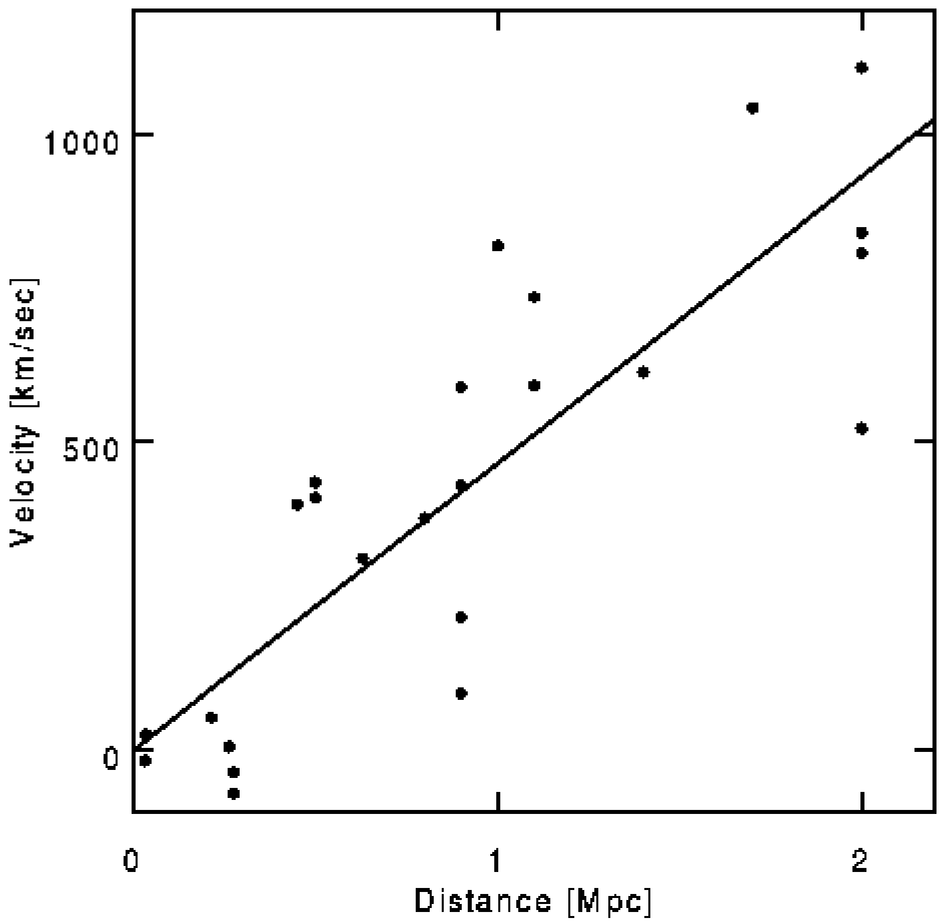
Cosmology: The Expanding Universe

Galaxies are much too distant to directly measure proper motions across the sky. But we can easily find their motion towards/away from us from Doppler shifts. In the 1920s, Hubble and others measured galaxy Doppler shifts and made a discovery of enormous importance:

Almost all galaxies show redshifts and almost no galaxies show blueshifts

The redshifts of faint (= distant) galaxies are larger than from bright (= nearby) galaxies

<>Galaxy redshifts are usually measured using the absorption lines of stars, the H-alpha line from hot hydrogen, the 21-cm radio line from cold hydrogen, or the overall color of their starlight (photometry). Galaxy redshifts are labeled **z** where $\mathbf{z = v / c = (l_{obs} - l_{em})\, c / l_{em}}$ where v is the velocity away from us, c is the speed of light, l_{obs} is the wavelength we observe and l_{em} is the wavelength emitted by the stars/gas. The result is that a very distant galaxy moving from us very close the speed of light will have a redshift much greater than 1.



Hubble & others found a linear relation between redshift and distance for samples of galaxies **$zc = v = H_o d$**
where v is the velocity away from us in km/s, d is the galaxy distance in Mpc, and H_o is **Hubble's constant** in km/s/Mpc. Hubble's constant H_o measures the rate at which galaxies are receding from our Galaxy. Its value has been debated for years, due to uncertainties in galaxy distance indicators. Today's best estimate from nearby galaxy measurements is **H_o = 72 +/- 8 km/s/Mpc** based on distances to nearby galaxies measured from Cepheid variables with the Hubble Space Telescope (Freedman 2003).

Hubble's discoveries raised some profound and troubling questions:

Why are galaxies only redshifted? What causes Hubble's Law?
It appears we are at the center of an explosion! Do all galaxies know we are here, and are racing away from us? Seems absurd! ***But there is one reasonable explanation .....***

The entire Universe is expanding, and observers on every galaxy will see the same $v = H_o d$ law.
1-dimensional analogy: smoothly pull a rubberband with dots representing galaxies
2-dimensional analogy: inflate a balloon with buttons representing galaxies

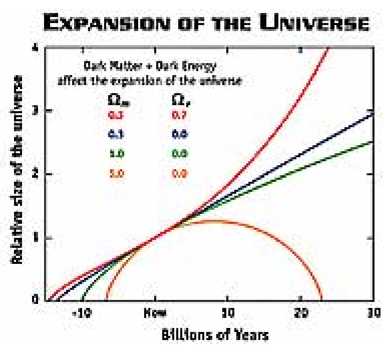
3-dimensional analogy: place a raisin cake in the oven and watch it rise
A linear Hubble Law occurs if the expansion is homogeneous and isotropic (same in all directions)

Some consequences of the expanding universe interpretation:

- The expansion began 8-15 billion years ago. The exact value depends mainly on the deceleration of the expansion due to the gravitational attraction of the matter in the Universe (stars, gas and especially Dark Matter).
- The most distant galaxies and quasars we can see were formed when the Universe was very young. The highest redshift quasar (z ~ 6.4) emitted its light when the Universe was only ~0.5 billion years old.

Theory of the Expanding Universe

Einstein's theory of General Relativity (1915) actually predicted an expanding universe, though he did not believe his own equations! In GR, mass-energy causes curvature in a 4-dimensional space-time. No mass gives a Euclidean geometry. An "open" universe has negative curvature. A "closed" universe is a hypersphere.



