



# Introduction to Science at Fermilab and beyond

Pedro A. N. Machado

# Your brand new, perfectly working computer freezes out of nowhere. Why?

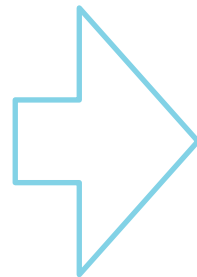
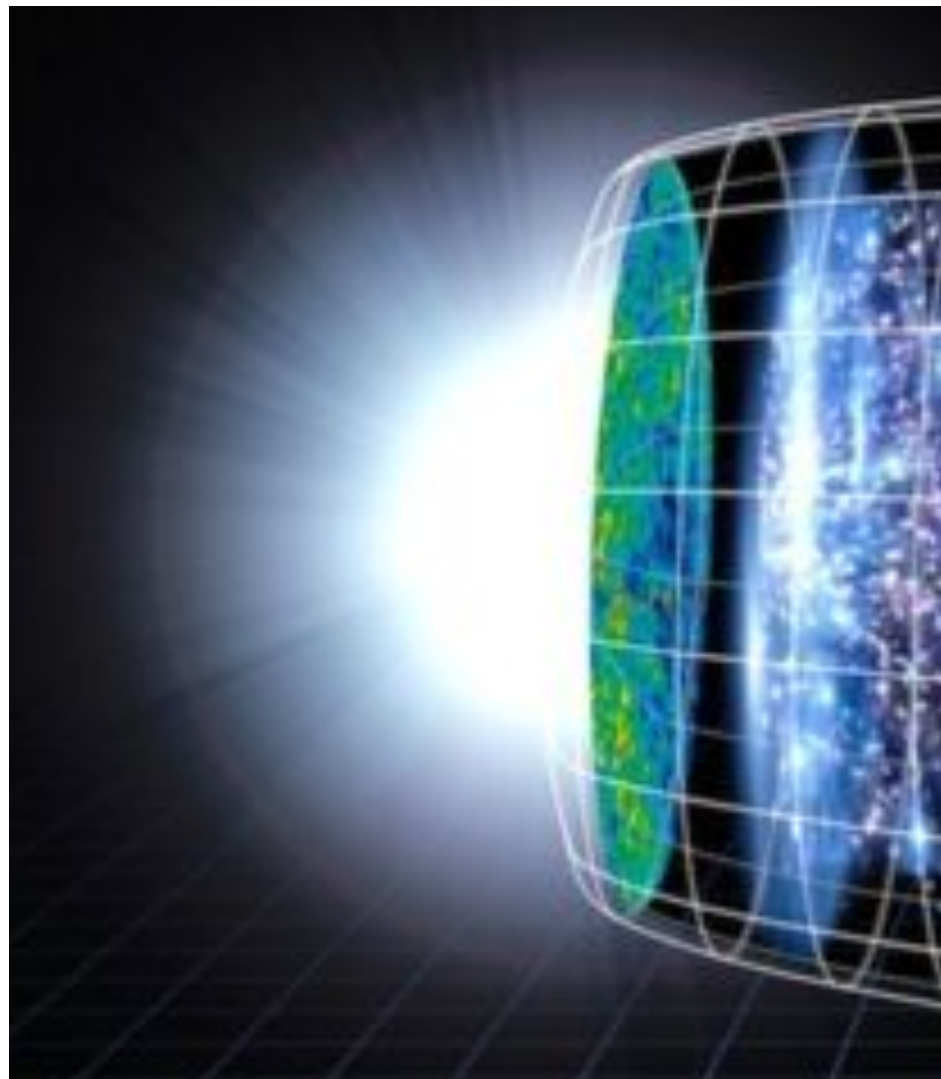
Hint: the culprit may be a few billion years old...



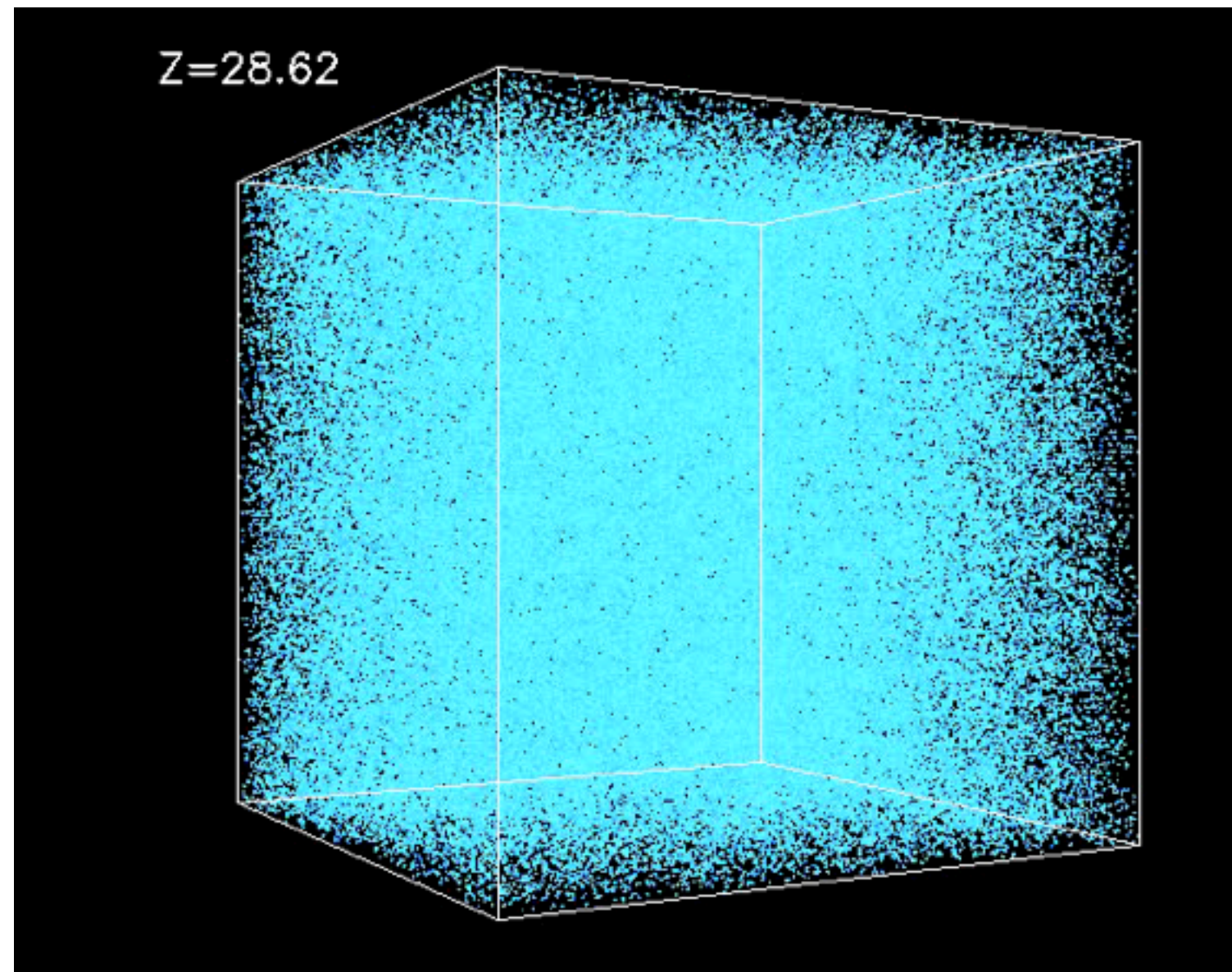
# Your brand new, perfectly working computer freezes out of nowhere. Why?

Hint: the culprit may be a few billion years old...

Universe goes kaboom  
(I mean, big bang)



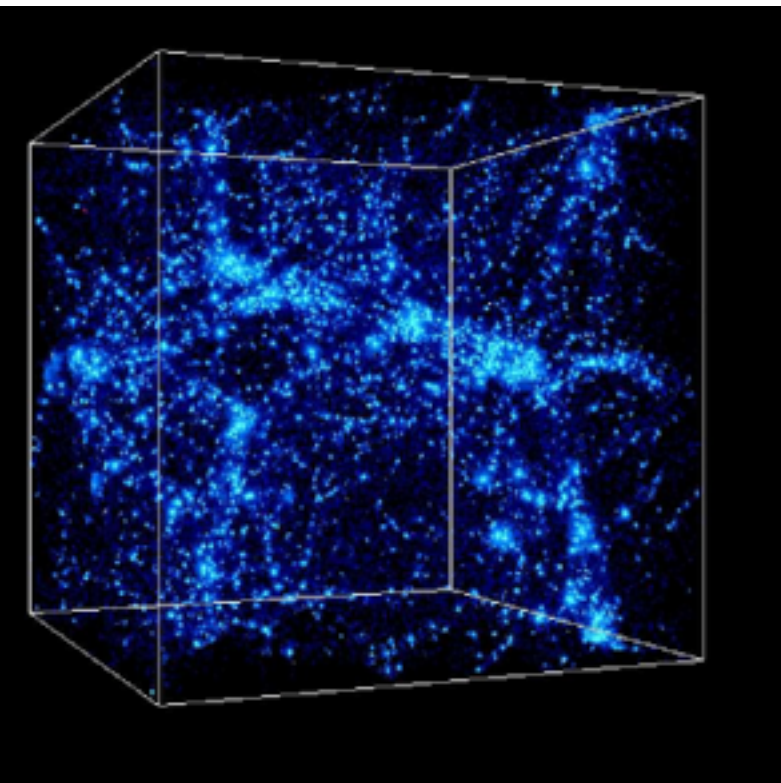
The presence of dark matter  
allows to form structure



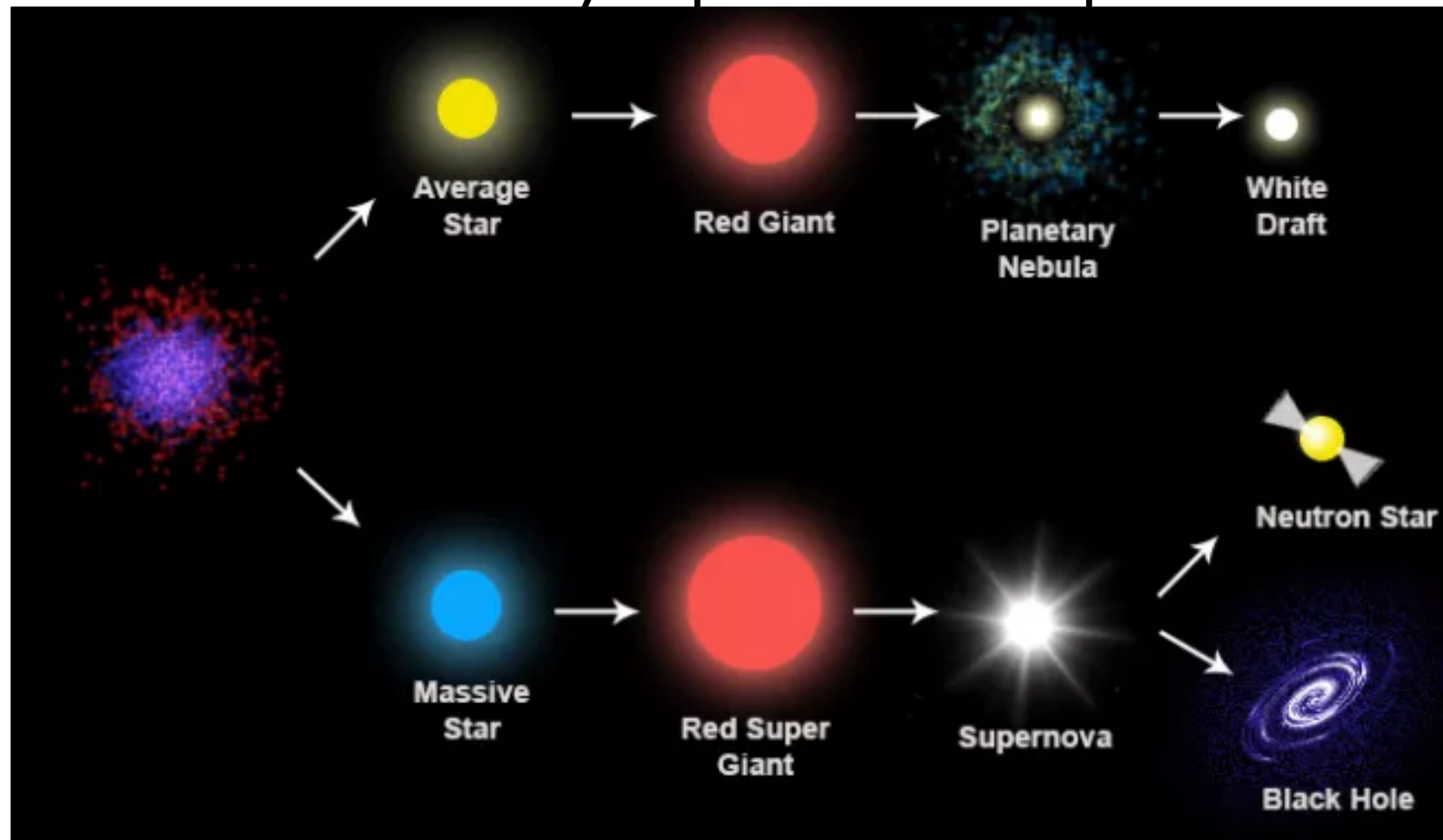
# Your brand new, perfectly working computer freezes out of nowhere. Why?

Hint: the culprit may be a few billion years old...

Structure (galaxies)  
form stars



Massive stars may explode into a supernova





# Your brand new, perfectly working computer freezes out of nowhere. Why?

Hint: the culprit may be a few billion years old...

SN explosion accelerate  
lots of debris (nuclei)



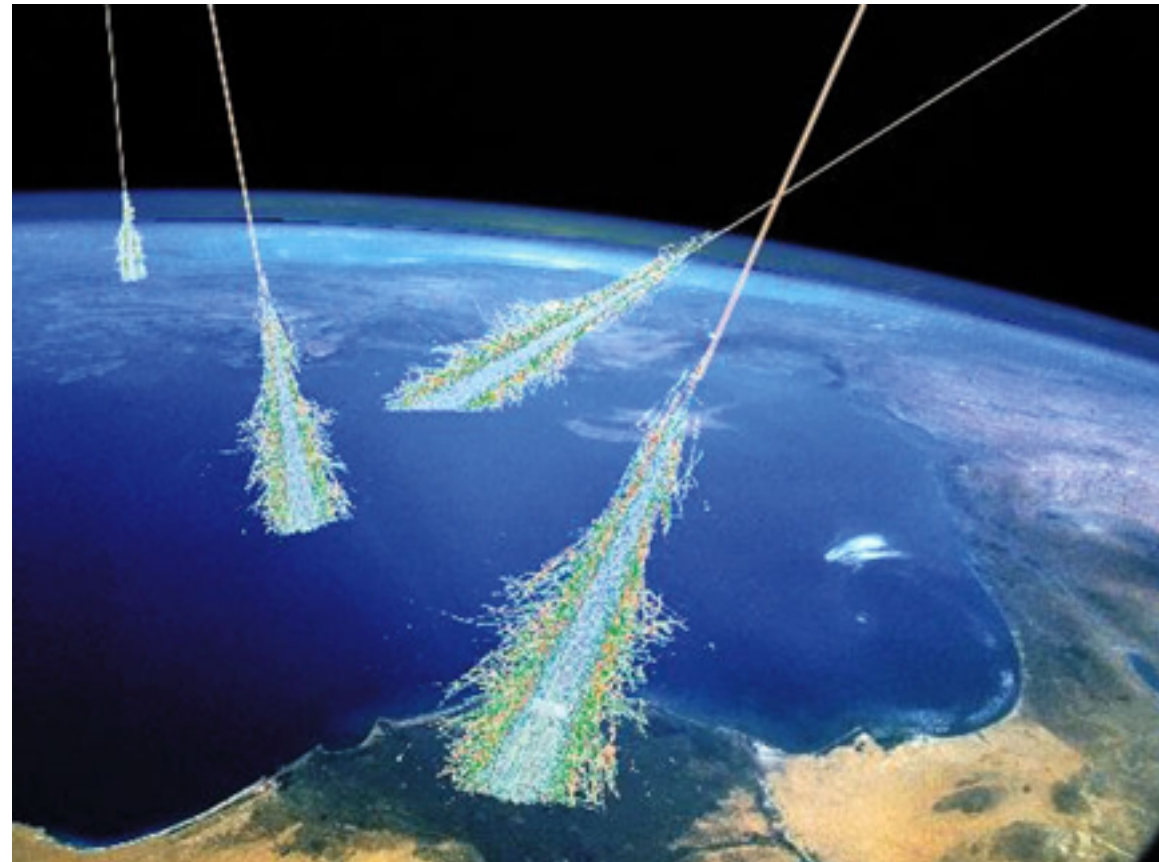
# Your brand new, perfectly working computer freezes out of nowhere. Why?

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When they reach the Earth, we call them cosmic rays





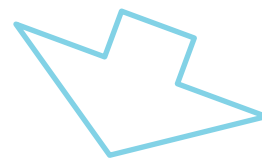
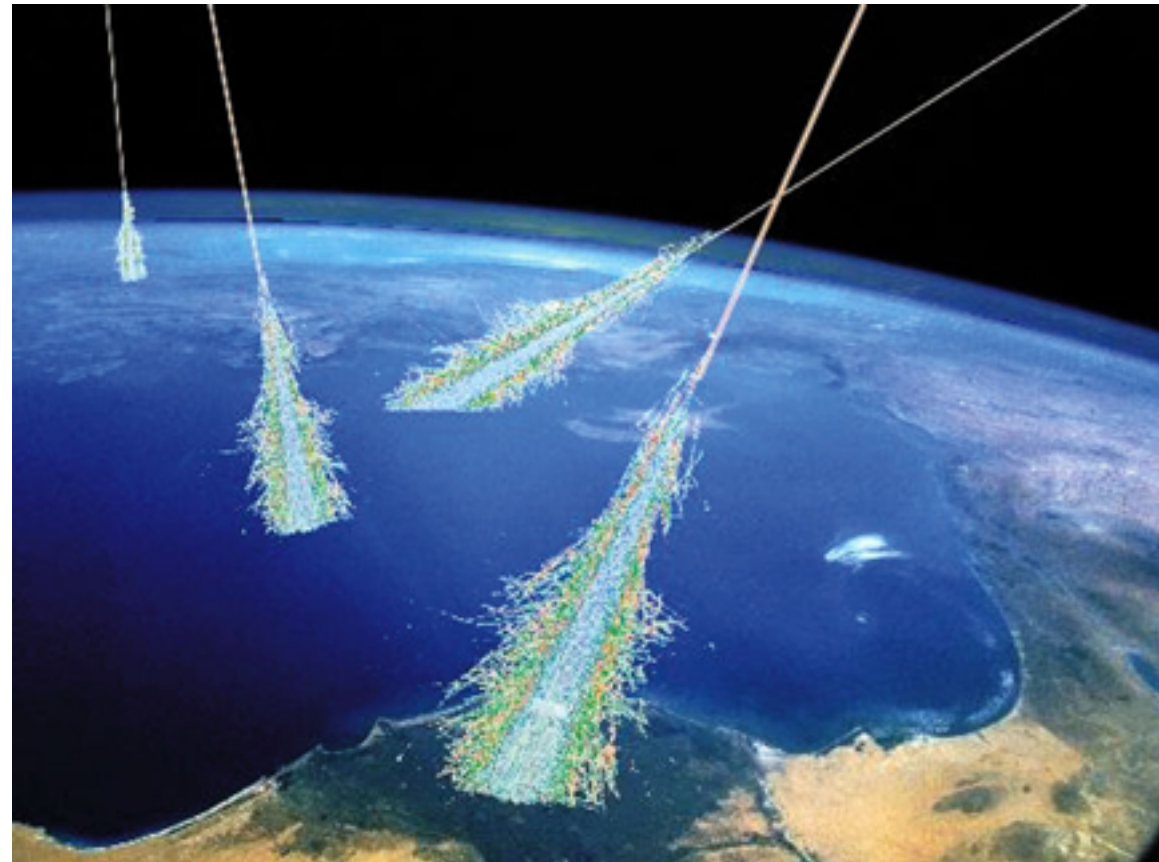
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SN explosion accelerate lots of debris (nuclei)



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Cosmic rays hitting your computer may flip a 0 to a 1 in the RAM memory and freeze it!!!

# Who am I?



# Who am I?

## Fortaleza, northeast of Brazil



## Federal University of Ceará



Join to science at Fermilab



# Who am I?

## São Paulo, southeast of Brazil



## University of São Paulo



and I spent some time in Paris  
(PhD) and Madrid (postdoc)



# Who am I?

- Associate scientist at Fermilab
- Theorist
- **Neutrinos**
- A bit of Higgs and dark matter

Gordan, friend and collaborator



- How to interpret experimental data in terms of specific theories
- Come up with theories that explain open questions in physics (where do neutrino masses come from?)
- Come up with new experimental setups and strategies

# What is science?





# What is science?

## From Wikipedia

Science (from Latin *scientia*, meaning "knowledge") is a systematic enterprise that builds and organizes knowledge in the form of testable explanations and predictions about the universe.



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## In summary:

blah blah blah blah blah blah blah blah blah blah blah blah blah blah  
blah blah blah blah blah blah blah blah blah blah blah blah blah blah  
blah blah blah blah blah

# What is science?

In my opinion science is the search for truth



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but there is a catch...

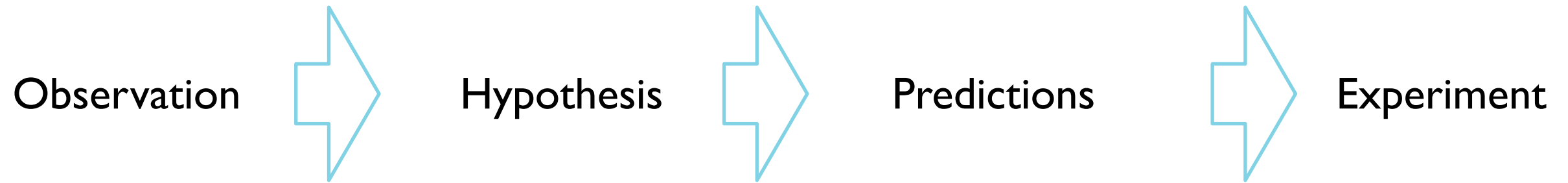
# What is science?

## How do we do it?

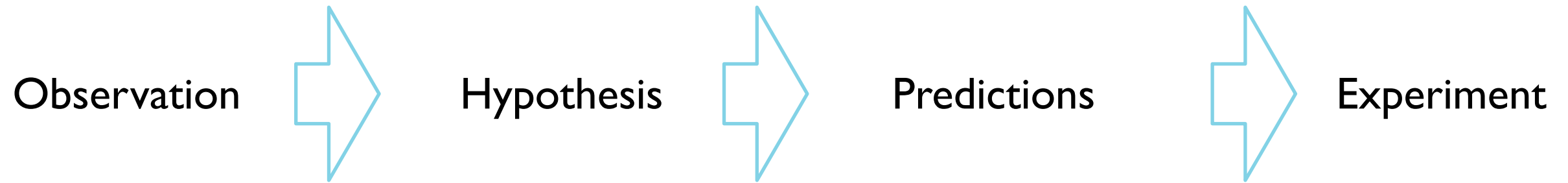
## The scientific method



# The scientific method



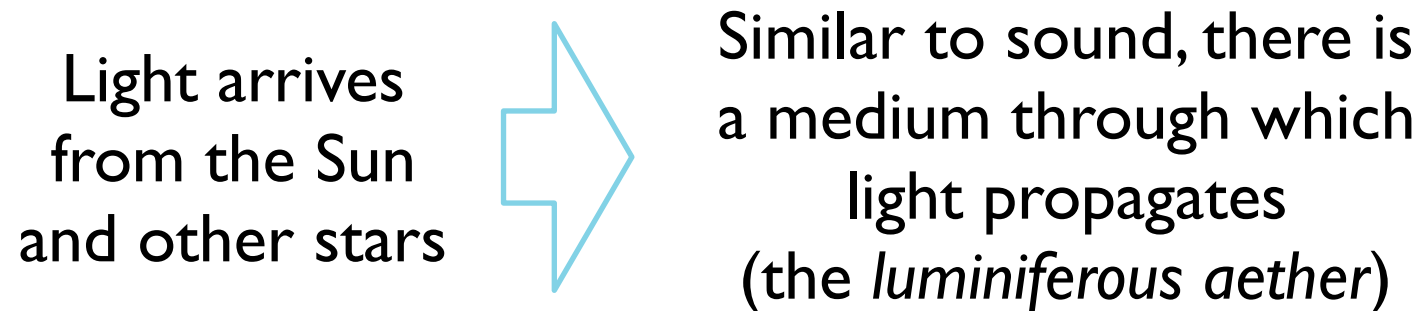
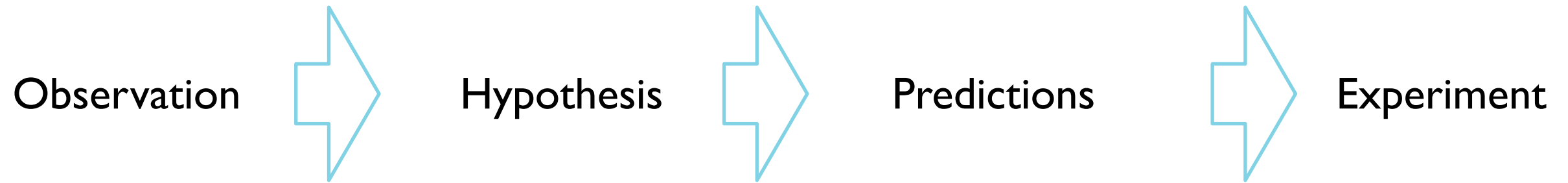
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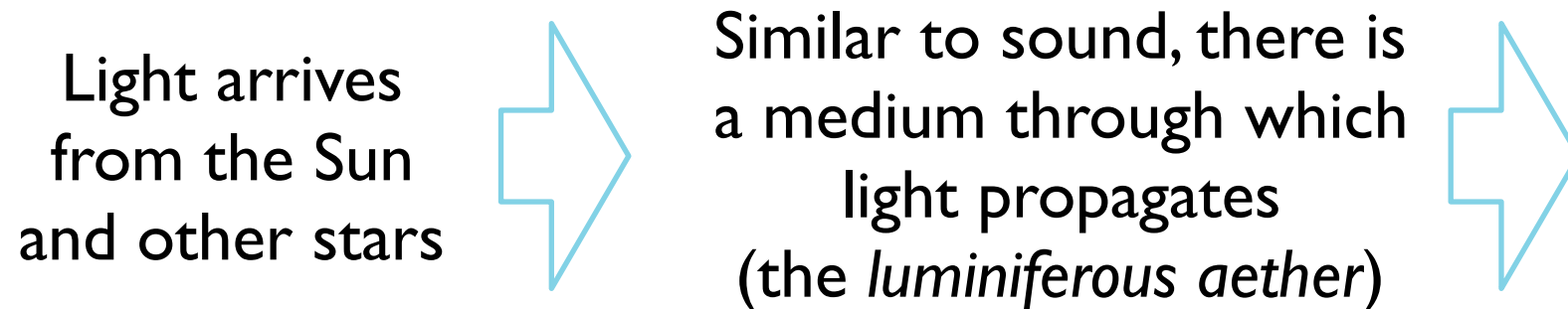
Light arrives  
from the Sun  
and other stars



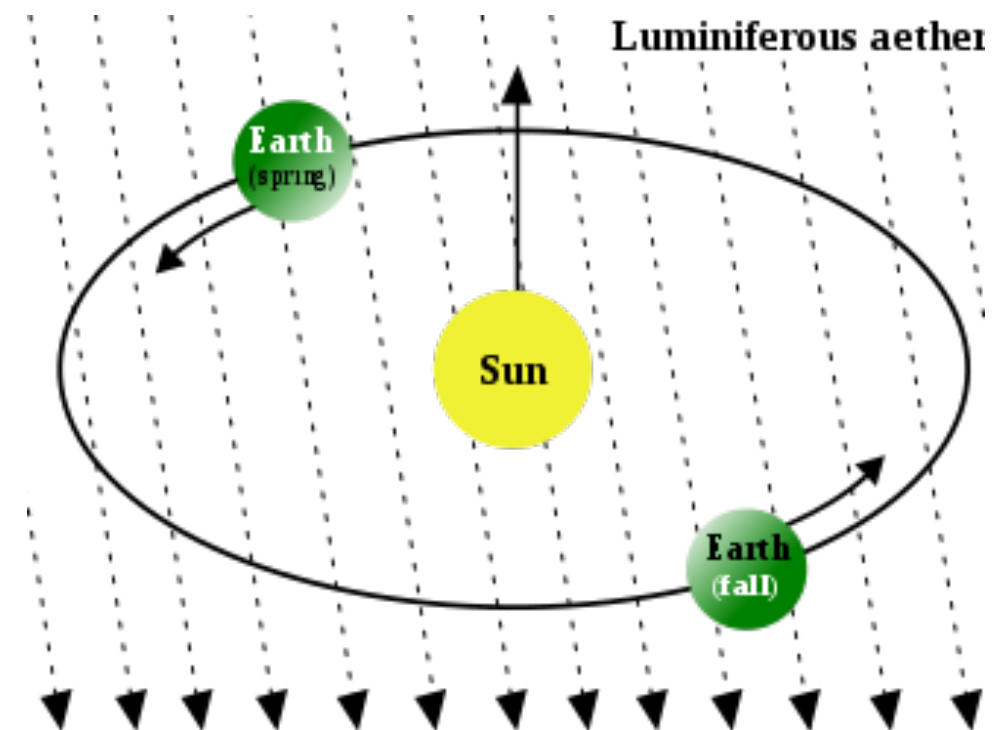
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# The scientific method

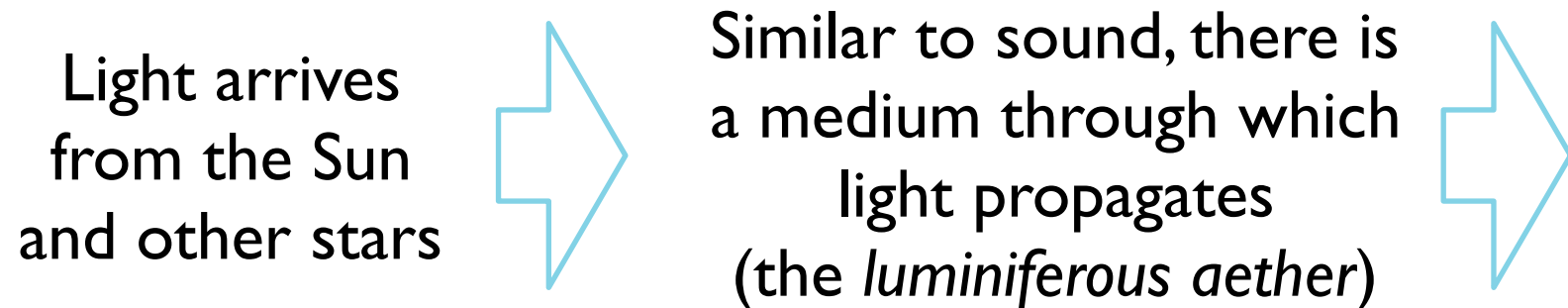


Since the Earth is moving through the aether, the speed of light depends on the direction it is emitted

