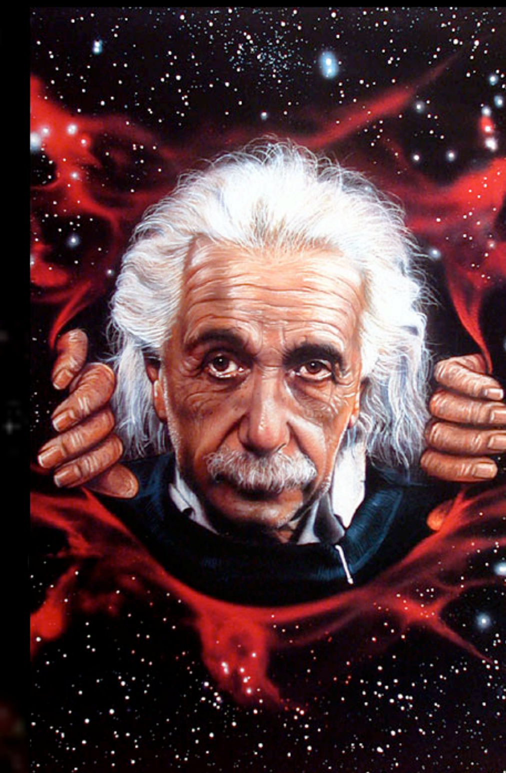
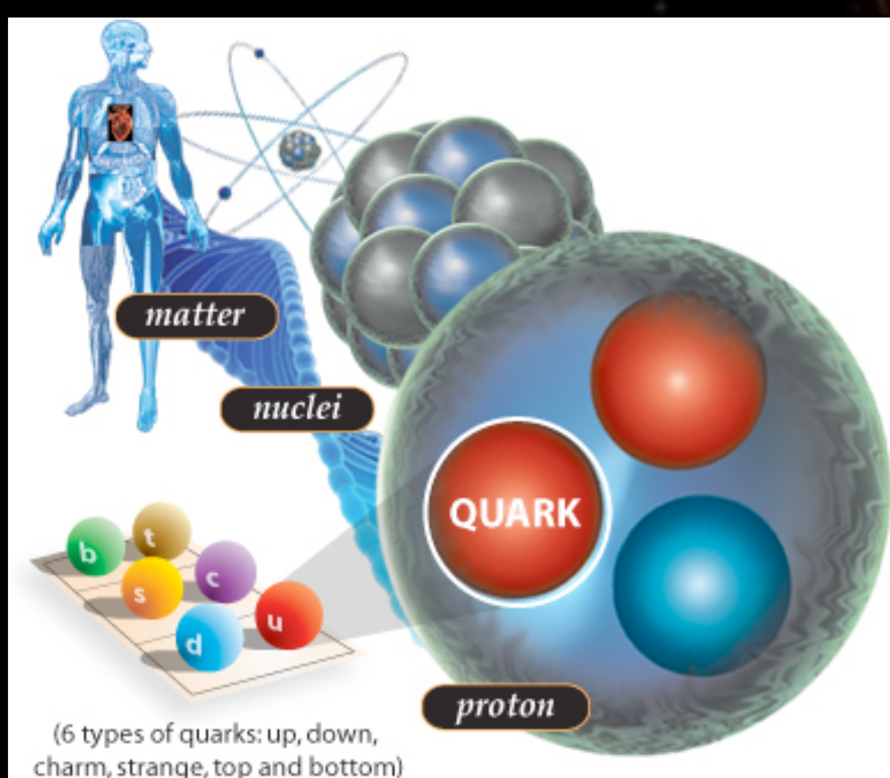
Some of the Big Puzzles in Particle Physics and Cosmology

