Our Universe: The Place We Live In

Seminar

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Contents

Galaxy:

A huge collection of stars in space, held together by gravity.

- **Universe**: Everything we can see around us. The sum total of all matter and energy

Astrophysics

- Physics of the Universe, stars and galaxies
- Still holds many mysteries
- What is our physical place in the Universe?

Cosmology

- Study of the origin and fate of our universe and everything in it
  - Theoretical principles & observations
- Deals with the largest scales in our Universe
- Questions
  - What are the basic physical laws that govern us and the universe?
  - What is our universe made of?
  - Can we explain the origin and evolution of the universe?
  - What is the nature of space/time/matter/energy?

Hubble's Law

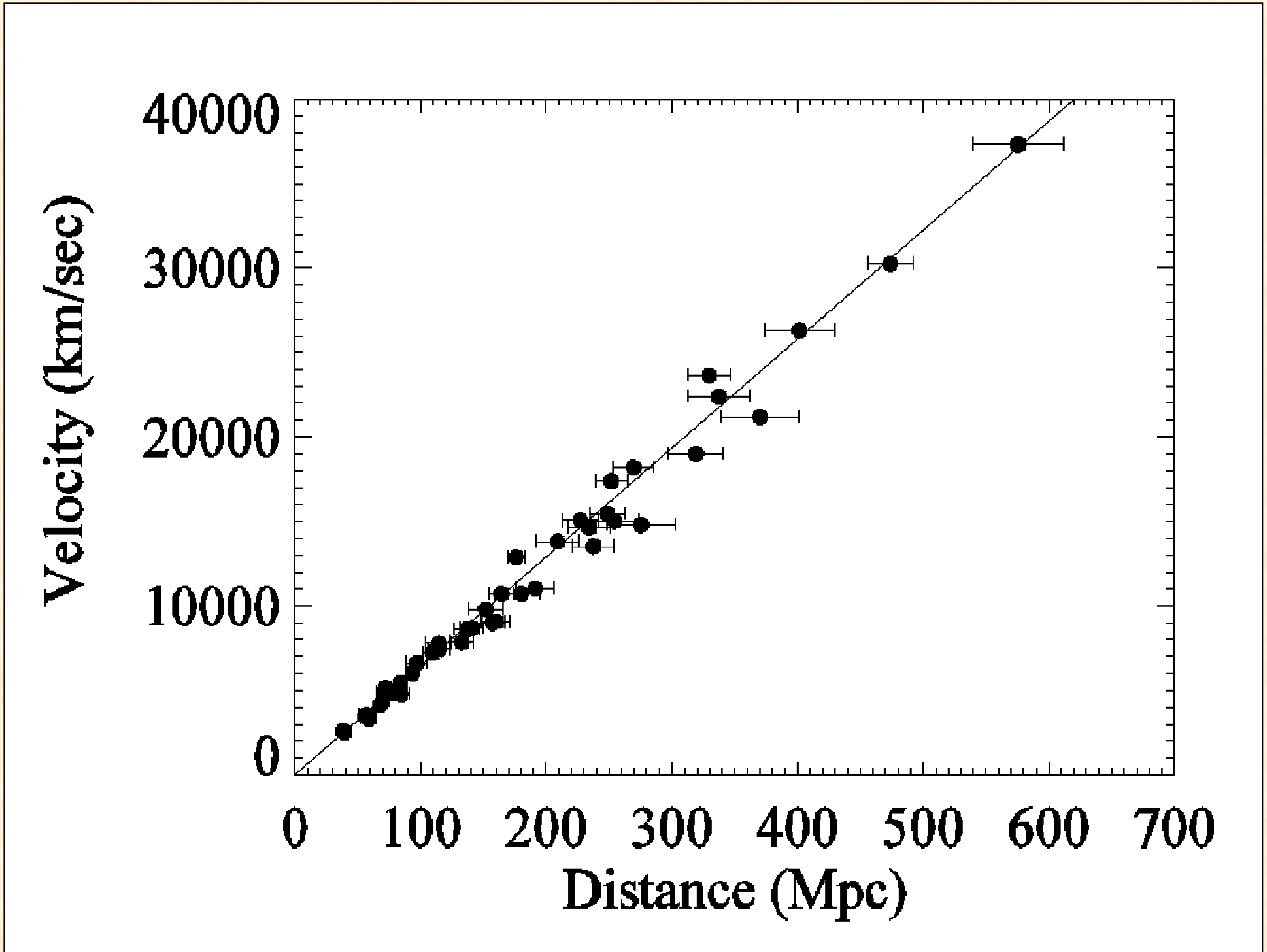
- Edwin Hubble (1920's)
- Galaxies moving away from us
- Further galaxies move away faster
- Distance between distant galaxies increases with time

→ The Universe is expanding

- H_0 = Hubble's Constant

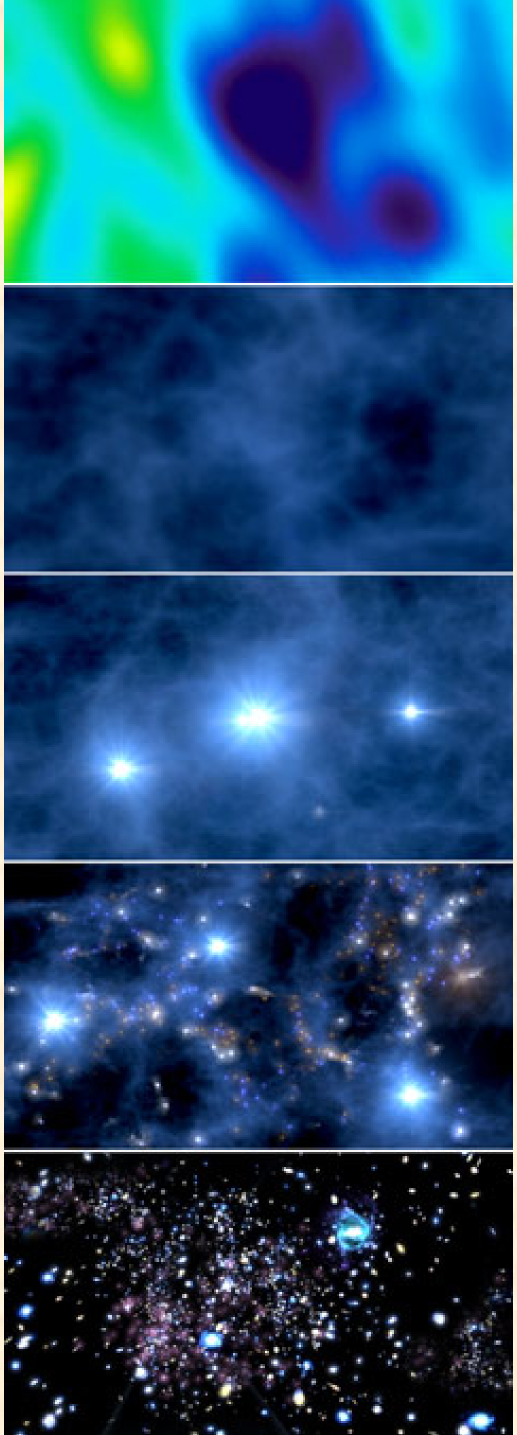
$$v = H_0 r$$

Outward Velocities vs. Distances of Galaxies



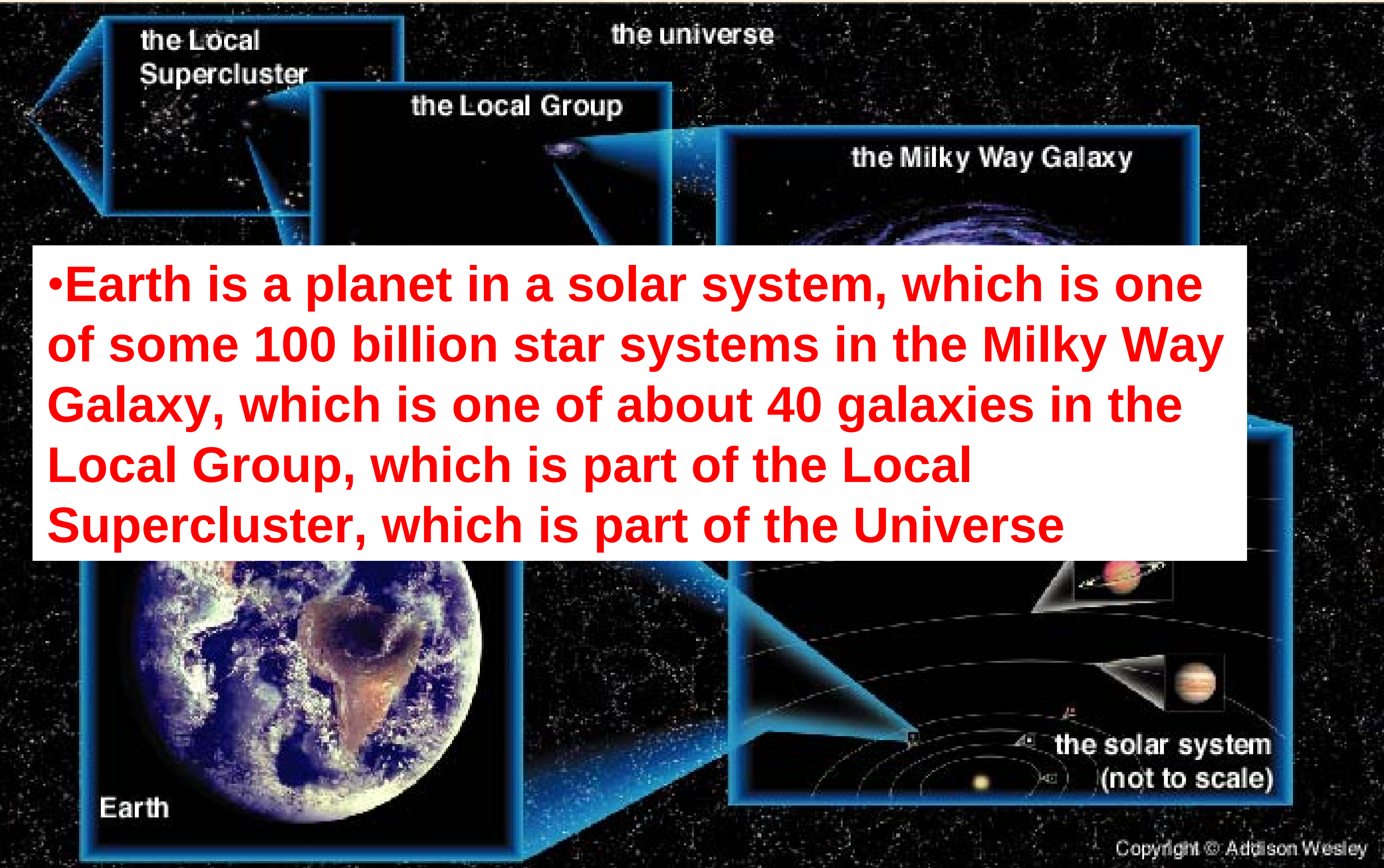
Beginning of the Universe – the Big Bang

- 1948: George Gamow published the first model saying that the universe started from a hot and dense fireball
- Fred Hoyle ridiculed this notion – “Universe did not begin with a Big Bang”
- If galaxies are moving apart now, they were closer together in the past. If their speed had been constant, they would all have been on top of one another, ~15 billion years ago
- If Einstein's General Theory of Relativity is correct, there is a singularity, a point of infinite density and spacetime curvature, where time has a beginning → Universe originates with a **Big Bang**



- From Big Bang to structures: galaxies, clusters, and **We** – the people on planet Earth

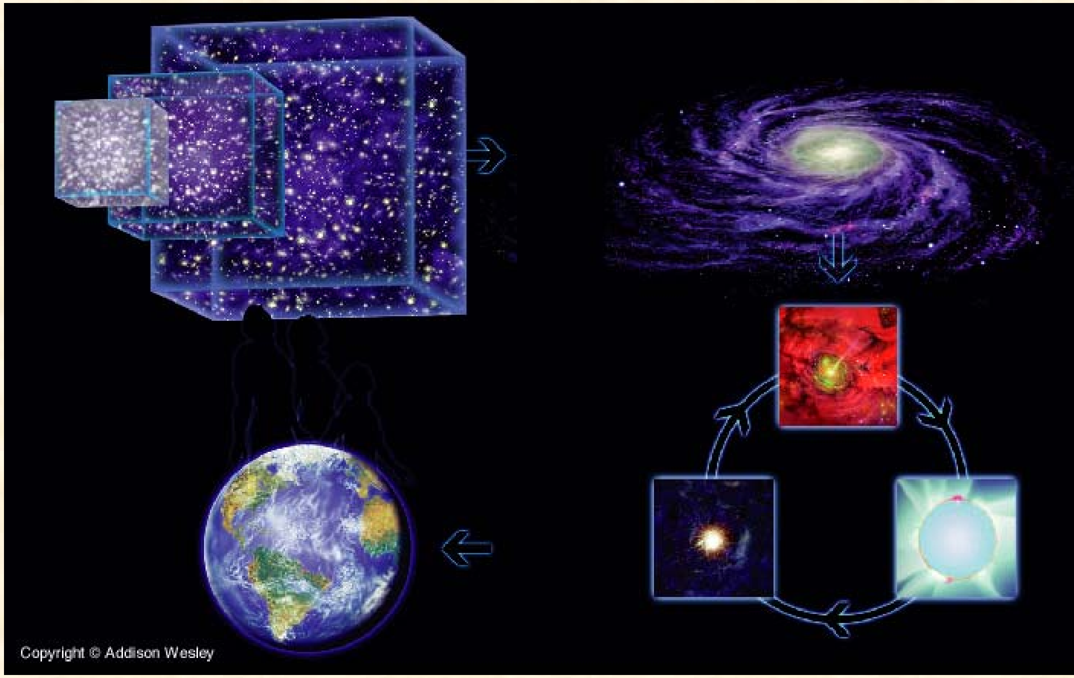
Our Place in the Universe



- **Earth is a planet in a solar system, which is one of some 100 billion star systems in the Milky Way Galaxy, which is one of about 40 galaxies in the Local Group, which is part of the Local Supercluster, which is part of the Universe**

What are We Made Of?

