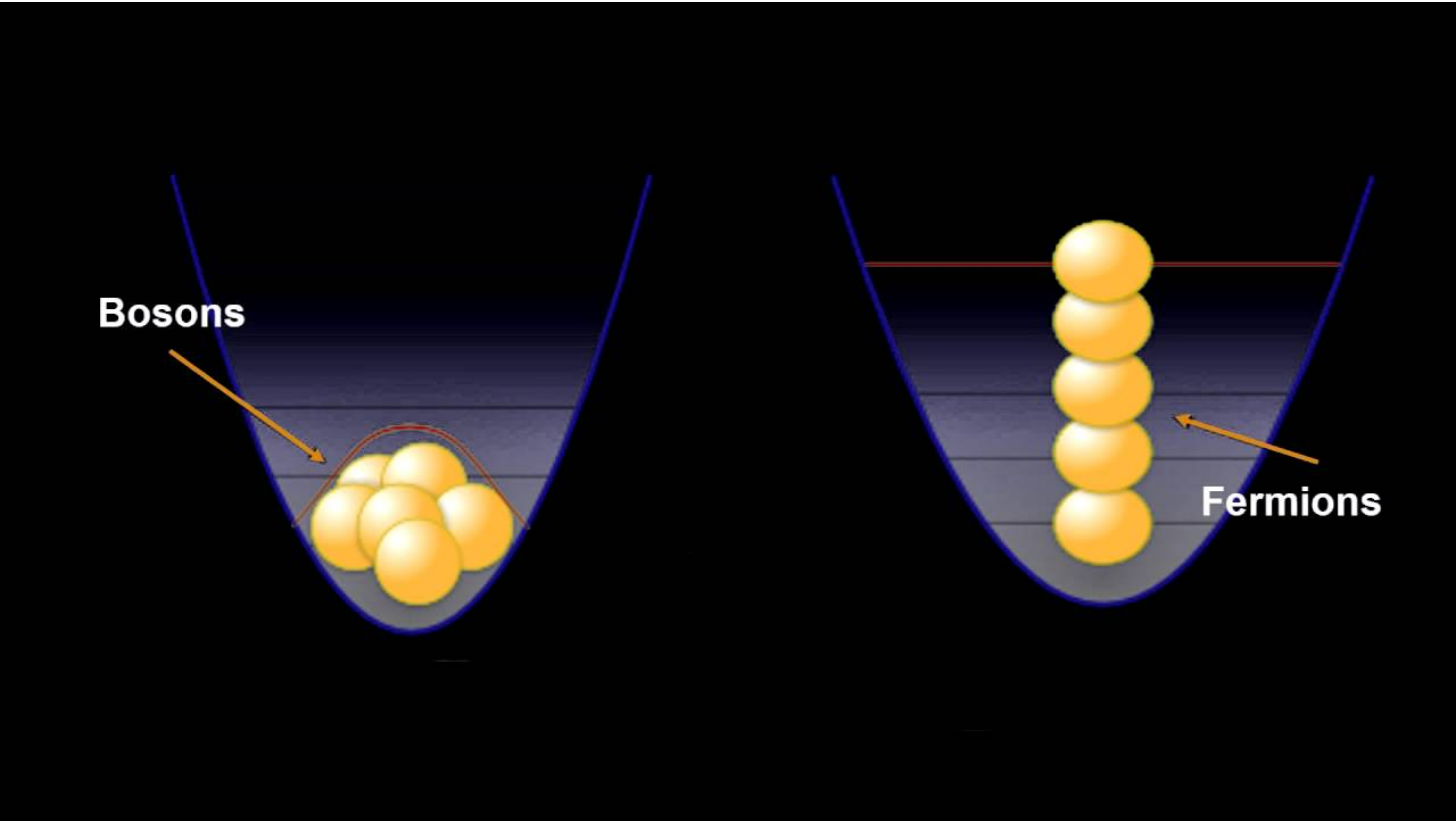
Quanta of the Third Kind:
Anyons

Physicists have long classified particles into two types, bosons and fermions.

Bosons and fermions exhibit very different behavior, when you bring several of them together.


Bosons
Fermions

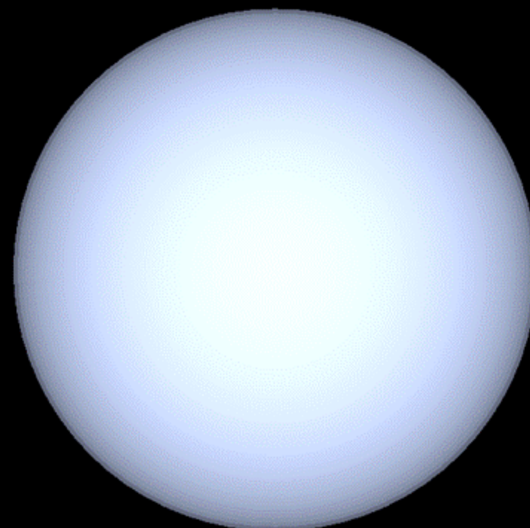
Basically, bosons “want to do the same thing”, while fermions “refuse to do the same thing”.

This property, called *quantum statistics,* has many striking consequences.

