# End-to-end quantum error mitigation for dynamic circuits

## and integration with error correction

**Werqshop NYC 2025**

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stay tuned/awake for the last teaser slide

# Mitigation & Correction

## QEM today and beyond..

- Often considered as a temporary pre-FTQC solution
- Long term: QEM-QEC hybrids may overcome difficulties of QEC:

  QEC for strong local errors, QEM for correlated error, leakage error etc.
  QEC reduces QEM sampling overhead


- **Our approach: QEM for dynamic circuits ⇒ automatically apply to QEC**

# Desired QEM features

What makes a good QEM method?

- **Bias-free** - theoretical assurance for convergence to the ideal noiseless value
- **Drift-resilience** - performance are not degraded when the noise parameters change during the experiment (noise drifts)

→ **Reliable results**

- **Bias-free** → Distribute shots over different backends or different qubit sets.
- **Drift-resilience** → Enables arbitrary long runtime on the same backend

↓

**Facilitates sampling overhead >1k**

# Our work on QEM

| | Scope | Drift-resilinet | Bias-free |
|---|---|---|---|
| **Adaptive KIK [1]** | Gate noise | ✔ | For moderate noise |
| **Layered KIK [2]** | Gate noise in dynamic circuits | ✔ | ✔ |
| **Pseudo twirling [3]** | Coherent errors (non Cliffords) | ✔ | ✔ |
| **Induced over-rotation in PST [4]** | Coherent errors (non Cliffords) | ✔ | ✔ |
| **Parity/Reset [5]** | mid-circuit meas. Prep. errors | ✔ | ✔* |

- Layered KIK: the only gate QEM that is drift resilient & bias free (TTBOK)
- Parity/Reset: the only readout mitigation that is drift resilient & bias free (TTBOK)


[1] I. Henao, J.P. Santos and R. Uzdin, npjqi 9, 120 (2023)

[2] B. Bar, J. P. Santos, and R. Uzdin, arXiv:2504.12457

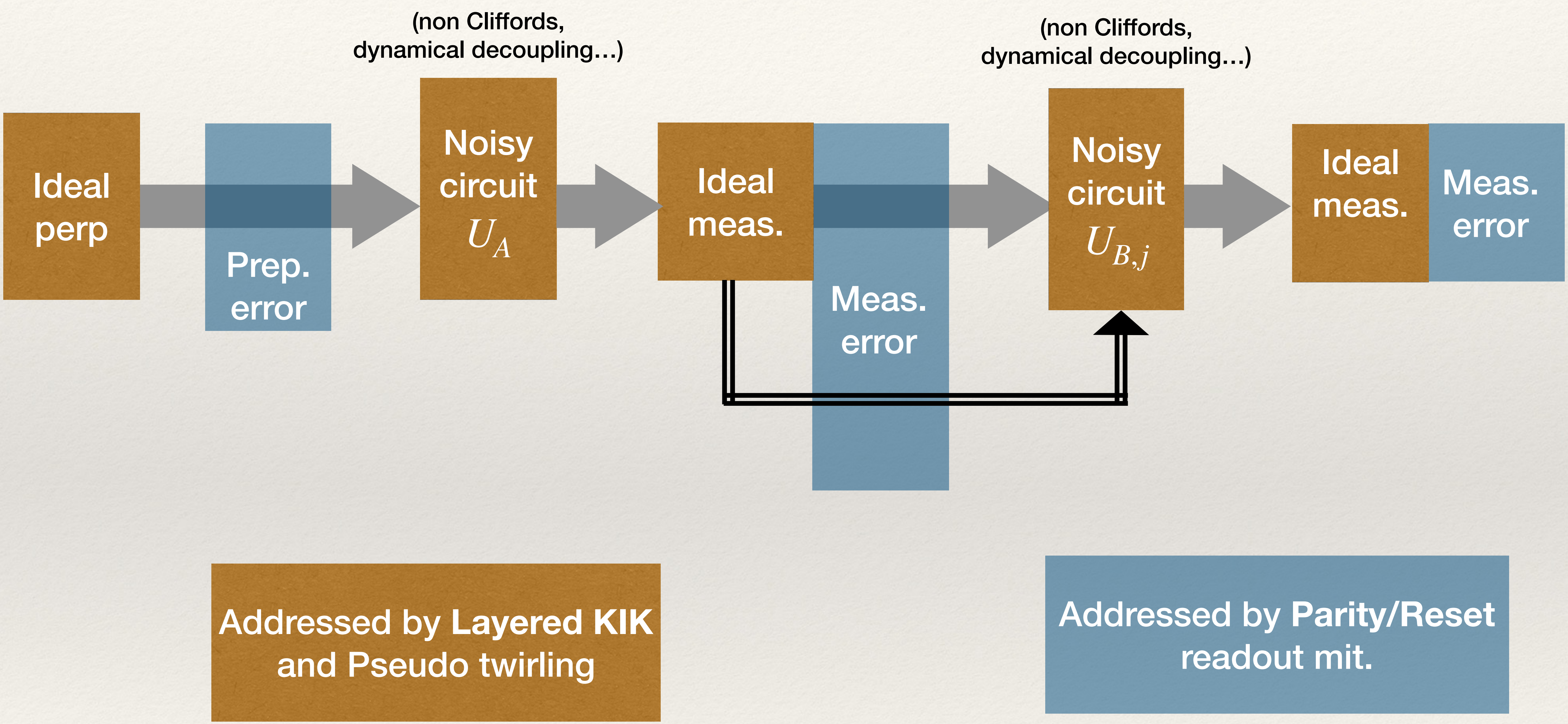
[3] J.P. Santos, B. Bar and R. Uzdin, npjqi 10, 100 (2024)

[4] T. Pandit, and R. Uzdin, arXiv:2407.06055

[5] J. P. Santos, and R. Uzdin, arXiv:2506.11270

# Our end-to-end quantum error mitigation for dynamic circuits

- Layered KIK [1]+Parity / Reset readout error mitigation [2]





[1] B. Bar, J. P. Santos, R. Uzdin "Layered KIK quantum error mitigation for dynamic circuits and error correction" arXiv:2504.12457

[2] J. P. Santos, R. Uzdin "Drift-resilient mid-circuit measurement error mitigation for dynamic circuits" arXiv:2506.11270

# Previous and new generation of the KIK gate error mitigation

Noisy circuit


$K$ noisy evolution operator (original circuit)

