JAVIER DUARTE

OCTOBER 20, 2018

SATURDAY MORNING PHYSICS

FERMILAB, BATAVIA, IL, USA

SYMMETRY, ANTIMATTER, AND SUPERSYMMETRY

OUTLINE

- Symmetry
- Antimatter
- Matter-antimatter asymmetry
- Supersymmetry

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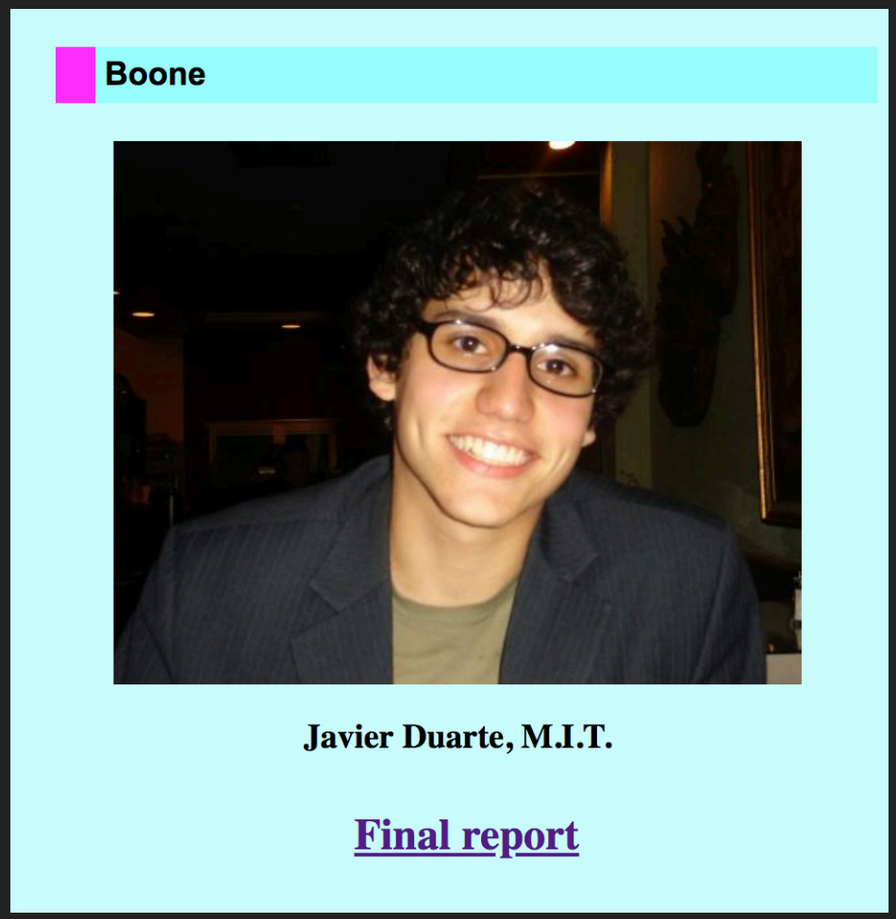

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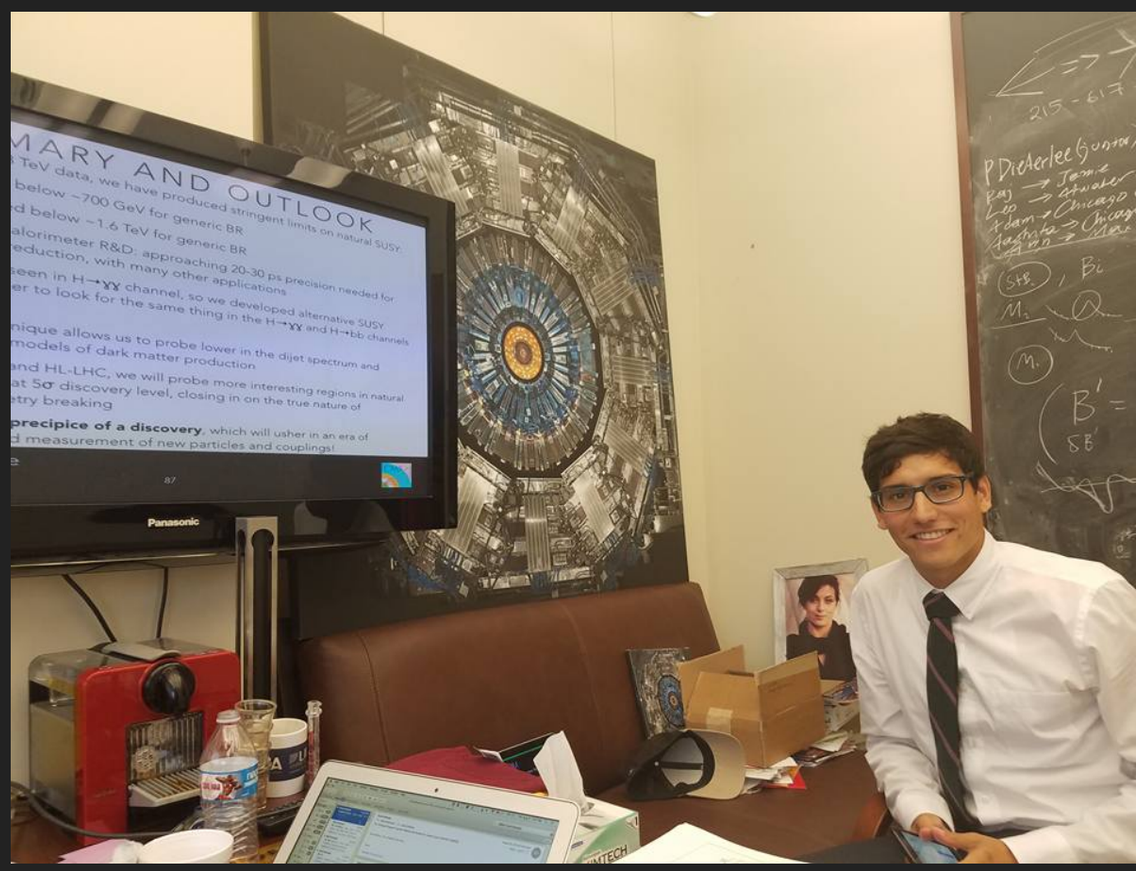

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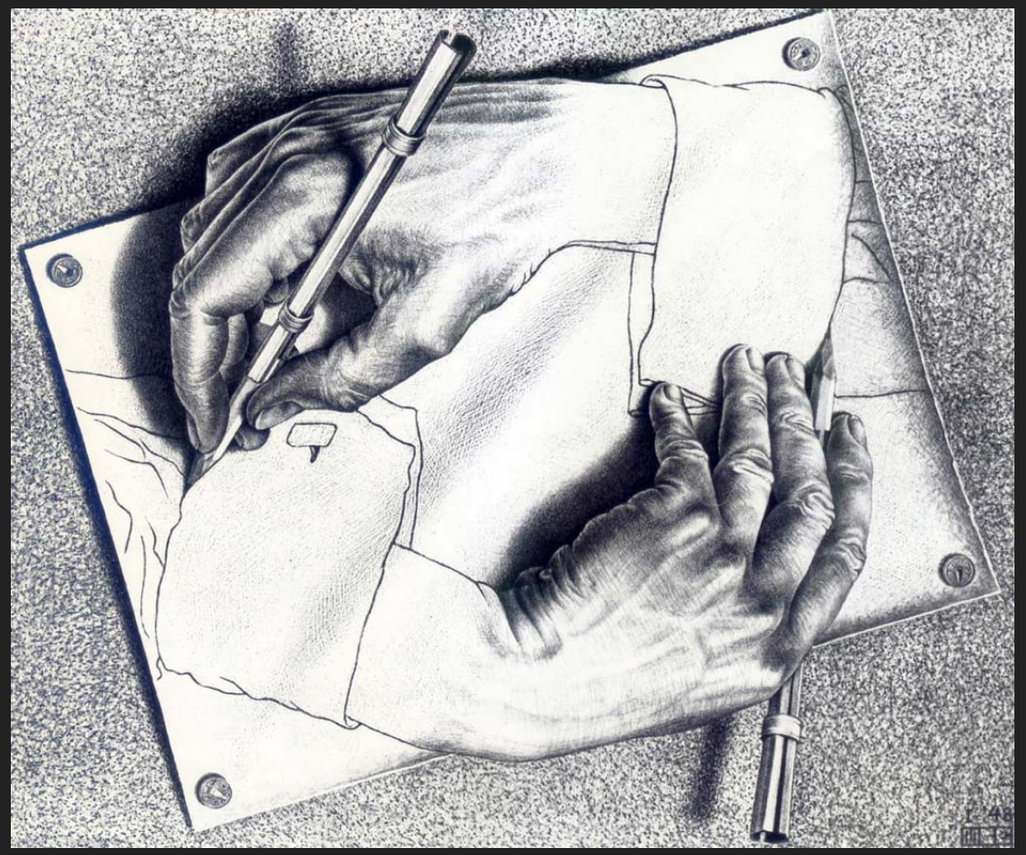

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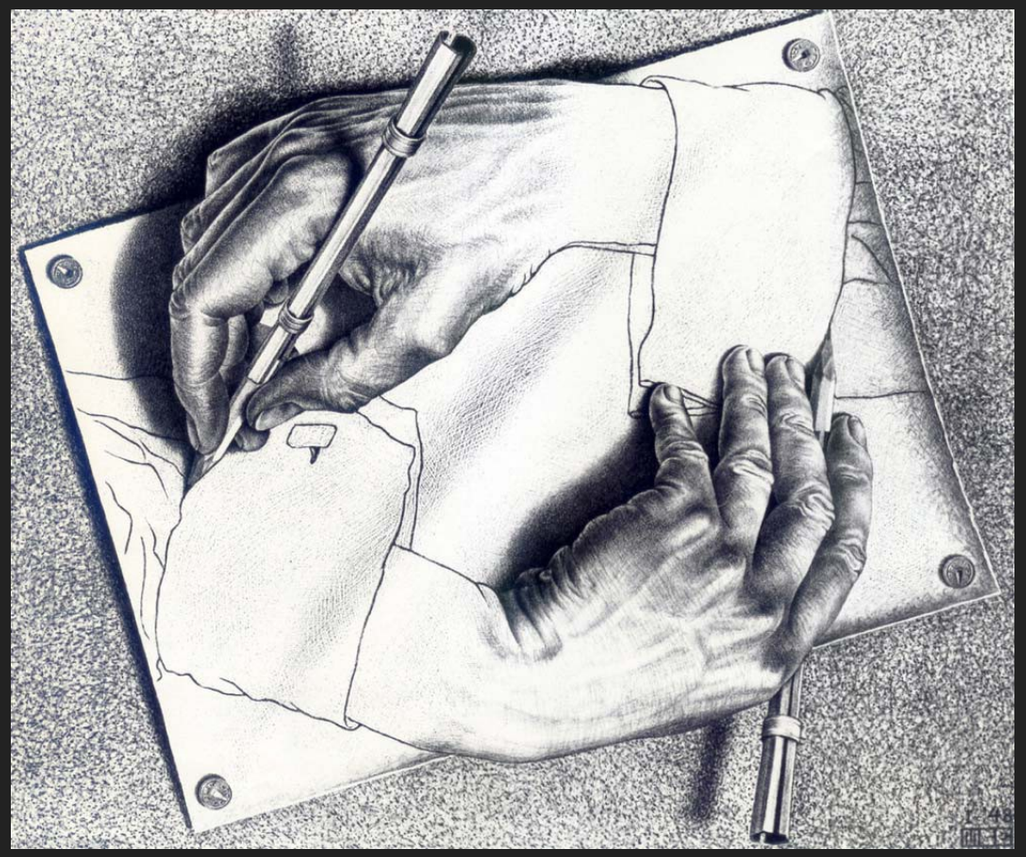

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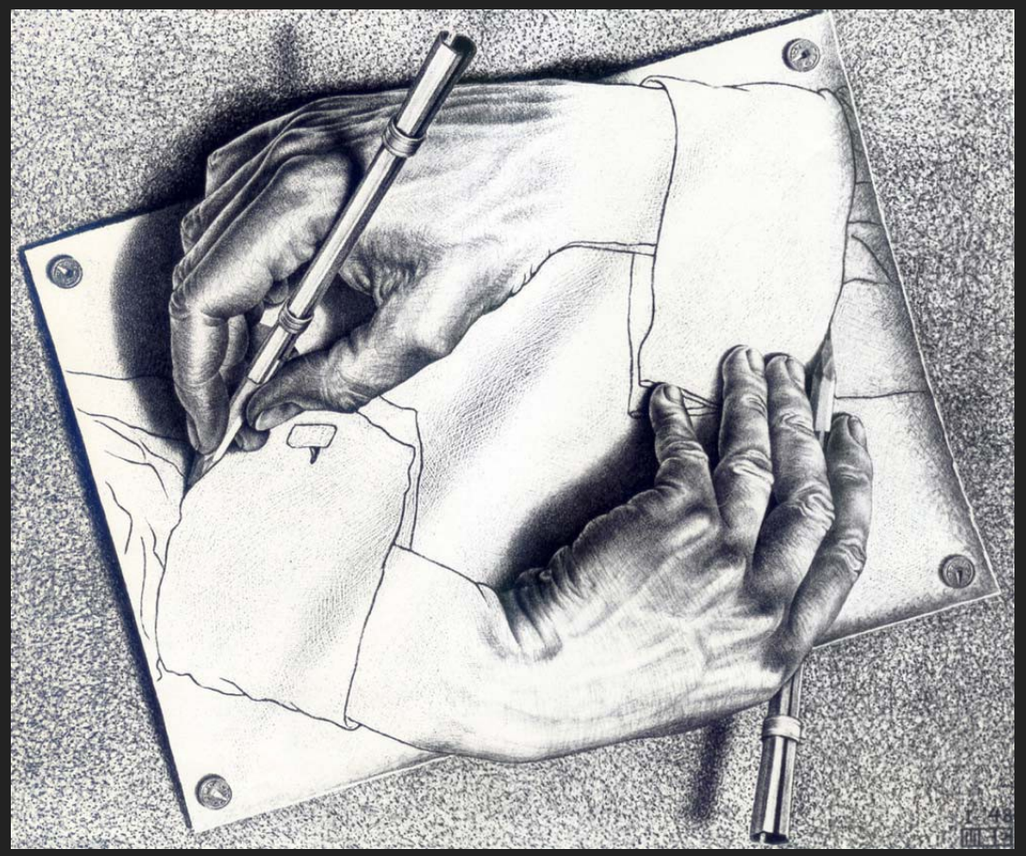

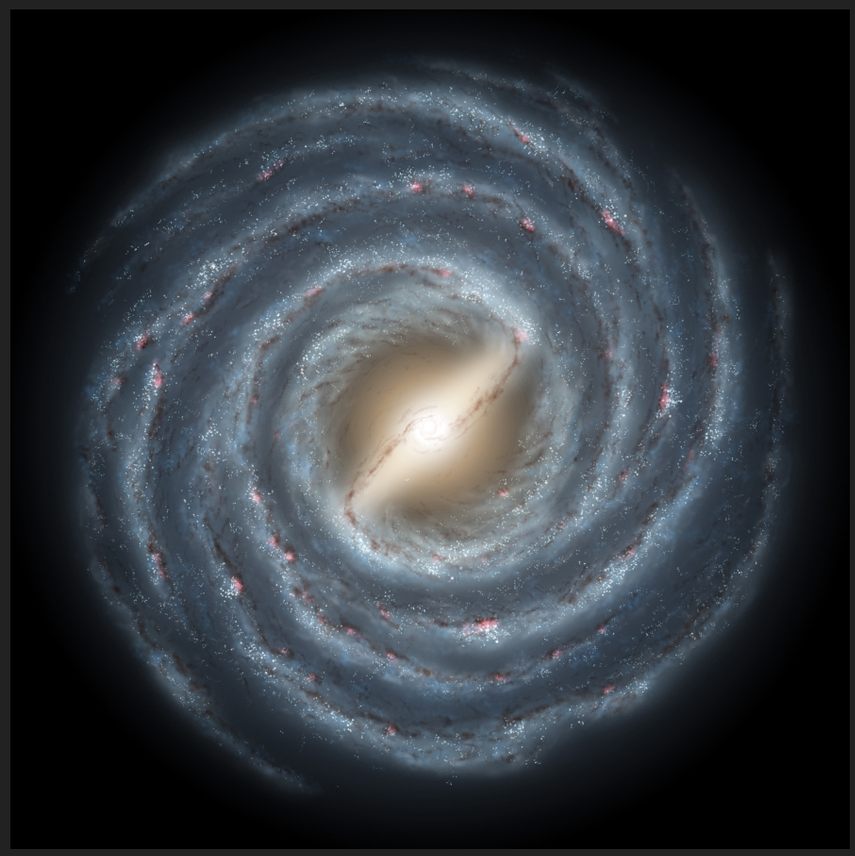

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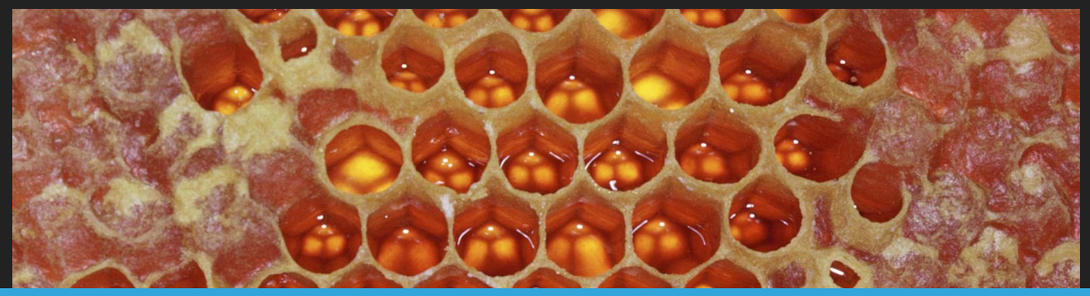
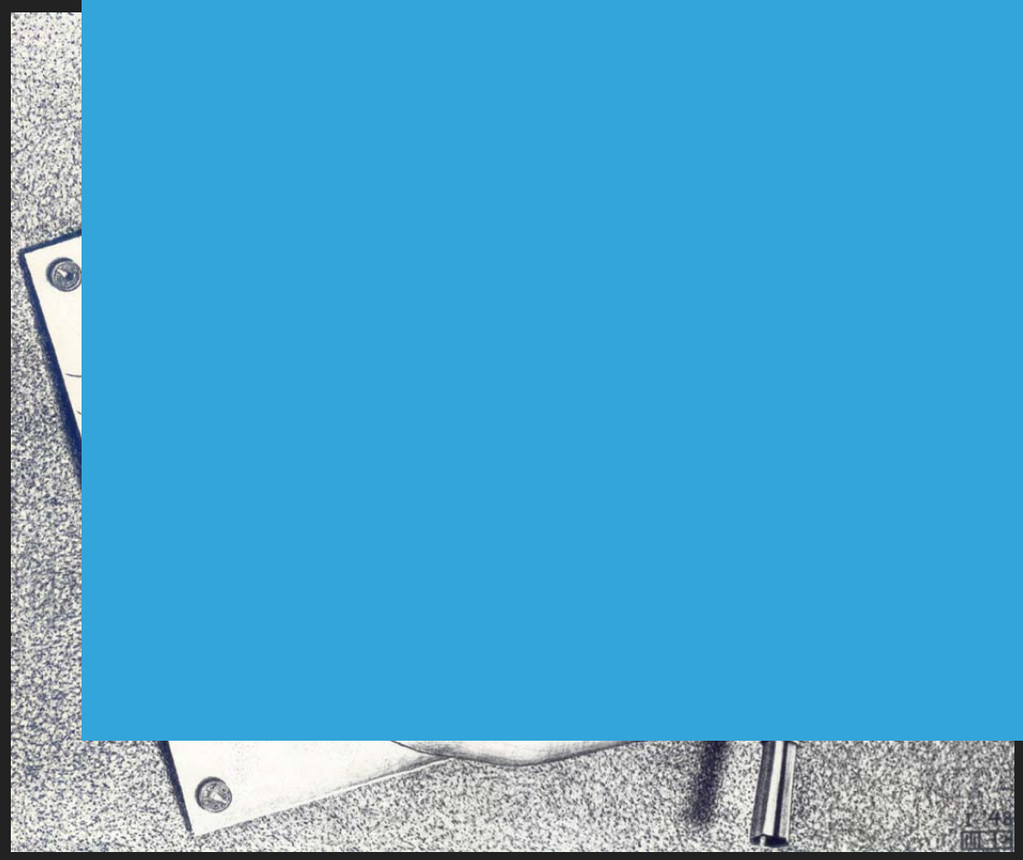


WHAT DO THESE ALL HAVE IN COMMON? HOW CAN WE GENERALIZE THIS INTO A MATHEMATICAL CONCEPT?



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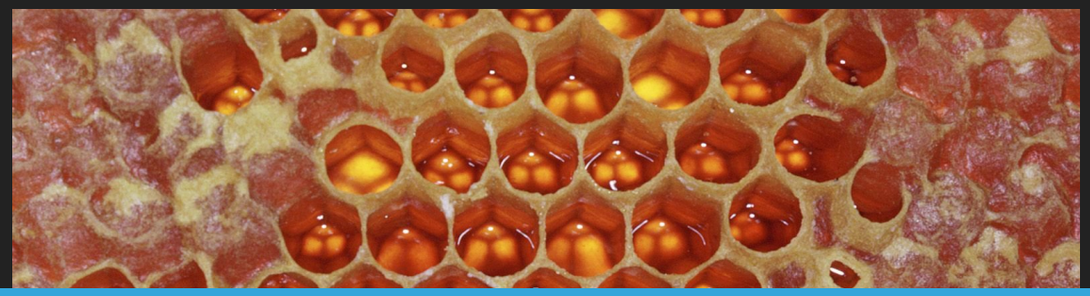

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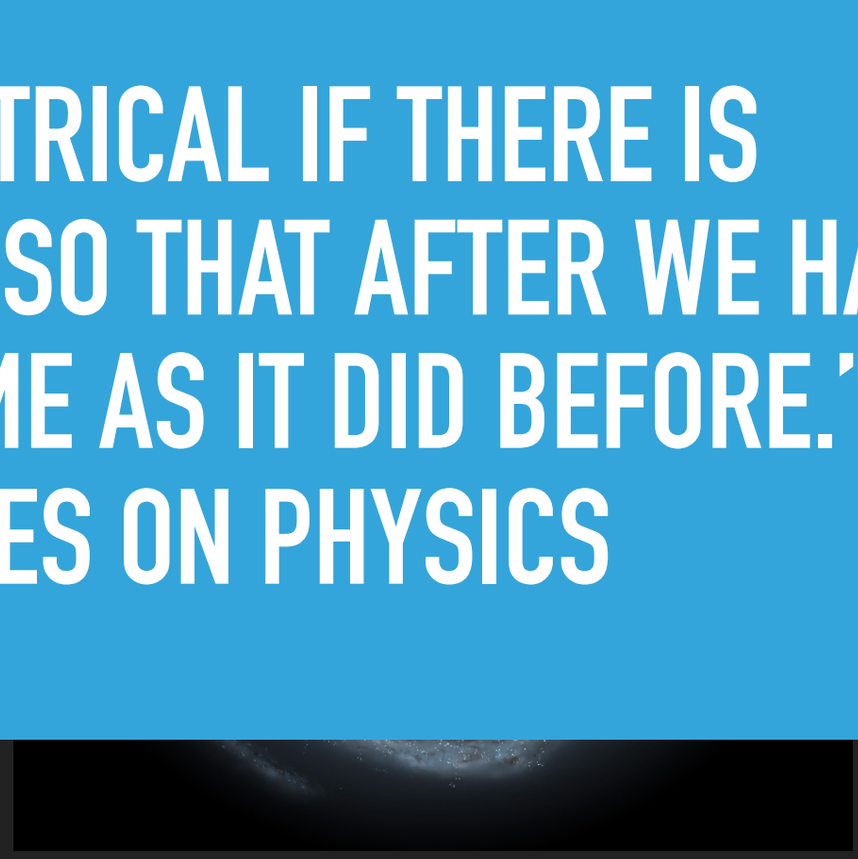

"... A THING IS SYMMETRICAL IF THERE IS SOMETHING WE CAN DO TO IT SO THAT AFTER WE HAVE DONE IT, IT LOOKS THE SAME AS IT DID BEFORE."
– FEYNMAN LECTURES ON PHYSICS

DISCRETE* SYMMETRIES OF PLANE FIGURES

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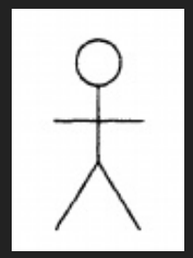

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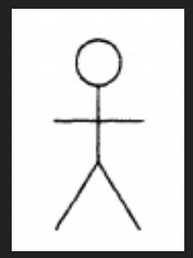

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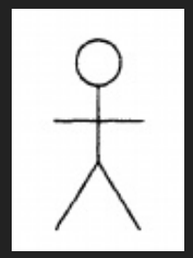

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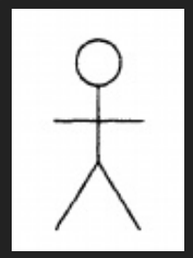

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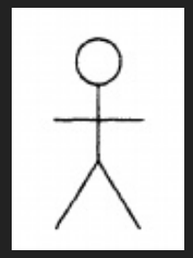

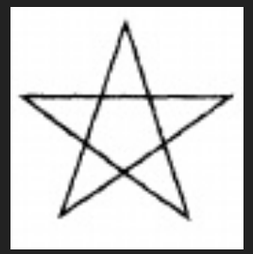

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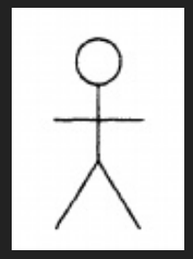

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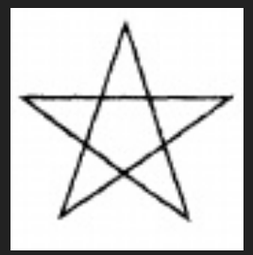

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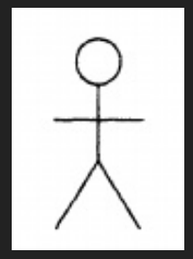

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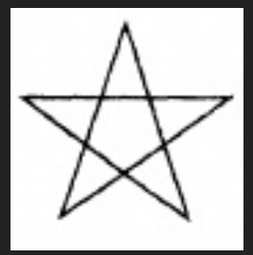

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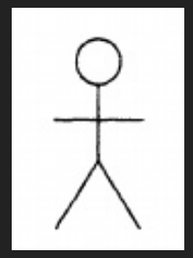

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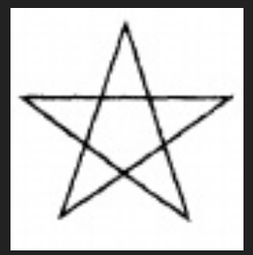

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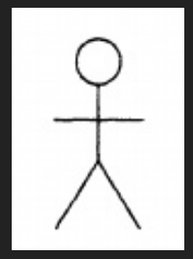

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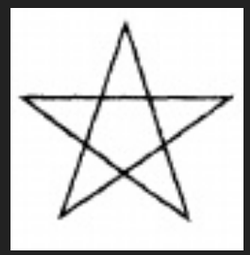

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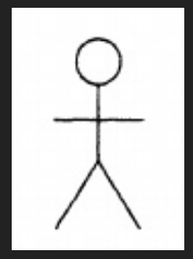

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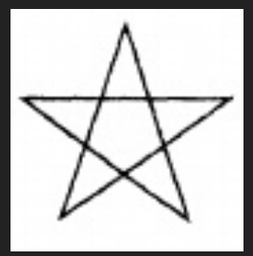

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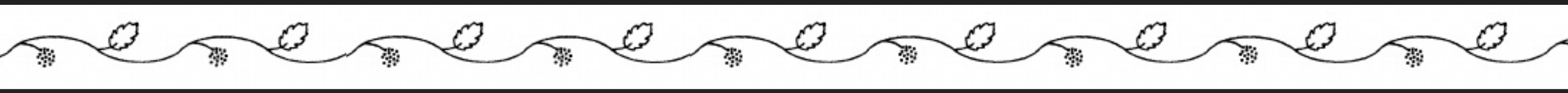

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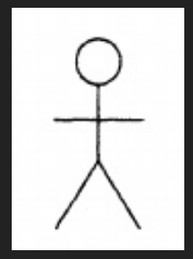

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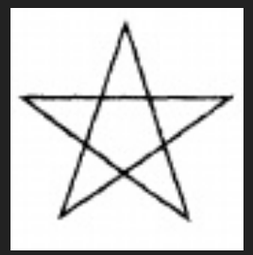

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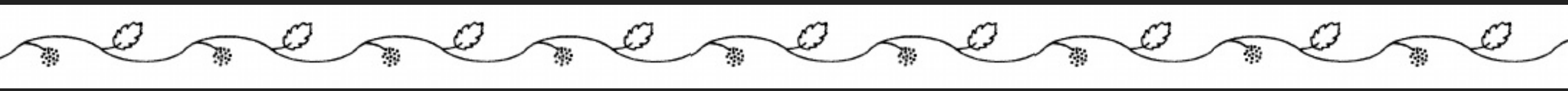