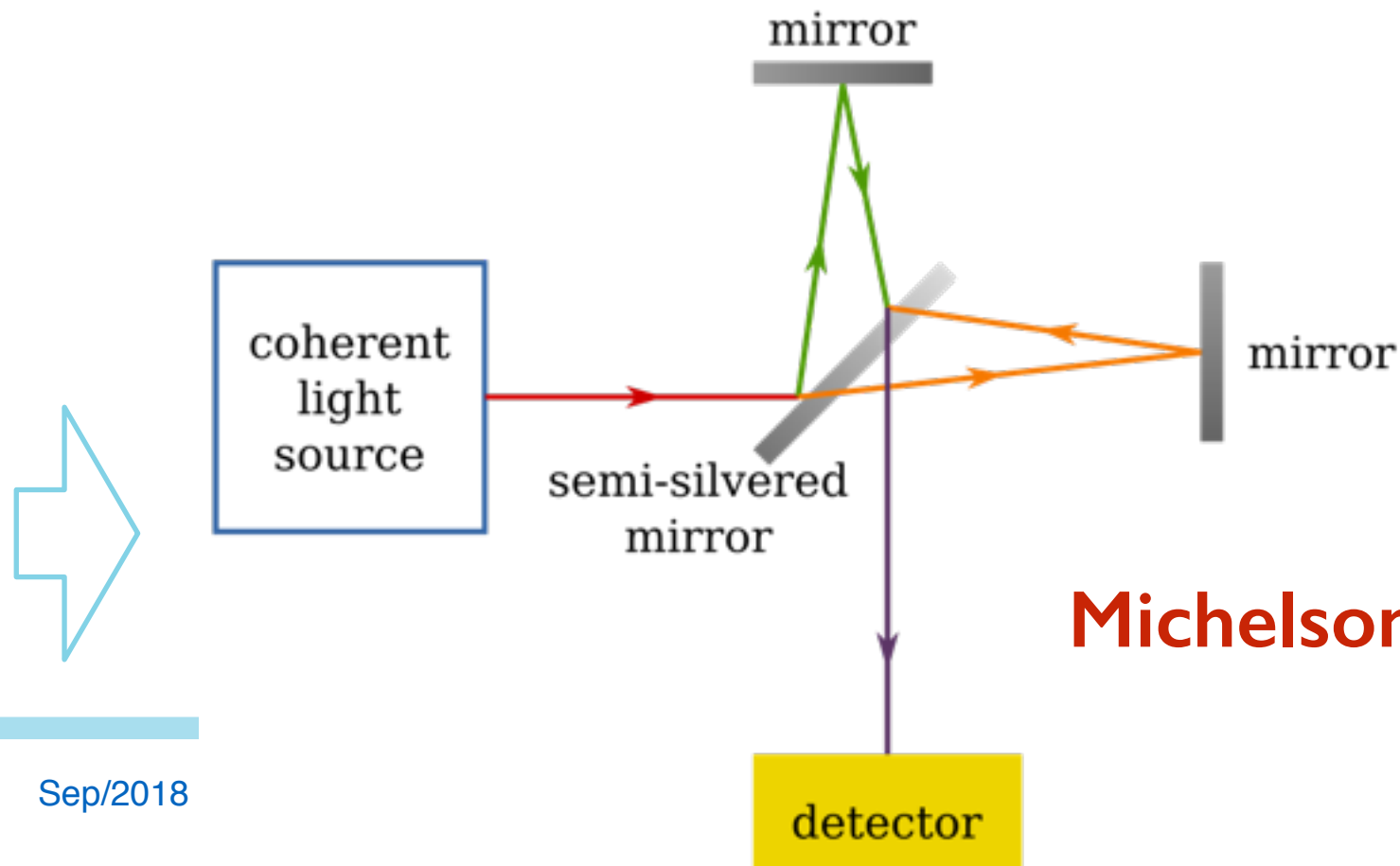
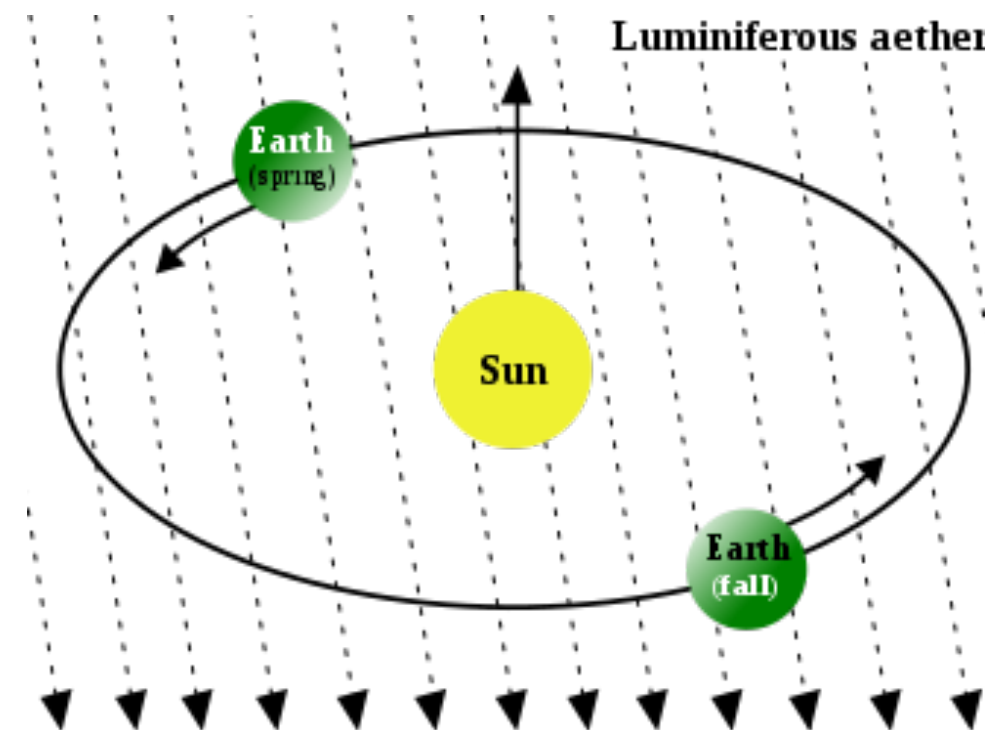




# The scientific method



Since the Earth is moving through the aether, the speed of light depends on the direction it is emitted



**Michelson-Morley experiment**

# The scientific method



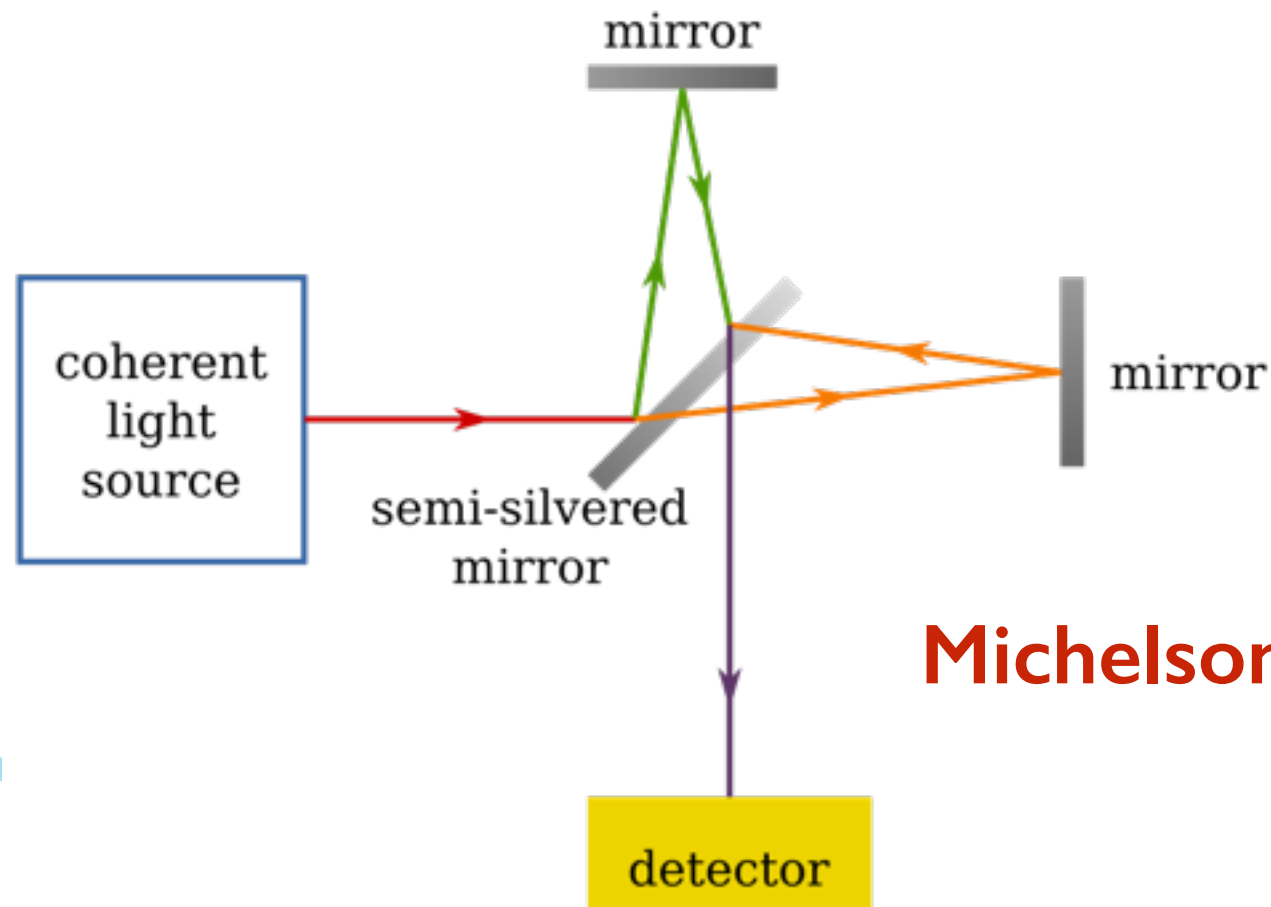
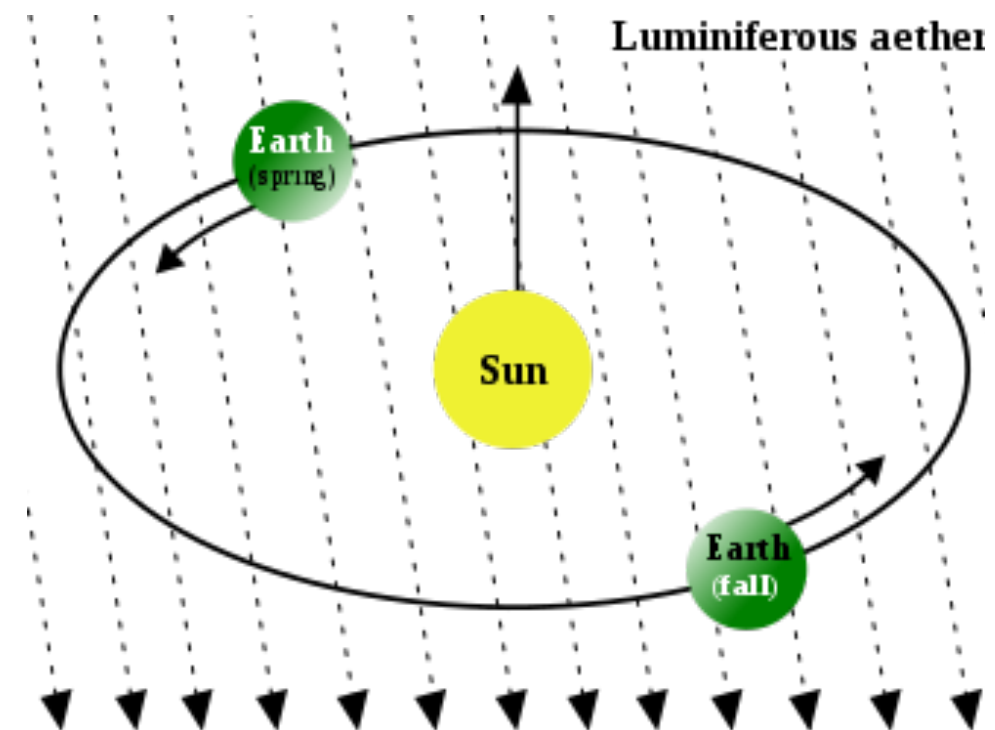
Light arrives from the Sun and other stars

Similar to

**Hypothesis rejected!**

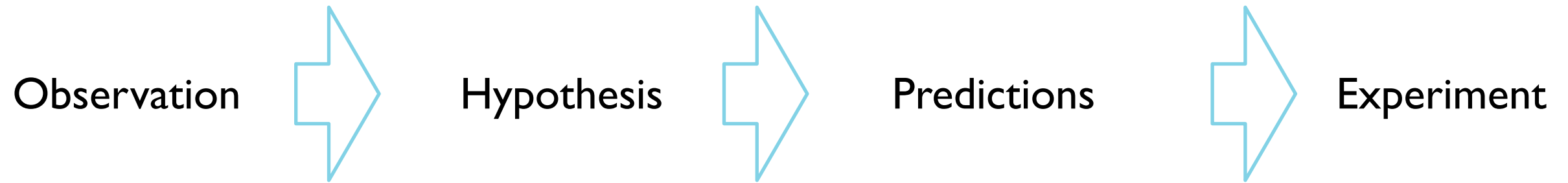
propagates (the *luminiferous aether*)

Since the Earth is moving through the aether, the speed of light depends on the direction it is emitted



**Michelson-Morley experiment**

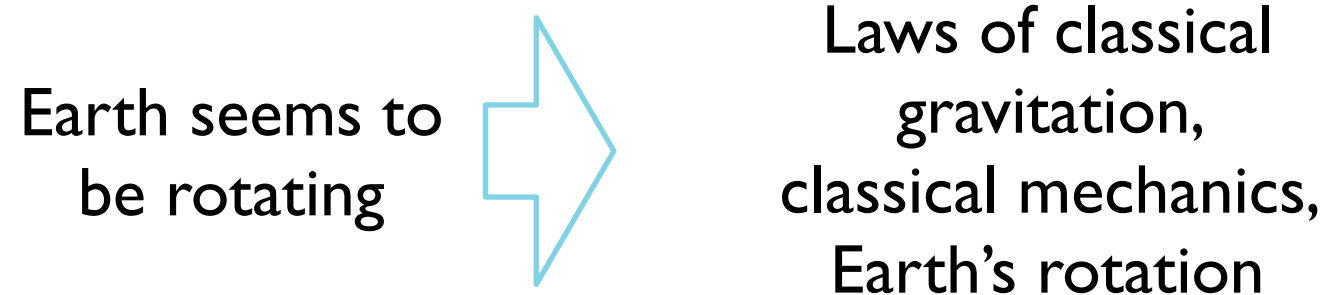
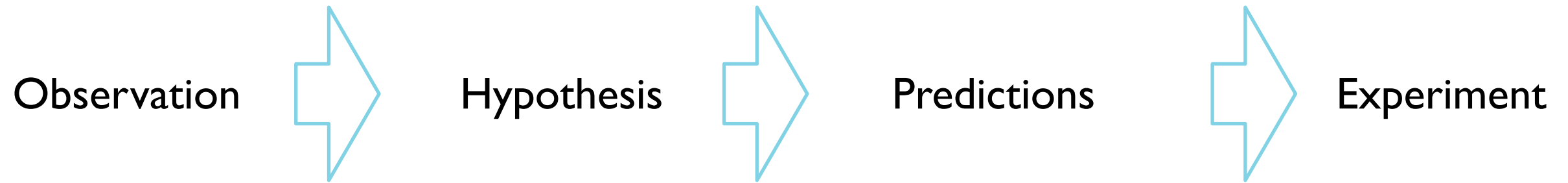
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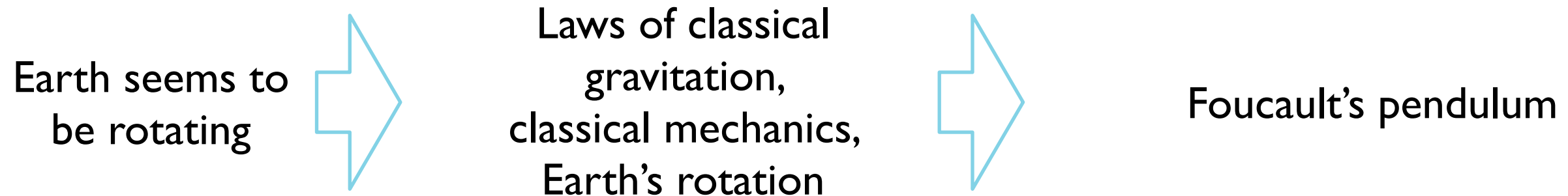
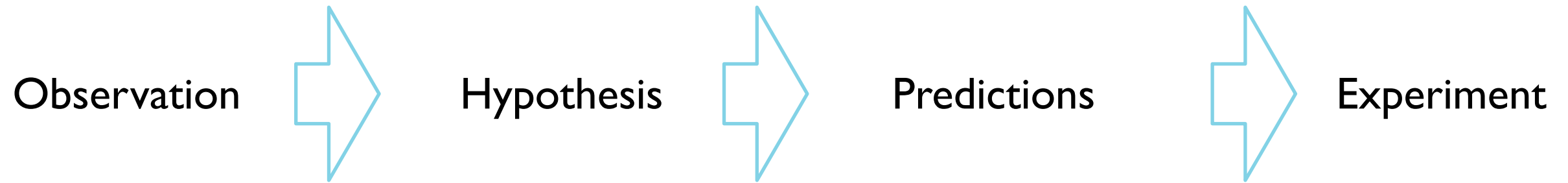
Earth seems to  
be rotating



# The scientific method

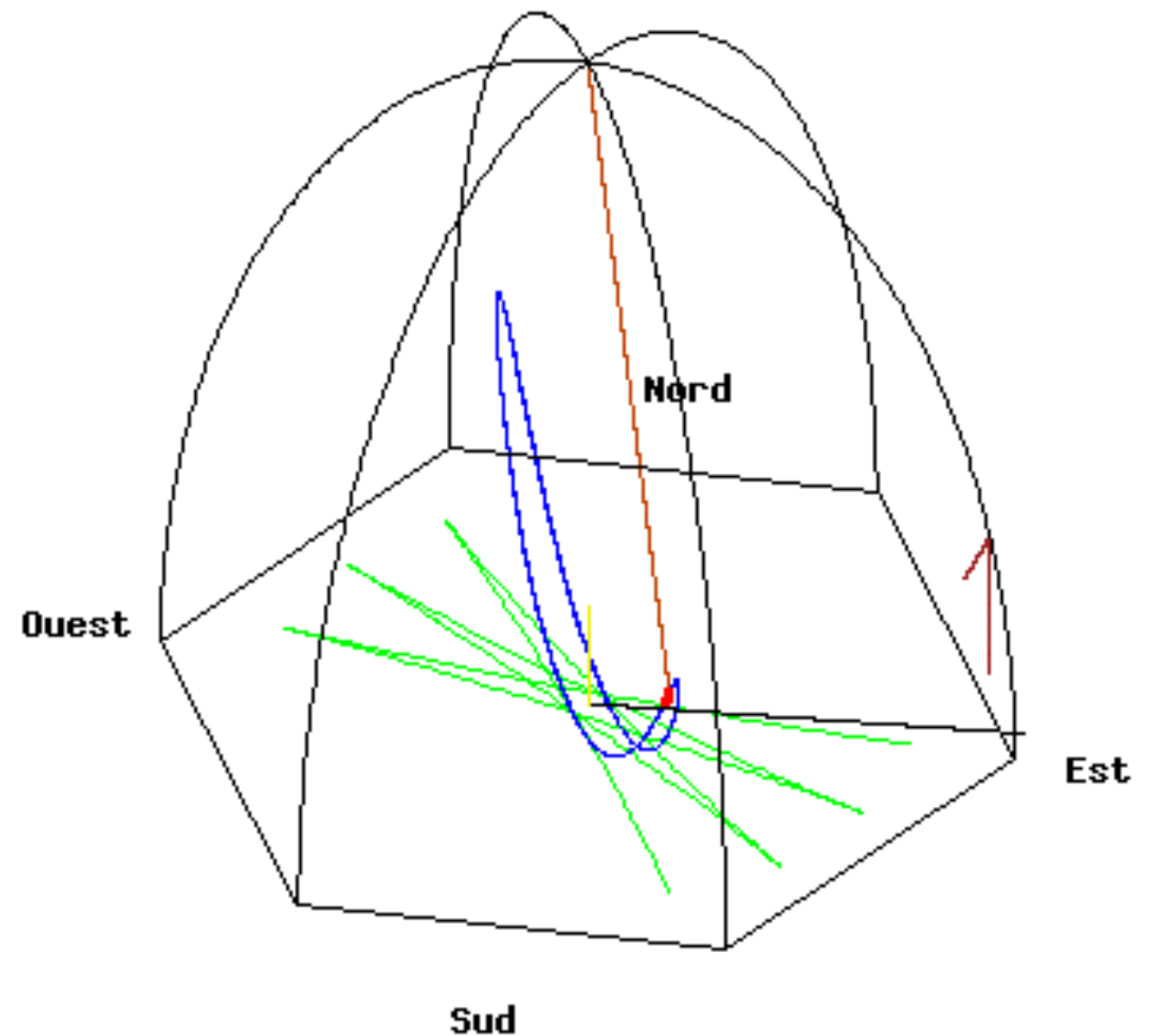
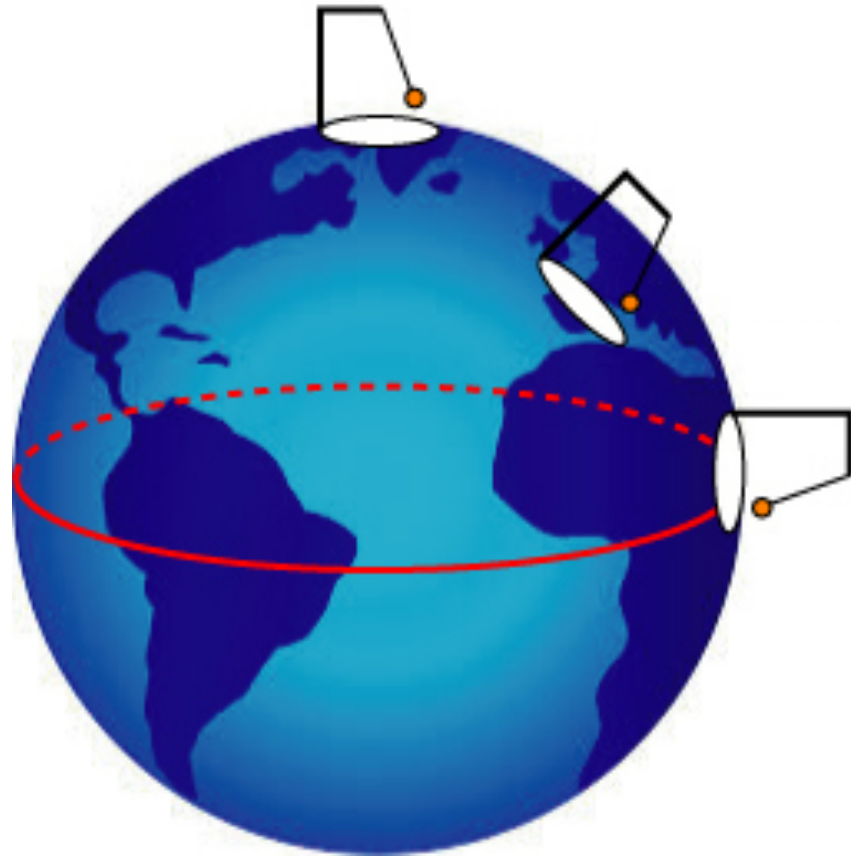


# The scientific method



# Foucault's Pendulum (1851)

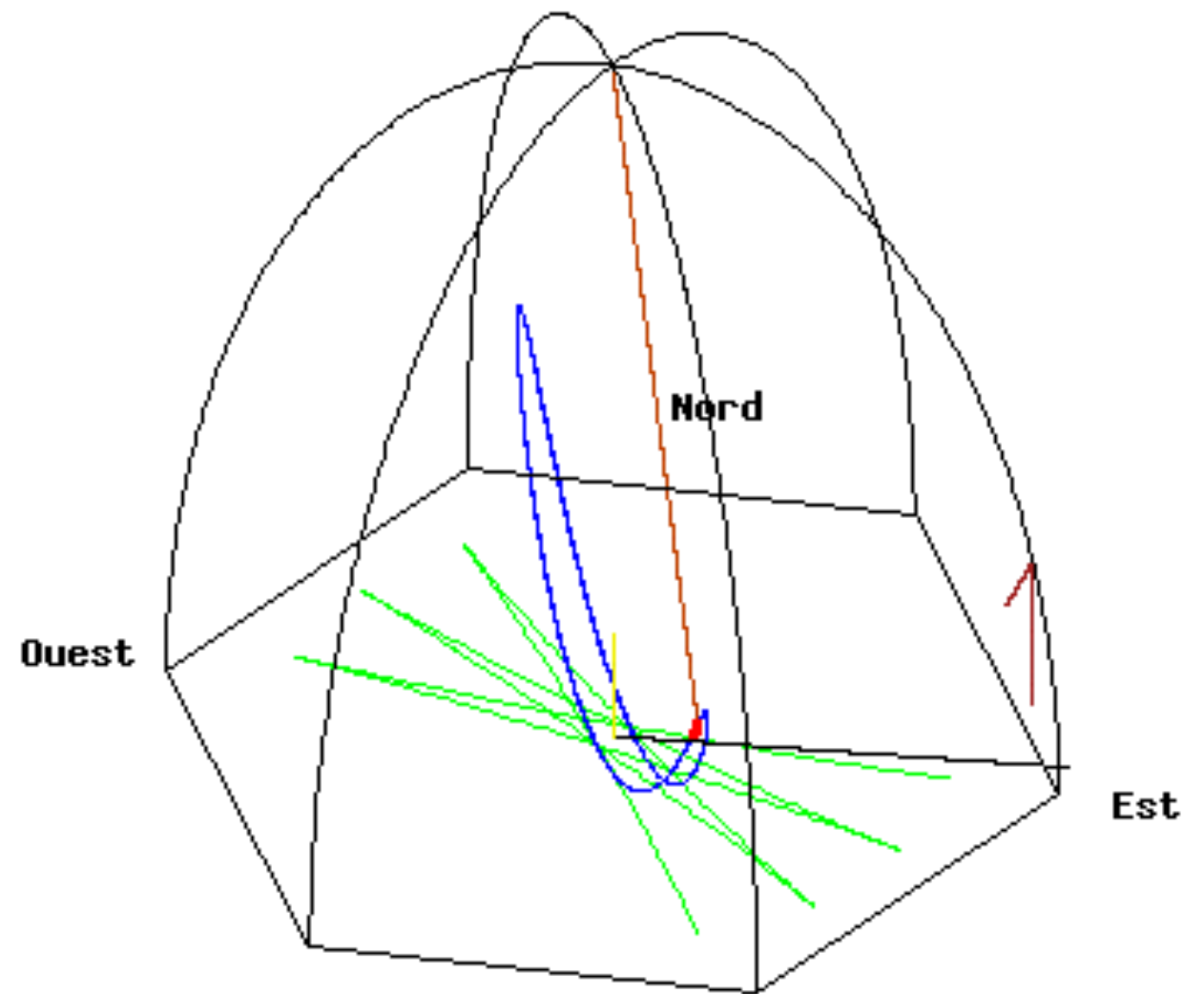
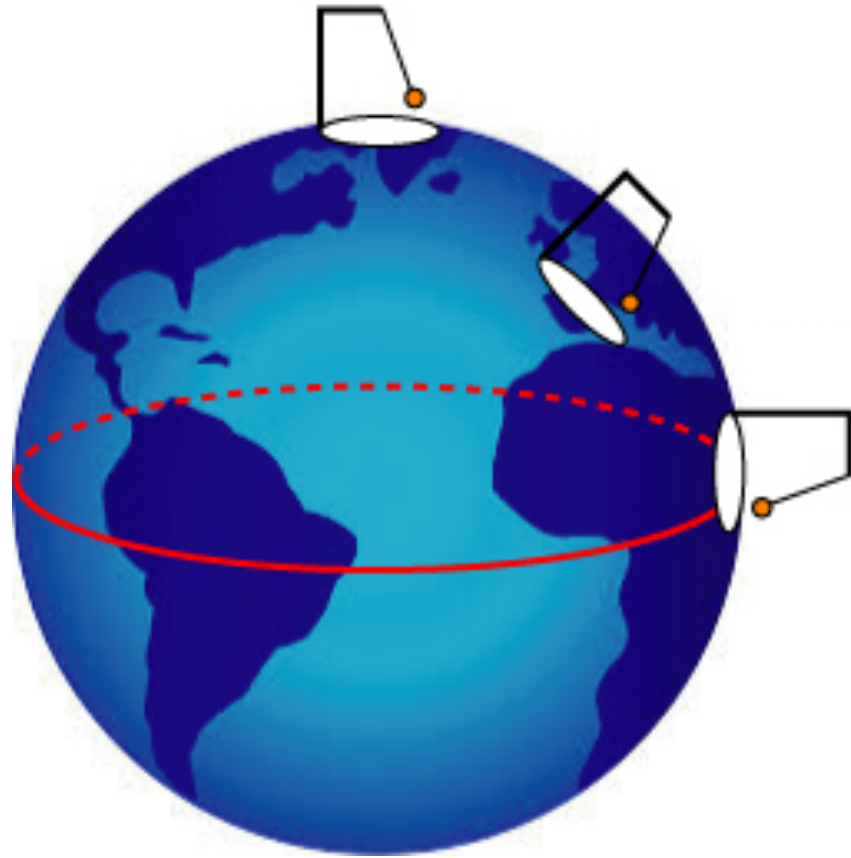
At north pole, pendulum is oscillating and Earth is rotating beneath it





# Foucault's Pendulum (1851)

At north pole, pendulum is oscillating and Earth is rotating beneath it

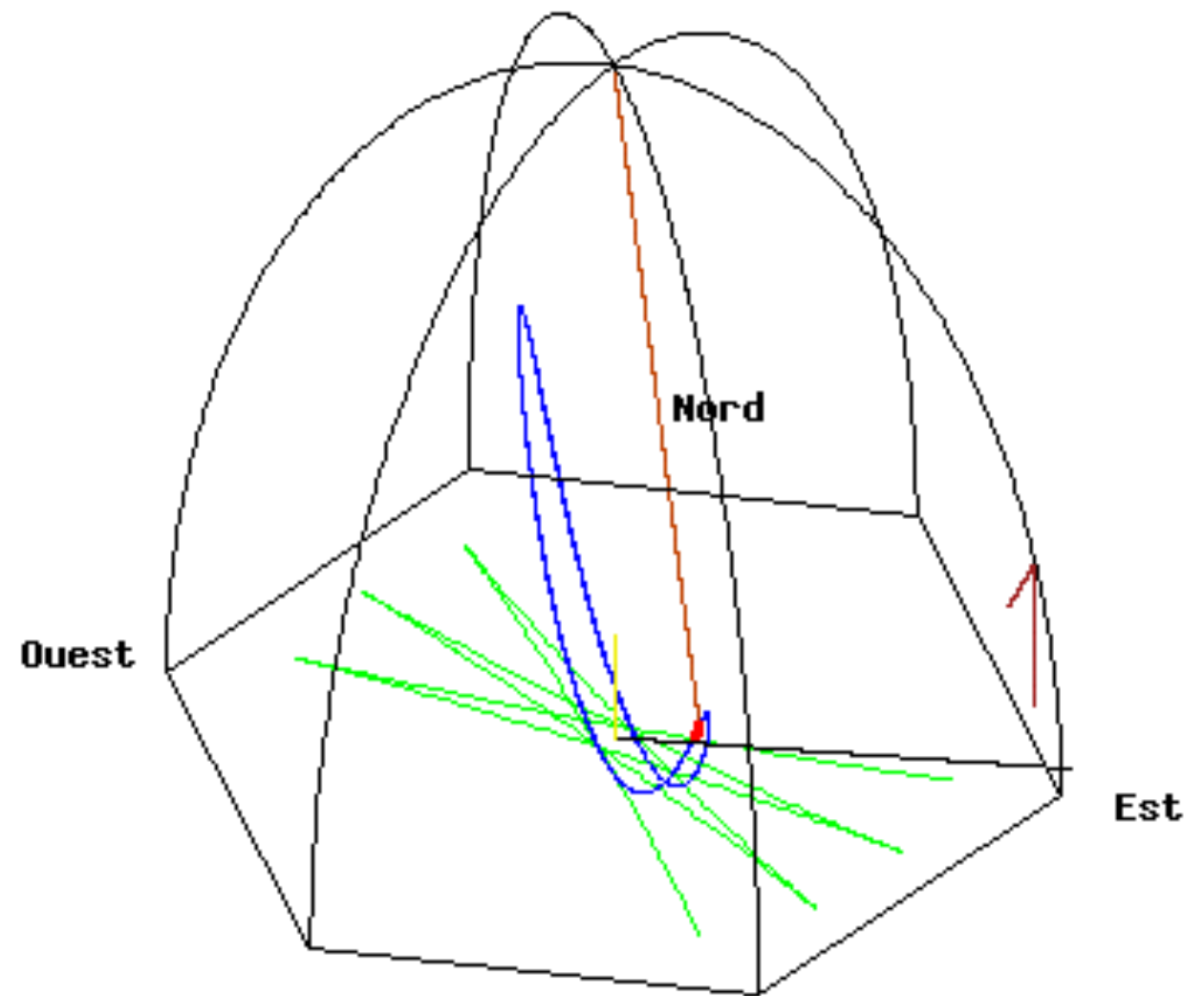
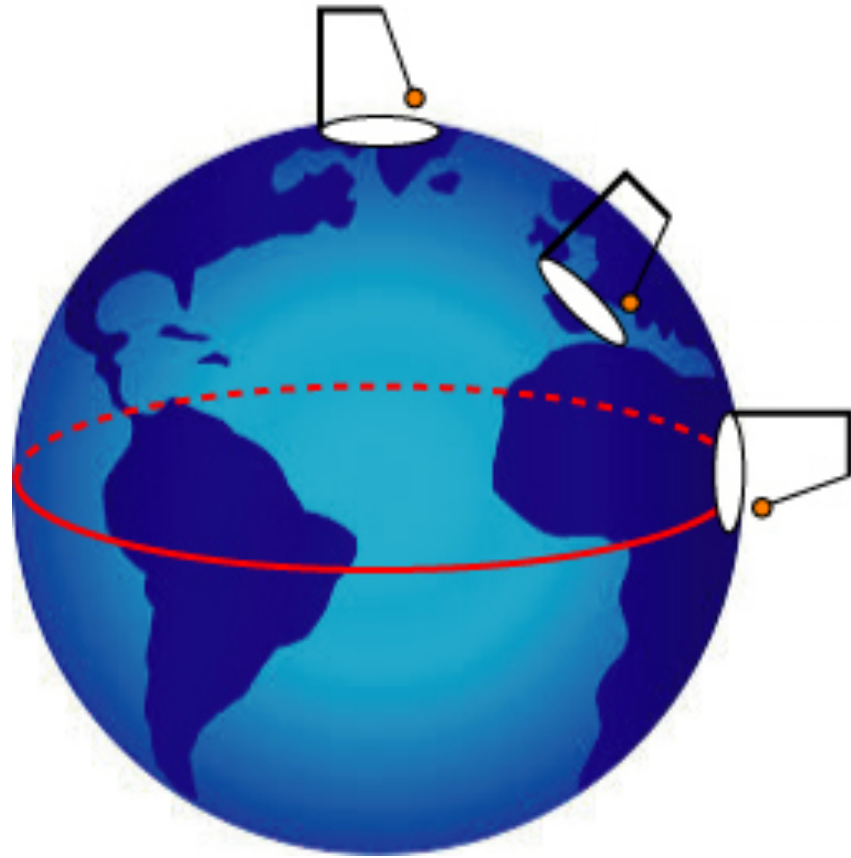


What happens to the precession at the south pole?