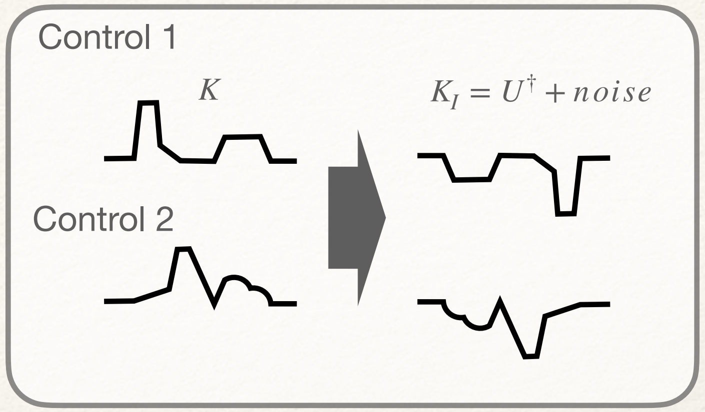
$K_I$ "pulse-inverse" evolution operator

'**Pulse-inverse**' circuit:

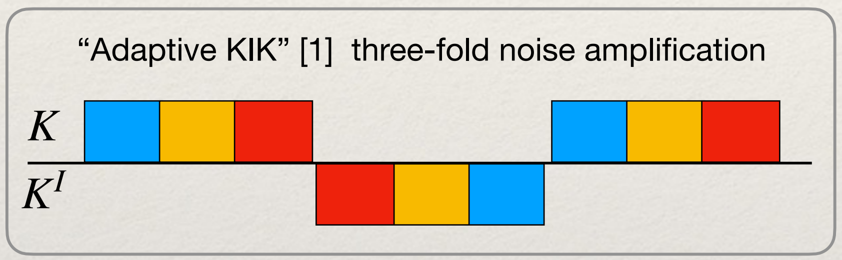
$K = UN$

$K(K_I K)^j \cong UN^{2j+1}$

Agnostic noise amplification



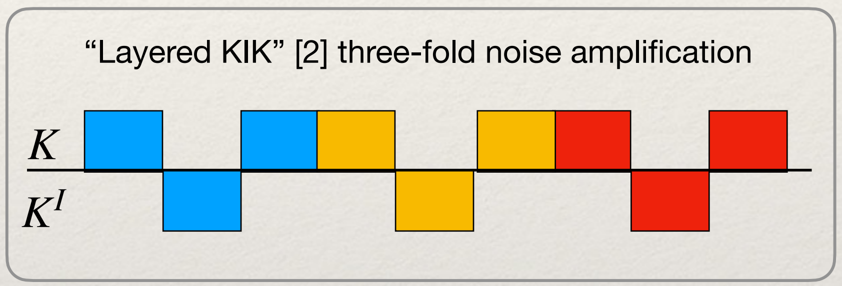

## Prev. gen.: Adaptive KIK [1]




- Bias-free for **moderate noise**
- Fully resilient to noise drifts
- Scalable
- Non-Clifford multi-qubit gates
- Significantly outperforms ZNE (Richardson's)

**Incompatible with mid-circuit measurements**

## New gen.: Layered KIK [2]




- Inherits all the "Adaptive KIK" advantages
- Bias-free for **strong noise**
- **Fully compatible with mid-circuit measurements**
- **No increase in the sampling overhead**

[1] I. Henao, J.P. Santos and R. Uzdin, npj Quantum Information 9, 120 (2023)

[2] B. Bar, J. P. Santos, R. Uzdin, arXiv:2504.12457

# Mid-circuit measurement error mitigation and integration with gate QEM

We use a purely stochastic model for the readout error:

$$p(t) = M(t)q$$

Measurement readout → $p(t)$

Assignment matrix / Confusion matrix → $M(t)$

Actual probability distribution of the qubits → $q$

- The readout error drifts in time ⇒ repeated calibrations.
- **In QEM experiments, drifts are more likely to occur due to the sampling overhead**

***Drift***: the change in $M(t)$ can be very large, but the change is slow ( > hundreds of shots)

**To achieve drift-resilient MCM mitigation, we use agnostic noise amplification**

Other approaches to MCM mitigation based on PEC:
(sensitive to time drifts, requires shot-based sampling of quasi prob.)

[1] RS Gupta, E Van Den Berg, M Takita, D Riste, K Temme, A Kandala PRA 109 , 062617 (2024)
[2] A Hashim, et al. PRX Quantum 6, 010307 (2025)
[3] JM Koh, DE Koh, J Thompson arXiv preprint arXiv:2406.07611

# Mitigation via amplification of measurement error

At first, mitigation appears to be straightforward $M = I + O(\epsilon)$

Step 1- Error amplification:

Assume that on top of the noise value $\langle A \rangle_M = \langle A \rangle_{ideal} + O(\epsilon)$

we can also measure $\langle A \rangle_{M^3}$ and $\langle A \rangle_{M^5}$

Step 2: Post-processing

$$\frac{3}{2}\langle A \rangle_M - \frac{1}{2}\langle A \rangle_{M^5} = \langle A \rangle_{ideal} + O(\epsilon^2)$$

1st ord. mitigation

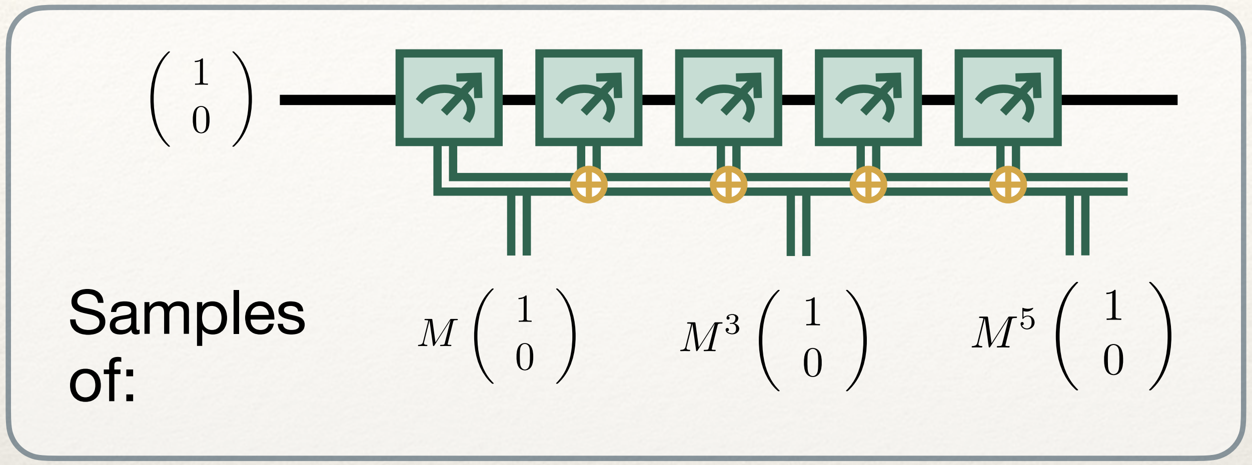
$$\frac{15}{8}\langle A \rangle_M - \frac{5}{4}\langle A \rangle_{M^3} + \frac{3}{8}\langle A \rangle_{M^5} = \langle A \rangle_{ideal} + O(\epsilon^3)$$

