Title: Weak and continuous measurements in superconducting circuits

Date: Jun 20, 2016 04:00 PM

URL: http://pirsa.org/16060040

Abstract: Superconducting circuit technology has rapidly developed over the past several years to become a leading contender for realizing a scalable quantum computer. Modern circuit designs are based on the transmon qubit, which coherently superposes macroscopic charge oscillations. Measurements of a transmon are fundamentally weak and continuous in time, with projective measurements emerging only after a finite duration. Adding gates, such measurements may then implement ancilla-based measurements of controllable strength. Recent experiments have used both types of weak measurement to great effect: for monitoring qubit evolution, and for showing violations of a hybrid Bell-Leggett-Garg inequality.

Institute for Quantum Studies

Group

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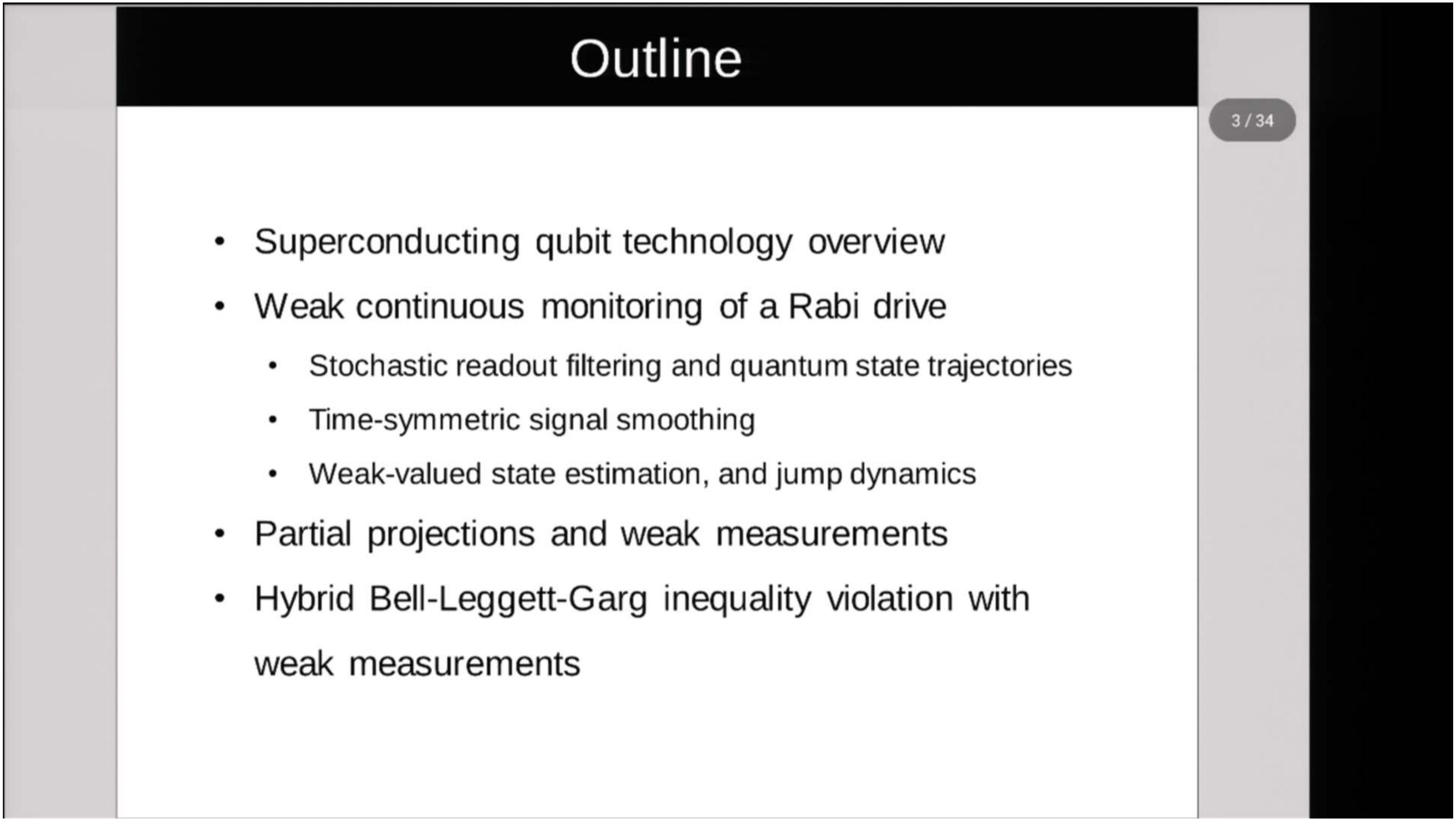
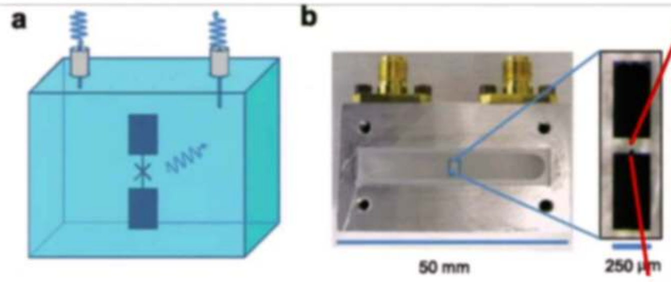
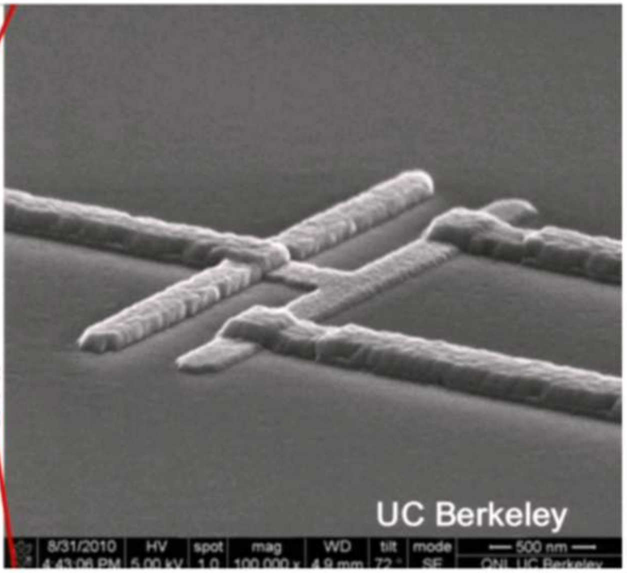


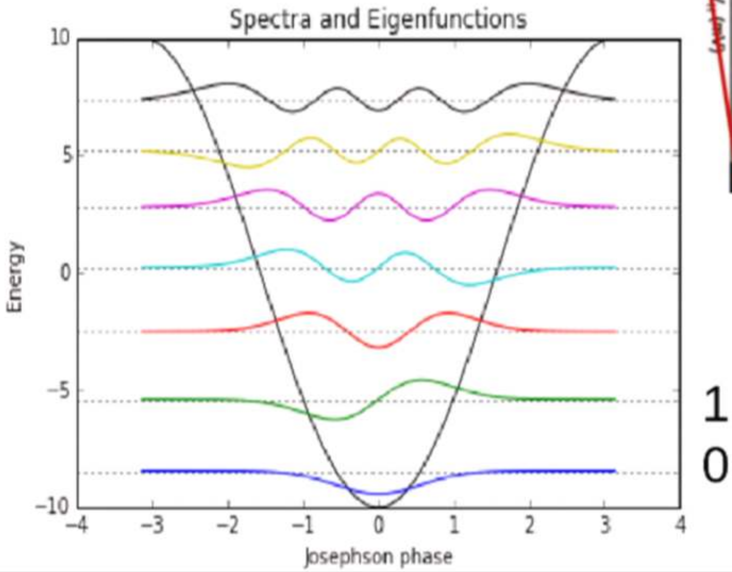
Outline

- Superconducting qubit technology overview
- Weak continuous monitoring of a Rabi drive
    - Stochastic readout filtering and quantum state trajectories
    - Time-symmetric signal smoothing
    - Weak-valued state estimation, and jump dynamics
- Partial projections and weak measurements
- Hybrid Bell-Leggett-Garg inequality violation with weak measurements

