

JAVIER DUARTE

MARCH 2, 2019

SATURDAY MORNING PHYSICS

FERMILAB, BATAVIA, IL, USA

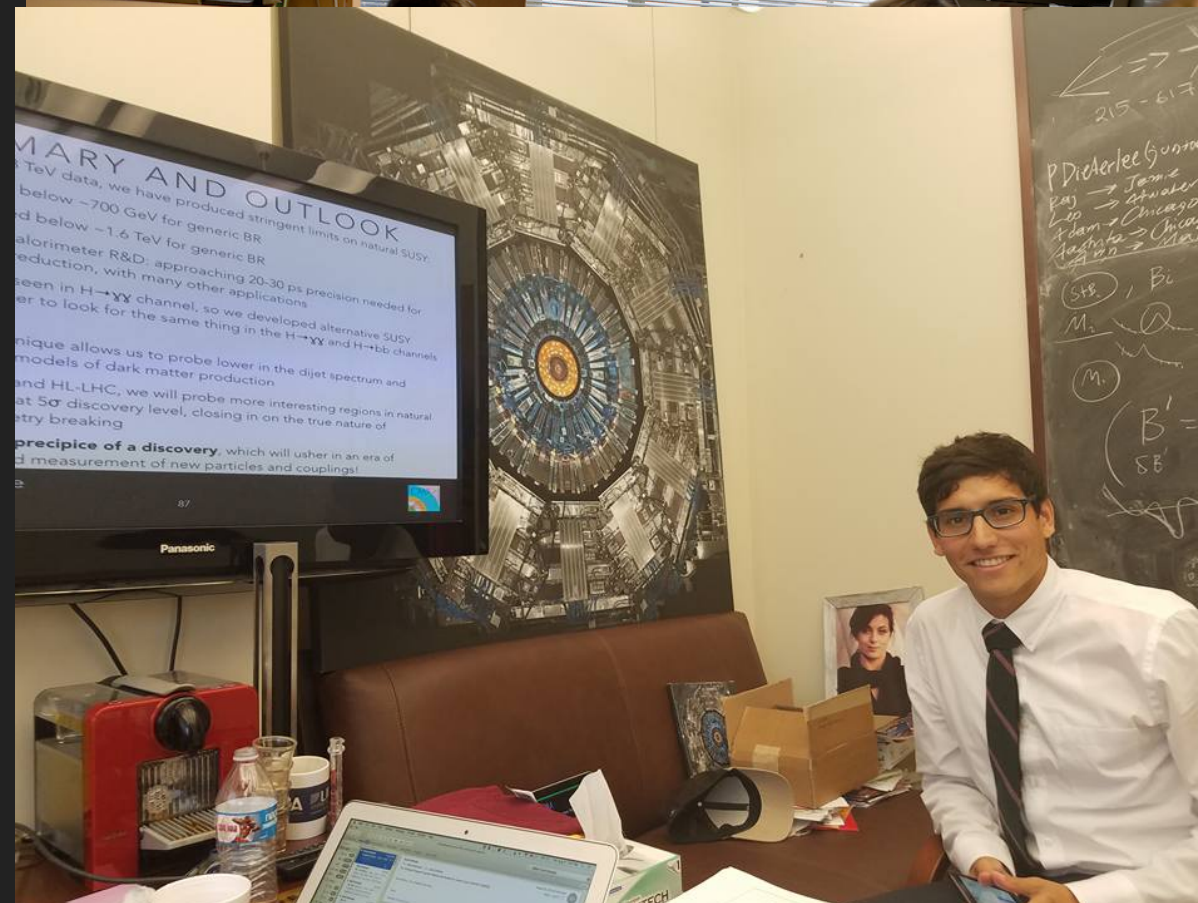
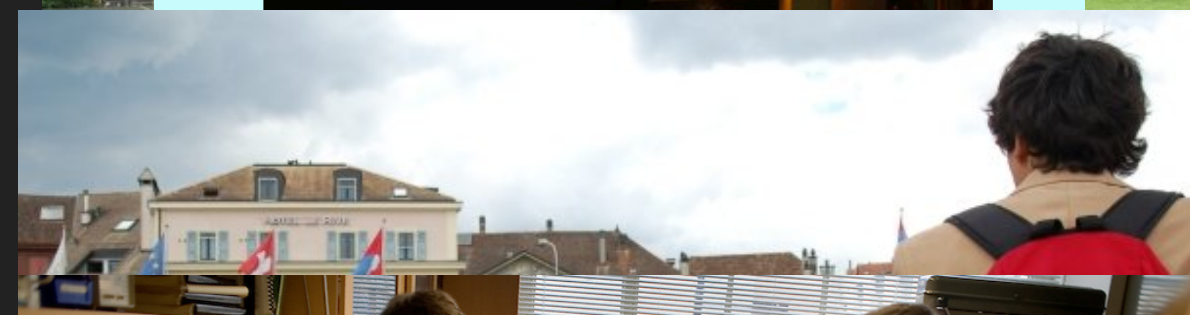
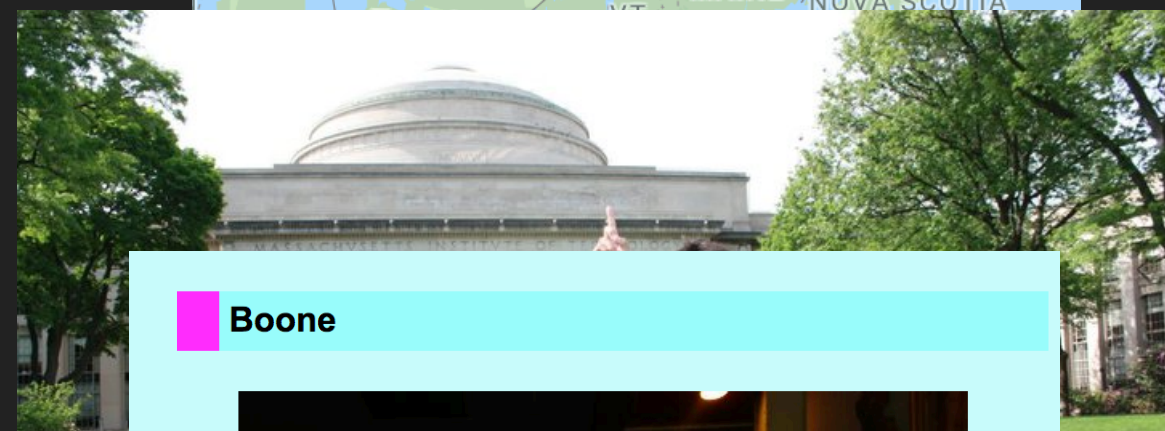
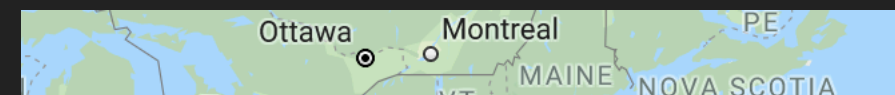
SYMMETRY, ANTIMATTER, AND SUPERSYMMETRY

- ▶ Symmetry
- ▶ Symmetry and conservation laws
- ▶ Antimatter
- ▶ The matter-antimatter asymmetry
- ▶ Supersymmetry

PERSONAL BIO

*REU = Research Experience for Undergraduates 3

- ▶ Originally from Cúcuta, Colombia
- ▶ Raised in Coram, NY (Long Island)
- ▶ Undergrad at MIT (2006-2010)
 - ▶ Came to Fermilab as a Nevis REU* student (summer 2007)
 - ▶ Went to CERN as a Michigan REU* student (summer 2009)
- ▶ Took a year and taught in MIT Junior Lab
- ▶ Grad student at Caltech/CERN (2011-2016)
- ▶ Lederman fellow at Fermilab



SYMMETRY

WHAT IS SYMMETRY?

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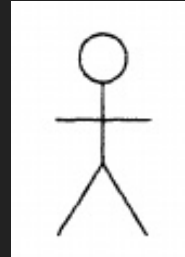
- ▶ It comes in many forms and pervades many domains:



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

**“... 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**

- ▶ Bilateral symmetry: reflection about the y-axis



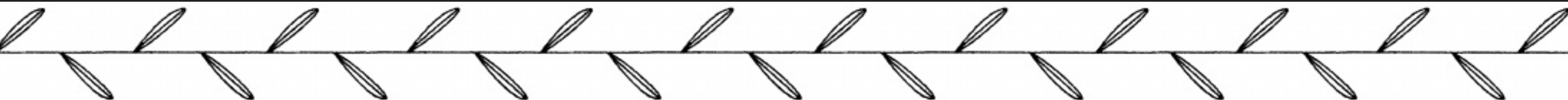
- ▶ Rotational symmetry: rotation about the origin