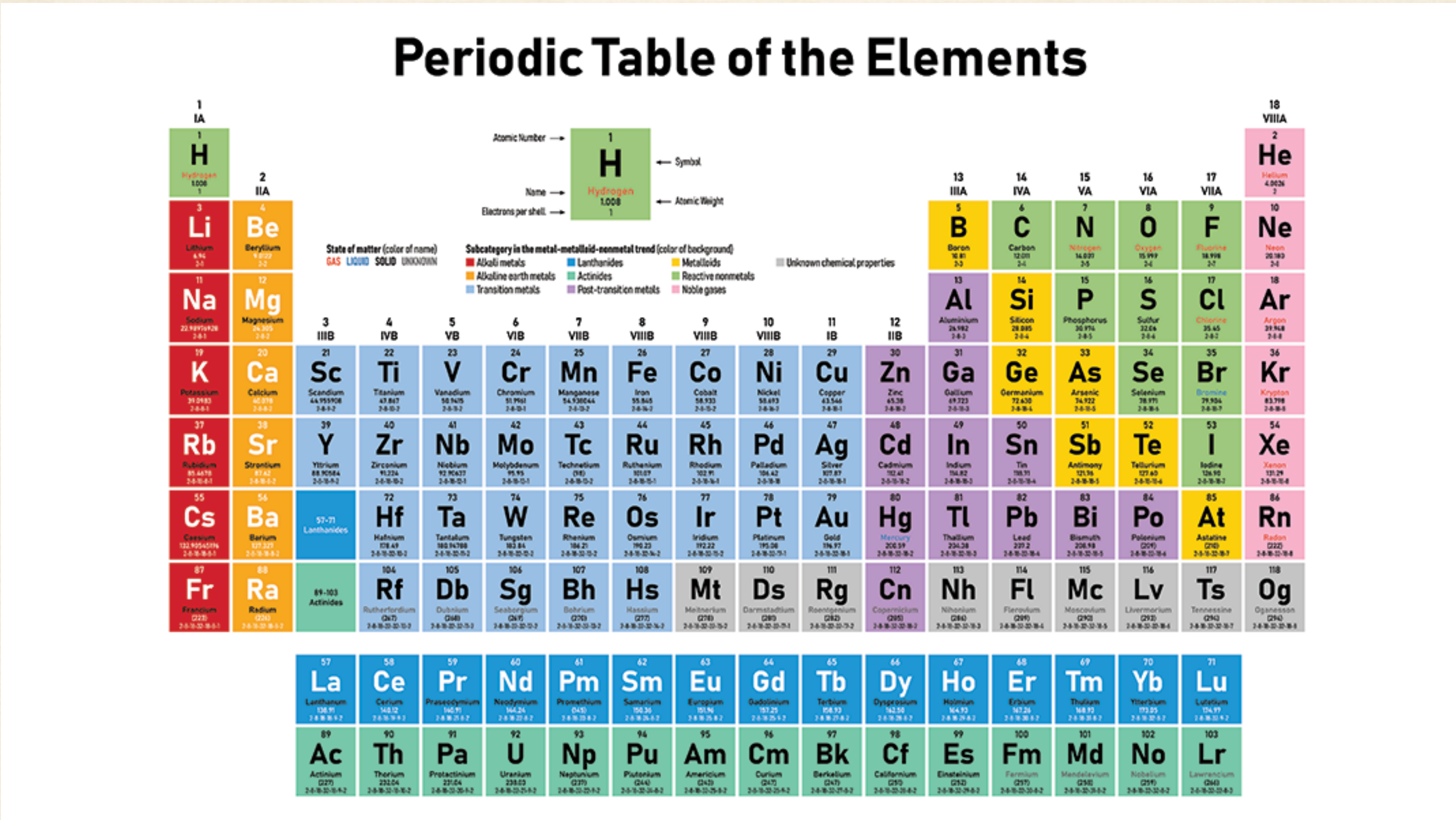




Josh Erlich

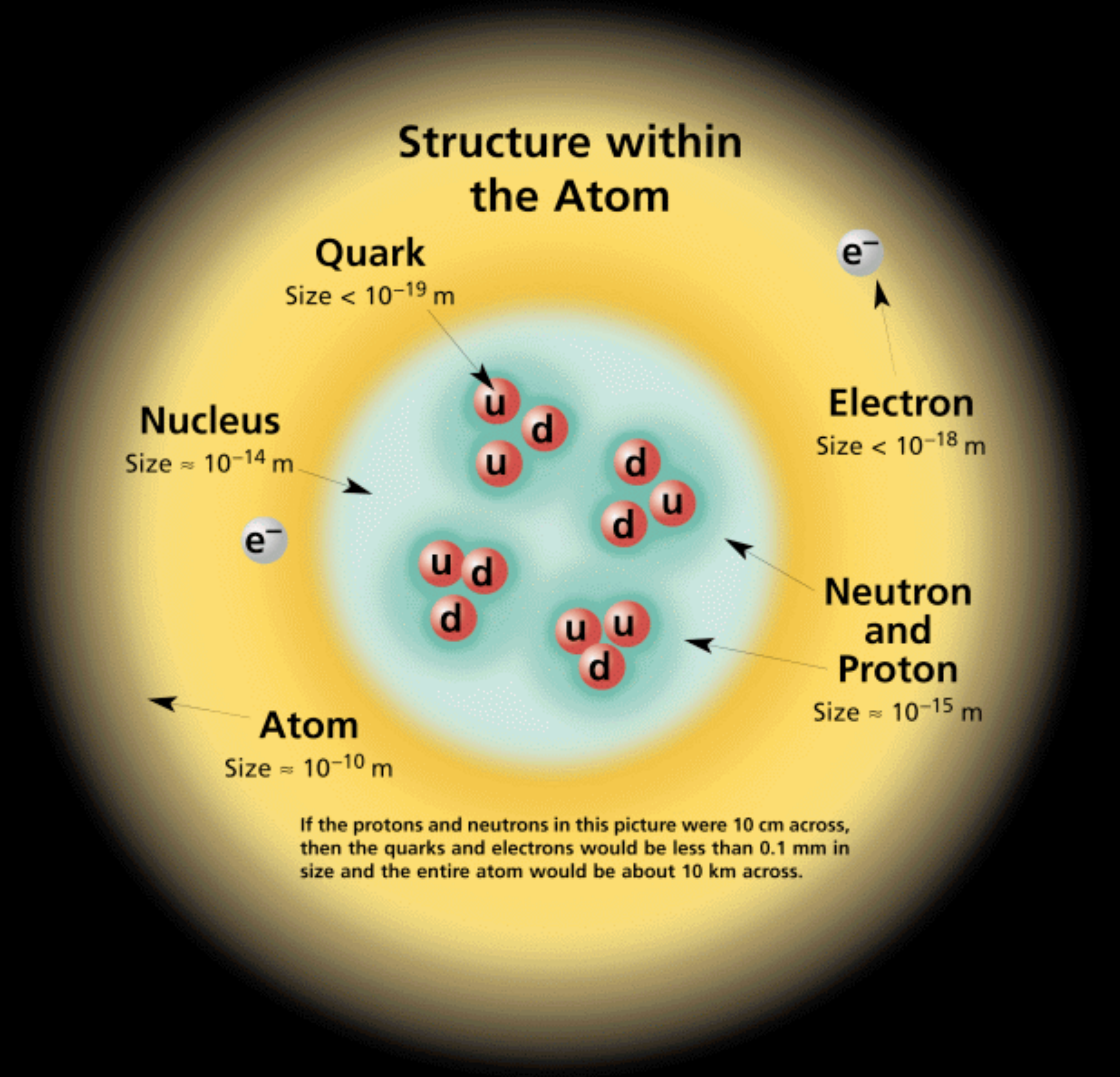
PHYS 212/309

April 12, 2022

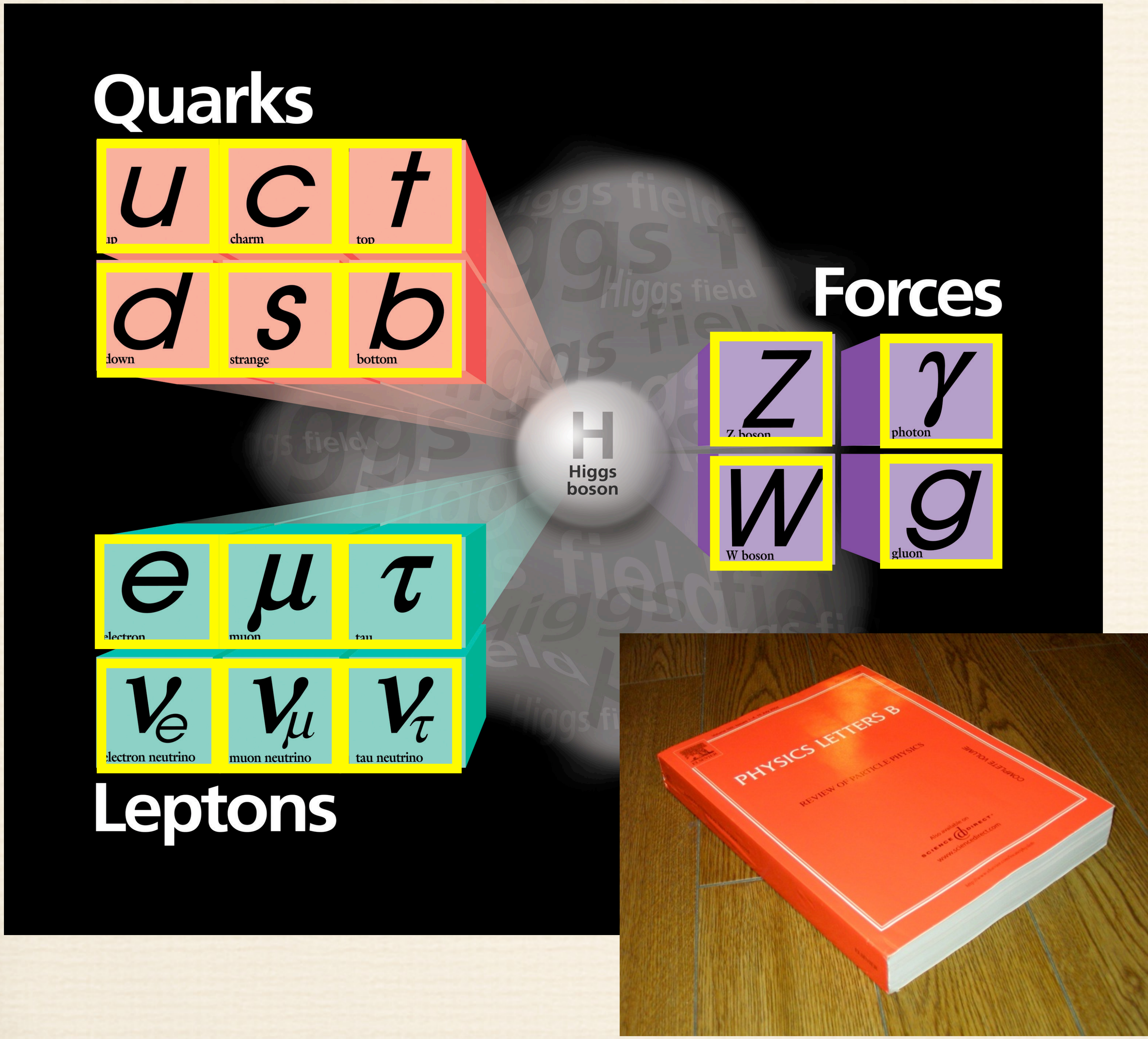


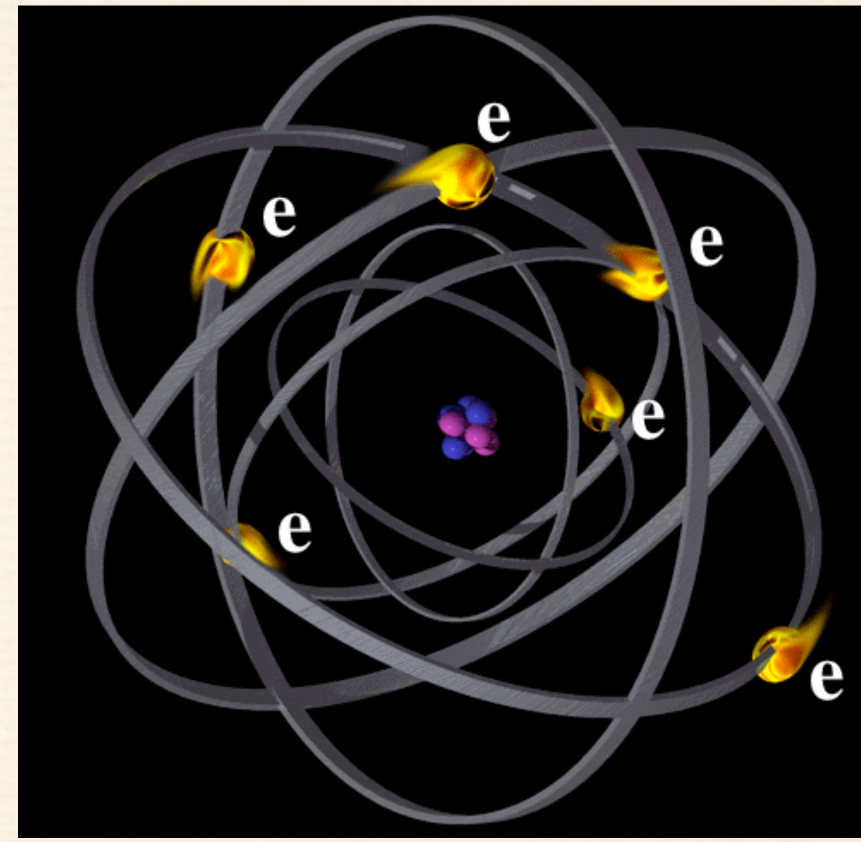
Periodic Table of the Elements
Atomic Number
Symbol
Name
Atomic Weight
Electrons per shell
State of matter (color of name)
GAS LIQUID SOLID UNKNOWN
Subcategory in the metal-metalloid-nonmetal trend (color of background)
Alkali metals
Alkaline earth metals
Transition metals
Lanthanides
Actinides
Post-transition metals
Metalloids
Reactive nonmetals
Noble gases
Unknown chemical properties
57-71 Lanthanides
89-103 Actinides
H He
Li Be B C N O F Ne
Na Mg Al Si P S Cl Ar
K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe
Cs Ba Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
Fr Ra Rf Db Sg Bh Hs Mt Ds Rg Cn Nh Fl Mc Lv Ts Og
La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
Ac Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr

Inside the atom



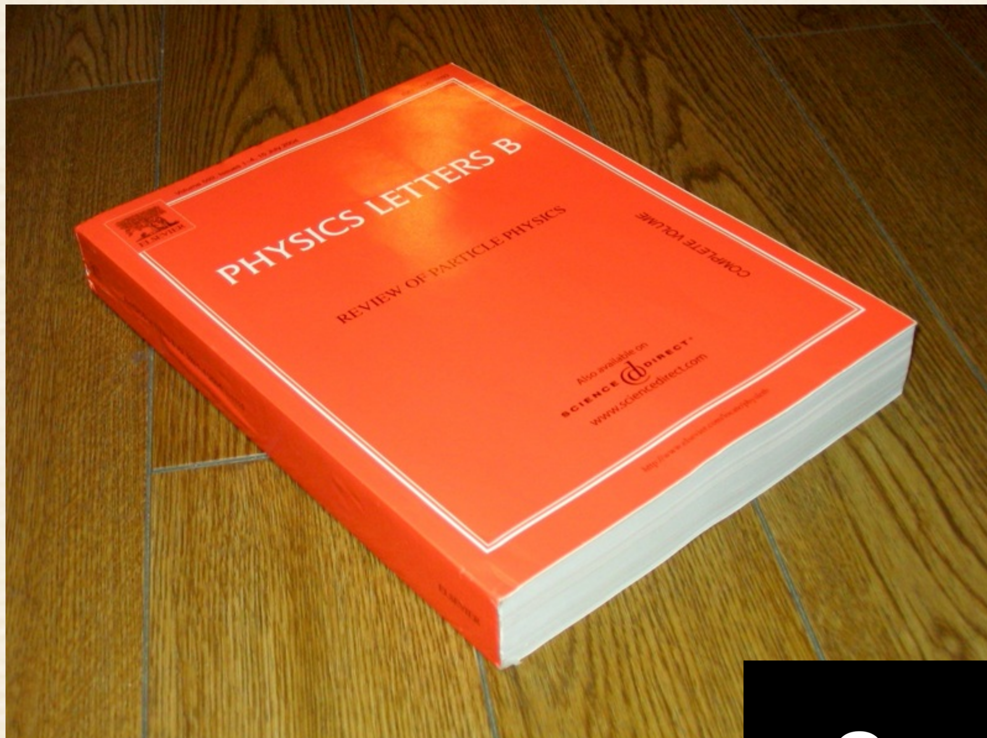
The Standard Model



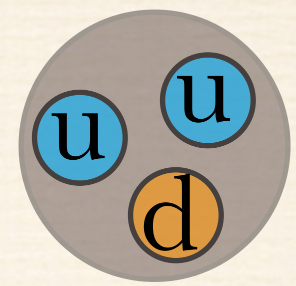


5% of the energy in the universe

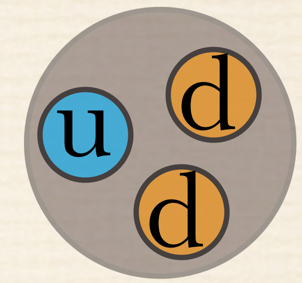
The Particle Zoo



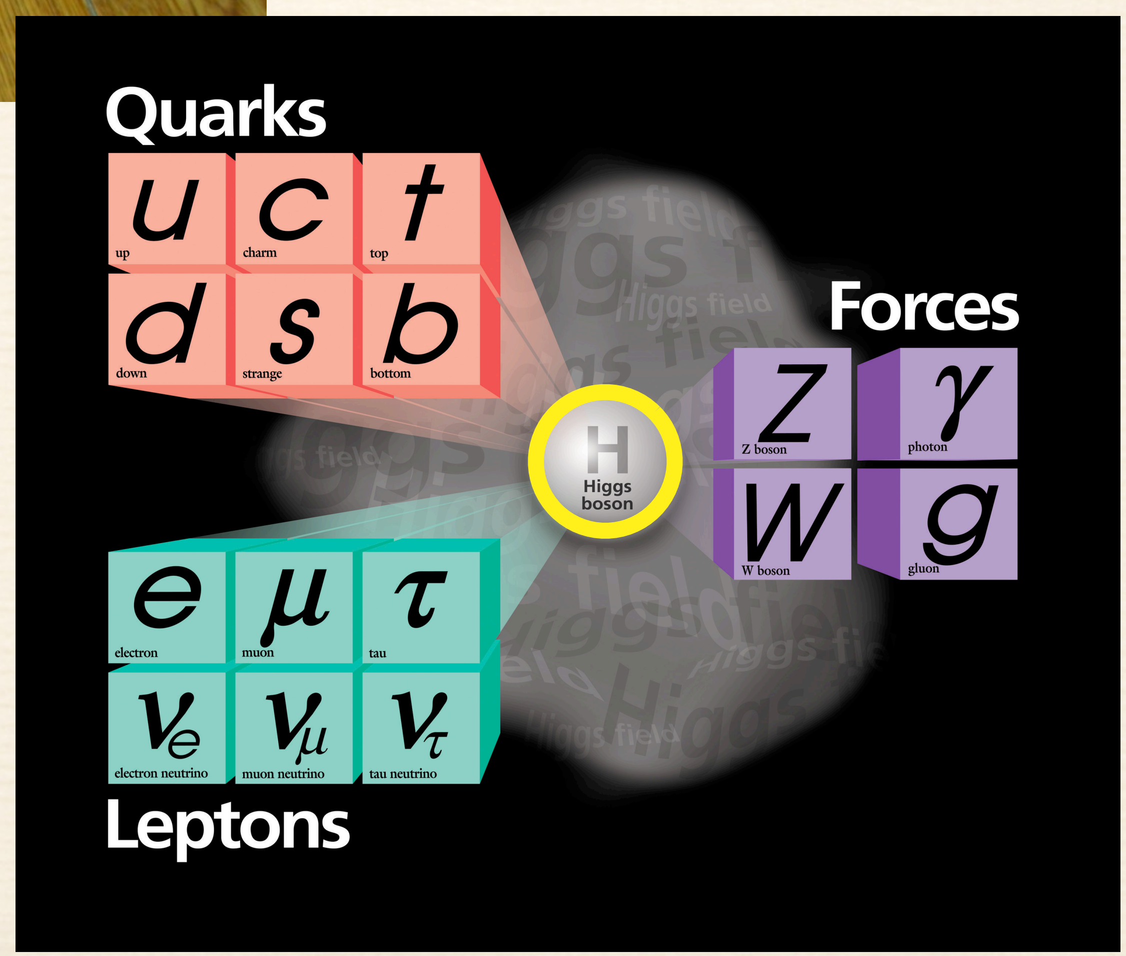
Proton



Neutron

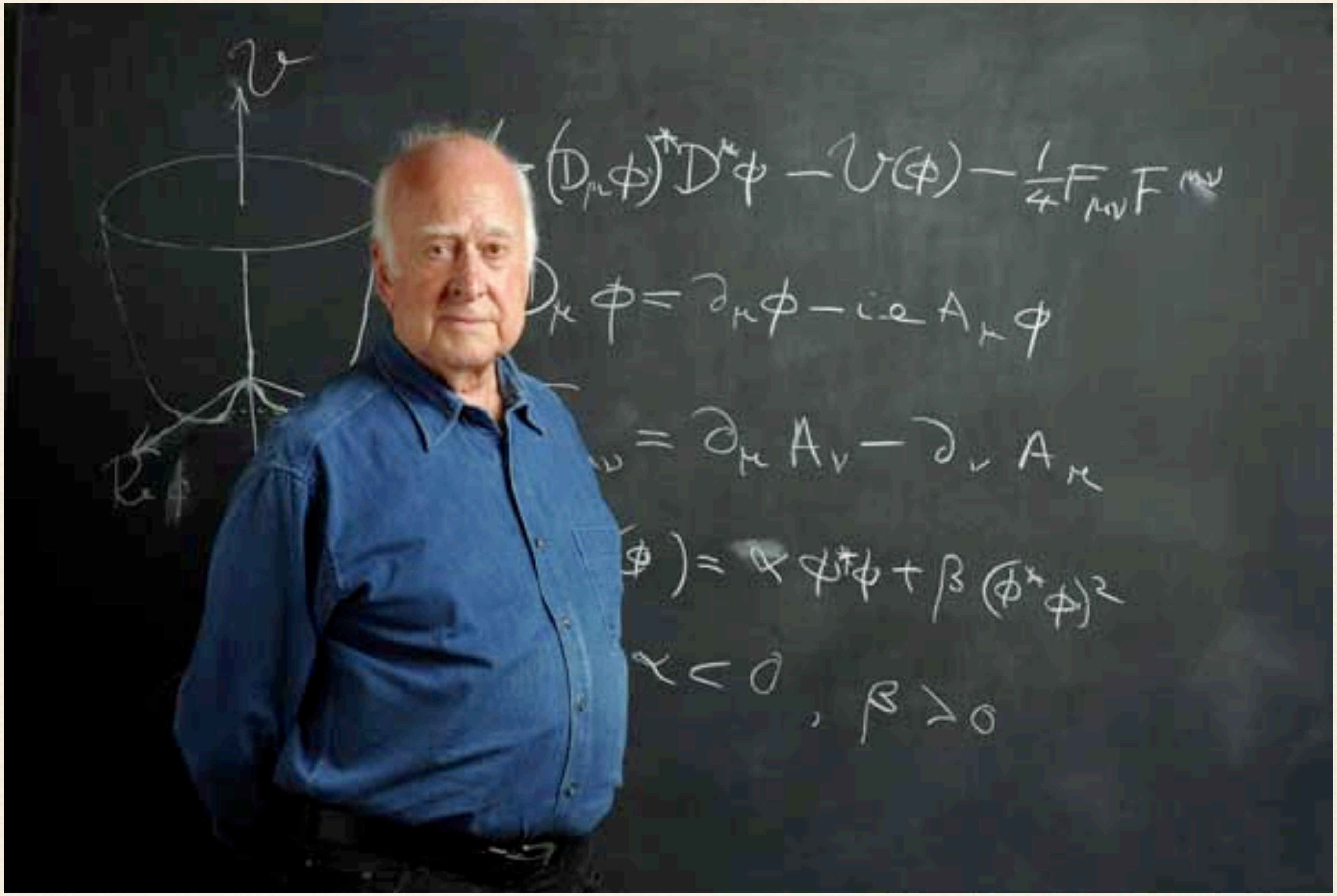


The Standard Model



Higgs to the rescue!

(and Brout, Englert, Guralnik, ...)



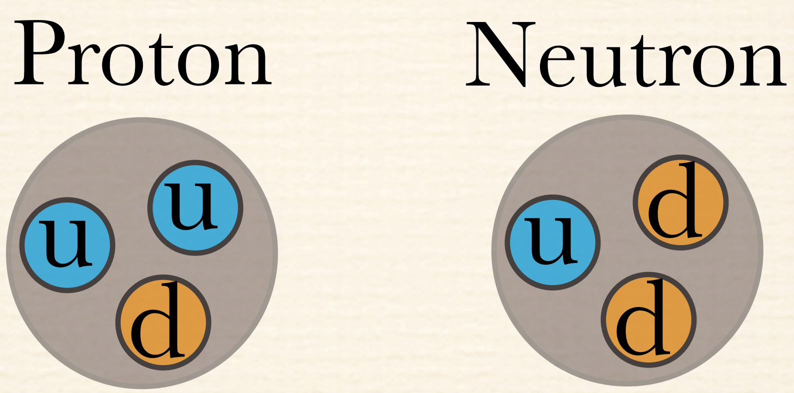
The Higgs Field and Mass

The Higgs field exists everywhere in space and is completely uniform.