Superconducting 3D Transmon qubit



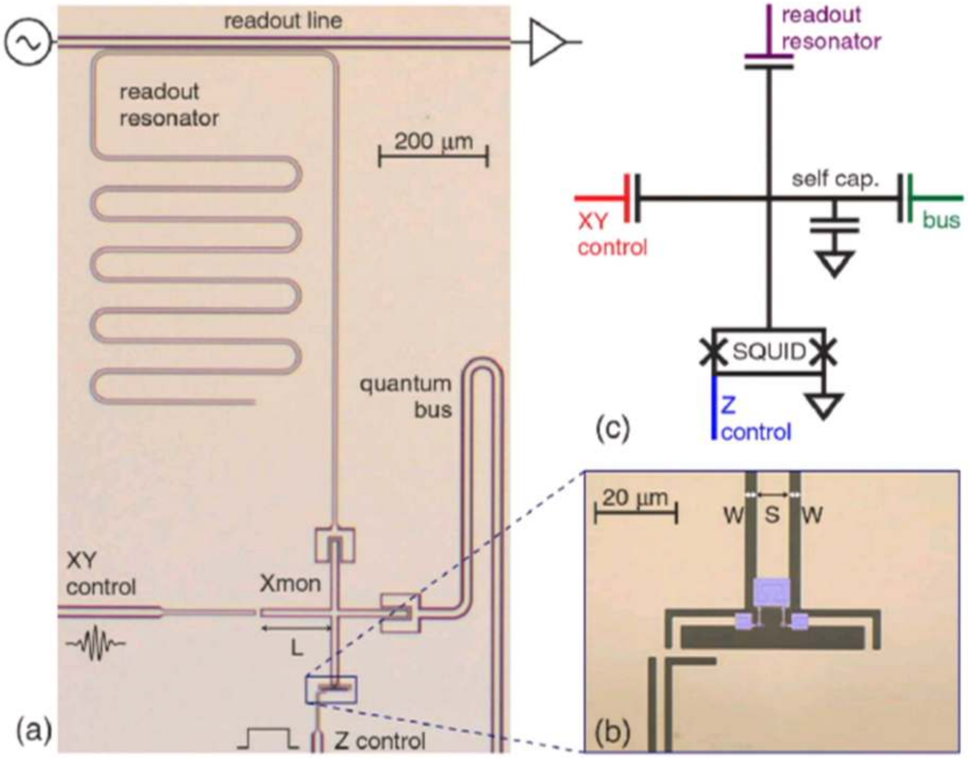


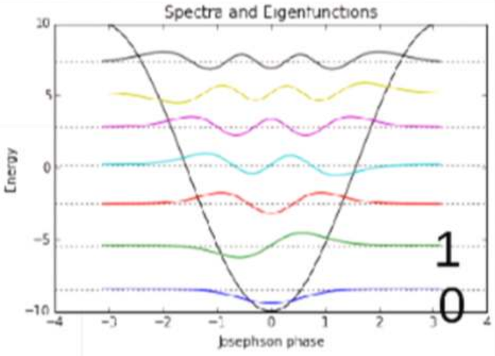


Transmon is LC oscillator with nonlinear inductance from a Josephson junction

qubit is the lowest two energy levels in a cosine potential well

2D planar Xmon qubit



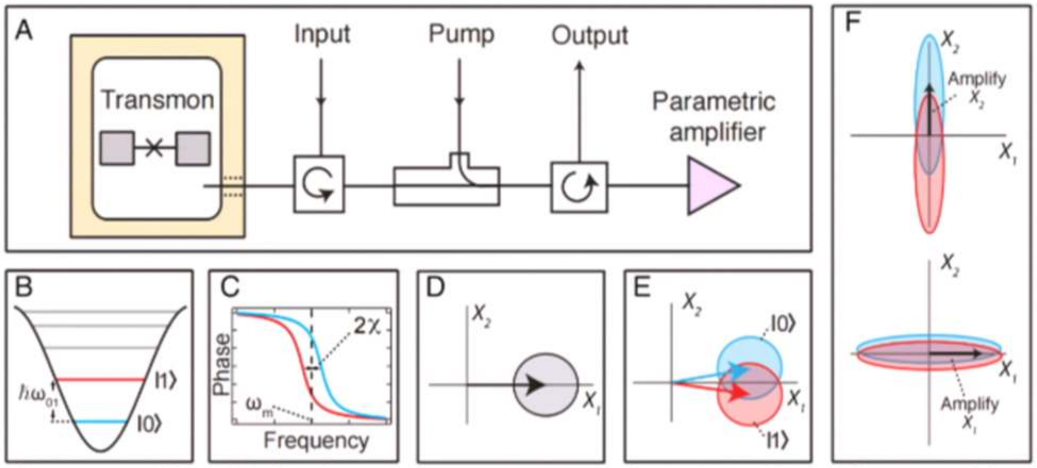


Xmon is a modified transmon optimized for a 2D lattice layout with nearest neighbor capacitive coupling

double Josephson junctions (SQUID) for flux control of qubit frequency

PRL **111**, 080502 (2013)

Circuit QED Qubit Measurement



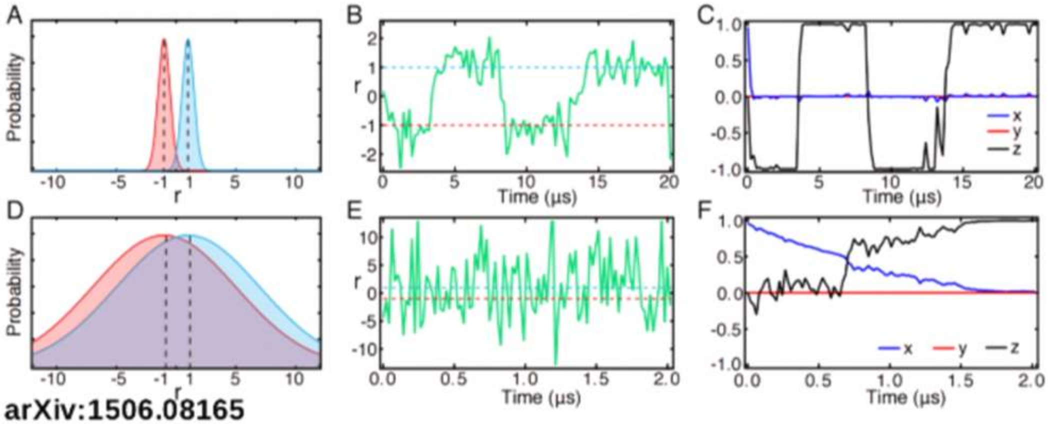
Transmon qubit

Cavity phase response

Cavity input

State-dependent cavity output

Phase-sensitive amplification



arXiv:1506.08165

Problem: Transmon on chip inside fridge – how to measure?

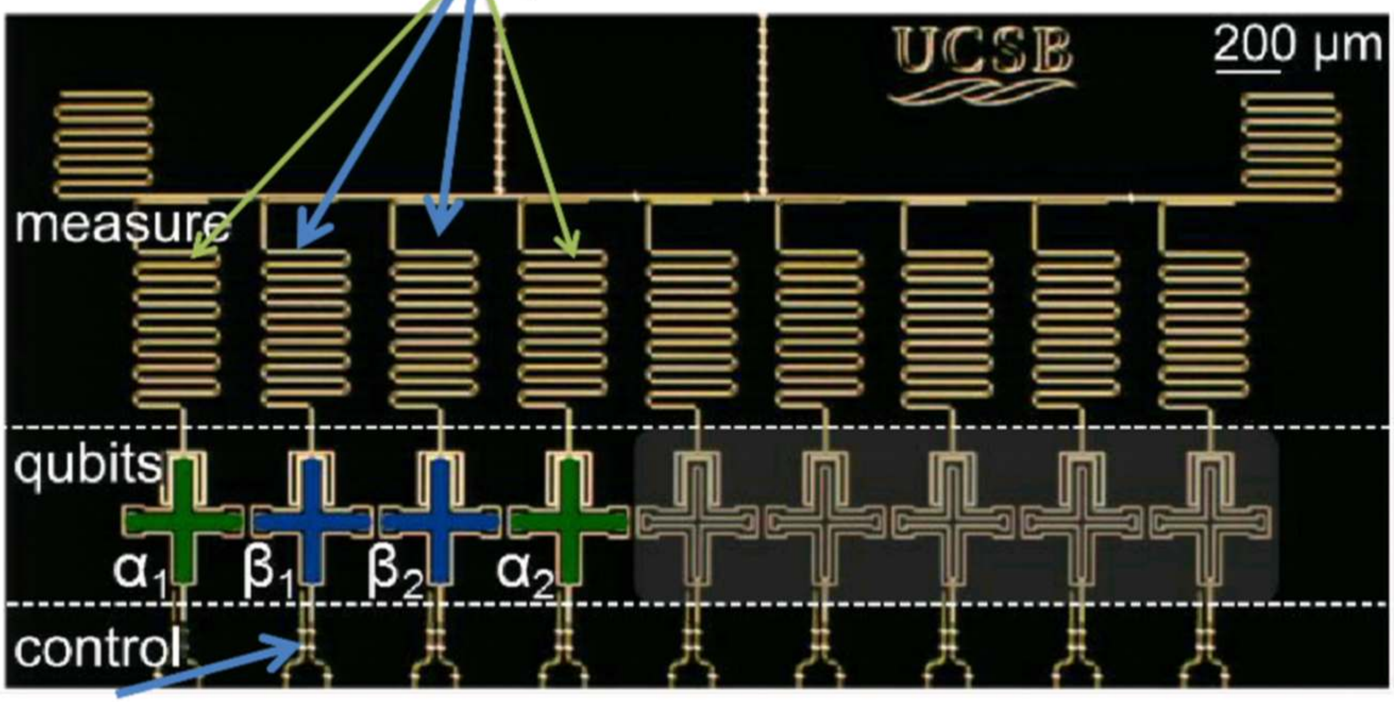
Solution: Use microwaves to peek at state-dependent frequency shift

Signal: Continuous noisy homodyne readout

Histograms: Gaussians centered on state-dependent means

Strength: Wide, overlapping peaks are *weak* (noisy) measurements that partially collapse the qubit less per unit time

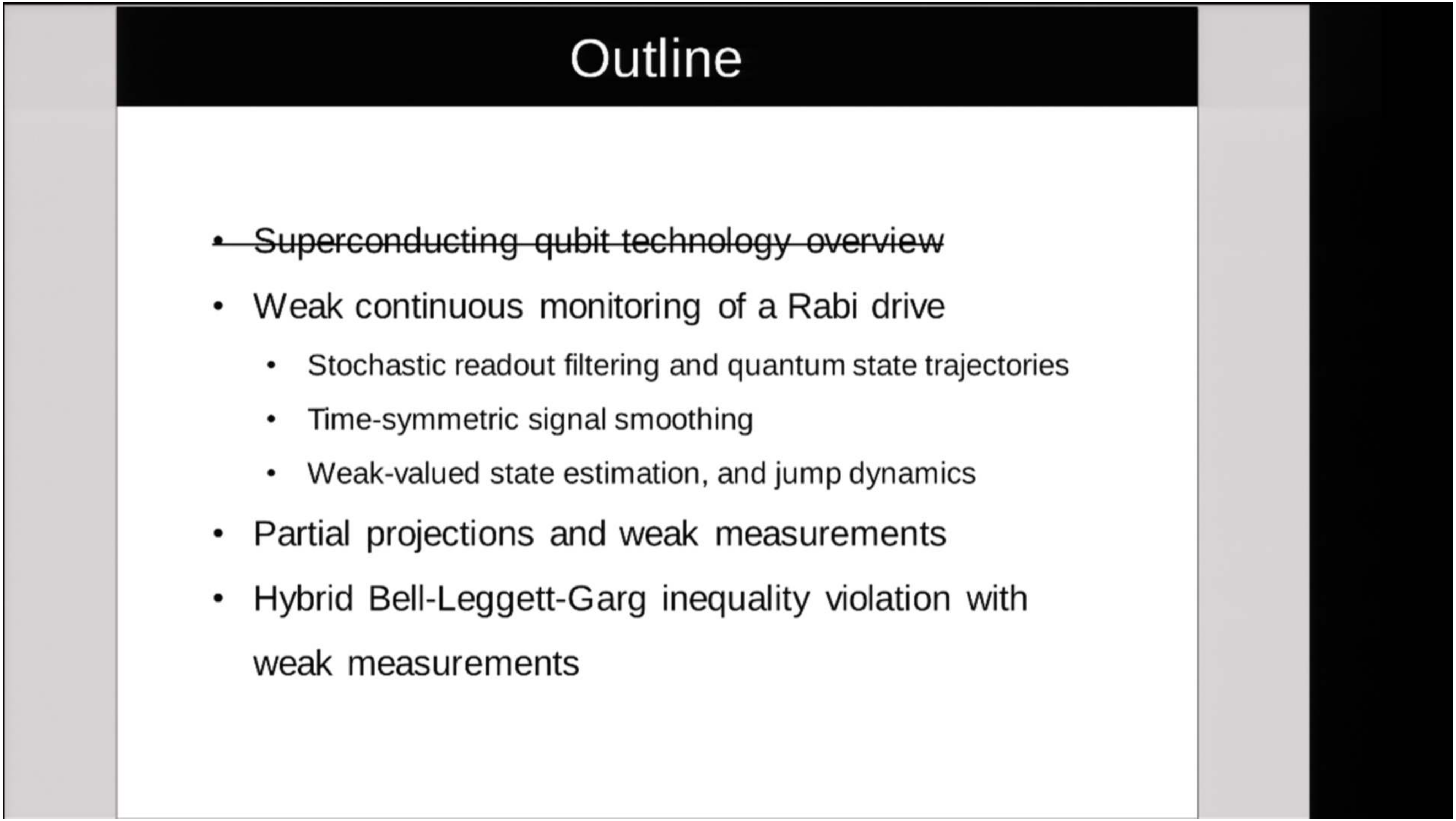
9 Xmon individual qubit control



Qubit microwave readout

Individual
microwave
controls

DC pulses: qubit-qubit ZZ interactions
AC pulses: fast single-qubit rotation gates