The Universe is closed and will recollapse if the density today exceeds the critical value:

Critical Density = 3 H_o^2 / 8 pi G = 1x10 $^{-29}$ g/cm^3 (for H_o=72).

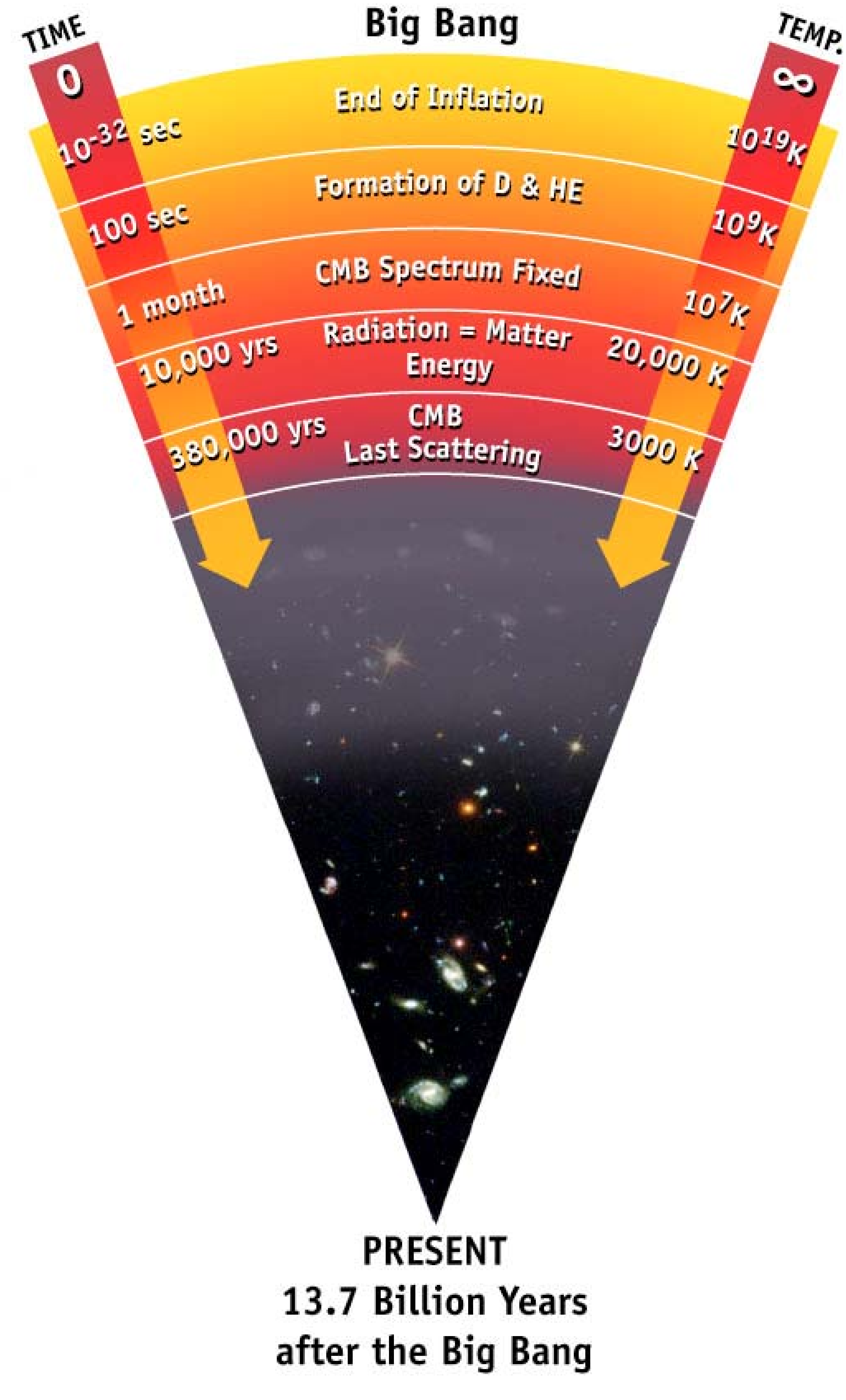
<>This 1 kilogram of matter (ordinary & dark matter) in the volume occupied by the Sun, or 10 atoms of hydrogen in a 1 cubic meter.

It is now clear, both from quantitative measurements of stars/gas/DarkMatter and from the CMB flucturations, that the Universe is open with density ~30% of the critical value. The Universe will thus expand forever.

What was the Universe like when it was young?

If you could run time backwards, the Universe looks like atoms in a box undergoing gravitational collapse! So, when the density was high, the temperature should be high, and nuclear reactions might occur, like in center of stars. The very beginning resembles a black hole where all matter is compressed into a tiny volume.

The idea that the Universe expanded from a very hot compressed state is called the ***hot Big Bang model*** It was introduced by George Gamow in the 1950s and developed during the 1960-80s. Let us trace the early history of the Universe in the Big Bang model, deduced by applying laws of physics (particle physics, nuclear physics, electromagnetism, and gravity) to the concept of the expanding Universe.