- a) Same as north pole
- b) Opposite of north pole
- c) No precession at all
- d) Pendula don't work there...

# Foucault's Pendulum (1851)

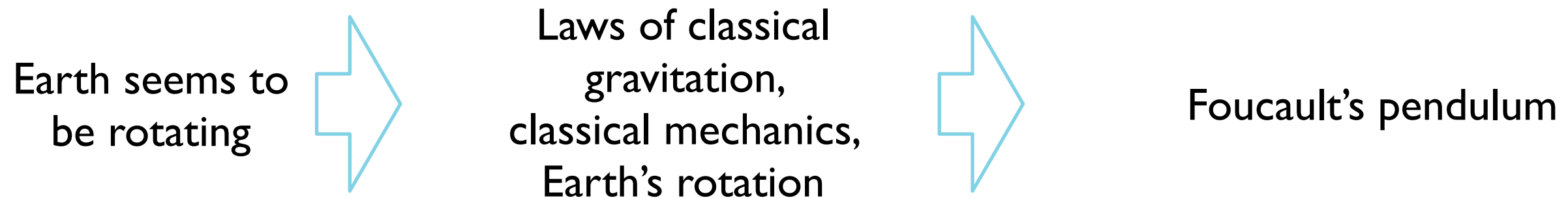
At north pole, pendulum is oscillating and Earth is rotating beneath it



What happens at the equator (where I am from)?

- a) Same as north pole
- b) Opposite of north pole
- c) No precession at all
- d) Pendula don't work there...

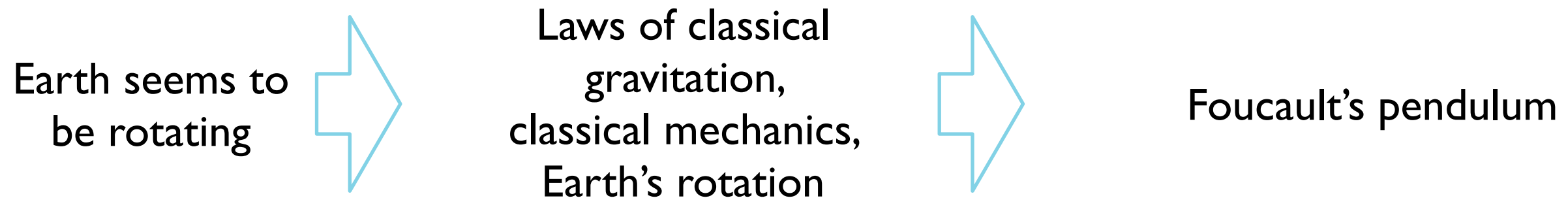
# The scientific method



Pantheon, Paris, France



# The scientific method



Pantheon, Paris, France



It works!

- a) Hypothesis confirmed
- b) Hypothesis rejected
- c) Neither, but theory more robust
- d) Science is a lie, gravity does not exist...

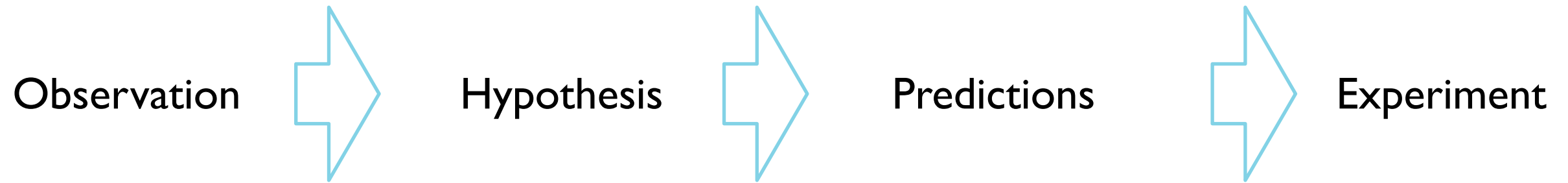


# What is science?

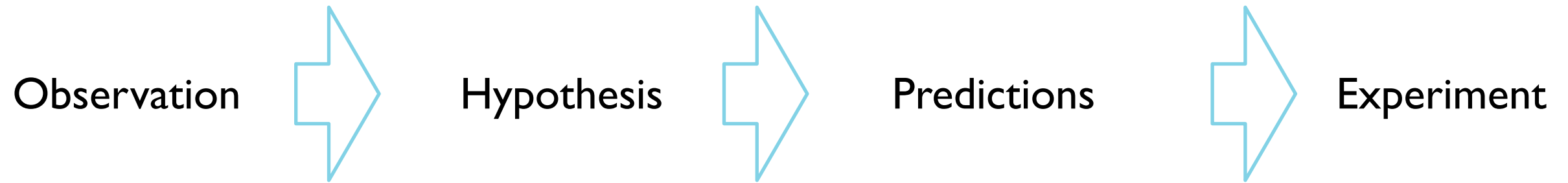
In my opinion science is the search for truth

The catch is that we cannot confirm a hypothesis, only reject it!  
But as more and more tests fail to reject certain hypothesis, we accept it as  
“as the truth as possible”

# The scientific method

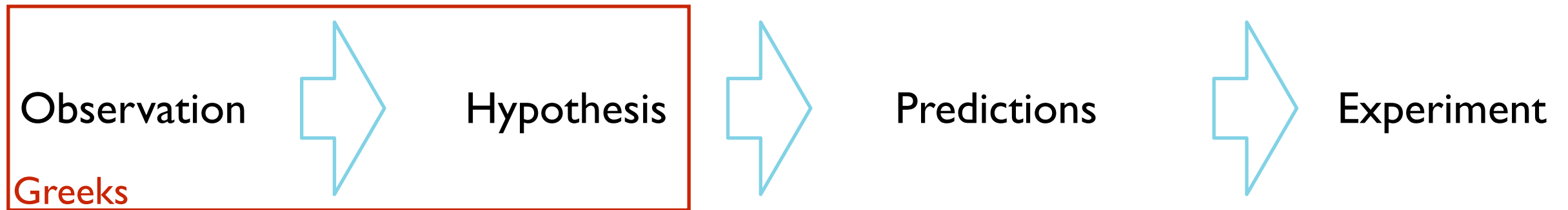


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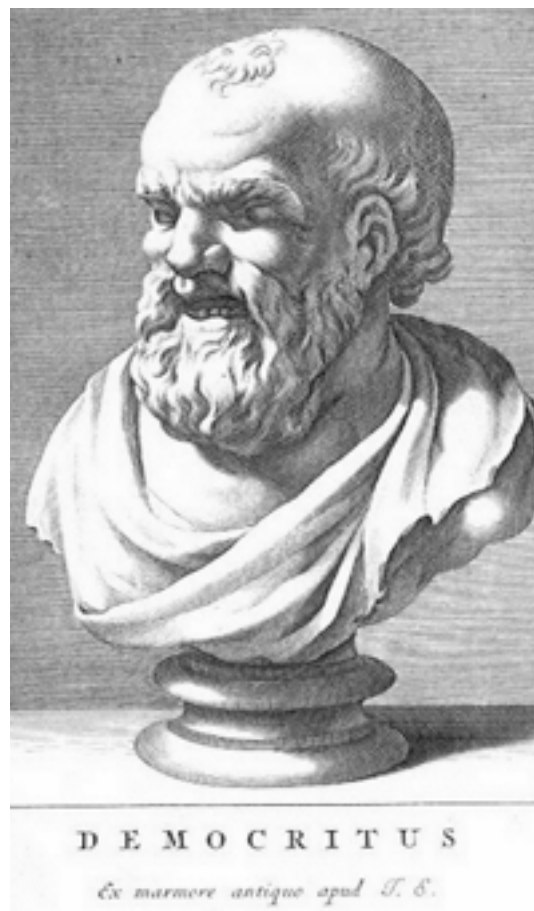


Not obvious at all!

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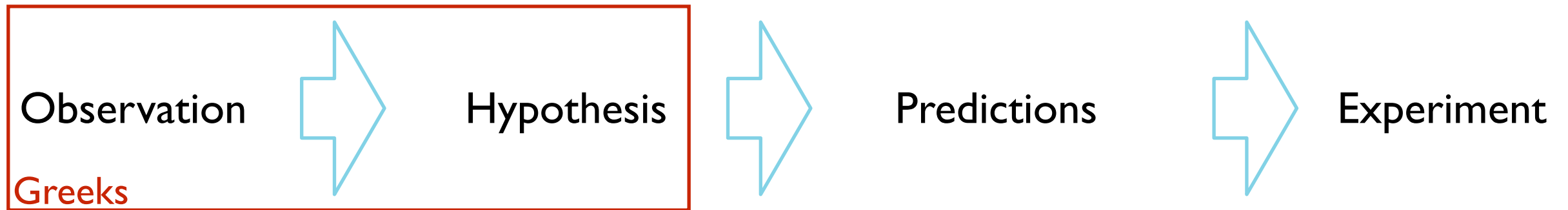


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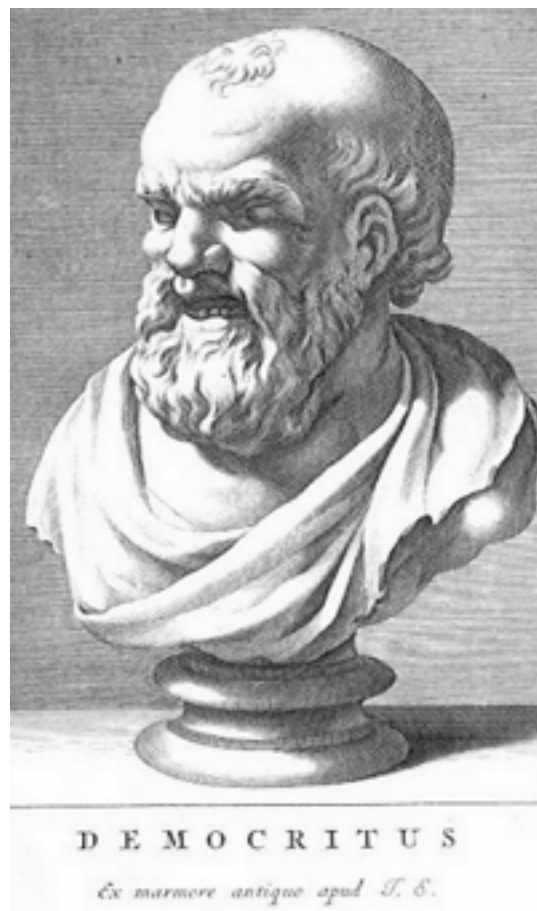




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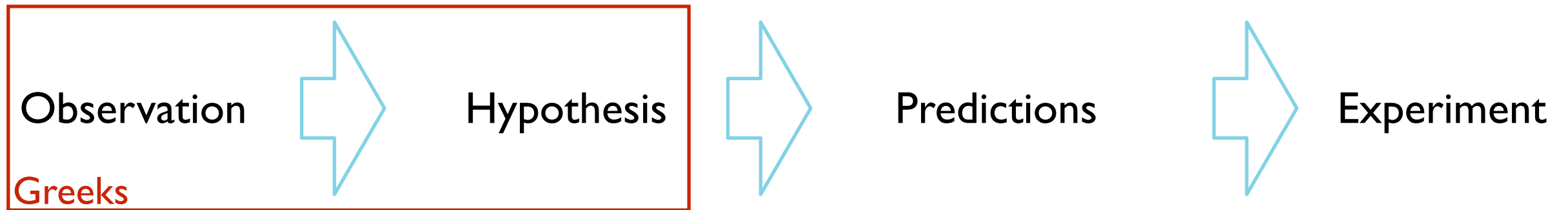
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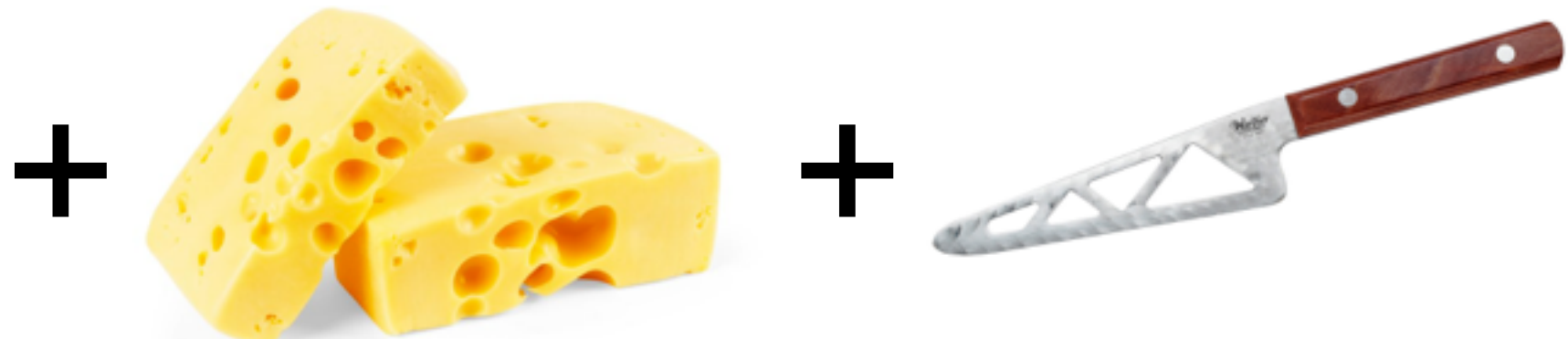
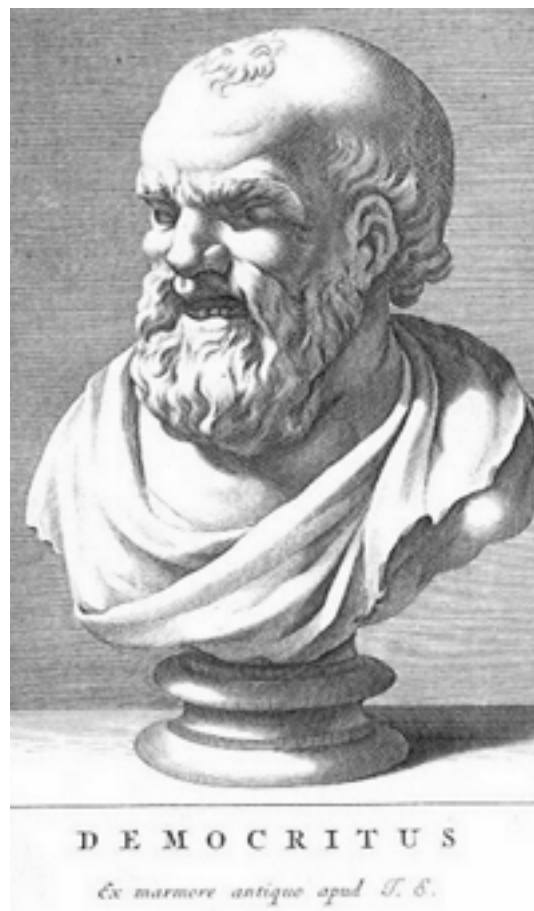
+



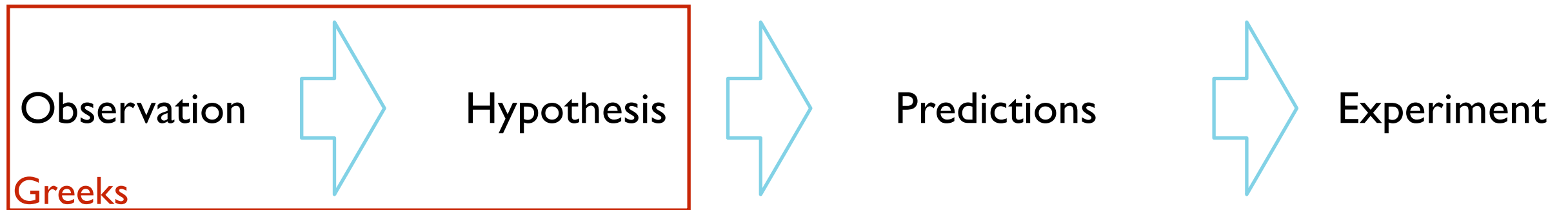
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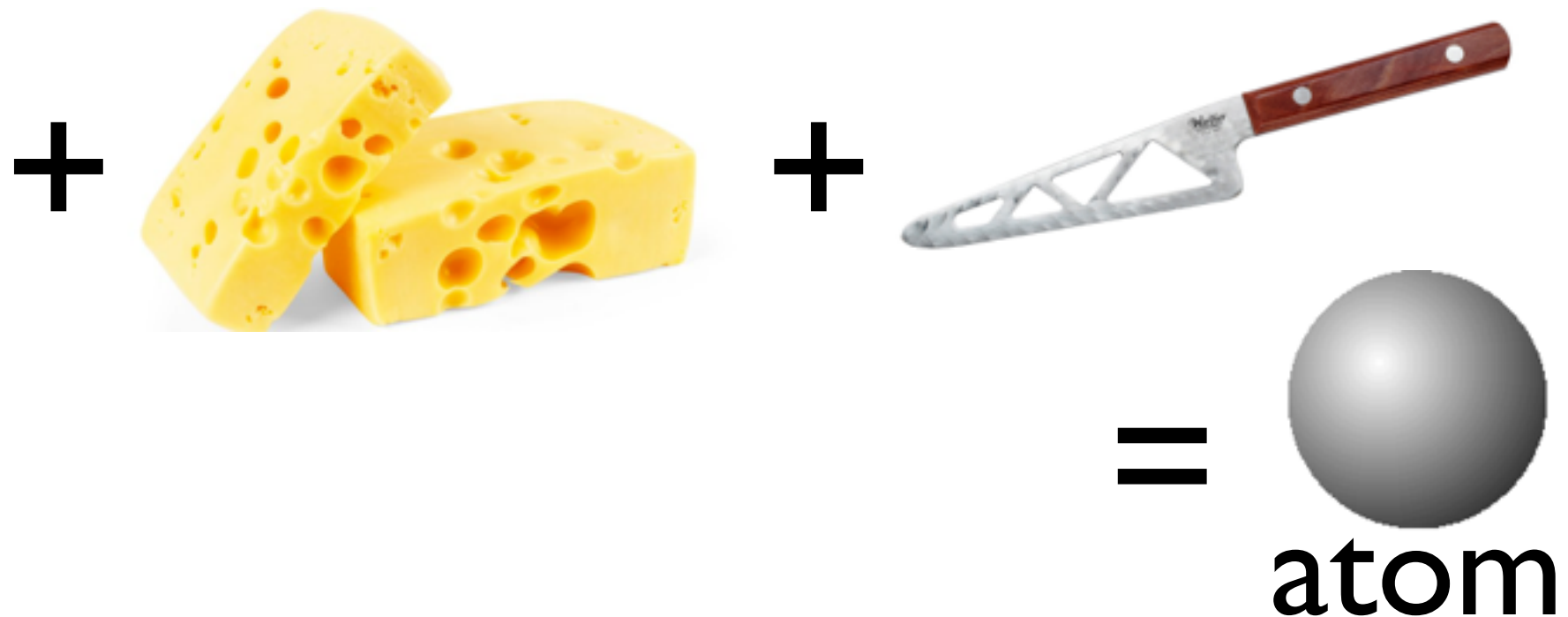
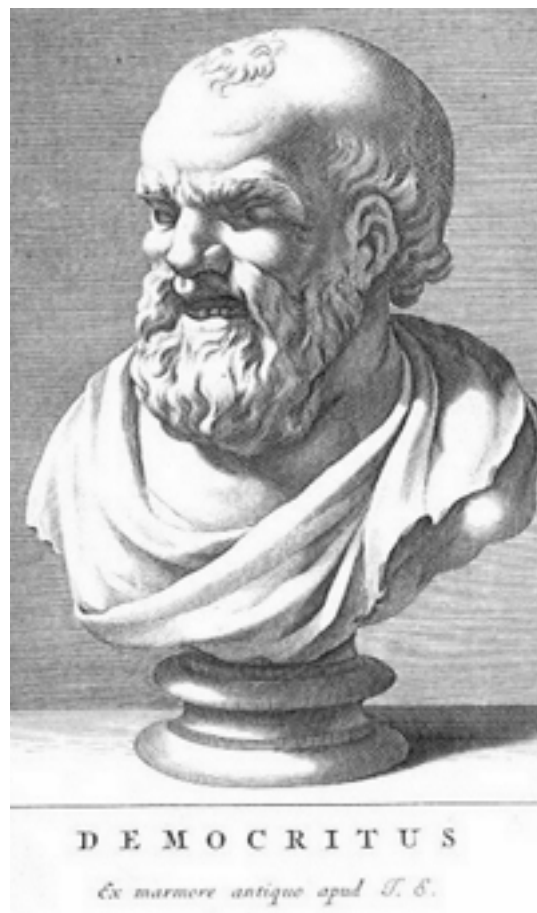
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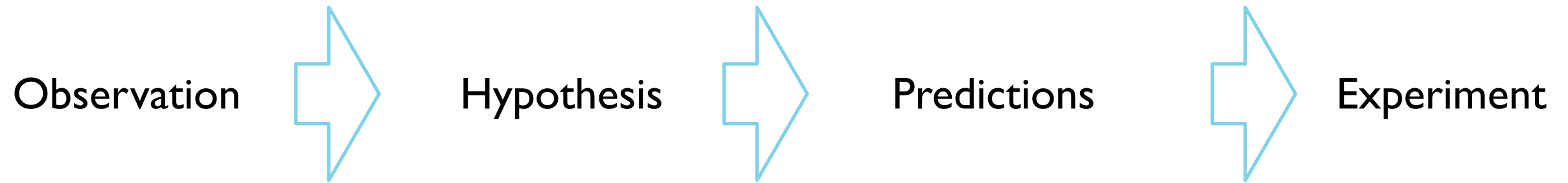
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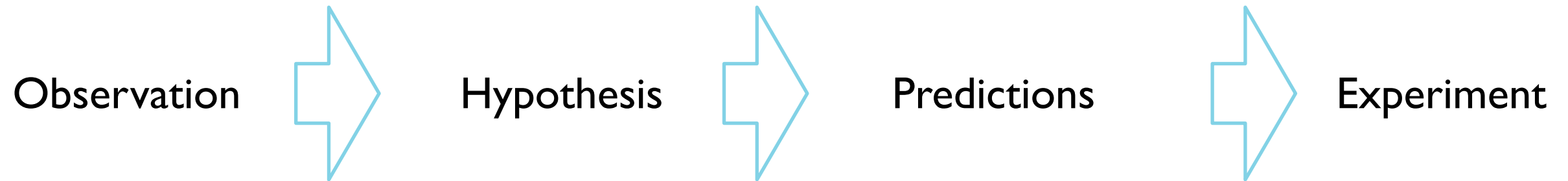


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Needs logics/mathematics for predictions



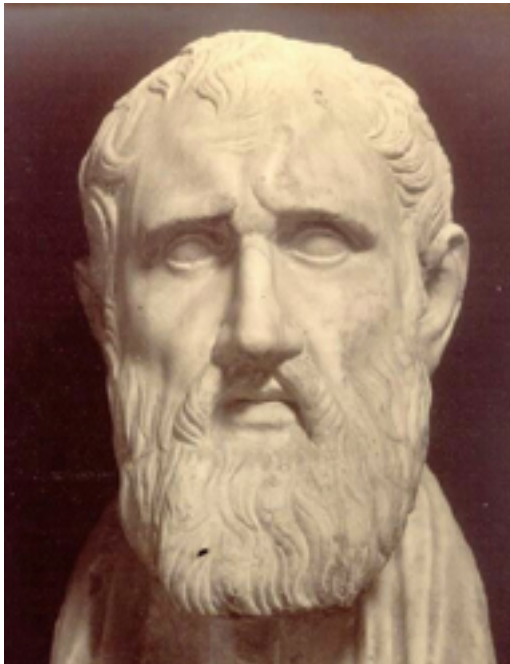
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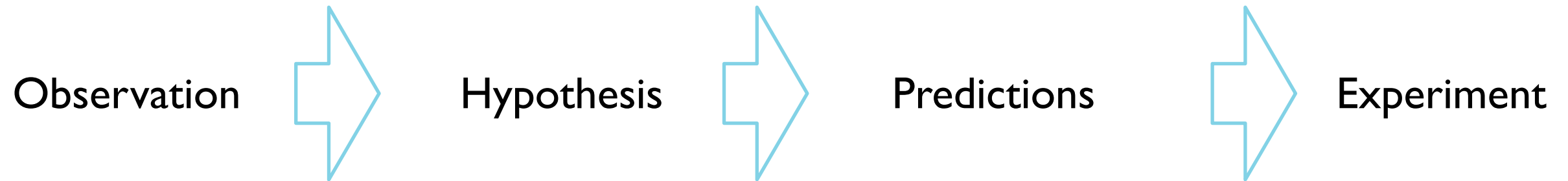
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Zeno of Elea



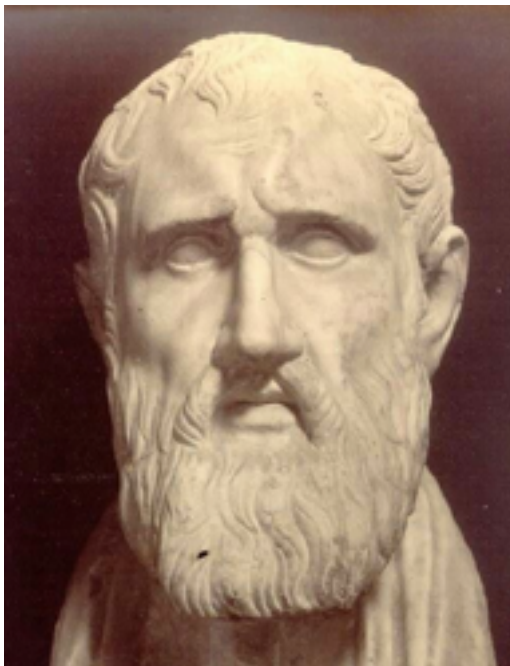
# The scientific method



Not obvious at all!

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Zeno of Elea



0  1

needs

0  1/2

needs

0  1/4

...

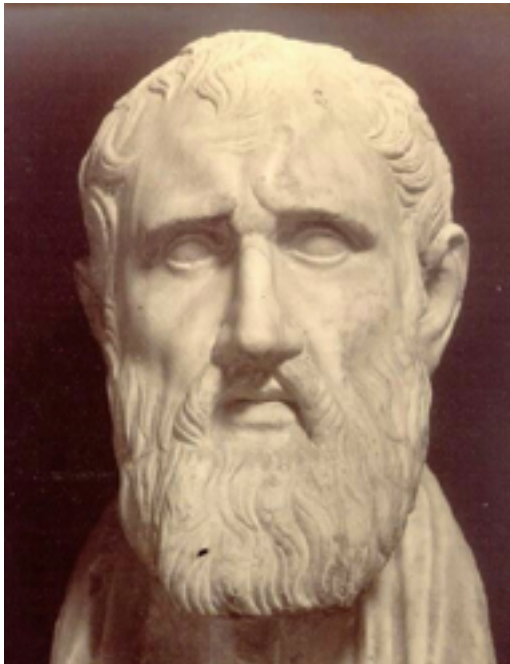
# The scientific method



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$$0 \longrightarrow 1$$

needs

$$0 \longrightarrow 1/2$$

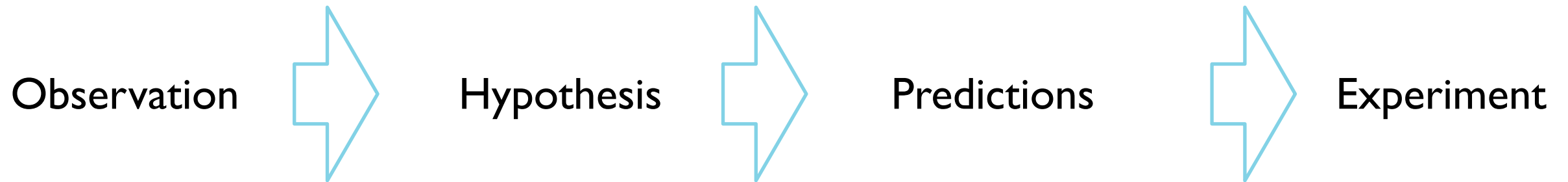
needs

$$0 \longrightarrow 1/4$$

...

$$1/2 + 1/4 + 1/8 + \dots =$$

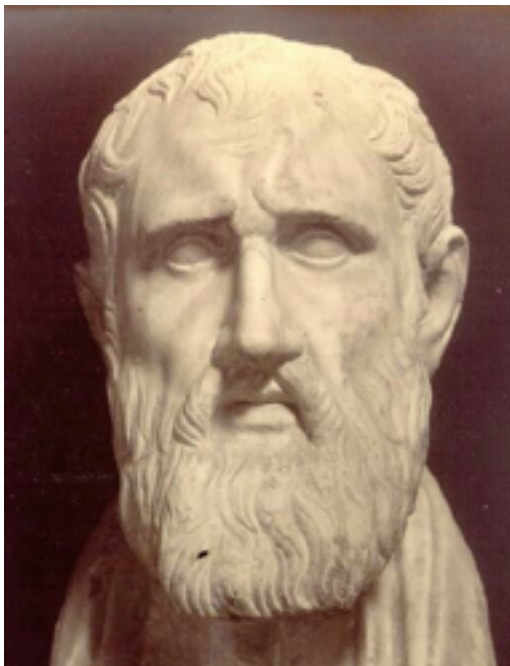
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needs

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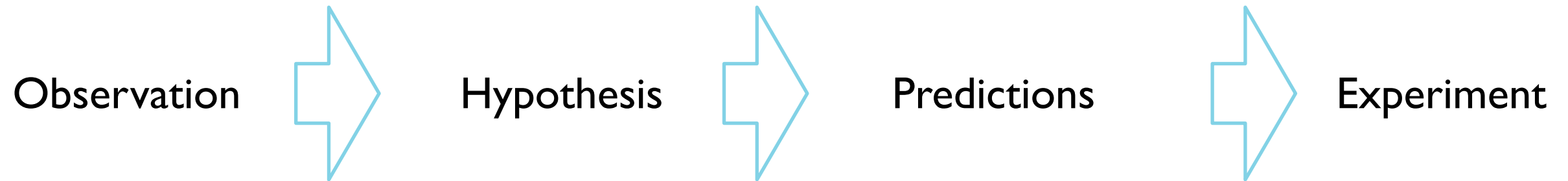
...

