

Physics at Fermilab

A
Saturday Morning Physics
Introductory Overview

by J. L. Barrow

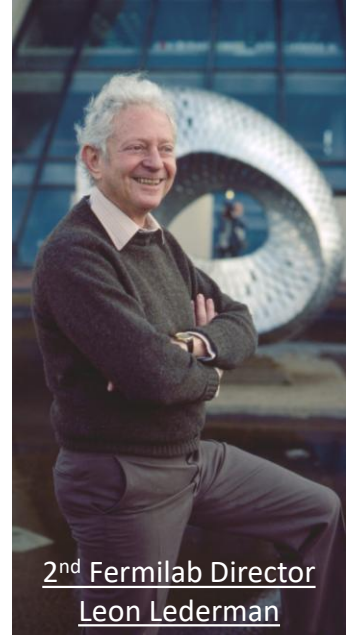
The University of Minnesota
with key inputs from Cristina Mantilla Suarez, FNAL

September 12th, 2026





Welcome to Saturday Morning Physics!



2nd Fermilab Director
Leon Lederman

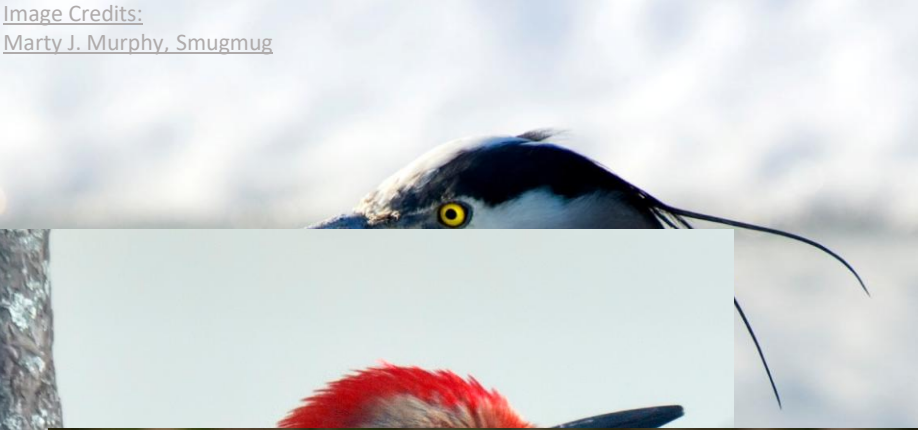
- Recording will be made available!
- All slides have many hyperlinks
 - Lots of further reading!
- Free to interrupt with questions
 - Please just raise your hand!
- **Hope:** Retain cool concepts!
- **Use:** Future sessions w/deeper understanding!

Fermilab Architecture & Sculptures

History of Art & Architecture

Möbius at Fermilab

Celebrating the Life & Legacy of Leon Lederman



Nature at Fermilab



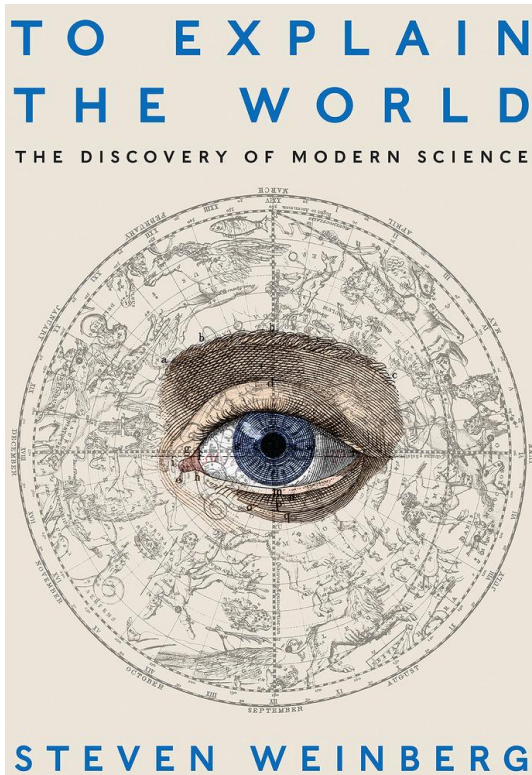
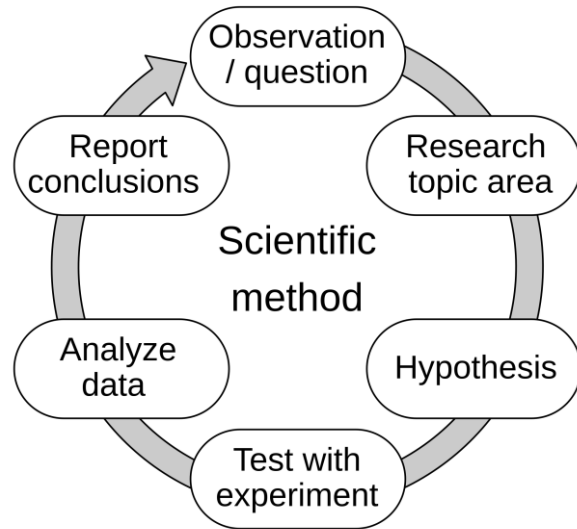


The DOE Complex



What is Modern Science?

By Efbrazil - Own work, CC BY-SA 4.0



World Science Festival Interview

Available at Barnes & Noble

- The *Scientific Method* developed over centuries
- Focused philosophical development $\geq 16^{\text{th}}$ century
 - Earlier developments occurred—arguably ununified
- **Essential steps of The Scientific Method**
 1. **Observation:** characterize/measure phenomena
 2. **Hypothesis:** theoretical explanation
 3. **Prediction:** understand implications of hypothesis
 - Design scenarios to directly test predictions (imagination!)
 - *Hopefully* with clean separation of competing predictions
 4. **Experiment:** test predictions under designed scenarios
- If predictions and experimental tests...
 - Disagree: *invalidate hypothesis* and associated theory
 - Agree: *fail to reject hypothesis* and associated theory
 - **We cannot definitively *prove* any scientific hypothesis**
- **Makes Science a philosophically *negative* discipline**



How to *do* science?

An example...

Back in 1850,
how could we *know* that the Earth rotates?

Question:

Back in 1850, how could we know the Earth rotates?



- Some key **observations (1)** suggested rotation...
 - Ancient astronomers knew stars appeared to move in circles
 - Incredibly important to understand for navigation!
 - Everyone knows about day and night...

**Why are these
observations not “proof”?**

Central Question:

How do we definitively show *relative motion*?



'Atlas Holding Up Heavens', Bernard Picart (1731)

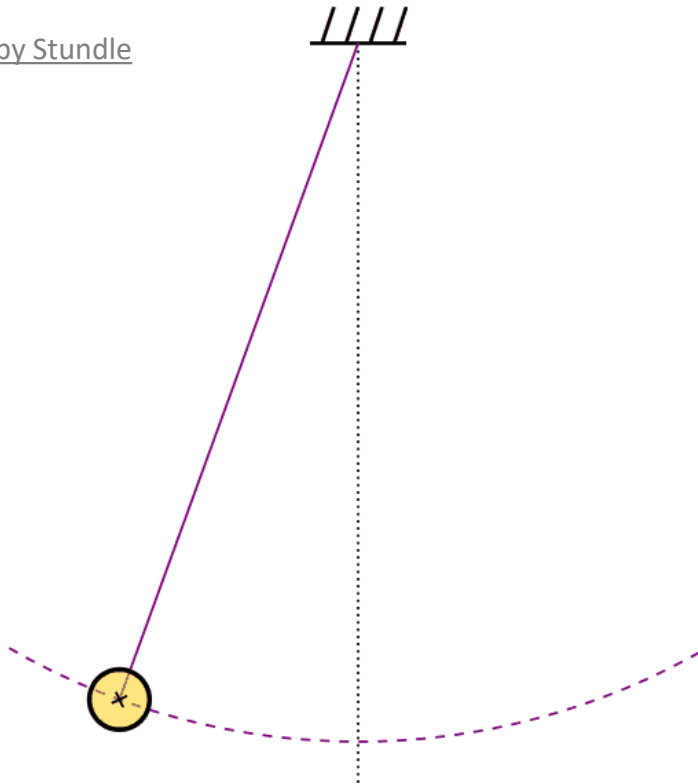
**Why are
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**How do we
definitively show
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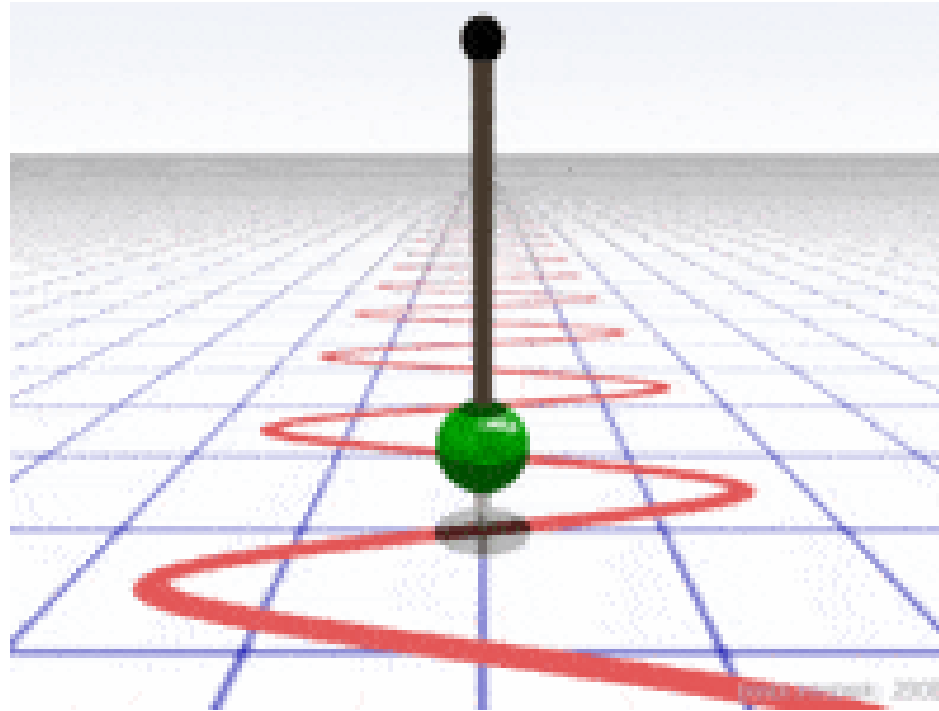


Intuition vs. Evidence

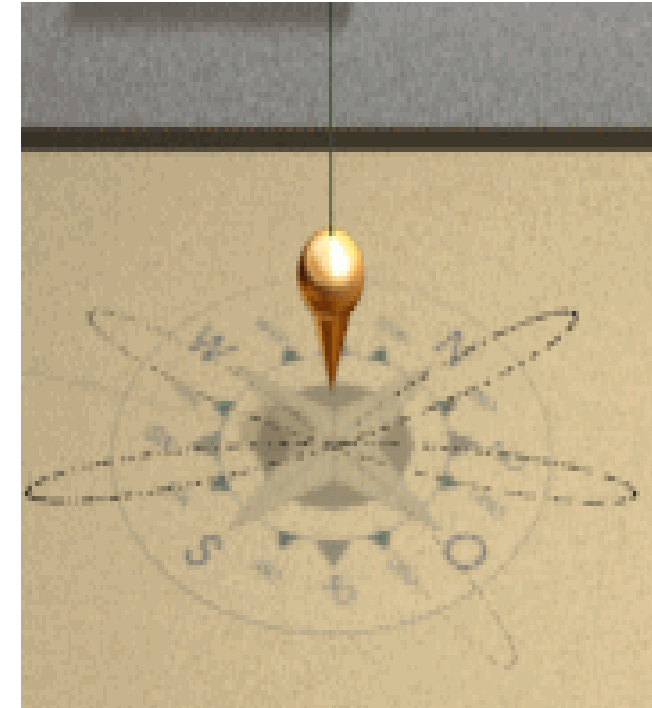
GIF by Stundle



Ib Physics: Simple Harmonic Motion



GIF adapted from Dominique Toussaint



Intuition:

Absent external forces, pendulums should oscillate forever on the same plane

([Galilean reference frame](#), his [work with pendulums](#))

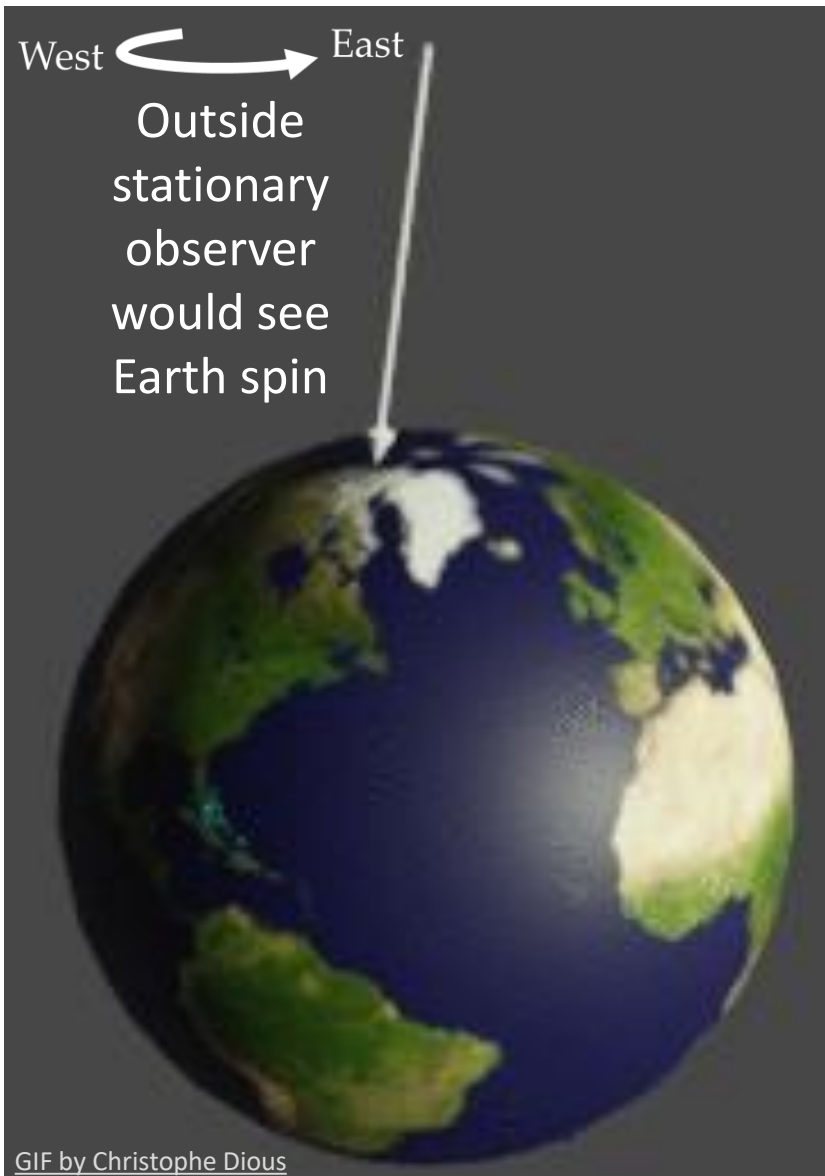
Evidence:
Pendulum appears to *precess*
(over hours—
sped up here)

Implication:
~~External forces?~~
External motion?

Hypothesis & Predictions

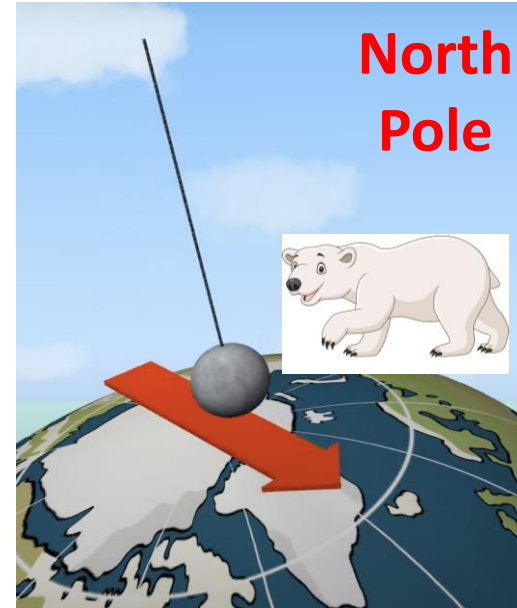
H) The Earth is a spinning sphere

P) Some latitudes will precess differently (or not at all?)



Local **North Pole** stationary observer would see precession of pendulum in opposite direction to Earth's spin

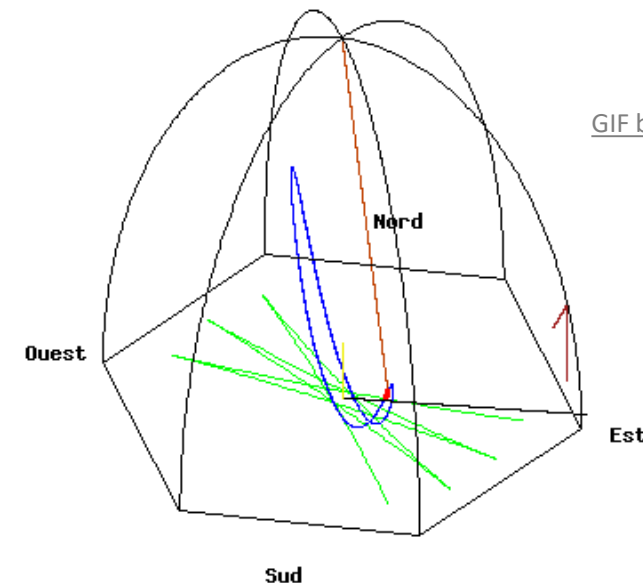
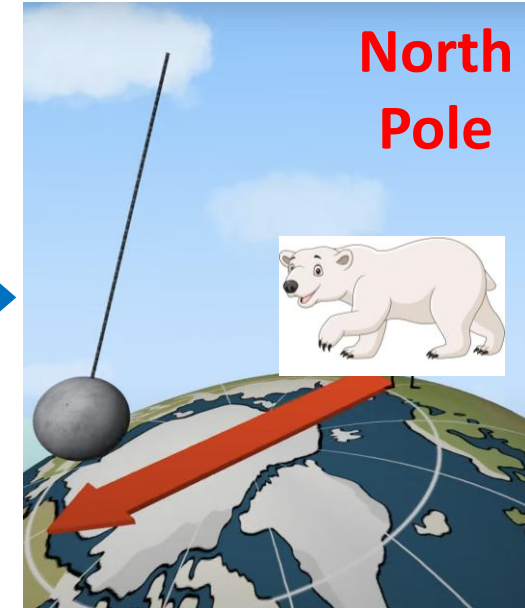
A red curved arrow pointing clockwise, indicating the direction of precession as seen from the North Pole.



Time

Passes

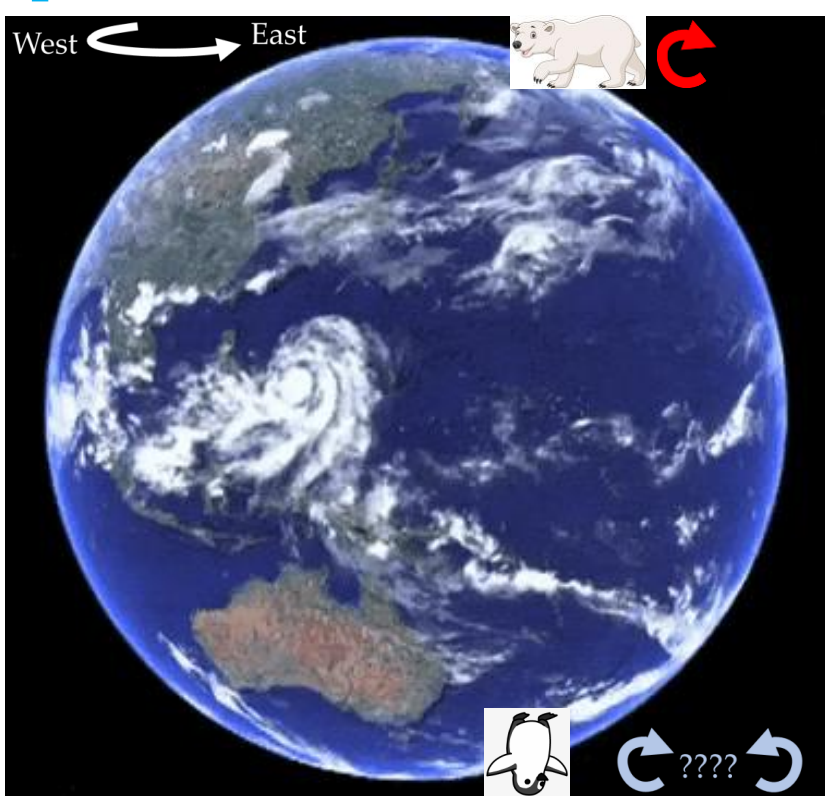
A blue arrow pointing from the left diagram to the right diagram, indicating the passage of time.

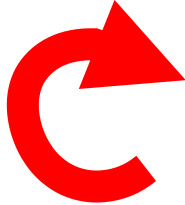


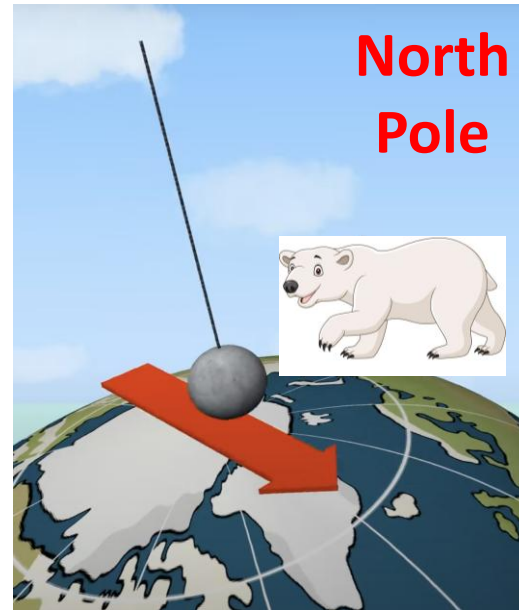
GIF by Prof. David Jeffrey (UNLV)

Let's Make Some Predictions...

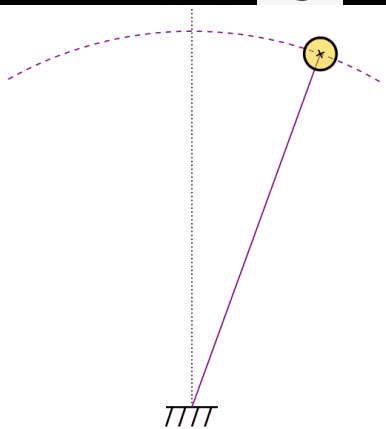
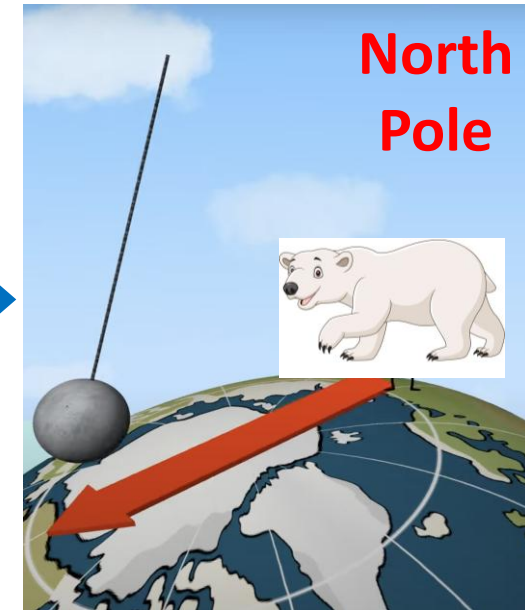
1) How will the pendulum appear to precess at the South Pole to a local observer?




Local
North Pole
stationary
observer
would see
precession of
pendulum in
opposite
direction to
Earth's spin



Time
Passes



a) Same as in North Pole

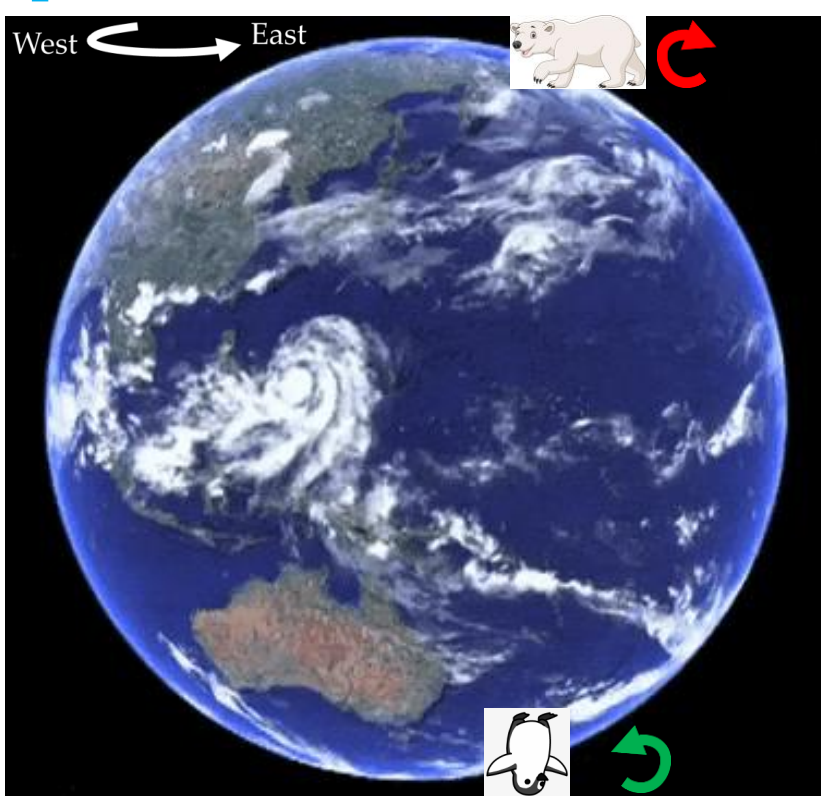
- Precesses clockwise

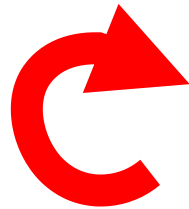
b) Opposite as in North Pole

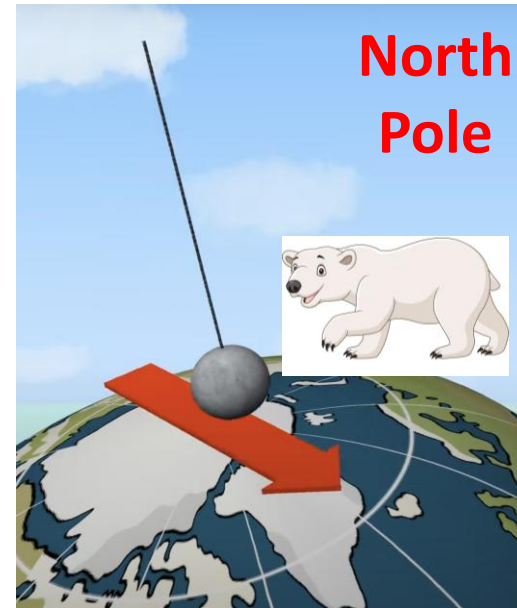
- Precesses counter-clockwise

Let's Make Some Predictions...

1) How will the pendulum appear to precess at the South Pole to a local observer?

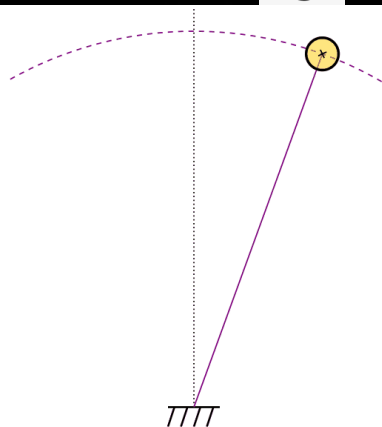
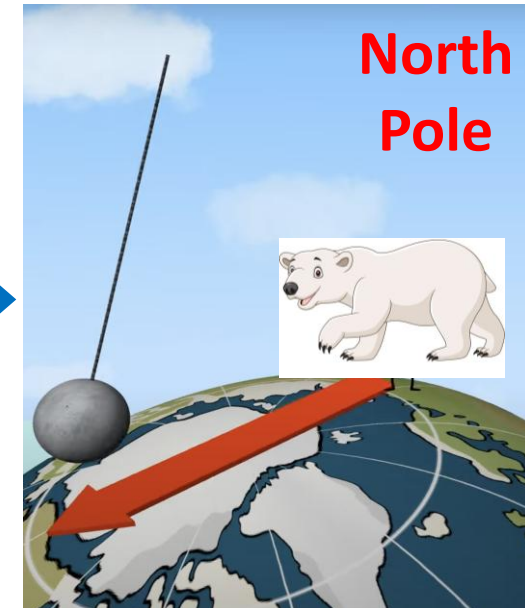



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Time

Passes



a) Same as in North Pole

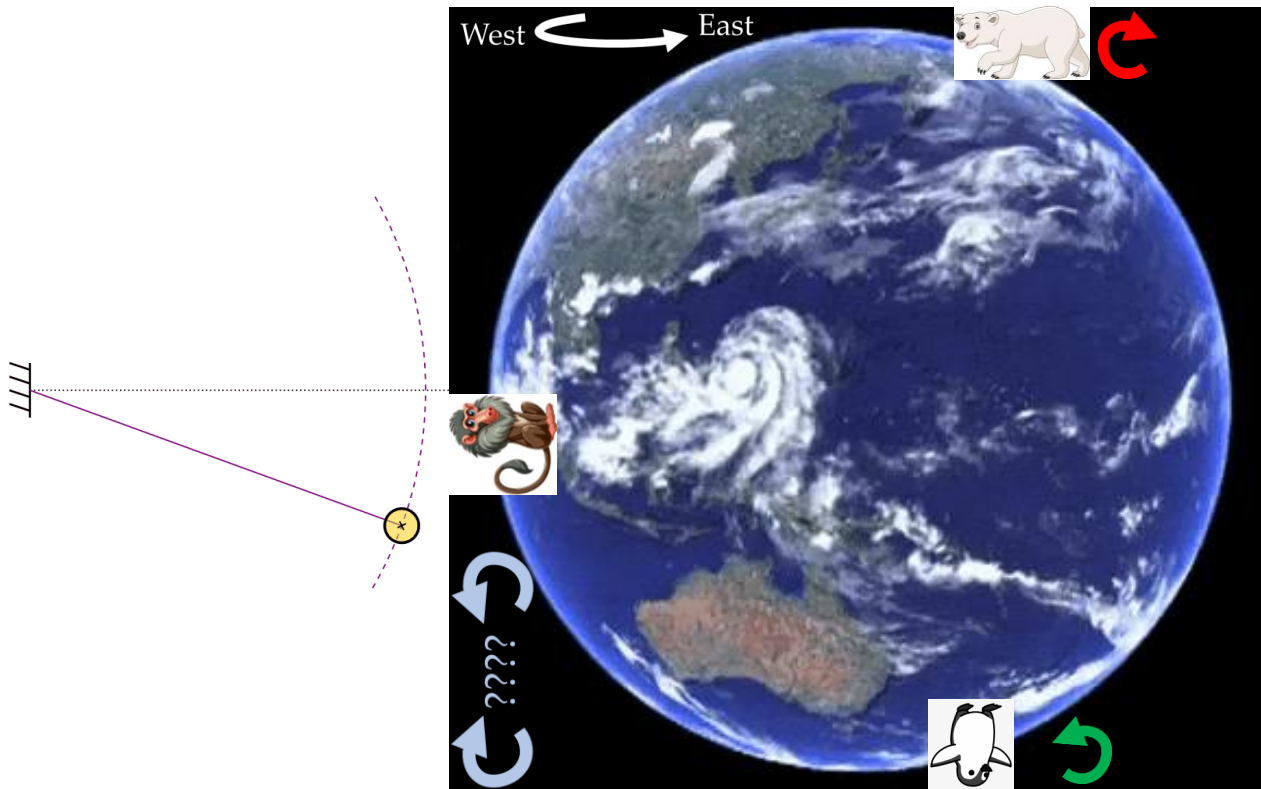
- **Precesses clockwise**

b) Opposite as in North Pole

- **Precesses counter-clockwise**

Let's Make Some Predictions...

2) How will the pendulum appear to precess at the Equator to a local observer?