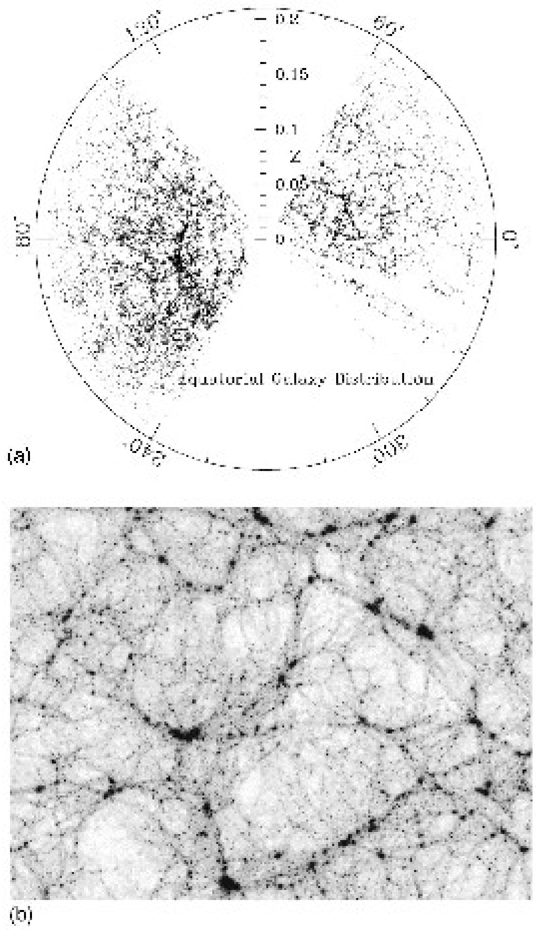
Big Bang
TIME
0
TEMP.
∞
End of Inflation
10-32 sec
10^19 K
Formation of D & HE
100 sec
10^9 K
CMB Spectrum Fixed
1 month
10^7 K
Radiation = Matter Energy
10,000 yrs
20,000 K
CMB Last Scattering
380,000 yrs
3000 K
PRESENT
13.7 Billion Years after the Big Bang

Big Bang history of the Universe

Age	Temp	Physical Conditions
< 0	...	Before the Big Bang. The Universe as we know it does not exist. We know, and can not know, anything about this.
0	infinite	All points in the Universe lie in a singularity. We do not understand this physically, though there are mathematical solutions to Einstein's equations of gravity for this.
10^{-35} sec	very high	**Inflation era.** Very brief phase of exponentially fast expansion. Universe filled with exotic particles not yet identified by physicists.
10^{-6} sec	10^{13} °K	Quarks & anti-quarks annihilate into gamma-rays, but a small fraction is left over to form regular matter (protons & electrons). Photons outnumber protons/electrons by a billion-to-one in our Universe. **Light dominated era.**
10^{2} sec	10^{7} °K	Protons combined to make ^{4}He (helium) nuclei, and traces of other light isotopes (^{3}He, ^{6} Li, ^{7}Li). These nuclear reactions are similar to those occurring today in the center of our Sun. Models make precise prediction that 23-25% of the protons should enter helium.
10^{6} yr	10^{4} °K	**Recombination era**. Universe has cooled so that the nuclei and electrons can combine to form neutral H and He atoms. Neutral atoms are decoupled from the light and are free to begin gravitational collapse. Start of the **matter dominated era.**
10^{9} yr	10^{2} °K	Early stars, supermassive black holes (--> quasars) and protogalaxies form.
9 10^{9} yr	10^{1} °K	One ordinary star with an ordinary planetary system forms in the disk of an ordinary spiral galaxy. The 3rd planet has liquid water and develops living organisms. That's us!
13.7 10^{9} yr	2.735 °K	**Today.** Photons have cooled from gamma-rays to microwaves. Distant galaxies continue to recede from each other according to $v=H_o d$. Nearby galaxies have collected into groups and clusters. Stars continue to form in spiral galaxy disks. One of the organisms on Earth tries to understand the Universe in 111 Forum, Penn State.
Future	cold	**Universe is open, expands forever.** Close galaxies merge, distant galaxies recede further away from each other. Stars gradually converh H to He and heavier elements. Eventually, Universe is dark, cold and left with radio photons, neutrinos,

		and remnants of stars (white dwarfs, neutron stars, black holes) and planets.

One aspect that is undergoing intensive study today is the development of large-scale structure after recombination. The physics is thought to be simple: Newtonian $1/r^2$ Newtonian gravity of the (yet-to-be identified) Dark Matter particles. The largest computers in the world are simulating the nonlinear evolution of skeets, filaments & voids, and the results (bottom panel below) are successfully compared to the clustering seen in galaxy redshift surveys (top panel).



Review of Cosmology so far:

- Hubble finds that mearly all galaxies have redshifts, and recessional velocities are proportional to galaxy distances (1920s--present). The only reasonable explanation is that the Universe is expanding homogeneously and isotropically, like an inflating balloon (1930s).

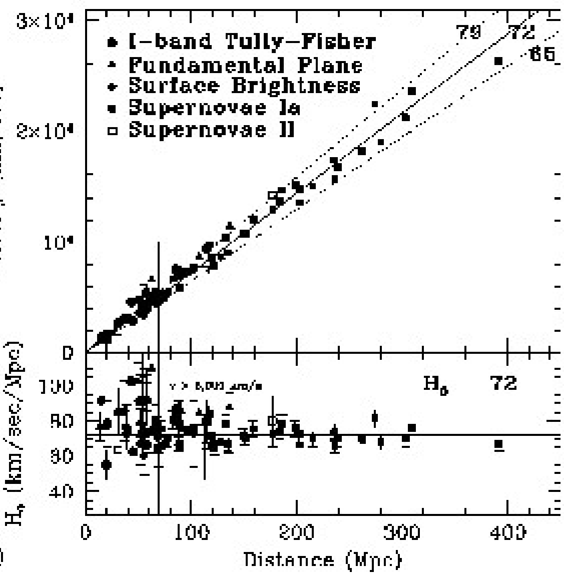
- This fits with Einstein's theory of gravity (General Relativity), which predicted an expansion (1915).