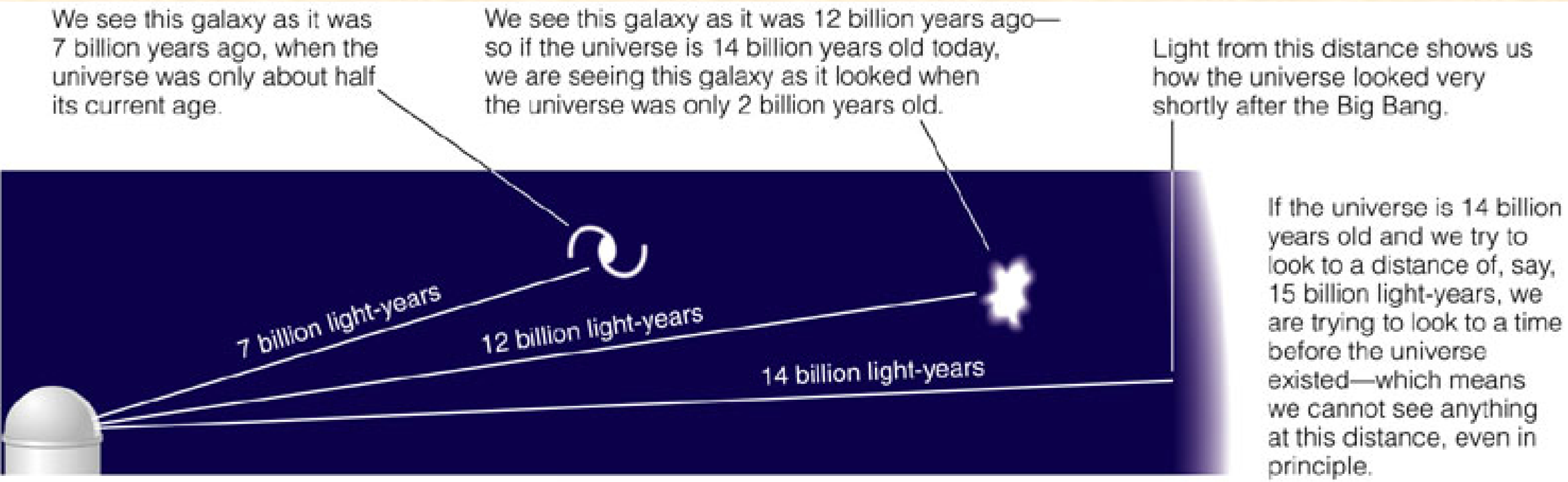
- First simple atoms were created during the Big Bang → Hydrogen and Helium
- All atoms heavier than H and He were created inside stars
- When a star dies, the heavier elements are expelled into space…. to form new stars and planets



- Many of the atoms in our bodies, and that make up the Earth, were created in the core of a star

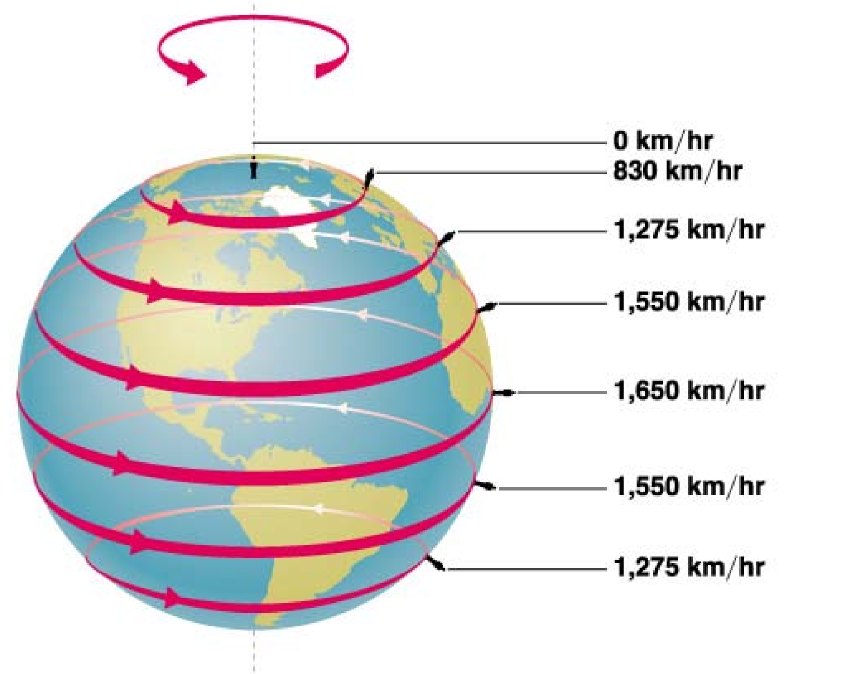
Looking out in space = Looking back in time

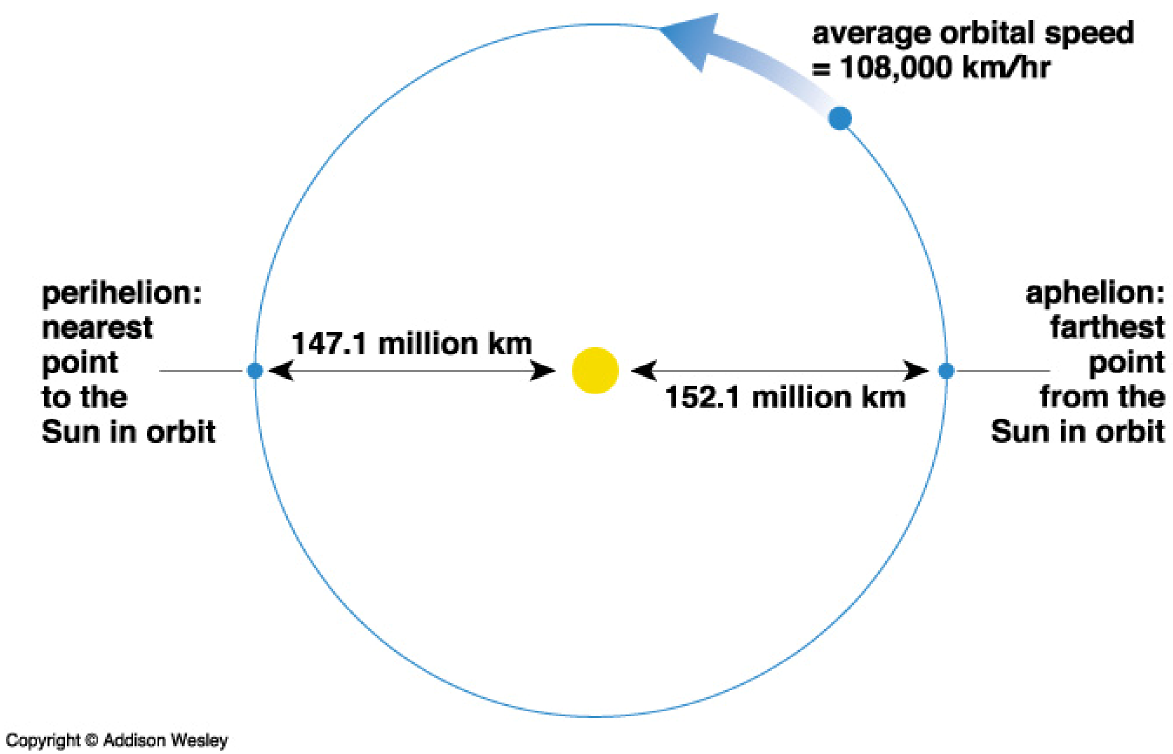
- The farther out we look into the Universe, the farther back in time we see



Our motion

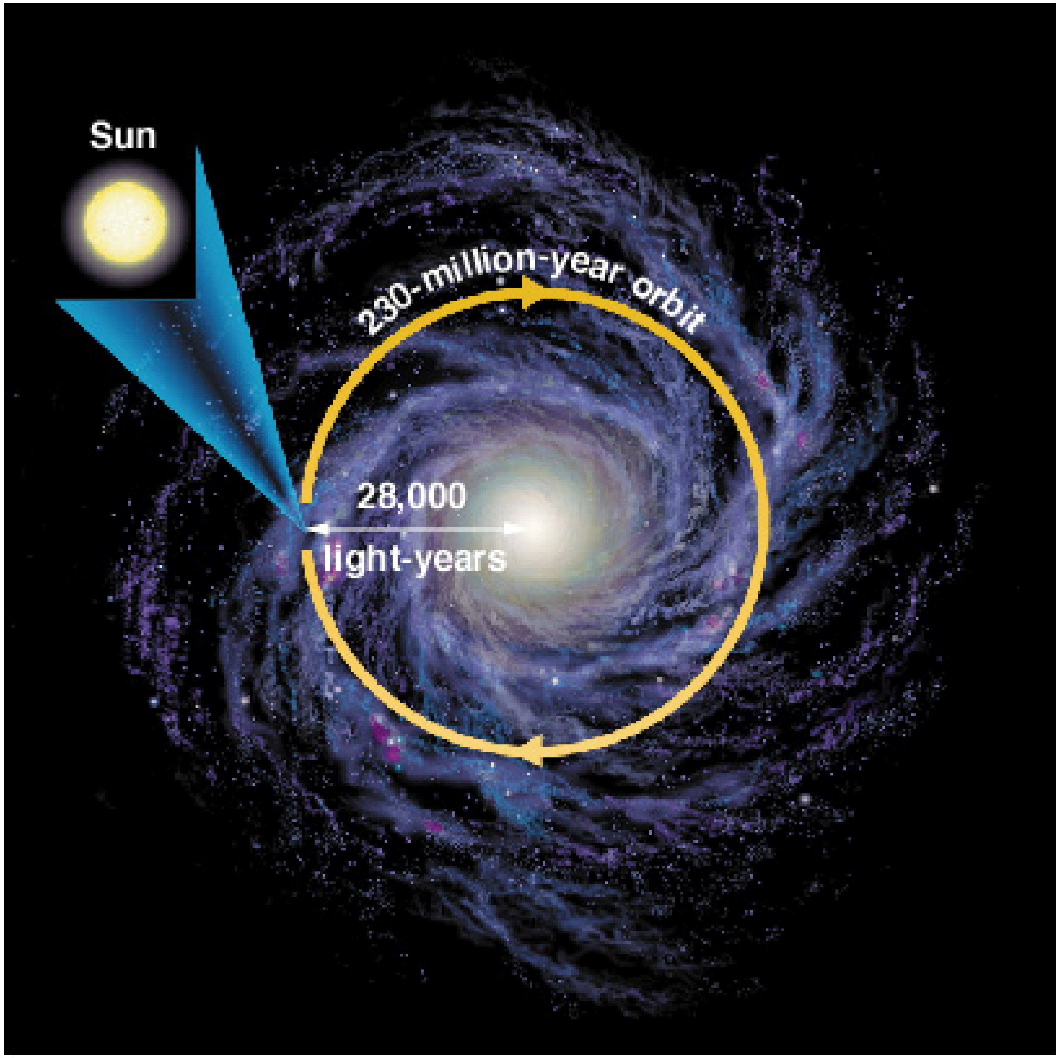
- The Earth rotates around it’s axis once every day



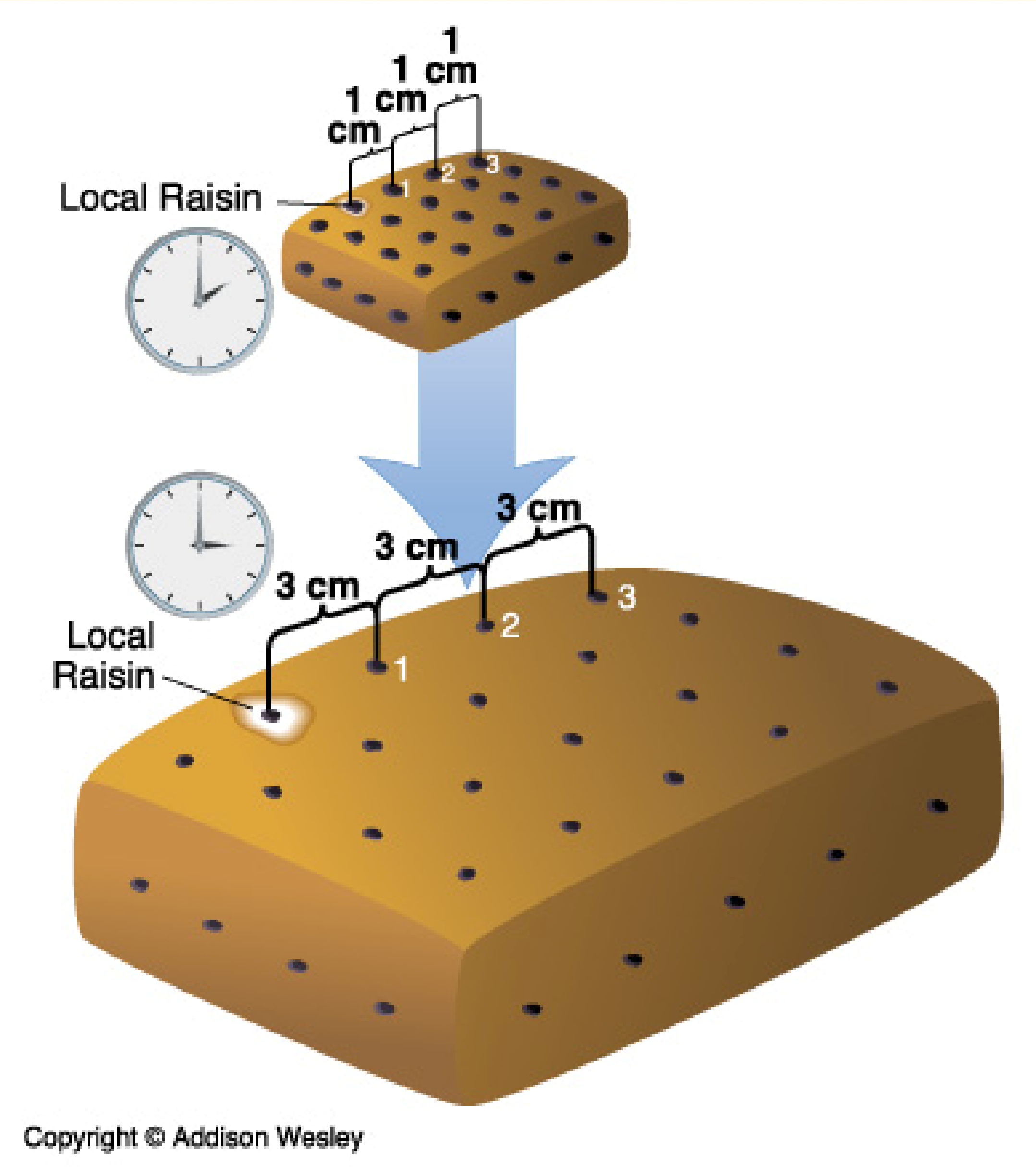


- The Earth orbits around the Sun once every year

- Our Sun and the stars of the local Solar neighborhood orbit around the center of the Milky Way Galaxy every 230 million years



