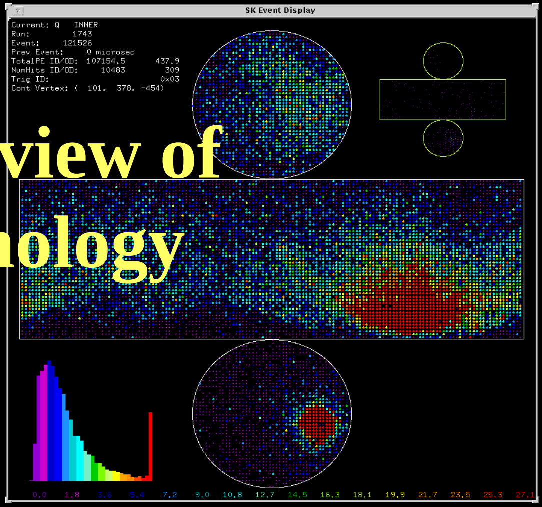
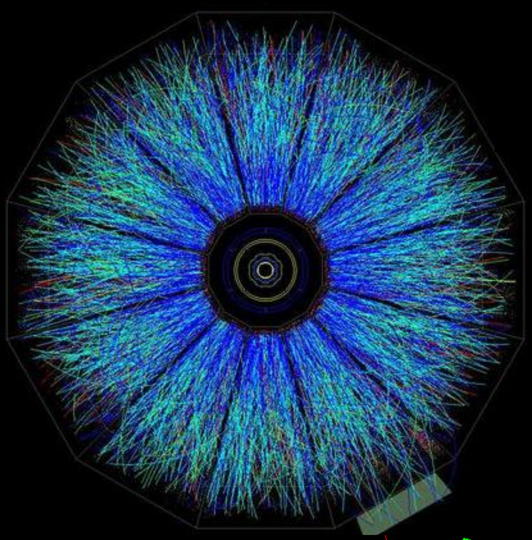
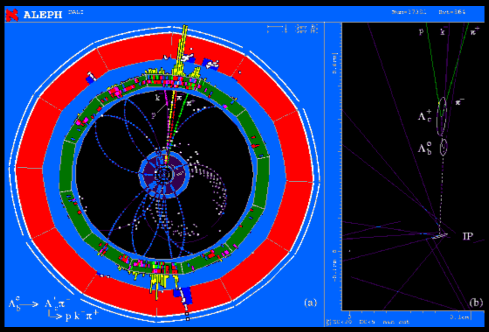
Physics 123
Blistering conceptual overview of particle physics and cosmology

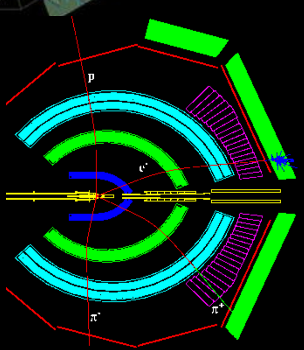


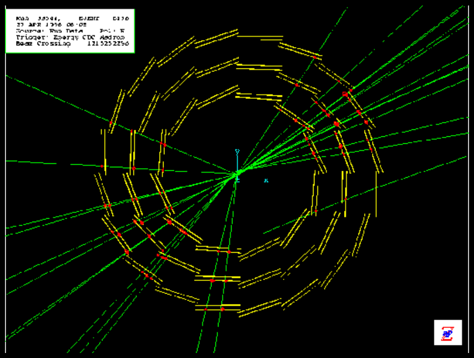


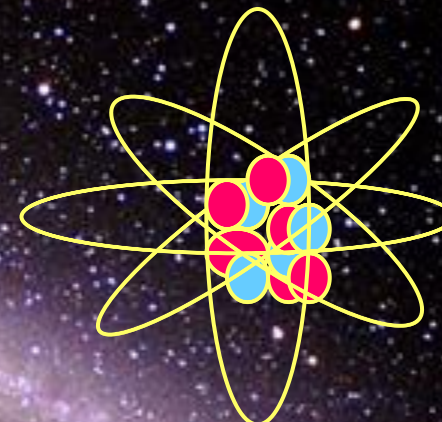
S. Manly
Univ. of Rochester



May 1, 2013

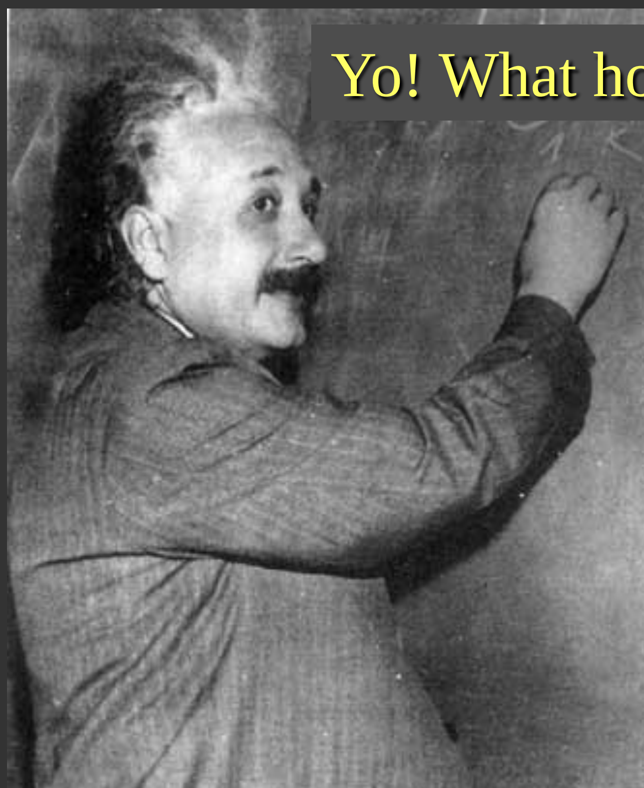




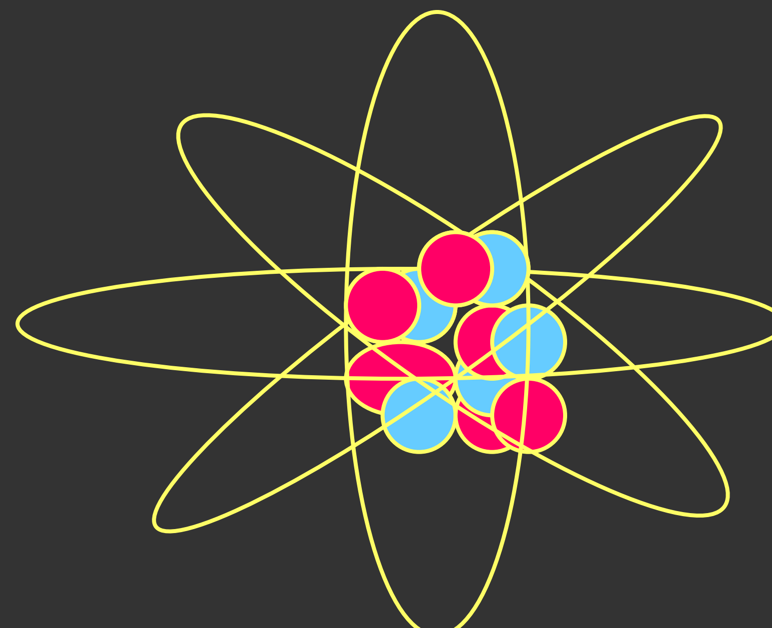


The intimate relationship between the very big and the very small

Inquiring minds want to know ...



Yo! What holds it together?



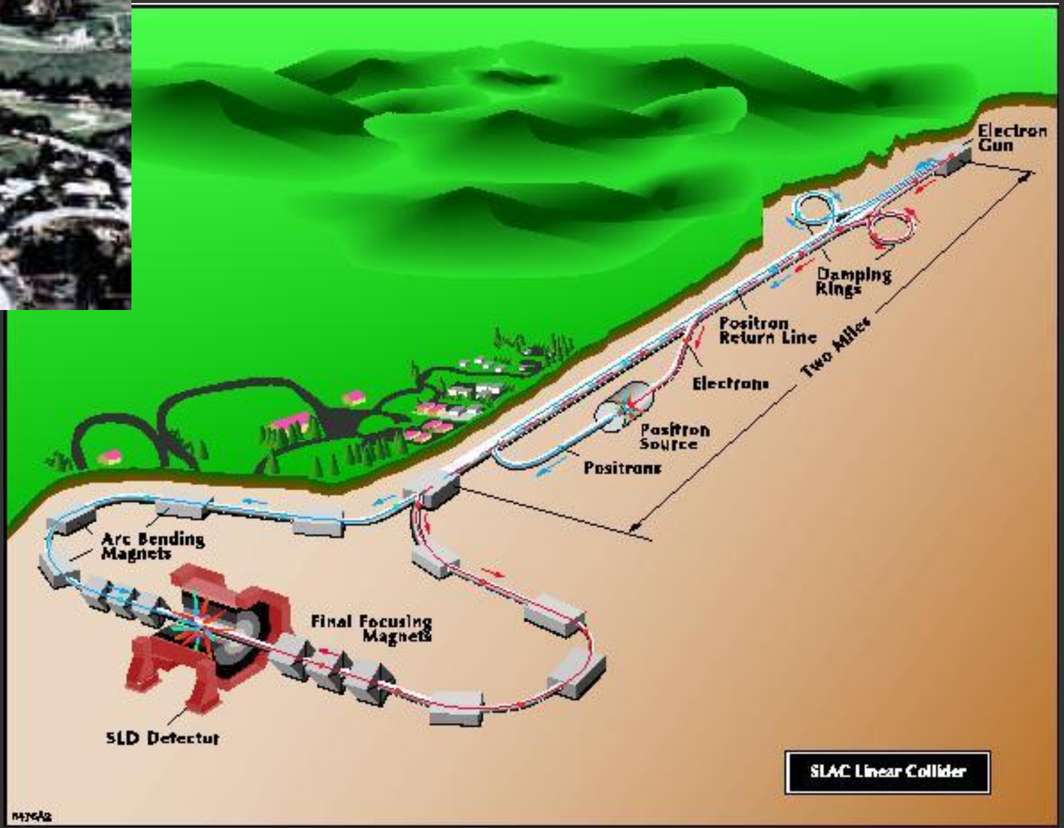

52
46
ACXIOM
27
HASTINGS

Fermi National Accelerator Laboratory (near Chicago)

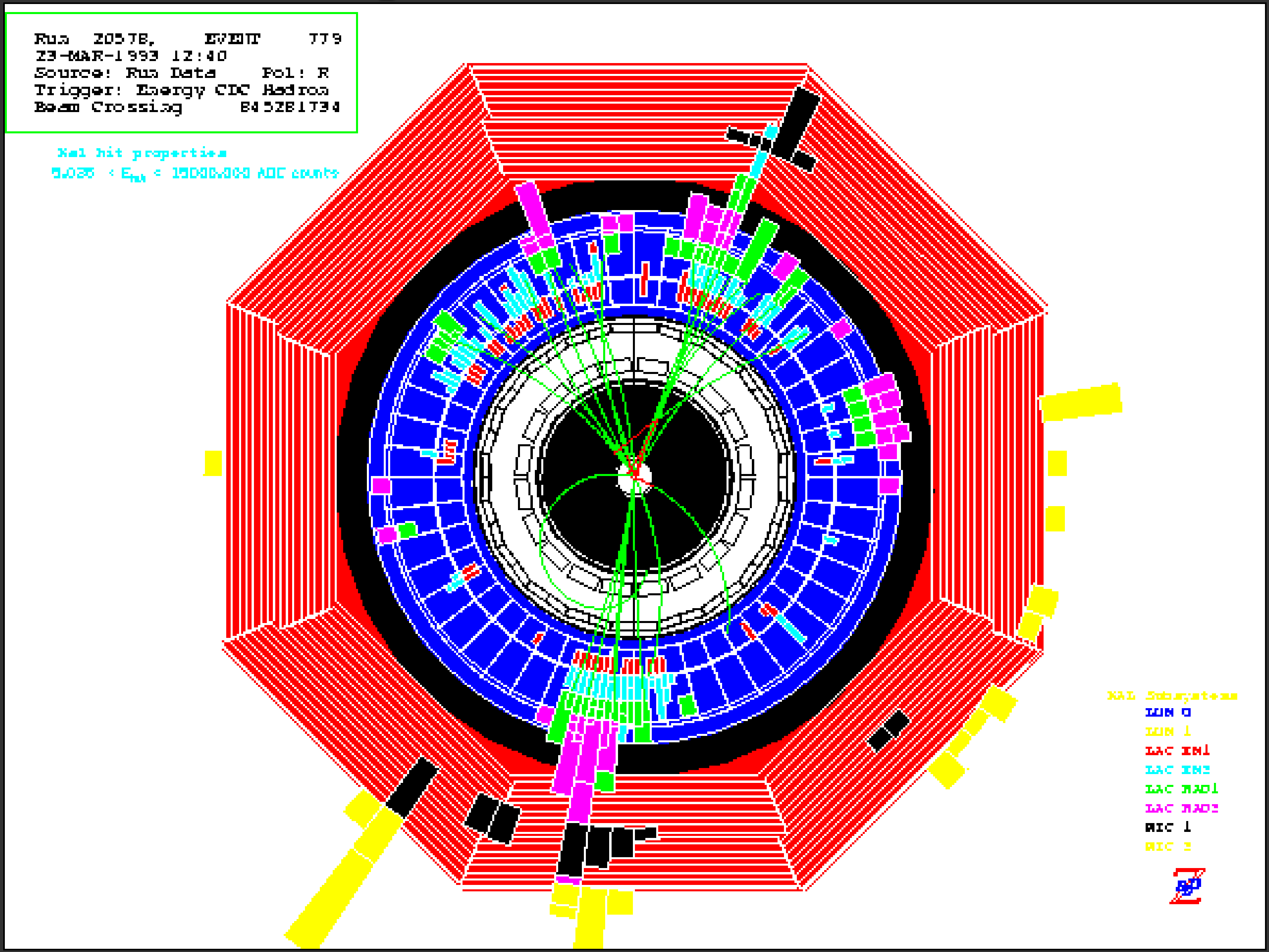
CDF

Minos

Stanford Linear Accelerator Center

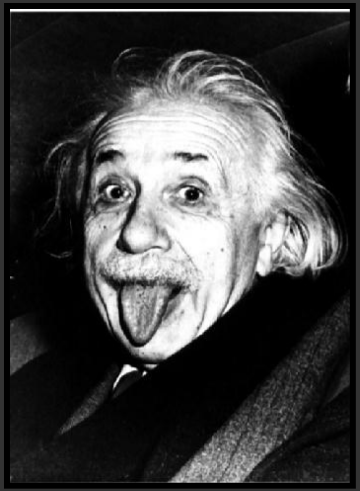


Event display from the SLD experiment at SLAC



What forces exist in nature?

What is a force?



How do they interact?

How do forces change with energy or temperature?

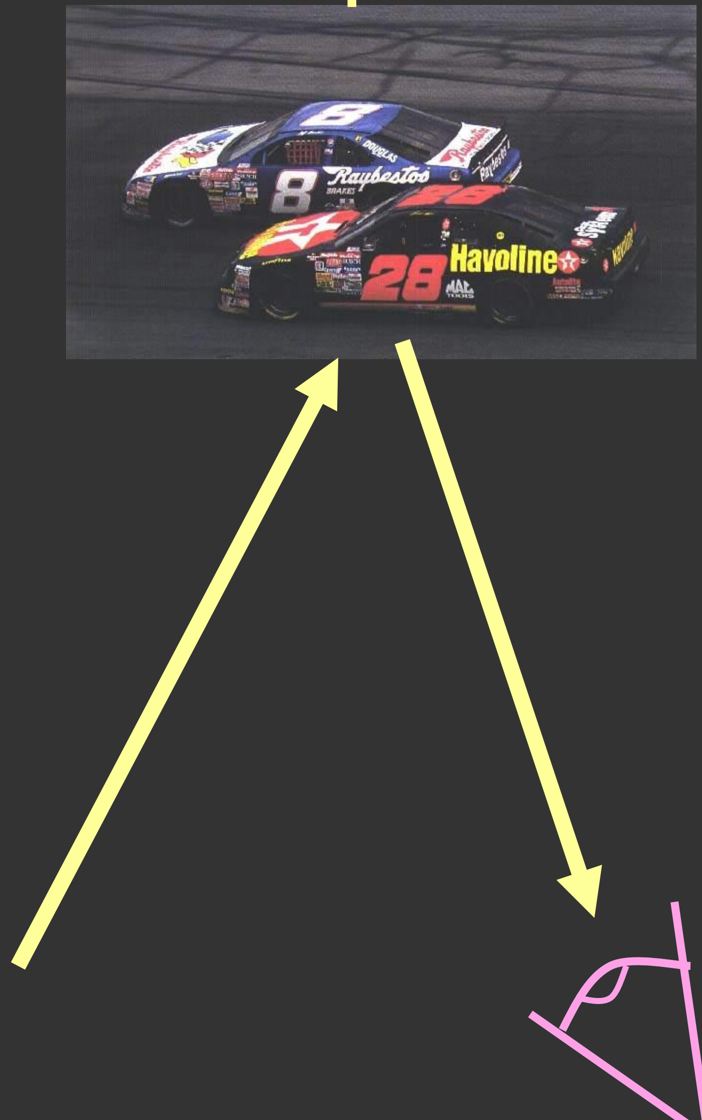
How has the universe evolved?

