# Observation of a discrete time crystal

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# About the author

## Observation of a discrete time crystal

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- Experimental quantum information science
- Quantum computing and quantum simulations with trapped atomic ions
- Quantum networks with atoms and photons
- Microfabricated atom trap structures

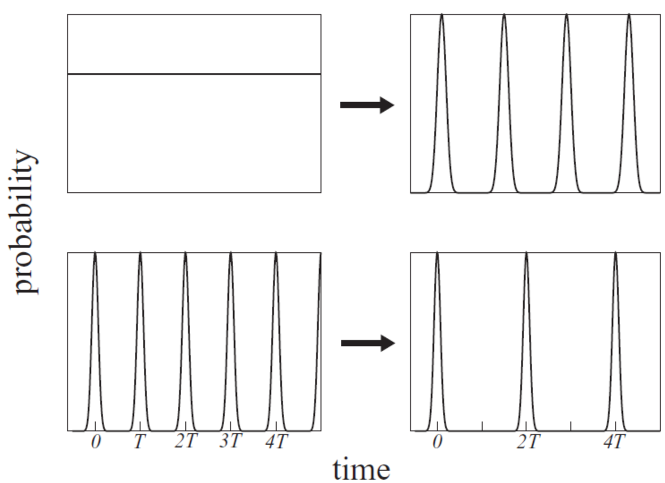
# ‘Time crystal’

Spatial translational symmetry breaking

liquid

Solid crystal

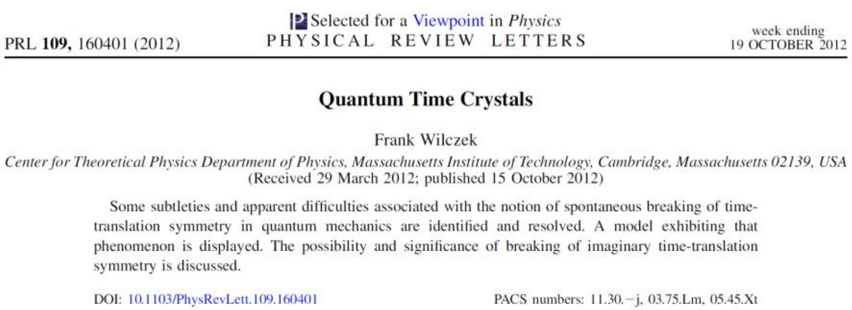
Time translation symmetry breaking




Krzysztof Sacha, Phys. Rev. A **91**, 033617 (2015)

# Brief history : time crystal

- The idea of a time crystal was proposed by Frank Wilczek, a professor at MIT and Nobel laureate, in 2012.


Selected for a Viewpoint in *Physics*

PRL **109,** 160401 (2012) PHYSICAL REVIEW LETTERS week ending 19 OCTOBER 2012

**Quantum Time Crystals**

Frank Wilczek

*Center for Theoretical Physics Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

(Received 29 March 2012; published 15 October 2012)

Some subtleties and apparent difficulties associated with the notion of spontaneous breaking of time-translation symmetry in quantum mechanics are identified and resolved. A model exhibiting that phenomenon is displayed. The possibility and significance of breaking of imaginary time-translation symmetry is discussed.

DOI: 10.1103/PhysRevLett.109.160401 PACS numbers: 11.30.−j, 03.75.Lm, 05.45.Xt

# Forbidden 'time crystal'

PRL **111,** 070402 (2013) PHYSICAL REVIEW LETTERS week ending 16 AUGUST 2013

**Impossibility of Spontaneously Rotating Time Crystals: A No-Go Theorem**

Patrick Bruno*

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(Received 26 June 2013; published 14 August 2013)

I present arguments indicating the impossibility of spontaneously rotating "quantum time crystals," as recently proposed by Frank Wilczek. In particular, I prove a "no-go theorem," rigorously ruling out the possibility of spontaneous ground-state (or thermal equilibrium) rotation for a broad class of systems.

