Big Bang Cosmology

Cosmology: the study of the Universe

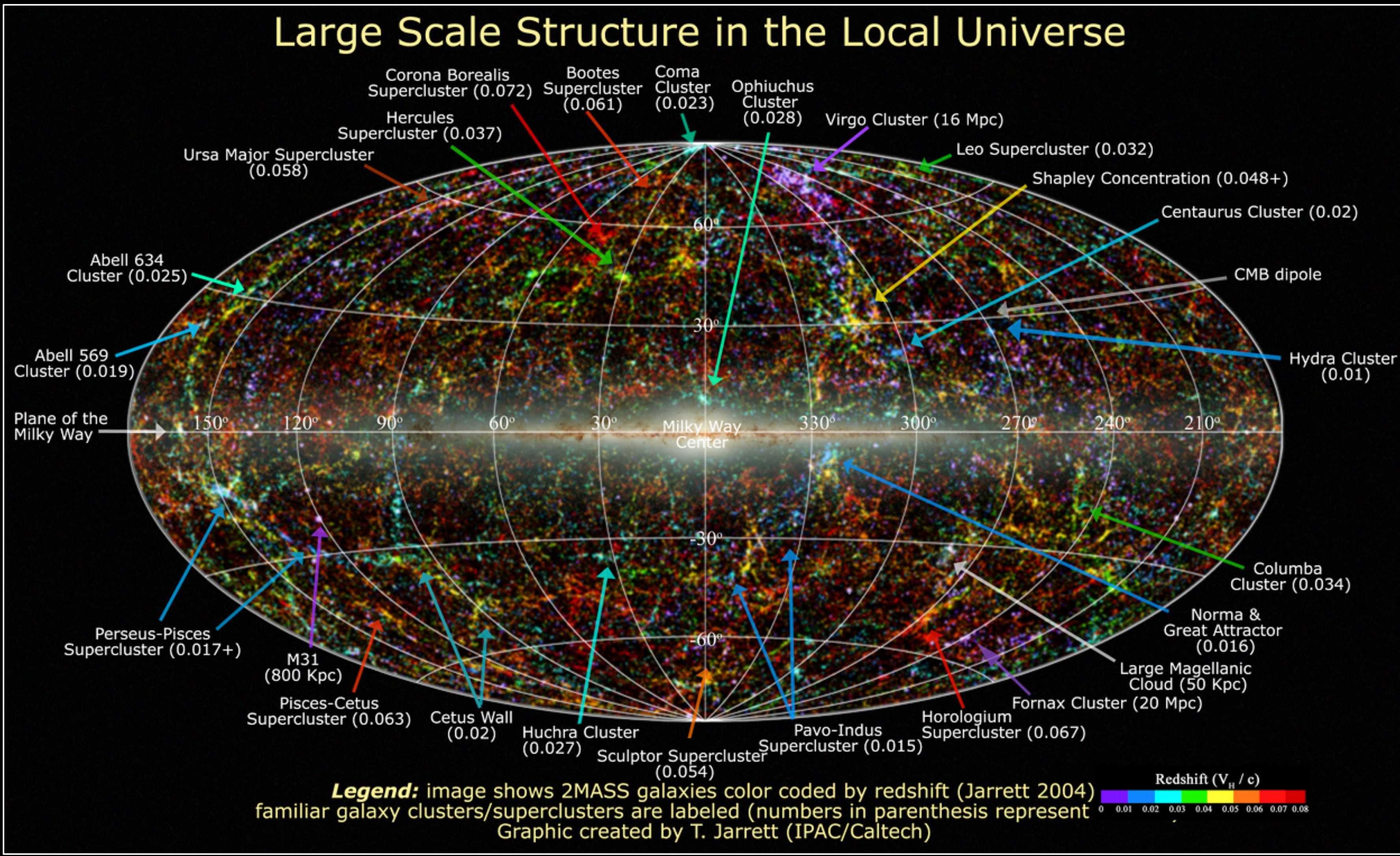
Cosmogony: the study of the <u>*origin*</u> of the Universe

Isotropic: the same in all directions

Reading: Chapter 26

Distribution of Galaxies

Clusters, voids, and walls,
but primarily isotropic!



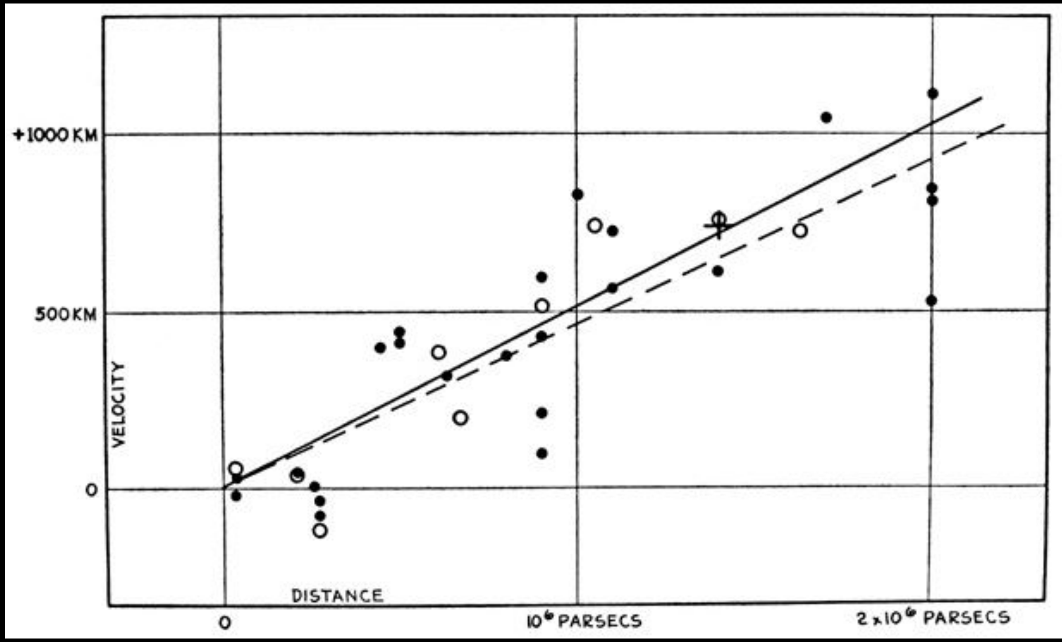
http://spider.ipac.caltech.edu/staff/jarrett/papers/LSS/2MASS_LSS_chart-NEW.jpg

Cosmic Expansion

In 1929 Edwin Hubble found that recession velocities of galaxies, as measured by red shift, increase linearly with distance.