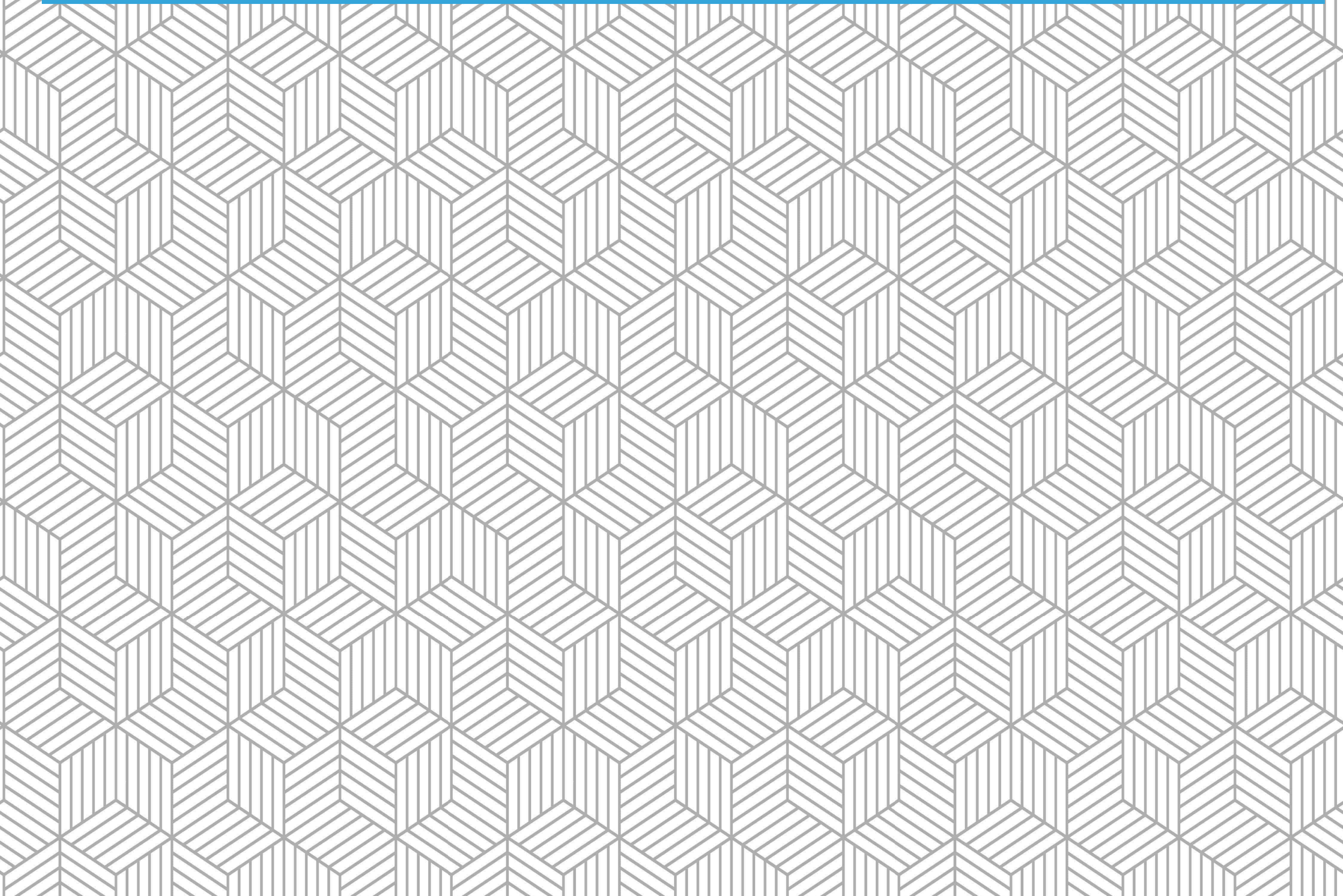
- ▶ Translational symmetry: translation along the x-axis



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



WHAT ARE THE SYMMETRIES OF THIS PATTERN?



TRANSLATION ALONG Y-AXIS BY 1?



TRANSLATION ALONG Y-AXIS BY 2?



TRANSLATION ALONG X-AXIS BY 1?

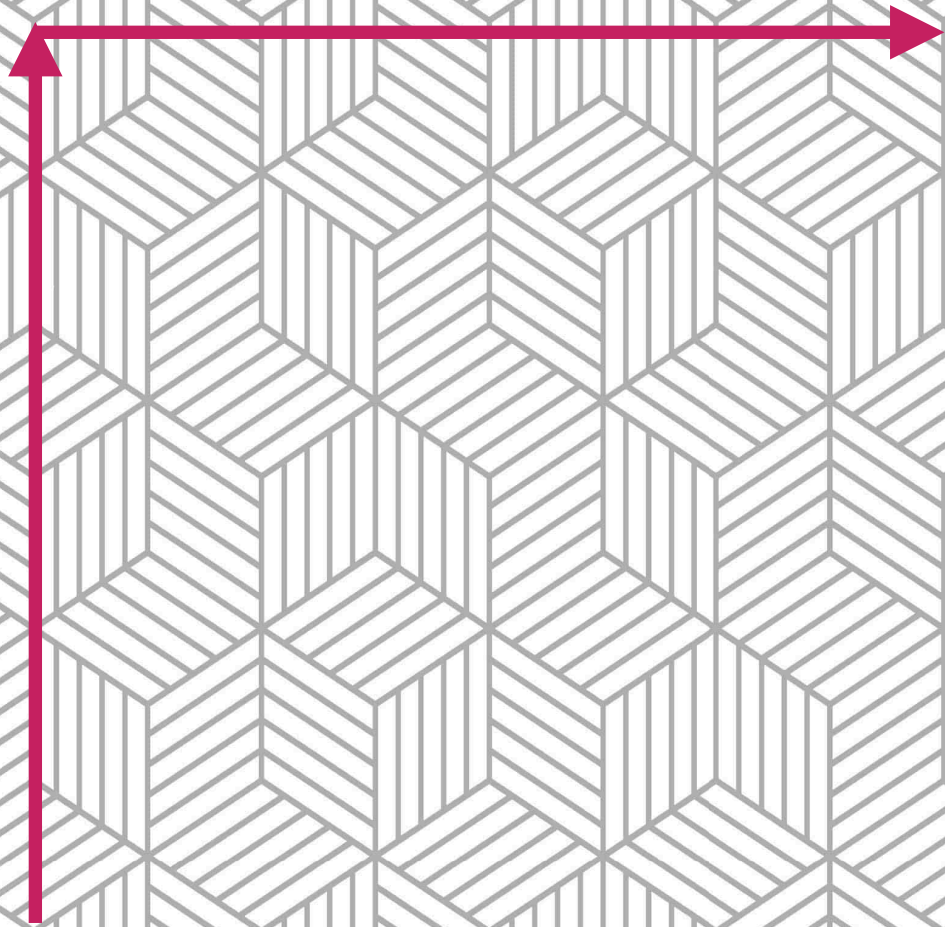


TRANSLATION ALONG X-AXIS BY 2?

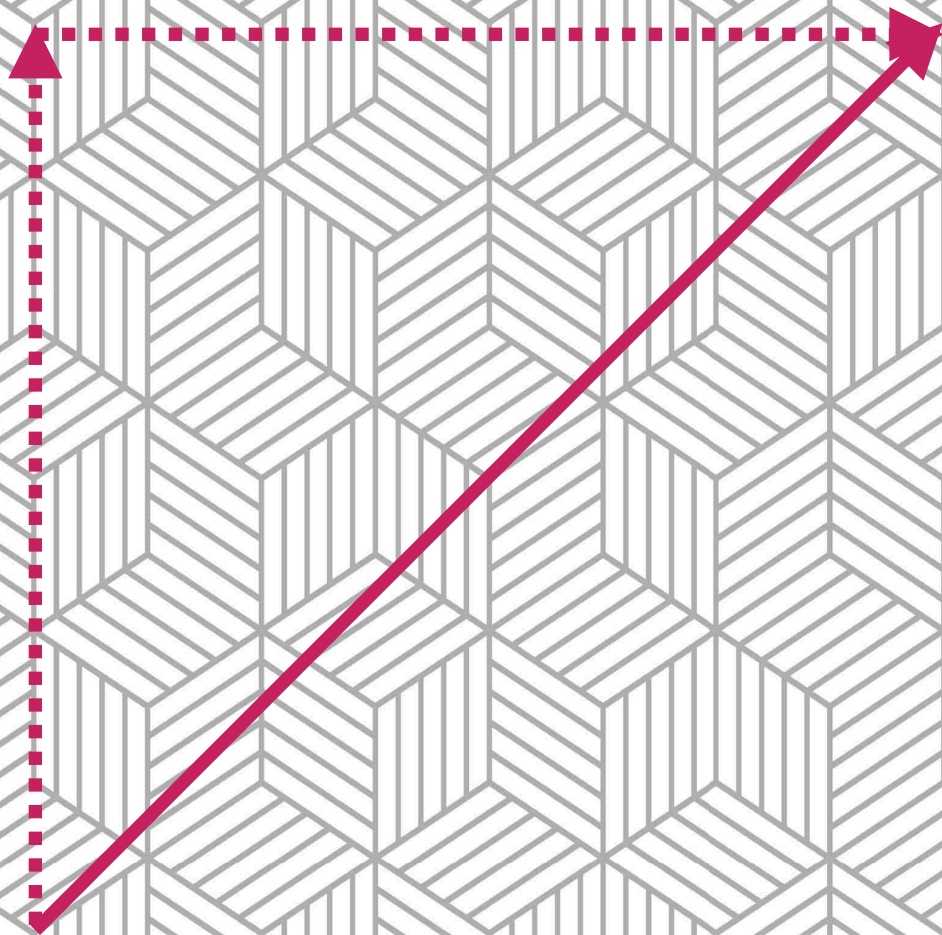


- ▶ Symmetry of a plane figure: a motion applied to the plane which preserves the original plane figure
- ▶ What is the rule for composing symmetries?
 - ▶ $(\text{Symmetry } 2) \bullet (\text{Symmetry } 1)$
 - ▶ = first, apply symmetry motion 1
then, apply symmetry motion 2
- ▶ Is this a good symmetry?