2nd ord. mitigation

**How to generate $M^{2j+1}$ ??**

# Agnostic readout error amplification via parity

- We amplify the readout error by using the parity of consecutive measurements

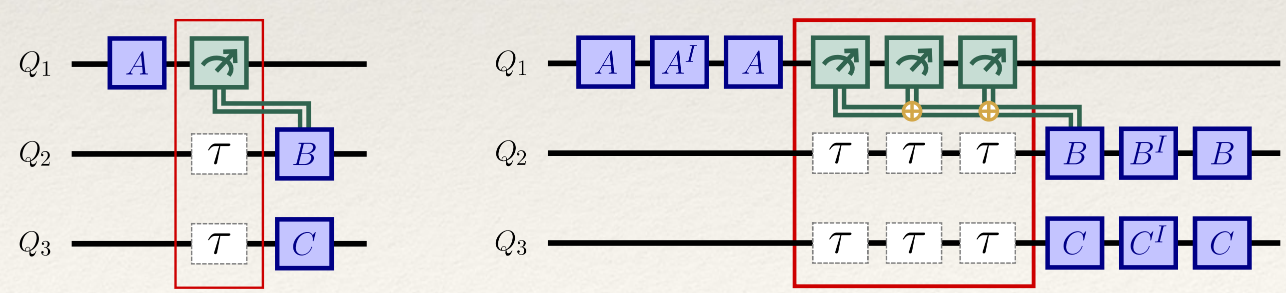



- For twirled $M$ of any size and correlation we find the fundamental relation

$$M^{2j+1}p \iff \text{Parity}(2j+1)$$

- We proved that the mitigation still works properly when $M$ is not twirled.
- Naturally integrates we the Layered KIK gate mitigation $\Rightarrow$ **End-to-end mitigation**
- All errors are uniformly amplified

uniform ×3 amplification

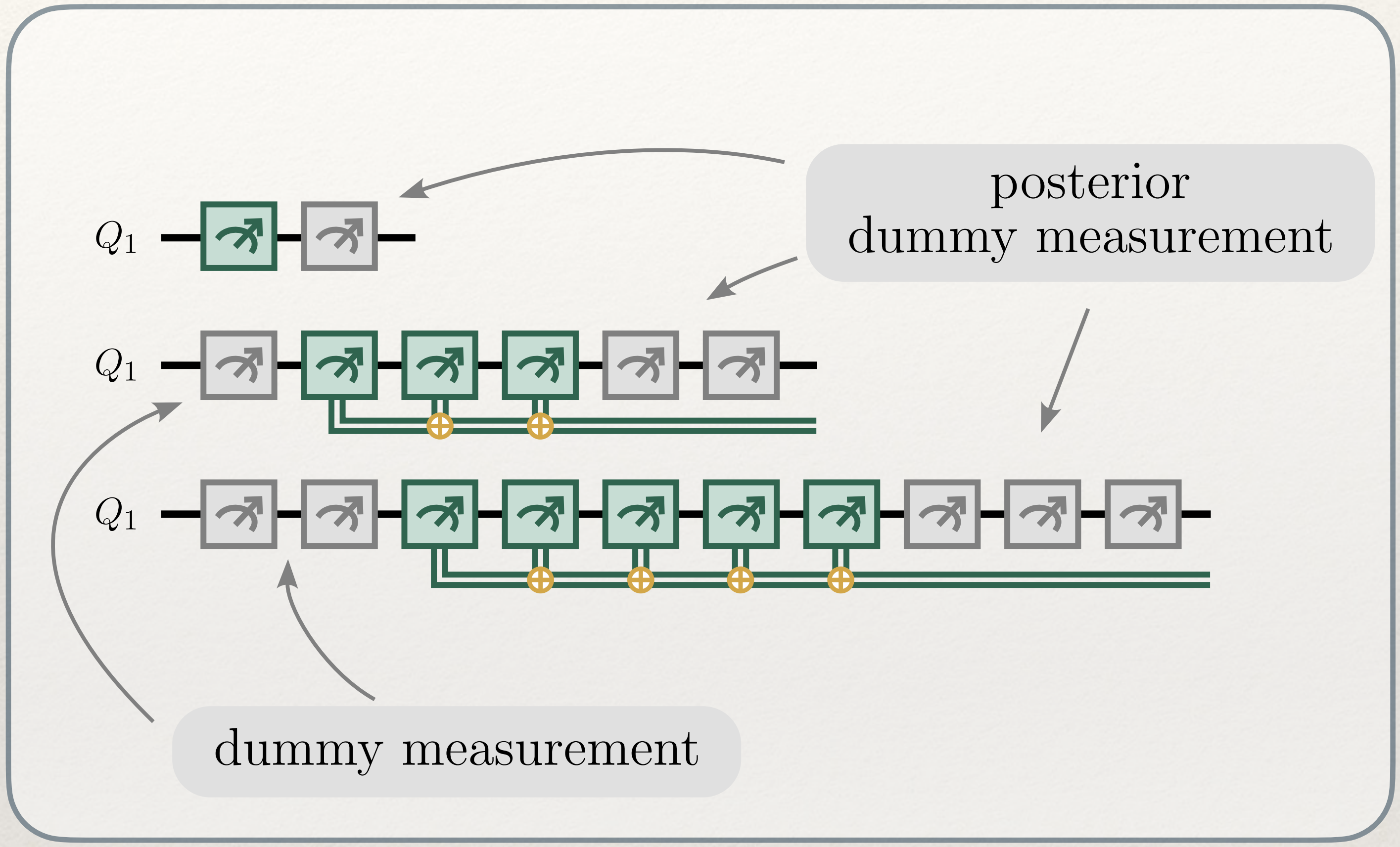



Experimental results available - ask me about it

# Accounting for the decay effect

- The qubit does just sit there waiting to be measured. It degrades from one measurement to another.

