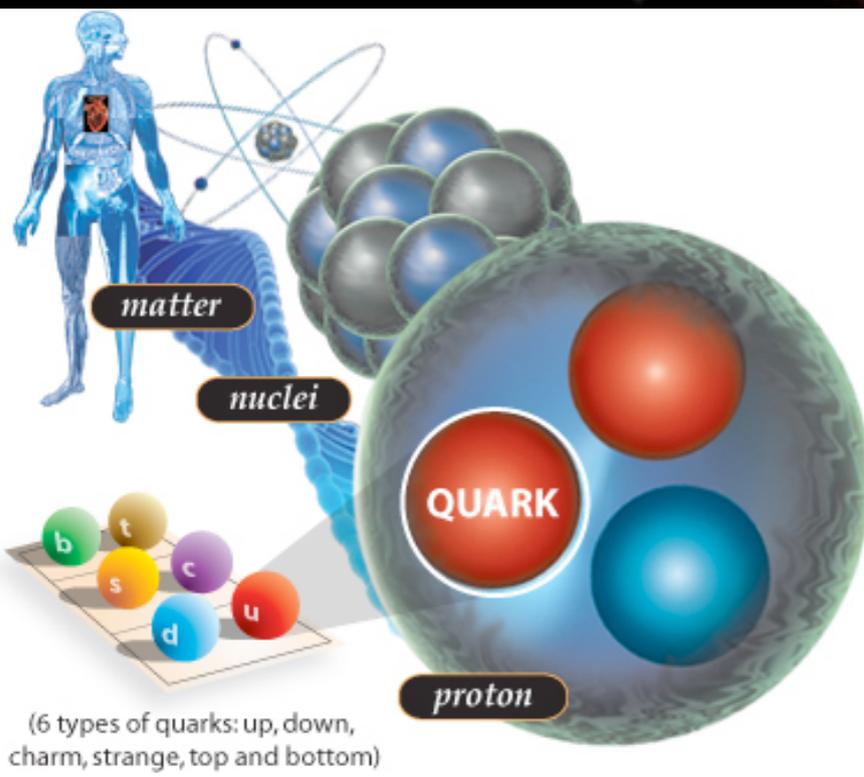
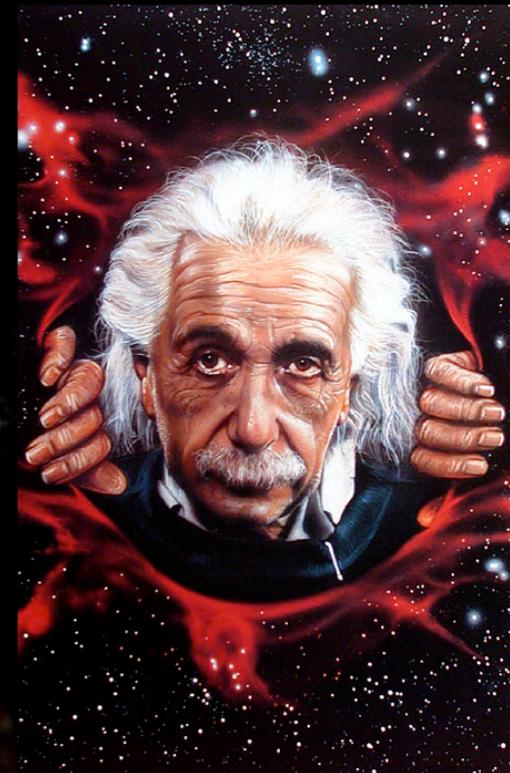


Some of the Big Puzzles in Particle Physics and Cosmology

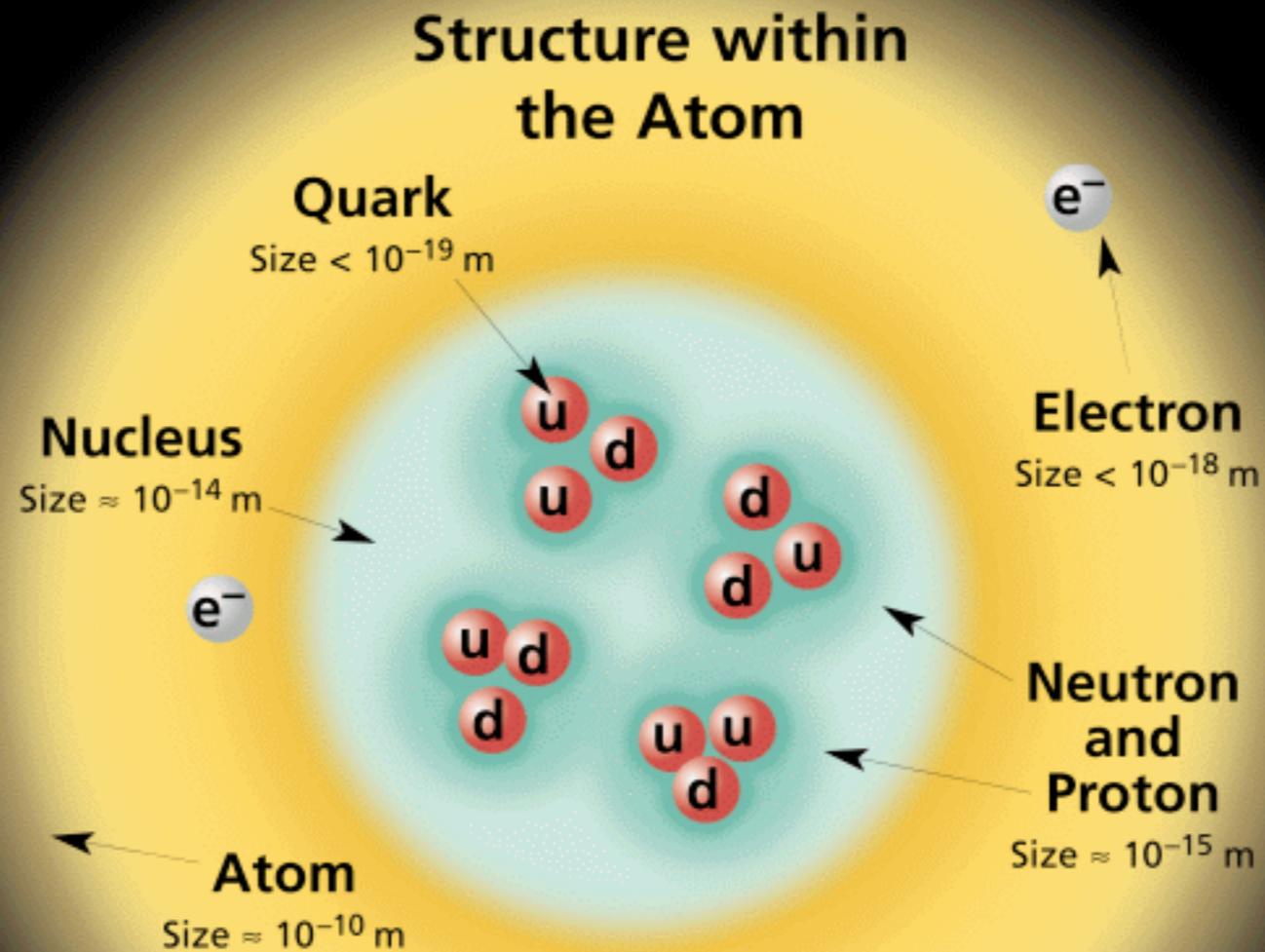


Josh Erlich
PHYS 212/309
April 12, 2022

Periodic Table of the Elements

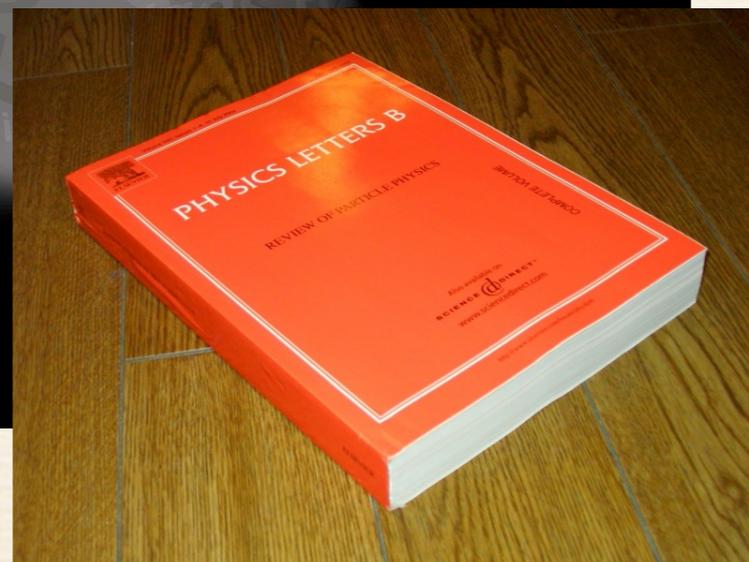
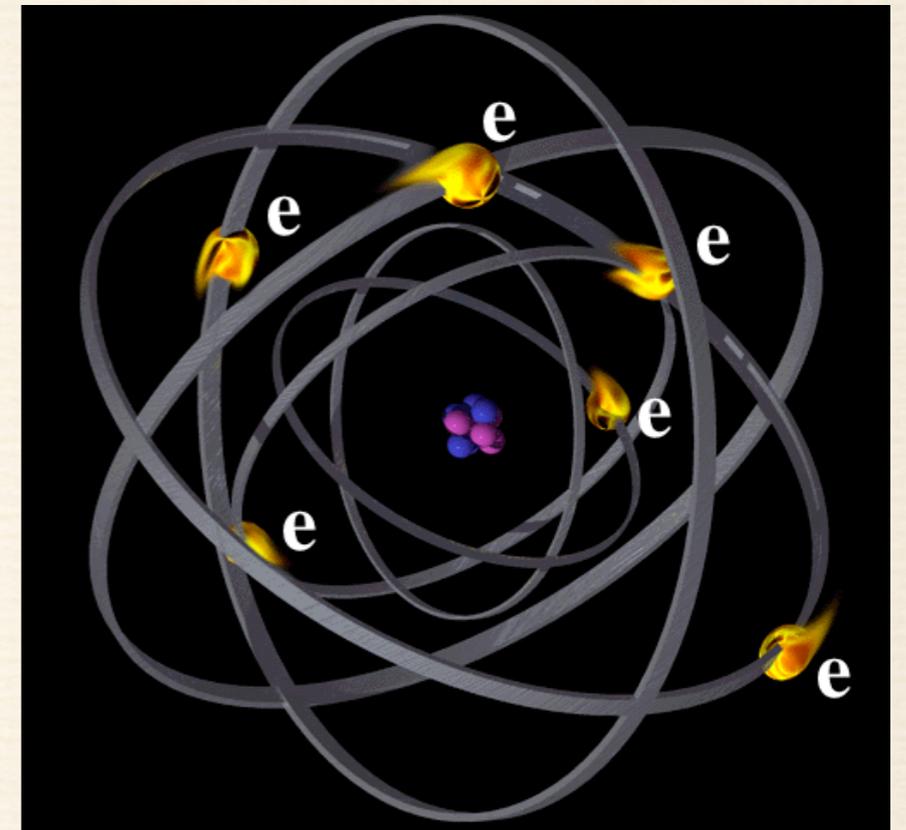
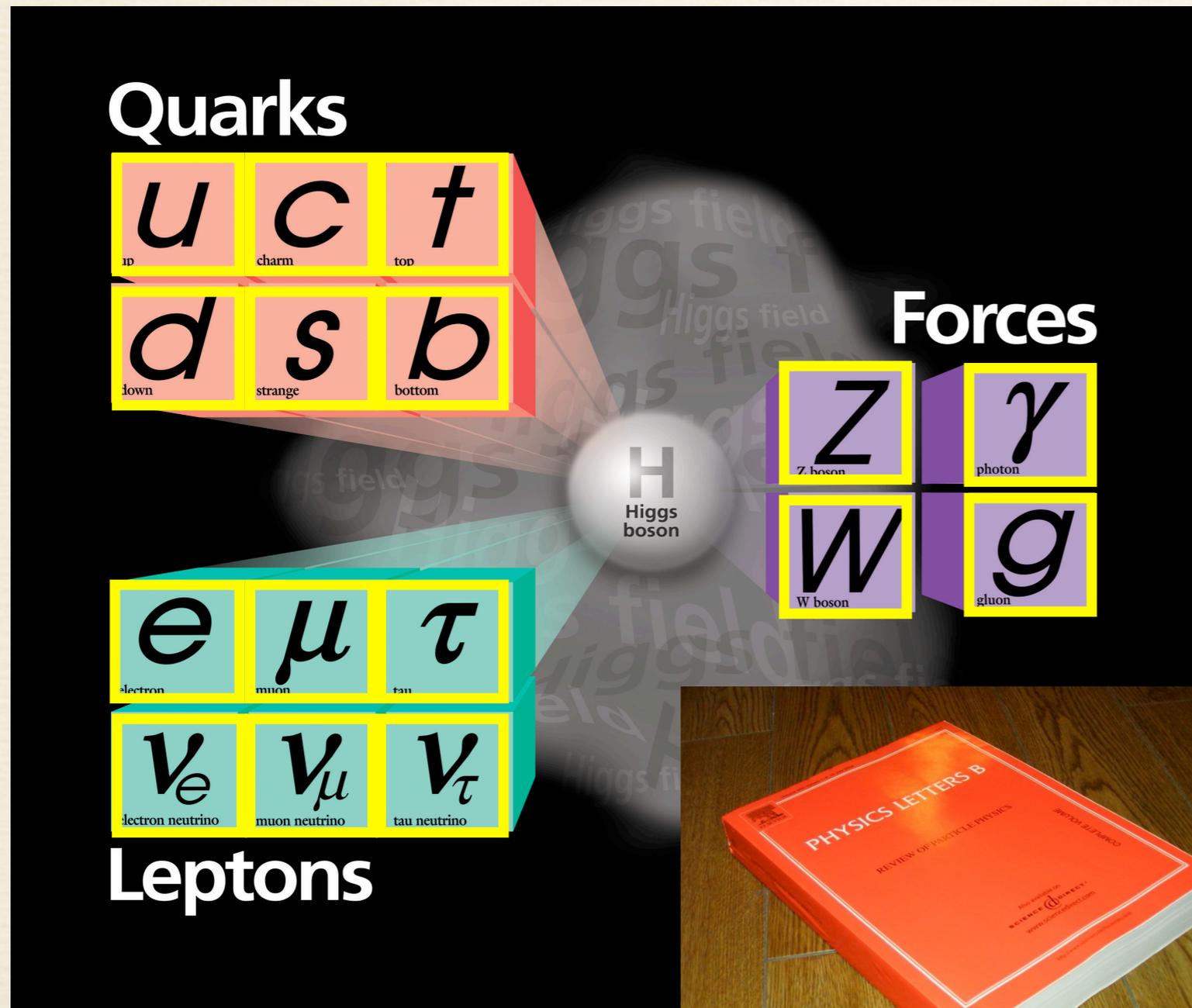
1 IA												18 VIIIA					
1 H Hydrogen 1.008												2 He Helium 4.0026					
3 Li Lithium 6.94	4 Be Beryllium 9.0122											5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.98976928	12 Mg Magnesium 24.305											13 Al Aluminum 26.9815385	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955908	22 Ti Titanium 47.88	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938044	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.630	33 As Arsenic 74.9216	34 Se Selenium 78.9718	35 Br Bromine 79.904	36 Kr Krypton 83.798
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90584	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.91	46 Pd Palladium 106.42	47 Ag Silver 107.87	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.757	52 Te Tellurium 127.603	53 I Iodine 126.905	54 Xe Xenon 131.29
55 Cs Cesium 132.90545196	56 Ba Barium 137.327	57-71 Lanthanides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.222	78 Pt Platinum 195.084	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium (226)	89-103 Actinides	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (264)	108 Hs Hassium (277)	109 Mt Meitnerium (278)	110 Ds Darmstadtium (285)	111 Rg Roentgenium (286)	112 Cn Copernicium (285)	113 Nh Nihonium (284)	114 Fl Flerovium (289)	115 Mc Moscovium (288)	116 Lv Livermorium (293)	117 Ts Tennessine (294)	118 Og Oganesson (294)
<p>Atomic Number → 1 ← Symbol</p> <p>Name → Hydrogen ← Atomic Weight</p> <p>Electrons per shell → 1</p>																	
<p>State of matter (color of name): GAS LIQUID SOLID UNKNOWN</p> <p>Subcategory in the metal-metalloid-nonmetal trend (color of background):</p> <ul style="list-style-type: none"> Alkali metals Alkaline earth metals Transition metals Lanthanides Actinides Post-transition metals Metalloids Reactive nonmetals Noble gases Unknown chemical properties 																	
57 La Lanthanum 138.905	58 Ce Cerium 140.12	59 Pr Praseodymium 140.90766	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93033	68 Er Erbium 167.259	69 Tm Thulium 168.93032	70 Yb Ytterbium 173.054688	71 Lu Lutetium 174.967			
89 Ac Actinium (227)	90 Th Thorium 232.04	91 Pa Protactinium 231.04	92 U Uranium 238.03	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (260)			