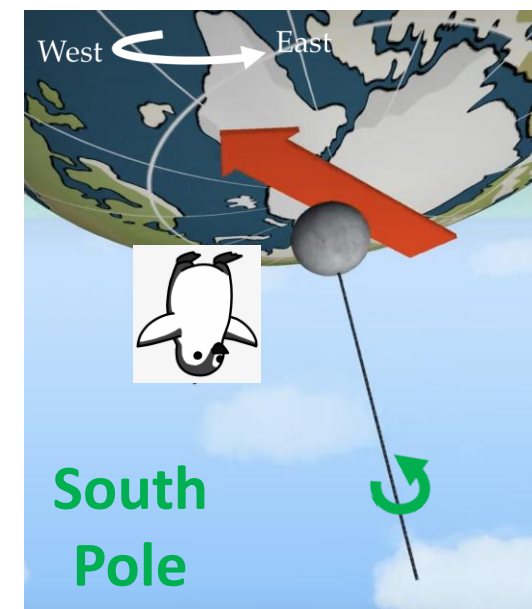
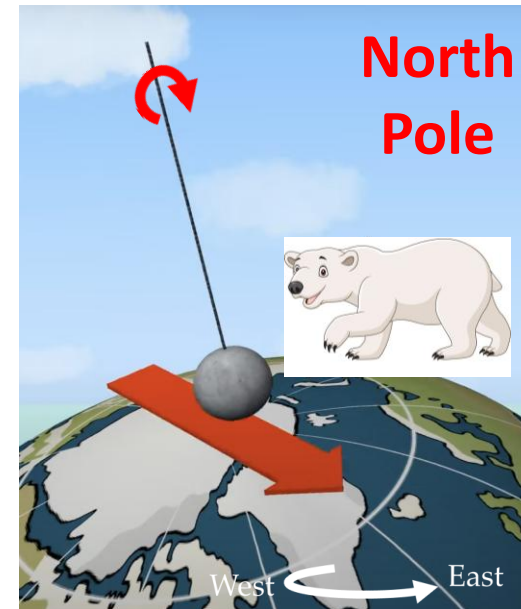
a) Same as in North Pole

- Precesses clockwise

b) Same as in South Pole

- Precesses counter-clockwise

Recall:



c) It won't precess

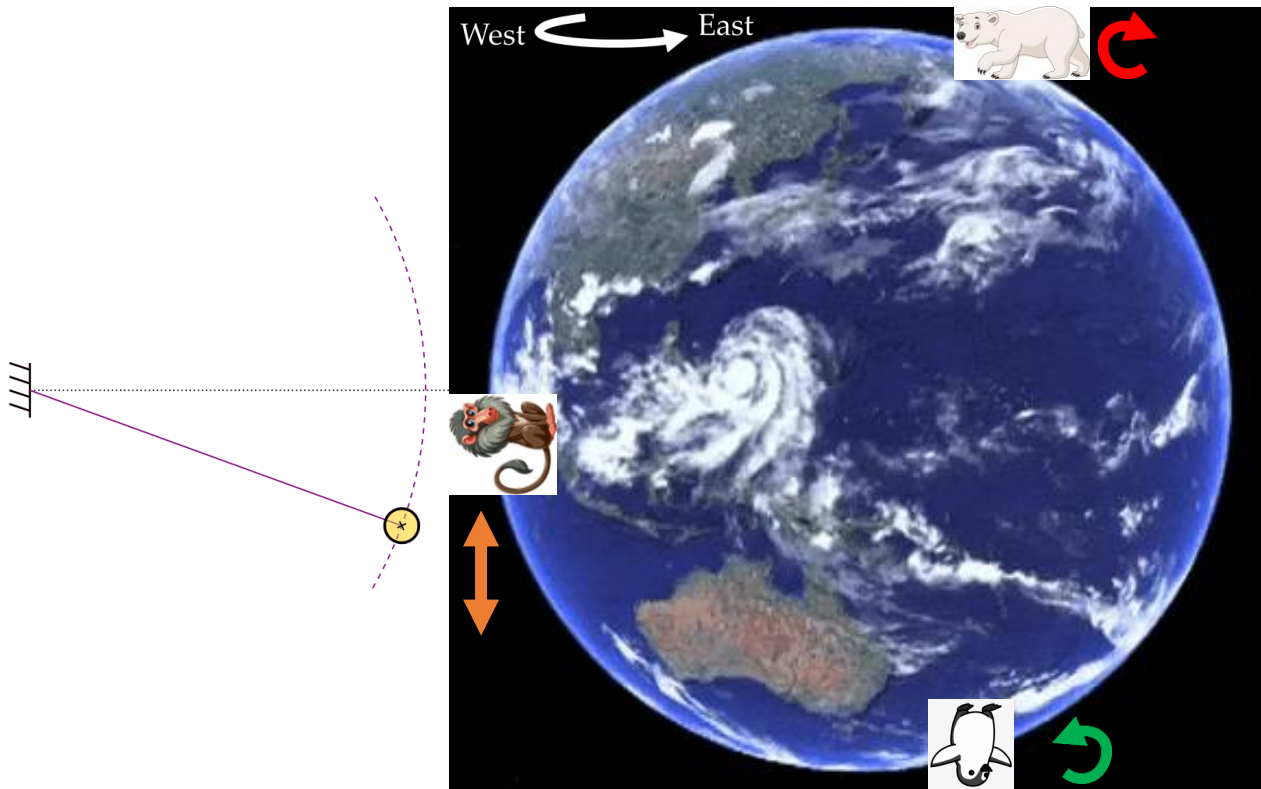
- Simple planar motion

d) It will stop moving

- Damping oscillation

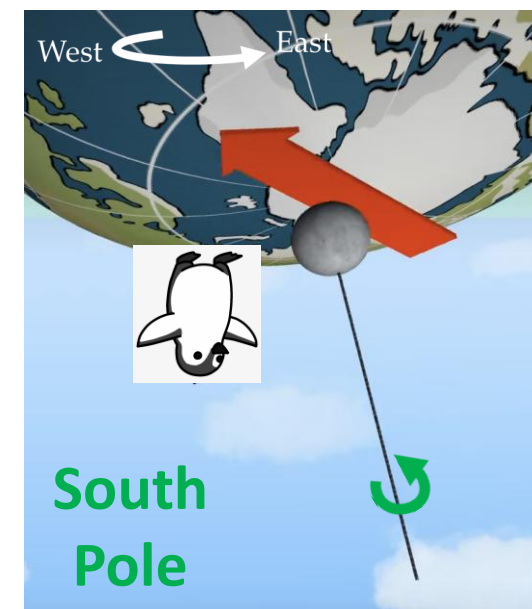
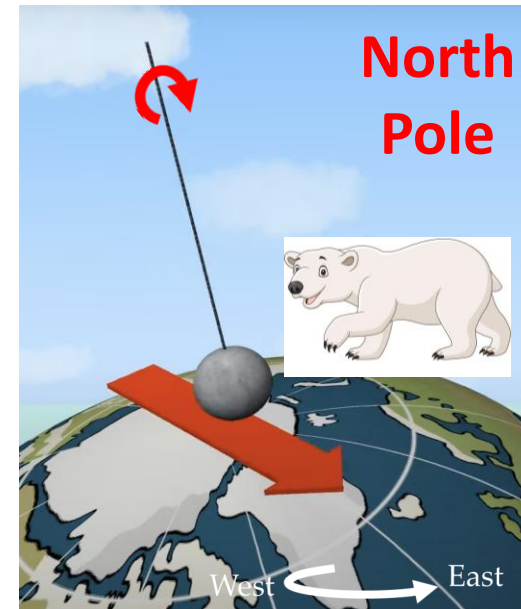
Let's Make Some Predictions...

2) How will the pendulum appear to precess at the Equator to a local observer?



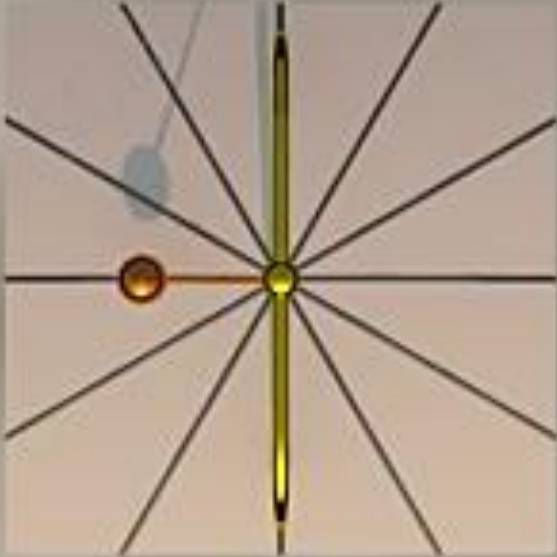
- a) Same as in North Pole
 - Precesses clockwise
- b) Same as in South Pole
 - Precesses counter-clockwise

Recall:

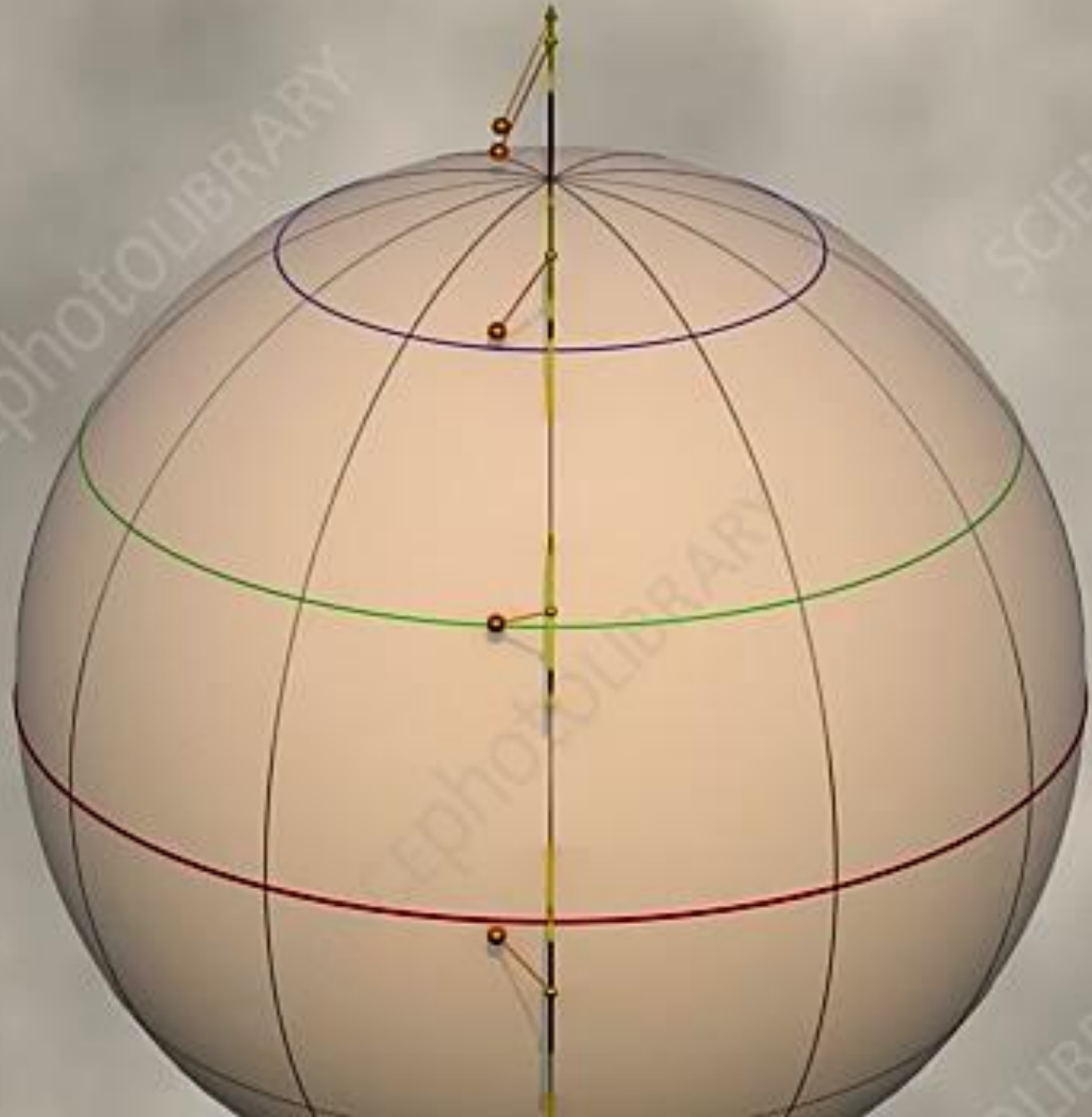
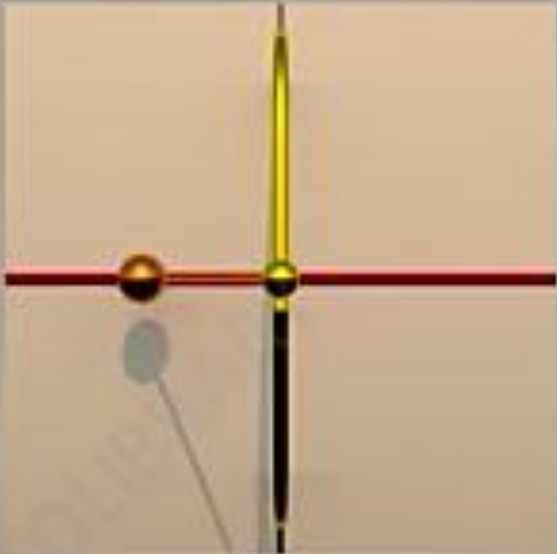


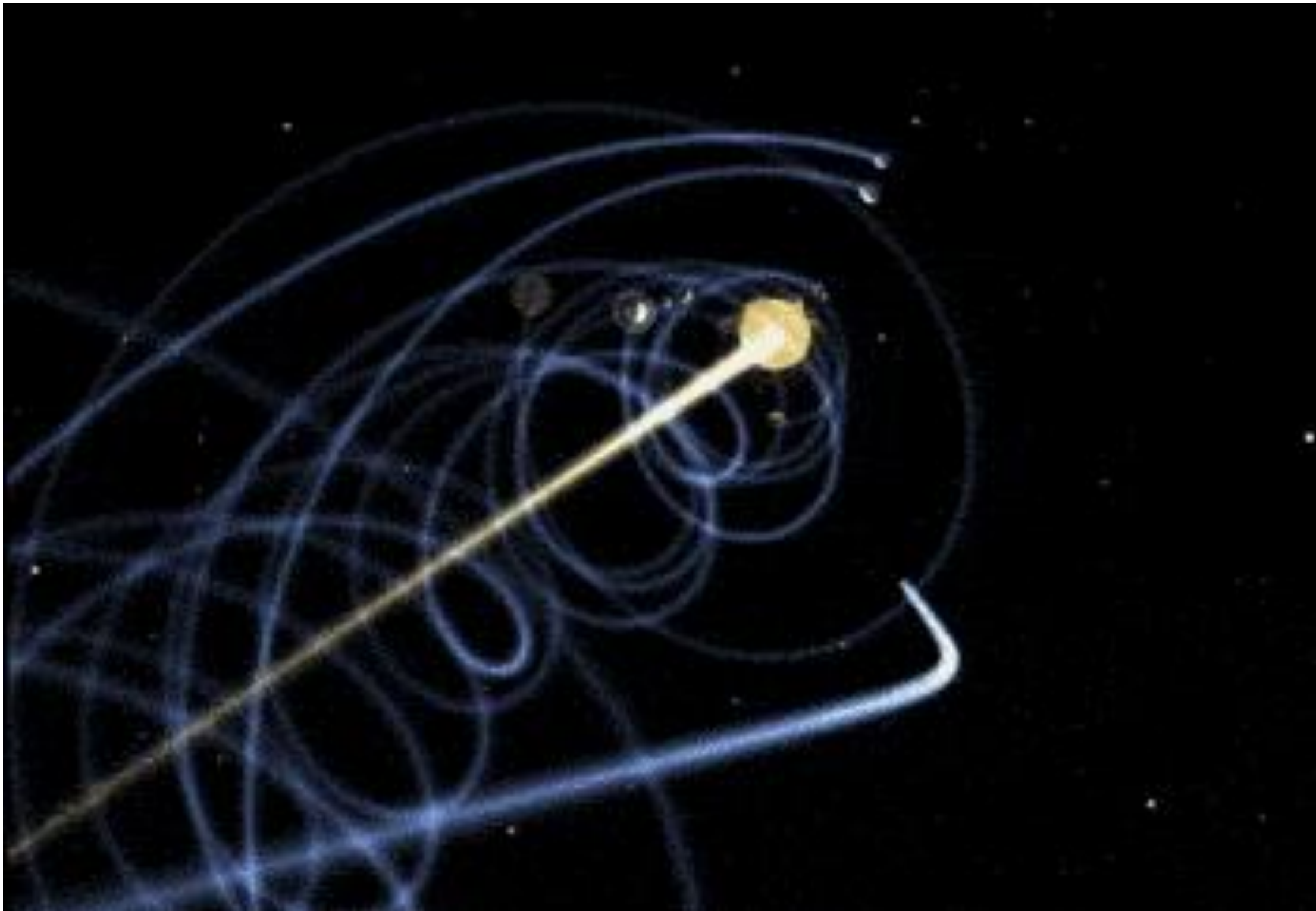
- c) It won't precess
 - Simple planar motion
- d) It will stop moving
 - Damping oscillation

North Pole:

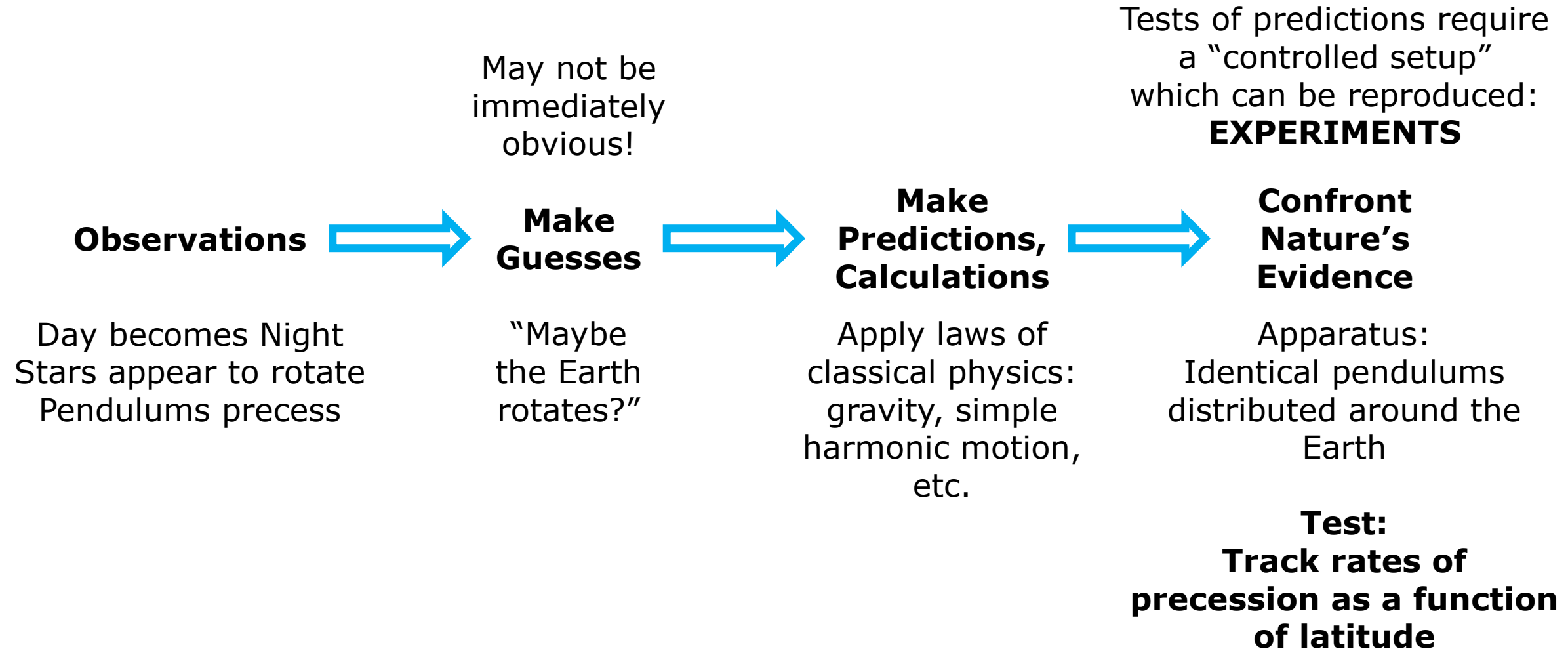


Equator:





How Did We Just Apply The Scientific Method?



Occam's Razor: ~ "of two competing theories, the simpler explanation of an entity is to be preferred"

What could have happened instead for this process?

- Of course, we built upon our previous understanding
 - Made today's practice of "hypothesis" and "prediction" easier
- In general, *our scientific process is never as clean*
 - a) Hypothesis can't be "confirmed" via matching predictions**
 - "Confirmed" here is a *colloquialism*—it is not logically correct!
 - **Intended meaning:** "Prediction found to match experimental observations"
 - **More precisely: our data *does not contradict* our predictions**
 - **Implication:** we have *failed to reject* the hypothesis and associated predictions
 - b) Hypothesis and predictions can contradict the data**
 - c) More often: predictions only "partially fit" the data**
 - Hypothesis must be improved *iteratively*, improving predictions
- **As more tests *fail to reject* a particular hypothesis, we generally accept it as a *possible truth* of Nature**

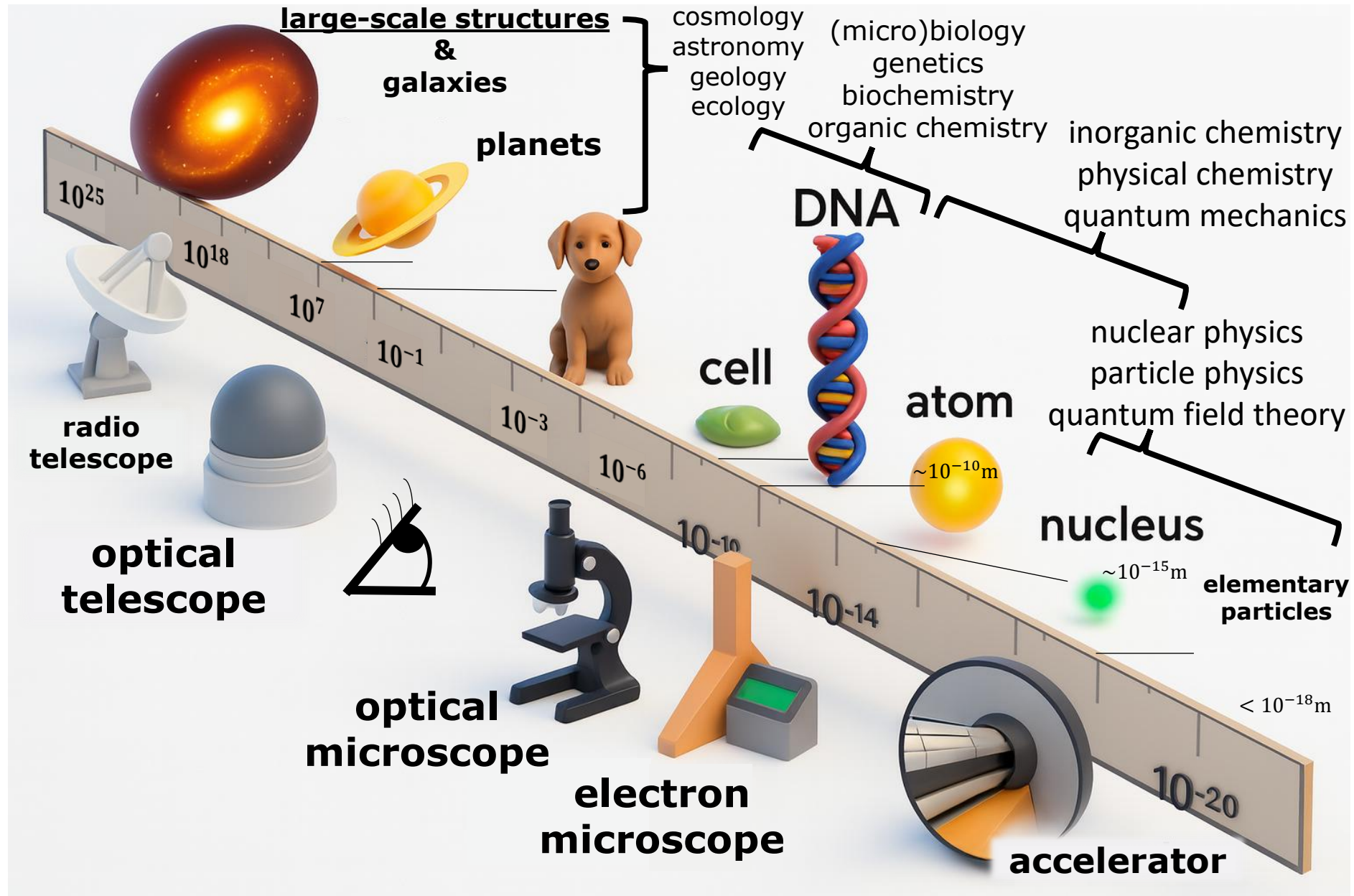
A Personal Challenge for You All

- Over the next months, you'll encounter many new ideas
- **These ideas and concepts act effectively as hypotheses**
- Challenge yourself to:
 - Consider the observational evidence
 - Try to understand presented ideas/concepts as hypotheses
 - Try to create some of your own alternative hypotheses—guess!
 - Play out several scenarios
 - Make predictions for both “main” and alternative hypotheses
 - Consider if experimental designs presented can encompass your alternatives
 - **Do the experimental observations contradict your alternatives?**

What are some kinds of science done today?

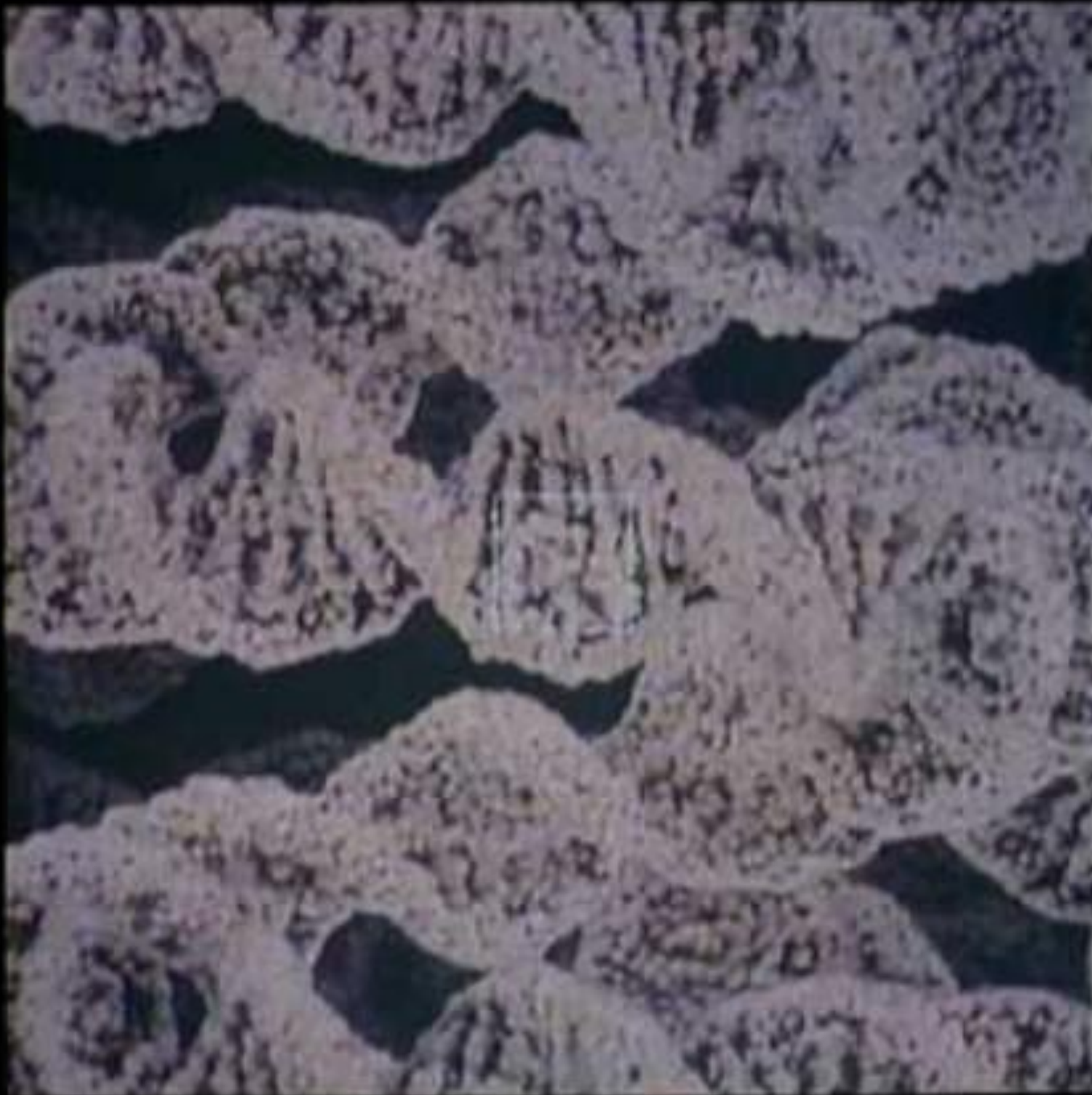
Will try to be relatively all-encompassing here—
will get to Fermilab's central study regimes later in the talk!

Types of Science as a Reductive Scale



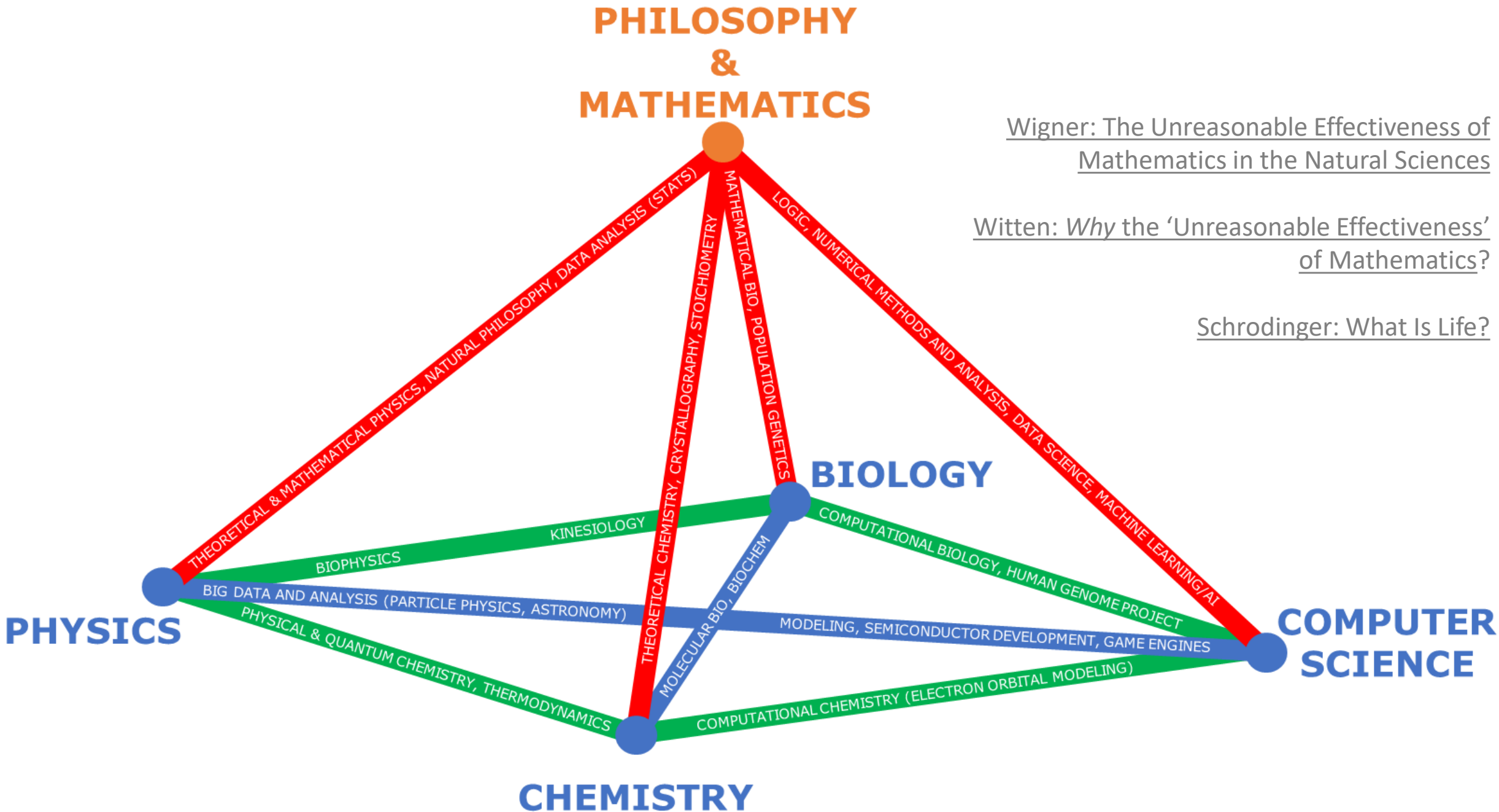
Powers of Ten Short Film (Charles & Ray Eames, 1997)

100 ångstroms



-8
10
meters

A Few Examples of Various Sciences Visualized as an Interdisciplinary Network



Wigner: The Unreasonable Effectiveness of Mathematics in the Natural Sciences

Witten: Why the 'Unreasonable Effectiveness' of Mathematics?

Schrodinger: What Is Life?