$1/2 + 1/4 + 1/8 + \dots =$

- a) zero
- b) one
- c) infinity
- d) all of the above at the same time



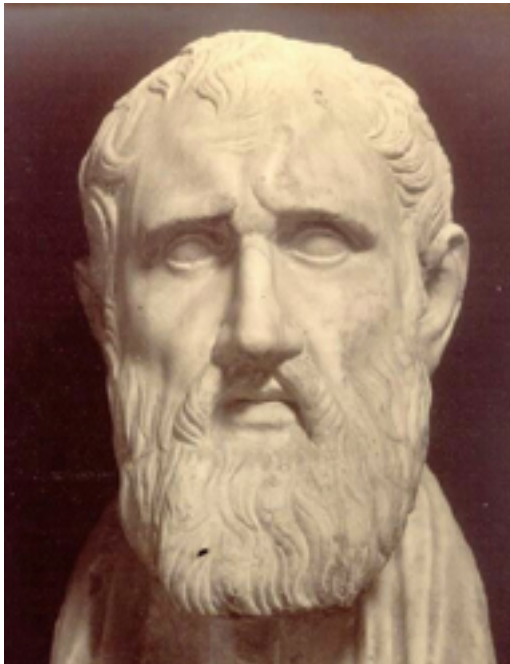
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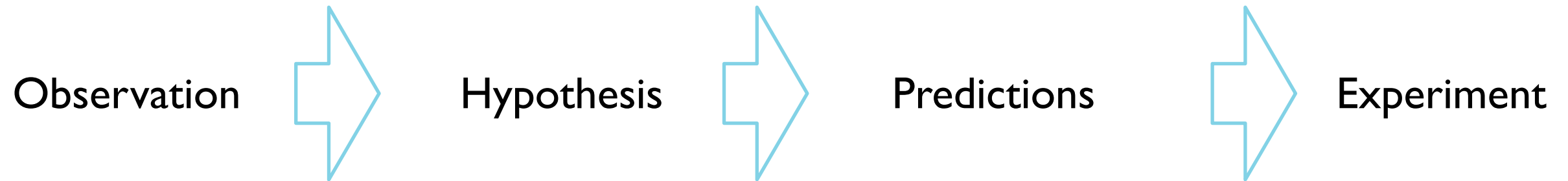
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$1/2 + 1/4 + 1/8 + \dots = \text{impossible}$   
(according to Zeno of Elea!)

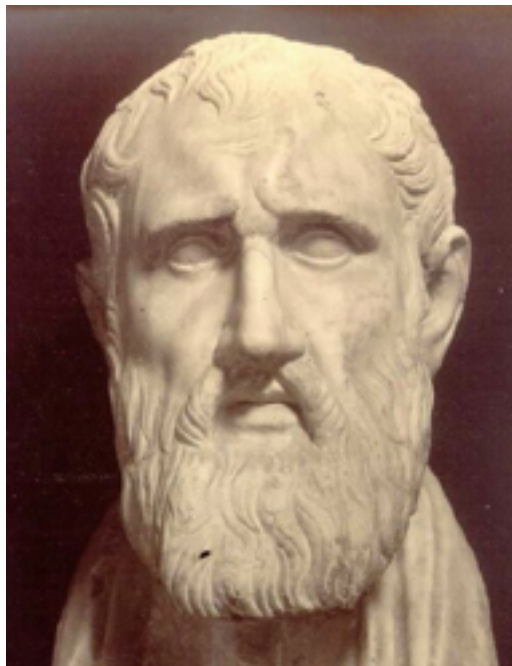
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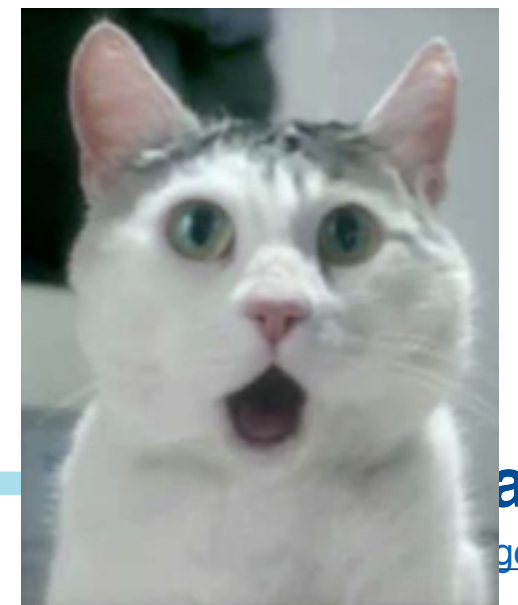
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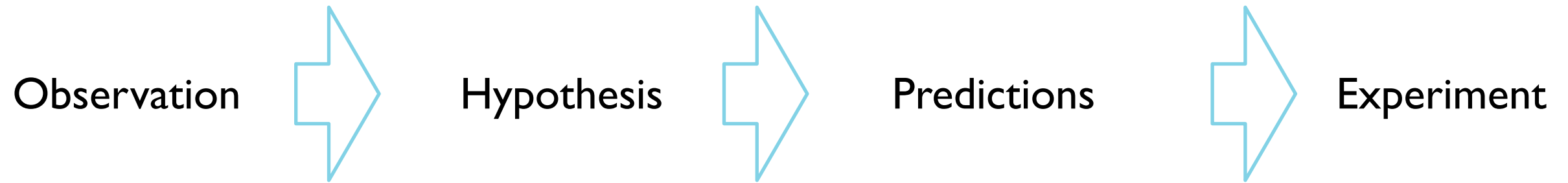
...

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Motion is impossible!



# The scientific method



Not obvious at all!

Needs logics/mathematics for predictions

Experiment needs to be done with great care (unbiased, controlled)

# The scientific method

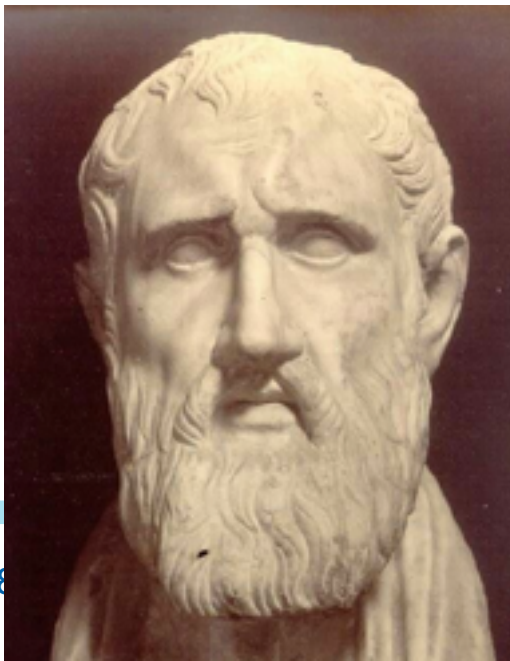


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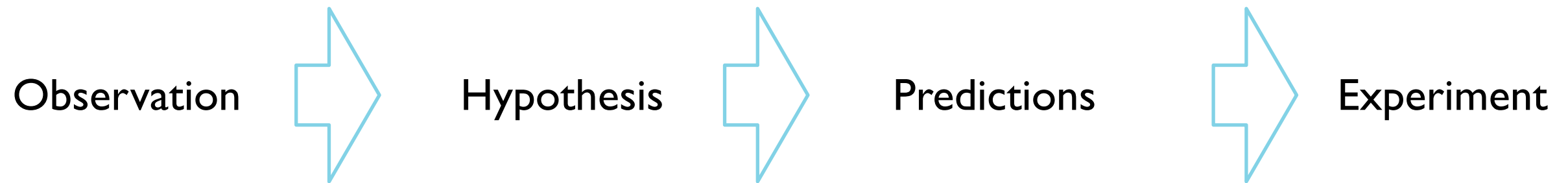
Experiment needs to be done with great care (unbiased, controlled)

Zeno of Elea



One grain of millet makes no sound when it falls  
A thousand grains make sound  
A thousand nothings become something  
**ABSURD!**

# The scientific method



Not obvious at all!

Needs logics/mathematics for predictions

Experiment needs to be done with great care (unbiased, controlled)

The choice of observation or question is **extremely important**



# The scientific method



Not obvious at all!

Needs logics/mathematics for predictions

Experiment needs to be done with great care (unbiased, controlled)

The choice of observation or question is **extremely important**

Experiment should be designed to refute hypothesis

# Physics

(I am including astronomy in Physics!)

Branch of science that studies the most basic aspects of Nature:

- What is the universe made of?
- What are the laws of Nature?
- Where does the universe comes from?

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Physics is very broad: particle physics, astronomy, astrophysics, cosmology, condensed matter physics, nuclear physics, ...

**The goal of Fermilab is to contribute to the search for the truth in Physics**

# Particle physics and cosmology



Astronomer Copernicus, Collegium Novum, Jagiellonian University



# Particle physics and cosmology



Frombork cathedral, Poland

Copernicus, 1473-1543

Astronomer Copernicus, Collegium Novum, Jagiellonian University



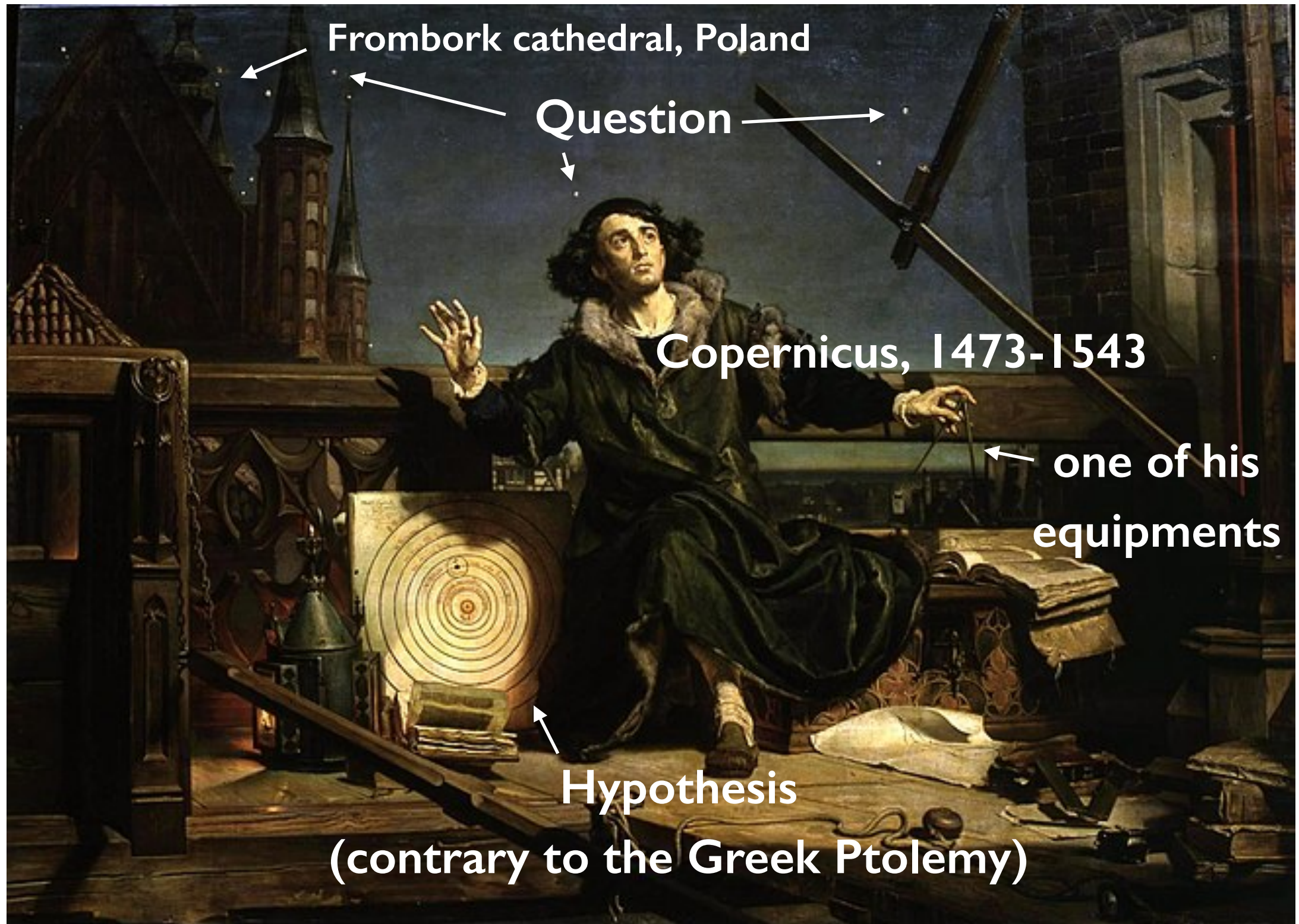
# Particle physics and cosmology



Astronomer Copernicus, Collegium Novum, Jagiellonian University



# Particle physics and cosmology





# Particle physics and cosmology

Galilei, 1564-1642

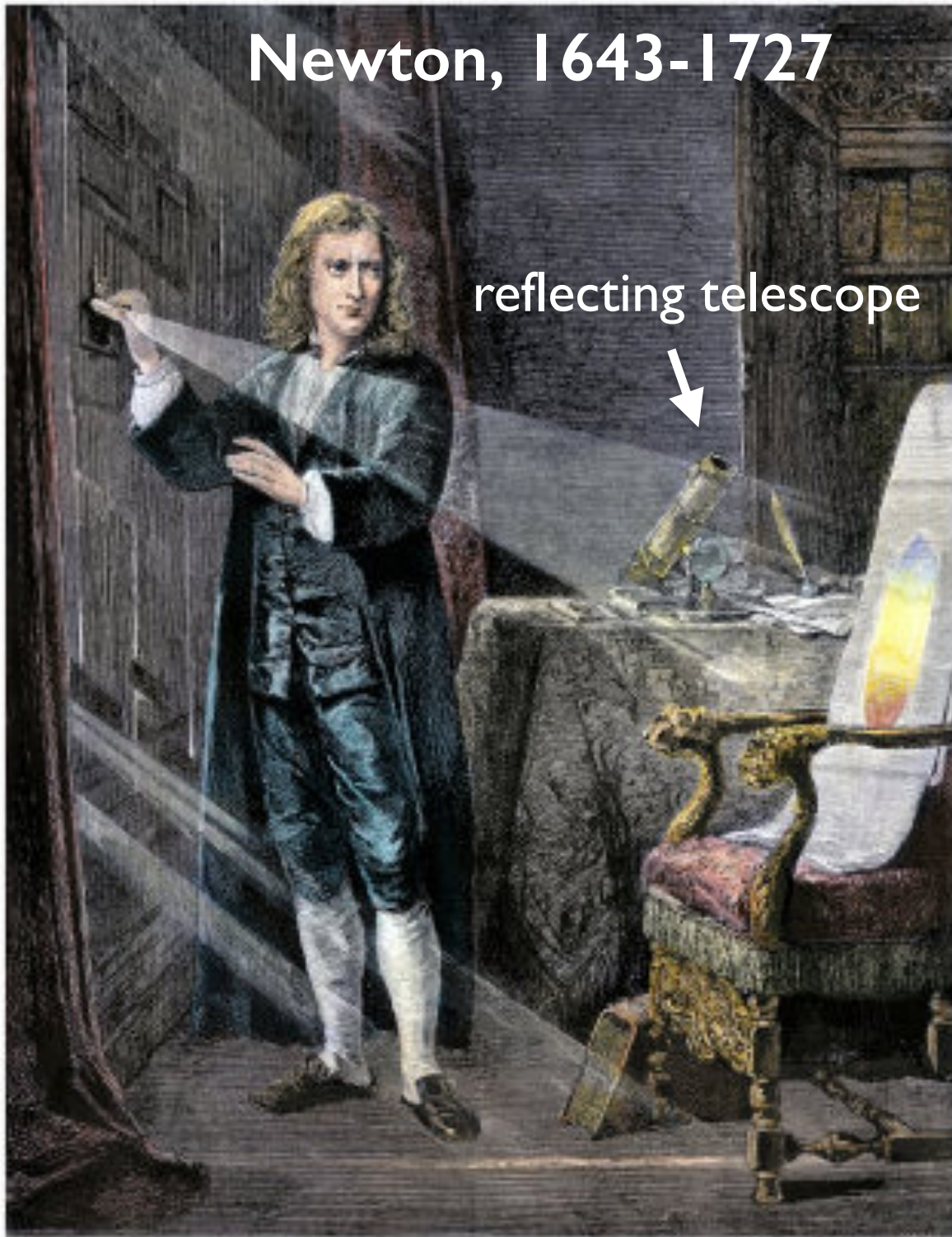
diffraction telescope

- Diffraction telescope
- Phases of Venus
- Jupiter's moons
- Milky way stars
- Sunspots
- ...
- Systematic approach
- Mathematics and laws of nature



# Particle physics and cosmology

Newton, 1643-1727



- Mathematics
- Optics
- Classical Mechanics
- Gravitation
- ...



# Particle physics and cosmology

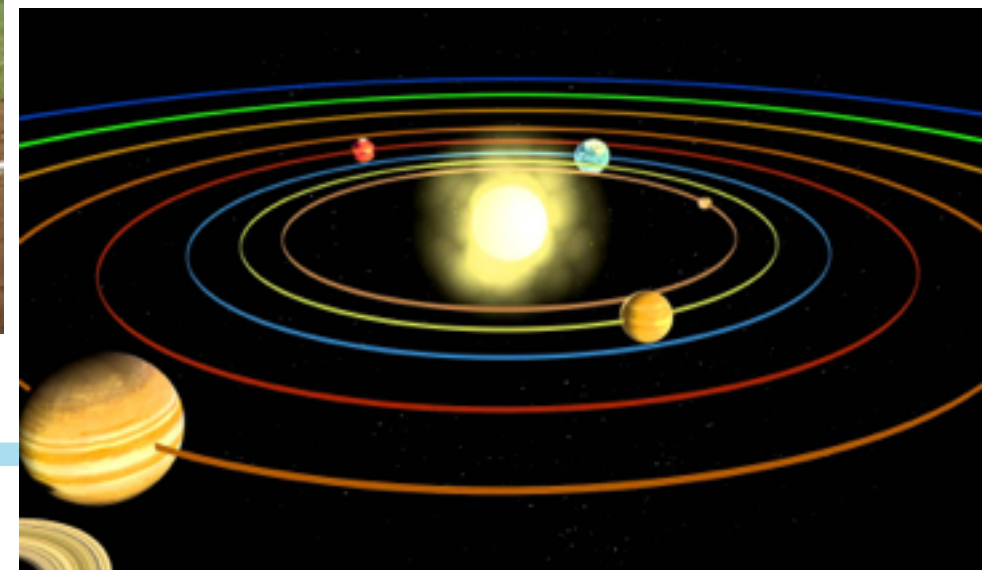
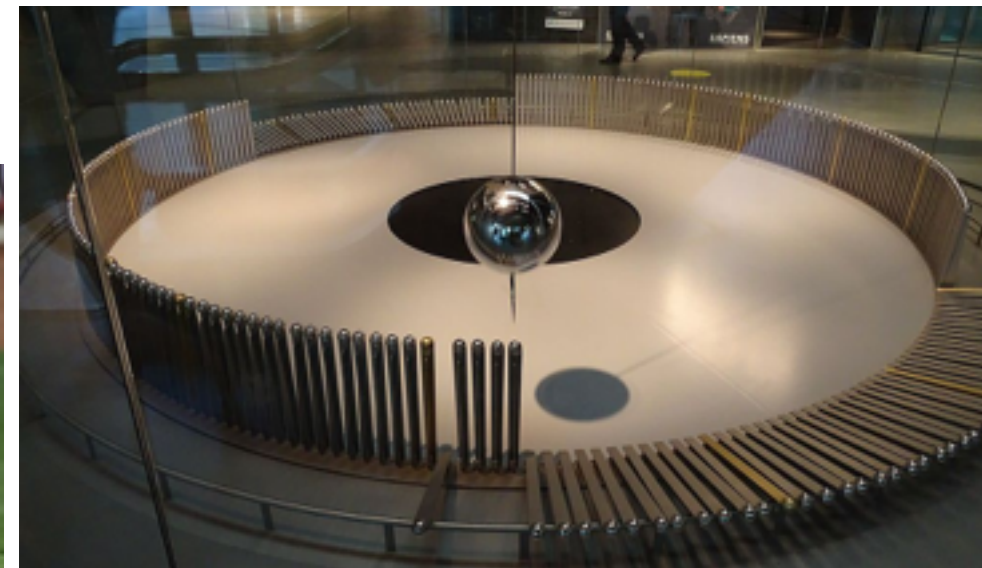
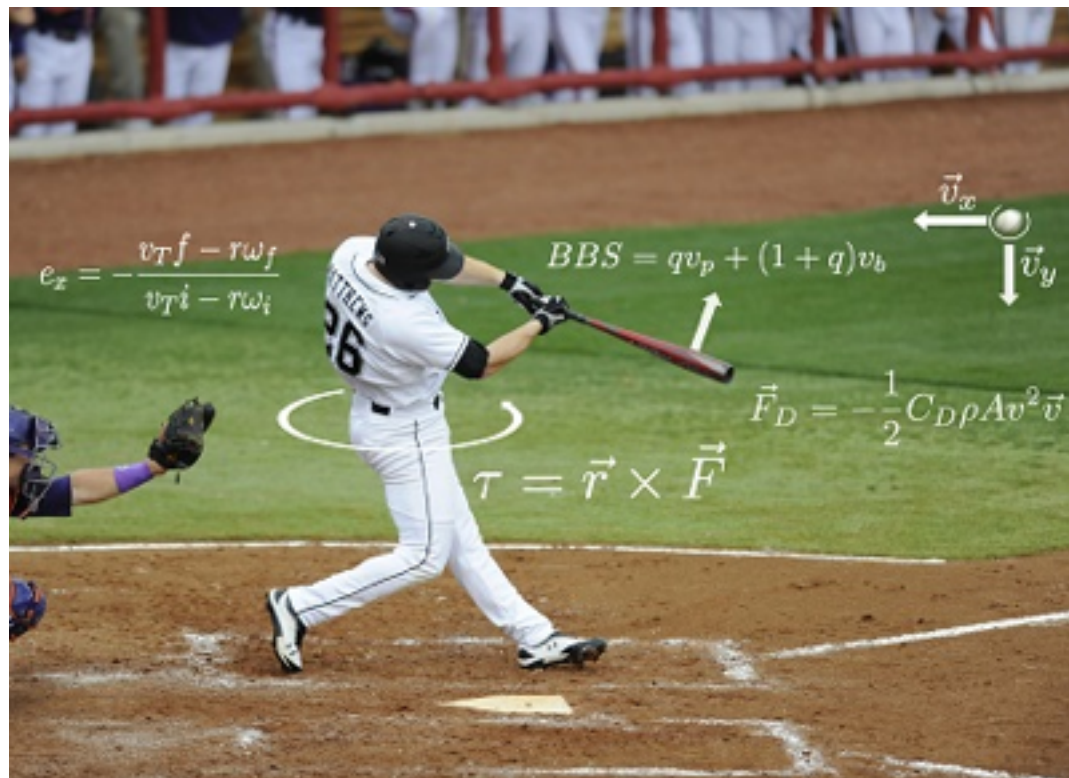
## Classical mechanics

From Newton's laws of motion and some information like position, velocity and forces, everything can be calculated: past and future of a system!

# Particle physics and cosmology

## Classical mechanics

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# Physics and society

Research in physics has led to great changes in society

Natural phenomena

Technology

Internet

Health

Communications

Transportation

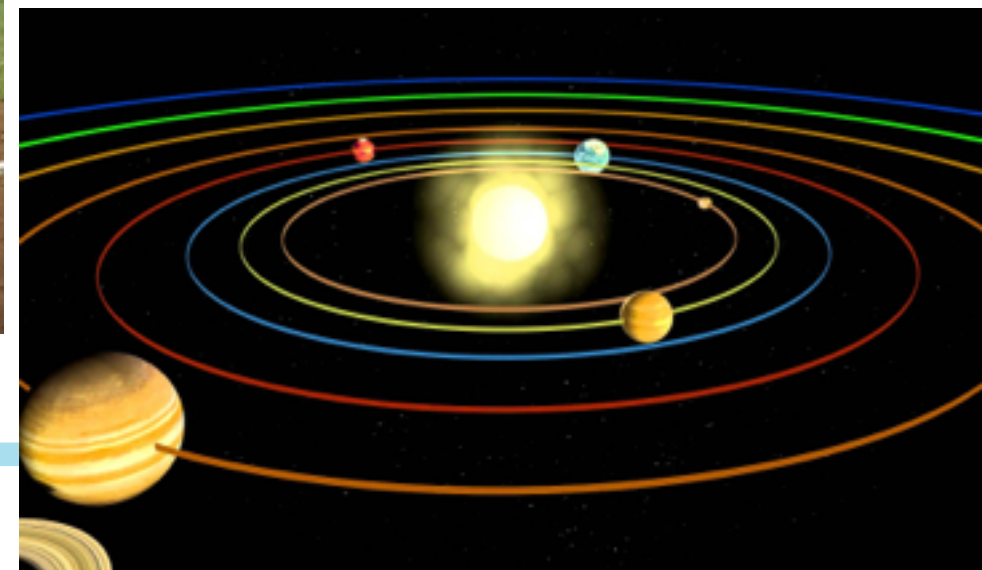
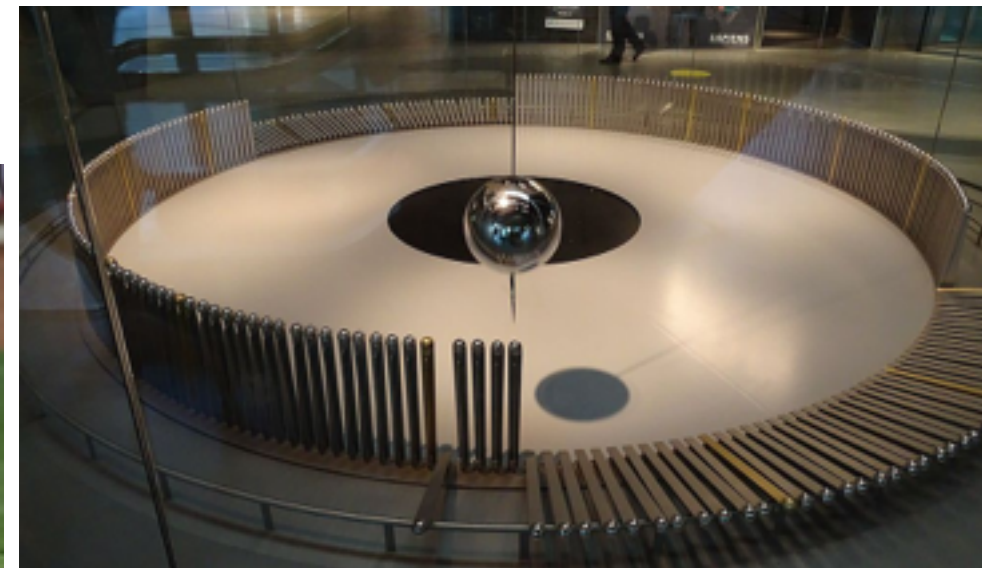
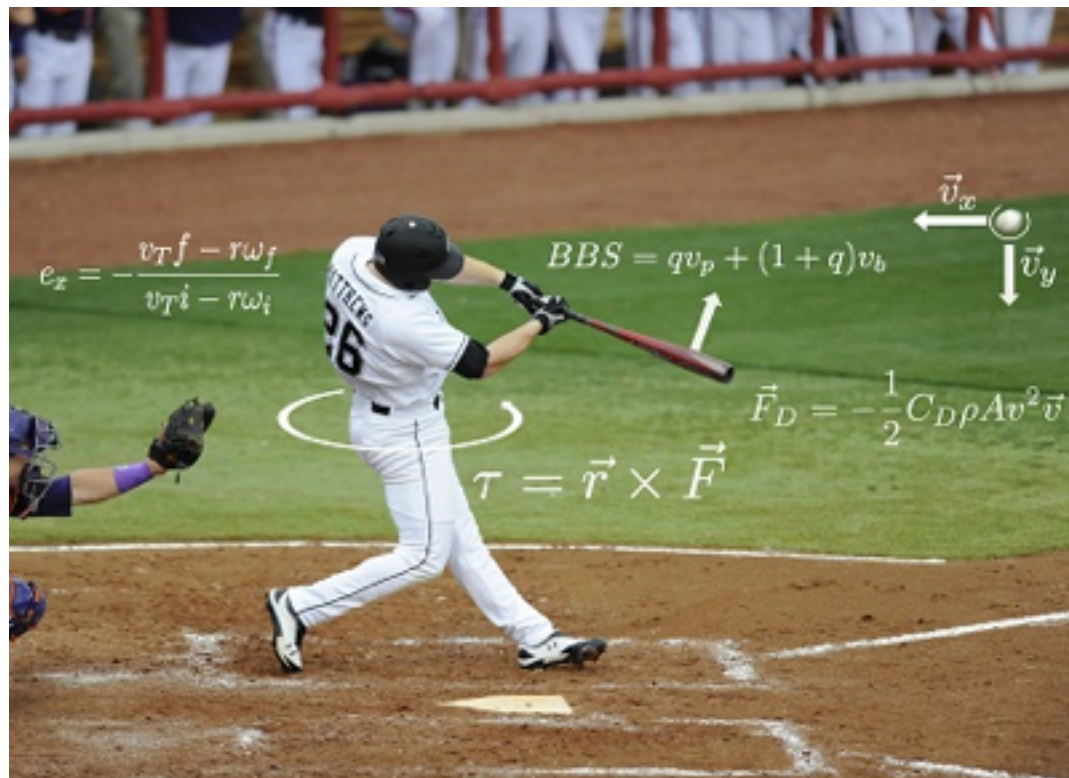
and much more...



# Particle physics and cosmology

## Classical mechanics

From Newton's laws of motion and some information like position, velocity and forces, everything can be calculated: past and future of a system!