TRANSLATION ALONG Y-AXIS BY 2 THEN X-AXIS BY 2

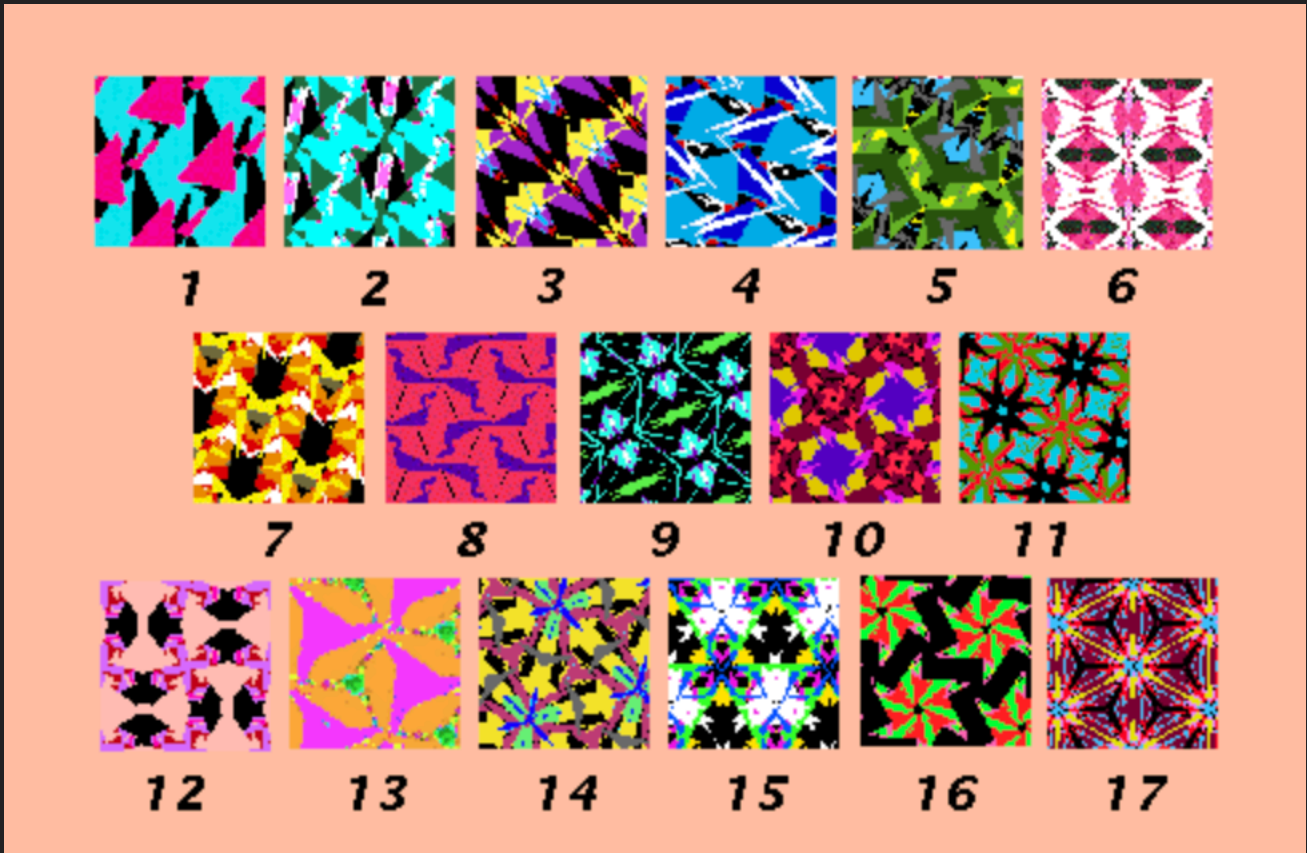


TRANSLATION DIAGONALLY BY $\sqrt{8}$



- ▶ Underlying mathematical structure to symmetry: *groups*
- ▶ A group is a **set G** and a **rule of composition " \bullet "** which forms a new element " $a \bullet b$ " from two elements a and b
- ▶ Four requirements:
 1. $a \bullet b$ is also in G (Closure)
 2. $(a \bullet b) \bullet c = a \bullet (b \bullet c)$. (Associativity)
 3. an element 1 exists such that $1 \bullet a = a \bullet 1 = a$ (Identity)
 4. an element a^{-1} exists such that $a \bullet a^{-1} = a^{-1} \bullet a = 1$ (Inverse)

<http://www2.clarku.edu/~djoyce/wallpaper/seventeen.html>



Symmetry group	IUC notation	Lattice type	Rotation orders	Reflection axes
1	p1	parallelogrammatic	none	none
2	p2	parallelogrammatic	2	none
3	pm	rectangle	none	parallel
4	pg	rectangle	none	none
5	cm	rhombus	none	parallel
6	pmm	rectangle	2	90°
7	pmg	rectangle	2	parallel
8	pgg	rectangle	2	none
9	cmm	rhombus	2	90°
10	p4	square	4	none
11	p4m	square	4 +	45°
12	p4g	square	4 *	90°
13	p3	hexagon	3	none
14	p31m	hexagon	3 *	60°
15	p3m1	hexagon	3 +	30°
16	p6	hexagon	6	none
17	p6m	hexagon	6	30°

+ = all rotation centers lie on reflection axes

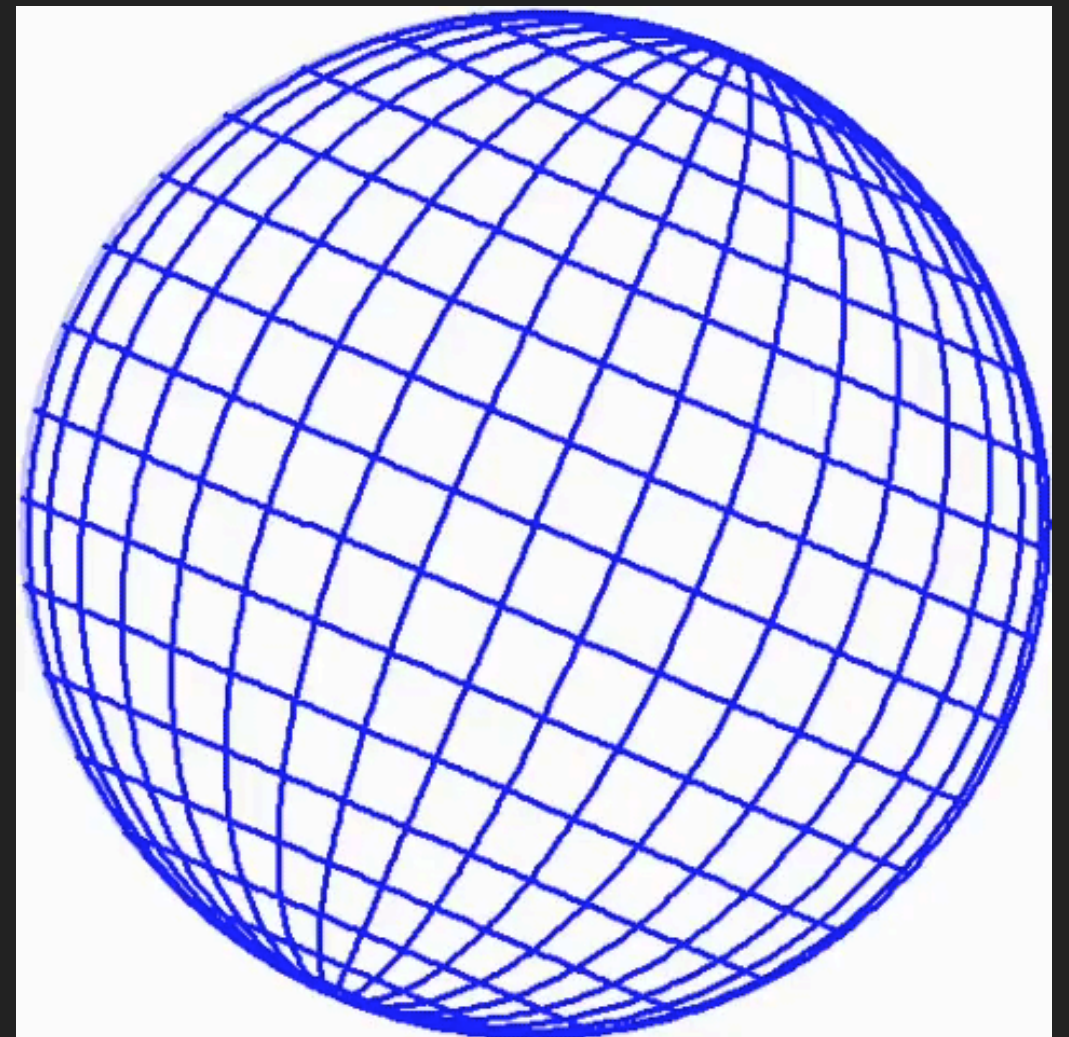
* = not all rotation centers on reflection axes

- ▶ Symmetry is an important principle in physics
- ▶ In particle physics, symmetries give rise to the **fundamental forces**
- ▶ Symmetries are also linked to fundamental laws of physics: ***conservation laws***

SYMMETRY AND CONSERVATION LAWS

- ▶ Symmetries can be discrete or **continuous***
- ▶ Continuous symmetry means you can transform the system by an infinitesimal amount and it's still a good symmetry