Hubble's Law:

$$v = H_0 d$$

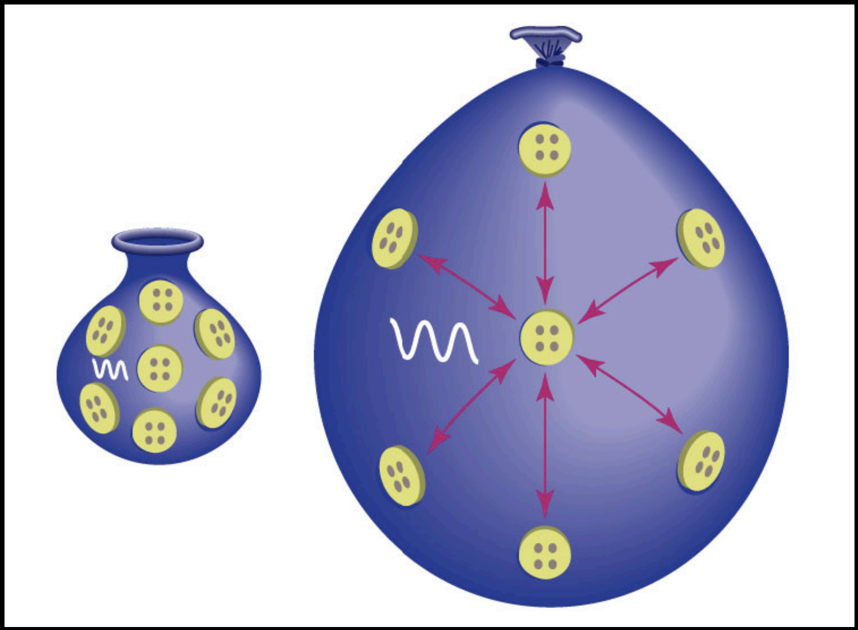


The constant slope, H_0, is known as the *Hubble constant*.

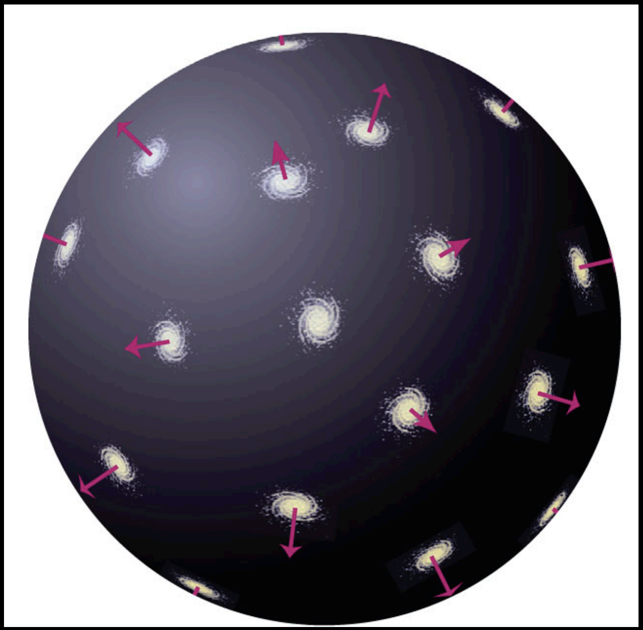
Practical use:
Measure the red shift *z*, convert that to recession velocity *v*, and solve for distance *d*.

Interpretation: the universe is expanding in all directions!

Analogy: expansion of the surface of a balloon



Buttons all move away from each other



Galaxies all move away from each other (but in 3 dimensions, not just 2)

Another analogy: raisin bread, with rising dough

The Hubble Law says that the recession speeds of galaxies are directly proportional to their distances. This simple relationship implies that:

1. The universe will have a finite lifetime
2. The universe has a finite age
3. The universe has a finite age, and will have a finite lifetime
4. My brain hurts

Hubble Time

The Hubble Law implies a finite age of the universe, which can be computed from Hubble's Law.

Using *d = vt* , how long did it take a galaxy to get out to distance *d* while traveling at speed *v* ?

$$d = vt \quad \text{and} \quad v = H_0 d$$

so

$$t = \frac{d}{v} = \frac{\cancel{d}}{H_0 \cancel{d}} = \frac{1}{H_0}$$

Which is called the *Hubble Time*

Age of the Universe

To get the units right we need to convert/cancel Mpc with km in (km/s), and convert seconds to years

$1 \text{ Mpc} = 3.086 \times 10^{22} \text{ m}$ $1 \text{ yr} = 3.156 \times 10^{7} \text{ s}$

Example: what is the Hubble time if $H_0 = 100$ (km/s)/Mpc ?

$$T_0 = \frac{1 \text{ Mpc}}{100 \text{ km/s}} \times \frac{3.086 \times 10^{22} \text{ m}}{1 \text{ Mpc}} \times \frac{1 \text{ km}}{1000 \text{ m}} \times \frac{1 \text{ yr}}{3.156 \times 10^{7} \text{ s}}$$

$$= \quad 9.8 \times 10^{9} \text{ yr} \quad \approx \quad 10 \text{ billion years}$$

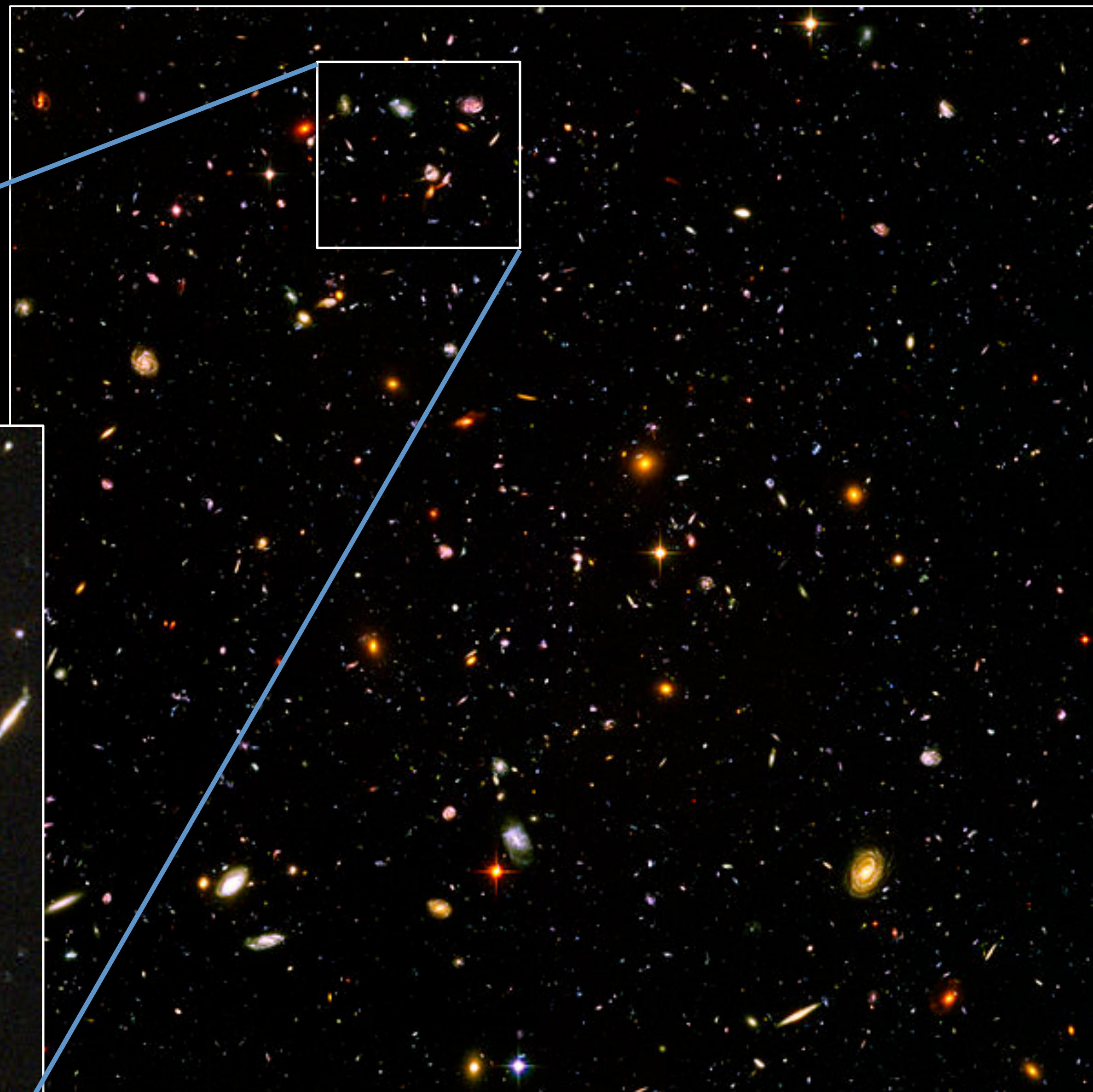
(Presents a problem if there are stars 12 Gyr old)

