945}(L-1) - \frac{1}{24}\,\psi^{(4)}(L) - \frac{1}{120}\,(L-1)\psi^{(5)}(L) - \zeta(5)\right]$$

functions: generalized harmonic numbers, zeta and polygamma

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$$H_{\mathrm{RI}} = J \sum_{i=1}^{N-\alpha} \sum_{\ell=1}^{N-i} \frac{\sigma_i^z \sigma_{i+\ell}^z}{\ell^6} + h(t) \sum_i \sigma_i^x + \sum_i m_i(t) \sigma_i^z + C_L(t)$$

- atoms on a line (open boundary conditions, $\alpha = 1$)

$$\hat{m}_i := J\big(H_{i-1,6} + H_{L-i,6}\big), \qquad H_{n,m} := \sum_{k=1}^{n} \frac{1}{k^m}$$

$$\sum_{i=2}^{L-1} \hat{m}_i = J\left[\frac{\pi^6}{945}(L-1) - \frac{1}{24}\,\psi^{(4)}(L) - \frac{1}{120}\,(L-1)\psi^{(5)}(L) - \zeta(5)\right]$$

  functions: generalized harmonic numbers, zeta and polygamma

- atoms on a ring (periodic boundary conditions, $\alpha = 0$)

$$\hat{m}_i = \frac{J}{945}\,(L^2-1)(191 + 23L^2 + 2L^4)\sin^6\frac{\pi}{L}$$

Differences with Ising model

- coupling between all sites, but relatively small effect
  example: next-to-nearest neighbor coupling J_2 for a ring

$$\underset{\text{(line)}}{0.016} \leq \frac{J_2}{J} \leq \underset{\text{(square)}}{0.125}$$

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- site-dependent and time-dependent longitudinal field
  $\rightarrow$ cannot be cancelled by tuning $\delta(t)$ except for translation-invariant chain (ring)

$$\hbar\delta \approx 2\hat{m}_i \quad \Longrightarrow \quad m_i \approx 10^{-2} J$$

  - line

$$\hat{m}_i \approx \begin{cases} 1.02 \times J & i = 1, N \\ 2.03 \times J & 1 < i < N \end{cases}$$

  - ring

$$(N \to \infty) \quad 2.035 \leq \hat{m}_i/J \leq 2.125 \quad (N = 4)$$

Outline: 5. Conclusion

Motivations

Benchmark protocol

Benchmark for neutral-atom QPU

Analytical results

Conclusion

Summary and outlook

Achievements:

- benchmark protocol $\texttt{MBQS}_\psi(\epsilon)$ for analog and digital QPUs
- implementation on Ruby QPU at TGCC
- study in details the propagation of correlations in Ising and Rydberg spin chains