DOI: 10.1103/PhysRevLett.111.070402 PACS numbers: 11.30.−j, 03.75.Lm, 05.45.Xt

PRL **114,** 251603 (2015) PHYSICAL REVIEW LETTERS week ending 26 JUNE 2015

**Absence of Quantum Time Crystals**

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(Received 28 March 2015; published 24 June 2015)

In analogy with crystalline solids around us, Wilczek recently proposed the idea of "time crystals" as phases that spontaneously break the continuous time translation into a discrete subgroup. The proposal stimulated further studies and vigorous debates whether it can be realized in a physical system. However, a precise definition of the time crystal is needed to resolve the issue. Here we first present a definition of time crystals based on the time-dependent correlation functions of the order parameter. We then prove a no-go theorem that rules out the possibility of time crystals defined as such, in the ground state or in the canonical ensemble of a general Hamiltonian, which consists of not-too-long-range interactions.

DOI: 10.1103/PhysRevLett.114.251603 PACS numbers: 11.30.-j, 05.70.Ln, 73.22.Gk

- Quantum time crystals in equilibrium are not possible!
- If the system is in Non-equilibrium?

# Time crystal In Non-equilibrium systems

PRL 117, 090402 (2016) PHYSICAL REVIEW LETTERS week ending 26 AUGUST 2016

**Floquet Time Crystals**

Dominic V. Else,[1] Bela Bauer,[2] and Chetan Nayak[2,1]
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(Received 6 April 2016; revised manuscript received 2 June 2016; published 25 August 2016)

We define what it means for time translation symmetry to be spontaneously broken in a quantum system and show with analytical arguments and numerical simulations that this occurs in a large class of many-body-localized driven systems with discrete time-translation symmetry.

DOI: 10.1103/PhysRevLett.117.090402

- Time translation symmetry breaking can occur in periodically driven(Floquet) system
- Resulting discrete time crystal

Selected for a Viewpoint in *Physics*
PRL 118, 030401 (2017) PHYSICAL REVIEW LETTERS week ending 20 JANUARY 2017

**Discrete Time Crystals: Rigidity, Criticality, and Realizations**

One of authors

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(Received 5 November 2016; published 18 January 2017)

Despite being forbidden in equilibrium, spontaneous breaking of time translation symmetry can occur in periodically driven, Floquet systems with discrete time-translation symmetry. The period of the resulting discrete time crystal is quantized to an integer multiple of the drive period, arising from a combination of collective synchronization and many body localization. Here, we consider a simple model for a one-dimensional discrete time crystal which explicitly reveals the rigidity of the emergent oscillations as the drive is varied. We numerically map out its phase diagram and compute the properties of the dynamical phase transition where the time crystal melts into a trivial Floquet insulator. Moreover, we demonstrate that the model can be realized with current experimental technologies and propose a blueprint based upon a one dimensional chain of trapped ions. Using experimental parameters (featuring long-range interactions), we identify the phase boundaries of the ion-time-crystal and propose a measurable signature of the symmetry breaking phase transition.