Hubble Ultra Deep Field

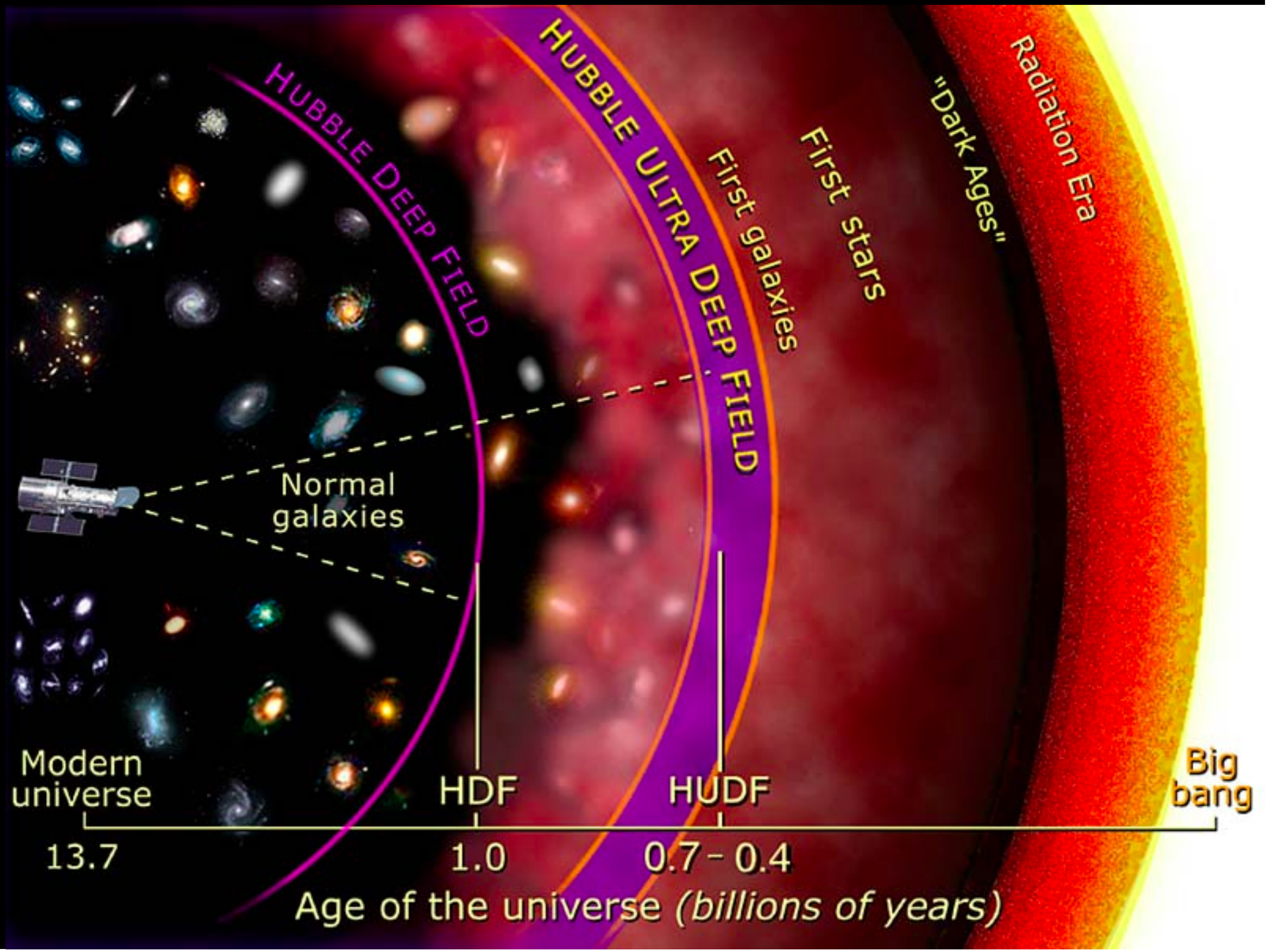
Hubble Space Telescope (HST)
collected data from
September 24, 2003
to January 16, 2004.

Deepest image ever taken –
about 13 billions years

Estimated to contain 10,000 galaxies!



