Symmetries of Time

Past, Present, and Future

Time Reversal, T

The Road to 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.

There are exactly two possible sources of T symmetry violation, that are consistent with those principles.

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

The other doesn’t happen.

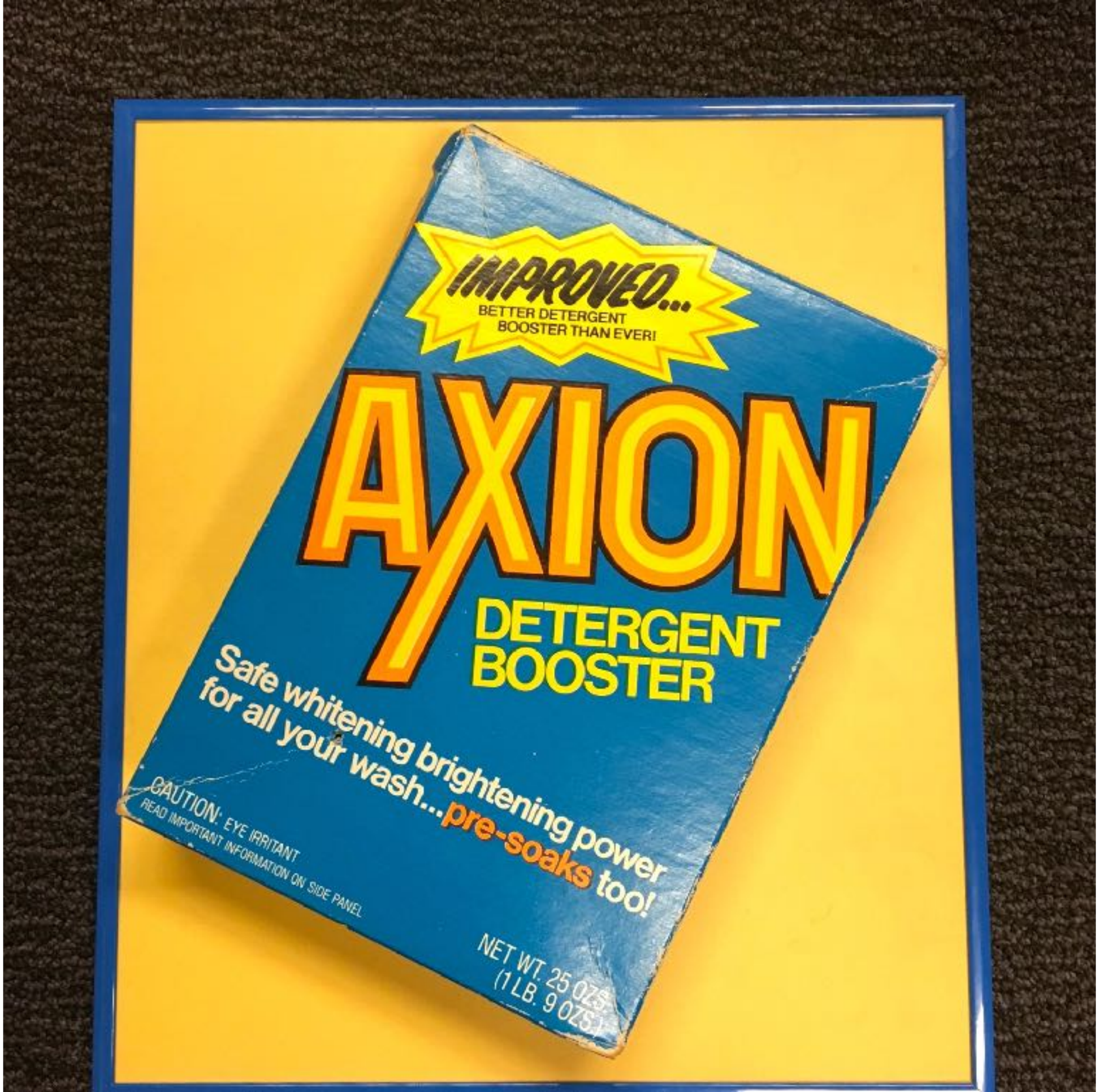
Why?

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.)

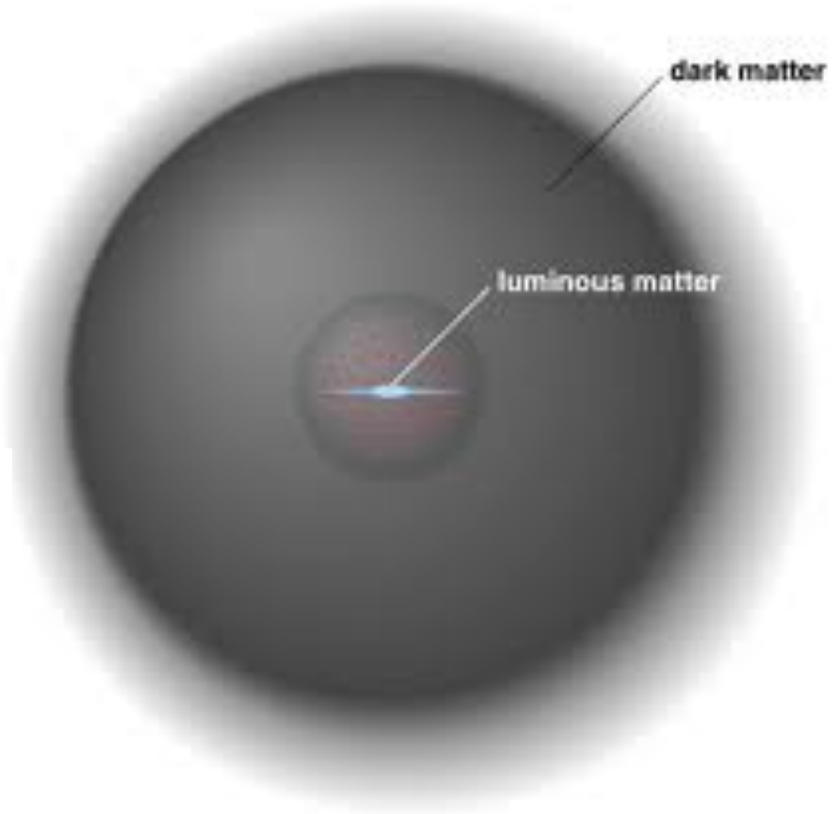
Do axions exist?

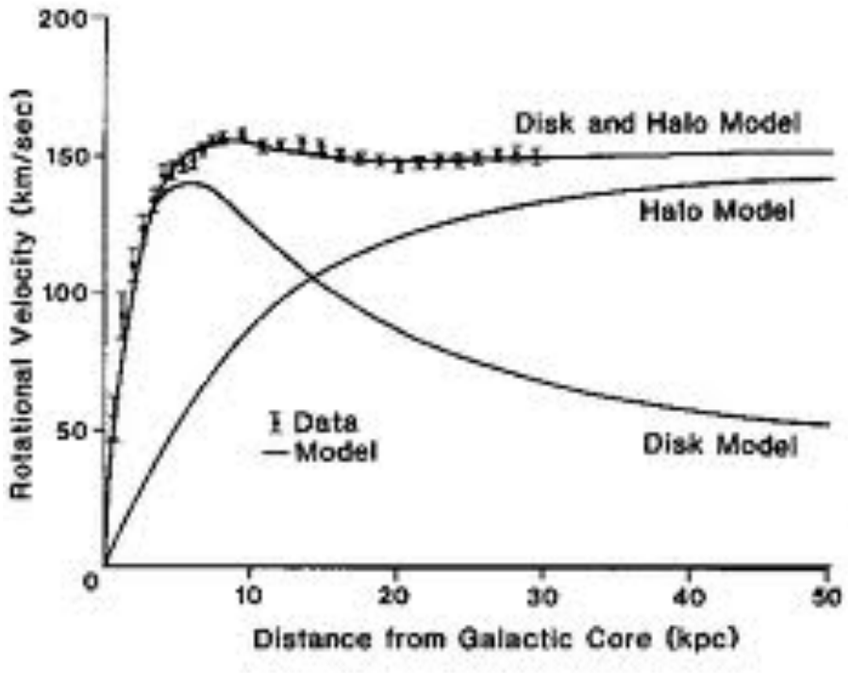
We still don’t know for sure - but in recent years the stakes have risen dramatically.