When Kim Kardashian enters a filled room her inertia is substantially increased.
The room interacts much less with Josh Erlich, so his inertia is not increased as much.

We're talking about fundamental particles.

The Higgs field gives mass to the fundamental particles, but protons and neutrons are not fundamental, and are 2000 times more massive than electrons.



Their mass comes mostly from the motion of the particles inside them, and their interactions. Remember $E = mc^2$.

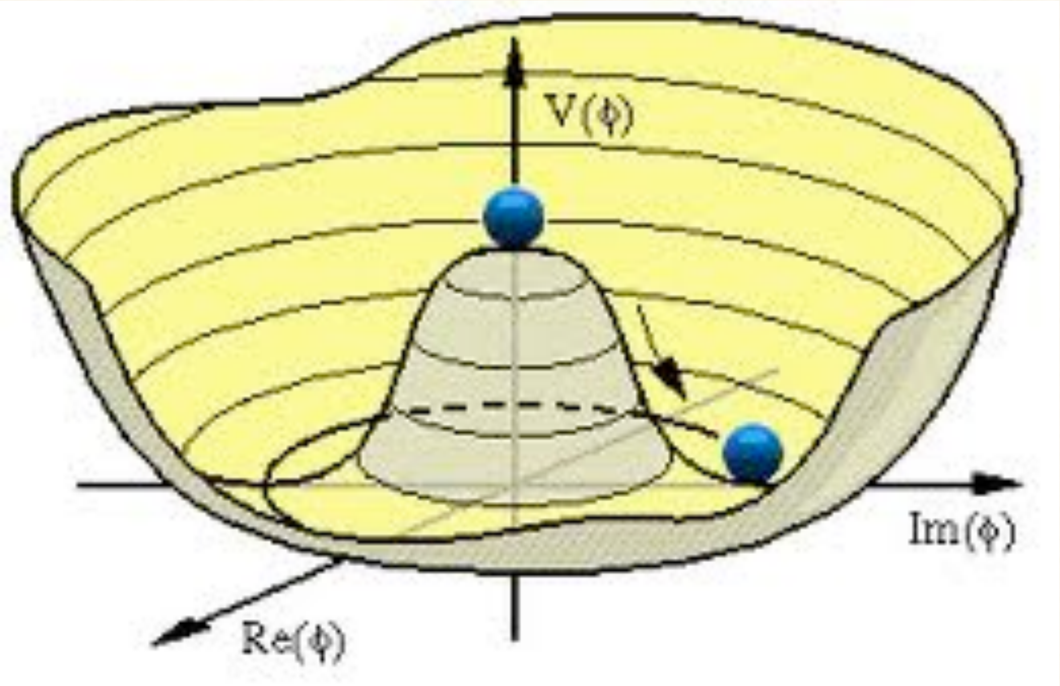
So most of this guy's mass is not due to the Higgs field.

The Higgs Boson

Just as photons are particles of the electromagnetic field, Higgs bosons are particles of the Higgs field.

An analogy would be a rumor of Kim Kardashian's pending appearance, moving from one side of the room to the other.

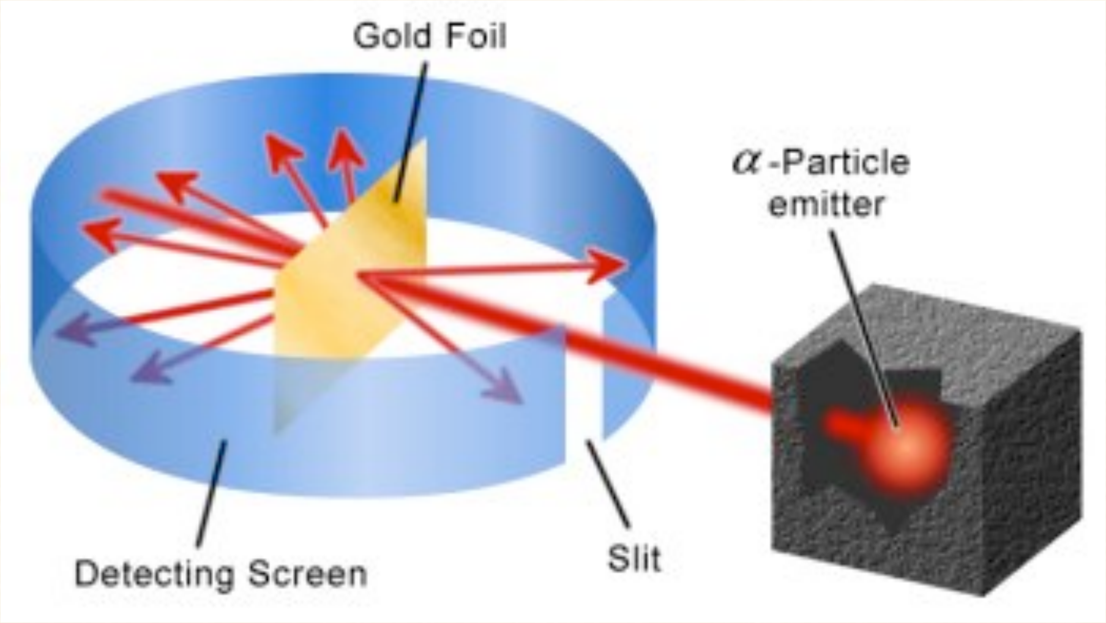
Why is there a Higgs field everywhere?

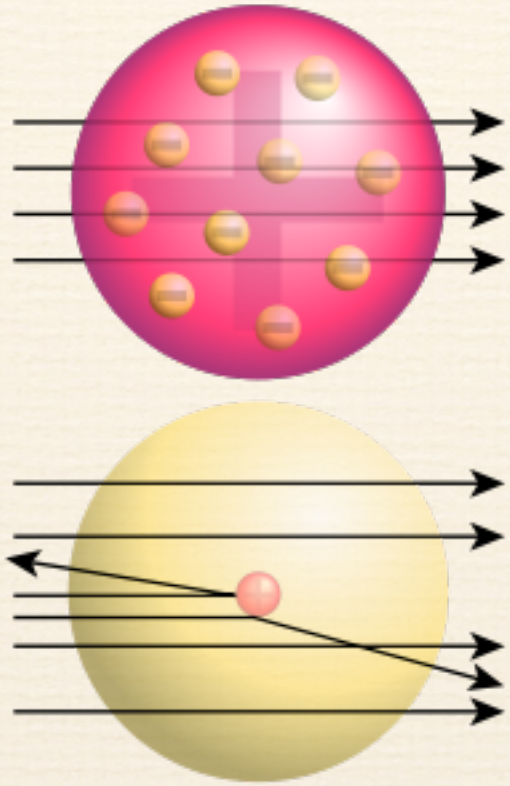


The Higgs field rests in a valley that minimizes the energy in the field. The valley only allows a nonvanishing Higgs field.

How to hunt for particles and interactions

Ernest Rutherford's Atom (1911)