Hubble Deep and Ultra Deep Fields



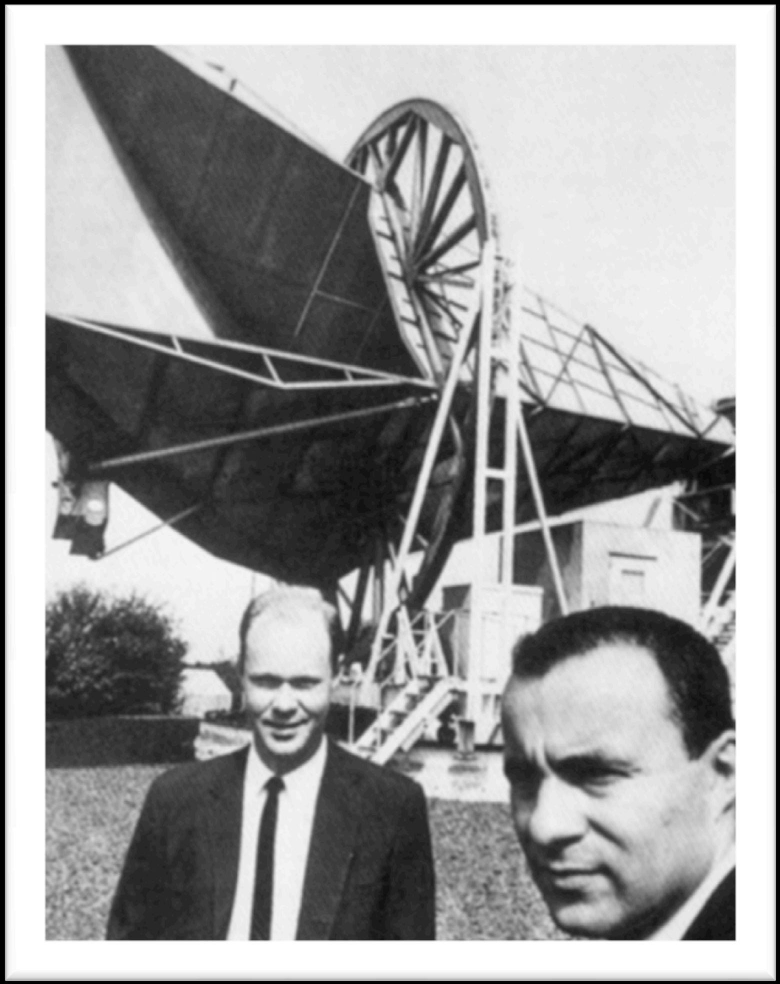
Cosmic Microwave Background

Penzias and Wilson detected constant, isotropic microwave signal while testing their equipment for another purpose.

The signal has a "black body" distribution corresponding to a temperature of about 3 K

George Gamow actually predicted this in 1940s but they were not aware of it.

Interpretation:
It is the last radiation from "decoupling",
when atoms first formed,
when the Universe had a temperature of 3000 K,
then red shifted by the cosmic expansion

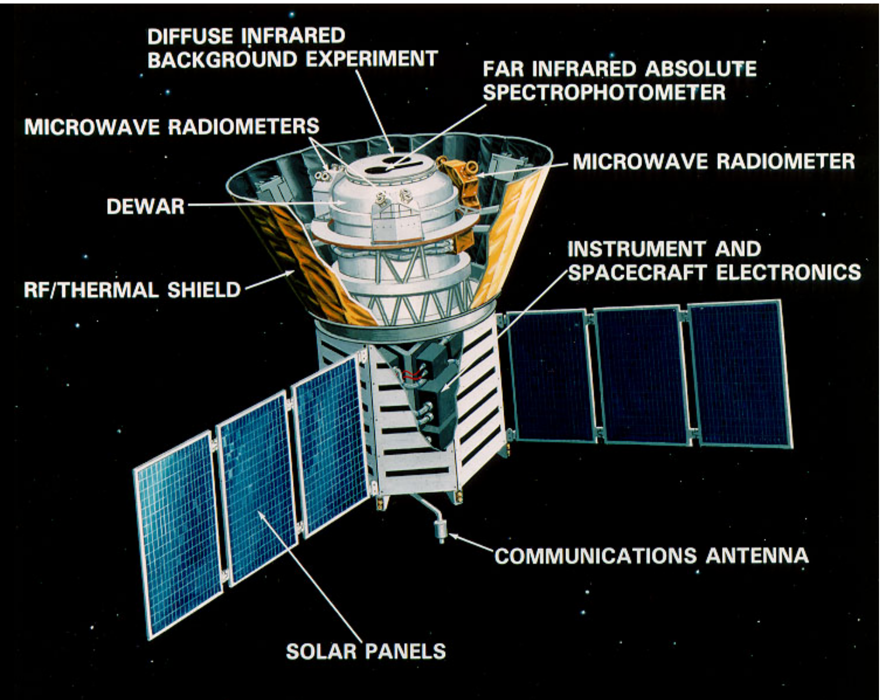


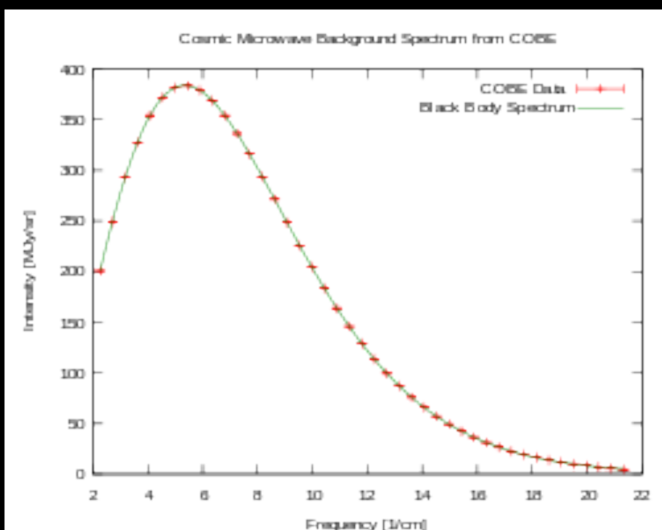
Robert Wilson and Arno Penzias with the radio antenna they used to discover the CMB in 1964-65. (Nobel Prize, 1978)

COBE

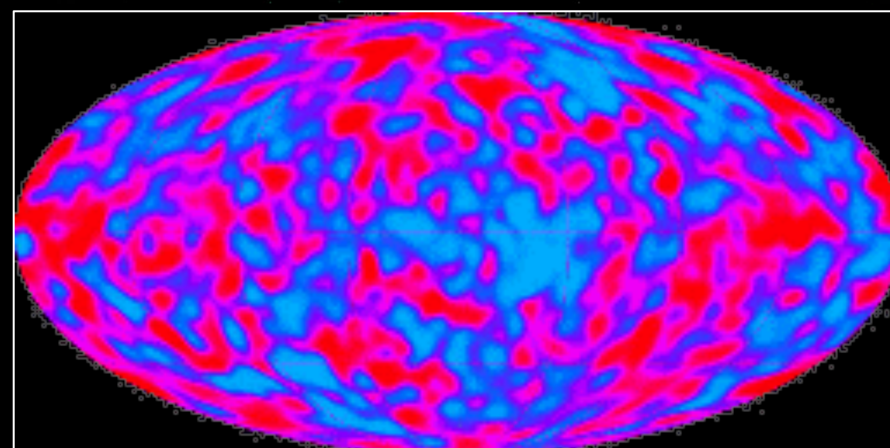
<u>CO</u>smic <u>B</u>ackground <u>E</u>xplorer

Satellite launched November 18, 1989 to measure the Cosmic Microwave Background (CMB) and to attempt to detect anisotropies. 4 years of data.