For example: rotation of a sphere by any angle

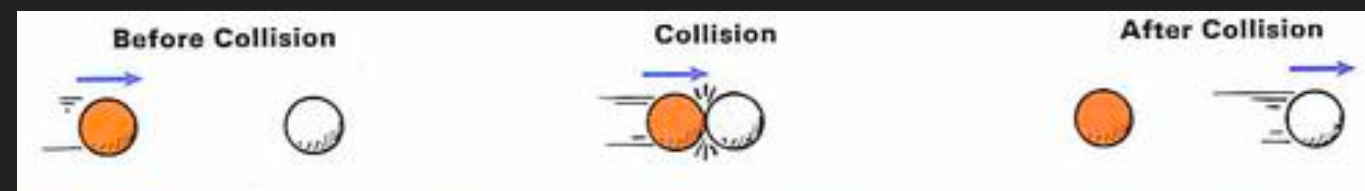
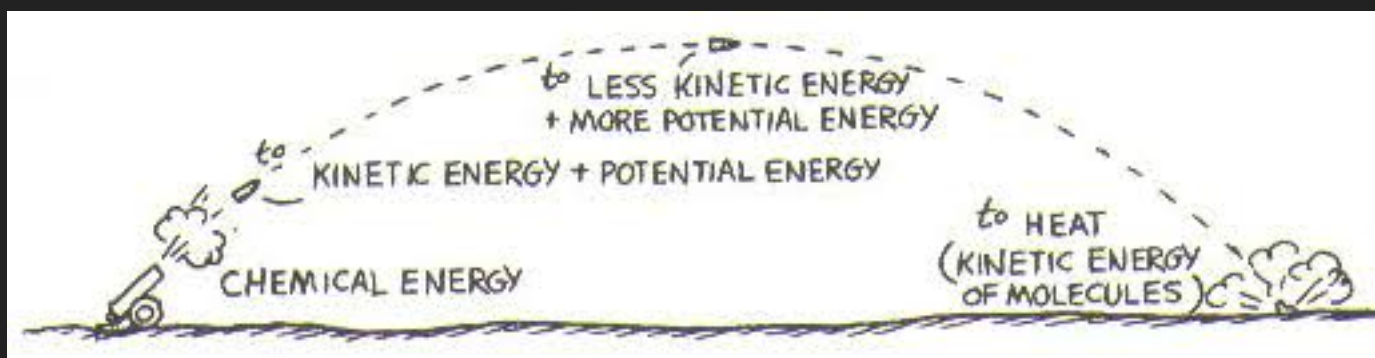
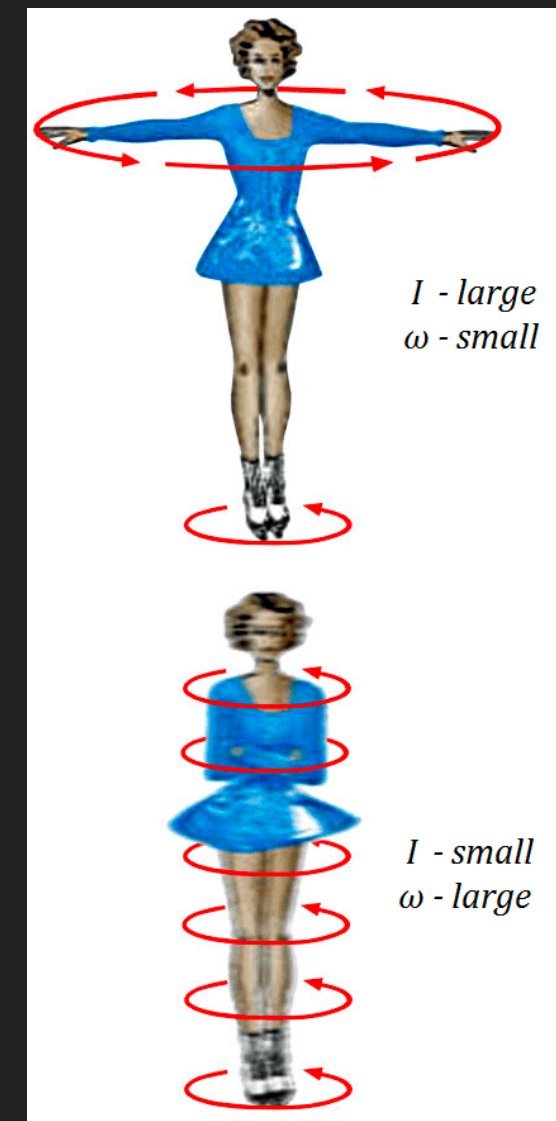
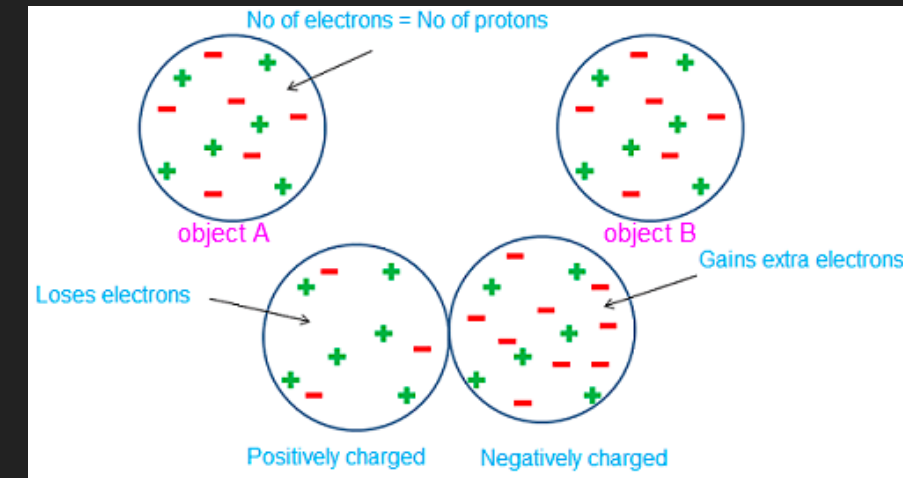


- ▶ The laws of physics are unchanged under what **continuous** transformations?
- ▶ Are they the same today as they are tomorrow?
 - ▶ Translation in time
- ▶ Are they the same in Chicago as they are in Batavia?
 - ▶ Translation in space
- ▶ Are they the same whether you're facing north or south?
 - ▶ Rotation in space
- ▶ Are they the same when you're in a uniformly moving car?
 - ▶ Uniform velocity motion

► In physics, what are the conservation laws?

- Conservation of energy
- Conservation of linear momentum
- Conservation of angular momentum
- Conservation of electric charge

► How are these related to symmetries?



EMMY NOETHER

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- ▶ 1882: Born in Erlangen



- ▶ 1904: Admitted to Erlangen as student of mathematics

- ▶ 1907: D. Phil. summa cum laude

- ▶ 1908-1915: Unpaid member of Erlangen Mathematical Institute



- ▶ 1915: Nominated to become "outside lecturer" in Göttingen, with unanimous support from the Math-Science Department
 - ▶ Historical-Philological Department opposed: "Concern that seeing a female organism might be distracting to the students."
- ▶ 1919: Assistant Professor in Göttingen
- ▶ 1922: Associate Professor
- ▶ 1932: Alfred Ackermann-Teubner Award, Plenary Lecture at ICM, Zürich
- ▶ 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

- ▶ **Every continuous* symmetry of a physical system has a corresponding conservation law**

Invariante Variationsprobleme.
(F. Klein zum fünfzigjährigen Doktorjubiläum.)
Von
Emmy Noether in Göttingen.
Vorgelegt von F. Klein in der Sitzung vom 26. Juli 1918¹⁾.

- ▶ How does this apply to our universe?

CONTINUOUS* SYMMETRIES OF PHYSICAL LAWS

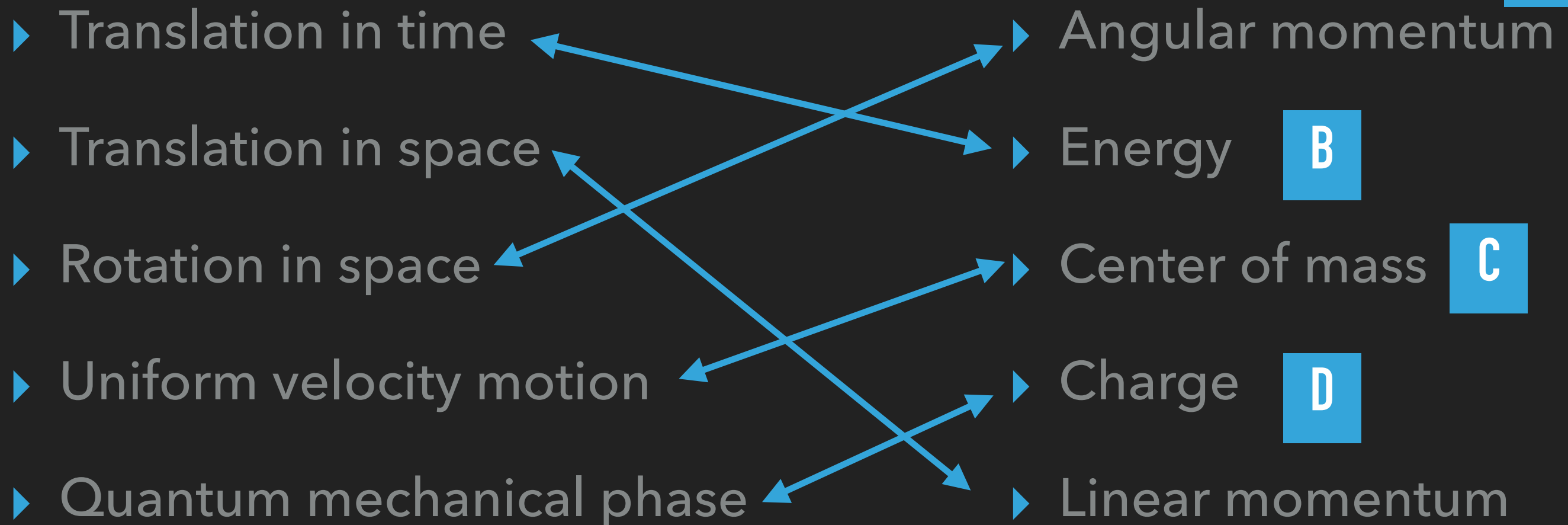
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- ▶ The laws of physics are unchanged under:

SYMMETRY

CONSERVED QUANTITY

WHICH MATCHES
WITH WHICH?



- ▶ Say the law of gravity was different tomorrow, $G' > G$

TODAY

$$F = \frac{GMm}{R^2} = mg$$

TOMORROW

$$F' = \frac{G'Mm}{R^2} = mg'$$

- ▶ Lift a big mass m to a great height h today

- ▶ The amount of energy I expend: $E = mgh$

- ▶ Let it fall tomorrow and compress a spring

- ▶ The amount of energy I gain back: $E' = mg'h$

- ▶ The net energy: $E' - E = m(g' - g)h > 0$

- ▶ There are also (possible) discrete symmetries, for example

SYMMETRY?

- ▶ Charge Conjugation (C) $e^{-} \leftrightarrow e^{+}$
- ▶ If you swapped every matter particle with its antimatter particle and vice versa, could you tell the difference?

