Astrophysics and Cosmology

Scratching the surface of the universe

- Sun
- Stellar story – Hetrzsprung-Russell Diagram
- Life of a star – Main sequence, Giants, Dwarfs, Neutron stars and black holes
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- Reference: Manton and Mee, The Physical World

The Sun

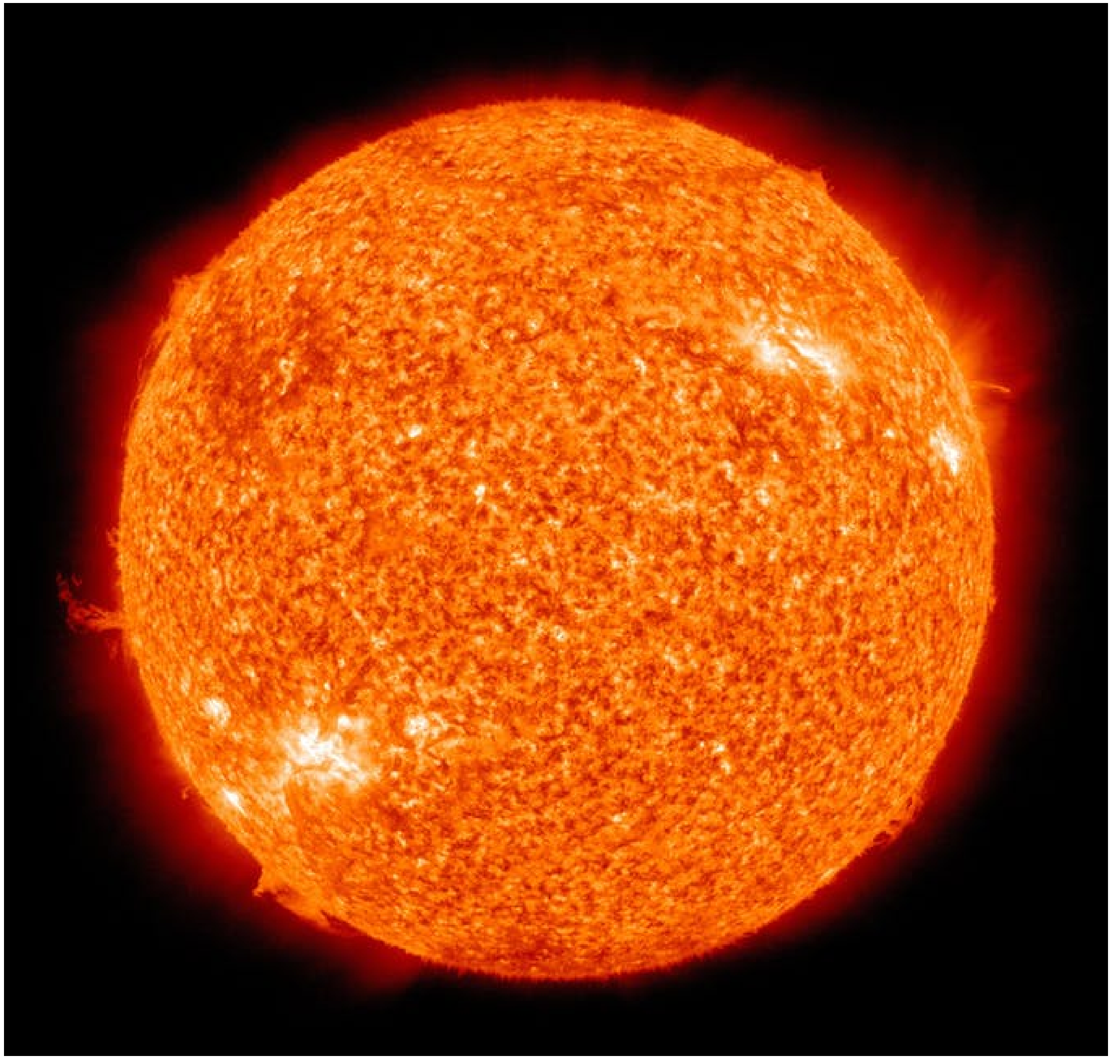
Radius = 7 x 10^8 meters

Mass = 2 x 10^30 kg

Density = 1.4 times water!

Mostly made of hydrogen
and helium

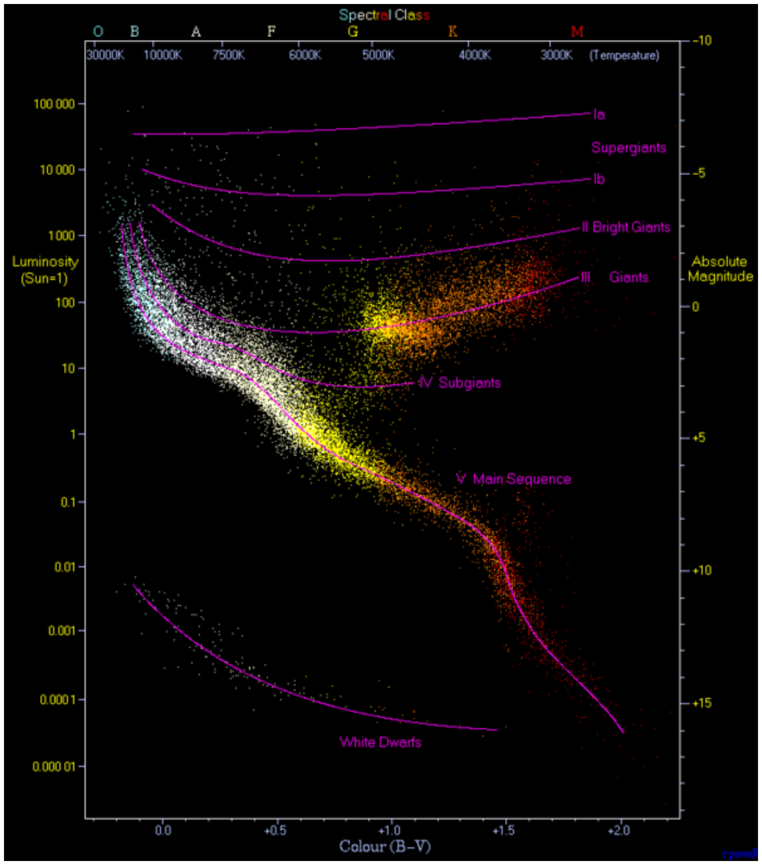
Surface temperature
~ 6000K

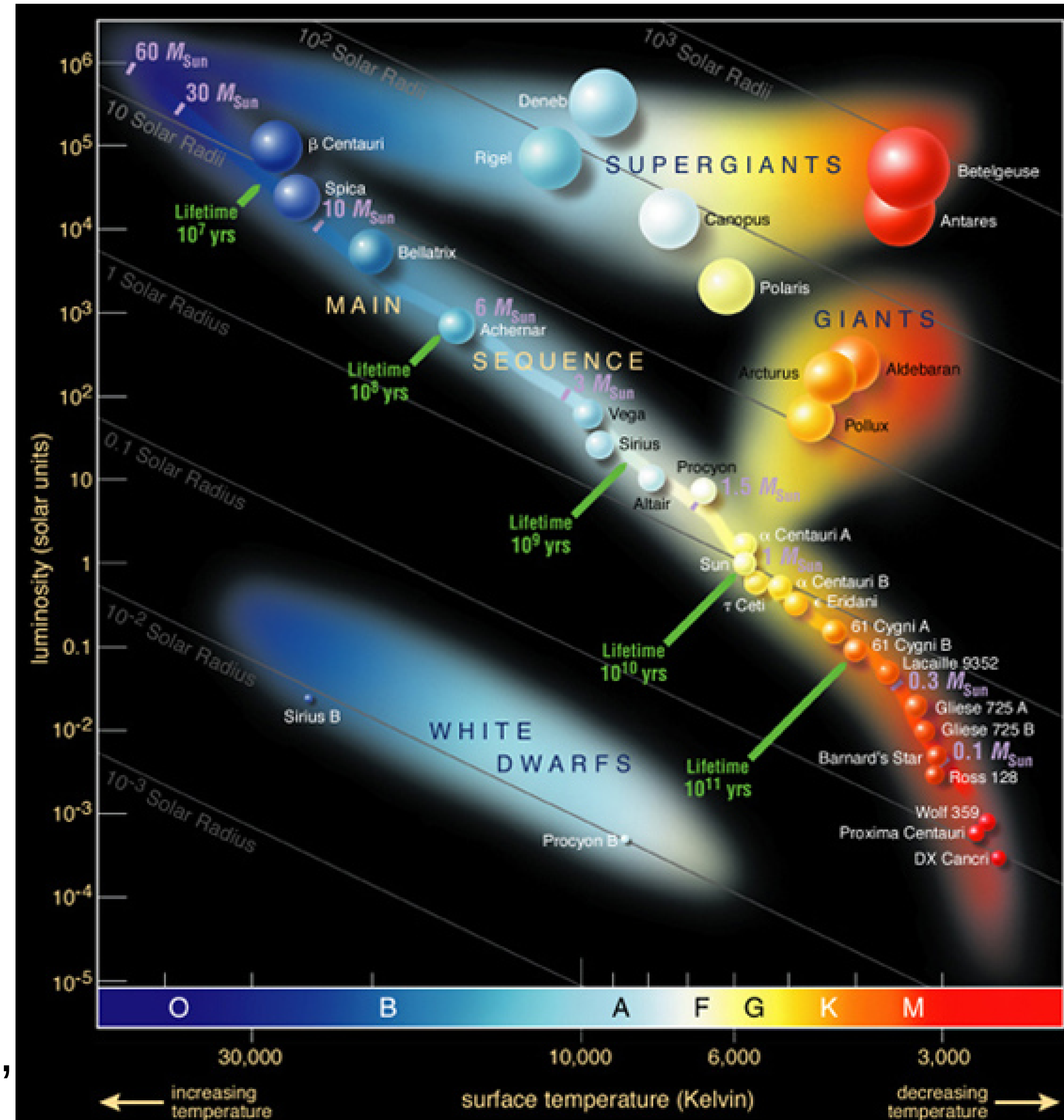


Stars

- Characterized by luminosity (“brightness/intensity”) and peak wavelength
- Peak wavelength can be used to determine the surface temperature
- Observations fall nicely into a picture called the Hertzsprung-Russel diagram

Hertzsprung-Russell Diagram





- Data from 22,000 stars from wikipedia
- Main sequence, Giants/supers, dwarfs

Stellar Story

- Stars from when gas clouds collapse under gravity
- Gas clouds are mostly hydrogen and helium (where did this come from?)
- Reduction of gravitation energy goes to heating the gas could in its densest part
- Temperatures can exceed millions of K, and this triggers nuclear fusion reaction which fuses hydrogen to helium
- The energy and consequent pressure sustains the star against further collapse
- These qualitative ideas can be made into nice models (experimentally tested)