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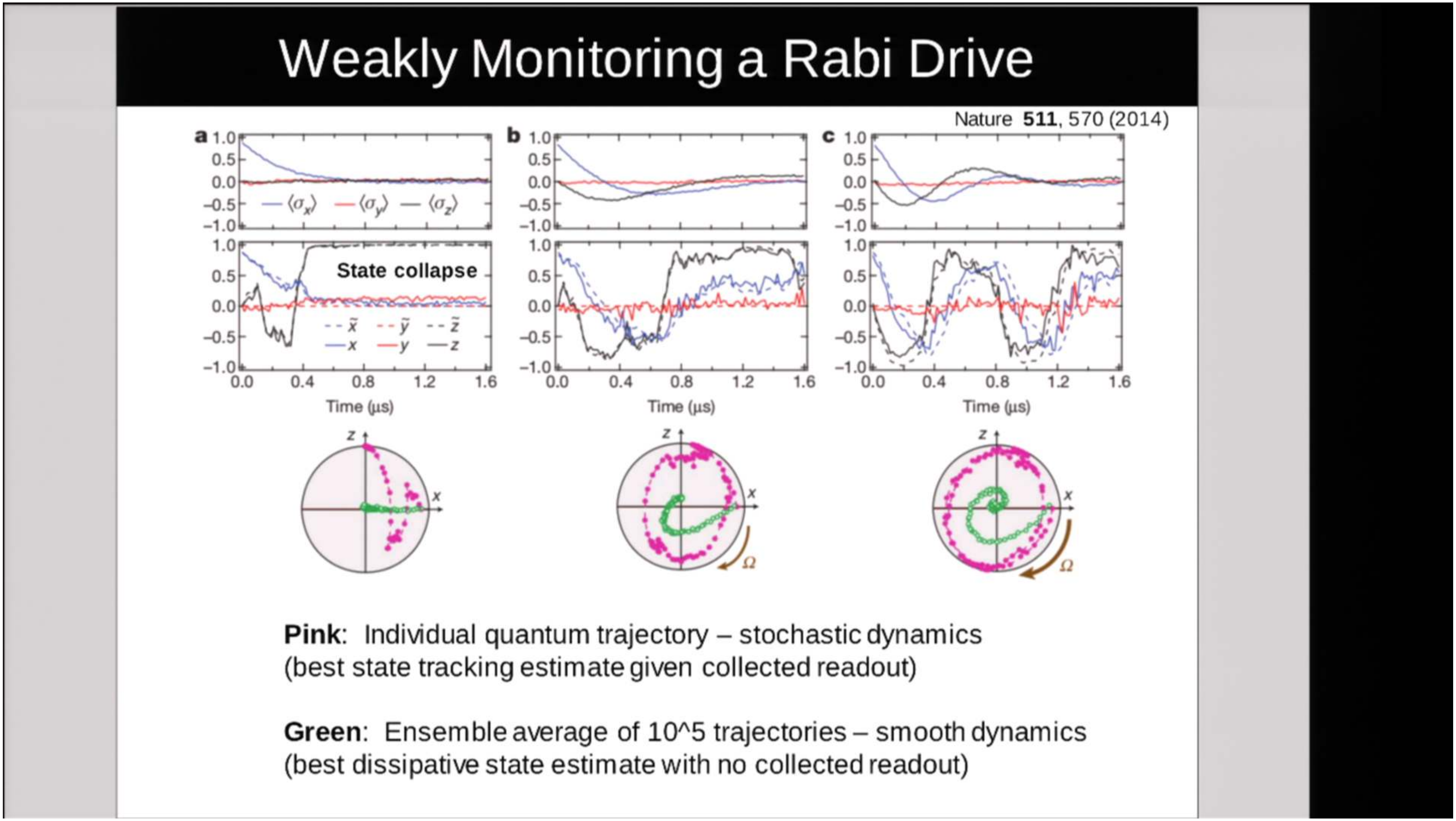


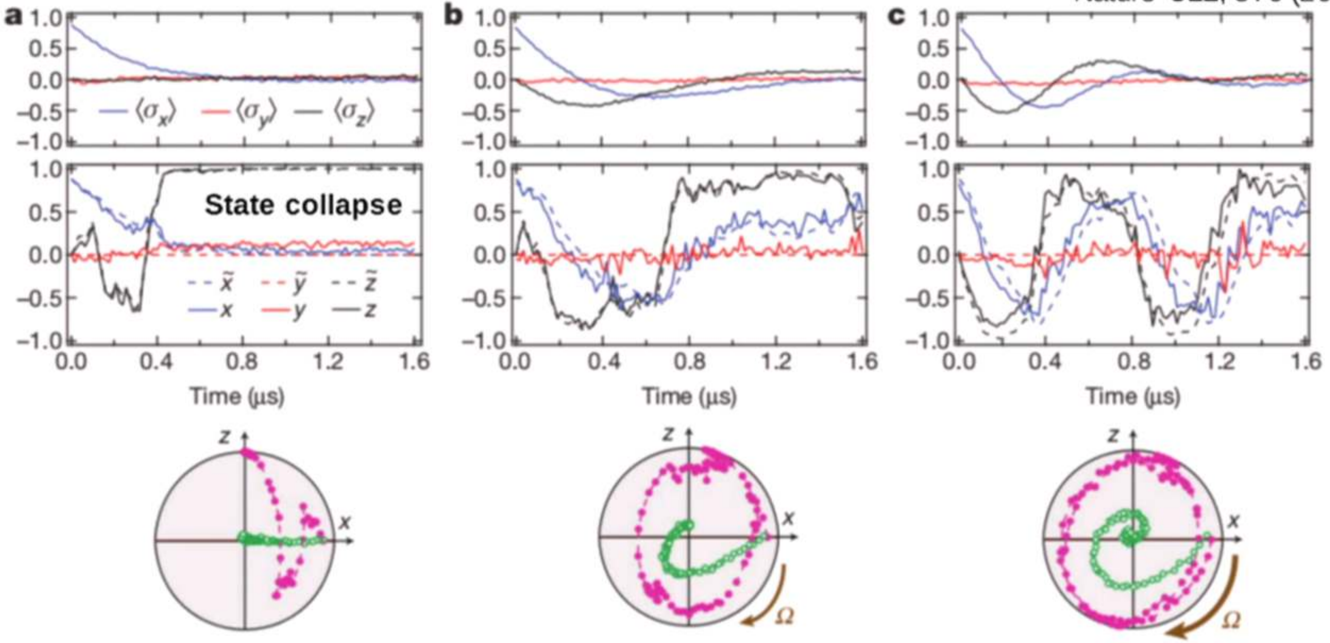
Weakly Monitoring a Rabi Drive

Nature **511**, 570 (2014)

Pink: Individual quantum trajectory – stochastic dynamics
(best state tracking estimate given collected readout)

Green: Ensemble average of 10^5 trajectories – smooth dynamics
(best dissipative state estimate with no collected readout)