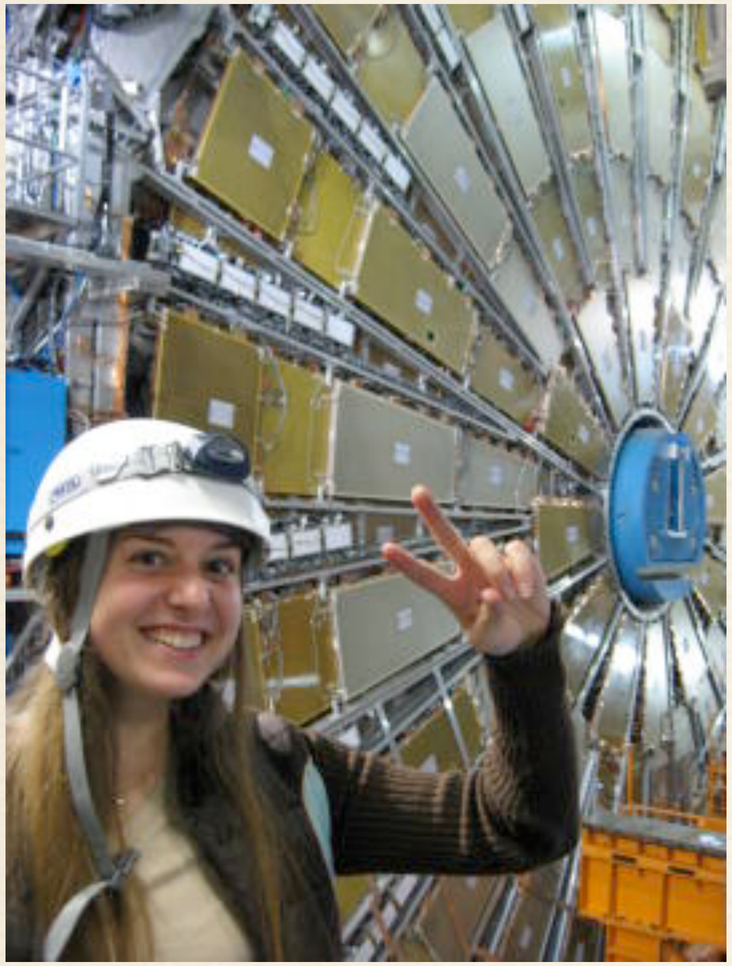


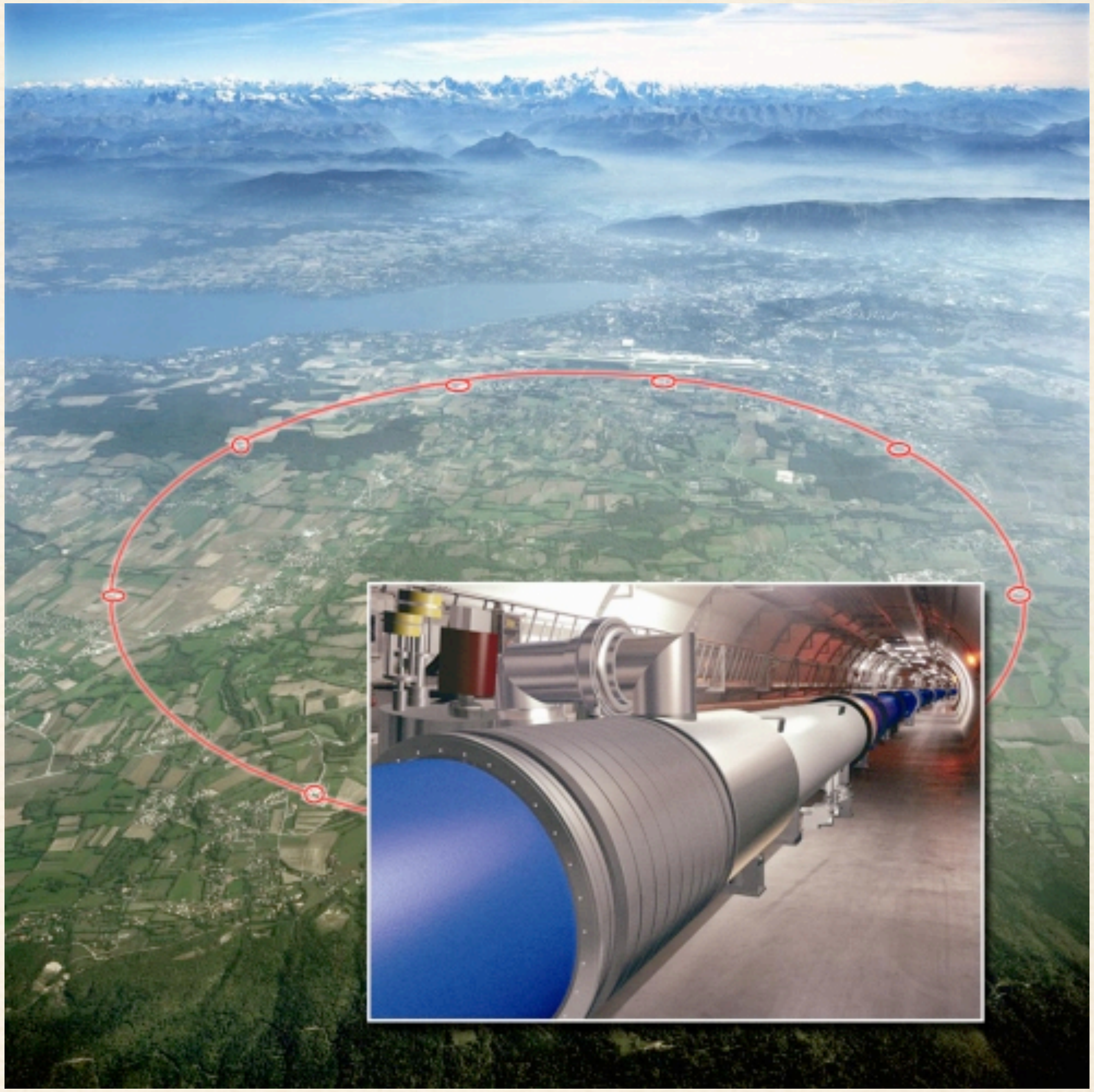


Modern Day Colliders

Jefferson Lab

Modern Day Colliders





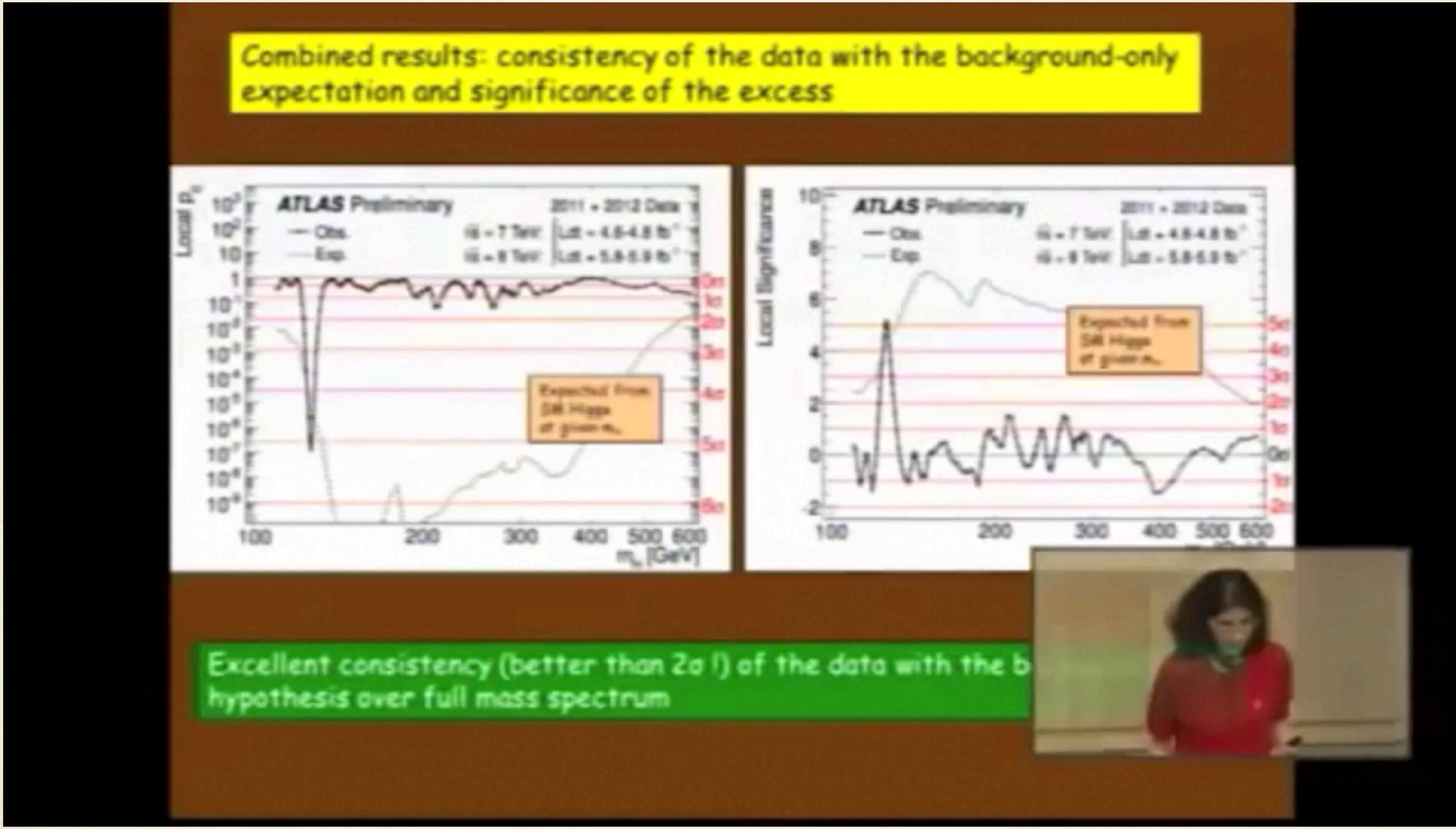
CERN

The Big Announcement

July 4, 2012.

A particle like the Higgs boson has been discovered!

The Big Announcement



CERN, July 4, 2012.

The first time that the entire NYT Science section is devoted to a single story

Chasing the Higgs Boson | INTRODUCTION PROMISED FIREBALLS GAME OF BUMPS STILL MISSING OOZING INTO VIEW OPENING THE BOX

Chasing the Higgs Boson

At the Large Hadron Collider near Geneva, two armies of scientists struggled to close in on physics' most elusive particle.

DENNIS OVERBYE
Published March 5, 2013 | 252 Comments

MEYRIN, Switzerland — Vivek Sharma missed his daughter.

A professor at the University of California, San Diego, Dr. Sharma had to spend months at a time away from home, coordinating a team of physicists at the Large Hadron Collider, here just outside Geneva. But on April 15, 2011, Meera Sharma's 7th birthday, he flew to

Illustration by Sean McCabe/Photographs by Daniel Auf der Mauer, Toni Albir, Fabrice Coffrini, Fred Merz

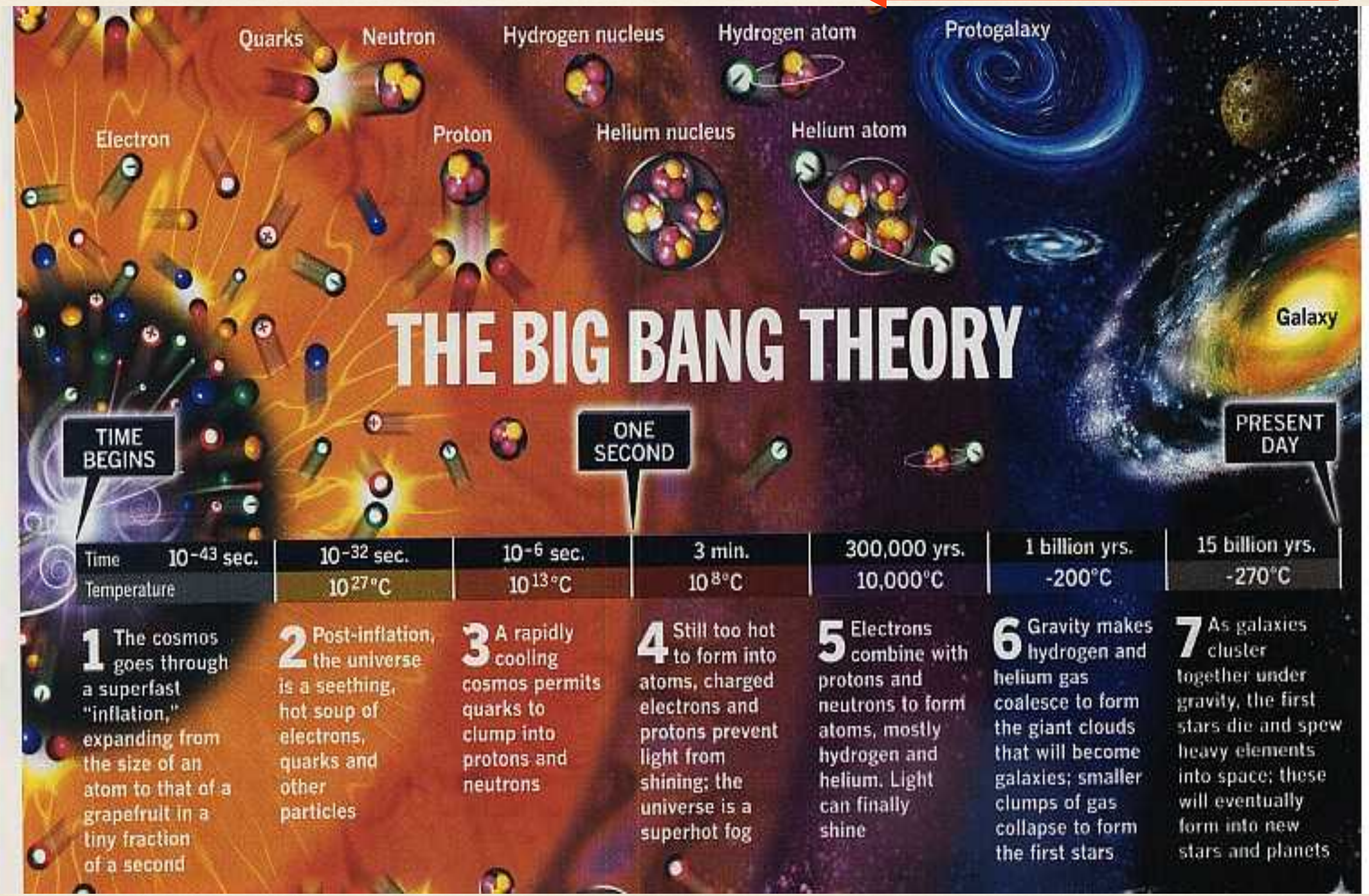
Peter Higgs, center, of the University of Edinburgh, was one of the first to propose the particle's existence. From left, physicists at CERN who helped lead the hunt for it: Sau Lan Wu, Joe Incandela, Guido Tonelli and Fabiola Gianotti.

October 8, 2013 Nobel announcement:
Nobel Prize in Physics won by Peter Higgs and Francois Englert.

all forces unified (?)

strong, EM, weak forces separate

high energy particle experiments probe conditions back in time

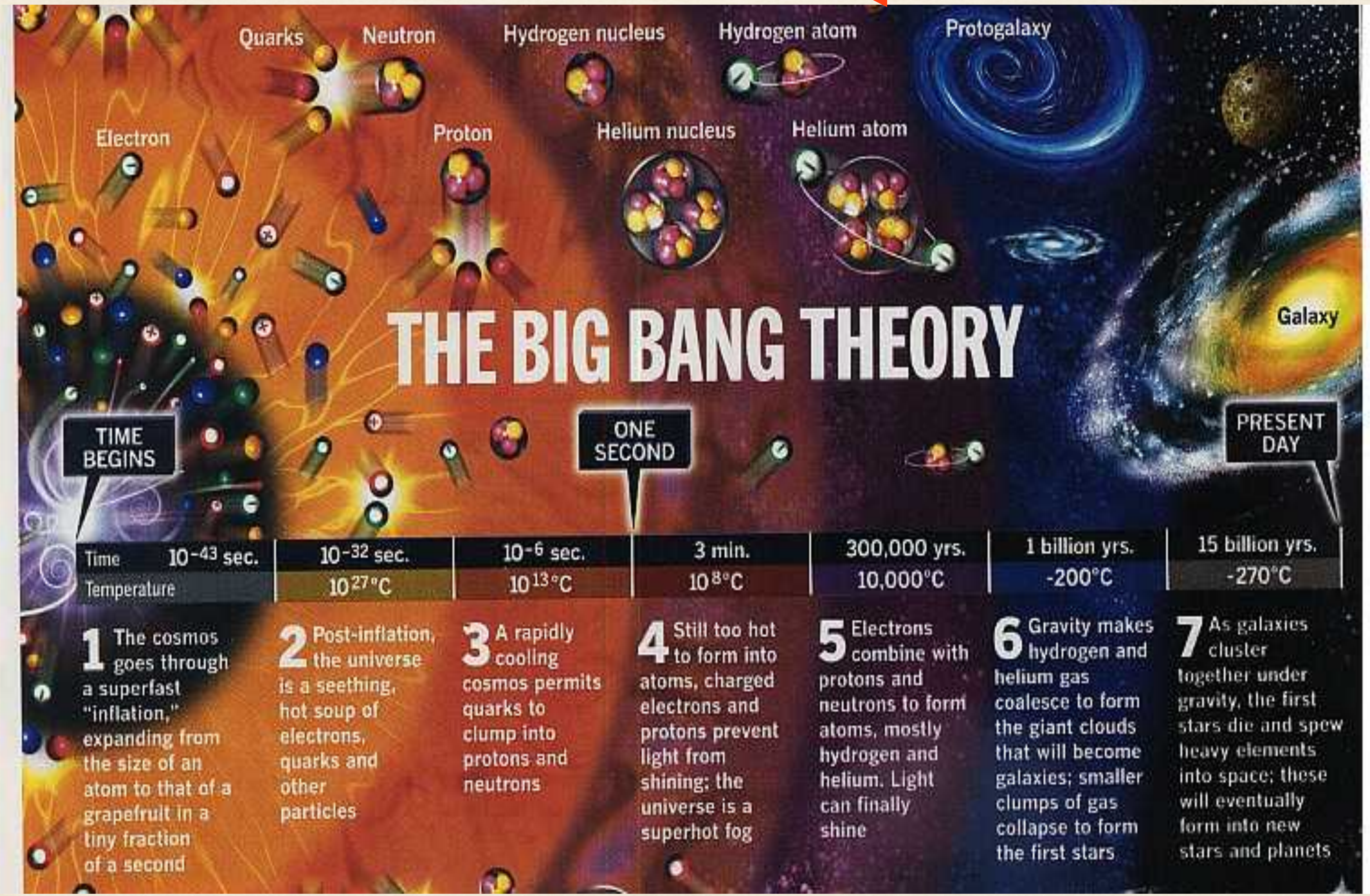


Puzzles in particle physics are tied to puzzles in cosmology.

all forces unified (?)

strong, EM, weak forces separate

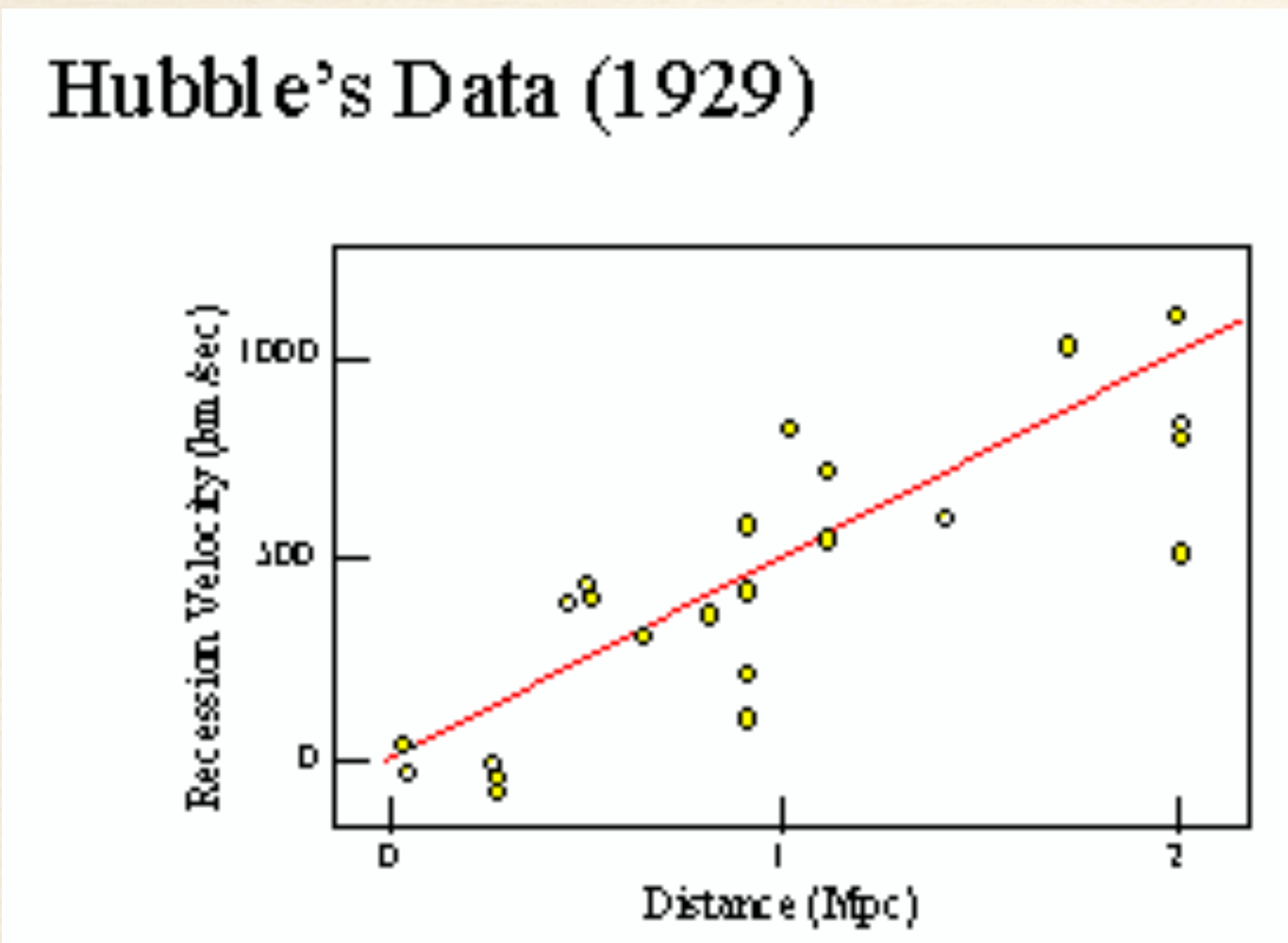
high energy particle experiments probe conditions back in time



Evidence for an Expanding Universe

In 1929 Hubble discovered that distant galaxies are receding from us.