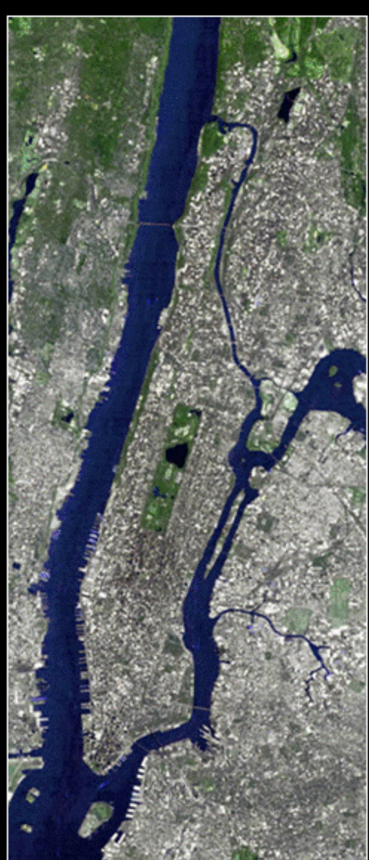
Electrons, neutrons, and protons are fermions:

Group → / Period ↓	1	2	3		4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc		22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y		40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
				*	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
				**	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

The shell structure of atoms and nuclei is a gift from Fermi statistics!



$M \approx 1.0\ M_{sun}$
$R \approx 5800$ km
$V_{esc} \approx 0.02c$



Manhattan
(spaceimaging.com)

$M = 1.5\ M_{sun}$
$R \approx 10$ km
$V_{esc} \approx 0.7c$

More gifts!

White dwarf: gravity balanced by quantum statistics (electrons)

A giant atom

Neutron star: gravity balanced by quantum statistics (neutrons)

A giant nucleus

Photons are bosons:

Anyons

For many years, physicists believed that bosons and fermions were the only possible kinds of particles.

But in the late 1970s and early 1980s some of us realized that if we lived in "Flatland" - a world with only two dimensions of space - there would be many other possibilities.

In 1982, I named the new kinds of particles *anyons*.

Anyons have a kind of memory.

They (or, more precisely, their wave function) keep track of how many times, and in what patterns, they’ve wound around one another.

The world-lines of two dimensional particles form braids in three dimensions.

The *world-lines* of two dimensional particles form braids in three dimensions.

Braids can be very complicated!

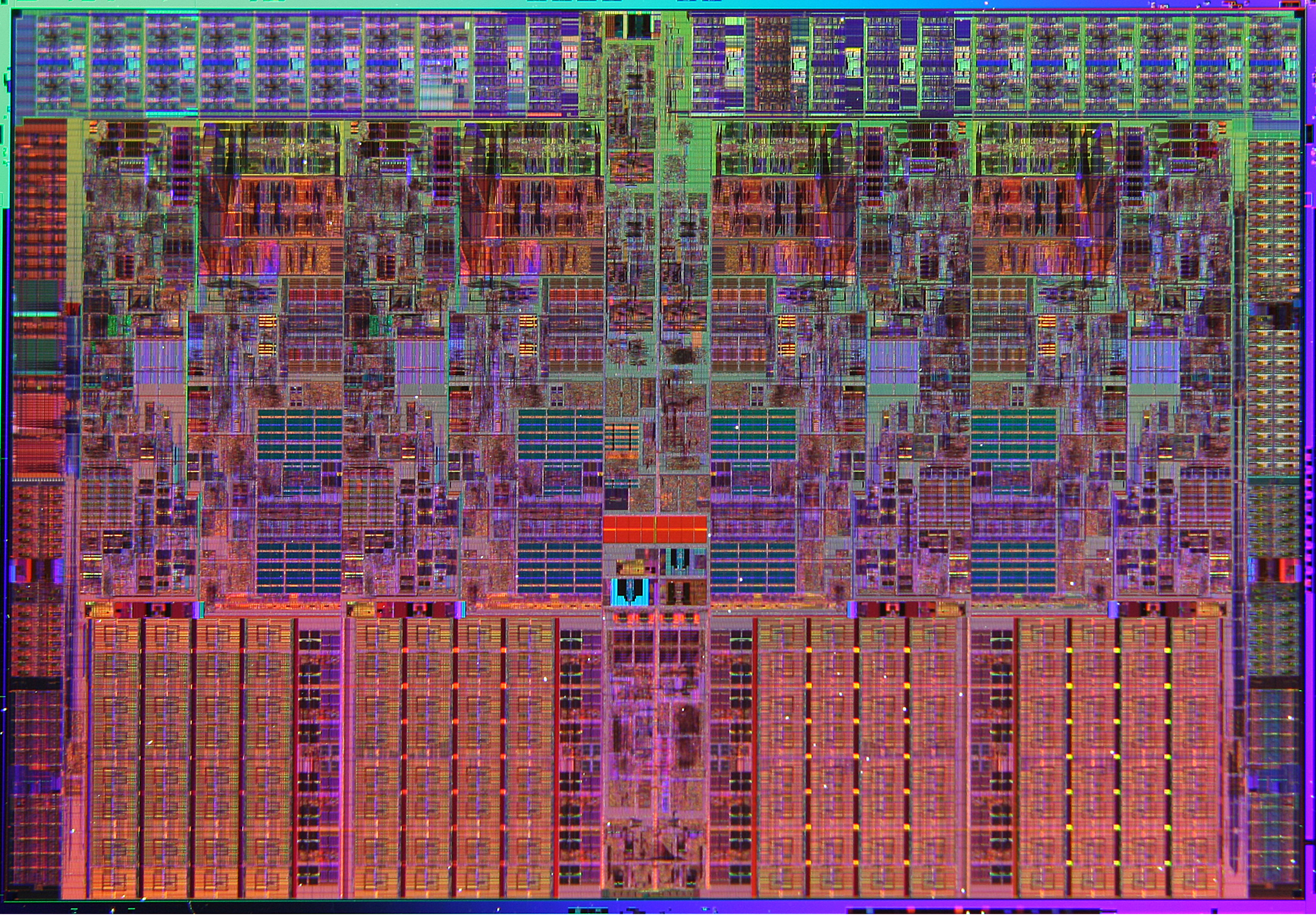
This means that systems of anyons can “remember” a lot, by getting tangled up.