Weakly Monitoring a Rabi Drive



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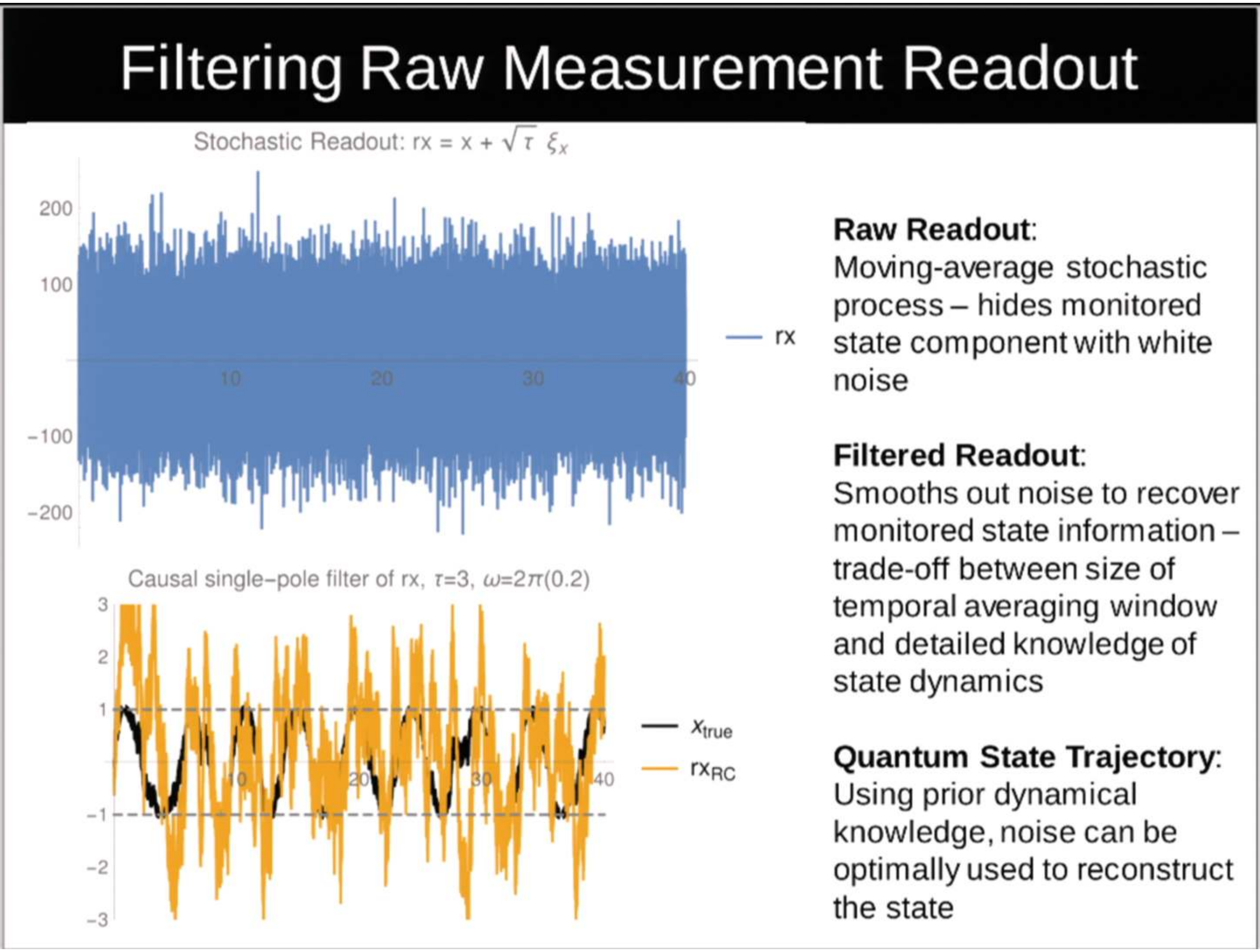
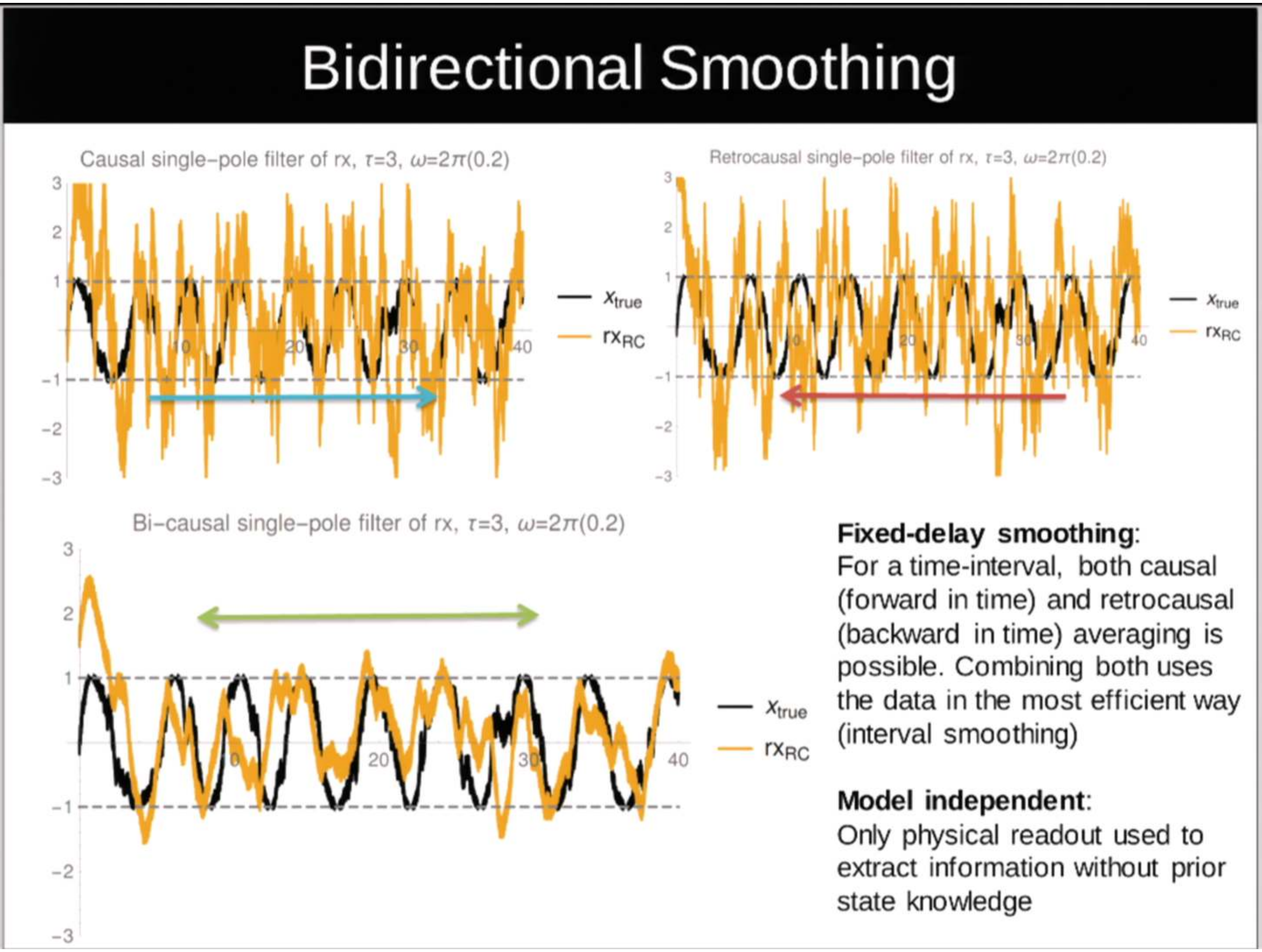


Filtering Raw Measurement Readout

Raw Readout:
Moving-average stochastic process – hides monitored state component with white noise

Filtered Readout:
Smooths out noise to recover monitored state information – trade-off between size of temporal averaging window and detailed knowledge of state dynamics

Quantum State Trajectory:
Using prior dynamical knowledge, noise can be optimally used to reconstruct the state

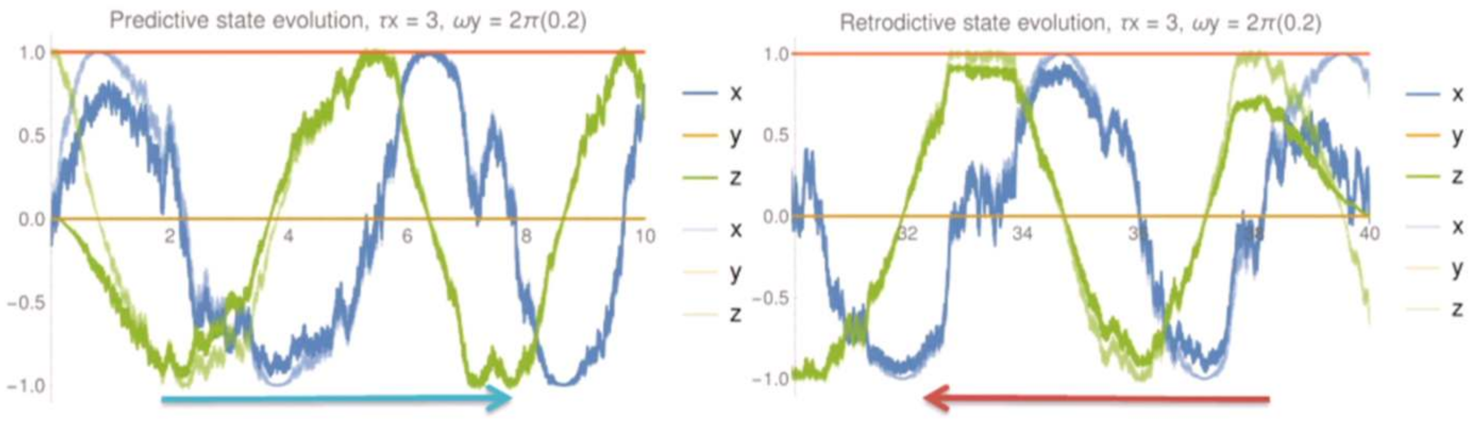


Bidirectional Smoothing

Fixed-delay smoothing:
For a time-interval, both causal (forward in time) and retrocausal (backward in time) averaging is possible. Combining both uses the data in the most efficient way (interval smoothing)

Model independent:
Only physical readout used to extract information without prior state knowledge

Erasure of Boundary Conditions



Forward and backward evolution:
The readout completely determines both the forward-evolved (predictive) quantum state, and the backward-evolved (retrodictive) quantum state, which are not the same

Readout determines evolution:
Boundary conditions only survive for a few collapse times – shown are two different prior and posterior boundary conditions converging to the same intermediary evolution

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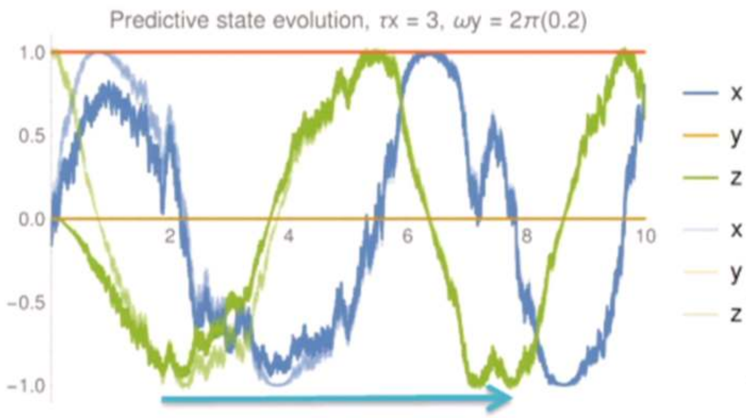

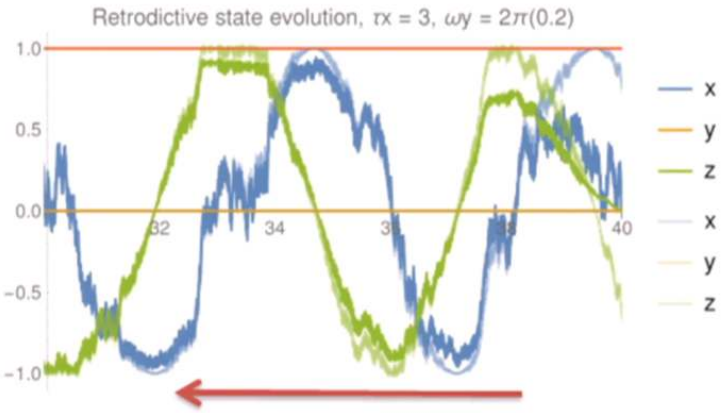

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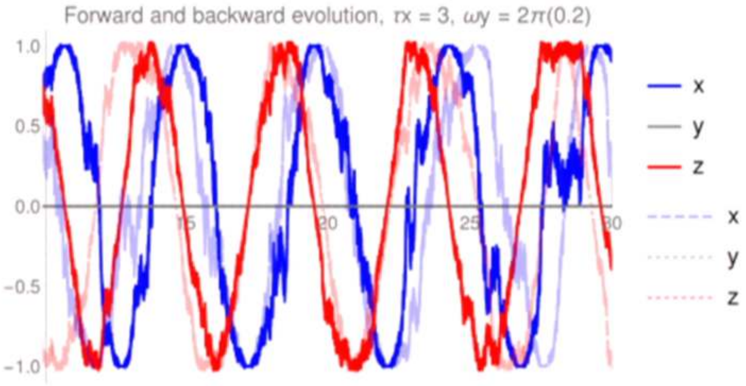
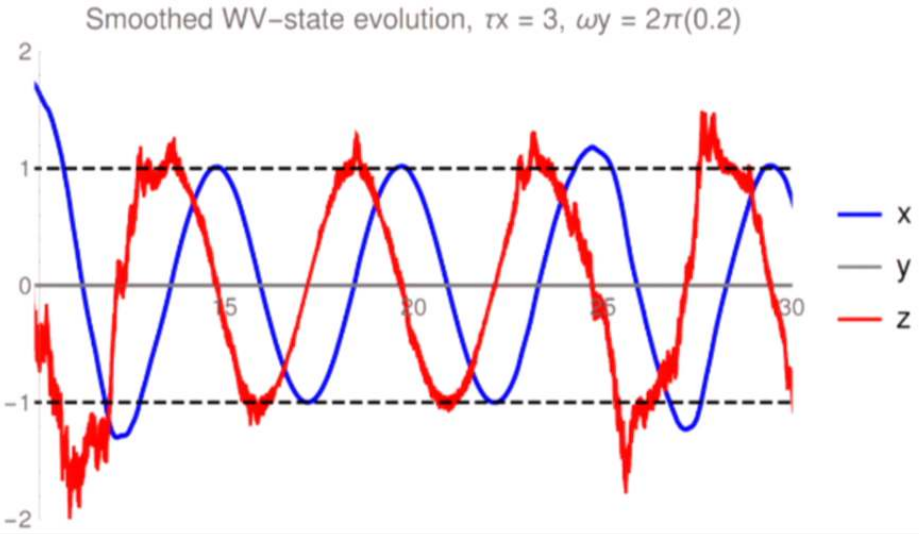
Weak Value as Best Estimate

