Augmenting Reality

Axions, Anyons, Time Crystals, Entangled Histories

Axions

Few aspects of experience are as striking as the asymmetry between past and future.

If you run a movie of everyday life backwards, it does not look like everyday life.


STOP
ODISSA

Yet time-reversal symmetry (T) was a notable property of the fundamental laws of physics for several centuries, starting with Newtonian mechanics, and continuing through general relativity and quantum electrodynamics.

Why?

As long as T symmetry appeared to be an exact, fundamental feature of physical law, it was unclear that asking “Why?” would be fruitful.

T symmetry might be rock bottom.

In 1964, James Cronin and Val Fitch discovered a subtle effect in K meson decays that slightly violates T symmetry.

⇒ T symmetry is **not** rock bottom.

It’s not even quite true - just very nearly so.

Why?

We've *almost* nailed it.

The basic, “sacred” principles of modern physics - relativity + quantum mechanics + local symmetry - are very powerful.

They allow exactly two possible sources of T symmetry violation.

One of them beautifully explains what Cronin and Fitch observed, and a lot more.

The other doesn’t happen.

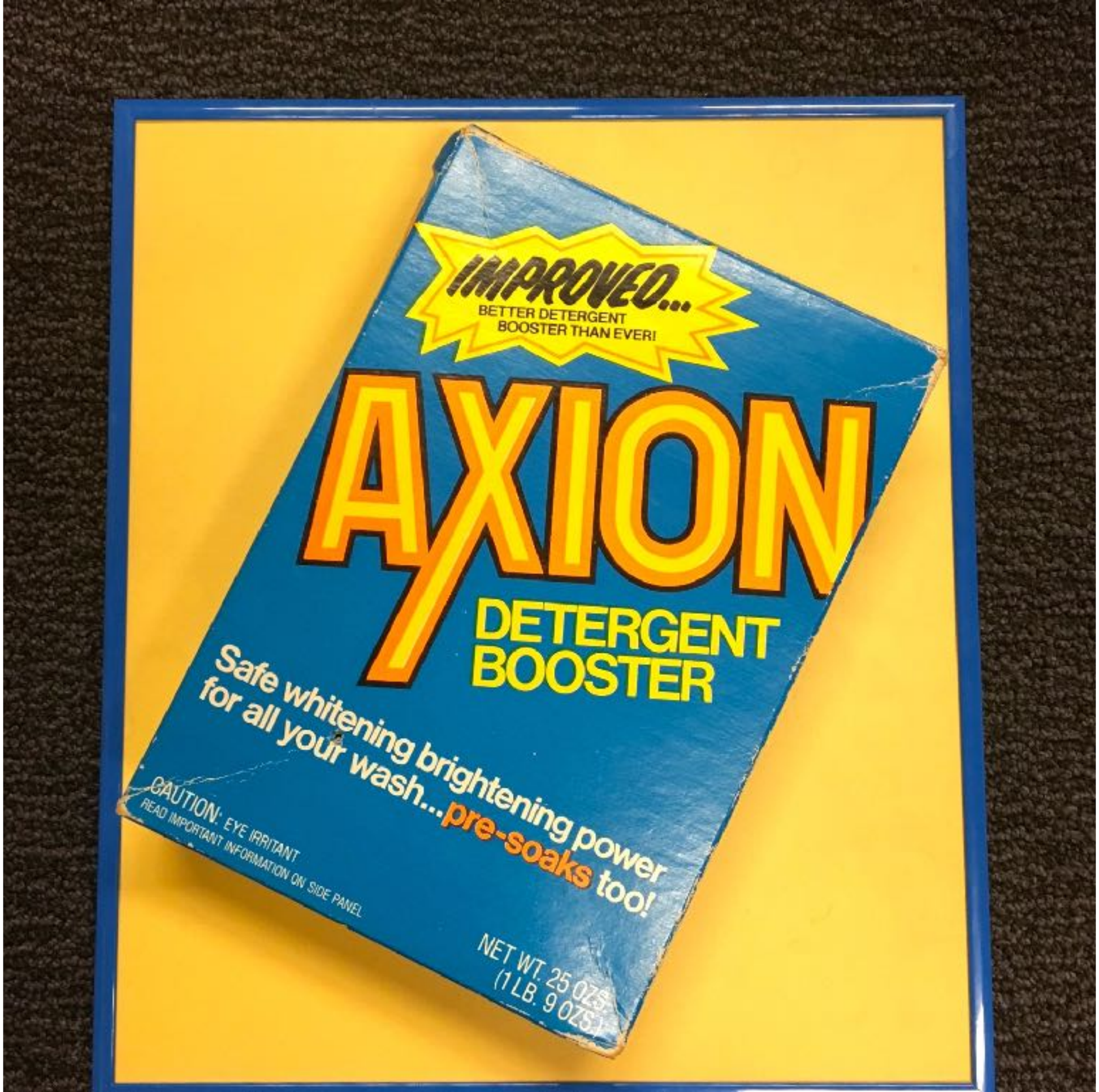
Why?

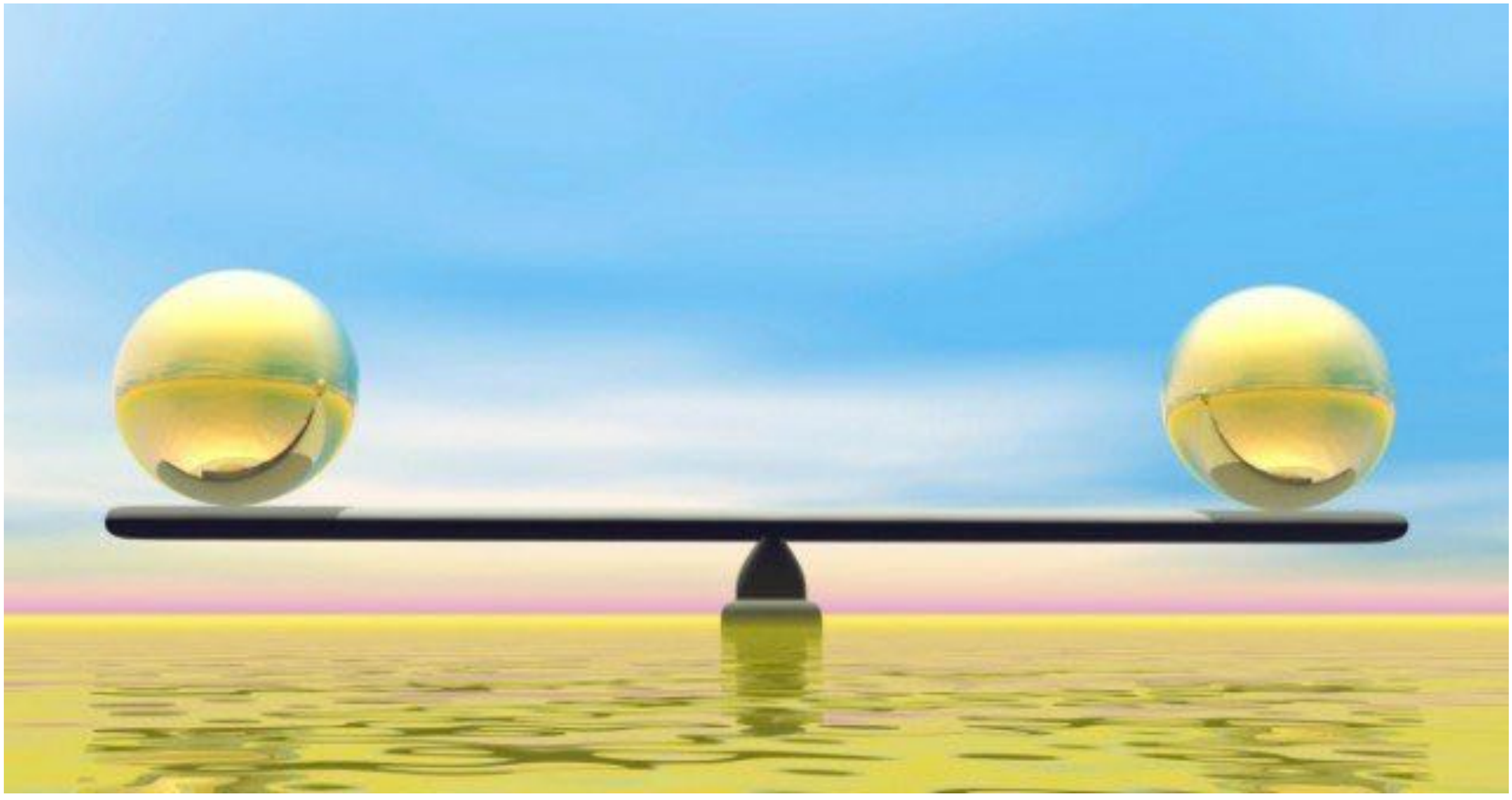
Over the past 40+ years, there have been several attempts to explain it, but only one has stood the test of time.