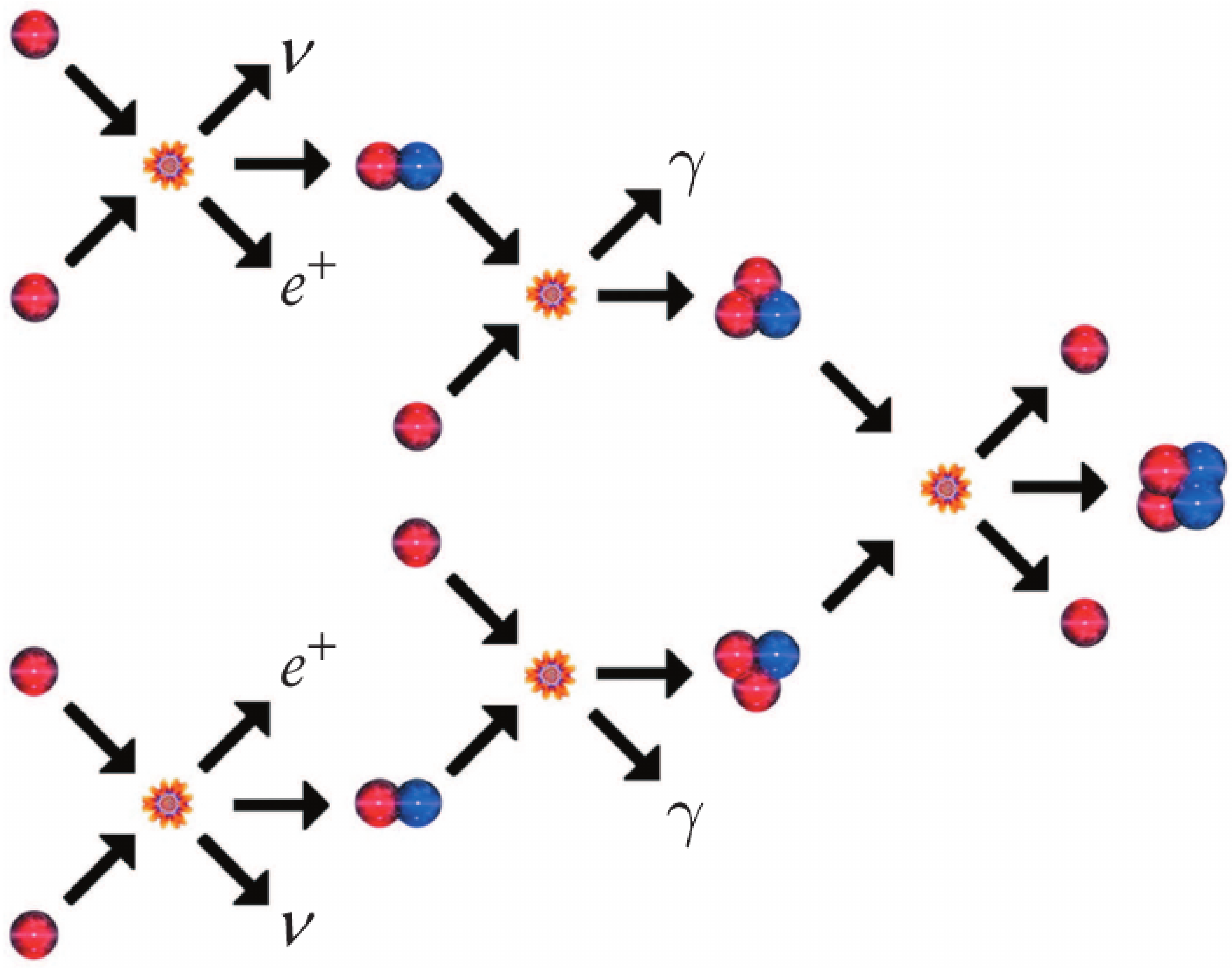
Important Ideas

- Virial theorem – relates gravitational energy reduction to ``internal energy''
- Mass-luminosity relation (Flux ~ Mass^3)
- Key puzzle of early 1900s – how do stars generate energy

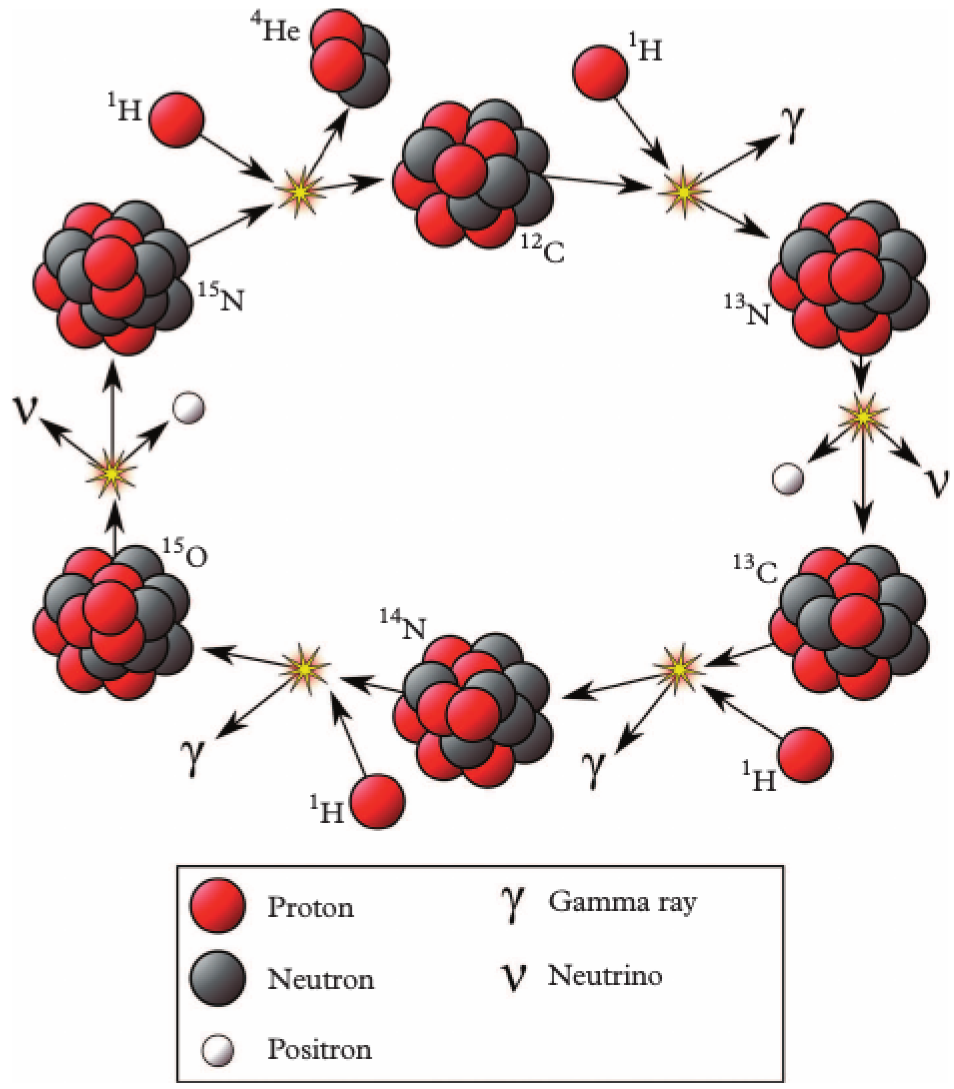
Life of a star

- A star starts off with a certain mass (from the collapsed cloud) mostly hydrogen and helium
- It “burns” hydrogen to helium – nuclear fusion
- There are several important ``routes’’ to fusion of hydrogen to helium
- Eg. Proton-proton chain, CNO cycle etc.

Proton-Proton Chain



CNO Cycle

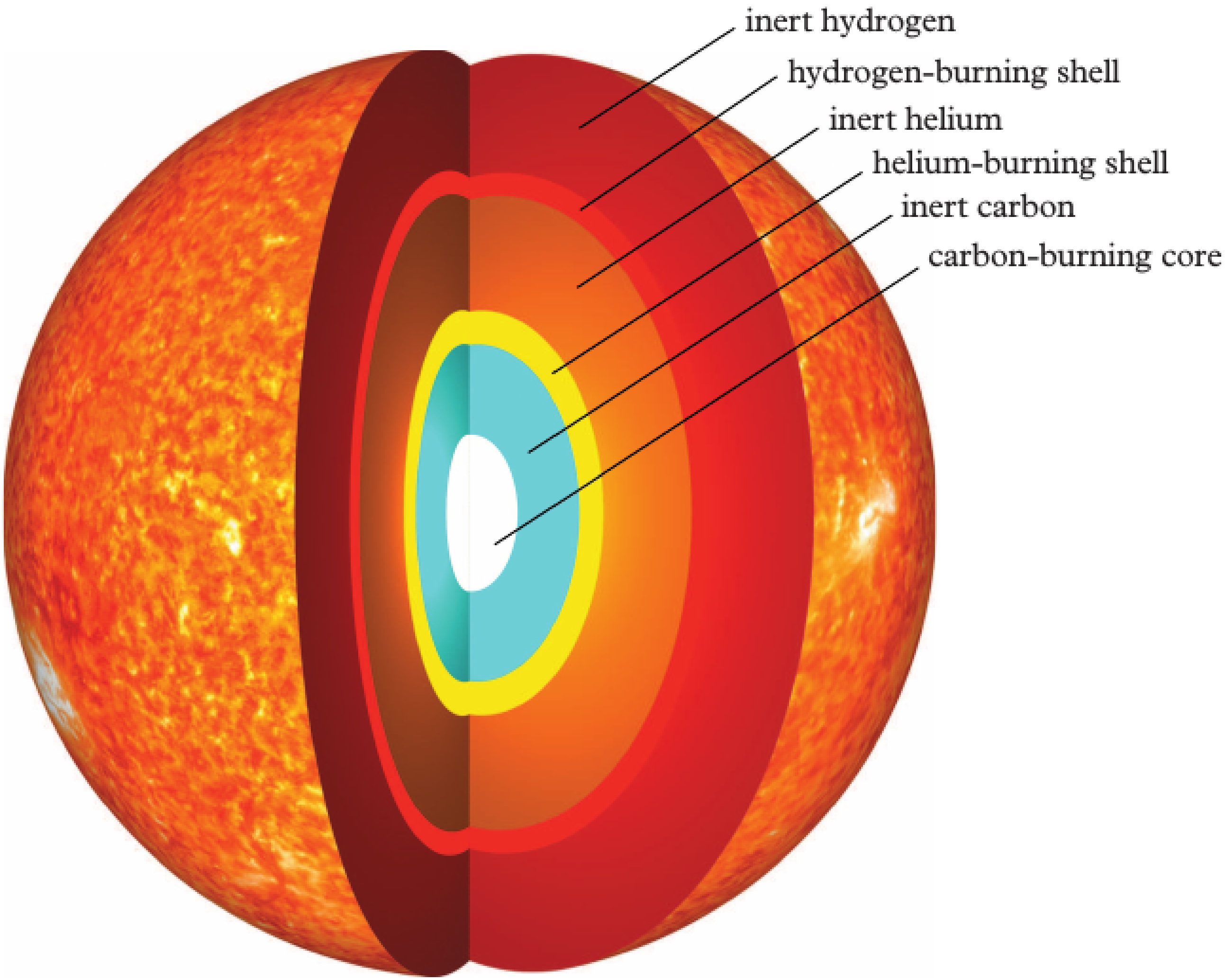


4He
1H
1H
γ
12C
15N
13N
ν
ν
15O
13C
14N
γ
γ
1H
1H
Proton
Neutron
Positron
γ Gamma ray
ν Neutrino

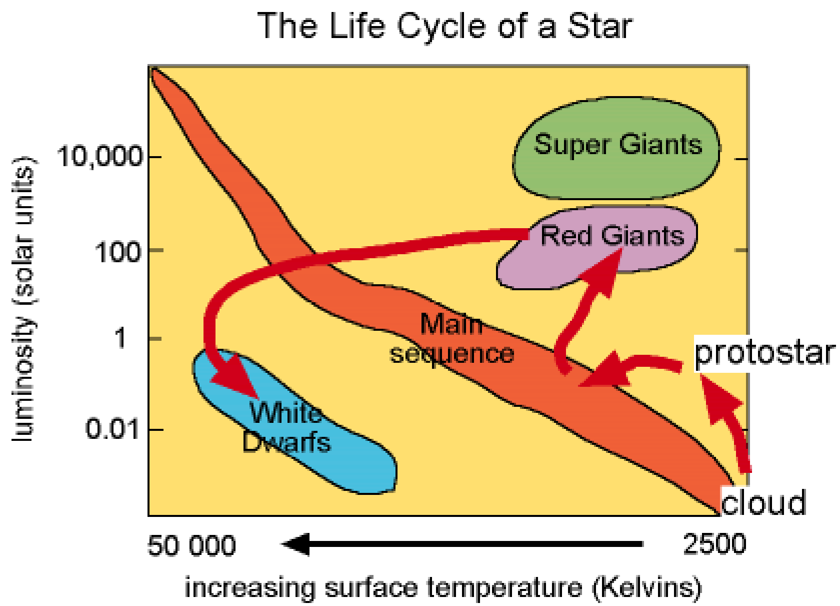
After hydrogen…

- Eventually the star will burn up all its hydrogen (fun fact: more massive stars will do this faster than smaller stars!)
- What happens after the hydrogen is burnt up?
- Gravity is still operative! Starts of the order of solar masses with start burning helium to sustain!
- This process makes the star bloat up...giving rise to the ``giant” starts (this is the fate of the sun as well...)