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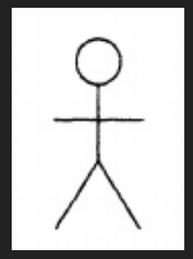

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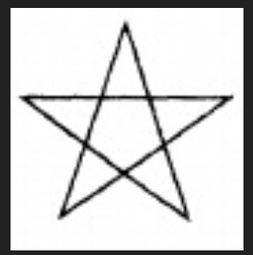

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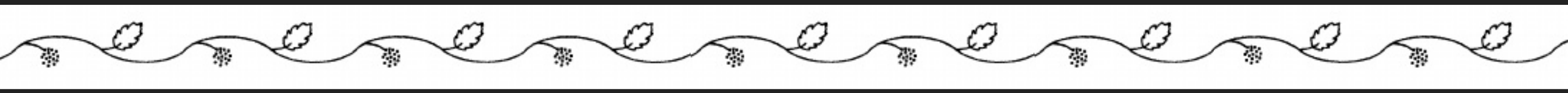

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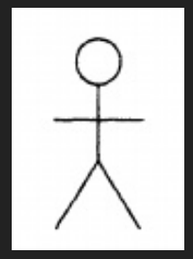

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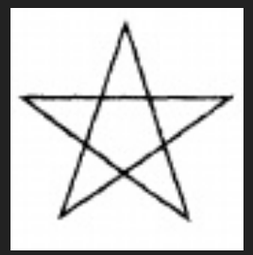

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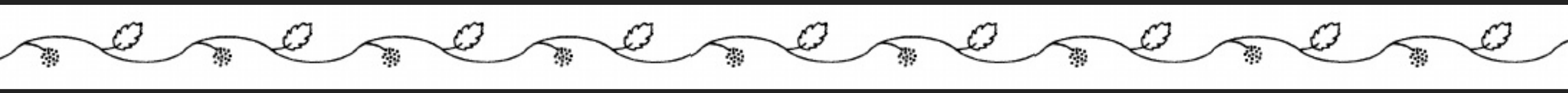

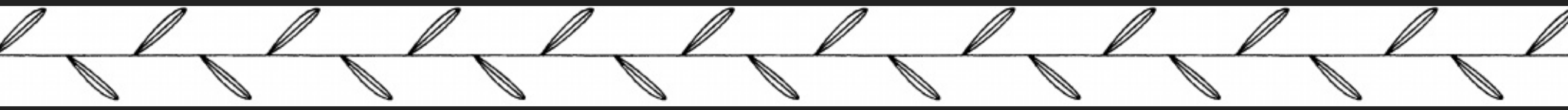

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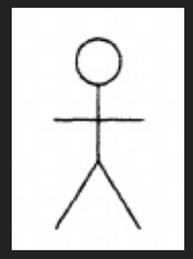

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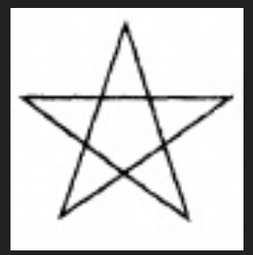

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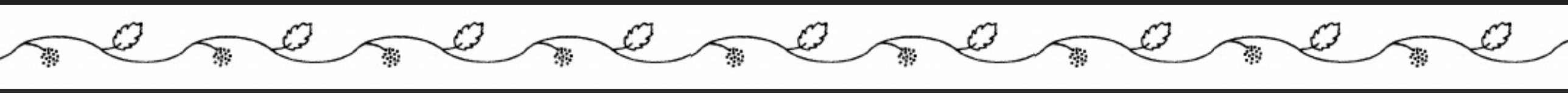

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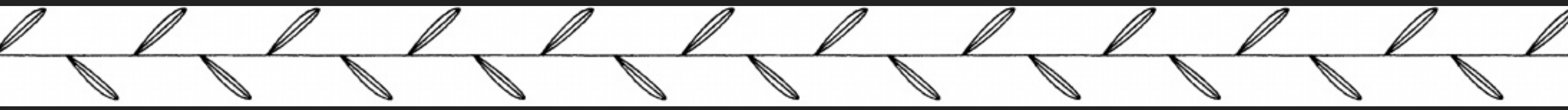

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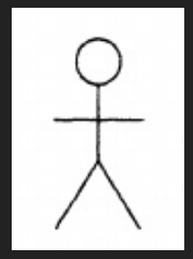

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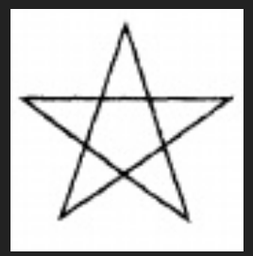

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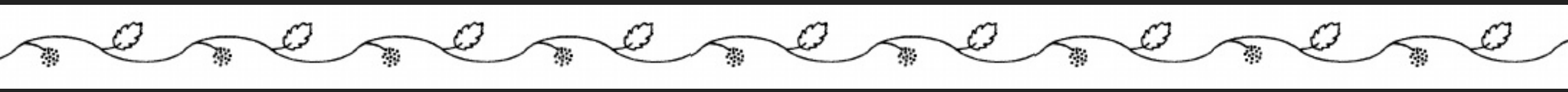

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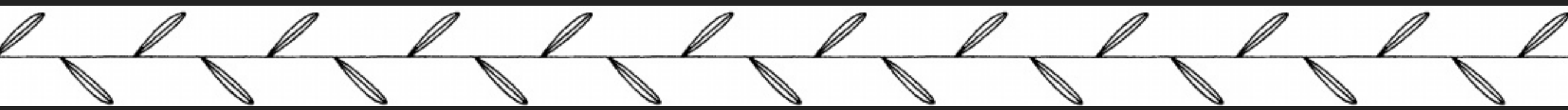

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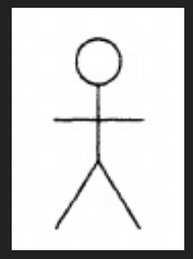

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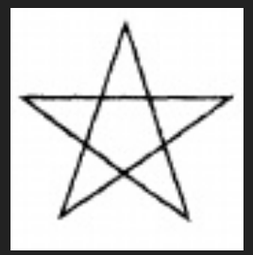

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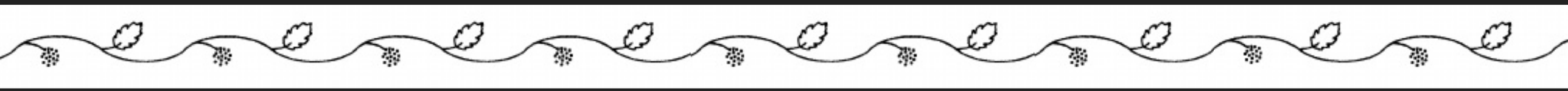
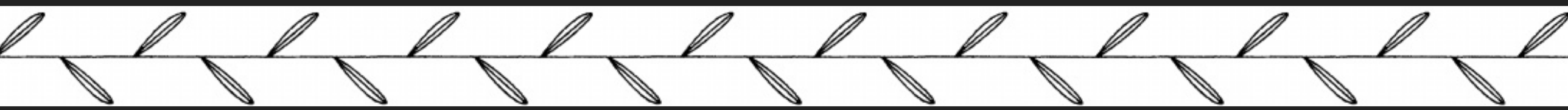


- Glide symmetry: translation along the x-axis then reflection about the x-axis



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  - = first, apply symmetry motion 1 then, apply symmetry motion 2

COMPOSITION TABLE

- Can we prove that they form a *group*?
- Let's start with closure: build the *composition table*

	1	2	3	4	5	6	7	8	9	10
1	1	2	3	4	5	6	7	8	9	10
2	2	4	6	8	10	12	14	16	18	20
3	3	6	9	12	15	18	21	24	27	30
4	4	8	12	16	20	24	28	32	36	40
5	5	10	15	20	25	30	35	40	45	50
6	6	12	18	24	30	36	42	48	54	60
7	7	14	21	28	35	42	49	56	63	70
8	8	16	24	32	40	48	56	64	72	80
9	9	18	27	36	45	54	63	72	81	90
10	10	20	30	40	50	60	70	80	90	100

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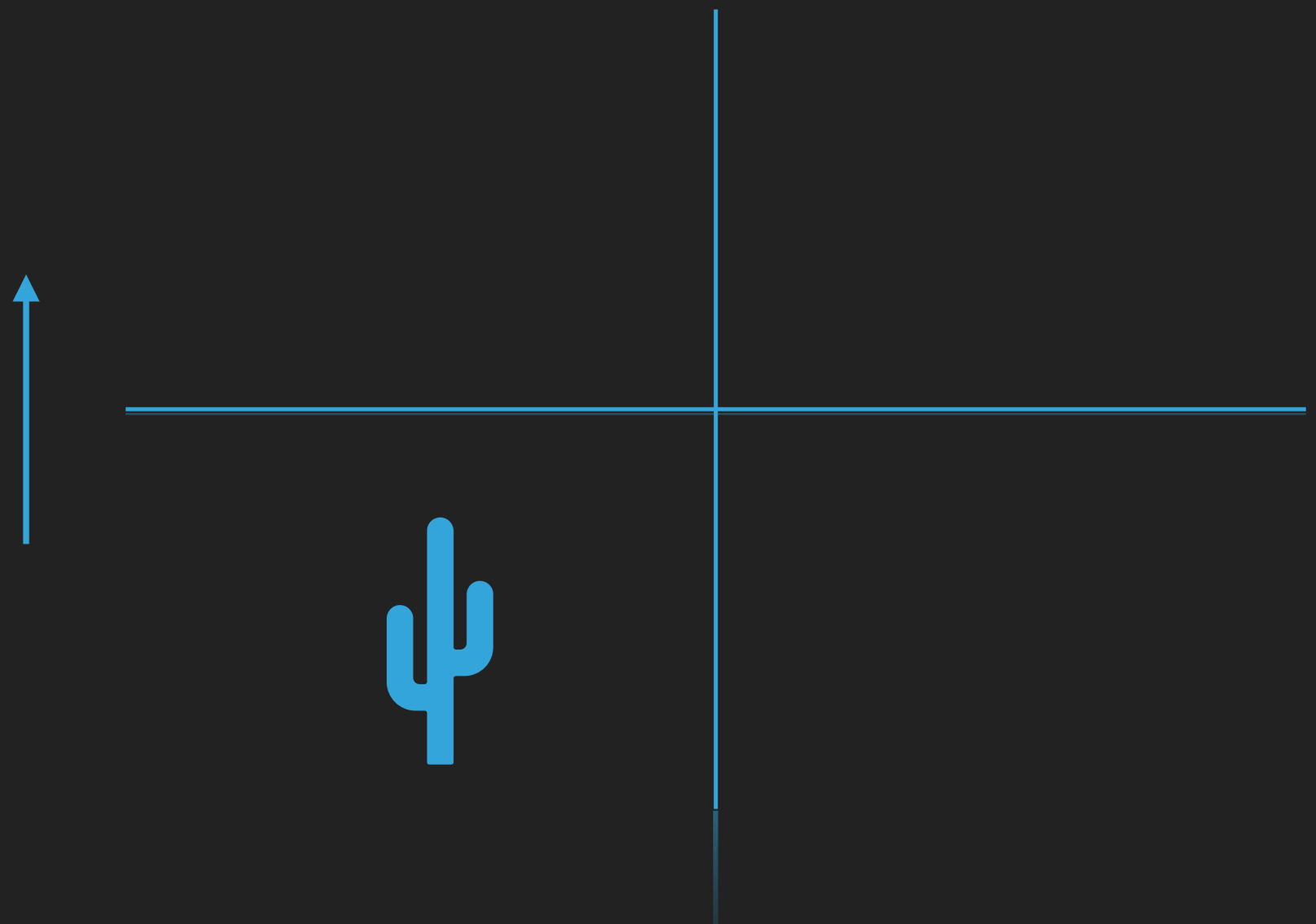
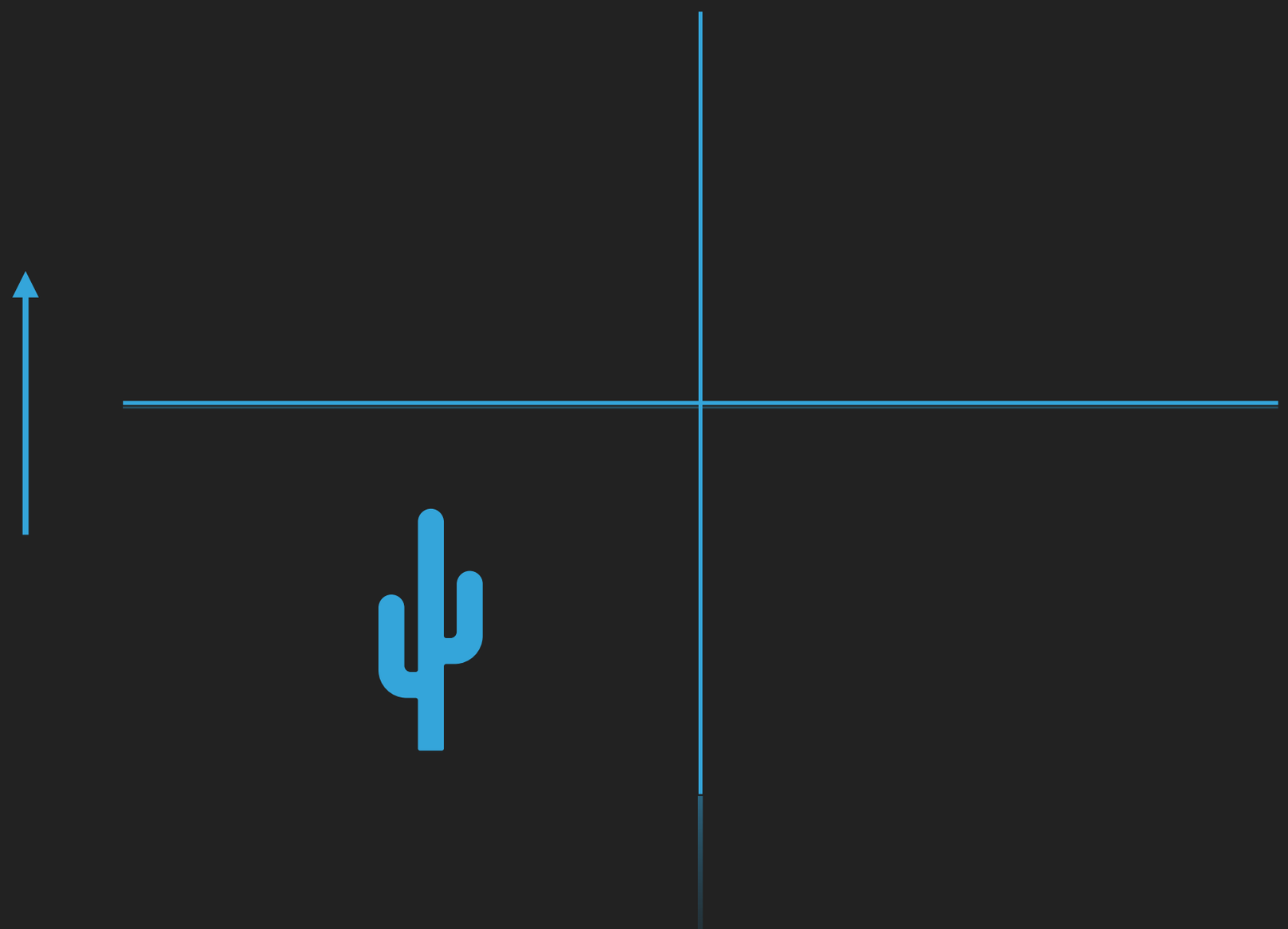
Symmetry 2 \ Symmetry 1	A Translation	B Rotation	C Reflection	D Glide
Translation				
Rotation				
Reflection		?		
Glide				

COMPOSITION TABLE



COMPOSITION TABLE

- Reflection about the x-axis



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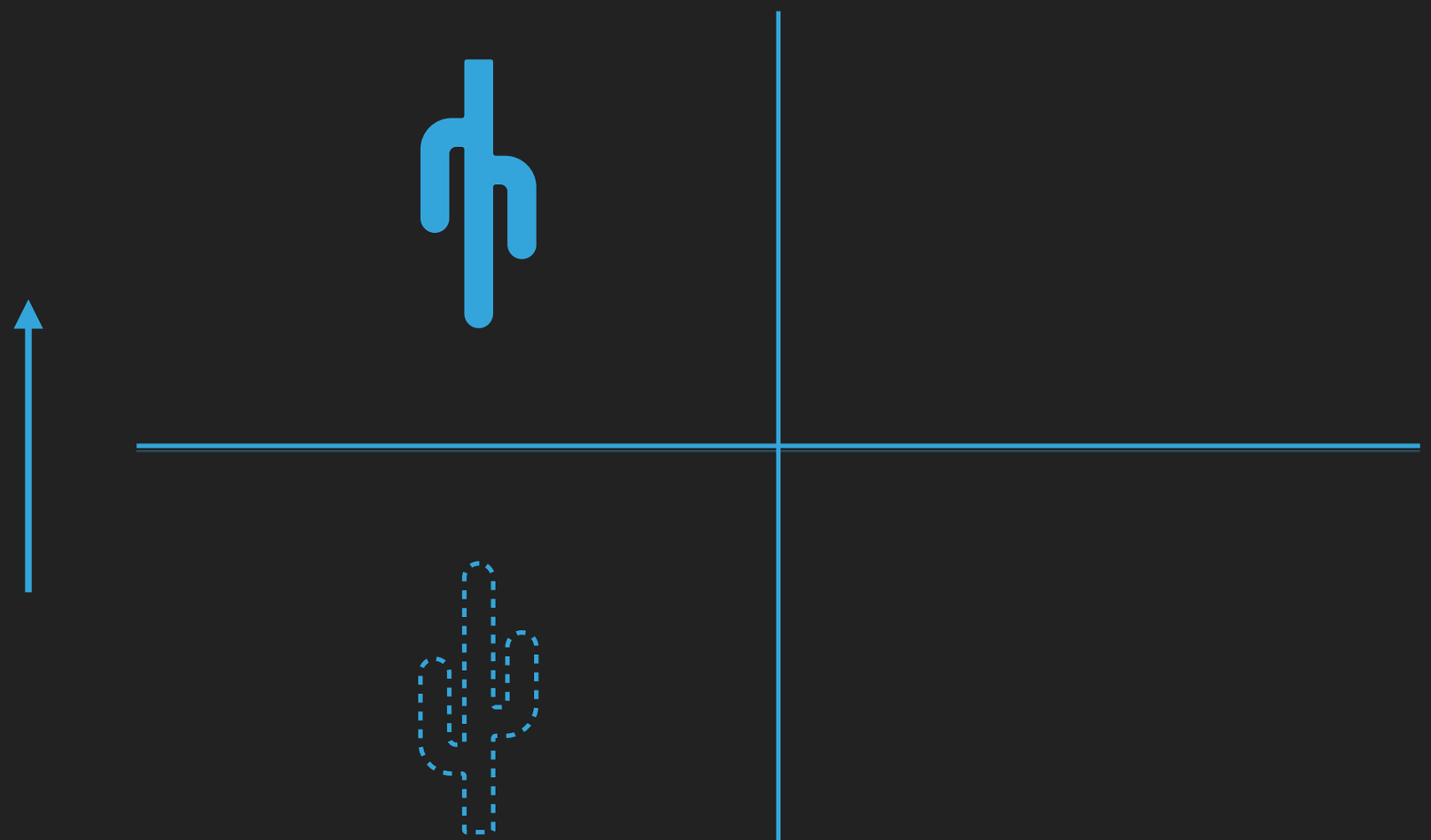

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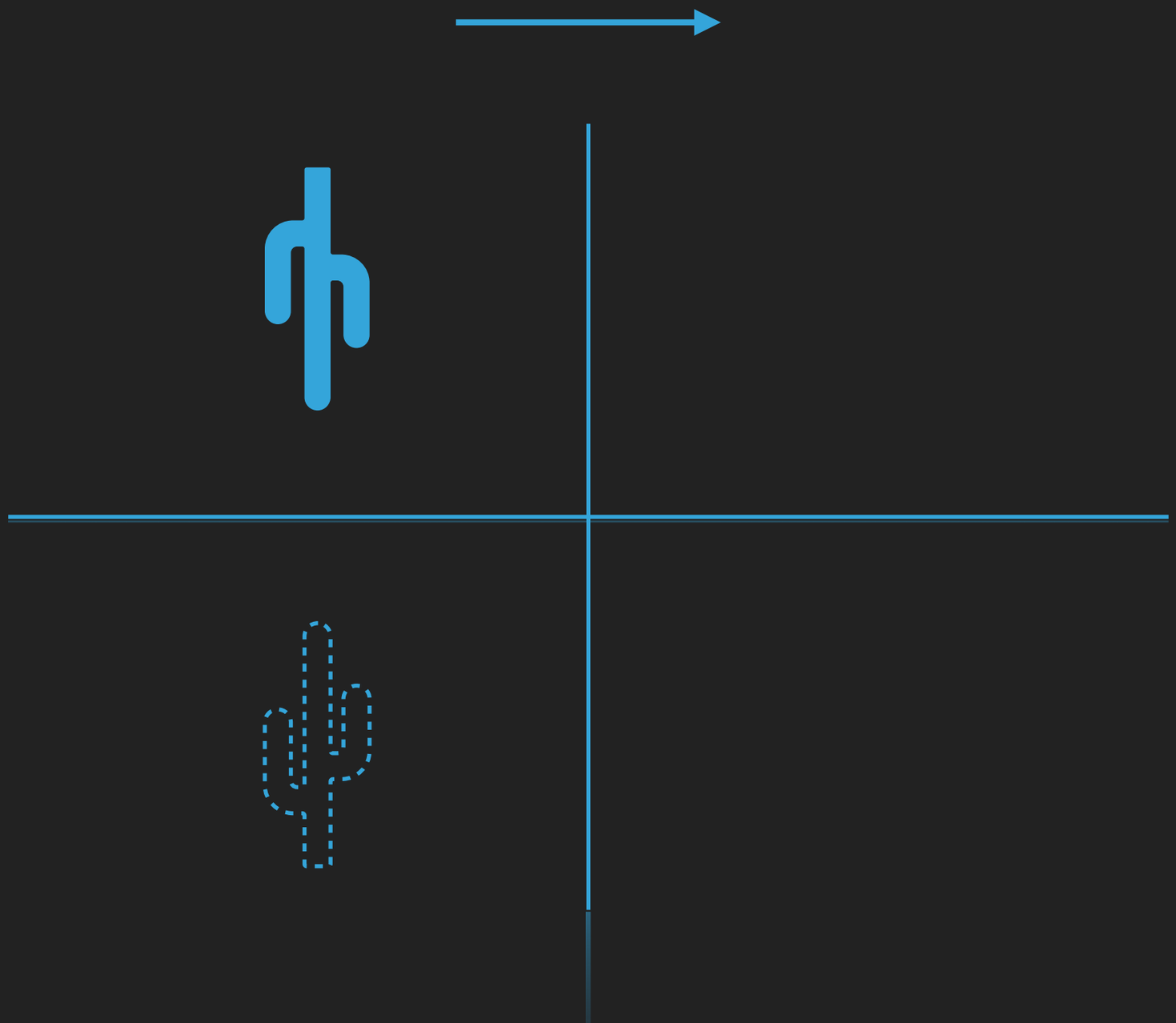
- Reflection about the y-axis



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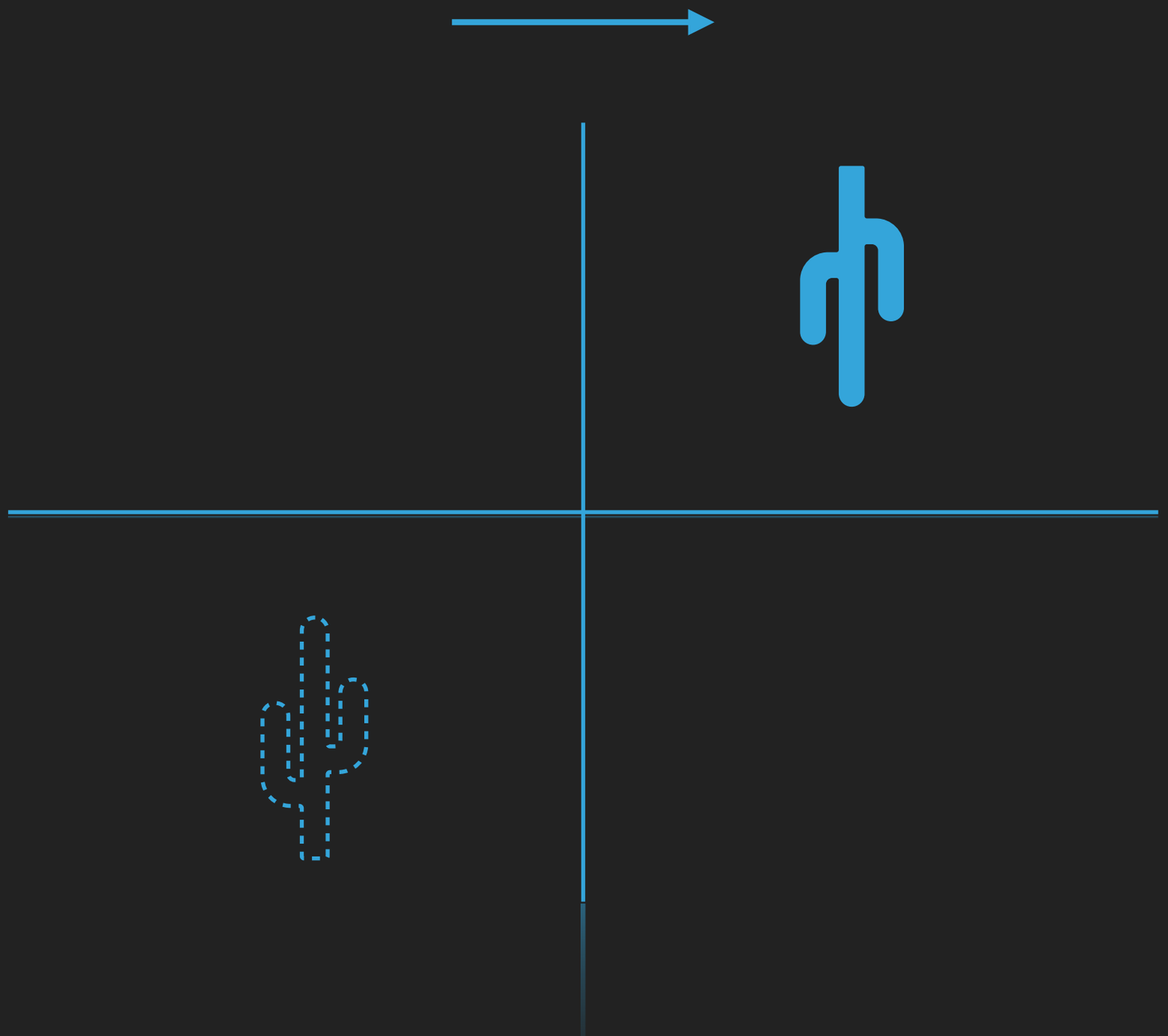