Mini-Ph.D. – Quantum Mechanics 101

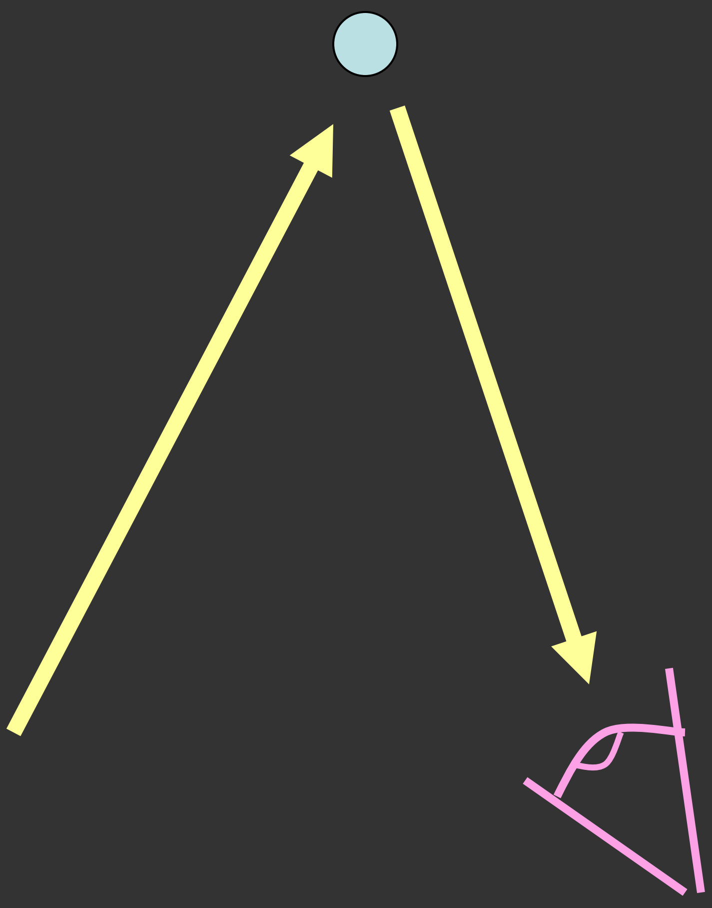
Lesson 1:

Size actually does matter.

Determine the postion and velocity of a car … no problem

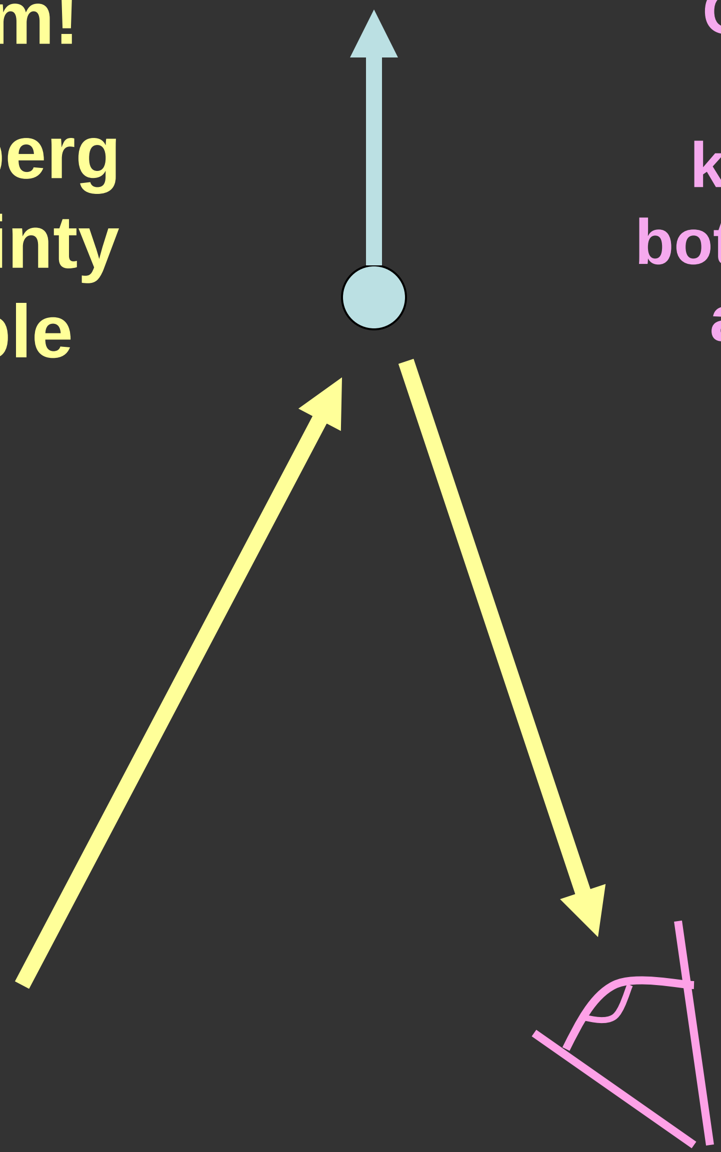


Determine the postion and velocity of a small particle … no problem



Problem!

Heisenberg uncertainty principle



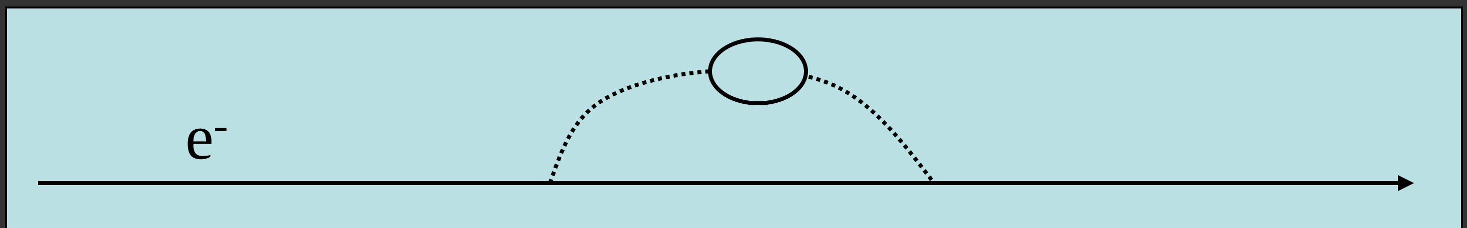
Cannot have perfect knowledge of both the position and velocity

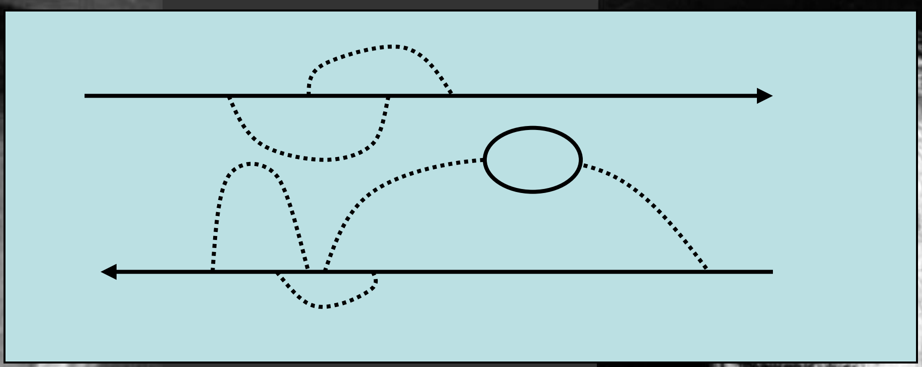
Heisenberg

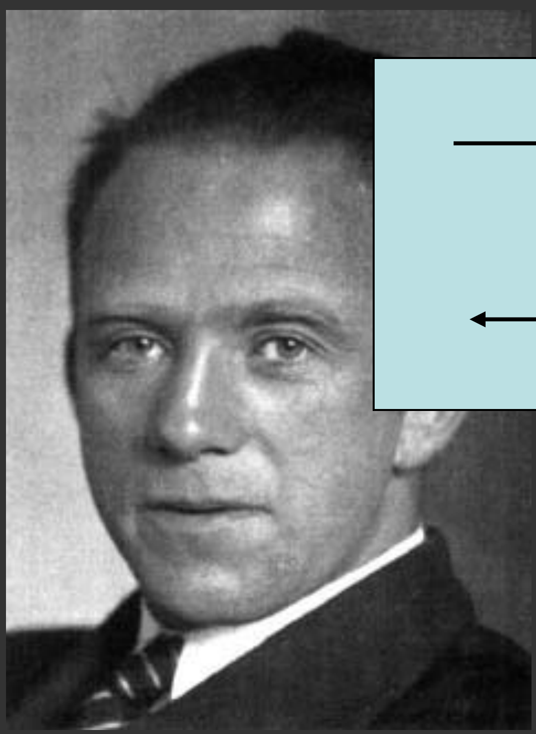
The fundamental nature of forces: virtual particles

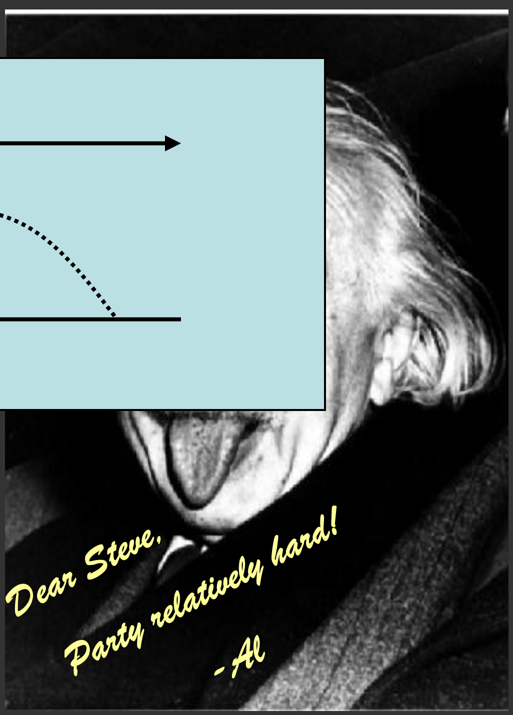
$\Delta E \Delta t \approx h$ Heisenberg

$E = mc^2$ Einstein









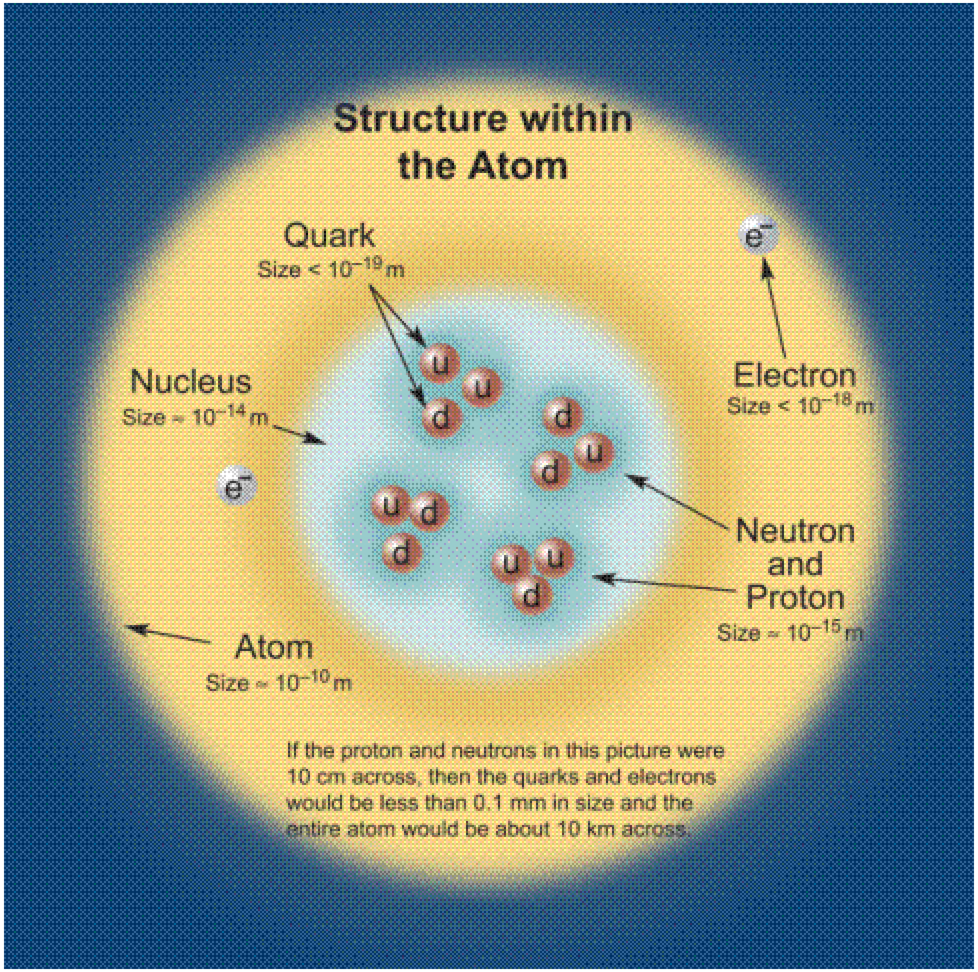
QUANTUM Field Theory → Exchange force

Standard Model of Particle Physics

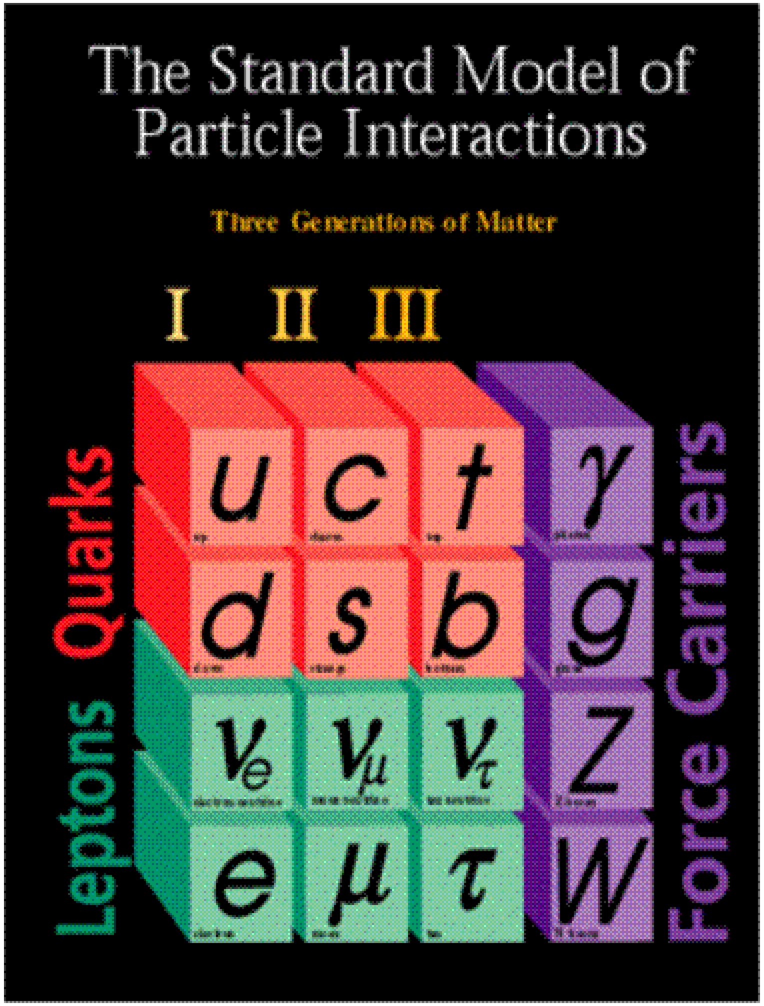
http://particleadventure.org/

http://hepwww.rl.ac.uk/Pub/Phil/ppintro/ppintro.html

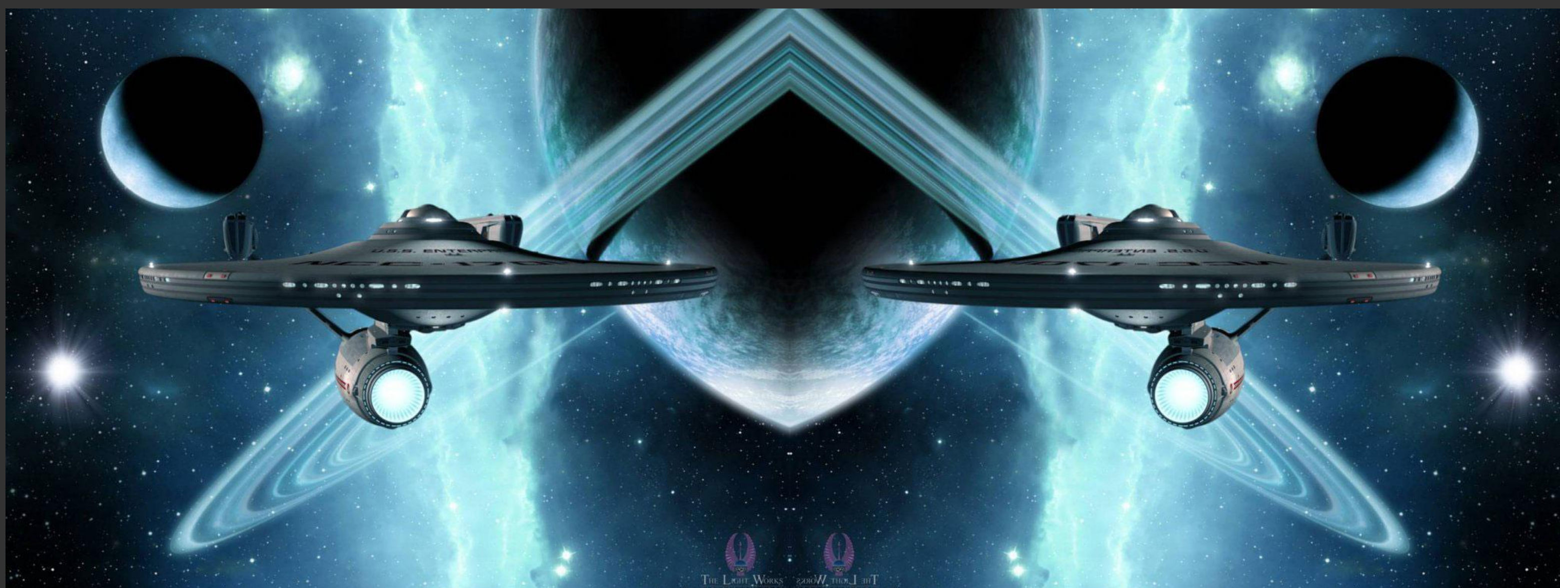
Decent online sources of information



The "Fundamental" particles

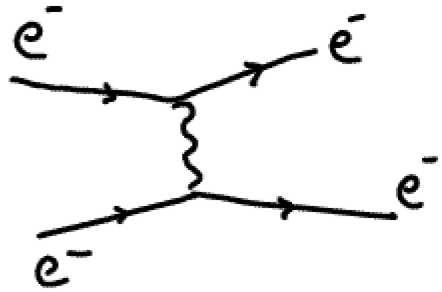


Antimatter Antimatter

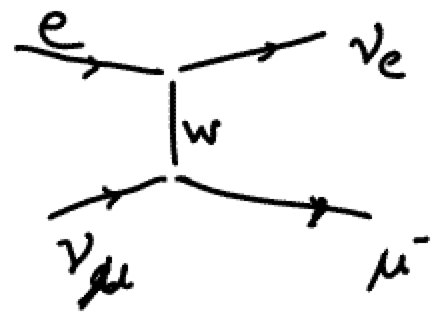


Same mass - Opposite electric charge and magnetic moment

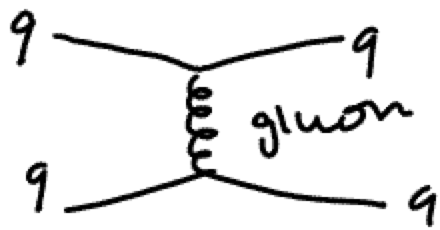
$\Delta E \Delta T \gtrsim h$



Electromagnetism



weak interaction



Strong force

BOSONS

force carriers
spin = 0, 1, 2, …

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

The Vacuum

-R. Kolb

Much ado about NOTHING:

Nothing is something

Nothing has energy

Nothing interacts with something

other particles

qqq

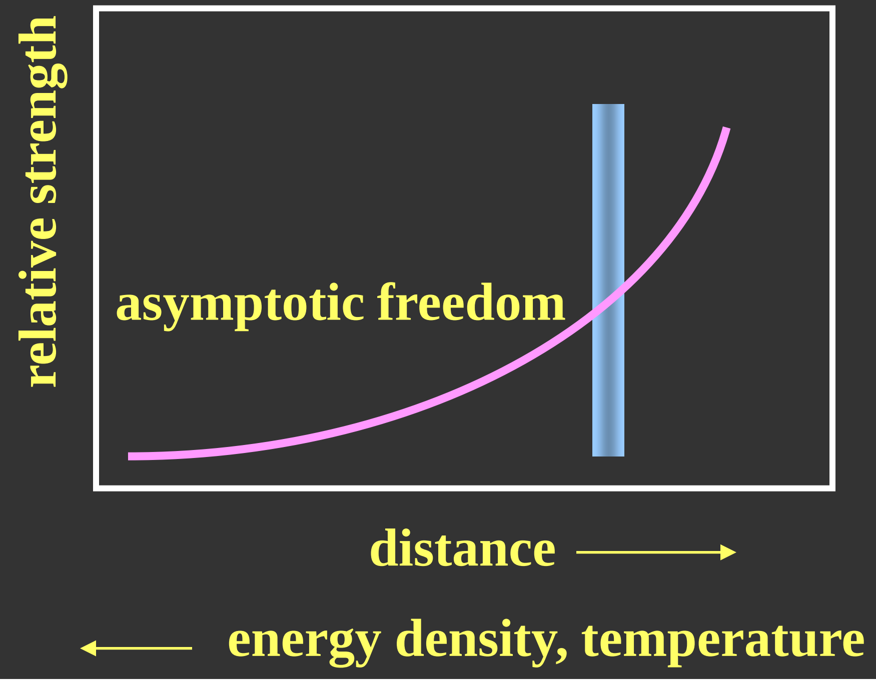
Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$ Baryons are fermionic hadrons. These are a few of the many types of baryons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	**uud**	1	0.938	1/2
$\bar{\mathbf{p}}$	antiproton	$\bar{\mathbf{u}}\bar{\mathbf{u}}\bar{\mathbf{d}}$	–1	0.938	1/2
n	neutron	**udd**	0	0.940	1/2
Λ	lambda	**uds**	0	1.116	1/2
Ω^-	omega	**sss**	–1	1.672	3/2

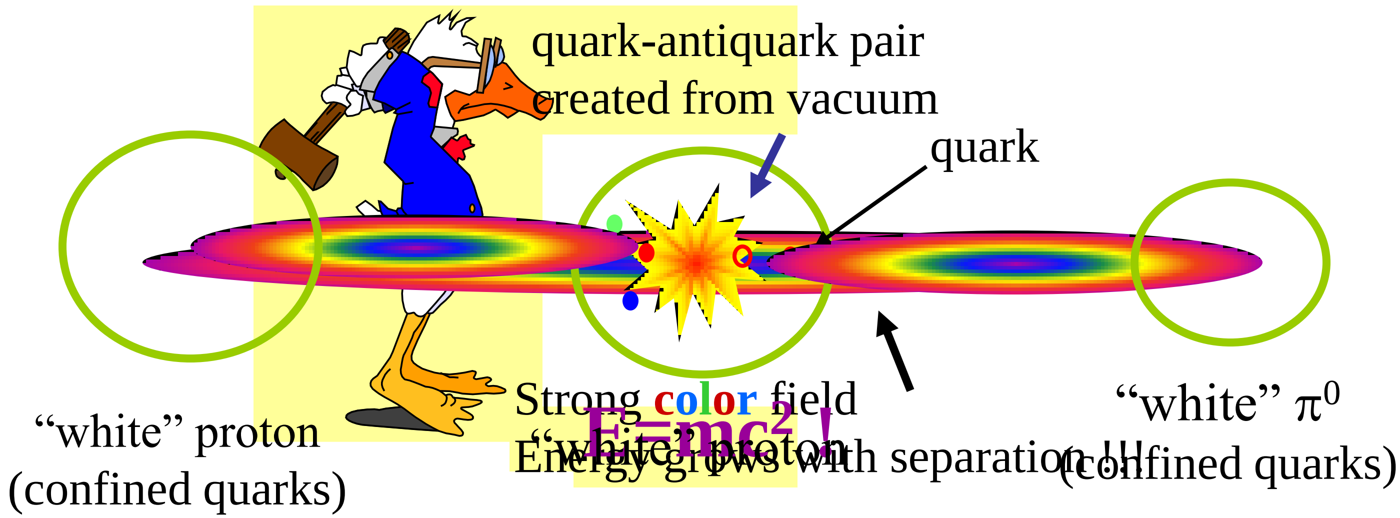
$q\bar{q}$

Mesons $q\bar{q}$ Mesons are bosonic hadrons These are a few of the many types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$\mathbf{u}\bar{\mathbf{d}}$	+1	0.140	0
$\mathbf{K}^-$	kaon	$\mathbf{s}\bar{\mathbf{u}}$	–1	0.494	0
ρ^+	rho	$\mathbf{u}\bar{\mathbf{d}}$	+1	0.776	1
B^0	B-zero	$\mathbf{d}\bar{\mathbf{b}}$	0	5.279	0
η_c	eta-c	$\mathbf{c}\bar{\mathbf{c}}$	0	2.980	0

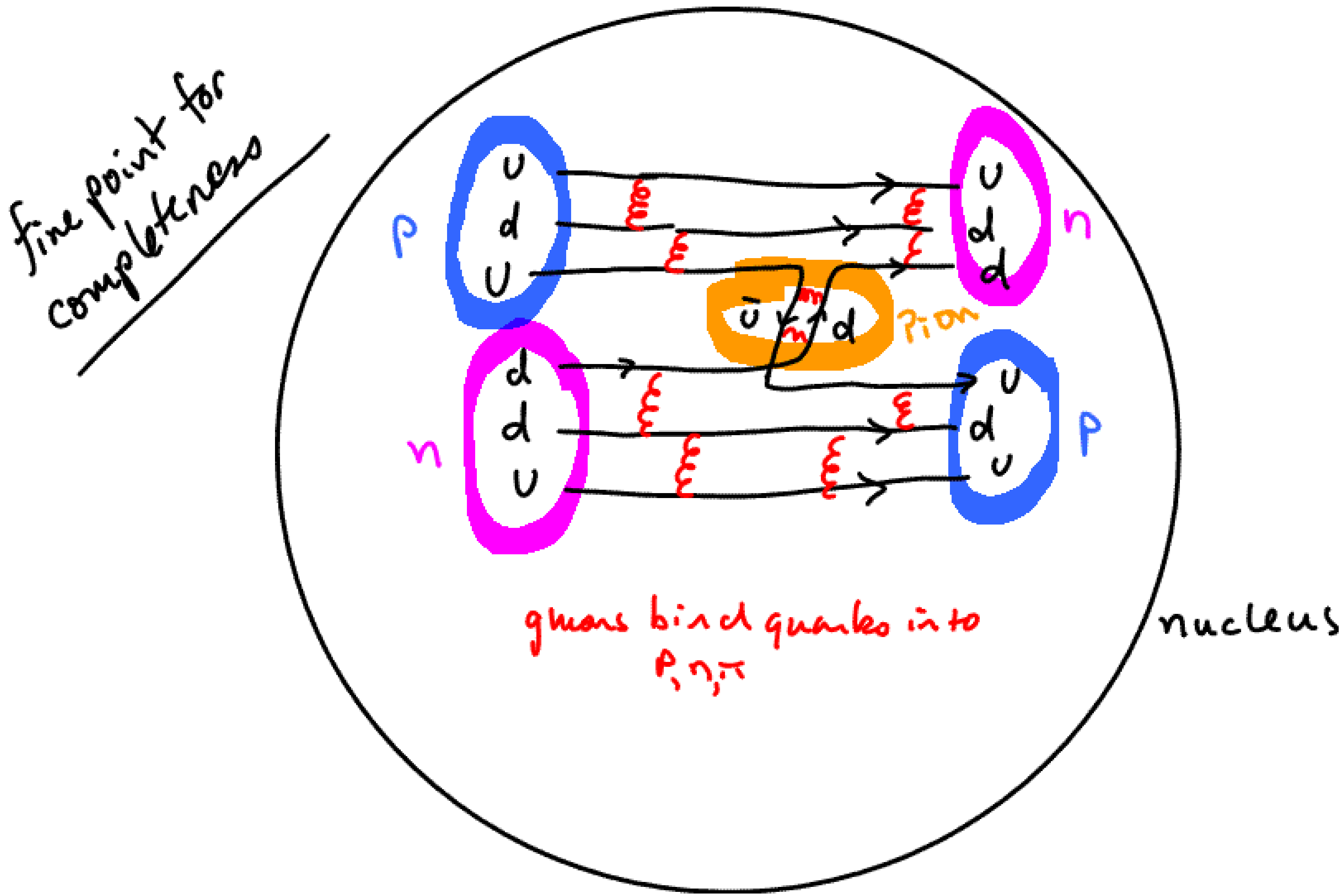
Quantum Chromodynamics
QCD

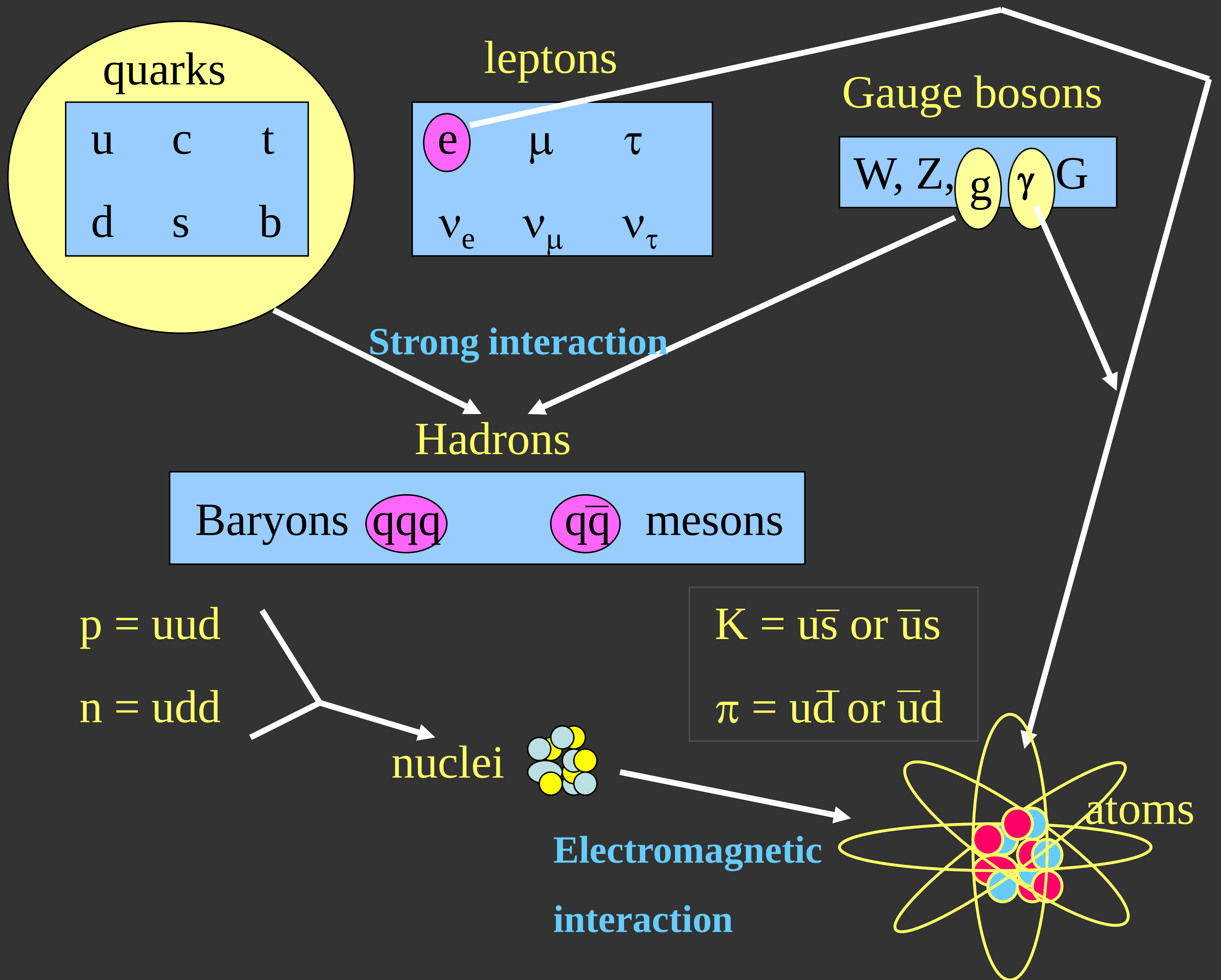
Why bare quarks have never been observed.