Inside the atom



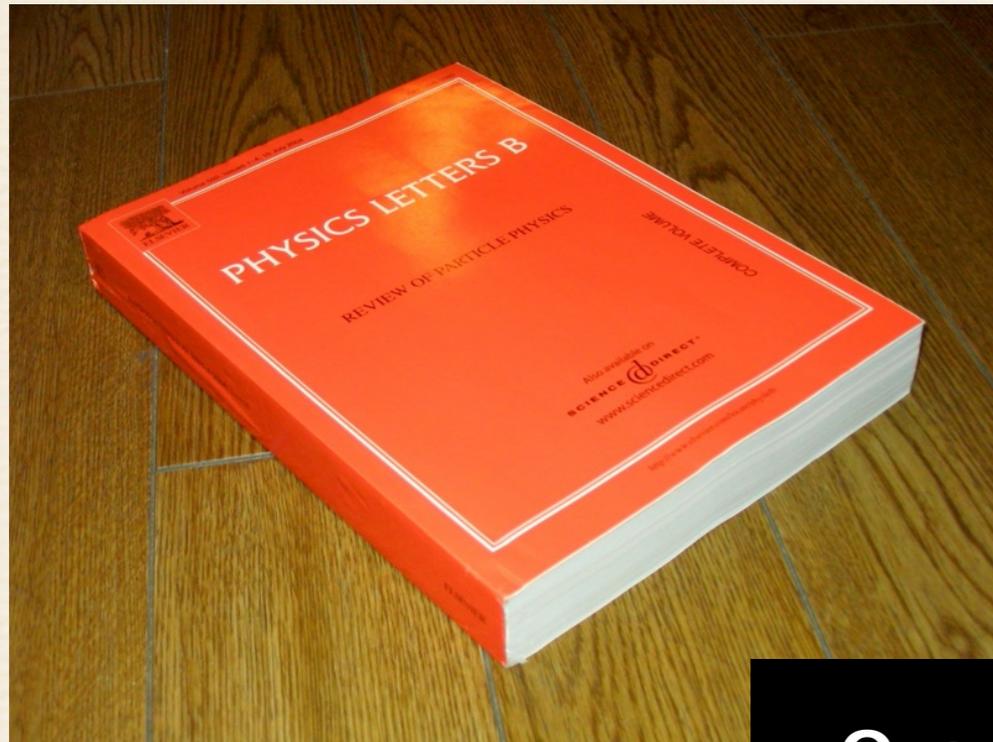
If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

The Standard Model

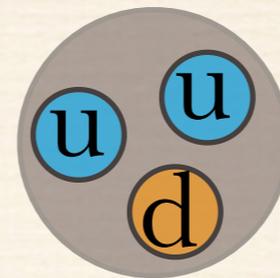


5% of the energy in the universe

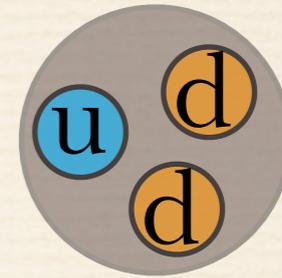
The Particle Zoo



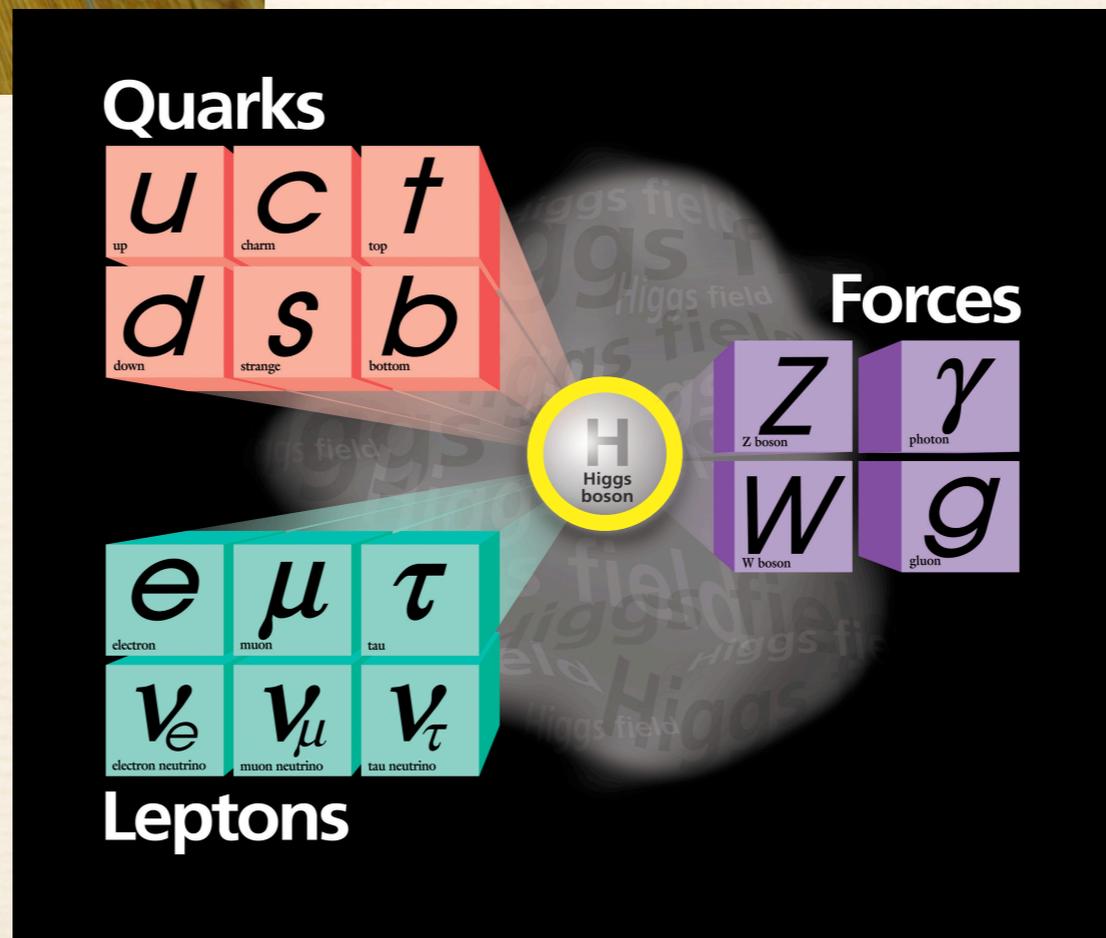
Proton



Neutron

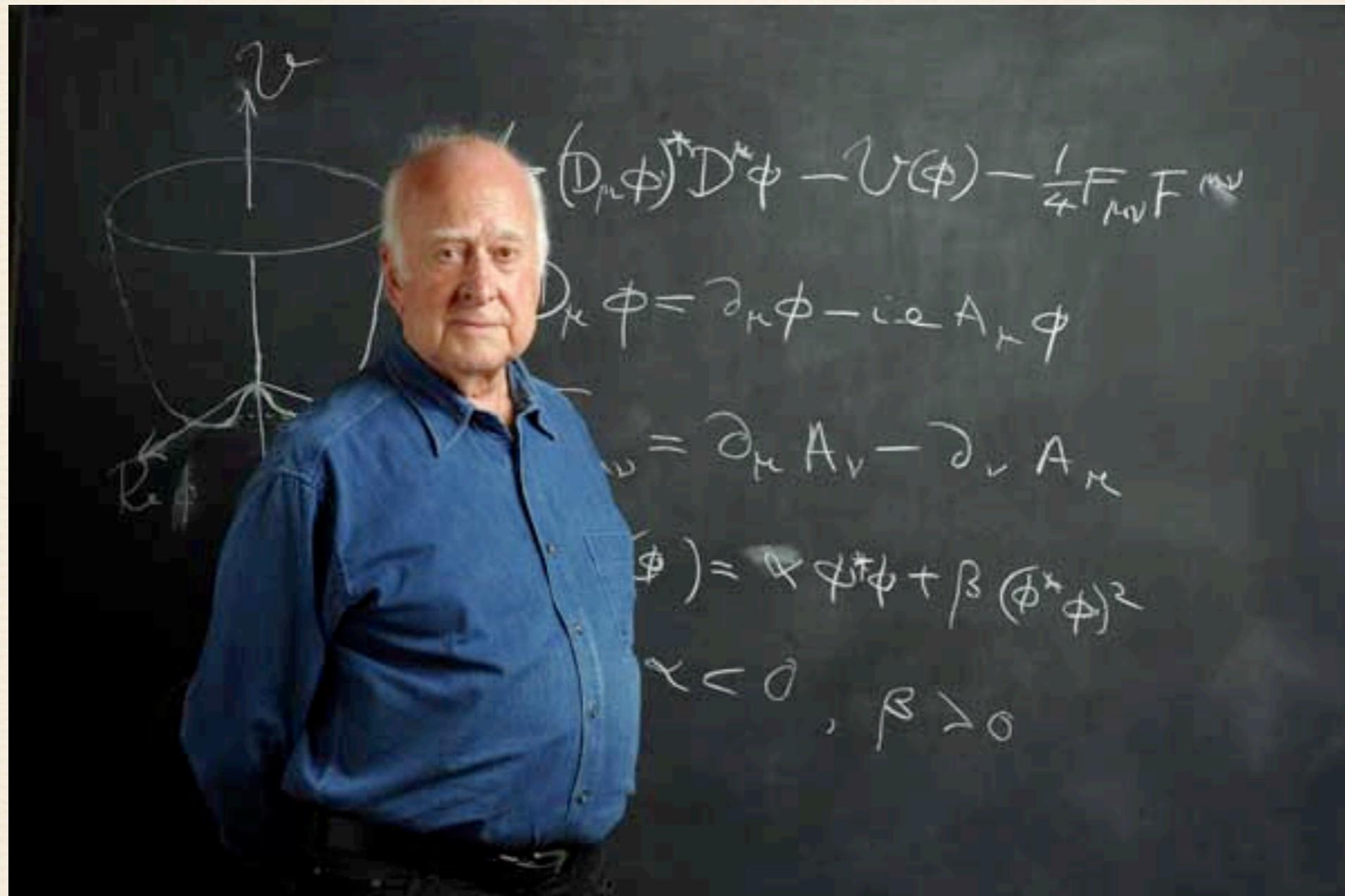


The Standard Model



Higgs to the rescue!

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



The Higgs Field and Mass

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



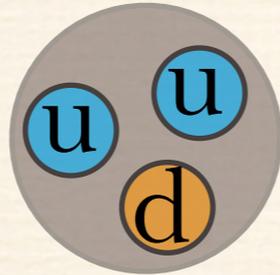
When Kim Kardashian enters a filled room her inertia is substantially increased.

The room interacts much less with Josh Erlich, so his inertia is not increased as much.

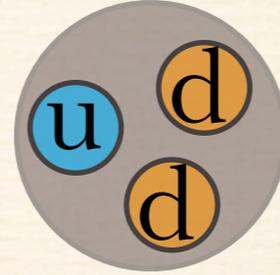
We're talking about fundamental particles.