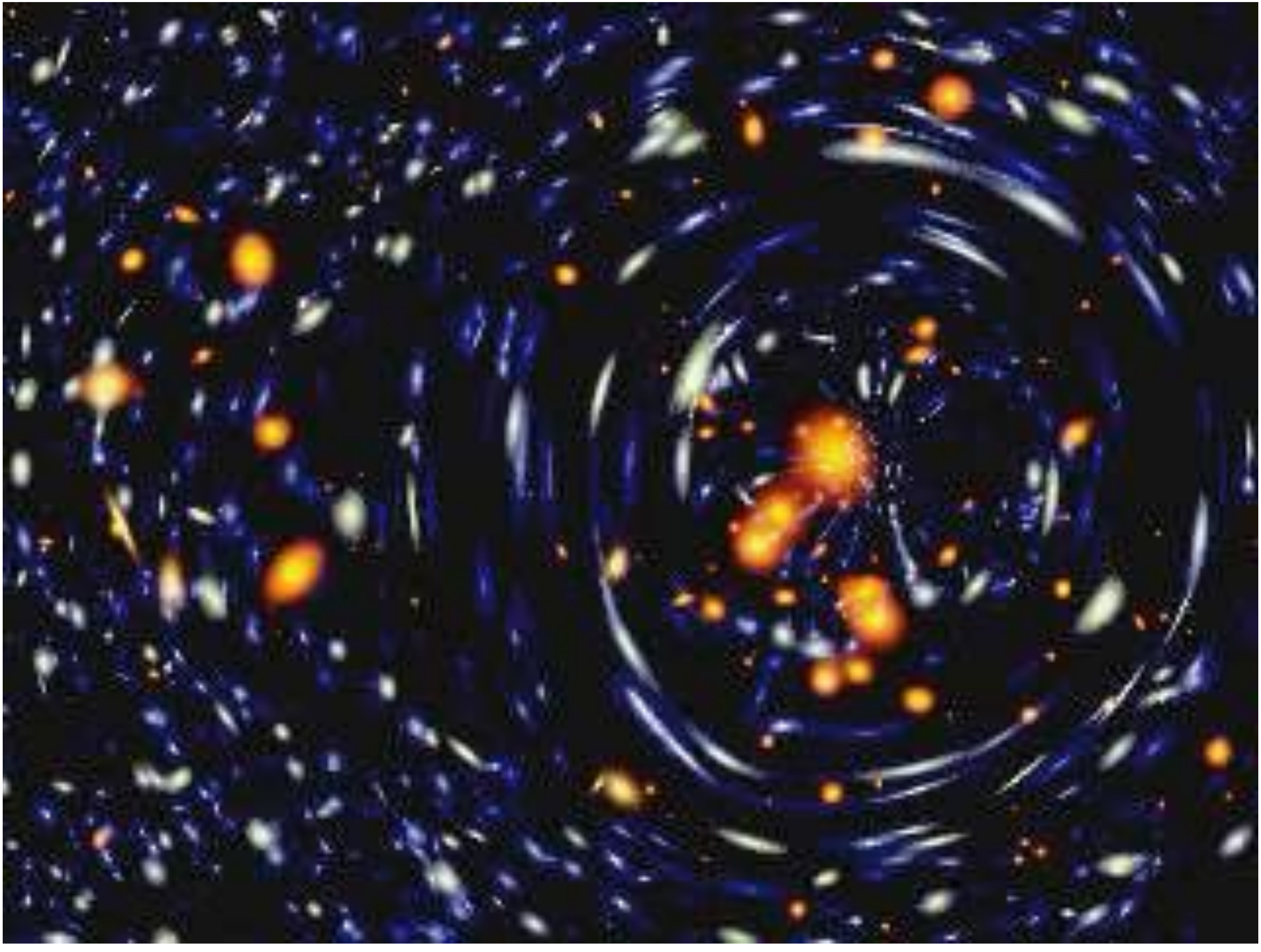
We can calculate that axions get produced in the big bang, and survive to this day.

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

Dark matter halo







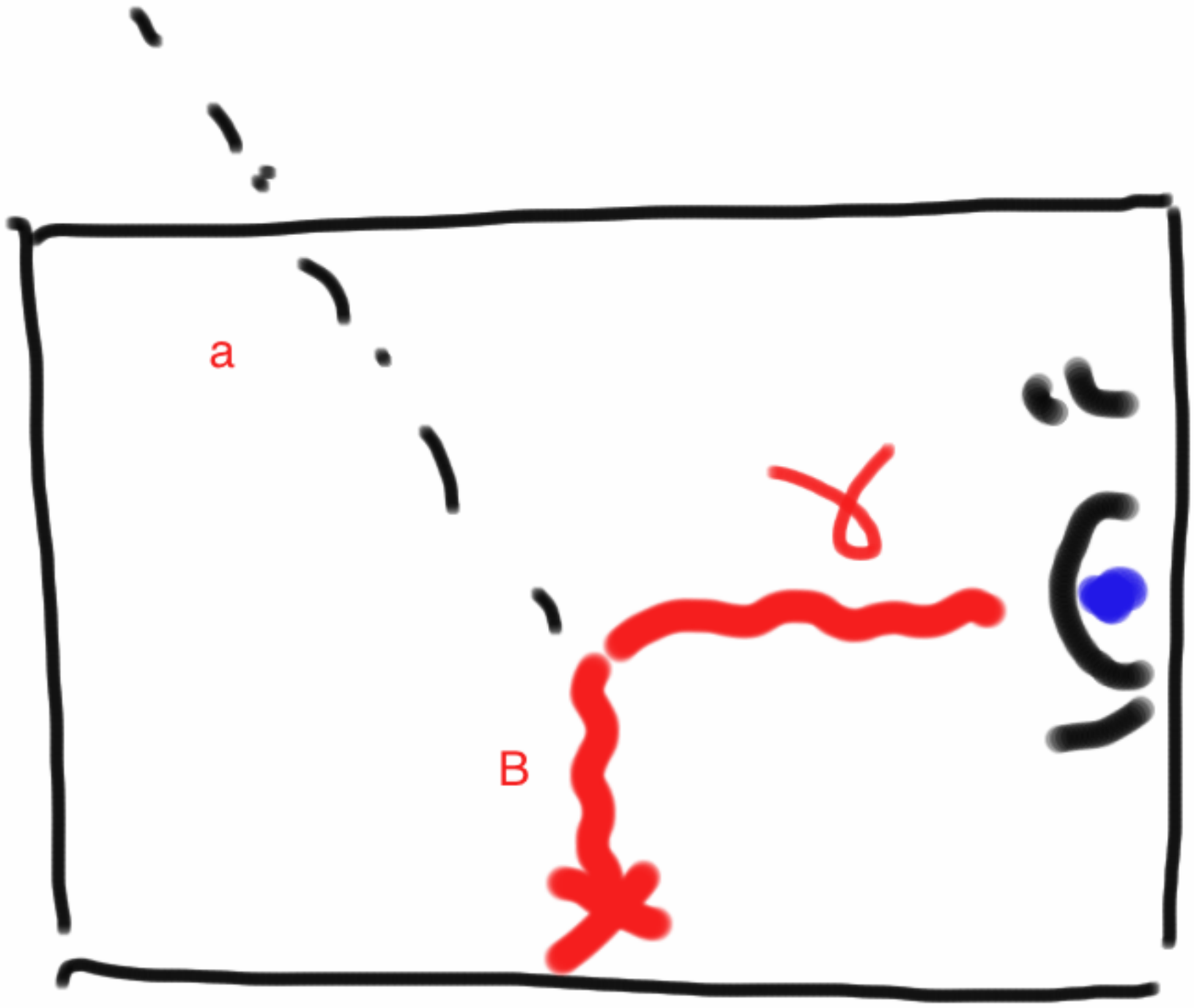
Bottom line, after a lengthy analysis:

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

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

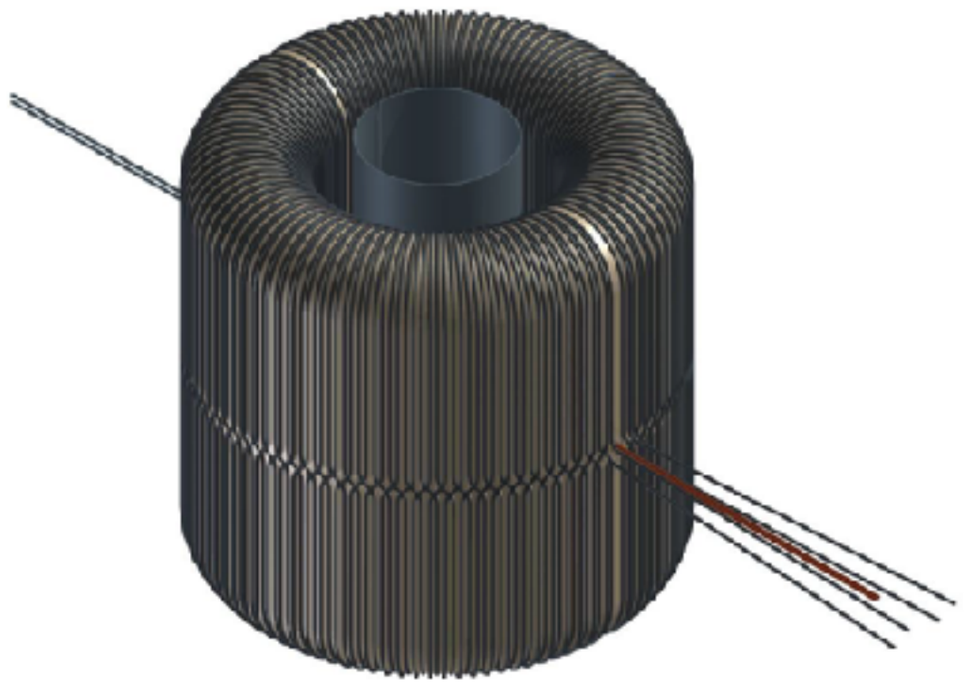
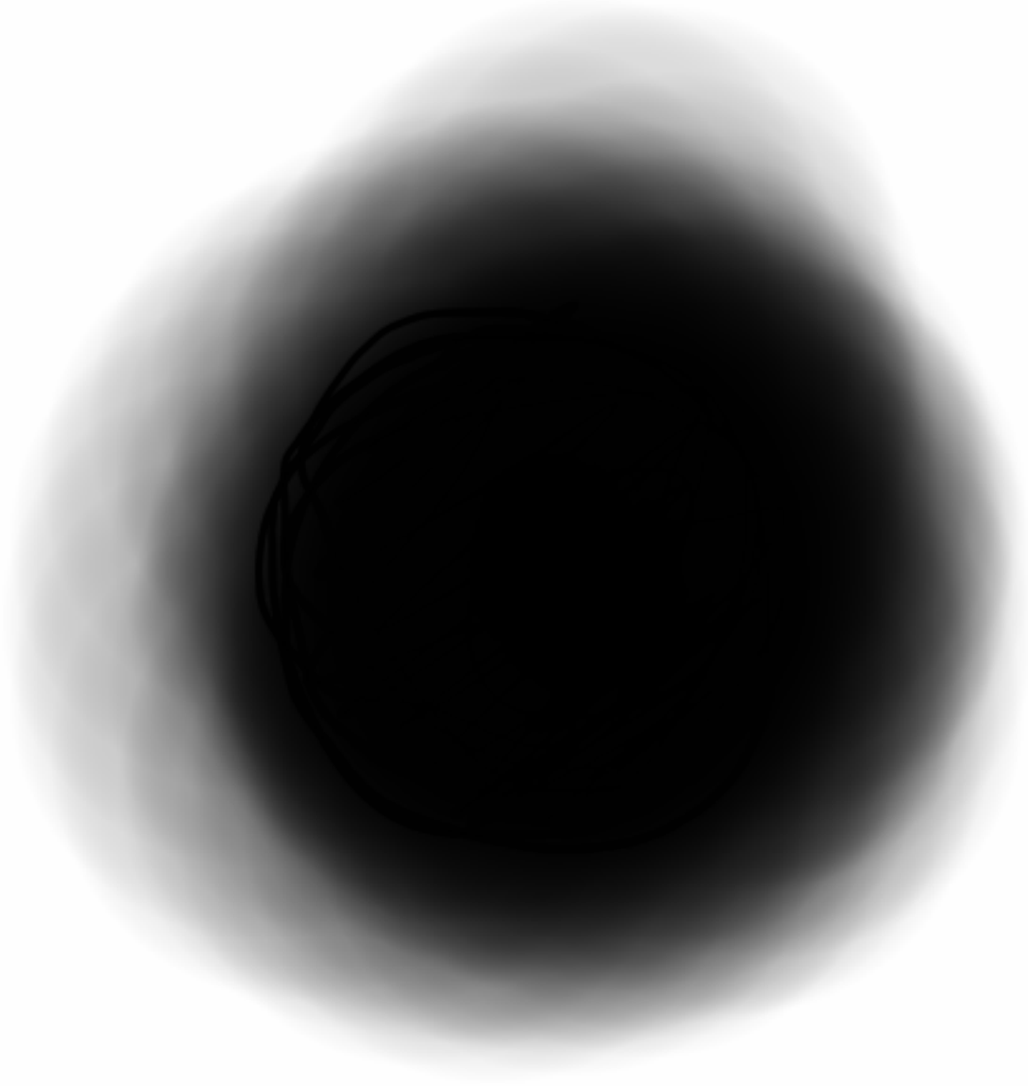
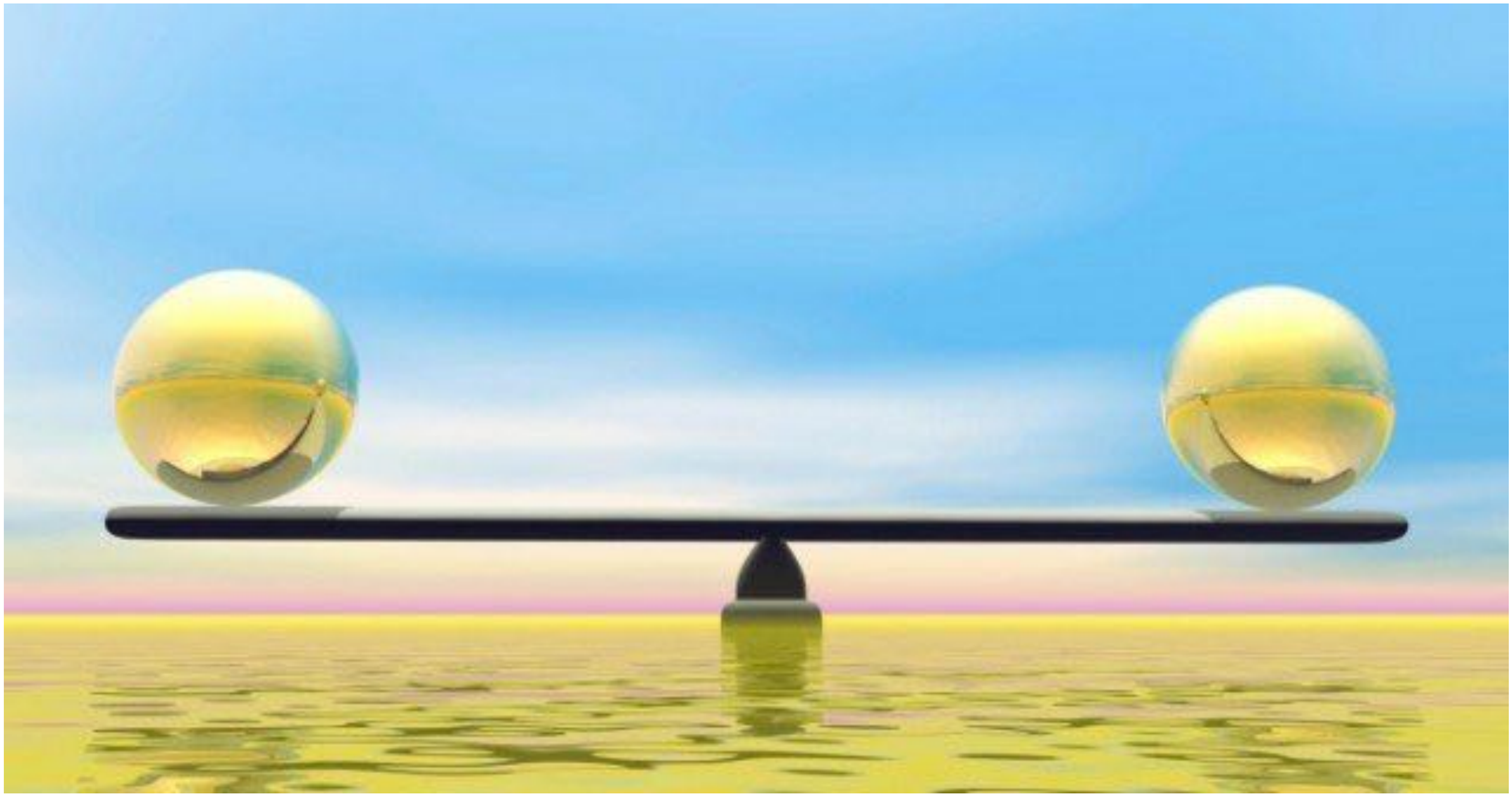


FIG. 1: A schematic of the ABRACADABRA-10cm toroidal geometry. The superconducting main coil sources a static azimuthal magnetic field. In the presence of axion DM, an effective oscillating current is induced following the magnetic field lines. The oscillating magnetic flux sourced by this effective 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




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



keeping the past and the future in balance

Time Translation, τ

The Road to Time Crystals

Time translation symmetry may be the most fundamental symmetry of all.