Confirmed the blackbody spectrum of the CMB



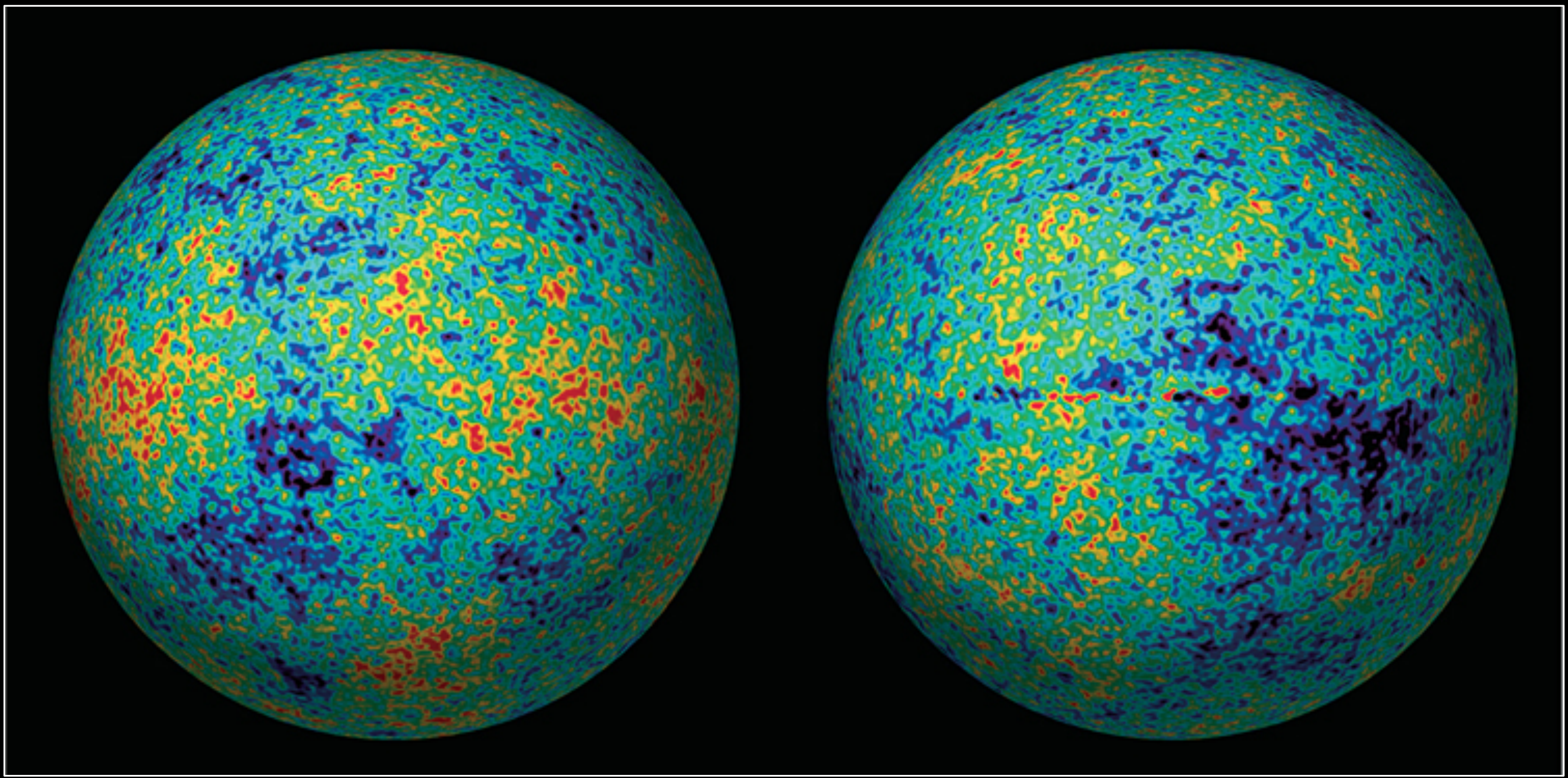
Found fluctuations in CMB at 10^{-5}

2006 Nobel Prize to George Smoot and John Mather

CMBR from WMAP

Temperature of the Universe: 2.74 K

Wilkinson Microwave Anisotropy Probe (WMAP) data show very small variations in CMBR, (on the order of 10^{-5}).

