Continuous Monitoring Unlocks Quantum-Enhanced Sensing in Dissipative Time Crystals

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Continuous monitoring turns dissipative time crystals into useful sensing resources. By extracting information from the emitted field throughout the dynamics, one can **overcome key tradeoffs** of critical quantum sensing and achieve enhanced long-time metrological performance. In particular, the strongest advantage appears in the **time-crystal phase**, where the Fisher-information rate shows **cubic scaling** with system size.

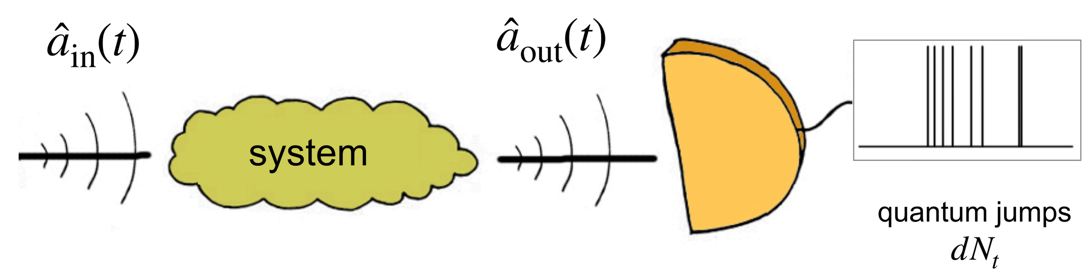
OVERCOMING CRITICAL SENSING DOWNSIDES VIA CONTINUOUS MONITORING

Near a phase transition, many-body states become highly sensitive to control parameters, so the quantum Fisher information (QFI) can **scale super-classically** with system size. However, there are downsides:

- The state is only sensitive at the critical point.
- Optimal measurements may be entangled and parameter dependent
- The time to reach critical state also diverges at the critical point

Estimation precision $\longrightarrow$ $\mathrm{Var}(\hat{\omega}) \geq \dfrac{1}{F_\omega}$ $\longleftarrow$ *State sensitivity (QFI)*

The solution: Continuous monitoring



Rather than only measuring the final state, we **continuously monitor the environment** into which the open quantum system dissipates. We then use this information to estimate the unknown parameter.

THE MODEL

The Boundary Time Crystal (BTC)

$$\frac{d\rho}{dt} = \mathcal{L}[\rho] = -i\omega[J_x,\rho] + \frac{2\kappa}{N}\mathcal{D}[J_-]\rho$$

Spin precession — *Collective damping*

$\omega < \kappa$	$\omega = \kappa$	$\omega > \kappa$
Stationary phase	***Critical point***	***Time-crystal phase***

At the critical point

Expectation: $F_\omega(\rho_{ss}) \sim N^{4/3}$ Super-classical!

Reality: *Taking the time to reach the steady state into account* $F_\omega(\rho_{ss})/T_{ss} \sim N$ The QFI rate reverts to the standard quantum limit

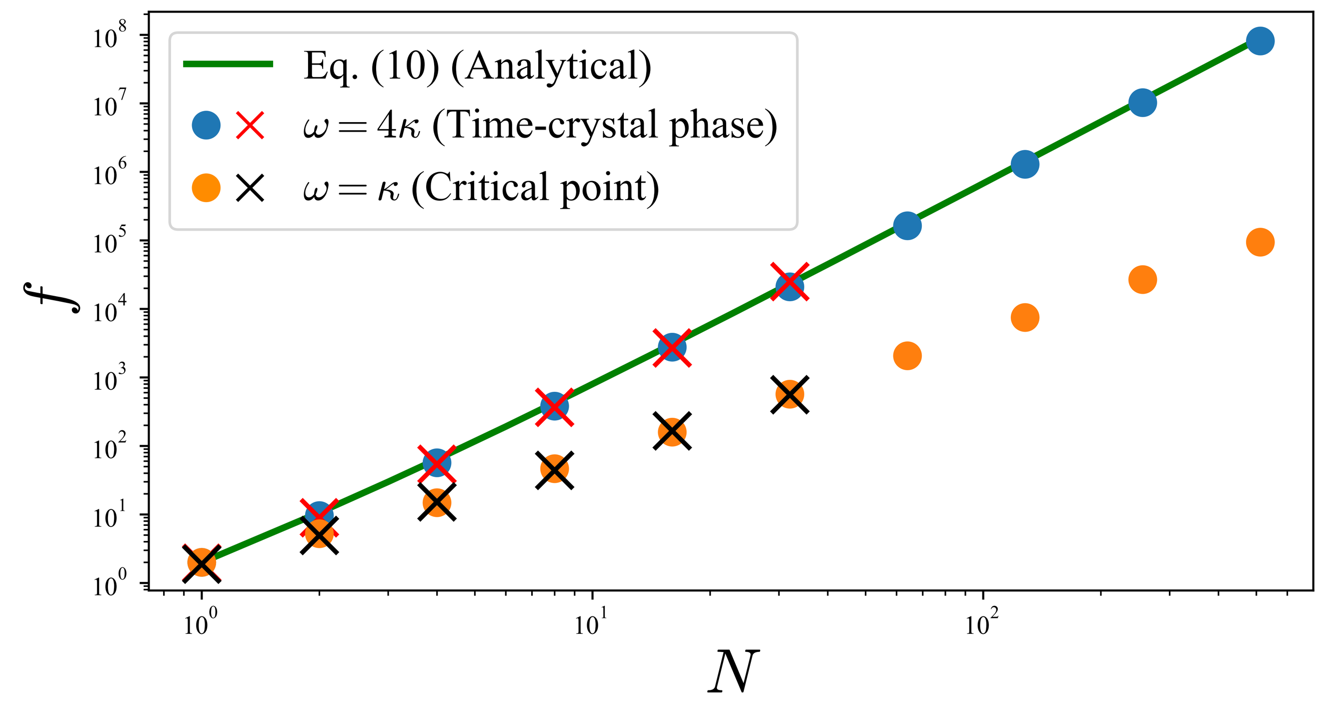
Continuous monitoring avoids this pitfall