Strangely enough, it doesn't seem to have a < 7 syllable name. I will call it $\boldsymbol{\tau}$.

$\boldsymbol{\tau}$ is the principle, which instructs us that we can discover eternal laws.

$\boldsymbol{\tau}$ is connected, through Noether's theorem, to the conservation of energy.

Spontaneous breaking of *spatial* translation symmetry is commonplace. Indeed, most common materials "like" to form crystals at low temperatures.

Physicists are accustomed to making analogies and connections between space and time.

Thus, it seems natural to ask whether there are states of matter corresponding to *time crystals*.



x →

Ordinary (space) crystal: Atoms



t →

Time crystal: Events

A beating heart is a sort of time crystal, but

it is not very precise

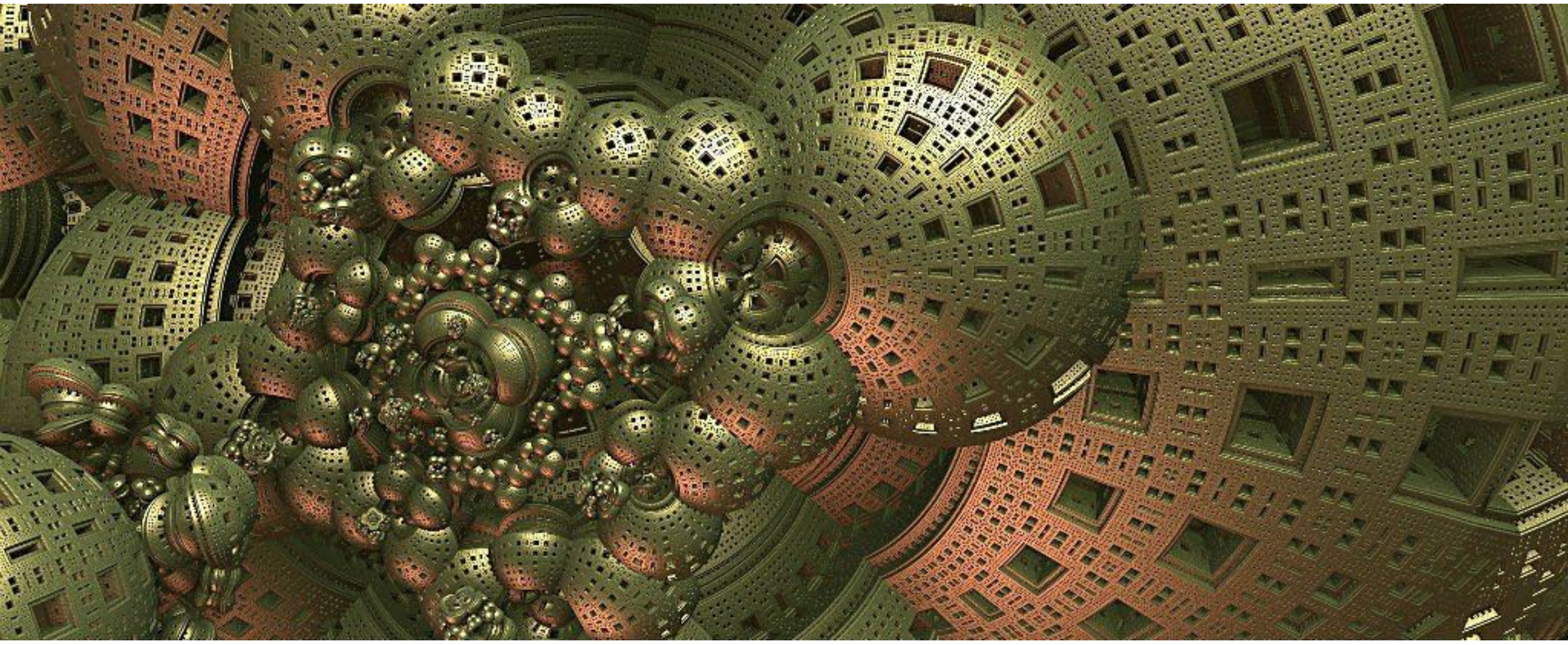
it requires feeding and maintenance

it is complicated

Q: Can $\boldsymbol{\tau}$ be broken *spontaneously* ?

This turns out to be a subtle question, which has recently borne fruit.

A: Yes.



Physicists Just Created the World's First Time Crystal

These things actually exist!

BEC CREW 7 OCT 2016

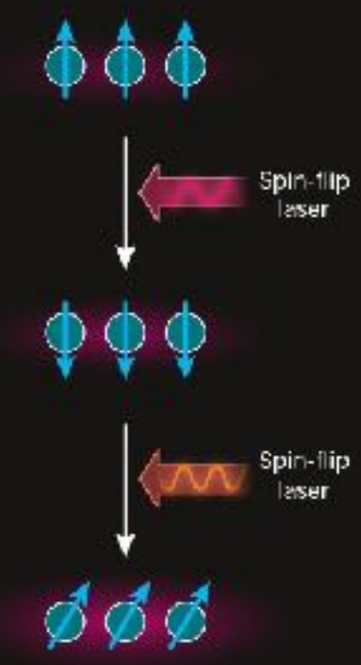
science alert



Nature,
9 March 2017

HOW TO CREATE A TIME CRYSTAL

Mineral crystals break symmetry in space because their atoms occupy fixed positions, so they look different when shifted. They also resist changes to their spatial structure. 'Time crystals' break symmetry in the time domain: they change from one moment to another, also with a repeating pattern that is resilient.

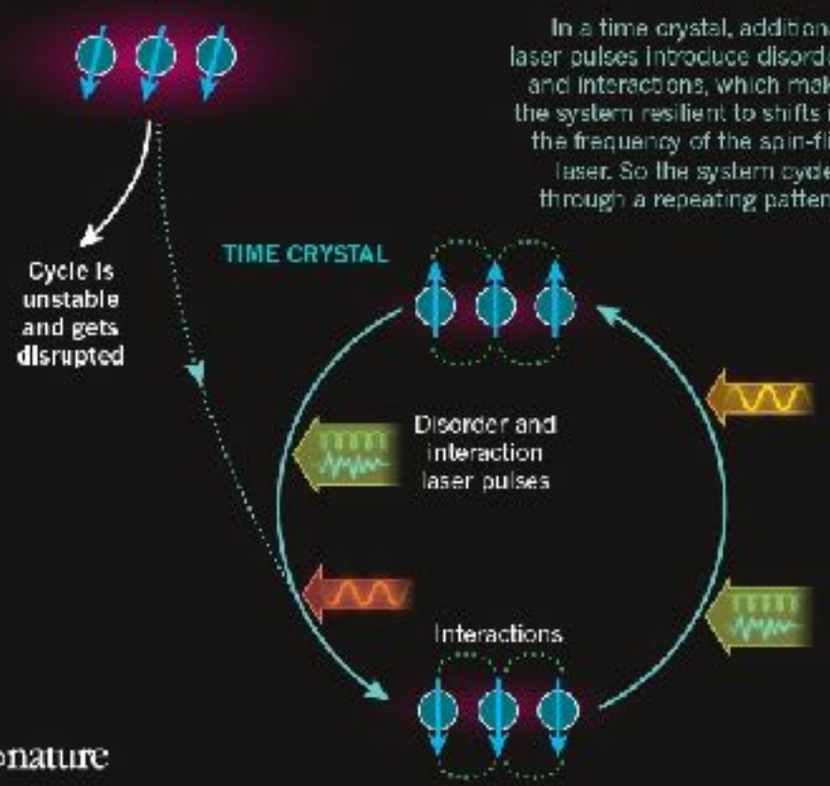


Researchers have created time crystals by firing lasers at a chain of ions. An appropriately tuned laser would flip the spins by 180°. A second, identical laser burst would return the spins to their original position.