DOI: 10.1103/PhysRevLett.118.030401

- A theory paper that propose  a time crystal experiment with spin of Ion chains

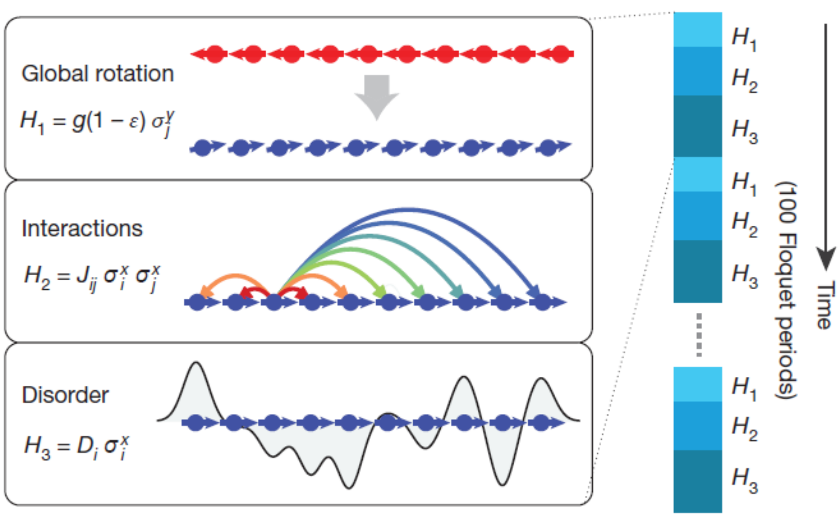
# Experimental scheme: Hamiltonian

Spin ½ particle chain with 10~14 particles in Ion trap

$^{171}Yb^{+}$ |F=0, $m_f$=0> , |F=1, $m_f$=0>

$$H = \begin{cases} H_1 = g(1-\varepsilon)\sum_i \sigma_i^y & \text{time } t_1 \\ H_2 = \sum_i J_{ij}\sigma_i^x\sigma_j^x & \text{time } t_2 \\ H_3 = \sum_i D_i\sigma_i^x & \text{time } t_3 \end{cases}$$

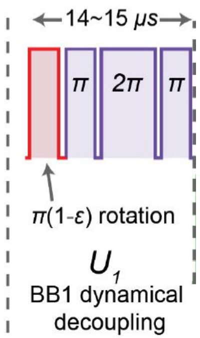
Floquet period: $T = t_1 + t_2 + t_3$




$$U(T) = e^{-iH_3t_3}e^{-iH_2t_2}e^{-iH_1t_1}$$

Pulses are generated by AOMs

# Global rotation




$$H_1 = g(1-\epsilon)\sum_i \sigma_i^y$$

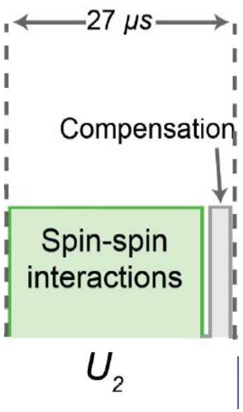
$g$: Rabi frequency $2gt_1 = \pi$
$\epsilon$: small perturbation

- Pair of Raman laser illuminate the entire the ion chain
- $\pi$ pulse $e^{-iH_1t_1}$ rotate the spins roughly half way of Bloch sphere.
- Response of the system is expected to be twice the drive period 2T

$$e^{-iH_1t_1} = \boxed{e^{-i\frac{\pi}{2}\sigma_i^\theta} e^{-i\pi\sigma_i^{3\theta}} e^{-i\frac{\pi}{2}\sigma_i^\theta}} e^{-i\frac{\pi}{2}(1-\epsilon)\sigma_i^y}$$

BB1 decoupling
Deviation reduced by third order

# Interaction : Ising Hamiltonian




$$H_2 = \sum_i J_{ij} \sigma_i^y \sigma_j^y$$

Spin dependent dipole force is applied

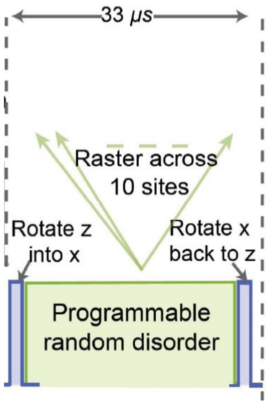
Bichromatic Laser beams with beat-note with the frequency of $\omega = \omega_0 \pm \mu$ gives spin-spin interaction ion in Lamb-Dicke regime

$$J_{ij} = \Omega^2 \omega_R \sum_{m=1}^{N} \frac{b_{i,m} b_{j,m}}{\mu^2 - \omega_m^2}$$