- We show analytically that by adding dummy measurement (orange) to reshape the decay noise scaling, it can be strongly mitigated.




No dummy meas. error is:

$$\epsilon^{m+1} + \frac{1}{2}\gamma$$

With dummy meas.:

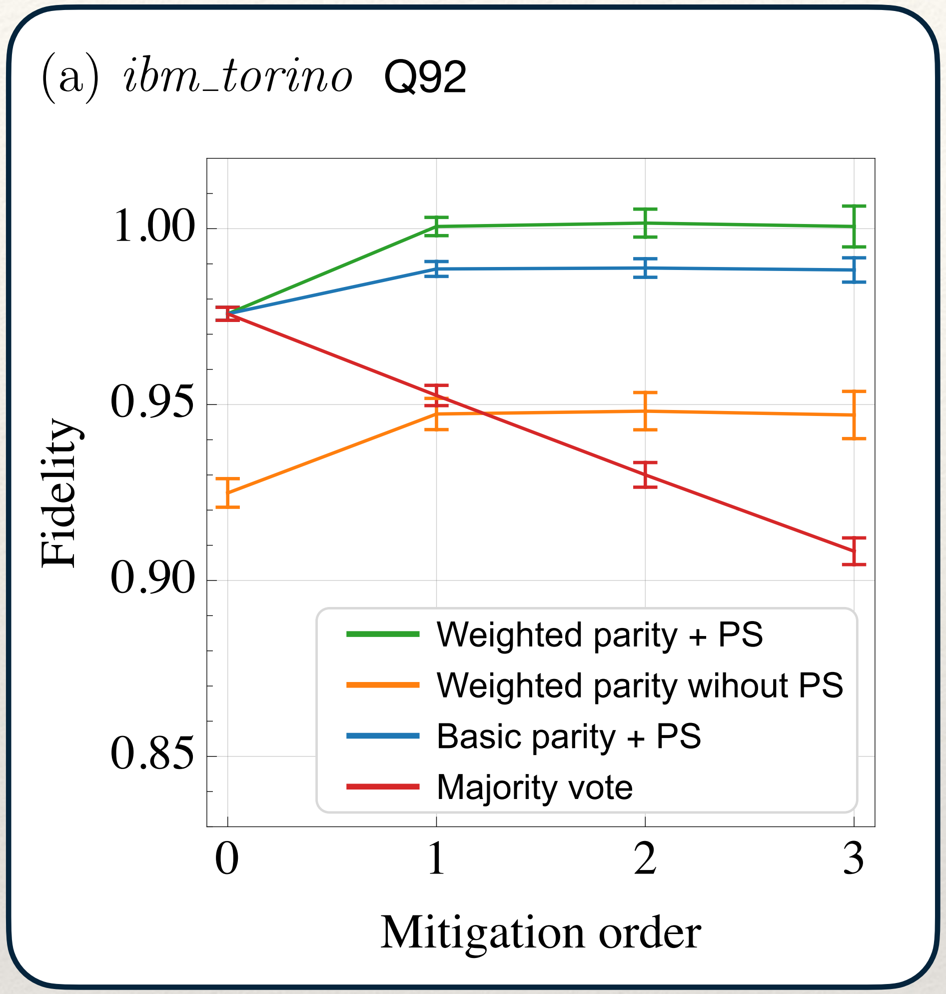
$$\epsilon^{m+1} + O(\gamma^2)$$

m is the mitigation order

- We also have an alternative approach called Weighted parity that does not require dummy measurements

# First experimental results (1q  prep & measure)

IBMQ




Dummy meas. parity $\epsilon^{m+1} + O(\gamma^2)$

Majority vote $\epsilon^{m+1} + (m + \frac{1}{2})\gamma$

- Like our other QEM method this method is also **drift resilient**
- Post-selection was use to remove prep. error.

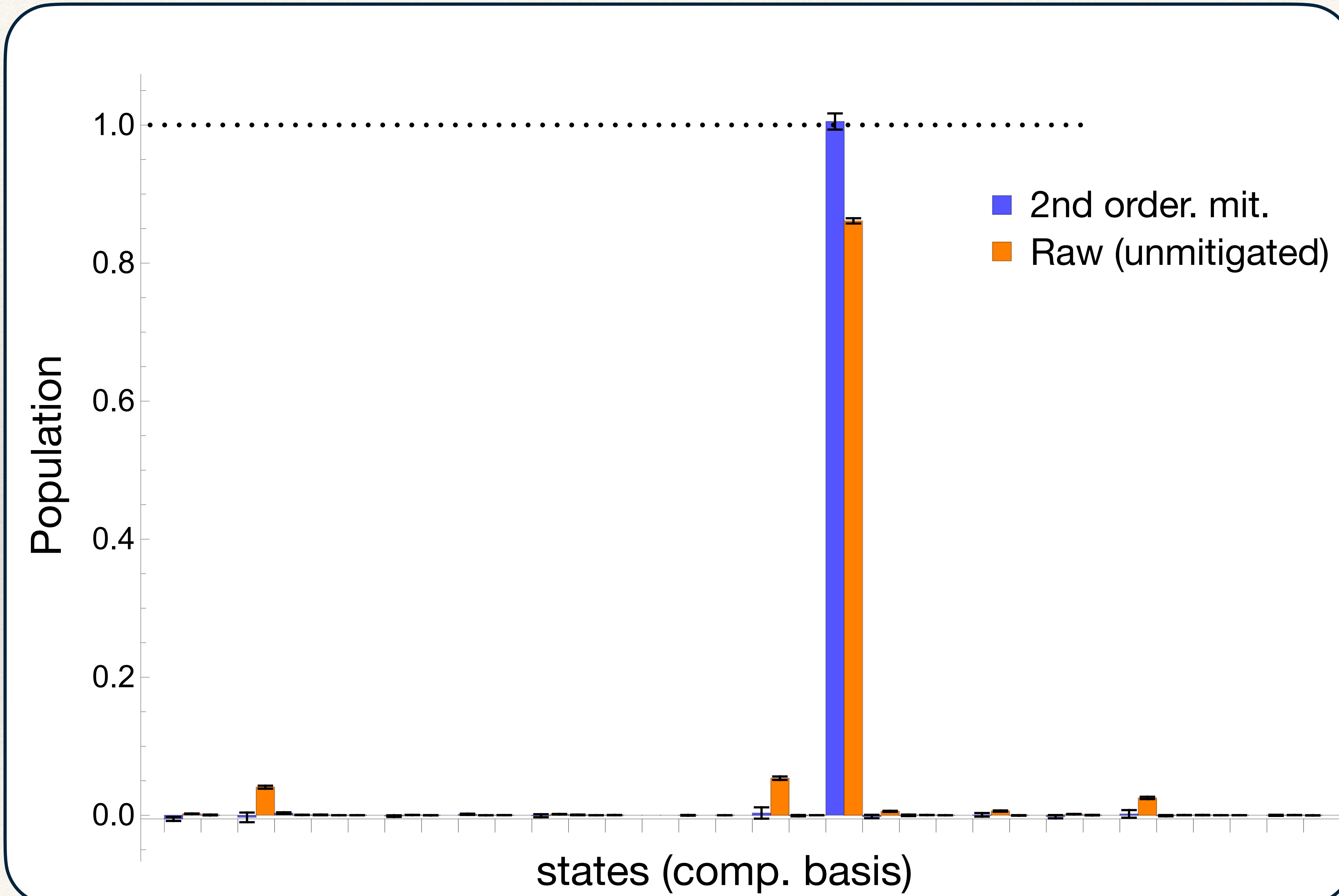
PS qubits='000'?