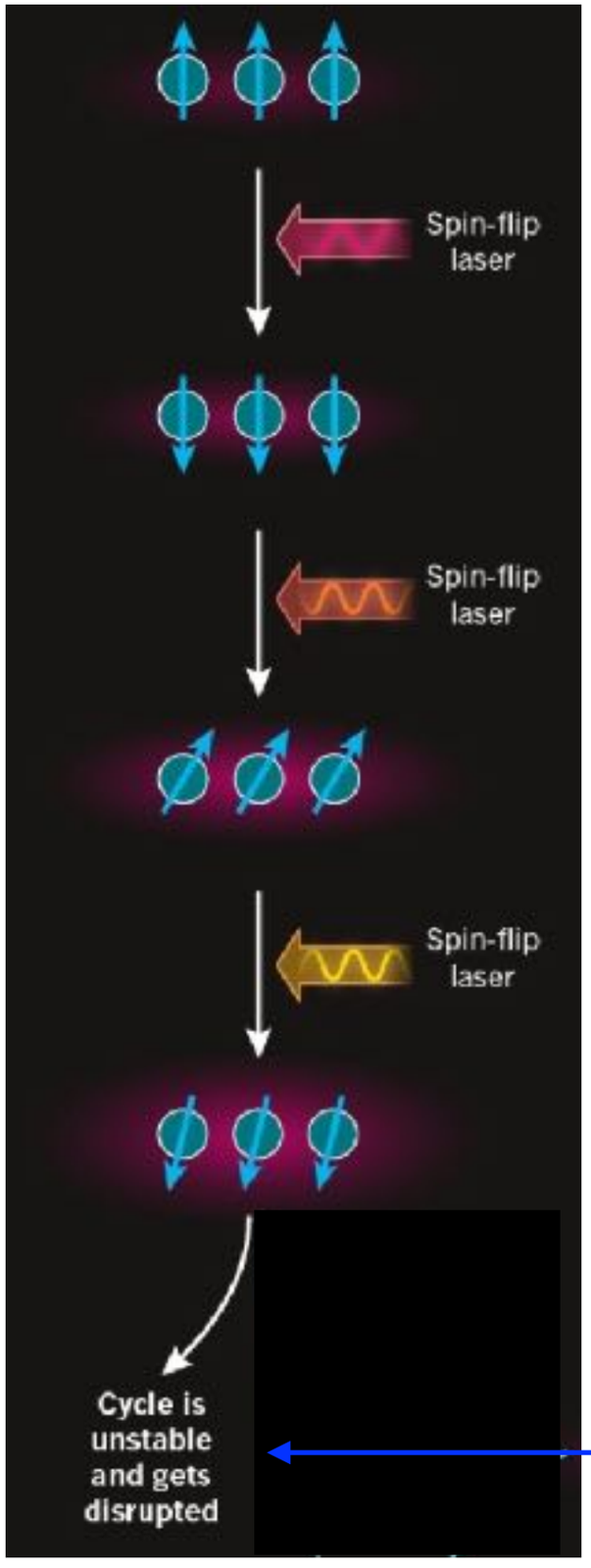
Any slight shifts to the frequency of the laser pulses would cause the ion spins to rotate by an amount different from 180°. So they would not reach their starting orientation after two bursts from the spin-flip laser.



In a time crystal, additional laser pulses introduce disorder and interactions, which make the system resilient to shifts in the frequency of the spin-flip laser. So the system cycles through a repeating pattern.



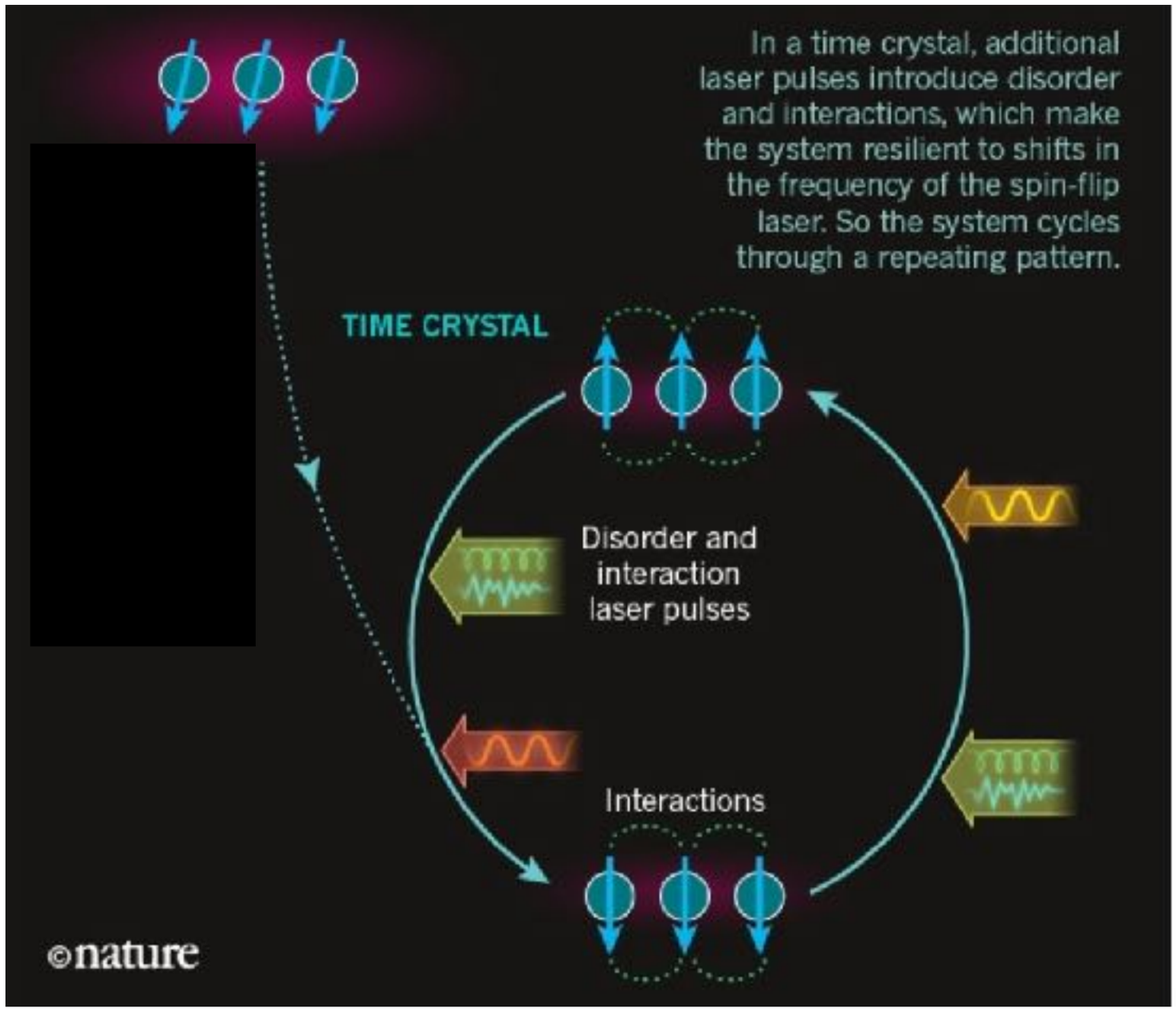
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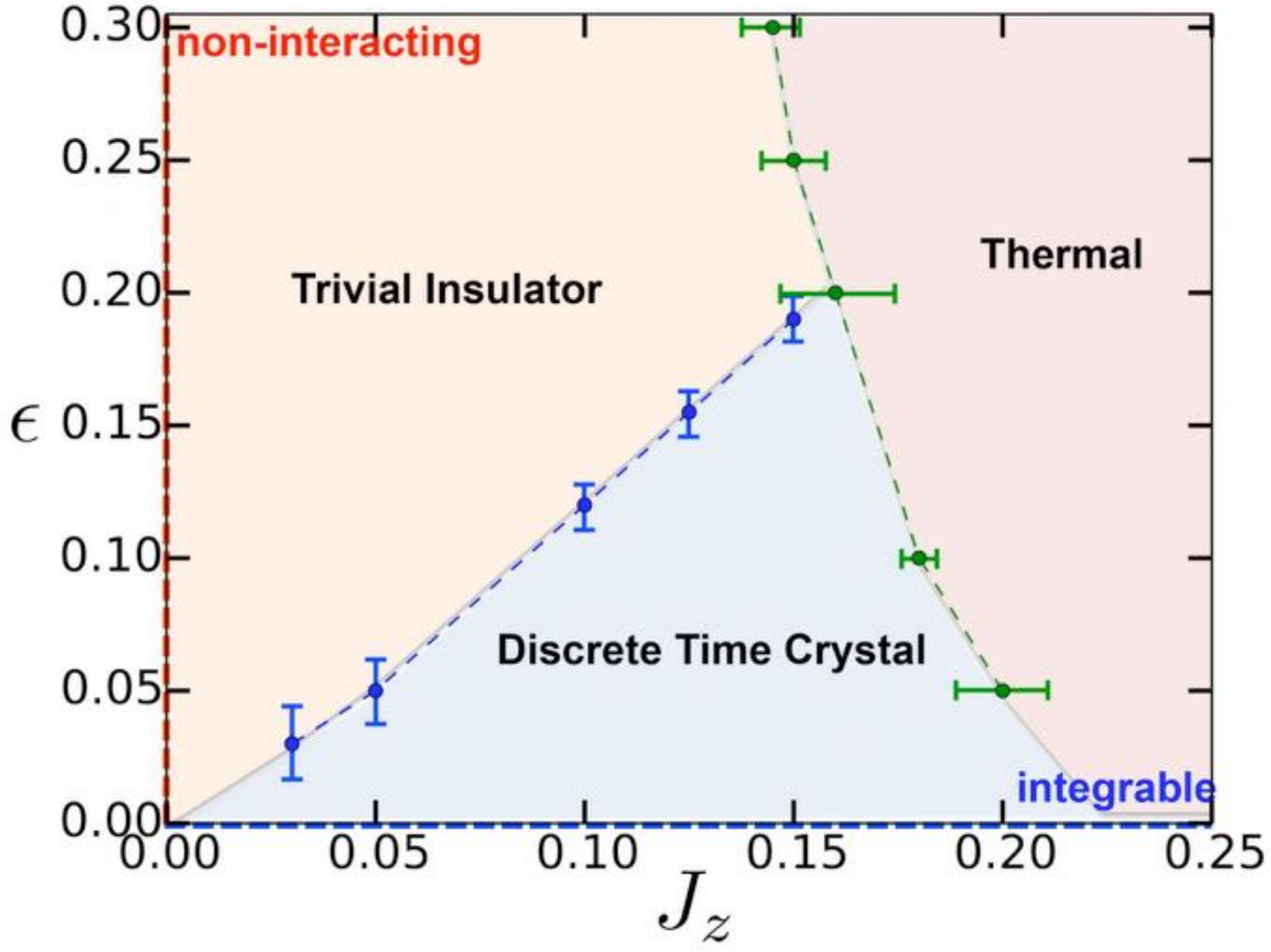
"normal" equilibration