- Many lines of observational evidence of the matter content (galaxy rotation curves, velocity dispersion of galaxy clusters, X-ray emitting gas in galaxy structures, gravitational lensing by galaxies and clusters) indicate **the Universe is open and will expand forever.**

Evidence for the hot Big Bang Model

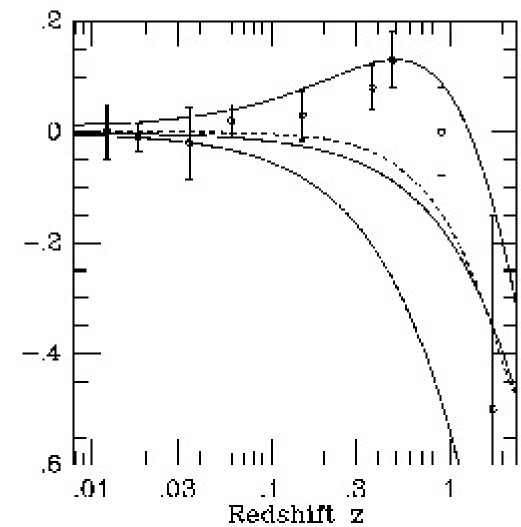
(1) Recession of the galaxies

Current galaxy redshift data confirm the linear Hubble law $v=H_o d$ with H_o =72 km/s/Mpc (top panel below). But, recent velocity/distance diagrams made with **Type Ia supernovae** show a slight nonlinear deviation (1999--, bottom panel). This implies that **the expansion of the Univese is accelelerating for unknown reasons. Space-time must be filled with some kind of dark energy that pushes outward.** The middle panel shows the measured deviations (the traditional linear relation would give a horizontal line here), and the bottom panel shows the revised diagram of the expansion of the Universe.



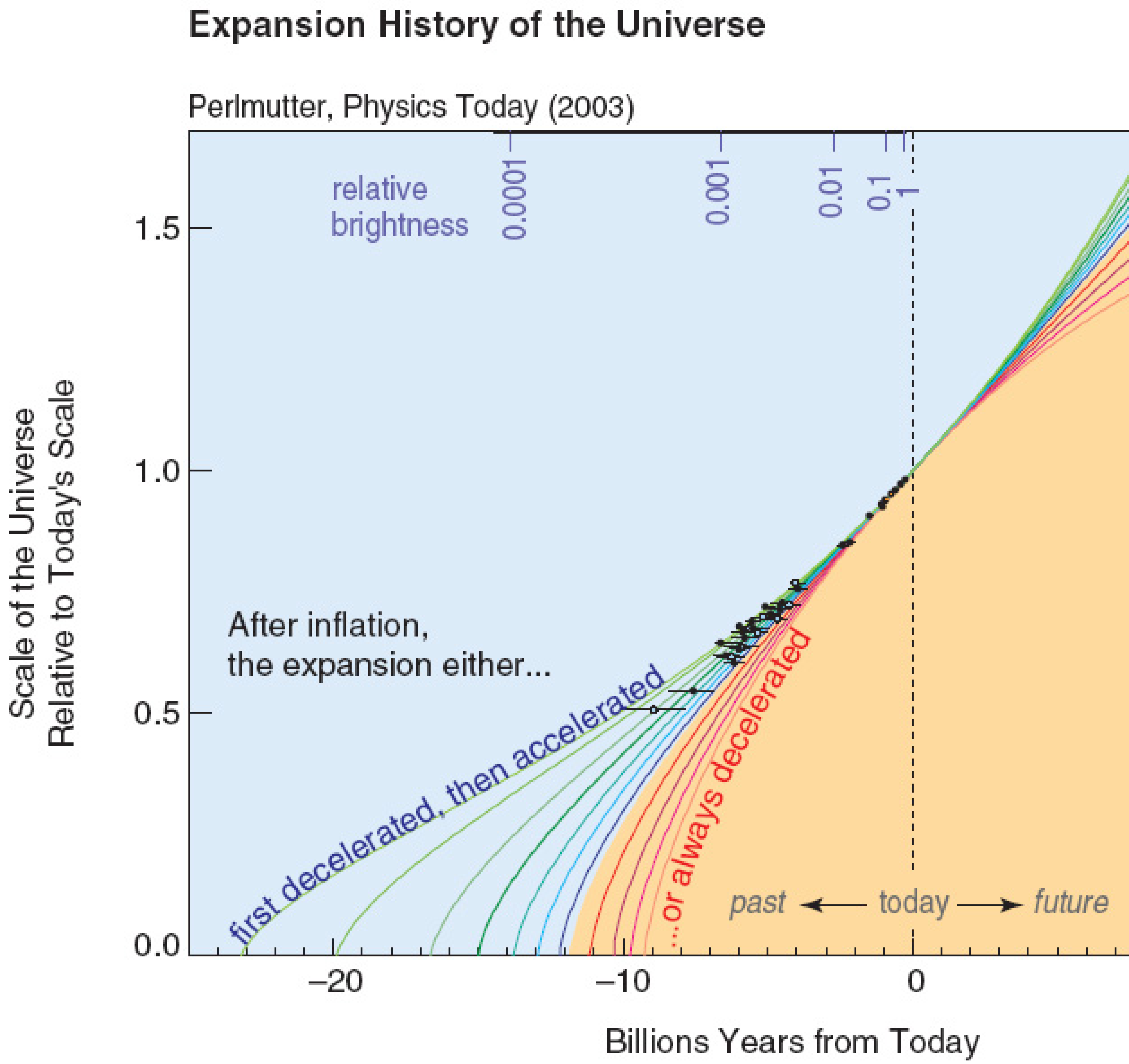
I-band Tully-Fisher
Fundamental Plane
Surface Brightness
Supernovae Ia
Supernovae II
79
72
65
Velocity (km/sec)
H₀ (km/sec/Mpc)
H₀ 72
Distance (Mpc)

(a)