The Milky Way moves with the expansion of the Universe



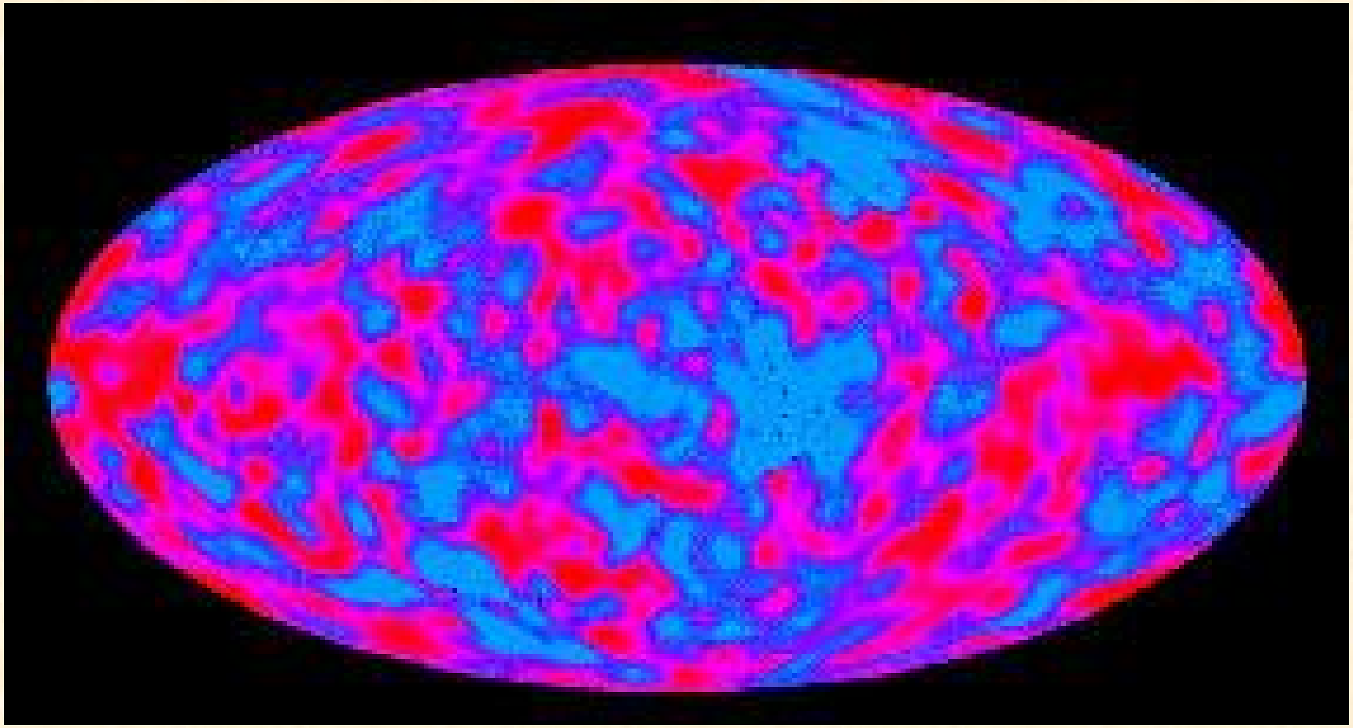
- Most galaxies appear to be moving away from us
- The farther away they are, the faster they are moving
  - Just like raisins in a raisin cake; they all move apart from each other as the dough (space itself) expands

Cosmic Microwave Background Radiation (CMBR)

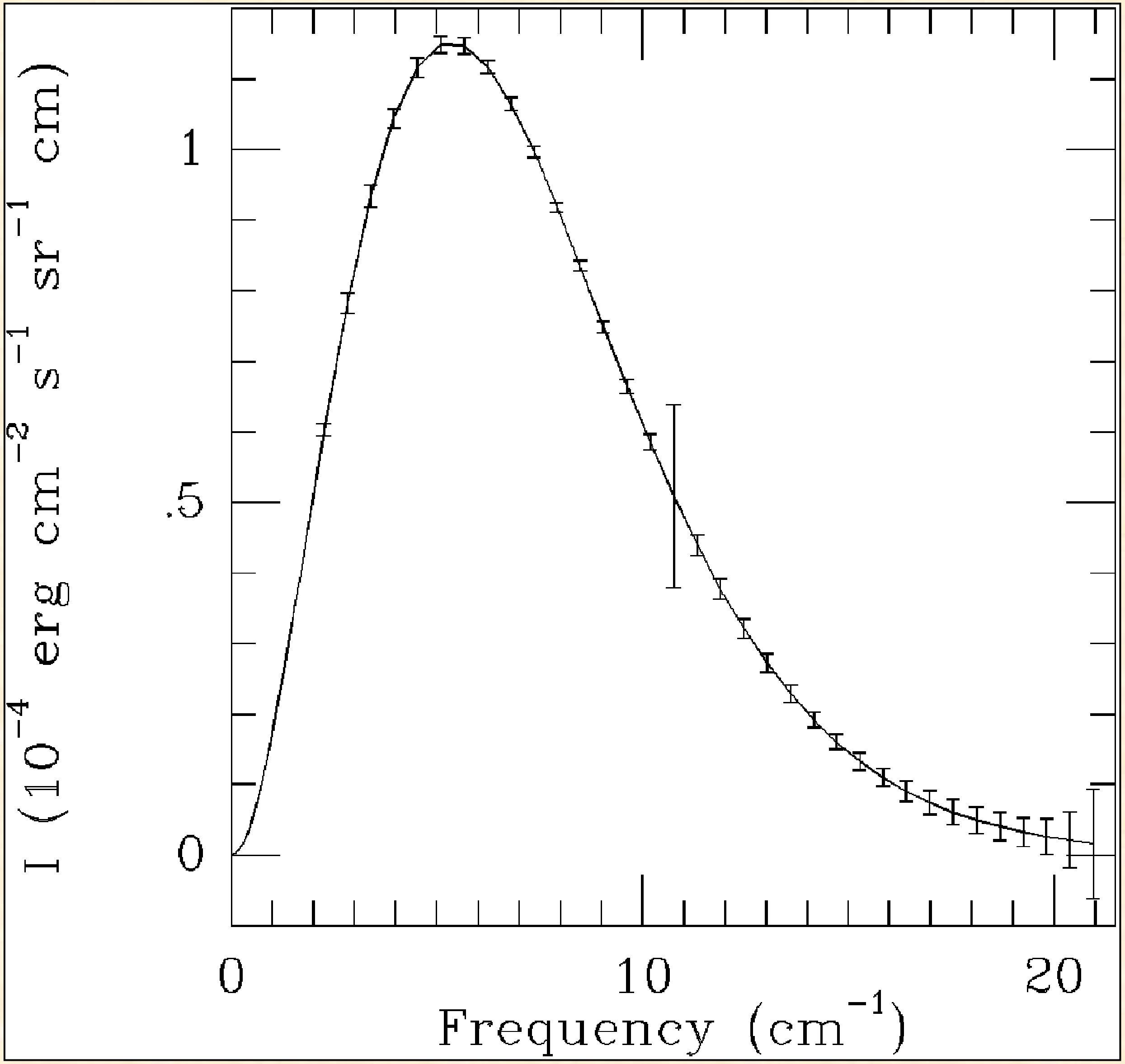
- Uniform faint background of microwaves throughout space
- 1965: Bell lab physicists Arno Penzias and Robert Wilson discovered CMBR by chance when building their low-noise communication antenna
- CMBR→ radiation left over from an early very hot and dense state of the Universe
- As the universe expanded, the radiation cooled to reach the faint remnant we observe today
- Observational evidence
  - Hot Big Bang theory
  - Universe had a very dense beginning

CMBR

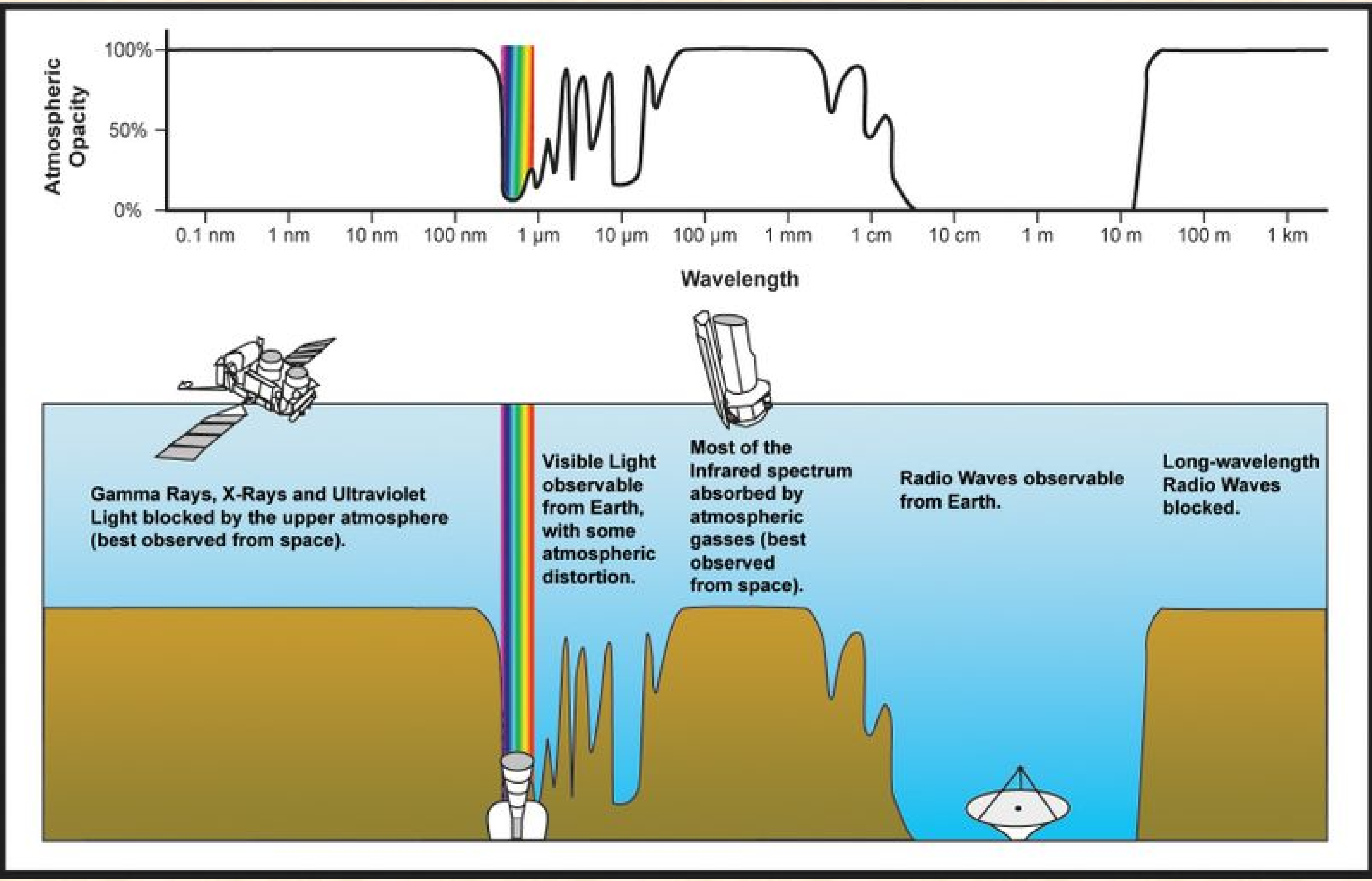
- Radiation of Universe coming from 13 billion light-yrs
- Baby picture of the universe – 300,000 years after the big bang
- Perfect Blackbody: 2.7 °K