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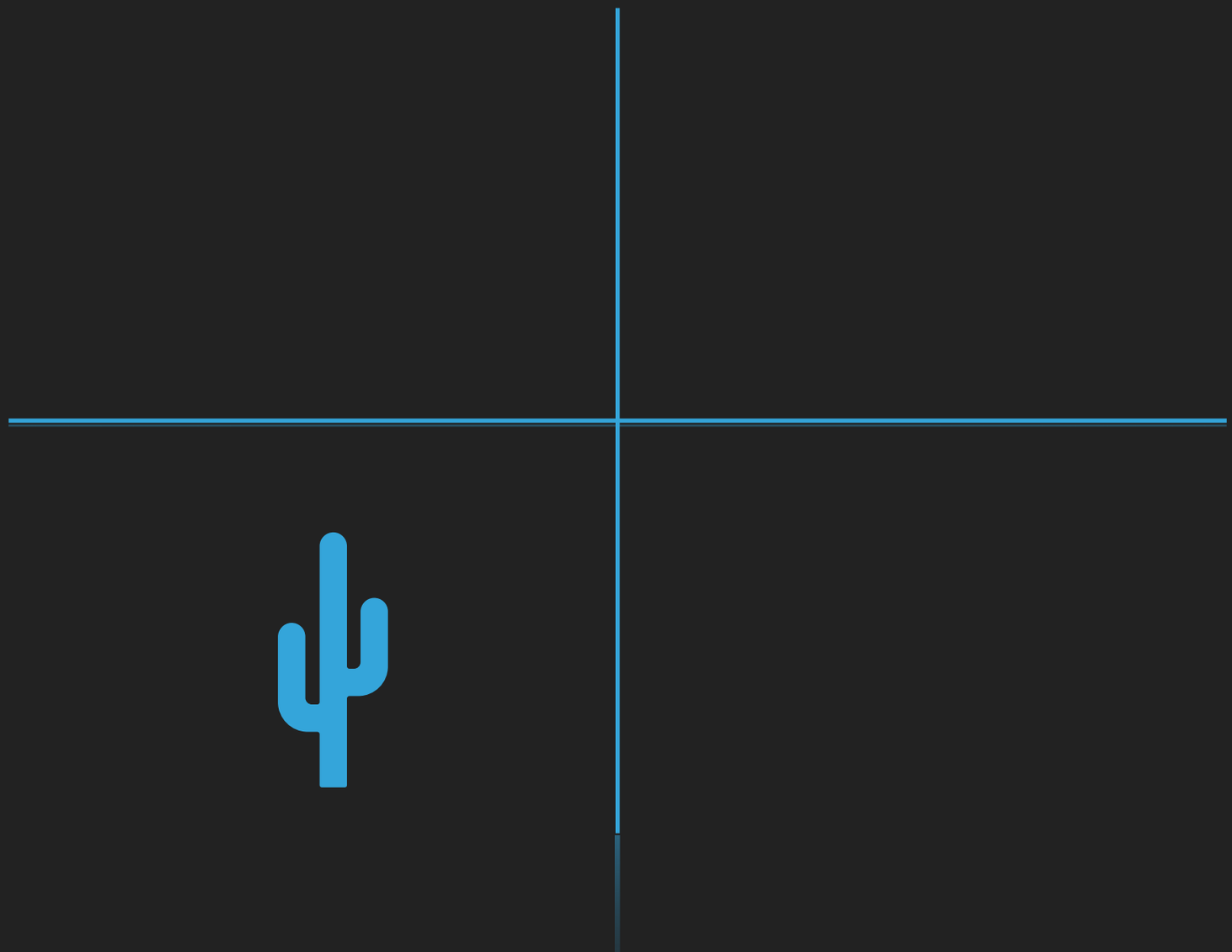
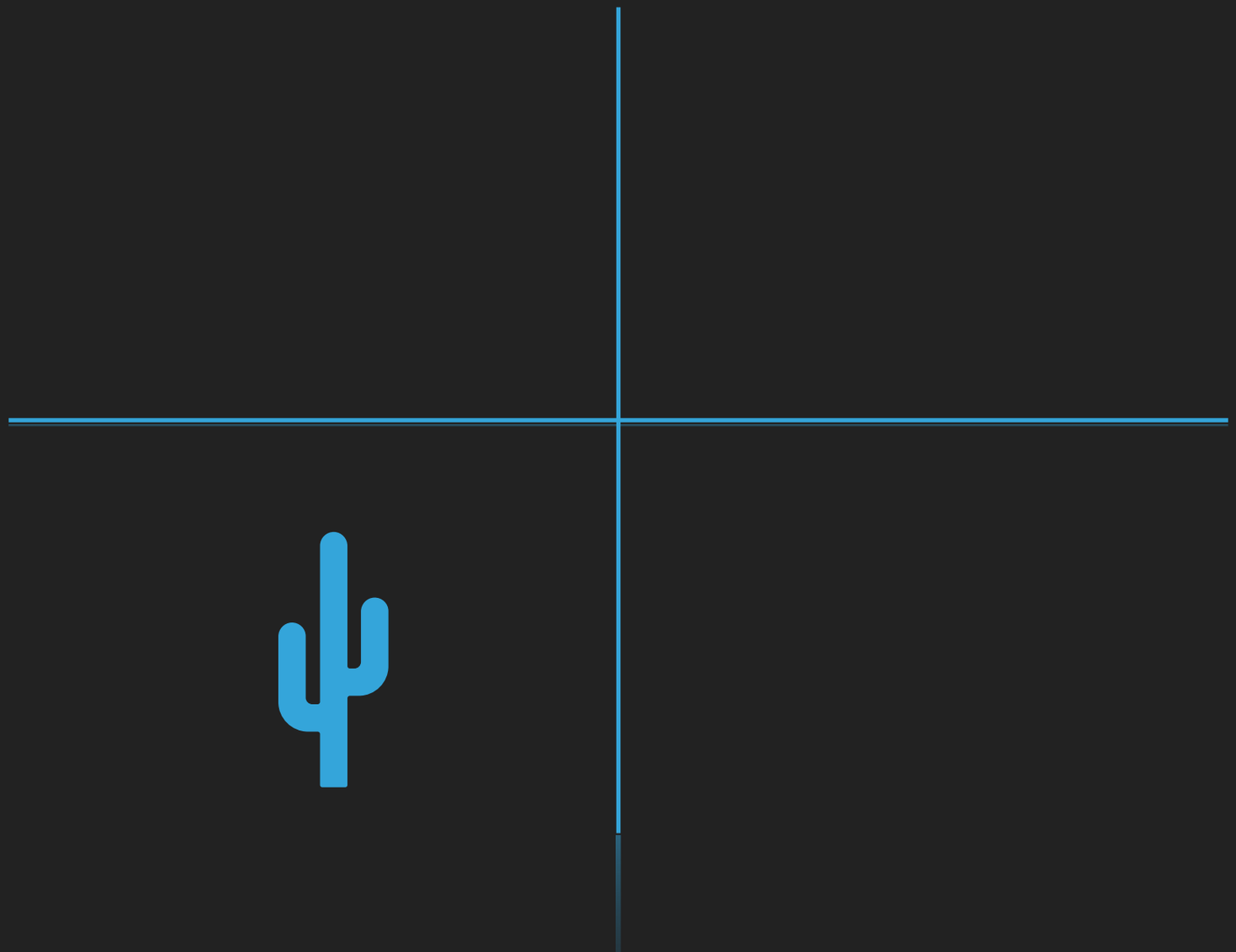


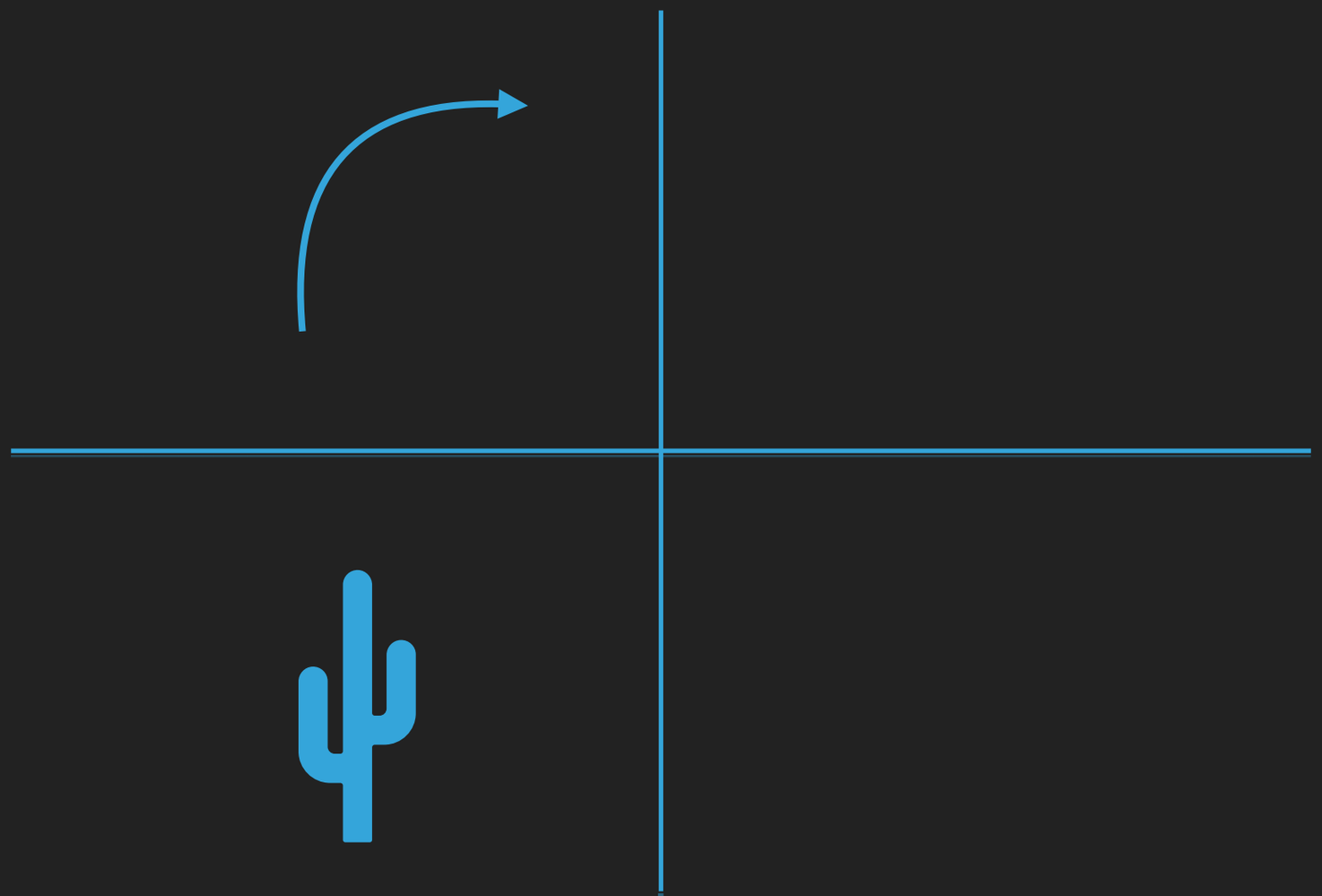
COMPOSITION TABLE

- Can we do it in one step?



COMPOSITION TABLE

- Can we do it in one step?
- Rotation about the origin by 180



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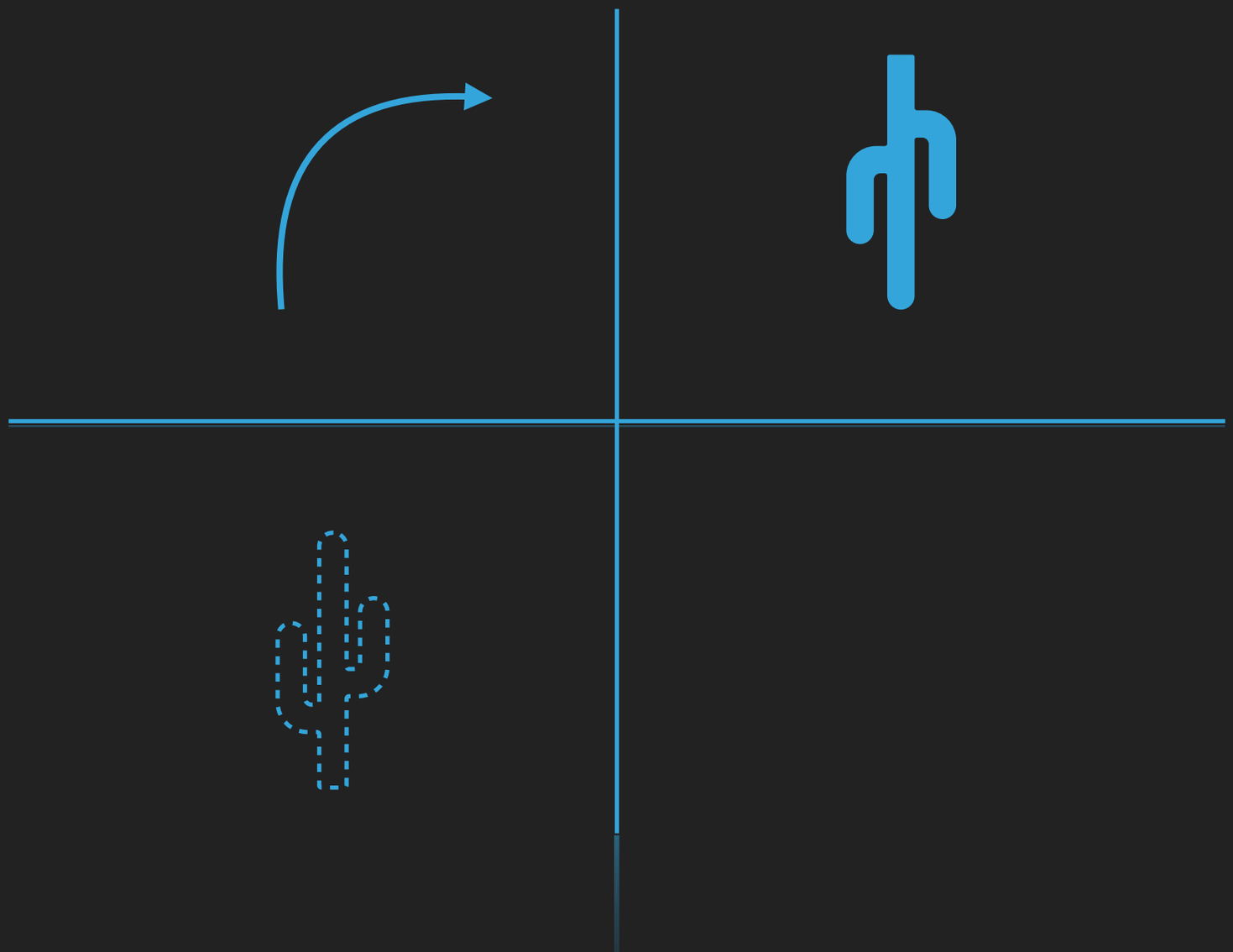

COMPOSITION TABLE

- Two reflections make a rotation

Symmetry 1

Symmetry 2	Translation	Rotation	Reflection	Glide
Translation				
Rotation				
Reflection		Rotation		
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Glide	Glide	Glide	Translation	Glide

SYMMETRY IN PHYSICS

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- Symmetry is an important principle in physics
  - In quantum field theory, certain symmetries in the theory give rise to the four fundamental forces*
- Symmetries are also inextricably linked to some of most fundamental laws of physics: ***conservation laws***

SYMMETRY AND CONSERVATION LAWS

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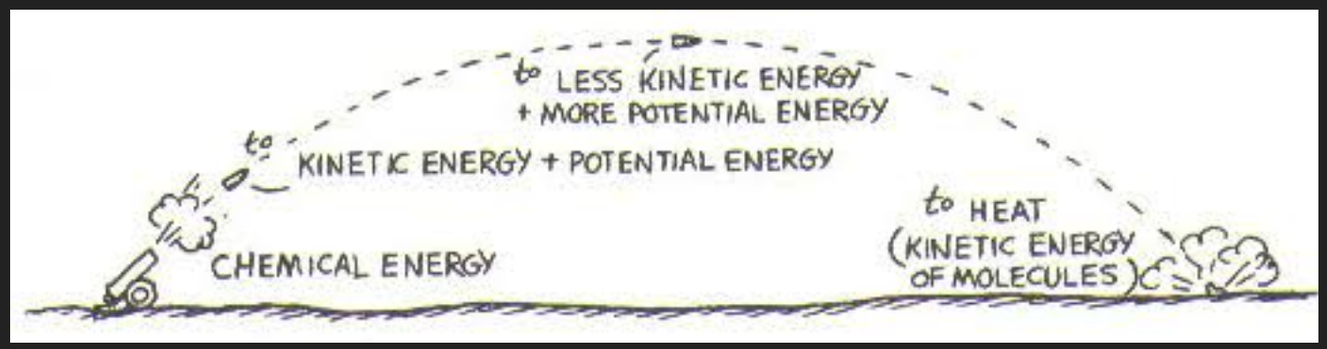

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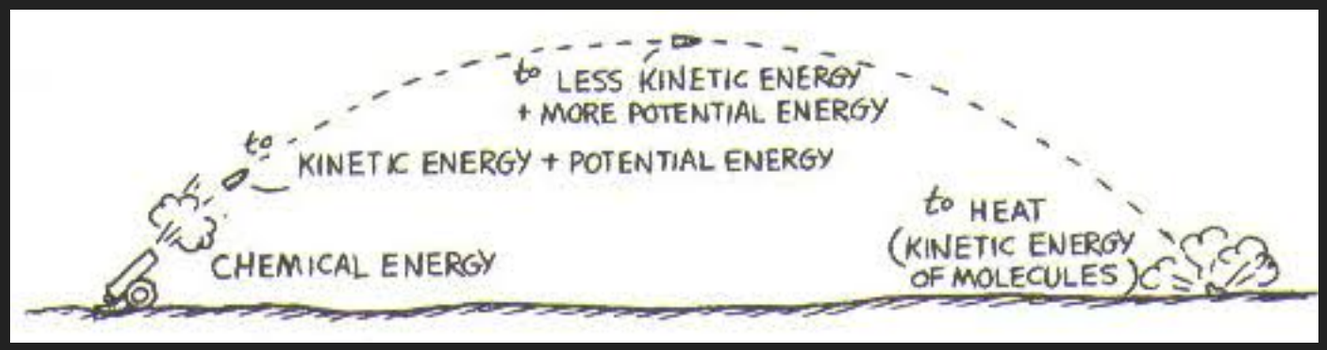

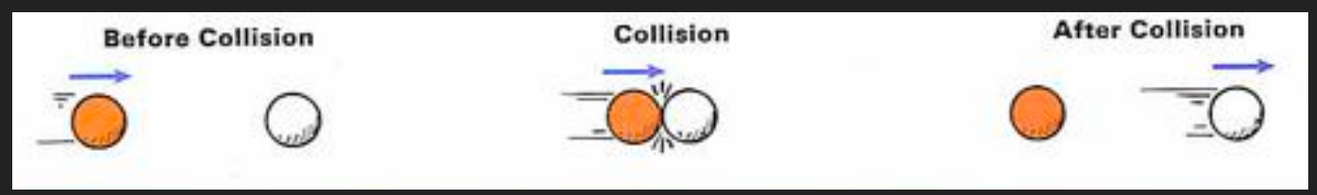

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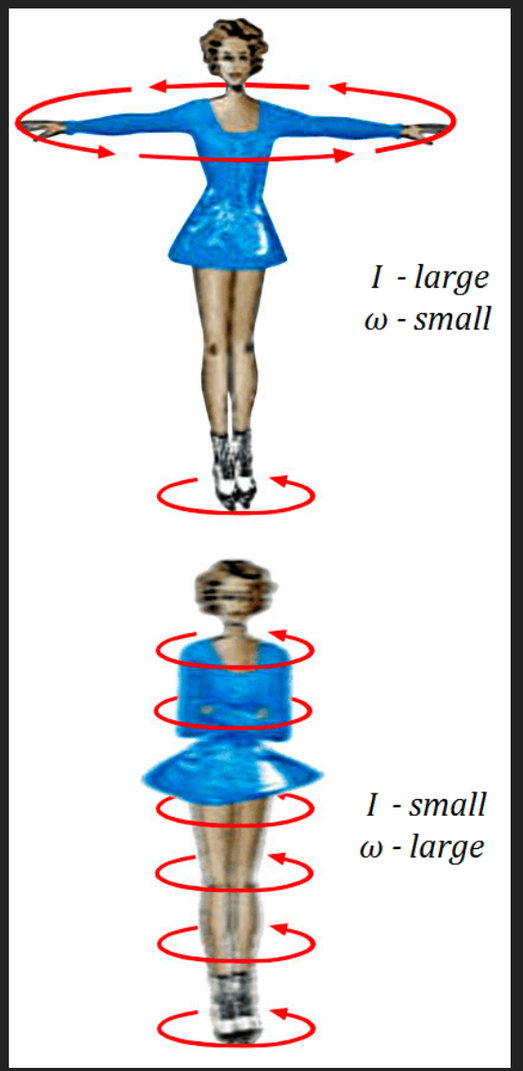

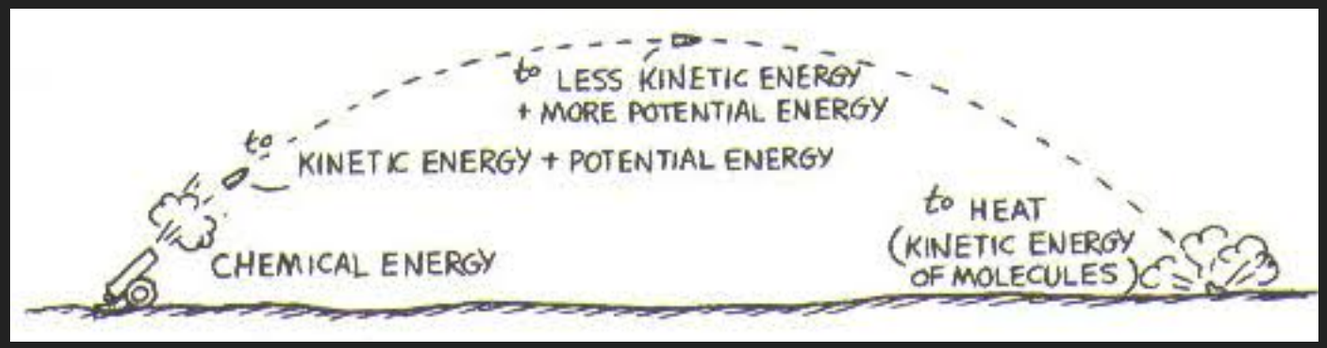

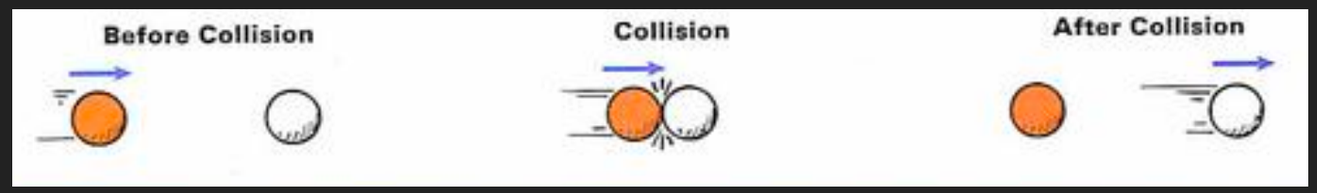

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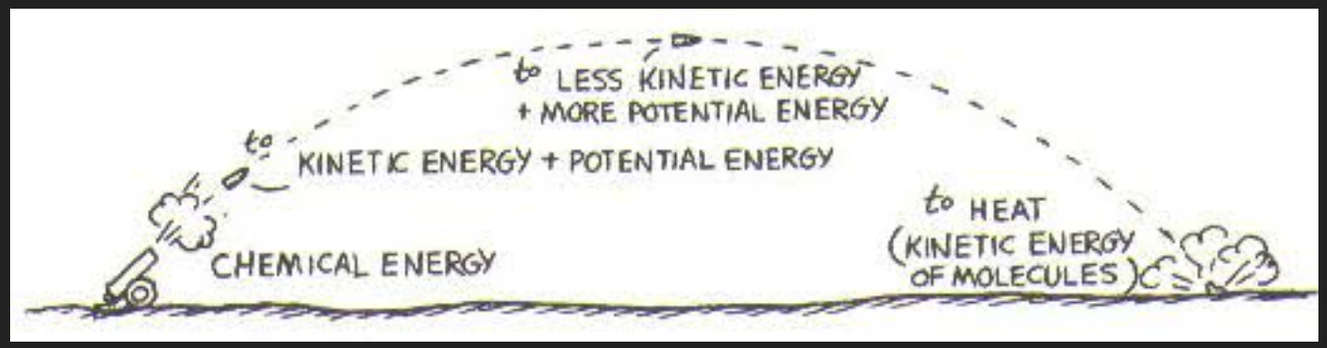

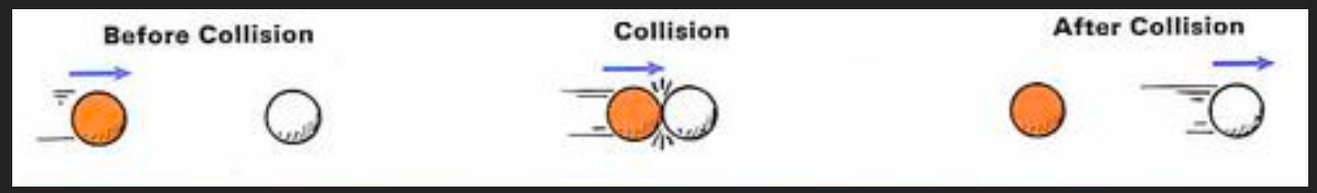

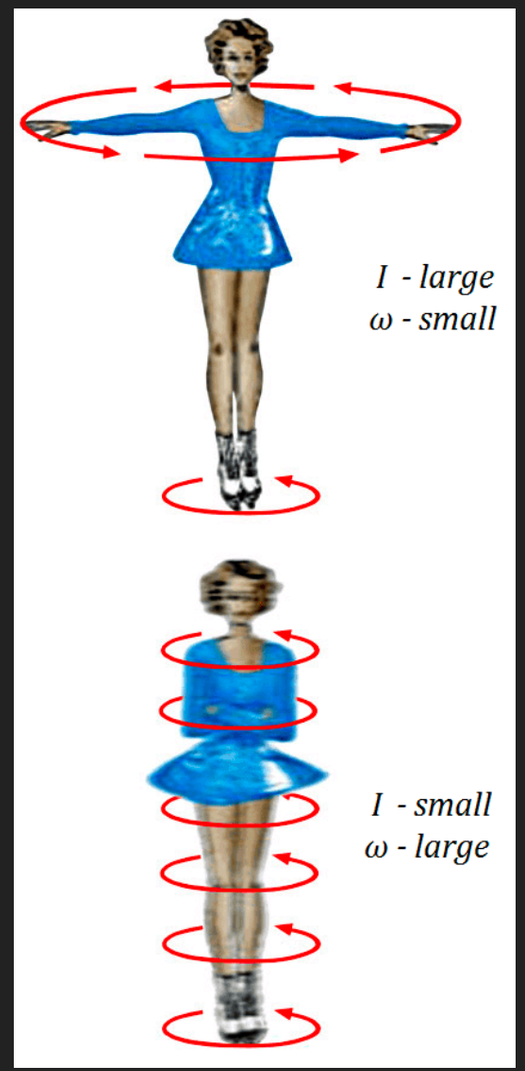

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- Energy conservation is the same except ***there are no blocks***: we compute abstract quantities which always sum to a constant

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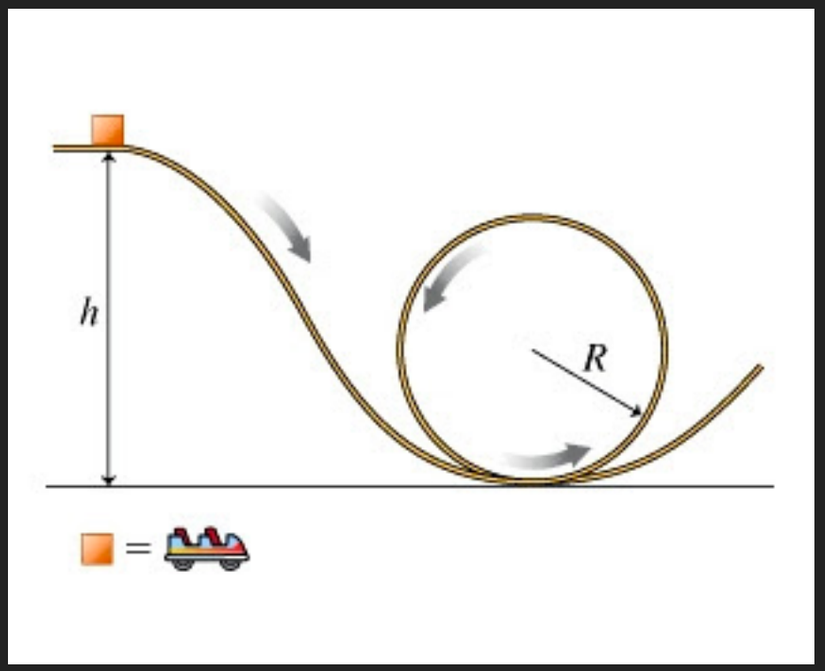

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- What are some forms?
  - Kinetic energy (translational and rotational)
  - Gravitational potential energy
  - Elastic energy

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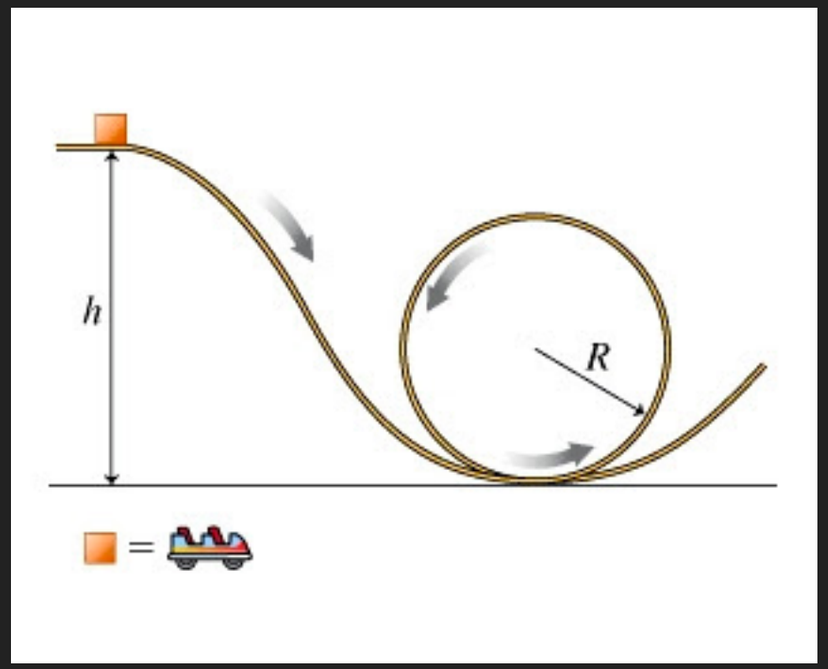