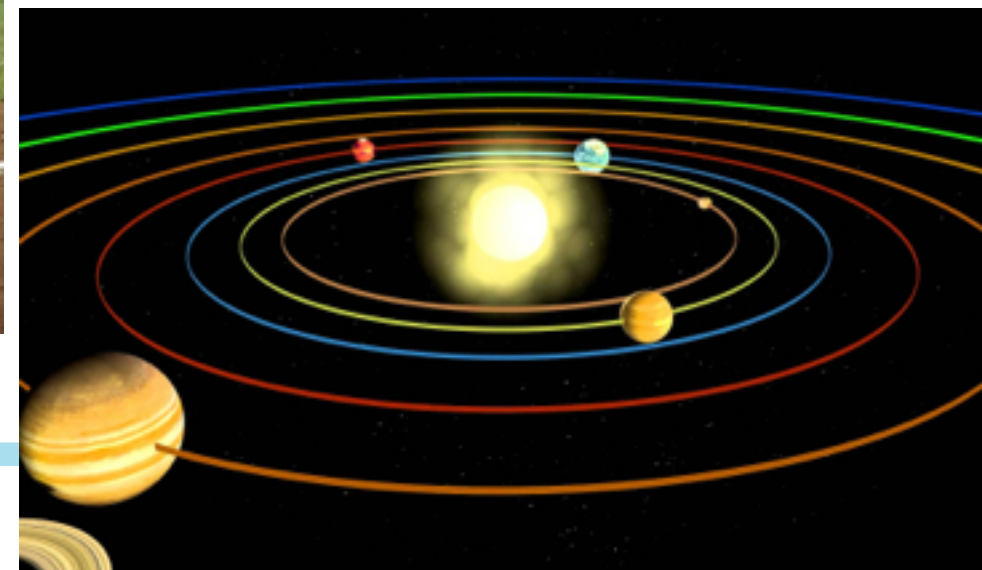


# Particle physics and cosmology

## Classical mechanics

From Newton's laws of motion and some information about position, velocity and forces on objects

On 1901, after 200 years of successful classical mechanics, Lord Kelvin said in a lecture that there were only two clouds over the dynamical theory of heat and light. These two clouds broke down classical mechanics!





# Particle physics and cosmology

The laws of physics: **quantum mechanics** and **relativity**

# Particle physics and cosmology

The laws of physics: quantum mechanics and relativity



Physics of very small scales

Observable quantities are *quantized*

Things are both particles and waves

Measurements have intrinsic limited precision

Dan's talk

# Particle physics and cosmology

The laws of physics: **quantum mechanics** and **relativity**



Physics of very small scales

Observable quantities are *quantized*

Things are both particles and waves

Measurements have intrinsic limited precision

Dan's talk



Physics of fast moving objects

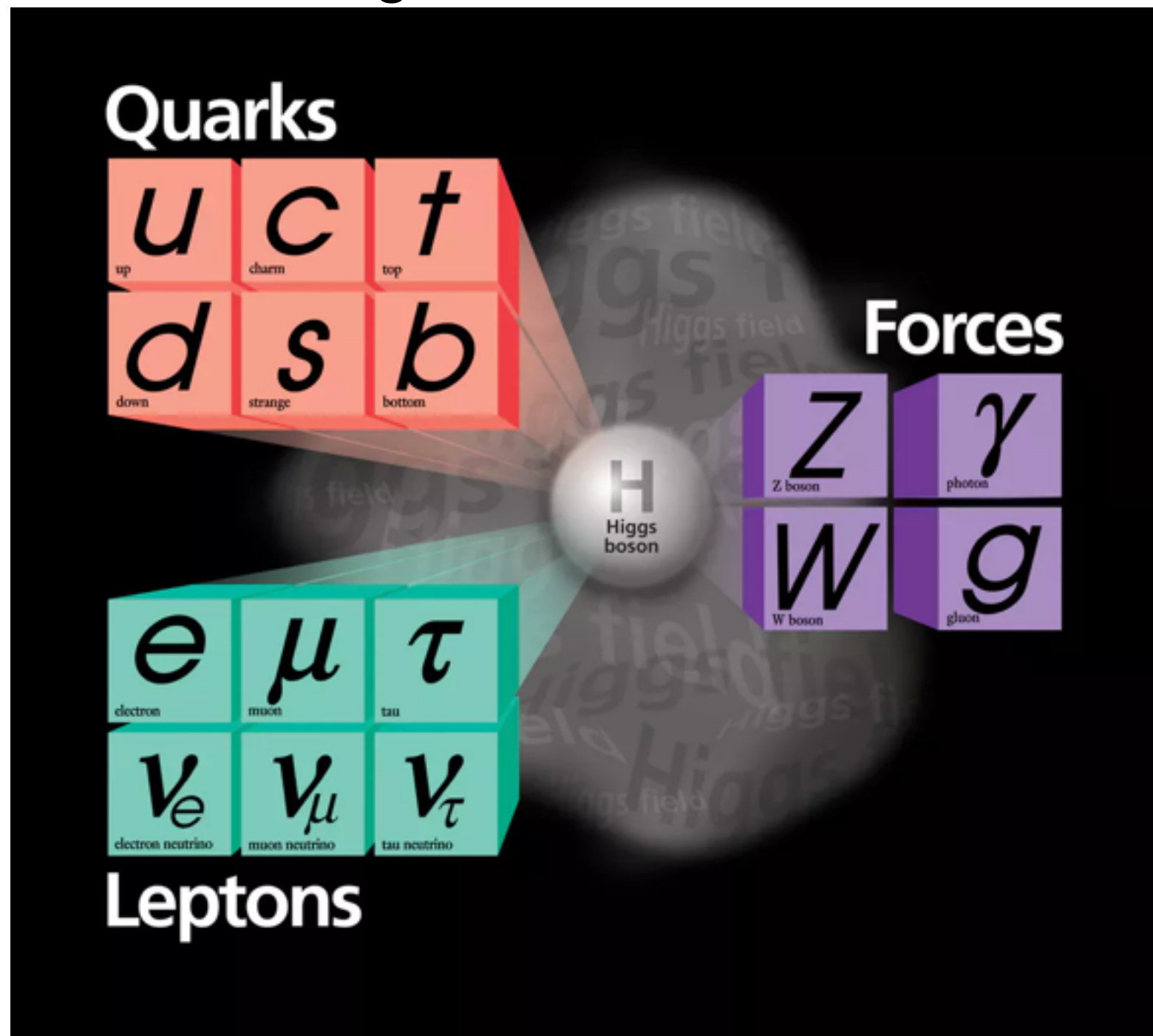
Physics is independent of the reference frame

The speed of light is the limit

Elliott's talk

# The standard model of particle physics

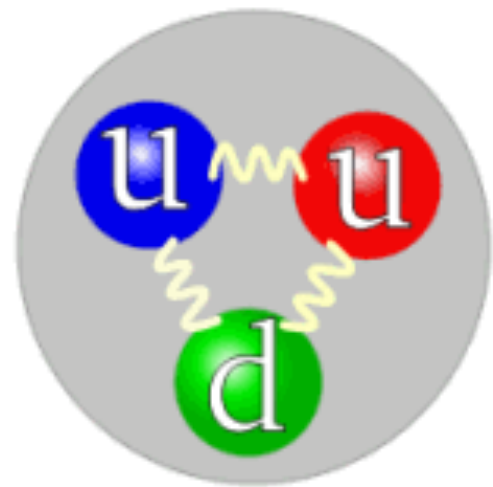
Building blocks of the universe



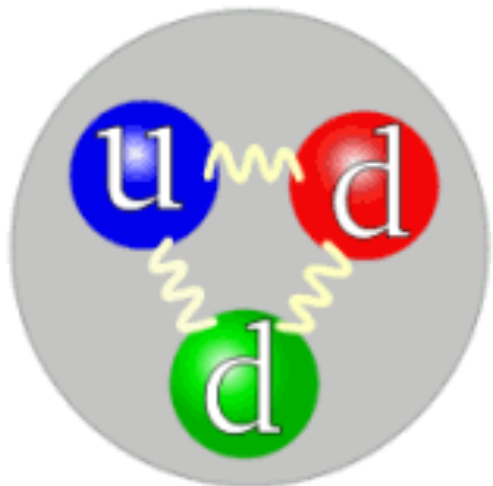
Cecilia's talk

# The standard model of particle physics

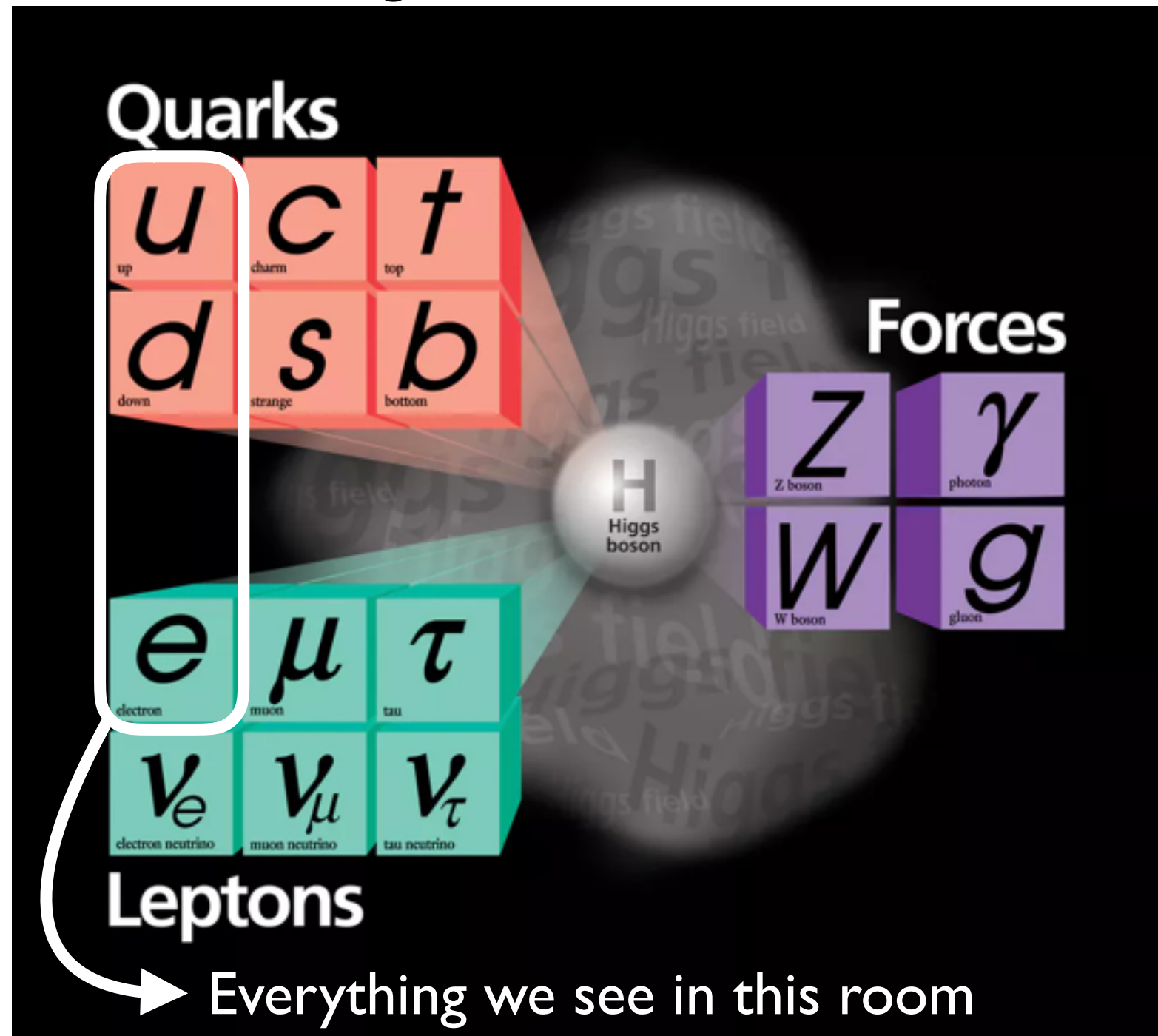
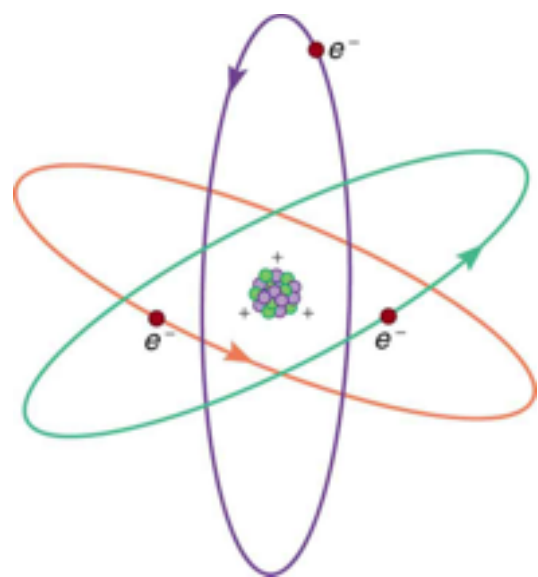
Building blocks of the universe