Processes in a giant star



Life of a star



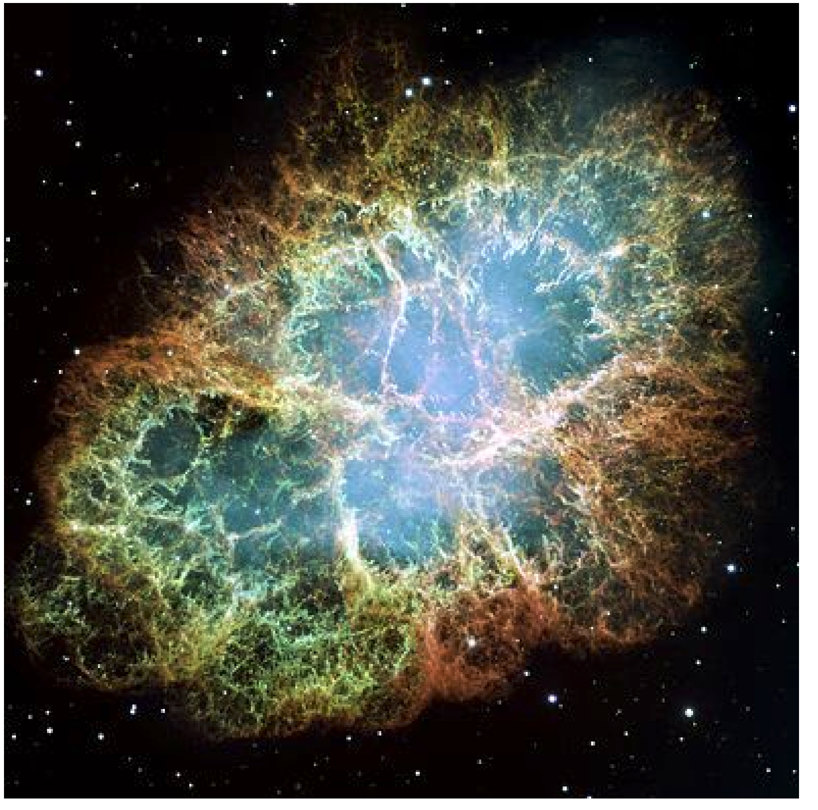
- Stars from the main sequence after burning hydrogen will evolve to a ``giant stage'' and burn up everything until fusion produces iron and nickel!
- There is no more fuel left to burn!

After all fusion...

- What happens when the star has exhausted everything?
- This depends on the mass of the star
- For small mass stars (below the Chandrasekhar limit ~ 1.5 Solar Mass) the fate is to become a White Dwarf
- In a White dwarf gravity is countered by the Pauli pressure of the electrons...very high density 10^6 of water...and small radius (like the earth)

After all fusion…supernova

- If the mass of the star is larger, then there is nothing to prevent the collapse of the star...leading to a violent explosion called the supernova...to core collapses leading to very high temperatures (10^11 K) which blows out everything in the star
- This violent explosion results in production of many heavy nuclei including gold!
- All elements heavier than Li were produced in stars or supernovae!
- We are all stardust!

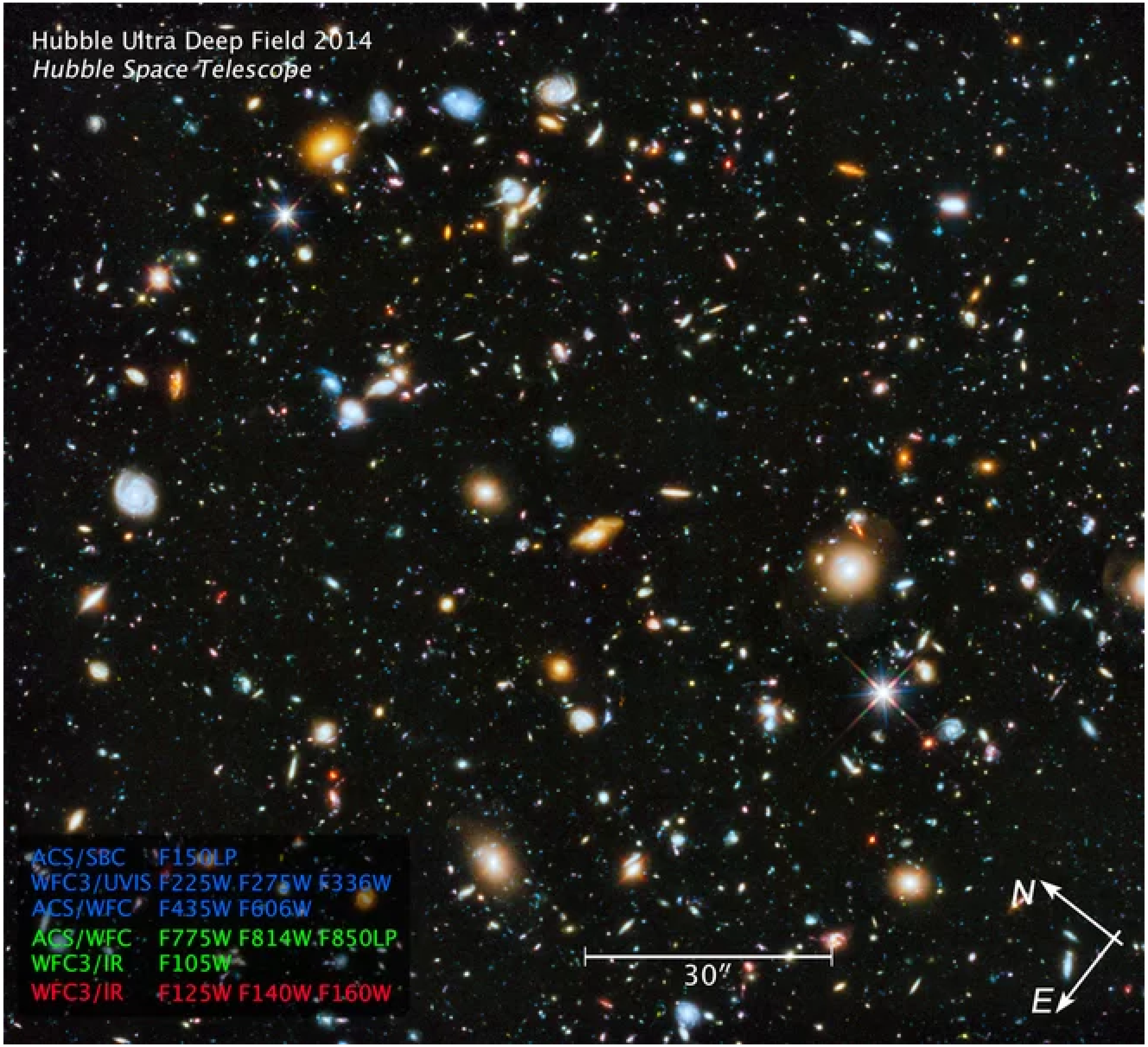


Remanant of supernova…

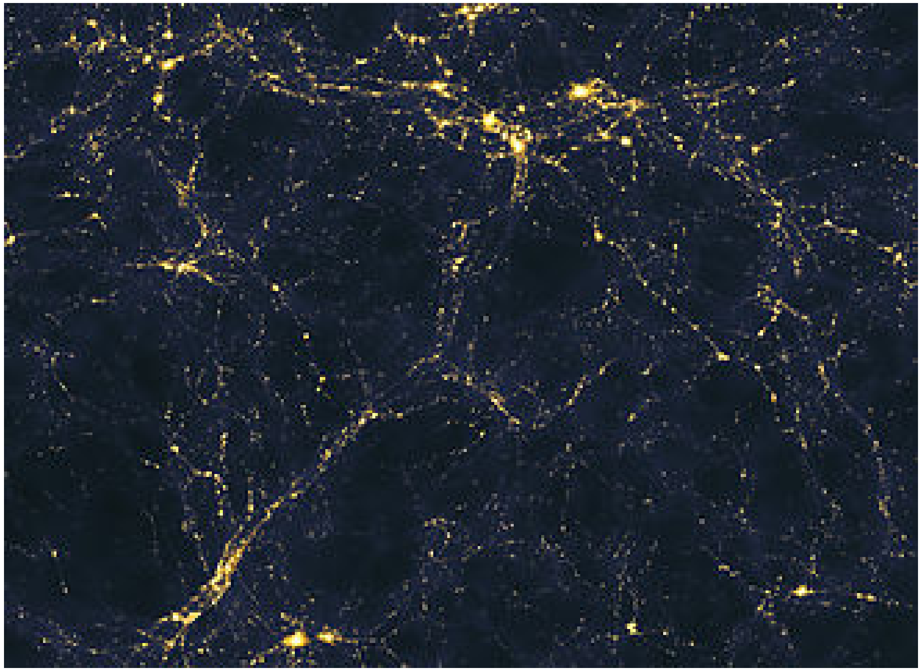
- Depending on the mass of the initial star the core of the star may become
- A neutron star – Neutron degeneracy pressure/and strong interactions keeps the star stable
- This requires tremendous densities...roughly 10^15 of water!
- Very small radius about 10-15 km!
- If the mass is more than about 2-3 solar masses the stars fate is to become a black hole

More structure…

- Stars come in groups...billions and billions of them...there are called galaxies…
- Galaxies come in clusters…
- And clusters come in superclusters …!



On the largest scales...



- Scale here is 50 million light years (computer simulation)!
- Over even larger scales the universe looks homogeneous...

Some questions…

- Where did the hydrogen ``come from”?
-
-

The Universe is Expanding:

If we look at distant galaxies, beyond our immediate galactic neighbors, we find that they are *all moving* away (receding) from us!