Intensity vs. frequency of CMB

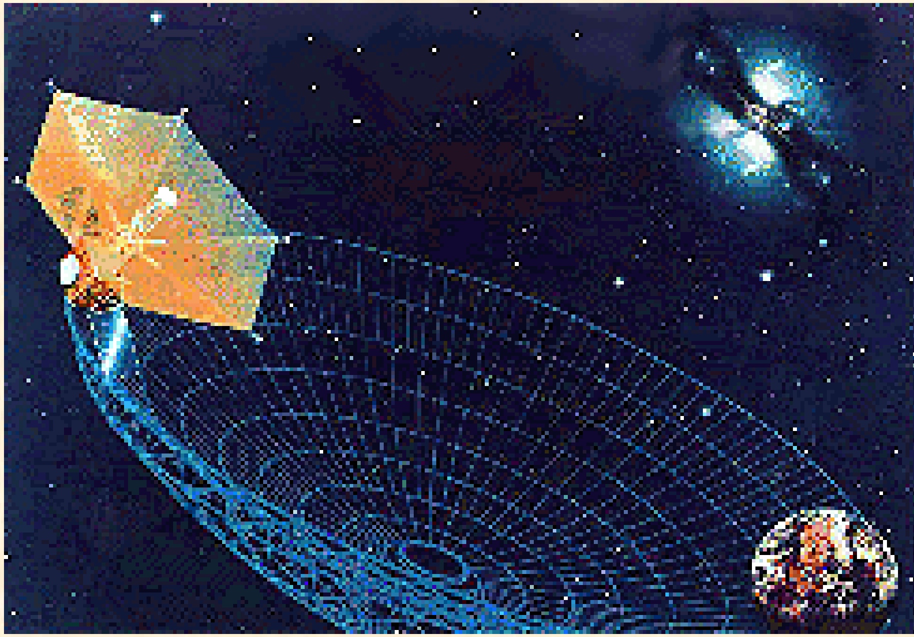


Atmospheric Electromagnetic Transmittance



Radio

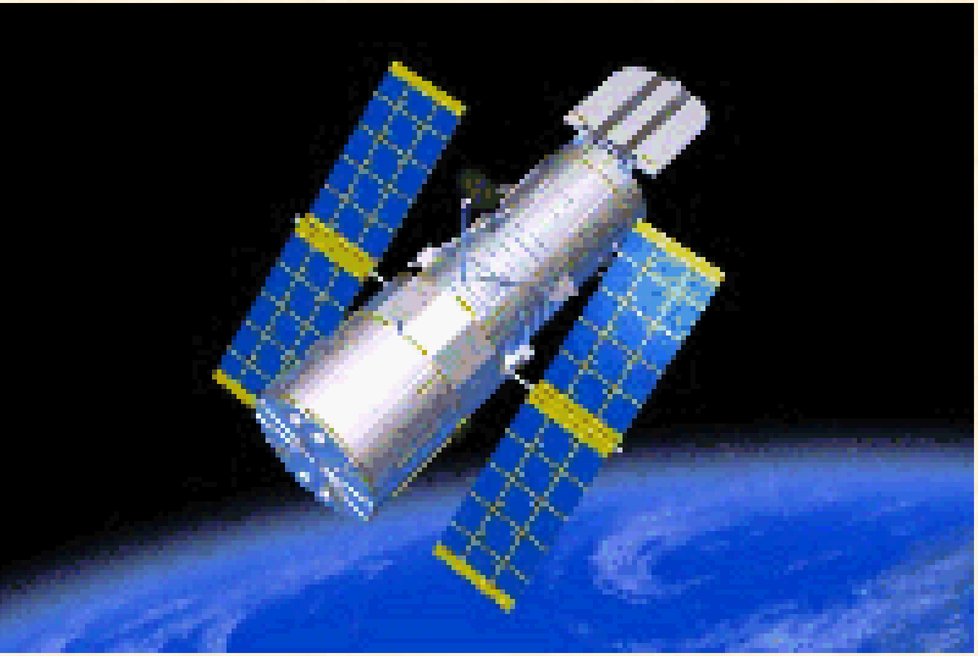
- Waves can reach ground
- Radio interferometry – combine data from two telescopes that are very far apart
- Telescopes:
  - Very Large Baseline Array (VLBA)
  - NRAO VLA Sky Survey (NVSS)
  - Space Very Long Baseline Interferometry (VLBI)
- Source:
  - Produced by electrons moving in magnetic fields



Infrared

- Telescopes:
  - Infrared Space Observatory (ISO)
  - Spitzer Space Telescope (formerly SIRTF, the Space Infrared Telescope Facility)
  - Stratospheric Observatory for Infrared Astronomy (SOFIA)
  - James Webb Space Telescope (JWST)
  - Far Infrared and Submillimetric Space Telescope (FIRST)
  - Infrared Astronomical Satellite (IRAS)
  - Two-micron All Sky Survey (2MASS)
- Source:
  - Cool clouds of dust and gas
  - Planets

Visible / Optical



- Telescopes:
  - Hubble Space Telescope (HST)
  - Ground–based telescopes
  - Sloan Digital Sky Survey
- Source:
  - Stars
  - Planets
  - Some satellites

Andromeda – our sister galaxy

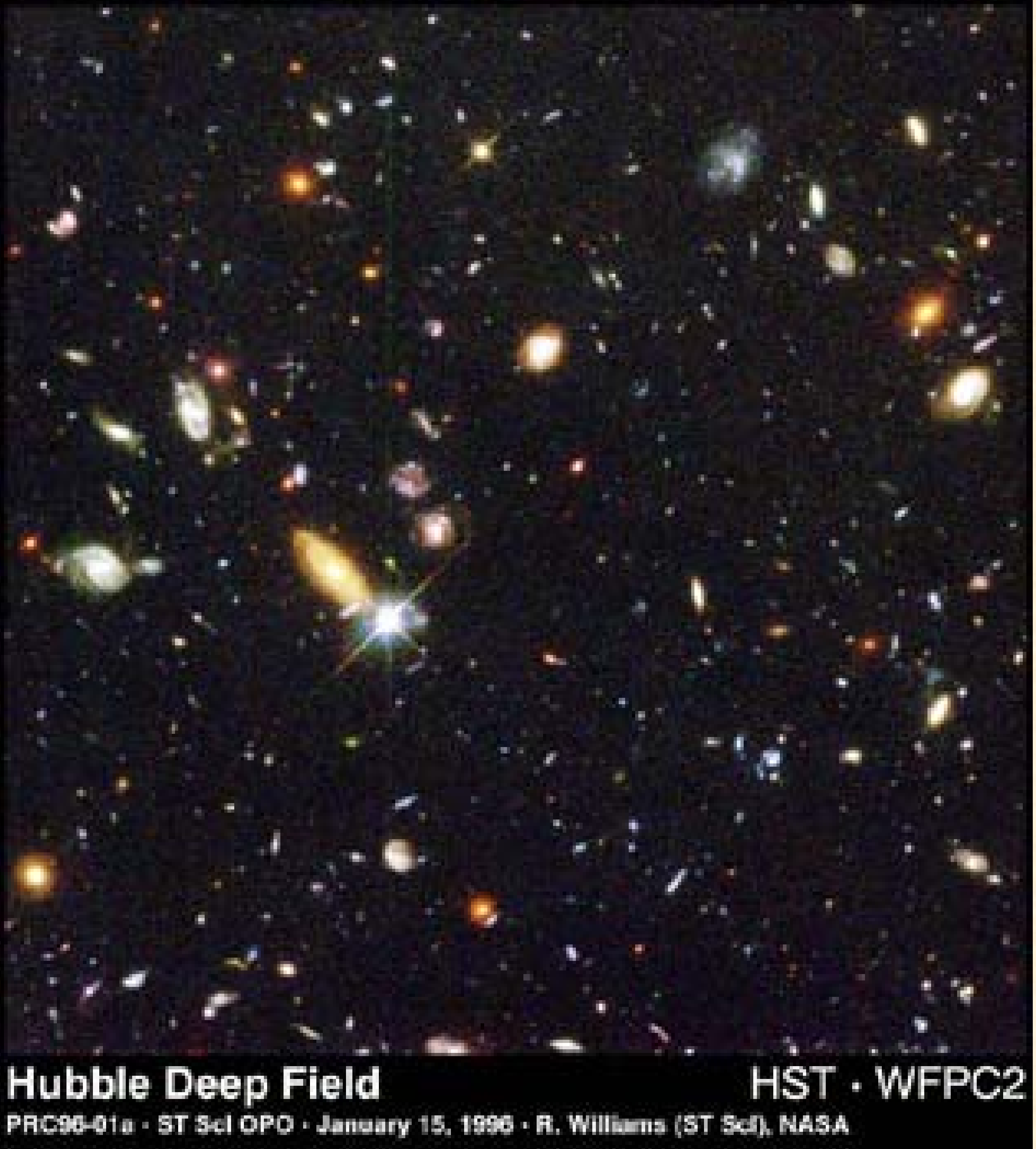
- 2×10^6 light–yrs away
- 100×10^9 stars
- 100,000 light–yrs across

Galaxy cluster A2218

- 3 x 10^9 light-yrs away, 1000 galaxies, 6 x 10^6 lt-yrs across

Galaxy Cluster Abell 2218 **HST • WFPC2**

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08



- Hubble Deep Field
- Galaxies up to 12 x 10^9 light-yrs away

Ultraviolet & Extreme UV

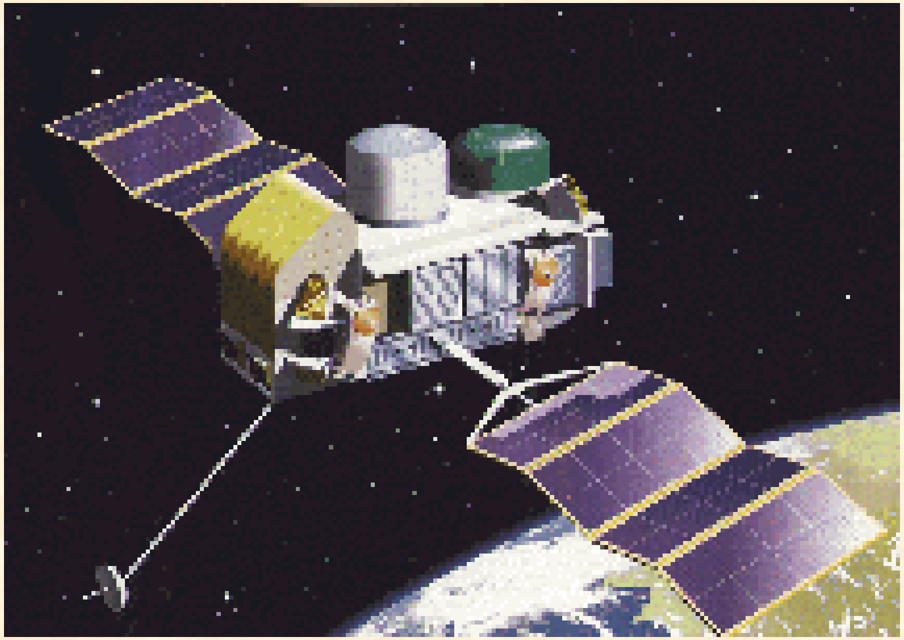
- Telescopes:
  - Extreme Ultraviolet Explorer (EUVE)
  - International Ultraviolet Explorer (IUE)
  - Hubble Space Telescope
  - Array of Low Energy X-ray Imaging Sensors (ALEXIS)
- Source:
  - Supernova remnants
  - Very hot stars
  - Proto-stellar clouds

X-ray

- Telescopes:
  - European X-ray Observatory Satellite (EXOSAT)
  - High-Energy Transient Experiment (HETE)
  - Roentgensatellit (ROSAT)
  - X-Ray Multi-mirror Mission (XMM)
  - Rossi X-ray Timing Explorer (RXTE)
  - Advanced Satellite for Cosmology and Astrophysics (ASCA)
  - Chandra X-ray Observatory (CXO)

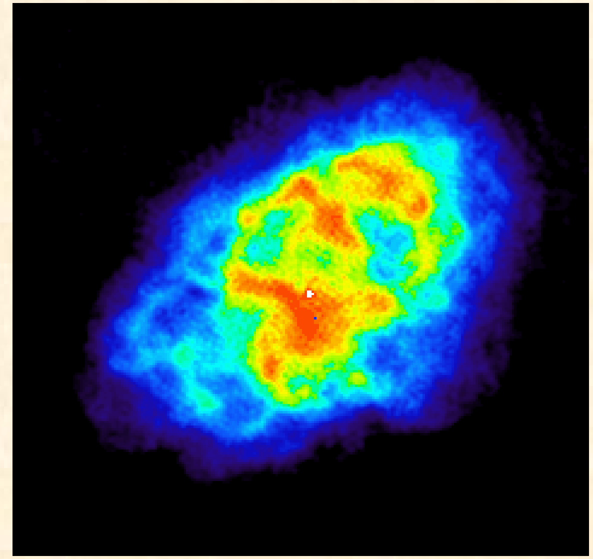
- Source:
  - Hot gas in galaxy clusters – ICM
  - Supernova remnants
  - Stellar corona

γ-ray



- Telescopes:
  - International Gamma-Ray Astrophysics Laboratory (INTEGRAL)
  - Compton Gamma-Ray Observatory (CGRO)
  - SWIFT
  - Gamma-Ray Large Area Space Telescope (GLAST)
- Source:
  - Accretion disks around black holes
  - Extragalactic relativistic jets