Tip by Liran Shirizly @IBM

- We used here an alternative to dummy measurement called **weighted parity**. W parity does not involve extra measurements.

# 5q experiment (prep & measure)

*ibm_brisbane*, input state 10101



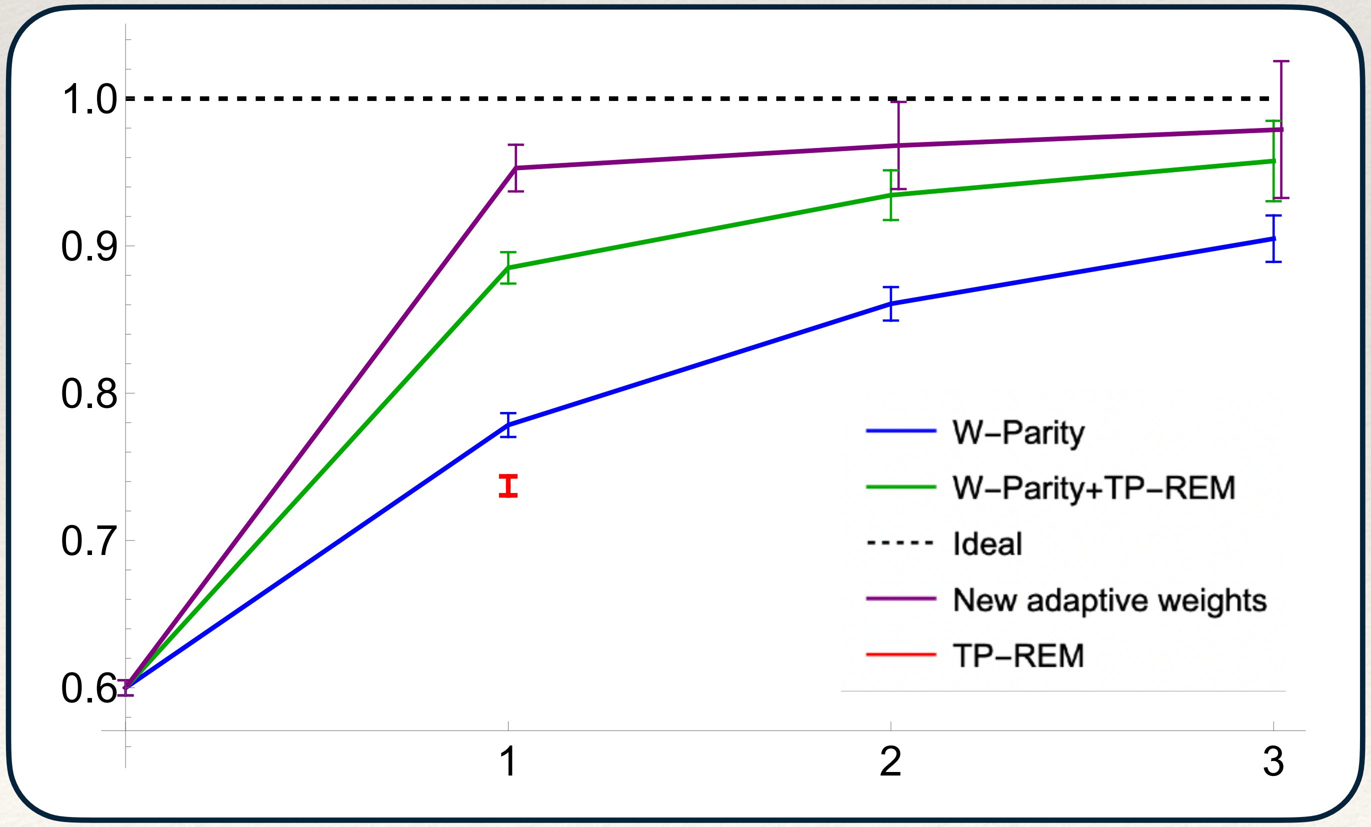

Our method automatically takes correlations into account

# Integration with other methods and scaling up: 20q on IBMQ

- Our approach can be integrated with more coarse method and cheaper method and turn them bias-free and drift resilient
- An example: integration with tensor product (local) matrix inversion (TP-REM)

$$M_{TP}^{-1} = M_1^{-1} \otimes M_2^{-1} \otimes M_3^{-1} \ldots$$

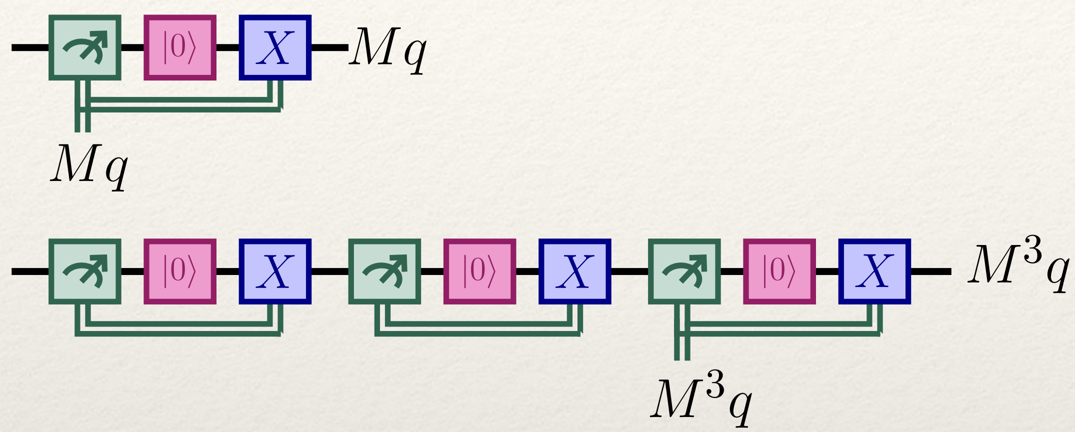
  - We used TP-REM from IBM website data and do not updated it.
  - The parity remove this residual correlation and noise-drift errors.
  - Data was collected in different days to demonstrate drift-resilience.