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

Proton



Neutron



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.



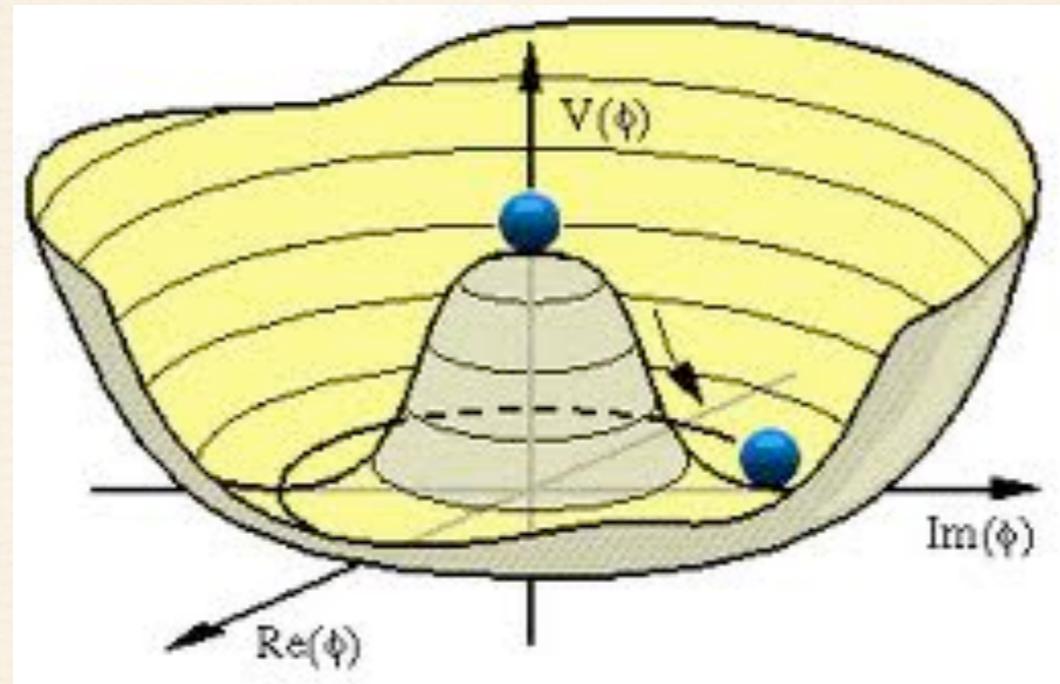
The Higgs Boson

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.

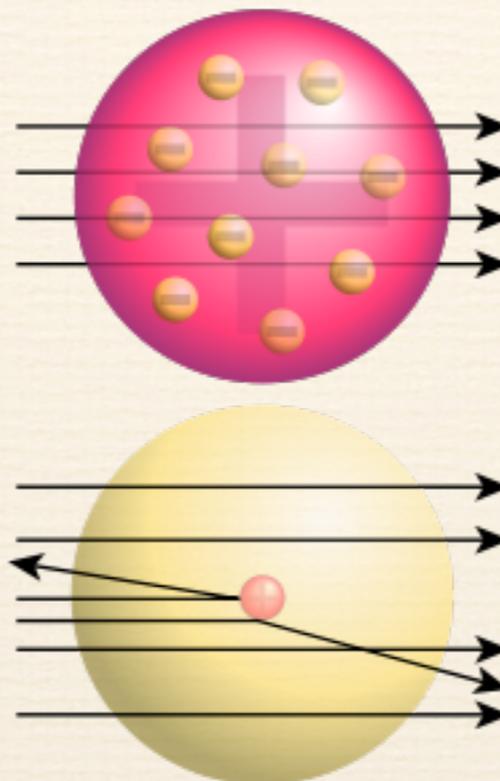
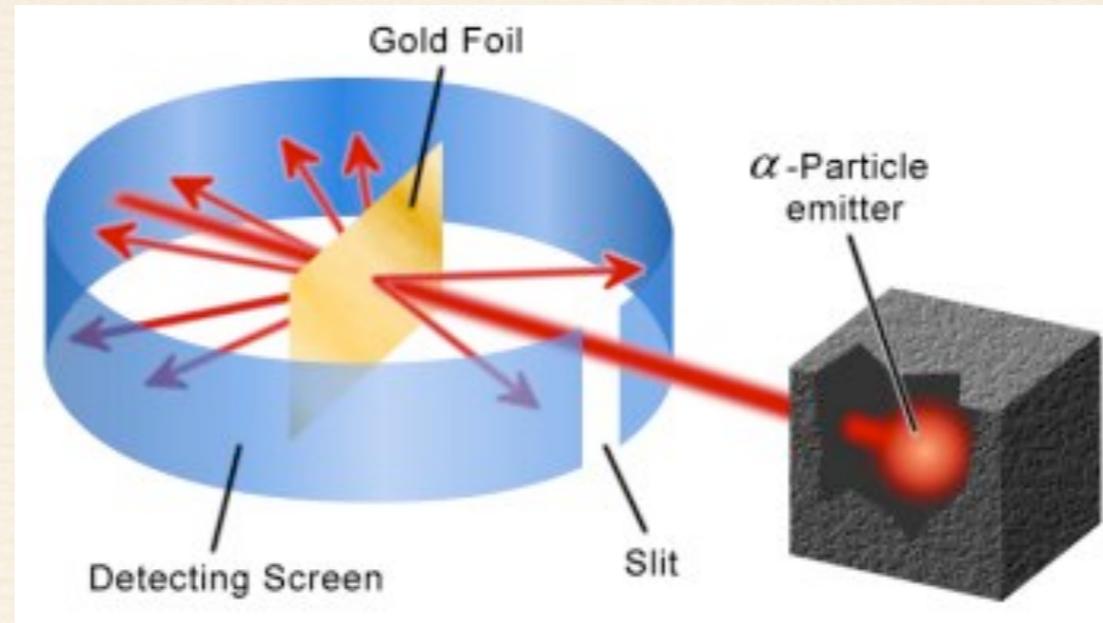
Why is there a Higgs field everywhere?



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)

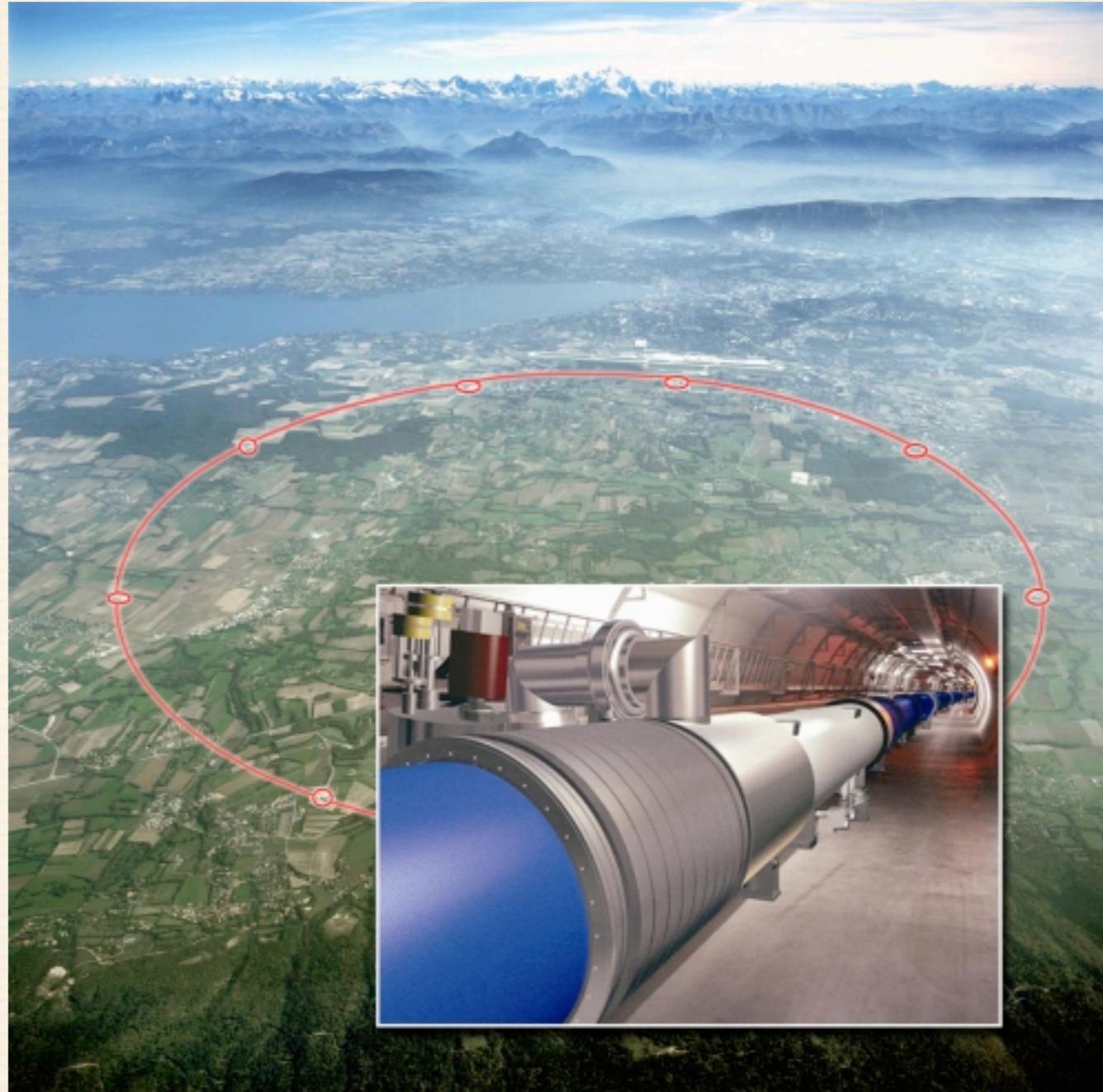
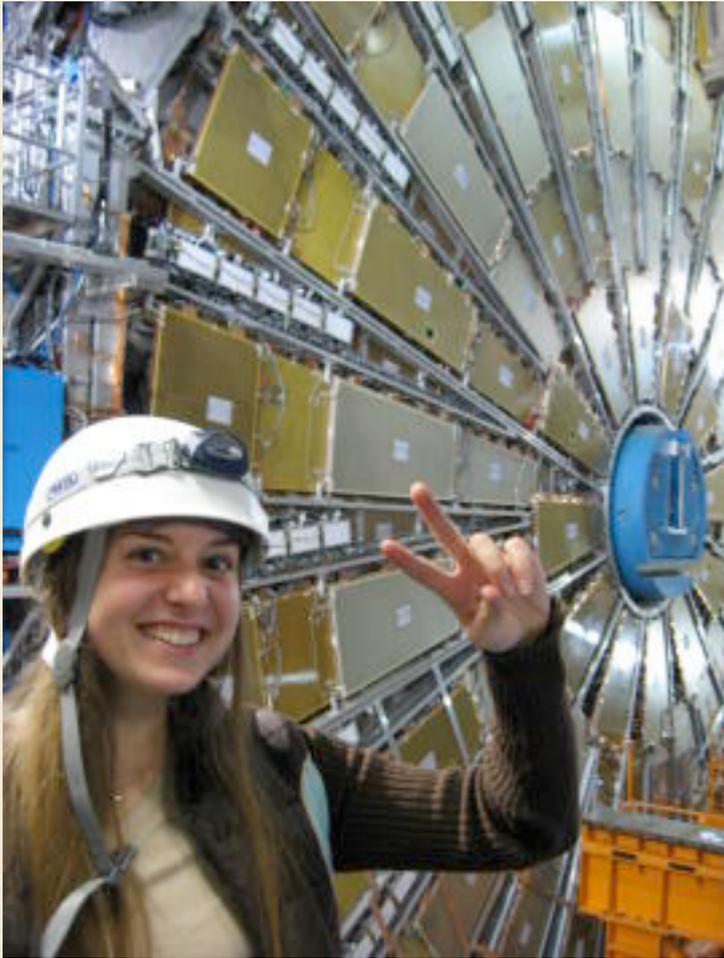


Modern Day Colliders



Jefferson Lab

Modern Day Colliders



CERN

The Big Announcement

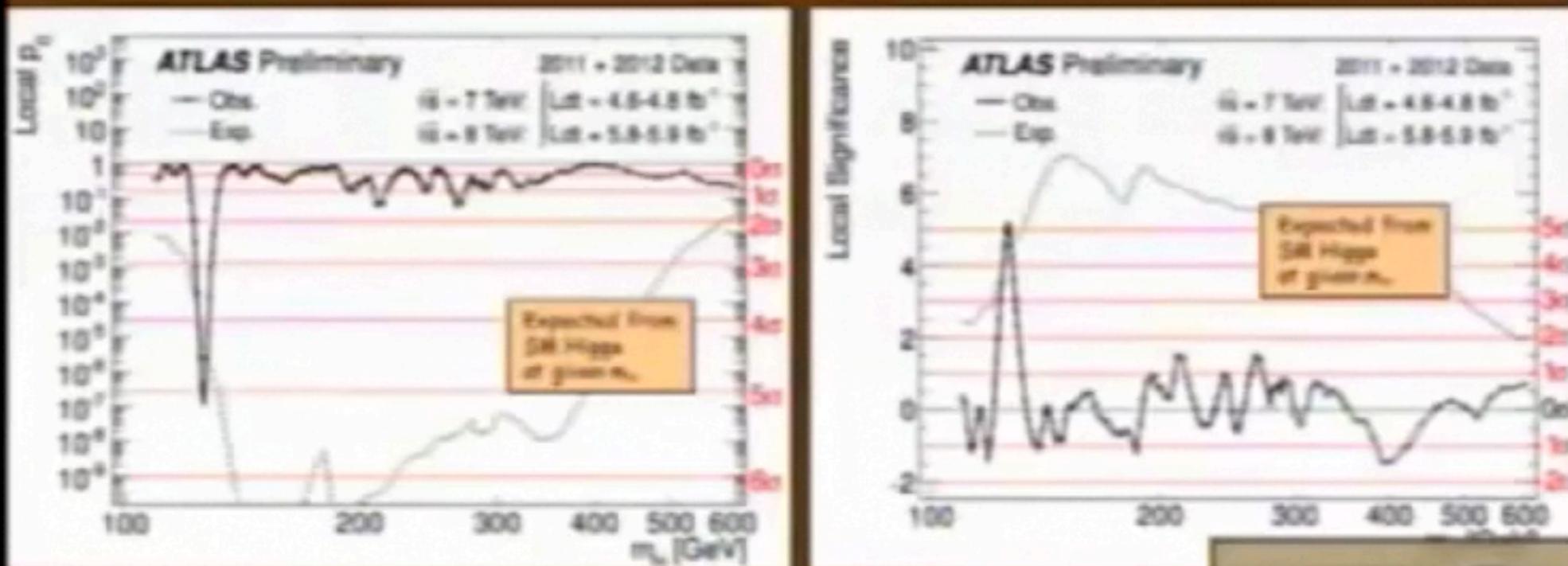


July 4, 2012.