In 1929 Edwin P. Hubble connected the recession speed *v* of a galaxy and its distance *r* from us—they are directly proportional:

$$v = Hr \qquad \text{(Hubble's law)}, \qquad\qquad H = 71.0\ \text{km/s}\cdot\text{Mpc} = 21.8\ \text{mm/s}\cdot\text{ly}.$$

H is called the ***Hubble constant.*** The value of H is usually measured in the unit kilometers per second-megaparsec (km/s Mpc), where the megaparsec is a length unit commonly used in astrophysics and astronomy:

$$1\ \text{Mpc} = 3.084 \times 10^{19}\ \text{km} = 3.260 \times 10^{6}\ \text{ly}.$$

The Hubble constant *H* has not had the same value since the universe began. *Extrapolating backwards*, Hubble's law is consistent with the hypothesis that the universe began with the big bang and has been expanding ever since.

If *H* is assumed constant, then the age of the universe, *T*, can be approximated as:

$$T = \frac{r}{v} = \frac{r}{Hr} = \frac{1}{H} \qquad \text{(estimated age of universe)}.$$

$$= 13.7 \times 10^{9}\ \text{y}.$$

Edwin Hubble's plot of the Velocity-Distance relationship for galaxies

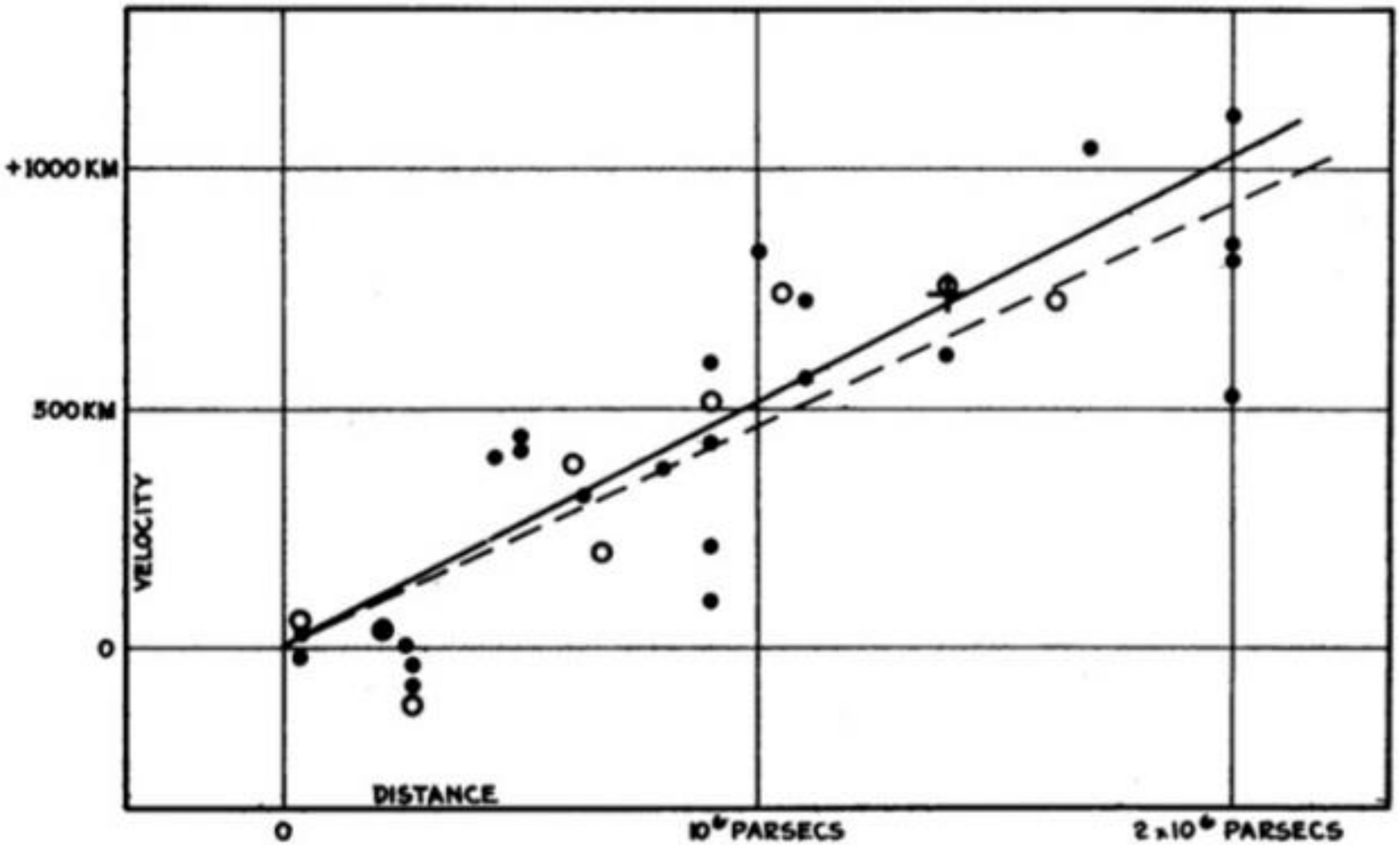


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

Example, Using Hubble's law to relate distance and recessional speed:

The wavelength shift in the light from a particular quasar indicates that the quasar has a recessional speed of 2.8×10^8 m/s (which is 93% of the speed of light). Approximately how far from us is the quasar?

KEY IDEA

We assume that the distance and speed are related by Hubble's law.

Calculation: From Eqs. 44-19 and 44-21, we find

$$r = \frac{v}{H} = \frac{2.8 \times 10^8 \text{ m/s}}{21.8 \text{ mm/s} \cdot \text{ly}} (1000 \text{ mm/m})$$
$$= 12.8 \times 10^9 \text{ ly}. \qquad \text{(Answer)}$$

This is only an approximation because the quasar has not always been receding from our location at the same speed v; that is, H has not had its current value throughout the time during which the universe has been expanding.

The most distant objects that we can detect are ***quasars (quasistellar objects***), which are the extremely bright cores of galaxies that are as much as 13 x10^9 ly from us. Each such core contains a gigantic black hole. As material (gas and even stars) is pulled into one of those black holes, the material heats up and radiates a tremendous amount of light, enough for us to detect in spite of the huge distance. Therefore, we "see" a quasar not as it looks today but as it once was, when that light began its journey to us billions of years ago.

Example, Using Hubble's law to relate distance and Doppler shift:

A particular emission line detected in the light from a galaxy has a detected wavelength $\lambda_{det} = 1.1\lambda$, where λ is the proper wavelength of the line. What is the galaxy's distance from us?

KEY IDEAS

(1) We assume that Hubble's law ($v = Hr$) applies to the recession of the galaxy. (2) We also assume that the astronomical Doppler shift of Eq. 37-36 ($v = c\,\Delta\lambda/\lambda$, for $v \ll c$) applies to the shift in wavelength due to the recession.

Calculations: We can then set the right side of these two equations equal to each other to write

$$Hr = \frac{c\,\Delta\lambda}{\lambda}, \tag{44-23}$$

which leads us to

$$r = \frac{c\,\Delta\lambda}{H\lambda}. \tag{44-24}$$

In this equation,

$$\Delta\lambda = \lambda_{det} - \lambda = 1.1\lambda - \lambda = 0.1\lambda.$$

Substituting this into Eq. 44-24 then gives us

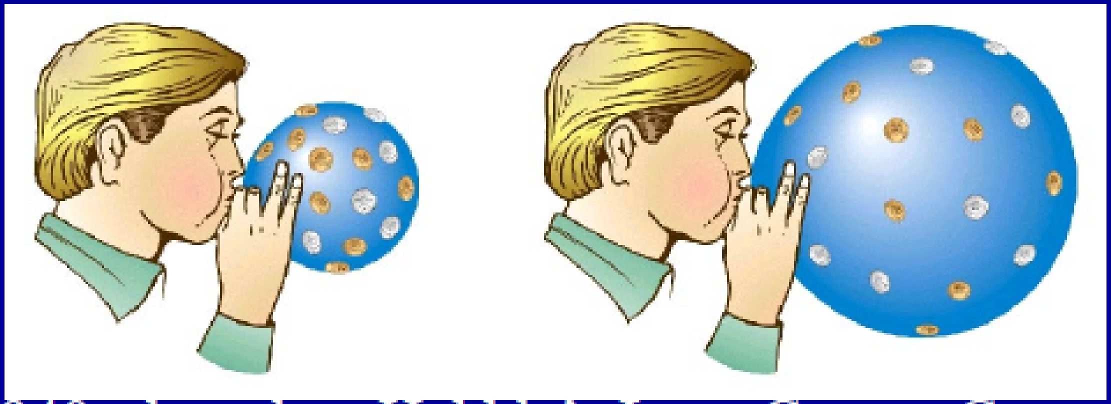
$$r = \frac{c(0.1\lambda)}{H\lambda} = \frac{0.1c}{H}$$

$$= \frac{(0.1)(3.0 \times 10^8\ \text{m/s})}{21.8\ \text{mm/s}\cdot\text{ly}}(1000\ \text{mm/m})$$

$$= 1.4 \times 10^9\ \text{ly}. \qquad \text{(Answer)}$$

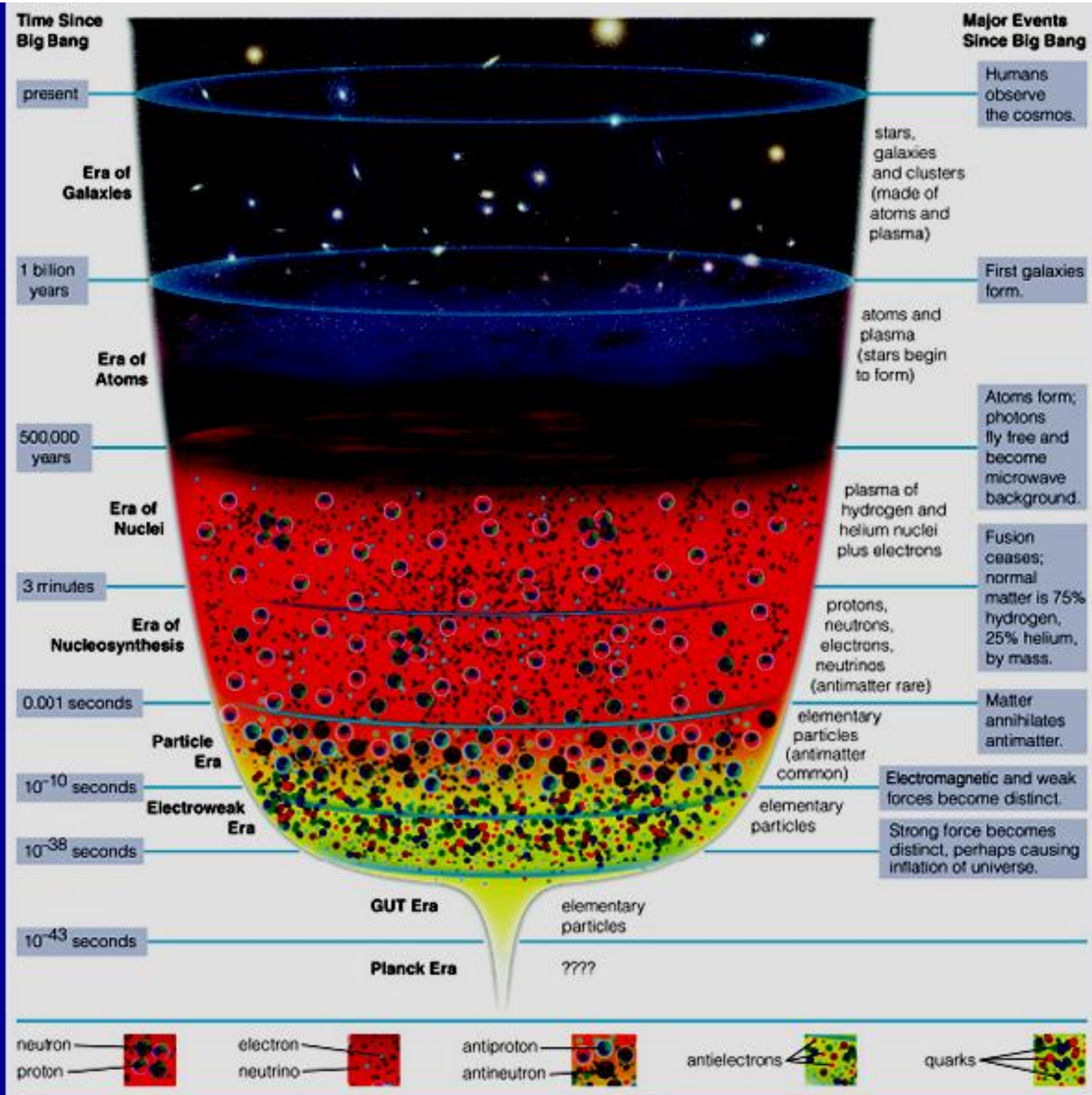
The Universe Is Expanding : Hubble's ***cosmological redshifts***