Pre-20th Century Physics

e.g. Modern $\gtrsim$ High School / Early College-Level Physics

- Forces & Laws of Motion (17th century, *a la* [Newton](#))
 - Gravity as a central potential (inverse square law: $1/r^2$)
 - Modern (HS): [Lagrangian](#) (18th), [Hamiltonian](#) mechs. (19th)
- Concepts of kinetic & potential energy
 - (HS) Key inputs to modern mechs.—[Principle of Least Action](#)
- Electricity & Magnetism (18th-19th, basics in HS)
 - (HS) [Maxwell's Eqns.](#), 1860's unification: *electromagnetism*
 - (HS) Light as an [electromagnetic wave](#)—[wave mechanics](#)
- Thermodynamics (19th)
 - A key progenitor of [the industrial revolution](#)
- Optics and waves (18th-19th)
 - Telescopes, microscopes; sound, light

Some Post-20th Century Physics

e.g. Modern $\gtrsim$ College & Graduate-Level Physics

- Molecular and atomic physics ($> \underline{1905}$)
- [Special relativity](#) (1905)
- [General relativity](#) (1915)
- [Quantum theory](#) (1905, $\geq 1920\text{s}$)
- [Radioactivity](#) ($> 1890\text{s}$), [Nuclear theory](#) ($\geq 1930\text{s}$)
- [Quantum field theory](#) ($\gtrsim 1950\text{s}$)
 - [The Standard Model](#) ($\gtrsim 1970\text{s}$)
- Modern astronomy ($\gtrsim 1920\text{s}$) & [cosmology](#) ($\gtrsim 1930\text{s}$)
 - Optical and radio astronomy
 - [Hubble's Law](#) (Hubble's "constant")
 - "[Dunkle materie](#)" (1933, $\gtrsim 1970\text{s}$)
 - Lambda-CDM (ΛCDM) [standard model of cosmology](#)
- Condensed matter / modern material science ($\geq 1920\text{s}$)
 - [Ising Model](#) as an application of thermodynamics & quantum

Terrence Tao -- The Cosmic Distance Ladder, Part I -- 3Blue1Brown

Terrence Tao -- The Cosmic Distance Ladder, Part II -- 3Blue1Brown



JWST -- Webb's First Deep Field -- Wikipedia

Exploring Some of the Current Scientific Paradigm

Some selected topics in Modern Science,
and a few of Fermilab's continuing contributions to it

HOW DID OUR UNIVERSE BEGIN?

Some 13.8 billion years ago our entire visible universe was contained in an unimaginably hot, dense point, a billionth the size of a nuclear particle. Since then it has expanded—a lot—fighting gravity all the way.

Inflation

In far less than a nanosecond a repulsive energy field inflates space to visible size and fills it with a soup of subatomic particles called quarks.
Age: 10^{-32} milliseconds
Size: Infinitesimal to golf ball

Early building blocks

The universe expands, cools. Quarks clump into protons and neutrons, the building blocks of atomic nuclei. Perhaps dark matter forms.
.01 milliseconds
0.1-trillionth present size

First nuclei

As the universe continues to cool, the lightest nuclei, of hydrogen and helium, arise. A thick fog of particles blocks all light.
.01 to 200 seconds
1-billionth present size

First atoms, first light

As electrons begin orbiting nuclei, creating atoms, the glow from our infant universe is unveiled. This light is as far back as our instruments can see.
380,000 years
.0009 present size

The "dark ages"

For 300 million years this cosmic background radiation is the only light. Clumps of matter that will become galaxies glow brightest.
380,000 to 300 million years
.0009 to 0.1 present size

Gravity wins: first stars

Dense gas clouds collapse under their own gravity—and that of dark matter—to eventually form galaxies and stars. Nuclear fusion lights up the stars.
300 million years
0.1 present size

Antigravity wins

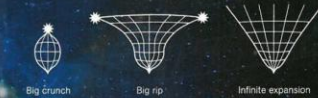
After being slowed for billions of years by gravity, cosmic expansion accelerates again. The culprit: dark energy. Its nature: unclear.
10 billion years
.77 present size

Today

The universe continues to expand, becoming ever less dense. As a result, fewer new stars and galaxies are forming.
13.8 billion years
Present size

HOW WILL IT END?

Which will win in the end, gravity or antigravity? Is the density of matter enough for gravity to halt or even reverse cosmic expansion, leading to a big crunch? It seems unlikely—especially given the power of dark energy, a kind of antigravity. Perhaps the acceleration in expansion caused by dark energy will trigger a big rip that shreds everything, from galaxies to atoms. If not, the universe may expand for hundreds of billions of years, long after all stars have died.



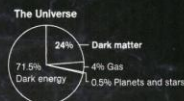
Galaxies ripped apart by rapid expansion

COSMIC QUESTIONS

In the 20th century the universe became a story—a scientific one. It had always been seen as static and eternal. Then astronomers observed other galaxies flying away from ours, and Einstein's general relativity theory implied space itself was expanding—which meant the universe had once been denser. What had seemed eternal now had a beginning and an end. But what beginning? What end? Those questions are still open.

WHAT IS OUR UNIVERSE MADE OF?

Stars, dust, and gas—the stuff we can discern—make up less than 5 percent of the universe. Their gravity can't account for how galaxies hold together. Scientists figure about 24 percent of the universe is a mysterious dark matter—perhaps exotic particles formed right after inflation. The rest is dark energy: an unknown energy field or property of space that counteracts gravity, providing an explanation for observations that the expansion of space is accelerating.



WHAT IS THE SHAPE OF OUR UNIVERSE?

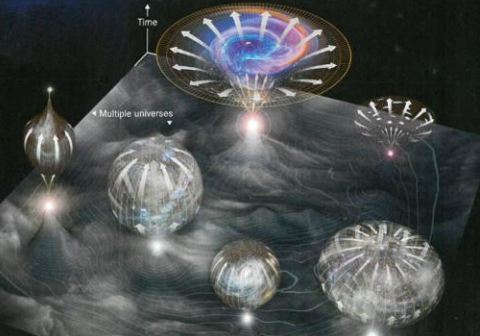
Einstein discovered that a star's gravity curves space around it. But is the whole universe curved? Might space close up on itself like a sphere or curve the other way, opening out like a saddle? By studying cosmic background radiation, scientists have found that the universe is poised between the two: just dense enough with just enough gravity to be almost perfectly flat, at least the part we can see. What lies beyond we can't know.

The Unknown Beyond
What we can't see. The possible shapes are:



DO WE LIVE IN A MULTIVERSE?

What came before the big bang? Maybe other big bangs. The uncertainty principle holds that even the vacuum of space has quantum energy fluctuations. Inflation theory says our universe exploded from such a fluctuation—a random event that, odds are, had happened many times before. Our cosmos may be one in a sea of others just like ours—or nothing like ours. These other cosmos will very likely remain forever inaccessible to observation, their possibilities limited only by our imagination.



N Fly through the universe on our digital edition.
ILLUSTRATION: PAUL F. HARRIS, NGM STAFF; TAVIA GIBERTI/ISTOCK; ART: WOODFIN CAMPBELL; SOURCES: CHARLES BRANNETT, JOHNS HOPKINS UNIVERSITY; MICHAEL S. TURNER, UNIVERSITY OF CHICAGO
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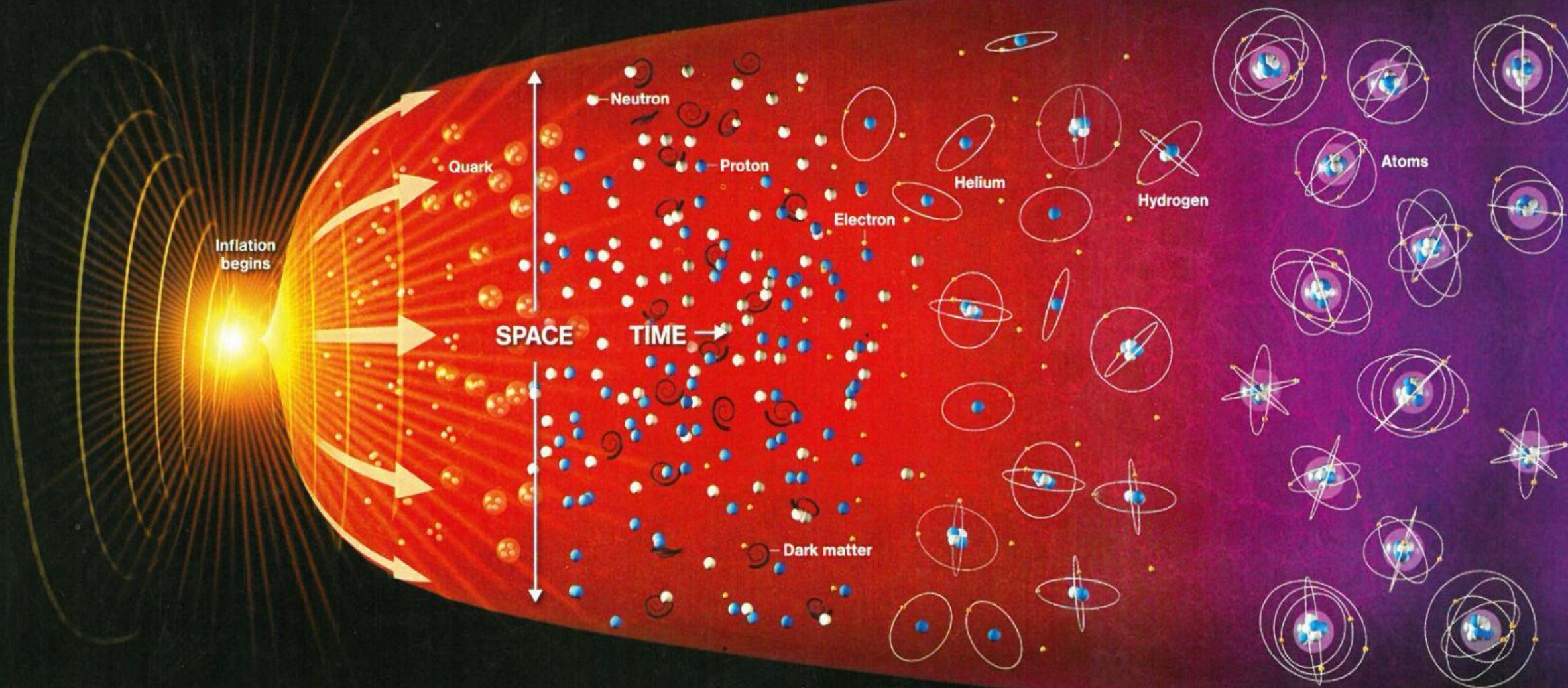
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10 billion years

.77 present size

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13.8 billion years

Present size



Our solar system

Stars

Galaxies

Dark energy accelerates

Observable Universe

The universe began 13.8 billion years ago. Because it has been expanding ever since, the farthest observable edge is now 47 billion light-years away.

47 billion
light-years

The Unknown Beyond

What we can't see. The possible shapes are:



Sphere



Saddle



Flat

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Big crunch



Big rip



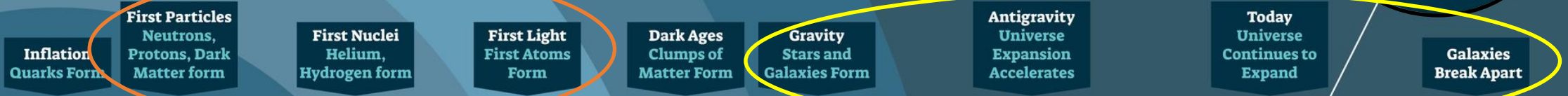
Infinite expansion

Galaxies ripped apart
by rapid expansion

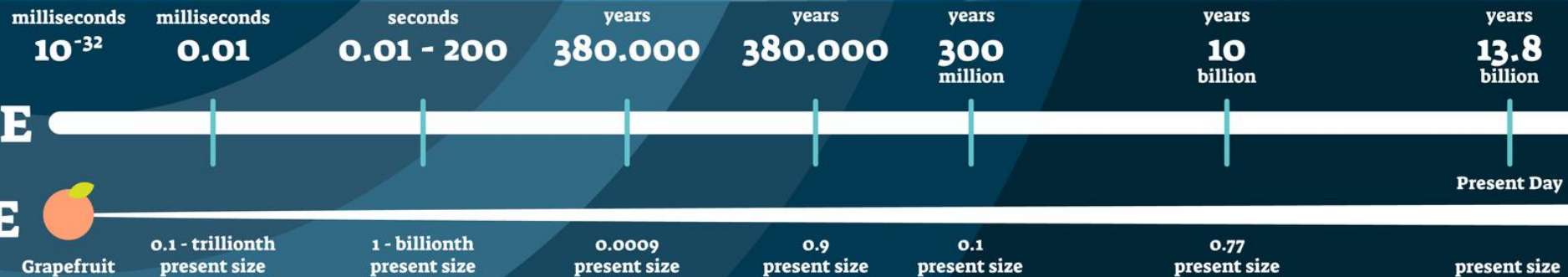
Break

The energy regimes of
most of
particle & nuclear physics

You are
here!



The scales of study within
cosmology & astrophysics



Science Today at Fermilab

Beyond Both Theory and Experiment!

- Particle physics

- Accelerator physics

- Quantum sciences

- Cosmology

- Astrophysics

- Particle detector R&D

- Machine learning / AI

- Data science

- Electronics

- Engineering

A Personal Summary: 'Beyond Reductionism'

Fermilab staff collectively study the very small & the very large, attempting to understand their structural interdependencies

Some Open Questions

Considering Only Particle Physics & Cosmology

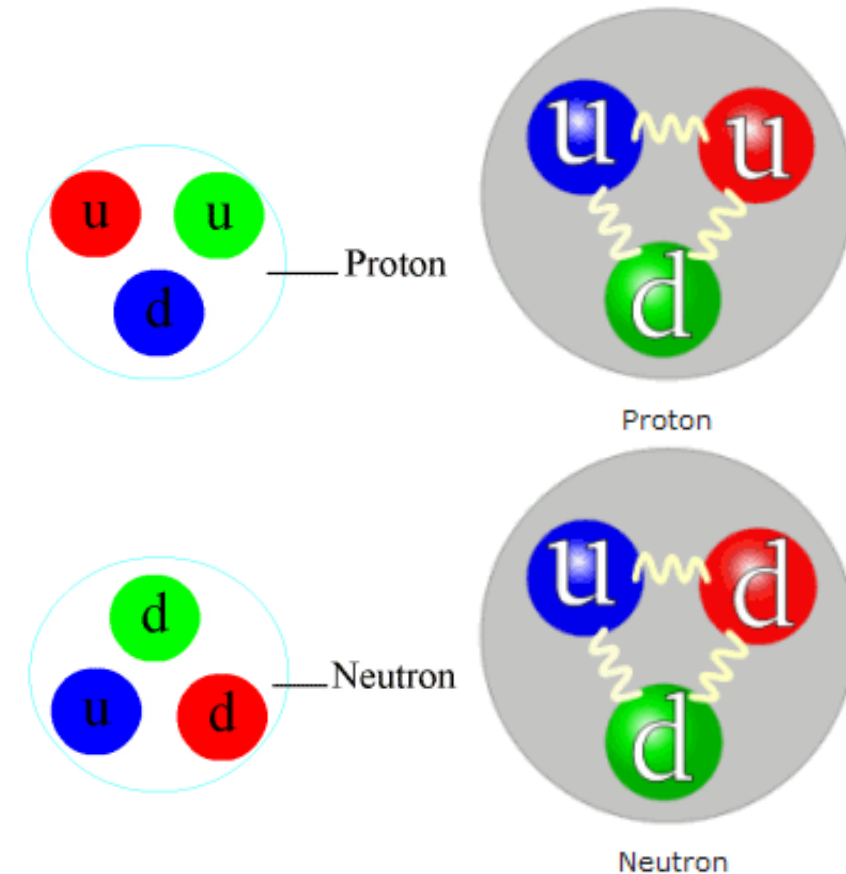
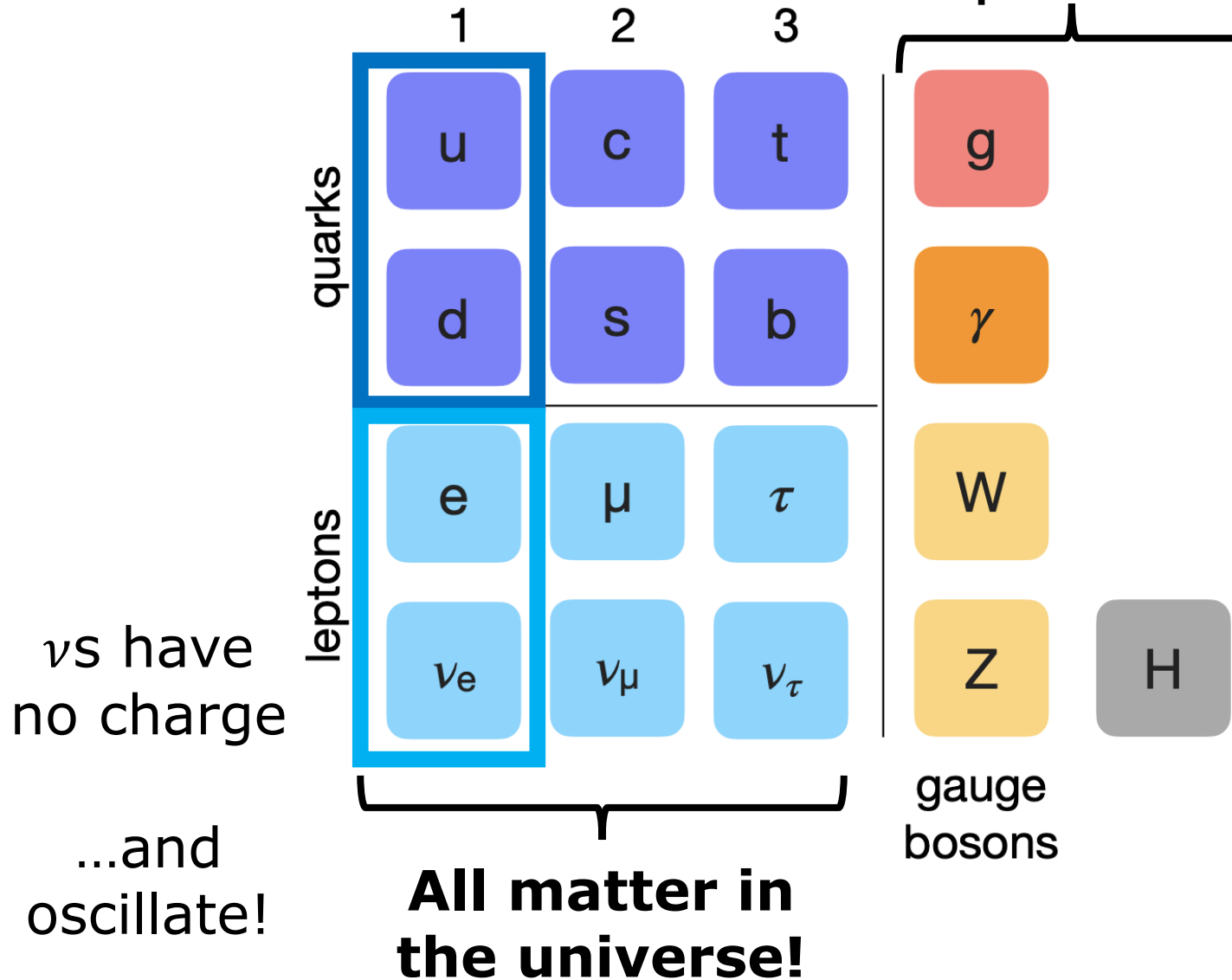
- Why did matter (~~antimatter~~) survive the Big Bang?
 - Antimatter just like matter: same mass w/opposite charge
- What is the mass of the neutrinos?
- What is the nature of dark matter?
- Why is the universe expanding?
- Are there other new elementary particles or forces?

The Fundamental Blocks of Matter

The Standard Model of Particle Physics

Cousins (generations)
related by symmetry

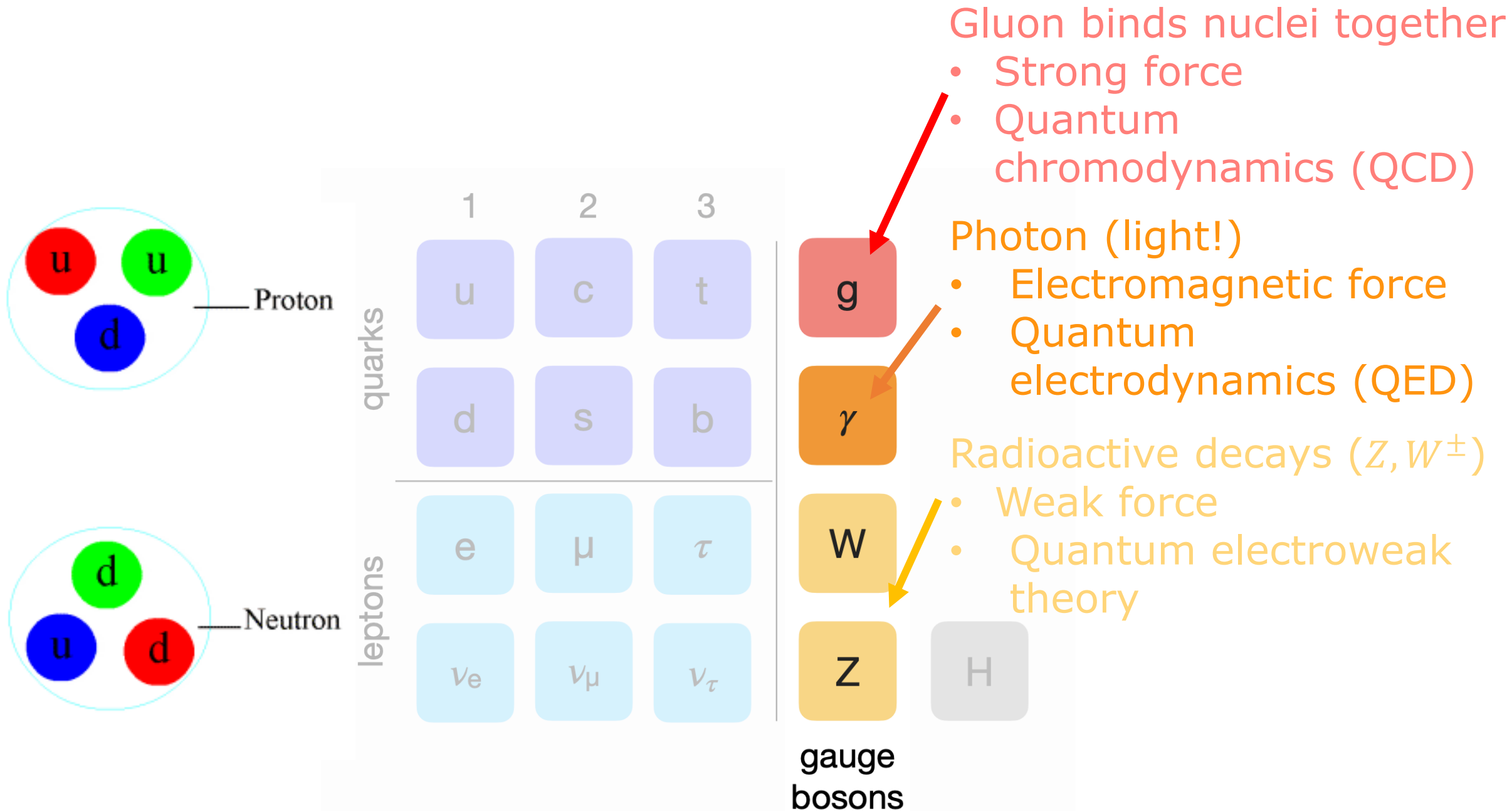
Interactions
between all
particles!



Composite particles made
of *quarks*
Hadrons:
Nucleons, Mesons

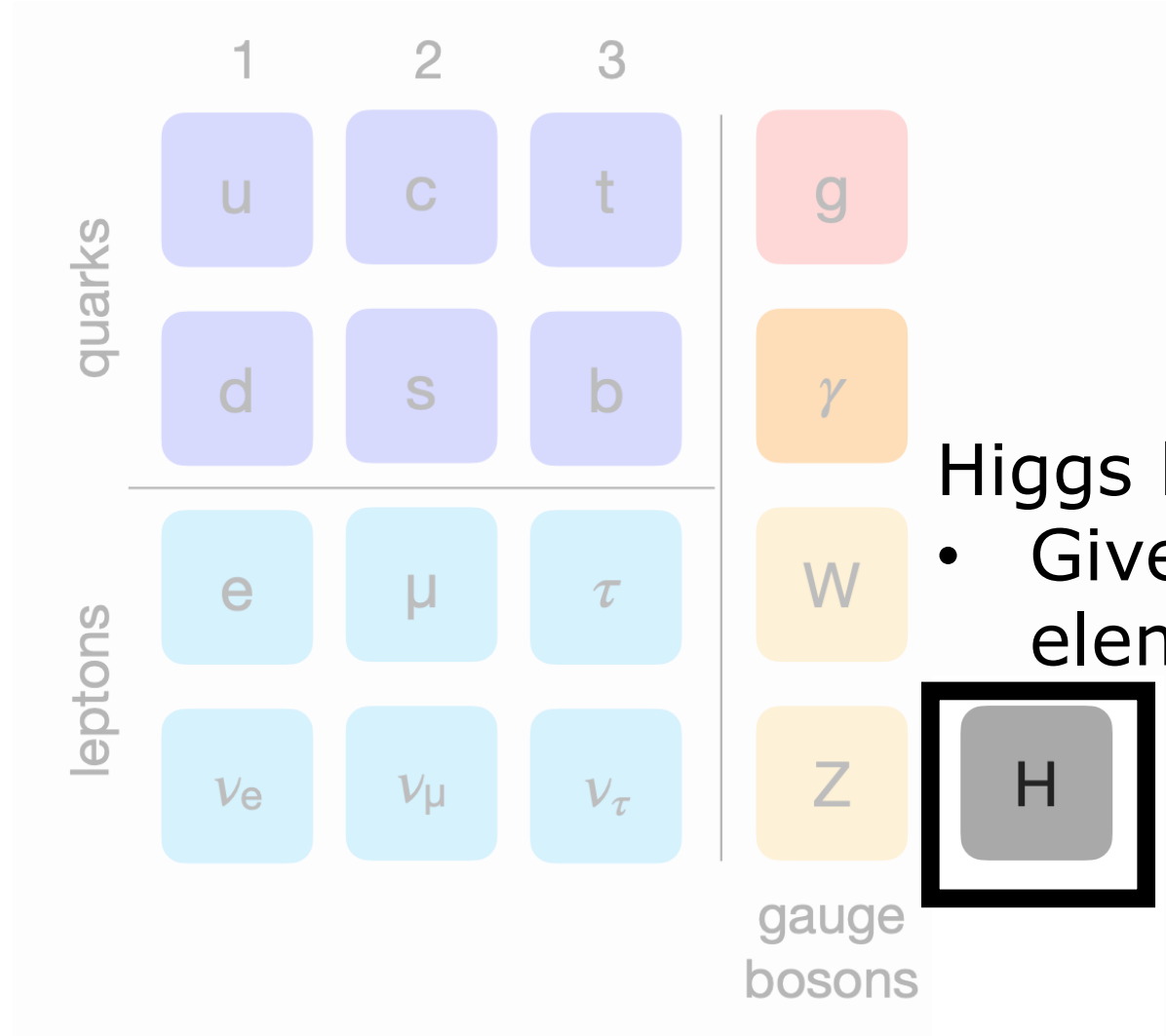
The Fundamental Blocks of Matter

The Standard Model of Particle Physics



The Fundamental Blocks of Matter

The Standard Model of Particle Physics

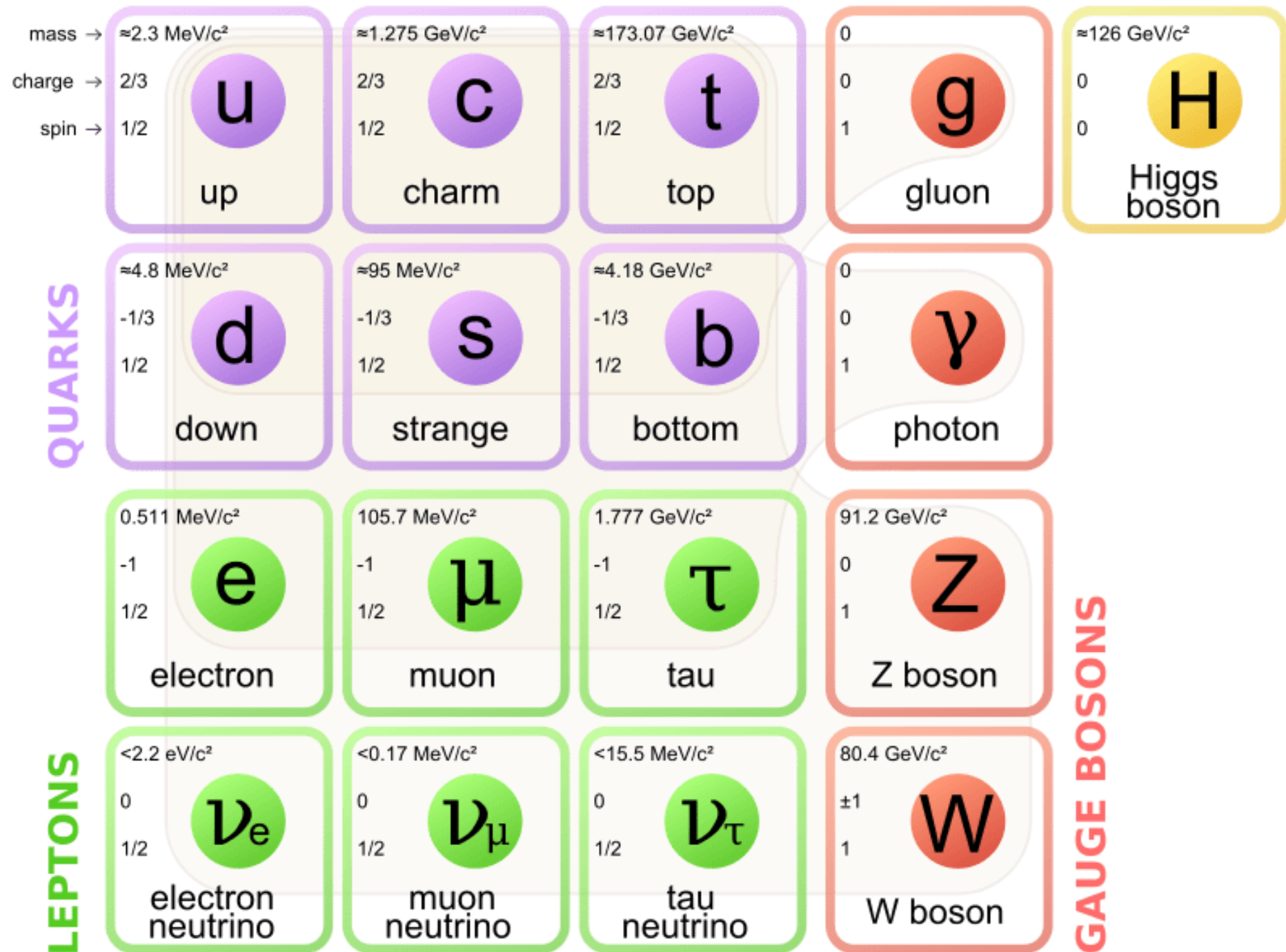


Higgs boson

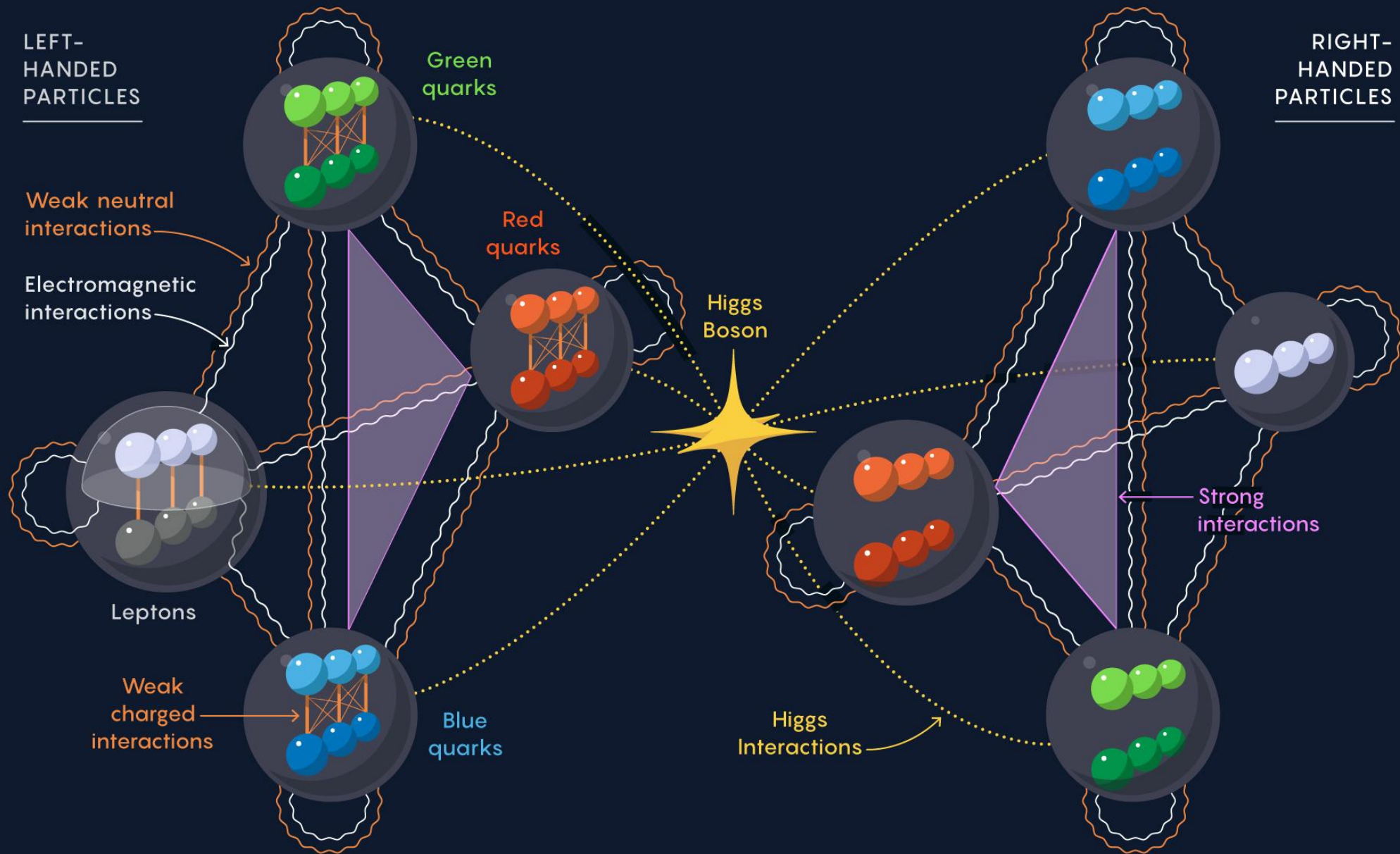
- Gives mass to most elementary particles

**But not
generally
to ν s!**

The Standard Model of Particle Physics



Other Standard Model Representations

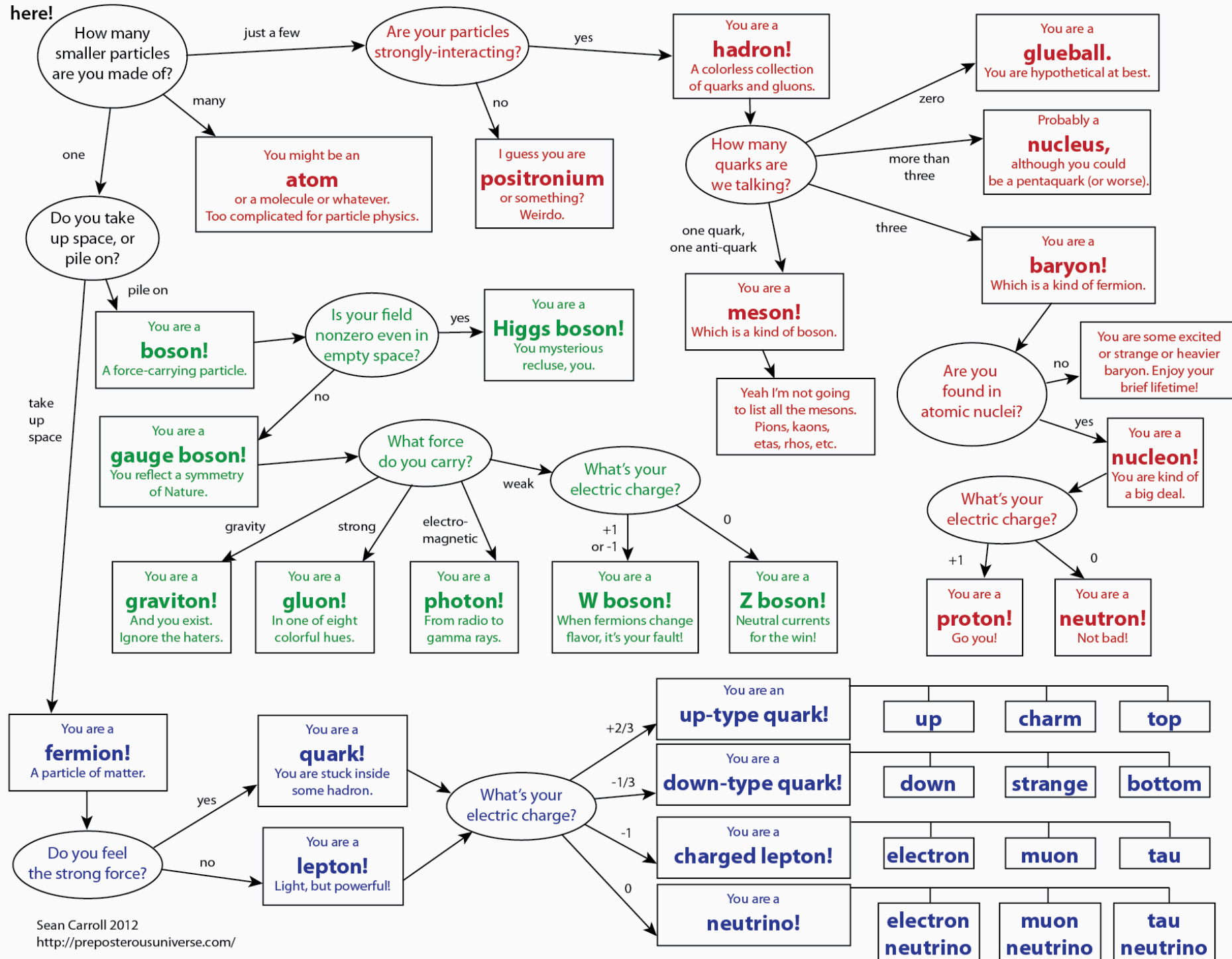


What Particle Are You?