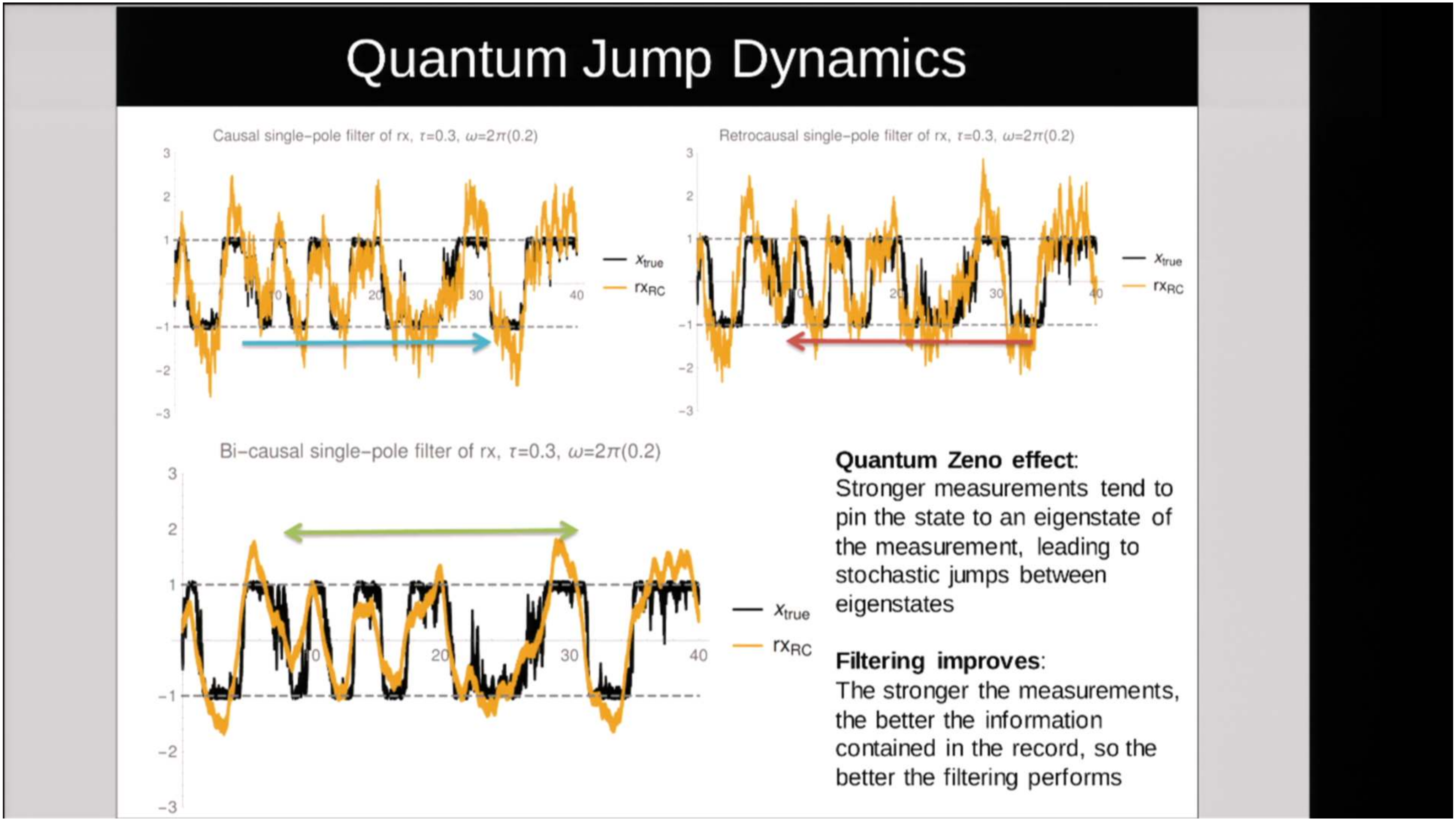




Forward and backwards states disagree in between: Which is the "correct" state?

Weak Value minimizes error: Given prior and posterior states, the real part of the weak value minimizes the RMS error for an observable, and is thus the best estimate of the observable value in between.

WV-state fixed by readout: Since both prior and posterior states are fixed, the WV estimates of the state components are also fixed. Magically, the monitored component becomes almost completely smooth with such an estimate (but may stray from eigenvalue bounds).



Quantum Jump Dynamics

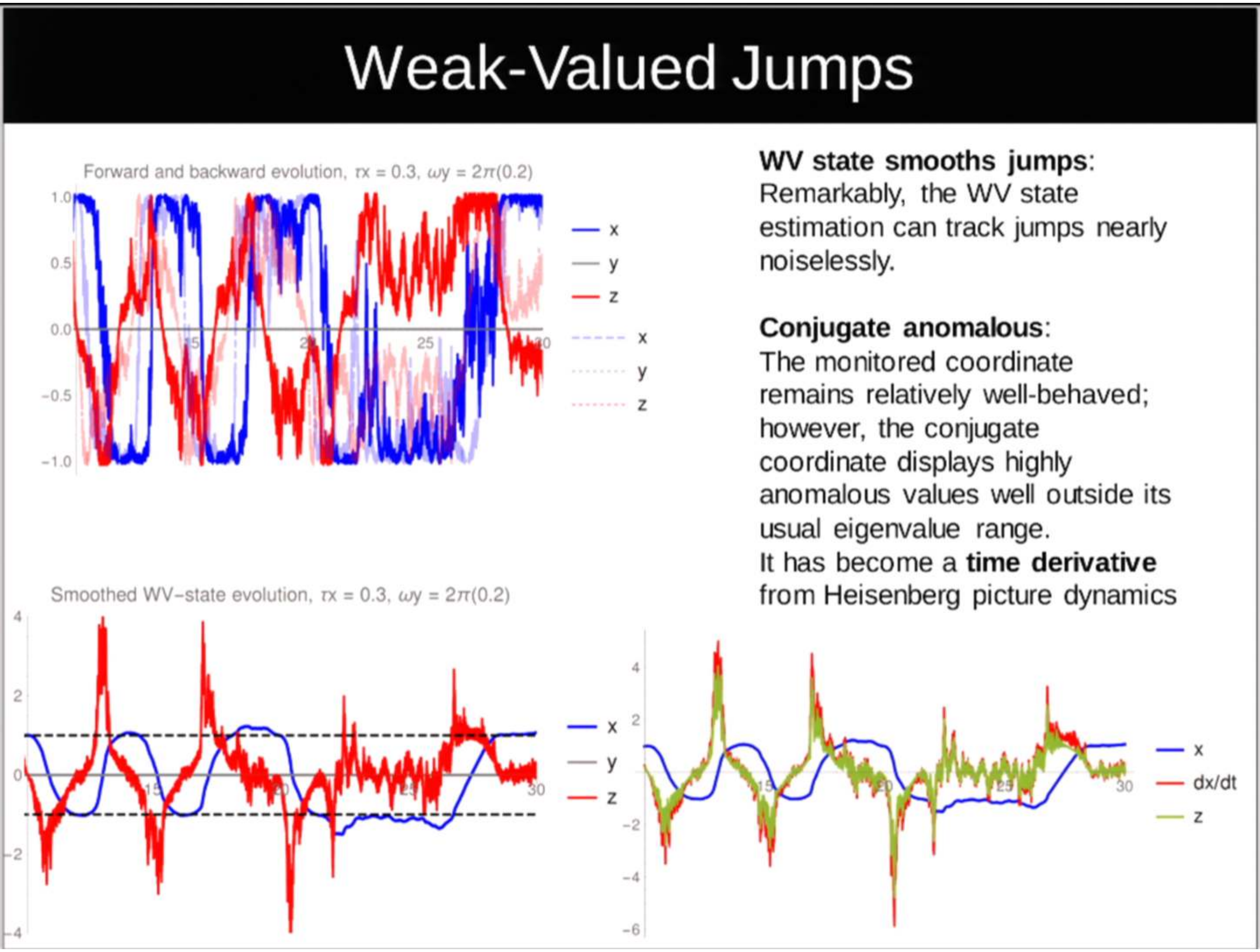
Causal single–pole filter of rx, τ=0.3, ω=2π(0.2)

Retrocausal single–pole filter of rx, τ=0.3, ω=2π(0.2)

Bi–causal single–pole filter of rx, τ=0.3, ω=2π(0.2)

Quantum Zeno effect:
Stronger measurements tend to pin the state to an eigenstate of the measurement, leading to stochastic jumps between eigenstates