We promote the unwanted term to a *dynamical* entity - a “field”, which *evolves* to zero.

The new field is made of a new kind of particle.

I named it the *axion*, in homage to a laundry detergent:


IMPROVED...
BETTER DETERGENT
BOOSTER THAN EVER!
AXION
DETERGENT
BOOSTER
Safe whitening brightening power
for all your wash...pre-soaks too!
CAUTION: EYE IRRITANT
READ IMPORTANT INFORMATION ON SIDE PANEL
NET WT. 25 OZS.
(1 LB. 9 OZS.)



keeping the past and the future in balance

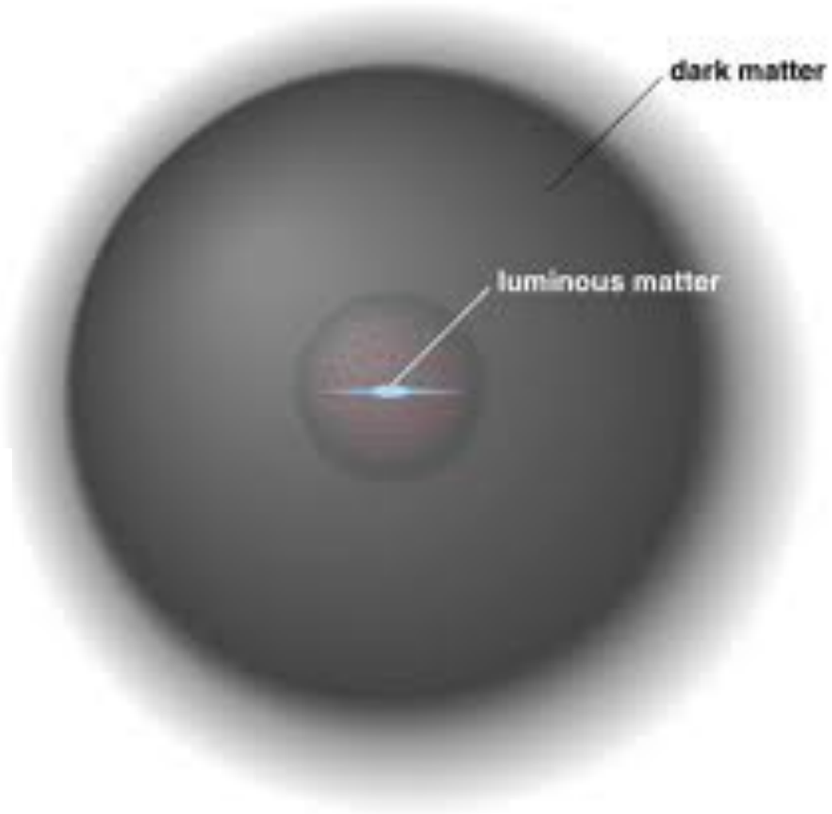
Do axions exist?

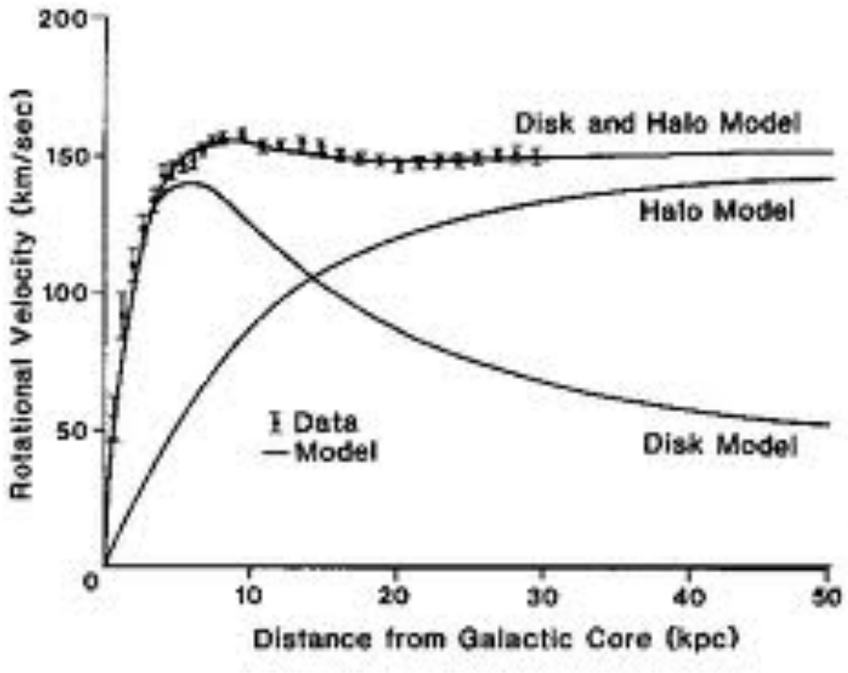
We still don’t know for sure - but in recent years the stakes have risen dramatically.

We can calculate that axions get produced in the big bang, and survive to this day.

The relic axion gas has properties consistent with the observed properties of the astronomers' "dark matter".