The universe is expanding!

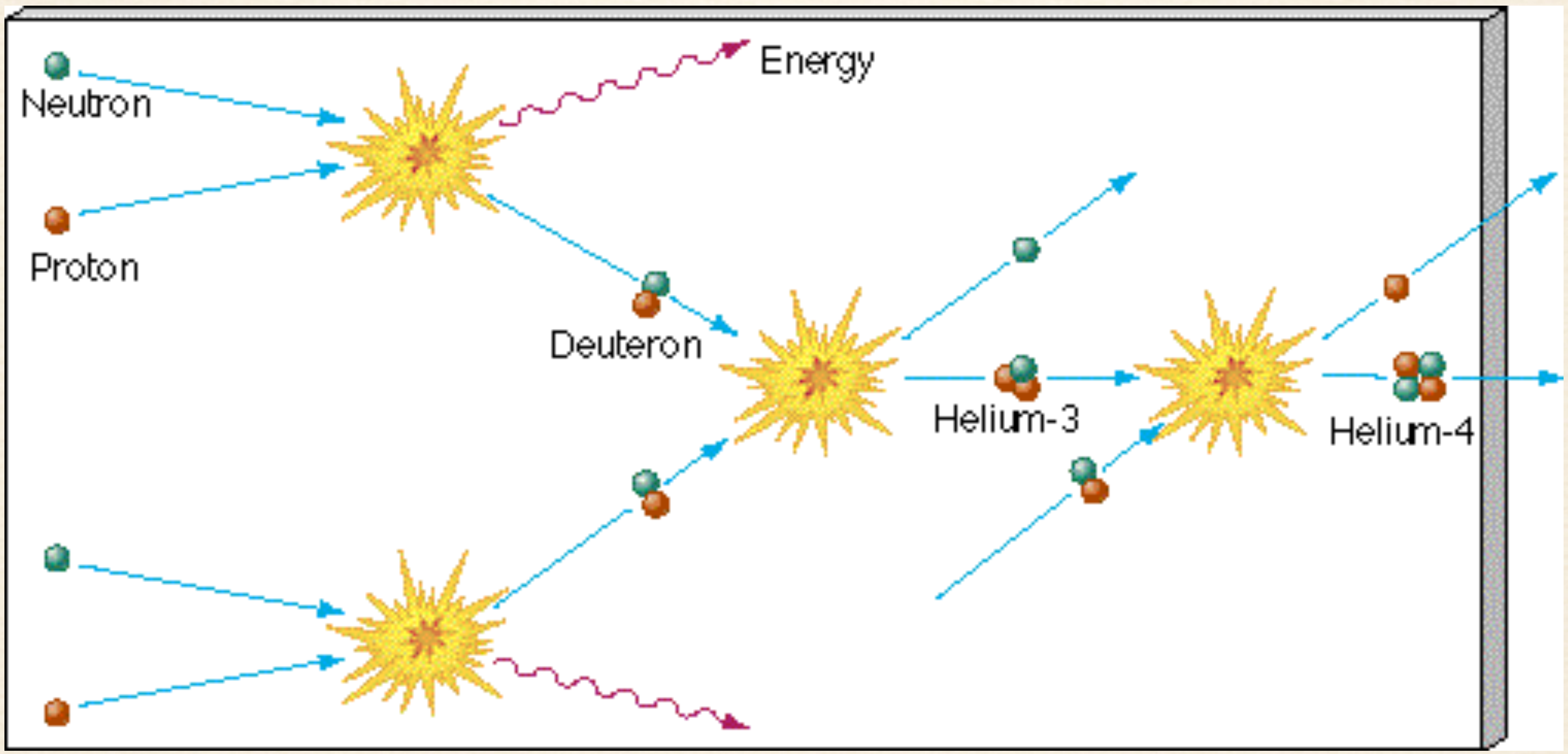


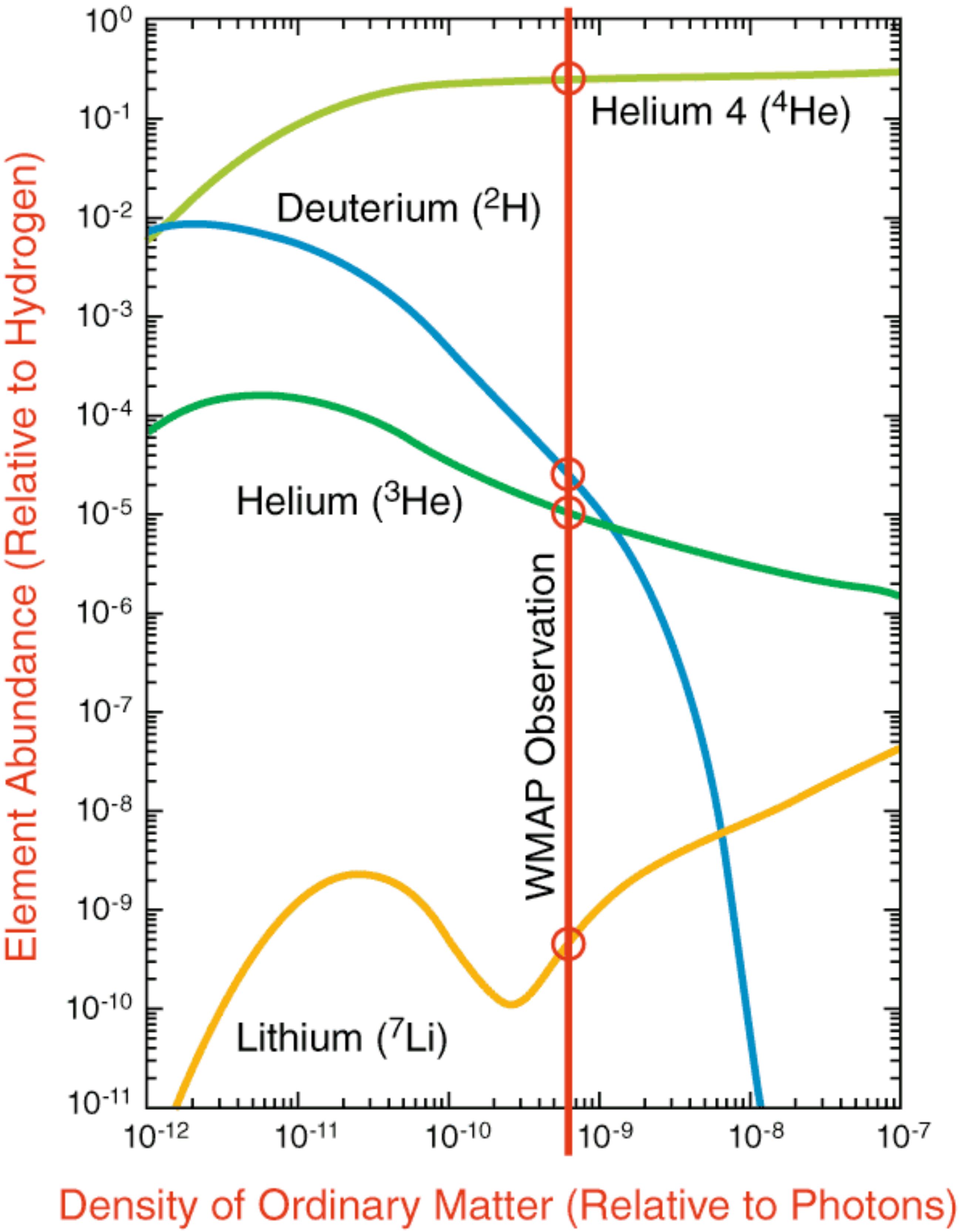
H_0 = "Hubble constant"
= 70 km/s/Mpc
(measured value)

Creation of the light elements

For temperatures above 10^{10} Kelvin, nuclei can't exist.

Below 10^{10} Kelvin, fusion gives rise to light nuclei.





NASA/WMAP Science Team
WMAP101087

Element Abundance graphs: Steigman, Encyclopedia of Astronomy and Astrophysics (Institute of Physics) December, 2000

$$^4\mathrm{He}: \; 24.5 \pm 0.5\%$$

$$^3\mathrm{He}: \; (1.7 \pm 0.2) \times 10^{-5}$$

$$\mathrm{D}: \; (3 \pm 0.5) \times 10^{-5}$$

$$^7\mathrm{Li}: \; (6 \pm 1) \times 10^{-10}$$

Dark Matter and Dark Energy

You may have heard of dark matter and dark energy.

Why do we believe that the universe is filled with mysterious stuff if we can’t see it?

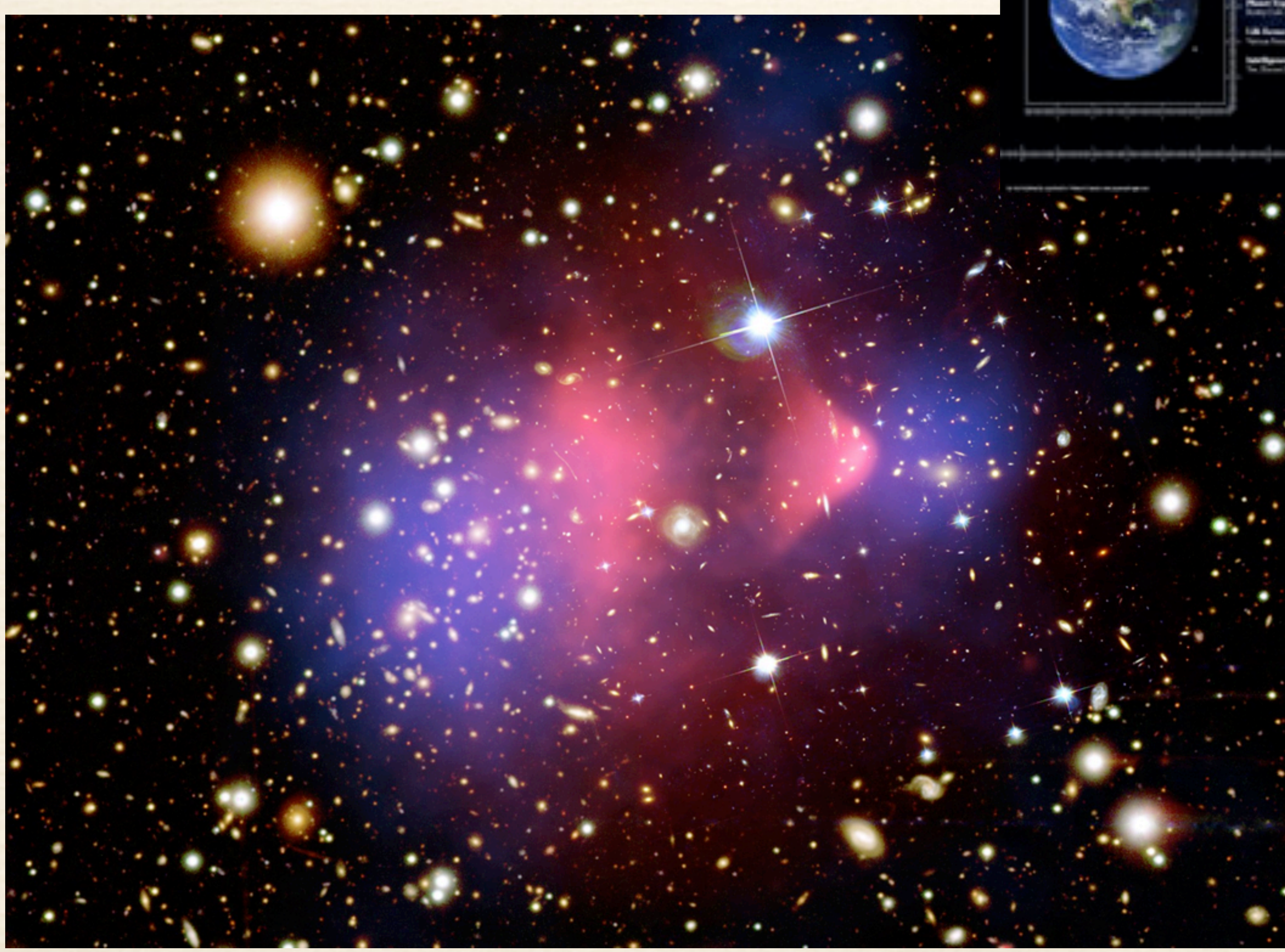
http://www.oddee.com/item_98259.aspx

Hmm, that's strange.