A particle like the Higgs boson has been discovered!

The Big Announcement

Combined results: consistency of the data with the background-only expectation and significance of the excess



Excellent consistency (better than 2σ) of the data with the b hypothesis over full mass spectrum



CERN, July 4, 2012.



Chasing the Higgs Boson | INTRODUCTION | PROMISED FIREBALLS | GAME OF BLAMPS | STILL MISSING | DOZING 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, 2012 | 212 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 McCole/Photographs by Daniel Aul der Weiser, Tom Albi, Fabrice Coffrin, 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 Incandella, Guido Tonelli and Fabiola Gianotti.



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

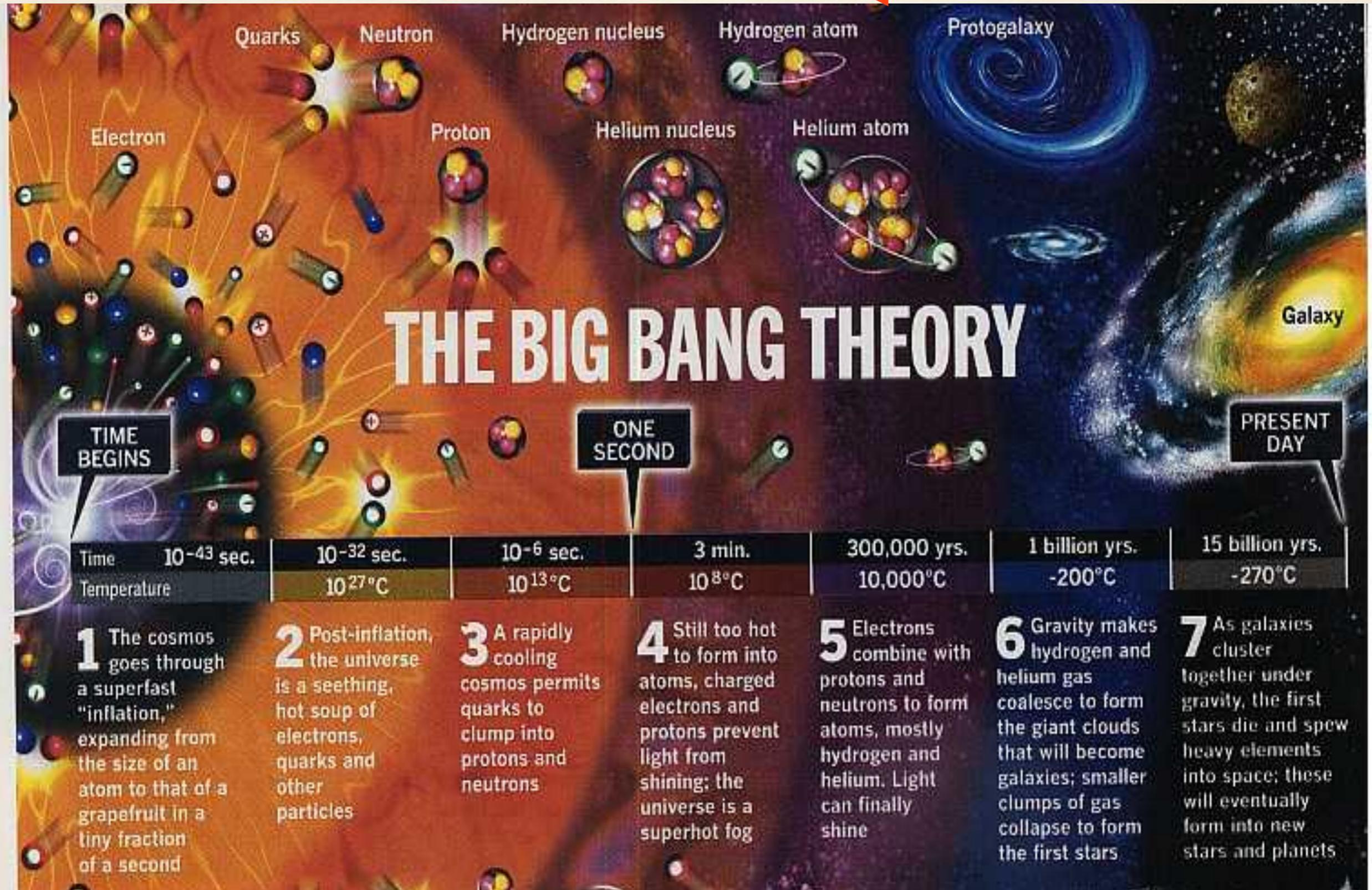


October 8, 2013 Nobel announcement:
Nobel Prize in Physics won by Peter Higgs and
Francois Englert.

all forces unified (?)

strong, EM, weak forces separate

high energy particle experiments probe conditions back in time

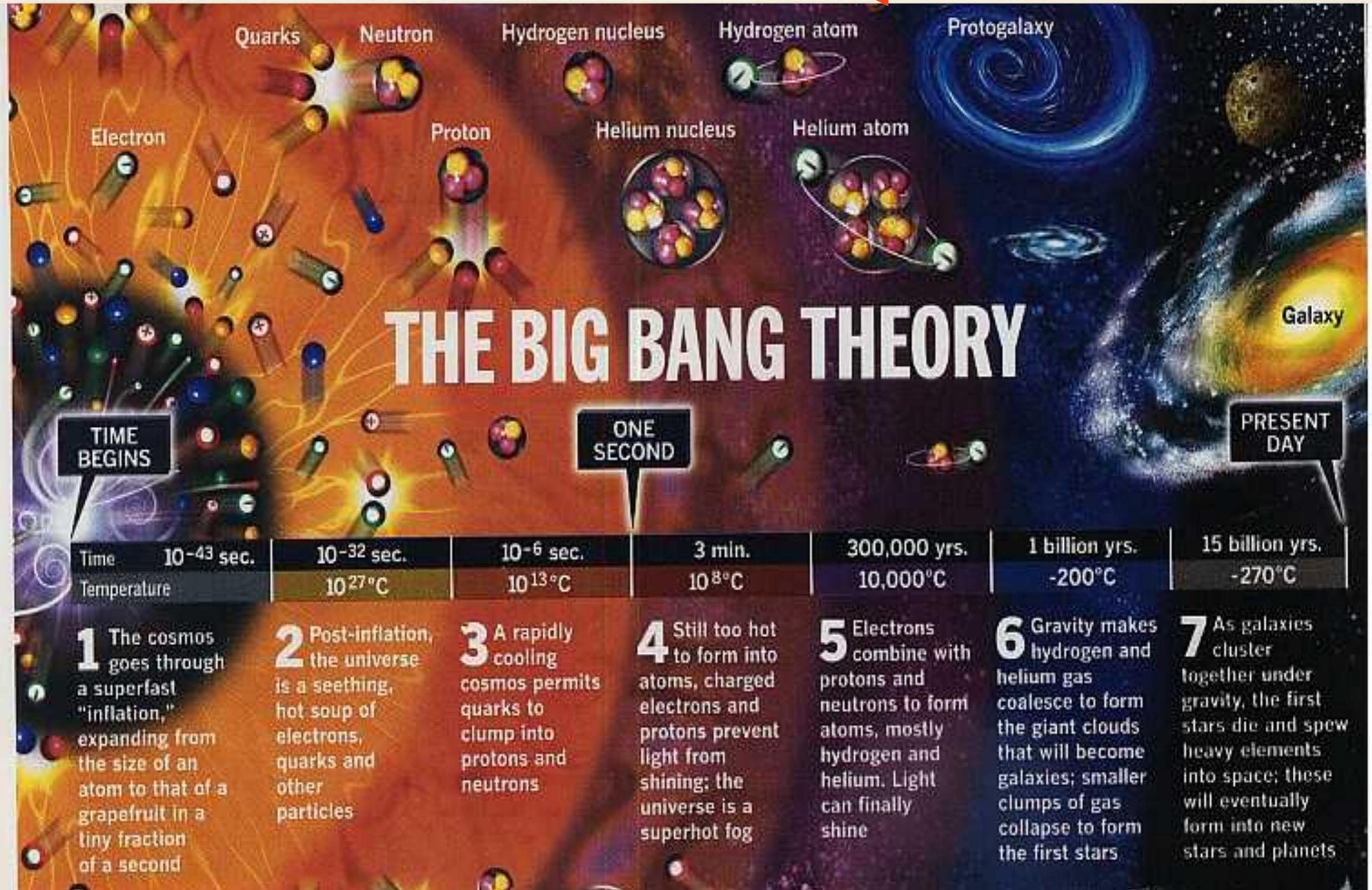


Puzzles in particle physics are tied to
puzzles in cosmology.

all forces unified (?)

strong, EM, weak forces separate

high energy particle experiments probe conditions back in time

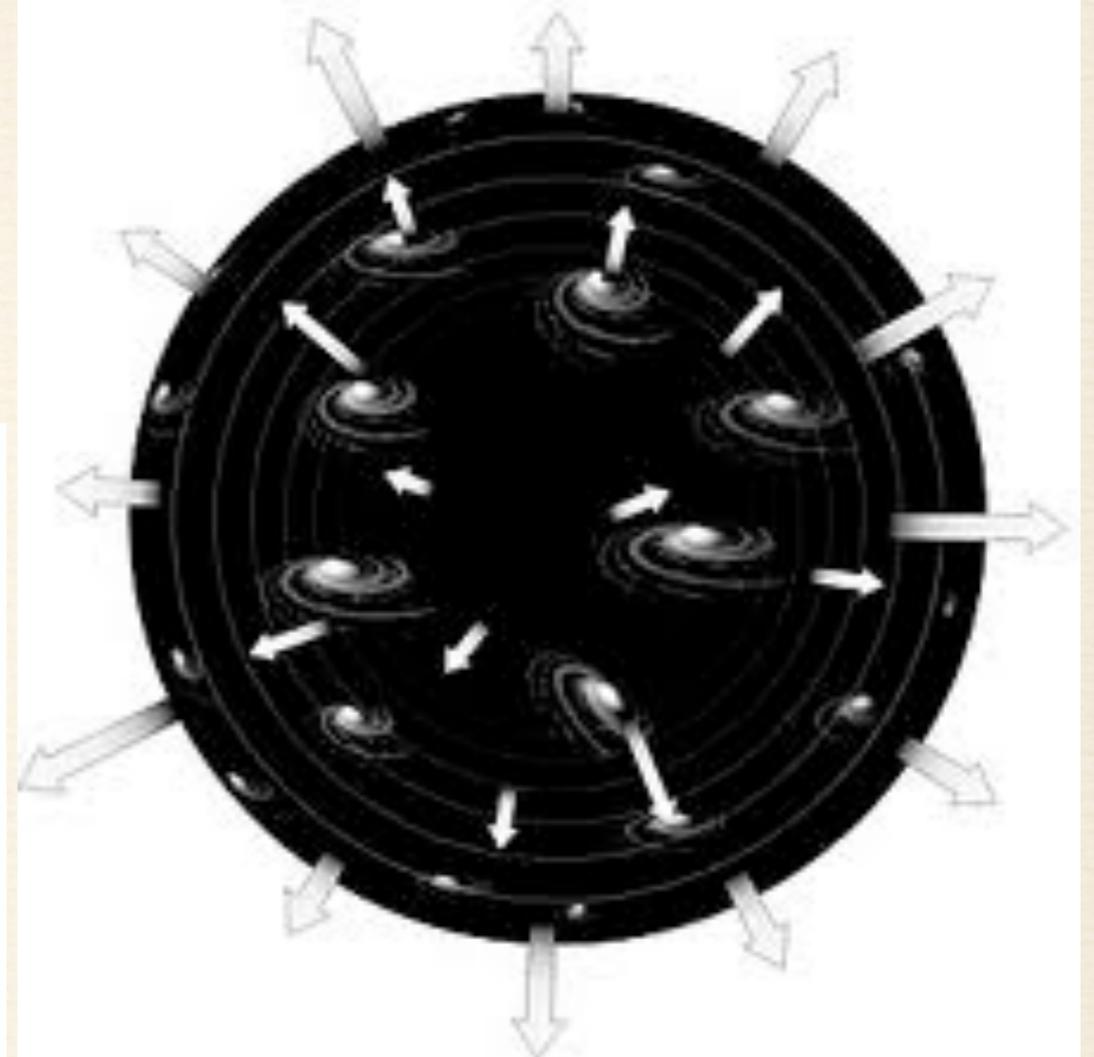
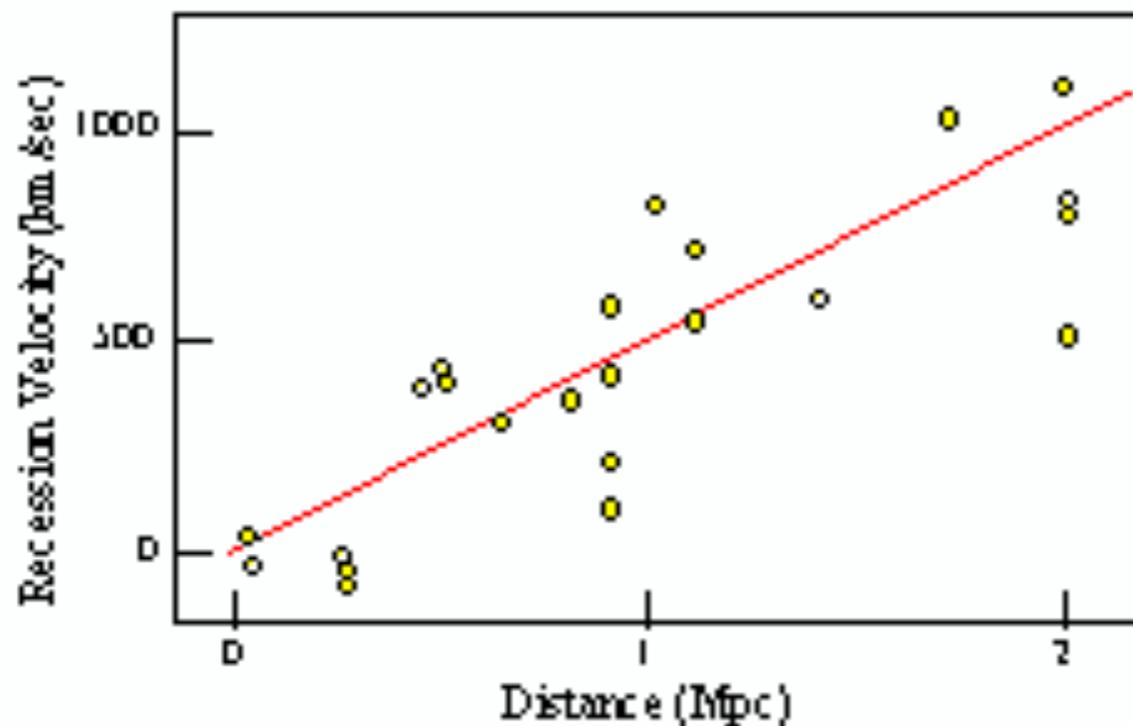


Evidence for an Expanding Universe

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

The universe is expanding!