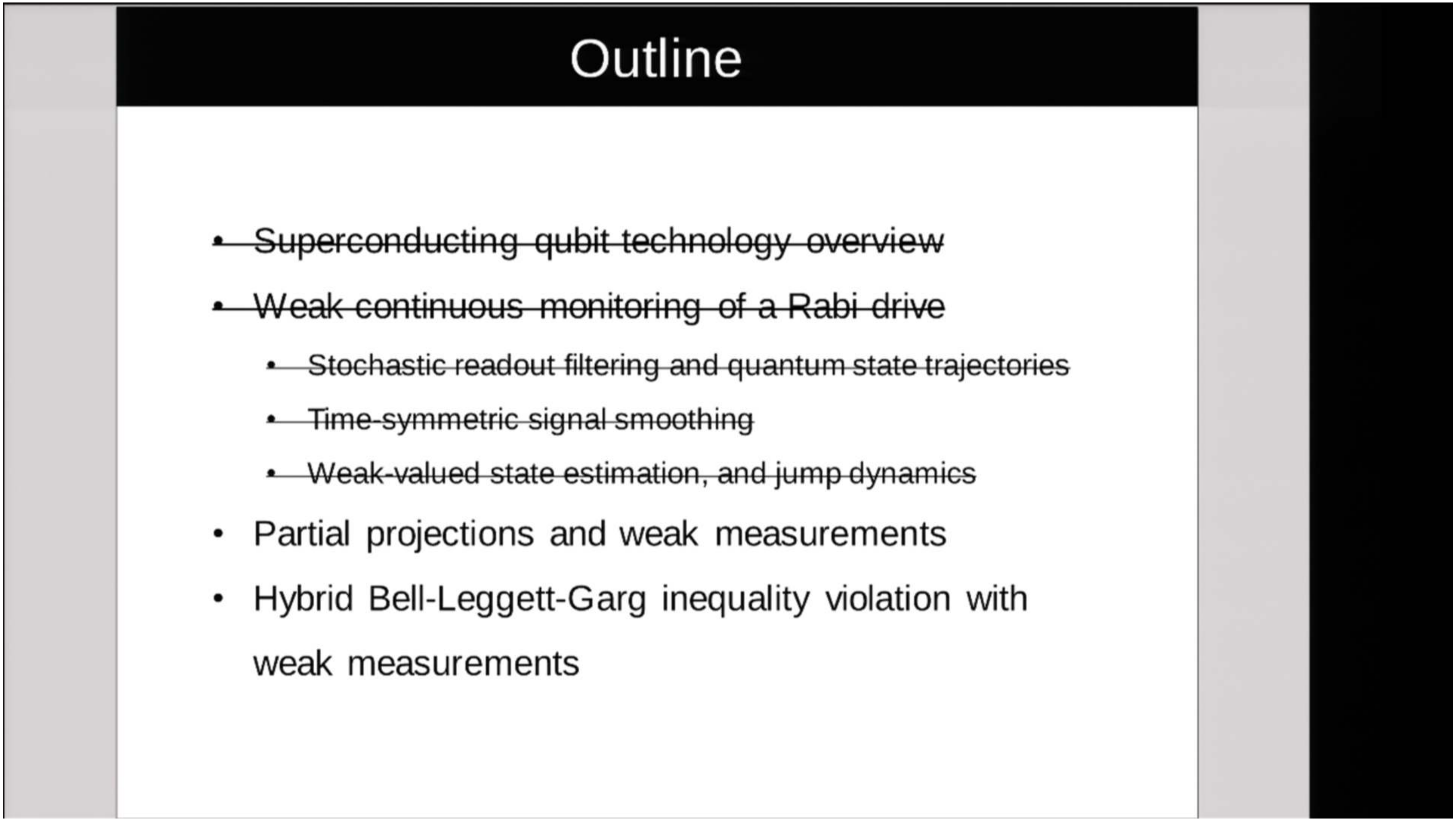
Filtering improves:
The stronger the measurements, the better the information contained in the record, so the better the filtering performs



Weak-Valued Jumps

WV state smooths jumps:
Remarkably, the WV state estimation can track jumps nearly noiselessly.

Conjugate anomalous:
The monitored coordinate remains relatively well-behaved; however, the conjugate coordinate displays highly anomalous values well outside its usual eigenvalue range.
It has become a **time derivative** from Heisenberg picture dynamics



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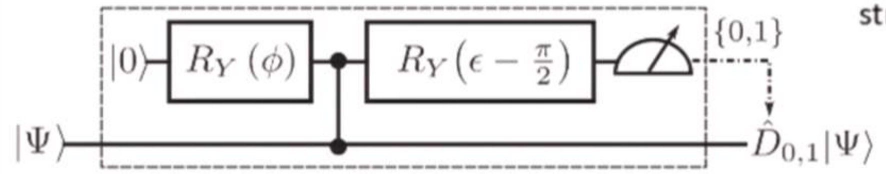
Partial Projection Circuit

Any qubit measurement is a combination of unitary rotations and a **partial projection** with two possible outcomes:

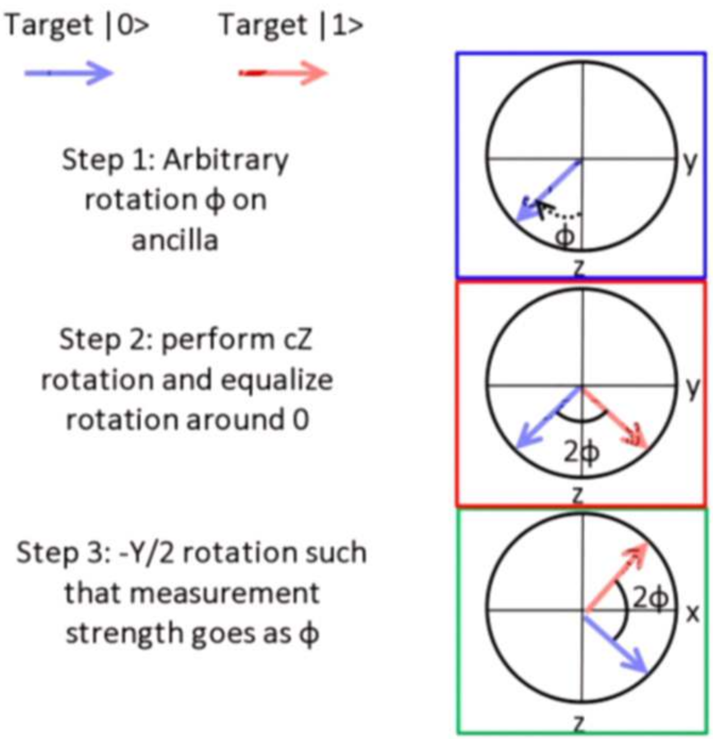
$$D_0 = \sqrt{p}\,|0\rangle\langle 0| + \sqrt{1-q}\,|1\rangle\langle 1|,$$

$$D_1 = \sqrt{1-p}\,|0\rangle\langle 0| + \sqrt{q}\,|1\rangle\langle 1|,$$

An ancilla qubit with a control-Z gate can be used to implement any desired partial projection in a tightly controlled way



Use ancilla qubit



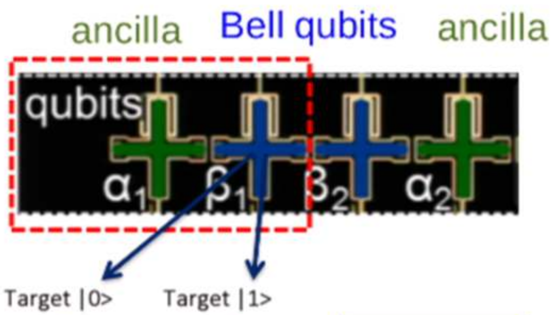
Step 1: Arbitrary rotation ϕ on ancilla

Step 2: perform cZ rotation and equalize rotation around 0

Step 3: -Y/2 rotation such that measurement strength goes as ϕ

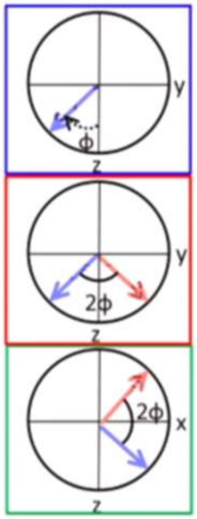
JD, PRA **90**, 032302 (2014)

Microwave pulse implementation



Target |0>

Target |1>



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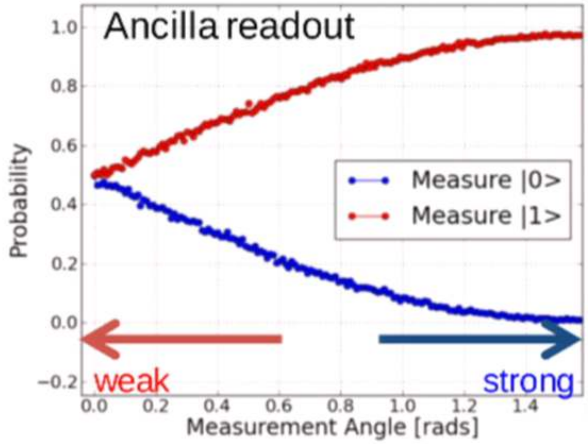
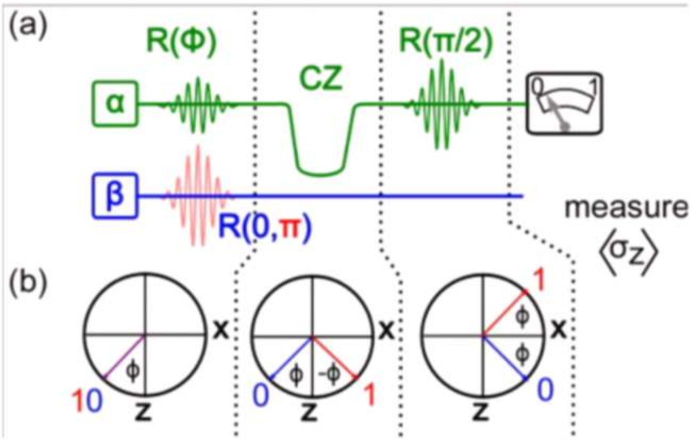
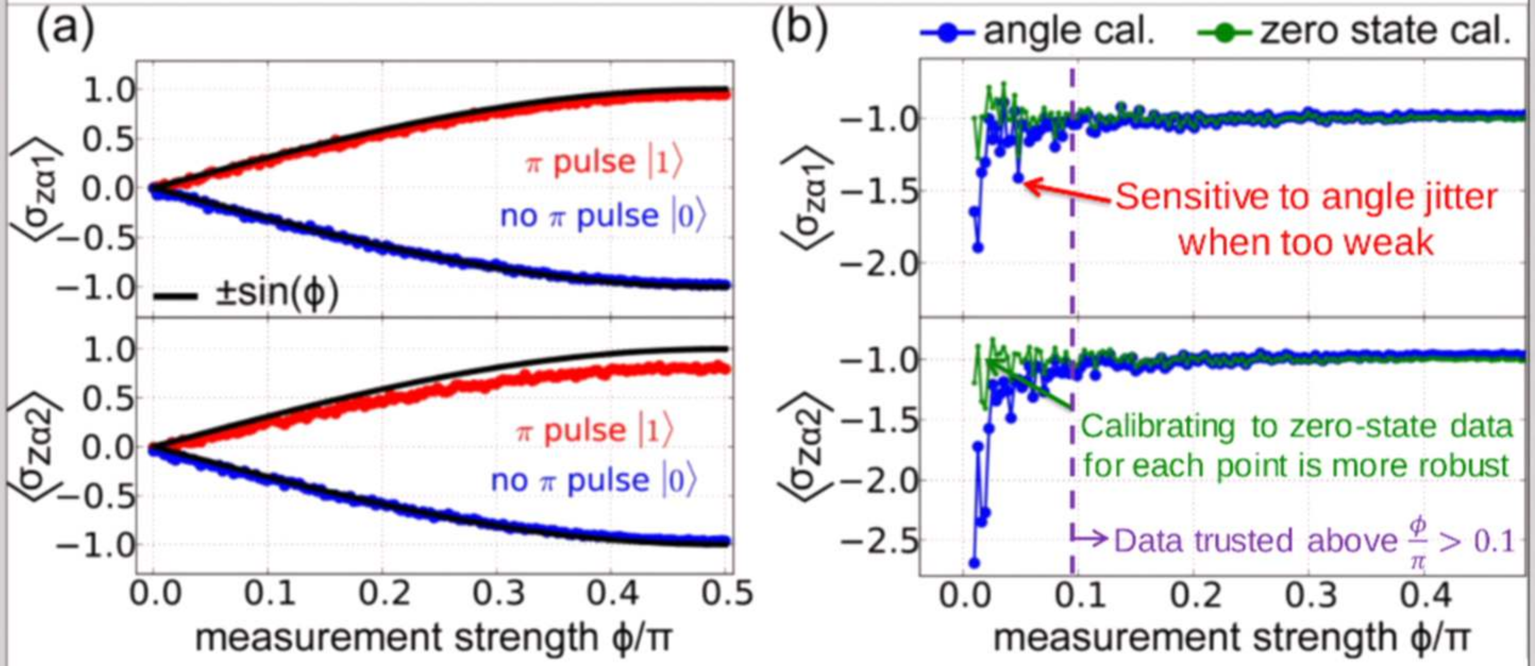