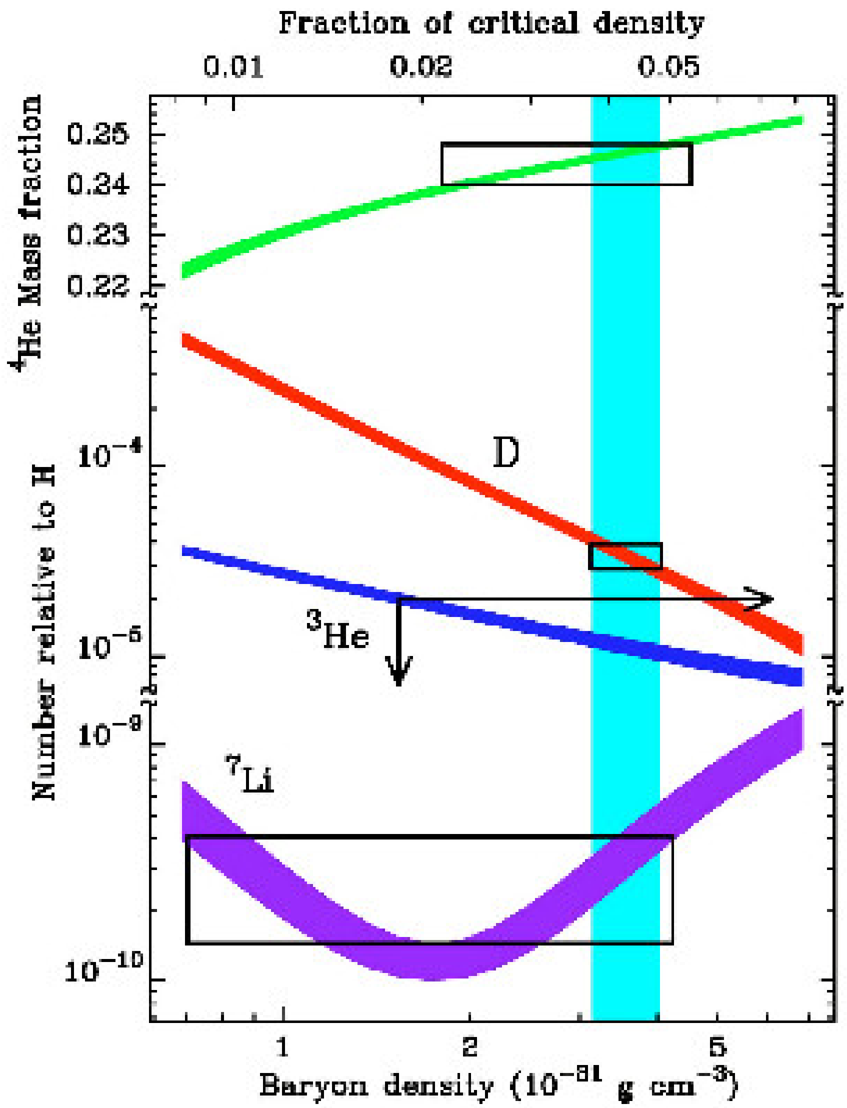
5 log (H₀d_L) [Δ(m−M)]
Redshift z

(b)