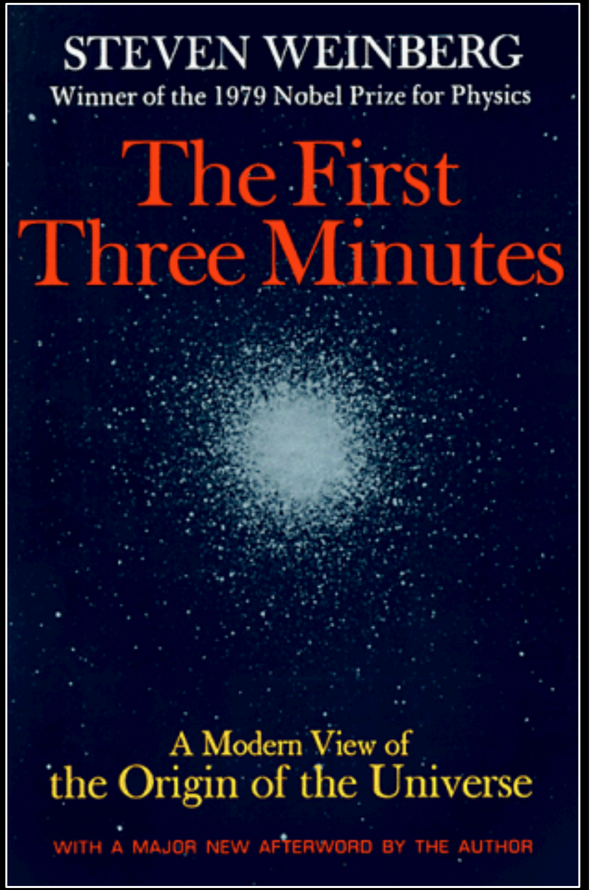


Red: slightly warmer

Blue: slightly cooler

The First Three Minutes

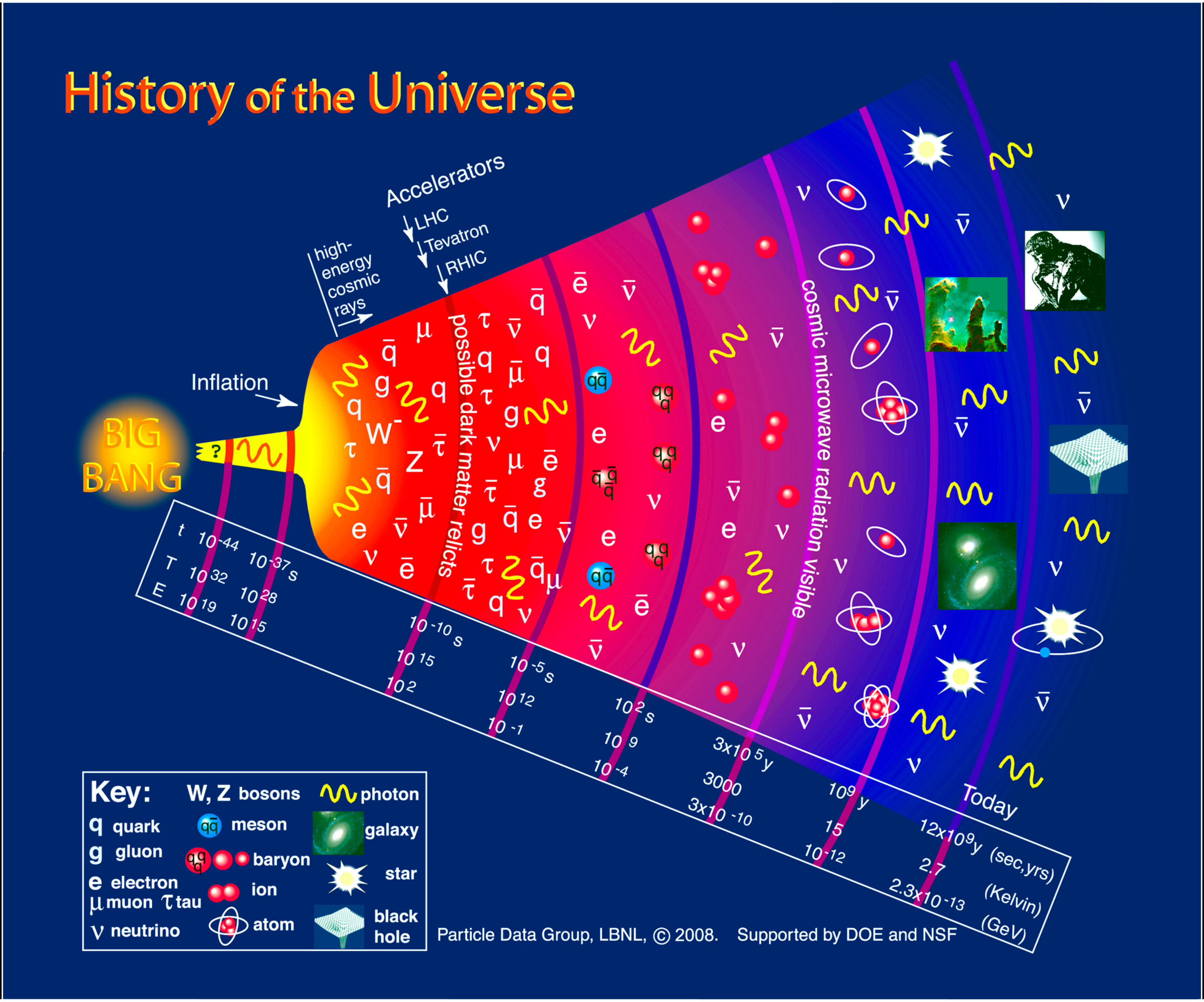
Time	Temperature	
10^{-6} s	10^{13} K	quark-gluon plasma
10^{-5} s	4×10^{12} K	baryons and mesons
1000 s	10^{9} K	deuterons, nucleosynthesis
…..	….	
380,000 yr	3000 K	"decoupling" --> CMBR
500 Myr	15 K	stars and galaxies form
13 Gyr	3 K	today



Steven Weinberg, Nobel Prize 1979

"High Energy" physics of subatomic particles becomes important for understanding the earliest history of the universe (and vice-versa).

This is why some reporters refer to the CERN collider as a "time machine".

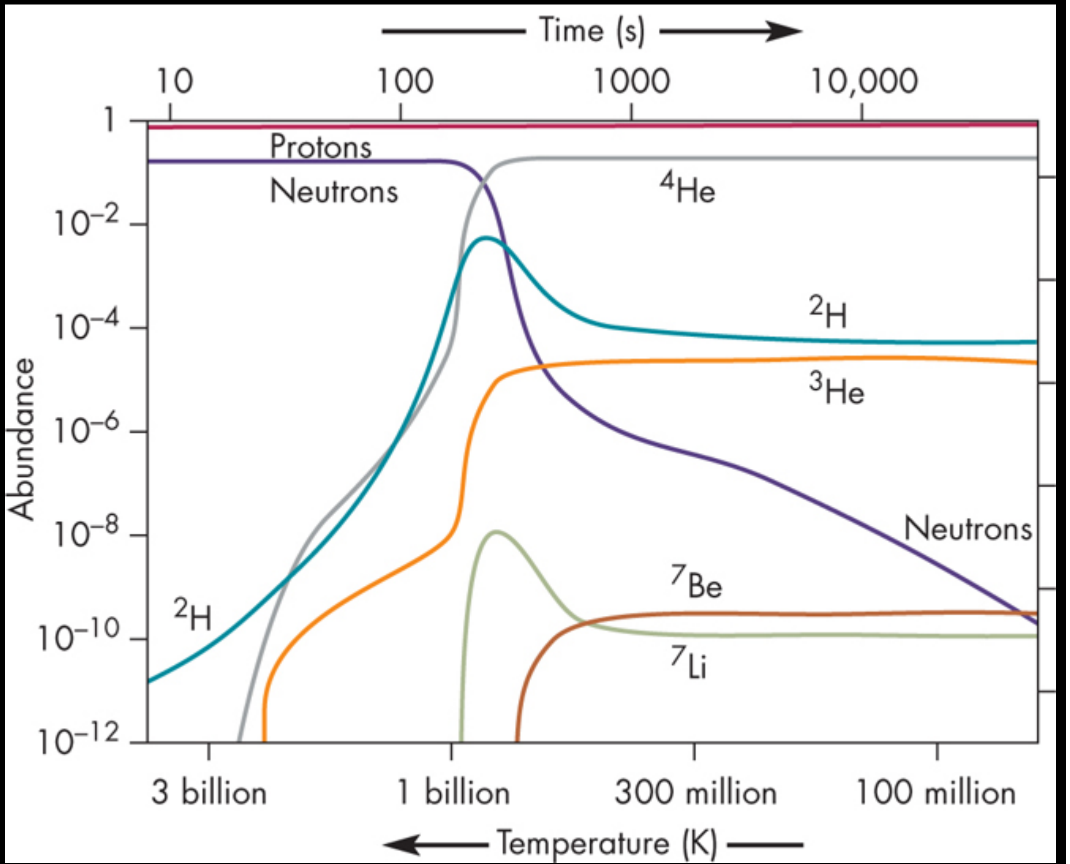

History of the Universe
BIG BANG
Inflation
high-energy cosmic rays
Accelerators
LHC
Tevatron
RHIC
possible dark matter relics
cosmic microwave radiation visible
t 10^{-44} 10^{-37} s
T 10^{32} 10^{28}
E 10^{19} 10^{15}
10^{-10} s
10^{15}
10^{2}
10^{-5} s
10^{12}
10^{-1}
10^{2} s
10^{9}
10^{-4}
3x10^{5} 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
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Big Bang Nucleosynthesis

For a brief while, the temperature and density on the early universe would have been high enough to fuse protons and neutrons into light elements, including ^{4}He, ^{3}He, ^{7}Be, ^{7}Li, ^{2}H

The oldest stars are thought to contain these elements in their original "primordial abundances"

Data from the oldest stars therefore provide constraints on models of the Big Bang, such as the initial density of protons and neutrons.