Thanks to Mike Lisa (OSU) for parts of this animation nucleon-nucleon force – exchange of π (pion)




quarks
u c t
d s b
leptons
e μ τ
ν_e ν_μ ν_τ
Gauge bosons
W, Z, g γ G
Strong interaction
Hadrons
Baryons qqq
$q\bar{q}$ mesons
p = uud
n = udd
$K = u\bar{s}$ or $\bar{u}s$
$\pi = u\bar{d}$ or $\bar{u}d$
nuclei
atoms
Electromagnetic
interaction

2010 APS J.J. Sakuri Prize Winners

Tom Kibble

Gerald Guralnik

UR’s own Carl Hagen

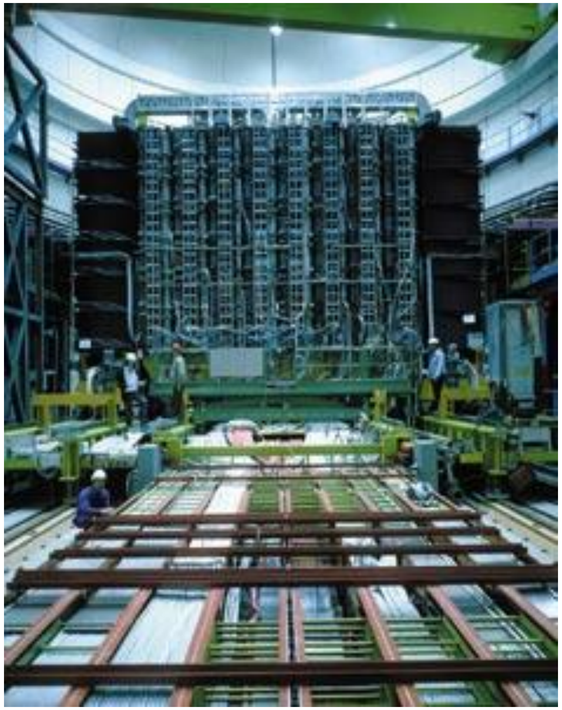
Francois Englert

Robert Brout

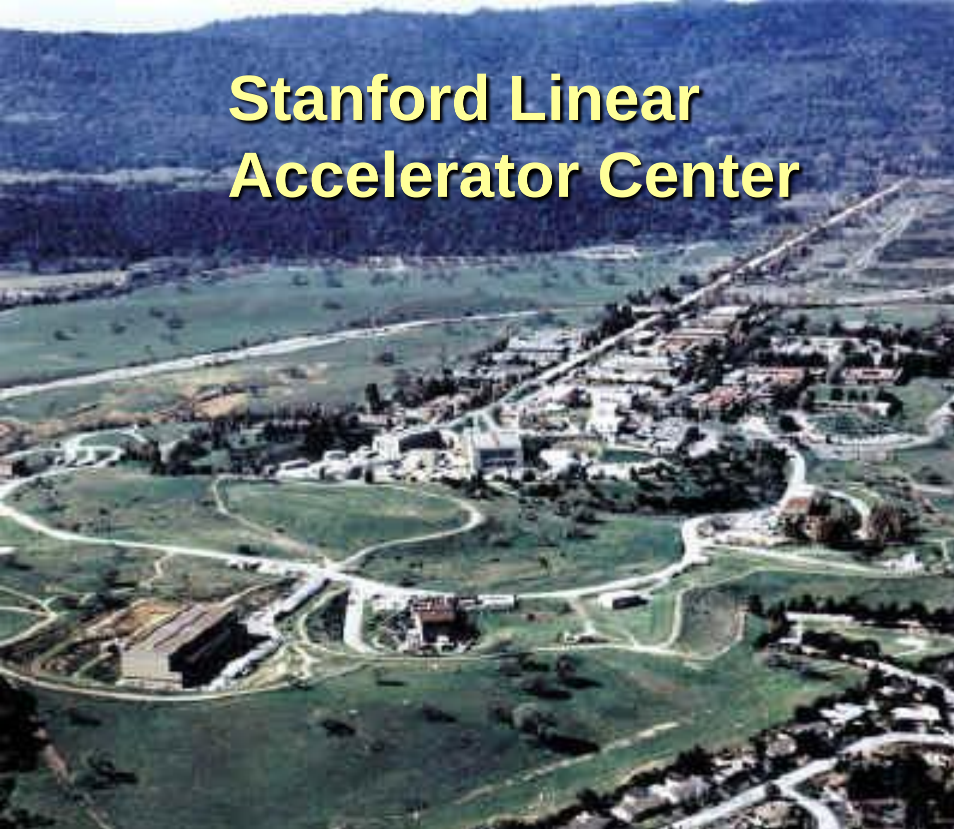
© Pressens Bild

10 December 1979. Salam receives the Nobel Prize from King Carl XVI Gustav of Sweden.

Oops … woohoo!   There it is!   LHC 125-ish GeV

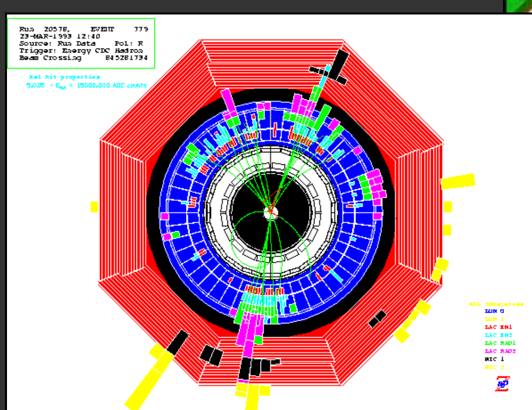




Stanford Linear Accelerator Center

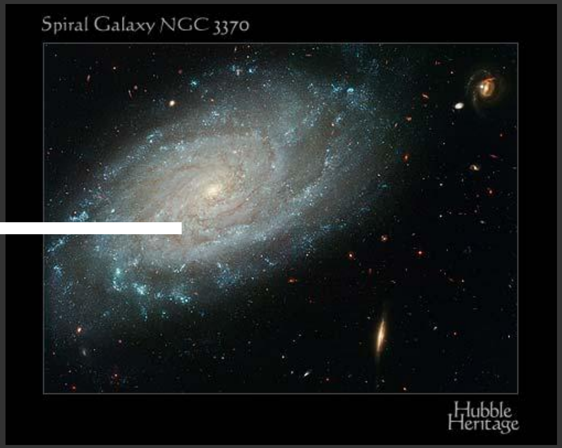


In the 1990's physicists studied the W and Z in minute detail in experiments at SLAC (SLC) and CERN (LEP)

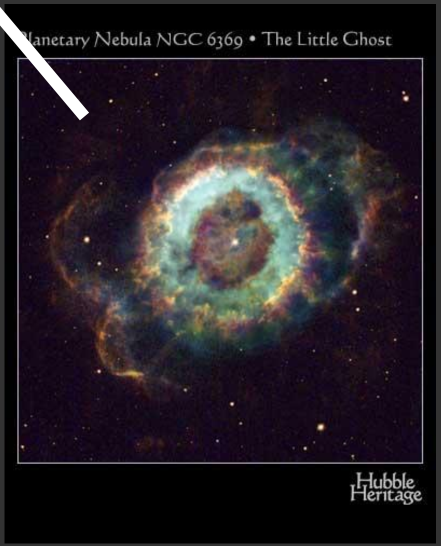
The Standard Model passed with flying colors.



On to the very big …



Telescopes are time machines



1 Mpc= 1 Megaparsec = 3×10^{22} m

1 light year = 9×10^{15} m

Light travels from NYC to San Francisco in 1/100 second
…. and it travels 1 Mpc in 3 million years

Vesto Slipher (1875-1969) Lowell Observatory discovers a strange thing in 1912 …

Most nearby galaxies are moving away from us

Made use of the Doppler shift in atomic spectra

Check out http://galileoandeinstein.physics.virginia.edu/more_stuff/flashlets/doppler.htm

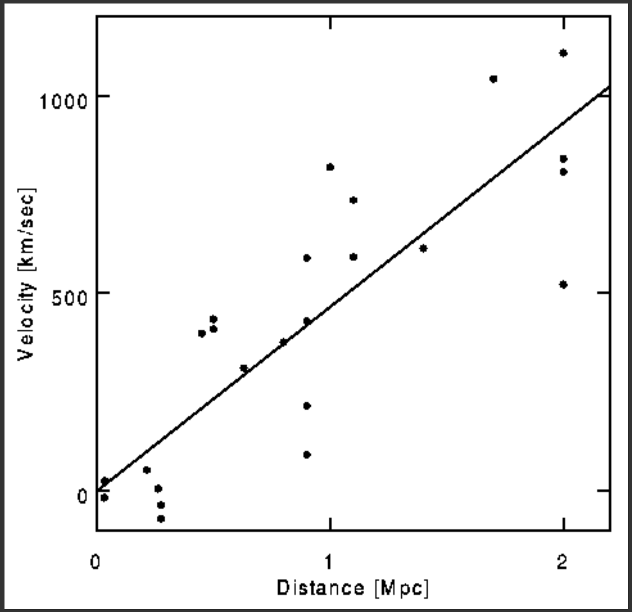
Hubble

Edwin Hubble (1889-1953) and Milton Humason (1891-1972) at Mount Wilson Observatory combine Hubble's distance measurements (Cephied variable stars) with Slipher's reshift information and discover …

Humason (from AIP)

Galaxies that are further away are moving away from us faster

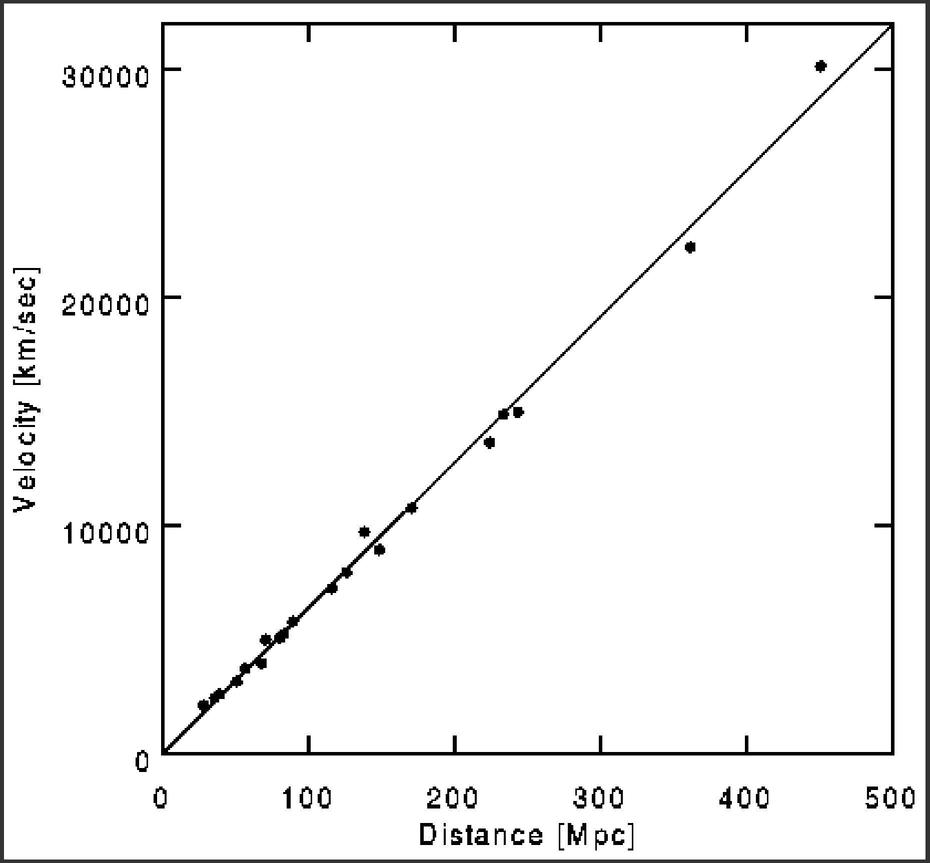
Hubble's Law V=Hd



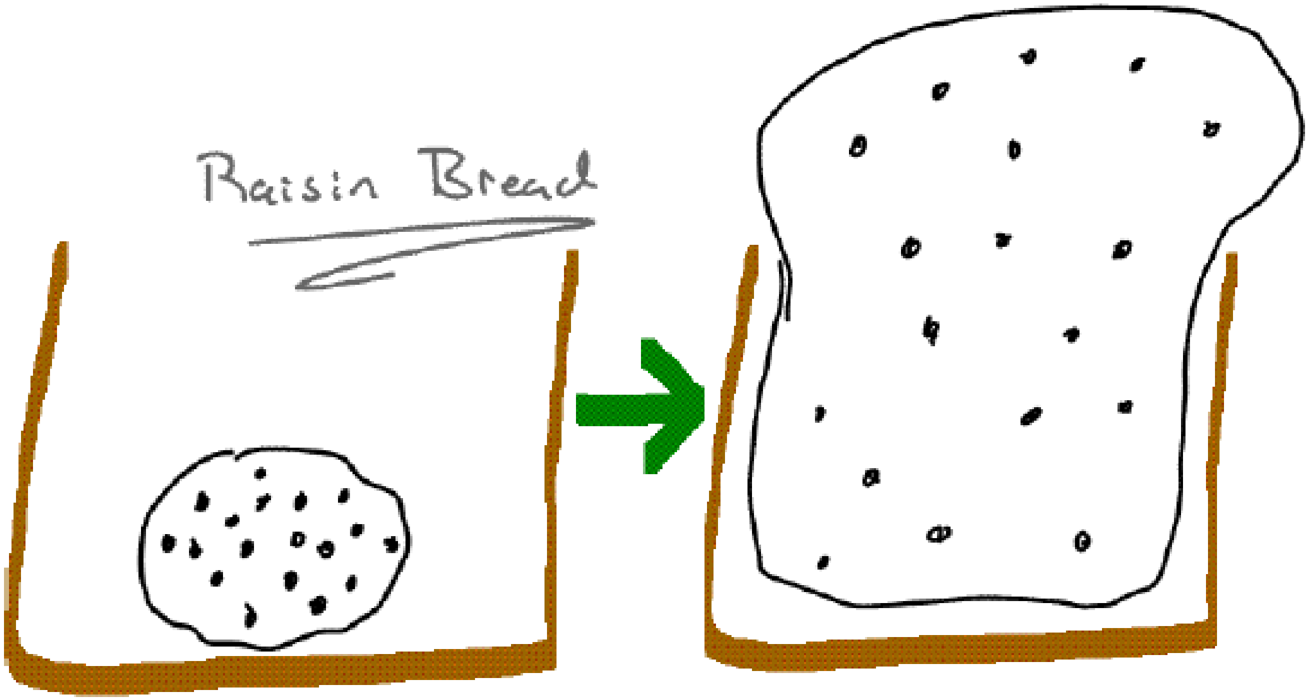
Light travels from NYC to San Francisco in 1/100 second
….   and it travels 1 Mpc in 3 million years

Welcome to the "expanding universe"!!

extrapolate back in time find the age of the universe → 13.7 billion years.

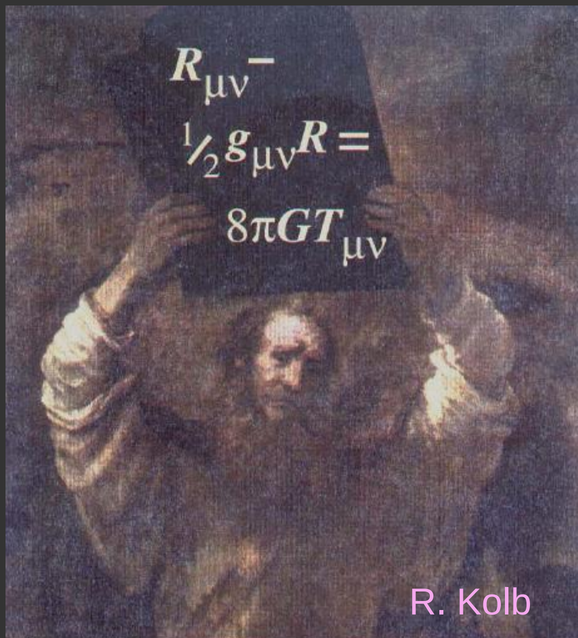


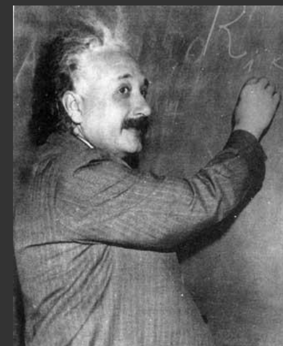
Type Ia SNe from Riess, Press and Kirshner (1996)



Think of the universe as more like a butt than a zit …

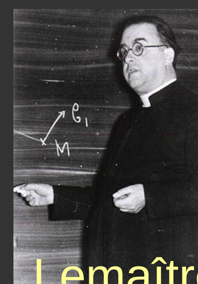
Hot Big Bang Theory – some of the players