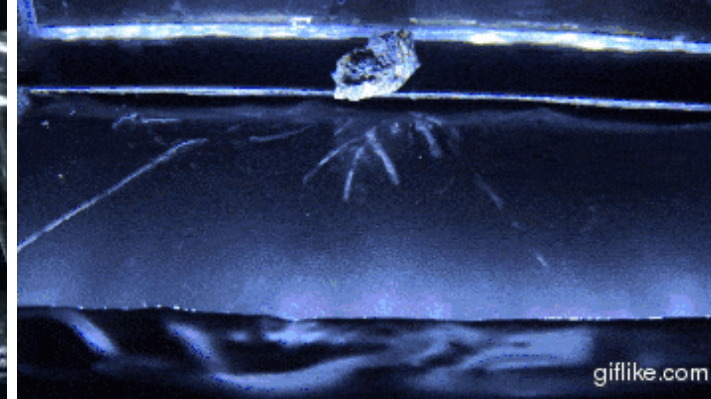
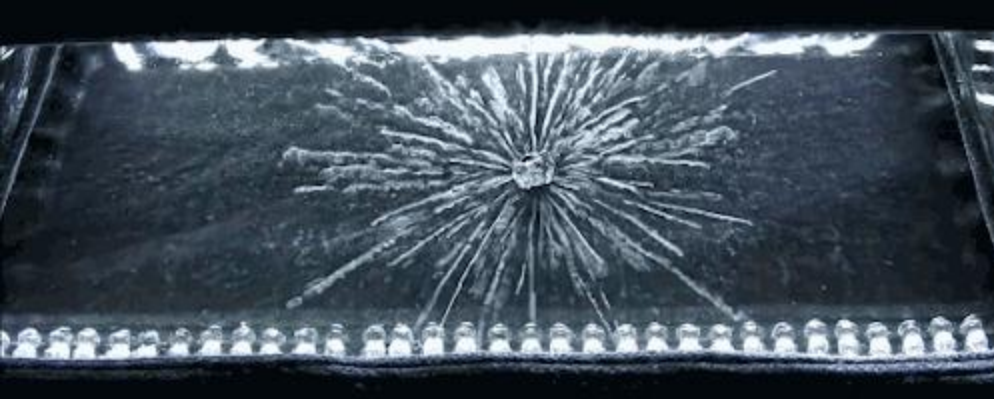
Color code:
 elementary fermions
 elementary bosons
 composite particles

Start here!

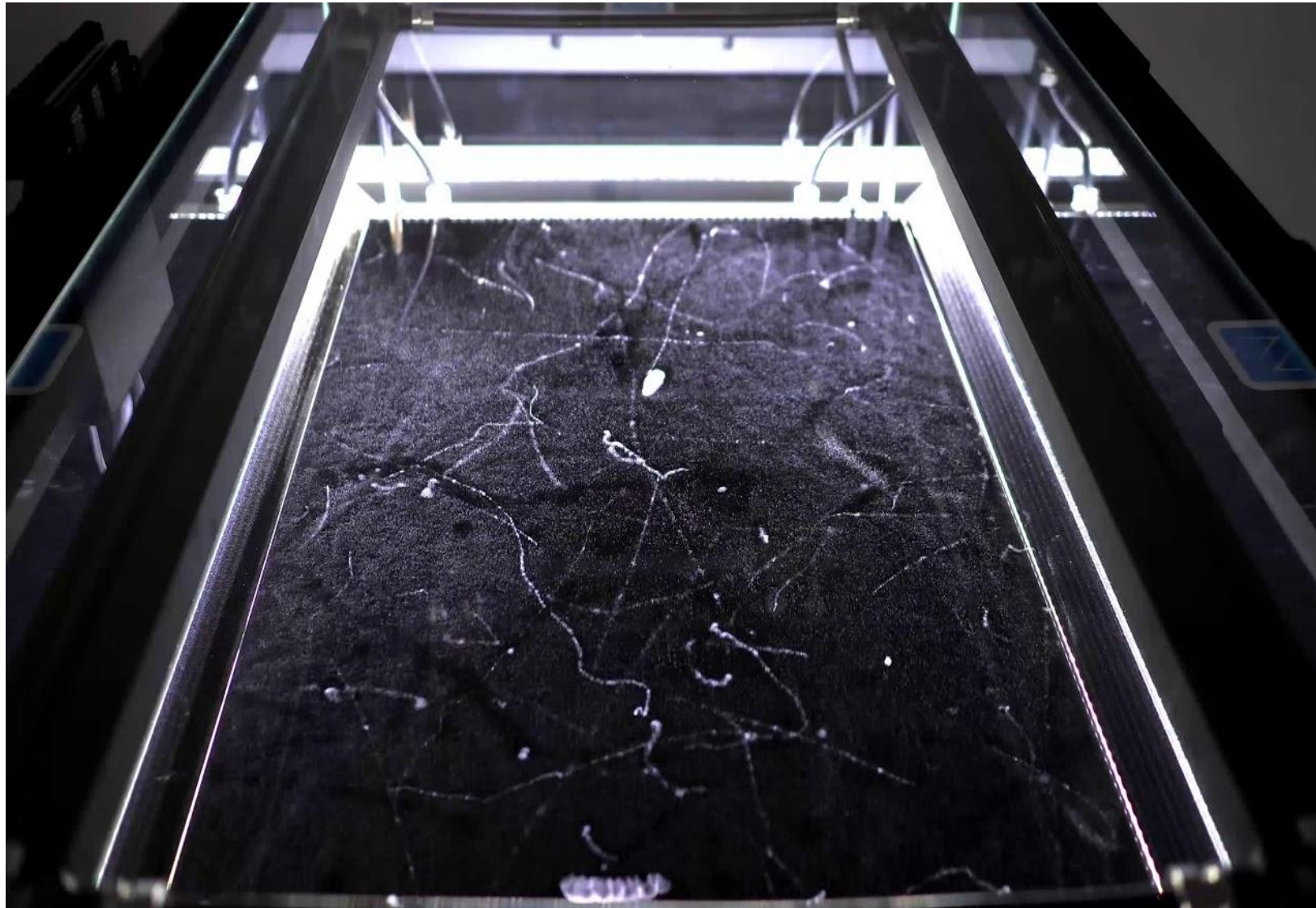
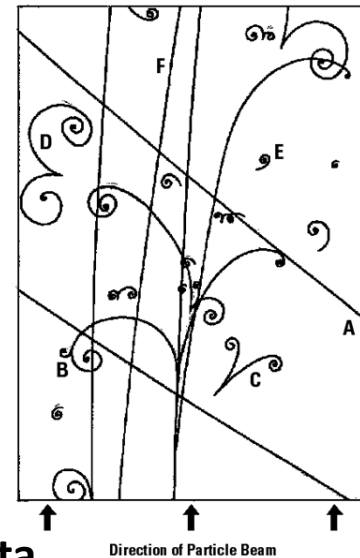
(Standard Model particles only! Dark matter and other exotica not welcome.)



Sean Carroll 2012
<http://preposterousuniverse.com/>



Fermilab
Bubble Chamber
(1972)

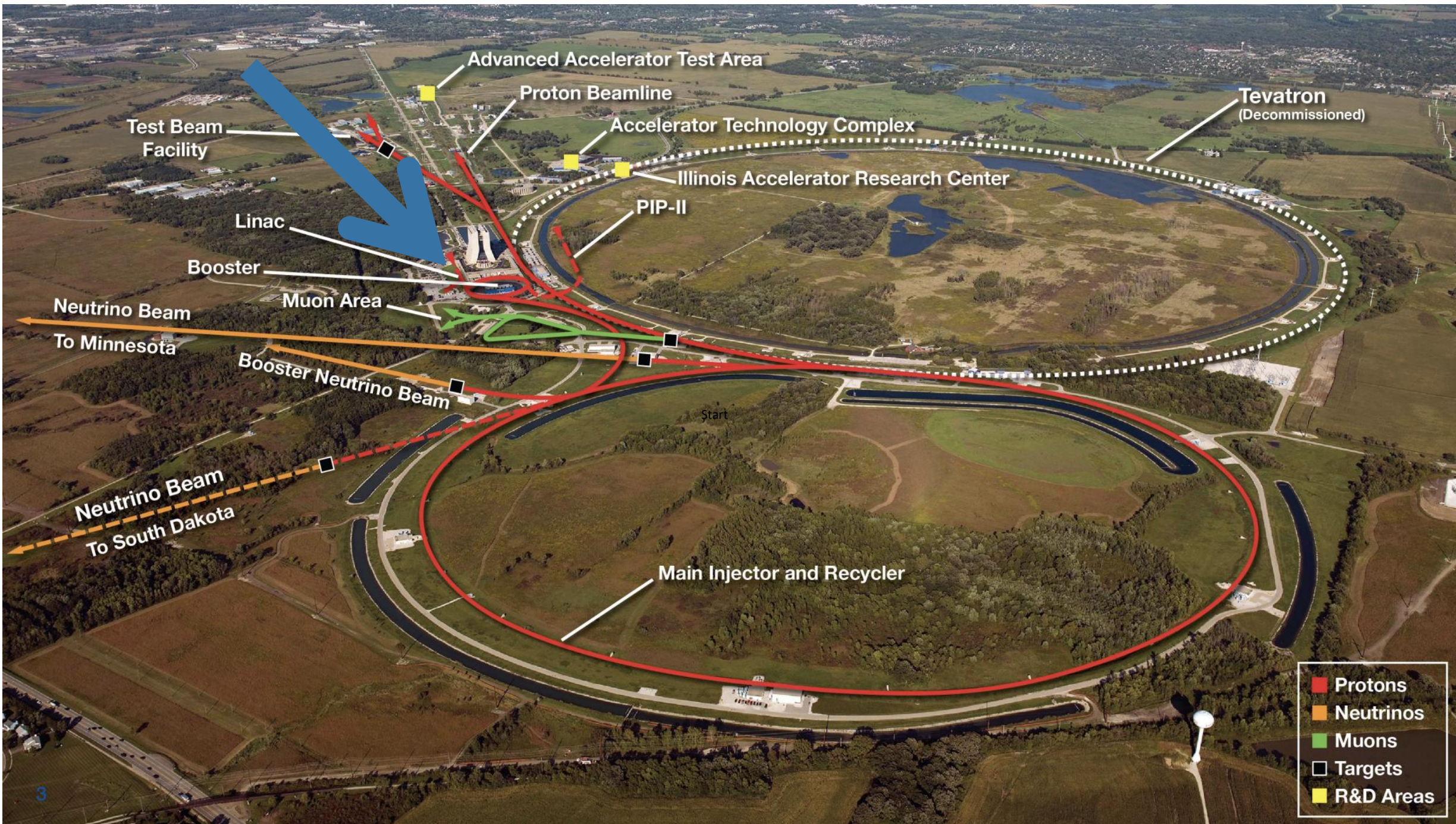


[Fermilab
QuarkNet -
How to Build a
Cloud Chamber](#)

[How does a
cloud chamber
work?](#)

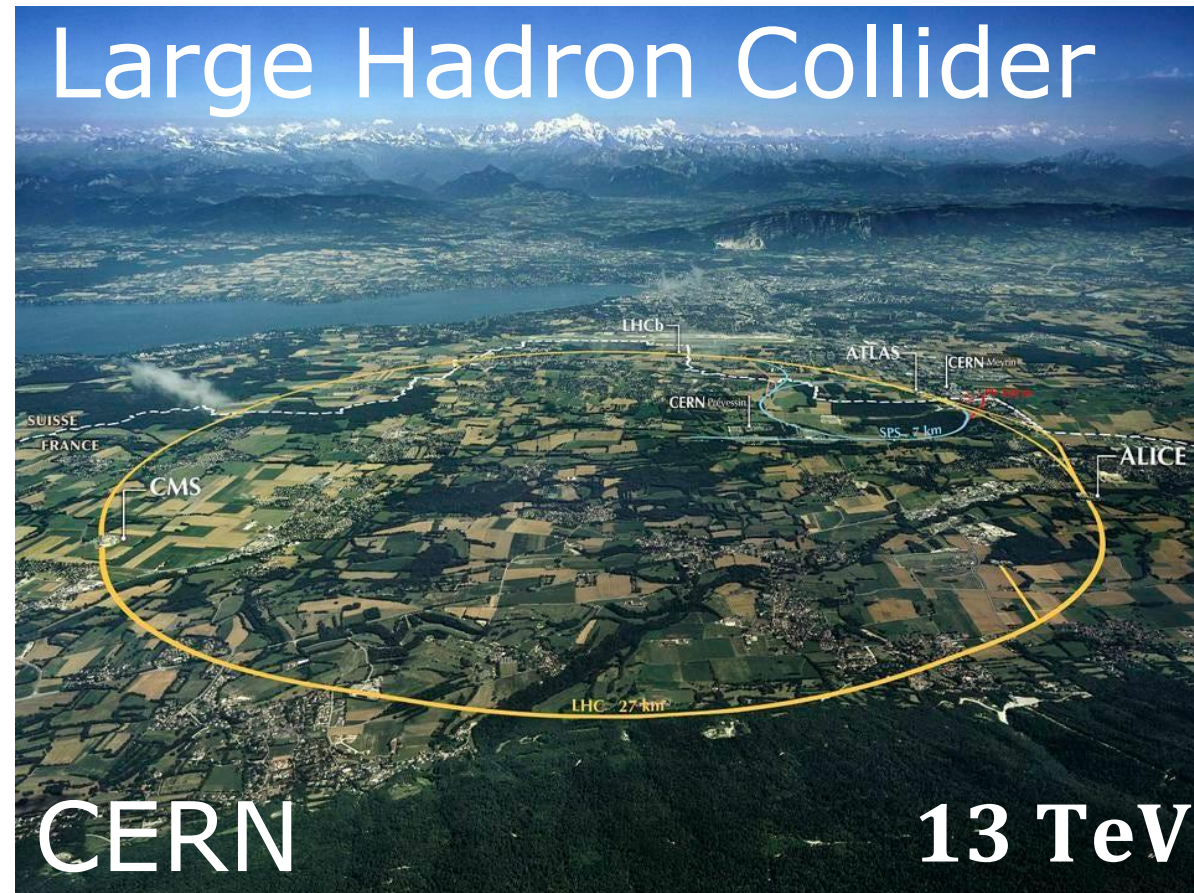
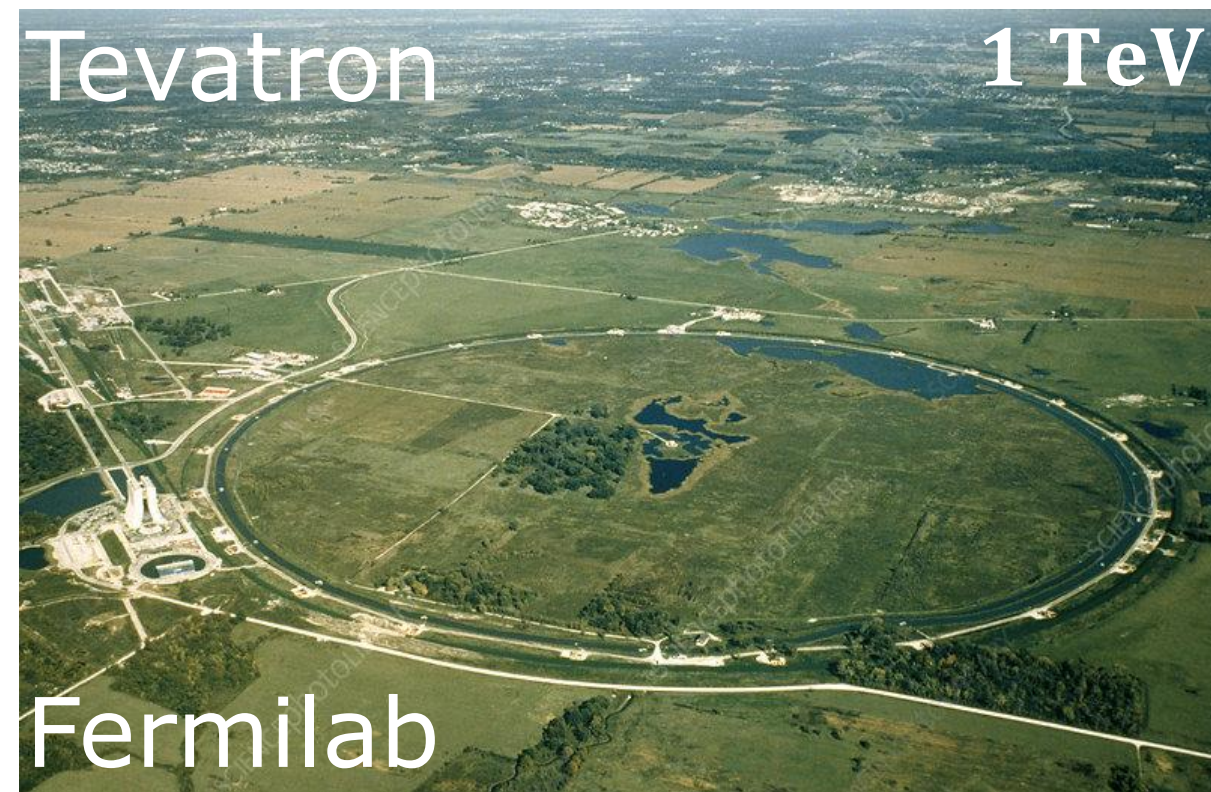
[50 years ago,
Fermilab
turned to
bubbles](#)

Modern detectors follow different principles—obtain same results: particle type, mass, charge, momenta

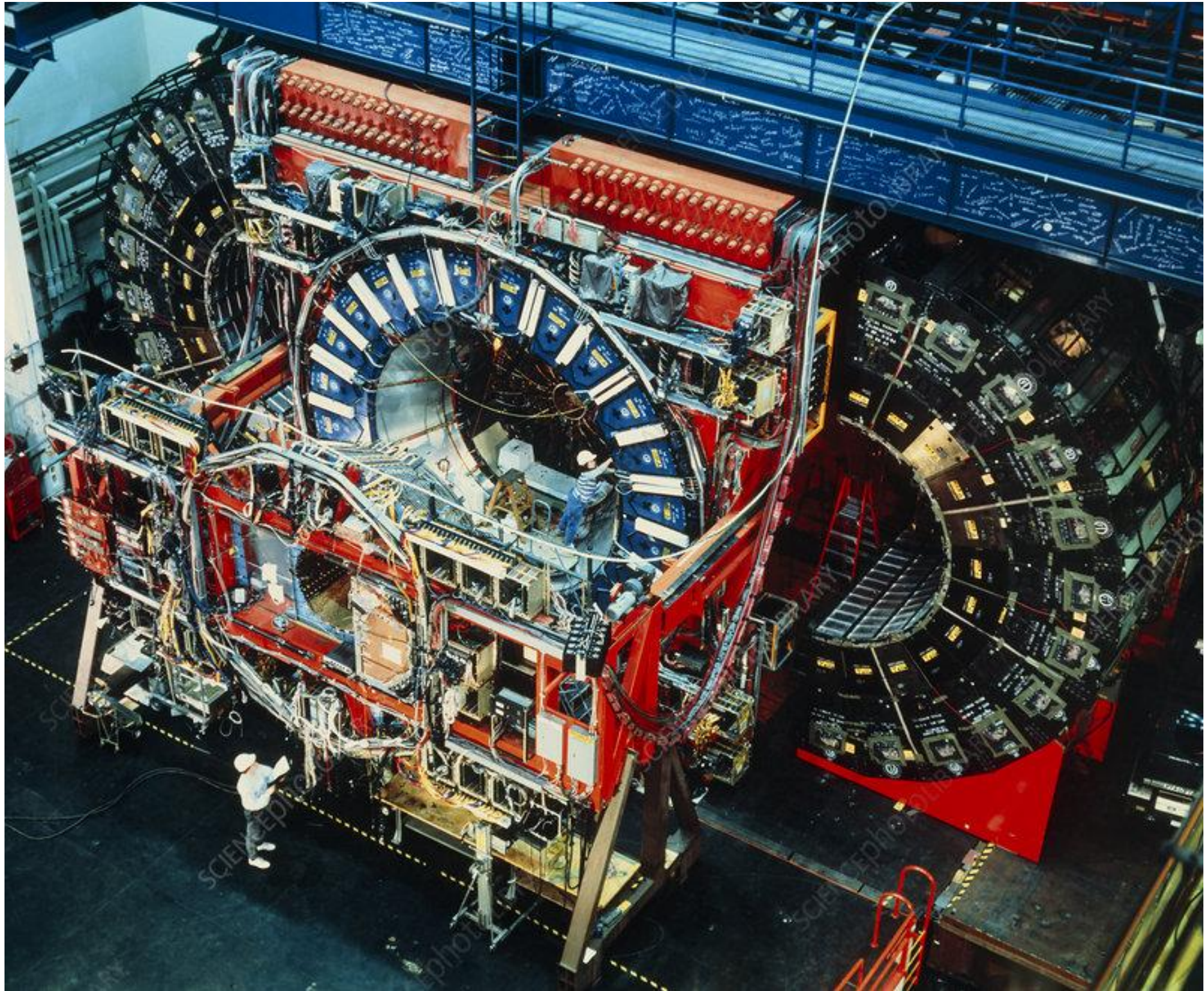


From the Tevatron to the LHC

Trillions of protons racing around $\sim 10,000$ times per second at $0.9999999991c$



The \$21,000,000,000 hole in Texas: America's Missing Collider—Bobby Broccoli Film



[Collider Detector Facility \(CDF\) at Fermilab - Science Photo Library](#)



LHCb

ATLAS

CERN Meyrin

CERN Prévessin

SPS 7 km

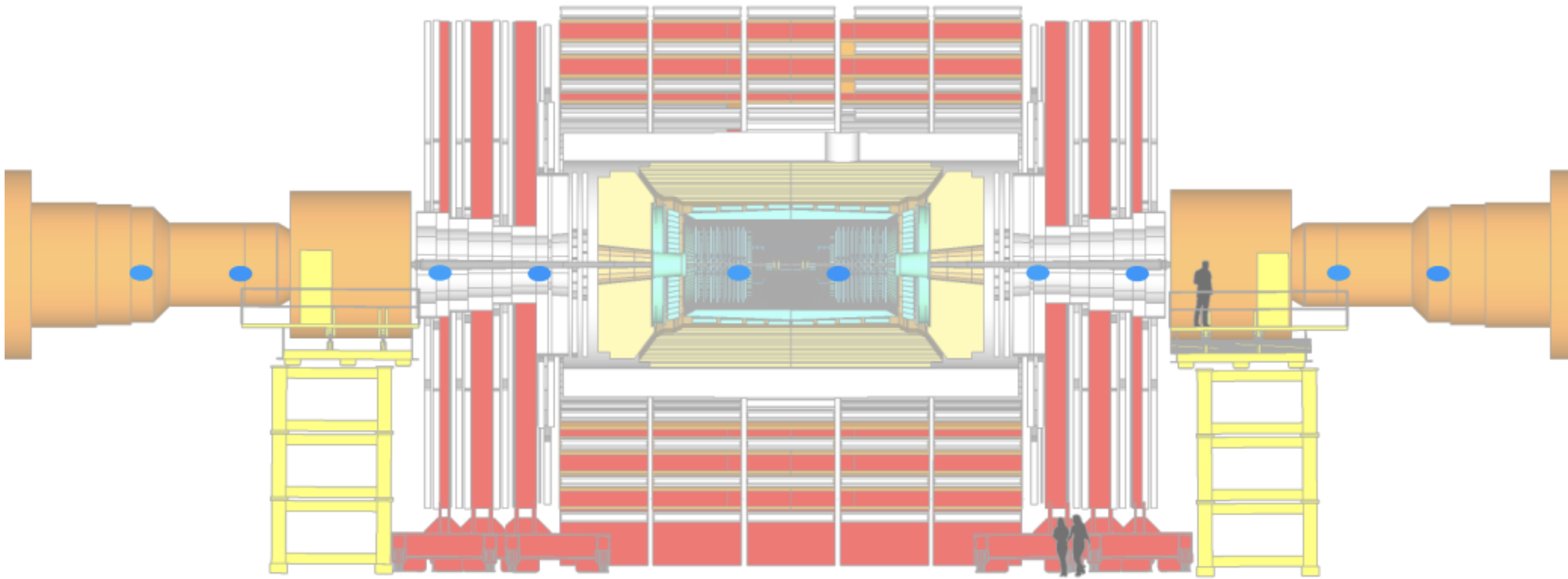
ALICE

LHC 27 km

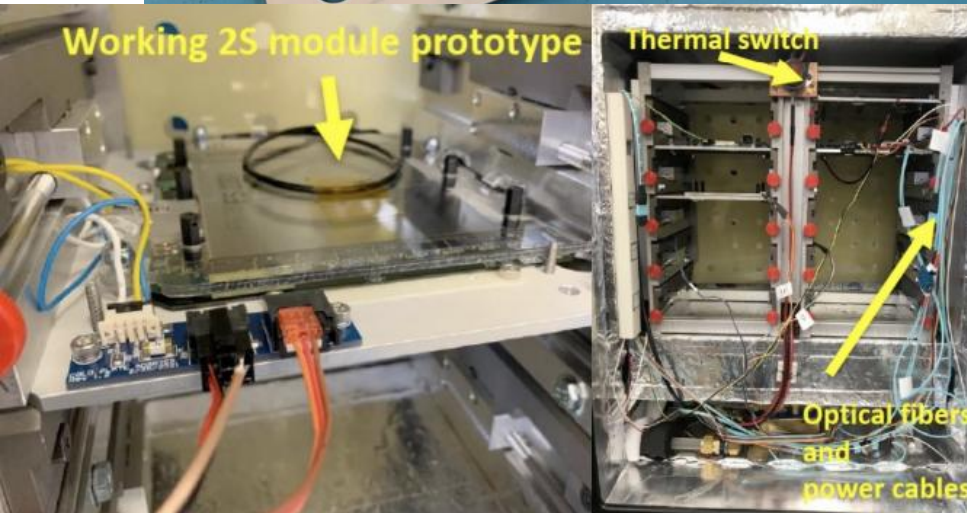
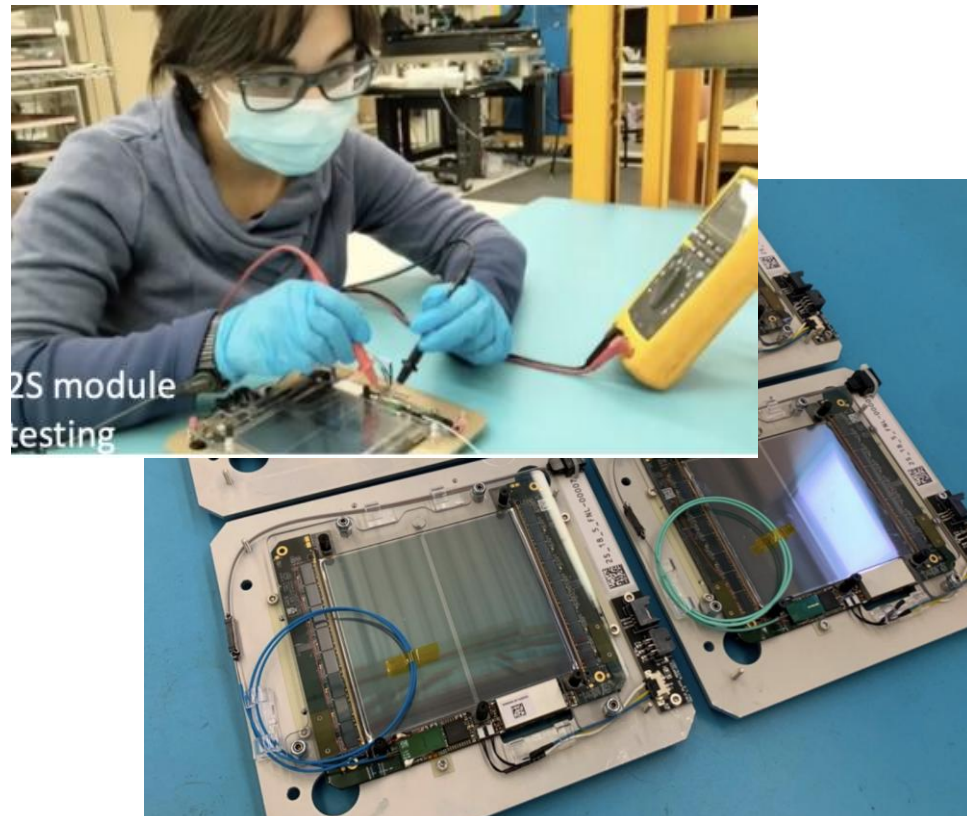
CMS