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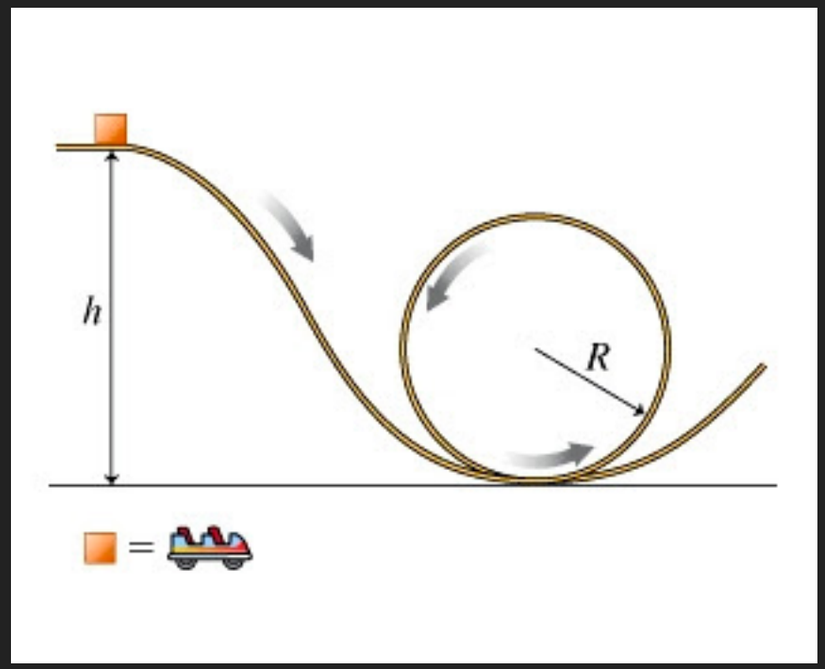

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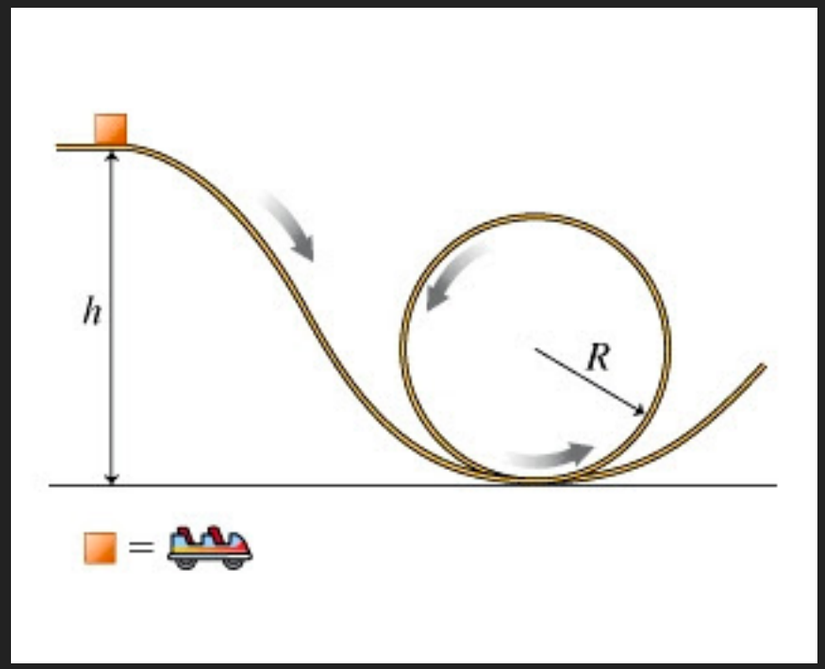

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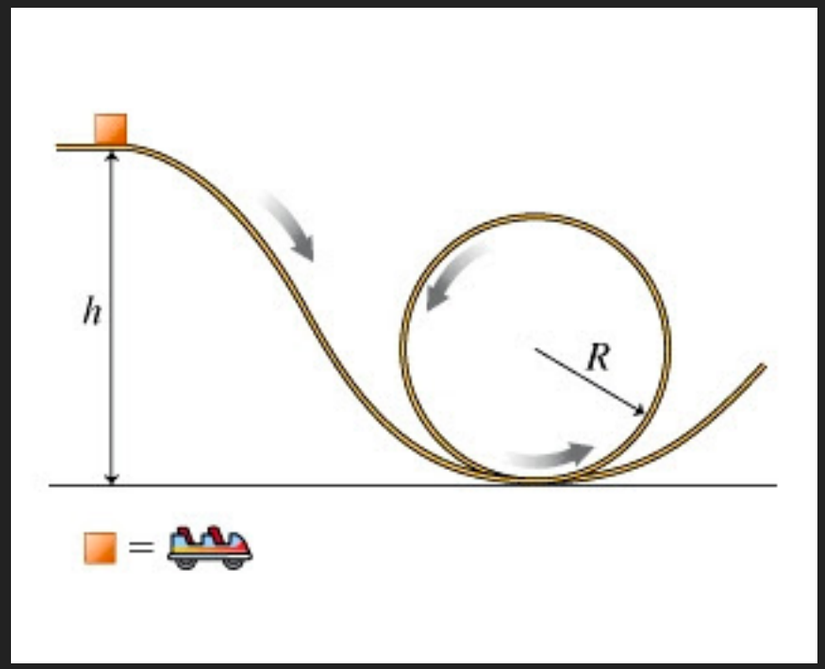

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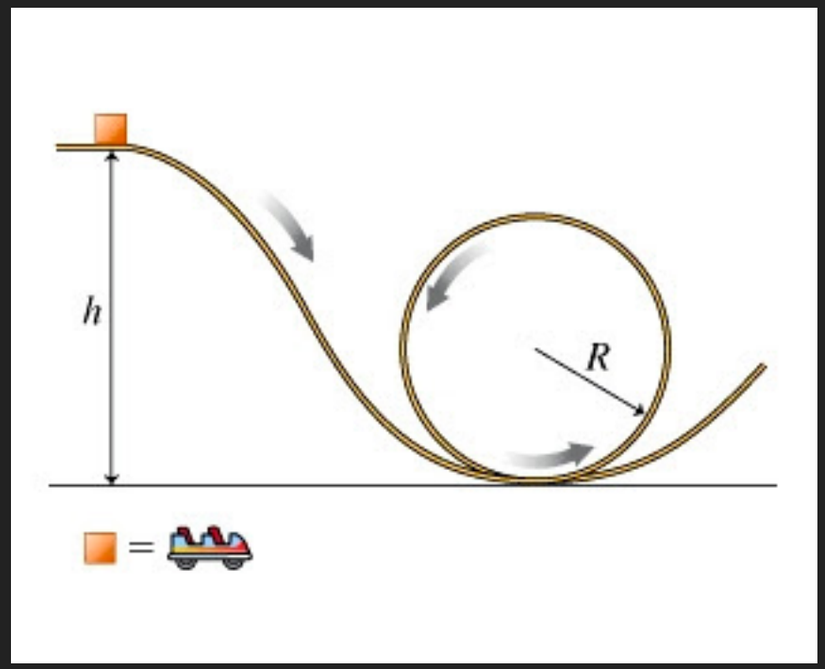

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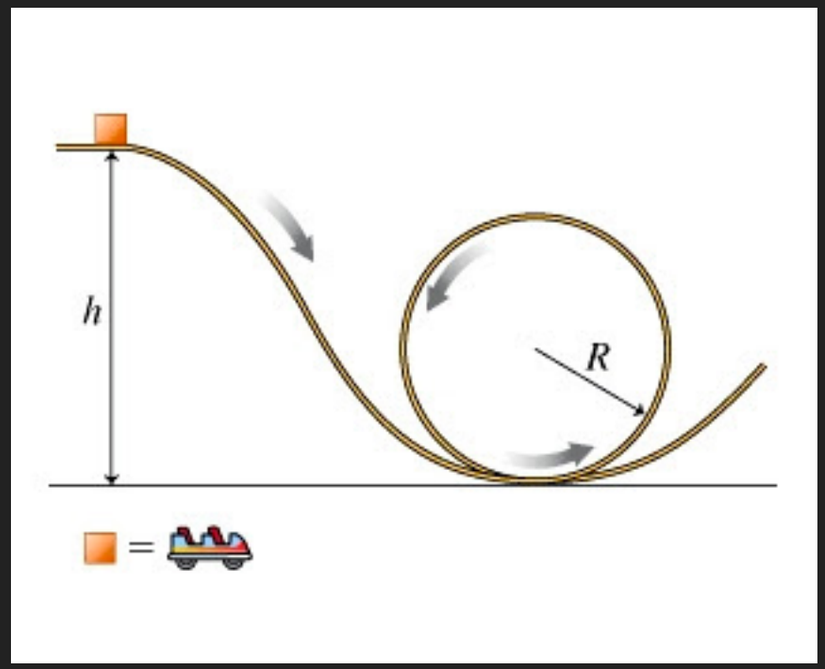

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  - Noether's theorem explains…

Invariante Variationsprobleme.

(F. Klein zum fünfzigjährigen Doktorjubiläum.)

Von

Emmy Noether in Göttingen.

Vorgelegt von F. Klein in der Sitzung vom 26. Juli 1918[1]).

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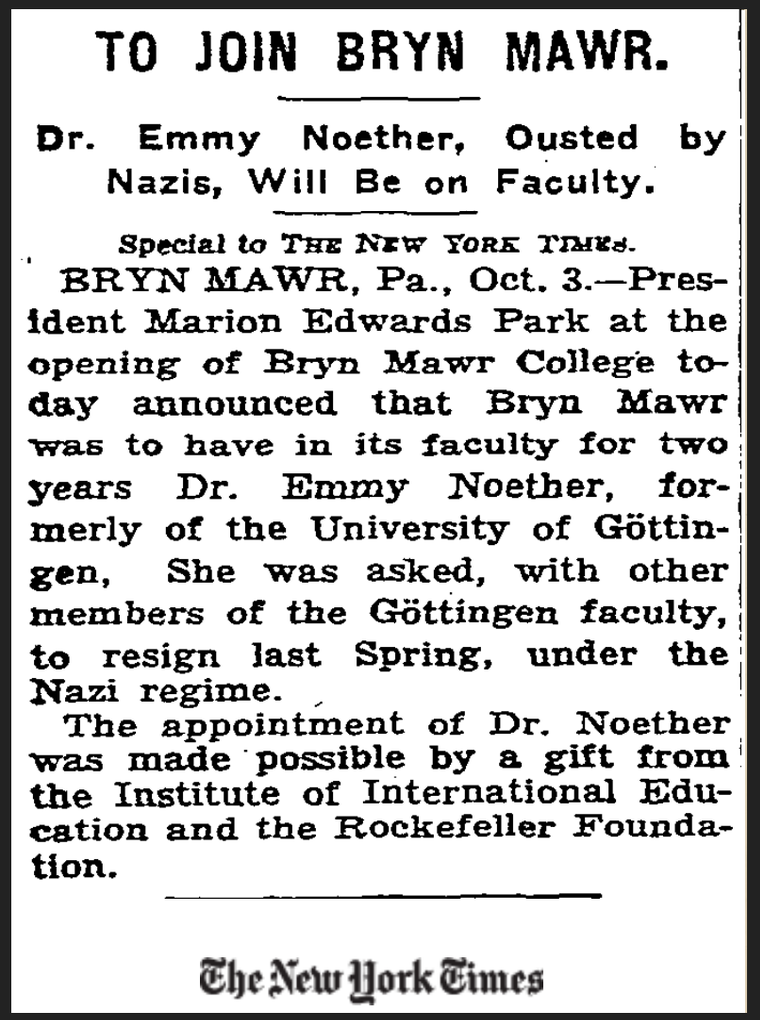
- 1933: Expelled from Math/Physics Faculty by Nazi regime!
- 1933–1935: Bryn Mawr



TO JOIN BRYN MAWR.

Dr. Emmy Noether, Ousted by Nazis, Will Be on Faculty.

Special to THE NEW YORK TIMES.

BRYN MAWR, Pa., Oct. 3.—President Marion Edwards Park at the opening of Bryn Mawr College today announced that Bryn Mawr was to have in its faculty for two years Dr. Emmy Noether, formerly of the University of Göttingen, She was asked, with other members of the Göttingen faculty, to resign last Spring, under the Nazi regime.

The appointment of Dr. Noether was made possible by a gift from the Institute of International Education and the Rockefeller Foundation.

The New York Times

NOETHER'S THEOREM

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- How does this apply to our universe?

CONTINUOUS* SYMMETRIES OF PHYSICAL LAWS

- The laws of physics are unchanged under:

SYMMETRY

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- Translation in space
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SYMMETRY	CONSERVED QUANTITY
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Quantum mechanical phase	Linear momentum

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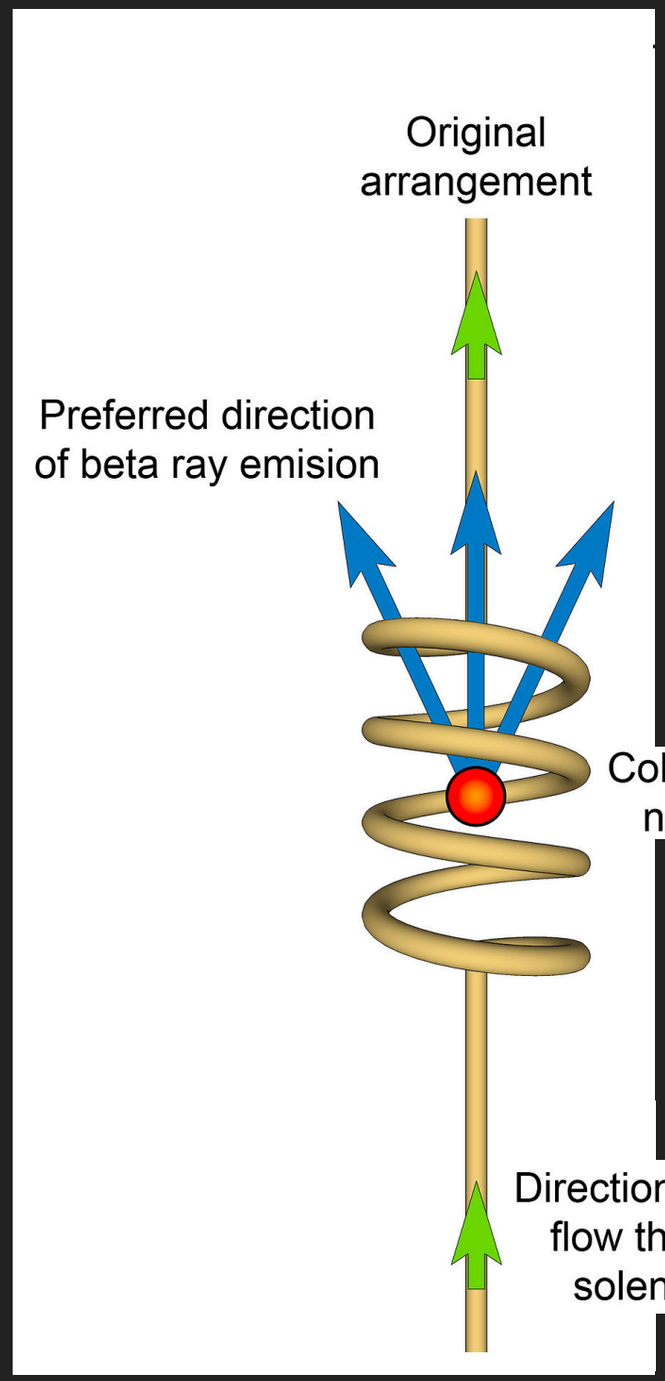
- Exchange Identical Particles $(x_1, x_2) \rightarrow (x_2, x_1)$

PARITY?

- Wu experiment (1956)



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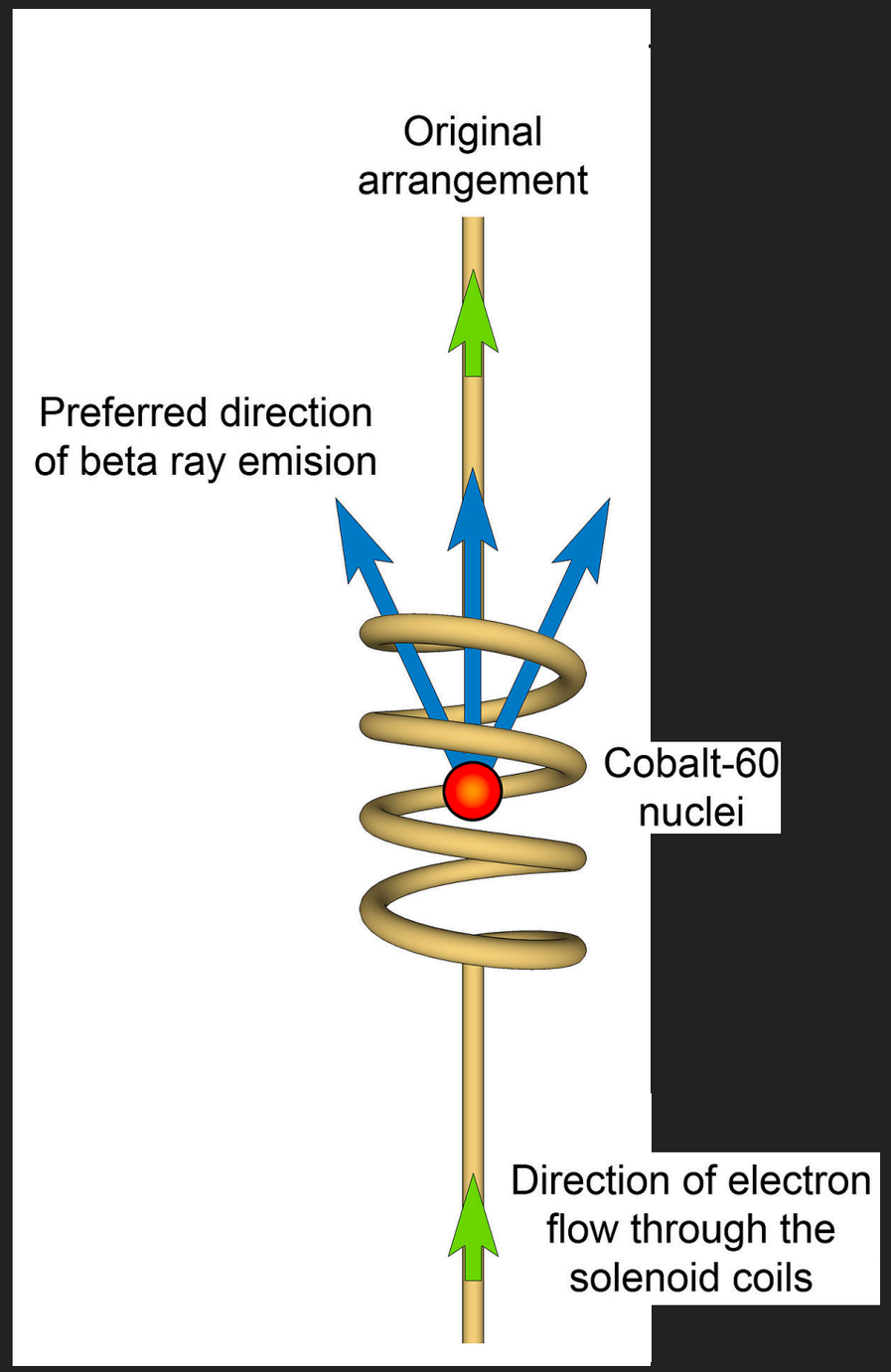

What if we flip the coils of the experiment (like in a mirror)?

A Electrons will go up

B Electrons will go down

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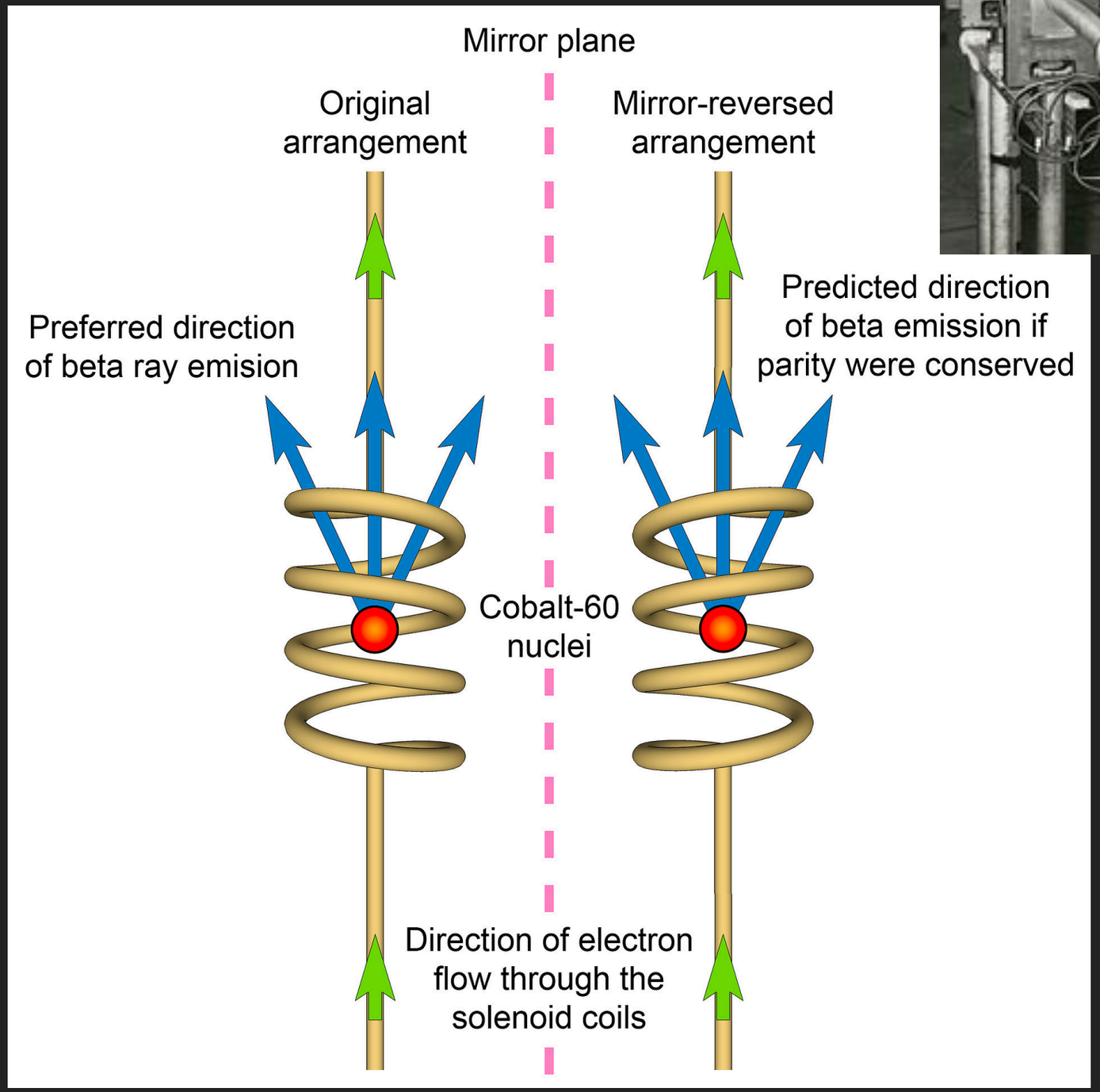

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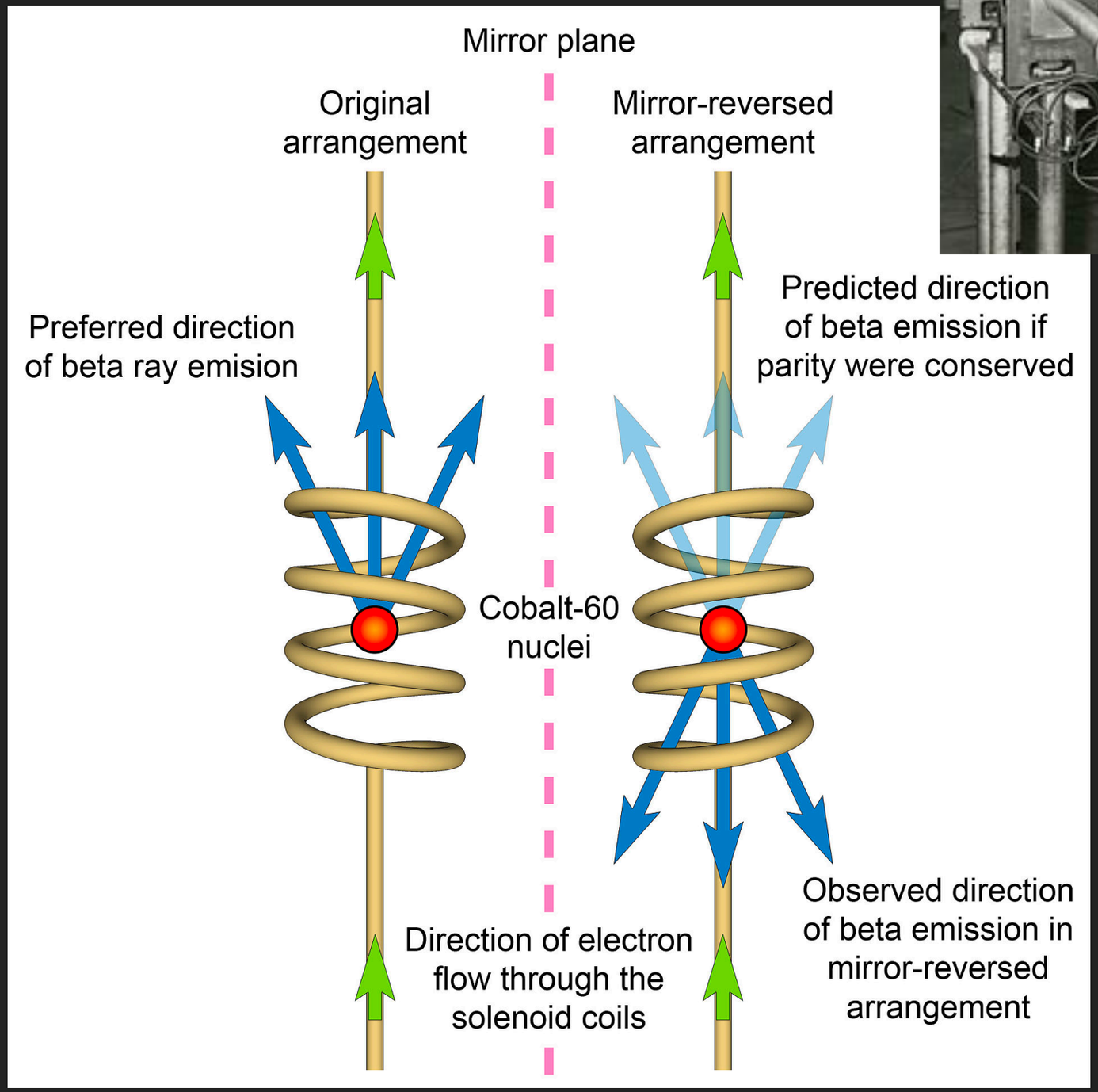

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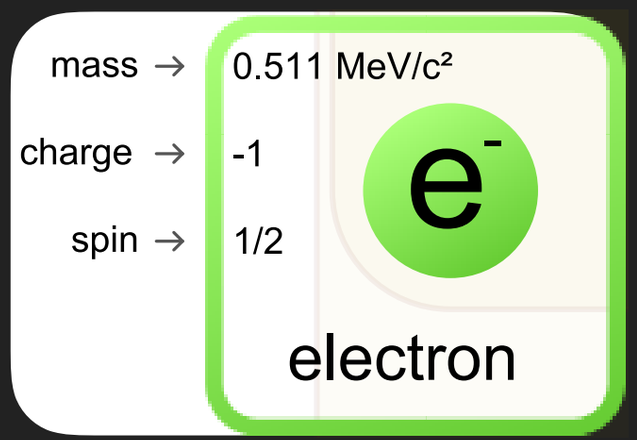
- These *broken* symmetries, especially CP-symmetry, determine how much **antimatter** we should see around us

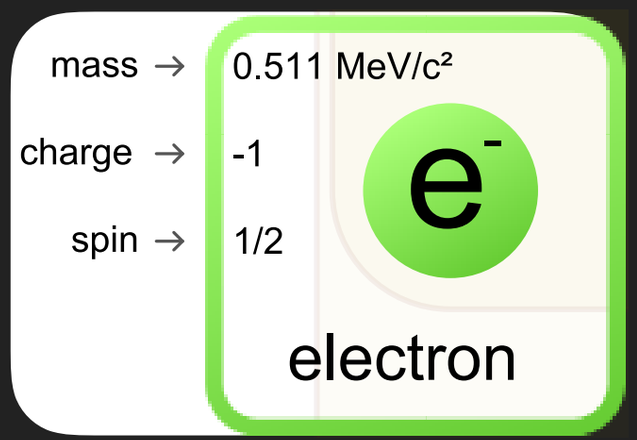
ANTIMATTER

WHAT IS ANTIMATTER?