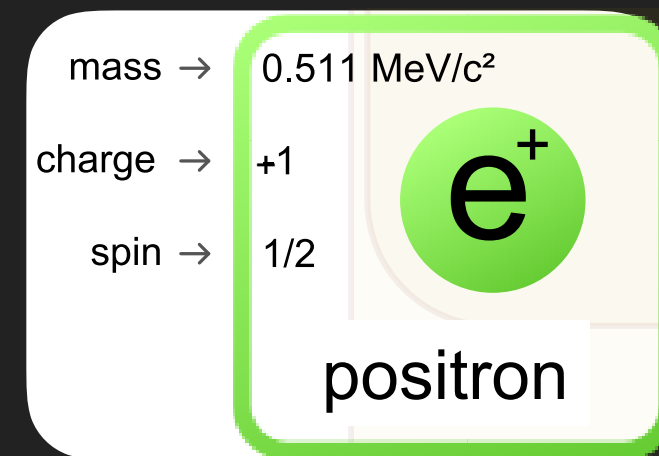
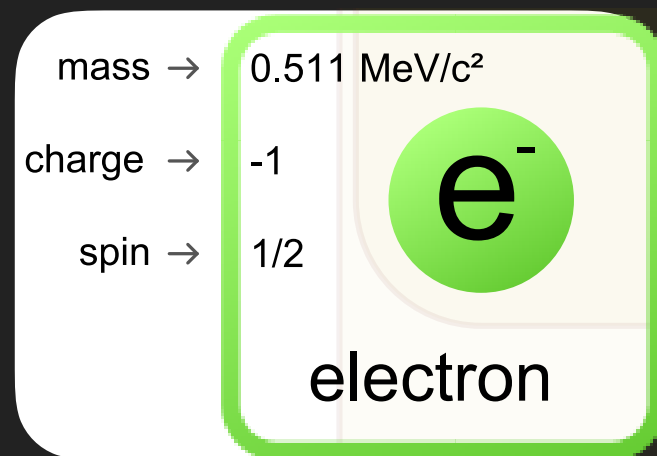
A visualization of the cosmic web, showing a complex network of dark matter filaments and galaxy clusters. The filaments are depicted as glowing purple and blue lines, while the clusters are shown as bright yellow and orange regions. The background is a deep black space filled with numerous small, distant stars.

ANTIMATTER

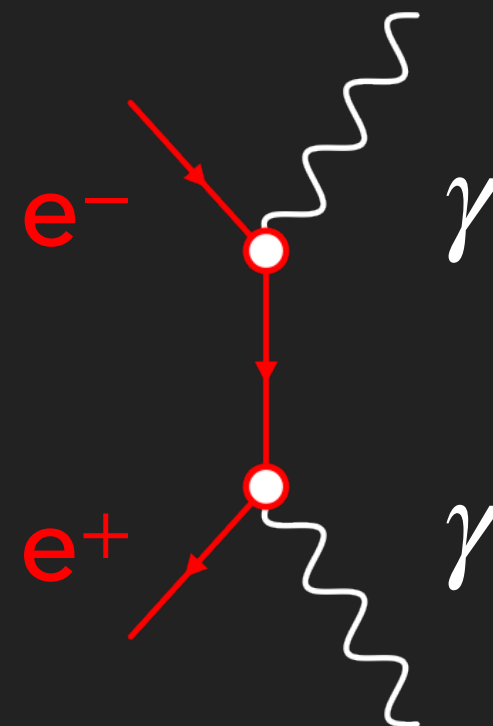
WHAT IS ANTIMATTER?

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



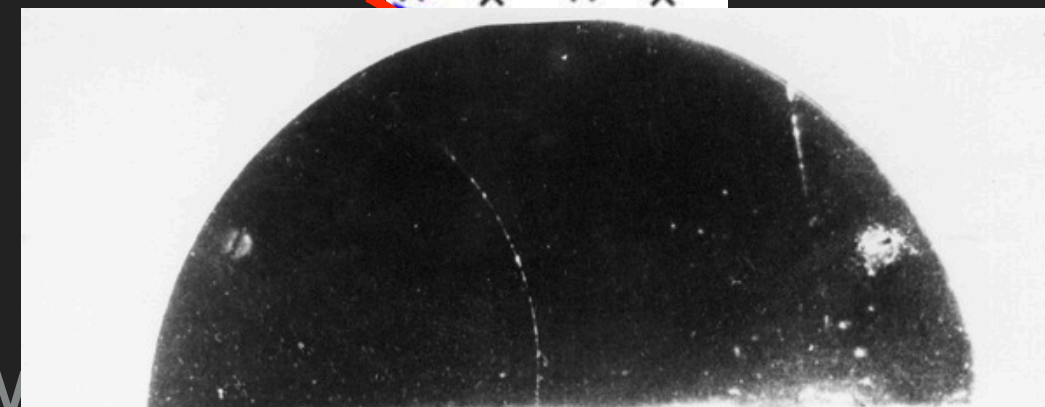
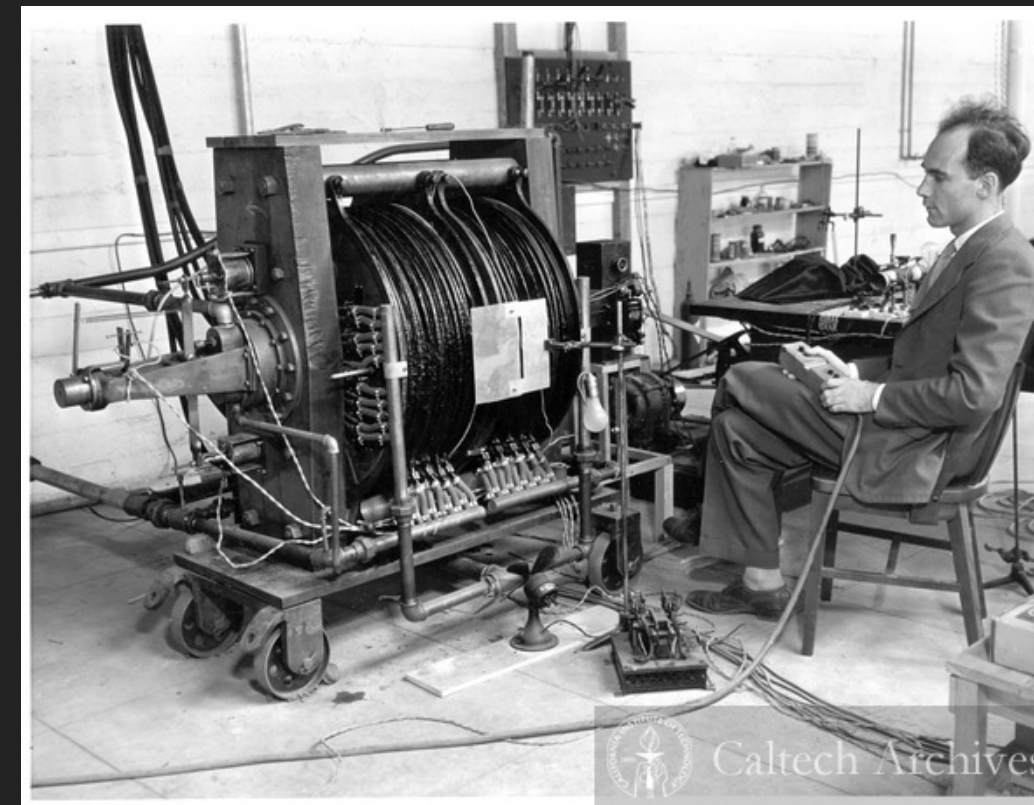
- ▶ A particle and its antiparticle can annihilate into a pair of light particles (*photons*)



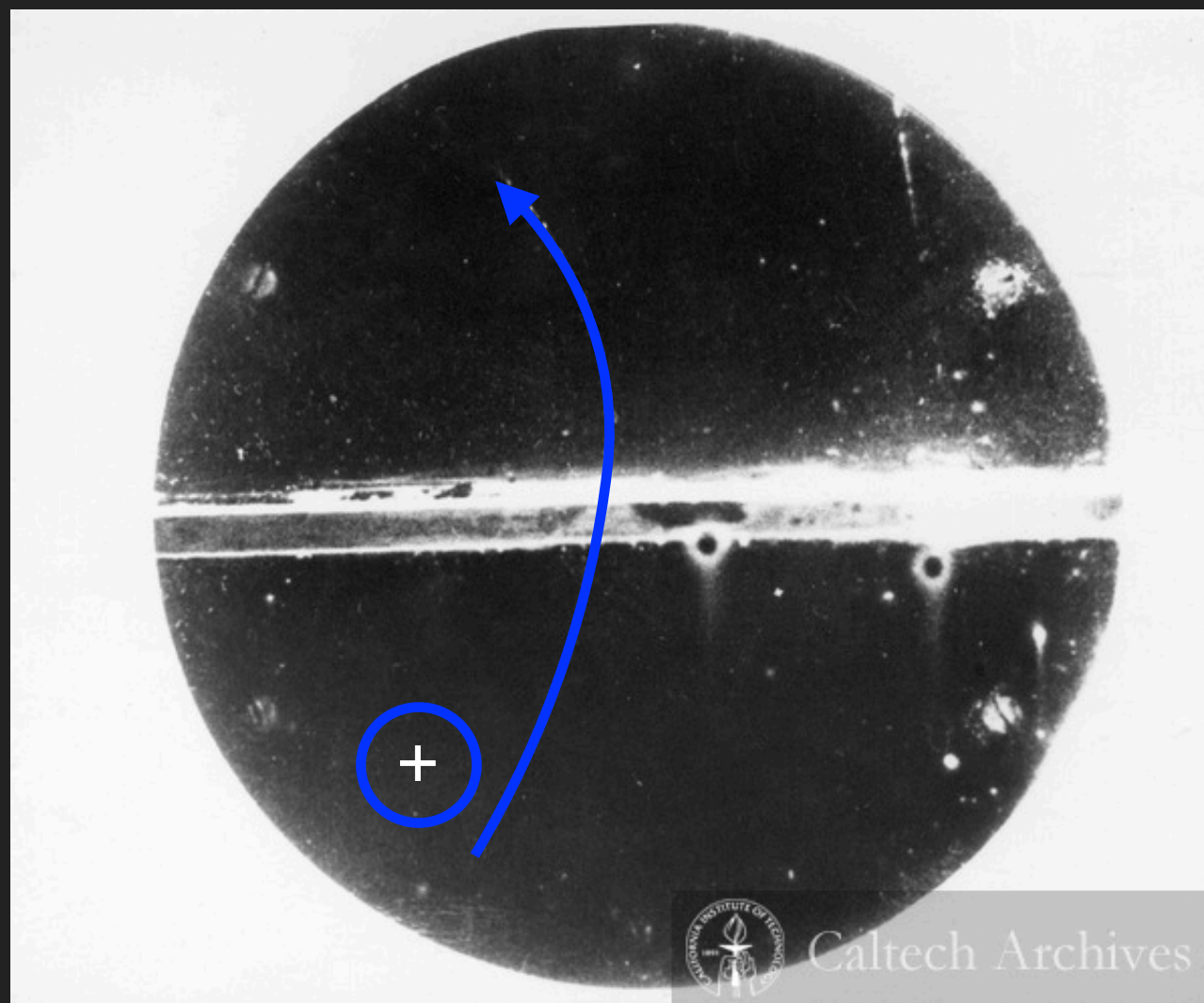
DISCOVERY OF ANTIMATTER

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- ▶ Carl Anderson observed tracks from cosmic rays in his bubble chamber at Caltech in 1932
- ▶ Charged particles bend in a magnetic field
- ▶ At the time, only protons (+) and electrons (−) were known, but protons make “thick” tracks
- ▶ Two possibilities:
 - ▶ a negative electron moving down
 - ▶ a “positive” electron moving up