The Crab Nebula – a supernova remnant

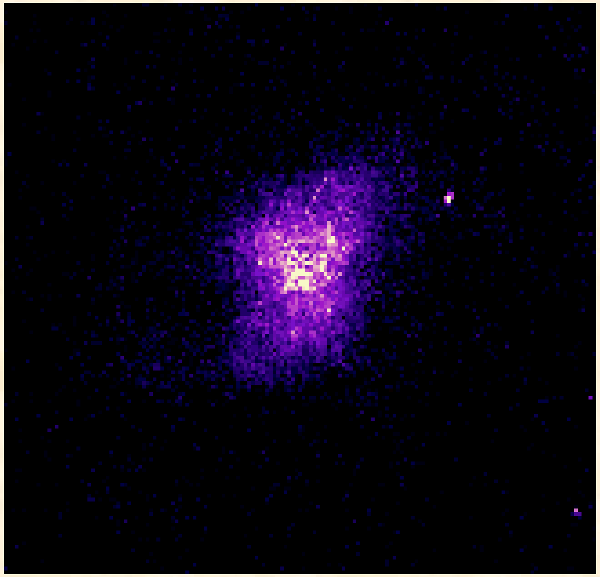


Radio

- From unbound electrons spiraling around inside the nebula; pulsar flashes

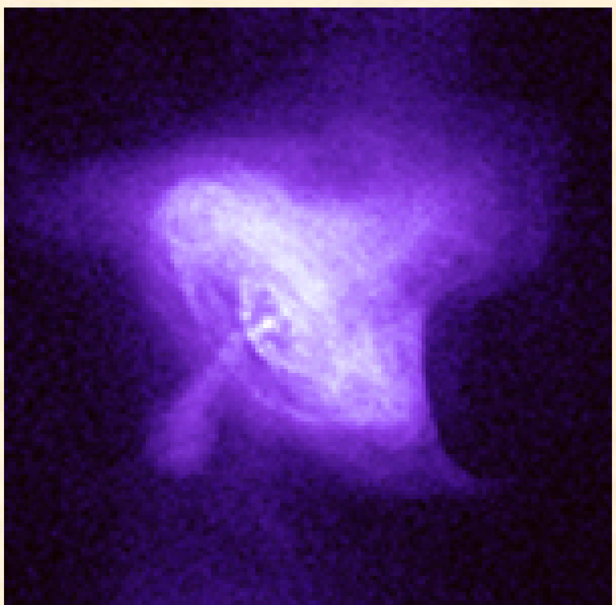
Optical

- Filaments → Leftover of the original outer layers of the star blown off by supernova, still expanding
- Extrapolating backwards in time shows that the filaments first started expanding away from the center around 1040-1070 A.D. This agrees well with the 1054 A.D. supernova explosion



Ultraviolet

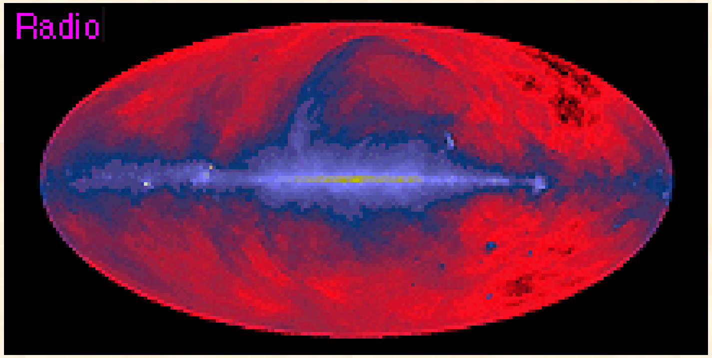
- Cooler electrons extend out beyond the hot electrons near the central pulsar

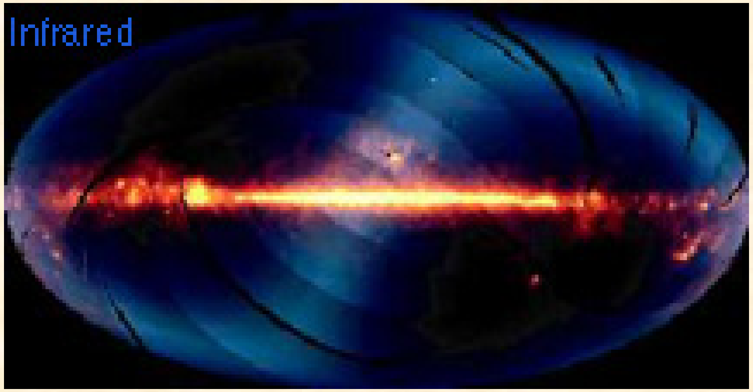


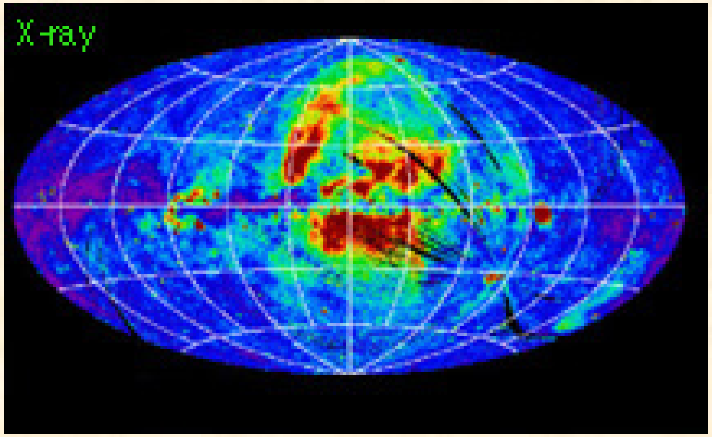
X-ray

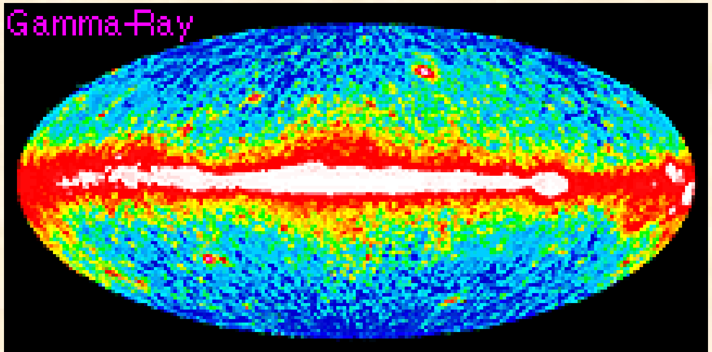
- Condensed core near the central pulsating neutron star
- Strong magnetic field near the surface of the neutron star “energizes” the electrons in it

Images of the entire sky (at different λ), centered on our Galaxy









ASTROSAT

- India's first multi-λ astronomy satellite
  - UV (1000 – 3000 Å)
  - Soft & hard x-ray (0.3 – 8 keV; 2 – 100 keV)
- Scheduled for launch in mid 2007
- Collaboration: ISRO, TIFR, IIA, RRI, IUCAA, PRL, BARC, SNBNCBS

Cosmology

- Cosmological principle
  - Universe is Homogeneous & Isotropic on large scales (> 100 Mpc)
  - Laws of science are universal
- Universe (space itself) expanding; distance, D between widely separated points increases as dD/dt ~ D (= *Hubble Law*)
- Universe expanded from a very dense, hot initial state (*Big Bang*)
- Expansion of universe – mass & energy content – explained by laws of GTR → *Fate of universe*
- Structure formation in small scales (< 10-100 Mpc) by gravitational self organization

Cosmological Parameters

- Critical density, ρ_C – density that makes space just flat

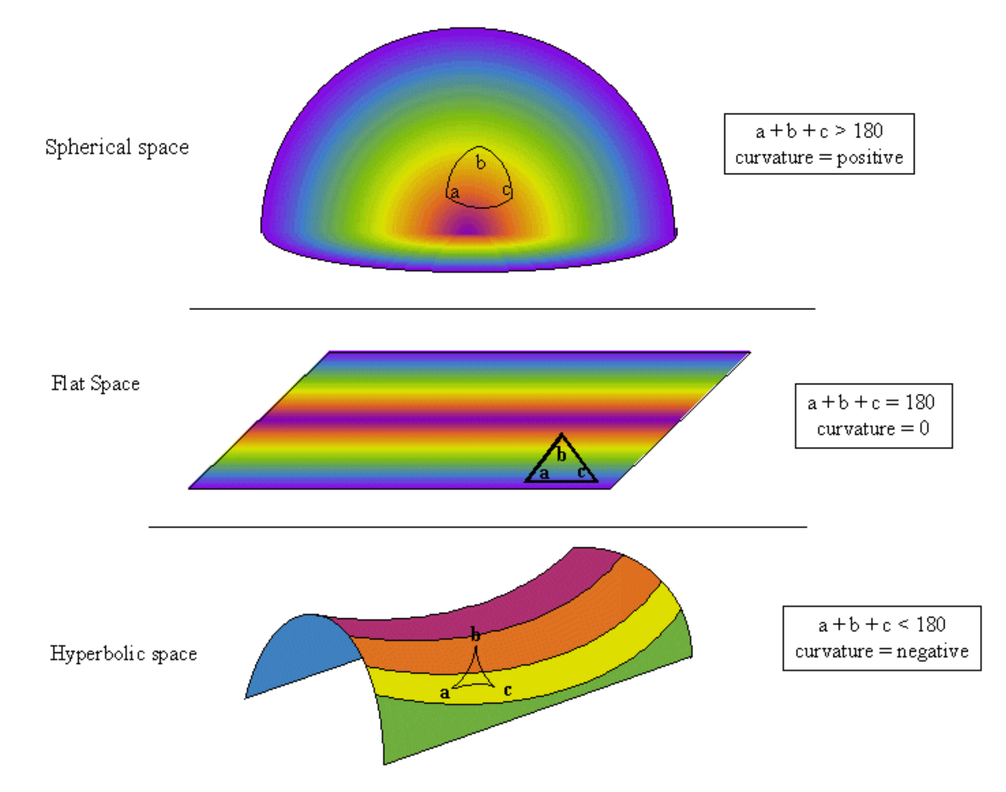
$$\rho_C = \frac{3H_0^2}{8\pi G}$$

- H_0 = Hubble constant = v / r

- Density parameter, $\Omega = \rho / \rho_C$
- $\Omega_{TOT} = \Omega_M + \Omega_\Lambda + \Omega_K$
- $\Omega_M = \rho_M/\rho_C$
  - Matter (visible+dark)
- $\Omega_\Lambda = \Lambda / 3H_0^2$
  - Vacuum energy
- $\Omega_K = -k / R_0^2 H_0^2$
  - Curvature term
  - If flat, k = 0

Curvature of Space

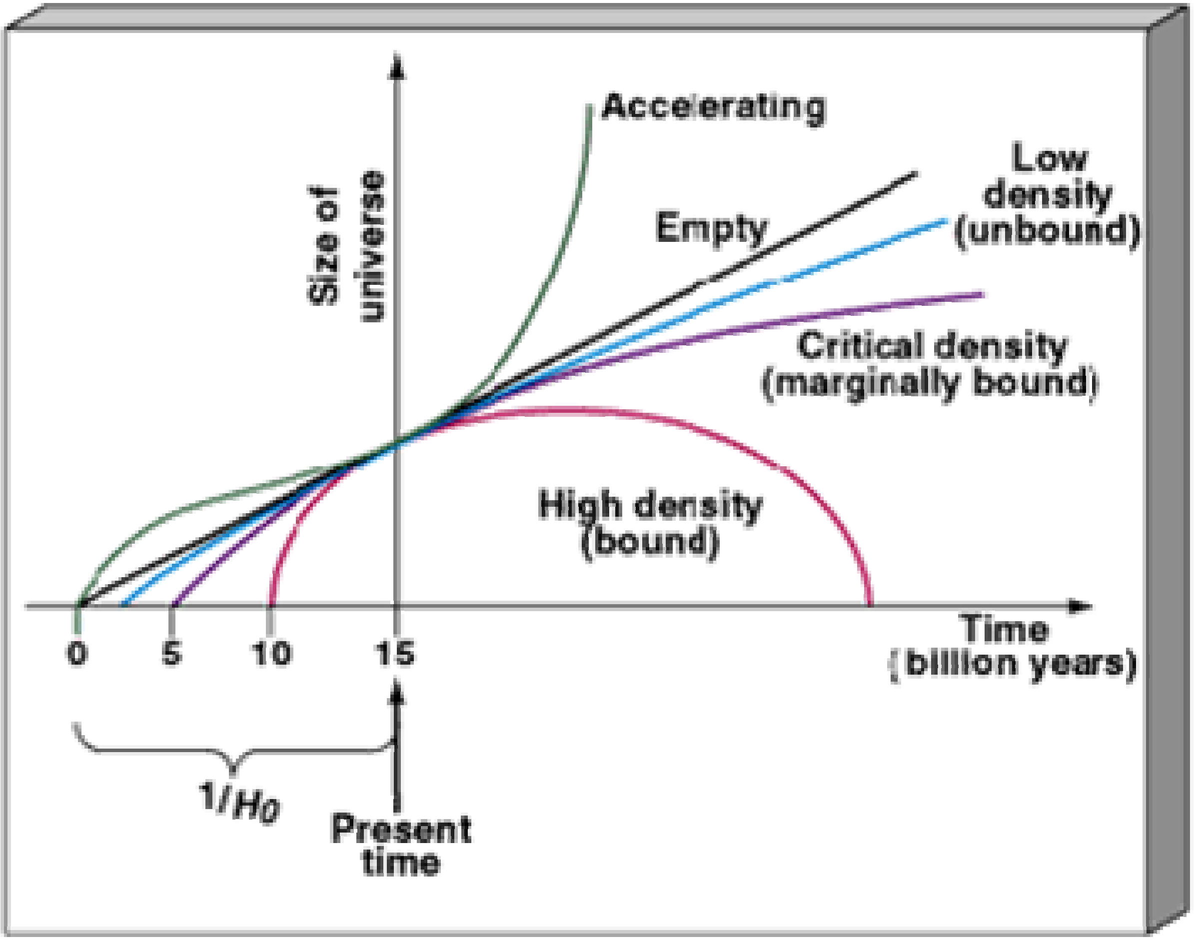
- Positive curvature – Closed – contract in future
- Zero curvature – Flat – stop expansion in future & stationary
- Negative curvature – Open – expand forever