Dark matter halo





Dark Matter smoking gun

- Two galaxies colliding
- The regular matter (red) interacts, i.e., collides (friction) with each other
- The dark matter (blue) moves unaffected…



Bottom line:

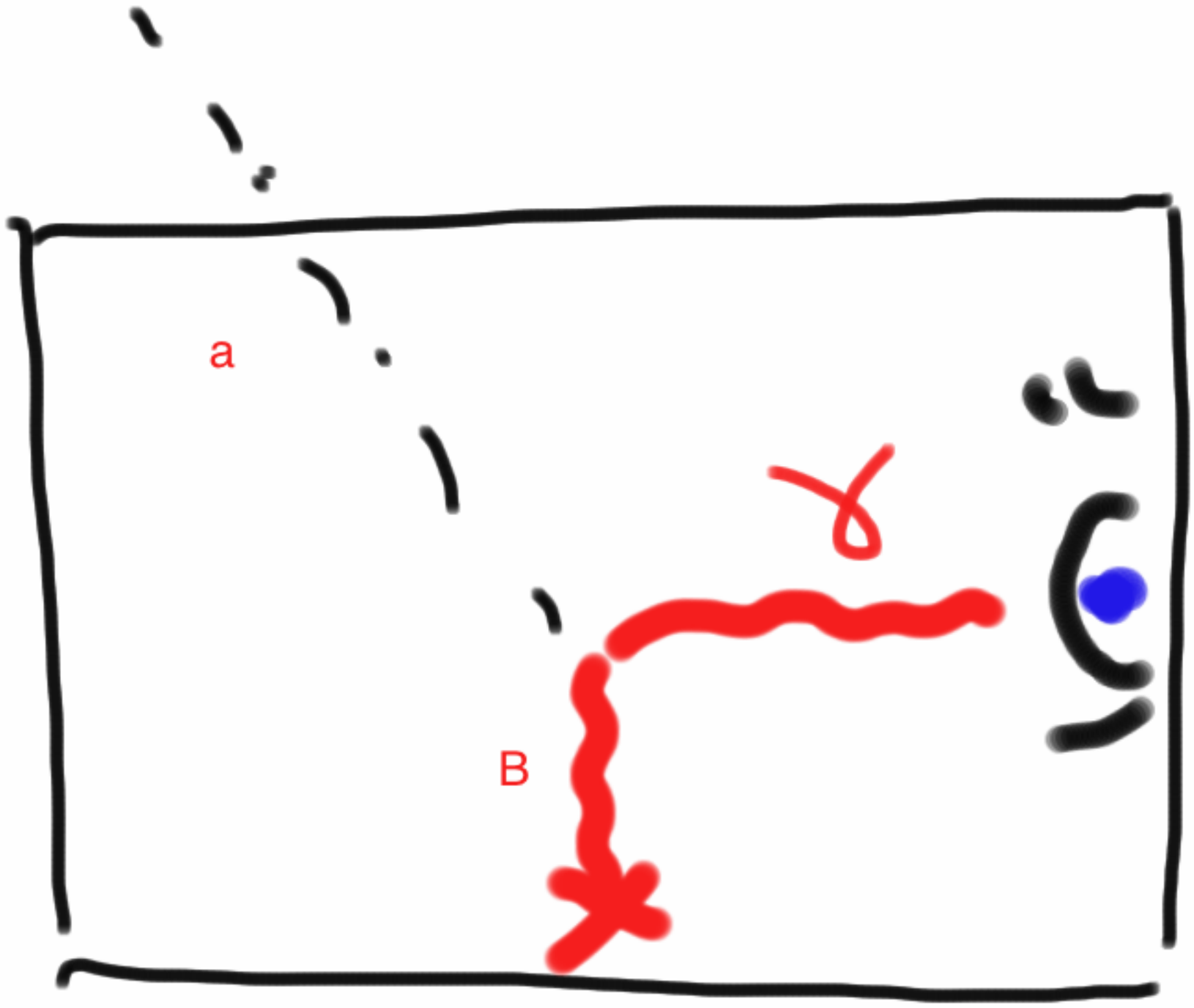
If axions exist at all, they must contribute significantly to the dark matter. Plausibly, they dominate it.


9:36 AM
70%
CP765
Axion
HP 60 / 60
Ghost / Poison
Type
0.07 kg
XS
Weight
1.42 m
Height
45849
STARDUST
23
GASTLY CANDY
POWER UP
2500
2
EVOLVE

Several clever strategies for axion detection have emerged.

It’s won’t be easy, but many determined people are at work …


KUSP
KOREA
SCIENCE PROGRAM
Center for Axion
&
Precision Physics


a
B

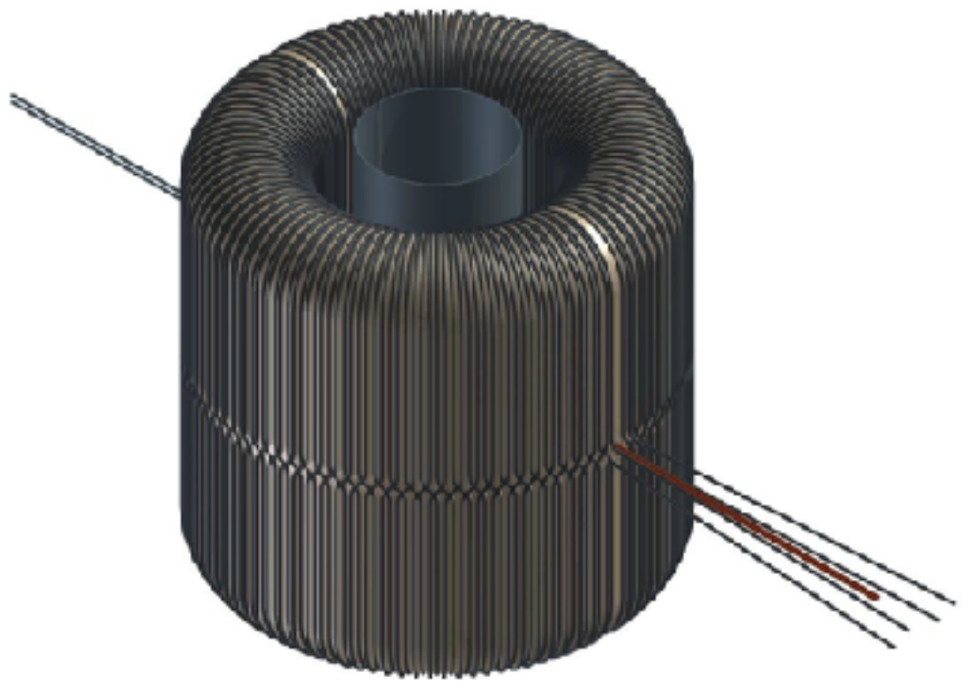
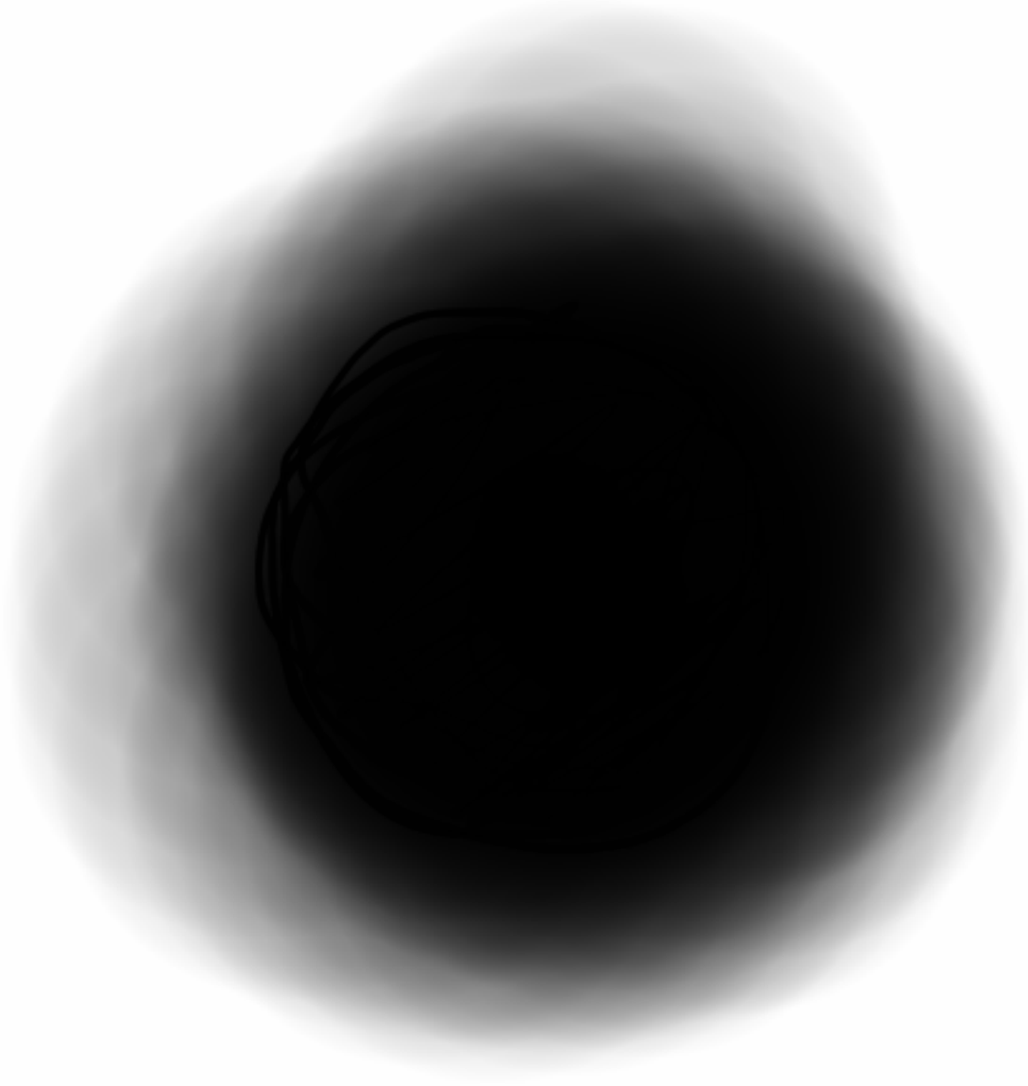