They also process lots of information at once, simply by moving around.

Of course, we don’t live in a two-dimensional world.

But we can create such worlds, and visit them!

- and use them!



Modern Processor

In 1984, I predicted that the stable concentrations of energy - the “quasiparticles” - within a known state of 2D matter, the so-called fractional quantum Hall effect, would be a specific kind of anyon.

Fractional Statistics and the Quantum Hall Effect

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The statistics of quasiparticles entering the quantum Hall effect are deduced from the adiabatic theorem. These excitations are found to obey fractional statistics, a result closely related to their fractional charge.

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Extensive experimental studies have been carried out[1] on semiconducting heterostructures in the quantum limit $\omega_0\tau >> 1$, where $\omega_0 = eB_0/m$ is the cyclotron frequency and τ is the electronic scattering time. It is found that as the chemical potential μ is varied, the Hall conductance $\sigma_{xy} = I_x/E_y = \nu e^2/h$ shows plateaus at $\nu = n/m$, where n and m are integers with m being odd. The ground state and excitations of a two-dimensional electron gas in a strong magnetic field B_0 have been studied[2–4] in relation to these experiments and it has been found that the free energy shows cusps at filling factors $\nu = n/m$ of the Landau levels. These cusps correspond to the existence of an "incompressible quantum fluid" for given n/m and an energy gap for adding quasiparticles which form an interpenetrating fluid. This quasiparticle fluid in turn condenses to

where $z_j = x_j + iy_j$. A state having a quasihole localized at z_0 is given by

$$\psi_m^{+z_0} = N_+ \prod_i (z_i - z_0)\psi_m, \tag{2}$$

while a quasiparticle at z_0 is described by

$$\psi_m^{-z_0} = N_- \prod_i (\partial/\partial z_i - z_0/a_0^2)\psi_m, \tag{3}$$

where $2\pi a_0^2 B_0 = \phi_0 = hc/e$ is the flux quantum and $N_\pm$ are normalizing factors.

To determine the quasiparticle charge e^*, we calculate the change of phase γ of $\psi_m^{+z_0}$ as z_0 adiabatically moves around a circle of radius R enclosing flux ϕ. To determine e^*, γ is set equal to the change of phase,

$$(e^*/\hbar c)\oint \vec{A}\cdot d\vec{l} = 2\pi(e^*/e)\phi/\phi_0, \tag{4}$$

At the time, I thought this prediction would be verified in a matter of months.

Instead, it took almost forty years.

Finally, in April 2020, came good news:


Anorexia's roots in genes and the brain p. 124
Histone modification and cocaine addiction pp. 134 & 197
An anthropoid primate from South America pp. 136 & 194
Science
$15
10 APRIL 2020
sciencemag.org
AAAS
EXOTIC STATISTICS
Anyons show their true colors in a tiny collider pp. 131 & 173

Bartolomei *et al.*, *Science* **368**, 173–177 (2020) 10 April 2020

MESOSCOPIC PHYSICS

Fractional statistics in anyon collisions

H. Bartolomei[1]*, M. Kumar[1]*†, R. Bisognin[1], A. Marguerite[1]‡, J.-M. Berroir[1], E. Bocquillon[1], B. Plaçais[1], A. Cavanna[2], Q. Dong[2], U. Gennser[2], Y. Jin[2], G. Fève[1]§

Two-dimensional systems can host exotic particles called anyons whose quantum statistics are neither bosonic nor fermionic. For example, the elementary excitations of the fractional quantum Hall effect at filling factor $\nu = 1/m$ (where m is an odd integer) have been predicted to obey Abelian fractional statistics, with a phase ϕ associated with the exchange of two particles equal to π/m. However, despite numerous experimental attempts, clear signatures of fractional statistics have remained elusive. We experimentally demonstrate Abelian fractional statistics at filling factor $\nu = 1/3$ by measuring the current correlations resulting from the collision between anyons at a beamsplitter. By analyzing their dependence on the anyon current impinging on the splitter and comparing with recent theoretical models, we extract $\phi = \pi/3$, in agreement with predictions.