Look at all that mass!

http://www.oddee.com/item_98259.aspx

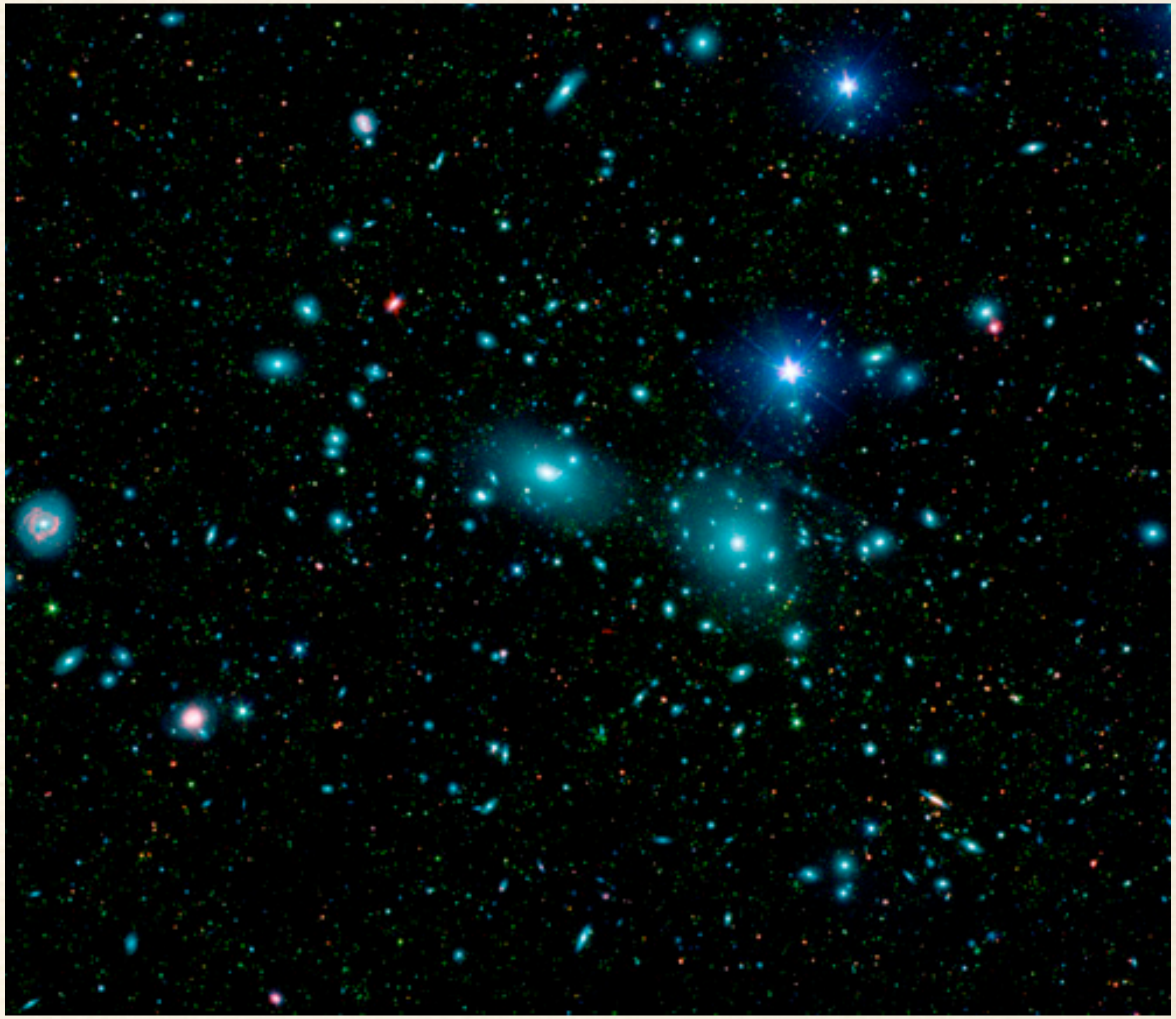
Matter in the Universe



Dark Matter

Fritz Zwicky
(1930s)

Galaxies in the Coma Cluster are moving so quickly that they should not be bound by the gravitational attraction of the observed mass in the cluster.



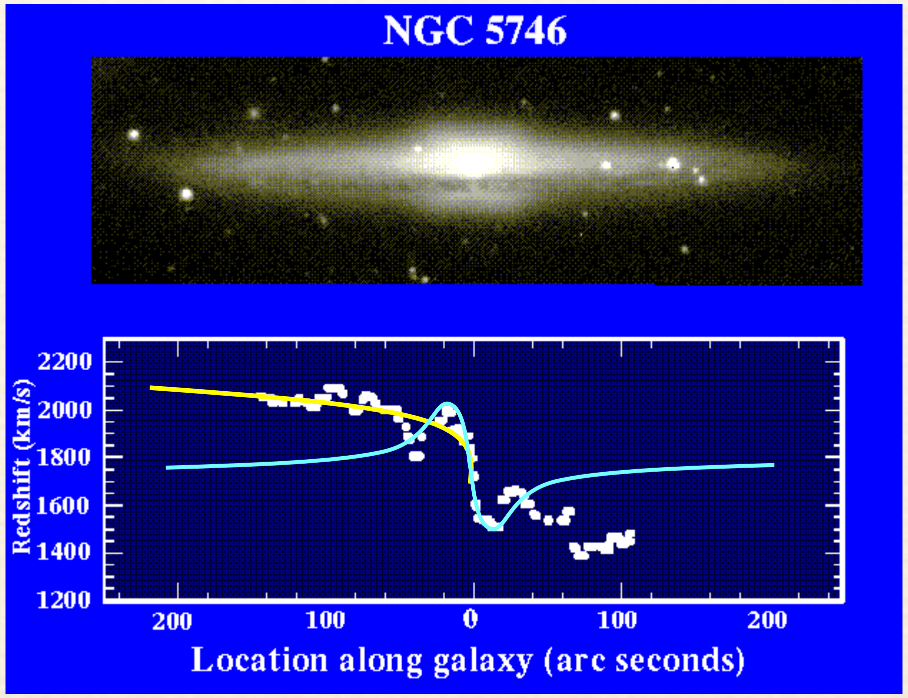
Coma Cluster
NASA, SDSS
>1000 galaxies bound by gravity

Galactic Rotation

Vera Rubin

The farther a star is from the center of a galaxy, the weaker the force of gravity on it and the slower it should rotate, right?

Wrong!



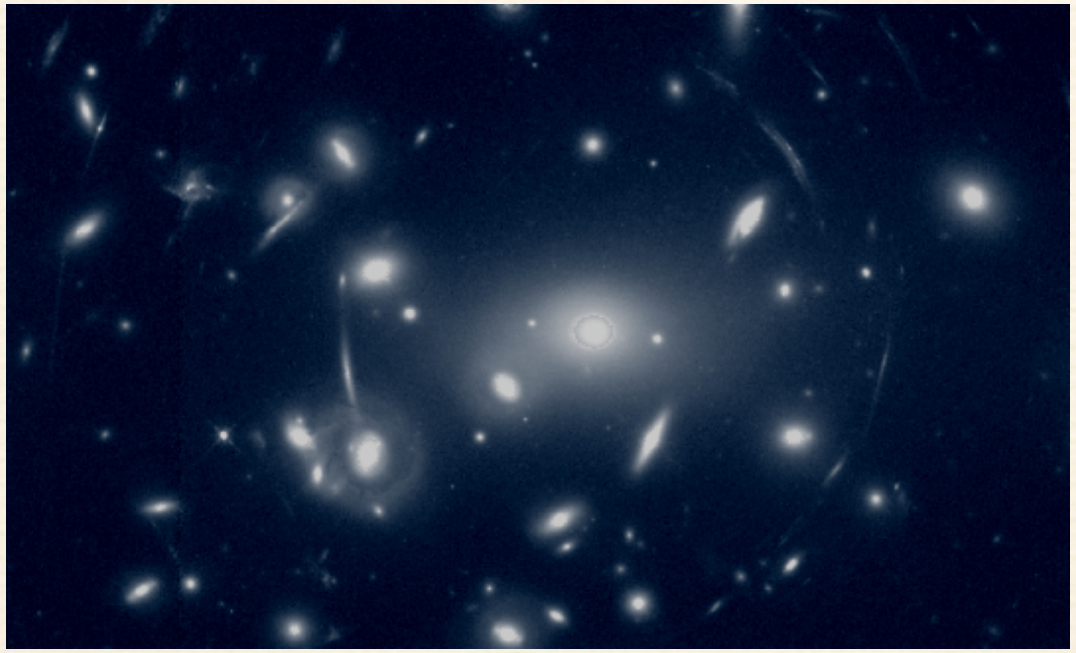
Bill Keel http://www.astr.ua.edu/gifimages/ngc5746.gif

$$\frac{v^2}{r} = \frac{GM}{r^2}$$

Gravitational Lensing

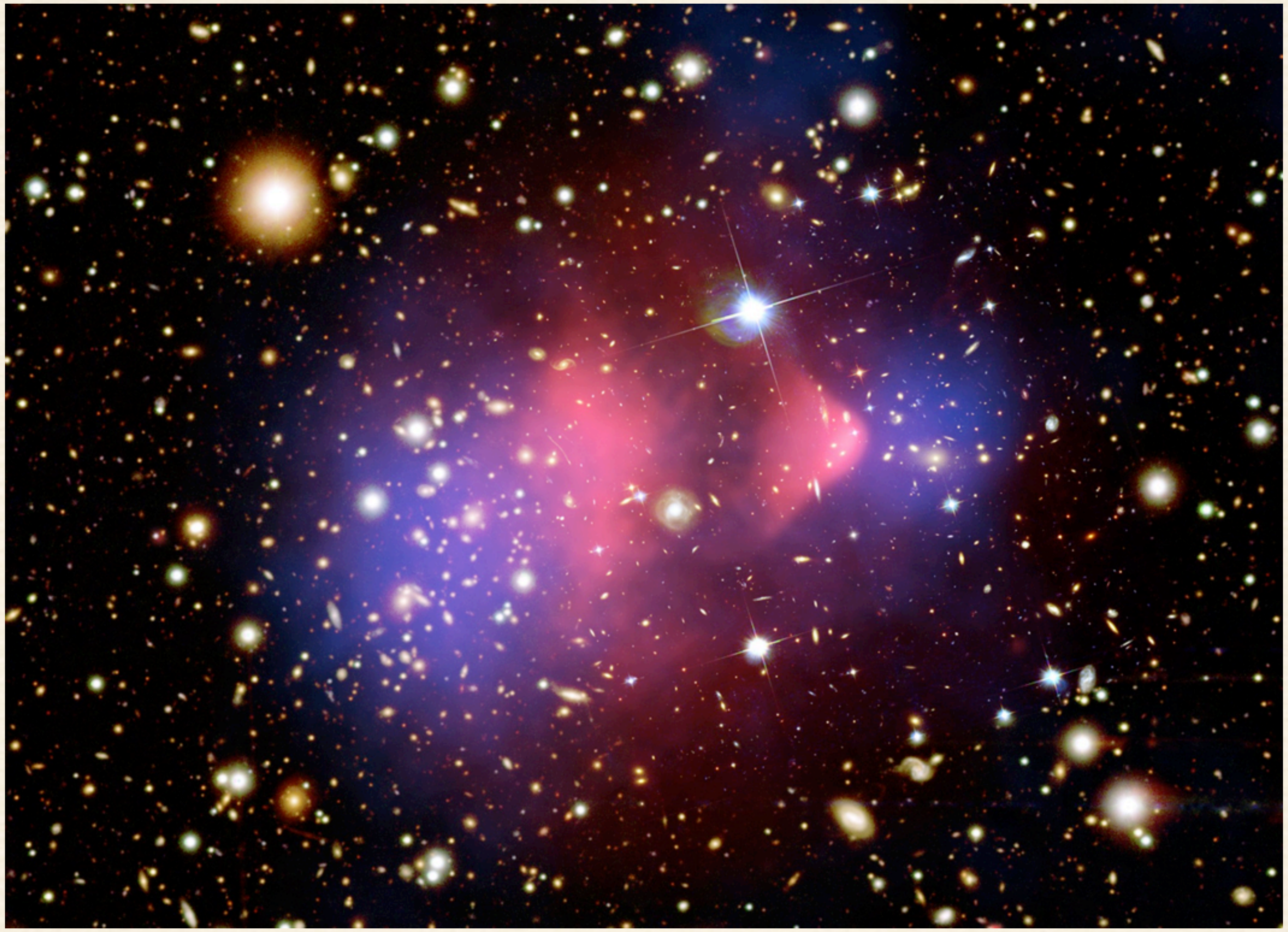
Light is bent by gravity, so we can weigh an object in the line of sight of a distant galaxy by measuring how much the light from the galaxy bends.

This way we can also estimate how much dark matter there is in the universe.

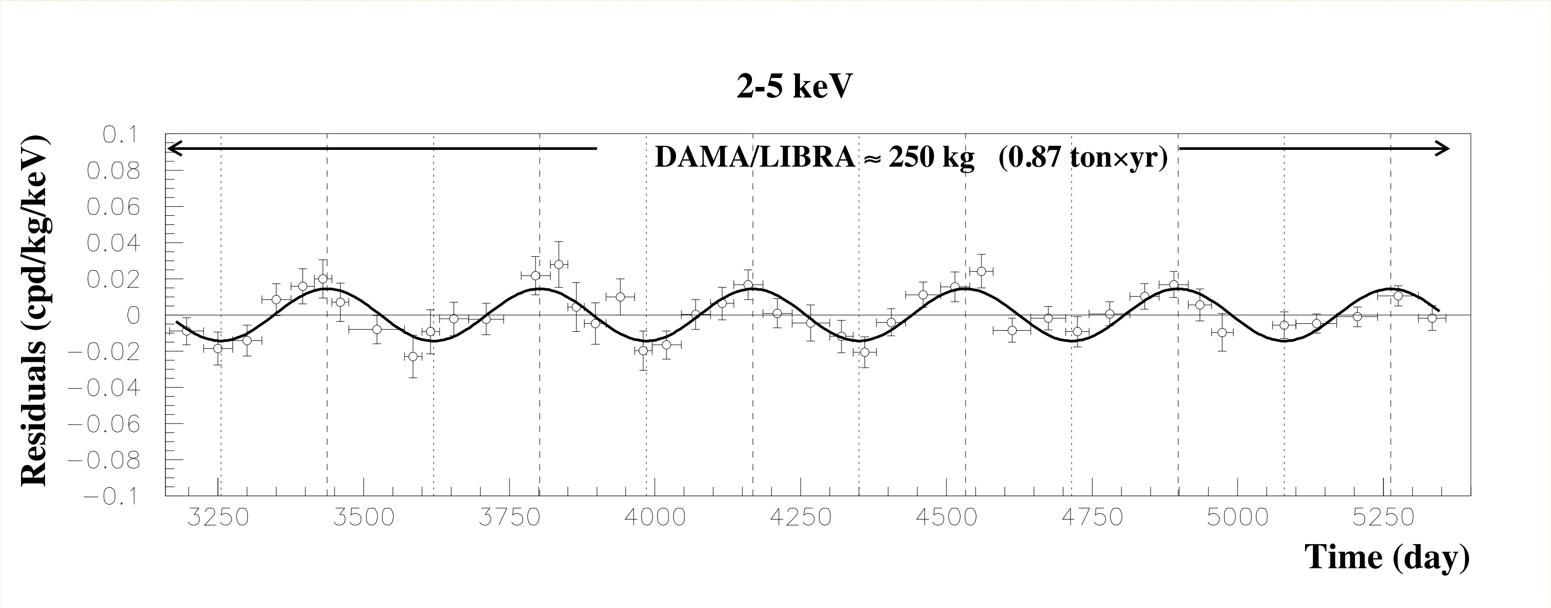


http://www.cacr.caltech.edu/SDA/digital_sky.html

The Bullet Cluster



Chandra X-ray Observatory, 2006



1997-Present: DAMA Experiment sees annual modulation of energy deposited in a crystal

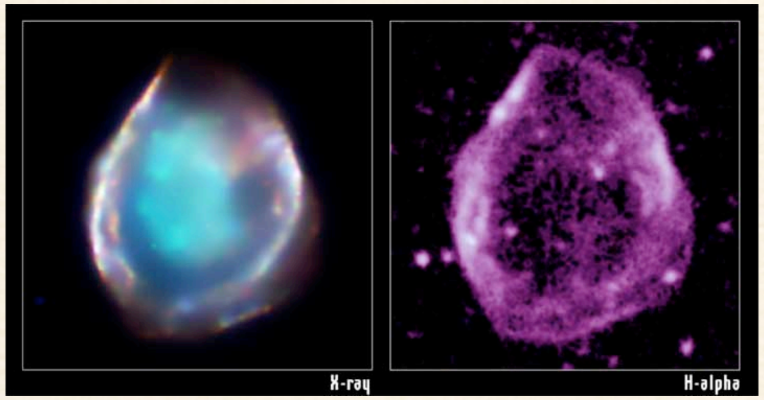
Type Ia Supernovae

As we probe deep into space we also probe back in time because light travels at a finite speed.