FIG. 1: A schematic of the ABRACADABRA-10cm toroidal geometry. The superconducting main coil sources a static azimuthal magnetic field. In the presence of axion DM, an effective oscillating current is induced following the magnetic field lines. The oscillating magnetic flux sourced by this effective current is picked up by a superconducting cylinder in the center of the toroid and read out through a SQUID. A test coil will wrap the inside of the torus so that an azimuthal oscillating current may be injected in order to mimic a real signal and calibrate the detector. The entire toroid and SQUID readout will be inside of a superconducting shield (not shown), inside of the dilution refrigerator.

abracadabra white paper



Anyons

Since the discovery of wave-particle duality, and its elaboration in quantum theory, we understand that the basic units of all forms of matter - including light - the same sort of thing: “wavicles”, “laves” …

or, by analogy with qubits: quarticles.

But when we consider the behavior not of single quarticles, but of groups of them, we find that quarticles divide into two great kingdoms, bosons and fermions.

Bosons are collectivists. They like to do the same thing.

(Technically, they like to occupy the same quantum state.)

Photons are bosons. A laser beam is an excellent example of their boson-ness in action.

Fermions are individualists. They hate to do the same thing.

(They refuse to occupy the same quantum state: Pauli's exclusion principle.)

Electrons are fermions. The "solidity" of matter is an excellent example of their fermion-ness in action.

In a 3-dimensional (or more) world, that's all there is.

In a 2-dimensional world - in Flatland - things get much more interesting, theoretically.

Less is more.

The reason is closely related to the theory of knots.

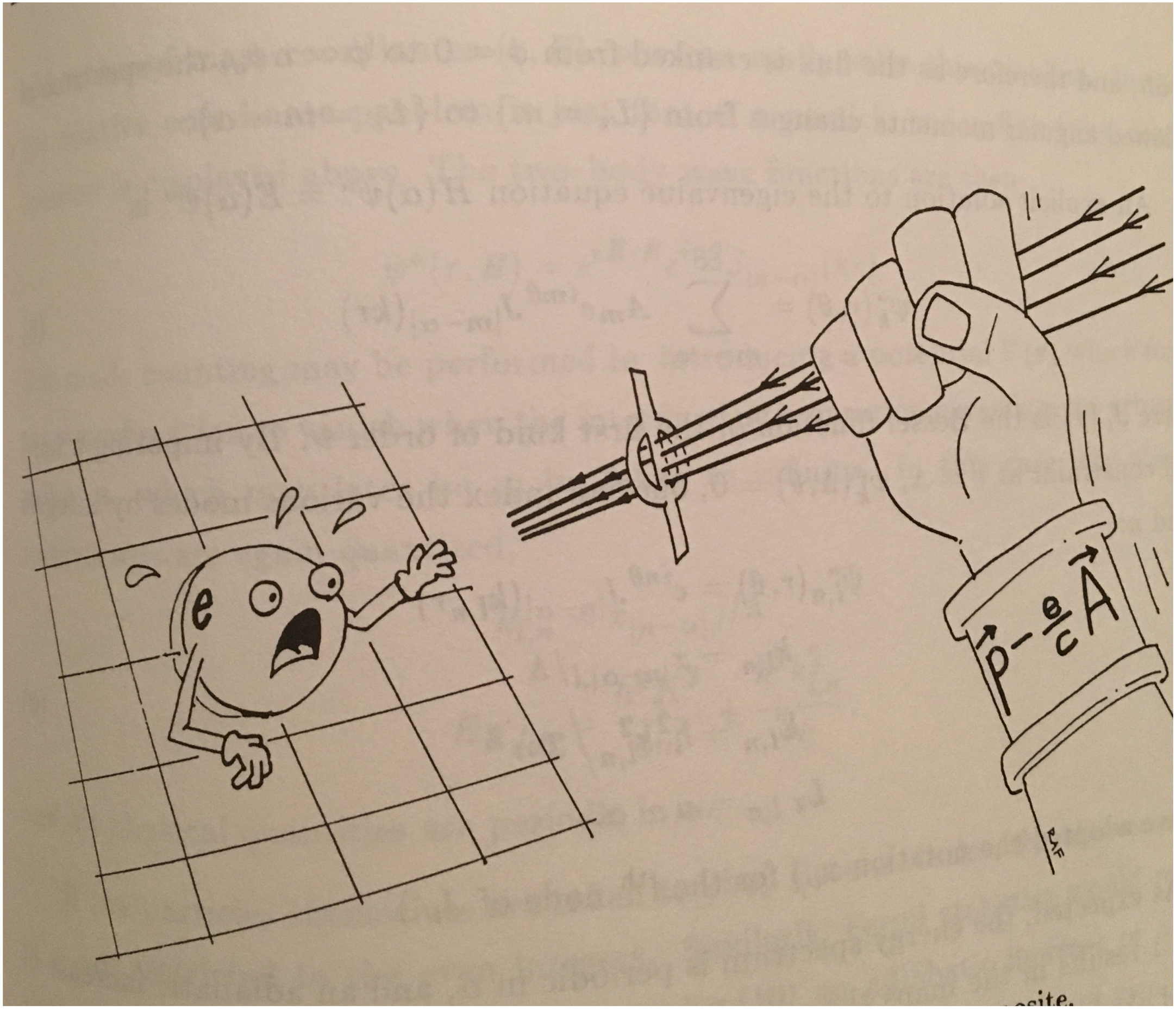
(In 4 dimensions, knots are not knotty.)