WHAT IS ANTIMATTER?

- Antimatter is exactly the same as matter except one attribute is flipped: the *charge*



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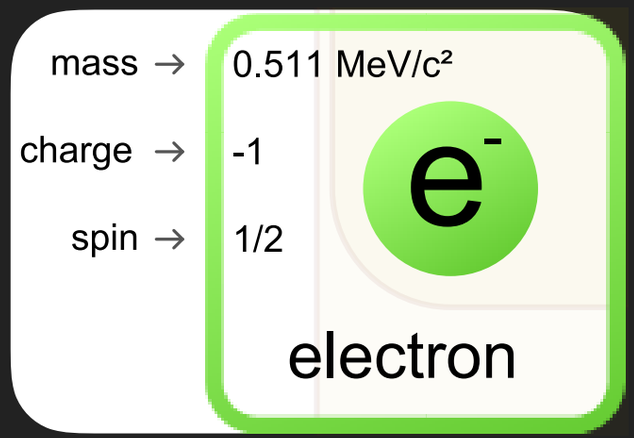

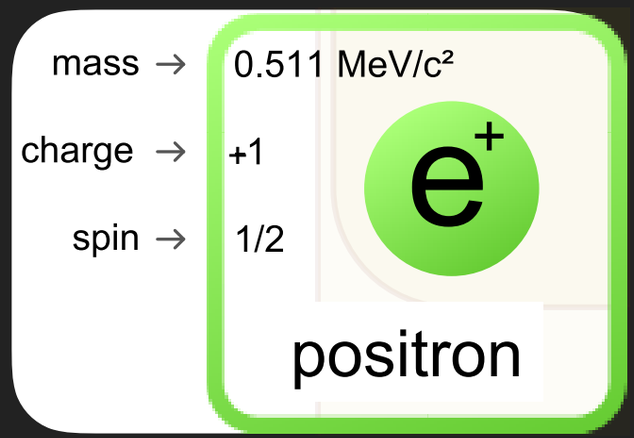

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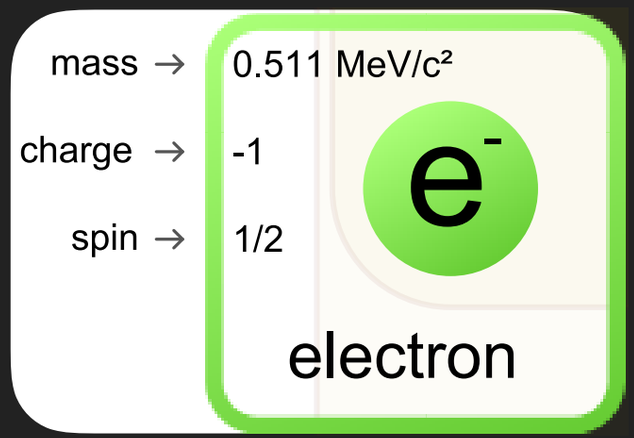

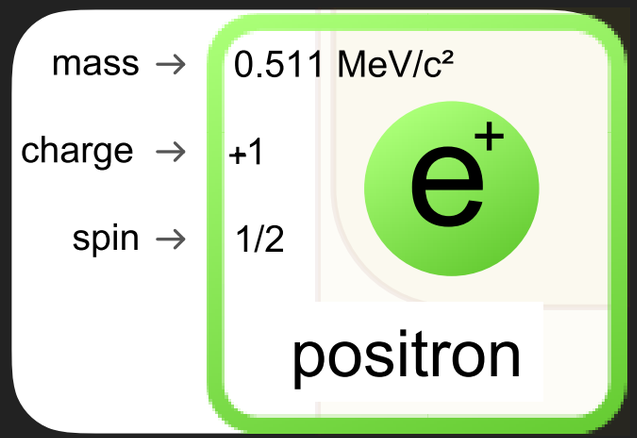

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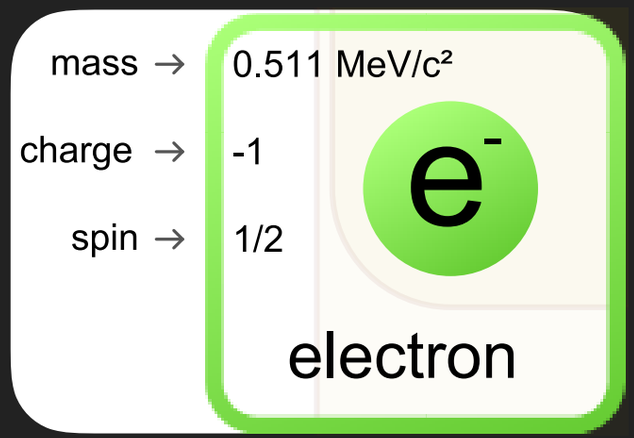

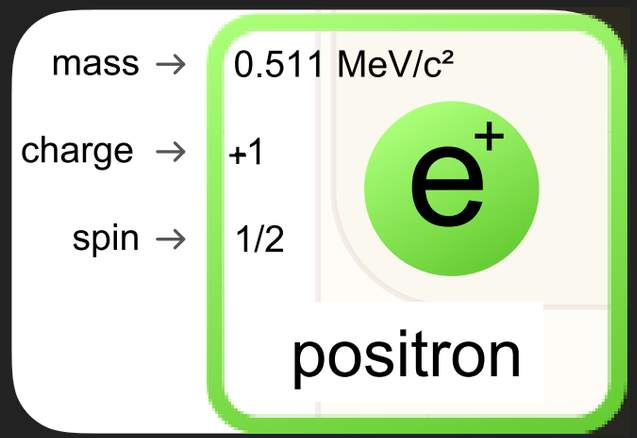

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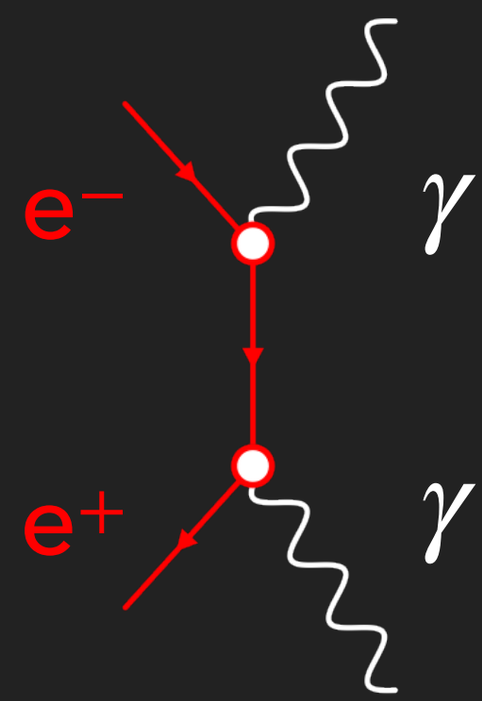
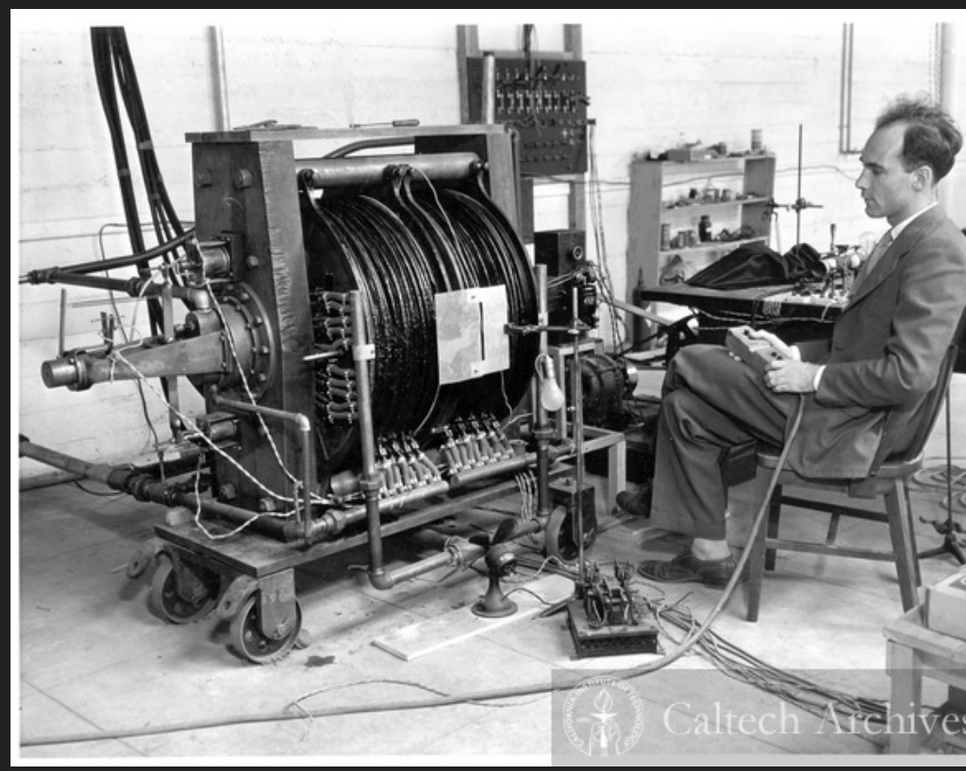
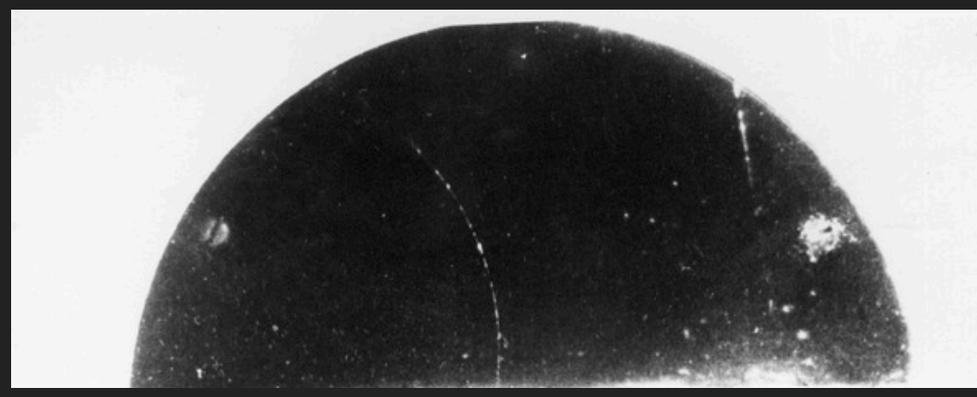


DISCOVERY OF ANTIMATTER





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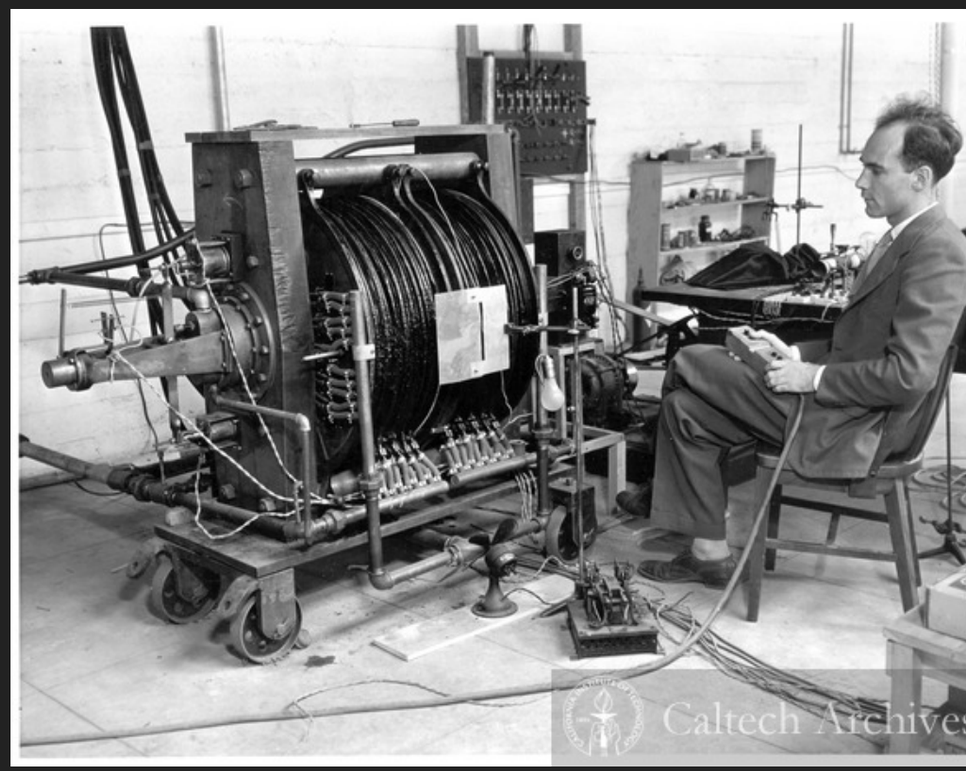

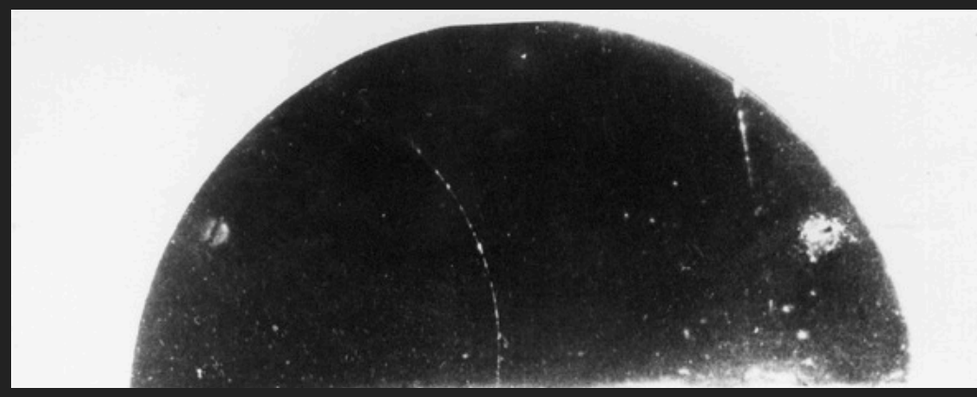

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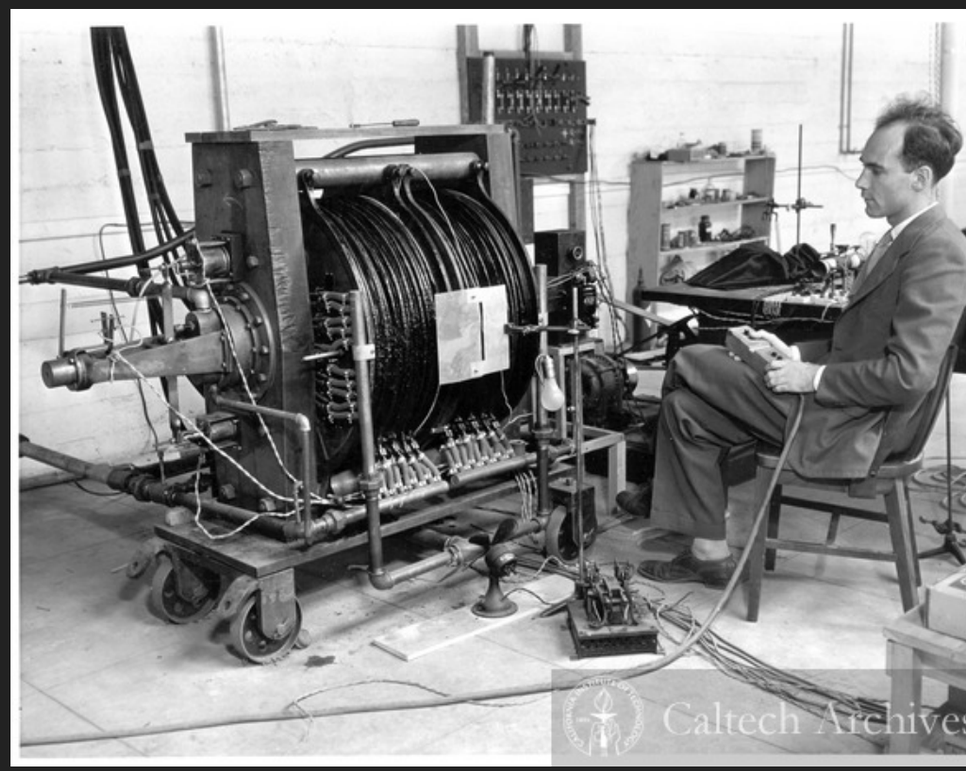

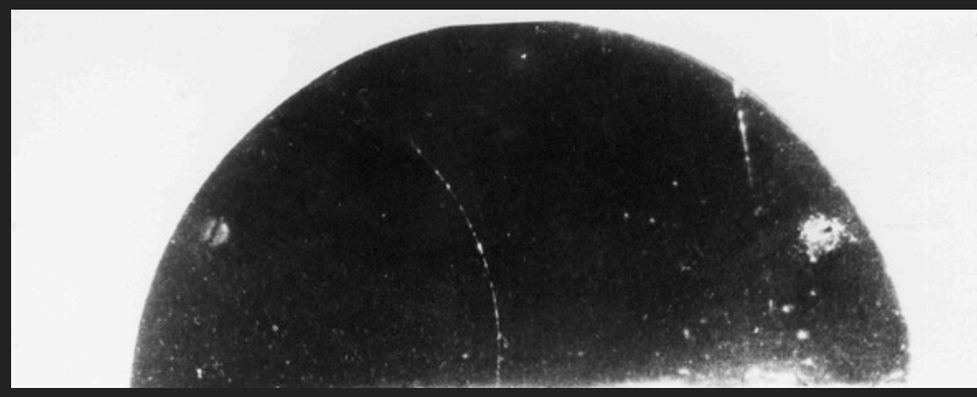

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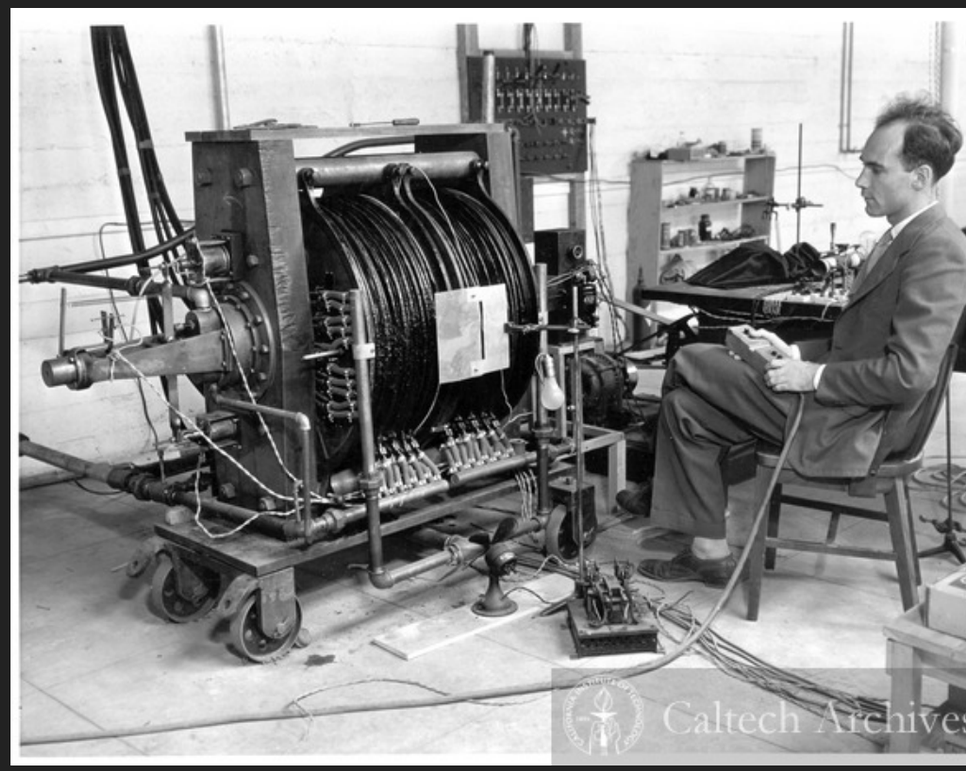

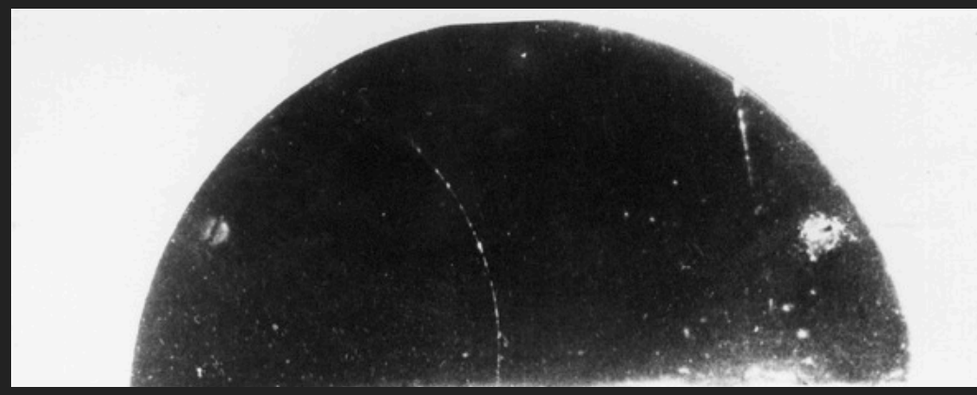

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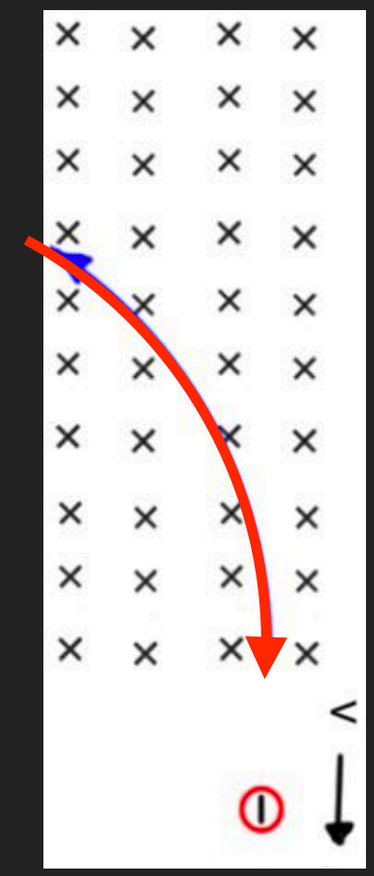

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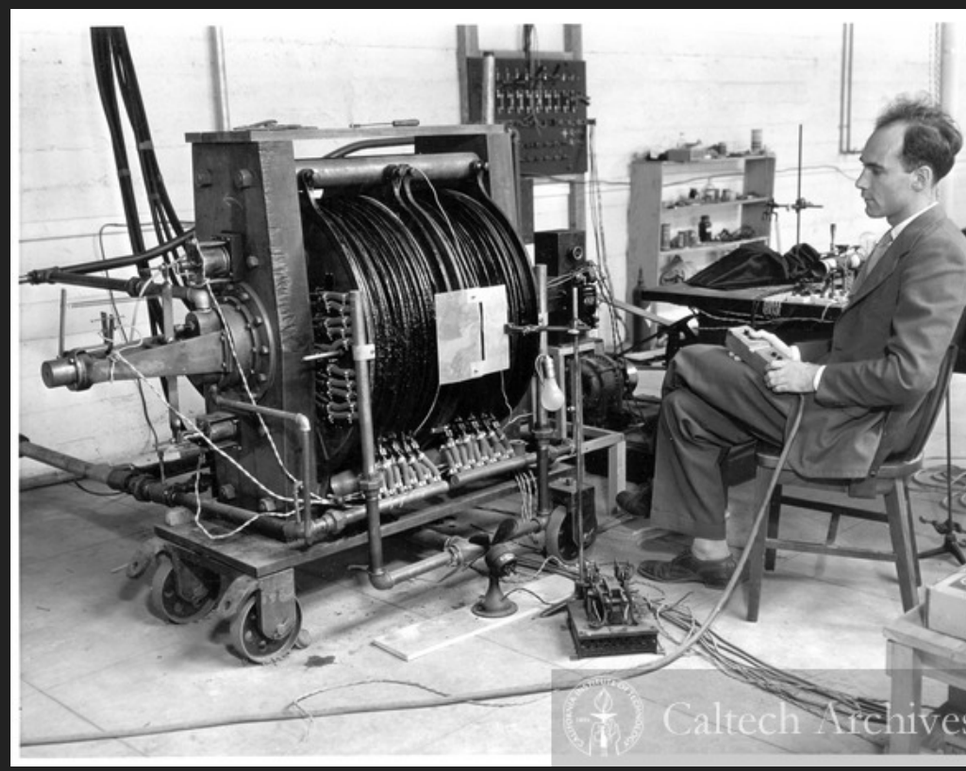