structured equilibrium

interaction ⇒ desire to synchronize

disorder ⇒ ability to synchronize (diversity of “leaders”)



Norman Yao, UC Berkeley

Big picture:

The study of $\boldsymbol{\tau}$ breaking is revealing shortcomings in the hitherto conventional view of “equilibrium”, notably including the emergence of robust, self-organized quantum structures in noisy, randomized systems.



rapid commercialization!

Mechanical Time Crystals

Spin Chains - Ring Molecules? - Molecular Machines??

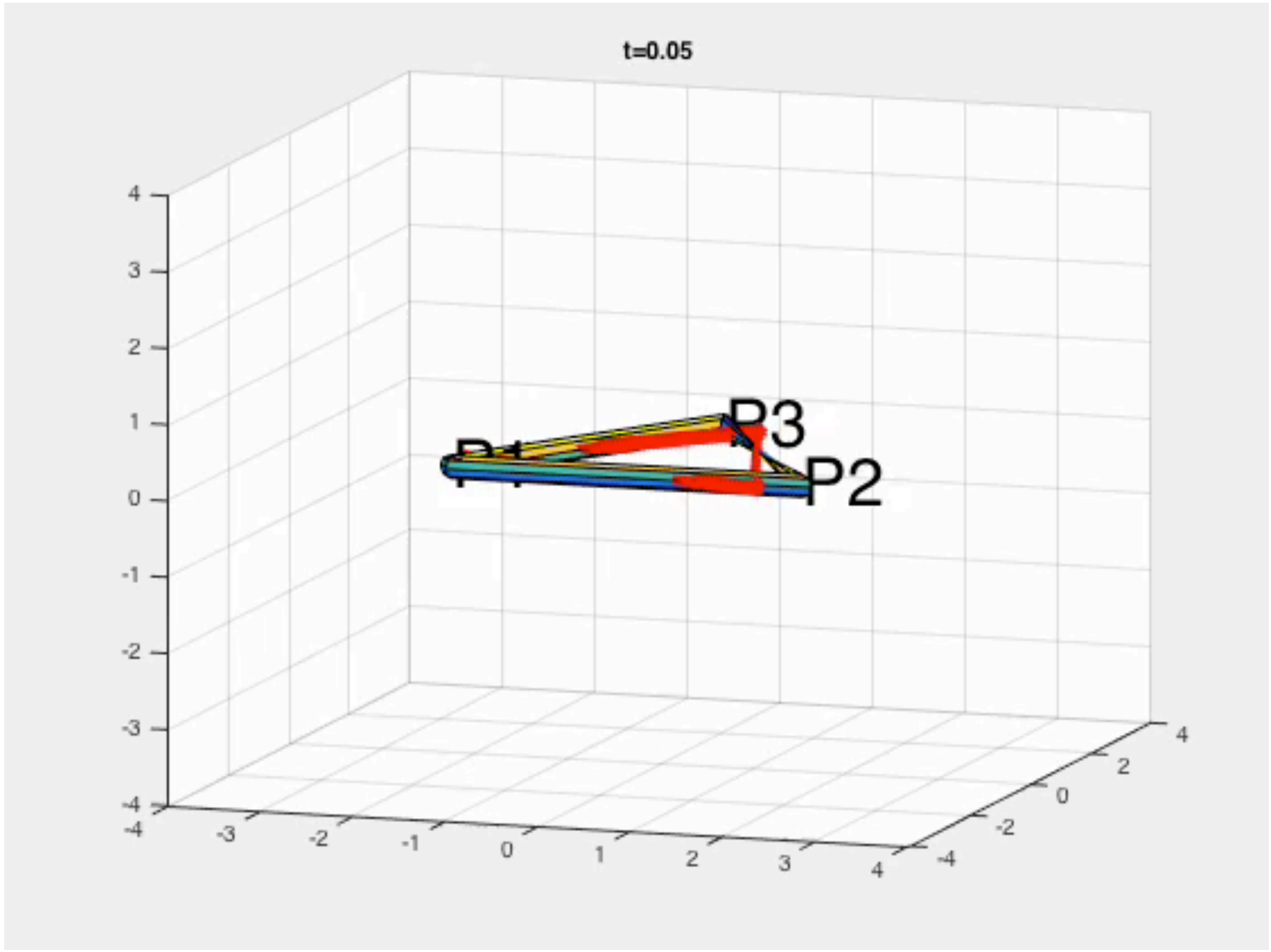
$$
\begin{aligned}
H &= \sum_{j=1}^{N} c_j \, \vec{s}_j \cdot \vec{s}_{j+1} \\
s_{N+1} &\equiv s_1 \\
0 &= \sum_{j=1}^{N} \vec{s}_j
\end{aligned}
$$

With $s_j = r_j - r_{j-1}$, this can serve as an unconventional, “minimal” model of ring molecule dynamics.