- Play the scenario backwards and forward



- In the 1940s, based on Hubble's Law, George Gamow proposed the universe began in a colossal explosion about 10 billion years ago
  - Based on experimental data (like we will see today) we now believe that Universe began as a singularity in spacetime
    - Where energy density and spacetime curvature were infinite
      - We don't know what exactly happened between t=0 to t=10^{-43} s
        - [redacted]
          - » Temperature of the Universe was about 10^{30} K
      - After that time (10^{-35} s) the Universe has expanded & is well explained by known theories of (strong, weak, EM and Gravity) interactions
          - » Temp = $10^{28} \rightarrow 10^{16}$ K, universe is a hot quark-electron soup

History Of The Universe Since Origin



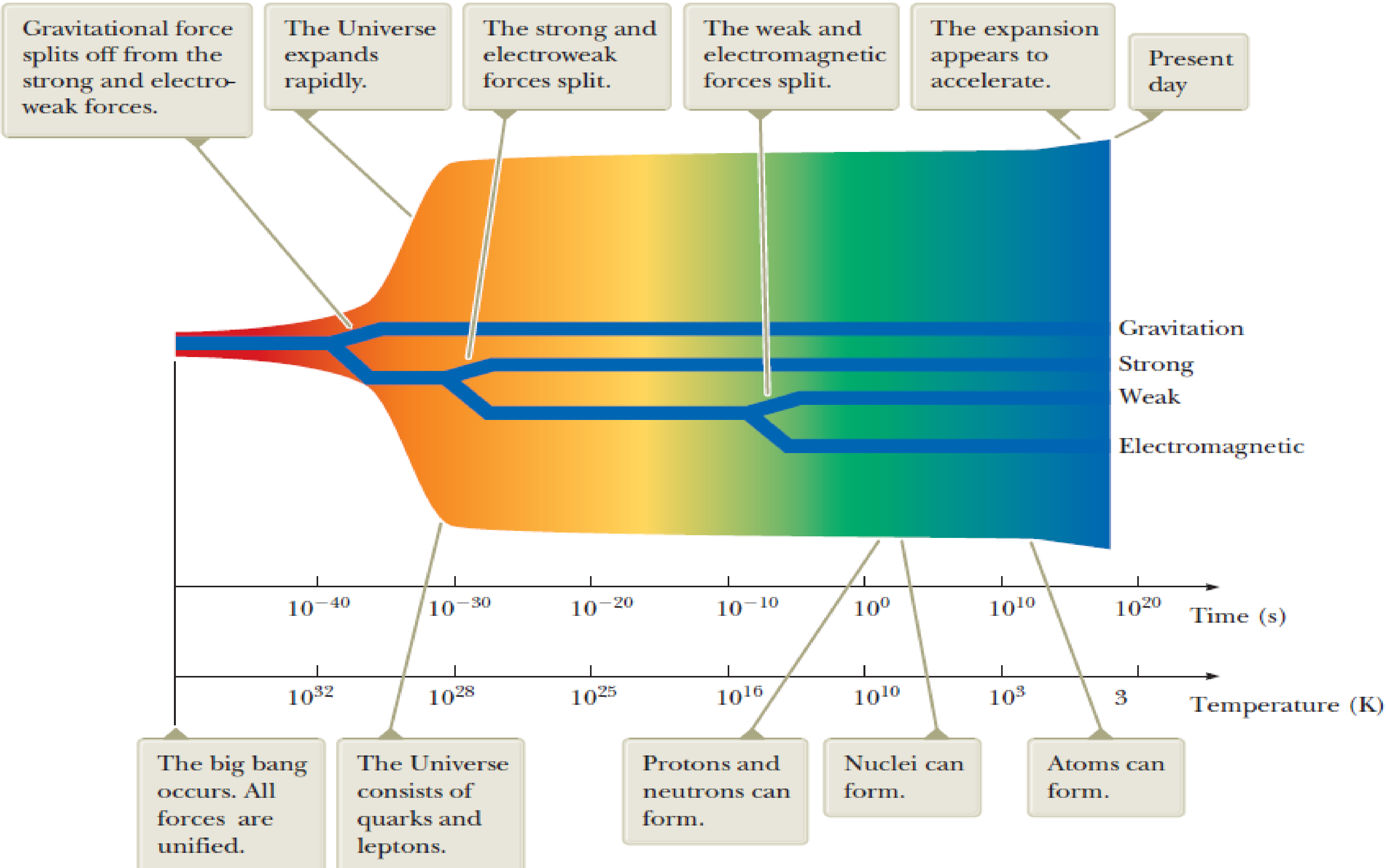
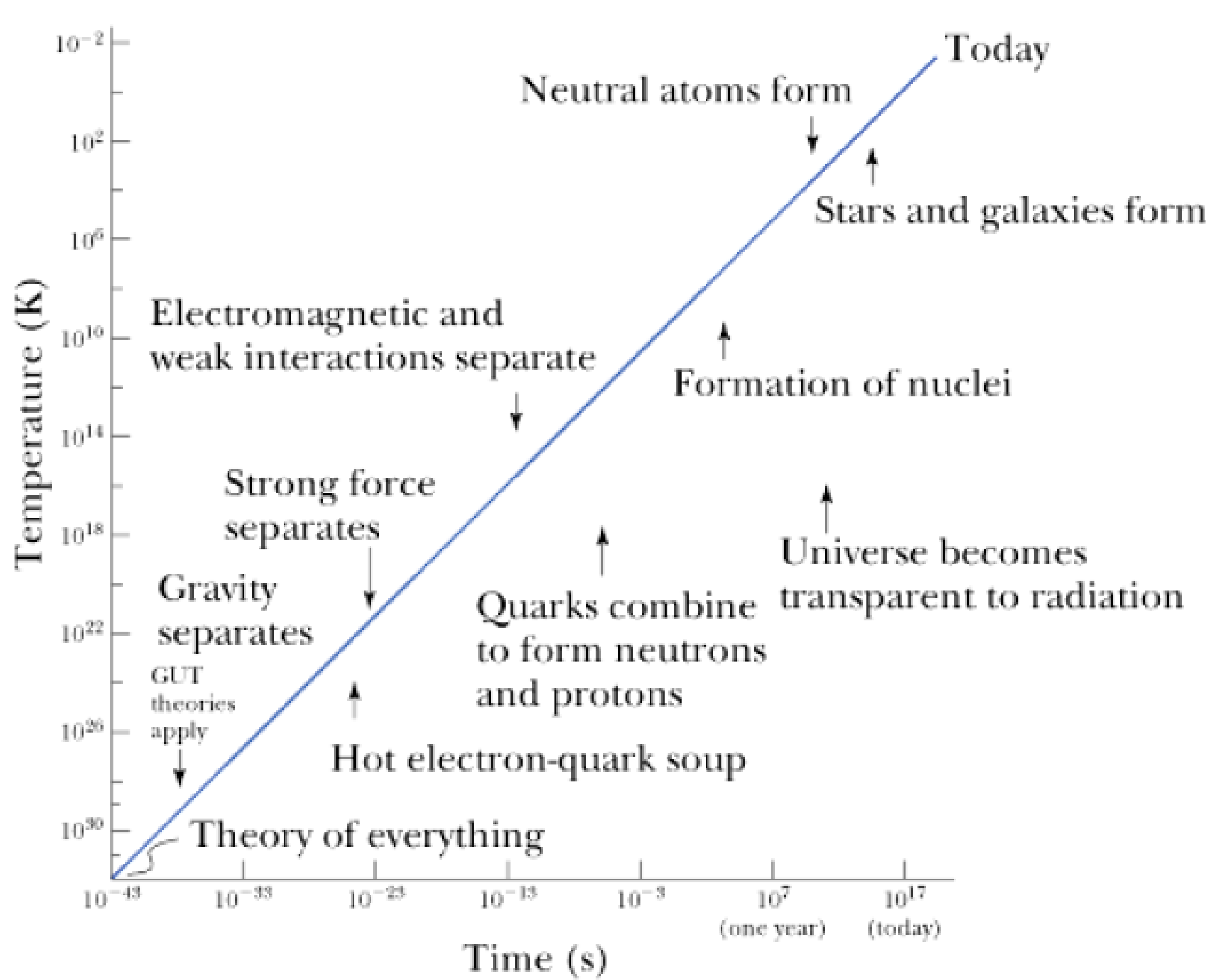
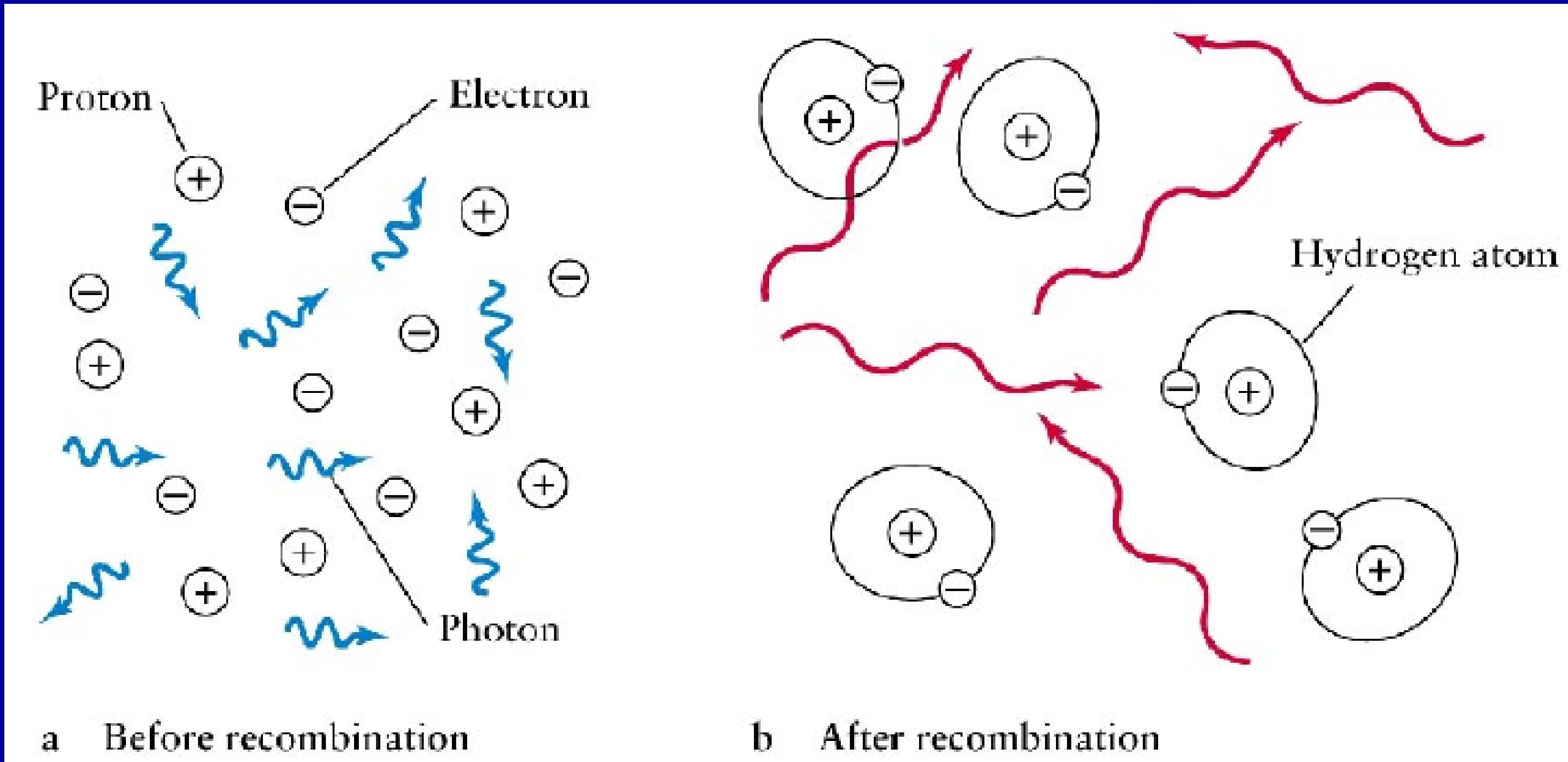