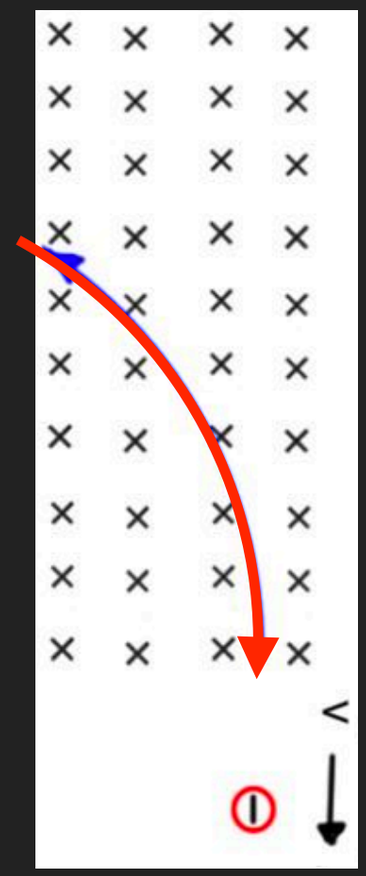

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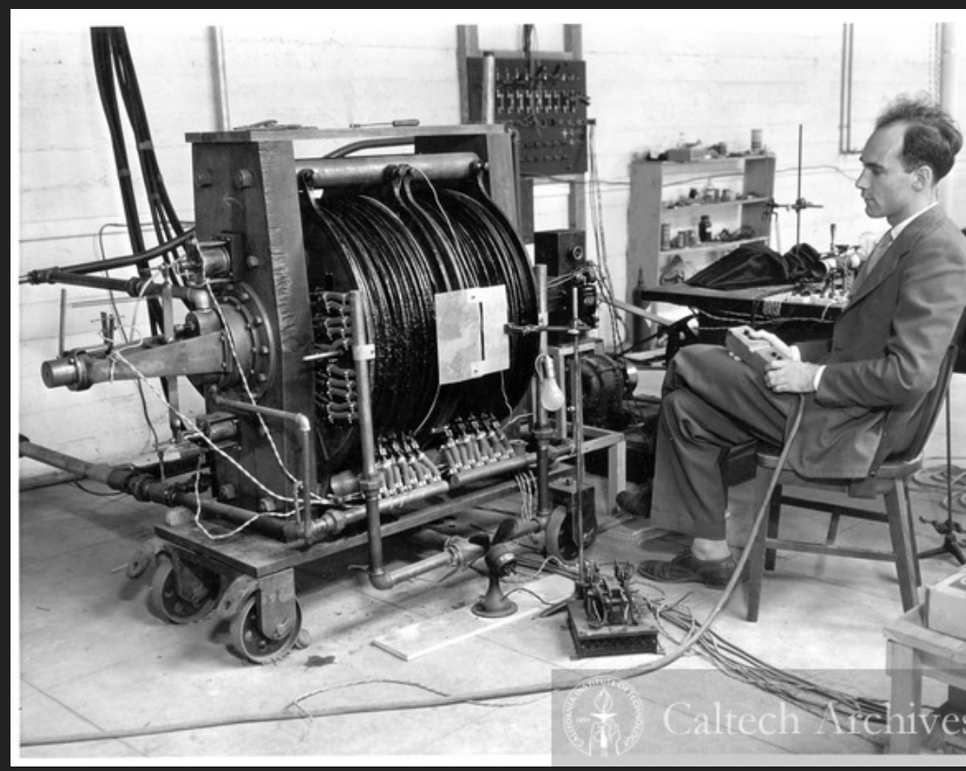
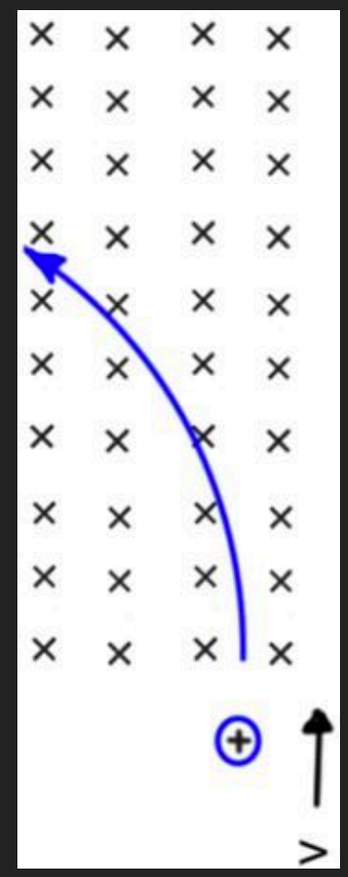
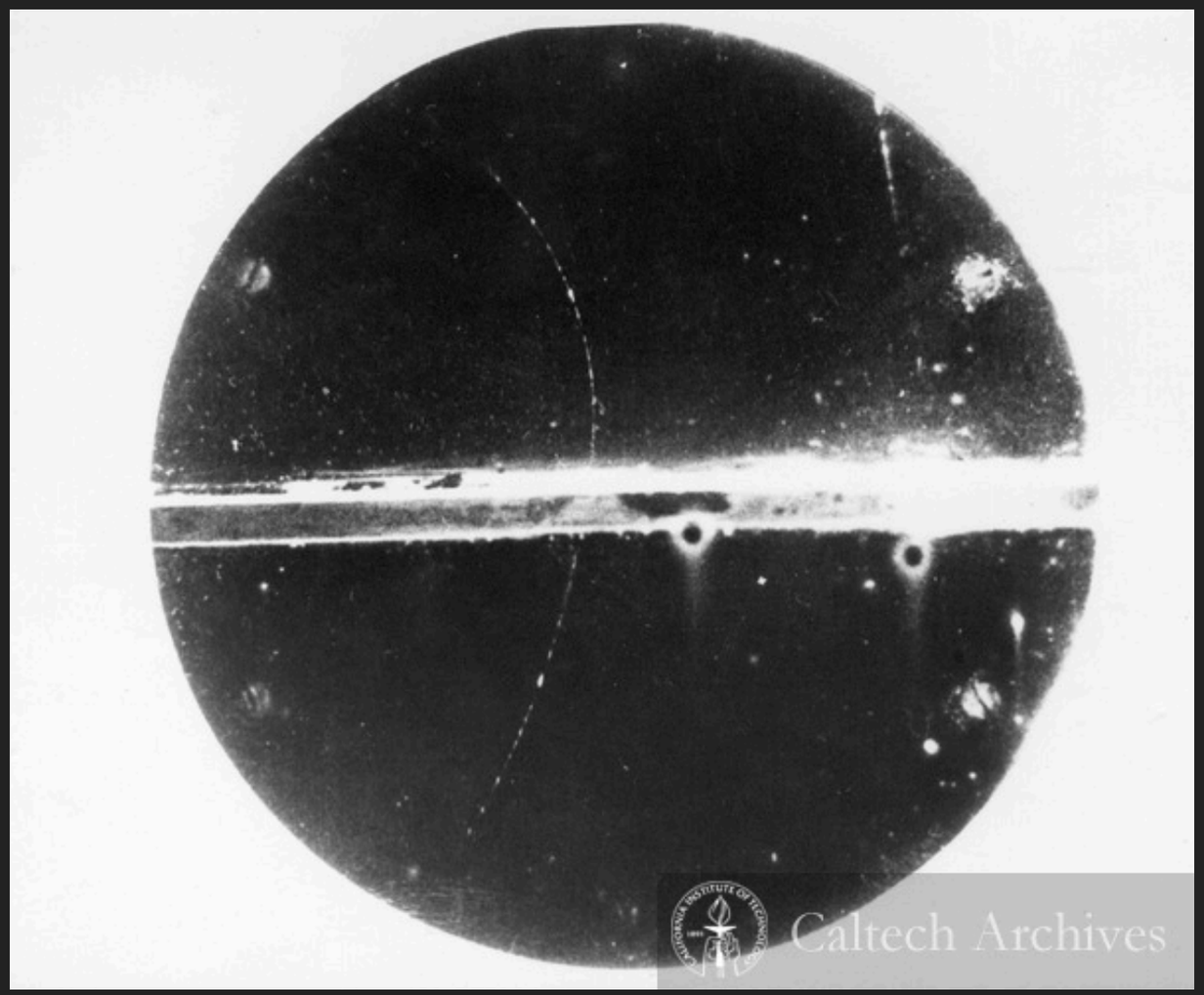




DISCOVERY OF ANTIMATTER

- To determine which it was, Anderson inserted a block of lead, which slows down the particle and increases the curvature
- Which way is it going?



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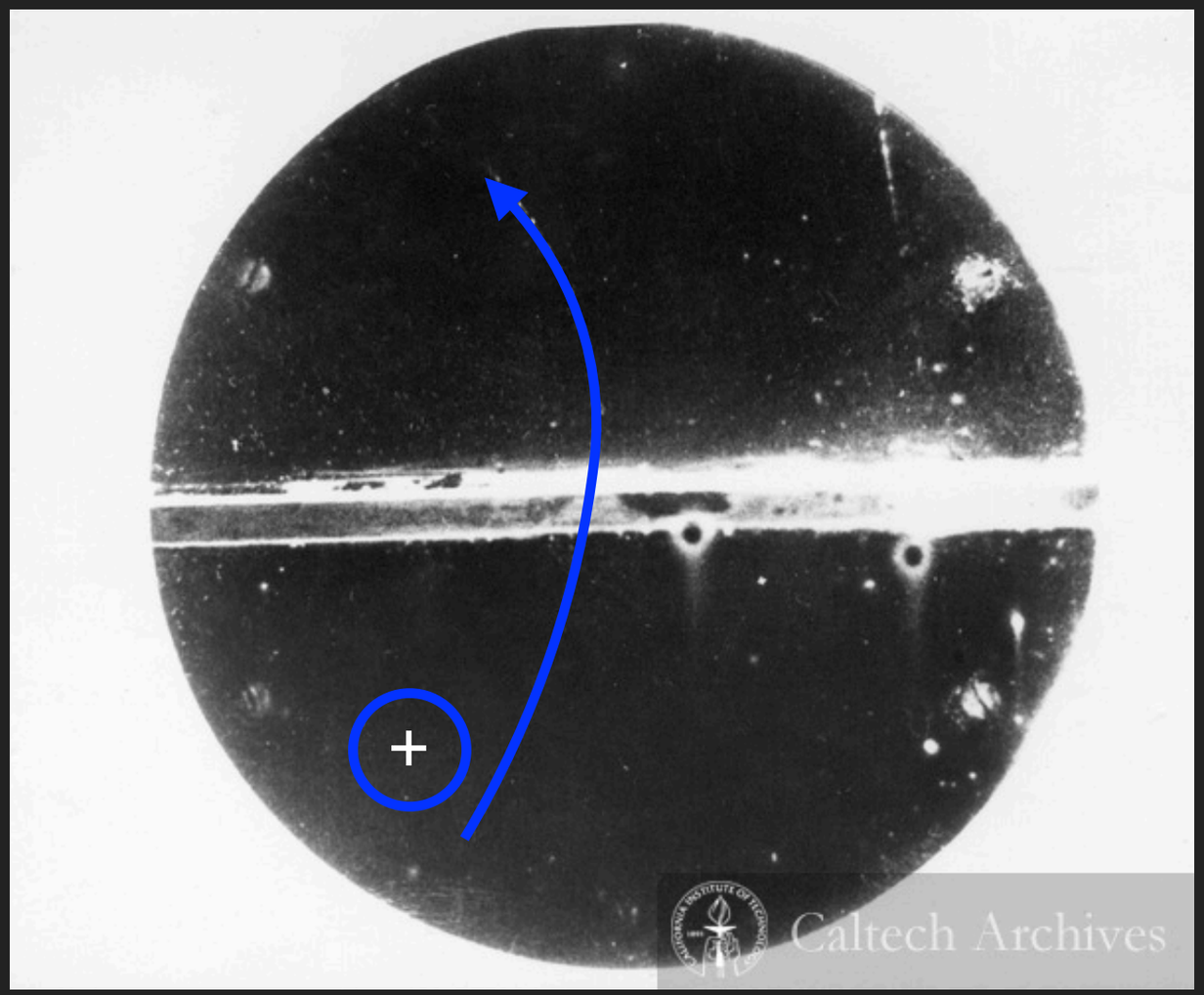
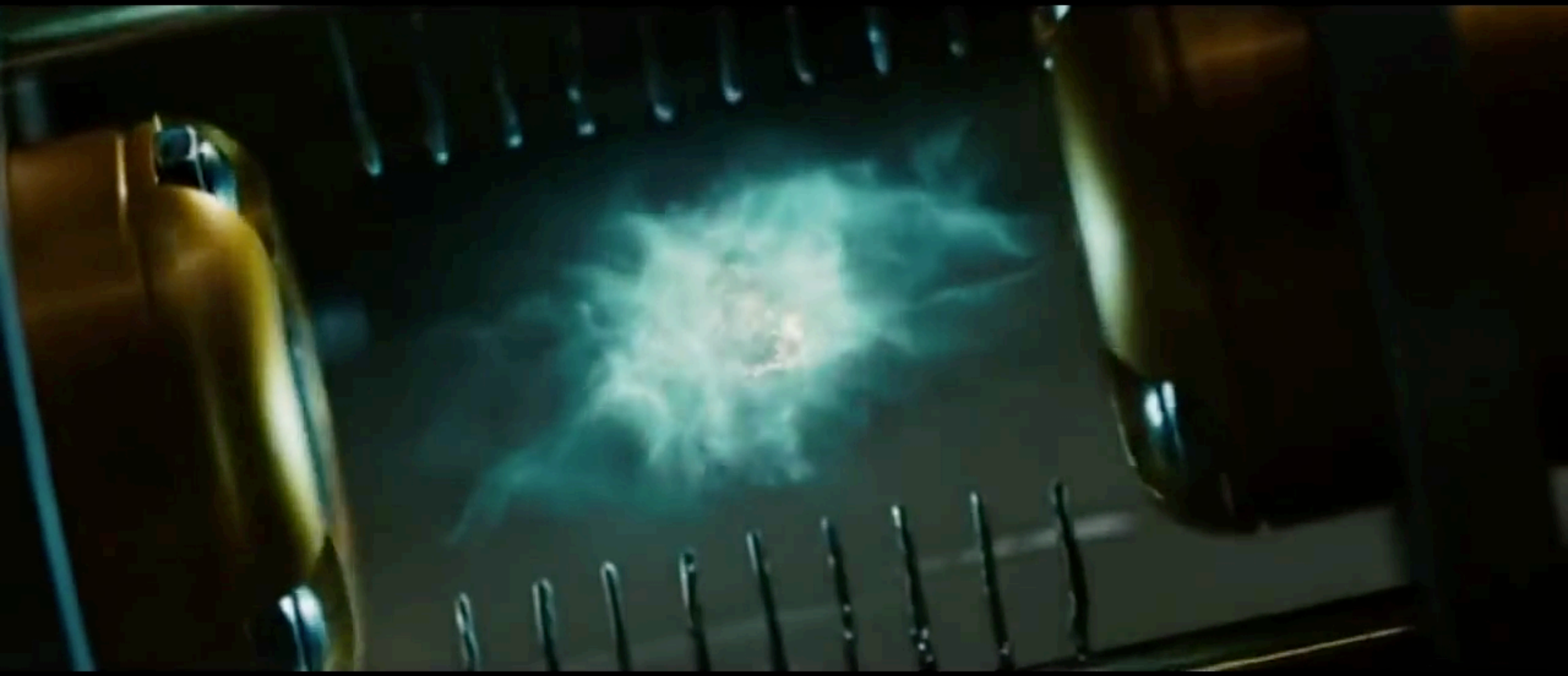


ANTIMATTER BOMB?

Angels & Demons (2009)

https://www.youtube.com/watch?v=5wXtm7YIRWM



1 gram of antimatter

ANTIMATTER BOMB?

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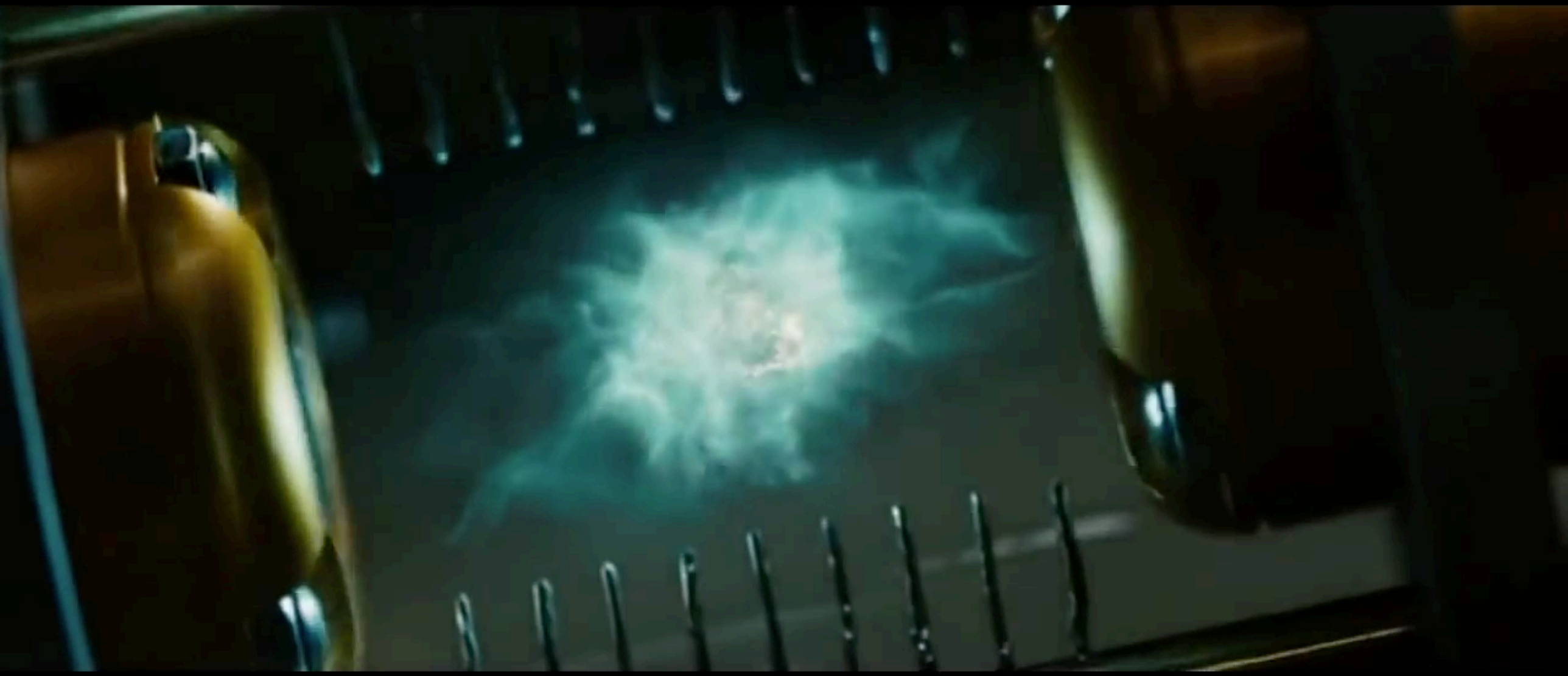

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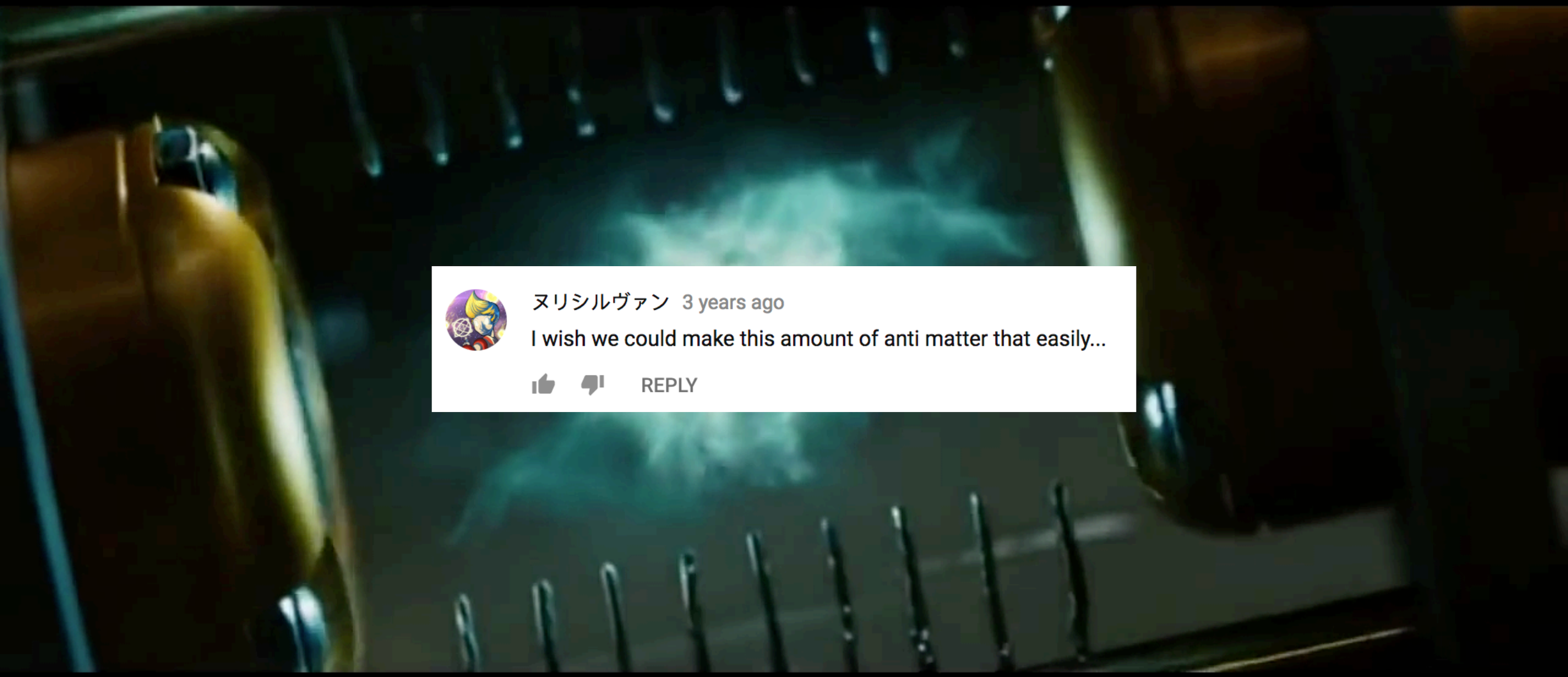
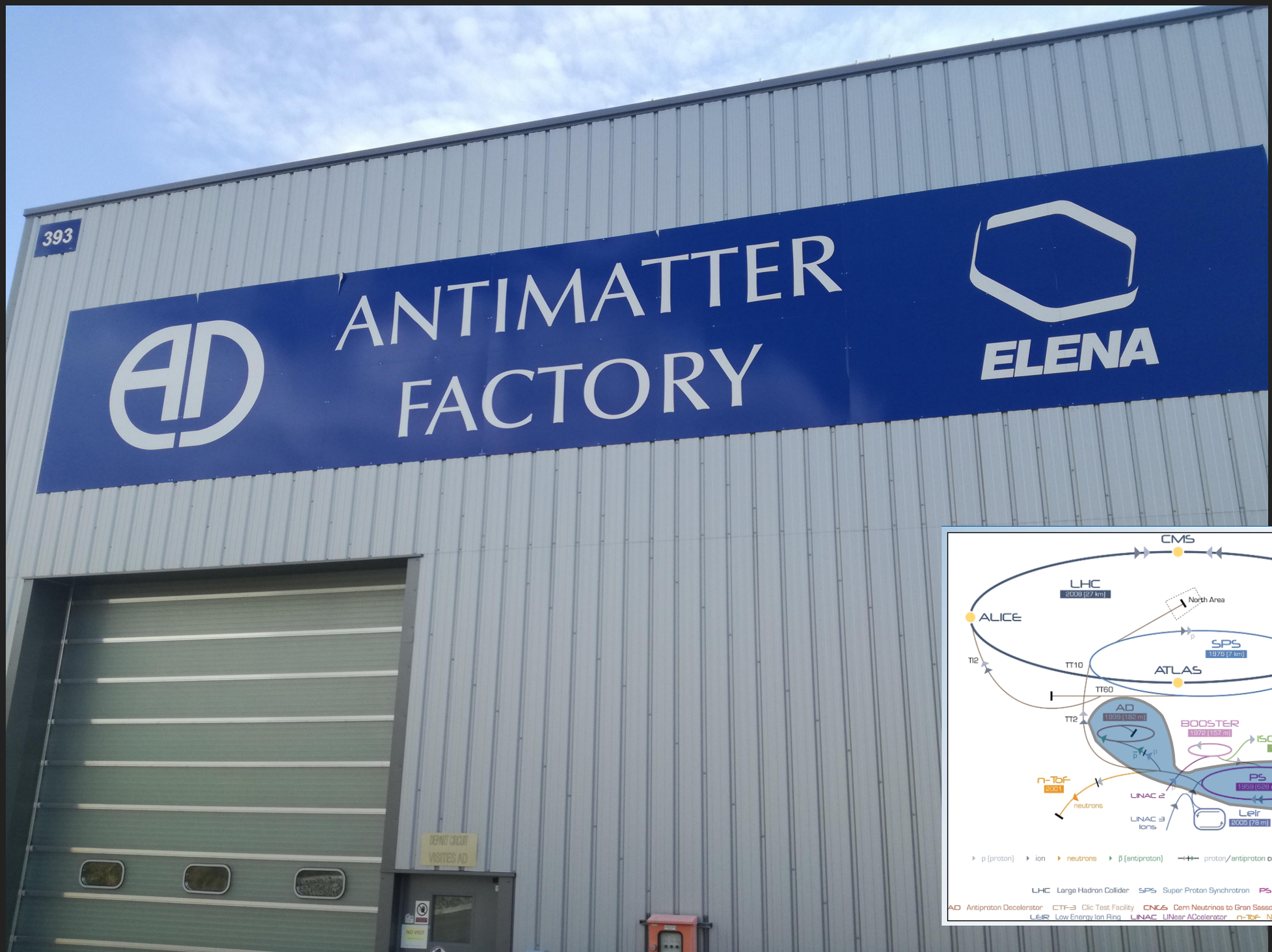


1 gram of antimatter

HOW DO WE MAKE ANTIMATTER?

HOW DO WE MAKE ANTIMATTER?

- At the antimatter factory of course!



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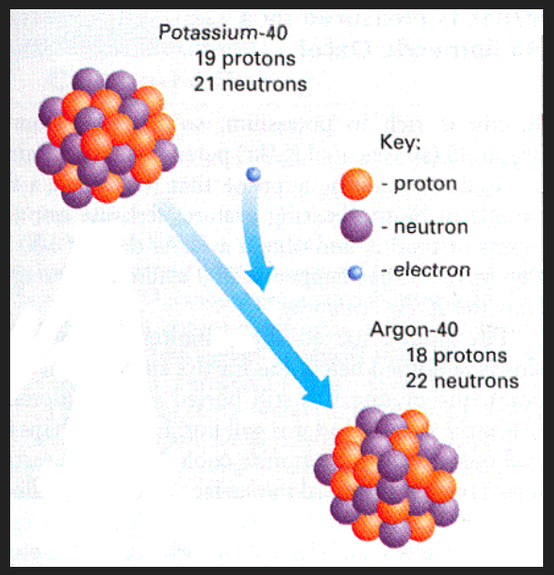

HOW DO WE MAKE ANTIMATTER?

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  - Positrons from Potassium-40: your body produces about 180 positrons per hour!

$$p + p \rightarrow \bar{p} + p + p + p$$

  - Antiprotons from high energy collisions of a proton beam on a fixed target of metal

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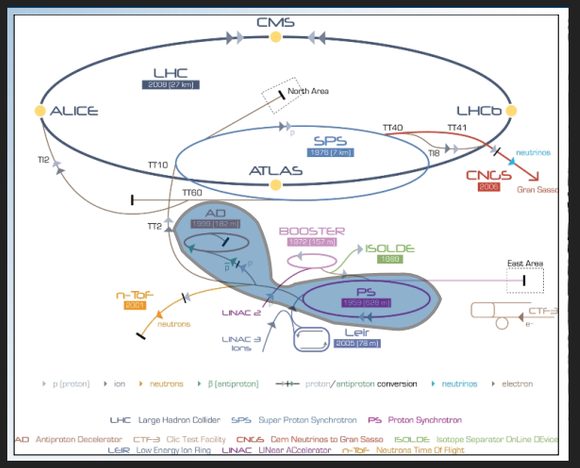

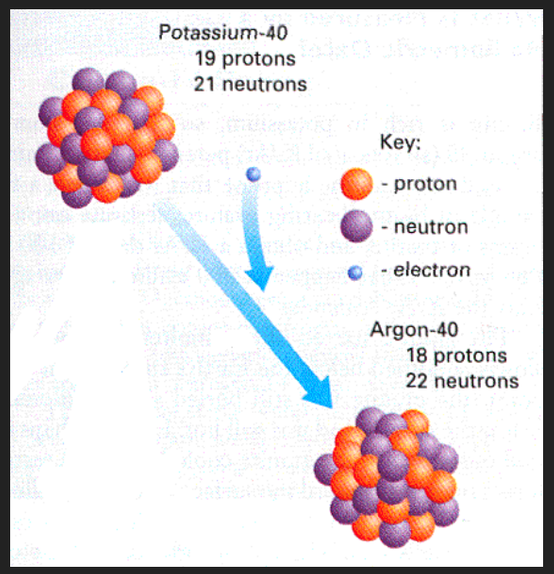

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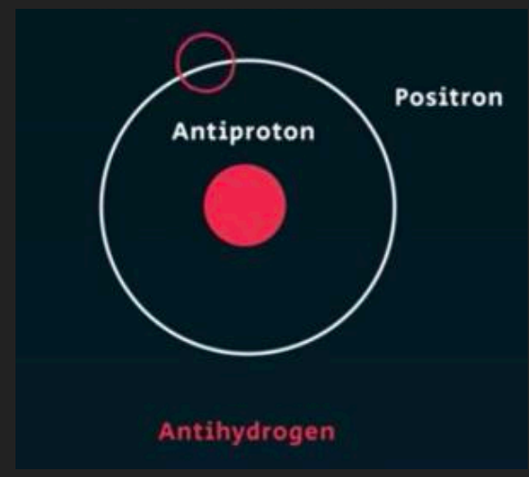
- Even if CERN used its accelerators only for making antimatter, it could produce no more than about 1 billionth of a gram per year
  - 1 gram of antimatter would take about 1 billion years!
- The total amount of antimatter produced in CERN's history is less than 10 nanograms - only enough energy to power a 60 W light bulb for 4 hours

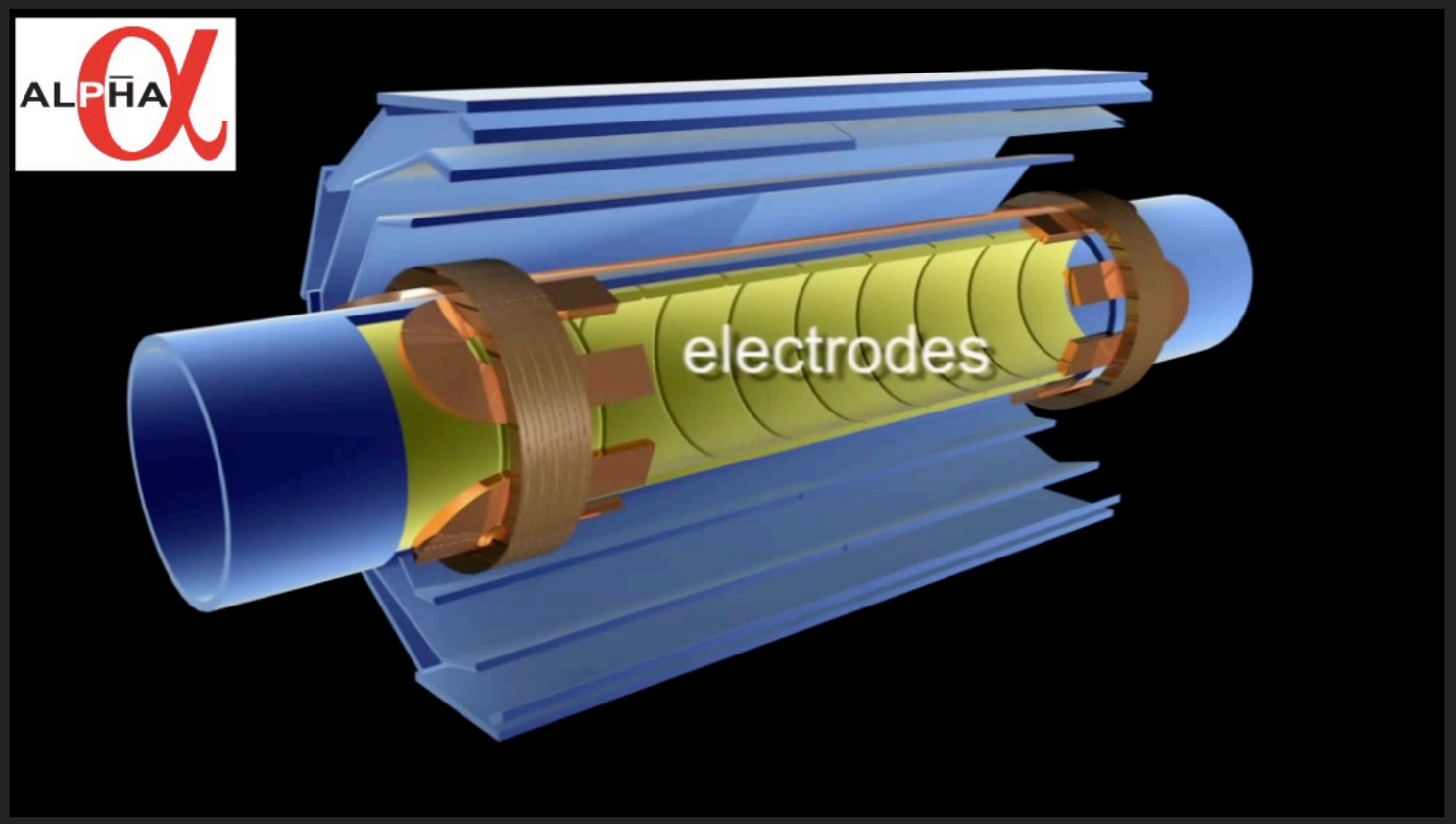
TRAPPING & STORING ANTIMATTER

- We can trap and store antiprotons and postirons with electric fields



- Antiatoms (like antihydrogen) are neutral!
  So we have to use magnetic fields to trap them

- To measure antimatter, we have to let it annihilate!