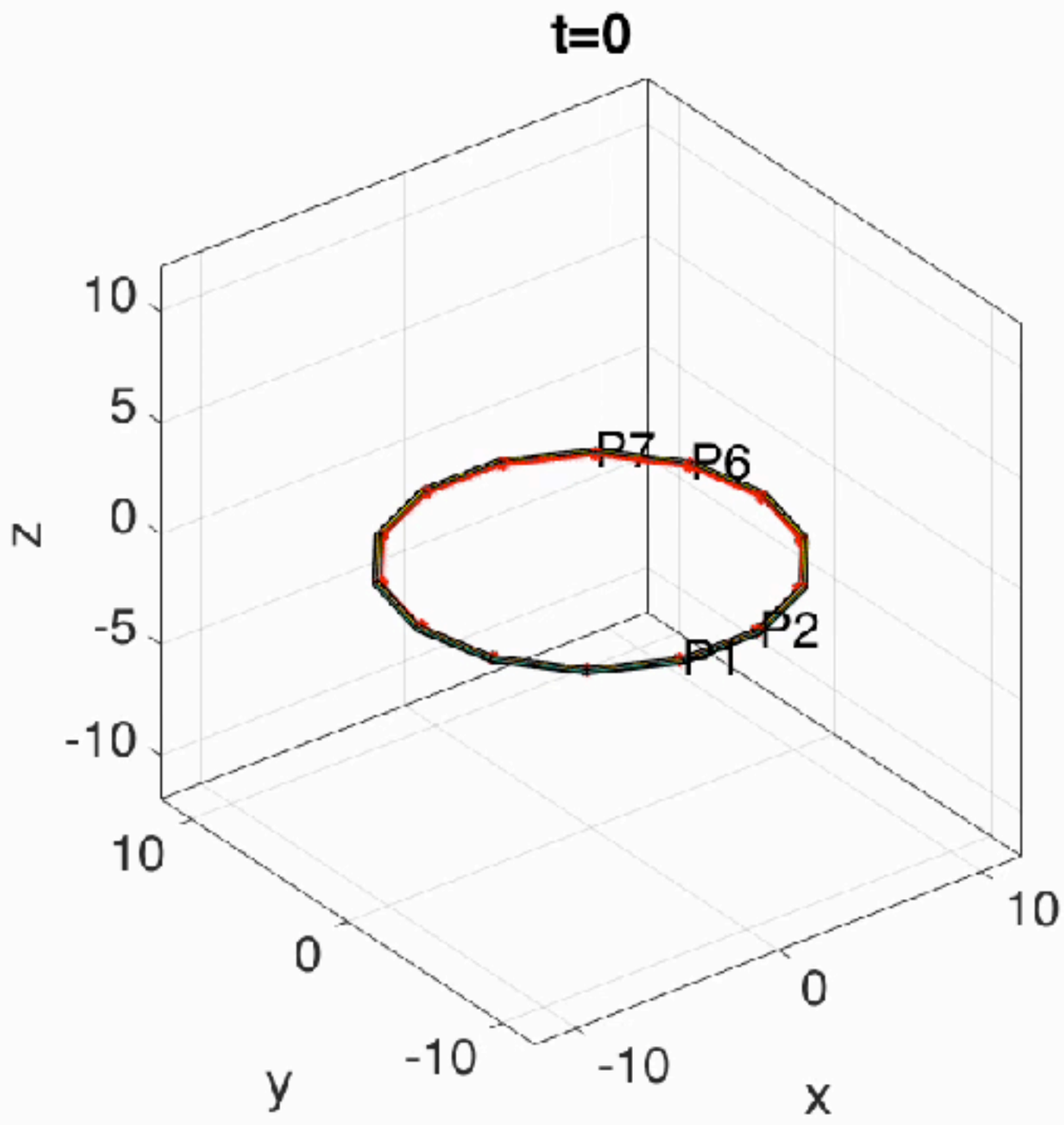
Generically, there is motion in the ground state (emergent precession).

$$
\begin{aligned}
\frac{d\vec{s}_j}{dt} &= \{H, \vec{s}_j\} \\
\{s_j^\alpha, s_k^\beta\} &= \delta_{jk}\, \epsilon^{\alpha\beta\gamma}\, s_j^\gamma
\end{aligned}
$$

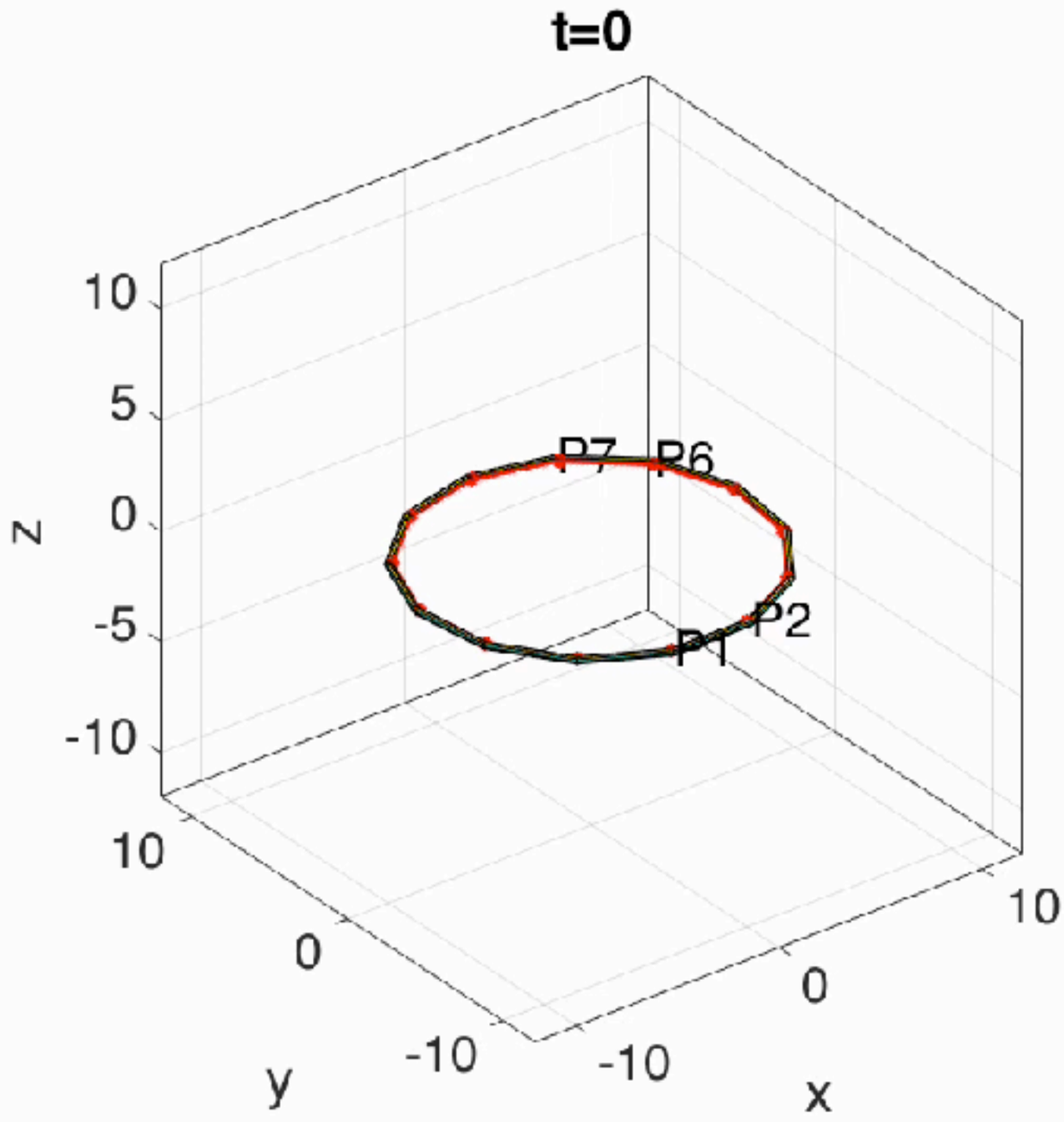
$$
\frac{d\vec{s}_j}{dt} = \frac{\partial H}{\partial \vec{s}_j} \times \vec{s}_j
$$



Triangle (1, 1, -1)