I named the new kinds of particles *anyons,* as in “anything goes”.

Experimenters can construct a wide variety of two-dimensional worlds, also known as thin layers of material.

In some of them, electrons fission into anyons.

For the electrons, this can be a shattering experience …


e
$\vec{P} - \frac{e}{c}\vec{A}$

… but their offspring, which are anyons, emerge with brilliant new powers.

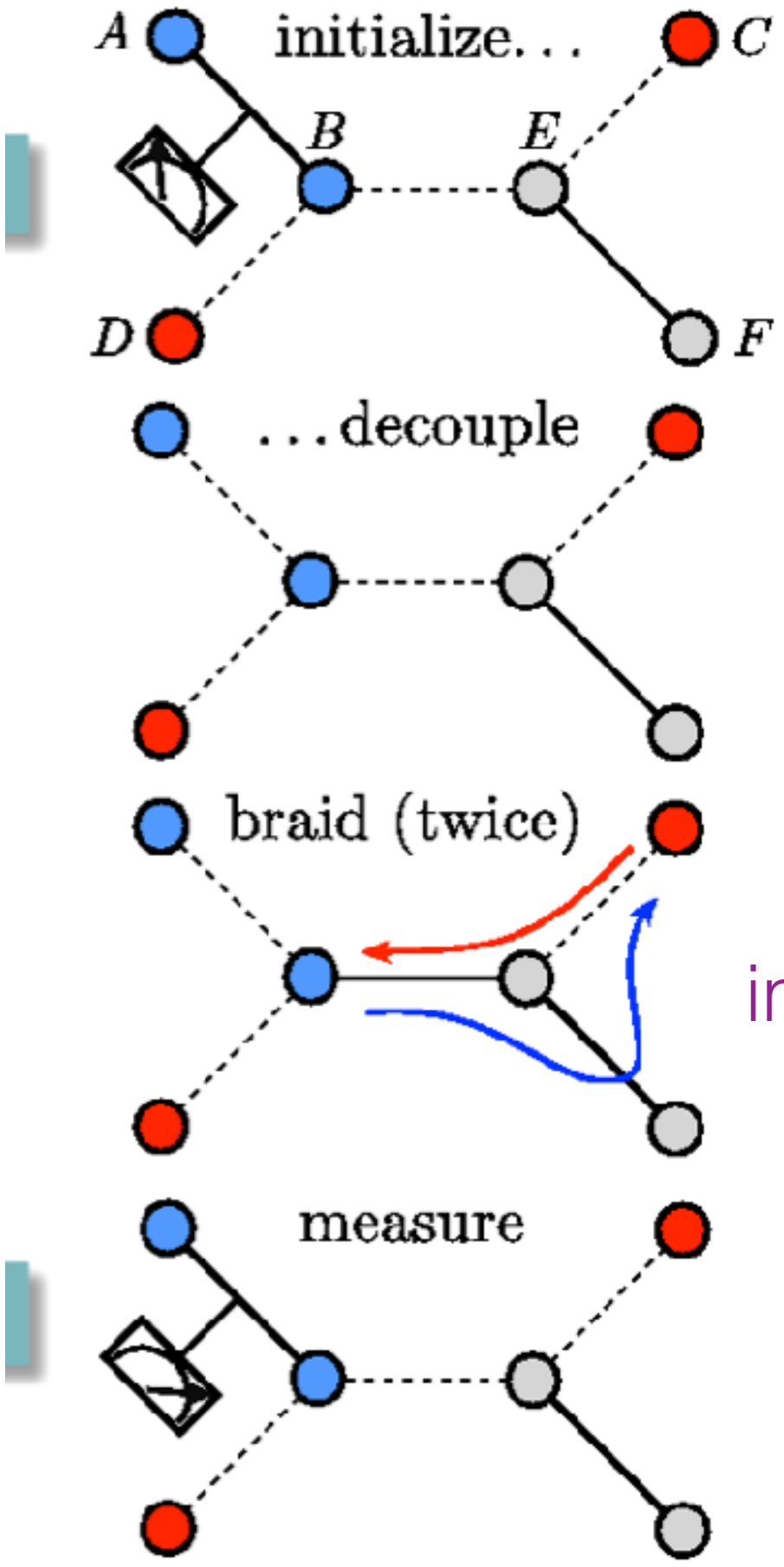
Anyons, unlike bosons or fermions, have memories.


9:35 AM
70%
CP651
Anyon
HP 67 / 67
Electric
Type
XS
43.36 kg
Weight
0.99 m
Height
45849
STARDUST
34
VOLTORB CANDY
POWER UP
1600
2
Spark
Electric
Hyper Beam
120

Some sorts of anyons support a very rich collective memory.

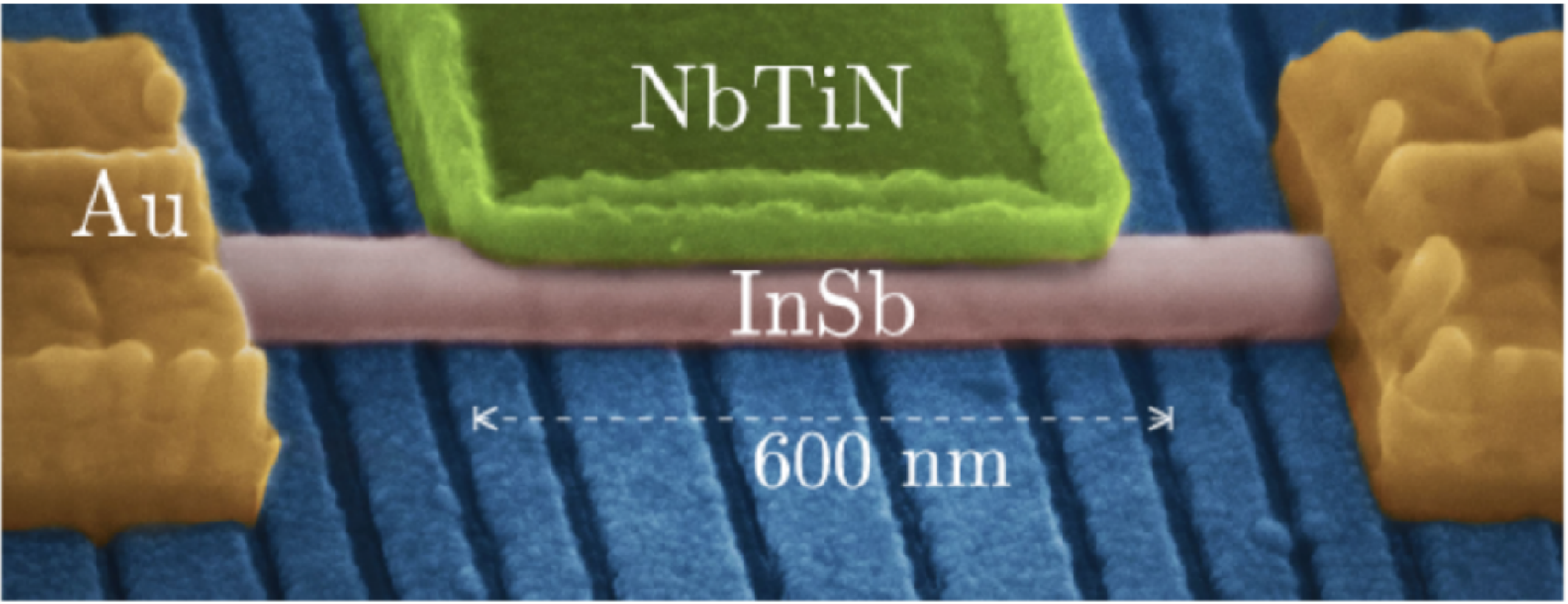
When you wind them around each other, their wave-function changes, making a record of what you've done.