Figure 46.16 A brief history of the Universe from the big bang to the present. The four forces became distinguishable during the first nanosecond. Following that, all the quarks combined to form particles that interact via the nuclear force. The leptons, however, remained separate and to this day exist as individual, observable particles.

History of The Universe: Some Milestones



Universe was hot opaque plasma in first 300K years

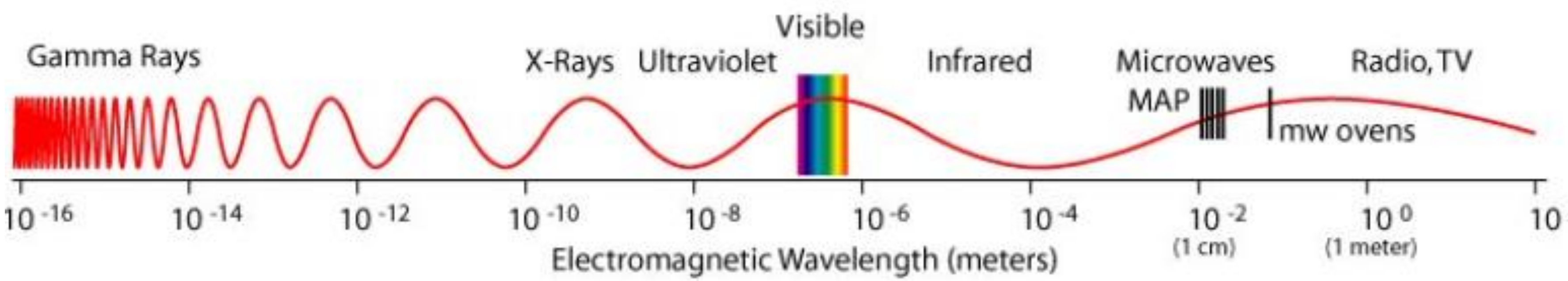


At t = 300,000 years, the universe was finally cool enough from its initial *primordial fireball* that electrons and protons could combine to form atoms (era of recombination)

Big Bang & Cosmic Microwave Radiation

- The compact intense fireball of matter & radiation expanded, cooled, underwent series of transitions at specific temps/time
- Between 5 minutes to $\simeq$ 100,000 years, universe consisted of plasma of H and He nuclei (and electrons) in thermal equilibrium with radiation
- Once temperature fell below $E=kT = 13.6$ eV (B.E. of Hydrogen)
  - Hydrogen could form and not be broken up (like when things were hotter)
  - Now matter and radiation were decoupled and Universe became transparent
- Radiation left behind ($T = 3000K$) could travel all over the Universe and continue to be Cosmologically red-shifted to longer and longer wavelengths
- Observer today would expect this radiation to come from all sides and to have a radiation spectrum like a blackbody at 2.7K (dominant in Microwave Frequency)
- Since then Gravity became dominant influence, density fluctuations led to formation of galaxies, stars etc

The light that is reaching us has been stretched out as the universe has stretched, so light that was once beyond gamma rays is now reaching us in the form of microwaves.

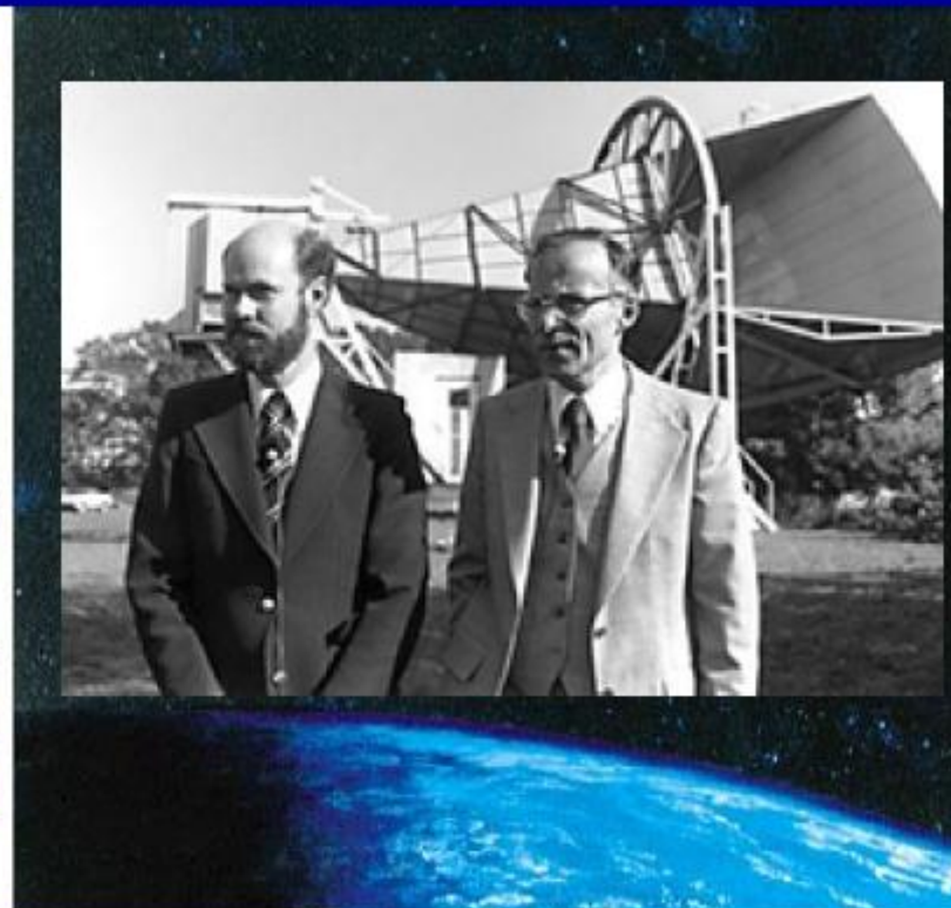


The Cosmic Microwave Radiation that fills all space is evidence of a hot Big Bang

Pure Serendipity !!

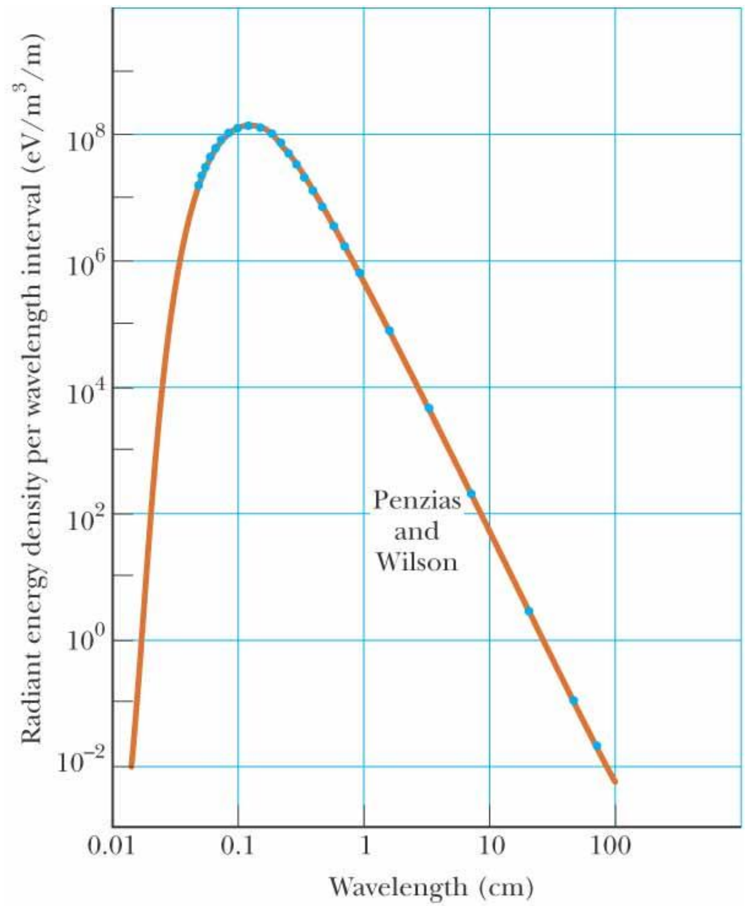
1963:Bell Lab Horn Antenna detected a Microwave signal from all parts of sky