Inflation

While the "standard" Big Bang story explains a lot, there are a few remaining problems:

Horizon Problem – points on opposite sides of the CMBR look the same, but could not have been in causal contact at the time of decoupling. Why?

Flatness Problem – Application of Einstein's General Theory of Relativity (GR) allows the universe to have positive or negative curvature (see §26.2), but the Universe appears to be flat. This requires $\Omega = \rho/\rho_c = 1.000000....$ Why?

Structure Problem – While the Universe is uniform at the largest scales, there are structures (clusters, walls, voids) which must have developed from irregularities at the time of decoupling. What caused those irregularities? What set their scale?

These problems are all solved if we assume a period of extreme expansion at around 10^{-34} s until 10^{-32} s.

The universe would have doubled in size 100 times! $2^{100} \approx 1.27 \times 10^{30}$

Particle physicists have models, but no complete explanation of the cause of "Inflation"

Dark Energy

Two separate groups of astronomers developed methods to use Type Ia supernovae in distant galaxies as standard candles (1998).

At great distances they found a deviation from the Hubble Law!

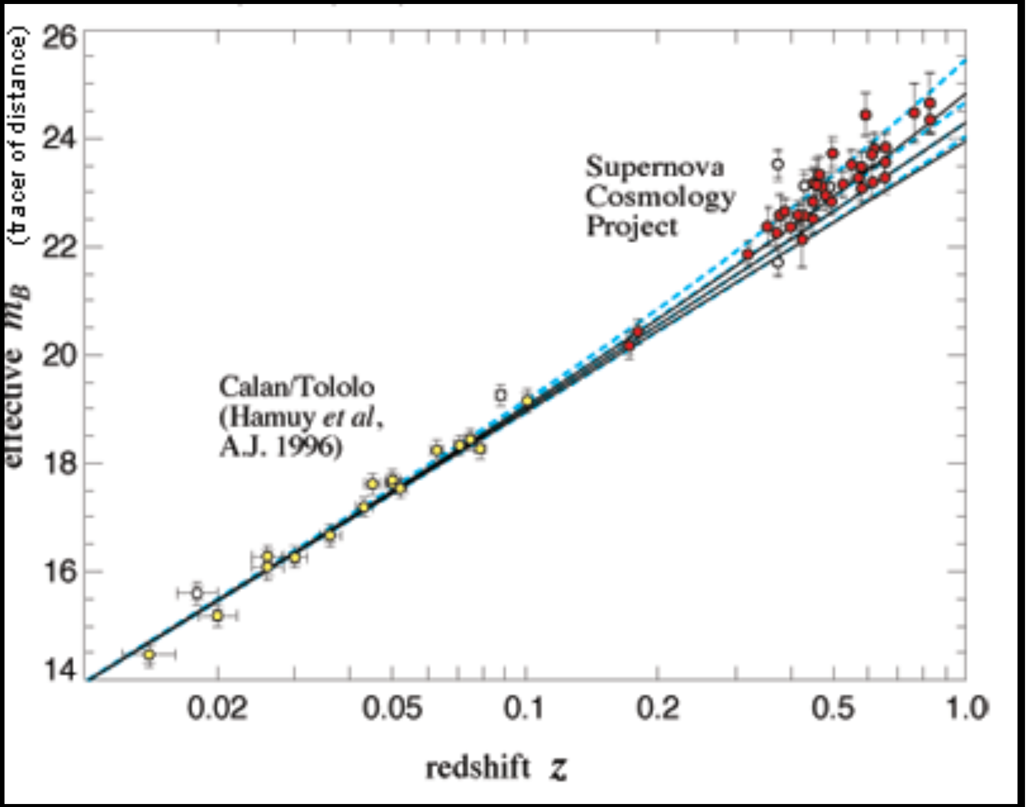
For a given red shift the object is farther away than expected.

Or . . .

At greater distances the recession velocity is less than expected

➔Recent recession velocities greater

➔The universe is "accelerating"



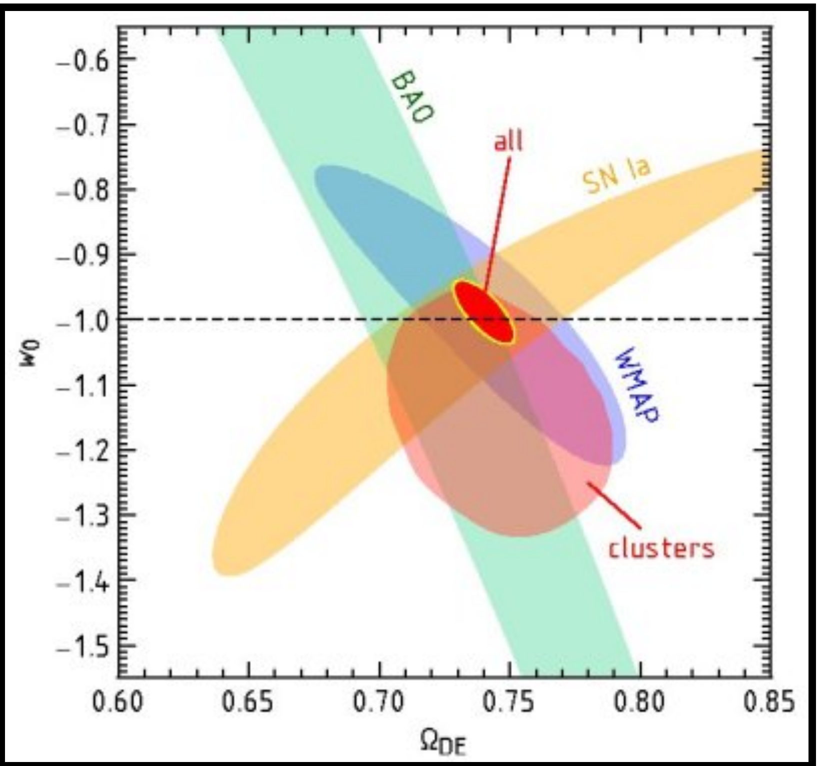
Perlmutter et al.,1998, Astrophysical Journal, v. 516

2011 Nobel Prize to Perlmutter, Schmidt and Riess

Observations from

- Type Ia supernovae
- WMAP CMBR
- Chandra X-Ray galaxy clusters
- Baryon Acoustic Oscillations

all provide overlapping tests of the dark matter hypothesis.