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In this experiment, people observed behavior in between the “no” of fermions and the “go” of bosons.

In June, there was even better news:

Direct observation of anyonic braiding statistics at the ν=1/3 fractional quantum Hall state

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(Dated: June 26, 2020)

Utilizing an electronic Fabry-Perot interferometer in which Coulomb charging effects are suppressed, we report experimental observation of anyonic braiding statistics for the $\nu = 1/3$ fractional quantum Hall state. Strong Aharonov-Bohm interference of the $\nu = 1/3$ edge mode is punctuated by discrete phase slips consistent with an anyonic phase of $\theta_{anyon} = \frac{2\pi}{3}$. Our results are consistent with a recent theory of a Fabry-Perot interferometer operated in a regime in which device charging energy is small compared to the energy of formation of charged quasiparticles [17]. Close correspondence between device operation and theoretical predictions substantiates our claim of observation of anyonic braiding.

BACKGROUND

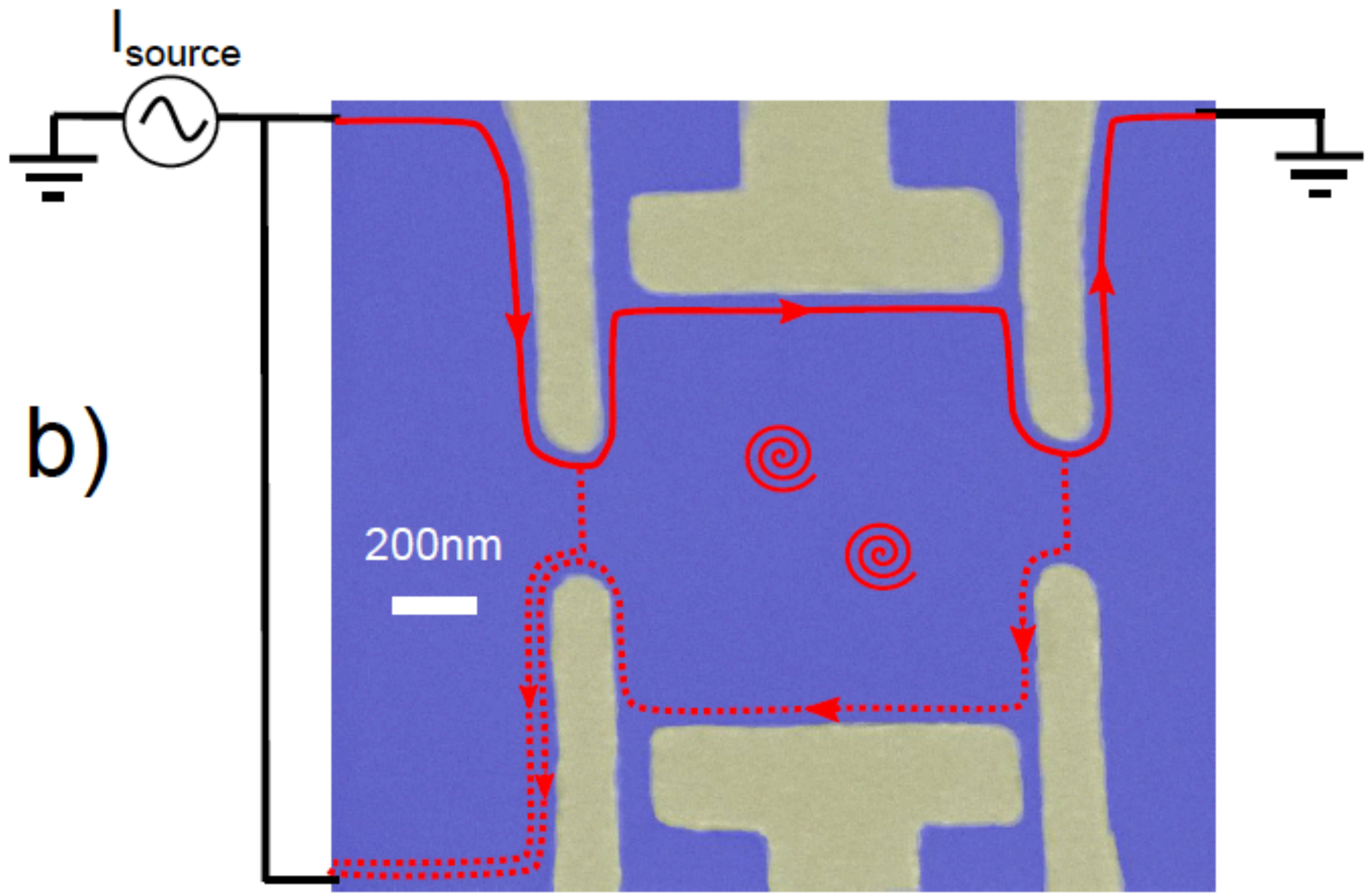
Quantum theory requires that all fundamental particles must be fermions or bosons, which has profound implications for particles' statistical behavior. However, theoretical works have shown that in two dimensions it is possible for particles to violate this principle and obey so-called anyonic statistics, in which exchange of particle position results in a quantum mechanical phase change that is not π or 2π (as for fermions or bosons), but a rational fraction of π [1, 2]. While anyons cannot exist as fundamental particles in nature, certain condensed matter systems are predicted to host exotic quasiparticles which obey a certain form of anyonic statistics.