So if we can probe **how fast** objects are receding from us as a function of their **distance** from us, then we also know the expansion rate of the universe as a function of time.

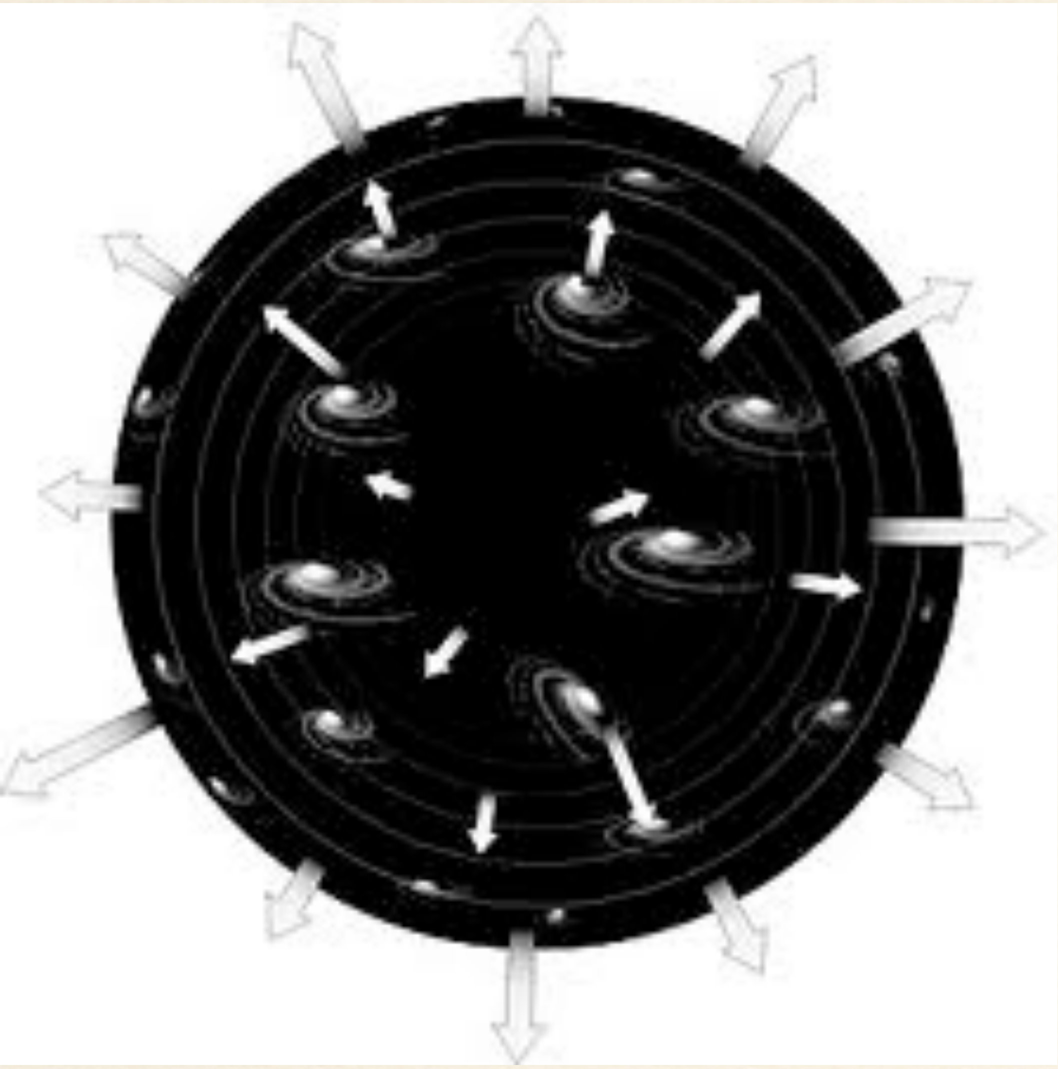
How fast? Use redshifts.

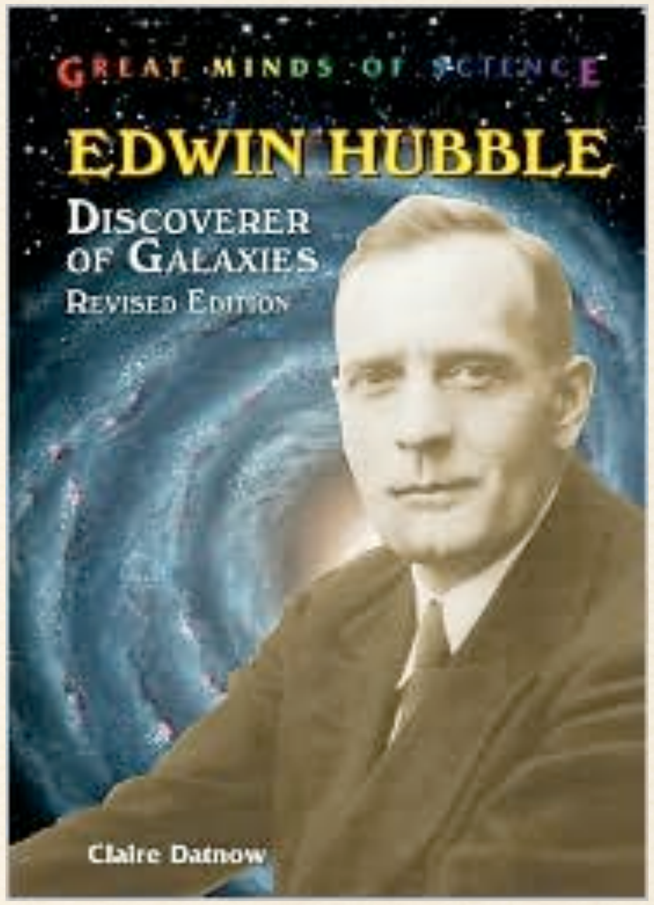
How far? Use a standard candle. That's where the Type Ia supernovae come in.



DEM L71
http://chandra.harvard.edu/photo/2003/deml71/

The Universe is Expanding

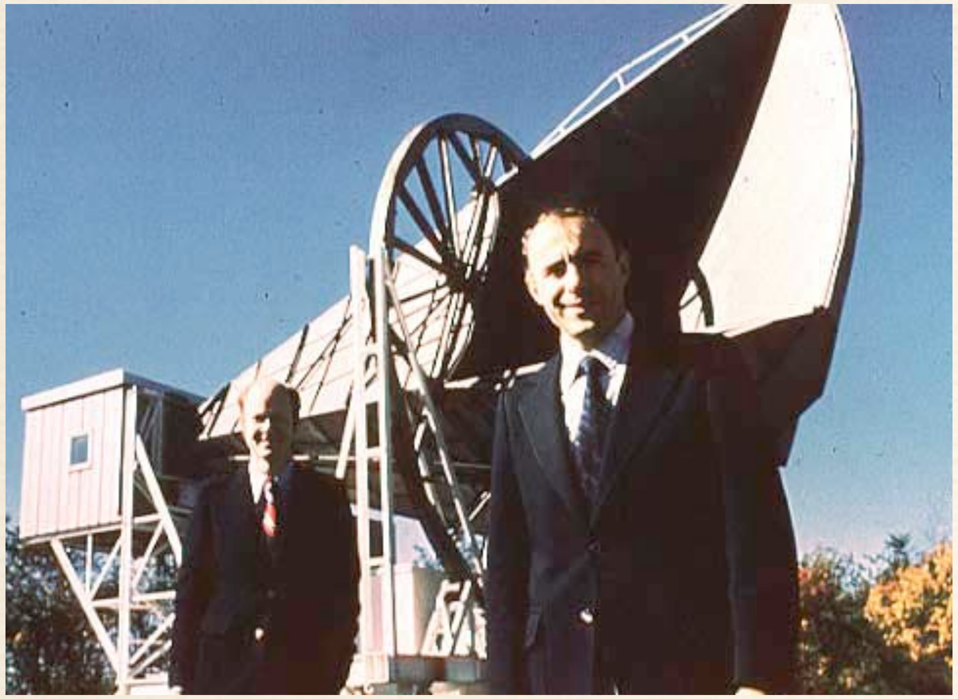




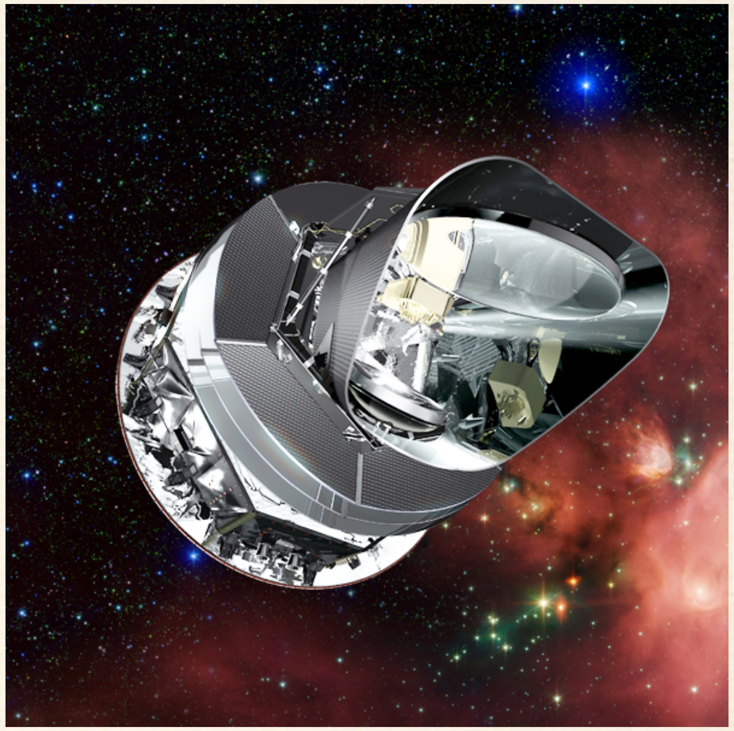
1998: The expansion is accelerating →
The universe is filled with "Dark Energy!"

Saul Perlmutter - Supernova Cosmology Project

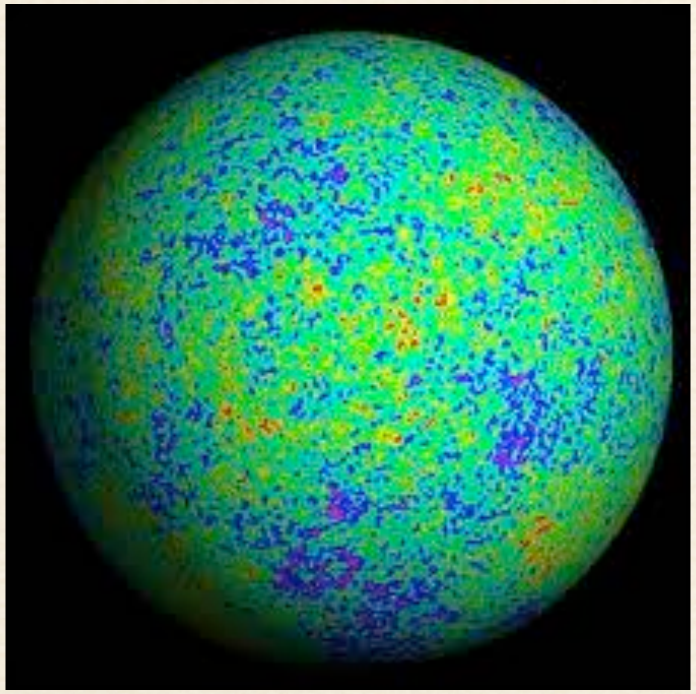
The Cosmic Microwave Background



Arno Penzias and Robert Wilson



Planck Satellite

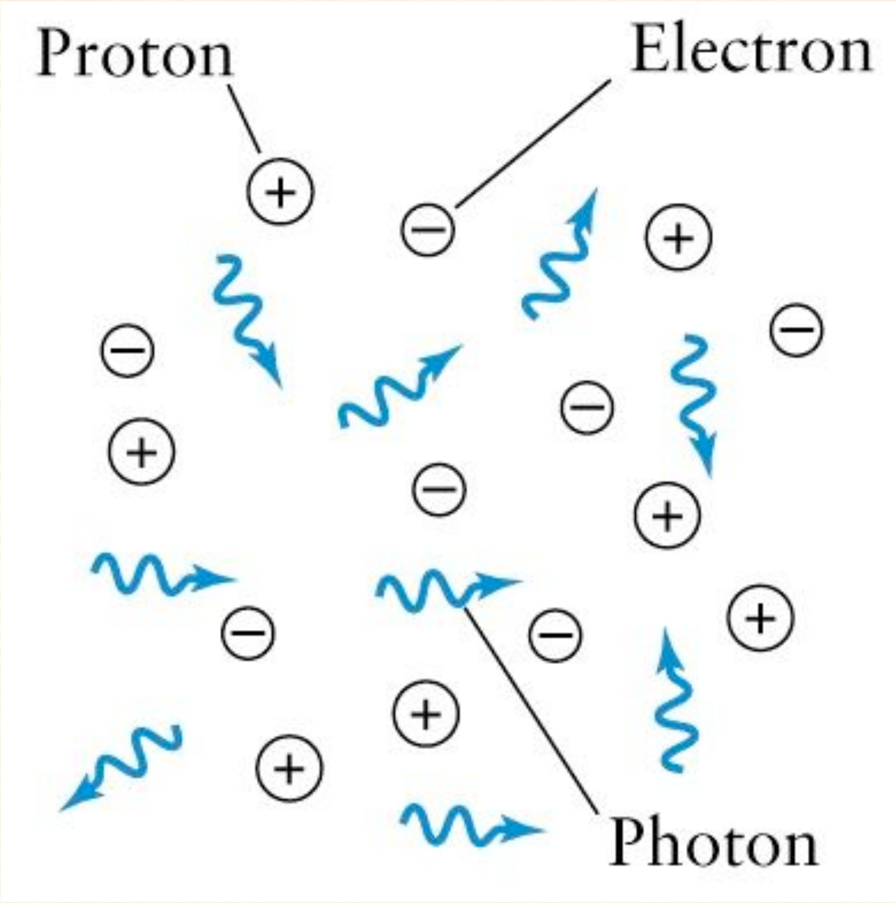


Hot and cold spots in the CMB

(Fast forward ⟶ Stars, galaxies, ...)