Hubble's Data (1929)

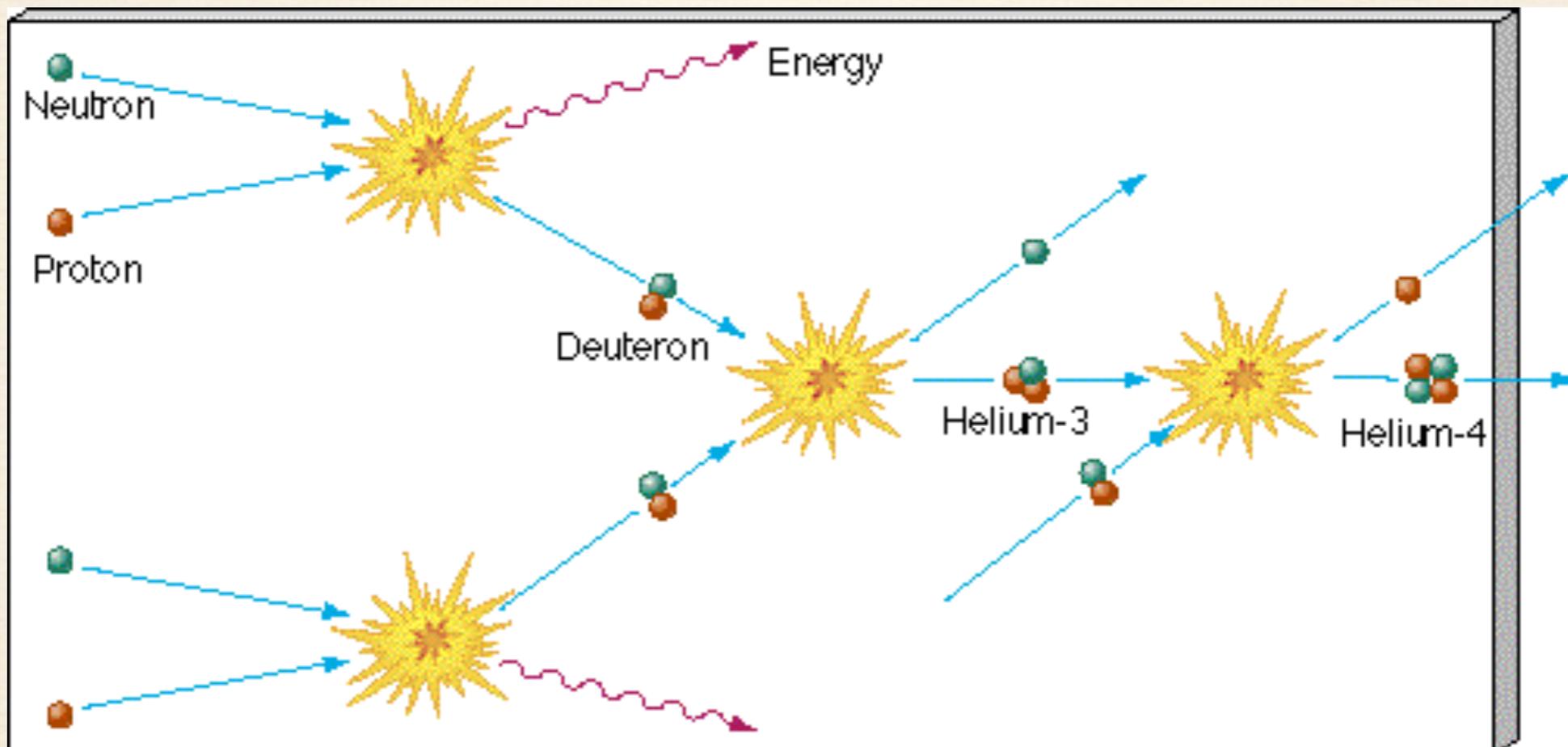


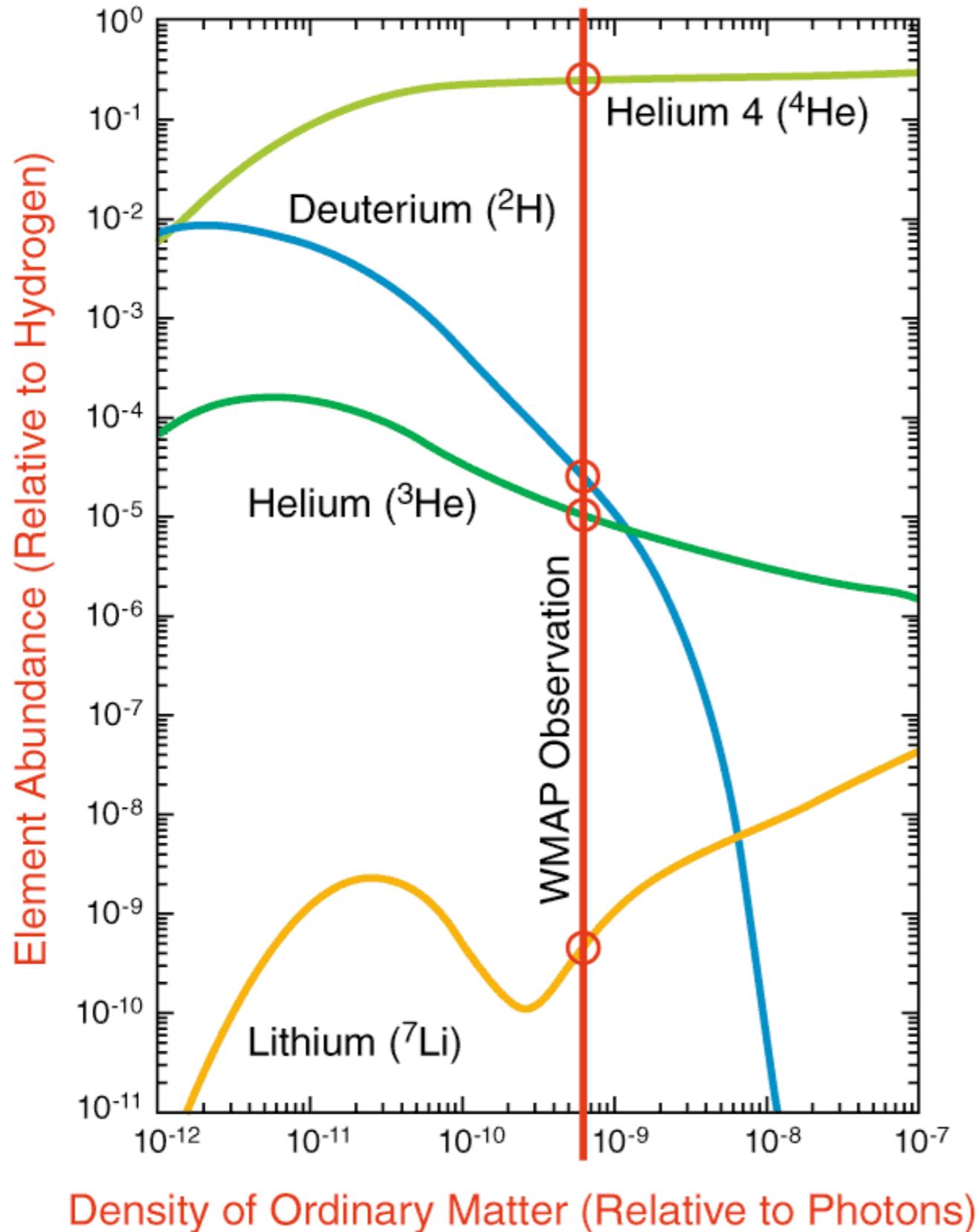
H_0 = "Hubble constant"
= 70 km/s/Mpc
(measured value)

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.





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

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

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

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

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?



Hmm, that's strange.

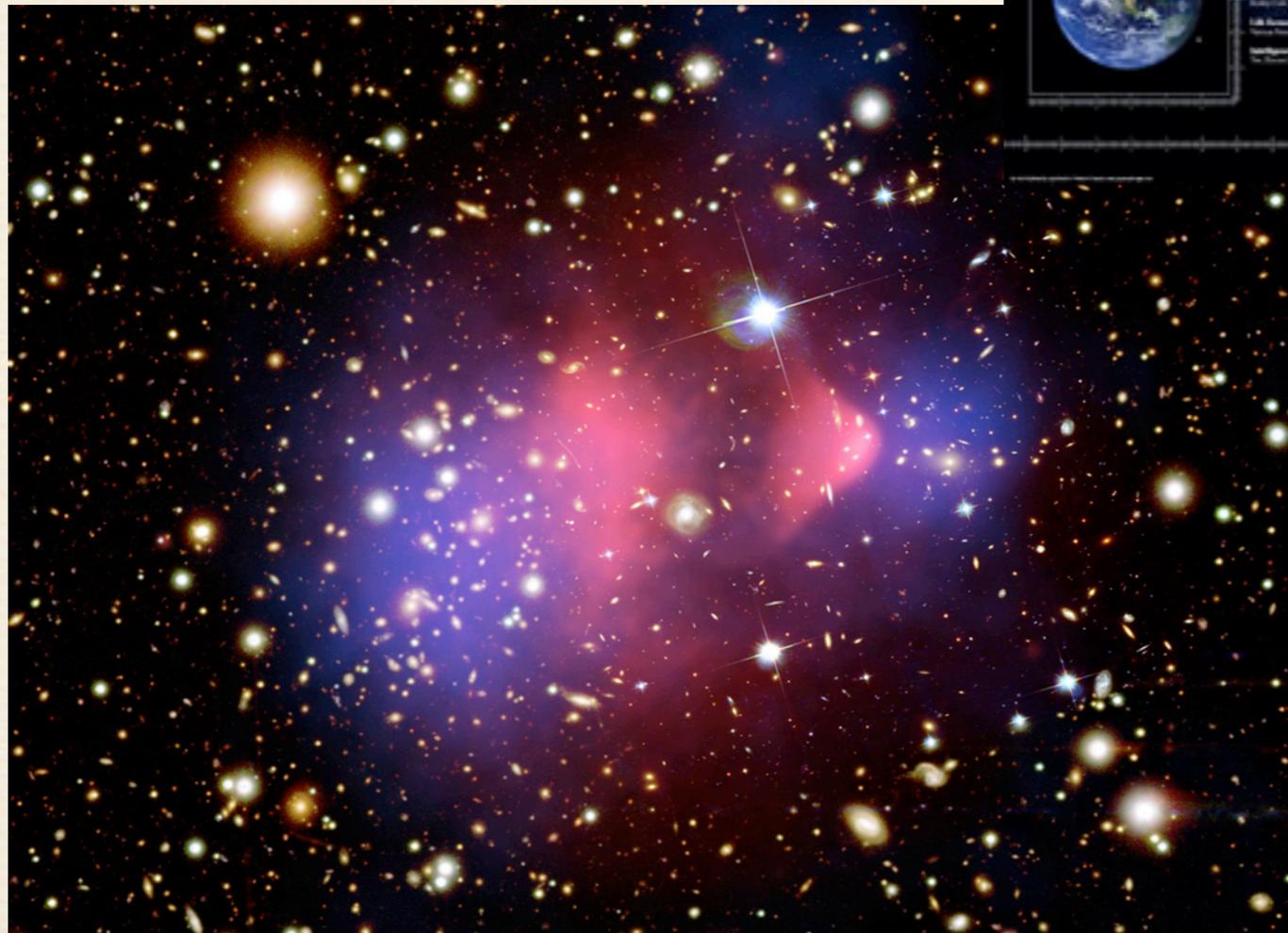
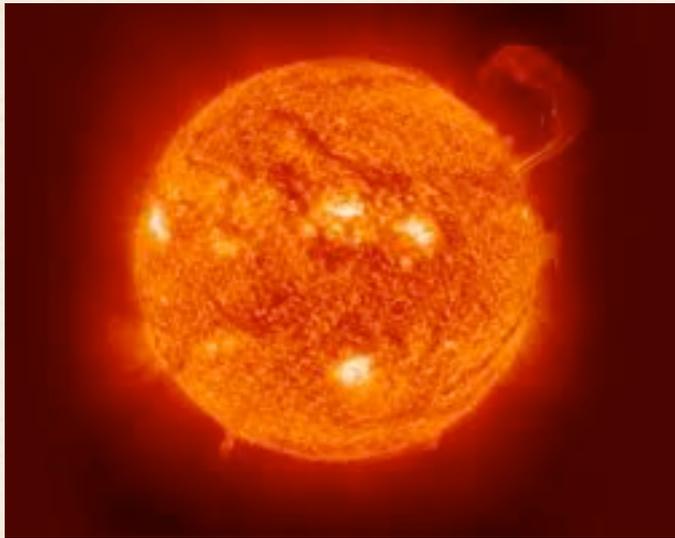
http://www.oddee.com/item_98259.aspx

Look at all that
mass!