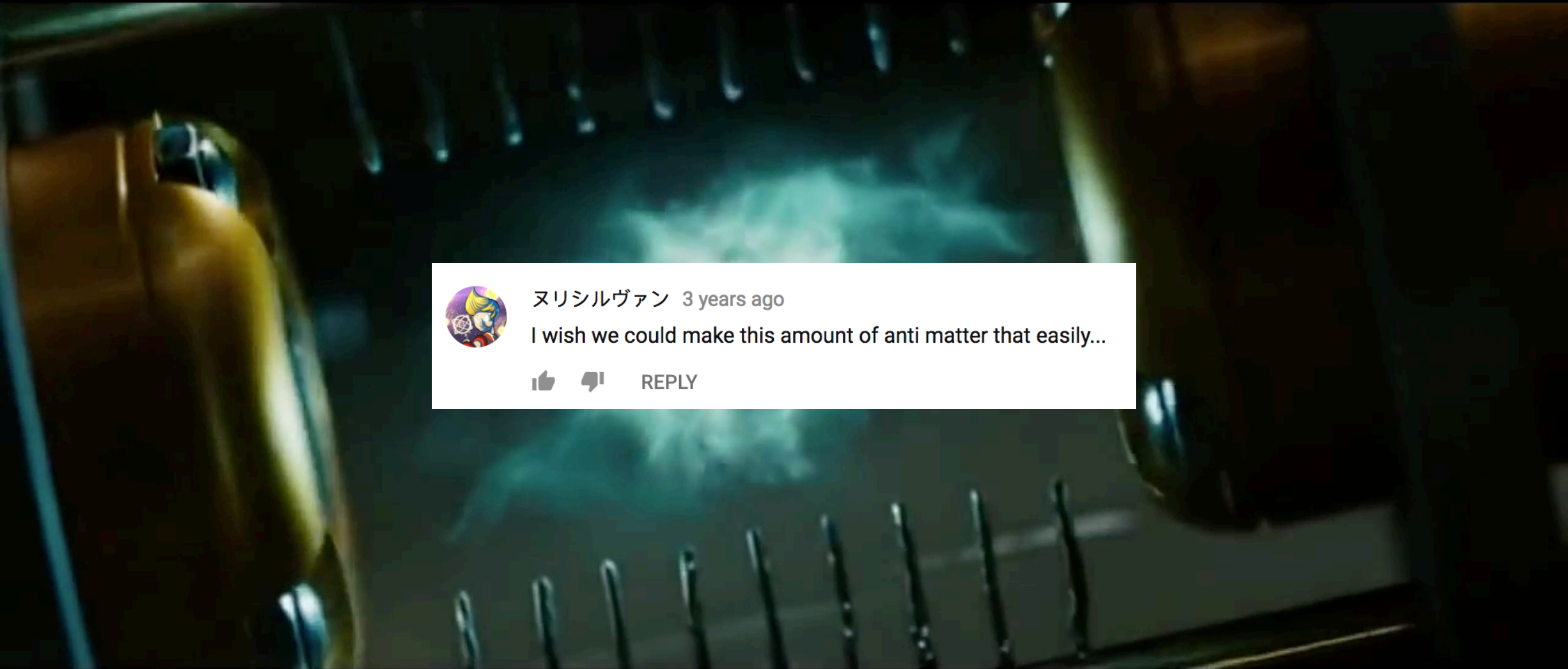


- ▶ To determine which it was, Anderson inserted a block of lead, which slows down the particle and increases the curvature
- ▶ Which way is it going?



Angels & Demons (2009)

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



ヌリシルヴァン 3 years ago

I wish we could make this amount of anti matter that easily...



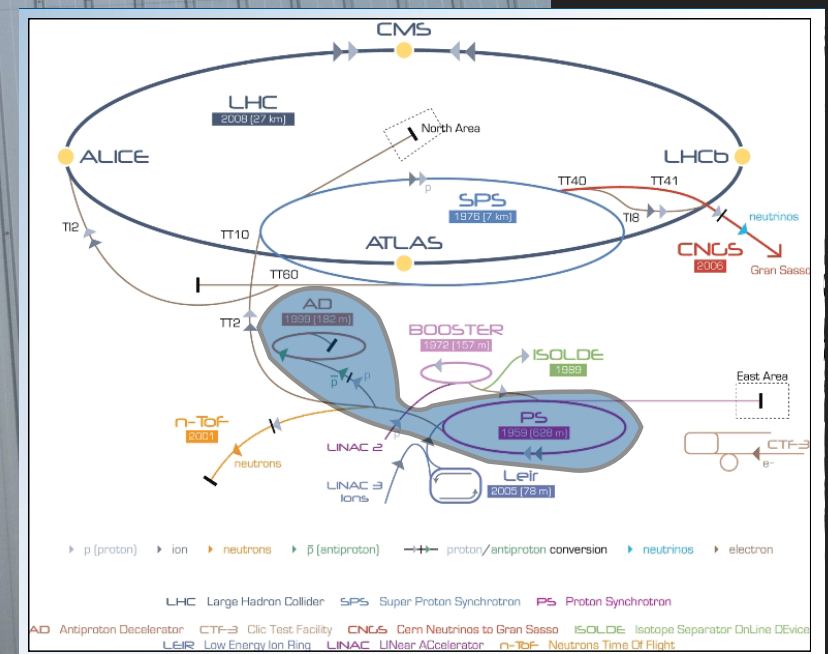
REPLY

1 gram of antimatter

HOW DO WE MAKE ANTIMATTER?

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- At the antimatter factory of course!



HOW DO WE MAKE ANTIMATTER?

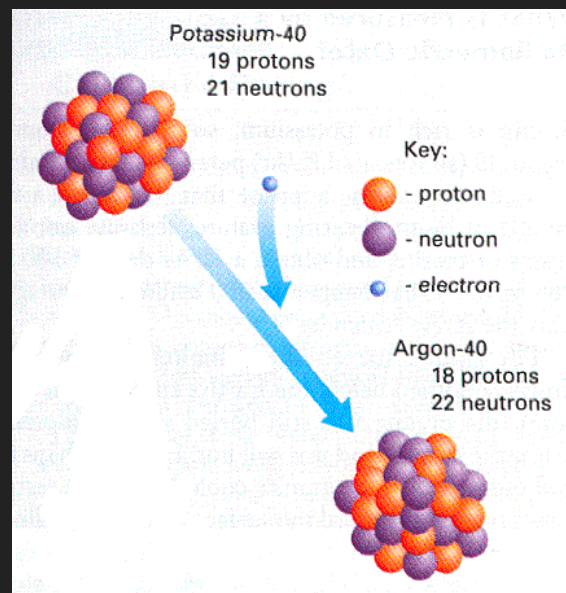
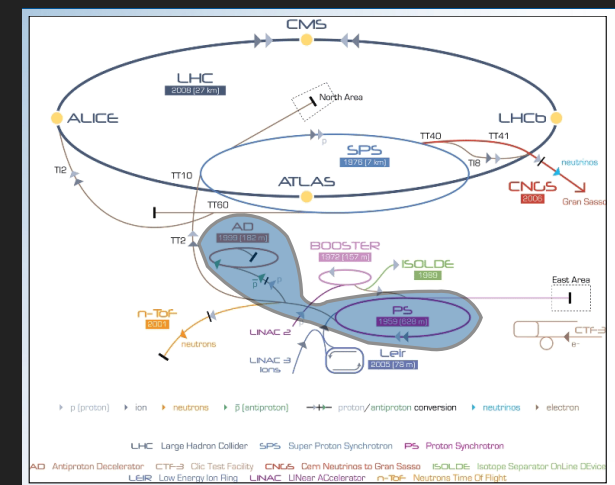
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► Some antimatter is easier to produce than others...