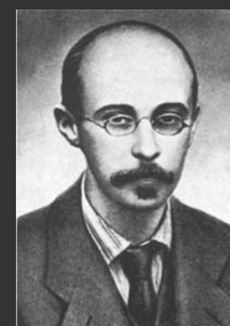


Einstein

General Relativity



Lemaître

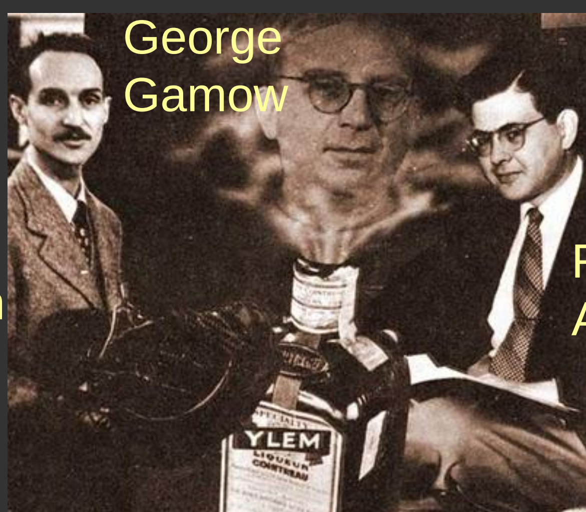


Friedmann

Expanding universe

Robert Walker

Howard Robertson



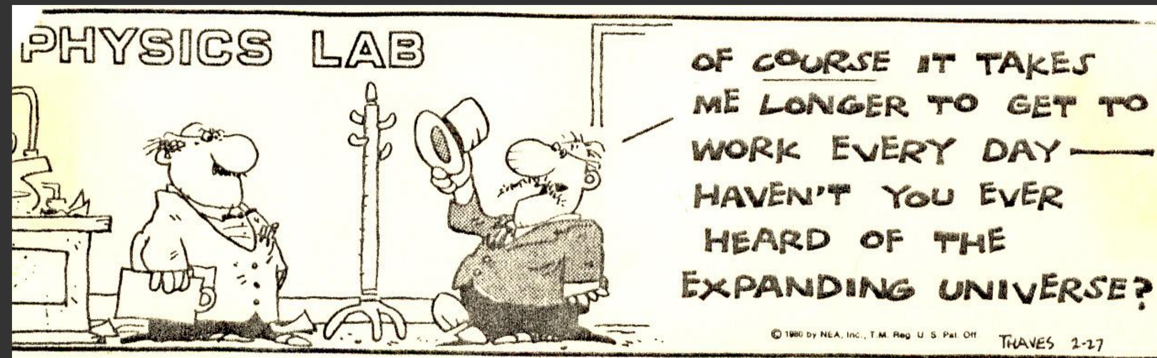
George Gamow

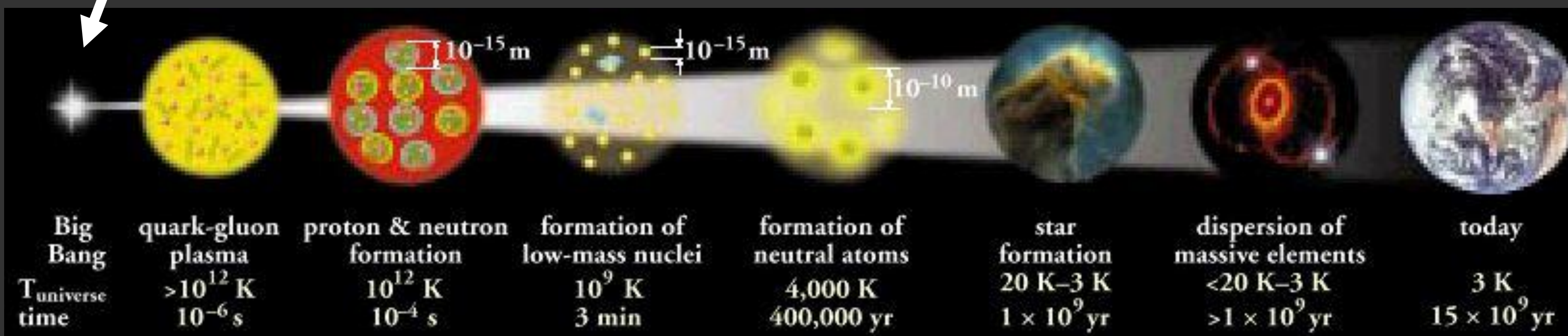
Robert Herman

Ralph Alpher

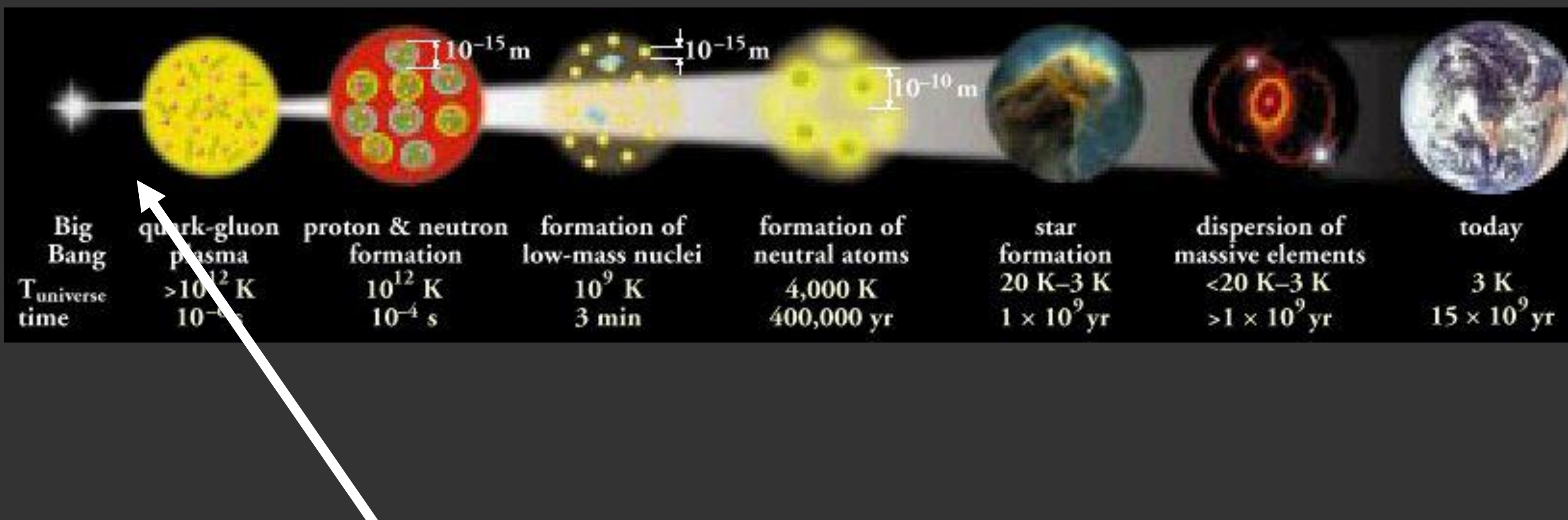
Big Bang nucleosynthesis

BANG!

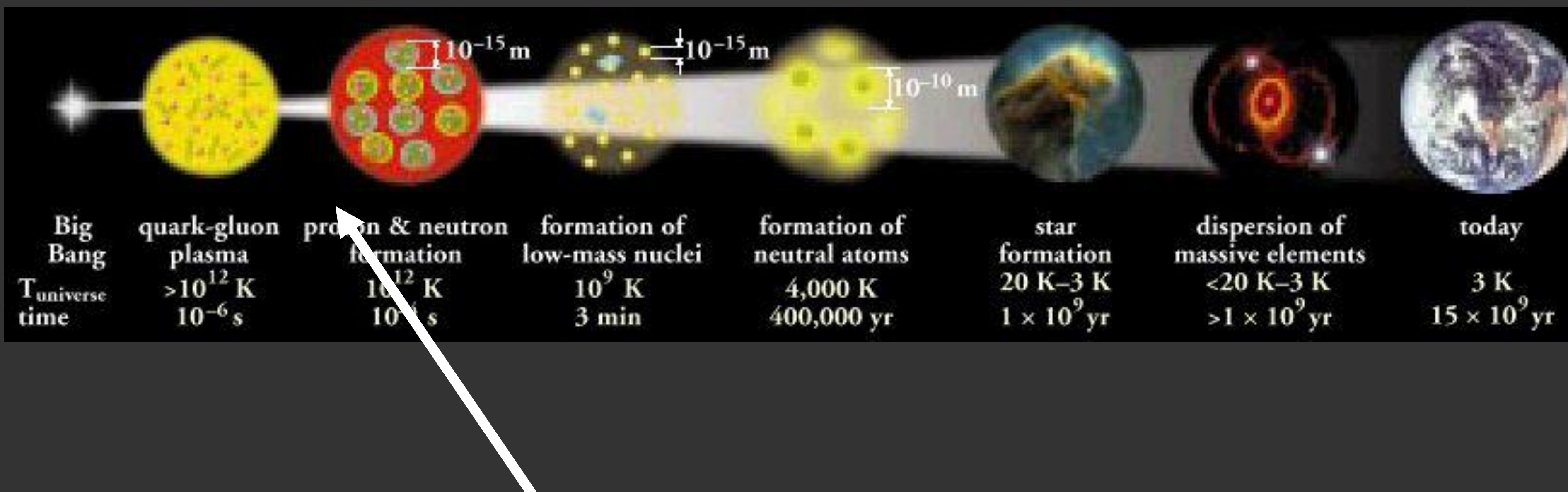

PHYSICS LAB
OF COURSE IT TAKES ME LONGER TO GET TO WORK EVERY DAY — HAVEN'T YOU EVER HEARD OF THE EXPANDING UNIVERSE?
THAVES 2-27


10^{-15} m
10^{-15} m
10^{-10} m
Big Bang
quark-gluon plasma
proton & neutron formation
formation of low-mass nuclei
formation of neutral atoms
star formation
dispersion of massive elements
today
$T_{universe}$
time
$>10^{12}$ K
10^{-6} s
10^{12} K
10^{-4} s
10^{9} K
3 min
4,000 K
400,000 yr
20 K–3 K
1×10^{9} yr
<20 K–3 K
$>1 \times 10^{9}$ yr
3 K
15×10^{9} yr

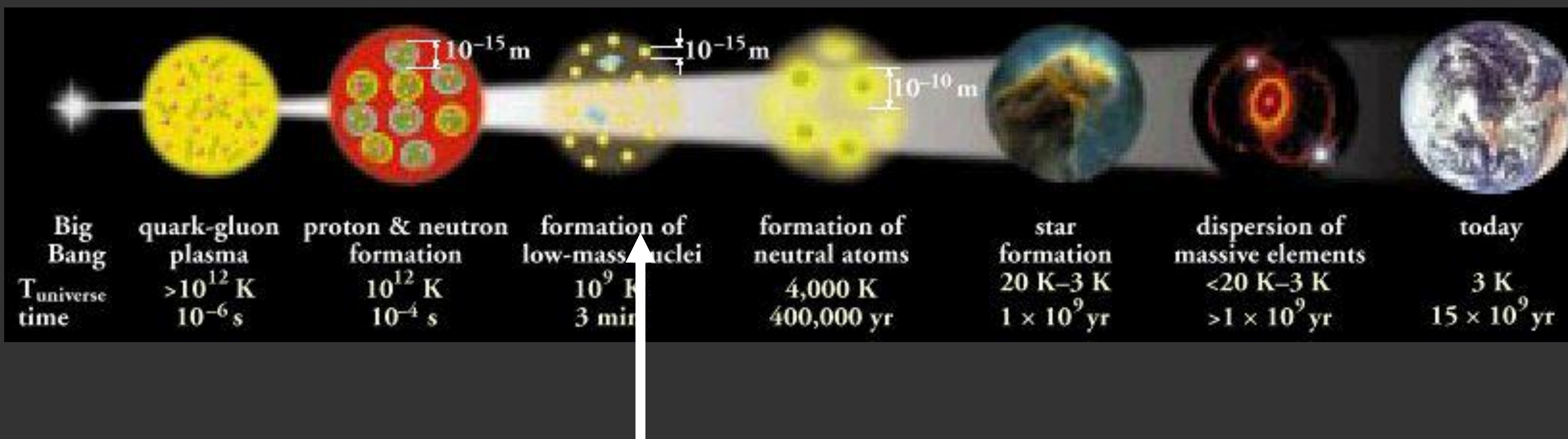
TIME



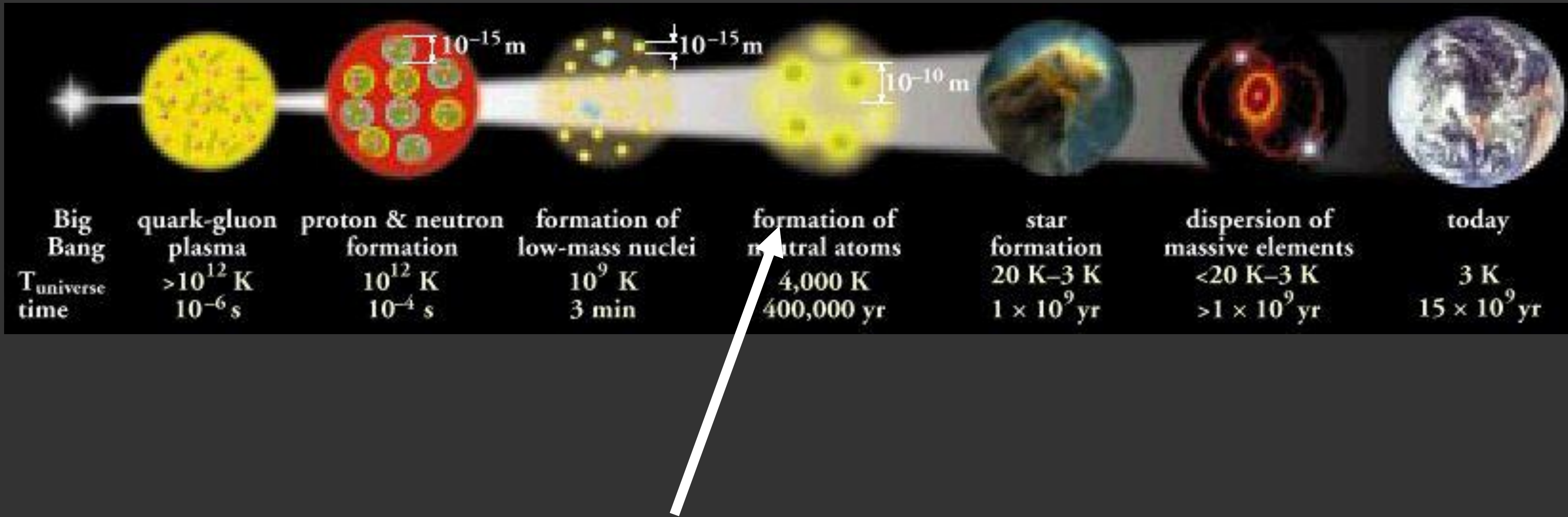
Very hot, dense primordial soup of fundamental particles



At 0.000001 second after bang, protons and neutrons form



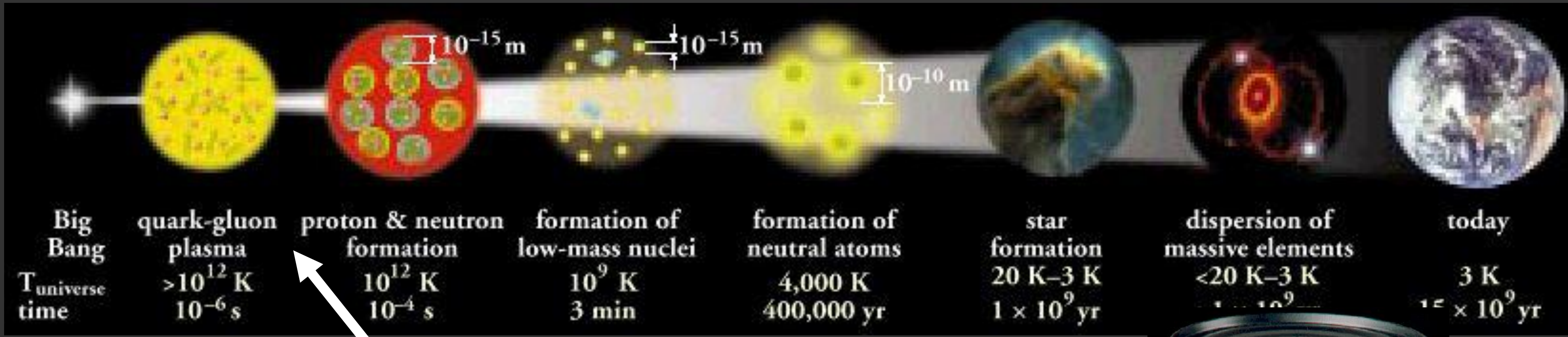
At 3 minutes, light nuclei form



At ~300,000 years, t = 3000 degrees, atoms form and light streams freely

Modern accelerators study processes at energies that existed VERY early in the universe

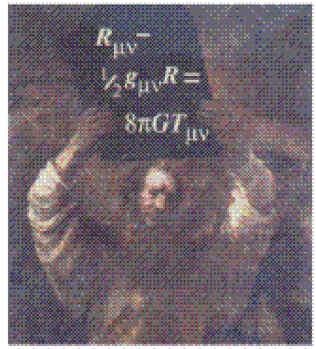
Another form of time travel !



What were forces like at those temperatures?

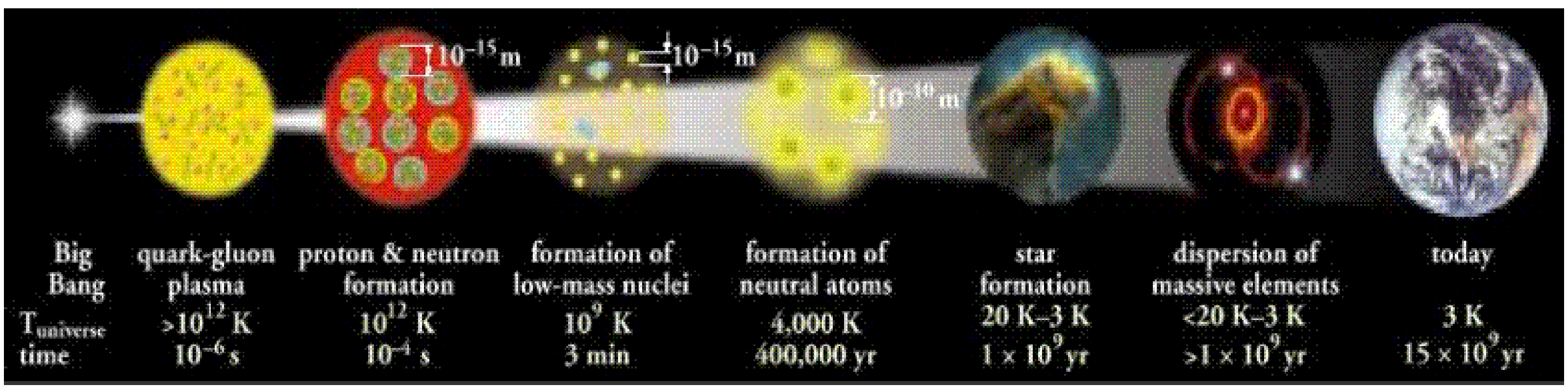
What types of particles existed?