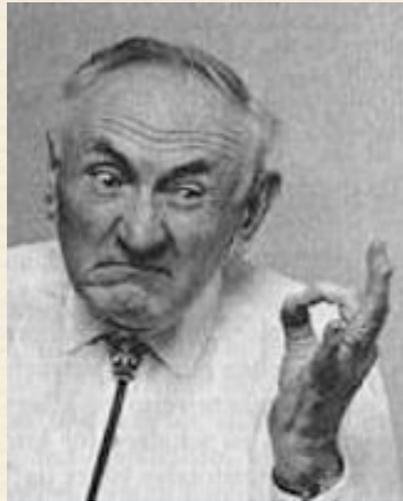


http://www.oddee.com/item_98259.aspx

Matter in the Universe

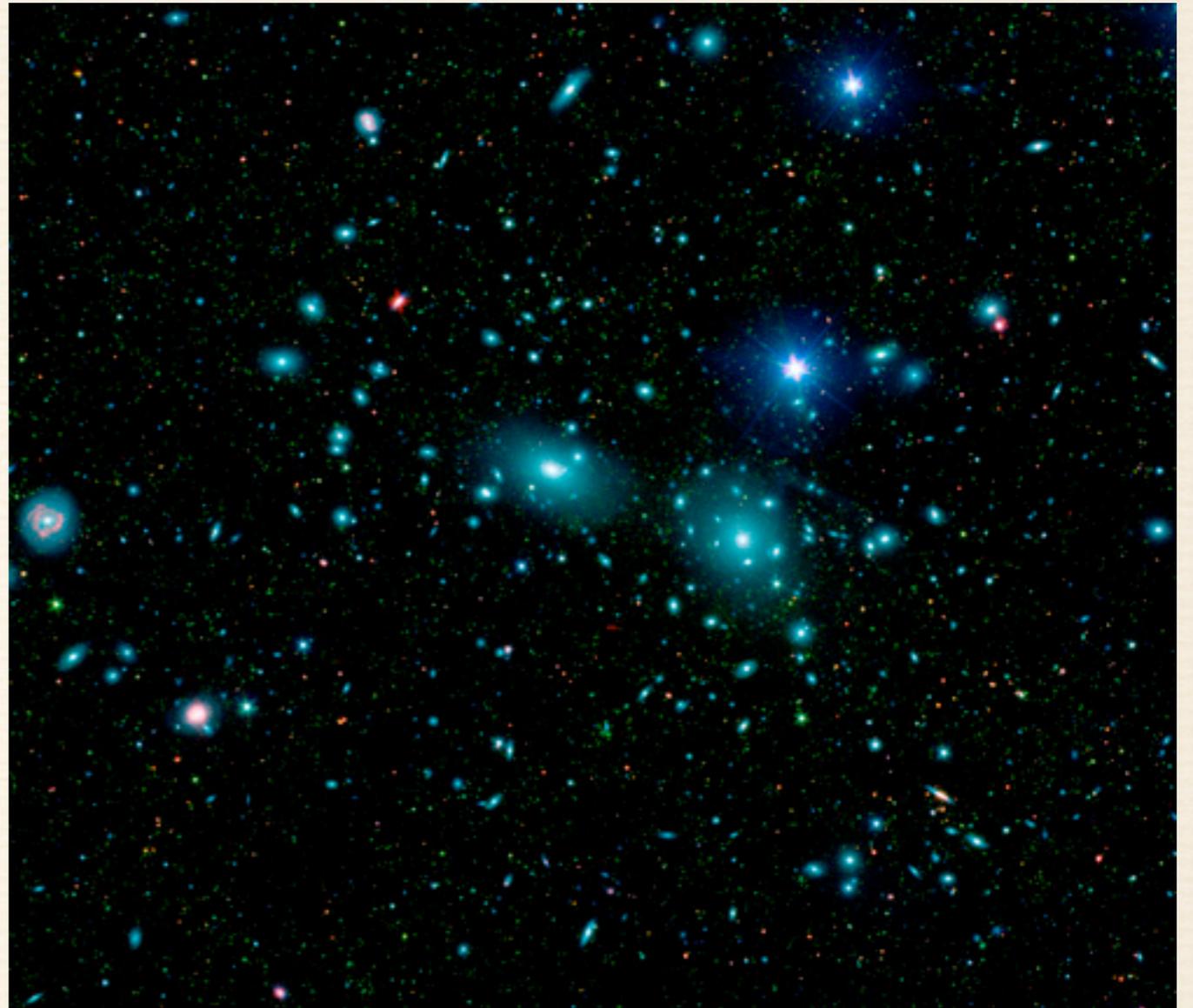


Dark Matter



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

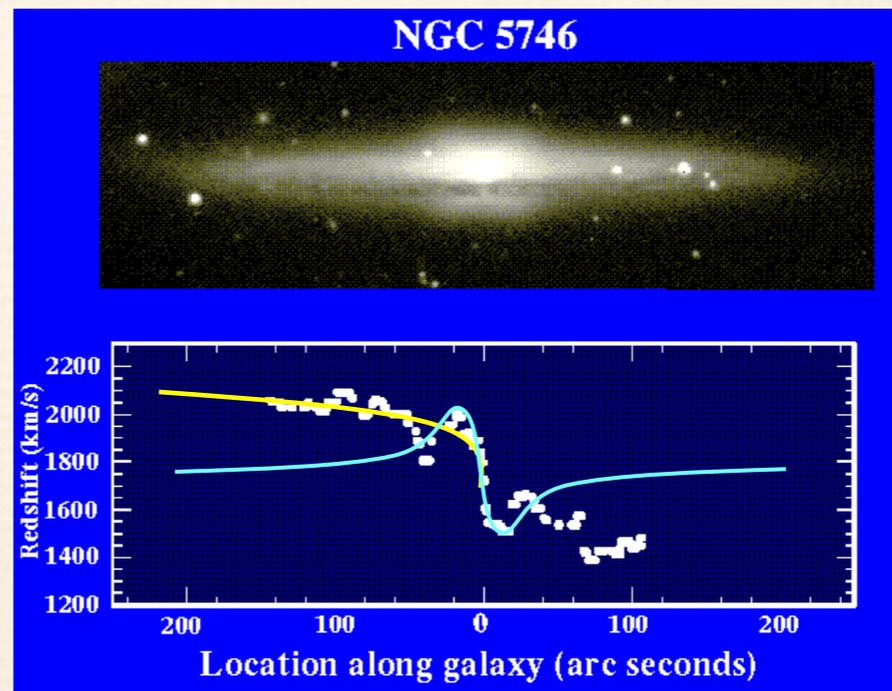


Vera Rubin



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!



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

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

Gravitational Lensing

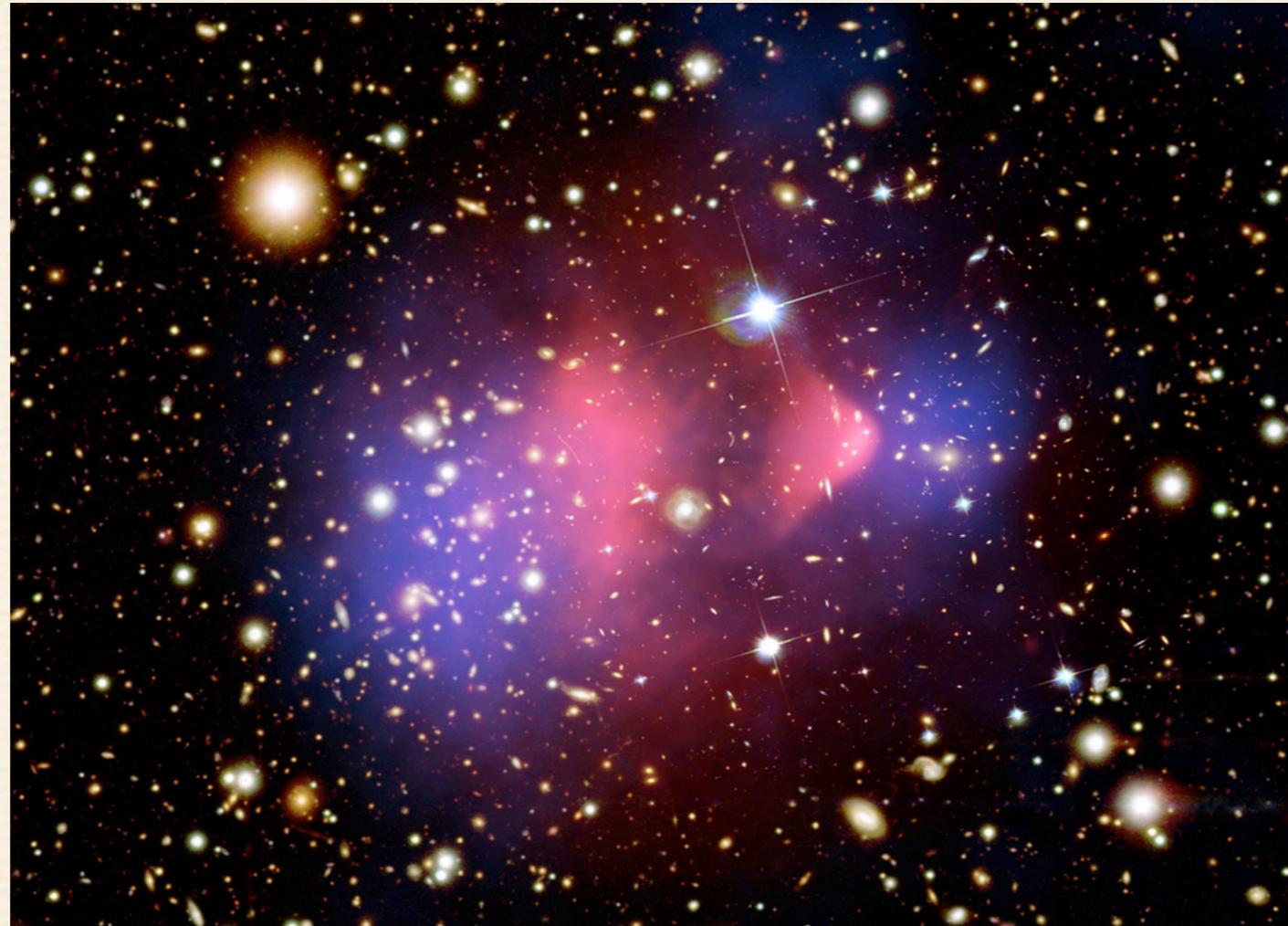
Light is bent by gravity, so we can weigh an object in the line of sight of a distant galaxy by measuring how much the light from the galaxy bends.

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

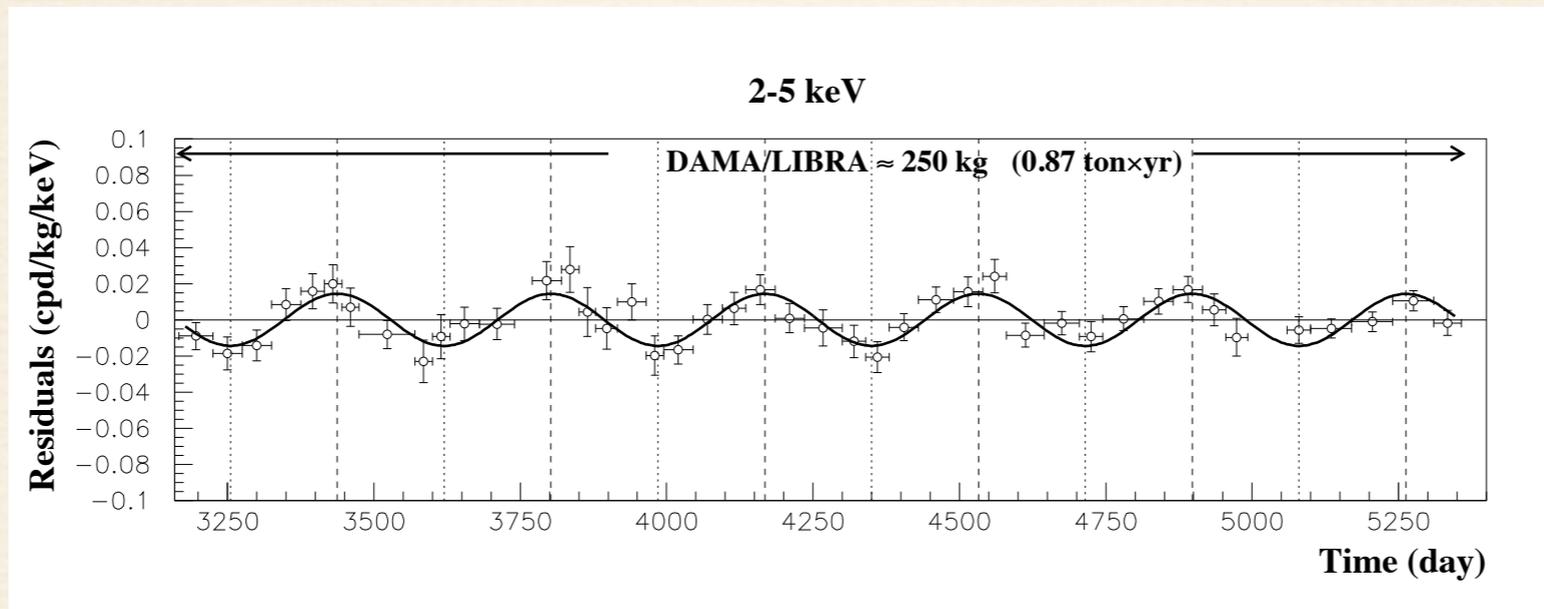


http://www.cacr.caltech.edu/SDA/digital_sky.html

The Bullet Cluster



Chandra X-ray Observatory, 2006



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

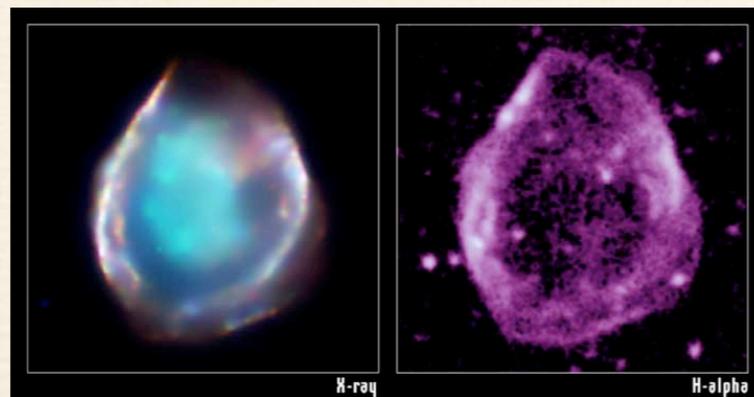
Type Ia Supernovae

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.