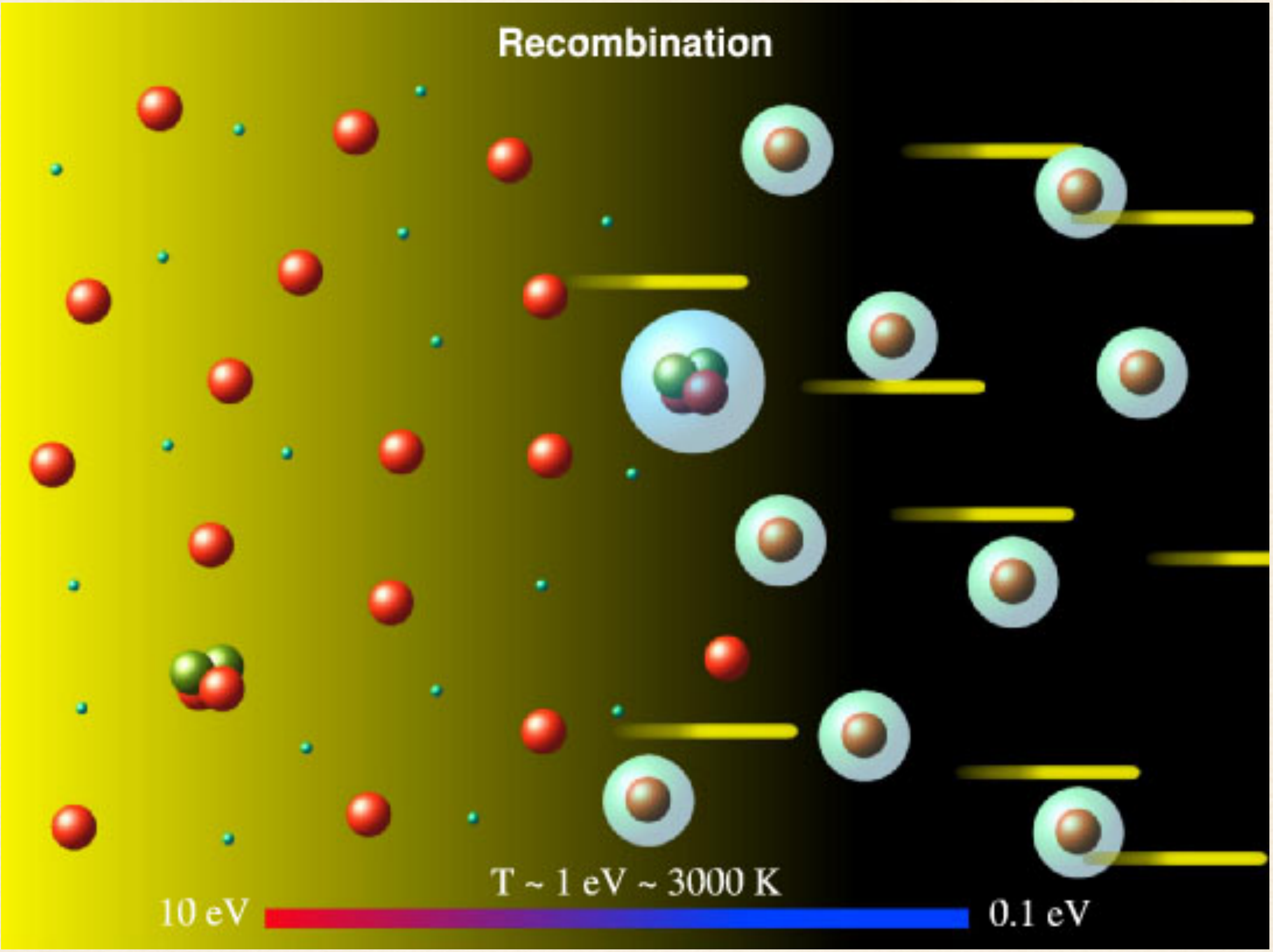
The Opaque Early Universe

The early universe was a soup of charged particles which scattered light.

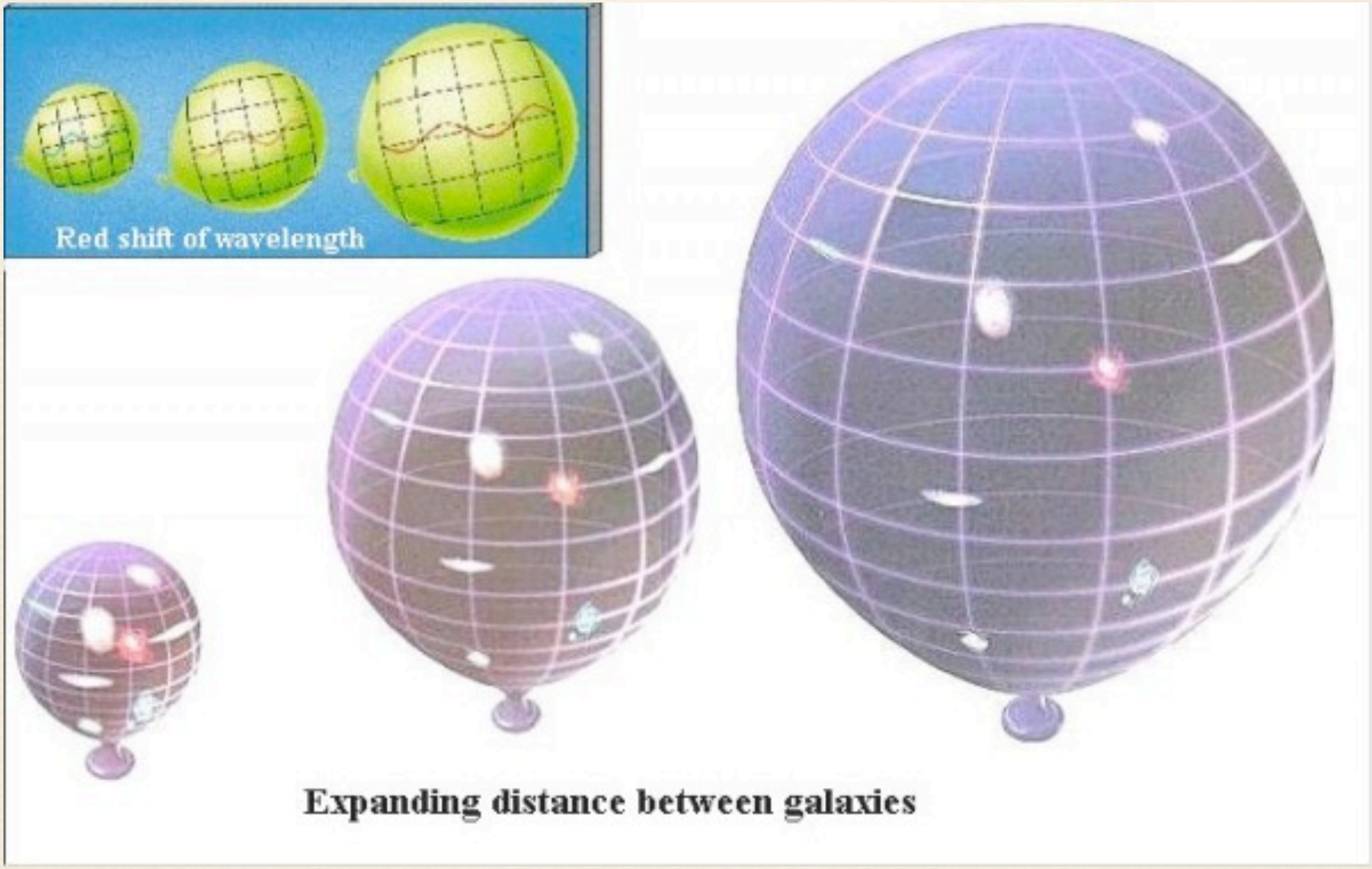


Then...

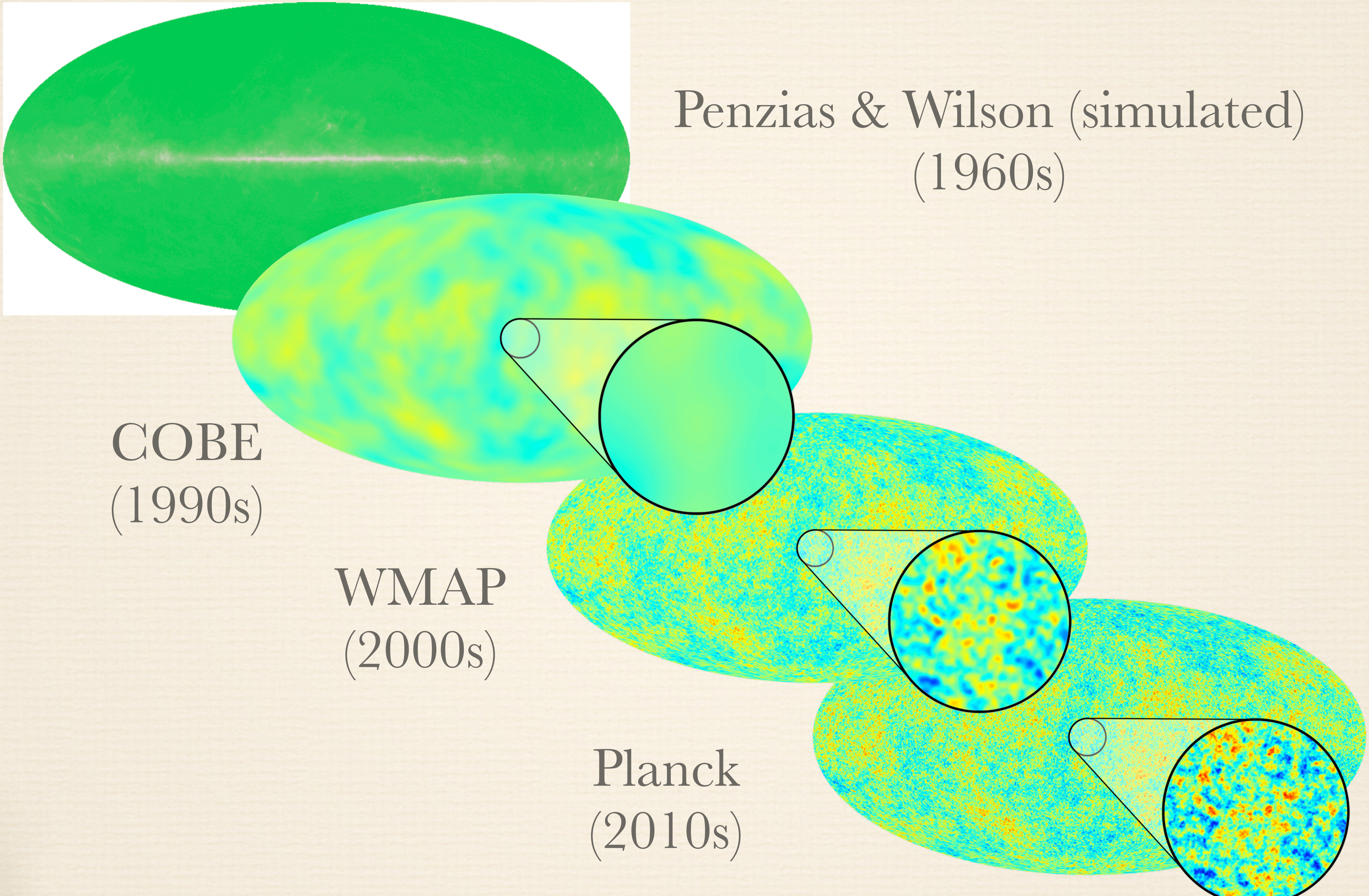
Recombination: Atoms Form!



Universe Expands and Cools
(light redshifts by factor of 1100)



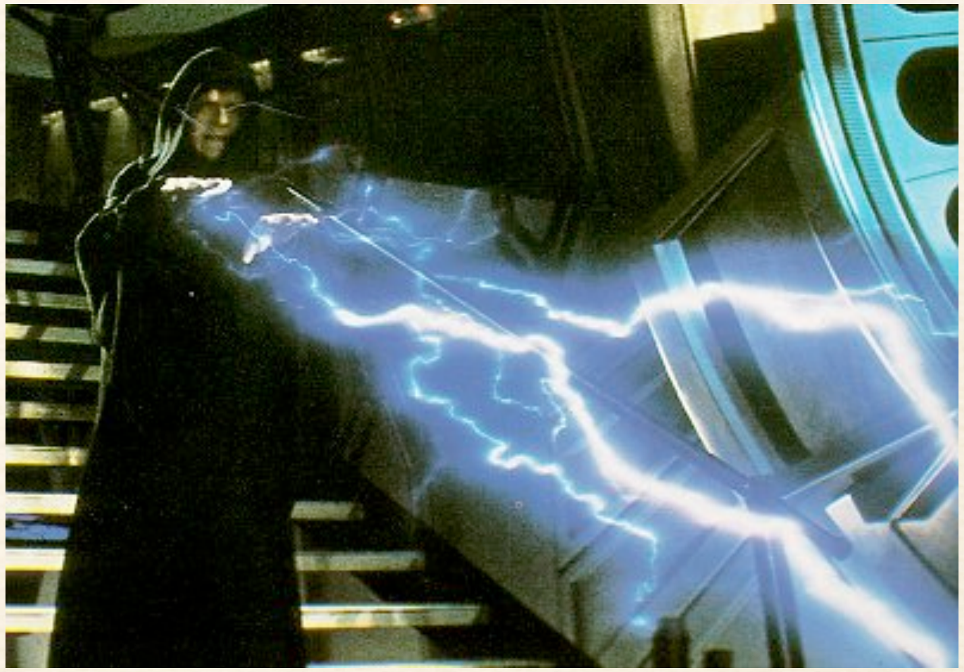
Temperature deviations in the CMB



So what is everything made of?

25%: Dark Matter

70%: Dark Energy



5%: Known Particles

Today's Big Puzzles in Particle Physics and Cosmology

There are always anomalies in experiments:

Details of B-meson decays don't seem to agree with the Standard Model. (LHCb)

The magnetic moment of the muon does not seem to agree with the Standard Model.

The W-boson mass is way off (as of last Thursday).

Most often experimental anomalies go away as more data is collected.

Today's Big Puzzles in Particle Physics and Cosmology

Fundamental Questions:

What is the missing matter? Could it be black holes?
What is the dark energy?
Why is the cosmological constant so small?
Why is the Higgs mass so small?
Is there supersymmetry?
Why is there as much matter vs antimatter as we observe? (Baryogenesis)
Are there right-handed neutrinos?
Axions?
Got GUTs?

What is gravity and why is it so weak?
What are space and time?

Today's Big Puzzles in Particle Physics and Cosmology

Fundamental Questions:

How does gravity fit together with the Standard Model?
How many dimensions of space are there?
What caused the moment of creation?

....It will take many bright young scientists to answer these questions.