$\Omega$: Rabi frequency  $\omega_m$: trap frequency

$\omega_R$: recoil energy  $b_{i,m}$: normal mode matrix

# Disorder

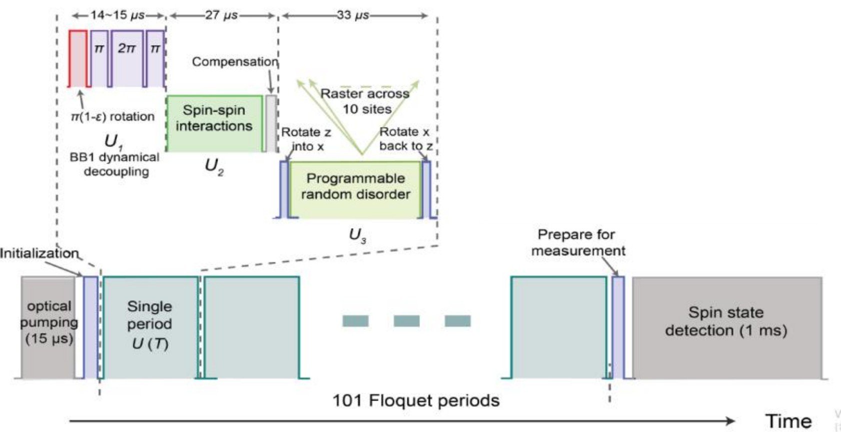



$$H_3 = \sum_i D_i \sigma_i^x$$

- Programmed disorders are applied (fourth-order AC stark shift)
- Localize the system (Related to stability of time crystal)

$$e^{-iH_3 t_3} = e^{-i\frac{\pi}{4}\sigma_i^y} e^{-iD_i\sigma_i^z t_3} e^{-i\frac{\pi}{4}\sigma_i^y} = e^{-iD_i\sigma_i^x t_3}$$

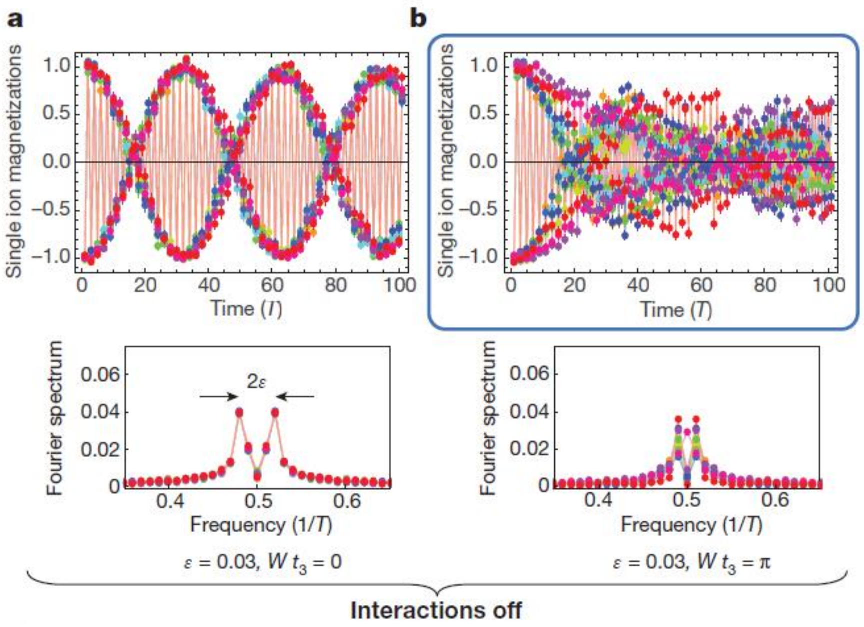
# Experimental scheme: time sequence




- Initialize spin state : $|\psi_0\rangle = |\downarrow\rangle_x = \frac{1}{\sqrt{2}}(|\downarrow\rangle_z + |\uparrow\rangle_z)$
- Around 100 times Floquet unitary operations (~75 μs)
- Measure spin magnetization through spin-dependent fluorescence