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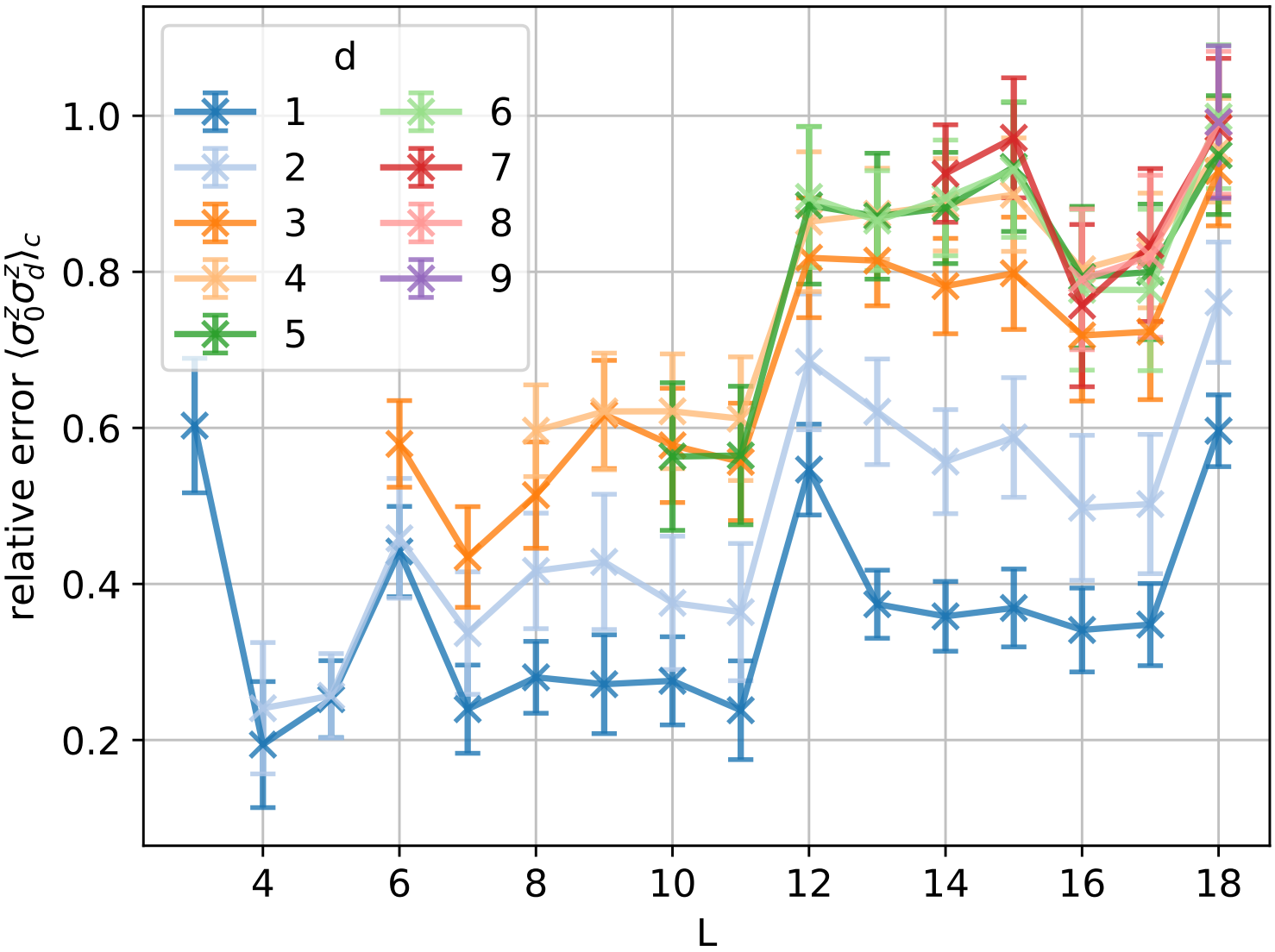
Future directions:

- open-source implementation and compare different platforms
- generalize benchmark to $2d$ geometries
- building blocks for analog simulations (quantum control state preparation, error mitigation...) [2507.07875, Carrera-HE-Misguich]
- test many-body physics questions on neutral-atom QPUs