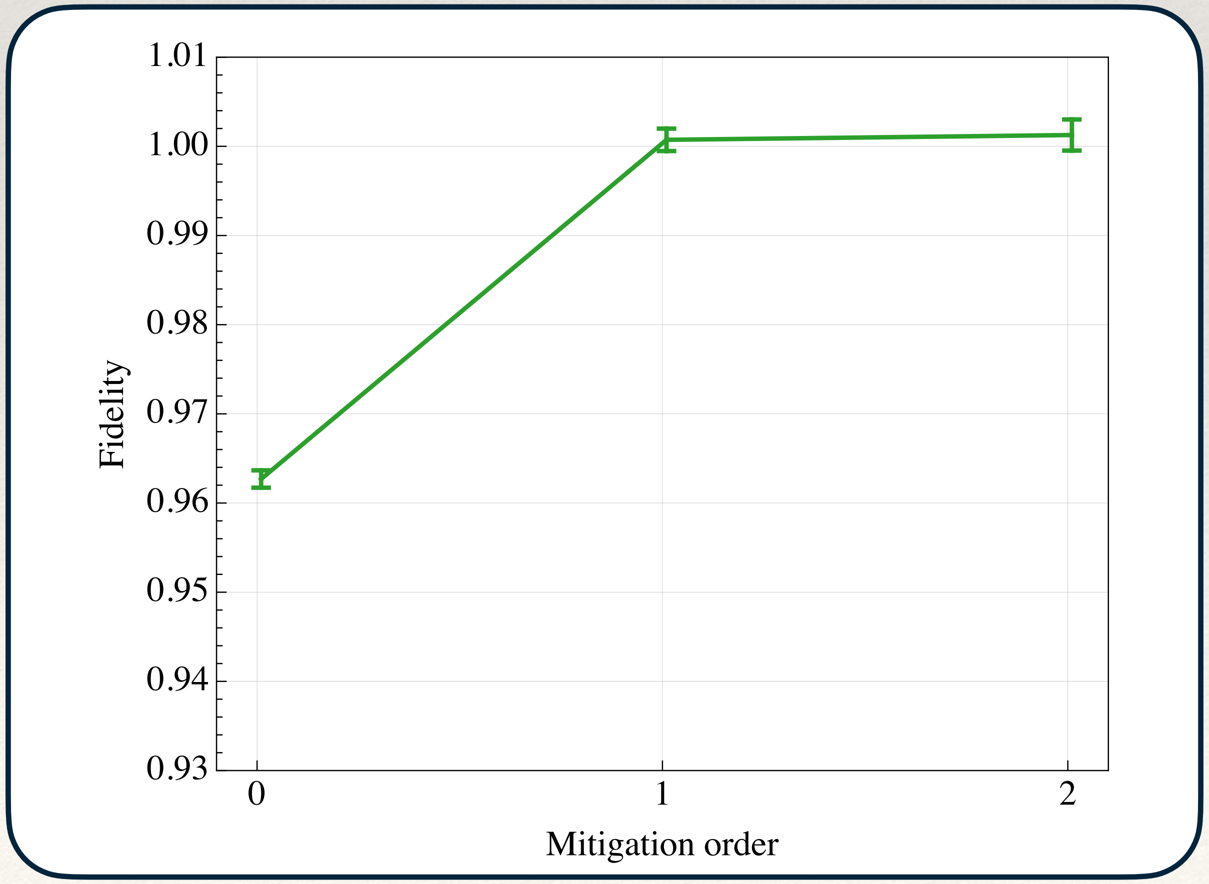

- Inconsistent results without twirling suggest non-Markovian effect (e.g. from spectator qubits)
- Imperfect initial state (post-selection and noisy X gates)

# Reset-based readout mitigation

- Do **not** use parity in trapped ions. The measurement demolish the (classical) state.
- Instead we developed this reset-based scheme:




- ## 10-qubit experiment on Quantinuum H1

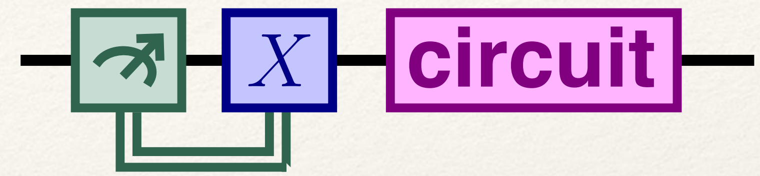



No twirling was used

# How to mitigate (amplify) preparation errors?

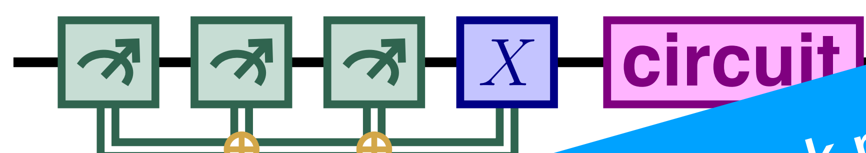
- Conditional reset: prep. error is determined by the measurement error.
- Amplify the meas. error ⇒ amplify the prep error

Conditional reset




- We introduce: Parity-based amplification of preparation error

Error amplified conditional reset

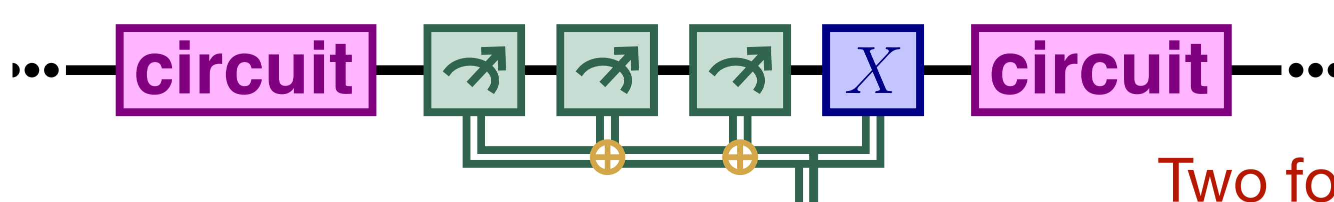



drift-resilient

Experimental results available - ask me about it

- We sugges ... mitigation
  get the me ... ent data from the terminating measurement of the previous shot.