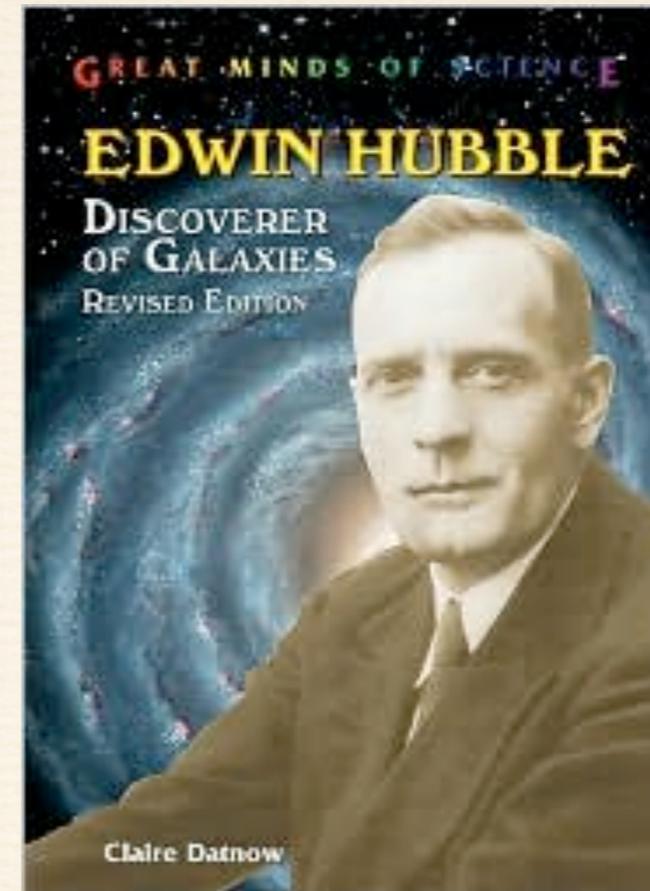
How far? Use a standard candle. That's where the Type Ia supernovae come in.



DEM L71

<http://chandra.harvard.edu/photo/2003/deml71/>

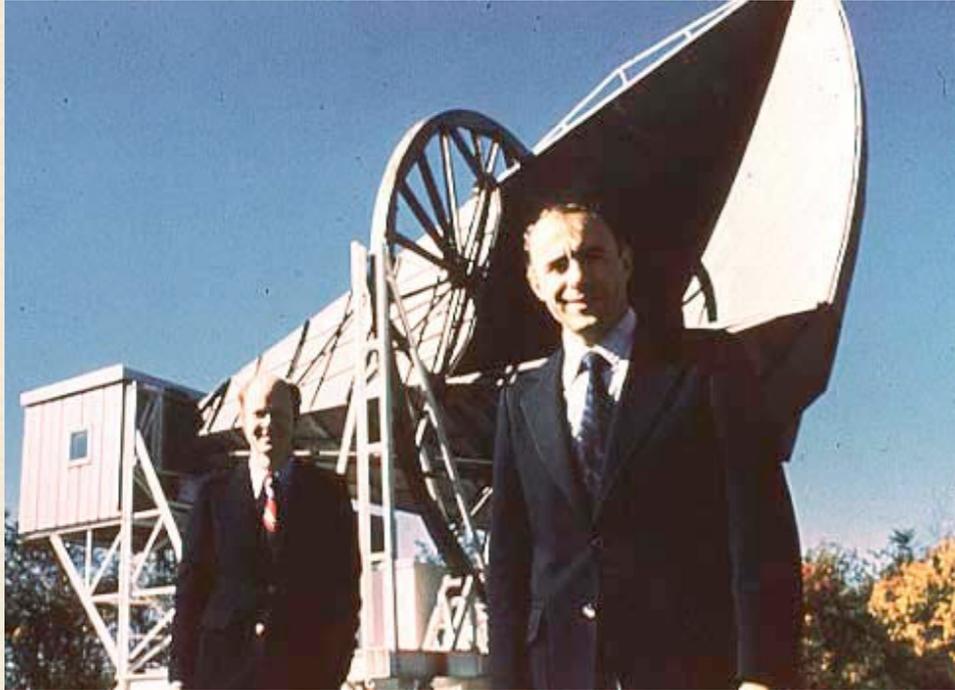
The Universe is Expanding



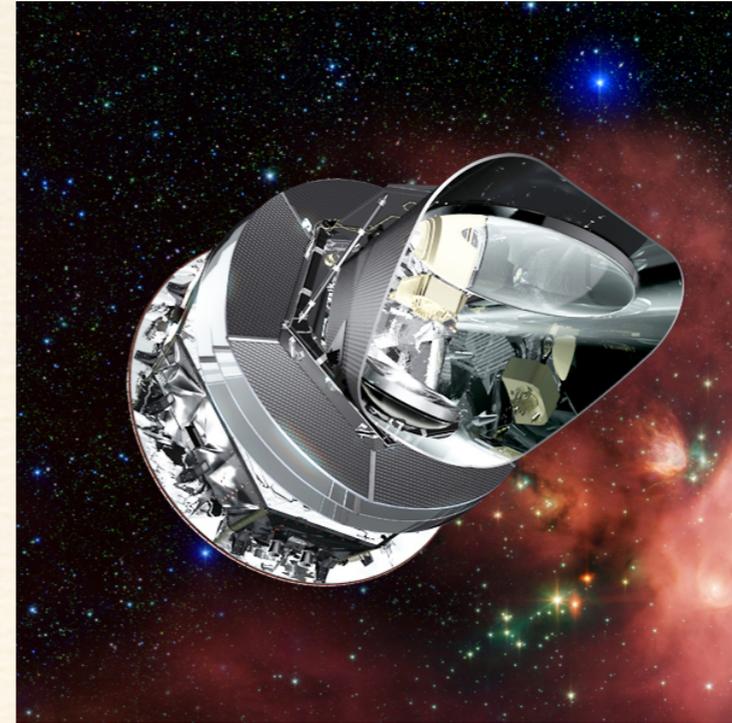
Saul Perlmutter - Supernova Cosmology Project

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

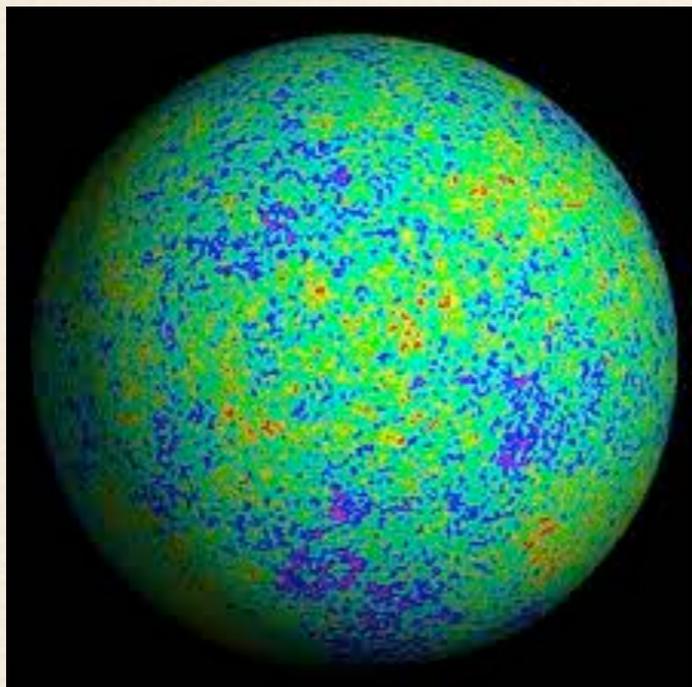
The Cosmic Microwave Background



Arno Penzias and Robert Wilson



Planck Satellite

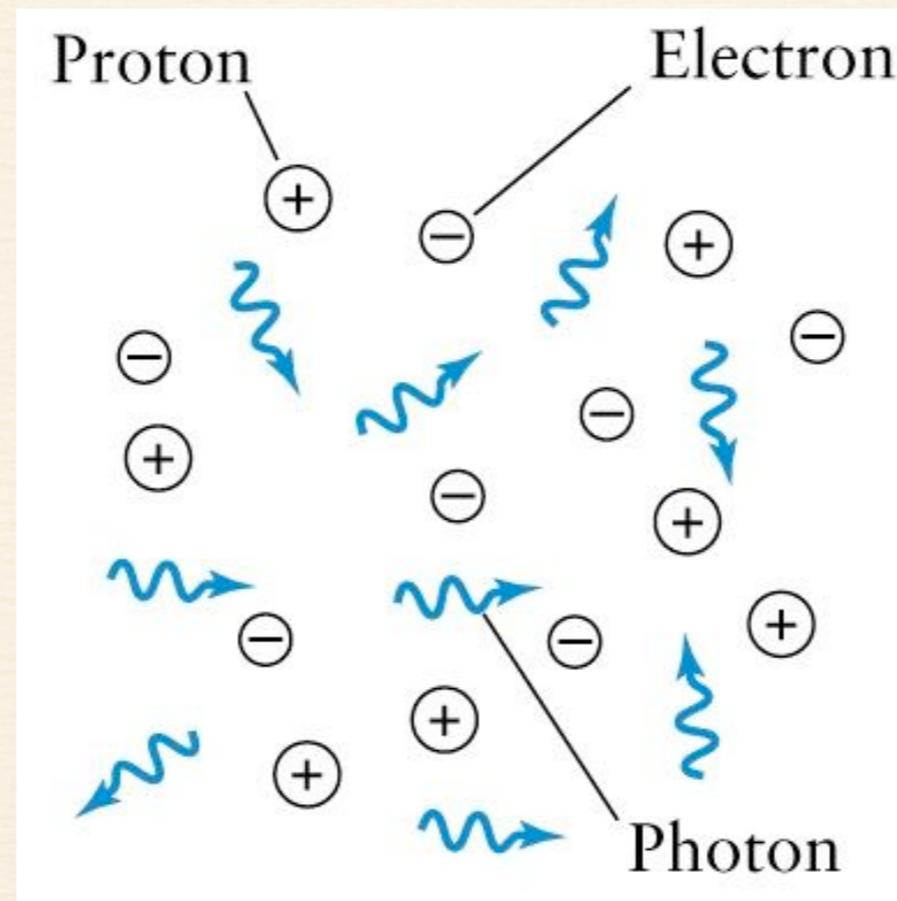


Hot and cold spots in the CMB

(Fast forward → Stars, galaxies, ...)