Nobel : Penzias & Wilson

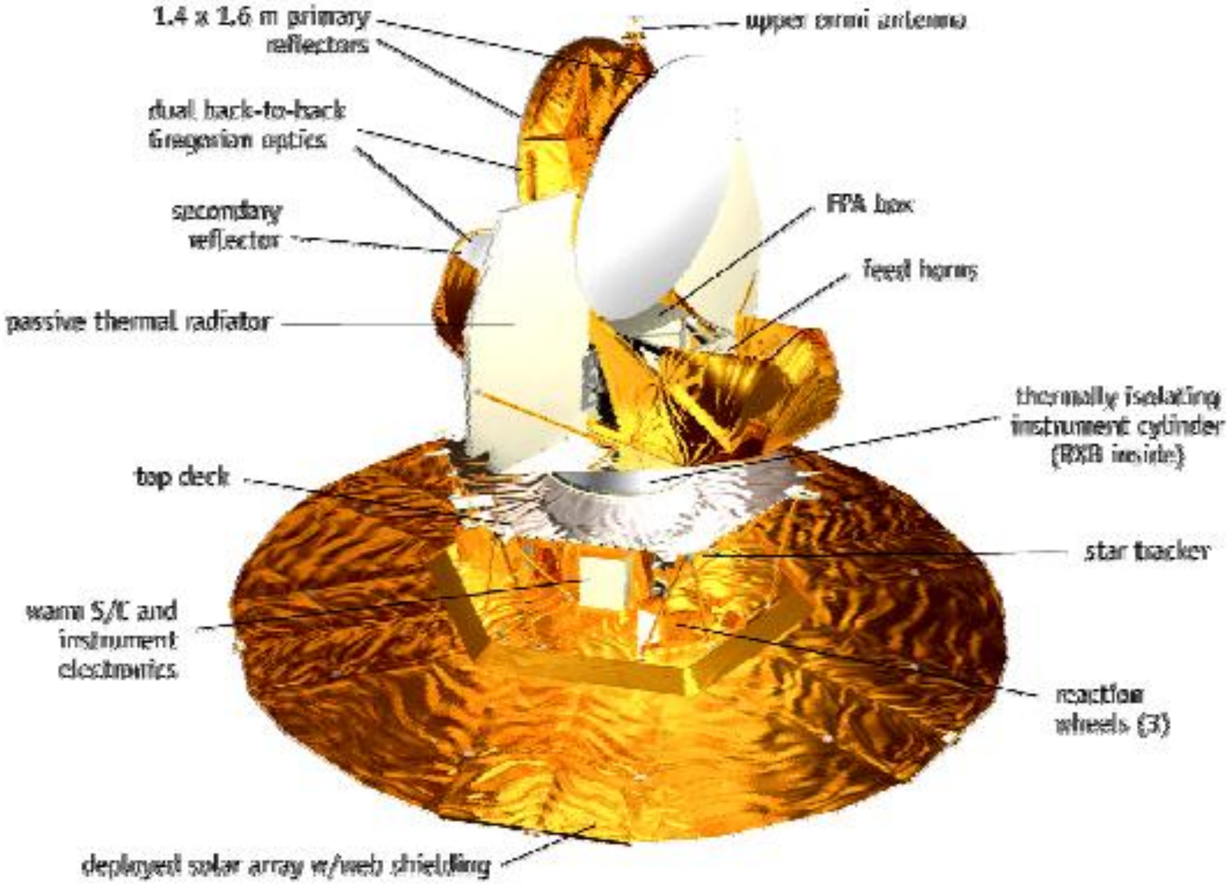


Cosmic Background Radiation (CBR)

- CBR represents the cosmic "glow" left over from the Big Bang
- The radiation was nearly isotropic – i.e., had equal strengths in all directions
- The wavelength distribution fits that of a black body at 2.7K
- There are small irregularities that allowed for the formation of galaxies and other objects
- The COBE satellite found that the background radiation had irregularities that corresponded to temperature variations of 0.0003 K



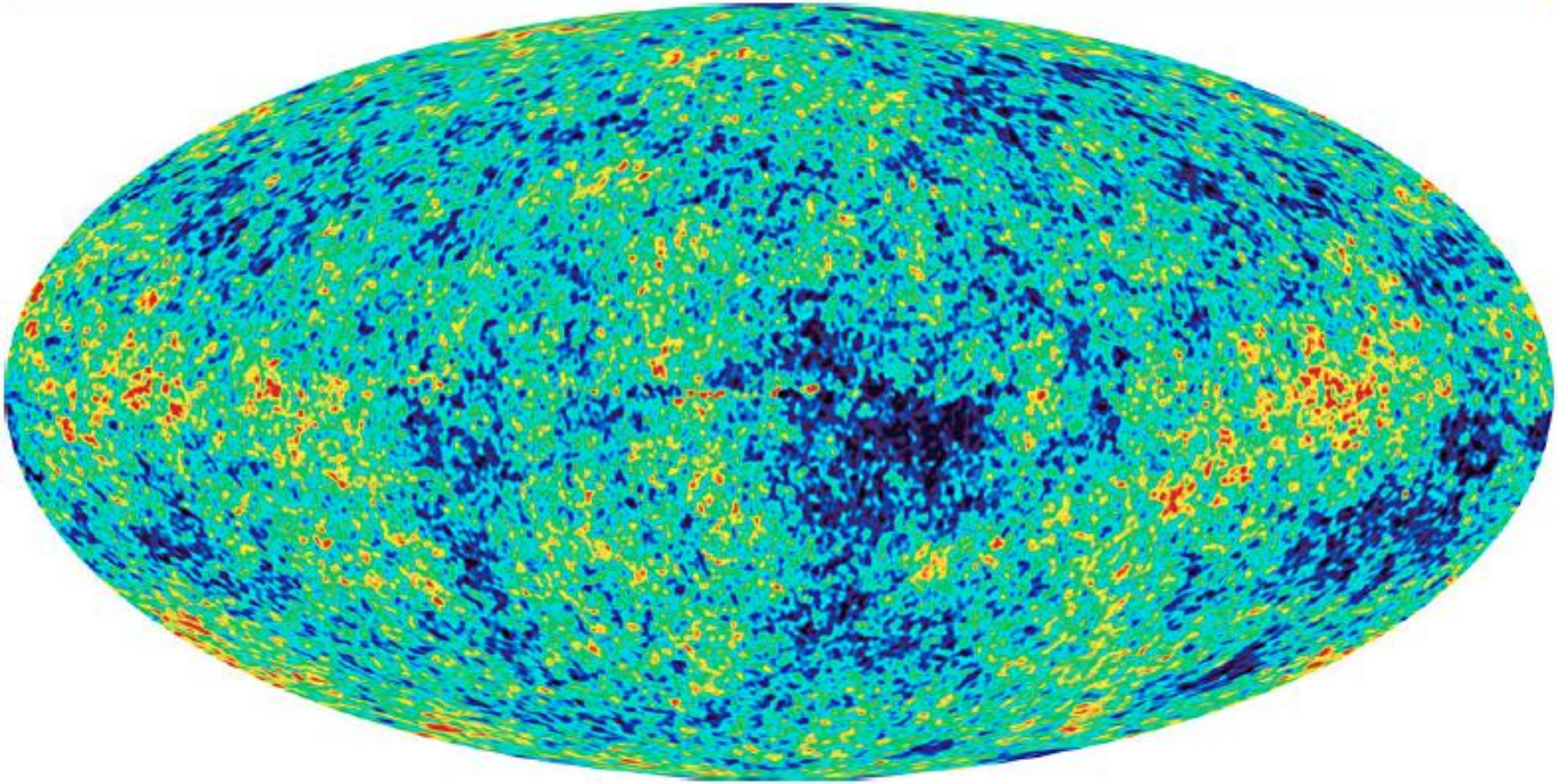
The WMAP Microwave Telescope: 2003



The WMAP instrument consists of a set of passively cooled microwave radiometers with 1.4 x 1.6 meter diameter primary reflectors to provide the desired angular resolution. Measuring the temperature of the microwave sky to an accuracy of one millionth of a degree requires careful attention to possible sources of systematic errors.

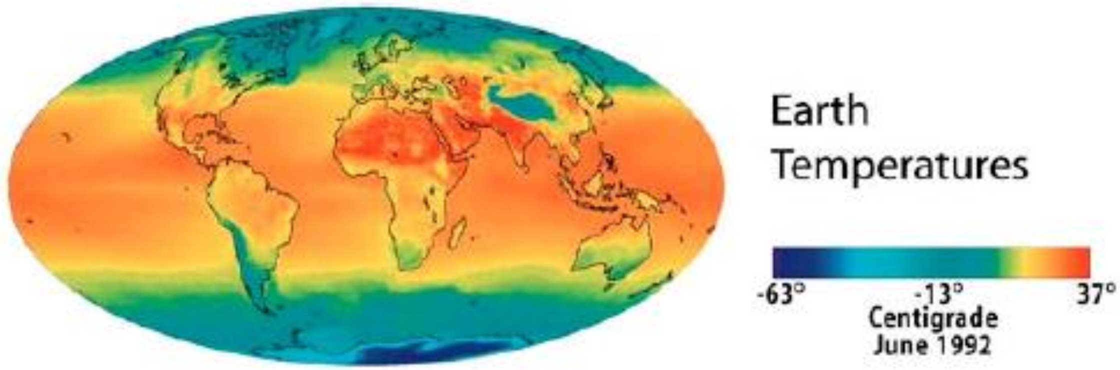
The composite/aluminum spacecraft is 150 inches (3.8 meters) high by 198 inches (5 meters) wide. WMAP weighs 1,850 pounds (840 kilograms) and is supplied with 419 Watts of power

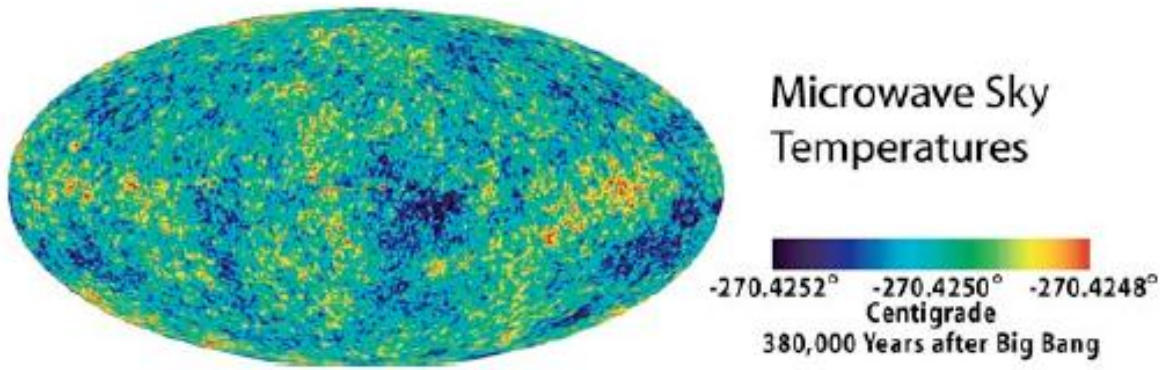
Baby picture of the Universe: 2003



The first detailed, all-sky picture of the infant universe. The WMAP image reveals 13 billion+ year old temperature fluctuations (shown as color differences) that correspond to the seeds that grew to become the galaxies. Encoded in the patterns are the answers to many age-old questions, such as the age and geometry of the Universe