Timeline

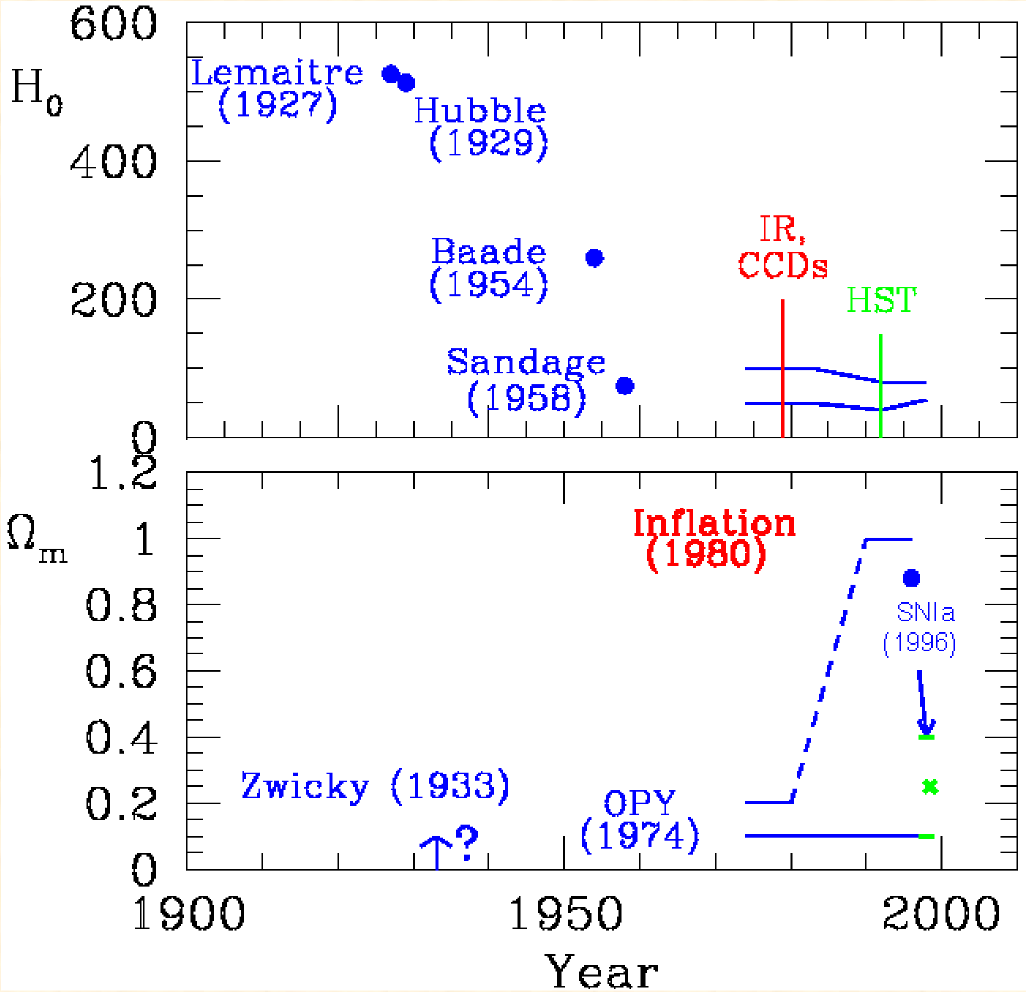
- 1905 – Einstein's STR, 1916 – GTR
- 1917 – Einstein's static cosmological model with Λ
- 1922 – Friedman: non-static model
- 1927 – Lemaitre: expanding Universe
- 1930 – Hubble: observed the expansion; Einstein dropped Λ ("biggest blunder")
- 1948 – Particle theory (QED) predicts non zero vacuum energy, but $\Lambda_{QED} = 10^{120}\Lambda_{other}$
- 1965 – CMBR discovered
- 1980's –
  - Inflation theory → Flat universe ($\Omega_{TOT} = 1$)
  - Dark matter
- 1990's - $\Omega_{LUM} \sim 0.02\text{-}0.04$, $\Omega_{DARK} \sim 0.2\text{-}0.4$, $\Omega_{REST} = ?$
- 1998 – Accelerating universe
- Present model – FLAT universe (with matter and vacuum energy)

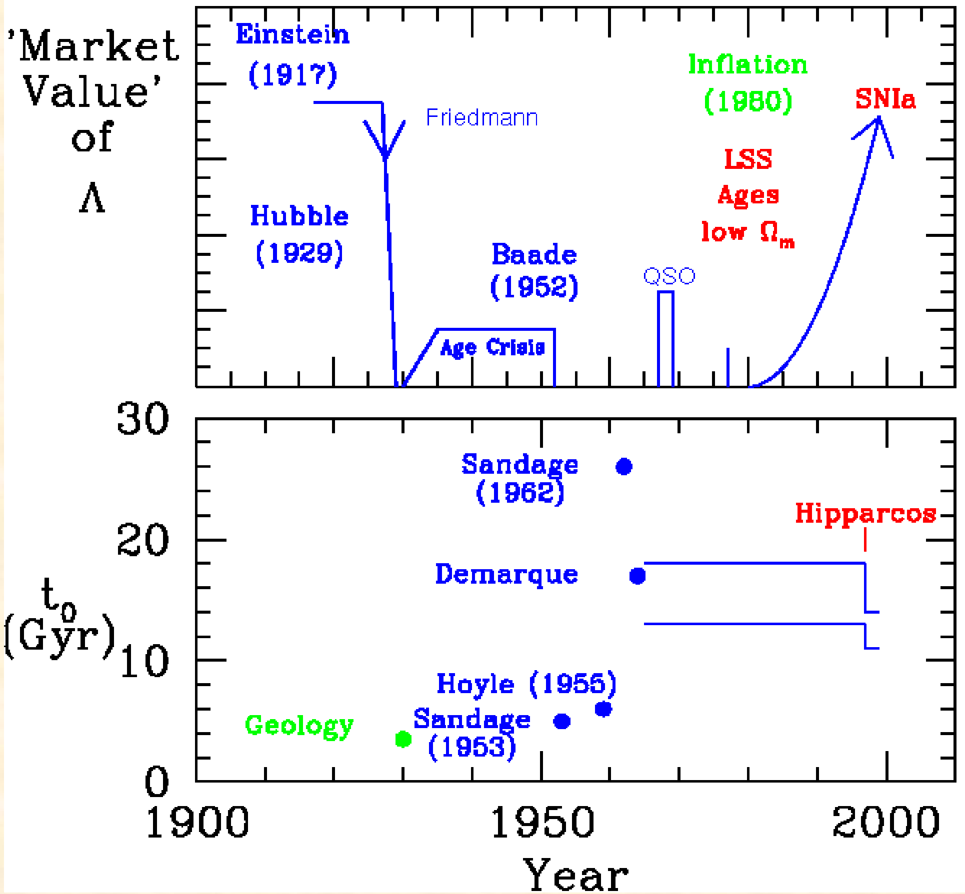
Age of the Universe in Different Models



Current values

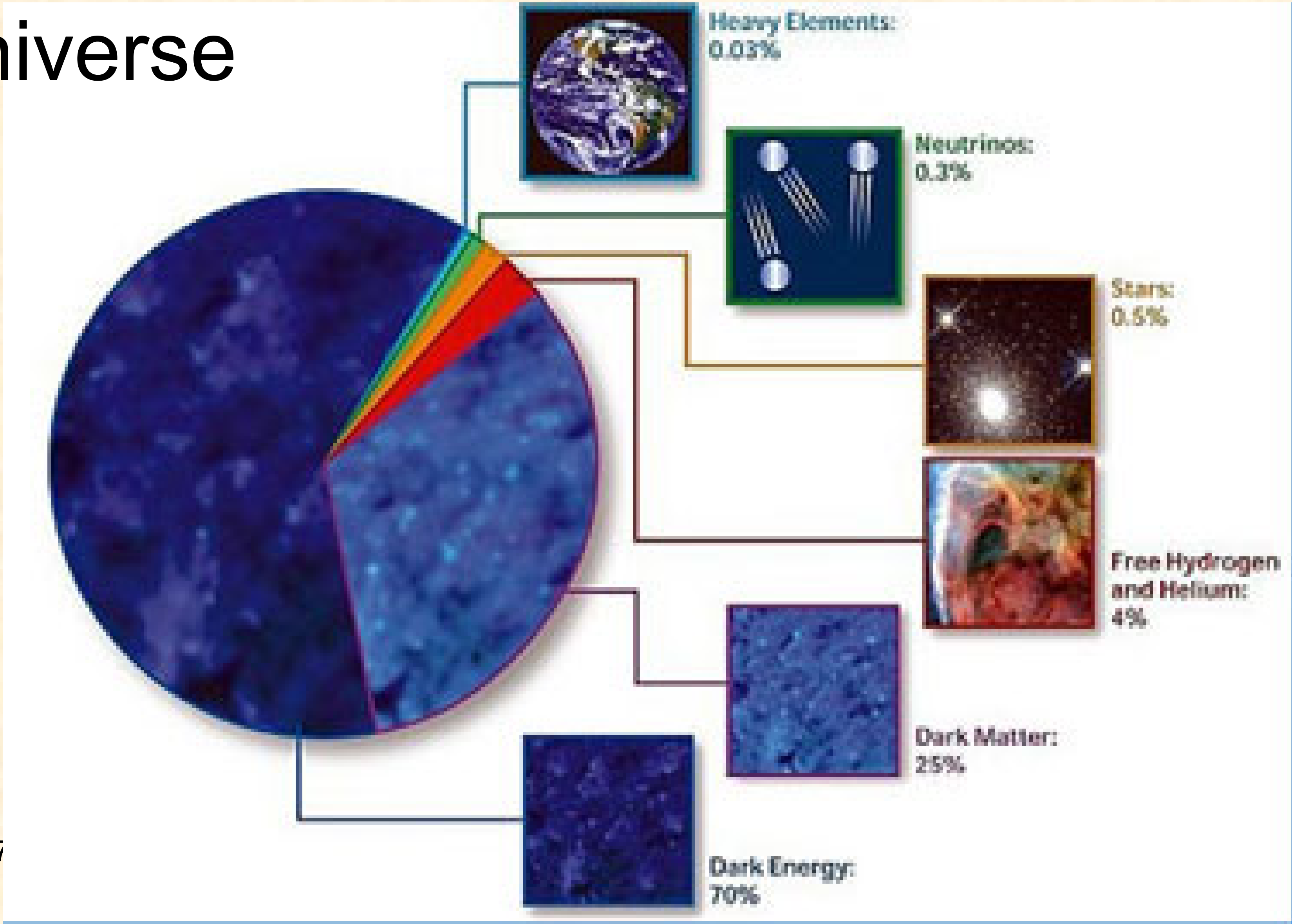
- H_0
  - Gravitational lens time delay method
  - Galaxy cluster studies
    - (50 –100) km/s/Mpc
    - H_0 ~ 72 km/s/Mpc
- Ω_M
  - Cluster velocity dispersion
  - Weak gravitational lens effect
    - $\Omega_{visible}$ ~ 0.02 – 0.04
    - Ω_{dark} ~ 0.25
    - Ω_M ~ 0.3



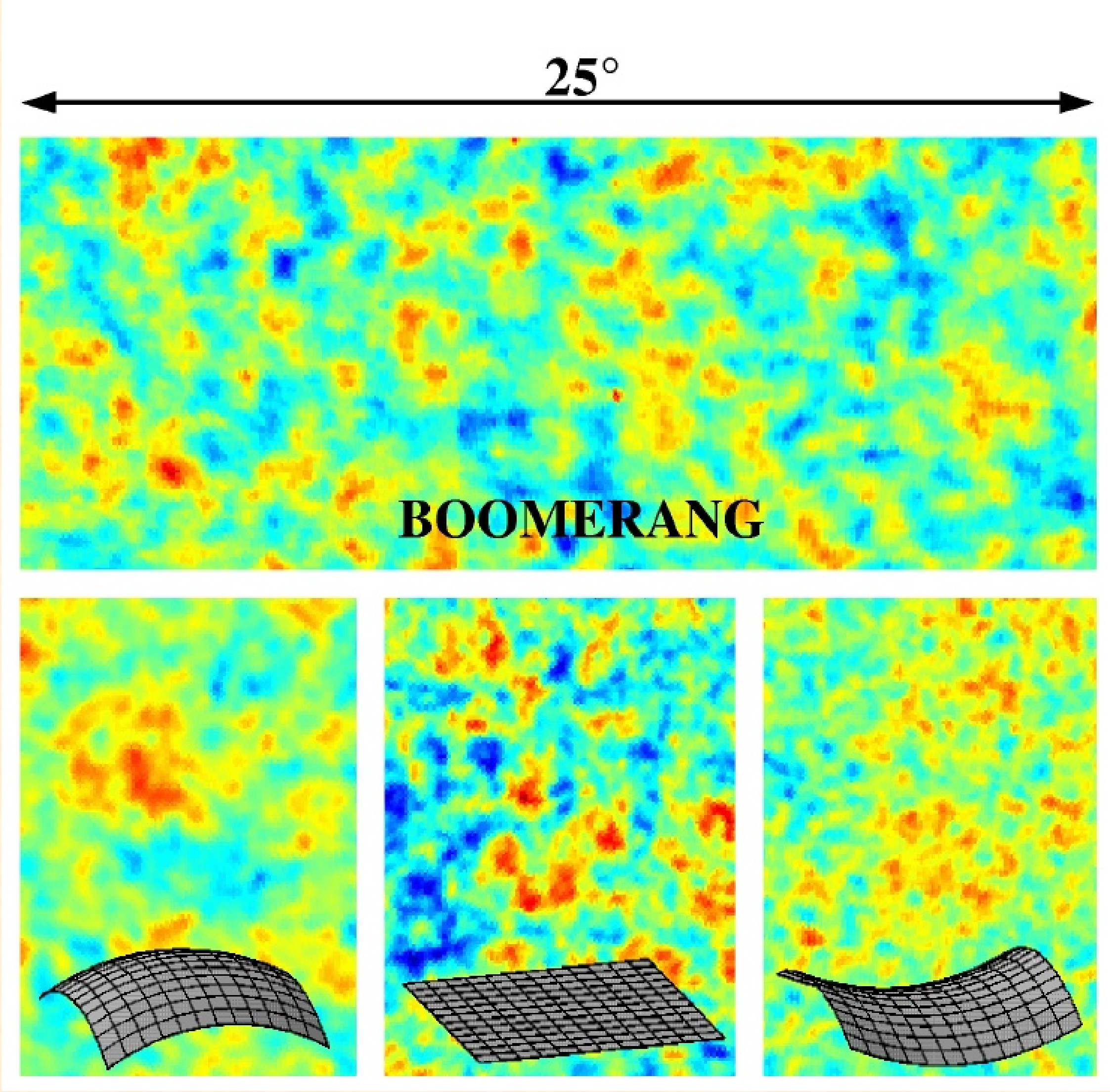


- Ω_Λ
  - Energy density of vacuum
  - Discrepancy of > 120 orders of magnitude with particle physics theory
  - $\Omega_\Lambda \sim 0.7$
    - SN Type Ia
    - WMAP