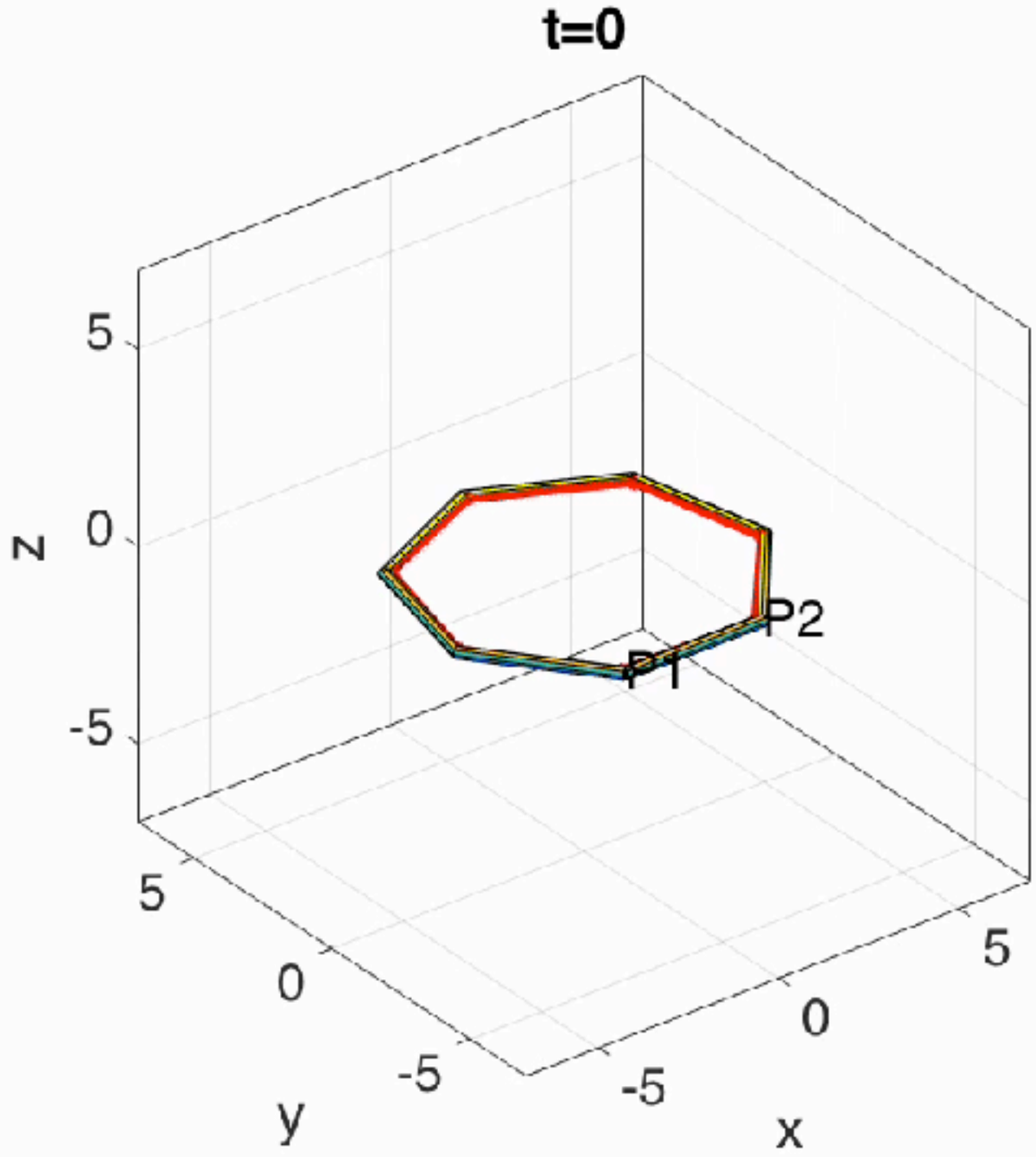
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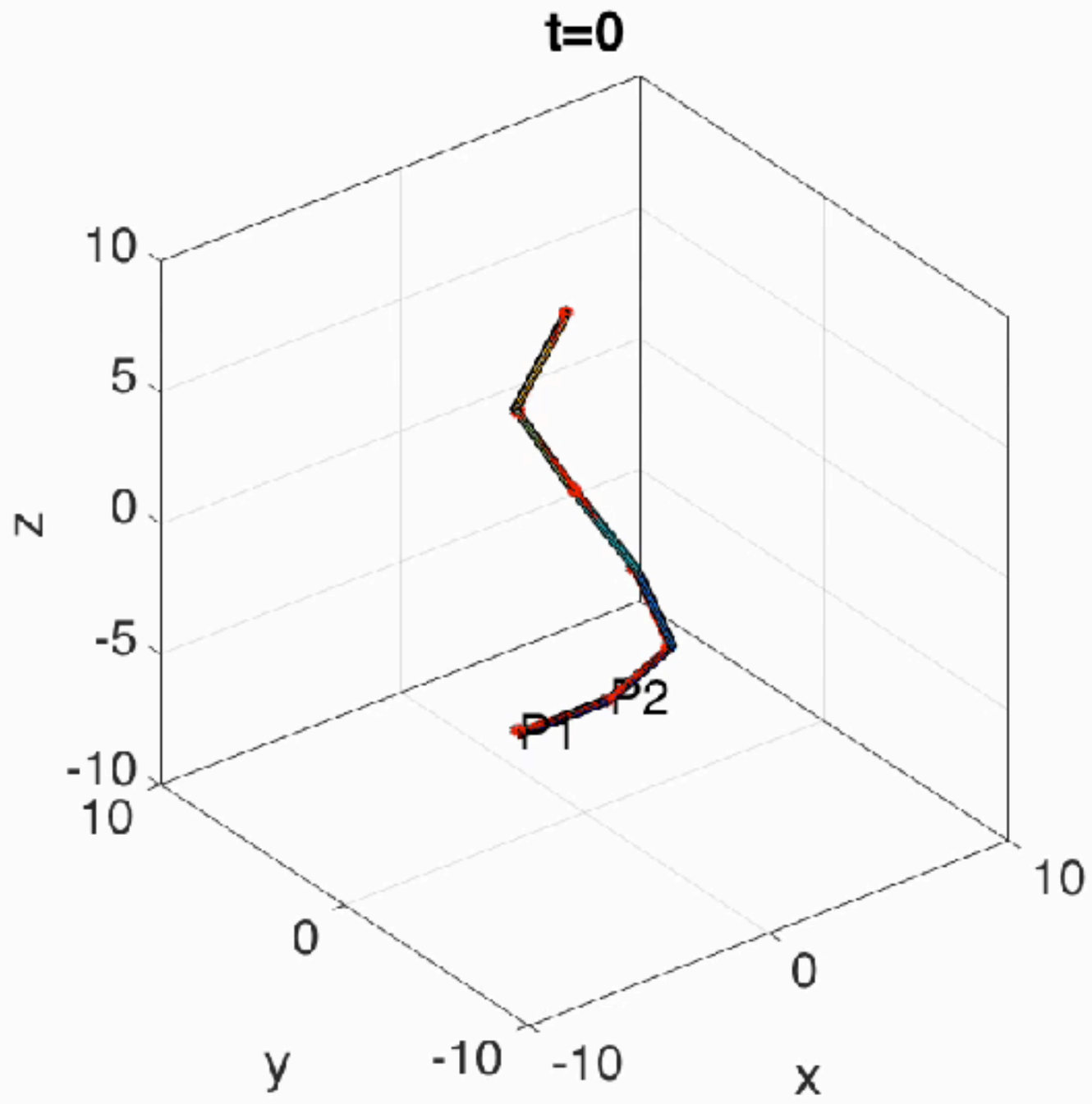
(1, .8, 1, .8, 1, .8, .8, 1, .8, 1, .8, 1, .8)

Very interesting things happen when we add

"volume" interactions $\propto s_j \cdot (s_{j+1} \times s_{j+2})$



Uniform volume interaction



Volume interaction at end

Temi

Mixing Up Past and Future

We generally regard the equations of physics as a recipe for evolving states:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} \alpha \\ \beta \end{pmatrix} = \begin{pmatrix} \gamma \\ \delta \end{pmatrix}$$

Laws **Initial State** **Final State**

The evolution is given by a unitary operator.

Formally, we can invert this relation, to infer the past from the future.

How about a mixed formulation - giving emergent future a chance, treating past and future more symmetrically?

Given $\boldsymbol{\alpha}$, $\boldsymbol{\delta}$ - to determine $\boldsymbol{\beta}$, $\boldsymbol{\gamma}$:

$$\begin{pmatrix} \gamma \\ \beta \end{pmatrix} = \begin{pmatrix} A - BD^{-1}C & BD^{-1} \\ -CD^{-1} & D^{-1} \end{pmatrix} \begin{pmatrix} \alpha \\ \delta \end{pmatrix}$$

This gives a unique solution so long as Det D ≠ 0.

Since Det D = 0 requires two real numbers to vanish, generically Det D ≠ 0 , and even Det D(t) ≠ 0.

This line of thought can guide us through interesting adventures:

Time-symmetric big bang cosmology

Warring thermodynamic arrows

“Free will” and paradoxes of causal loops

In the future, some clarity may emerge.