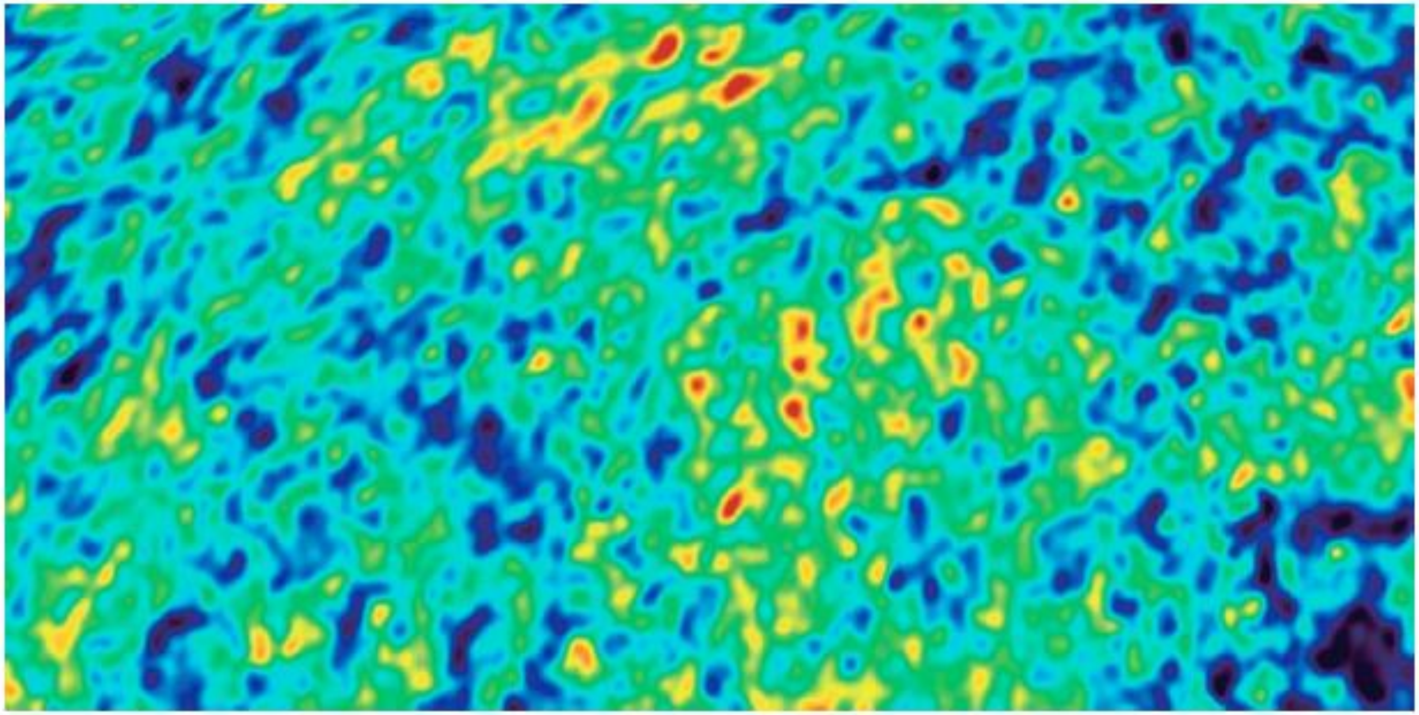
Temperature Maps





The temperature map of the Earth is a picture of data from the Earth's surface. The image captured by WMAP is from when the temperature of the universe became low enough for atoms to form, allowing light to travel great distances (to us). It is analogous to the surface of the clouds we see on an overcast day. Light travels through the clouds, but we only see the detail on the cloud's surface.

How the Universe got its spots !



The data brings into high resolution the seeds that generated the cosmic structure we see today. These patterns are tiny temperature differences within an extraordinarily evenly dispersed microwave light bathing the Universe, which now averages a frigid 2.73 degrees above absolute zero temperature. WMAP resolves slight temperature fluctuations, which vary by only millionths of a degree.

The new data support and strengthen the Big Bang and Inflation Theories

44.13: Dark Matter:

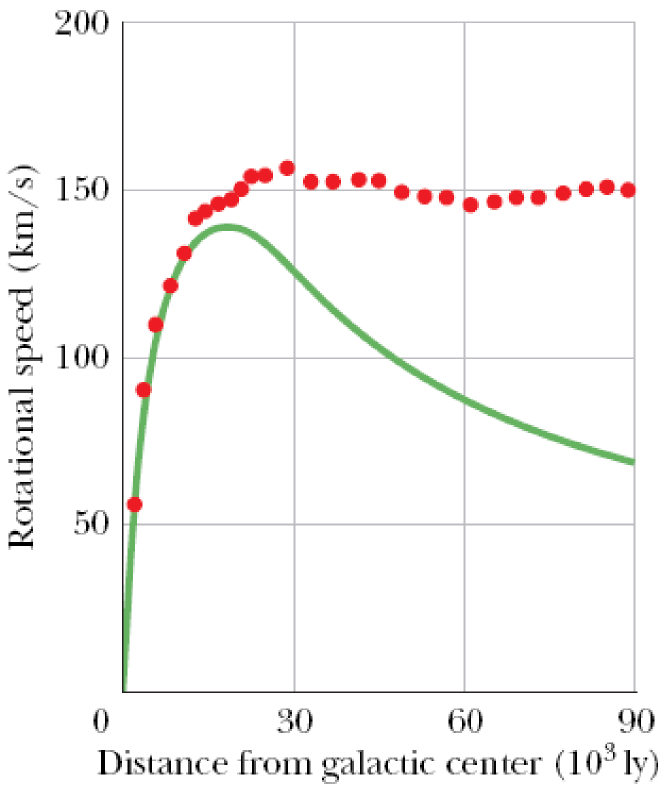


Fig. 44-5 The rotational speed of stars in a typical galaxy as a function of their distance from the galactic center. The theoretical solid curve shows that if a galaxy contained only the mass that is visible, the observed rotational speed would drop off with distance at large distances. The dots are the experimental data, which show that the rotational speed is approximately constant at large distances.

The only explanation for the findings that is consistent with Newtonian mechanics is that a typical galaxy contains much more matter than what we can actually see. The visible portion of a galaxy represents only about 5 to 10% of the total mass of the galaxy.

In addition to these studies of galactic rotation, many other observations lead to the conclusion that the universe abounds in matter that we cannot see.

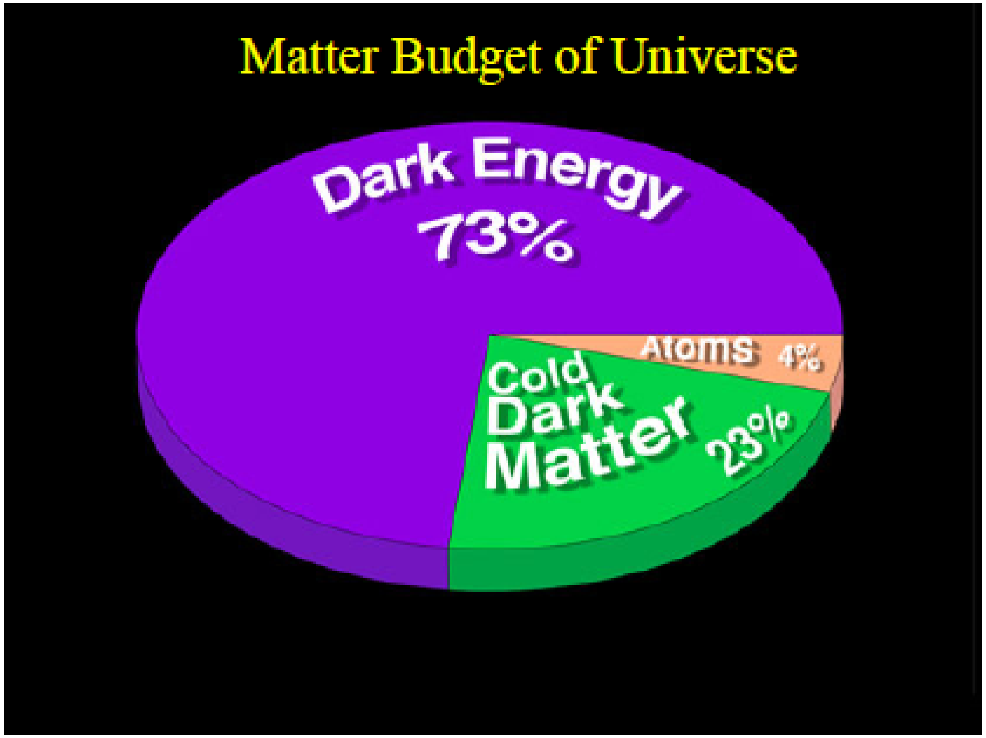
This unseen matter is called ***dark matter*** because either it does not emit light or its light emission is too dim for us to detect.

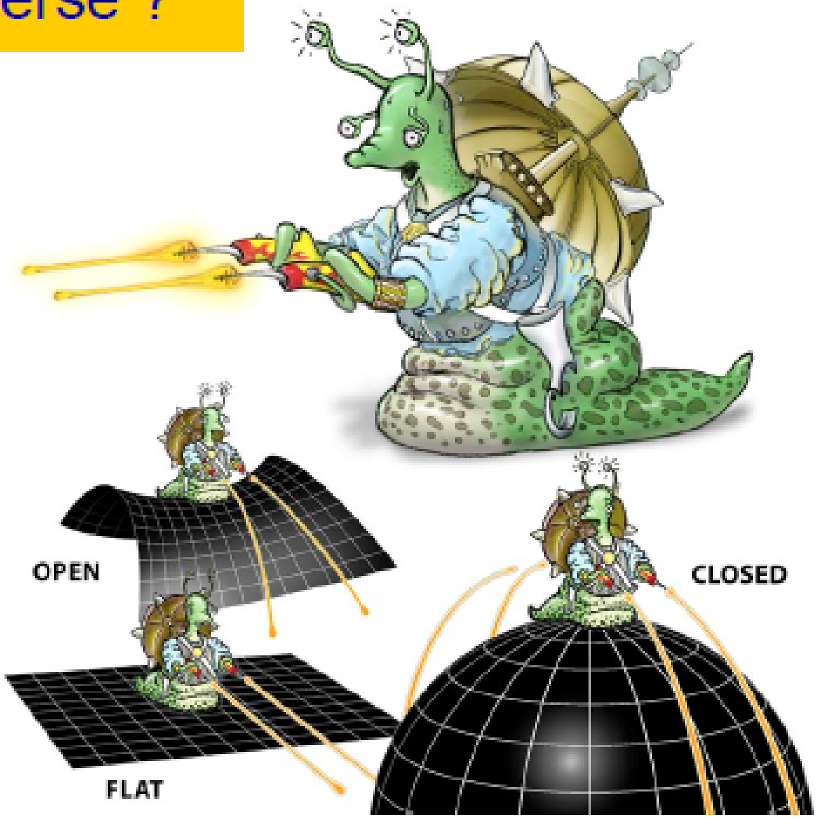
This dark normal matter is only a small part of the total dark matter. The rest is called ***nonbaryonic dark matter*** because it does not contain protons and neutrons.

Another Remaining Question About the Universe

- Is there mysterious energy in the universe?
  - Observations have led to the idea that the expansion of the universe is accelerating
  - To explain this acceleration, *dark energy* has been proposed
  - The dark energy results in an effective repulsive force that causes the expansion rate to increase

Geometry & The Fate Of The Universe ?





The amount of dark matter and energy in the universe plays a crucial role in determining the geometry of space. If the density of matter and energy in the universe is less than the critical density, then space is open and negatively curved like the surface of a saddle. If the density exactly equals the critical density, then space is flat like a sheet of paper. If the density is greater than critical density, then space is closed and positively curved like the surface of a sphere. In this latter case, light paths diverge and eventually converge back to a point. The Inflationary Theory, an extension of the Big Bang theory, predicts that density is very close to the critical density, producing a flat universe, like a sheet of paper.

WMAP has determined, within the limits of instrument error, that the universe is flat and will expand for ever due to the dark energy (whose nature is not understood)

Some Questions in Astro/Particle Physics

- Why so little antimatter in the Universe?
- Why do quarks and leptons form similar but distinct families?
- Why are some particles charged and others not?
- Why do quarks carry fractional charge?
- What determines the masses of fundamental particles?
- How does one quantize Gravity?
- How does one make up a theory unifying gravity with all the other forces?

A New Perspective – String Theory

- **String theory** is one current effort at answering some of the previous questions
- It is an effort to unify the four fundamental forces by modeling all particles as various vibrational modes of an incredibly small string
- The typical length of a string is 10^{-35} m
  - This is called the **Planck length**
- According to the string theory, quantized modes of vibration of the string give rise to the different elementary particles in the Standard Model

Some features of String Theory

- It requires space-time to have ten dimensions
  - Four of the ten dimensions are visible to us, the other six are *compactified* (curled)
- One prediction of string theory is **supersymmetry** (SUSY)
  - It suggests that every elementary particle has a superpartner (differing in spin by half a unit) that has not yet been observed
  - Supersymmetry is a broken symmetry and the masses of the superpartners are above our current capabilities to detect