Composition of our Universe



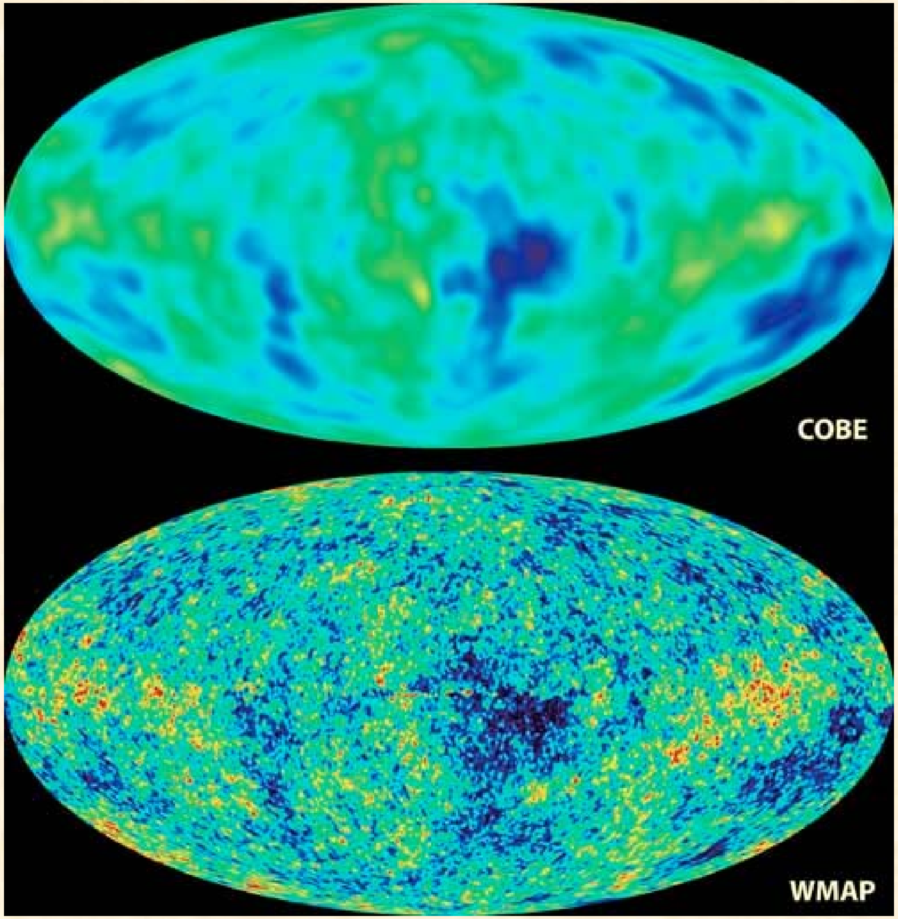
CMB Fluctuation Result of Balloon Experiment



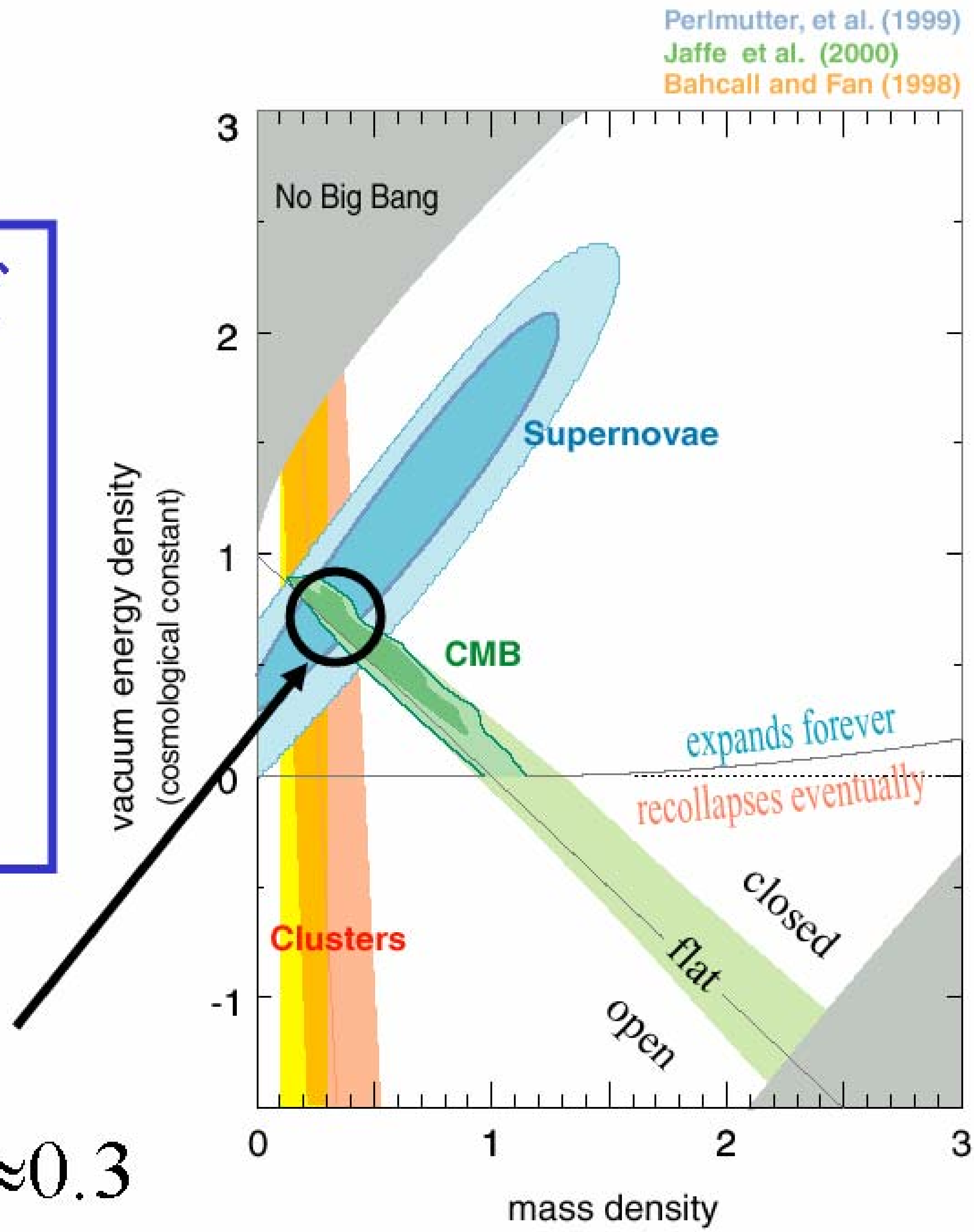
- Result best matches with Flat Space

Microwave Background Fluctuations

- Ground & balloon based experiments
  - Flat – 15 % accuracy
- WMAP
  - Measures basic parameters of Big Bang theory & geometry of universe
  - Flat – 2 % accuracy

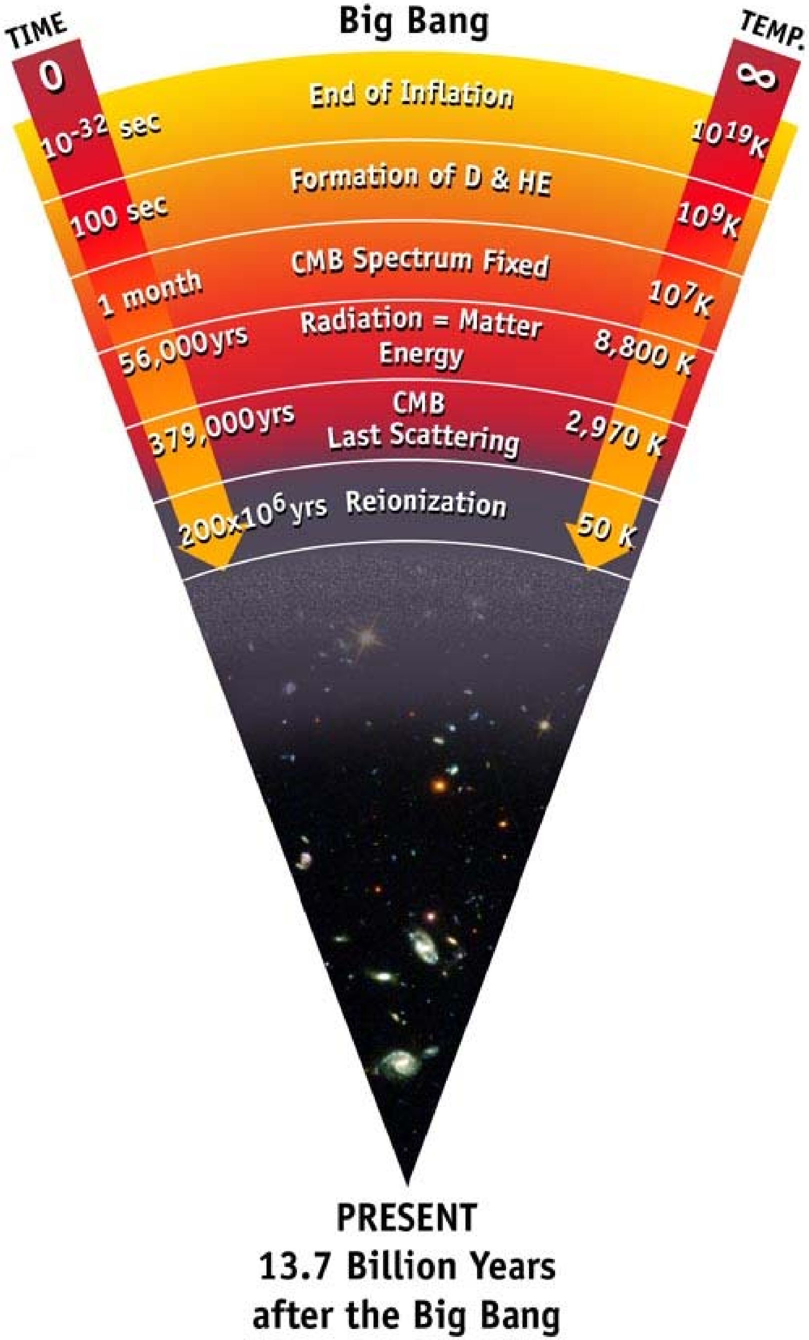


Combination of SNe, matter density, and CMBR makes dark energy inescapable



You are here:

$\Omega_\Lambda \approx 0.7 \quad \Omega_m \approx 0.3$



Age of universe

- 13.7 billion years
  - 1% error margin

WMAP result summary

- Light in WMAP picture from 379,000 years after Big Bang
- First stars ignited 200 million years after Big Bang
- Contents of Universe :
  - 4 % atoms, 23 % Cold Dark Matter, 73 % Dark Energy
- Fast moving neutrinos do not play any major role in evolution of structure of universe. They would have prevented the early clumping of gas in the universe, delaying the emergence of the first stars, in conflict with new WMAP data

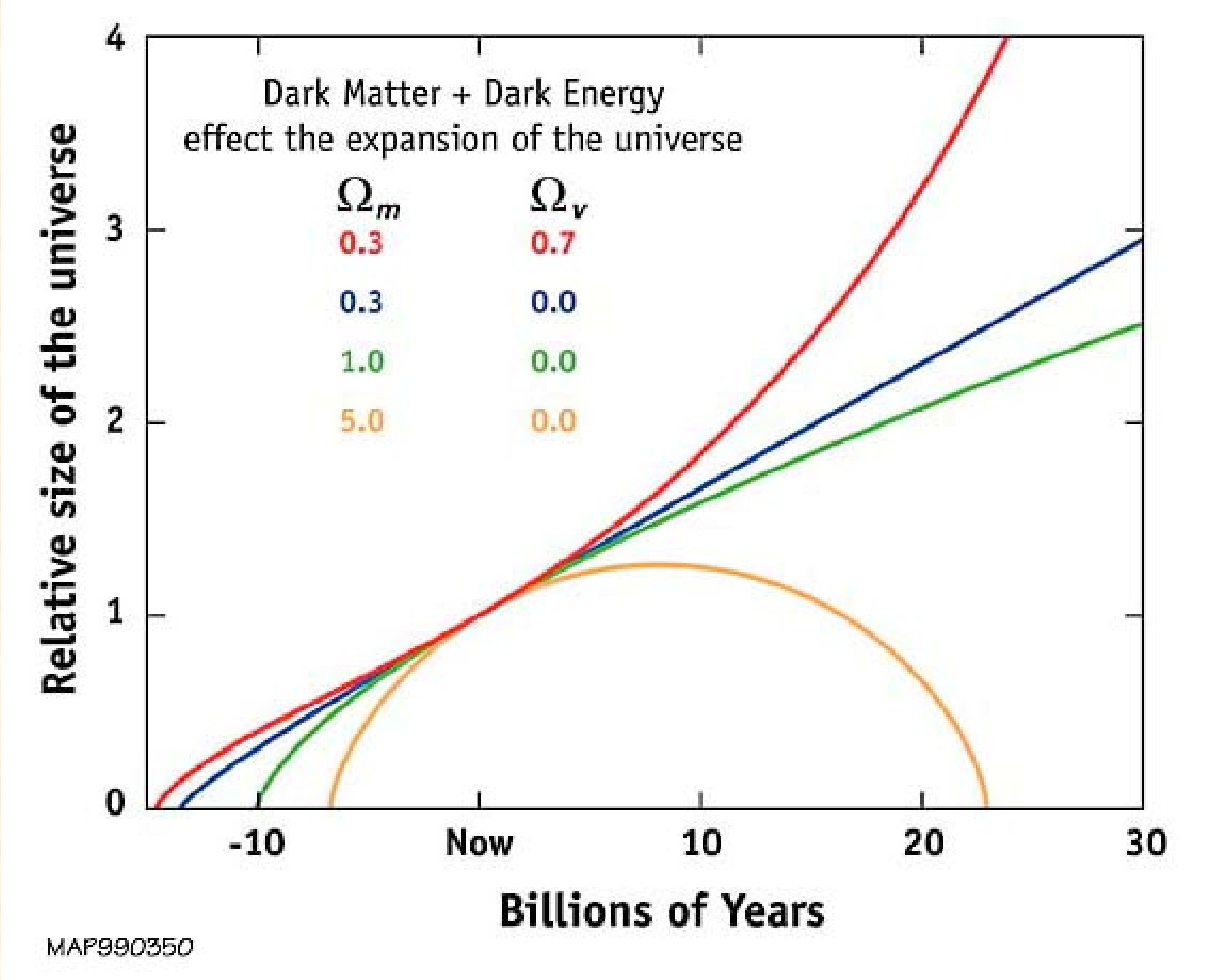
WMAP results

- New evidence for Inflation (in polarized anisotropic signal)
- For the theory that fits our data, the Universe will expand forever. (The nature of the dark energy is still a mystery. If it changes with time, or if other unknown and unexpected things happen in the universe, this conclusion could change)