SUISSE
FRANCE

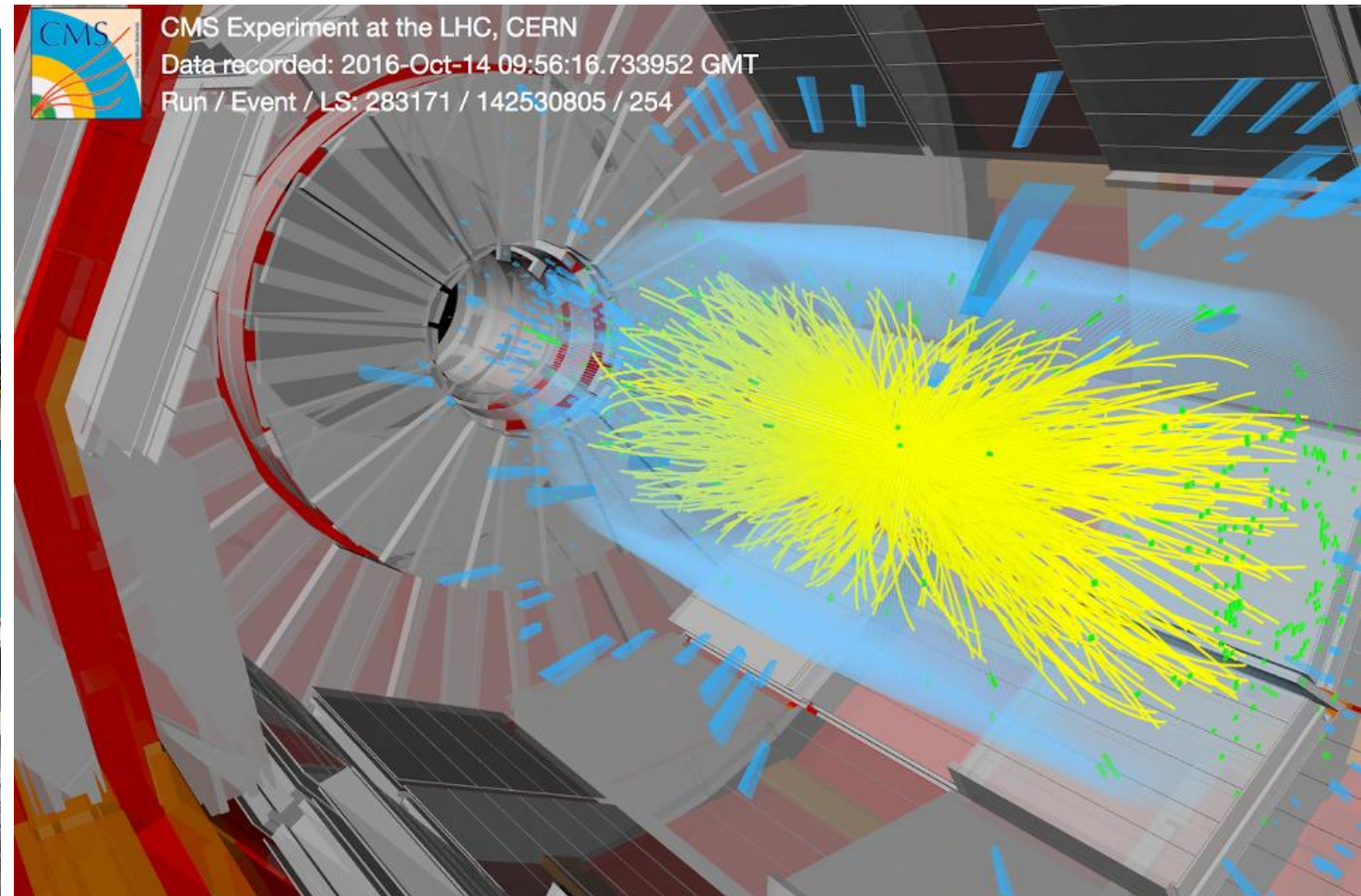
The CMS Experiment at the LHC



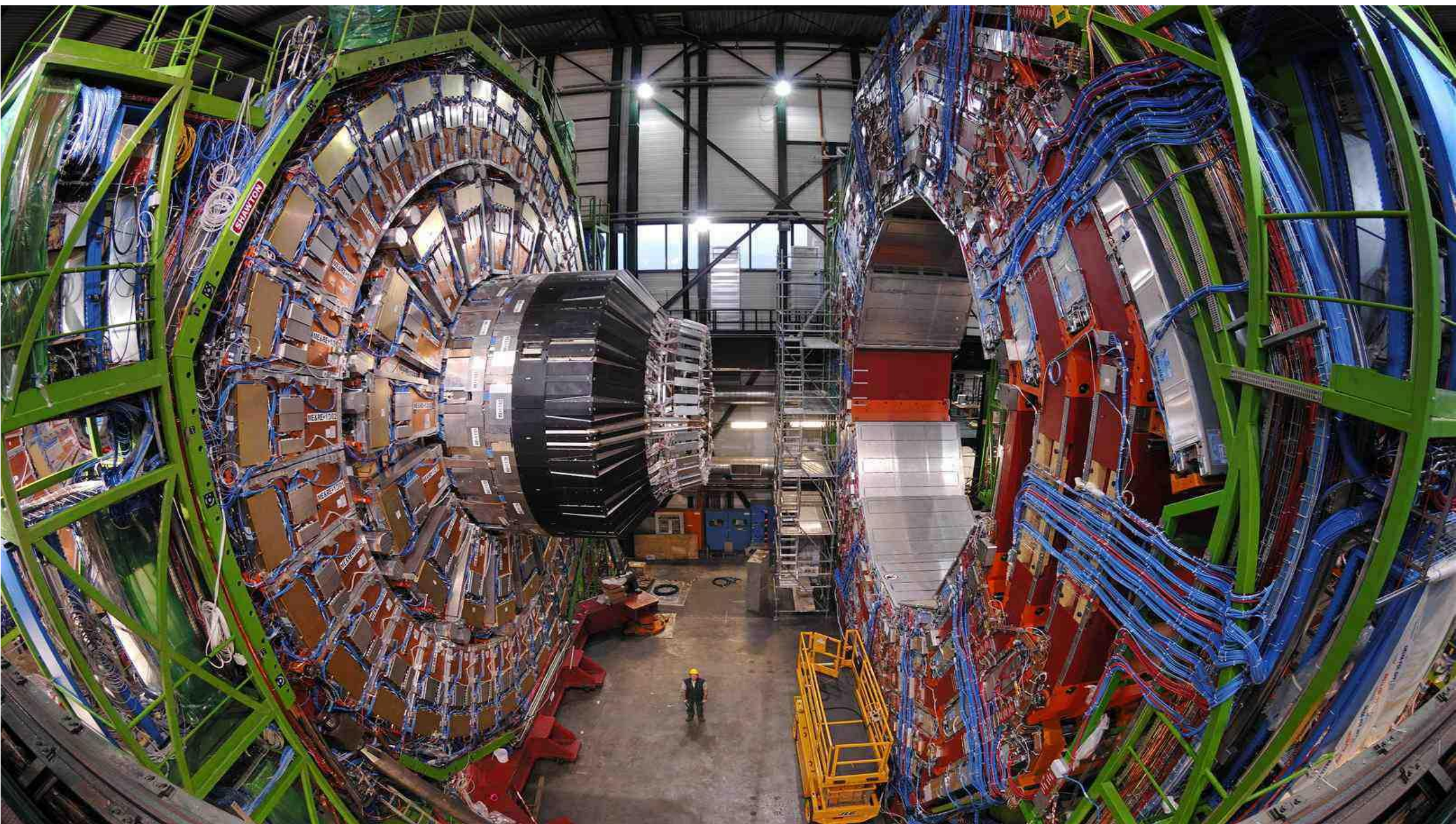
The LHC Community at Fermilab



Building new detectors



Analyzing data of current detectors



"All the News
That's Fit to Print"

The New York Times

Late Edition

Today, sunny to partly cloudy, mild or hot, high 85. Tonight, mostly clear, low 72. Tomorrow, mostly sunny, hot and humid, high 88. Weather map appears on Page B1.

VOL. CLXI... No. 55,823

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NEW YORK, THURSDAY, JULY 5, 2012

\$2.50

Oil Backed Up, Iranians Put It On Idled Ships

*Subterfuge at Tankers
as Embargo Tightens*

By THOMAS FREDRICK
and CLIFFORD KIRKIN

BANDAR ABBA, Iran — The hulking tanker *Neposue* was floating aimlessly this week in the warm waters of the Persian Gulf, a fresh coat of black paint barely concealing its true identity as an Iranian ship loaded with hundreds of thousands of barrels of oil that no one is willing to buy.

The ship's real name was Iran Ashraf, and it was part of a fleet of about 65 Iranian tankers serving an floating storage facilities for Iranian oil, each one given a nautical makeover to conceal its origin and make a buyer easier to find. The *Neposue* had been floating there for a month, and local fishermen said there were two

ROMNEY NOW SAYS HEALTH MANDATE BY OBAMA IS A TAX

SHIFT RENEWS CRITICISM

Move Aligns Him With
Conservative Voices
Within His Party

By JEREMY W. PETERS

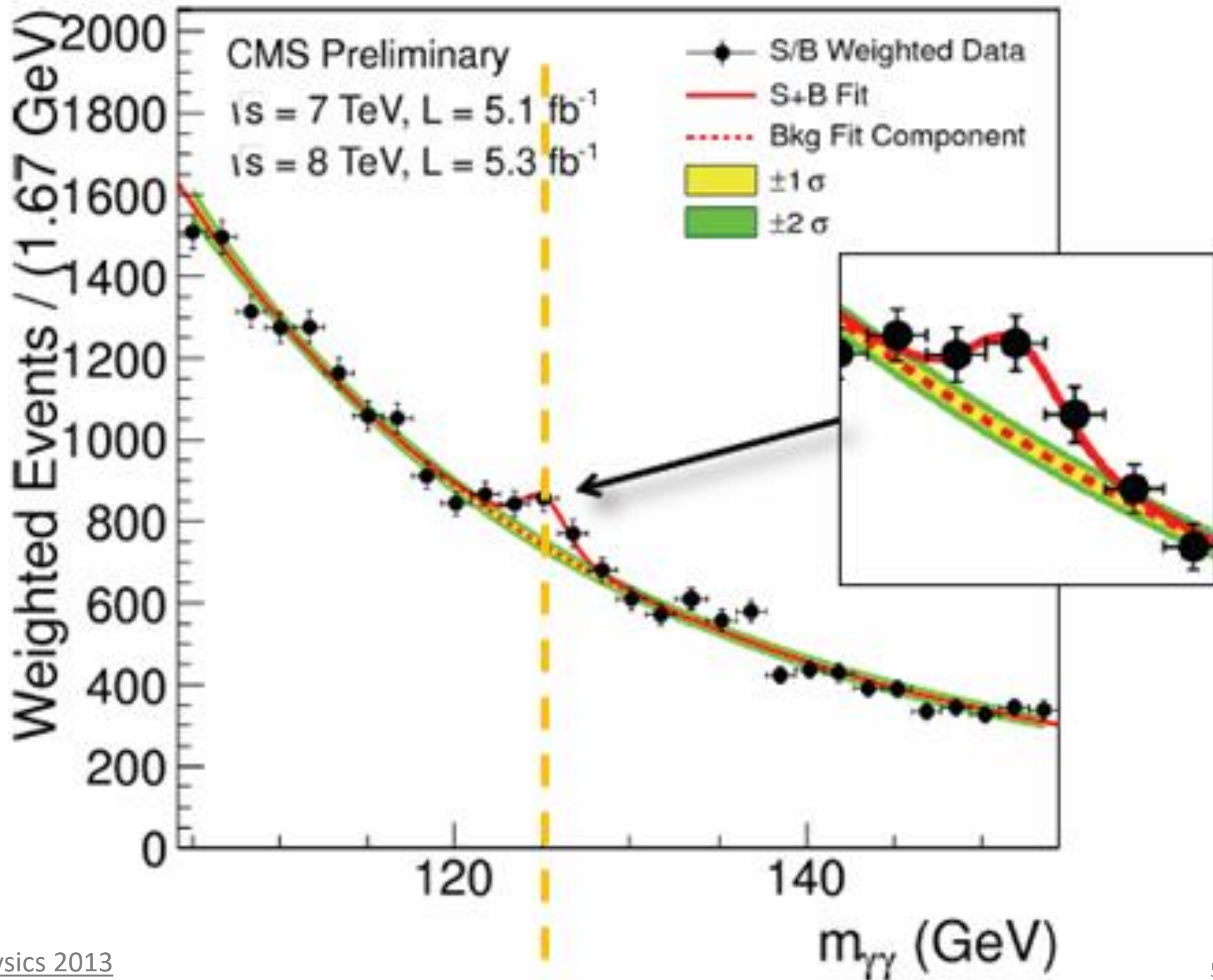
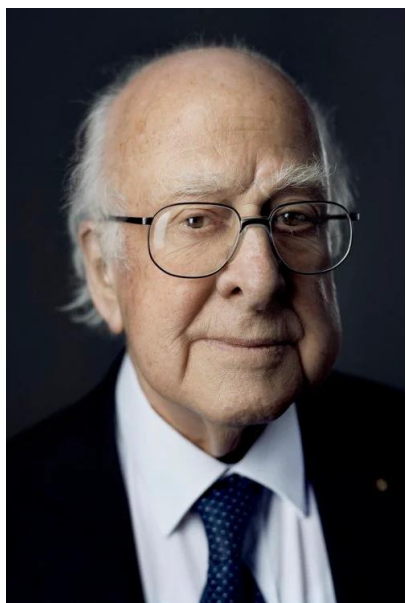
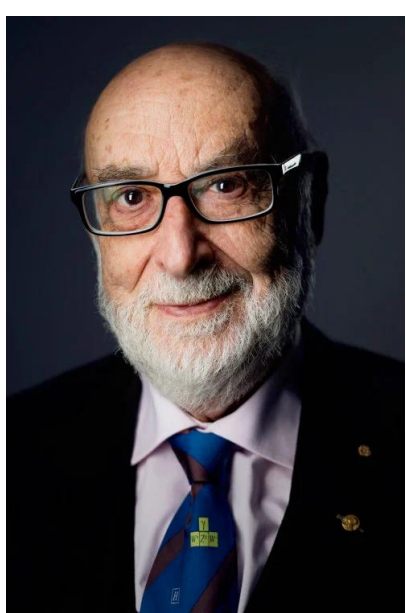
WOLFEBORO, N.H. — Mr. Romney declared on Wednesday that President Obama's health care mandate was in fact a tax, shifting his campaign's characterization of the law and aligning himself with the conservative voices in his party.

Mr. Romney's remarks, made in a hastily arranged interview with CBS News on a national holiday, prompted renewed criticism that he was willing to ad-

Physicists Find Elusive Particle Seen as Key to Universe

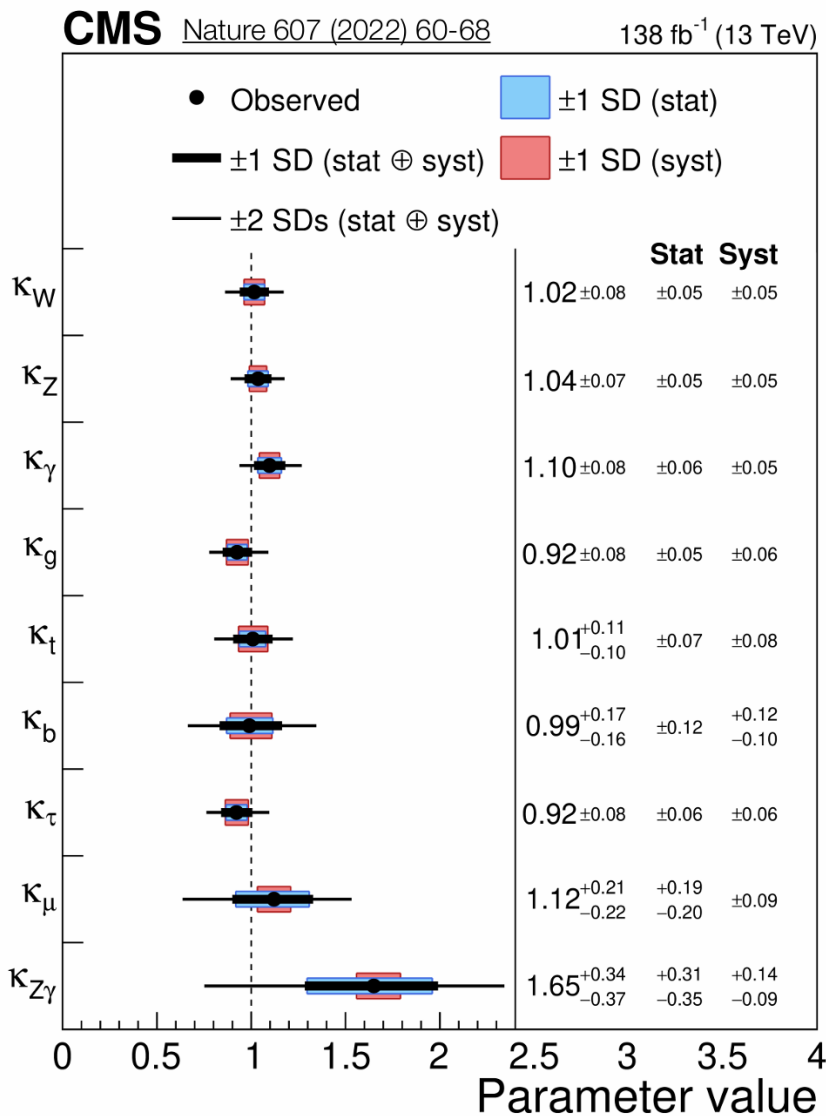
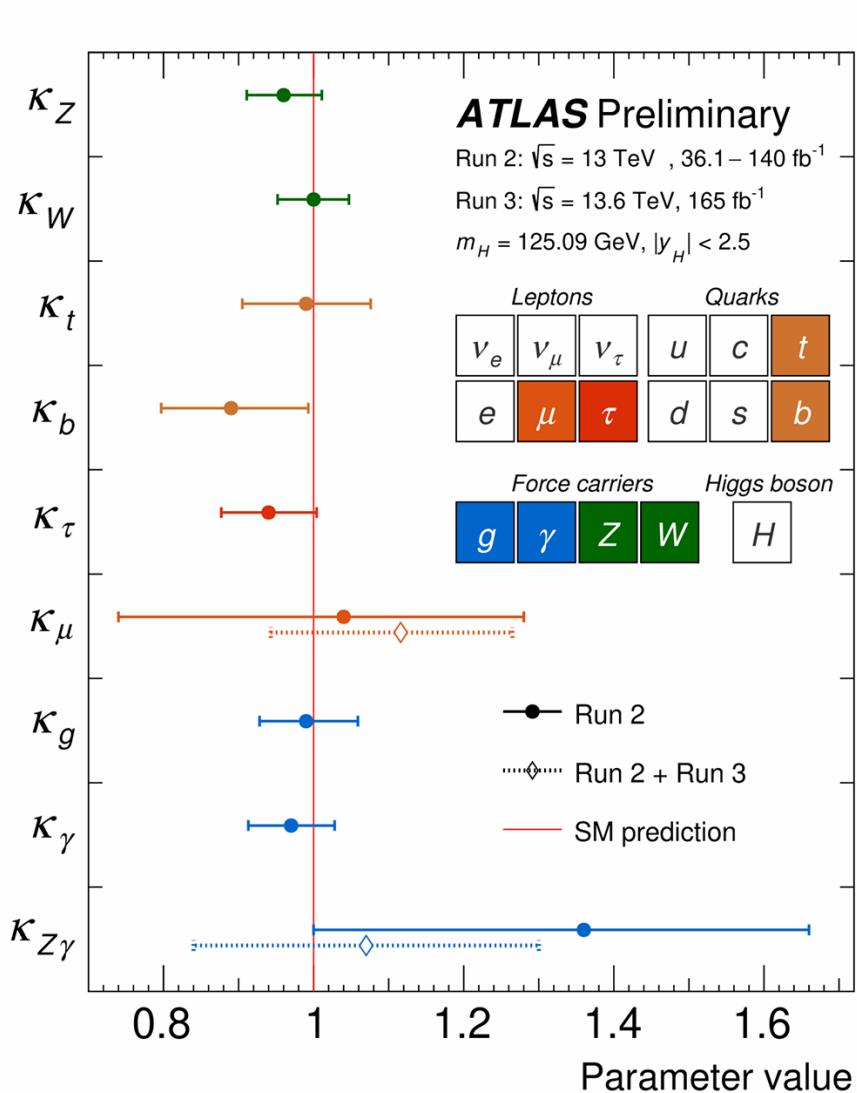


Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson.



The Robustness of the Standard Model

The SM ***extremely successful*** predicting outcomes of almost all experiments so far



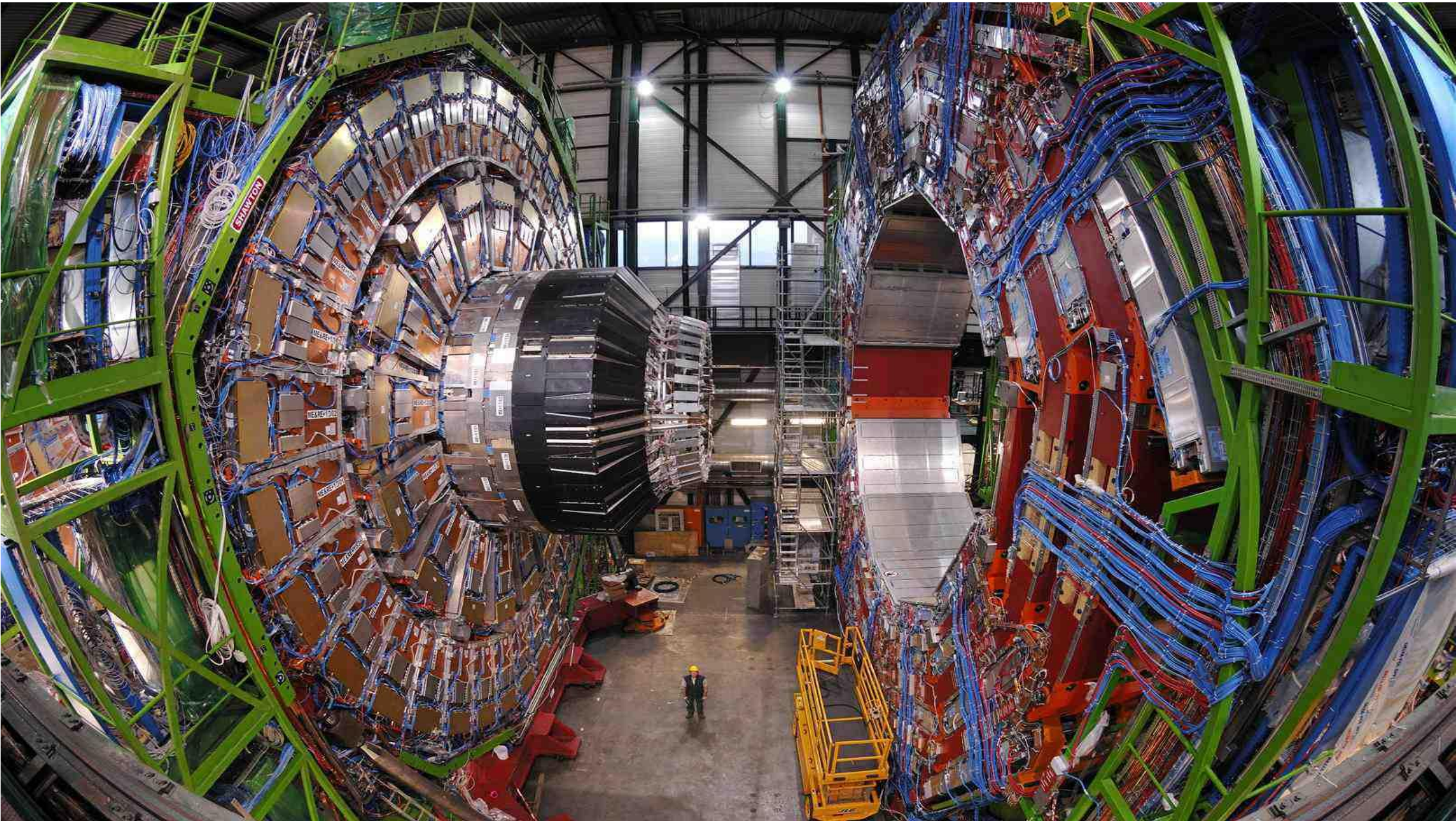
One of Fermilab's goals:

- Test the SM as much as possible!

Where does the SM break down?

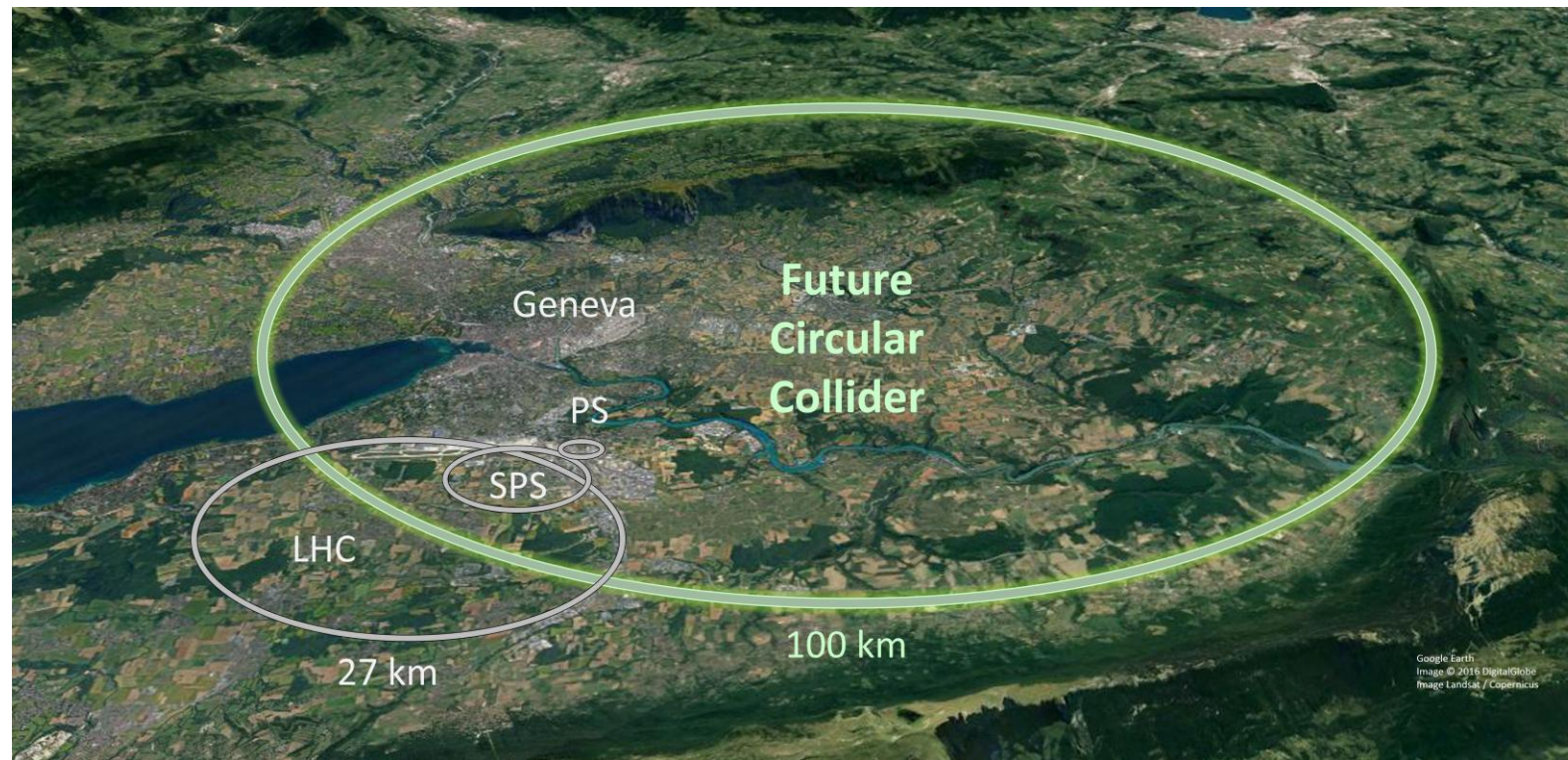
How does it break?

Still Searching for What's Next



What Will the Next Collider Be?

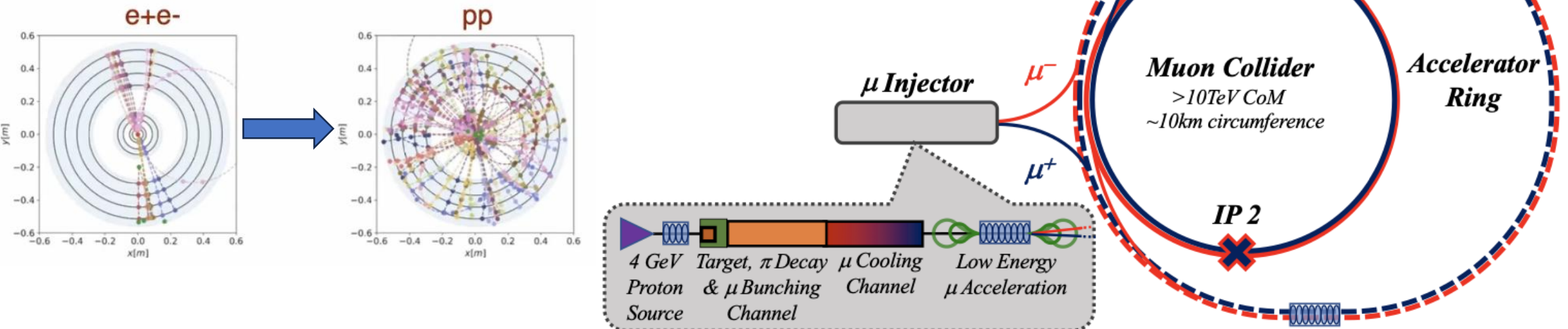
Electron Circular (or Linear) Collider



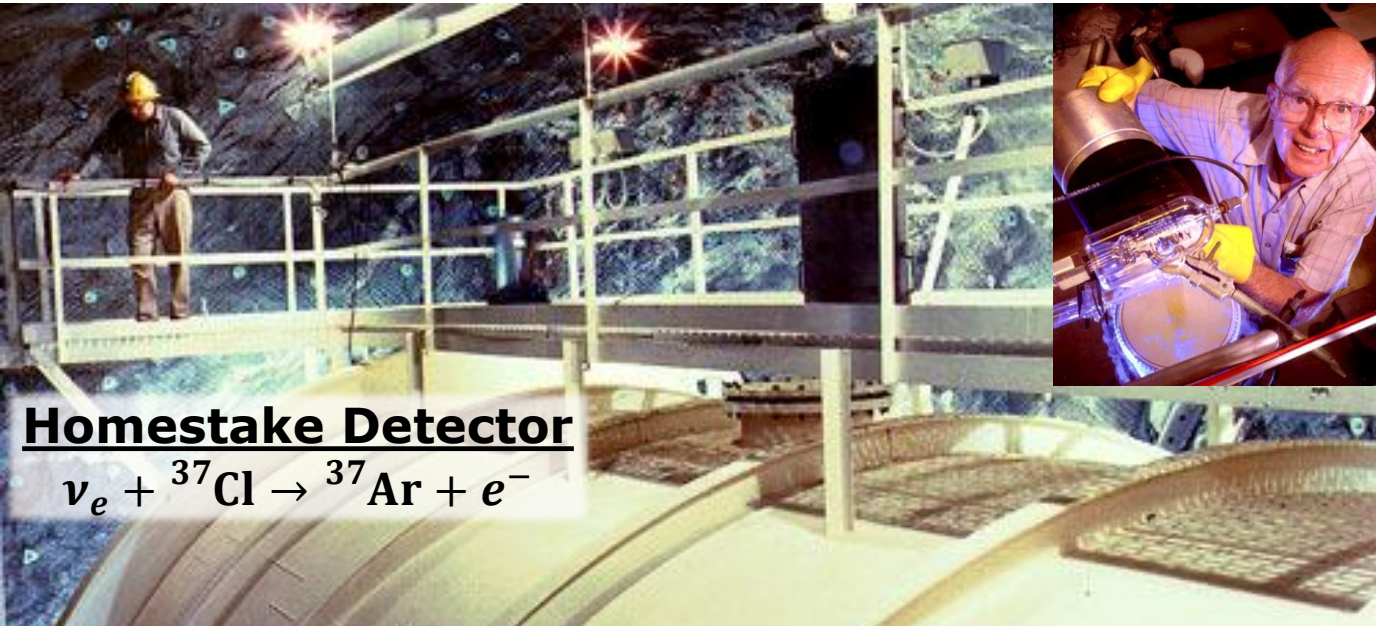
Fermilab actively contributes to the international particle physics community via CERN and the LHC

Fermilab is actively exploring a new collider—in the US!