Proton



Neutron

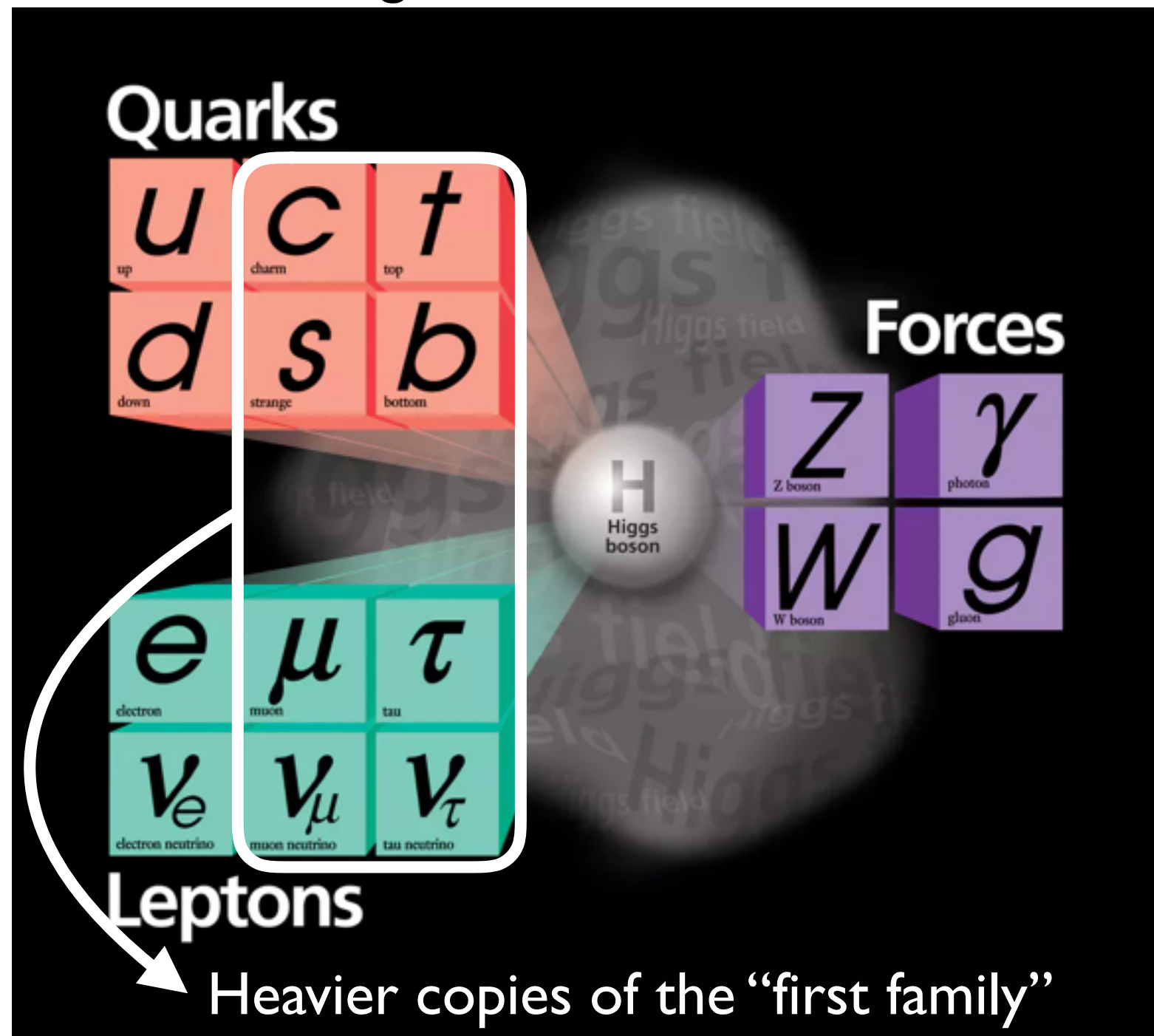


Cecilia's talk



# The standard model of particle physics

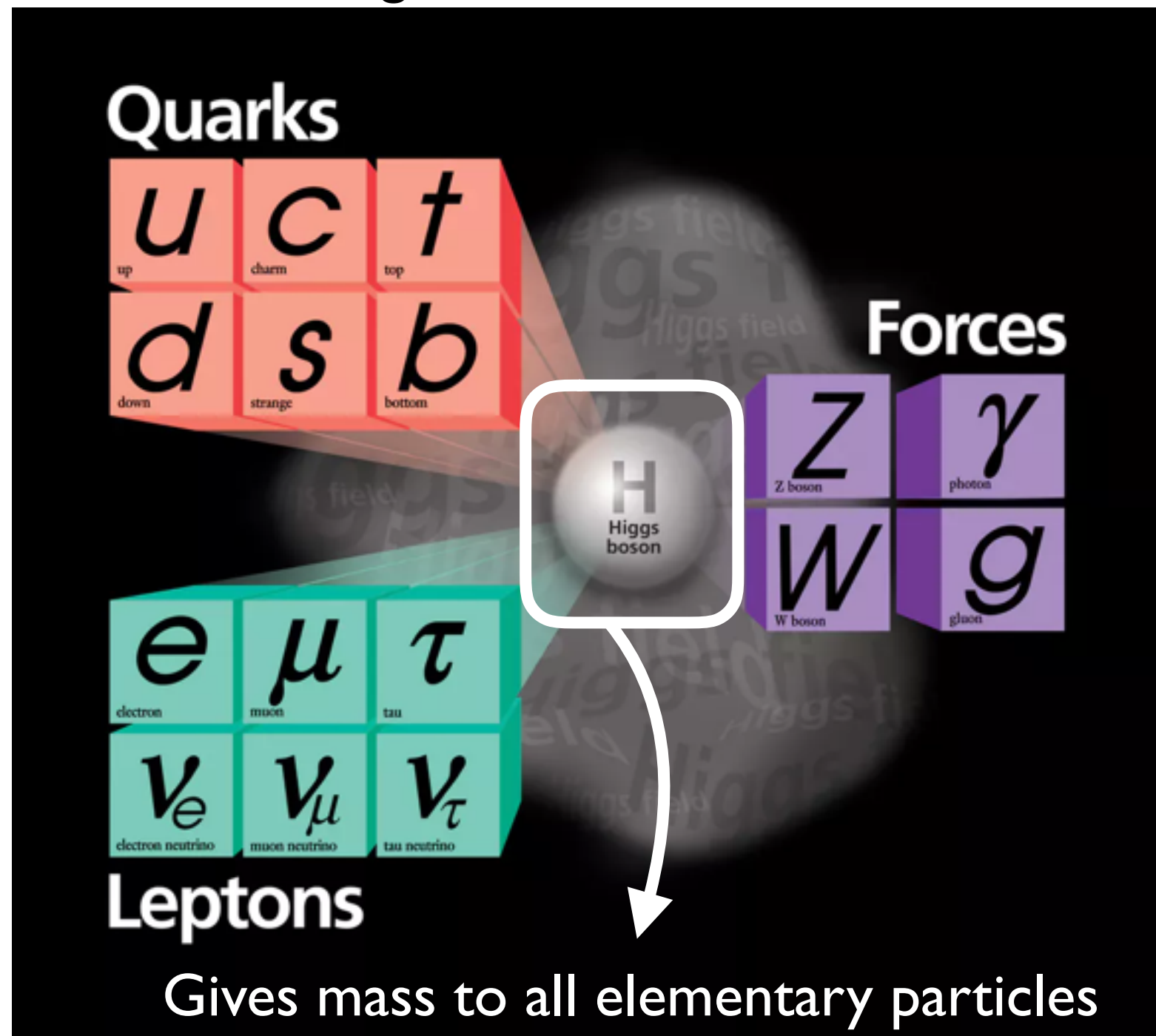
Building blocks of the universe



Cecilia's talk

# The standard model of particle physics

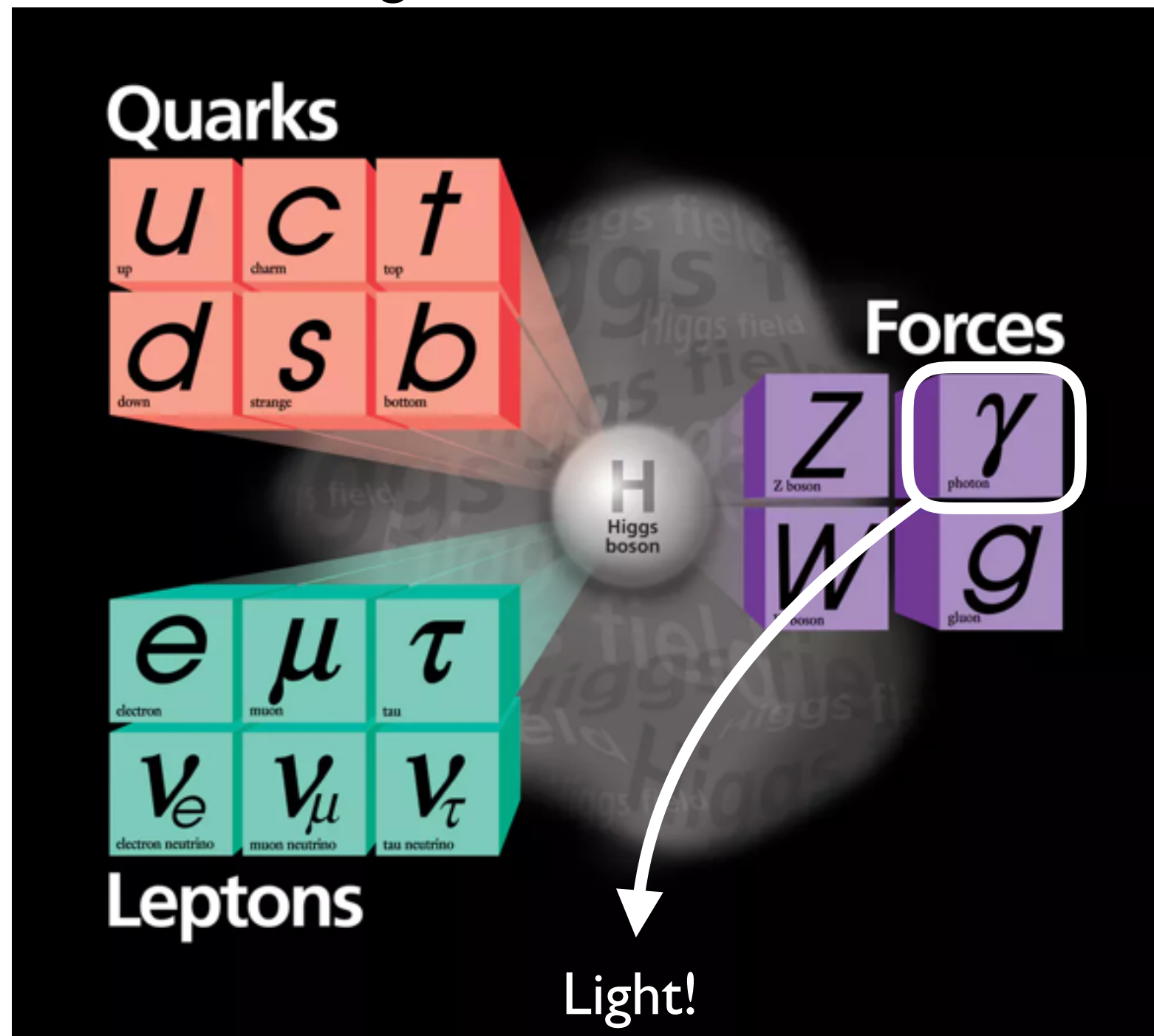
Building blocks of the universe



Cecilia's talk

# The standard model of particle physics

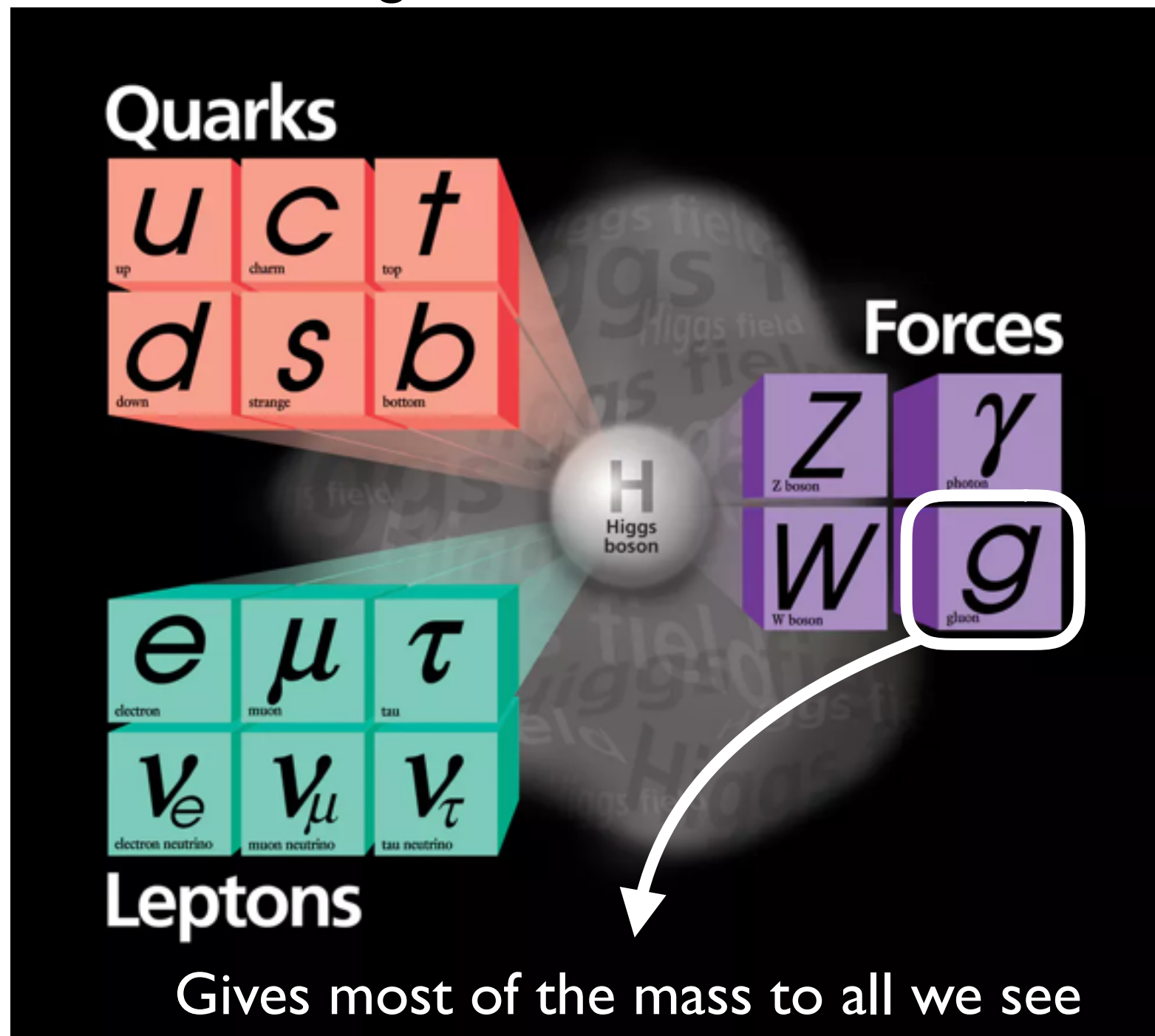
Building blocks of the universe



Cecilia's talk

# The standard model of particle physics

Building blocks of the universe

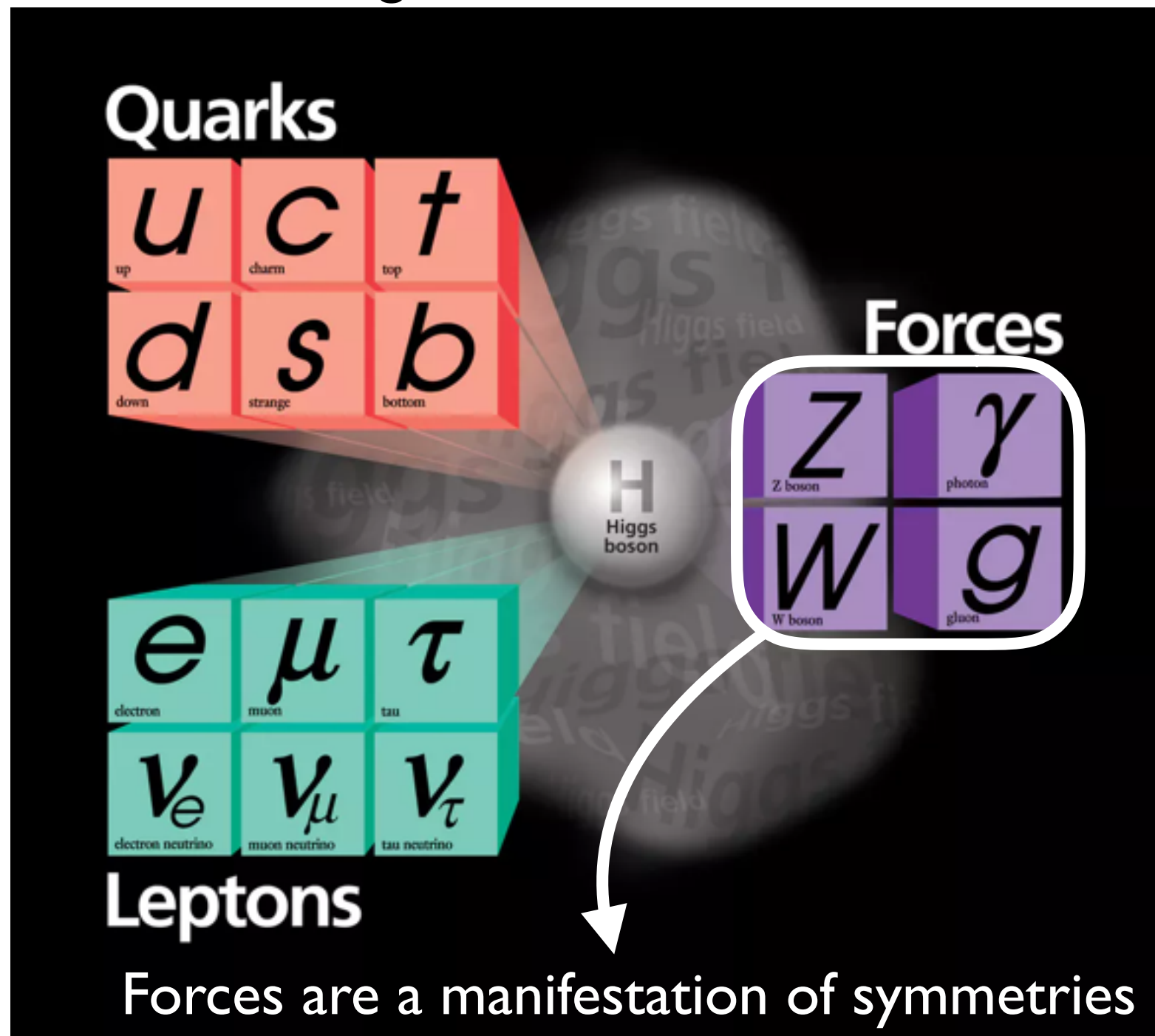


Cecilia's talk



# The standard model of particle physics

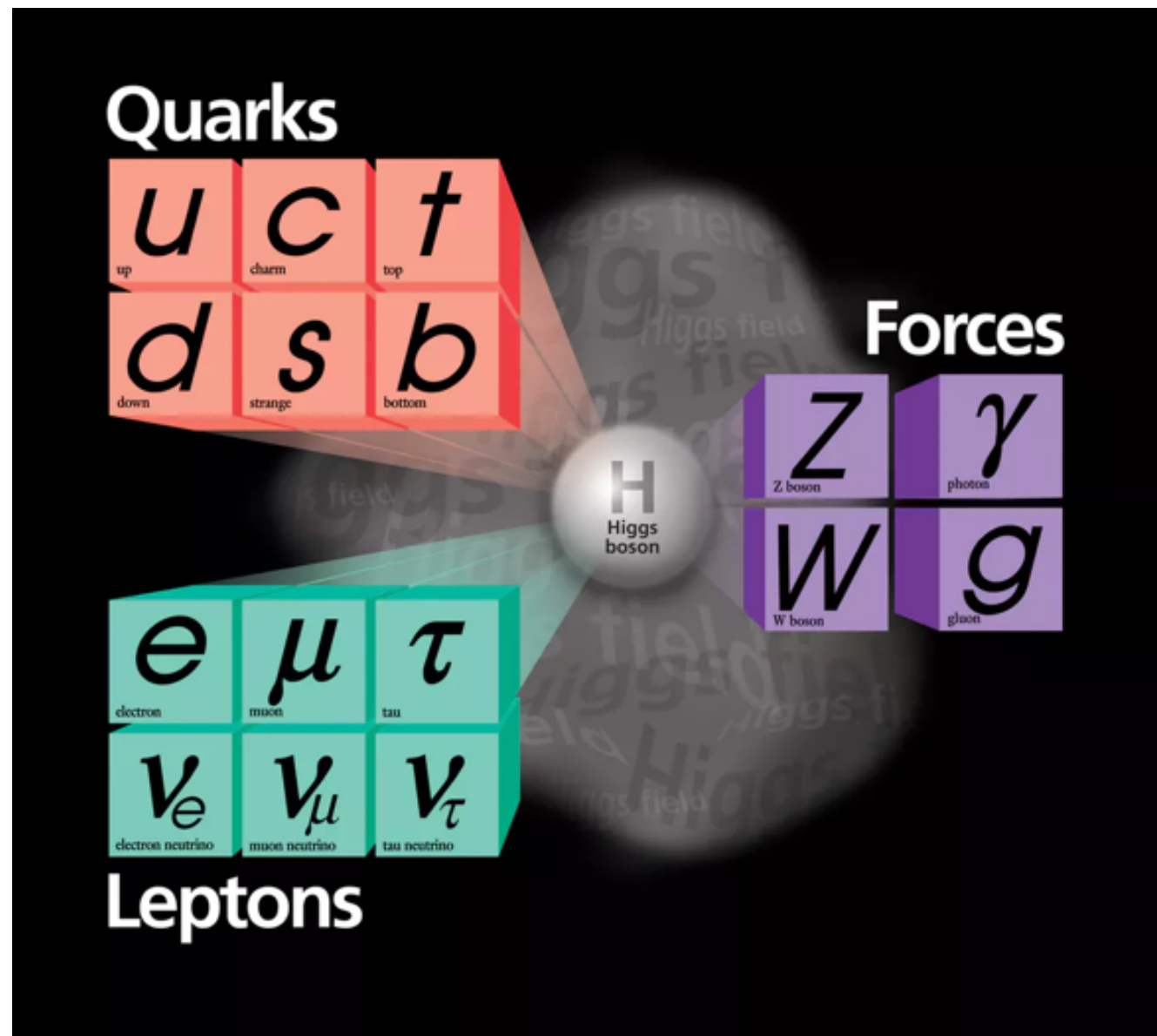
Building blocks of the universe



Cecilia's talk

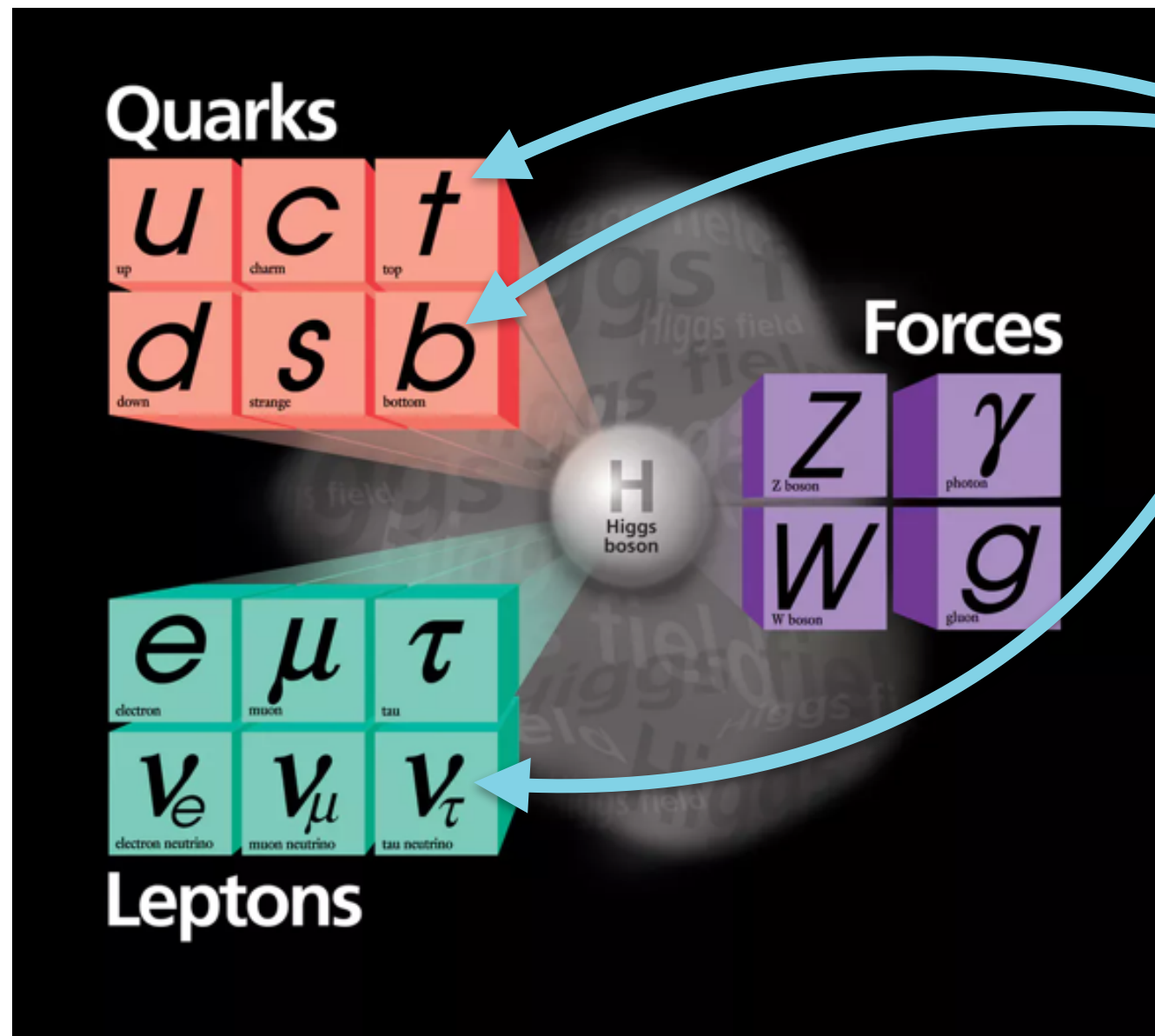
# Science at Fermilab and beyond

Fermilab, leading U.S. particle physics laboratory



# Science at Fermilab and beyond

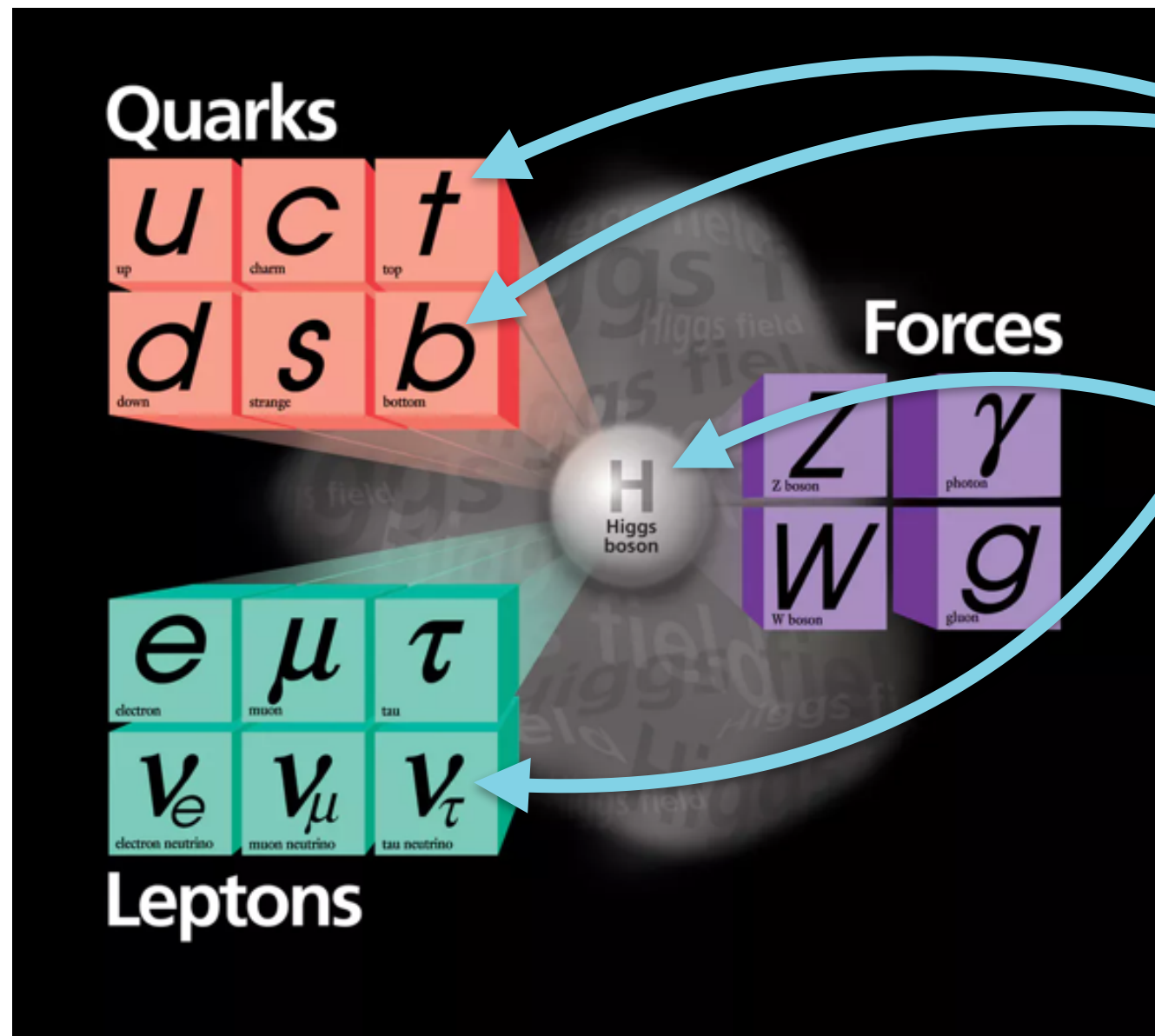
Fermilab, leading U.S. particle physics laboratory



Discovered at Fermilab!

# Science at Fermilab and beyond

Fermilab, leading U.S. particle physics laboratory



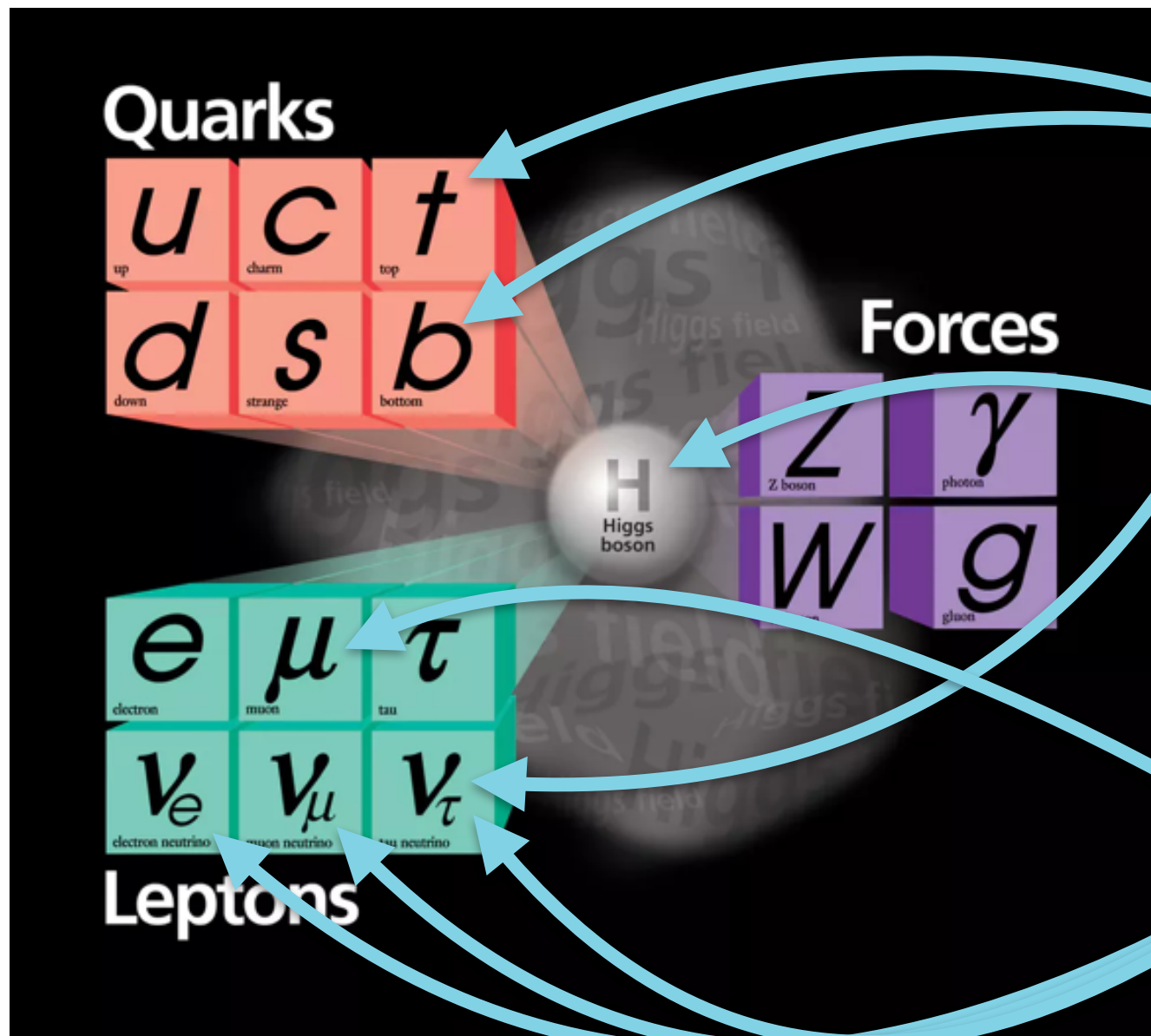
**Discovered at Fermilab!**

**Fermilab had major  
role in discovery**



# Science at Fermilab and beyond

Fermilab, leading U.S. particle physics laboratory



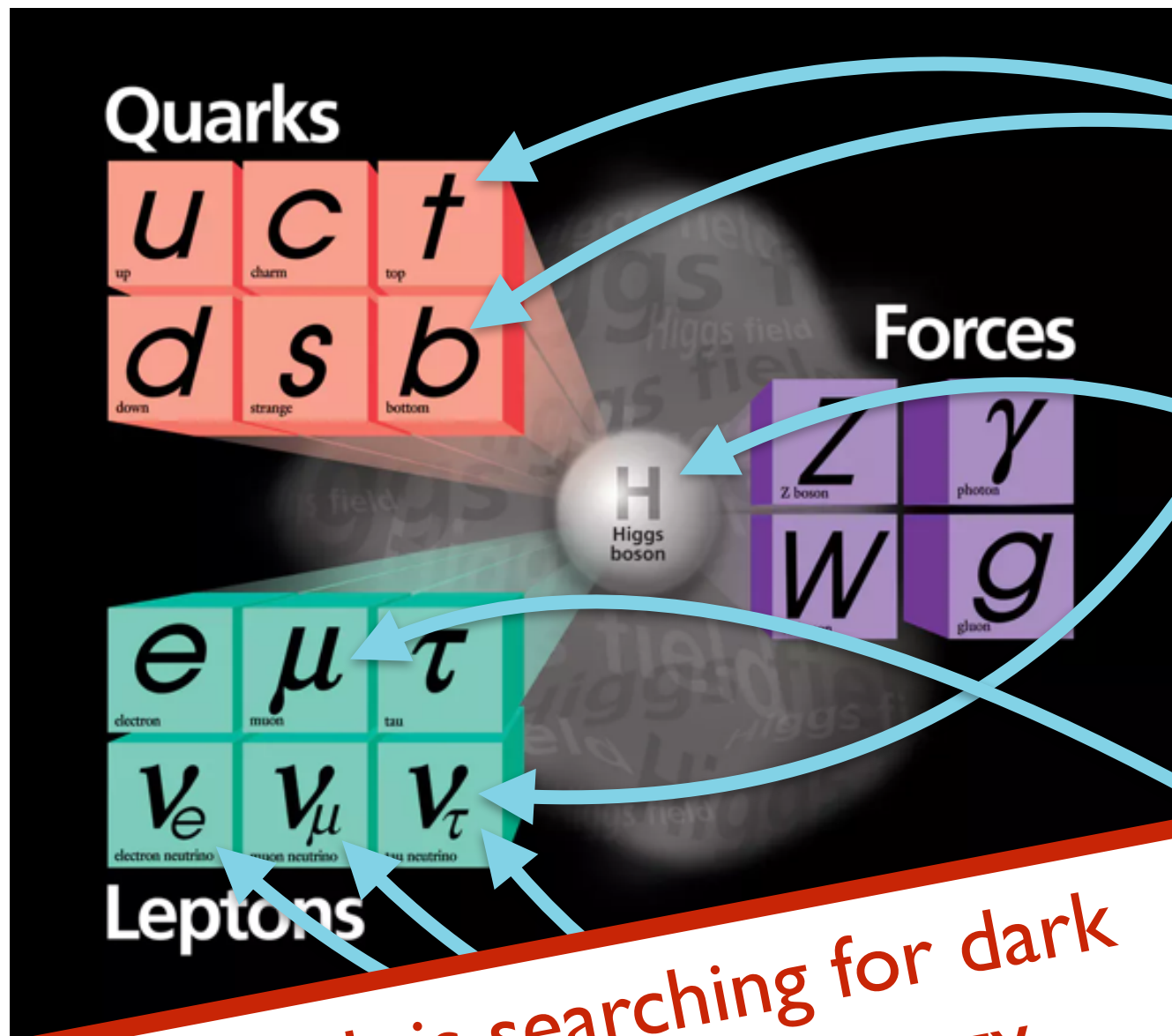
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**Being thoroughly studied  
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**Discovered at Fermilab!**

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**Being thoroughly studied  
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**Fermilab is searching for dark  
matter and dark energy**

# Science at Fermilab and beyond

Fermilab, leading U.S. particle physics laboratory

## Quarks



## Discoveries

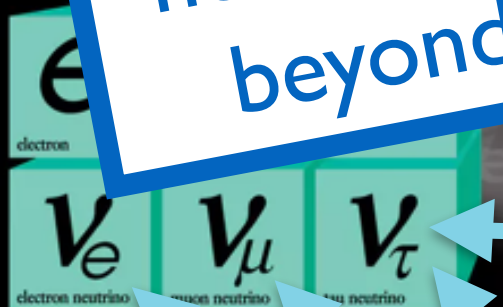
Fermilab theorists: important contributions to Higgs, top, neutrino, and dark matter physics; tools used at the LHC; beyond standard theories like Supersymmetry; etc etc

had major role in discovery

Being thoroughly studied at Fermilab

Fermilab is searching for dark matter and dark energy

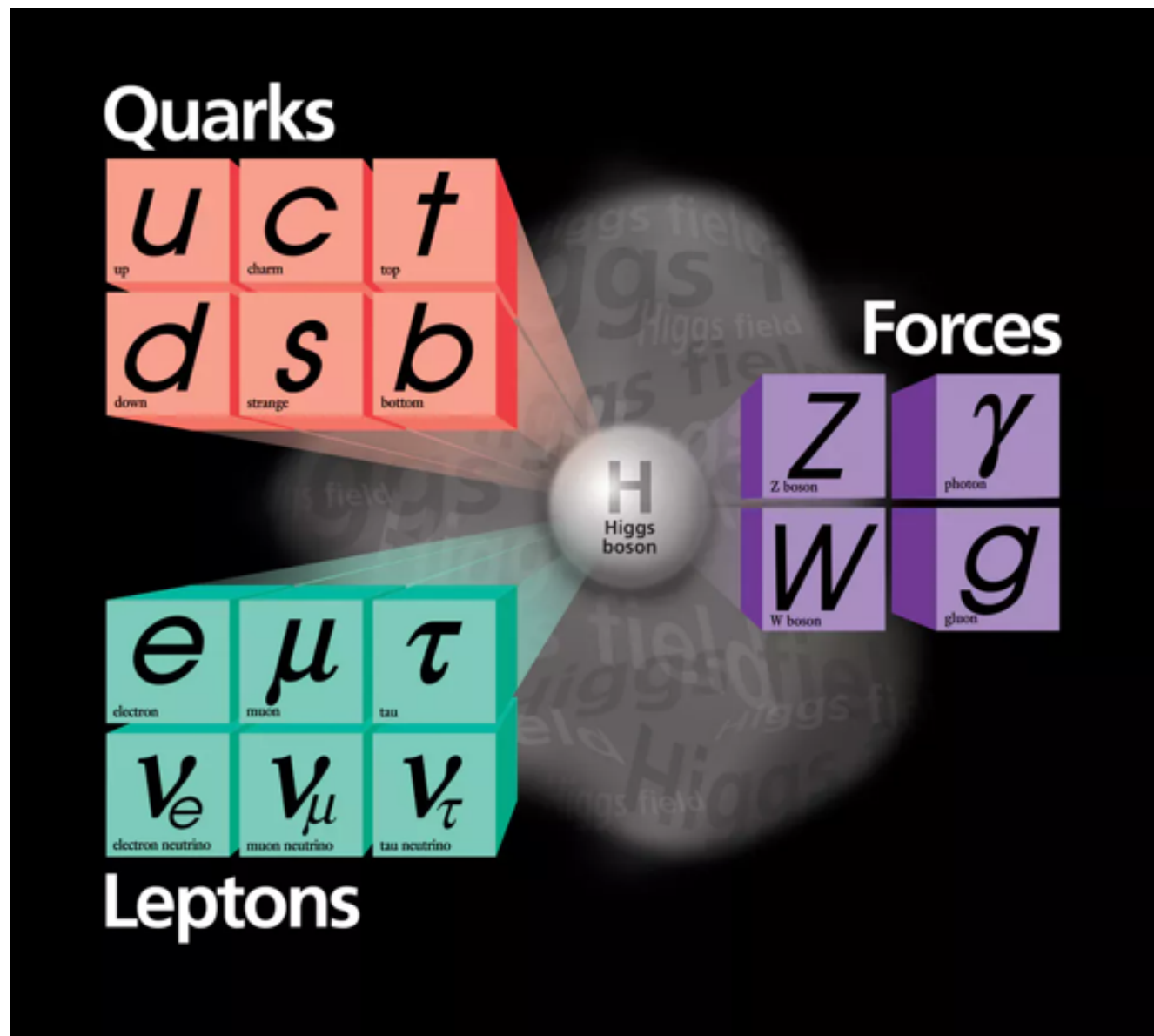
## Leptons



# Science at Fermilab and beyond

Fermilab, leading U.S. particle physics laboratory

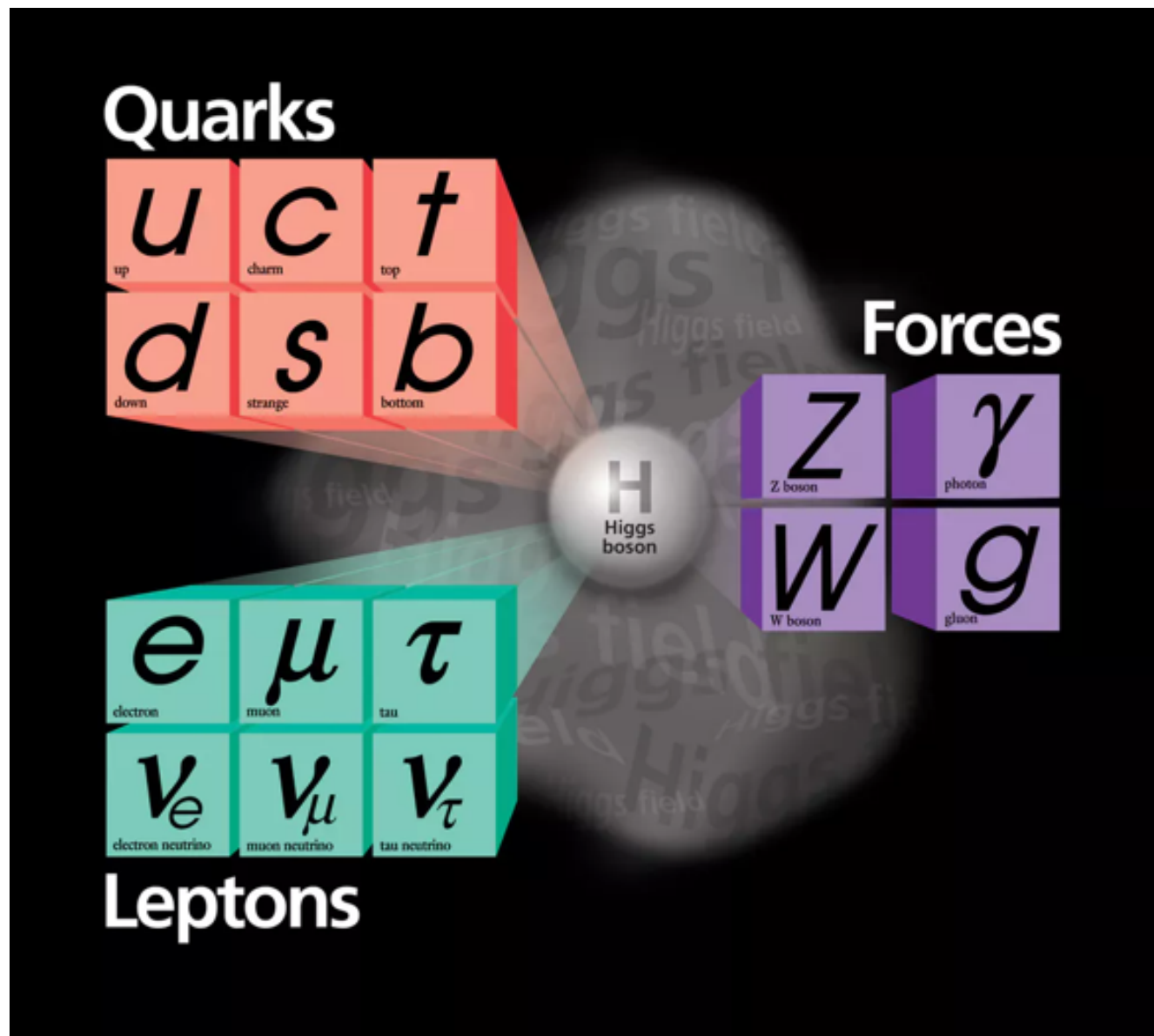
The standard model has been **extremely successful** in almost all experiments performed so far.





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Fermilab, leading U.S. particle physics laboratory



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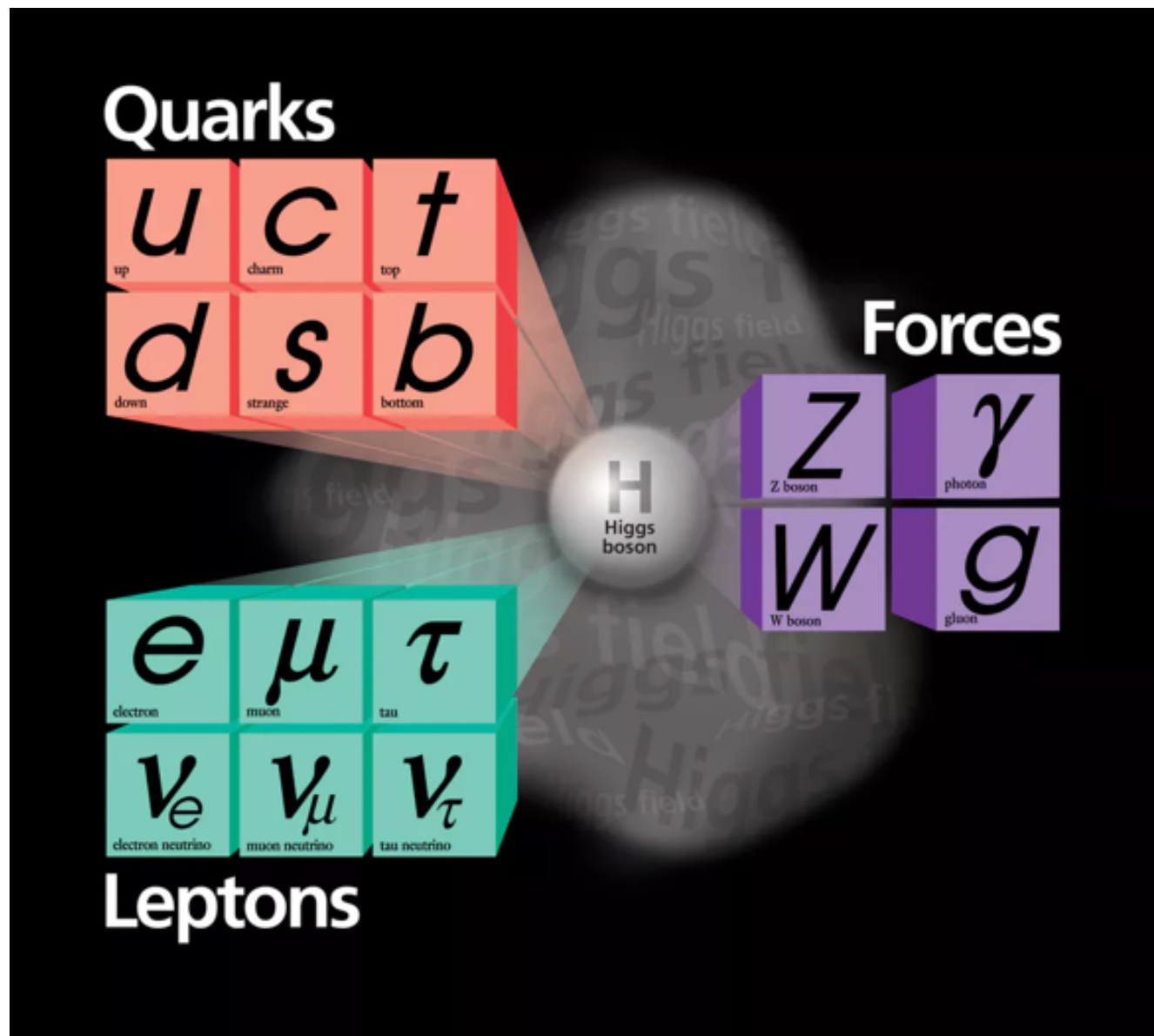
The goal of Fermilab is to test the standard model hypothesis as much as possible! Where does it break down? How?

Are we living a similar time as in 1901?  
Are the “clouds” we have been observing the edge of the standard model?