Why Believe? …



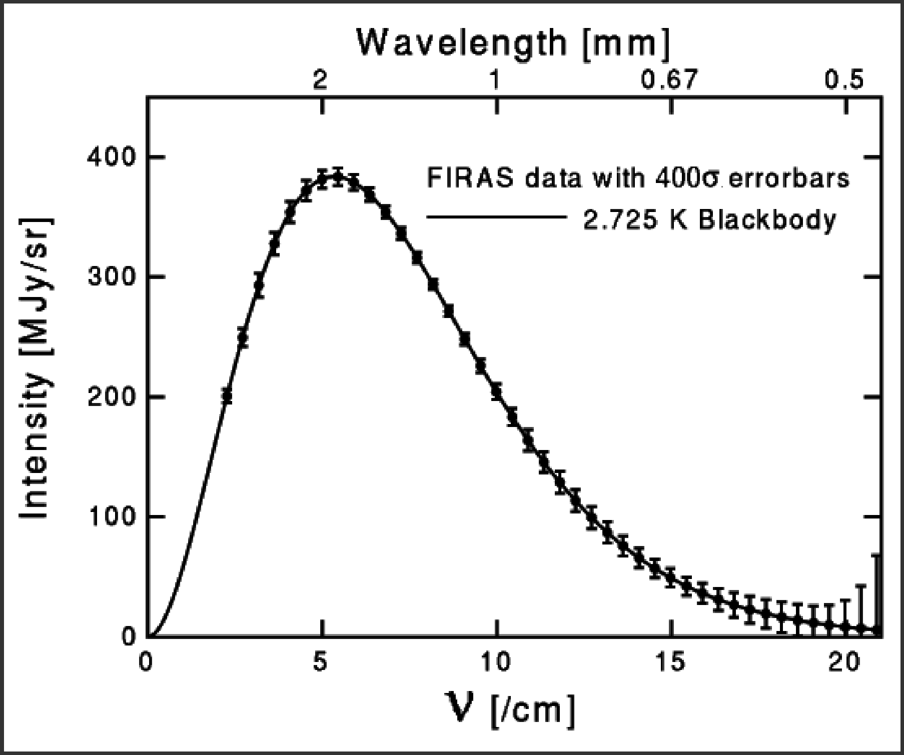
- R. Kolb

… in the Hot Big Bang?



Cosmic Microwave Background

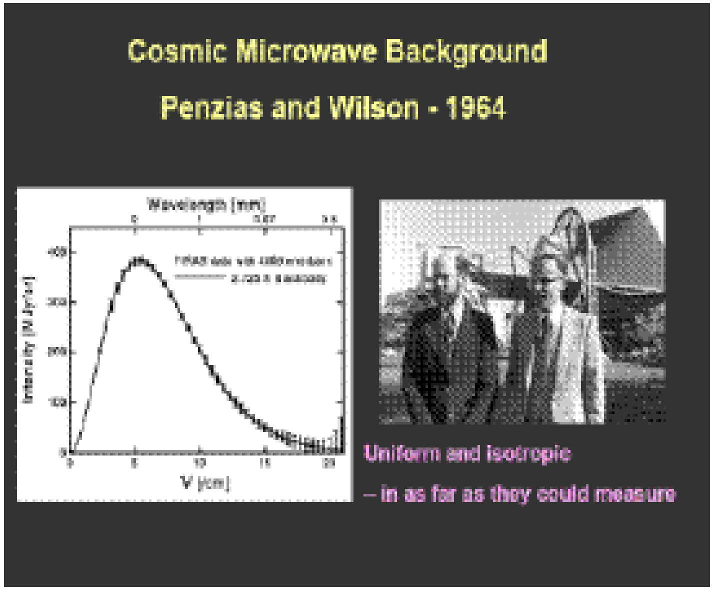
Penzias and Wilson - 1964



Uniform and isotropic

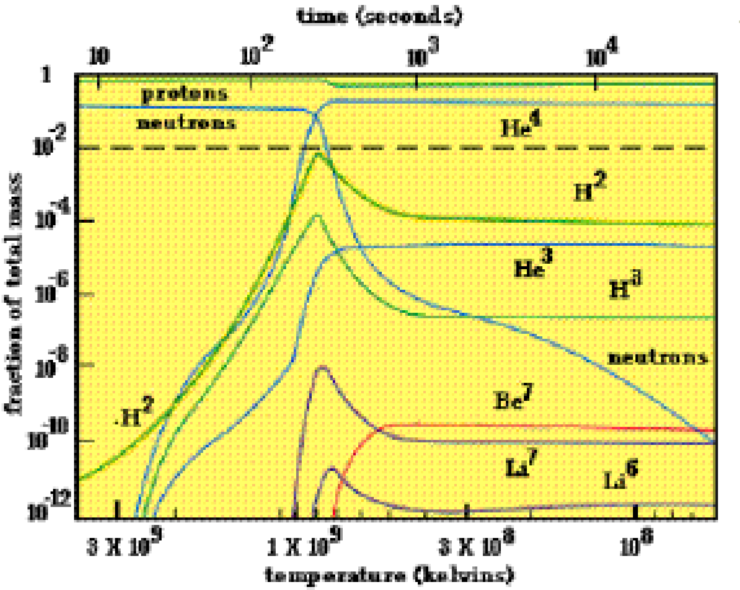
– in as far as they could measure

- Observe light from Time universe became Transparent
  - T ~ 400,000 years



- Perfect blackbody all directions in sky

- Amount of light nuclei in interstellar/intergalactic space agrees w/ expectation from Big Bang Nucleosynthesis
  - T ~ 3 minutes



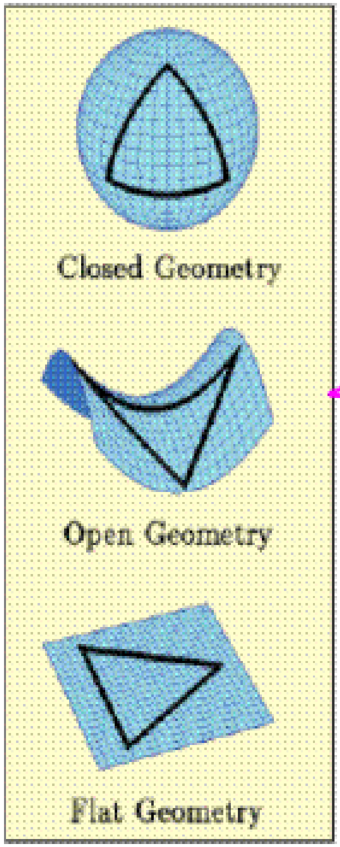
Problems w/ Big Bang

nonstatic universe expected from Relativity

Relativity allows space to have different curved geometries?

Which is our universe?

Flat space is a very special case!



Sum of angles in triangle

$>180°$ ← universe expands… slows down + collapses

$<180°$ ← universe expands forever

$=180°$ ← universe expands to a stop

Very special case

- **Singularity Problem** – Yikes!! All of the universe at a point?

- **Horizon Problem** – Why is universe so smooth and isotropic on large scales?

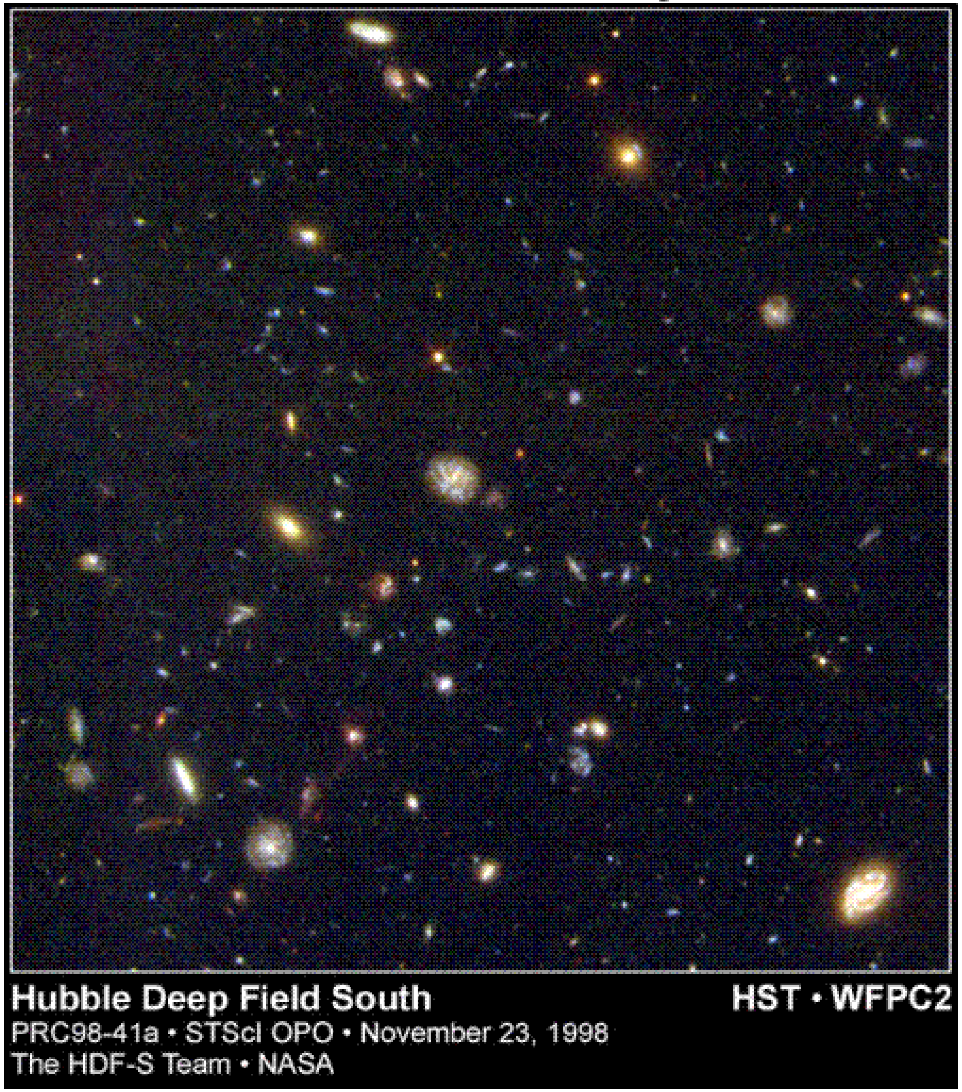
  Why CMB so smooth and isotropic

  at T = 400,000 yrs
  only parts of universe as large as 400,000 light years could be causally connected
  yet all at same temperature??

- **Flatness problem** – universe appears to be very close to "flat"... very special case.

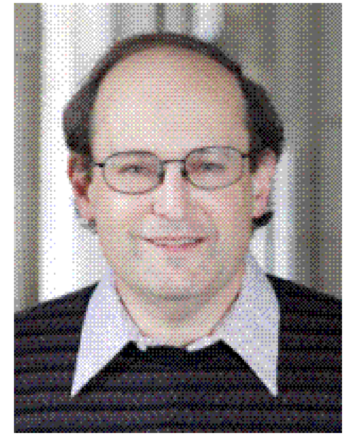
  Requires fine tuning of basic model

- large Scale Structure problem – how do galactic structures form in a perfectly homogenous universe?



Andrei Linde
(Stanford)

Cosmic Inflation
~1979

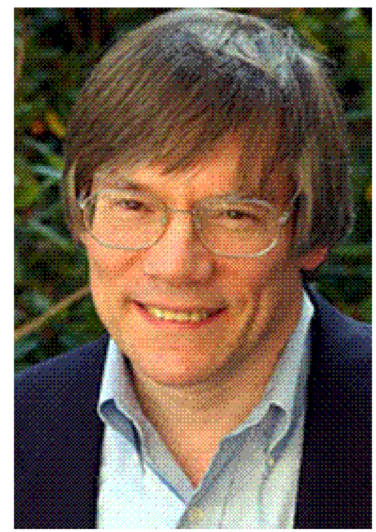


Paul Steinhardt
(Princeton)

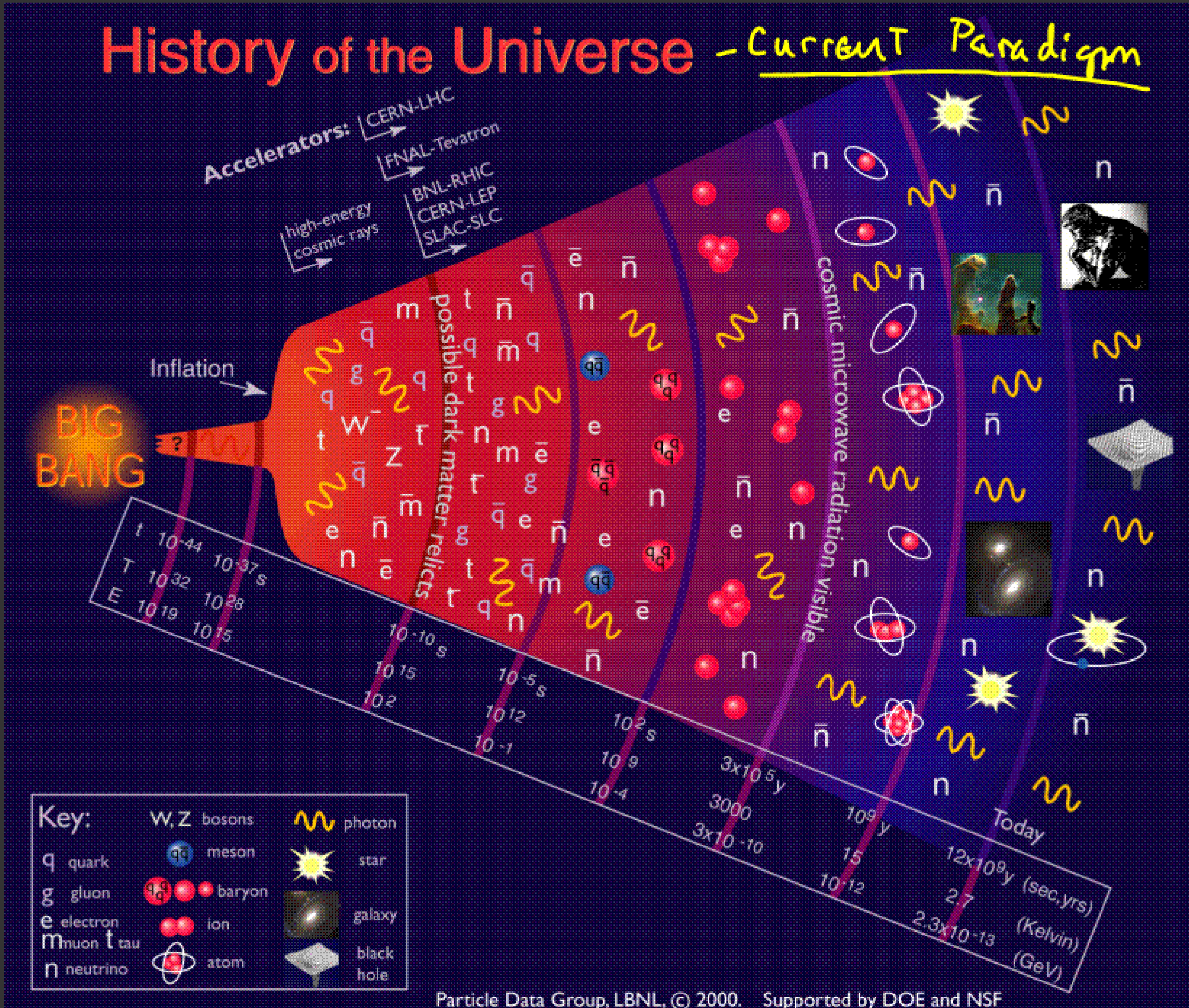
Andy Albrecht
(UC Davis)

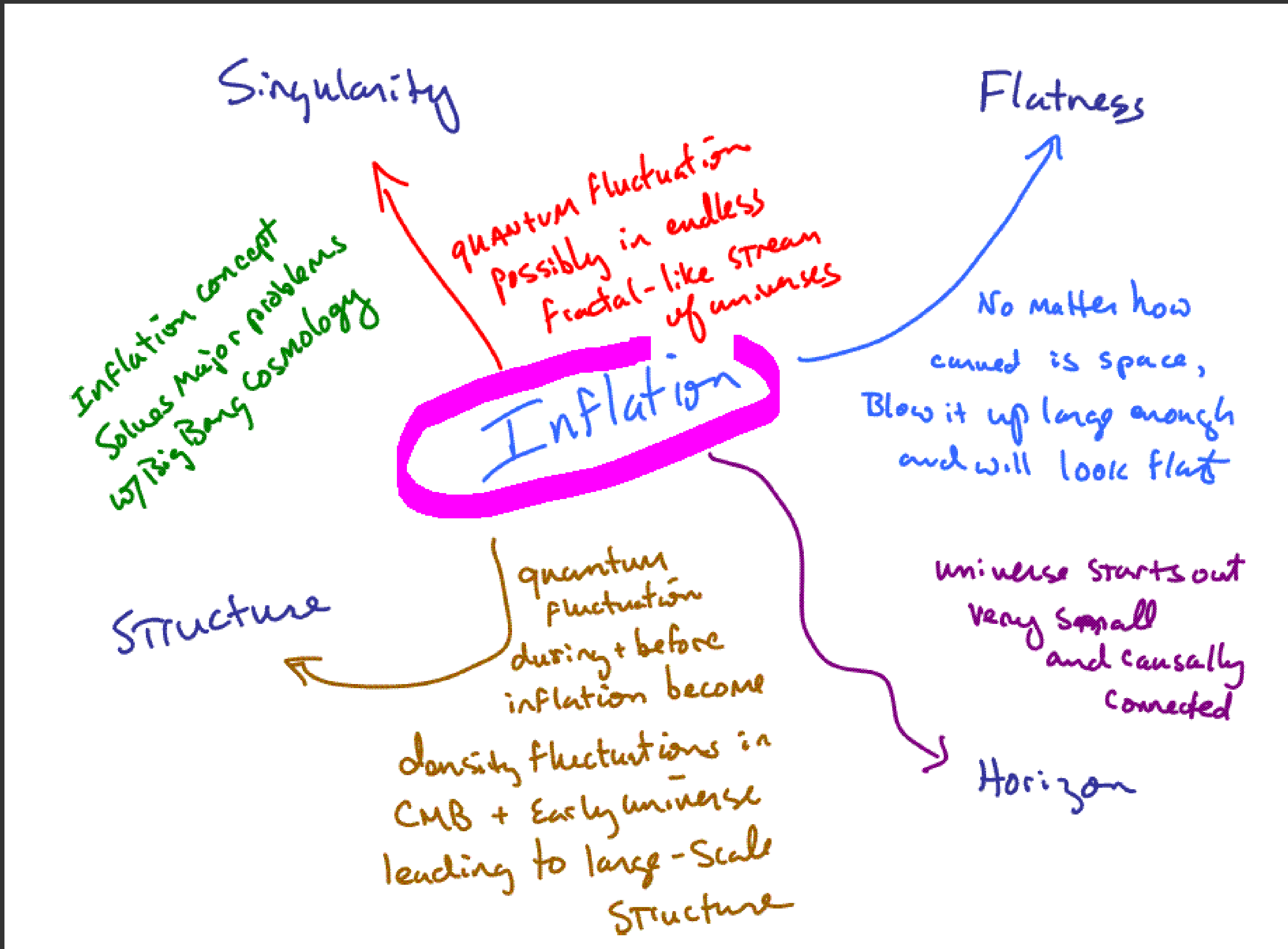
Idea used by many cosmological theories to solve basic problems w/ Big Bang Model