Unified SPAM mitigation



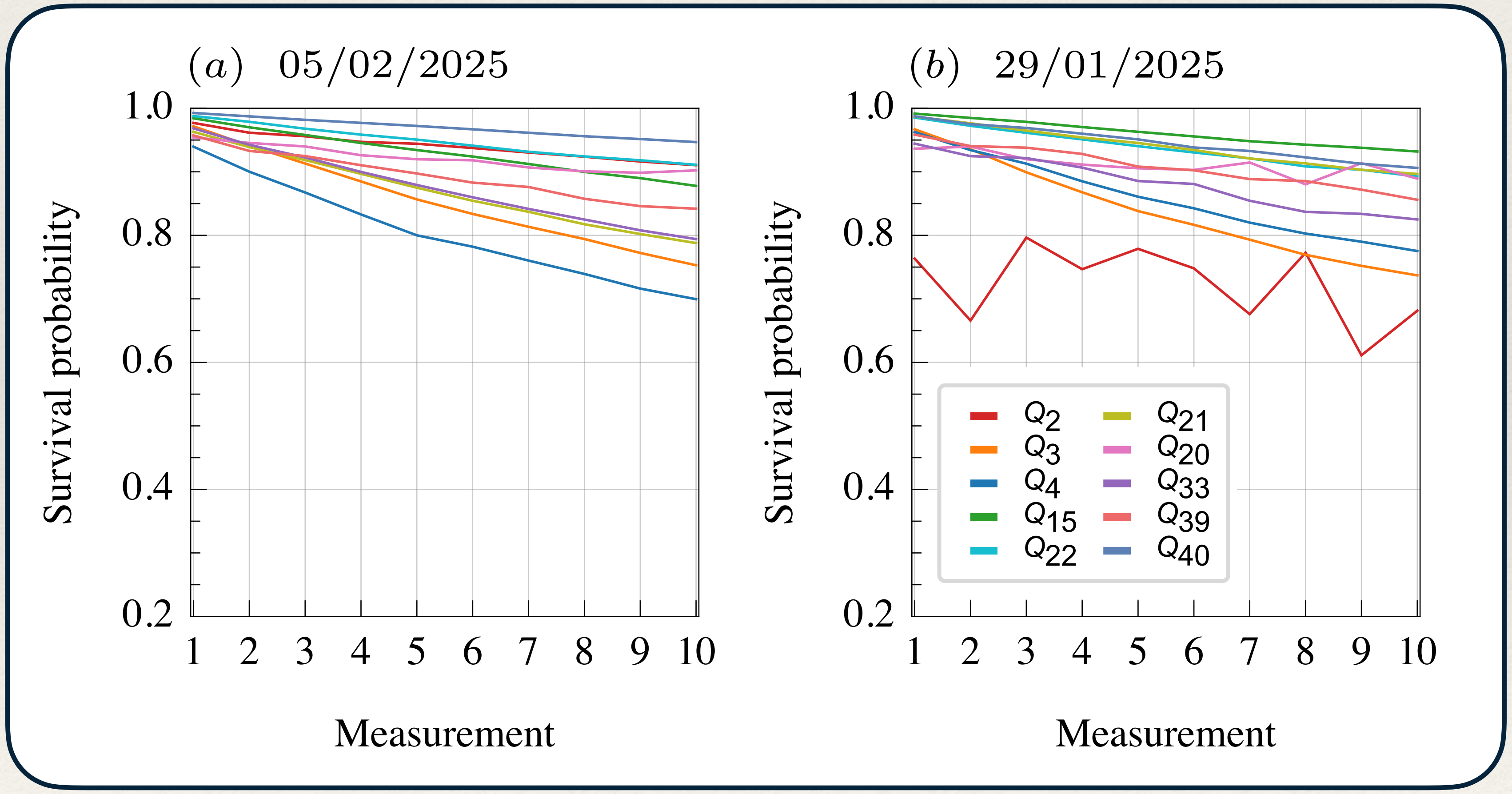

drift-resilient

Two for the price of one!

# Additional application of the parity/reset scheme

- Efficient alternative to gate-set tomography.
  - Removes the SPAM instead of characterizing it
- Qubit diagnostic during the target computation.