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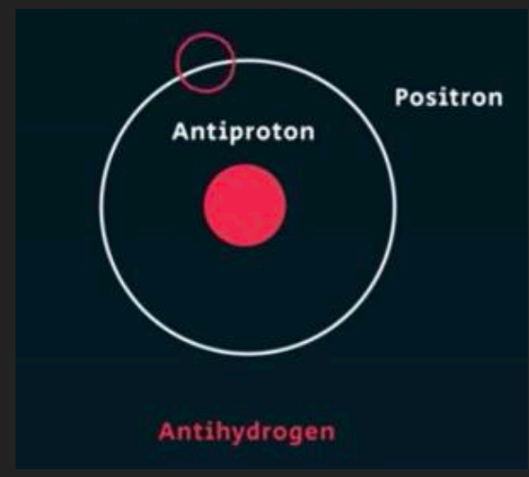

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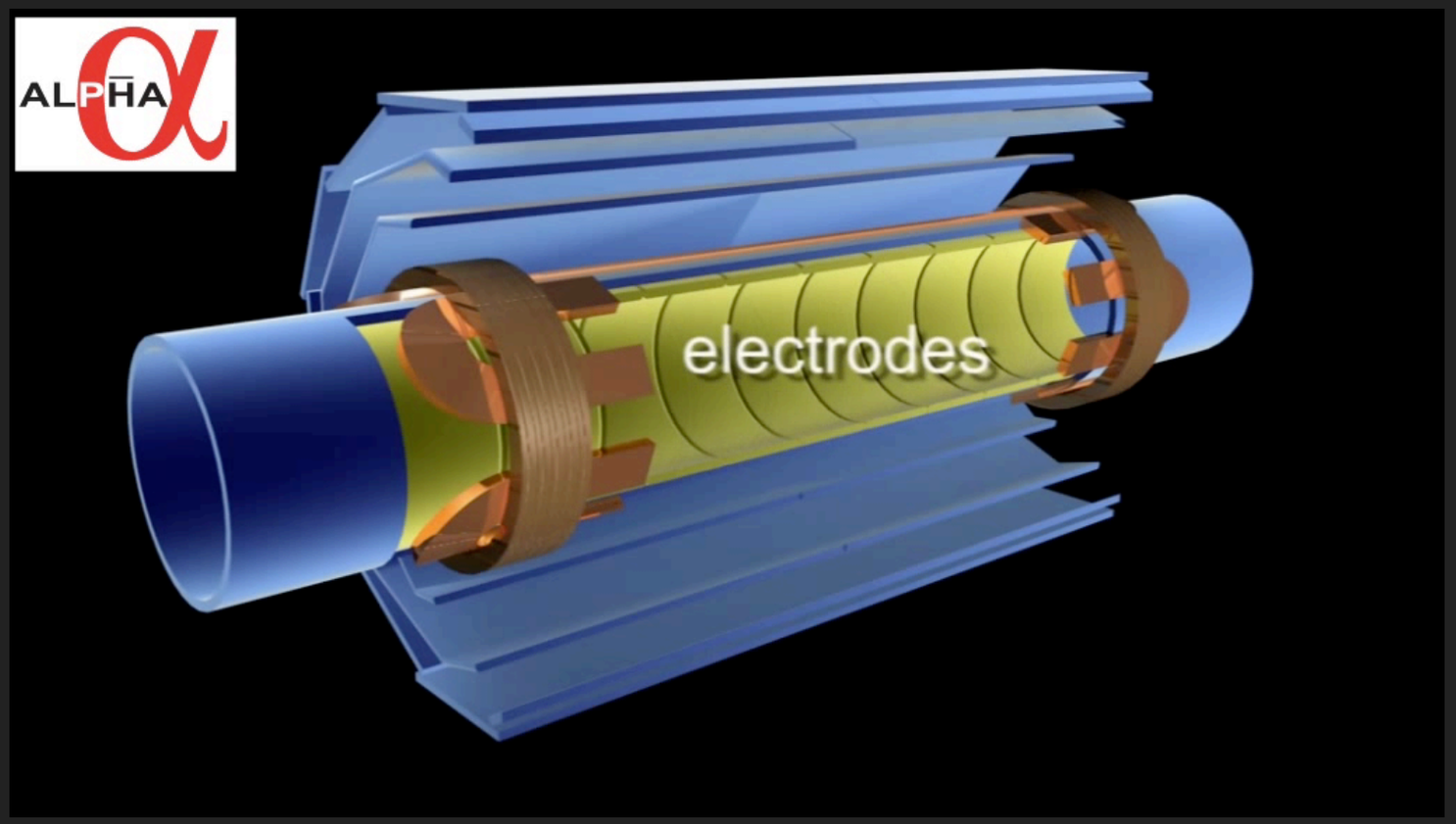

THE MATTER–ANTIMATTER ASYMMETRY

THE BIG BANG

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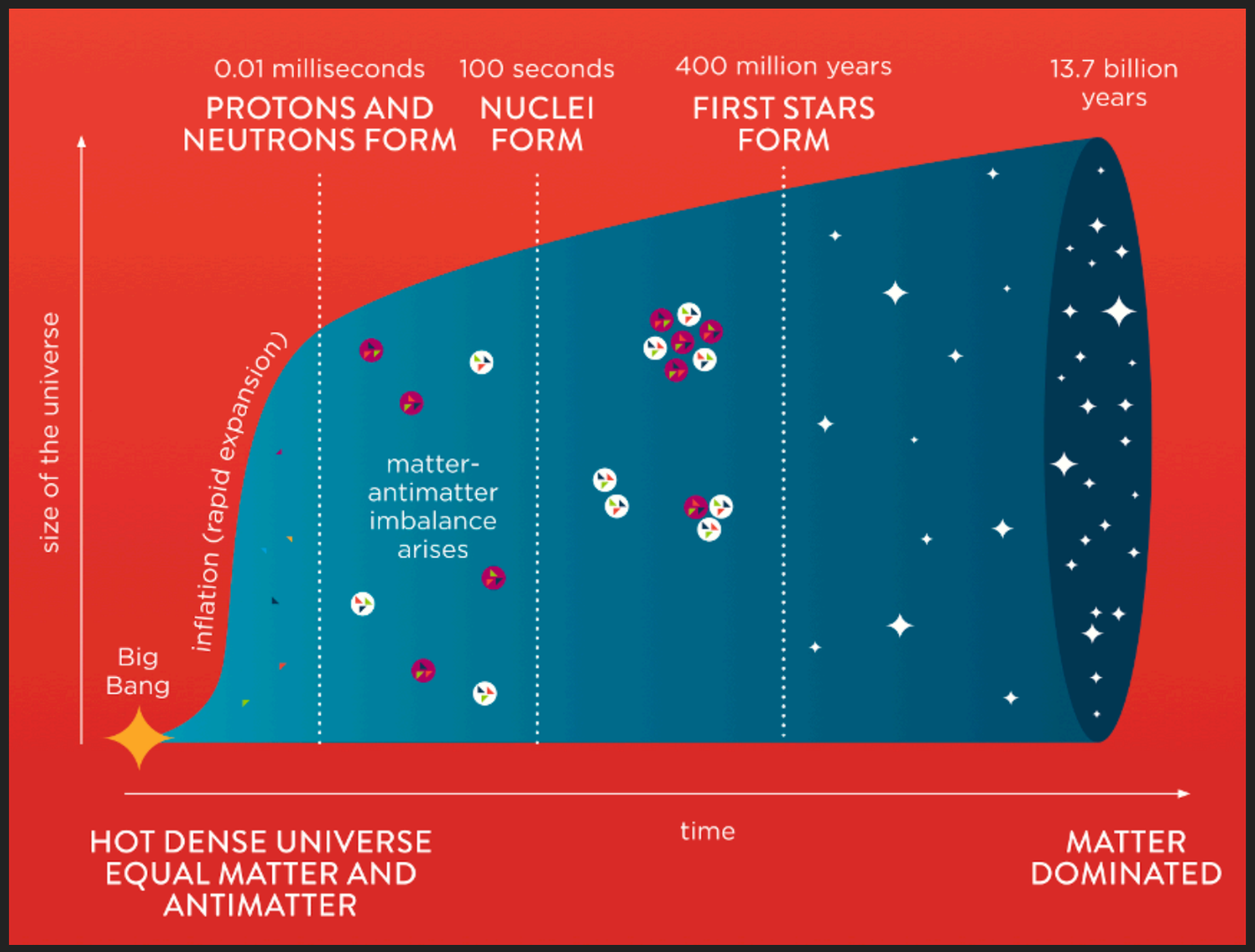
- We live in a matter-dominated universe



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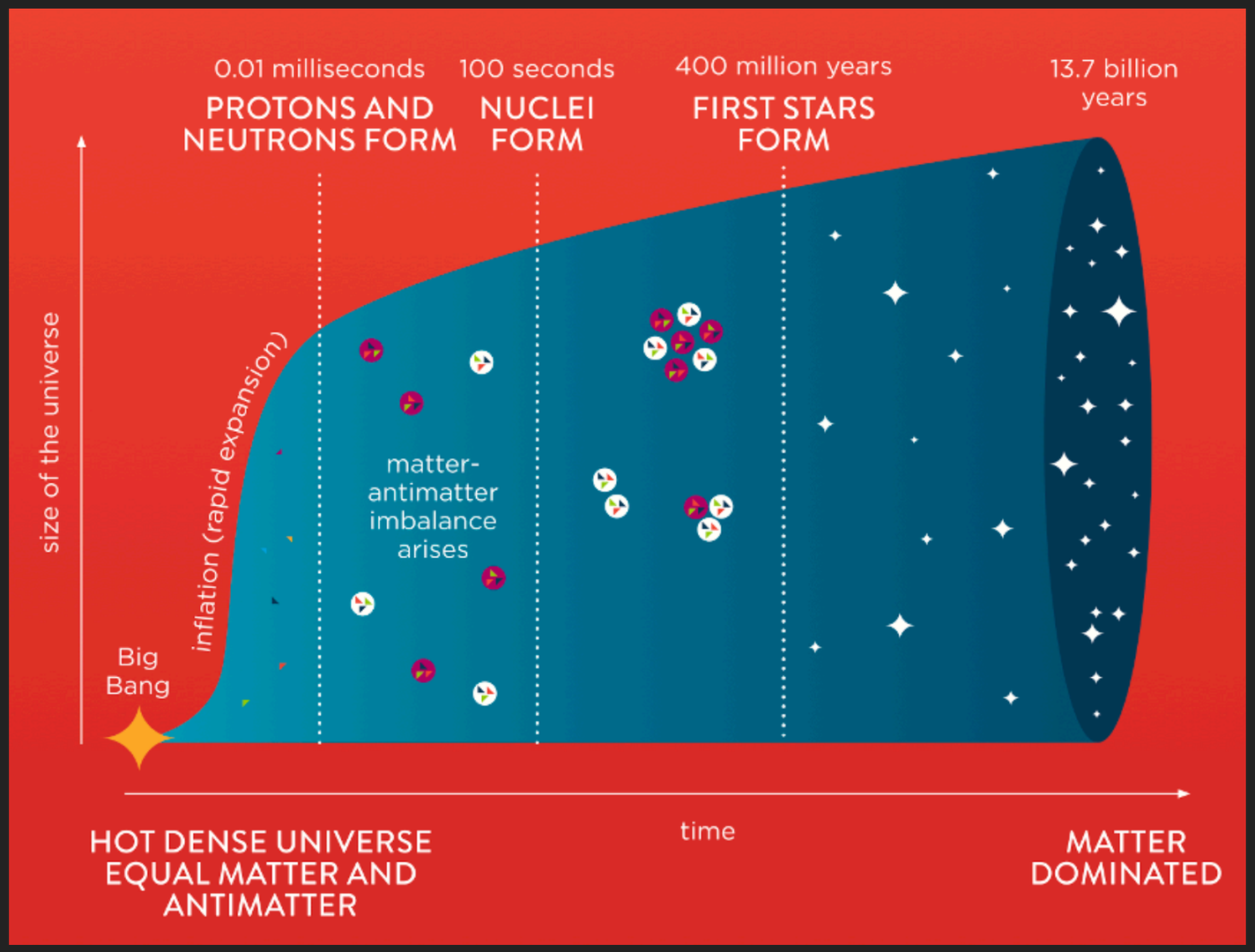
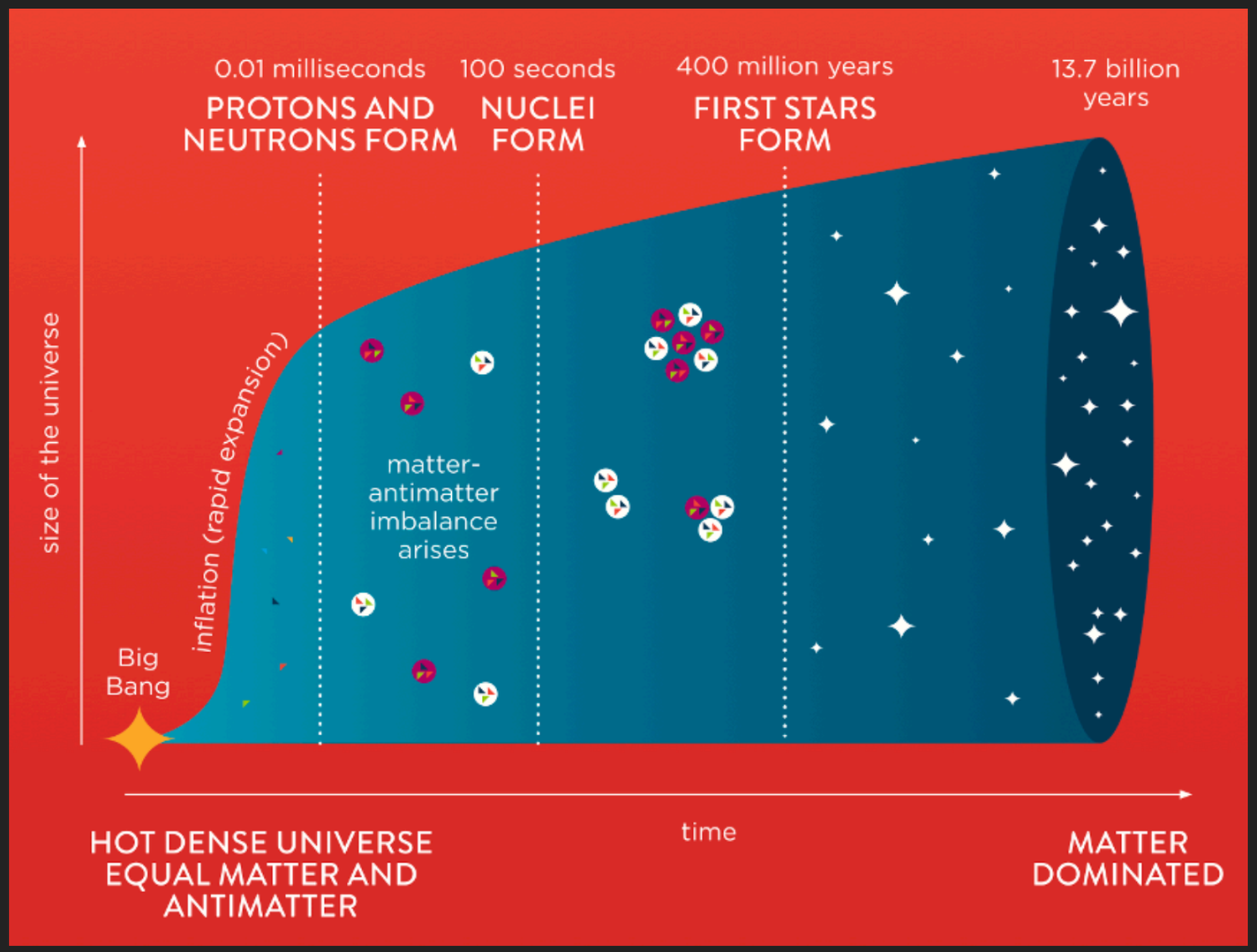
- We live in a matter-dominated universe
- Big Bang should have produced equal amounts of matter and antimatter



THE BIG BANG

- We live in a matter-dominated universe
- Big Bang should have produced equal amounts of matter and antimatter
- How did we get here? Where did all the antimatter go?



STEP 1: EQUAL MATTER AND ANTIMATTER
STEP 2: ???
STEP 3: PROFIT!!!

A TOY UNIVERSE SCENARIO A

https://github.com/jmduarte/Elastic-Collision

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- Question 1: If we start with an equal number of blue (10) and red (10) particles, can we end up with more blue particles than red particles?

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A TOY UNIVERSE SCENARIO B

- Say we have blue particles (matter), red particles (antimatter), both with mass m and green particles (light)
- The possible interactions from collisions are:
  - blue + red → green + green
  - green + green → blue + red
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- Question 2: If we start with an unequal number of blue (15) and red (5) particles, can we end up with more blue particles than red particles?

https://github.com/jmduarte/Elastic-Collision

A TOY UNIVERSE SCENARIO C

- Say we have blue particles (matter), red particles (antimatter), both with mass m and green particles (light)
- The possible interactions from collisions are:
  - blue + red → green + green
  - green + green → blue + red (90% of the time)
  - green + green → blue + blue (10% of the time)
    - (if green particles $E > 2mc^2$)
- Question 3: If we start with equal numbers of blue (10) and red (10) particles, can we end up with more blue particles than red particles?

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- Are we in scenario B or C?
  - We don’t know yet! We have found some asymmetric (CP-violating) interactions, but so far it’s not enough to explain the discrepancy!

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PHYSICAL REVIEW VOLUME 159, NUMBER 5 25 JULY 1967

All Possible Symmetries of the S Matrix*

SIDNEY COLEMAN† AND JEFFREY MANDULA‡
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts
(Received 16 March 1967)

We prove a new theorem on the impossibility of combining space-time and internal symmetries in any but a trivial way. The theorem is an improvement on known results in that it is applicable to infinite-parameter groups, instead of just to Lie groups. This improvement is gained by using information about the S matrix; previous investigations used only information about the single-particle spectrum. We define a symmetry group of the S matrix as a group of unitary operators which turn one-particle states into one-particle states, transform many-particle states as if they were tensor products, and commute with the S matrix. Let G be a connected symmetry group of the S matrix, and let the following five conditions hold: (1) G contains a subgroup locally isomorphic to the Poincaré group. (2) For any $M>0$, there are only a finite number of one-particle states with mass less than M. (3) Elastic scattering amplitudes are analytic functions of s and t, in some neighborhood of the physical region. (4) The S matrix is nontrivial in the sense that any two one-particle momentum eigenstates scatter (into something), except perhaps at isolated values of s. (5) The generators of G, written as integral operators in momentum space, have distributions for their kernels. Then, we show that G is necessarily locally isomorphic to the direct product of an internal symmetry group and the Poincaré group.

THE END OF SYMMETRY IN PHYSICS?

- Have we accounted for all possible symmetries of our universe?

- In 1967, it seemed that way…

- It turns out there is one possible extension which combines symmetries of space-time with discrete symmetries of particles…

SUPERSYMMETRY

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- We can swap the particles with the exchange operator *R* *with no observable effect*

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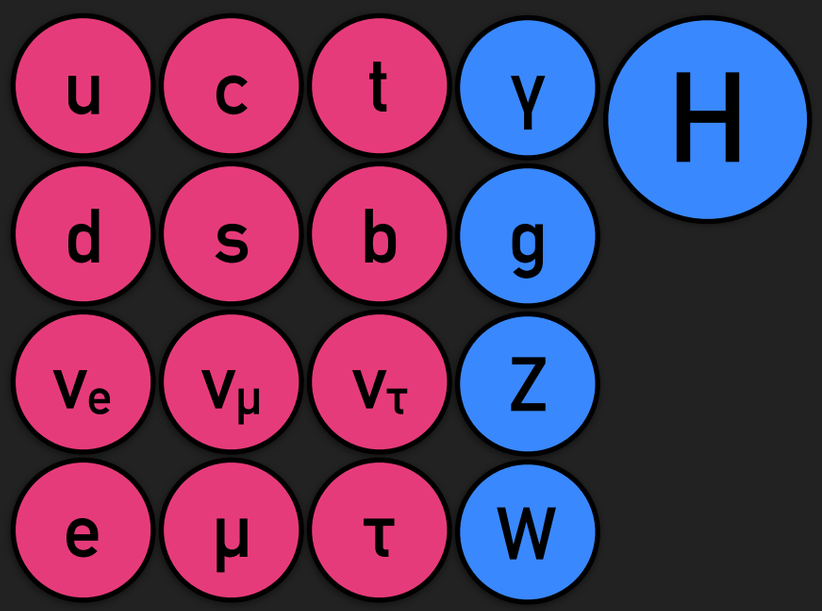
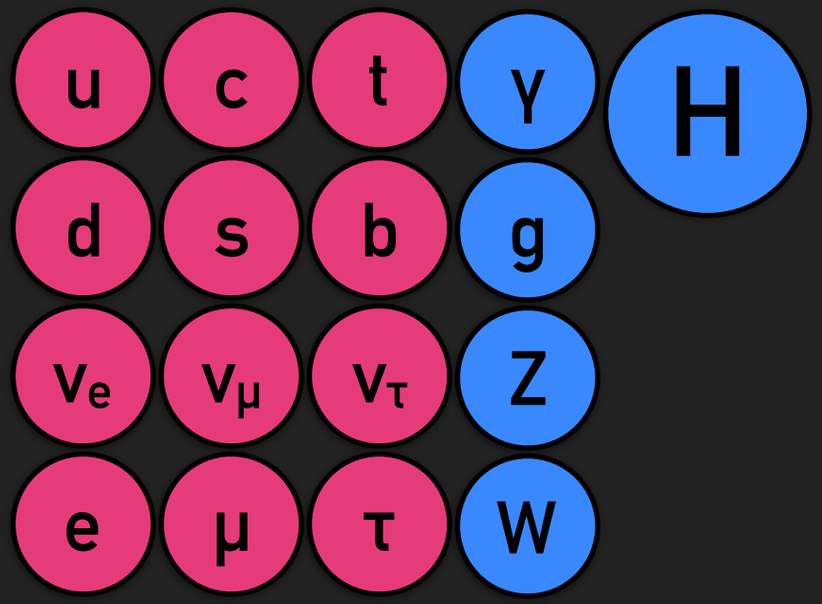
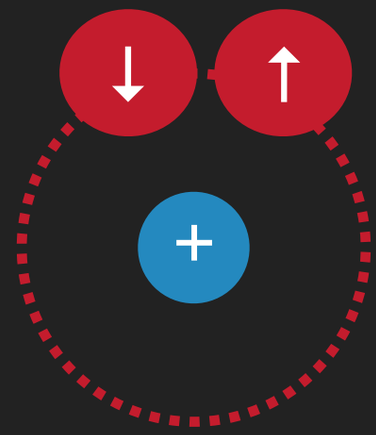
FERMIONS AND BOSONS



- Two kinds of particles: fermions and bosons
  - Fermions (wavefunction gets a – sign when swapped)
  - Bosons (wavefunction gets a + sign when swapped)

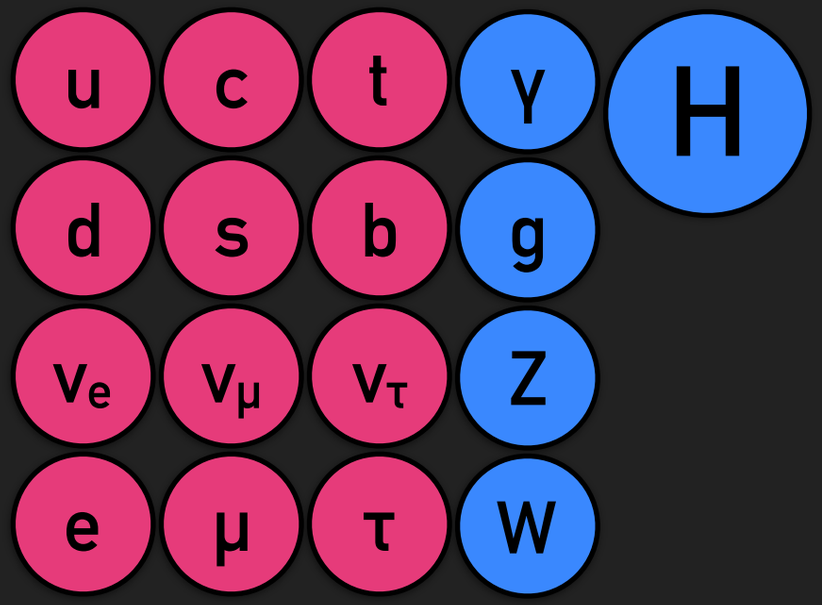
FERMIONS AND BOSONS





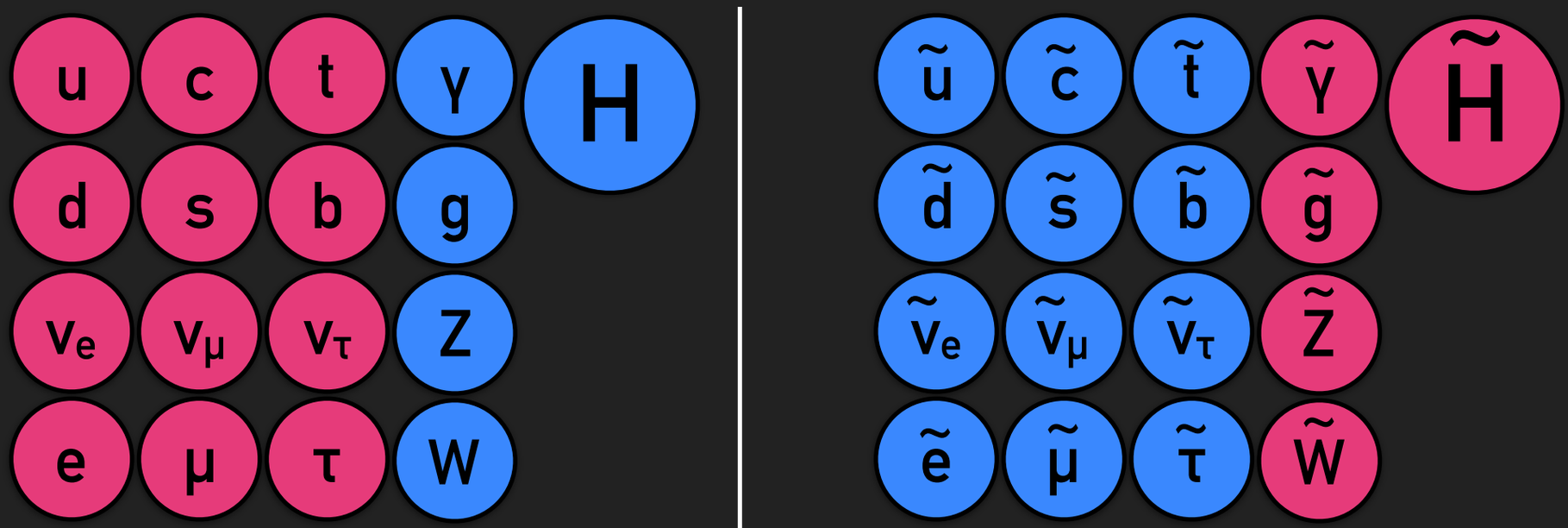
- Fermions obey the *Pauli exclusion principle*: no two fermions can occupy the same state!
- Bosons behave like “waves” and can carry forces: pushing and pulling other particles!