► 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

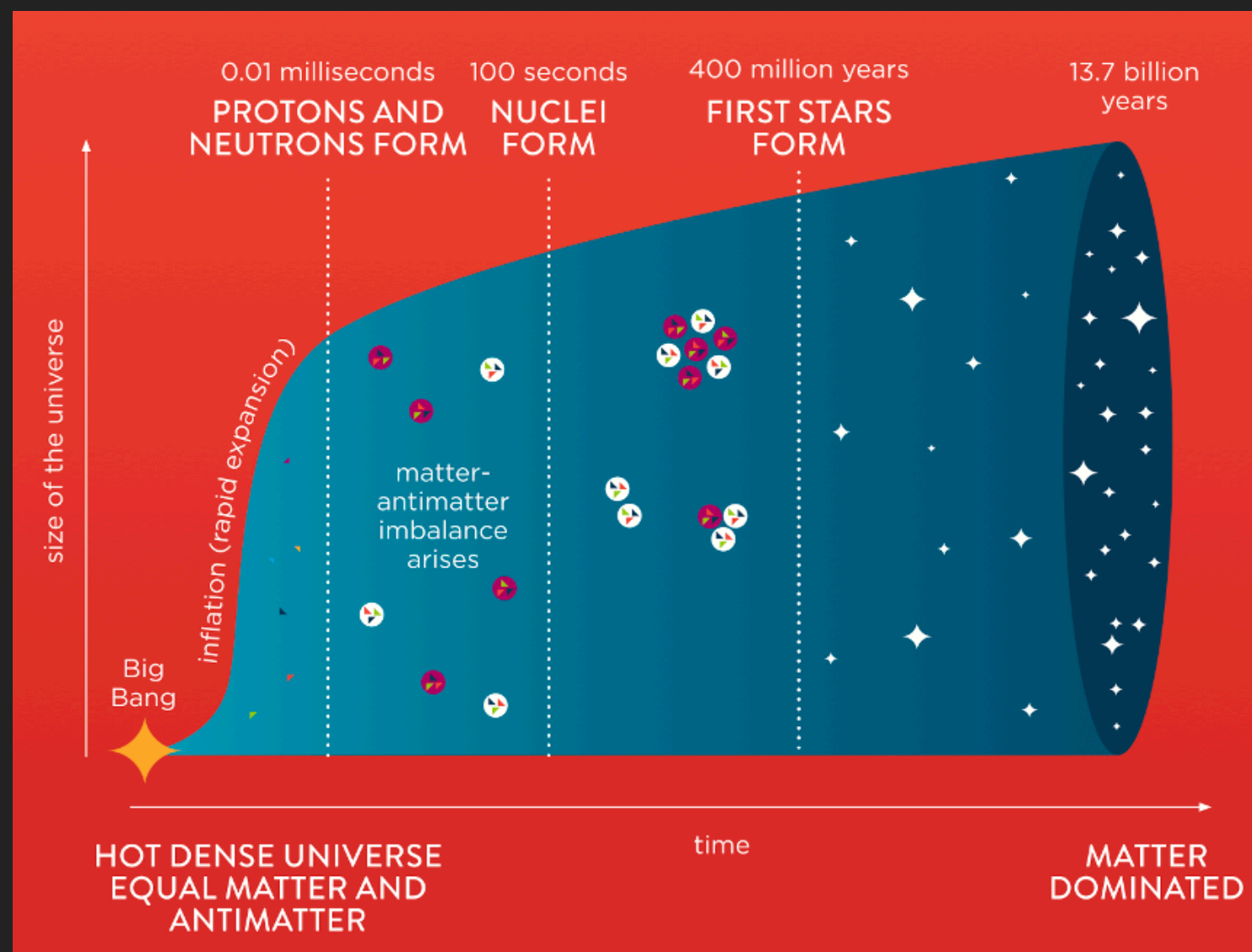


- ▶ Even if CERN used its accelerators only for making antimatter, it could produce no more than about 1 billionth of a gram per year
 - ▶ 1 gram of antimatter would take about 1 billion years!
- ▶ The total amount of antimatter produced in CERN's history is less than 10 nanograms - only enough energy to power a 60 W light bulb for 4 hours
- ▶ Making antimatter is tough work... if the laws of physics treat matter and antimatter the same, why isn't there a 50-50 mixture of matter and antimatter in the universe?

A visualization of the cosmic web, showing a complex network of dark matter filaments and galaxy clusters. The filaments are depicted as glowing, interconnected lines of purple and blue, with some brighter yellow and orange regions indicating denser areas of matter. The background is a deep black space filled with numerous small, distant stars.

THE MATTER-ANTIMATTER ASYMMETRY

- ▶ 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!!!

- ▶ 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 \rightarrow green + green
 - ▶ green + green \rightarrow blue + red
 - ▶ (if green particles have enough energy to produce two particles, $E > 2mc^2$)
- ▶ 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?

- ▶ 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 \rightarrow green + green
 - ▶ green + green \rightarrow blue + red
 - ▶ (if green particles have enough energy to produce two particles, $E > 2mc^2$)
- ▶ 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?

- ▶ 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 \rightarrow green + green
 - ▶ green + green \rightarrow blue + red (80% of the time)
 - ▶ green + green \rightarrow blue + blue (20% 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?

- ▶ Scenario A: equal amounts of matter and antimatter at the Big Bang produces a radiation-filled universe today
- ▶ Scenario B: more matter than antimatter at the Big Bang could produce a matter-filled universe today
- ▶ Scenario C: asymmetric interaction laws that favor matter could produce a matter-filled universe today
- ▶ Are we in scenario B or C?
 - ▶ We don't know yet! We have found some **matter-antimatter asymmetric interactions**, but so far it's not enough to explain the discrepancy!

- ▶ Have we accounted for all possible symmetries of our universe?
- ▶ In 1967, it seemed that way...

- ▶ It turns out that combining symmetries

PHYSICAL REVIEW

VOLUME 159, NUMBER 5

25 JULY 1967

All Possible Symmetries of the S Matrix*

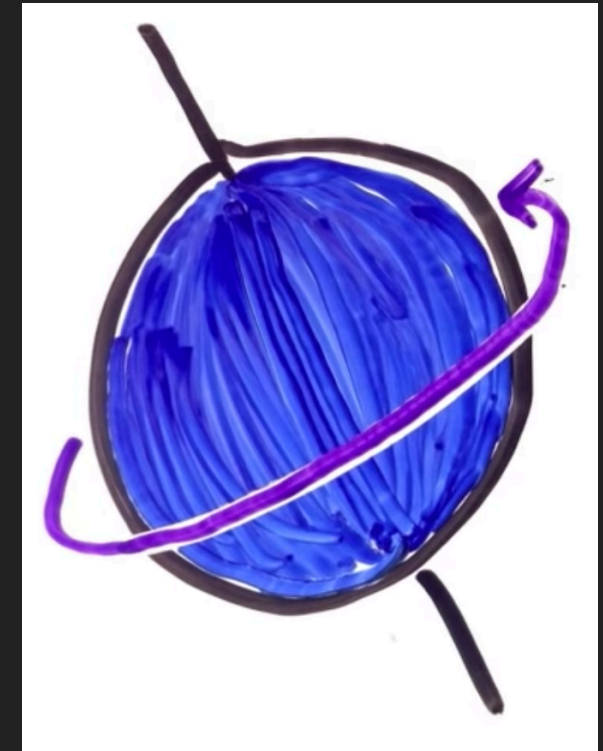
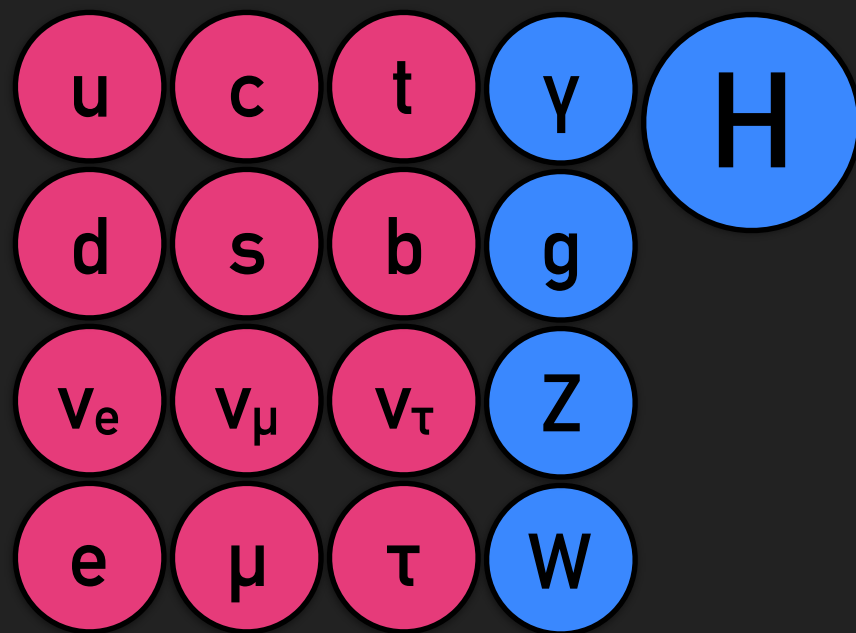
SIDNEY COLEMAN[†] AND JEFFREY MANDULA[‡]

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts

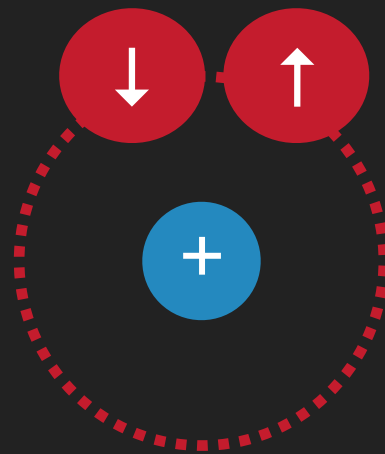
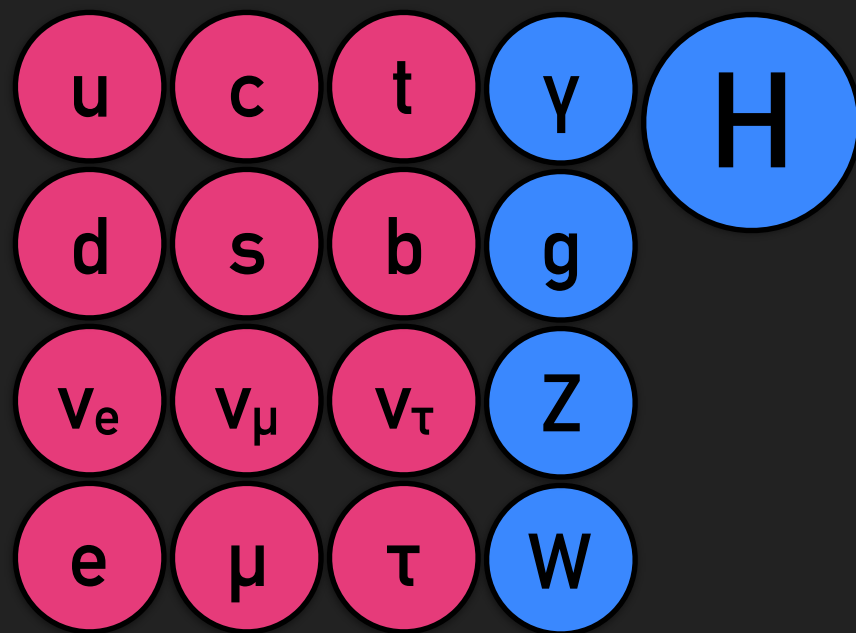
(Received 16 March 1967)

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.