Calibrating the Z-measurement

Rescale signal to known ± 1 Z-preparations



Sensitive to angle jitter when too weak

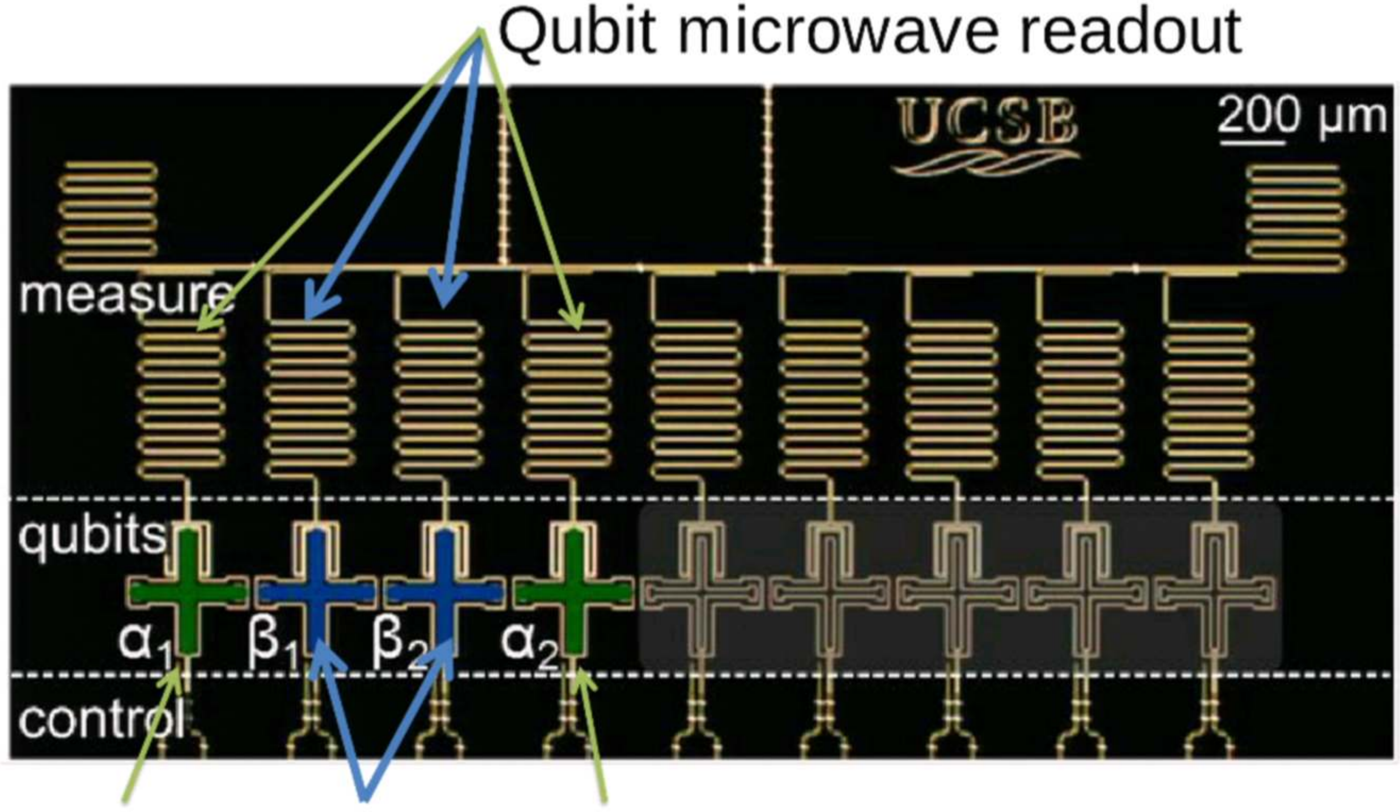
Calibrating to zero-state data for each point is more robust