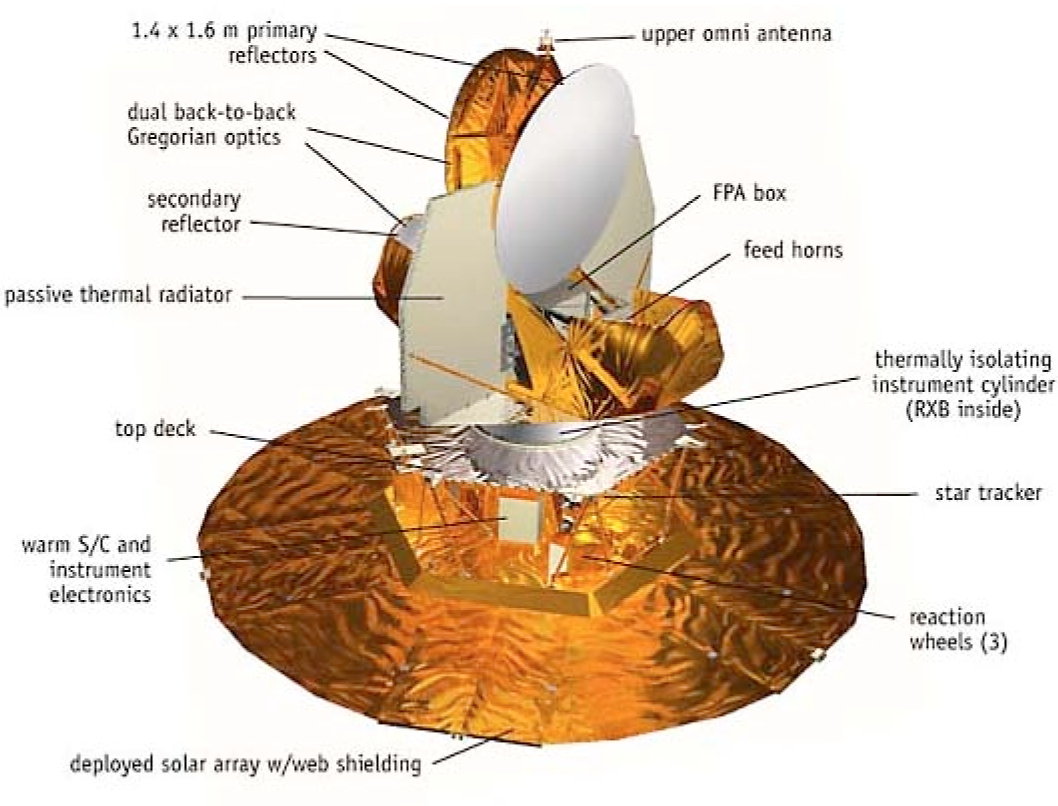


(2) Abundances of the light elements

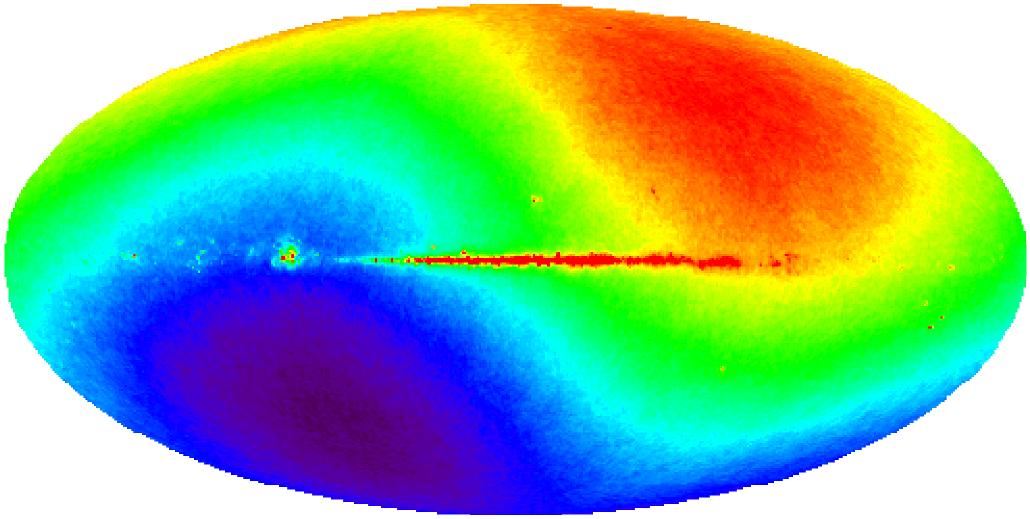
The hot Big Bang model makes precise predictions about the abundances of ^{4}He (24-26%), ^{2}H, ^{3}He, ^{6} Li and ^{7}Li, which are created during the first few minutes of the Big Bang. Measurements in stars, interstellar medium and in our solar system agree very well with these predictions. The plot below compares the observed abundances of these light elements (boxes) with predictions of the Big Bang model (colored bands). Note they all agree if the density of regular matter (atoms, elements) is ~4% of the critical density (vertical light-blue band). This is additional evidence that the Universe is open (i.e. expands forever).



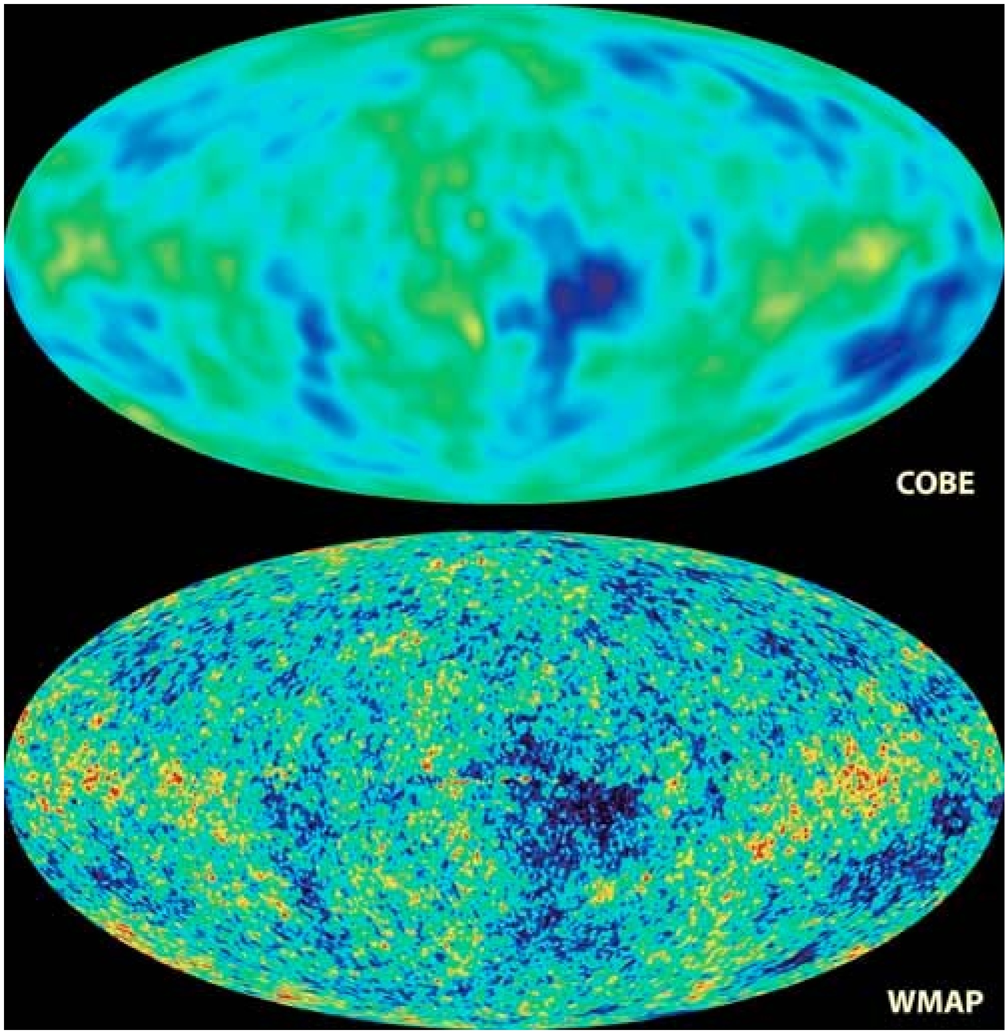
(3) Blackbody radiation with T ~ few degrees K prevading the Universe
The hot Big Bang model predicts that the Universe should be filled with photons, originally gamma rays, which have now cooled to be radio/microwave photons. This was spectacularly confirmed by Pensias & Wilson in 1965 who discovered the ***cosmic microwave background*** **(CMB)**: the entire sky is brilliantly bright at wavelengths around 1 mm. This was actually a serendipitous discovery: they were investigating static on microwave long-distance telephone calls!