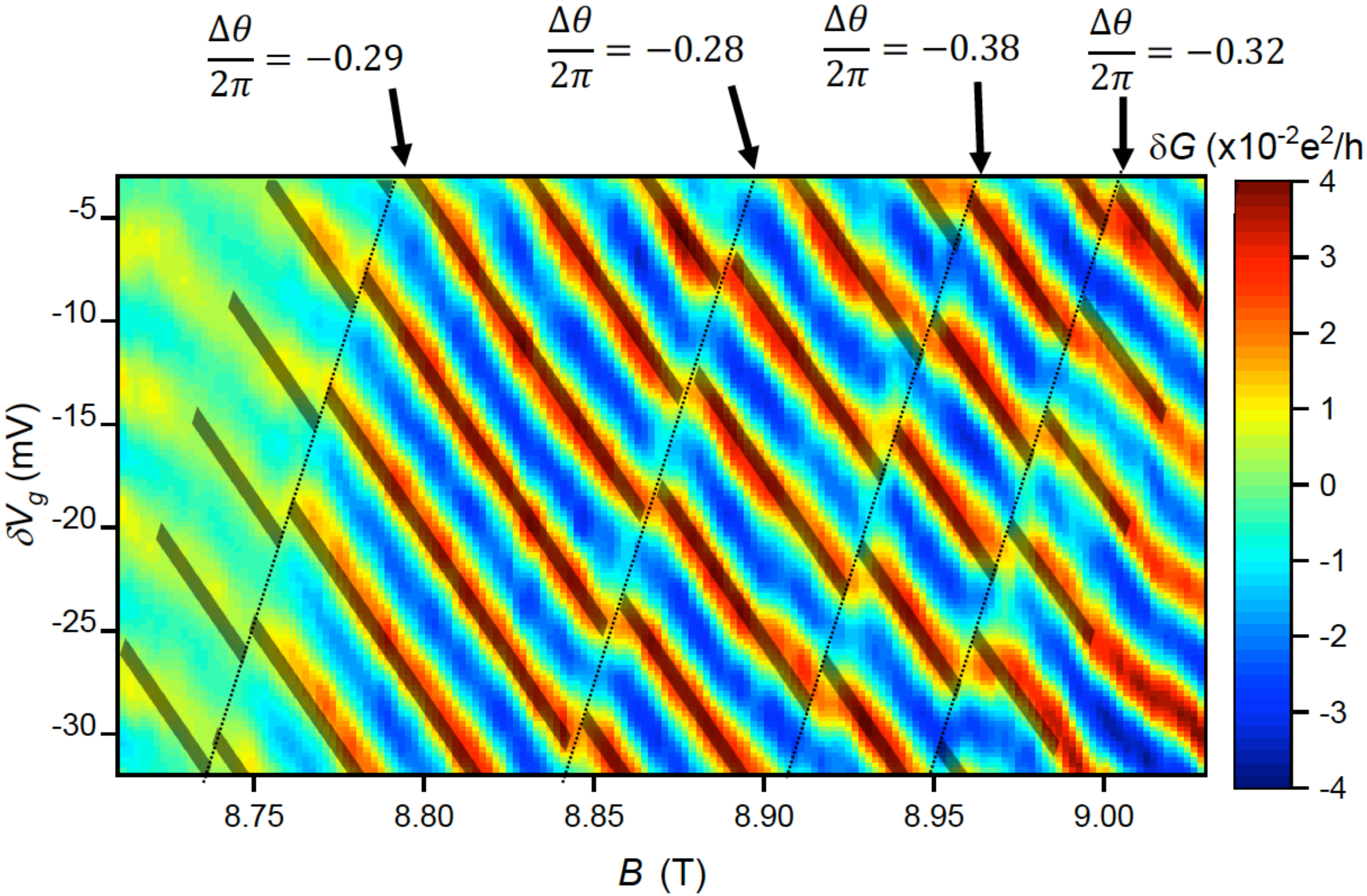
The quantum Hall effect is a remarkable example of a topological phase of matter occurring when a two-dimensional electron system (2DES) is cooled to low temperature and placed in a strong magnetic field. In the quantum Hall regime the bulk forms an insulator, and charge flows in edge currents which are topologically protected from backscattering and exhibit quantized conductance. The elementary excitations of fractional quantum Hall states [3] are not simply electrons, which obey fermionic statistics, but instead are emergent quasiparticles which are predicted to have highly exotic properties including fractional charge and anyonic statistics [4]. In two dimensions, two exchanges of particle positions are topologically equivalent to one quasiparticle encircling the other in a closed path [5], referred to as a braid; this is illustrated in Fig. 1a. The anyonic character of these quasiparticles is reflected in the fractional phase the system obtains from braiding; thus they are said to obey anyonic braiding statistics. The statistics of fractional quantum Hall states have been studied in theoretical [6, 7] and numerical [8–12] works. The anyonic phase does not depend on the trajectory taken but only on the number of quasiparticles encircled, making braiding another manifestation of topology in quantum Hall physics; this topological robustness has motivated aggressive pursuit of fault-tolerant quantum computation based on braiding operations in various condensed matter systems [5, 13–15]. In a recent experimental work anyonic statistics were inferred from noise correlation measurements [16]; however, direct observation of the anyonic phase in braiding experiments will further our understanding of the exotic behavior of quantum Hall quasiparticles and is a necessary step to towards quasiparticle manipulation.