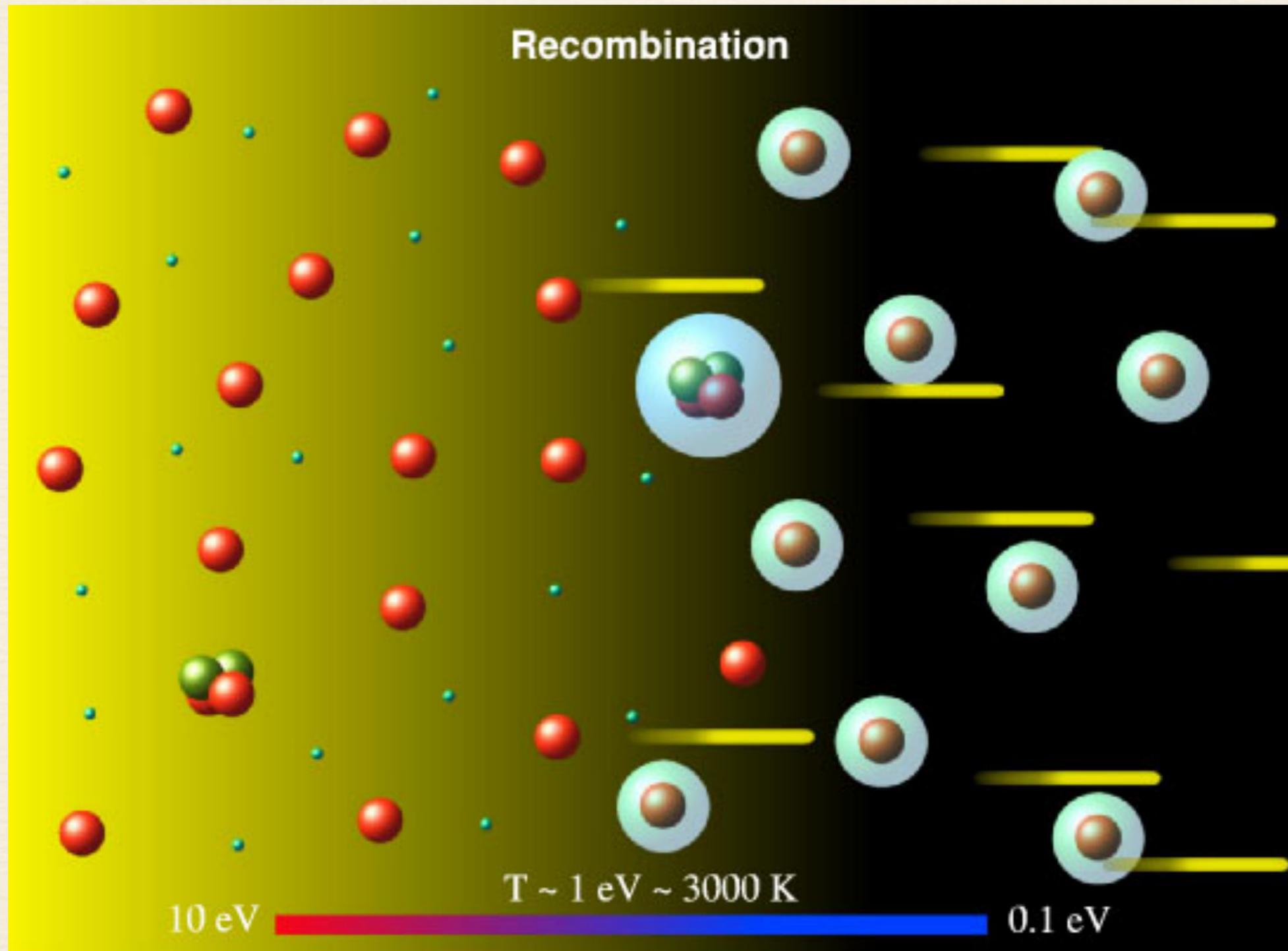
The Opaque Early Universe

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

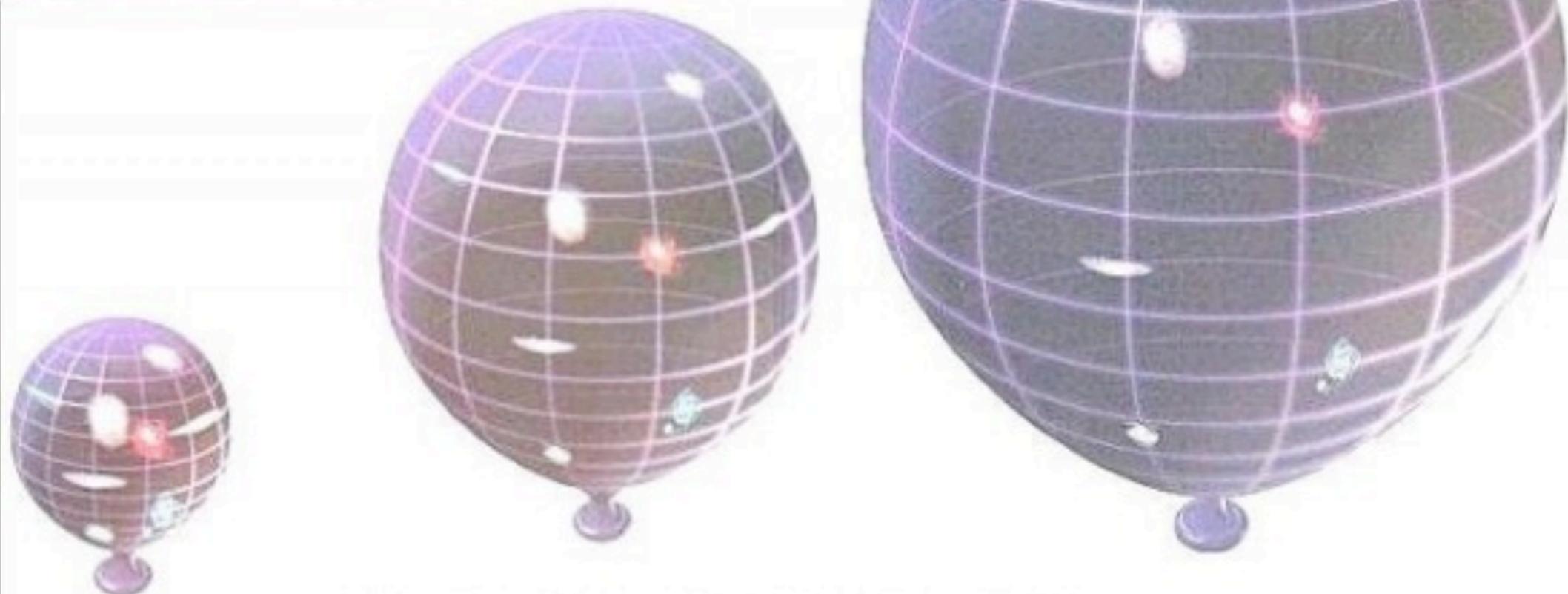
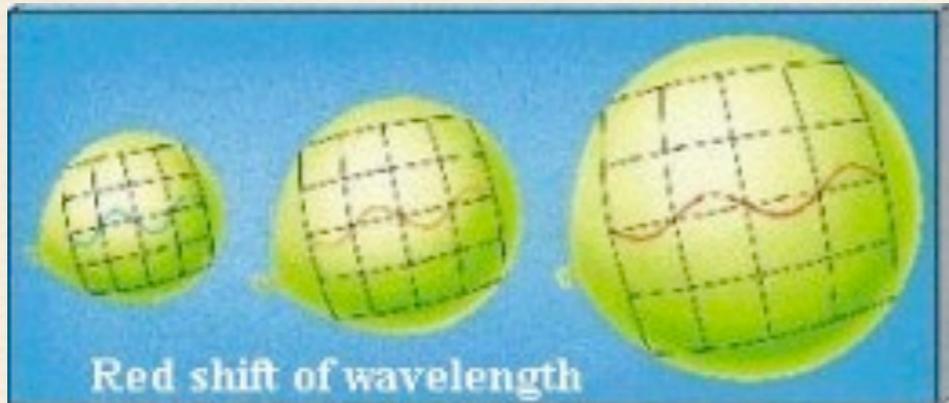


Then...

Recombination: Atoms Form!

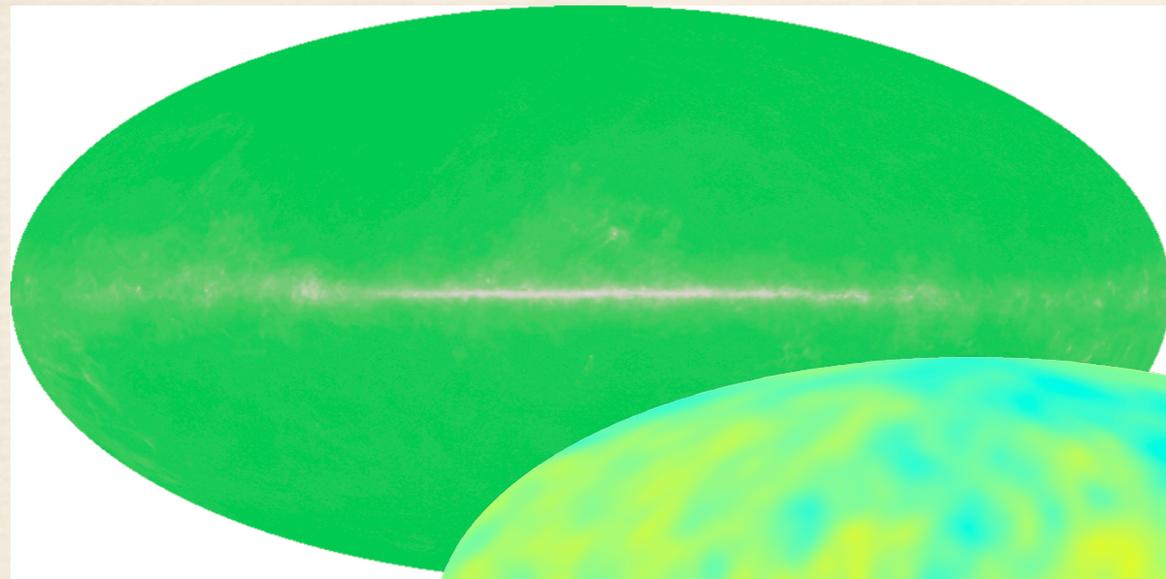


Universe Expands and Cools (light redshifts by factor of 1100)



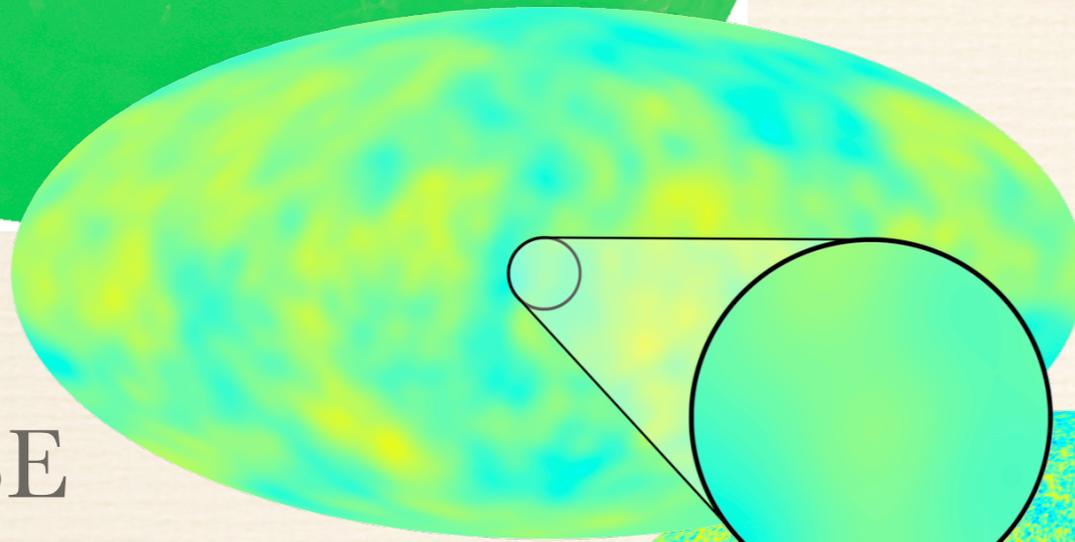
Expanding distance between galaxies

Temperature deviations in the CMB

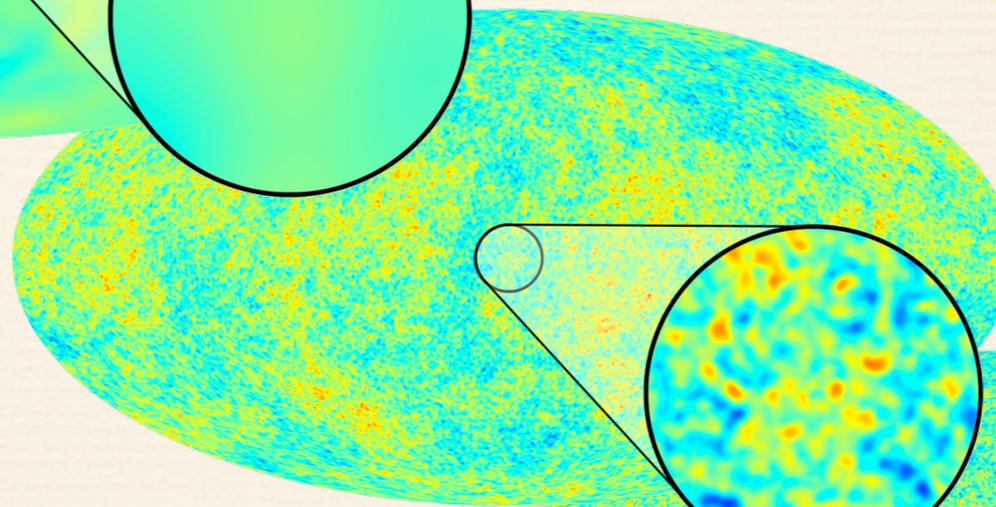


Penzias & Wilson (simulated)
(1960s)

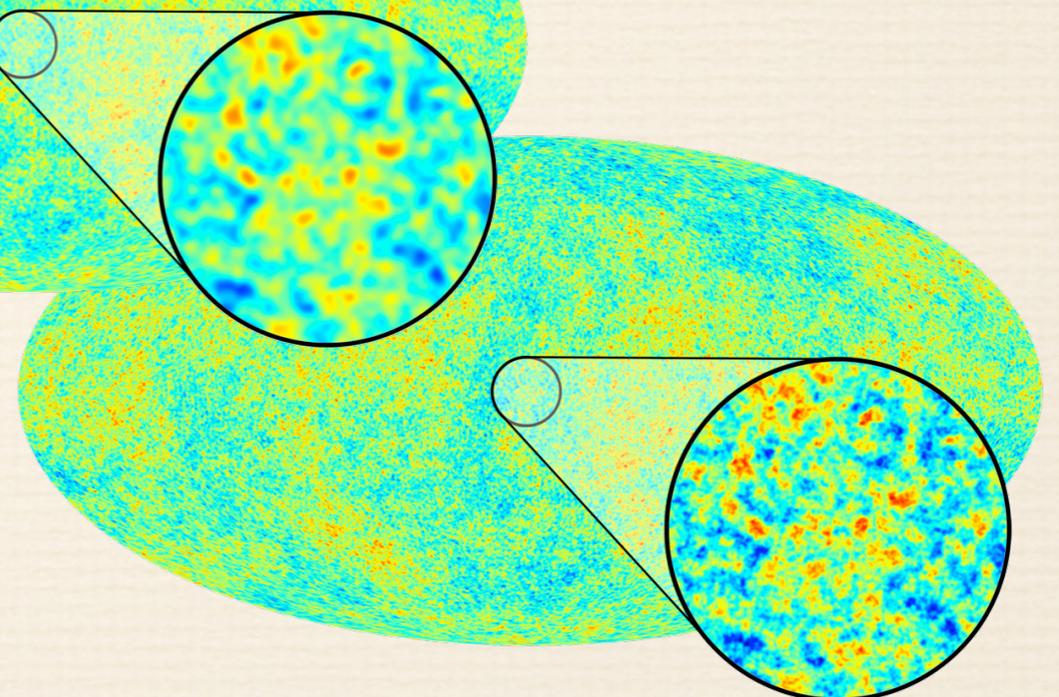
COBE
(1990s)



WMAP
(2000s)



Planck
(2010s)



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.