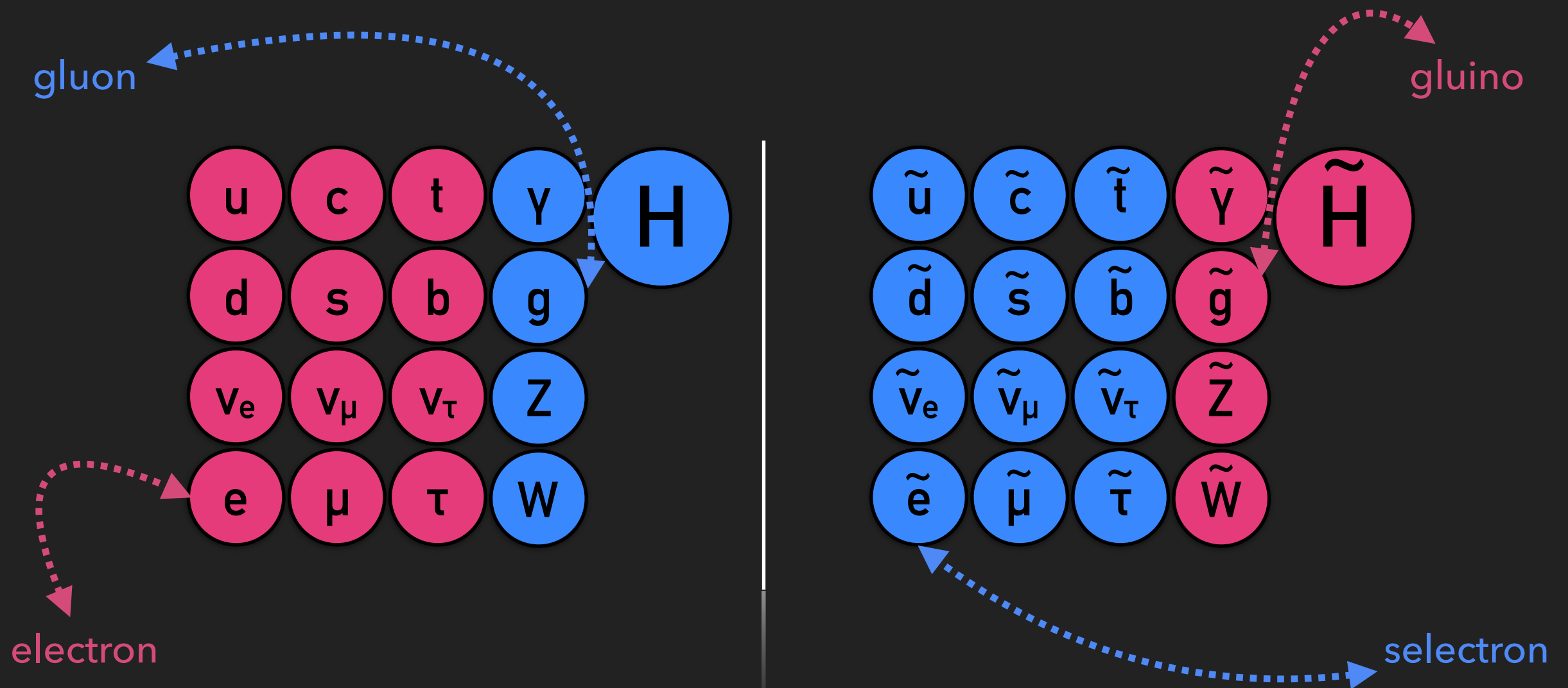
SUPERSYMMETRY



- ▶ Two kinds of particles: **fermions** and **bosons**
- ▶ **Fermions** have spin (quantum mechanical angular momentum) = $\hbar/2, 3\hbar/2, \dots$
- ▶ **Bosons** have spin = $0, \hbar, 2\hbar, \dots$



- ▶ **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!

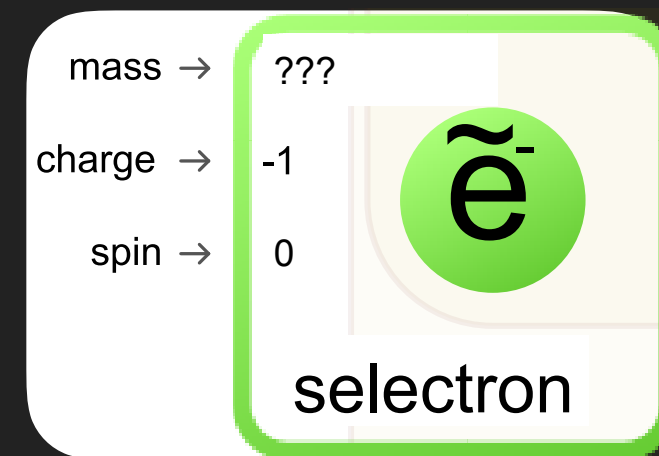
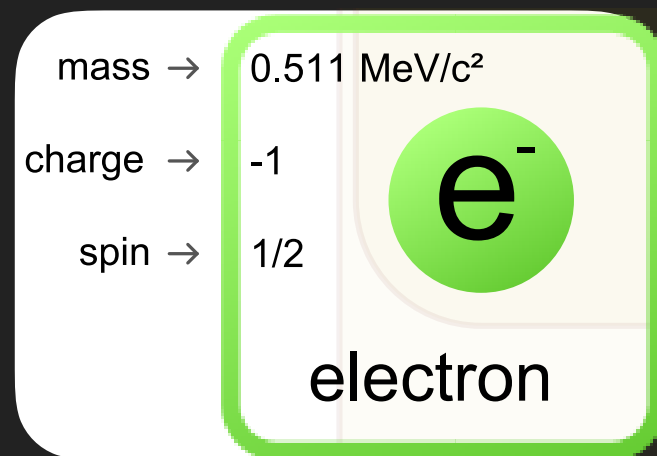


- Can we relate **fermions** (matter) and **bosons** (forces)?
 - Yes, via ***supersymmetry***: for every **fermion**, there exists a corresponding "superpartner" **boson** (and vice versa) with the same properties except one: the spin

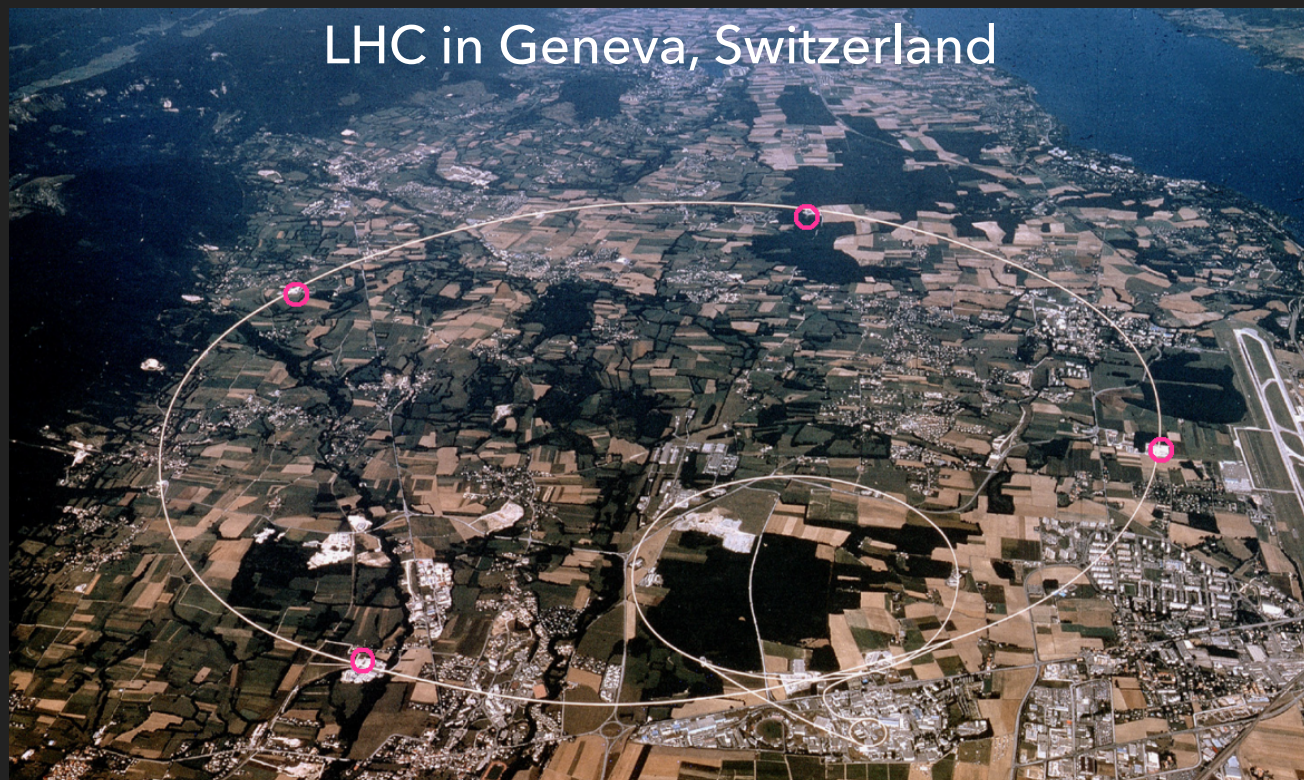
WHAT IS A SUPERPARTNER?

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



- ▶ But we would've seen such a particle! So supersymmetry must be a ***broken symmetry***: the masses are also different!
- ▶ The ***selectron*** must be much heavier



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

- ▶ Search has been on for supersymmetry for over 40 years... including my thesis!
- ▶ It may take the next generation of energy collider experiments (and some of you in the audience) to discover supersymmetry!
- ▶ Thanks for listening!

- ▶ Michel Artin. Algebra. <https://www.pearson.com/us/higher-education/program/Artin-Algebra-Classic-Version-2nd-Edition/PGM1714687.html>
- ▶ Richard Feynman. The Feynman Lectures on Physics. <http://www.feynmanlectures.caltech.edu/>
- ▶ Chloe Malbrunot. Antimatter in the Lab. <https://indico.cern.ch/event/716587/> <https://indico.cern.ch/event/716588/>
- ▶ C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson. Phys. Rev. 105, 1413 (1957). <https://doi.org/10.1103/PhysRev.105.1413>