Combined, they suggest the Universe is composed of:

Dark energy: 74% Matter: 26%

(of which 4% is regular matter, 22% is dark matter)

… and that dark energy behaves like a "cosmological constant" ($w_0 = -1$)

Einstein's Field Equations,

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu} R + g_{\mu\nu}\Lambda = \frac{8\pi G}{c^4}T_{\mu\nu}$$

with cosmological constant Λ

Einstein: "*the biggest blunder I ever made*"

The Fate of the Universe

The ultimate fate of the universe depends on the overall mass/energy density:

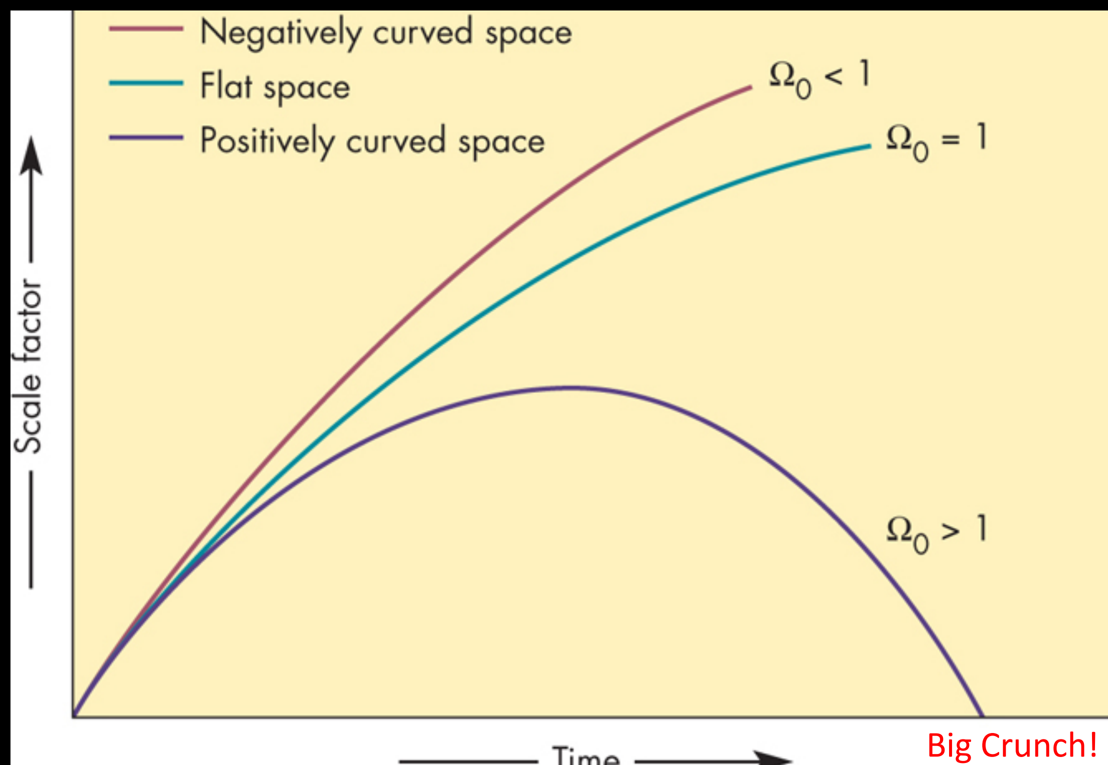
- Too much, and the Universe will collapse back on itself.
- Too little (or too much dark energy) and it will continue to expand forever.

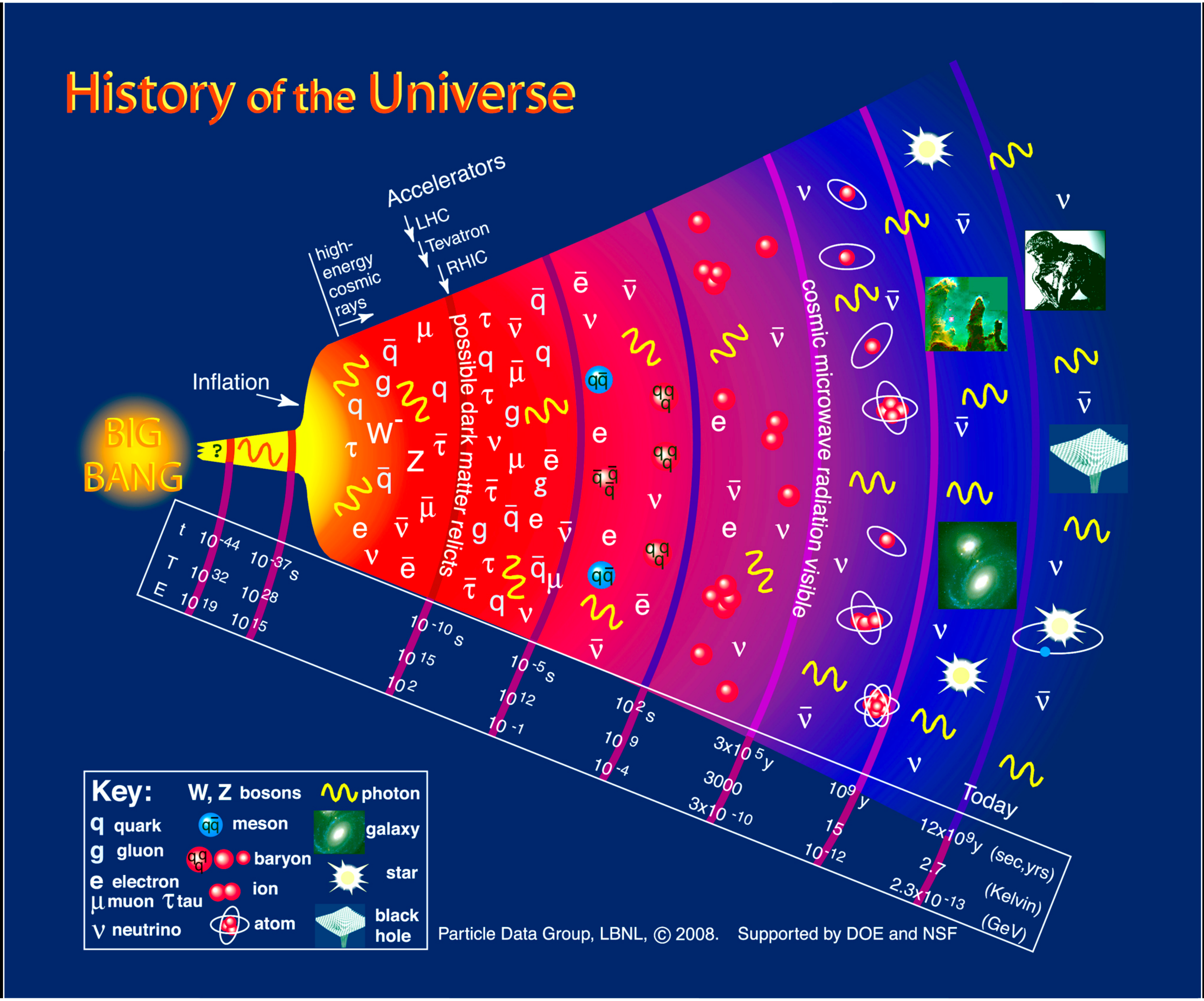
Density parameterized by

$$\Omega_0 = \frac{\rho}{\rho_c}$$

CMBR says:

$$\Omega_0 = 1.005 \pm 0.006$$

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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
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
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