At the critical point: $f_{\mathrm{signal}} := \lim_{T\to\infty} F_{\mathrm{signal}}(T)/T \sim N^{5/3}$

In the time crystal phase: $f_{\mathrm{signal}} \sim N^3$

BEYOND THE CRITICAL POINT

One major advantage of continuous monitoring is that the sensing advantage **does not rely on being at the critical point**. In fact, the long-time Fisher-information rate is even **larger in the time-crystal phase**.



We derive analytic results for a large class of dissipative time crystals

$$f_{\mathrm{signal}} = \frac{2N(N+2)}{3\kappa_{\mathrm{eff}}}$$ *For BTC:* $\kappa_{\mathrm{eff}} = \dfrac{\kappa}{N}$ $\longrightarrow$ $f_{\mathrm{signal}} \sim N^3$

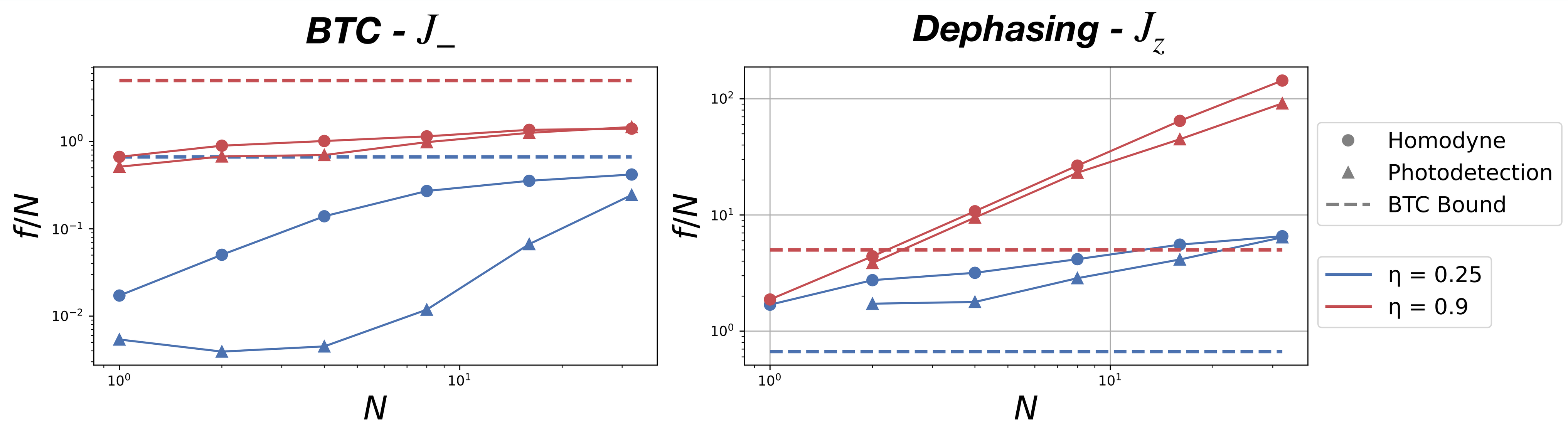
Another example this holds for is collective dephasing $J_- \to J_z$

IMPACT OF REALISTIC CONDITIONS (IMPERFECT DETECTION)

The previous results all assume perfect detectors. In reality, only a fraction, η, of the emitted field will be detected. This severely limits the attainable precision for the **BTC model** (collective damping), **reverting to the standard quantum limit.**

Noisy metrology bound PRX 7, 041009 $\longrightarrow$ $f_{\mathrm{signal}} \leq \dfrac{N}{2\kappa(1-\eta)}$ *For BTC*

However, this bound **does not apply to collective dephasing** model. Quantum enhanced estimation is still possible.



Restricted to the standard quantum limit

Quantum enhanced scaling

ORIGIN OF SCALING

To better understand the source of the quantum enhanced scaling we derived an upper bound on the information in the measurement signal.

$$f_{\mathrm{signal}} \leq 8\mathrm{Var}_{\rho_{ss}}(\partial_\theta H)\|\mathcal{L}^{\dagger+}\|_{\mathrm{op},S}$$

Quantum enhancement *Timescale enhancement*

CONCLUSIONS

- Continuous monitoring **restores and enhances** sensing performance in dissipative time crystals.
- In the time-crystal phase, the long-time Fisher information rate is enhanced and the advantage is **not limited to the critical point.**
- Under finite efficiency, **BTC reverts to standard quantum limit** scaling, while transverse **collective dephasing remains a more robust** platform for quantum-enhanced sensing.

READ MORE

Check out the paper: arXiv:2508.15448

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