# Science at Fermilab and beyond

Fermilab, leading U.S. particle physics laboratory

Open questions:

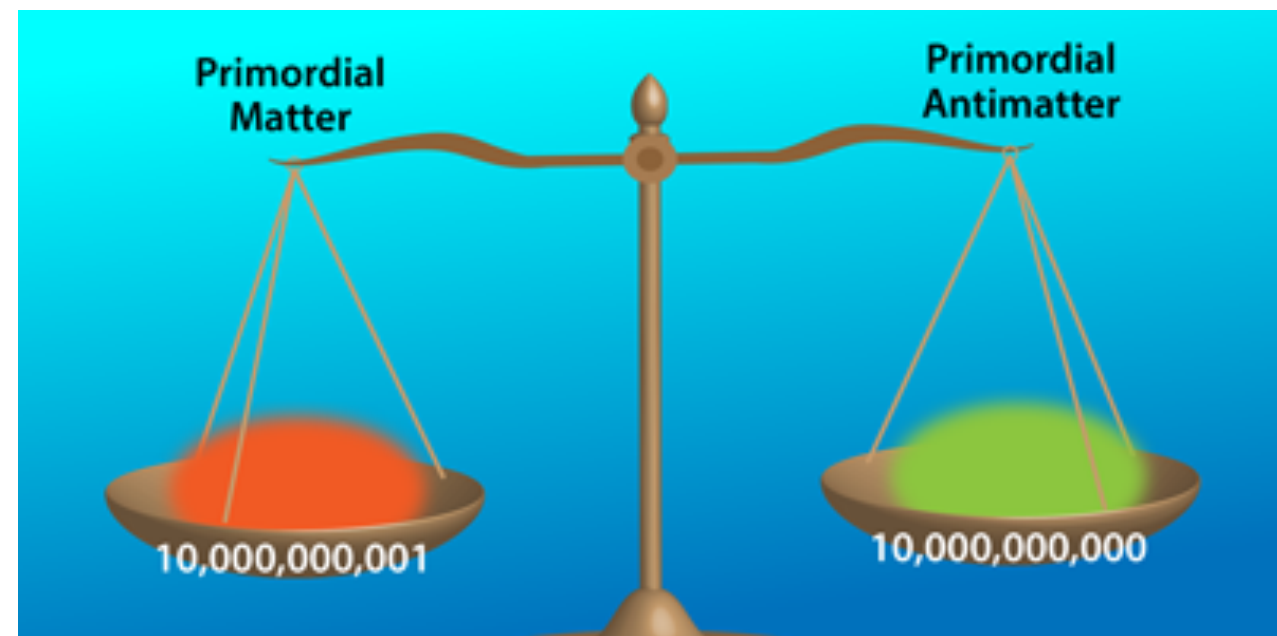
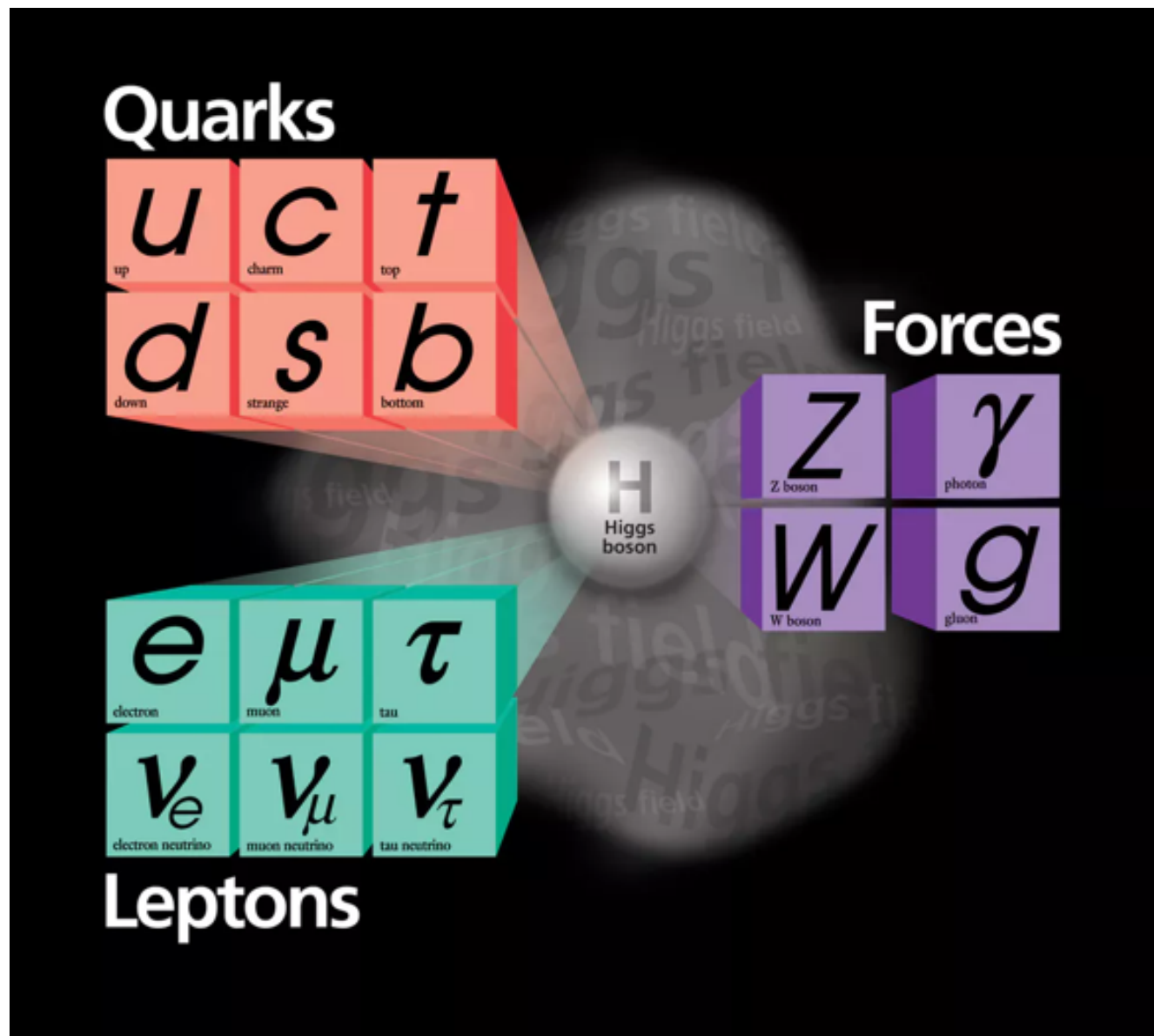


# Science at Fermilab and beyond

Fermilab, leading U.S. particle physics laboratory

Open questions:

How did matter (and not antimatter) survived in the big bang?



# Science at Fermilab and beyond

Fermilab, leading U.S. particle physics laboratory

Wait! What is antimatter?







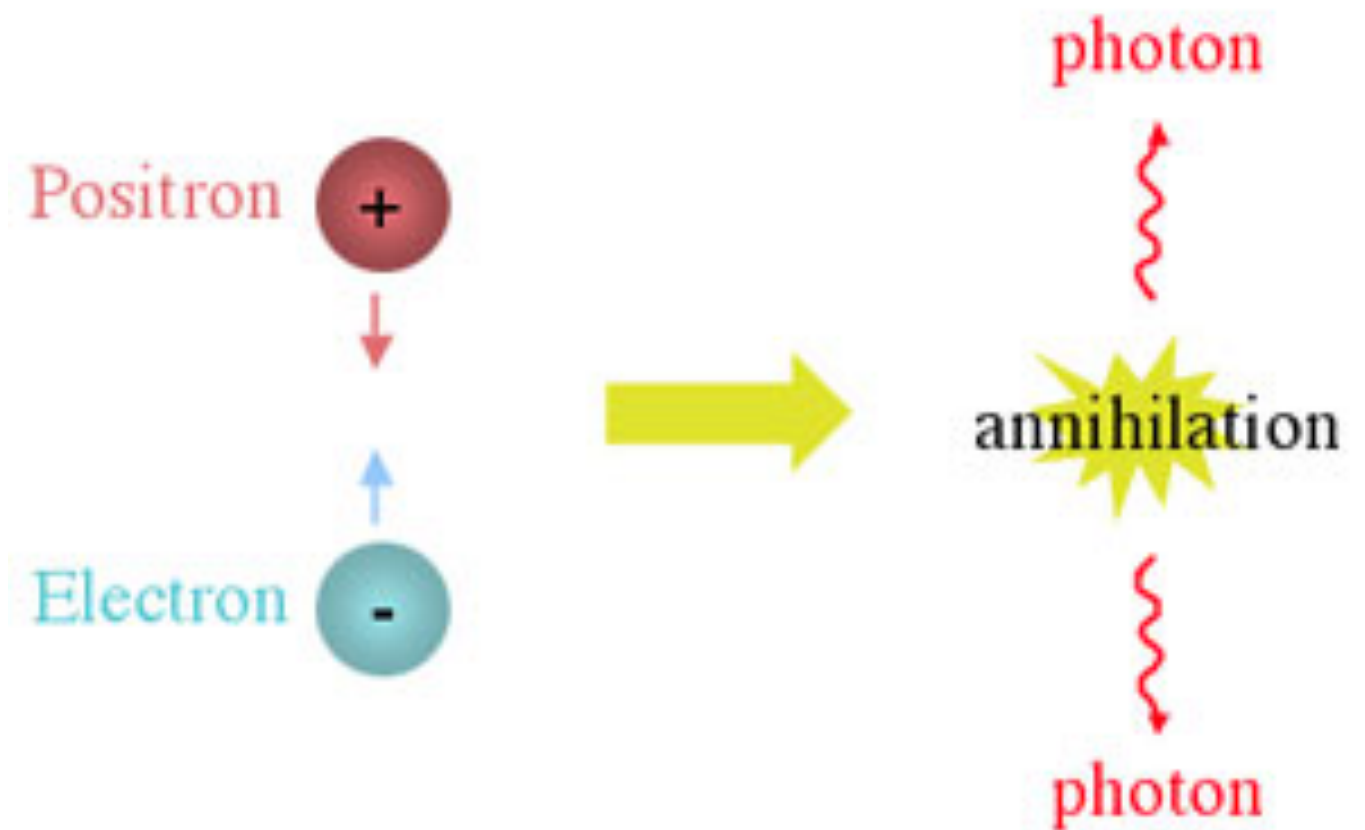
# Science at Fermilab and beyond

Fermilab, leading U.S. particle physics laboratory

Wait! What is antimatter?

Javier's talk

	Heavy	Light
Positive	 Proton (Matter)	 Positron (Antimatter)
Negative	 Anti-Proton (Antimatter)	 Electron (Matter)

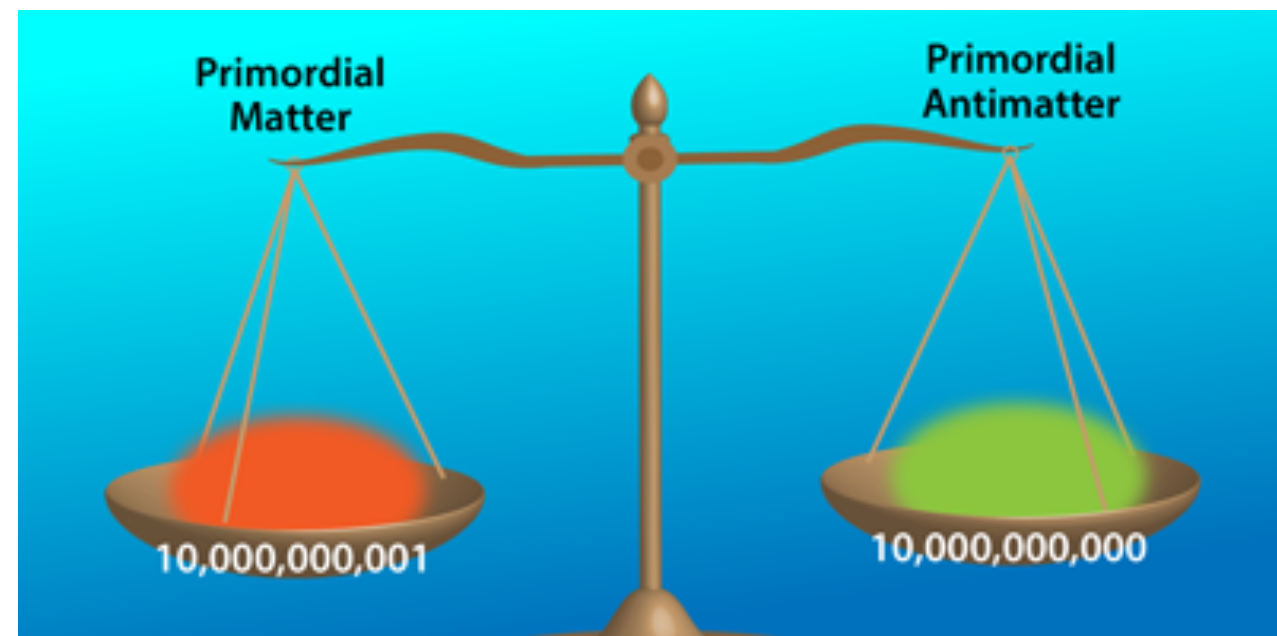
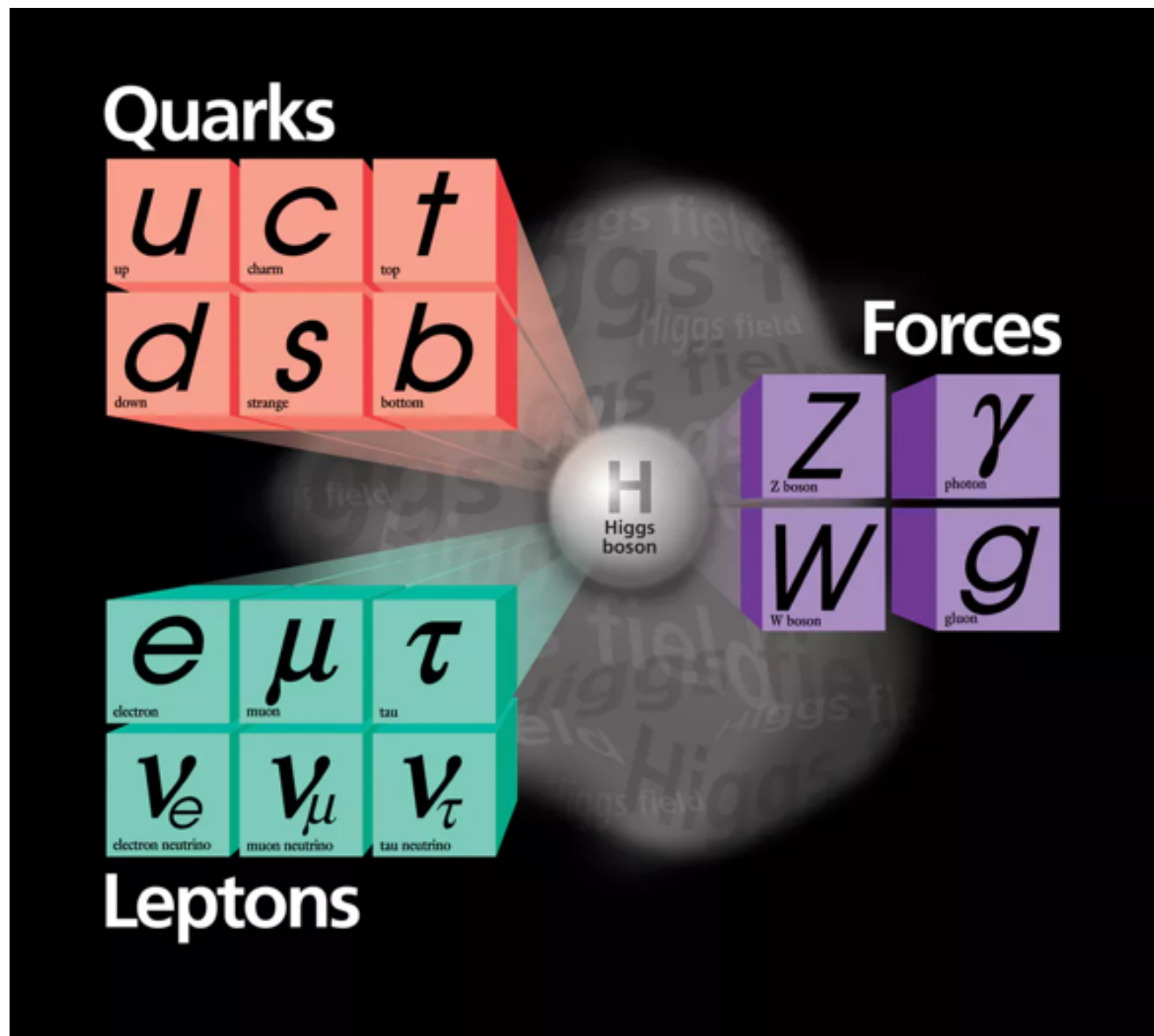


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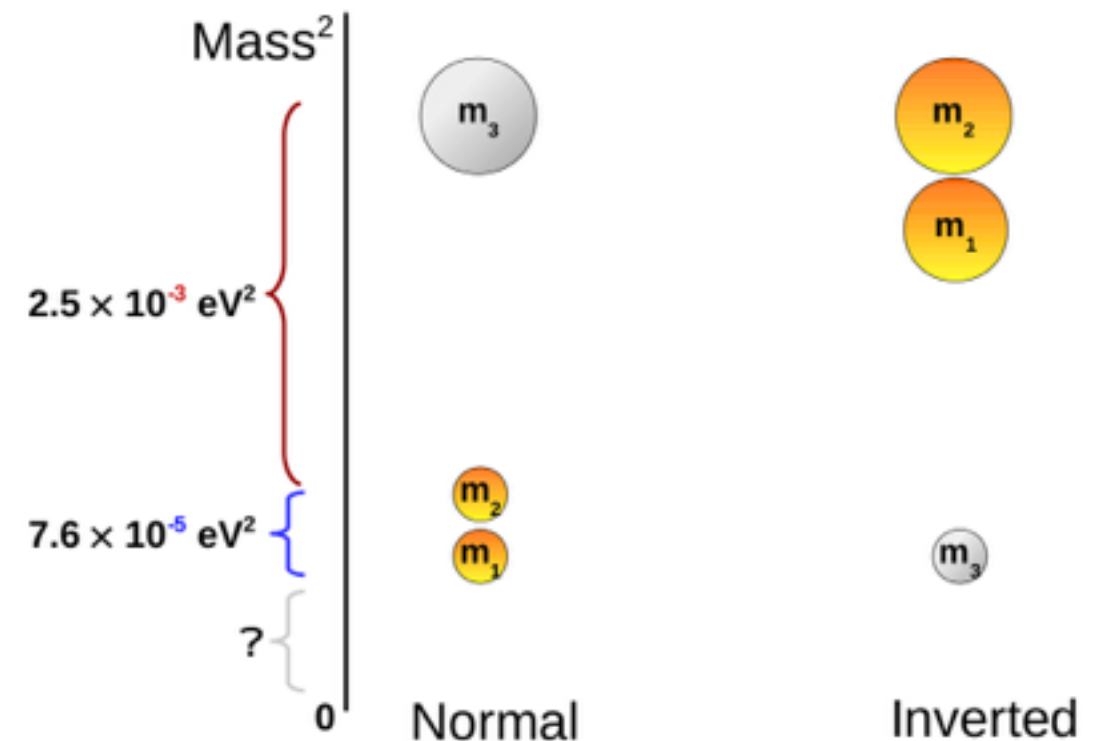
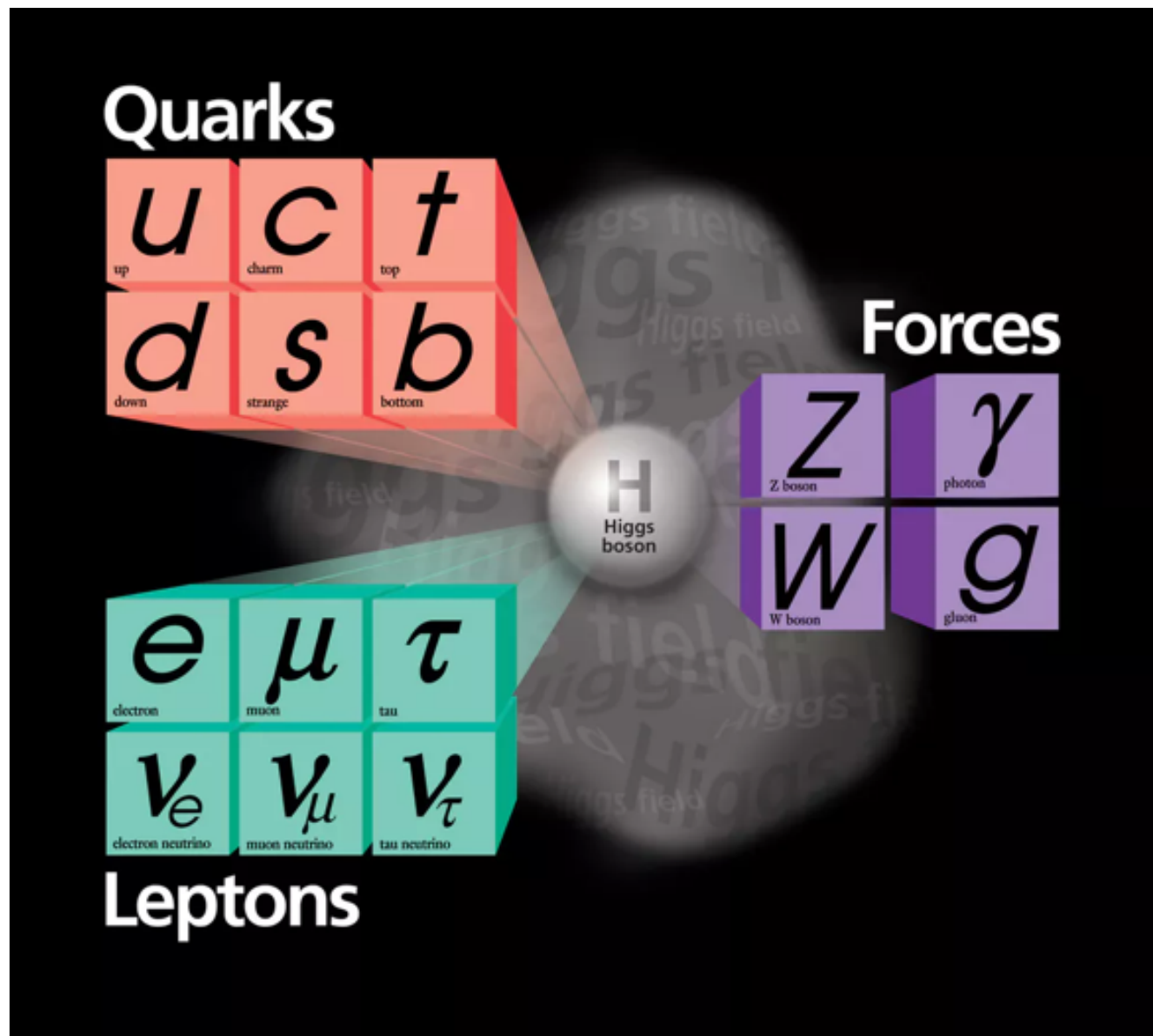
# Science at Fermilab and beyond

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What is the mass of the neutrinos?



# Science at Fermilab and beyond

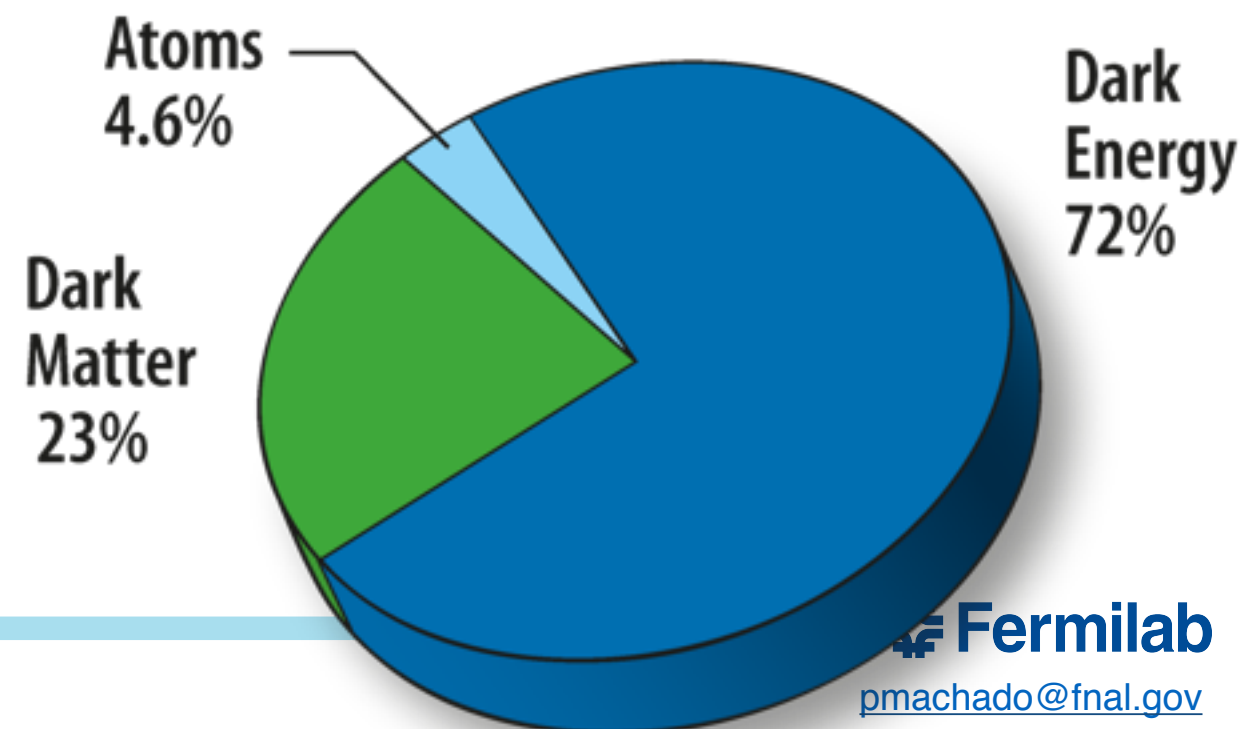
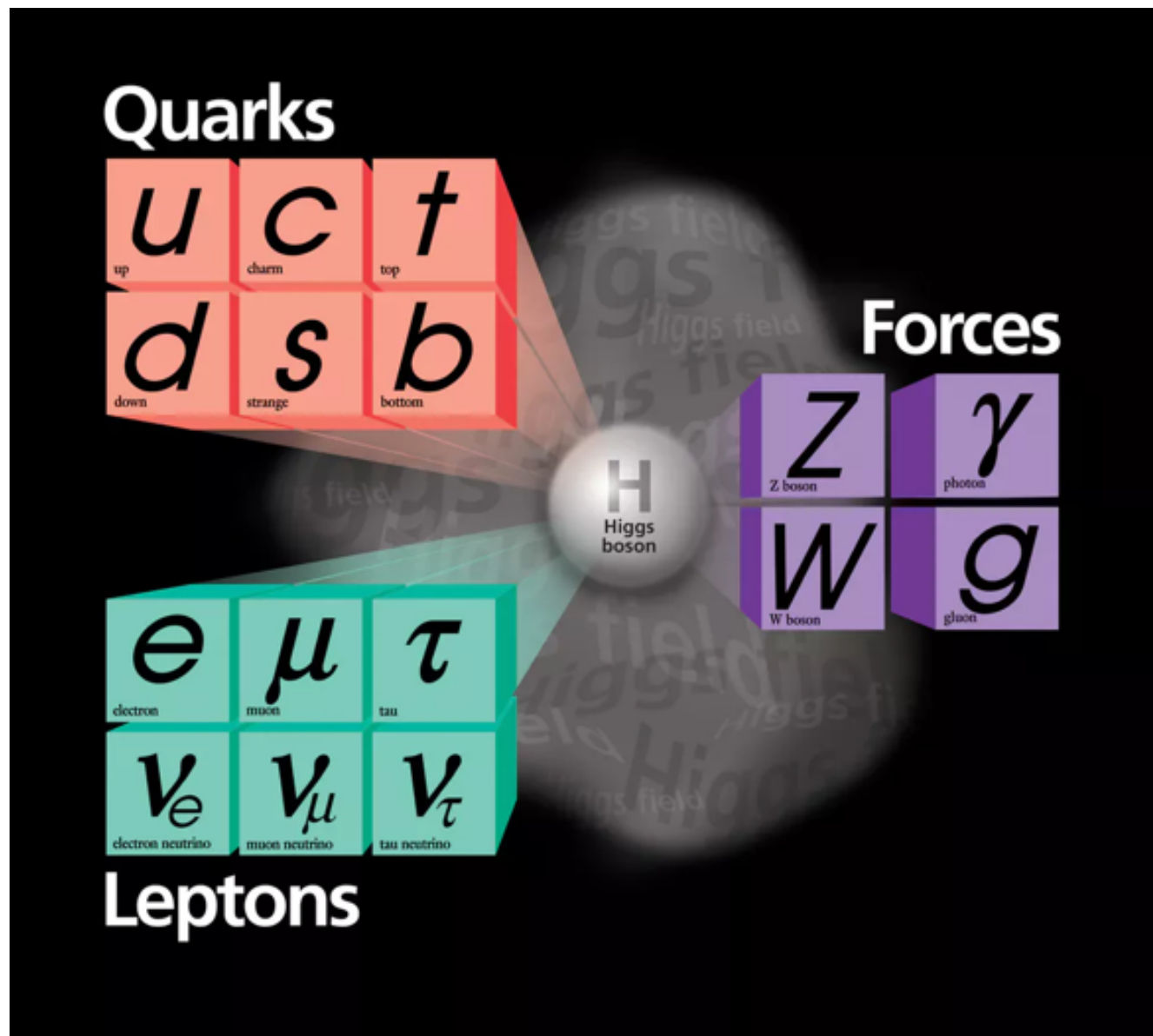
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# Science at Fermilab and beyond

Fermilab, leading U.S. particle physics laboratory

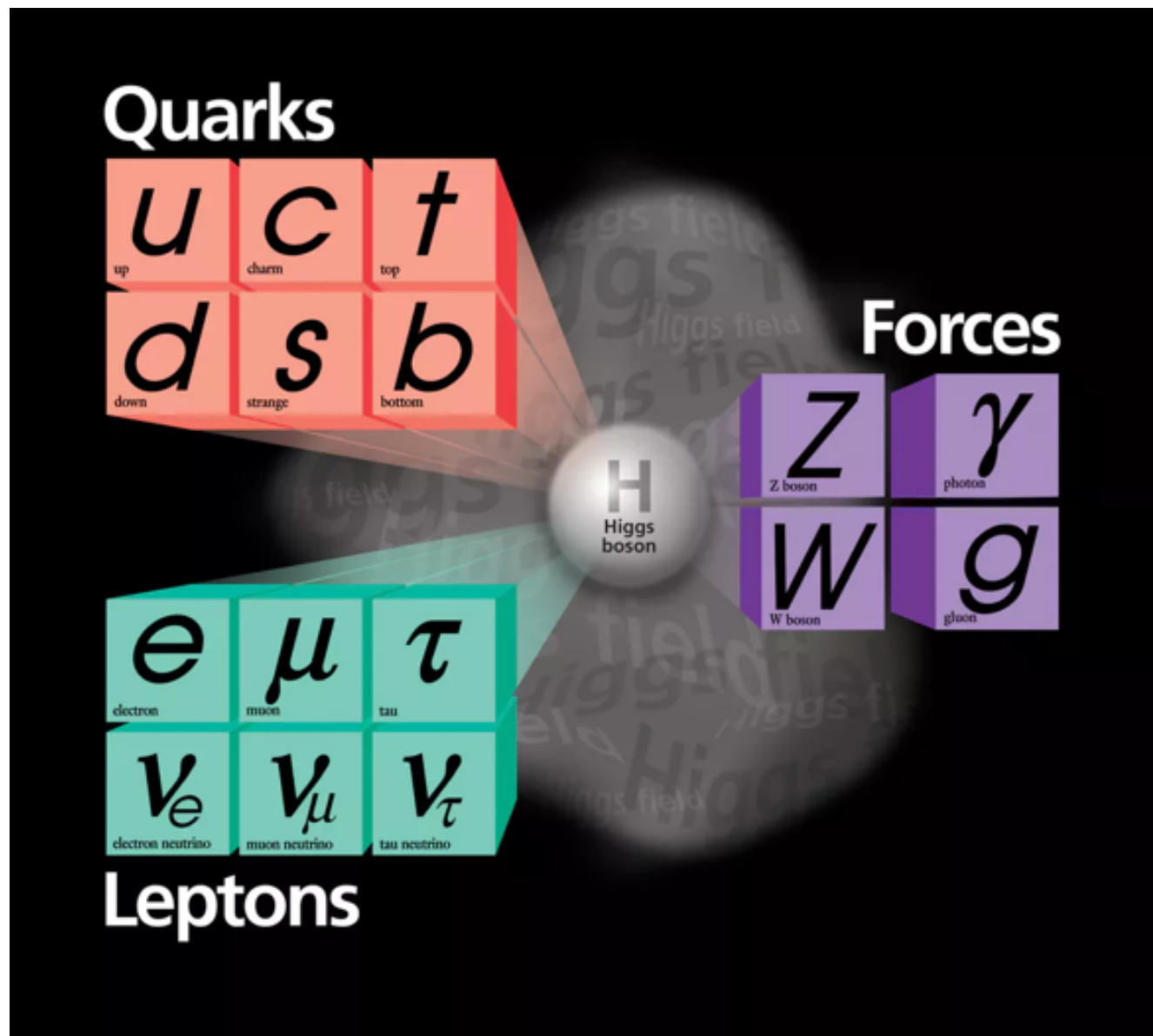
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Fermilab, leading U.S. particle physics laboratory