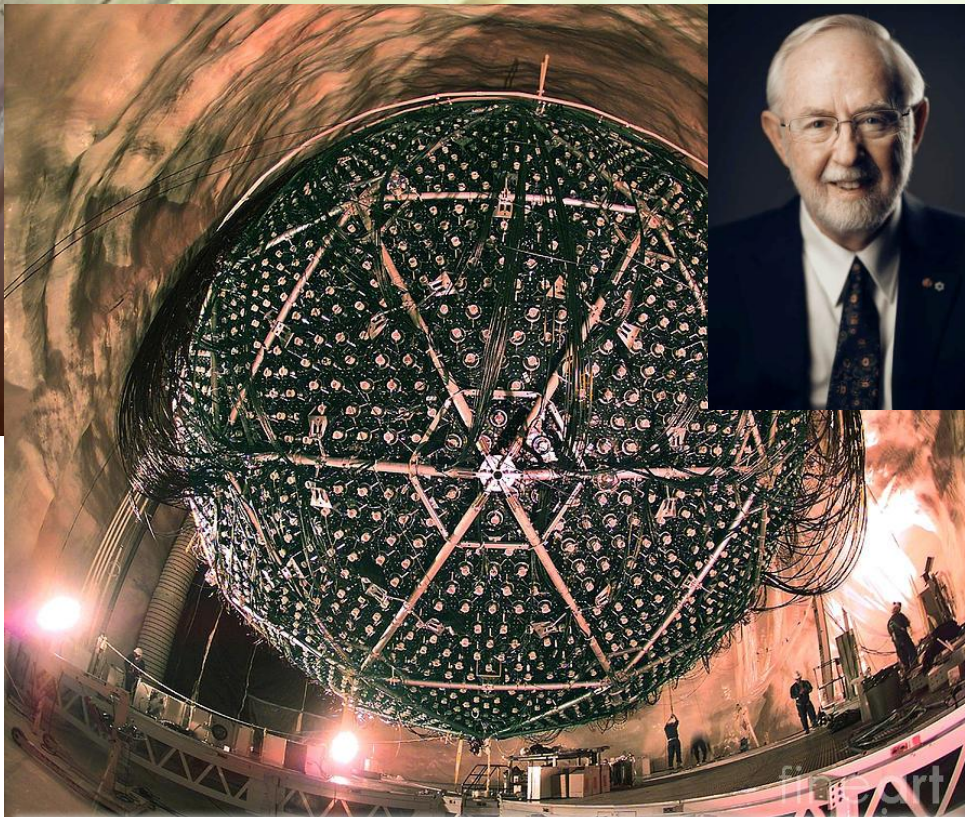
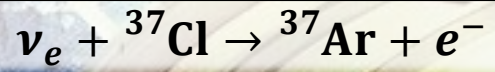
Muon Collider (@Fermilab?)



Neutrino Oscillations

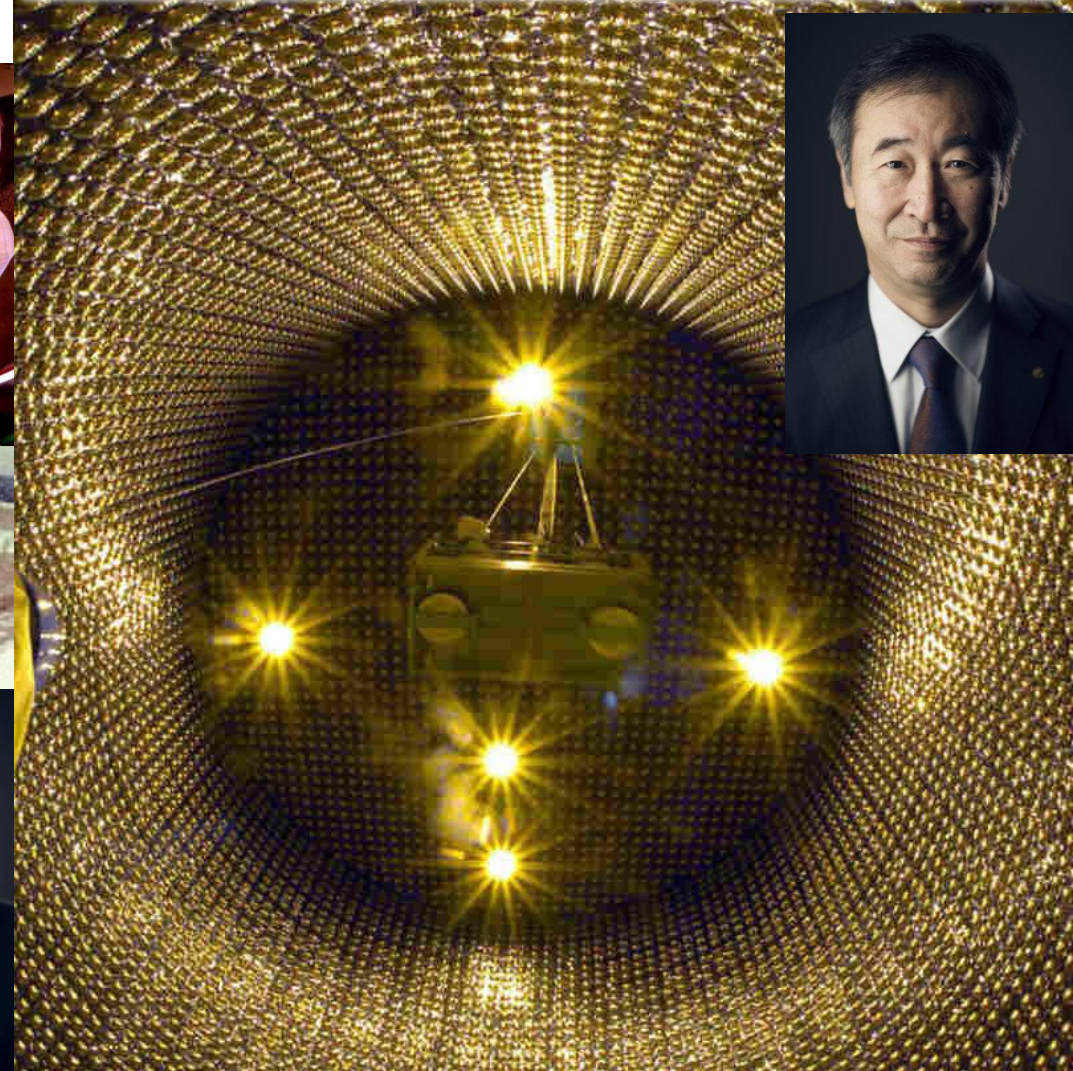


Homestake Detector

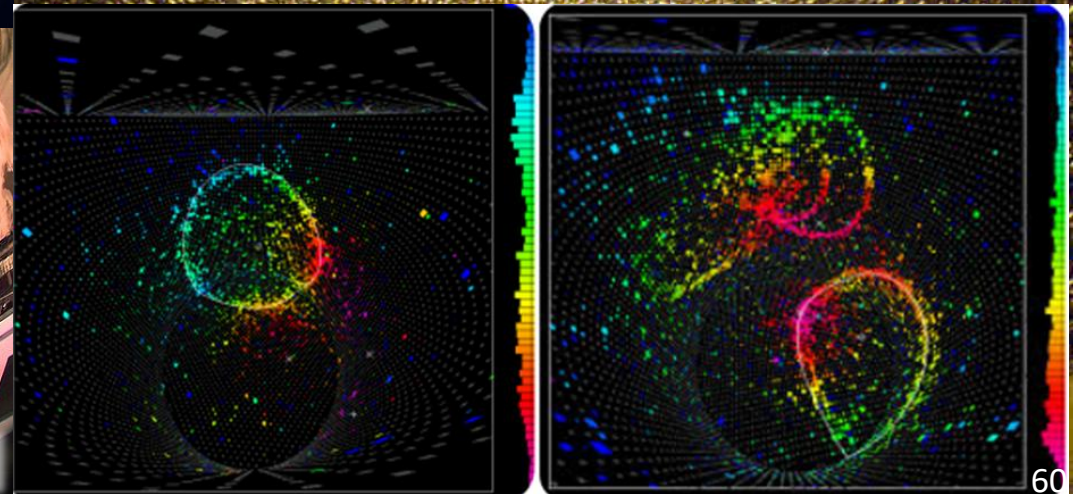


Sudbury Neutrino Observatory

Super-Kamiokande

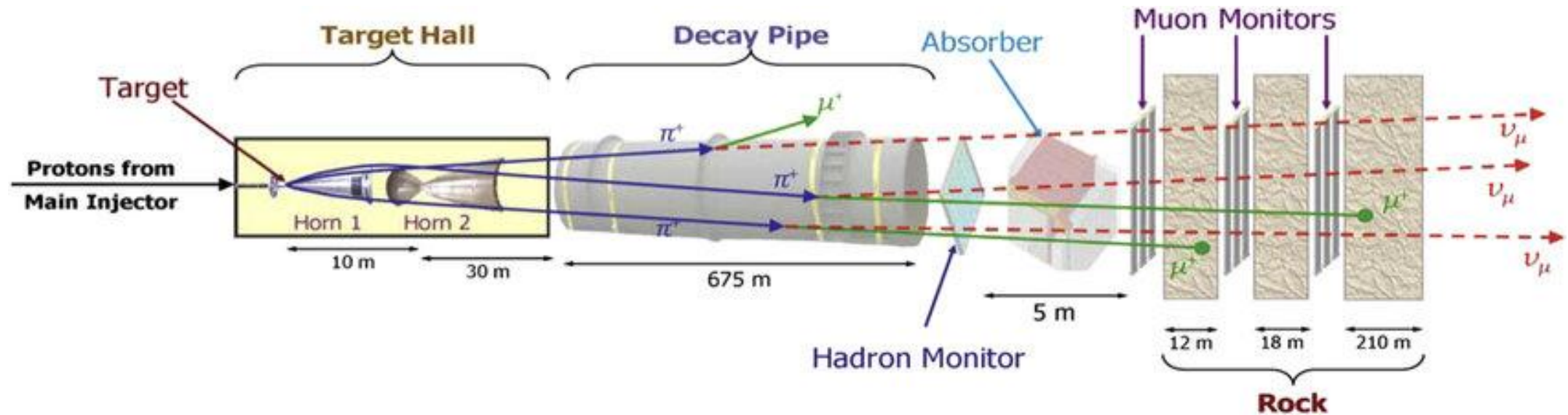
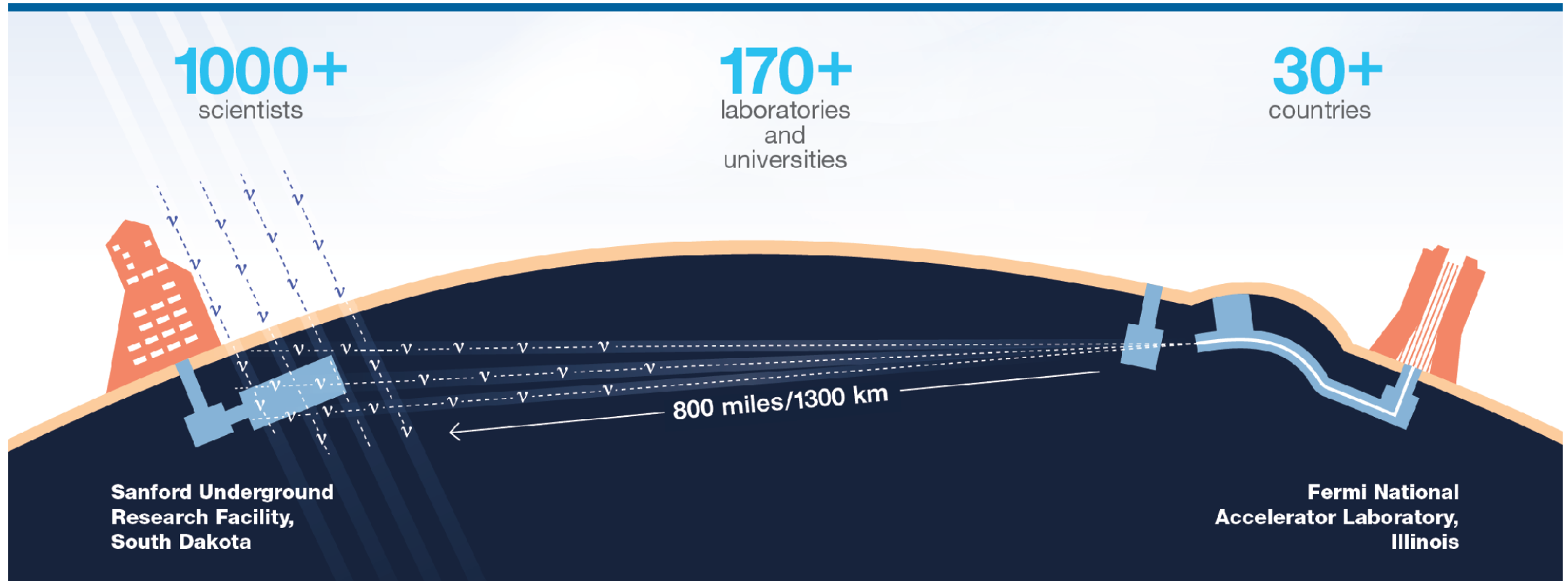


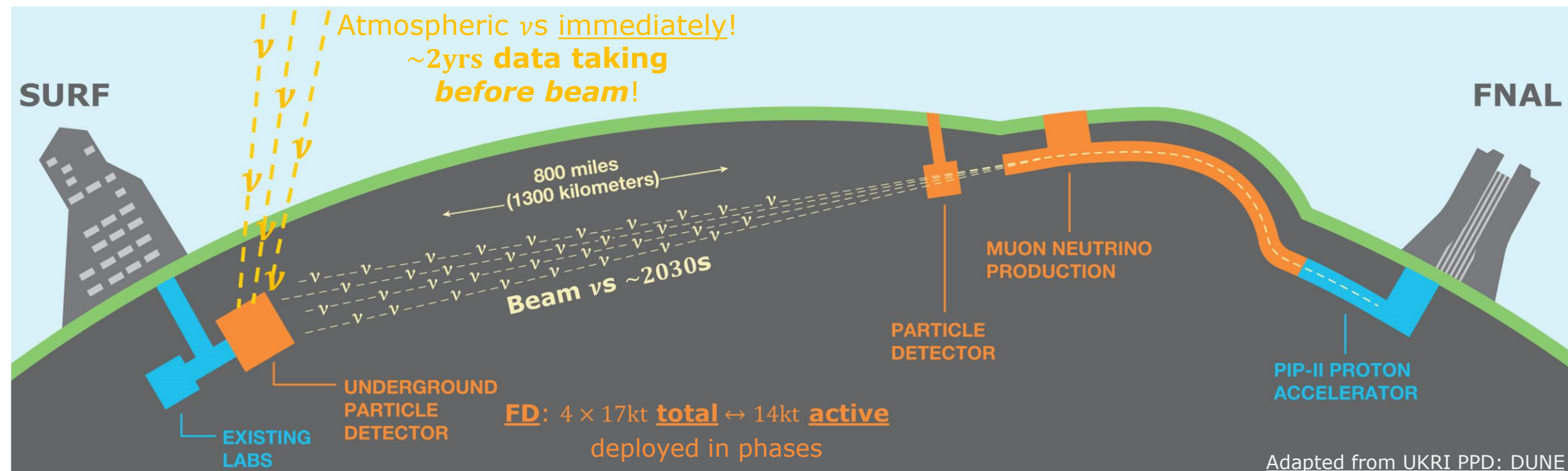
[2002 Nobel Prize in Physics](#)
[2015 Nobel Prize in Physics](#)



DUNE

The Deep Underground Neutrino Experiment





Liquid Argon Time Projection Chamber

Far Detectors located on 4910' level at SURF

- Excellent shielding to cosmogenic events—quiet!
 - ~4000 cosmics/day in single LArTPC FD module
 - Compare to ~4000 cosmics/s in MicroBooNE!

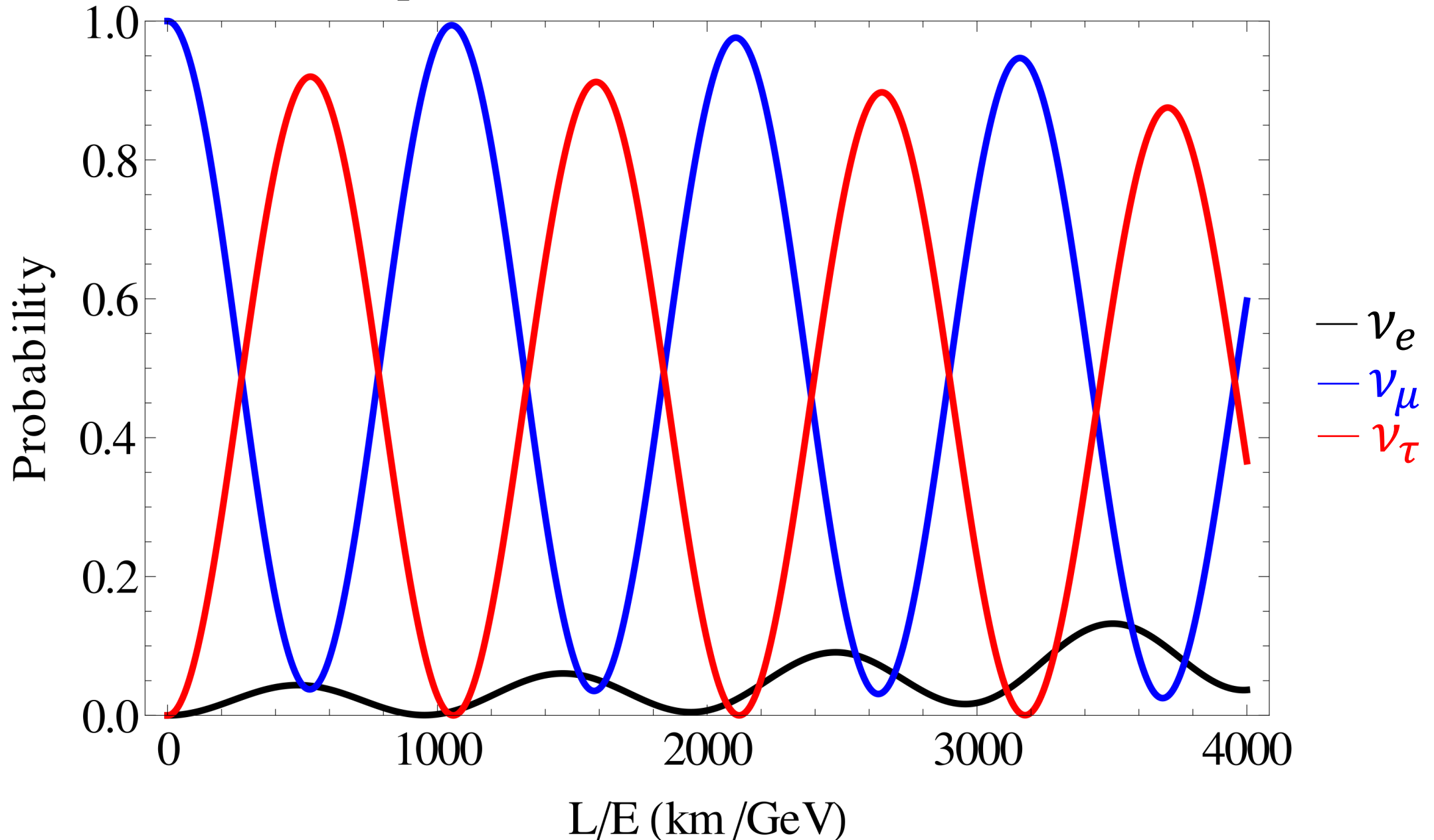
Global experiment of > 1400 collaborators!

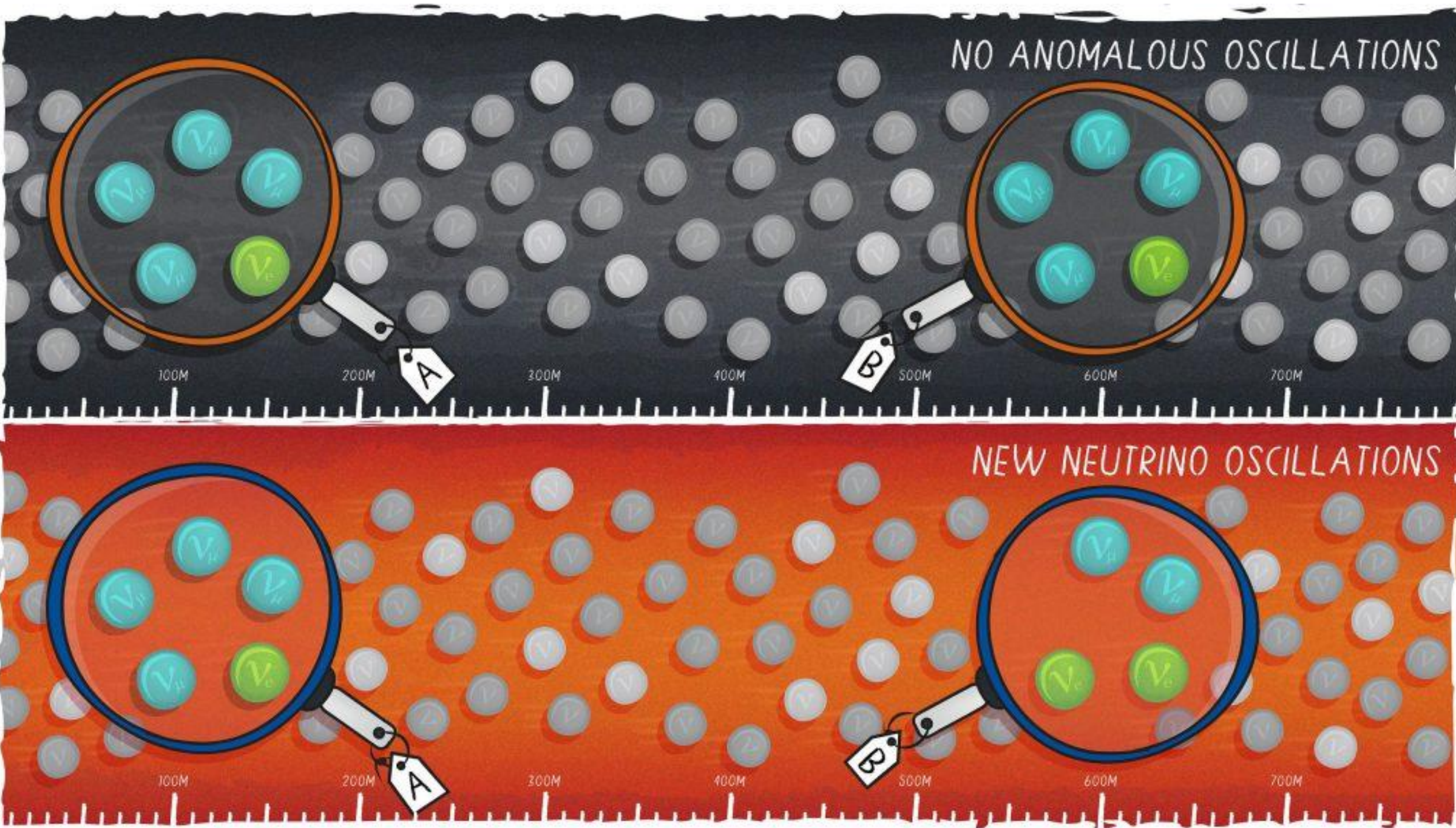
Atmospherics: first $\gtrsim$ 2 yrs DUNE ν data!



$$P_{\nu_\alpha \rightarrow \nu_\beta}(E_{\nu, \text{true}}, L) \approx \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E_{\nu, \text{true}}}\right)$$

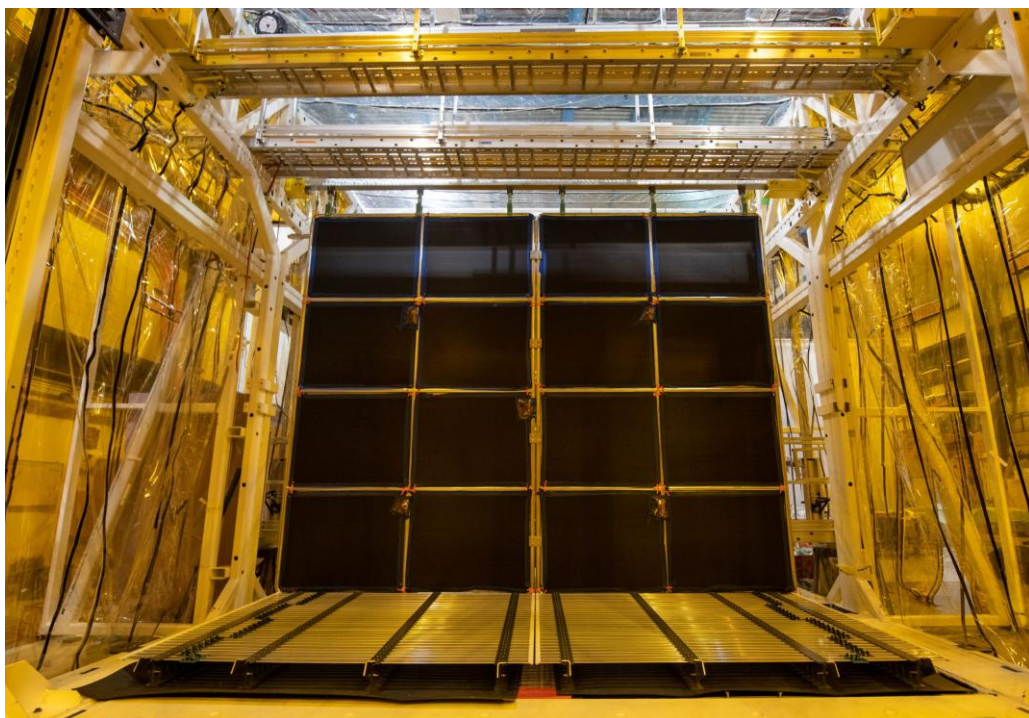
Oscillation probabilities for an initial muon neutrino



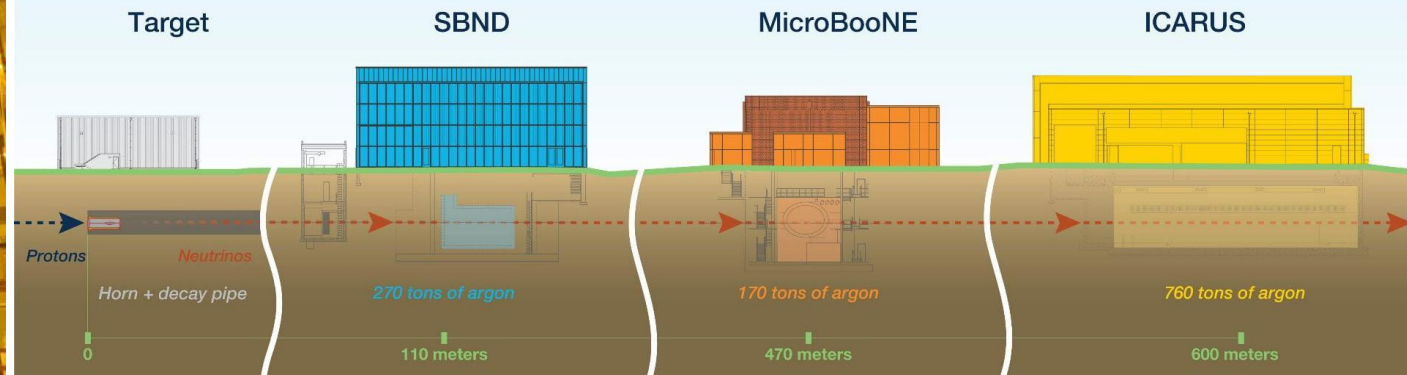


First neutrinos detected at Fermilab short-baseline detector

Detecting ν s & Studying Their Interactions

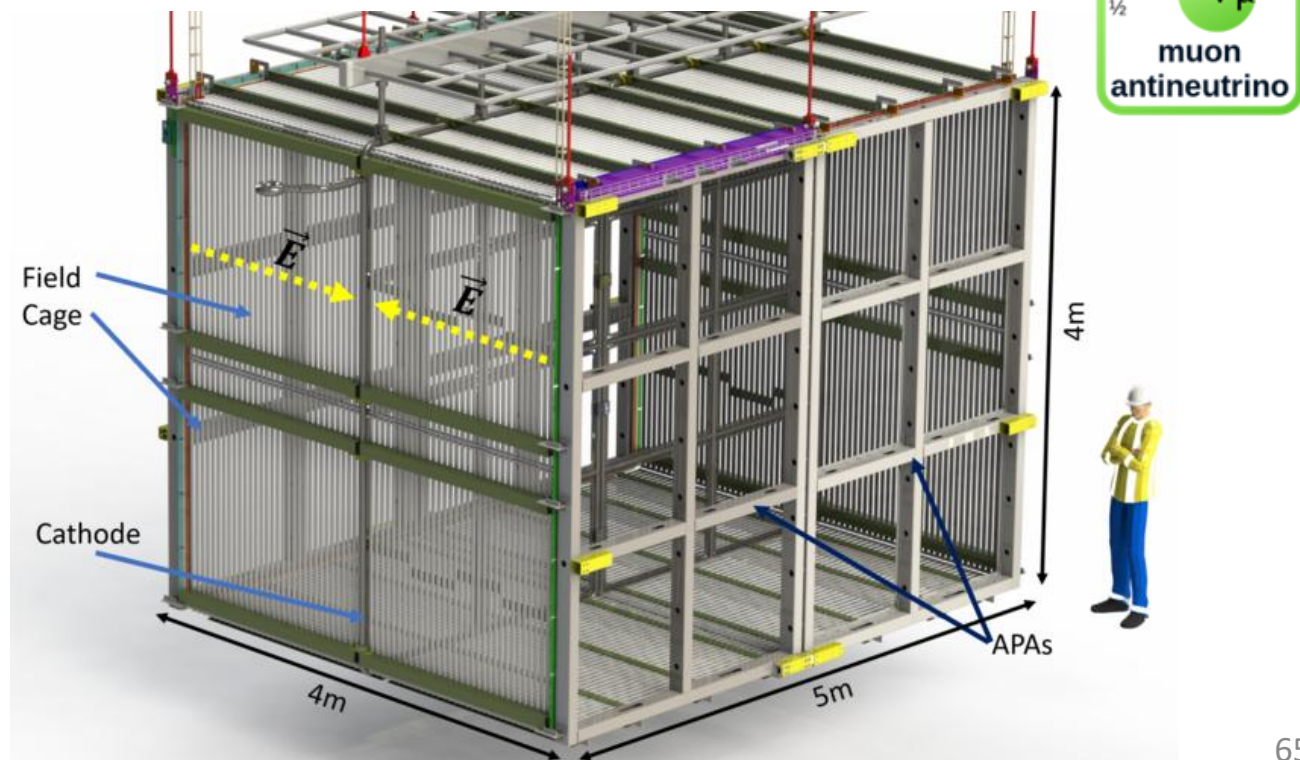


Short-Baseline Neutrino Program at Fermilab



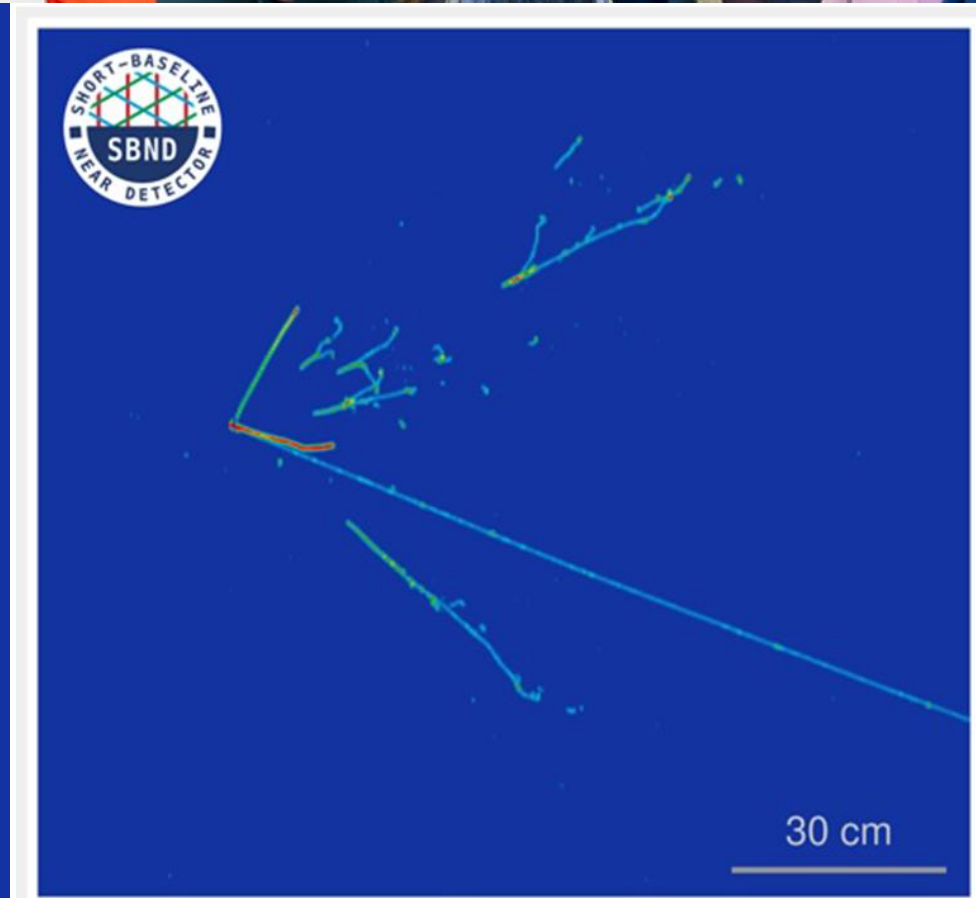
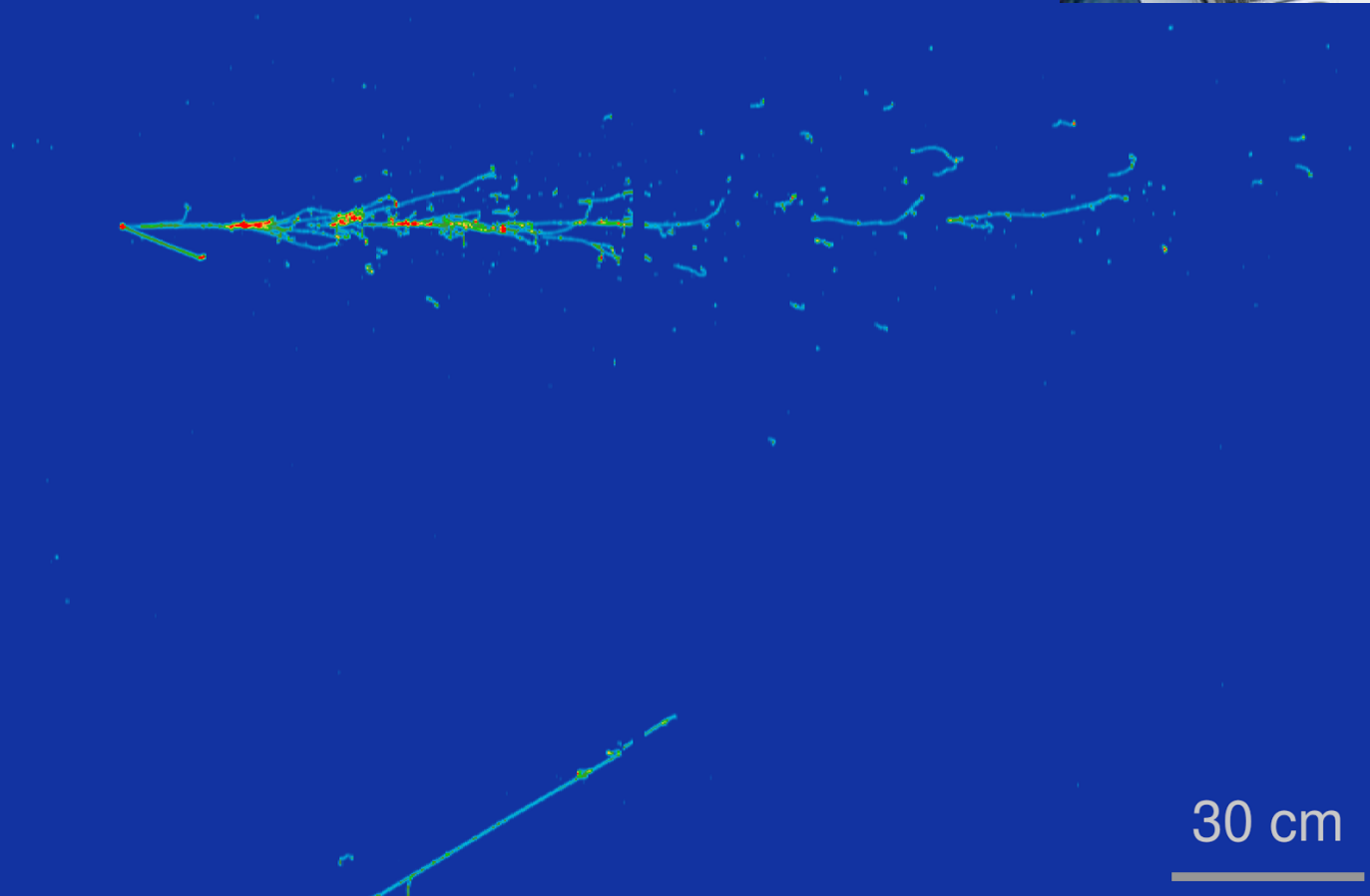
Recently constructed ν detector @Fermilab

- Filled w/wires & liquid Argon
- Like a bubble chamber!