→ Data trusted above $\frac{\phi}{\pi} > 0.1$

Two calibration methods: analytic ($\frac{\pm 1}{\sin\phi}$), and point-by-point

Superconducting 9 Xmon sample

Qubit microwave readout



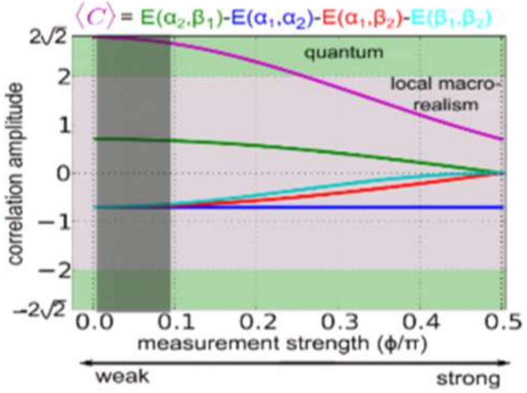
Ancilla qubit

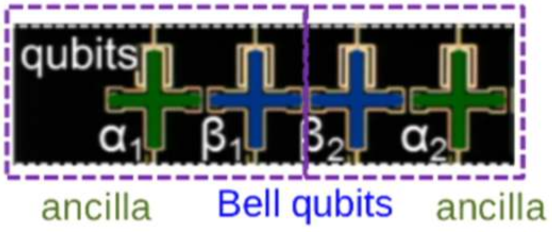
Bell qubits

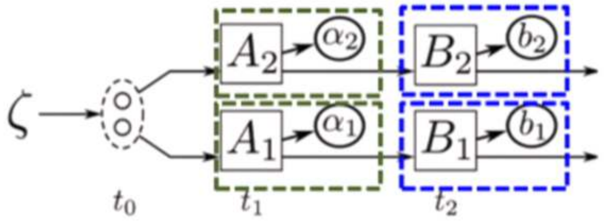
Ancilla qubit

4 qubit circuit can do two joint weak measurements

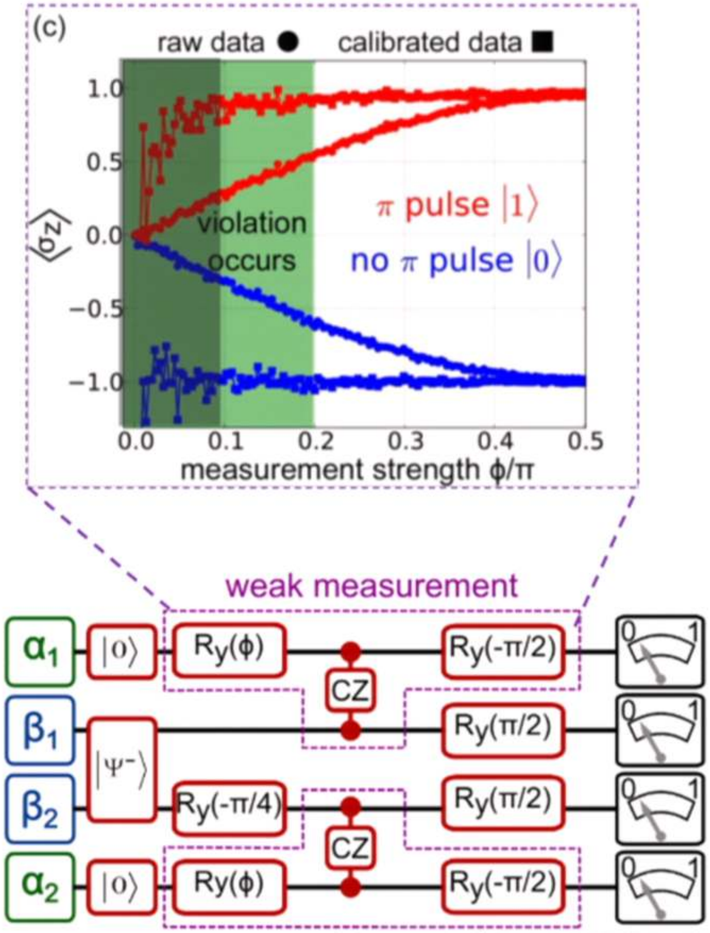
Bell-Leggett-Garg circuit





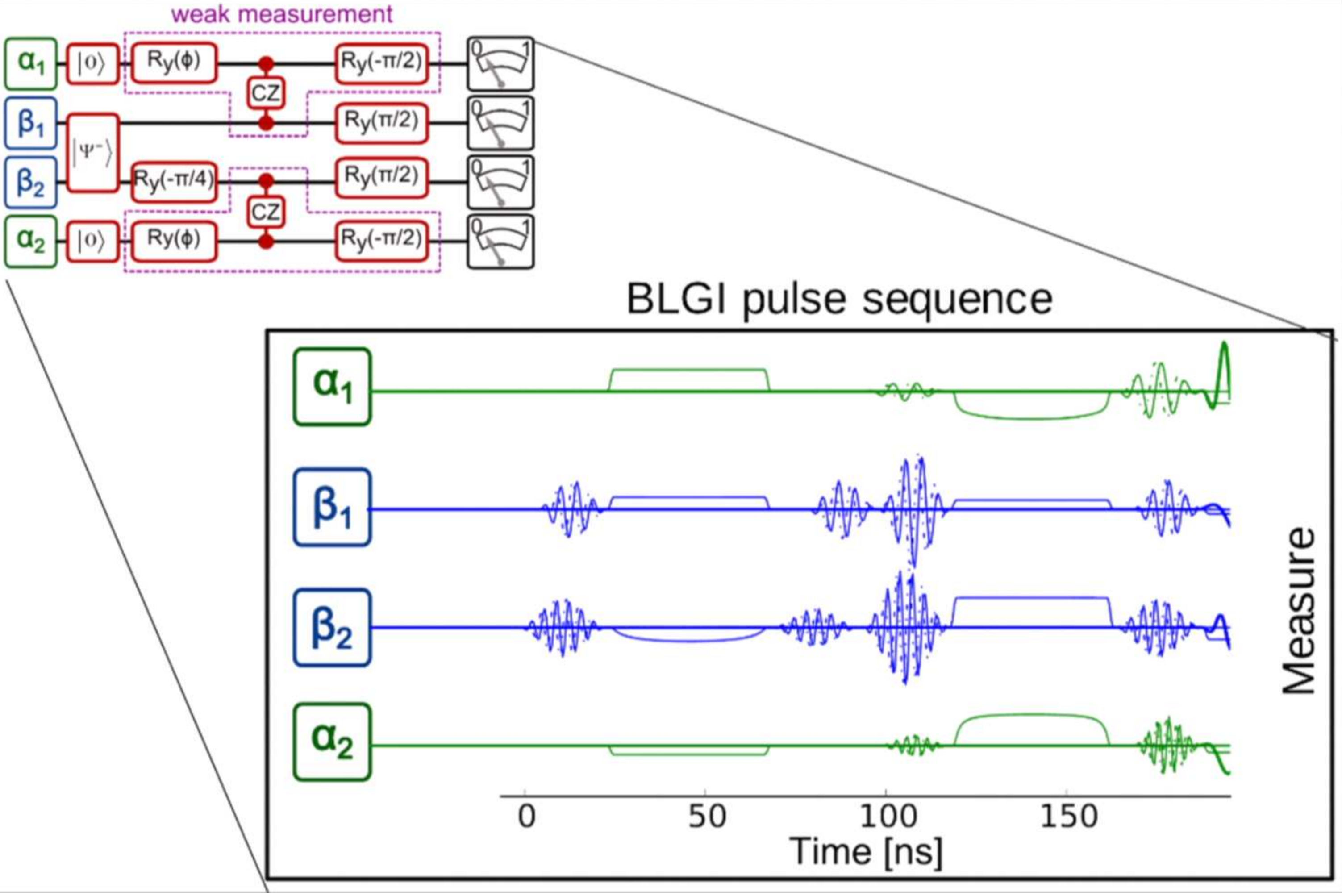


$$C = \alpha_1 \alpha_2 + \alpha_1 b_2 + b_1 \alpha_2 - b_1 b_2$$



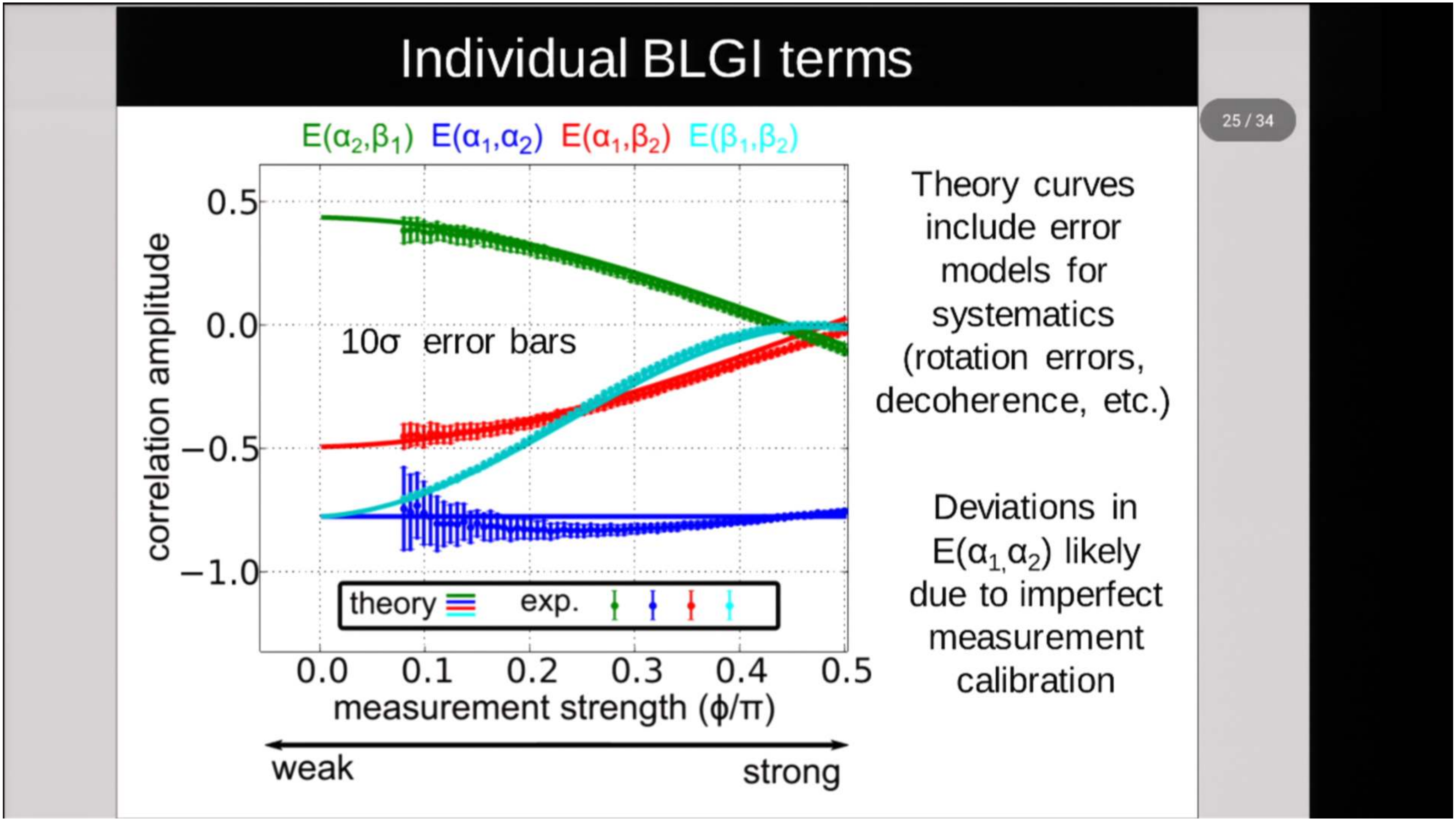
npj Quant. Inf. **2**, 15022 (2016)

BLGI microwave pulse sequence



BLGI pulse sequence

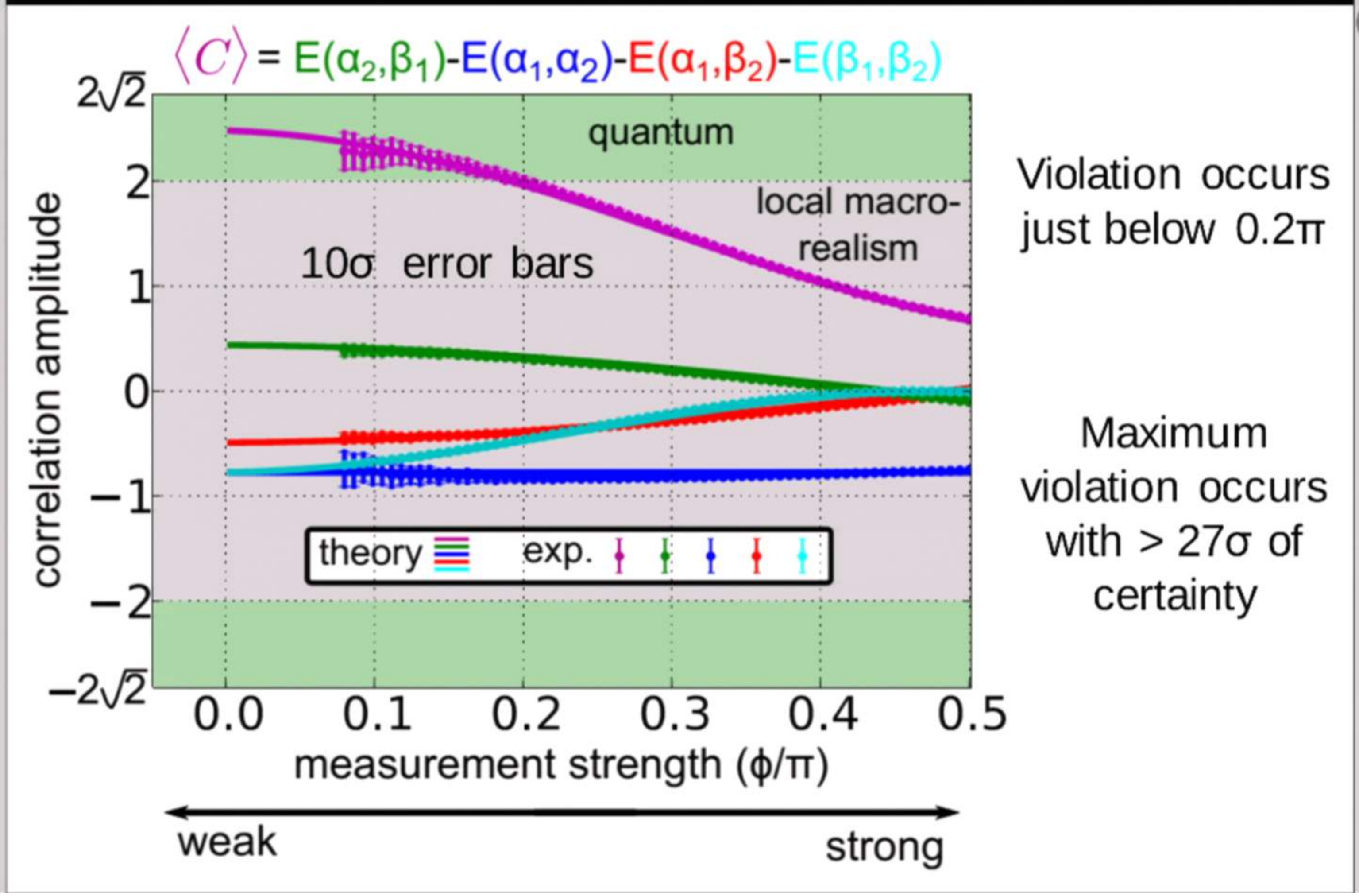
Individual BLGI terms



Theory curves include error models for systematics (rotation errors, decoherence, etc.)

Deviations in $E(\alpha_1,\alpha_2)$ likely due to imperfect measurement calibration

Full BLGI data - violation!



$\langle C \rangle = E(\alpha_2,\beta_1) - E(\alpha_1,\alpha_2) - E(\alpha_1,\beta_2) - E(\beta_1,\beta_2)$

Violation occurs just below 0.2π

Maximum violation occurs with > 27σ of certainty

Conclusions

- Superconducting processors work

- Both continuous weak measurements and discrete measurements of tunable strength are natural and useful

- Time-symmetric readout and state estimation has advantages