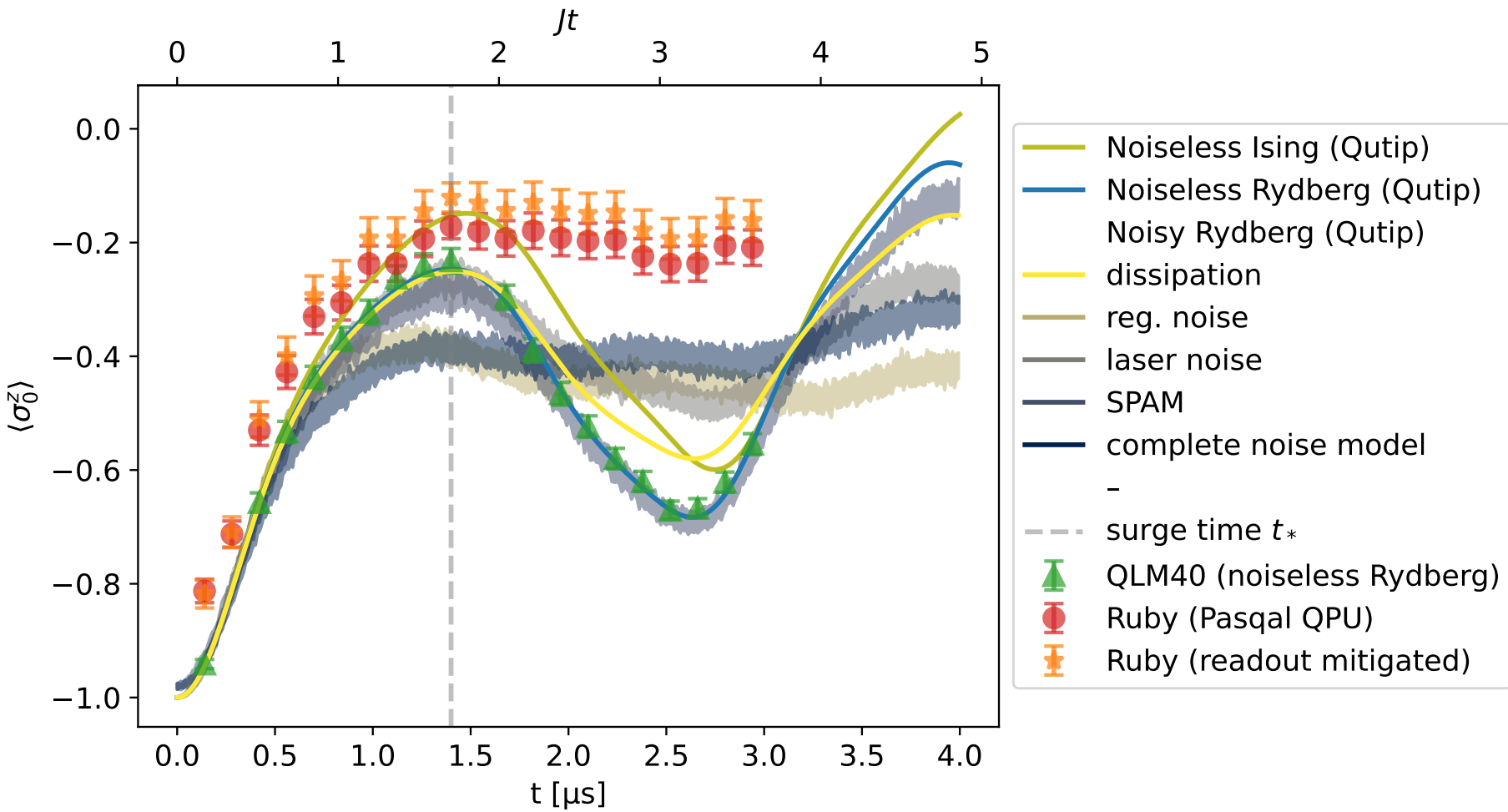
Outline: 6. Backup

Backup

Distance dependence of the relative errors

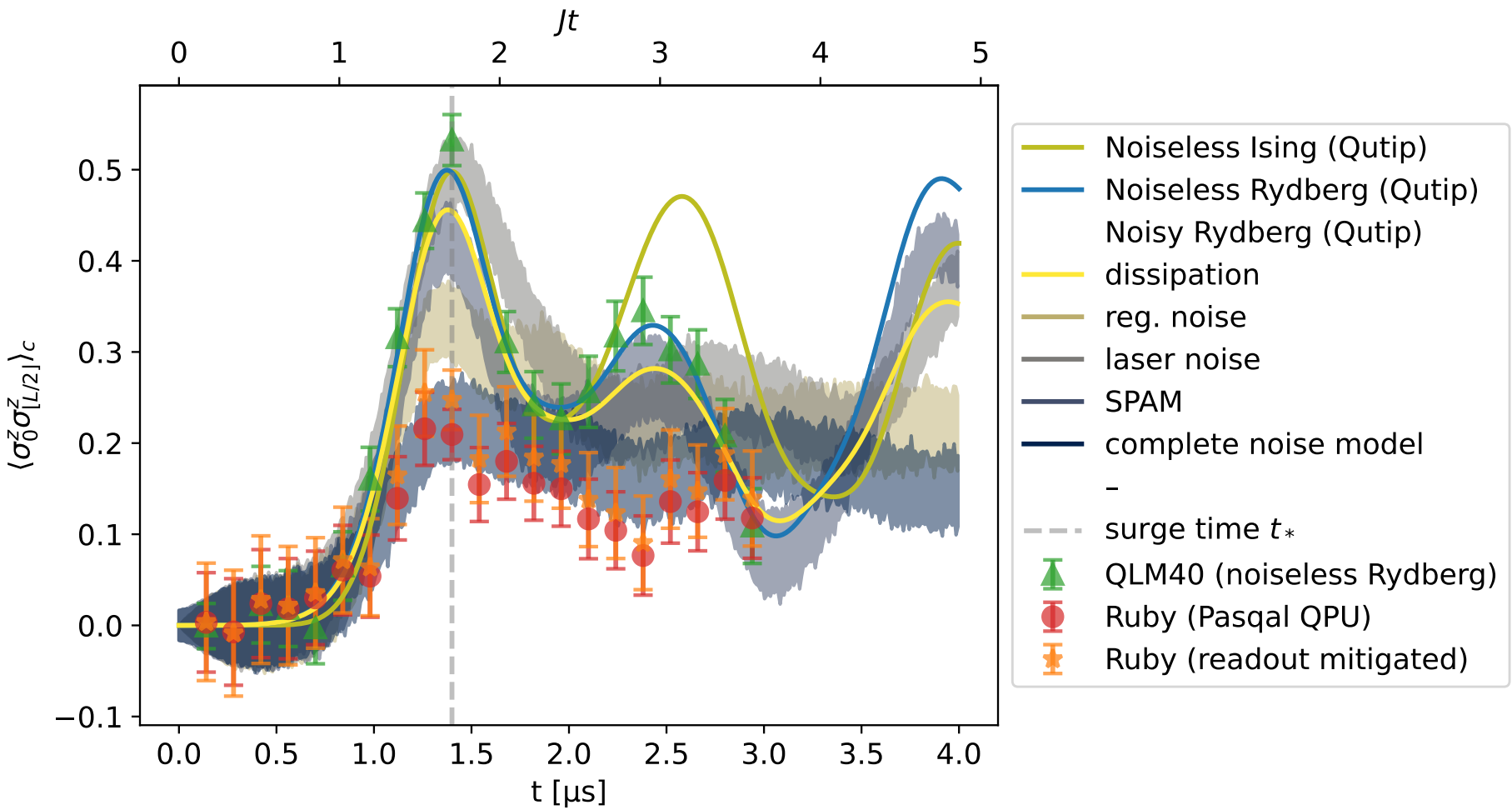


1-point correlation function: noise effects



$R = 7.5\,\mu\text{m}$, $|\psi_{\text{ini}}\rangle = |\downarrow \cdots \downarrow\rangle$, $L = 6$

2-point correlation function: noise effects



$R = 7.5\,\mu\text{m}$, $|\psi_{\text{ini}}\rangle = |\downarrow\cdots\downarrow\rangle$, $L = 6$

Readout mitigation

- Definitions

$$s = p_{\mathrm{fp}} + p_{\mathrm{fn}}, \qquad d = p_{\mathrm{fp}} - p_{\mathrm{fn}}$$