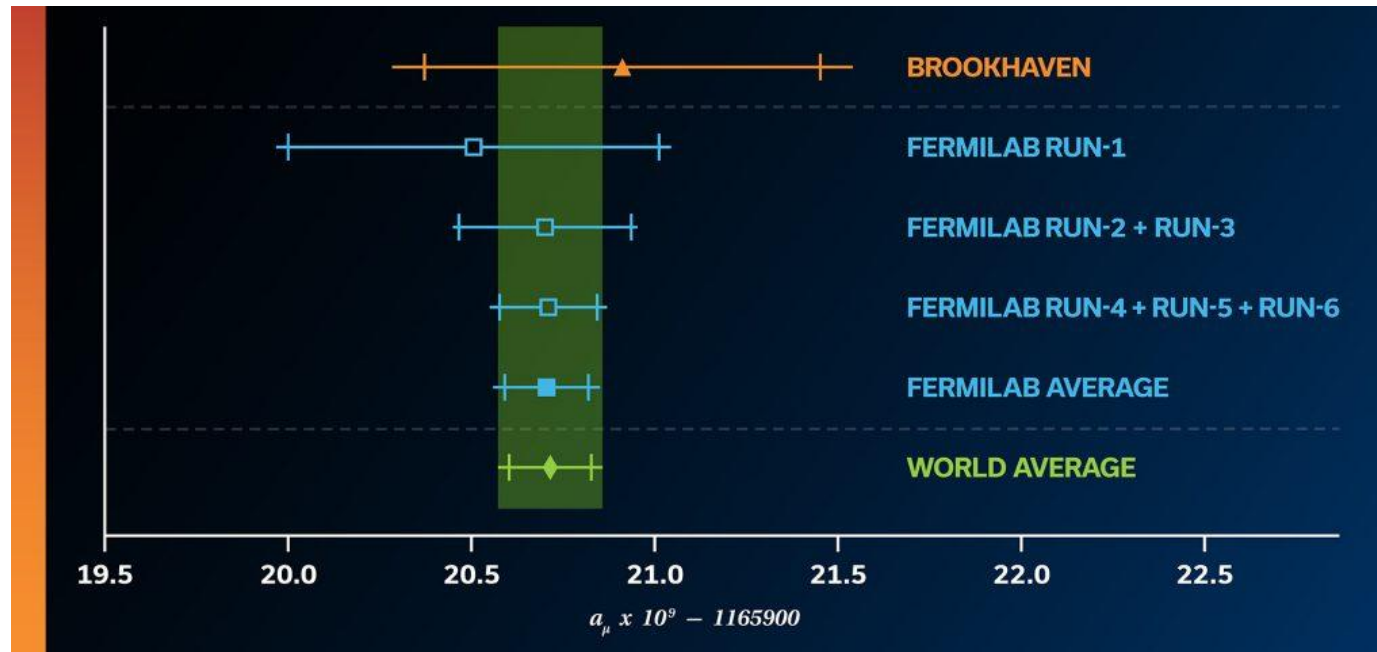
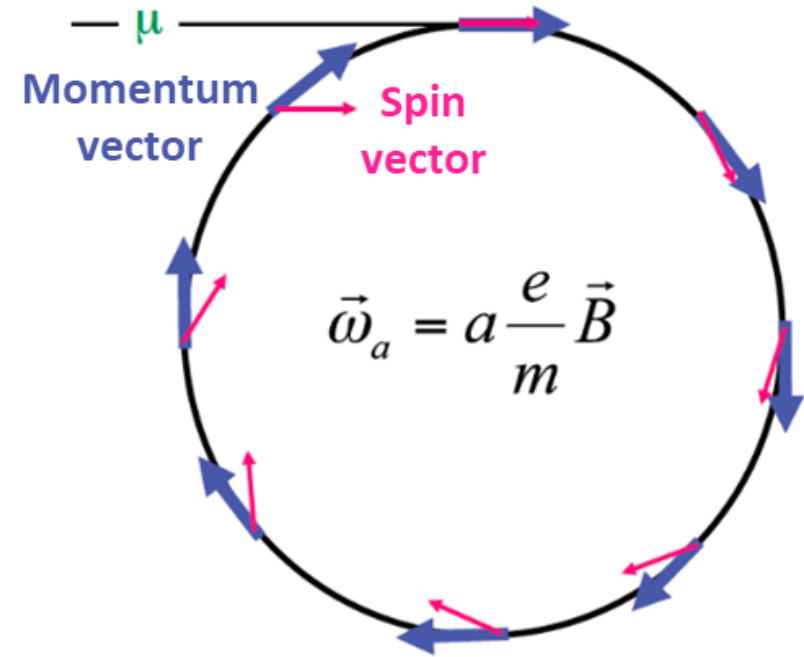
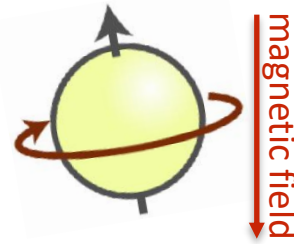
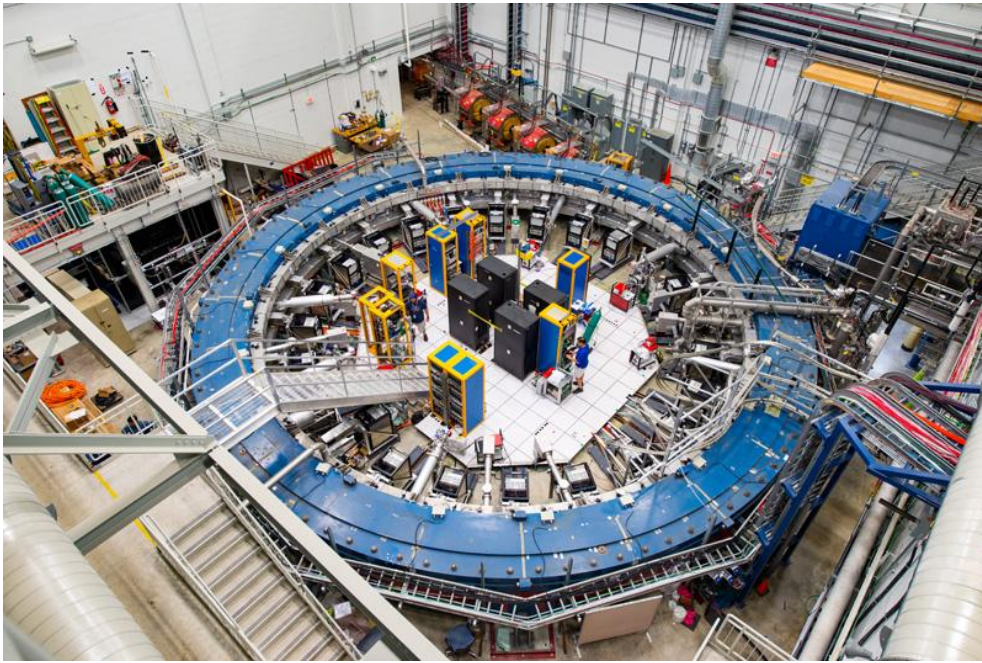
RUN 14729, EVENT 41
July 11, 2024



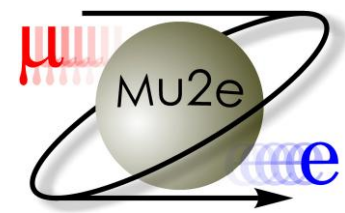
First neutrinos detected at Fermilab short-baseline detector

Muon Physics

The Now Completed g-2 Experiment



Muon g-2 announces most precise measurement of the magnetic anomaly of the muon



Muon Physics

The Future mu2e Experiment

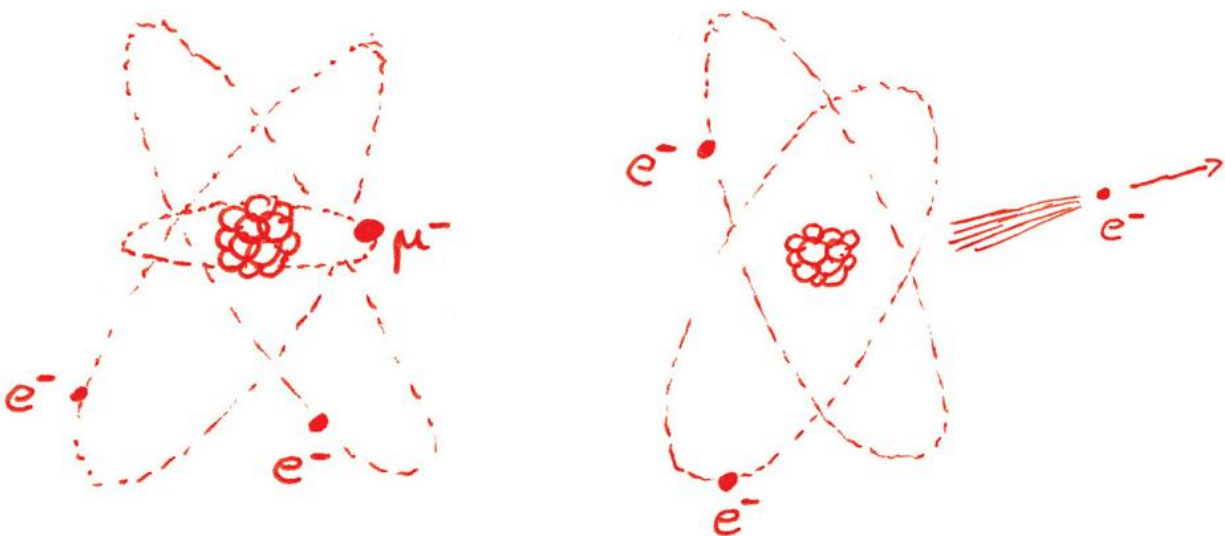
105.7 MeV/c ²	μ
-1	
1/2	
muon	

Muon production target & solenoid

Proton beam

Transport solenoid

Detector solenoid w/tracker and calorimeter



Science Today at Fermilab

Beyond Both Theory and Experiment!

- Particle physics

- Accelerator physics

- Quantum sciences

- Cosmology

- Astrophysics

- Particle detector R&D

- Machine learning / AI

- Data science

- Electronics

- Engineering

A Personal Summary: 'Beyond Reductionism'

Fermilab staff collectively study the very small & the very large, attempting to understand their structural interdependencies

3 Facts About the Universe

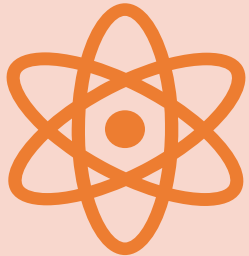


The universe is old, expanding, and this expansion is accelerated



85% of the mass in our universe is unknown: “dark matter”

- Components do not emit/absorb light



Only 15% composes everything we know

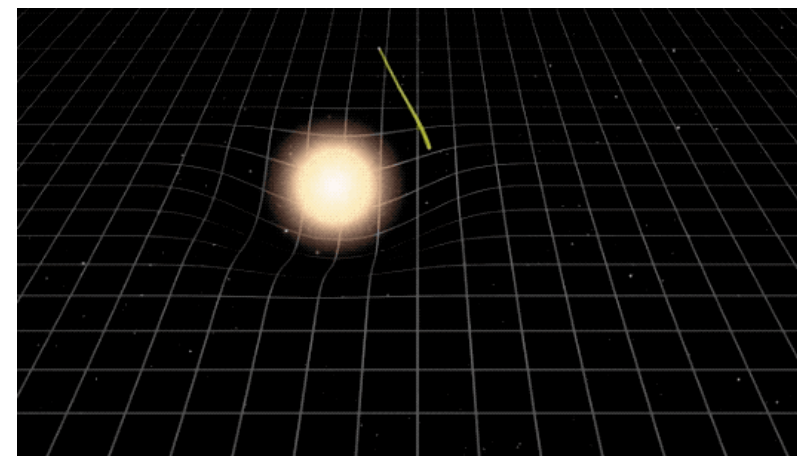
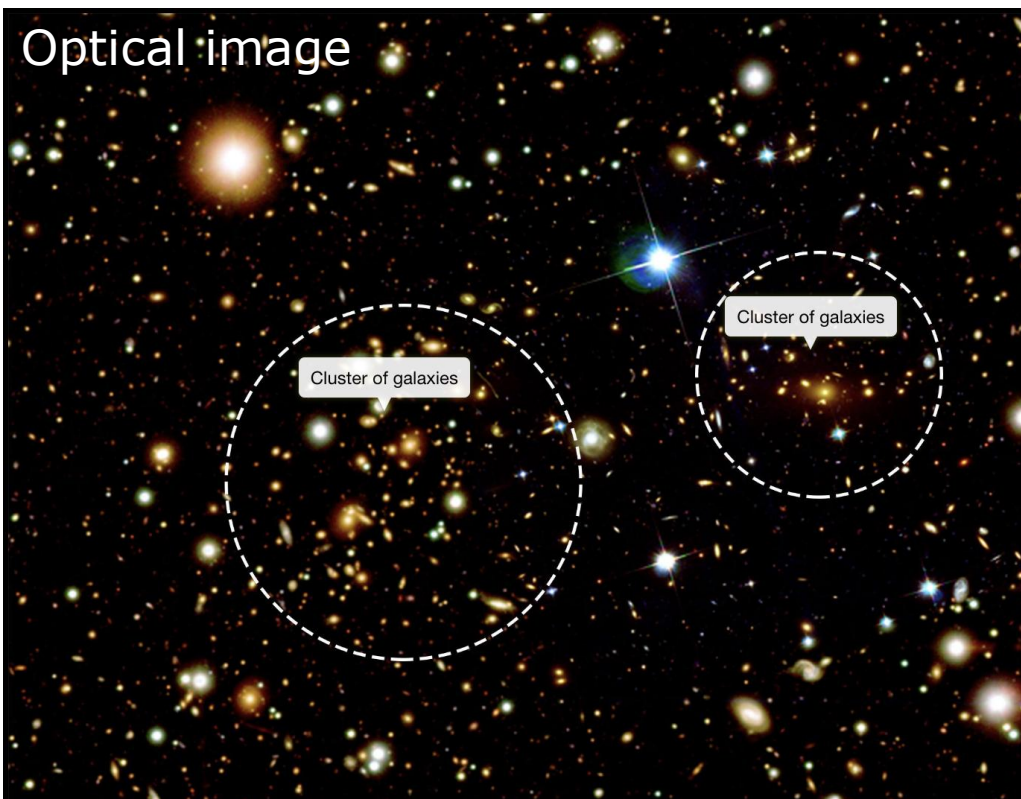
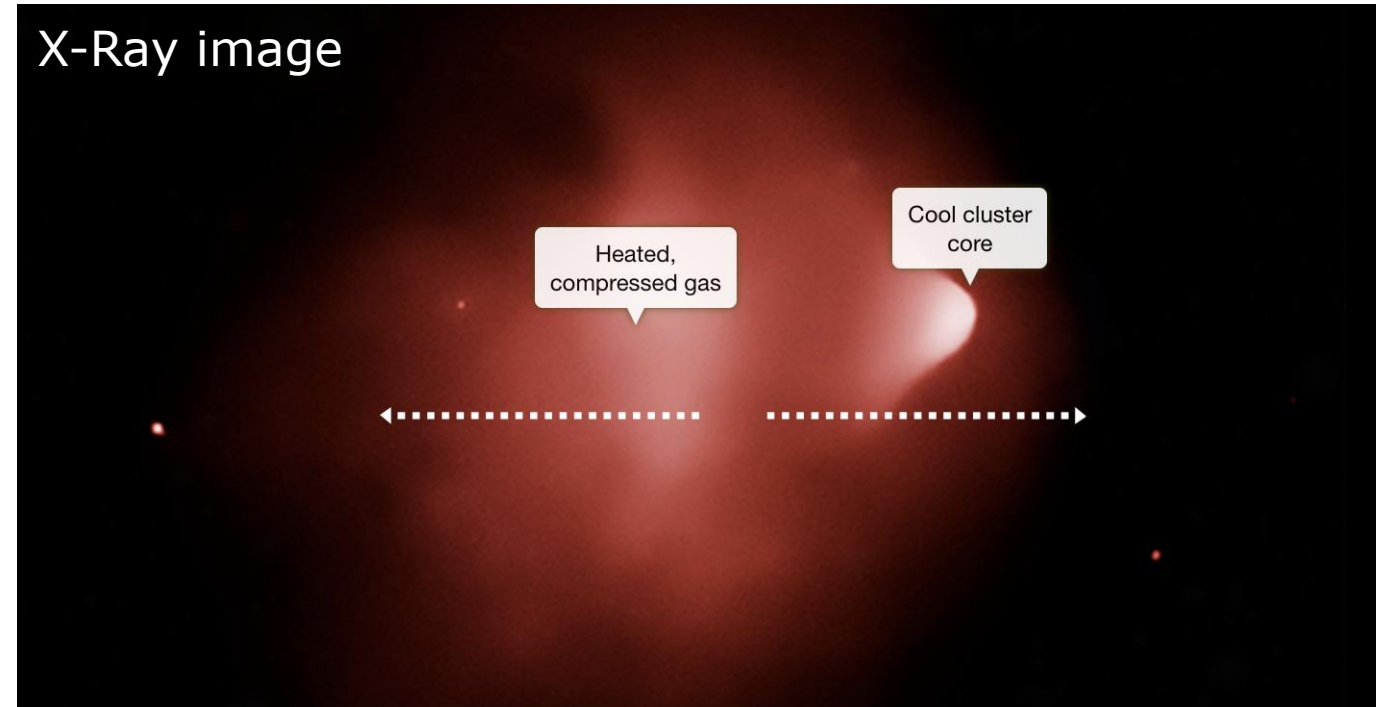
- Made of elementary particles

The Mystery of Dark Matter

The Bullet Cluster

- A high velocity galaxy merger
- Two ways to infer mass
 - X-Ray (pink/red)
 - **Gravitational lensing**
 - **Inferred mass** (blue)
- Blue: collisionless galaxies

X-Ray image

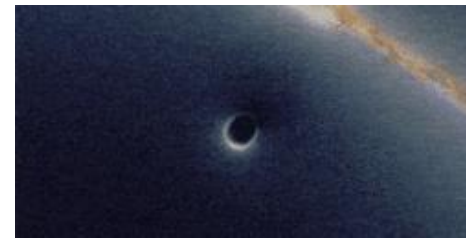


Black holes' lensing is wild!
[Interstellar Simulation](#)



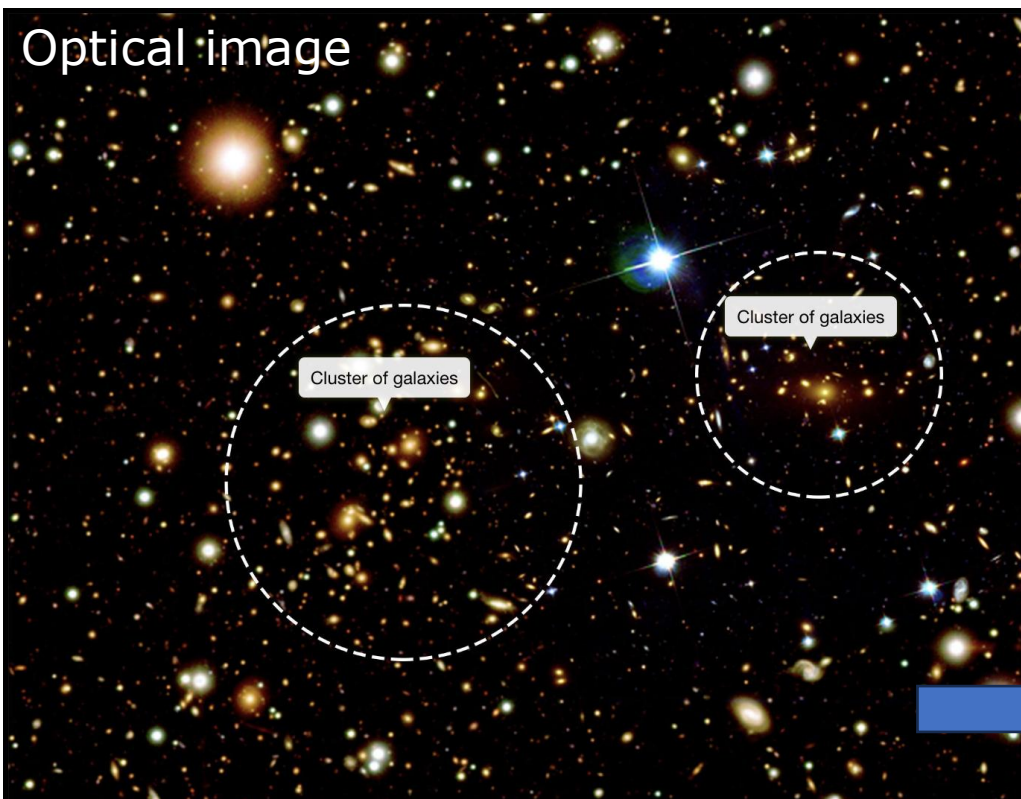
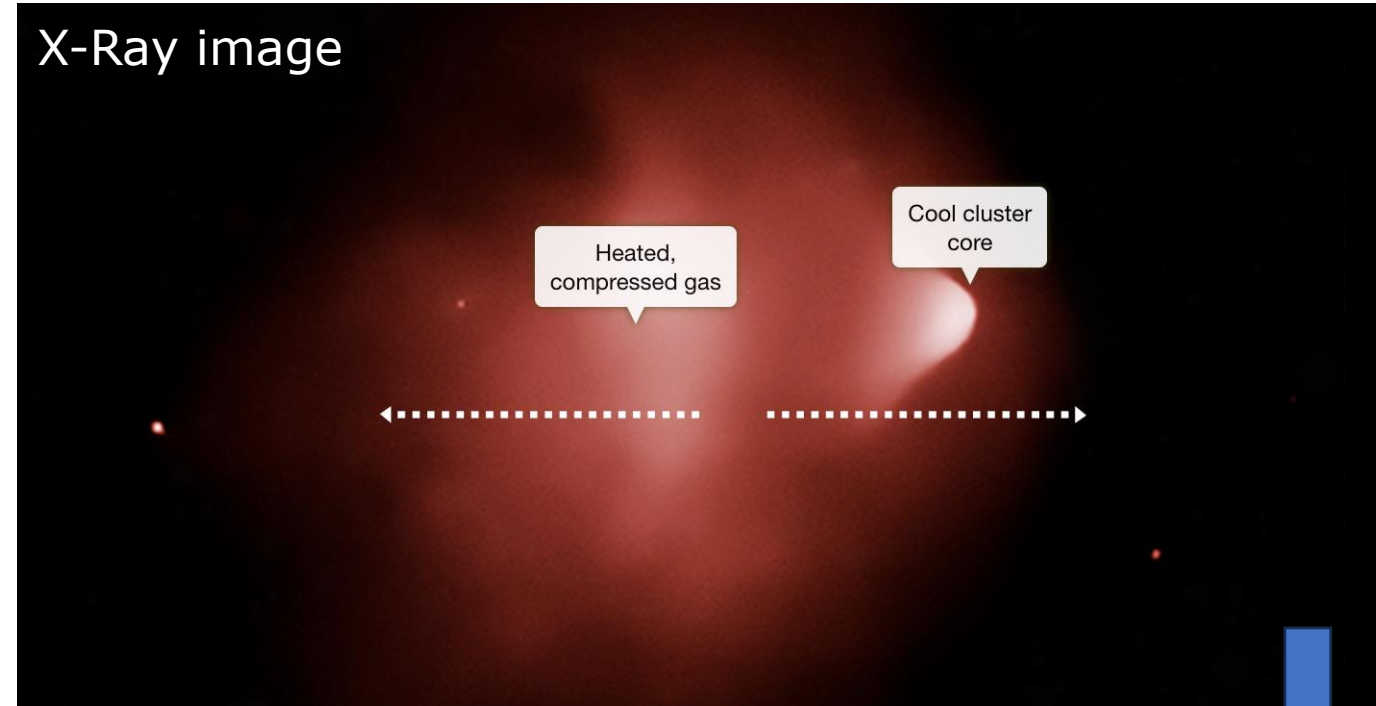
The Mystery of Dark Matter

The Bullet Cluster

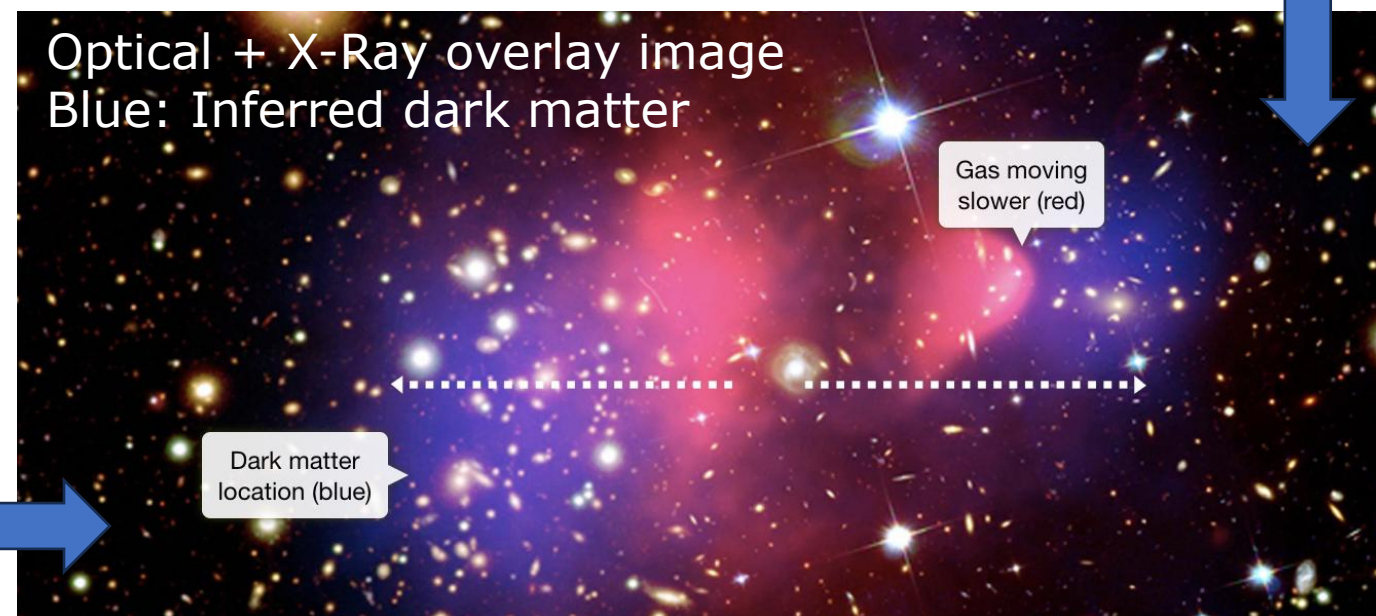


- A high velocity galaxy merger
- Two ways to infer mass
 - X-Ray (pink/red)
 - **Gravitational lensing**
 - **Inferred mass** (blue)
- Blue: collisionless galaxies

X-Ray image



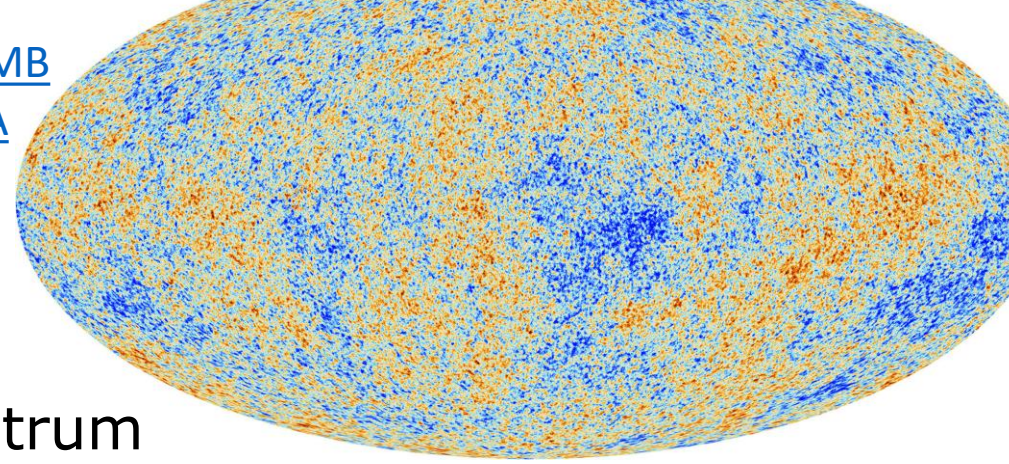
Optical + X-Ray overlay image
Blue: Inferred dark matter



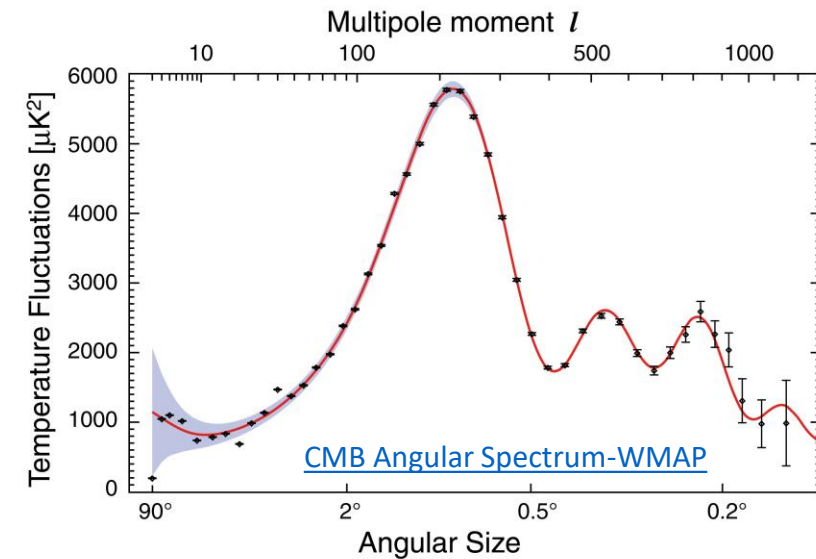
Dark Matter

What do we know?