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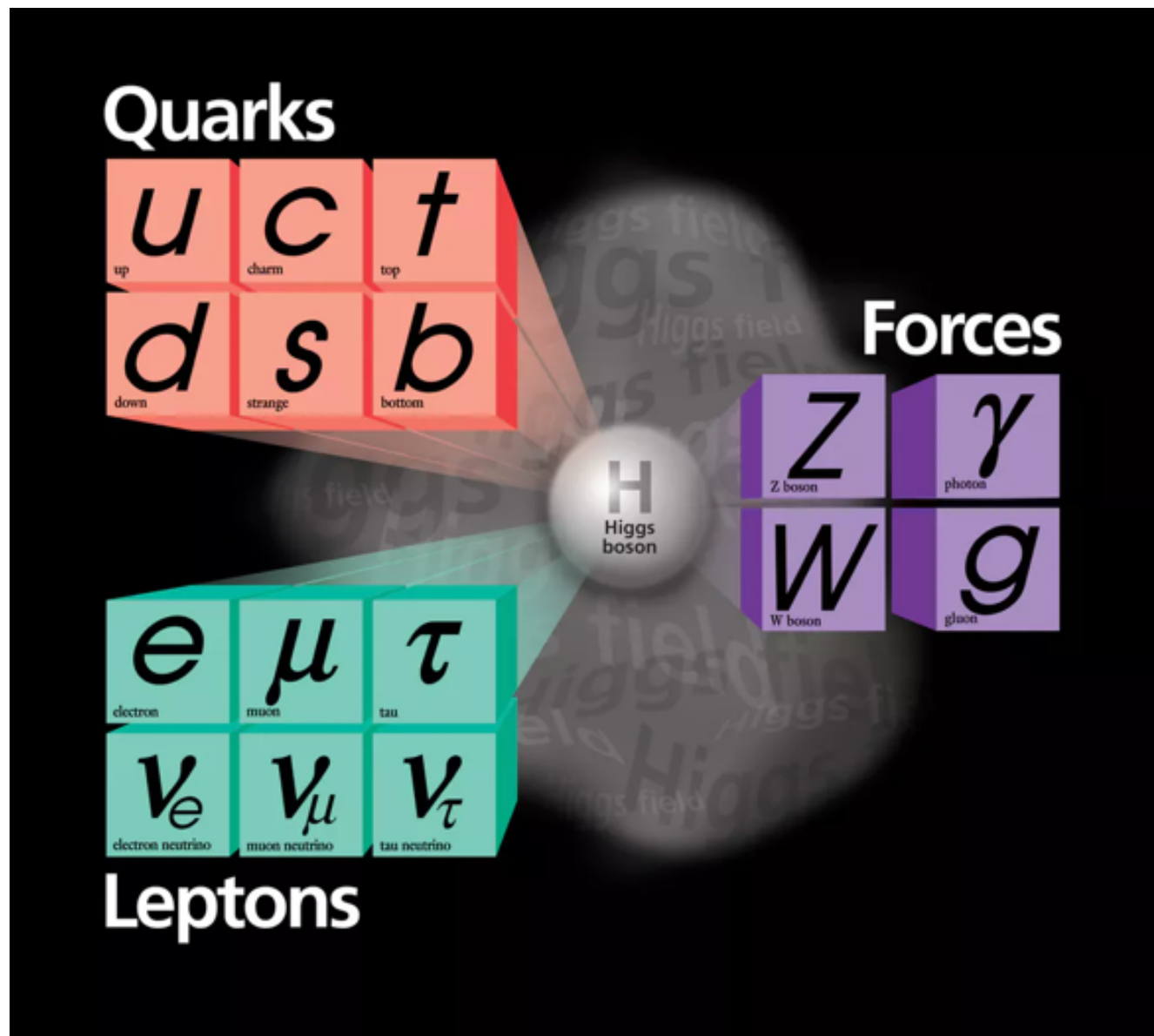
How did matter (and not antimatter) survived in the big bang?

What is the mass of the neutrinos?

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Why is the universe expanding?

Any reason behind the 3 families?



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Fermilab, leading U.S. particle physics laboratory

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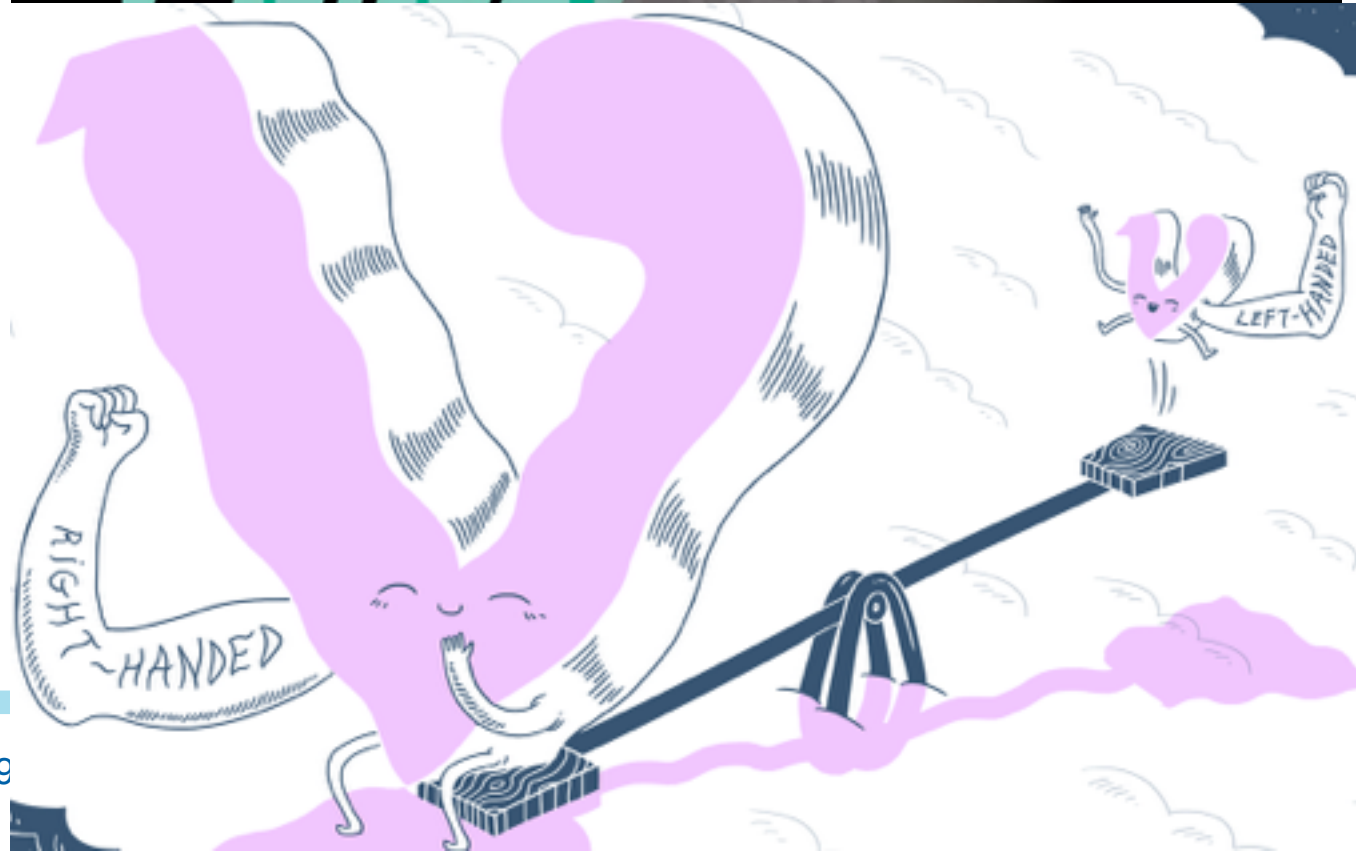
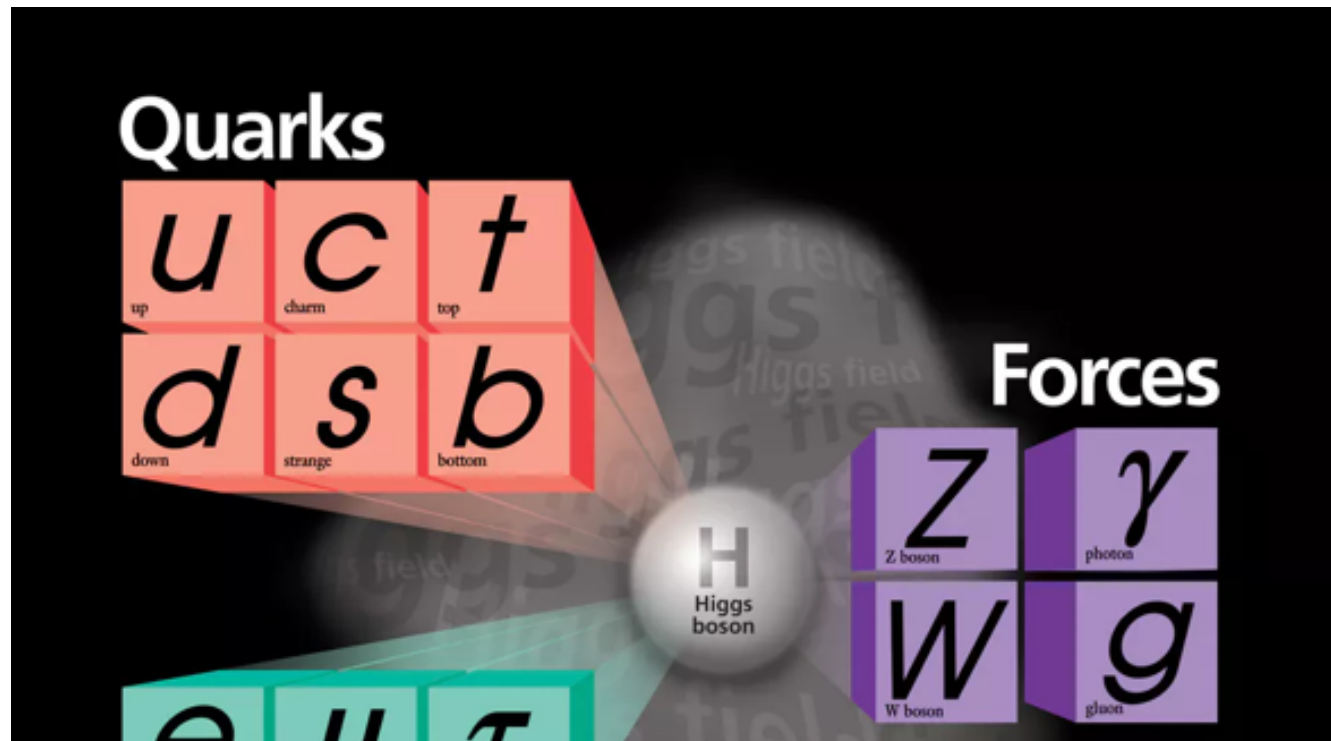
What is the mass of the neutrinos?

What is dark matter and dark energy?

Why is the universe expanding?

Any reason behind the 3 families?

What is the mechanism of neutrino masses?





# Science at Fermilab and beyond

Neutrino experiments at FNAL



**MINERvA**



**NOvA**





# Science at Fermilab and beyond

Neutrino experiments at FNAL



MINERvA



NOvA

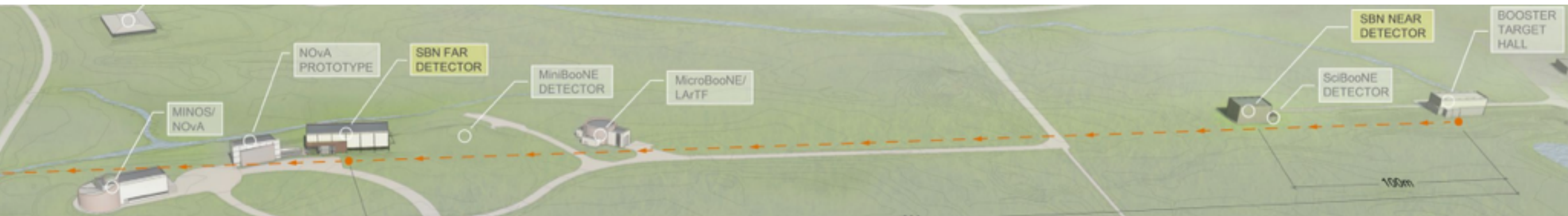




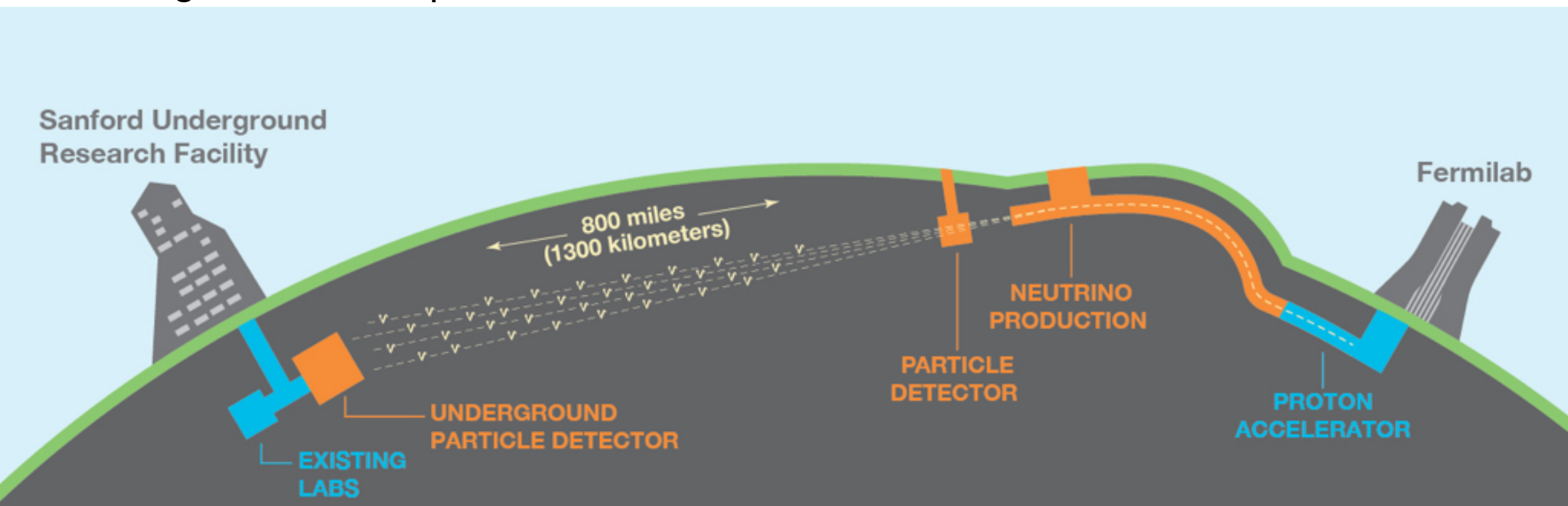
# Science at Fermilab and beyond

## Neutrino experiments at FNAL

### Short baseline neutrino program



**DUNE:** largest neutrino experiment ever - 175 institutions, 32 countries, 1000+ collaborators





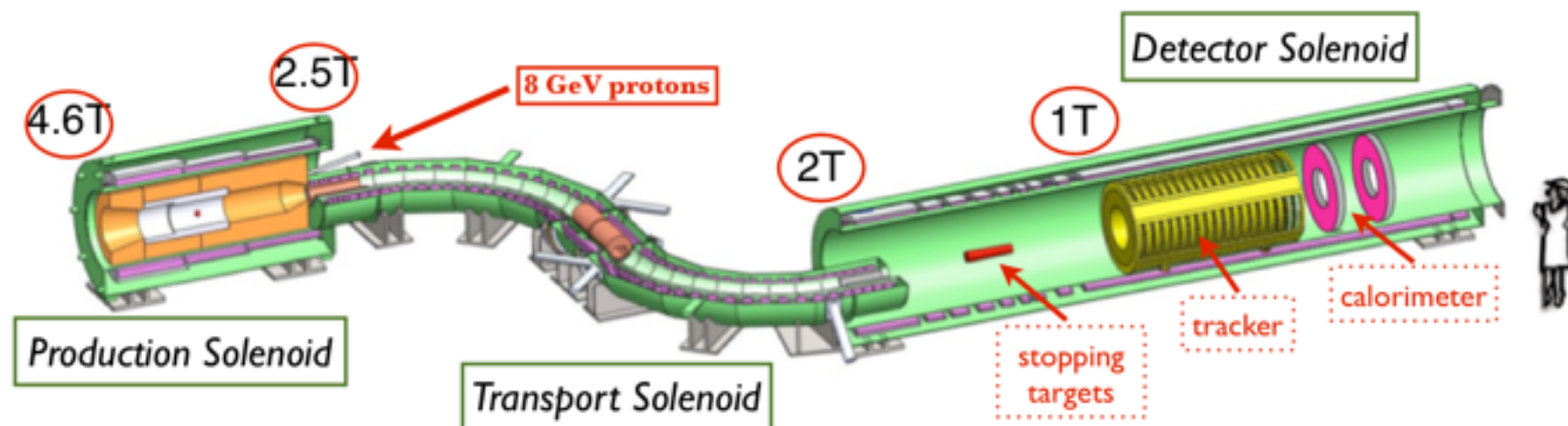
# Science at Fermilab and beyond

## Muon experiments at FNAL

### Muon g-2



### Mu2e





# Science at Fermilab and beyond

Ting Li's talk

dark matter /dark energy

## Dark Energy Survey



## CDMS/SuperCDMS

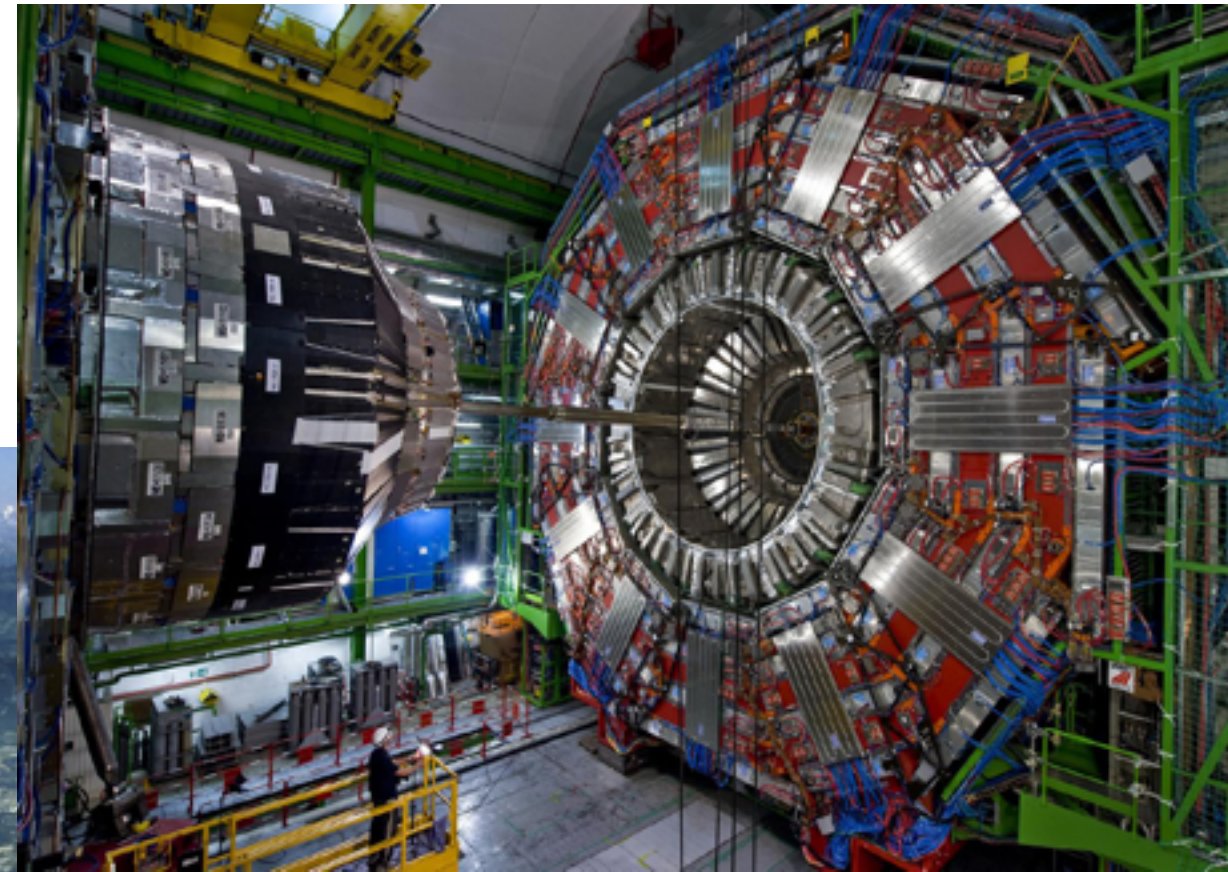




# Science at Fermilab and beyond

High energy frontier

**LHC:** 27 km, 10k+ collaborators, 100+ countries

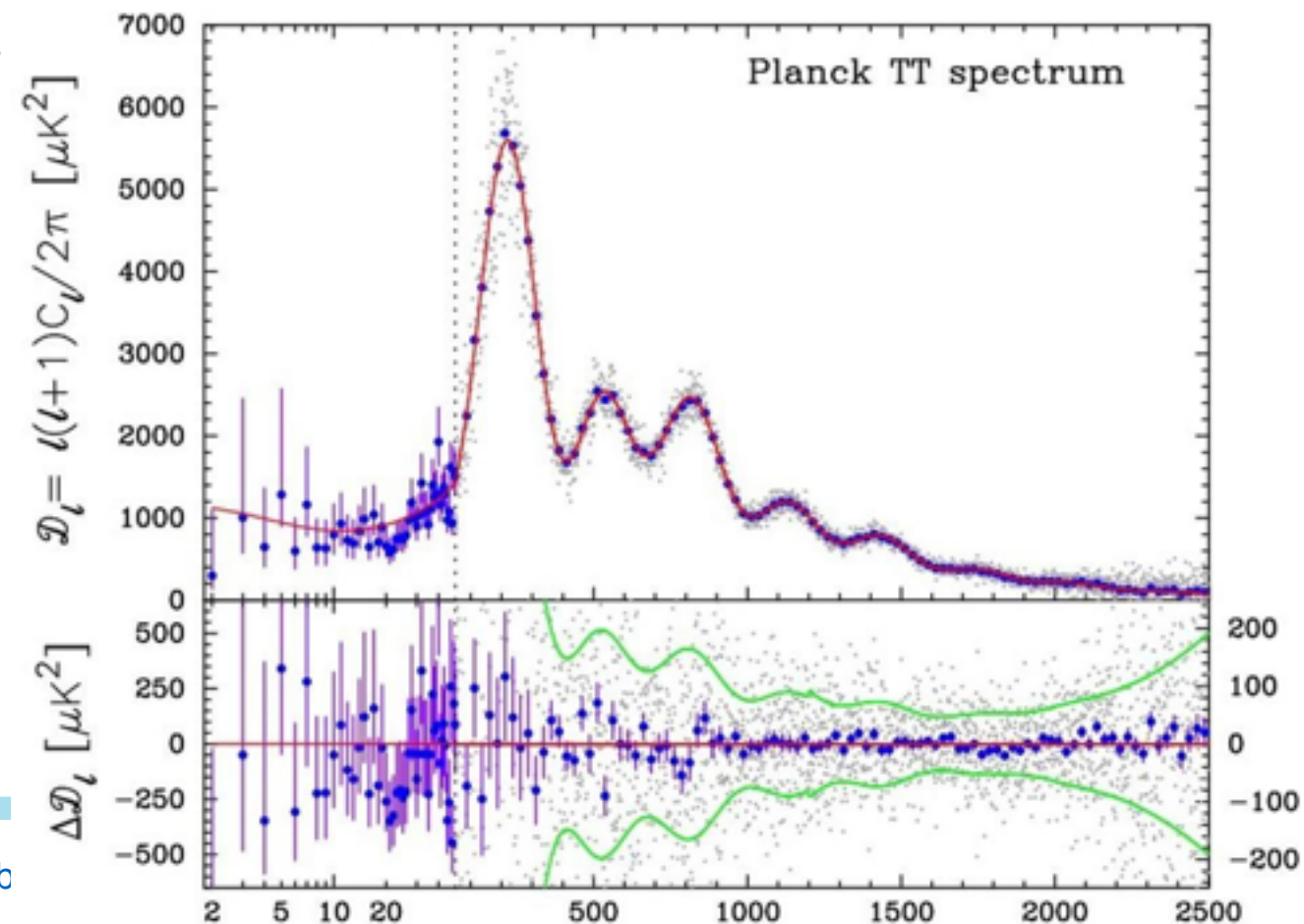
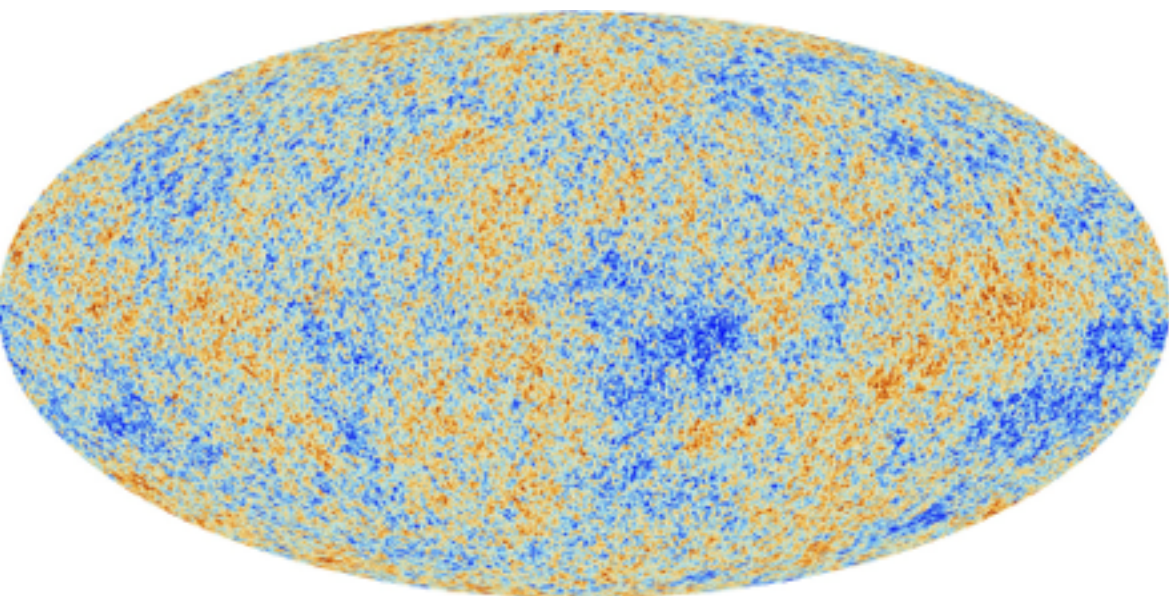
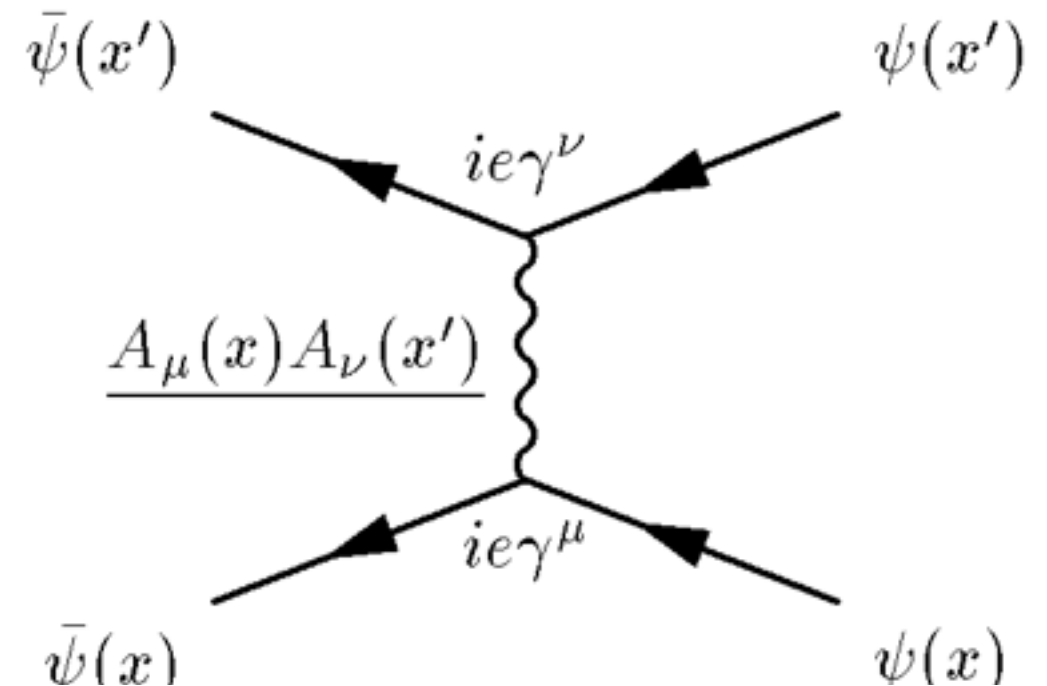




# Science at Fermilab and beyond

Theory

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i \bar{\psi} \not{D} \psi + h.c. \\ & + \bar{\psi} i \gamma_{ij} \psi \phi + h.c. \\ & + |D_\mu \phi|^2 - V(\phi)\end{aligned}$$



# Science at Fermilab and beyond

Earth, water, air, fire  
geocentrism

# Science at Fermilab and beyond

**Earth, water, air, fire  
geocentrism**

scientific method, calculus,  
telescopes, prisms, ...



**Heliocentrism  
Classical mechanics  
Electromagnetism**



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More math, optics,  
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Particle accelerators, satellites  
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Global experiments,  
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???



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**Fermilab's history**

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**Fermilab's history**

The standard model

Particle accelerators, satellites  
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Global experiments,  
detection technology, ...

**Fermilab's goal**

???

# Science at Fermilab and beyond

What do you want to know?