Electronic interferometry has been used to study edge physics in previous theoretical [17–25] and experimental [26–45] works, and has been proposed as an experimental means to observe anyonic braiding statistics [18, 20, 46, 47] including the highly exotic non-Abelian form of anyonic statistics [48–55]. An electronic Fabry-Perot interferometer consists of a confined 2DES using quantum point contacts (QPCs) to partition edge currents, as shown in Fig. 1b. Quasiparticles backscattered by the QPCs will braid around quasiparticles localized inside the interferometer; therefore changes in N_{qp}, the number of quasiparticles localized inside the interferometer, will result in a shift in the interference phase due to the anyonic contribution θ_{anyon} [18, 20, 46, 47], with $\theta_{anyon} = \frac{2\pi}{2p+1}$ for a Laughlin fractional quantum Hall state $\nu = \frac{1}{2p+1}$ [6, 7]. The interferometer phase difference θ is a combination of the Aharonov-Bohm phase scaled by the quasiparticle charge e^* and the anyonic contribution, written in Eqn. 1 [18, 20, 46]:

$$\theta = 2\pi \frac{e^*}{e} \frac{A_I B}{\Phi_0} + N_{qp}\theta_{anyon} \qquad (1)$$

The total current backscatterd by the interferometer will depend on $\cos(\theta)$, so the interference phase can be probed by measuring the conductance G across the device b)





Merged currents are sensitive to the number of anyons their paths enclose.

When the number of anyons inside jumps, then the current jumps.

Earlier, beautiful experiments in China had already demonstrated the fundamental anyon “braiding” behavior in an engineered system:

Emulating anyonic fractional statistical behavior in a superconducting quantum circuit