Inflationary Big Bang Models



Alan Guth (MIT)


History of the Universe
- Current Paradigm
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relics
cosmic microwave radiation visible
t 10^{-44} 10^{-37} s
T 10^{32} 10^{28}
E 10^{19} 10^{15}
10^{-10} s
10^{15}
10^{2}
10^{-5} s
10^{12}
10^{-1}
10^{2} s
10^{9}
10^{-4}
$3x10^{5}$ y
3000
$3x10^{-10}$
10^{9} y
15
10^{-12}
Today
$12x10^{9}$ y (sec,yrs)
2.7 (Kelvin)
$2.3x10^{-13}$ (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF


Inflation
Singularity
quantum fluctuation possibly in endless fractal-like stream of universes
Flatness
No matter how curved is space, Blow it up long enough and will look flat
Horizon
universe starts out very small and causally connected
Structure
quantum fluctuation during + before inflation become density fluctuations in CMB + Early universe leading to large-scale structure
Inflation concept Solves major problems w/ Big Bang cosmology

Incredible new data in the last 10 years

- Fluctuations in the Temperature /color of the CMB (1 part in 10^5)

Cobe, WMAP – satellites

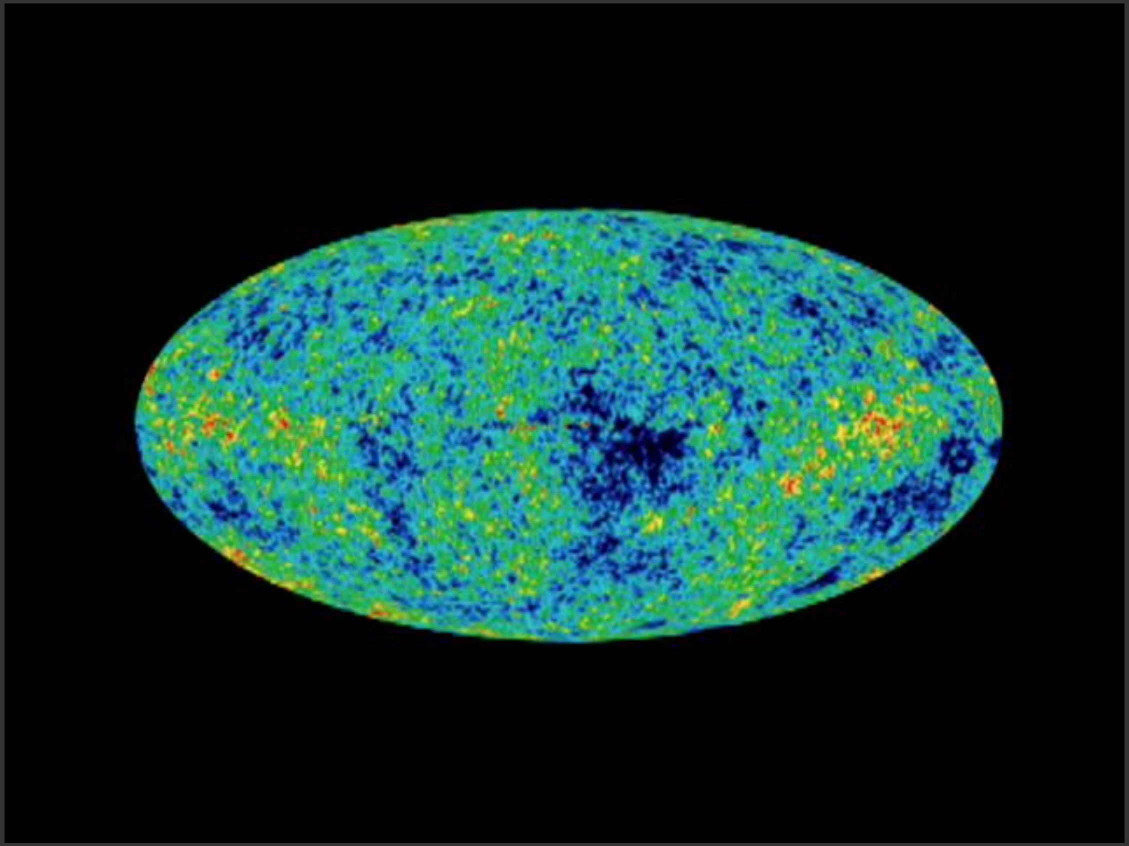
- universe is "flat"
- Expansion of the universe is Accelerating

observations of supernovae in distant galaxies

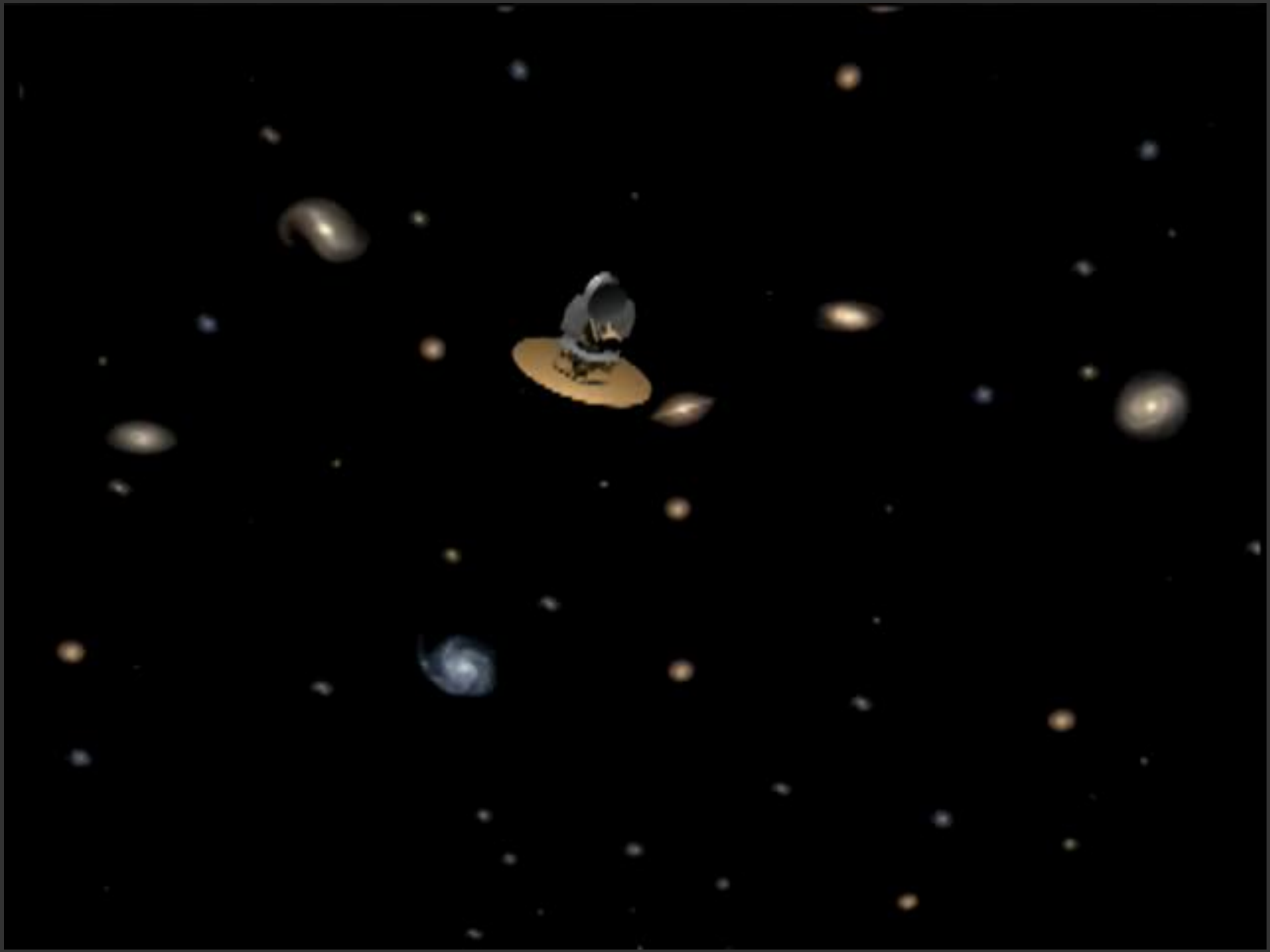
Two grps of scientists:
- Supernova Cosmology Project – Perlmutter at UC Berkeley
- High - Z Team

Very exciting development in last decade

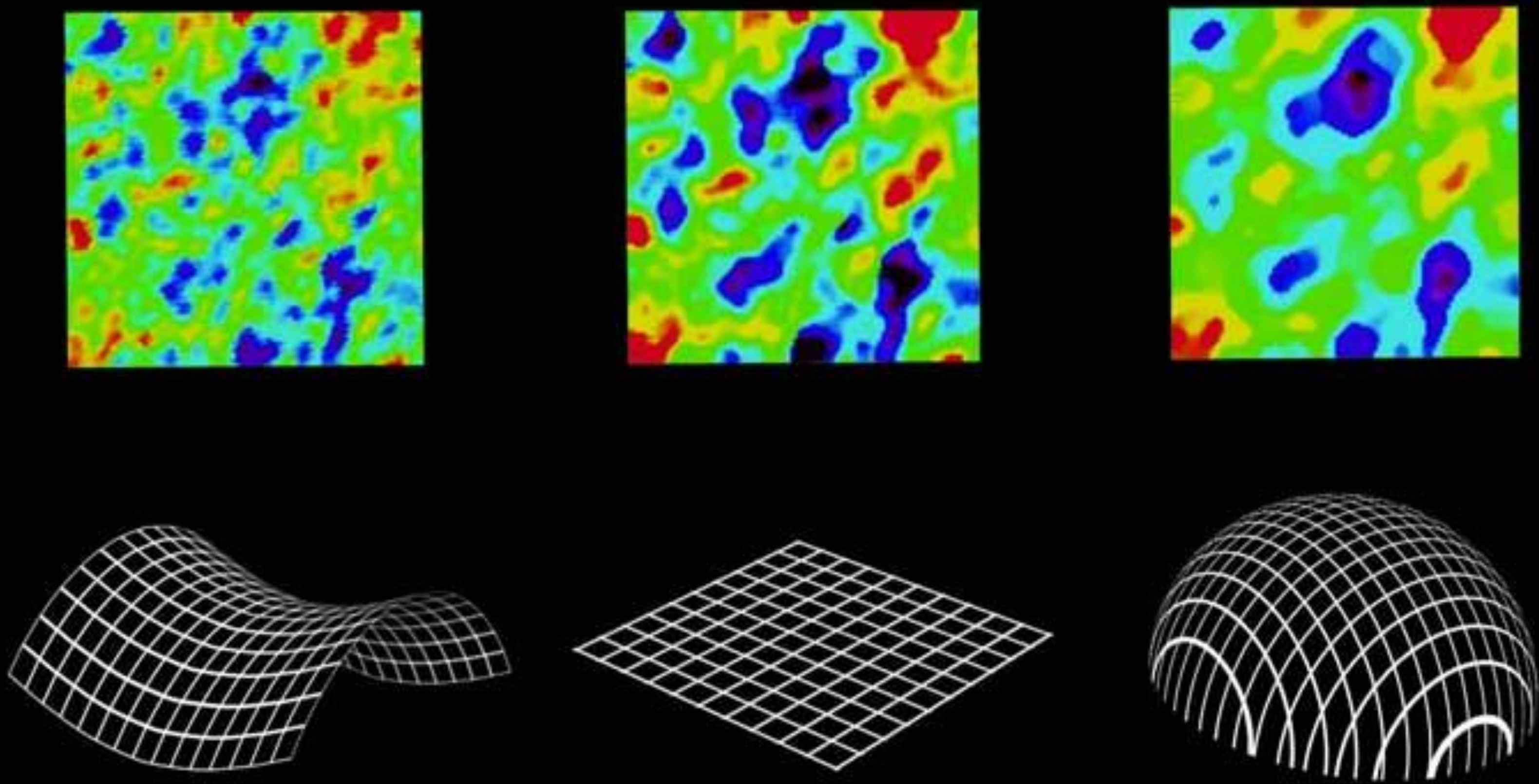
Observed fluctuations in the CMB temp



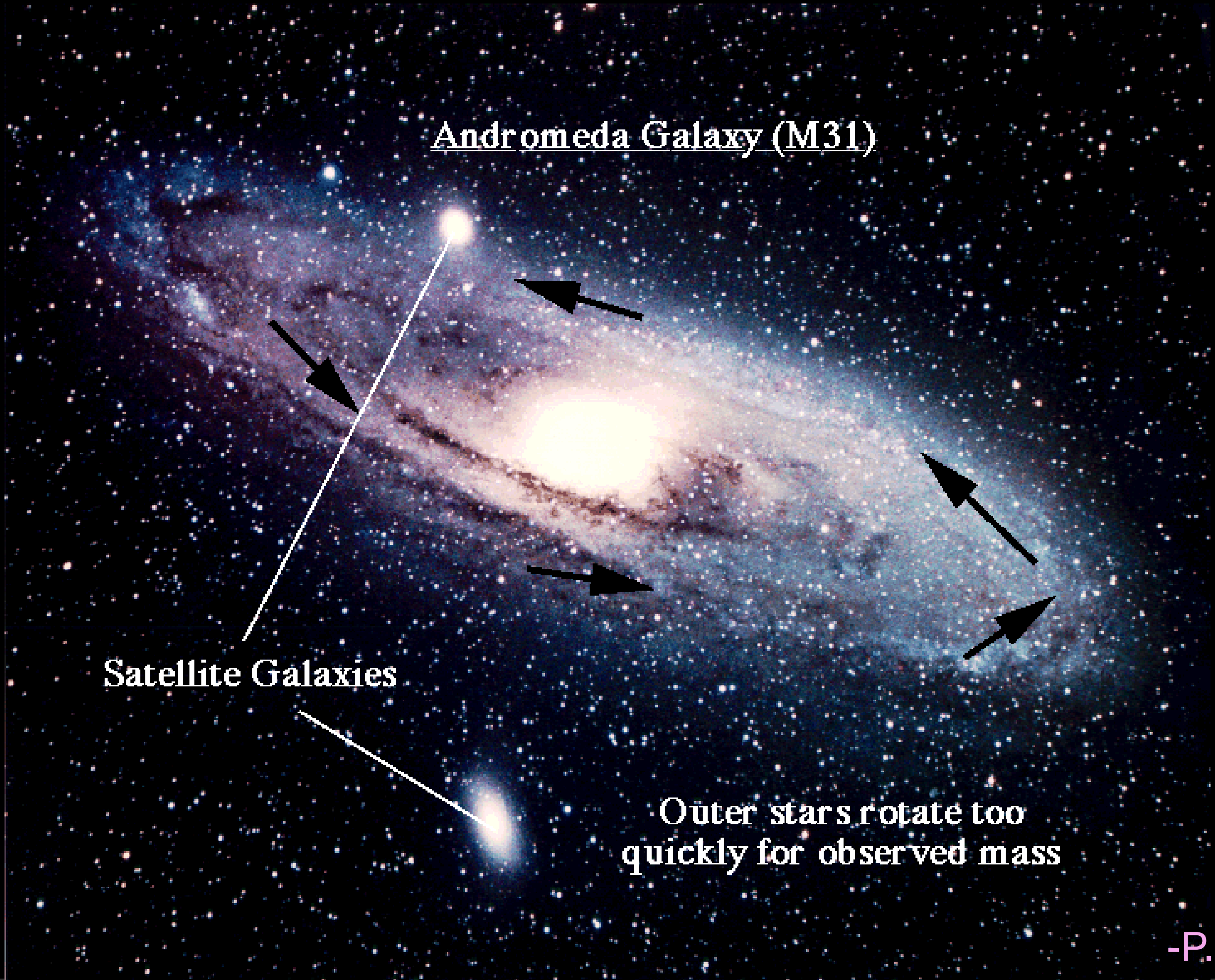
WMap data on the temperature fluctuations in the CMB



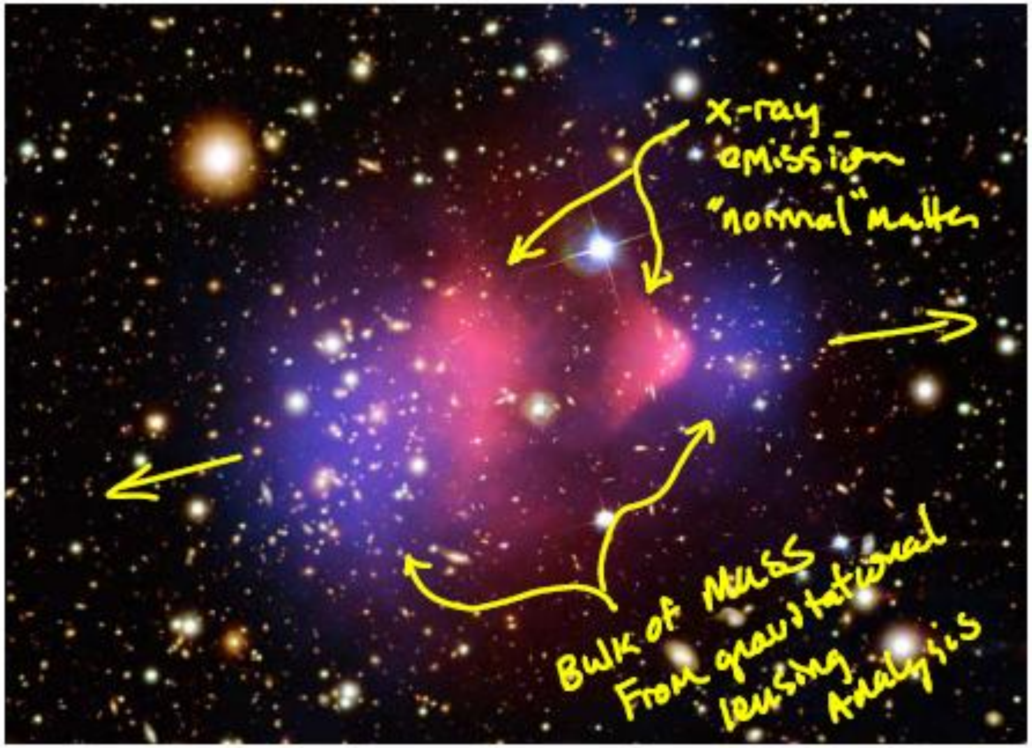
GEOMETRY OF THE UNIVERSE



We seem to be missing most of the mass in the universe!