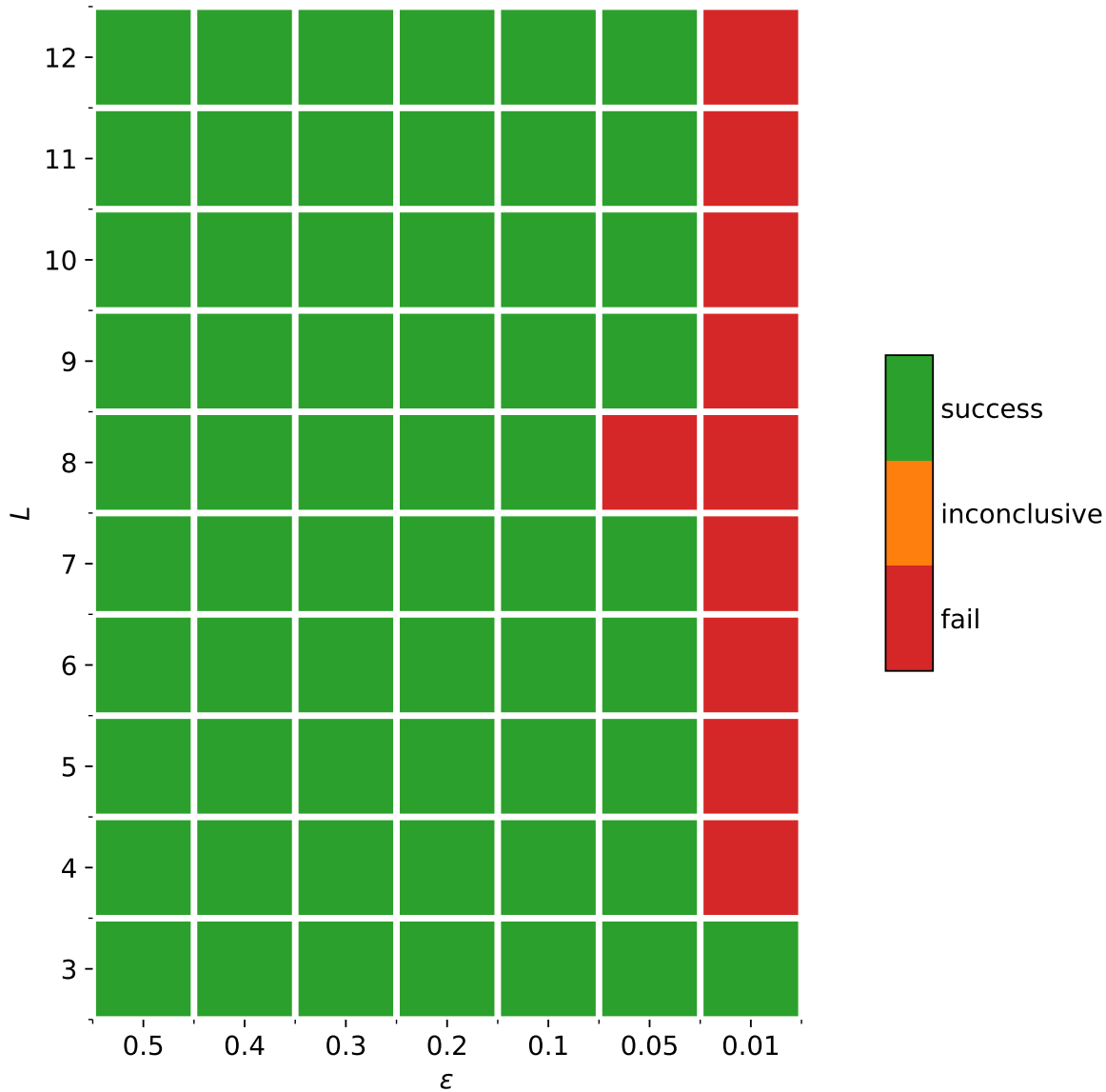
- 1-point function

$$\langle \sigma_i^z \rangle^{\mathrm{mit}} = \frac{\langle \sigma_i^z \rangle - d}{1 - s}$$

- 2-point connected function

$$\langle \sigma_i^z \sigma_j^z \rangle_c^{\mathrm{mit}} = \frac{\langle \sigma_i^z \sigma_j^z \rangle_c}{(1 - s)^2}$$

Volumetric plot noiseless Rydberg vs Ising



Fluctuations of measurements