SUPERSYMMETRY



- Can we relate fermions (matter) and bosons (forces)?
  - Yes, via ***supersymmetry:*** for every fermion, there exists a corresponding "superpartner" boson (and vice versa) with the same properties except one: the spin

SUPERSYMMETRY



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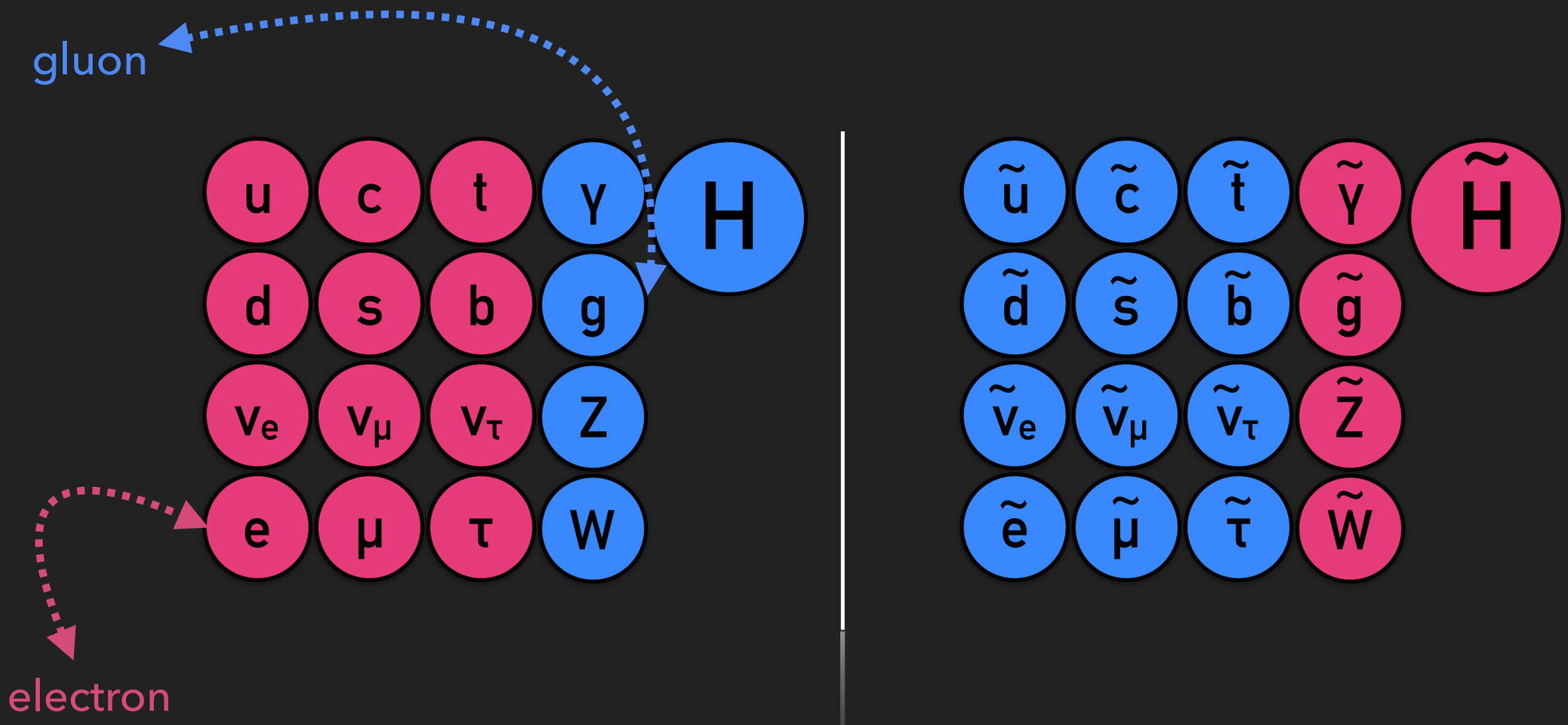

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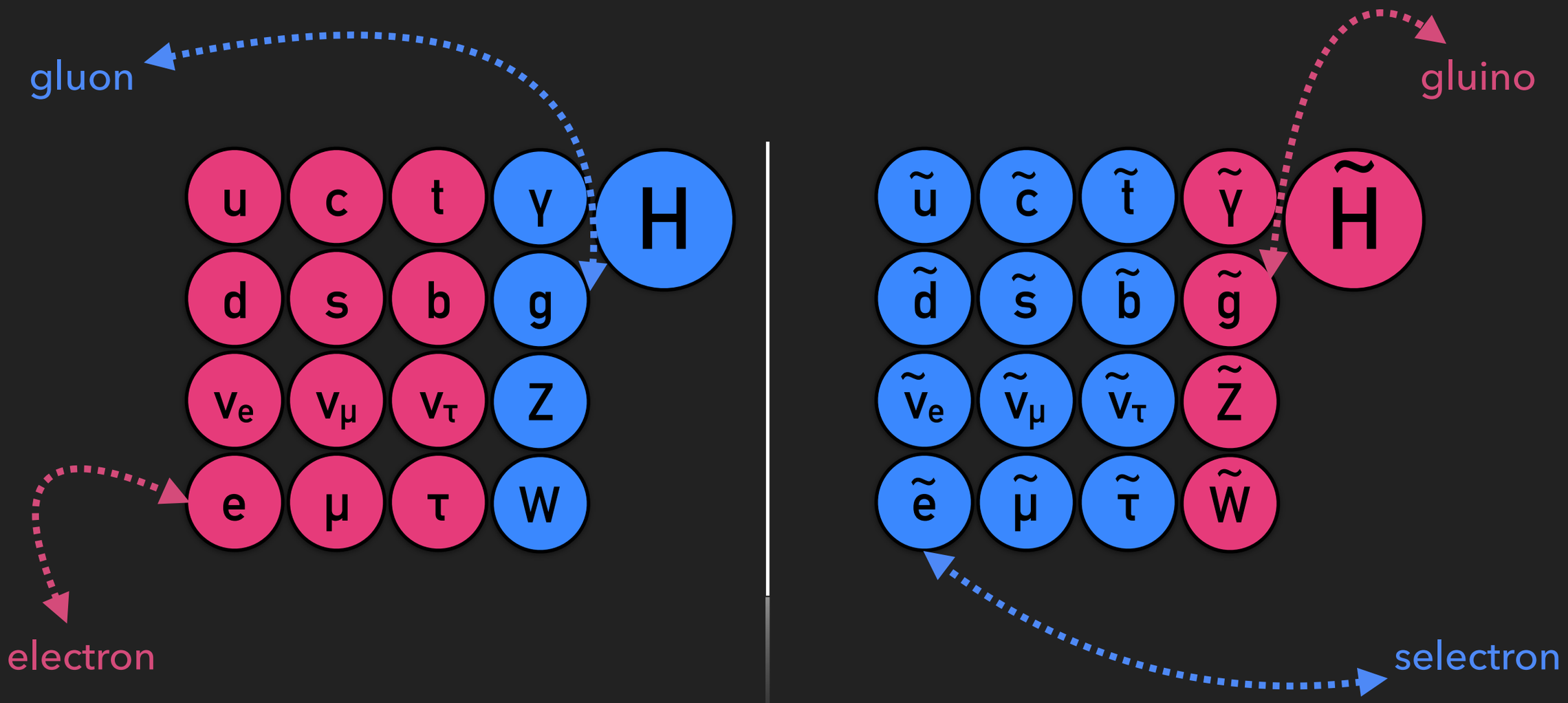

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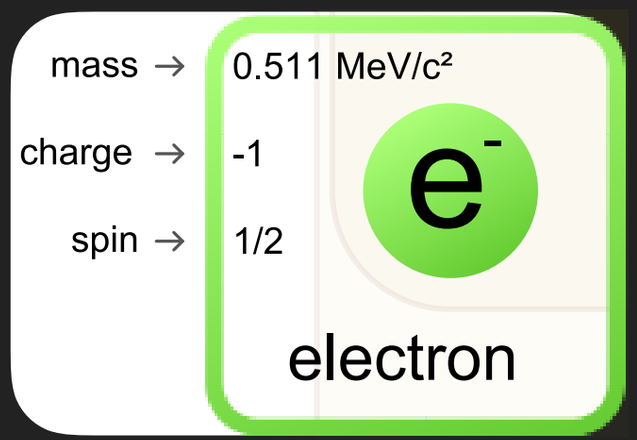
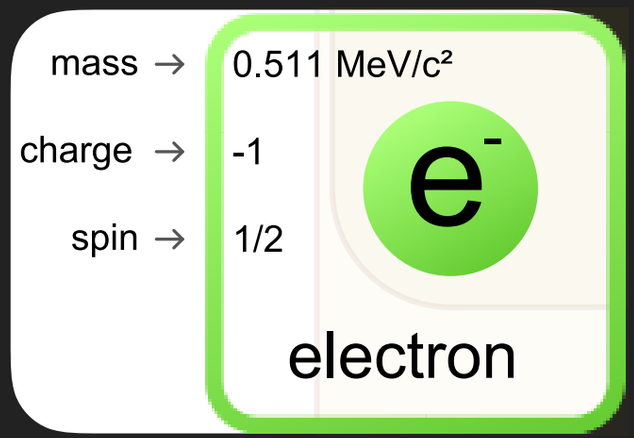
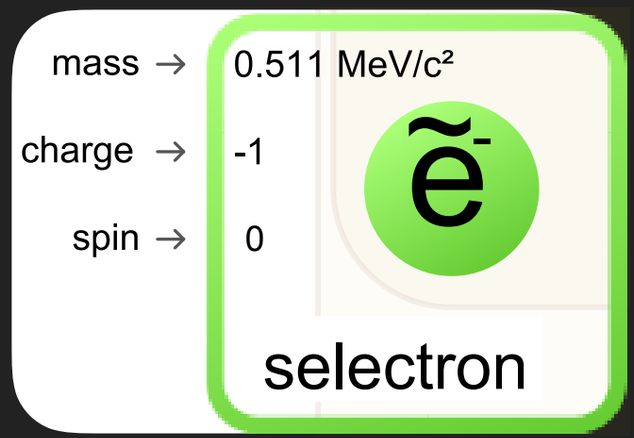
WHAT IS A SUPERPARTNER?



WHAT IS A SUPERPARTNER?

- Superpartner is exactly the same as the original except one attribute is different: the *spin*





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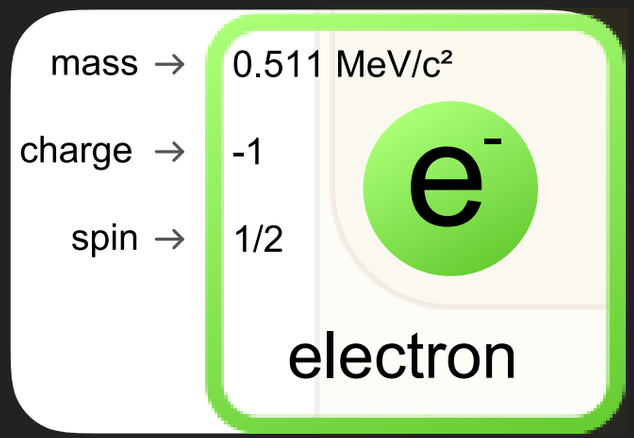

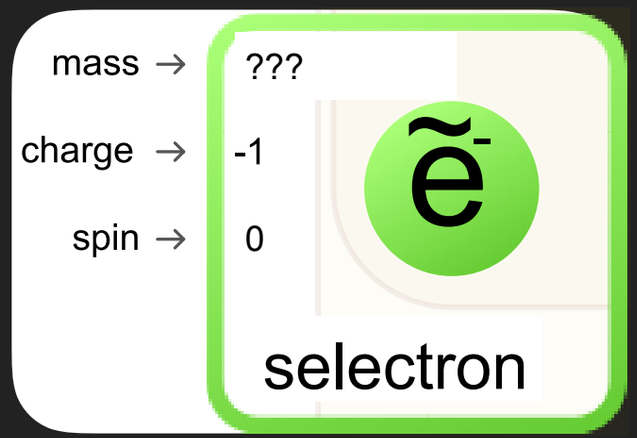

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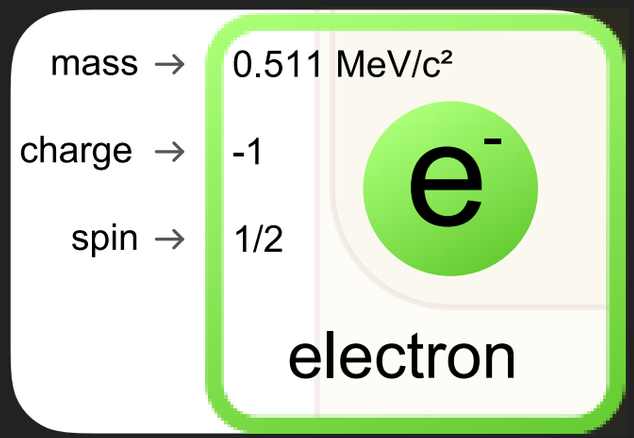

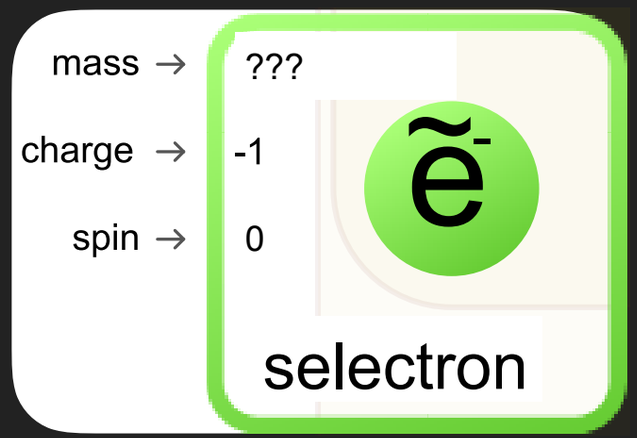

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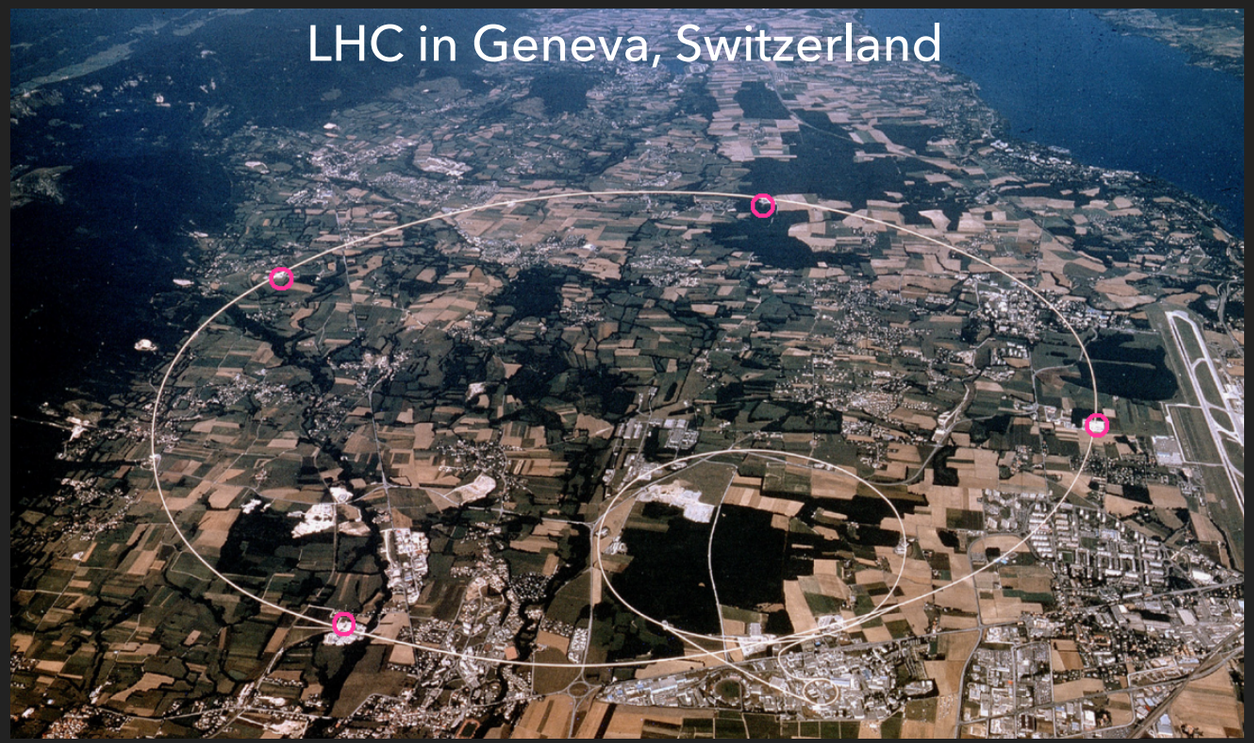
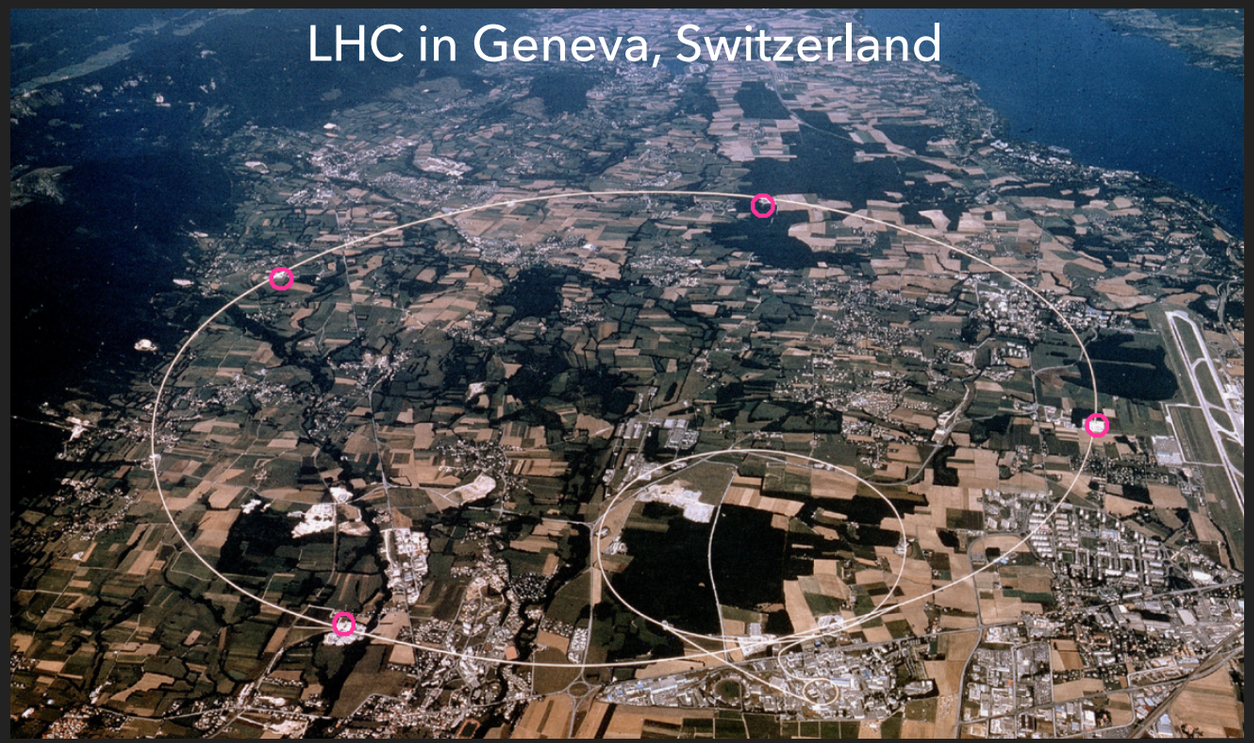
- The ***selectron*** must be much heavier

SUPERSYMMETRY AT THE LARGE HADRON COLLIDER



SUPERSYMMETRY AT THE LARGE HADRON COLLIDER



- Search has been on for supersymmetry for over 40 years…
  including my thesis!

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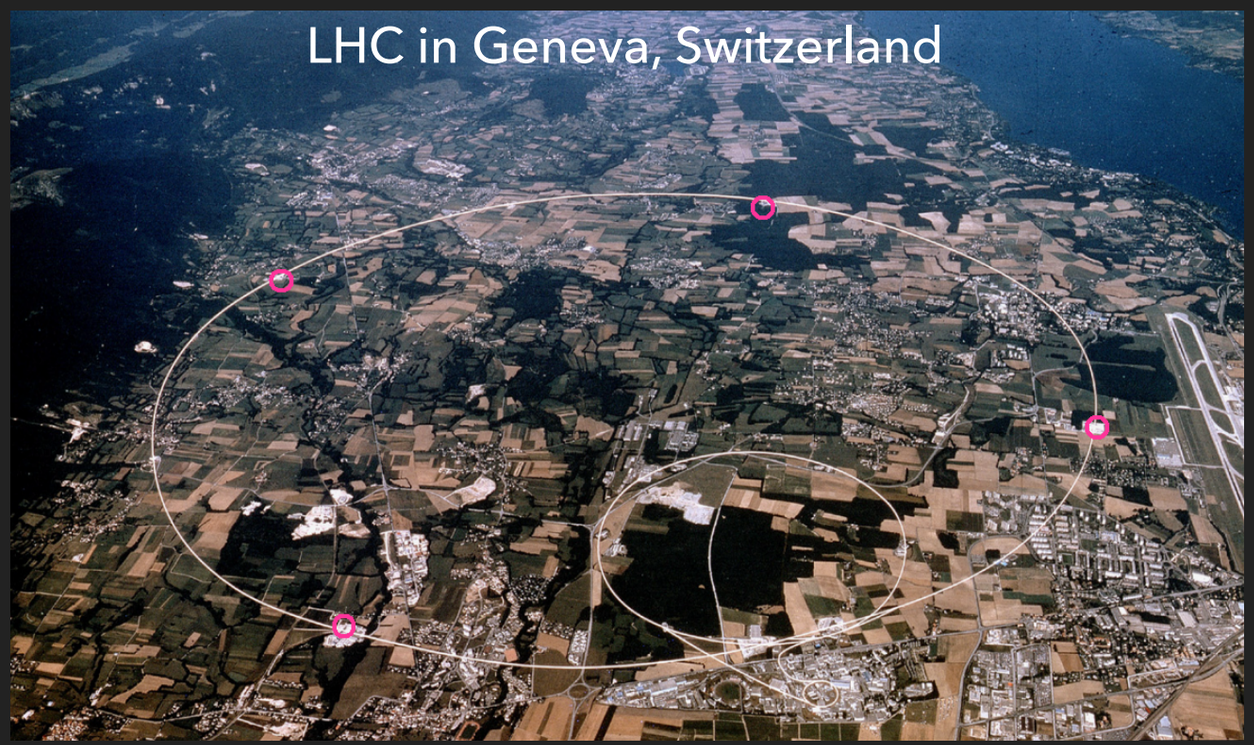

Naturalness confronts nature: searches for supersymmetry with the CMS detector in pp collisions at $\sqrt{s} = 8$ and 13 TeV

Thesis by
Javier M. G. Duarte

In Partial Fulfillment of the Requirements for the degree of
Doctor of Philosophy

Caltech

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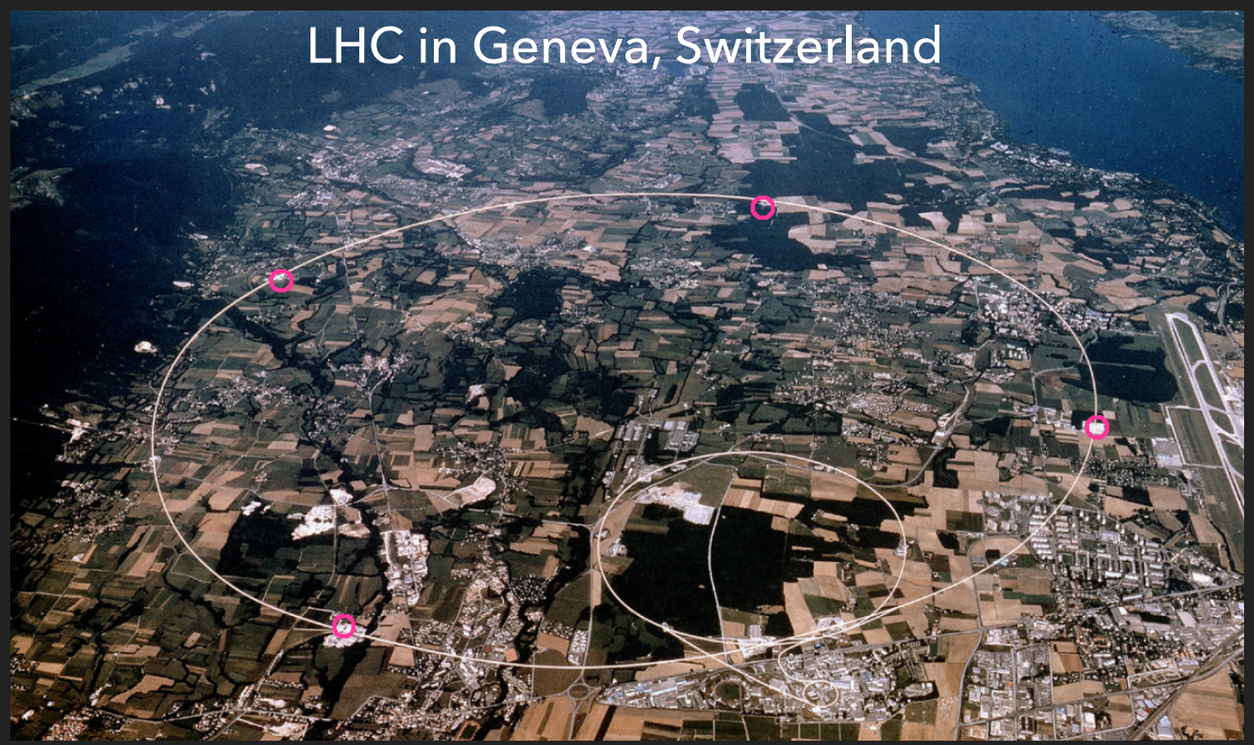

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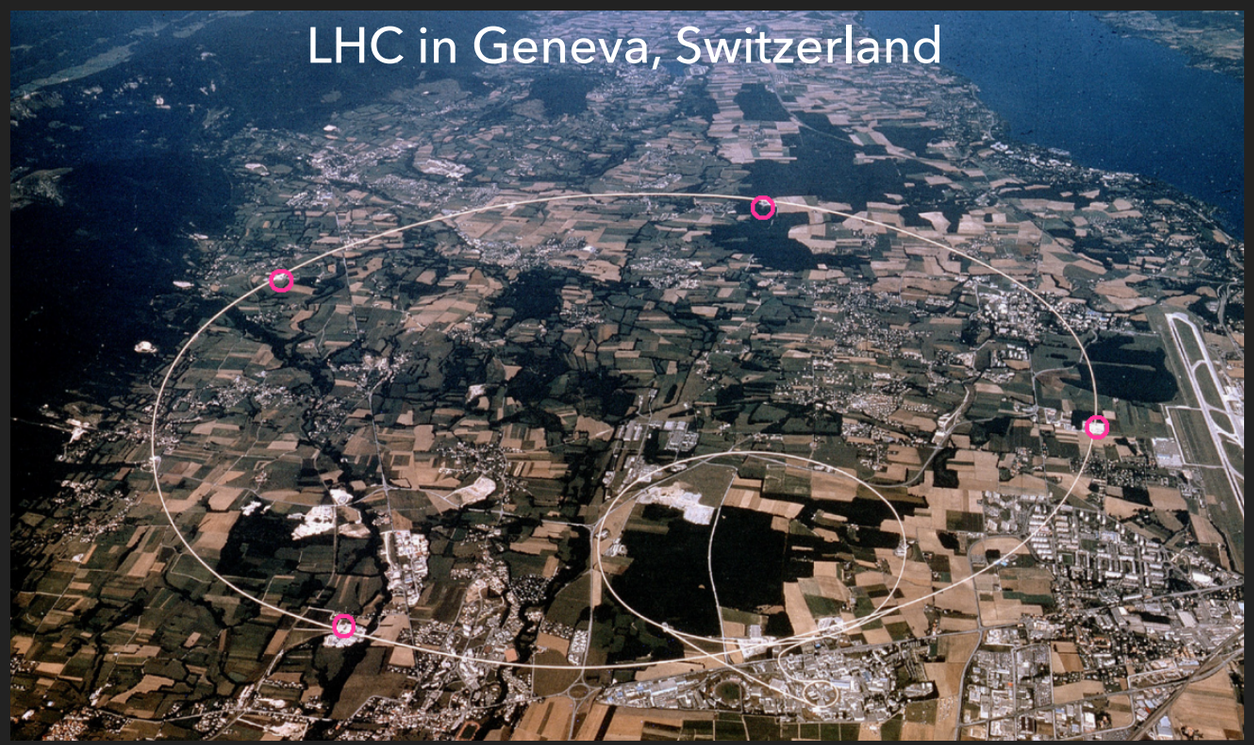

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- Thanks for listening!

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