*ibm_sherbrooke*

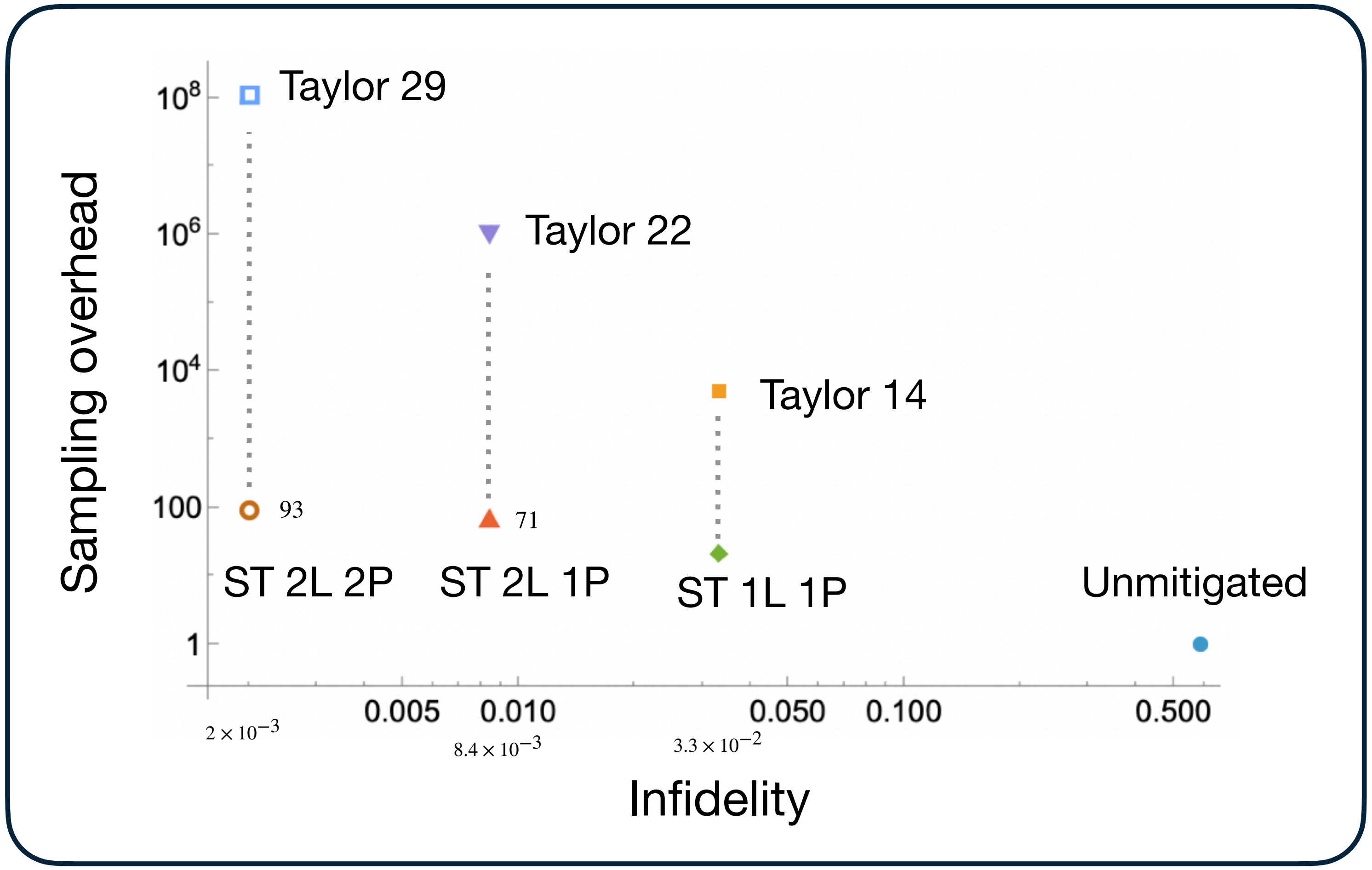


# Conclusions

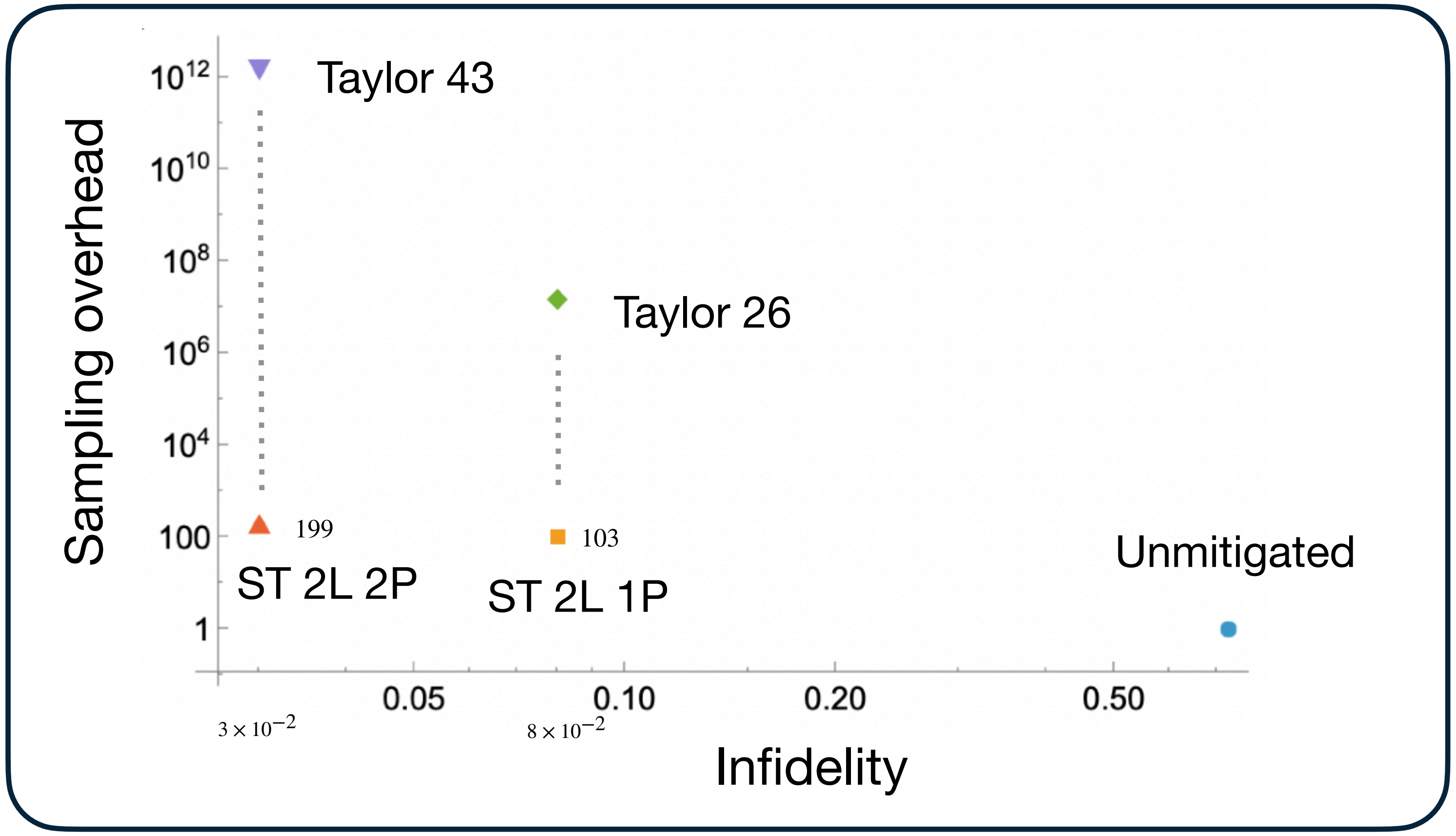
- We presented an end-to-end mitigation for dynamic circuits addressing: prep, gate, MCM, and terminating measurement errors.
- 1st drift-resilient readout error mitigation method.
- Our approach can be combined with other method and render them drift-resilient and bias-free.
- Ready for QEM-QEC experiments (collaborations are welcomed).
- Additional application of Parity/Reset error mitigation:
    - Efficient alternative to gate-set tomography.
    - Qubit diagnostic during the target computation.

# Teaser: Orders of magnitude improvement in sampling overhead

Initial fidelity 0.415




Initial fidelity 0.273



# Thank you for you attention!

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PhD and postdoc openings