This is the basis for "topological quantum computing", in which Microsoft is investing heavily.

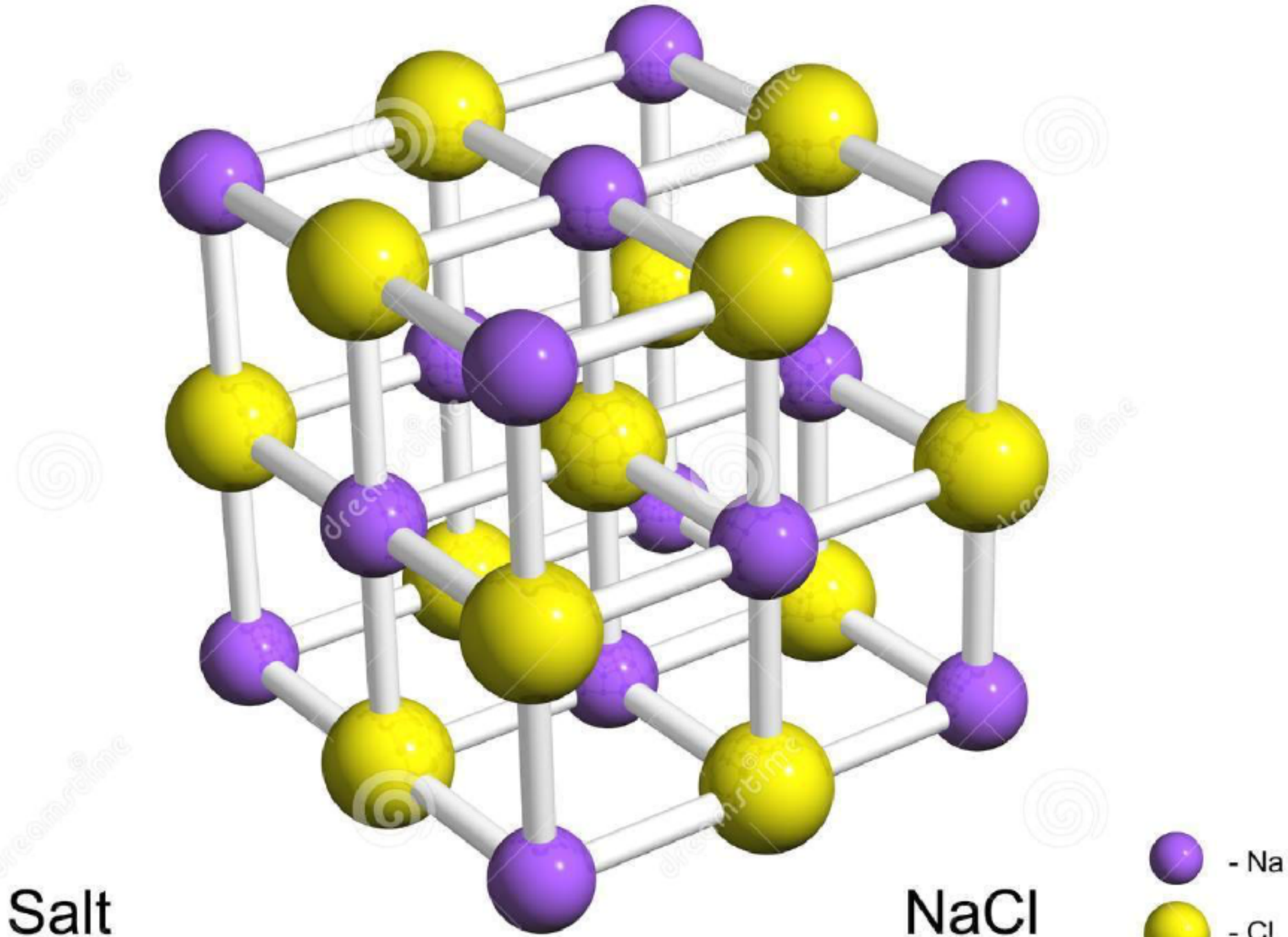


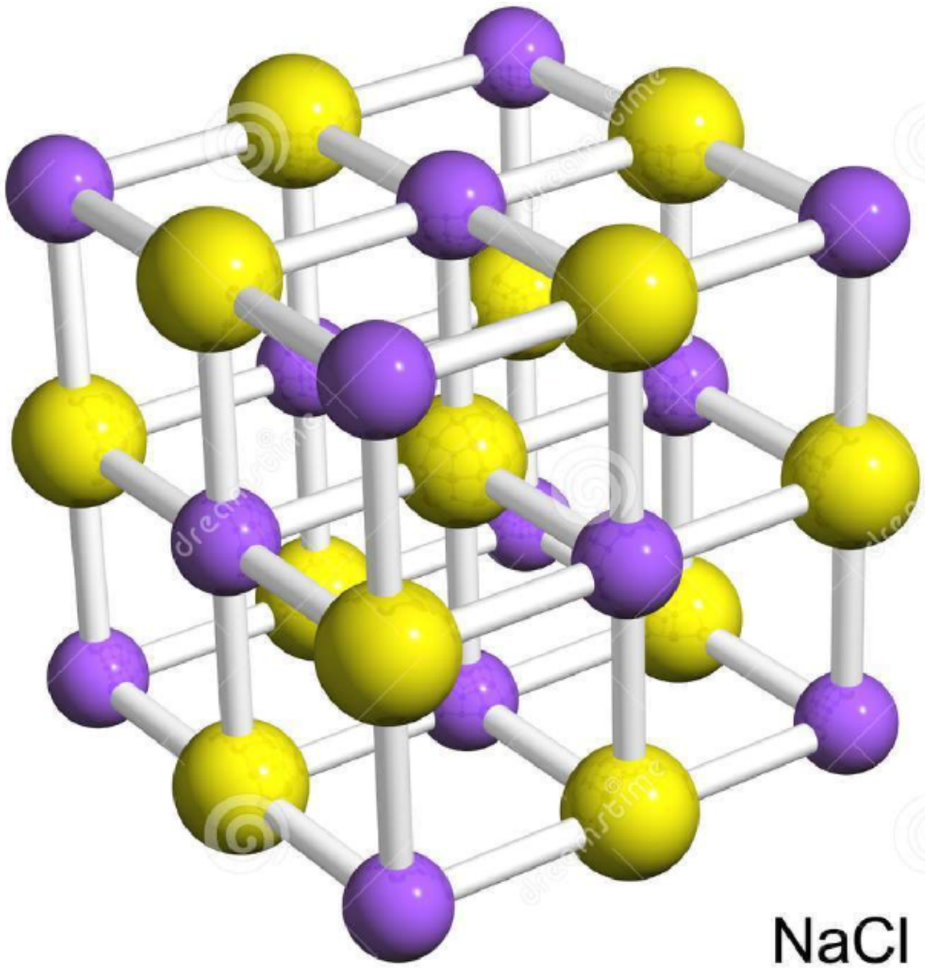
imprinting a memory

reading it out


NbTiN
Au
InSb
600 nm

Time Crystals


Salt
NaCl
- Na
- Cl

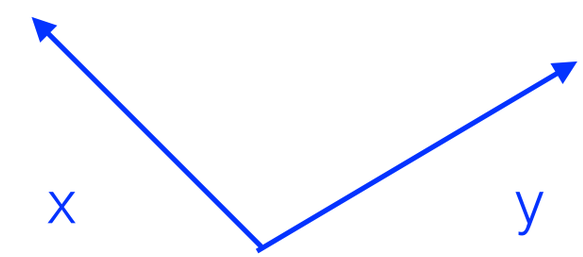


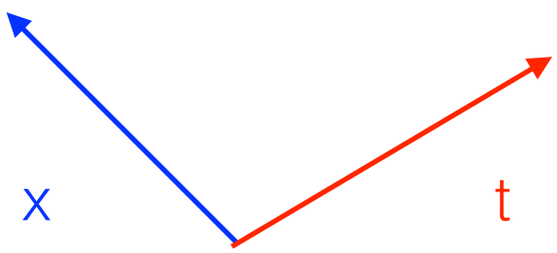
Salt

NaCl

- Na

- Cl





?

A beating heart is a sort of time crystal, but

it is complicated

it is not very precise

it requires constant feeding and maintenance

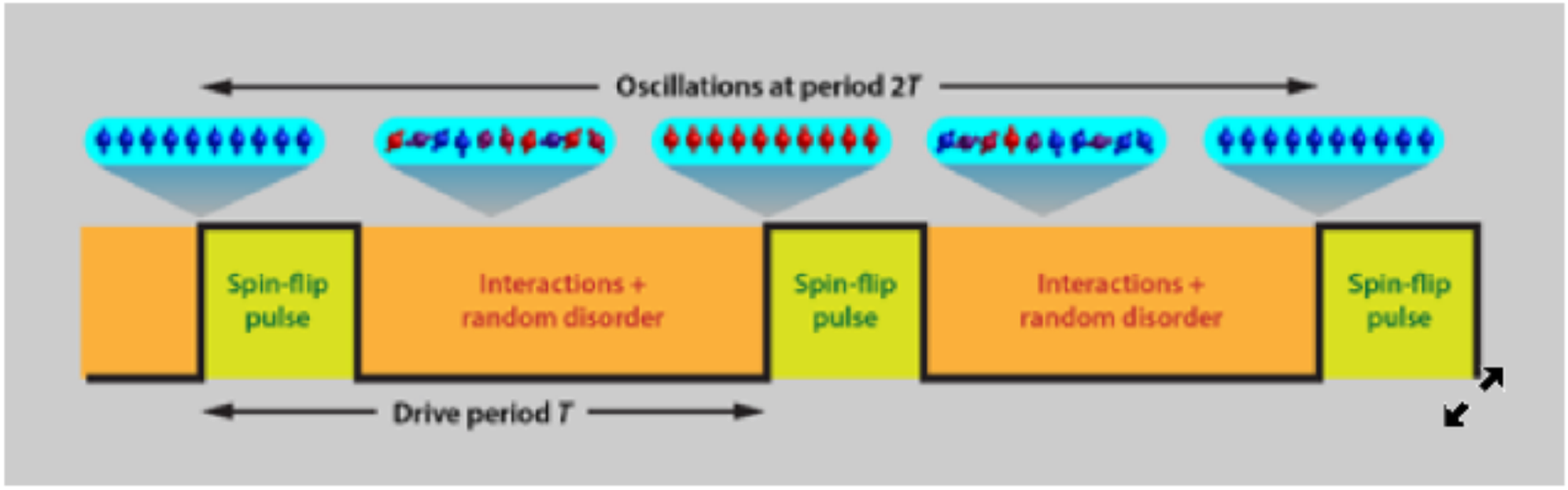
The game is to find time crystals do better in those regards: simple, precise, autonomous.

Viewpoint: How to Create a Time Crystal

Phil Richerme, Physics Department, Indiana University, Bloomington, IN 47405-7105, USA

January 18, 2017 • *Physics* 10, 5

A detailed theoretical recipe for making time crystals has been unveiled and swiftly implemented by two groups using vastly different experimental systems.



APS/**Alan Stonebraker**/Phil Richerme

Figure 1: Yao *et al.* [7] have developed a blueprint for creating a time crystal and a method for detecting it, which has been followed by two experimental groups [8, 9]. Quantum spins are subjected to imperfect spin-flip driving pulses and then allowed to int... **Show more**

Entangled Histories

Experimental physicists are achieving new levels of control over the production and manipulation of entanglement. Much of this effort is inspired by the vision of quantum computing.

It could be fruitful to consider other ways to exploit those new abilities.

In that spirit, I'd like to revisit some very basic aspects of quantum theory and measurement.

This will lead us to an enriched concept of history in quantum theory.

From the perspective of quantum theory, interference arises from the possibility of getting to the *same* final state through several distinct paths.

The probability for the overall process is then the square of the sum of amplitudes, which differs from the sum of the squares.

$$|A+B|^2 = |A|^2 + |B|^2 + (AB^* + A^*B)$$

interference term

For interference to occur the final state of the whole universe, including measuring devices and the external world, must be consistent with either of the two contributing processes having occurred.

So if you want to measure interference, it is crucial to maintain - or create! - ambiguity. I call this “strategic ignorance”.

To get two *histories* to interfere, we need to make sure that the final state of the world, including the final state of the measuring apparatus, does not allow us to distinguish which one happened.

That basic requirement is in some tension with the idea that measurement disturbs, or “collapses”, the wave function of the system being observed.

To get around this difficulty, we can correlate auxiliary bits with the system's sequence of states, through specific unitary operations, that do not disturb its evolution uncontrollably.