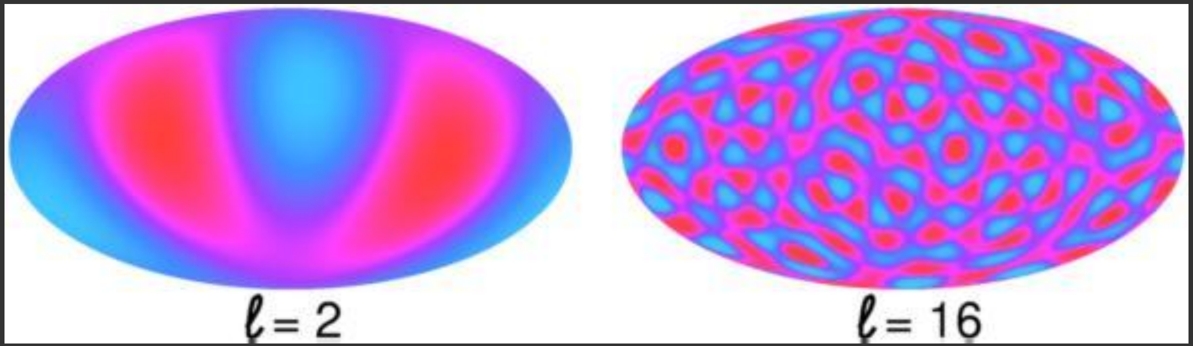
-P. Cushman

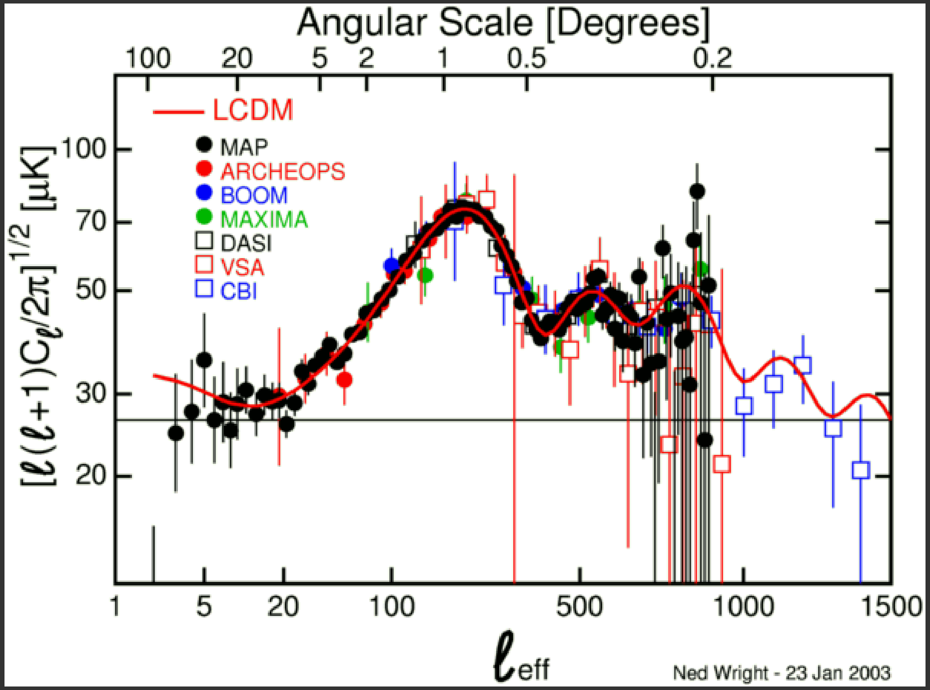


Bullet cluster
colliding galactic clusters

galaxies + Dark Matter
zip past

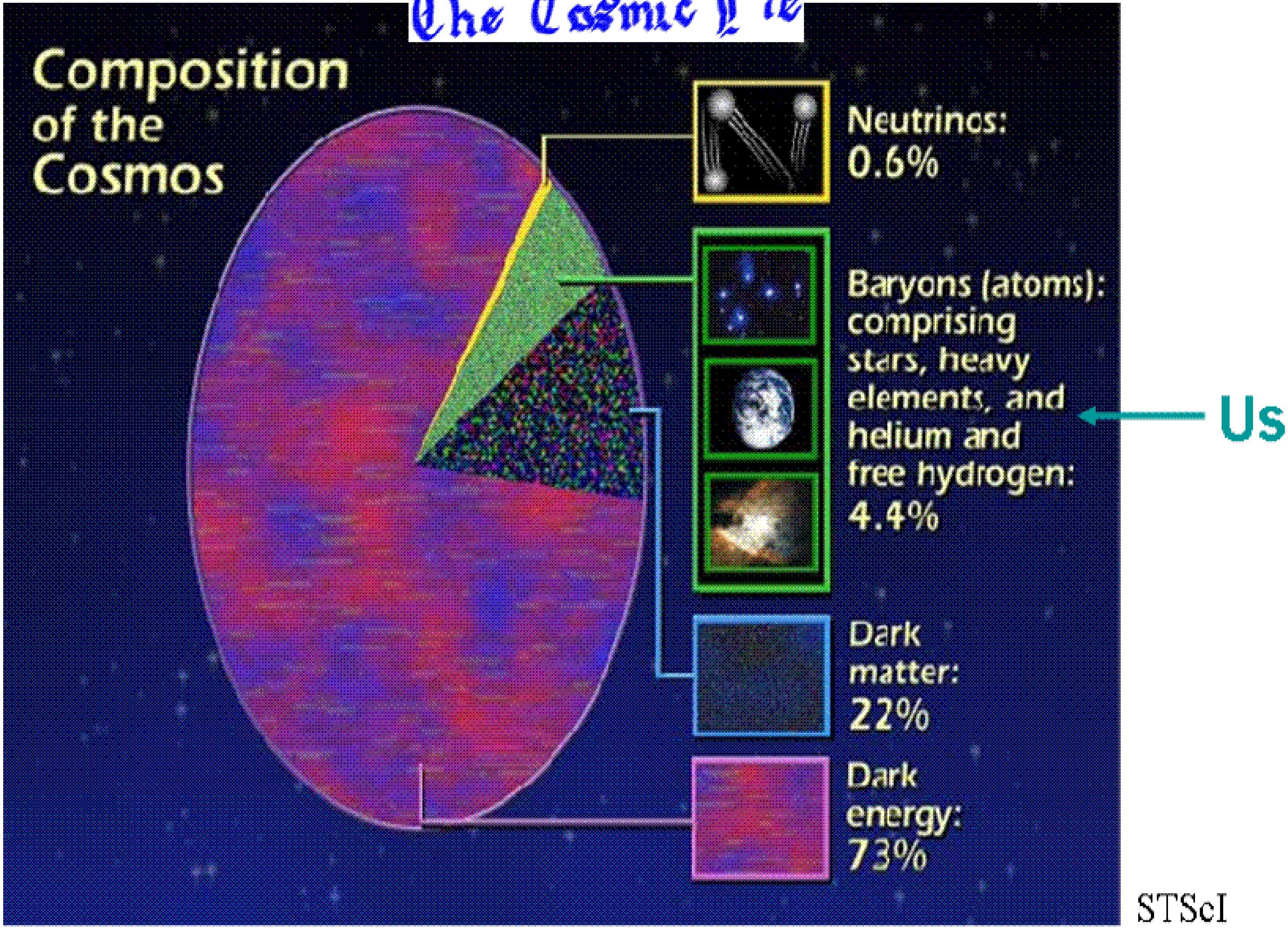
intergalactic gas slowed down





"Power spectrum" (size) of temperature fluctuations sensitive to different matter/energy components of the universe

The Cosmic Pie



STScI

95% of the universe is unknown!

figure from E. Linder LBL

Many, many missing pieces …

What is the nature of dark matter?

What is the nature of dark energy?

What does what the Higgs does in the Standard Model?

Do we know about all of the fundamental particles that exist?

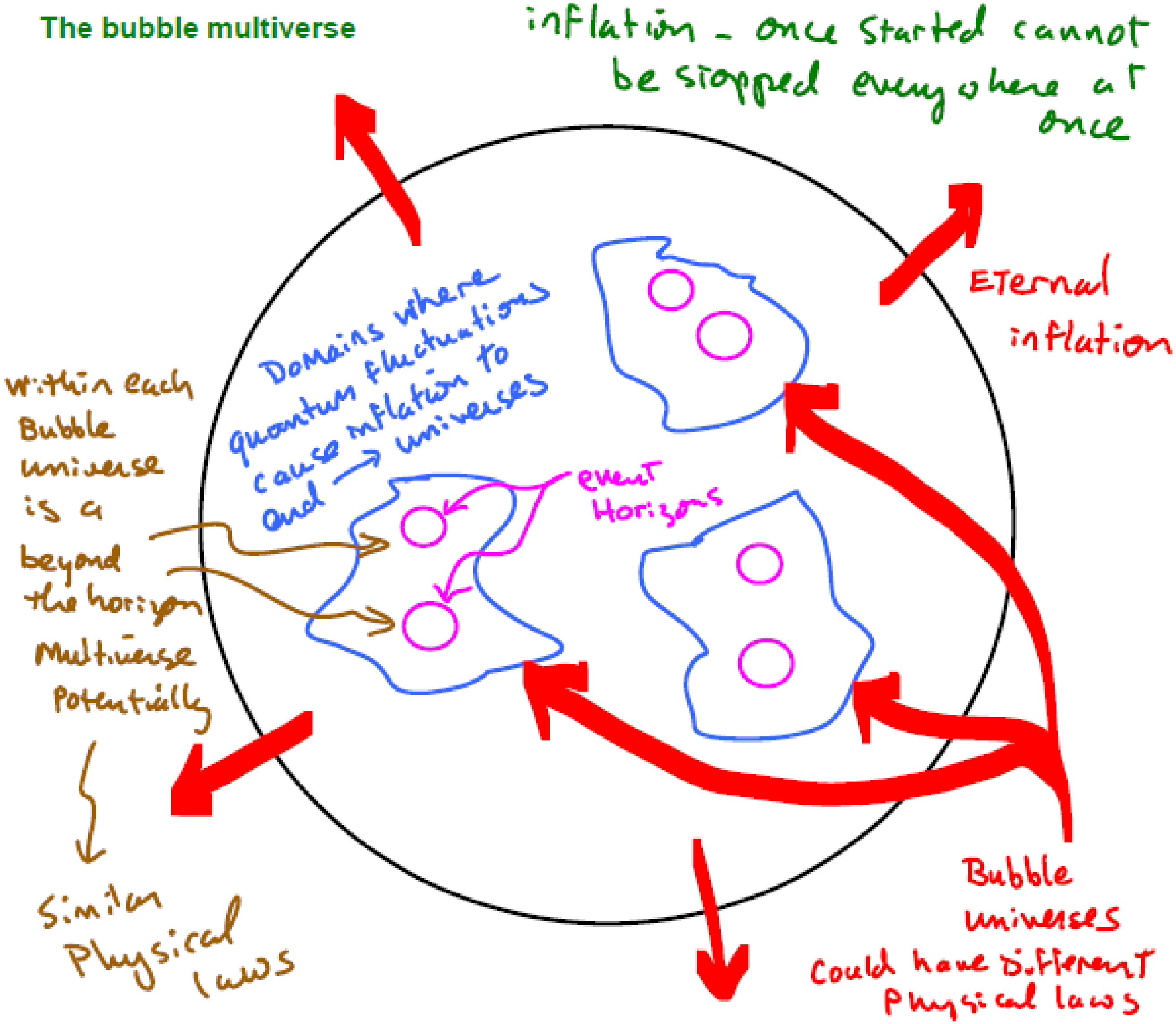
Why 3 families?

Why is the mass spectrum of fundamental particles as it is?

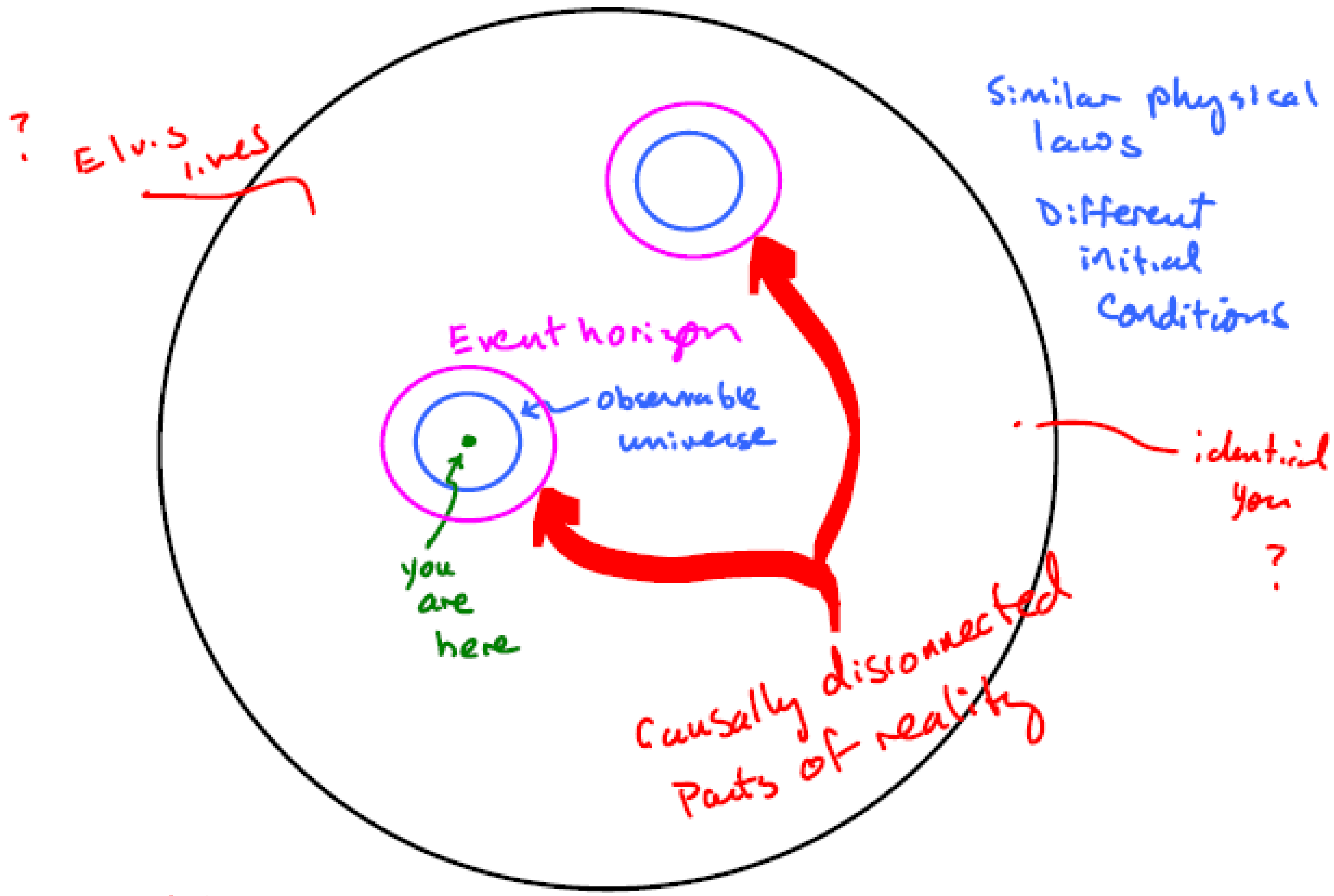
Why is the universe matter instead of antimatter?

Recent progress! But, as usual in science, we have new puzzles …

The bubble multiverse



Beyond the horizon multiverse



Inflation → countless # of such regions

We live in exciting times!