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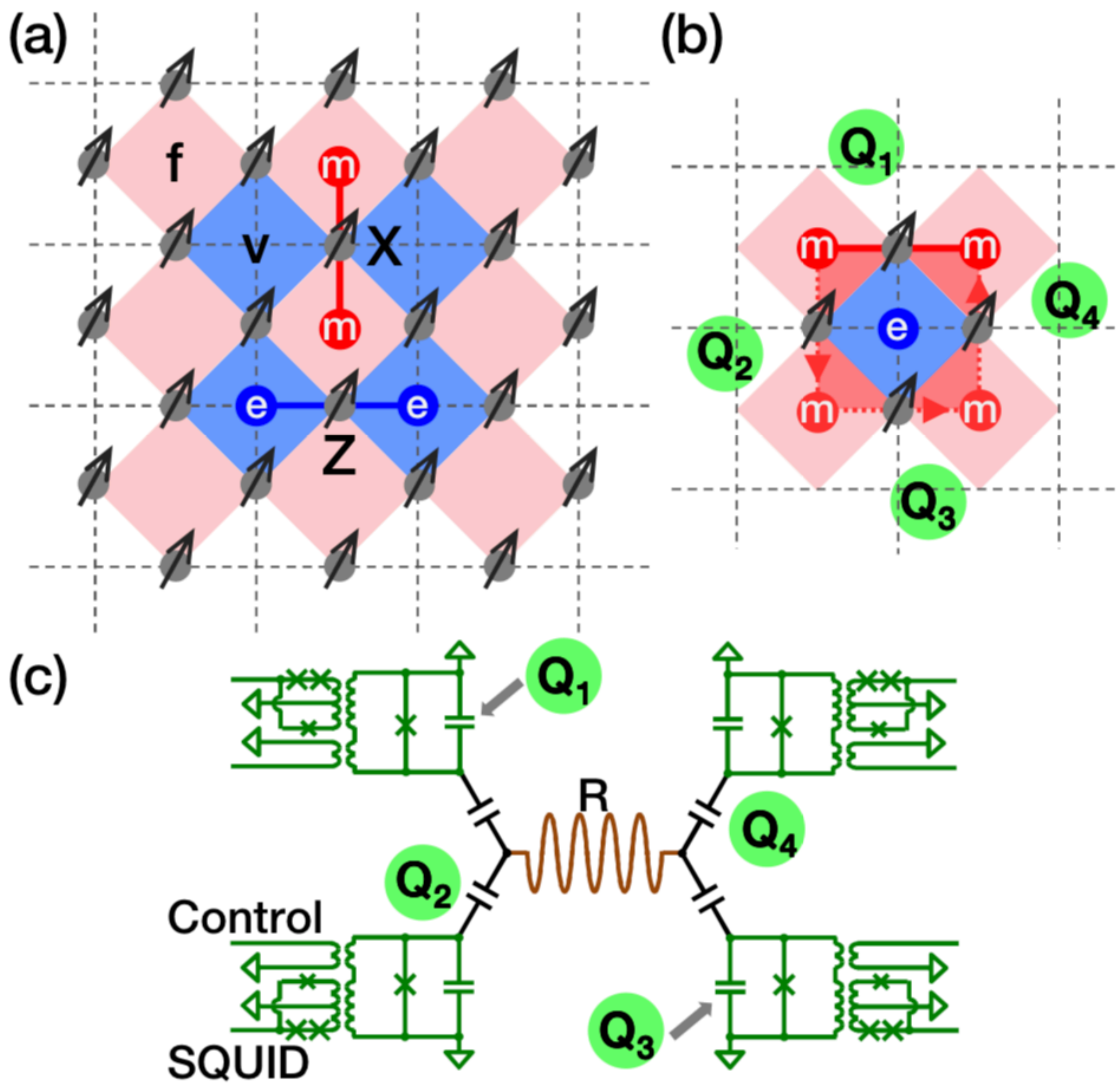
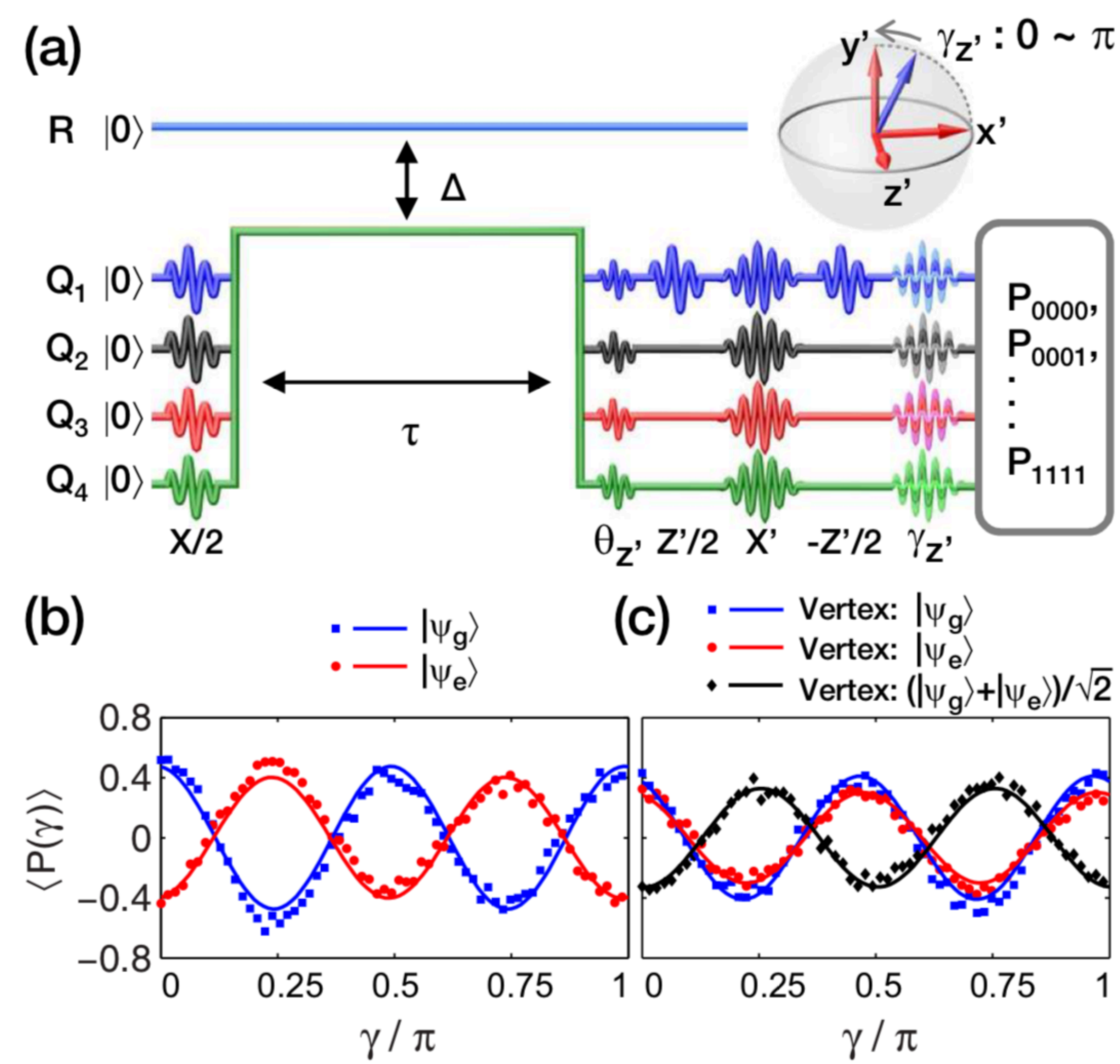
(Dated: September 11, 2018)

Anyons are exotic quasiparticles obeying fractional statistics, whose behavior can be emulated in artificially designed spin systems. Here we present an experimental emulation of creating anyonic excitations in a superconducting circuit that consists of four qubits, achieved by dynamically generating the ground and excited states of the toric code model, i.e., four-qubit Greenberger-Horne-Zeilinger states. The anyonic braiding is implemented via single-qubit rotations: a phase shift of π related to braiding, the hallmark of Abelian 1/2 anyons, has been observed through a Ramsey-type interference measurement.