[ESA—Planck and the CMB](#)
[CMB Analyzer—NASA](#)
[CMBverse Simulator](#)



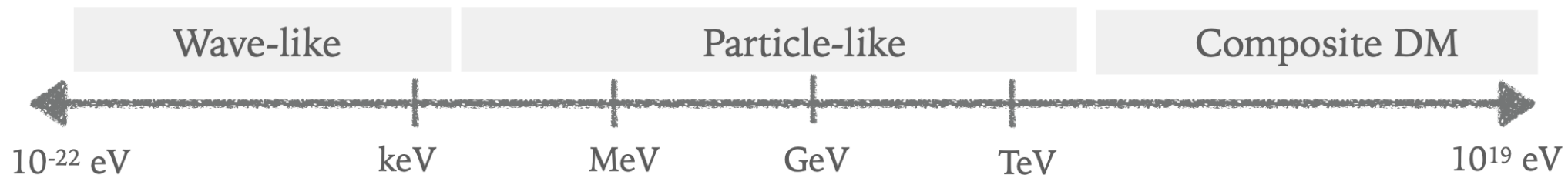
- Interacts **gravitationally**: e.g. it bends light
- **Dark**: does not radiate energy in the EM spectrum
- **Old and Stable**—does not decay!
 - Imprinted in the Cosmic Microwave Background and its lifetime: ~ 13 billion years
- **Cold**: moving slowly (nonrelativistic)
- **Abundant**: $\sim 5X$ times more abundant than matter
- **DM-to-OD ratio a key input to the Λ CDM model**
 - **Absolutely required for the fit to data!**
- What we **do not know**: *its mass*



10^{-22} PROTON MASSES

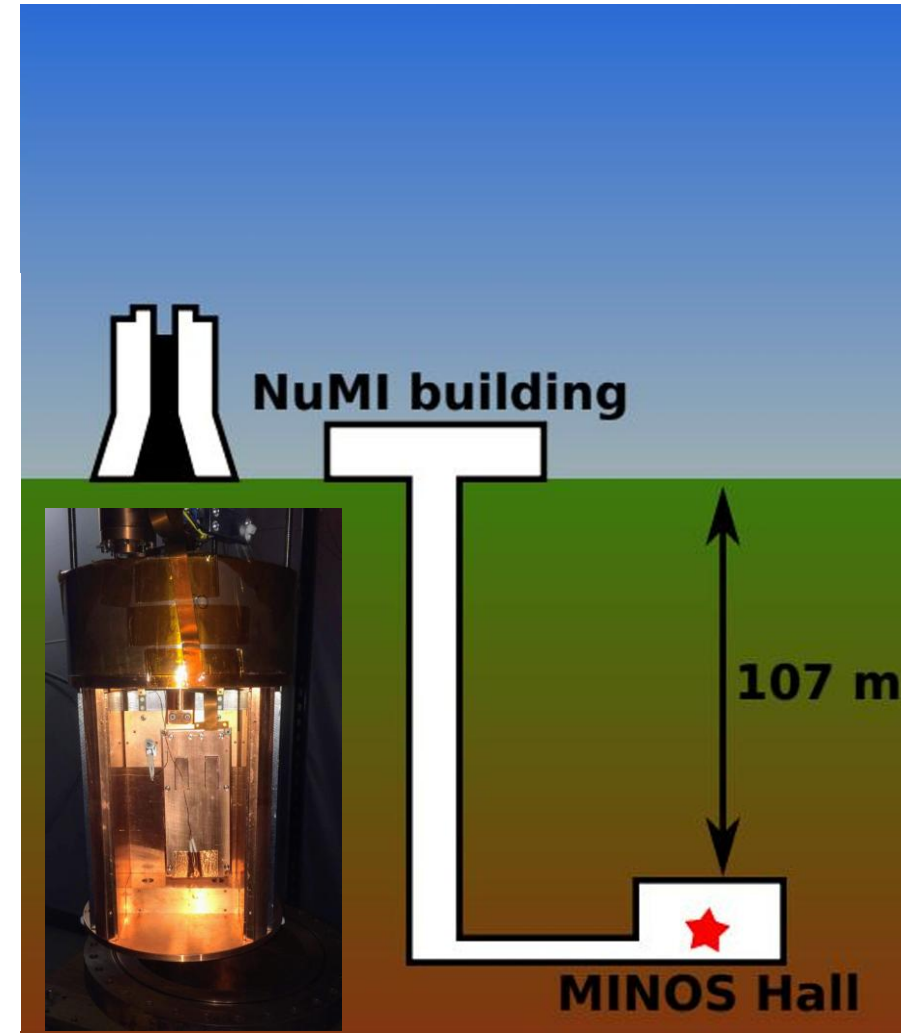
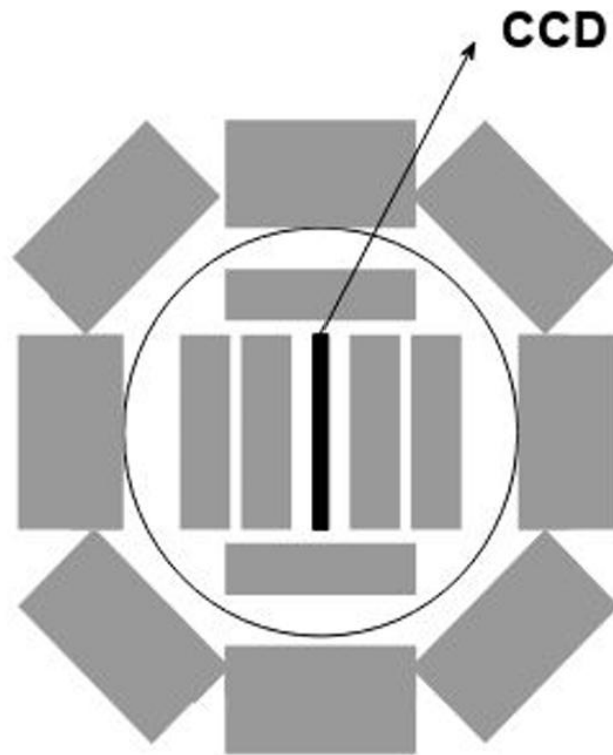
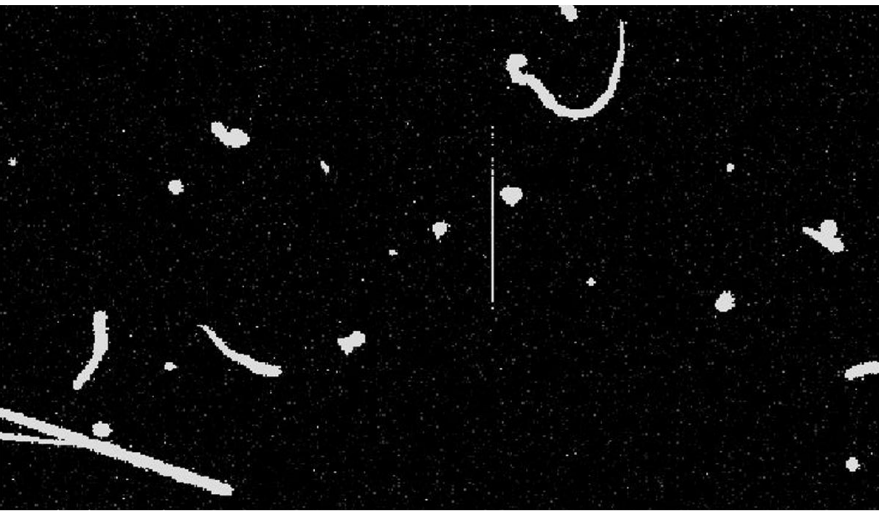
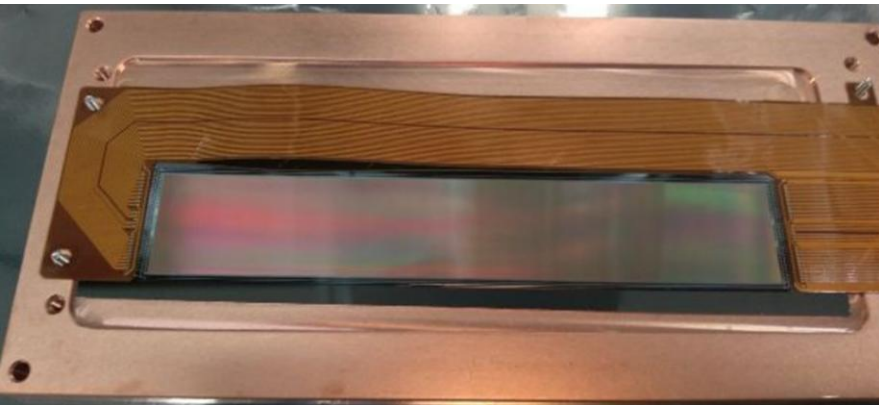
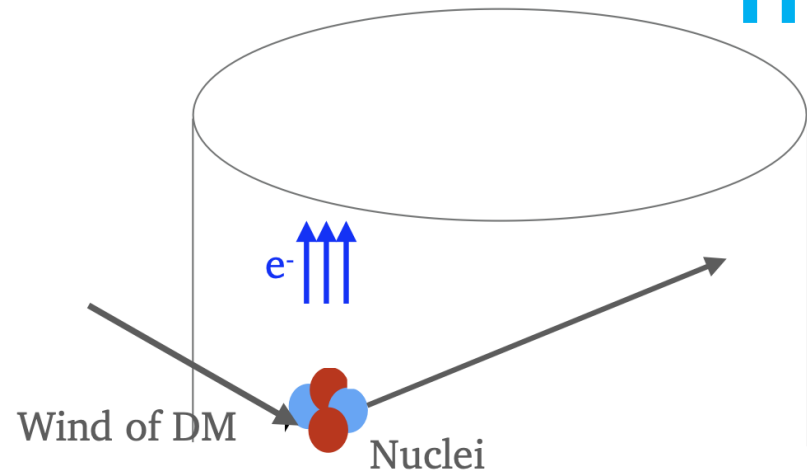
1 PROTON MASS

1 SOLAR MASS



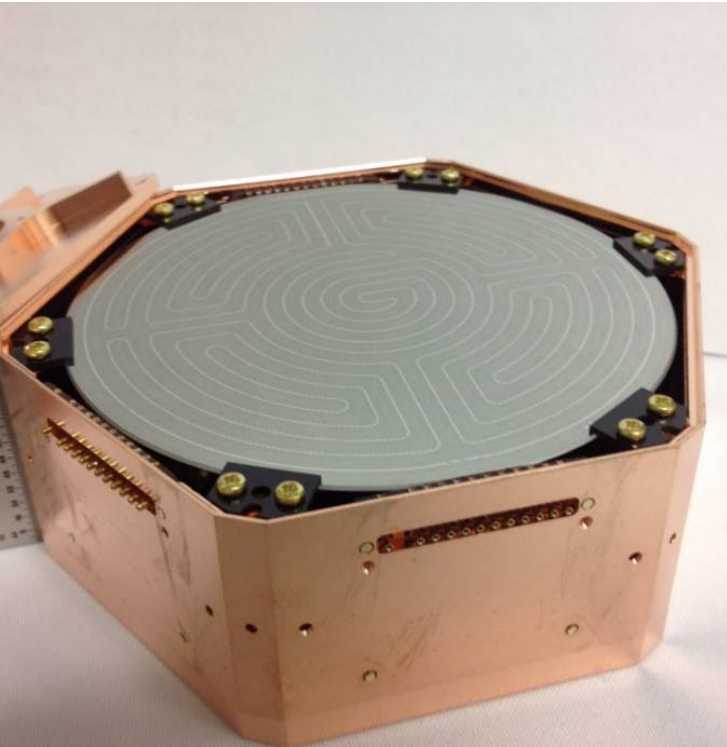
The Hunt for Dark Matter at Fermilab

The SENSEI Experiment



Detector Development at Fermilab

Aided by Condensed Matter & Quantum Physics



Germanium detector

- Can detect higher energy interactions



Semiconductor detectors

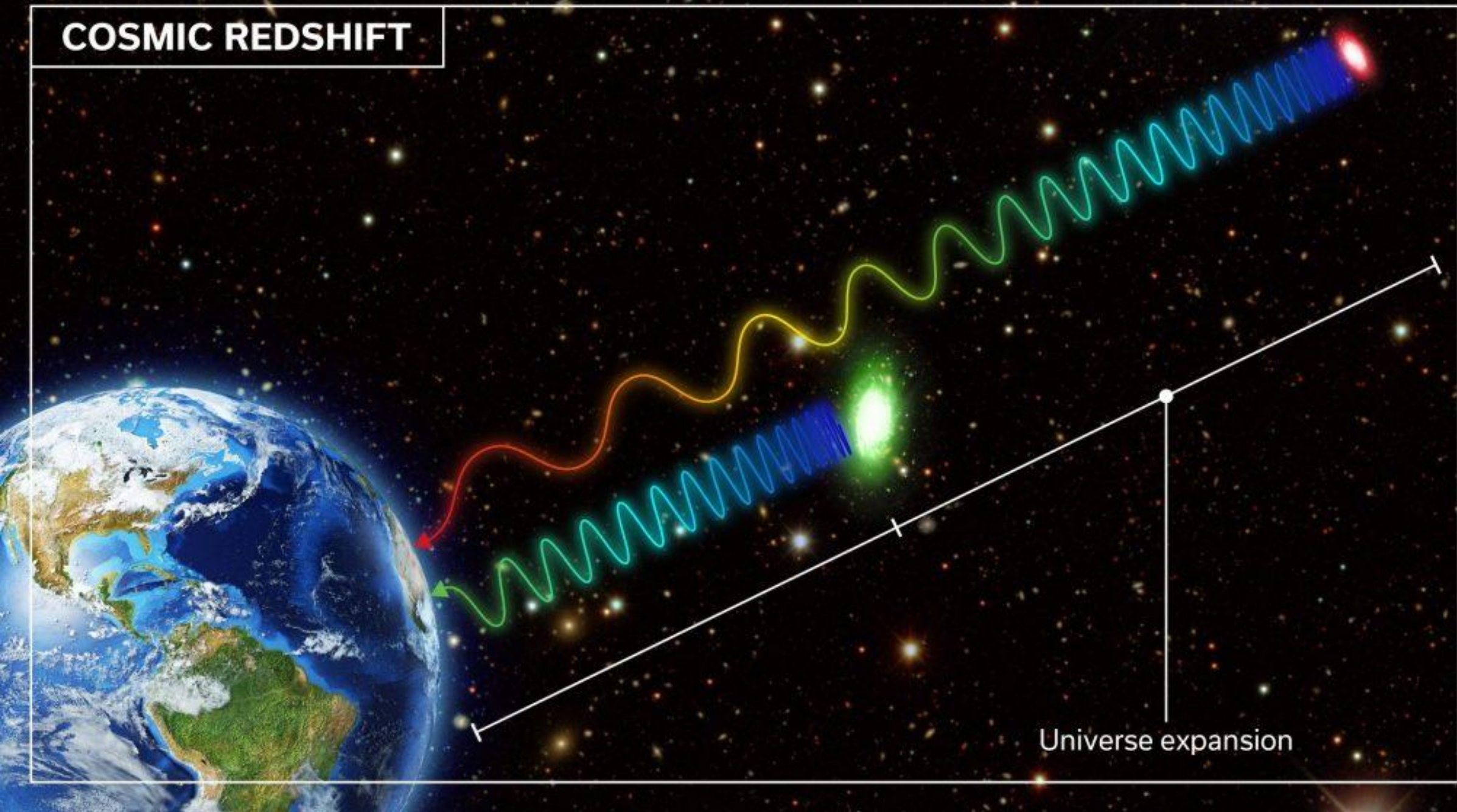
- Can detect electron-level interactions



Test stand for quantum detectors

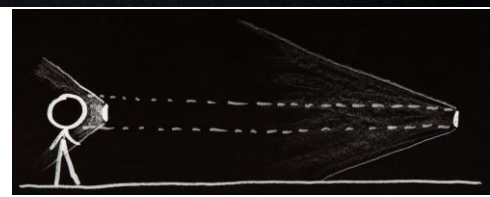
- Can go below electron energy threshold

COSMIC REDSHIFT



Accelerated Expansion of the Universe

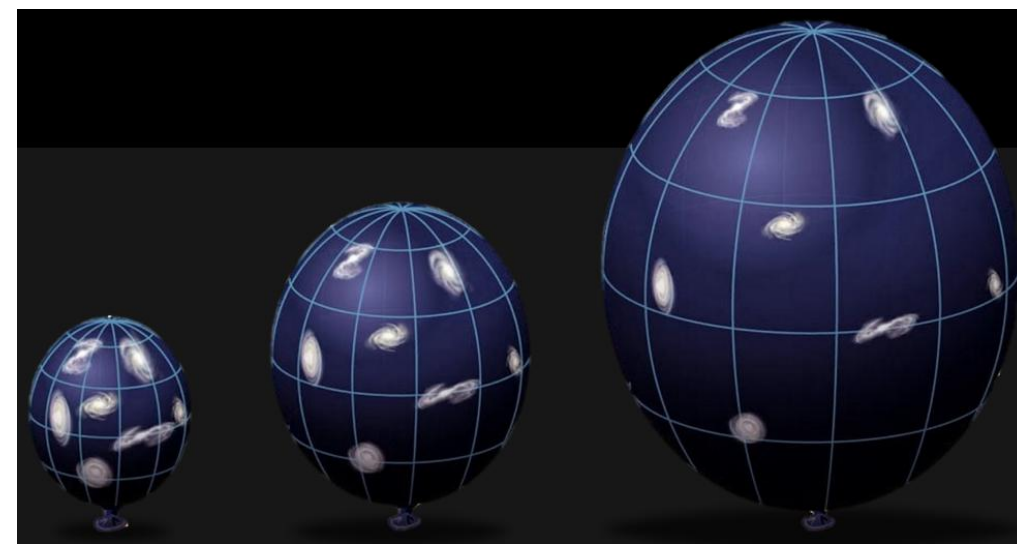
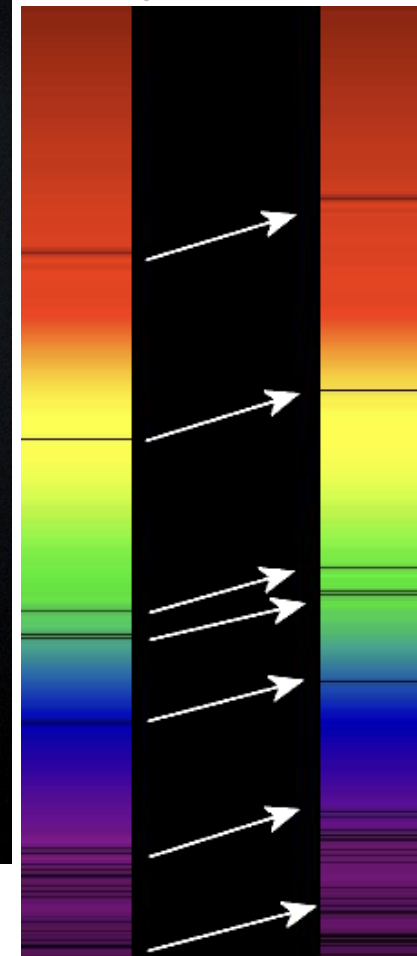
Distances between cosmic points are increasing,
just like a balloon



How bright we see

How bright it is

Example stellar
spectrum



If stars move away from us...

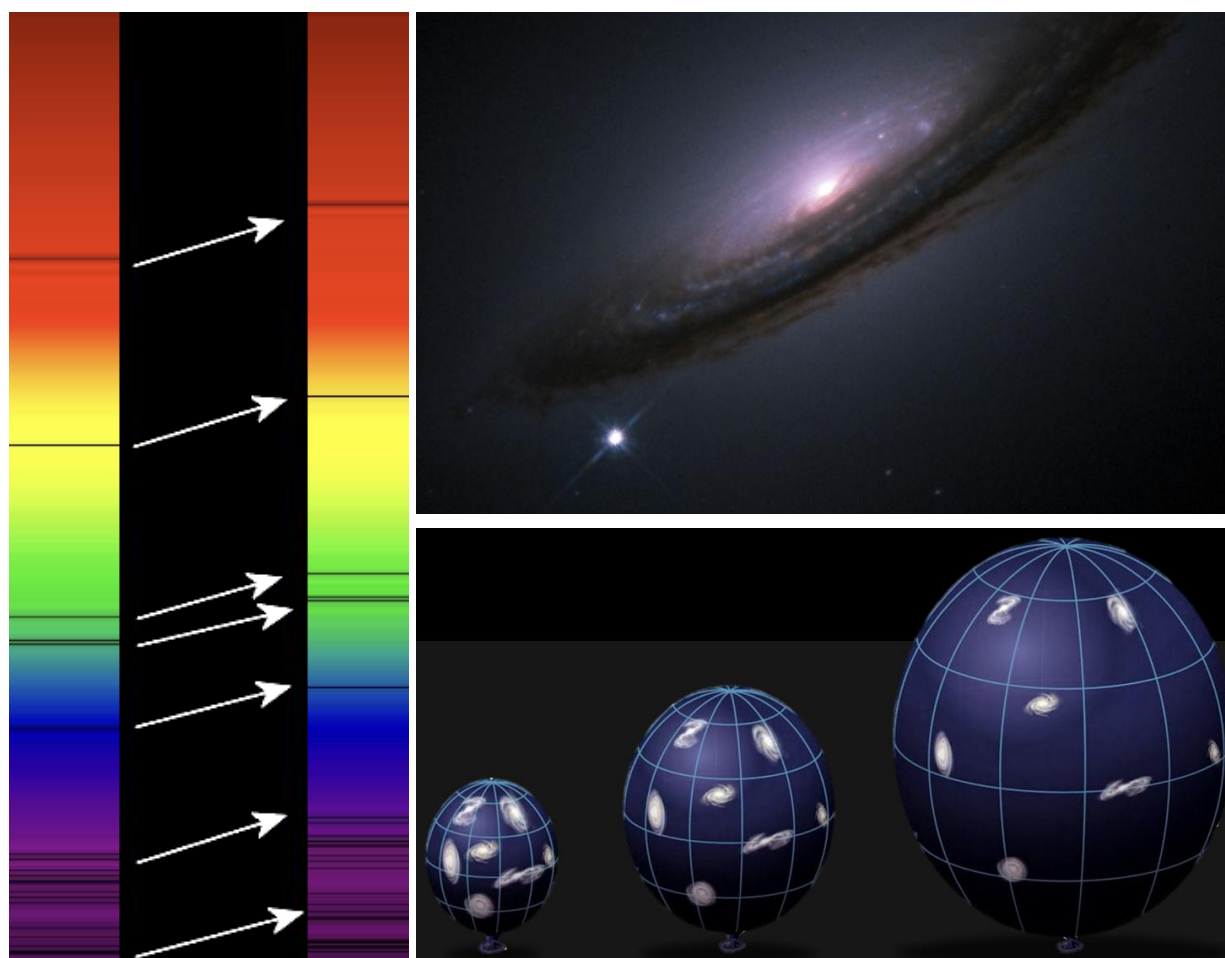
- Light would become *redder*
- **"Redshift"**—Doppler-like effect
 - Faster velocity—*more red*

How far away is it?

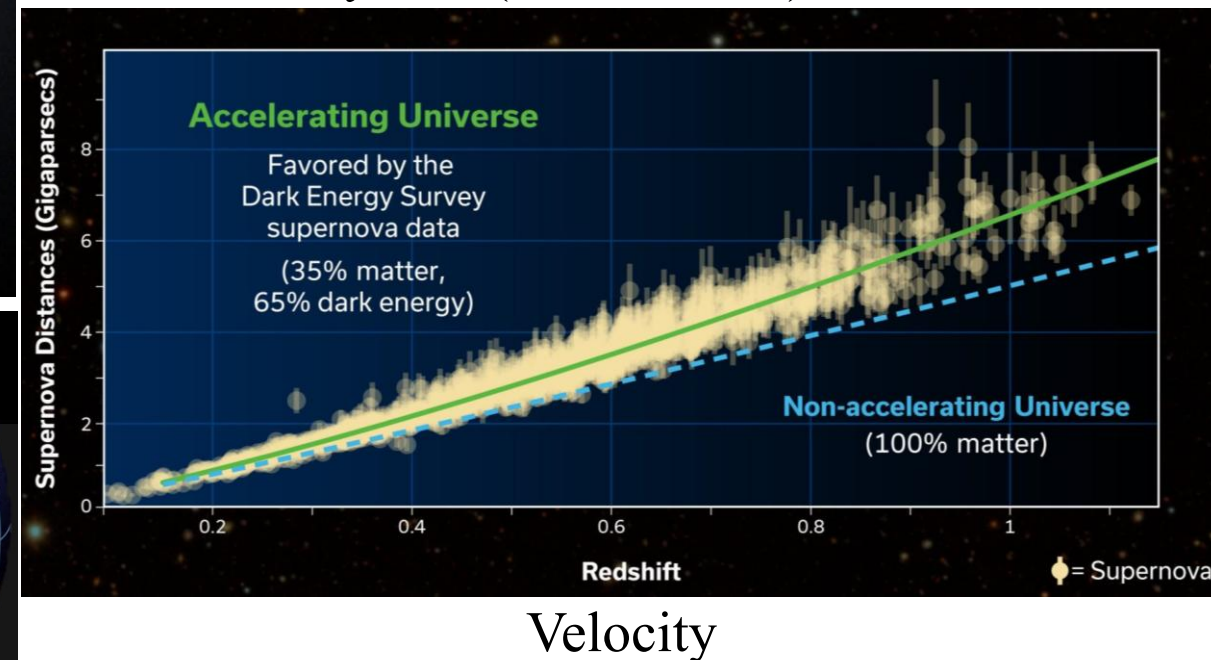
- How far back are we seeing?

Accelerated Expansion of the Universe

- Known relationship redshift vs distance
 - Higher redshift, greater distance
- Universe appears consistent with accelerated expansion
 - Farthest objects are moving away faster than nearest objects
- **Open question:** Why is this the case? $\Rightarrow$ "Dark Energy"

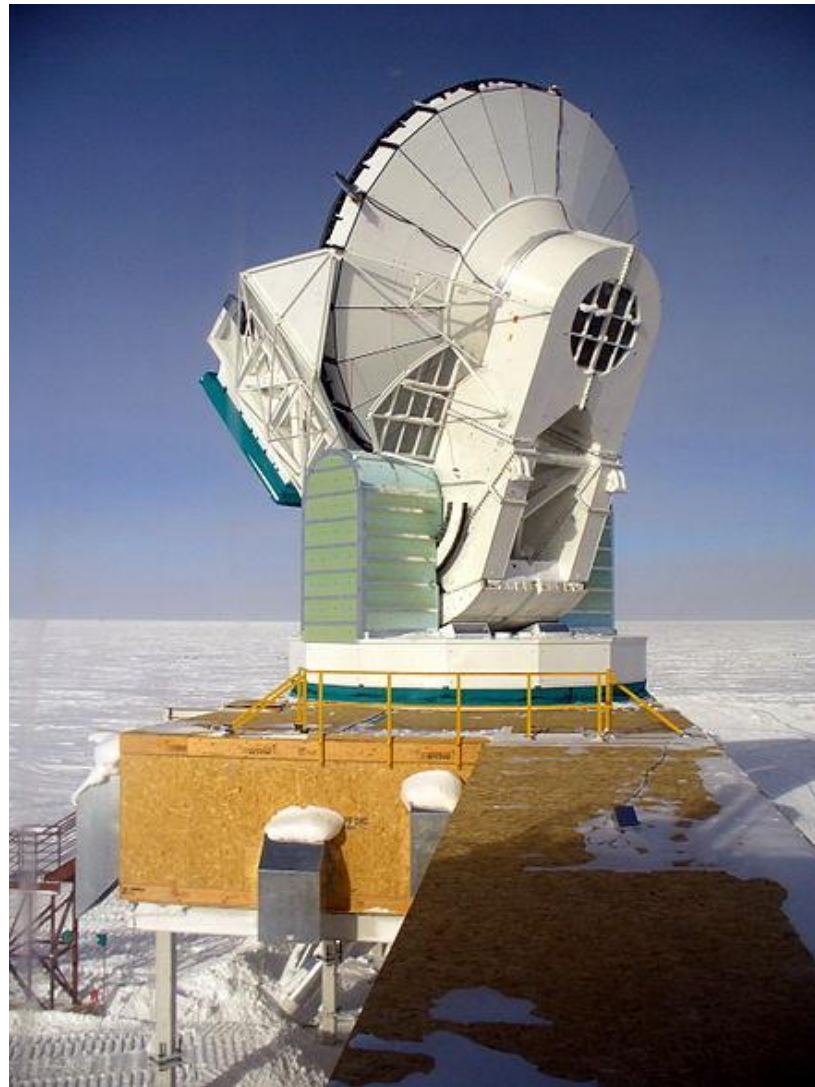


$$\text{Velocity} = H (\text{not constant}) \times \text{Distance}$$

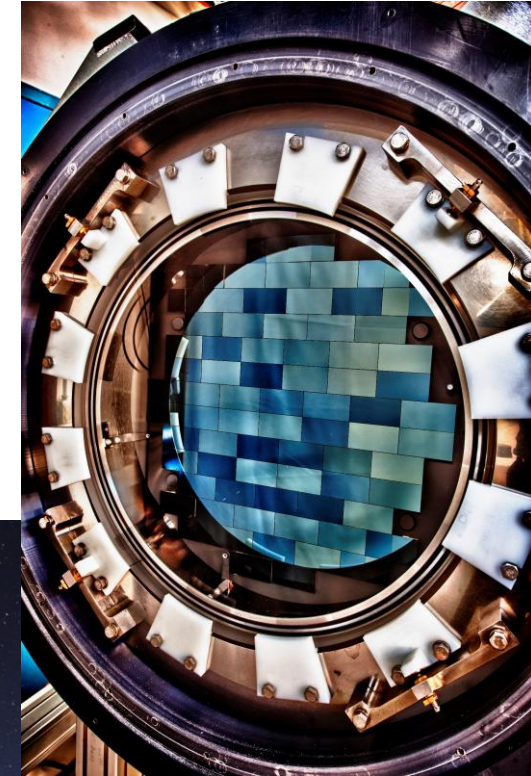


Advancing Cosmology at Fermilab

High resolution view of the CMB!



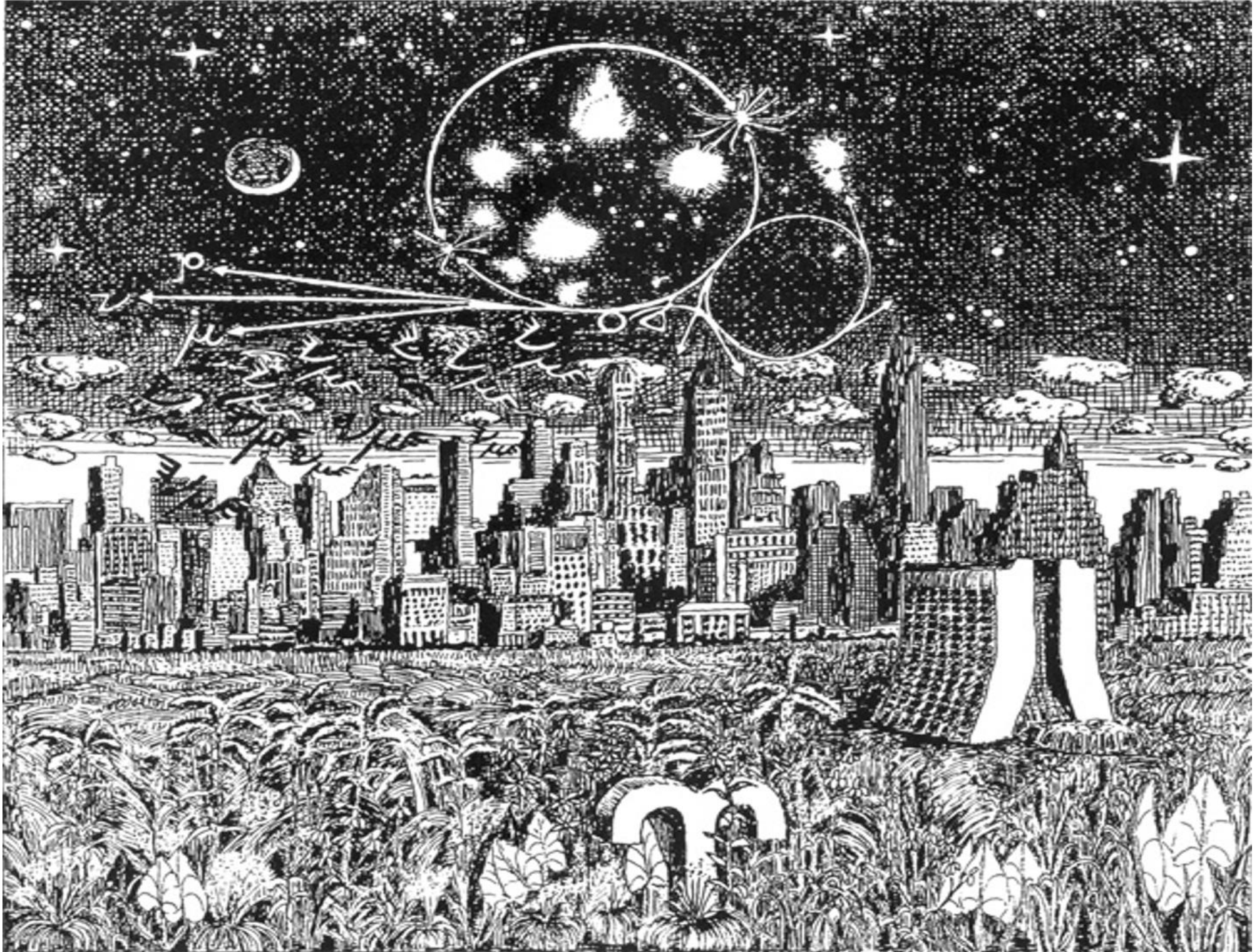
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The Dark Energy Survey gives clues about the nature of dark energy

Fermilab's Incredible Community





Q&A

Let's discuss more!

Also feel free to say hi afterward!