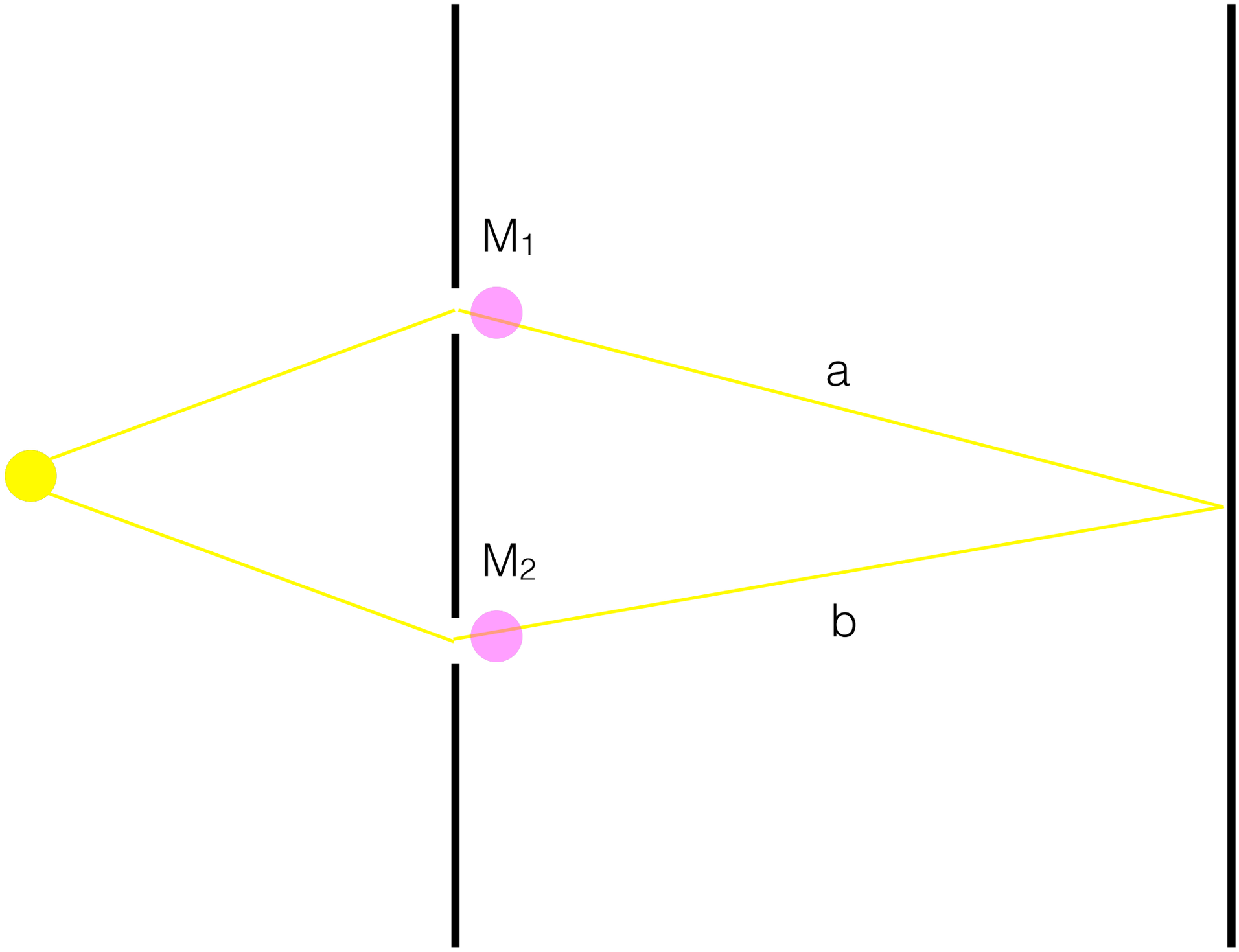
In this way we *monitor,* but do not not (irreversibly) *measure*, the system's behavior.

Later we can make measurements on the auxiliary bits, in principle, with great flexibility. We can project on entangled states of those auxiliary bits, for example.

Let me illustrate the basic idea using the classic 2-slit arrangement.

We imagine monitor bits behind each of the two slits, which implement a (unitary) CNOT on the particle's passage, and are set to $|\downarrow\rangle$ initially.

$$
\begin{aligned}
|\mathbf{Y}\rangle \otimes |\downarrow\rangle &\rightarrow |\mathbf{Y}\rangle \otimes |\uparrow\rangle \\
|\mathbf{N}\rangle \otimes |\downarrow\rangle &\rightarrow |\mathbf{N}\rangle \otimes |\downarrow\rangle \\
|\mathbf{Y}\rangle \otimes |\uparrow\rangle &\rightarrow |\mathbf{Y}\rangle \otimes |\downarrow\rangle \\
|\mathbf{N}\rangle \otimes |\uparrow\rangle &\rightarrow |\mathbf{N}\rangle \otimes |\uparrow\rangle
\end{aligned}
$$


M1
a
M2
b

If we measure the z-spin of M_1, we learn which slit the particle went through, and there is no interference. We get $|D_1|^2$ or $|D_2|^2$.

If we measure the *total spin* of $M_1 + M_2$, things are quite different. Then we get $|D_1 + D_2|^2/2$ when spin 1 appears, and $|D_1 - D_2|^2/2$ when spin 0 appears.

We can also consider more involved measurements, of course: e.g. shifting relative phase, linear combinations of total and z-spin, … .

We can also do things in the opposite order, measuring the position where the photon lands before investigating the spins. If the amplitudes for arrival from slits 1, 2 at the point in question are a, b, then the (unnormalized) density matrix is

$$\pi = \begin{pmatrix} |a|^2 & ab^* \\ ba^* & |b|^2 \end{pmatrix}$$

We can apply the same procedure, conceptually, to monitor aspects of a system's behavior at different times, that is its history.

Consider, for example, a spin 1/2 particle. We can monitor (but not measure) chosen components of its spin at several times t_1, t_2, t_3, … , using them as the control bits in CNOT gates, making monitor bits.

Collective measurements on the monitor bits give us unconventional takes on "what happened".

An example may be helpful:

A history space for a system is the tensor product of its Hilbert space of states at several times. We write the earlier times to the right of later times.

Our primary observables will be temporal operators, defined as ordered tensor products of operators defined at the chosen times, and linear combinations thereof.

Consider two temporal observables in history space: $[O]_{t2} \otimes [O]_{t1}$:

$$\begin{aligned} A &= \sigma_2 \otimes \sigma_1 \\ B &= \sigma_1 \otimes \sigma_3 \end{aligned}$$

They commute, and we have the joint eigenstate

$$v_{++} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \otimes \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ 1 \end{pmatrix} \otimes \begin{pmatrix} 1 \\ 0 \end{pmatrix} + i \begin{pmatrix} 0 \\ 1 \end{pmatrix} \otimes \begin{pmatrix} 0 \\ 1 \end{pmatrix} - i \begin{pmatrix} 1 \\ 0 \end{pmatrix} \otimes \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

It reflects the state of our knowledge after we measure ++ on the appropriate auxiliary bits.

It is an *entangled history.*

Thus we discover facts about the past of our system which cannot be captured by saying that it had a specific temporal sequence of properties, or states.

Rather, we infer its parallel evolution through several distinct sequences of properties.

Distinct histories (“worlds”) diverged, but later came together.

Entangled histories are a precise, tangible, mathematical reflection of the intuitive “many worlds” interpretation of quantum theory.

To make temporal entanglement observable, as a practical matter, we should focus on very small “worlds”, which haven’t diverged very much, and identify interference among them.

We can do that using small numbers of monitor bits, as sketched above.

We nurture Schrödinger kittens, short of Schrödinger cats.