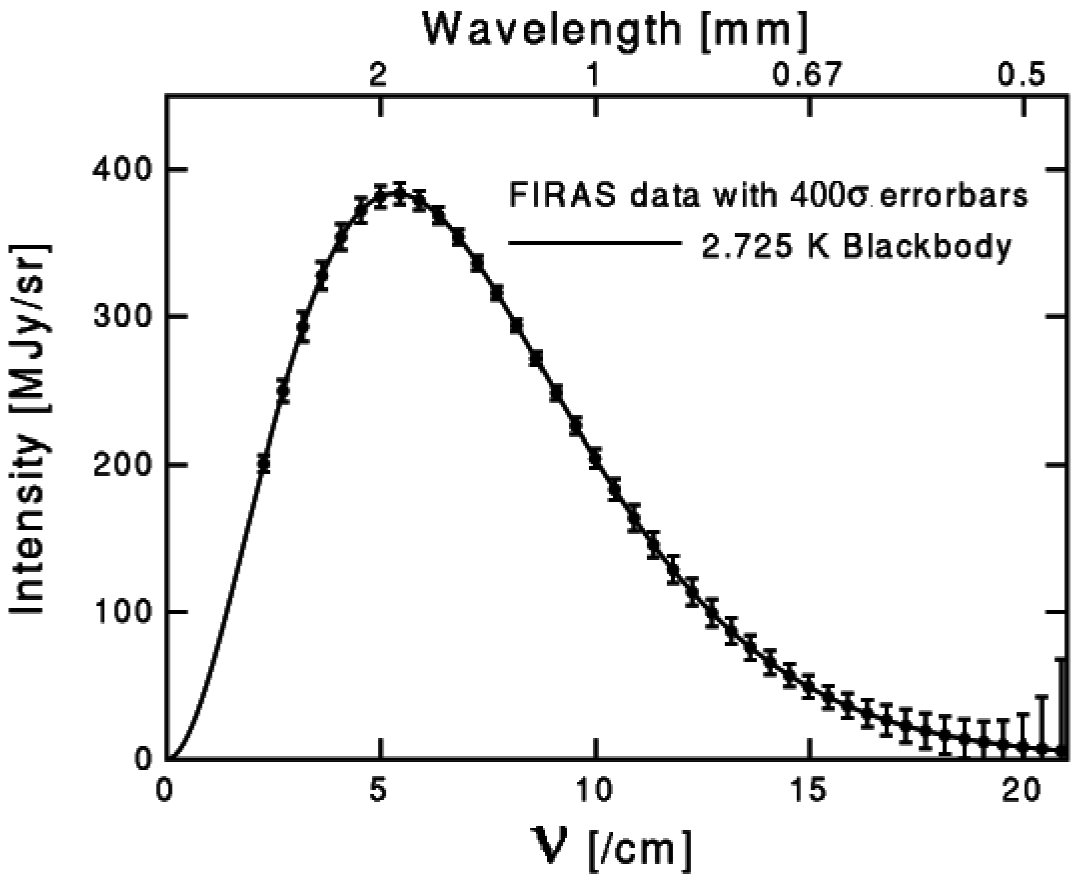


The CMB has been most carefully studied by the Cosmic Background Explorer (COBE, early 1990s) and Wilkinson Microwave Anisotropy Probe (WMAP, early 2000s) satellites, and experiments at the South Pole (2000s). Its spectrum is *precisely* a blackbody with temperature T = 2.725 K. Its distribution is extremely **isotropic** -- similar in all directions -- smoother than a billiard ball. But when measured with extraordinary precision (part-in-a-million), discovered tiny irregularities which emerged from the Big Bang and are the gravitational precursors of galaxies and galaxy clusters. The CMB is slightly hotter on one side of the sky than the other due to our Galaxy's individual motion with v~0.002c. This is shown in the CMB all-sky map below, where contamination by the Milky Way Galaxy is also seen.