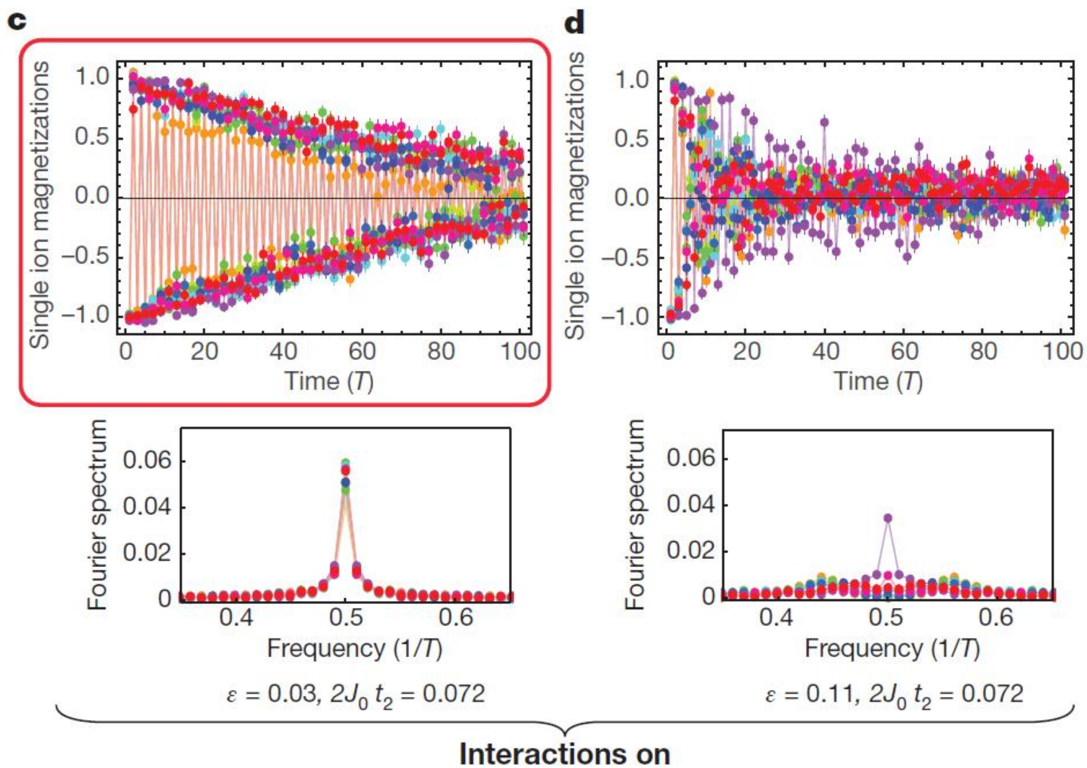
$$\langle \sigma_i^x(t) \rangle = \langle \psi_0 | \sigma_i^x(t) \sigma_i^x(0) | \psi_0 \rangle$$

# Experimental results : without spin-spin interaction




a: Only spin flip applied, splitting of spectrum due to $\epsilon$ is observed
b: a with disorder, spins presses with different lamour rates because of different individual fields

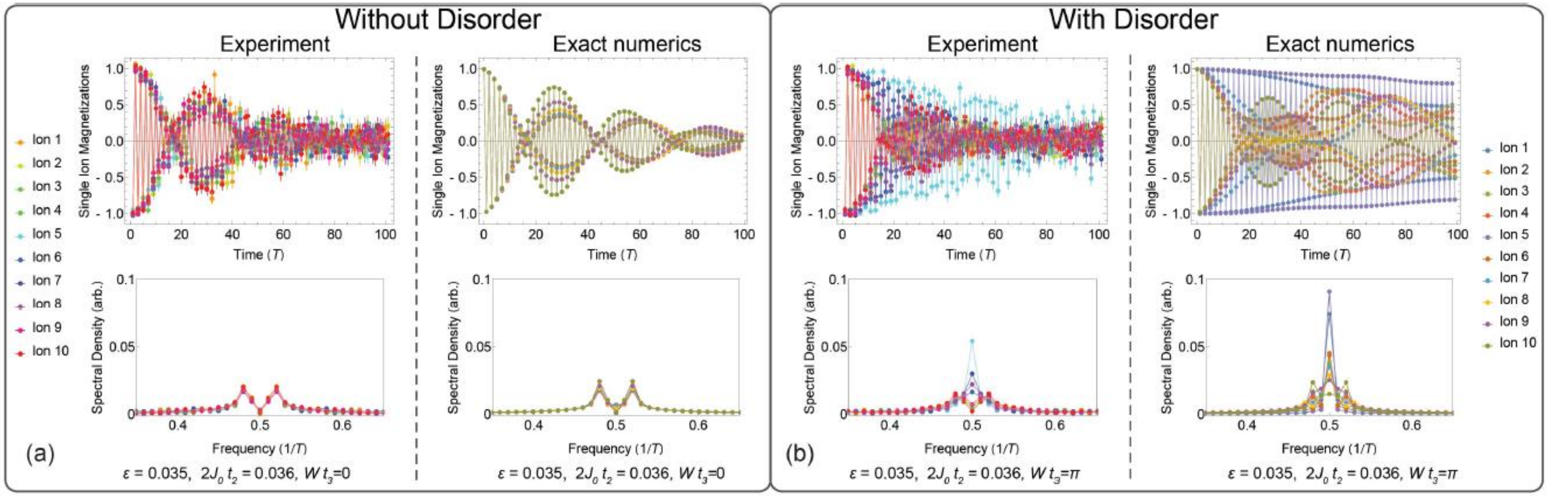
# Experimental results : rigidity of time crystal