PRL 117.110501 (2016)

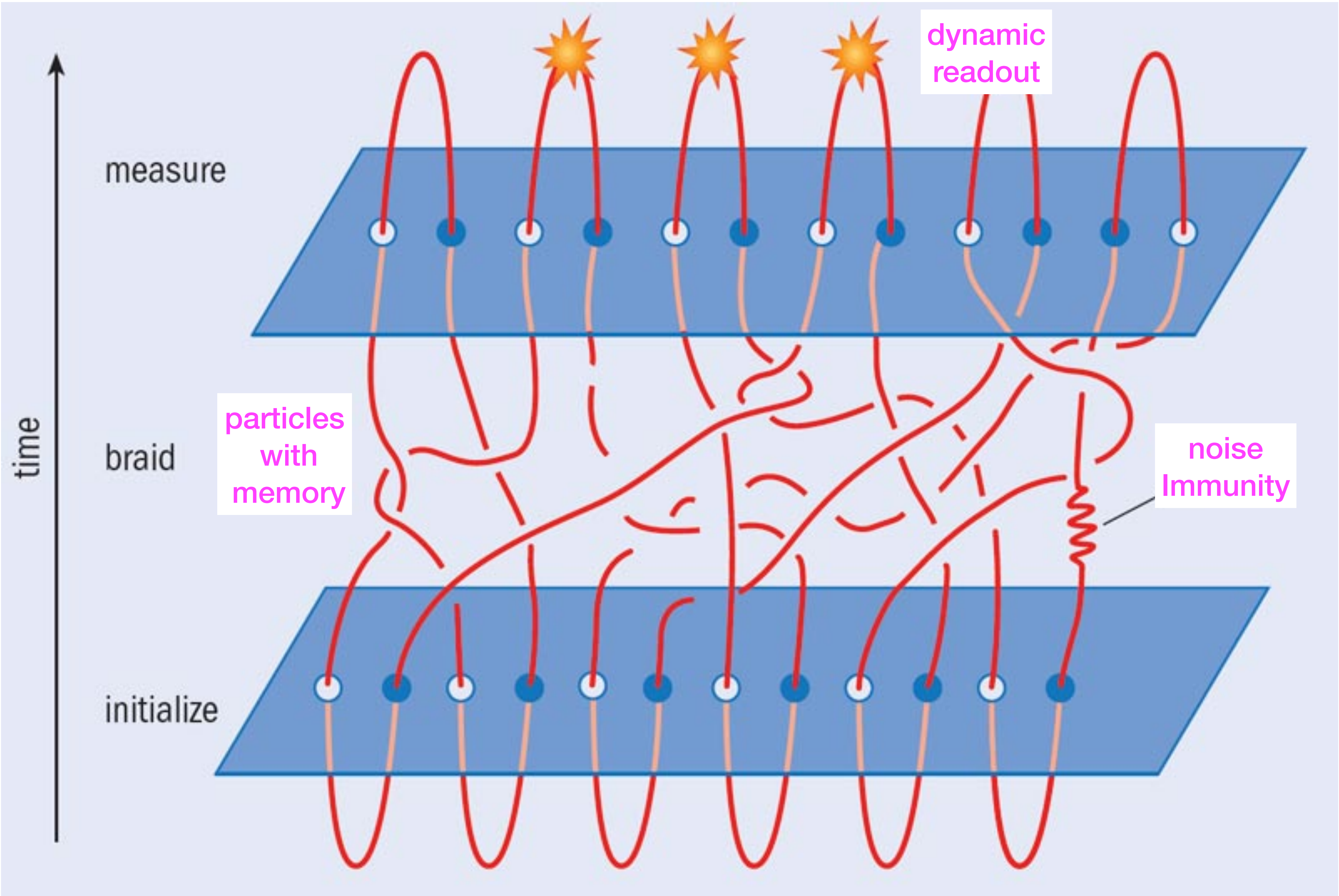




Mutual Statistics

These demonstration experiments are aimed at building up *resilient* quantum information storage (qubits), using a “toric code”.

Prospect and Conclusion



anyons for quantum computing

Many other interesting states of matter and engineered systems are predicted to contain various kinds of anyons.

Theory got way ahead of experiment, but now experiment is catching up!

Physicists will be exploring these anyonic worlds for years to come.

Braids are Beautiful

Quantum Sensing and Time Crystals

Time crystals are materials that exhibit spontaneous breaking of time translation symmetry.

There are more and less constraining definitions in use, that have more or fewer consequences, but apply to fewer or more examples.

There is a very general connection between spontaneous symmetry breaking and sensitivity to certain kinds of perturbations (basically, those that restore the symmetry!).

Superfluidity, superconductivity, phonons, spin waves, pions, … (“Nambu-Goldstone bosons”).

For time crystals, the appropriate perturbations are AC.

For example in Josephson junctions, we have Shapiro steps to detect microwave radiation.

There is interesting work to be done here.

Quantum Sensing and Quantum Computers

Quantum computers are exquisitely sensitive to decoherence.

For most purposes that is a bug, but for fundamental physics it raises an interesting opportunity to probe -

- Is it a *fundamental* bug?

Are there irreducible sources of decoherence in the universe?

Baby universes?

Slow approach to θ vacuum?