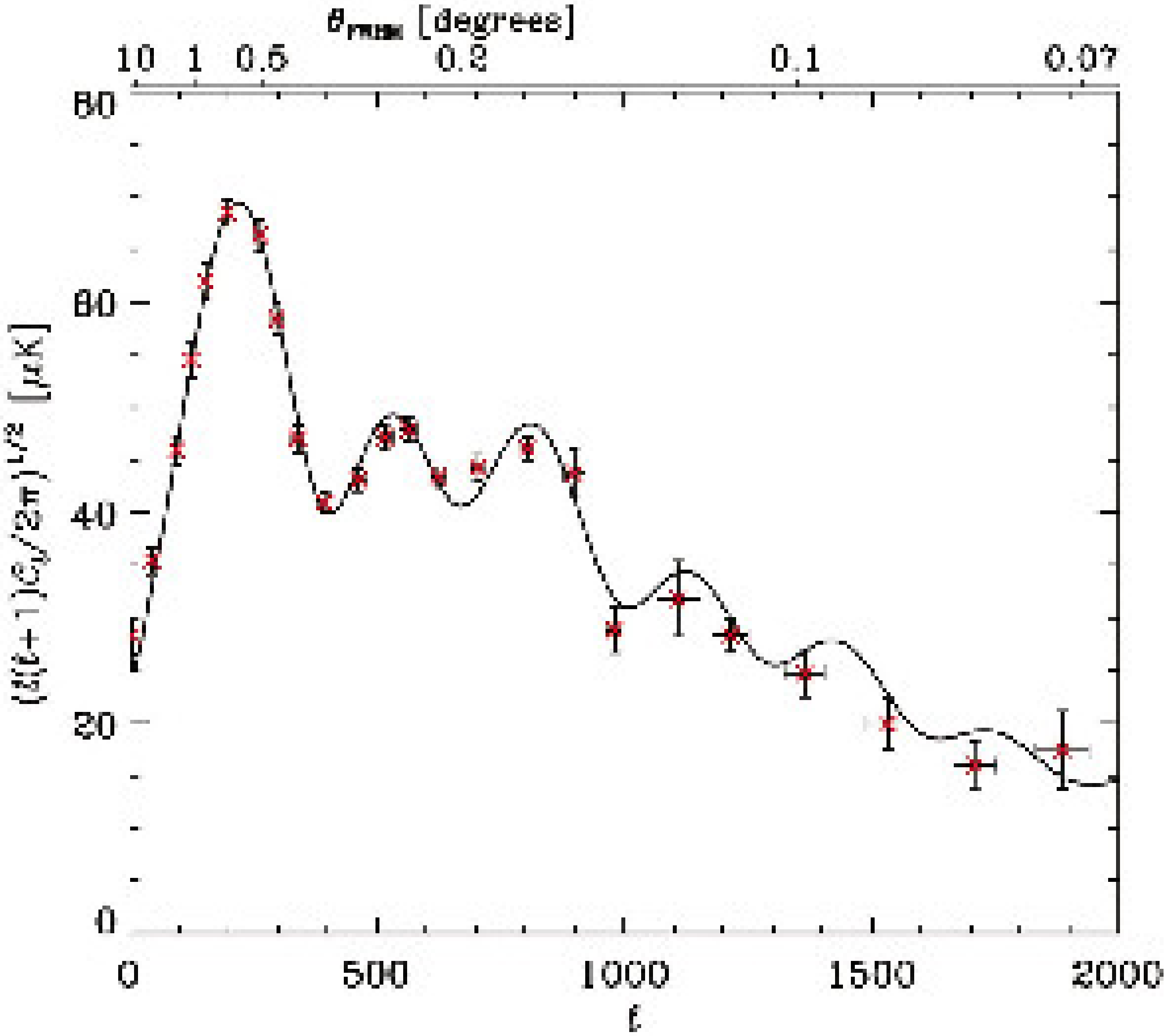


The images below show progress in our understanding of the CMB. The top panel shows the appearance of the entire sky in the microwave band from the COBE & WMAP satellites after removal of the Doppler dipole and a model of the Galactic contamination. The details shown give us much more precise constraints on the Big Bang, the density of the Universe, and its entire history.

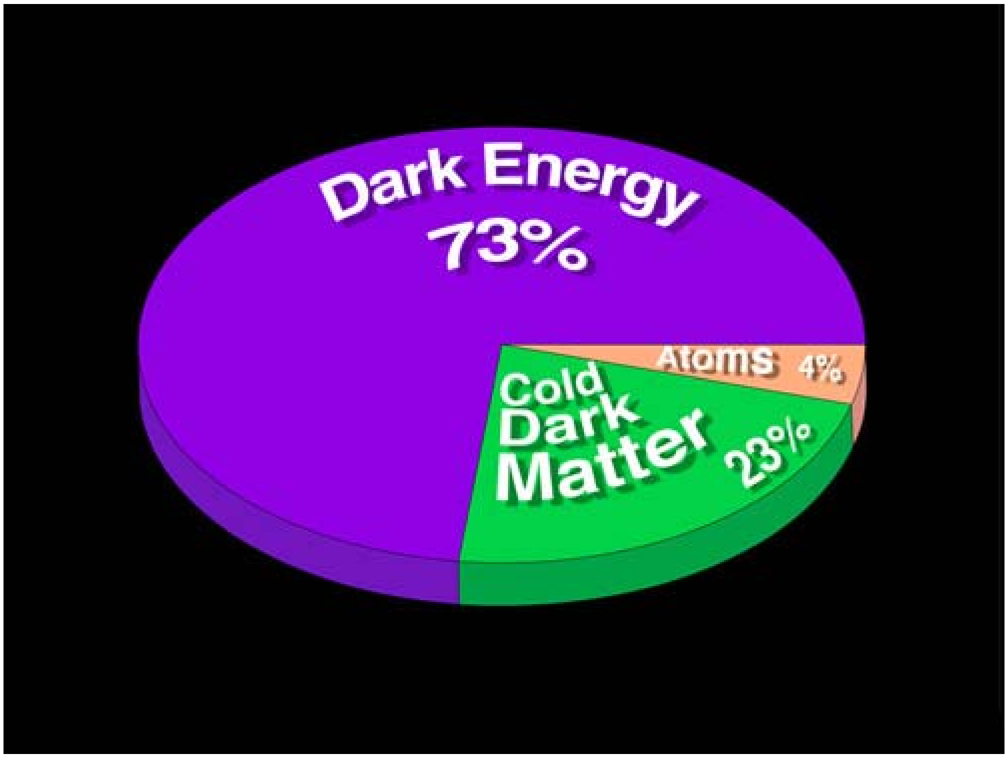

COBE
WMAP



Cosmologists have taken the Big Bang models based on Einstein's General Relativity and the physics of the early Universe (e.g. inflation, light-dominated era, recombination) and compared them to the WMAP fluctuations. The results are amazing: most models are rejected, and the acceptable model requires the same "accelerating Universe" implied by the Type Ia supernova Hubble diagram above! The plot below shows the "spectrum of fluctuations" in the WMAP image with the consensus cosmological model developed in 2003. The model gives precise measurements of cosmological parameters including Ho=72 km/s/Mpc (in complete agreement with the galaxy redshift measurements), density of baryonic (regular atoms) matter and Dark Matter (in complete agreement with the astronomers' measurements of galaxy content), density of Dark Energy (in complete agreement with the Type Ia SN diagram shown above), and other technical parameters of the Big Bang model. The results also agree with constraints provided by the statistics of large-scale structure (e.g. the galaxy two-point correlation function), measurements of X-ray clusters, constraints of light element abundances (diagram above), and other tests. Noone has confidently reported a discrepant measurement: finding a single star older than 14 Gyr, or a single primordial cloud with <24% helium. Note this is an **astrophysical model** not a **heuristic statistical model**, though statistical measures are used to fit the nonlinear functions and obtain parameter confidence intervals.



θ_FWHM [degrees]
10 1 0.5 0.2 0.1 0.07
80
60
40
20
0
(ℓ(ℓ+1)C_ℓ/2π)^1/2 [μK]
0 500 1000 1500 2000
ℓ



Cosmology today

The recession of the galaxies in all directions seems to require an expanding Universe, which in turn implies the Universe began in a hot Big Bang. This model is supported by the blackbody light (the Cosmic Microwave Background radiation) that fills the sky in all directions, and abundances of the light elements. The Big Bang model is now totally convincing. The latest results from Type Ia supernovae and fluctuations in the cosmic microwave background point to a very specific model:

- The Big Bang occurred 13.7 billion years ago.
- The sum of all mass and energy components of the Universe equals exactly the critical density. This validates the theory developed in the 1980-90s concerning the early inflation era. The Universe is open and will expand forever.
- Regular matter (atoms, elements, called "baryons" in the pie chart above) constitutes 4% of the contents of the Universe.
- Dark Matter constitutes 27% of the Universe. It has been known since the ~1960s, and we still don't know what it is made of. Probably some yet-to-be-discovered subatomic particle.
- Dark Energy constitutes 67% of the Universe. This is a brand new result which is not understood at all! We do not know why it is there, what its nature is (scalar field? quintessence?), or what caused it. Understanding Dark Energy is perhaps the most fundamental problem in physics today.