In time crystal phase, the spins lock to the subharmonic frequency of the drive period (Robust to the perturbation)

If perturbation become too strong, time crystal phase transit to symmetry unbroken phase

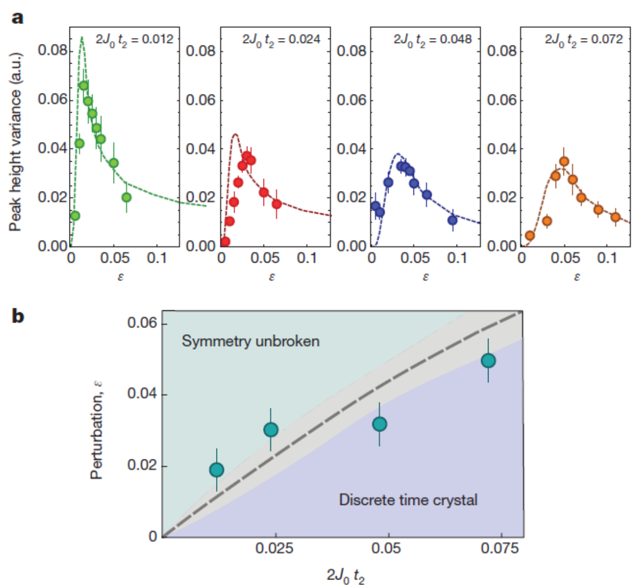
# Experimental results: role of disorder

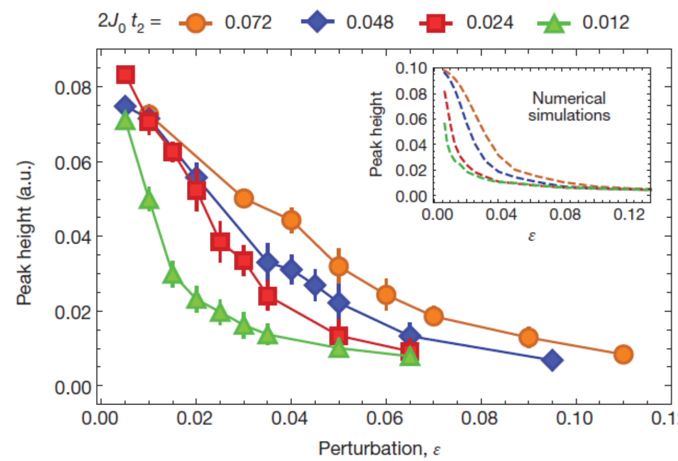


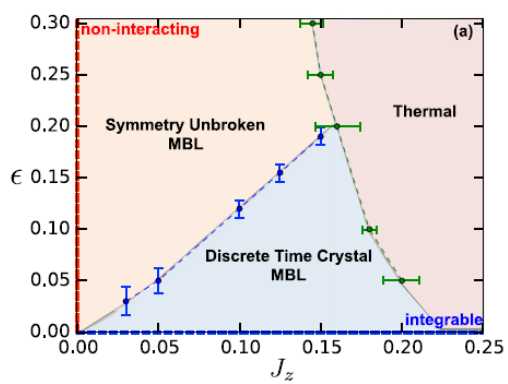

- Without disorder, the time crystal phase in unstable. Spin-spin interaction suppress the beat note.

- With disorder, the time crystal is stable subharmonic response is observed

# Experimental results: phase transition




N. Y. Yao et. al, Phys. rev. Lett. 118, 030401 (2017)

# Summary

- Observed time translation symmetry breaking in to discrete time crystal experimentally.
- Showed time crystal is robust to perturbations in the drive.
- Floquet system with long-range interaction can be useful tool for non-equilibrium quantum dynamics
- Can be used for quantum information tasks, such as a robust quantum memory.