Canonical cosmological parameters (from WMAP)

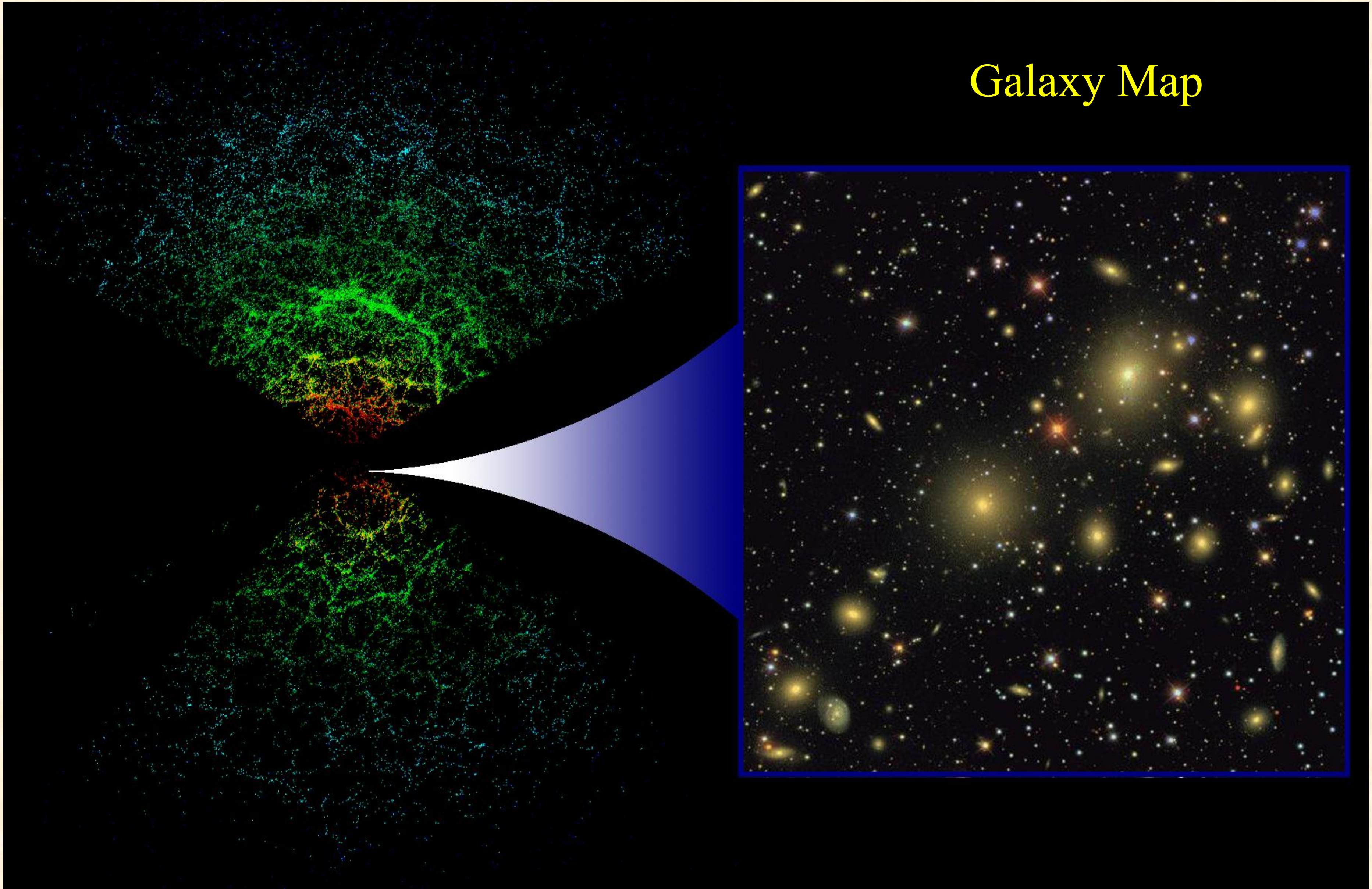
- H_0 = 71 (+ 4 – 3) km/s/Mpc
- $\Omega_{TOT} = 1.02 \pm 0.02$
- $\Omega_{\Lambda} = 0.73 \pm 0.04$
- $\Omega_{M} = 0.27 \pm 0.04$
- $\Omega_{Baryon} = 0.044 \pm 0.004$
  - n_b (baryon density) = $(2.5 \pm 0.1) \times 10^{-7}$ cm^{-3}
- $t_{Universe} = 13.7 \pm 0.2$ Gyr
- $T_{decoupling} = (379 \pm 8)$ kyr
- $T_{reionization}$ = 180 (+220 – 80) Myr (95% CL)

Possible kinds of universe

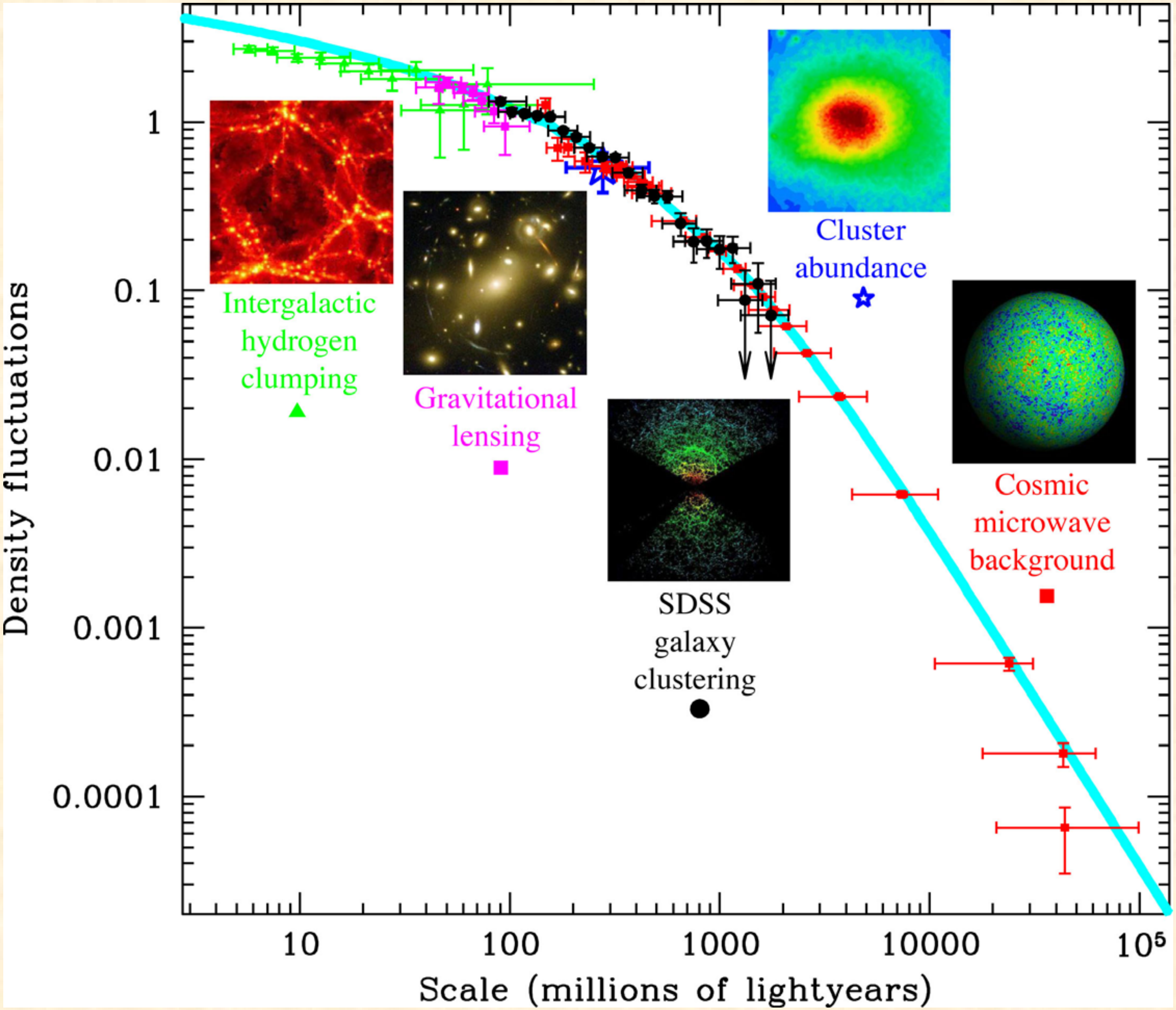


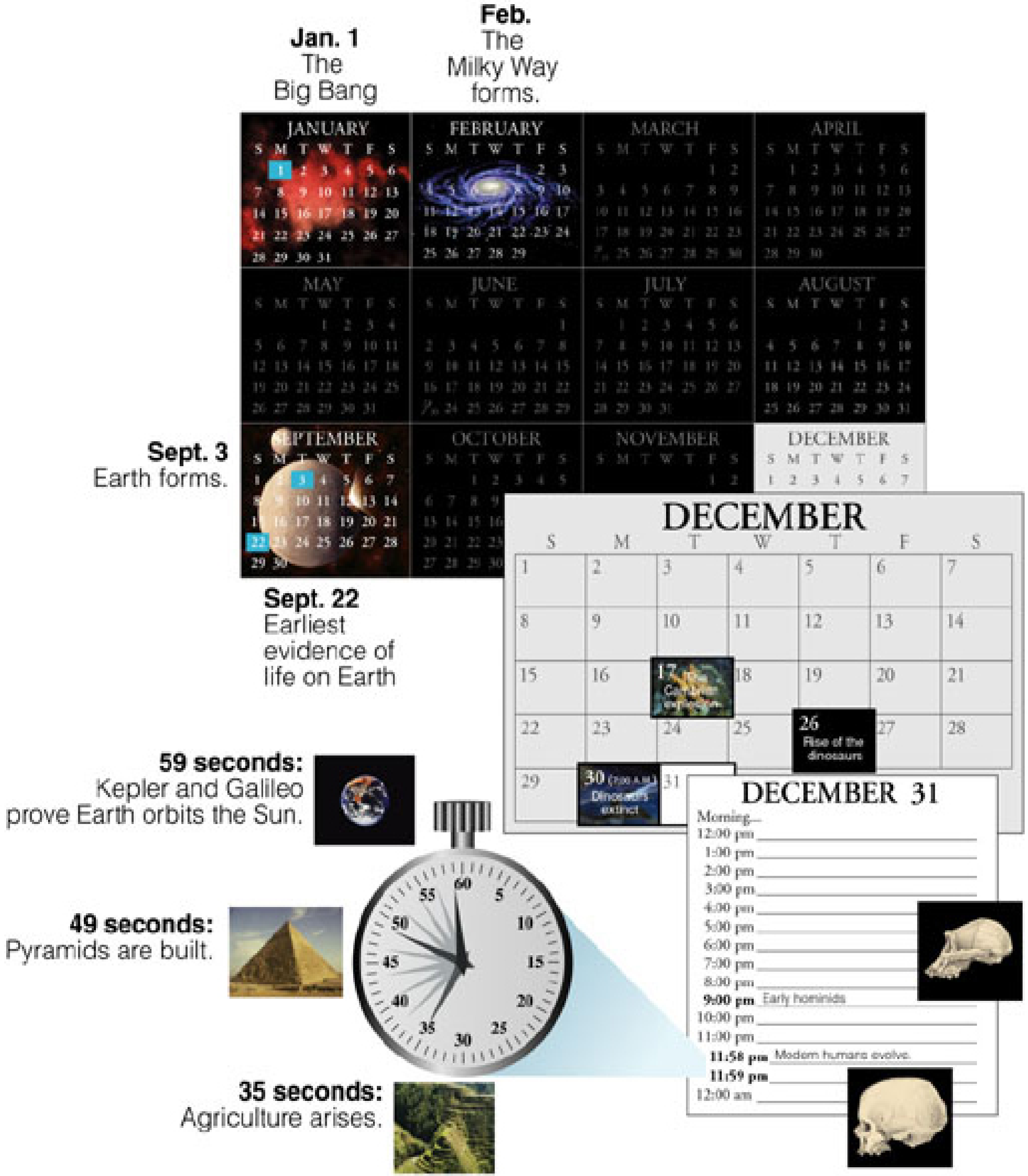
SDSS - Sloan Digital Sky Survey

5% atoms, 25% dark matter and 70% dark energy



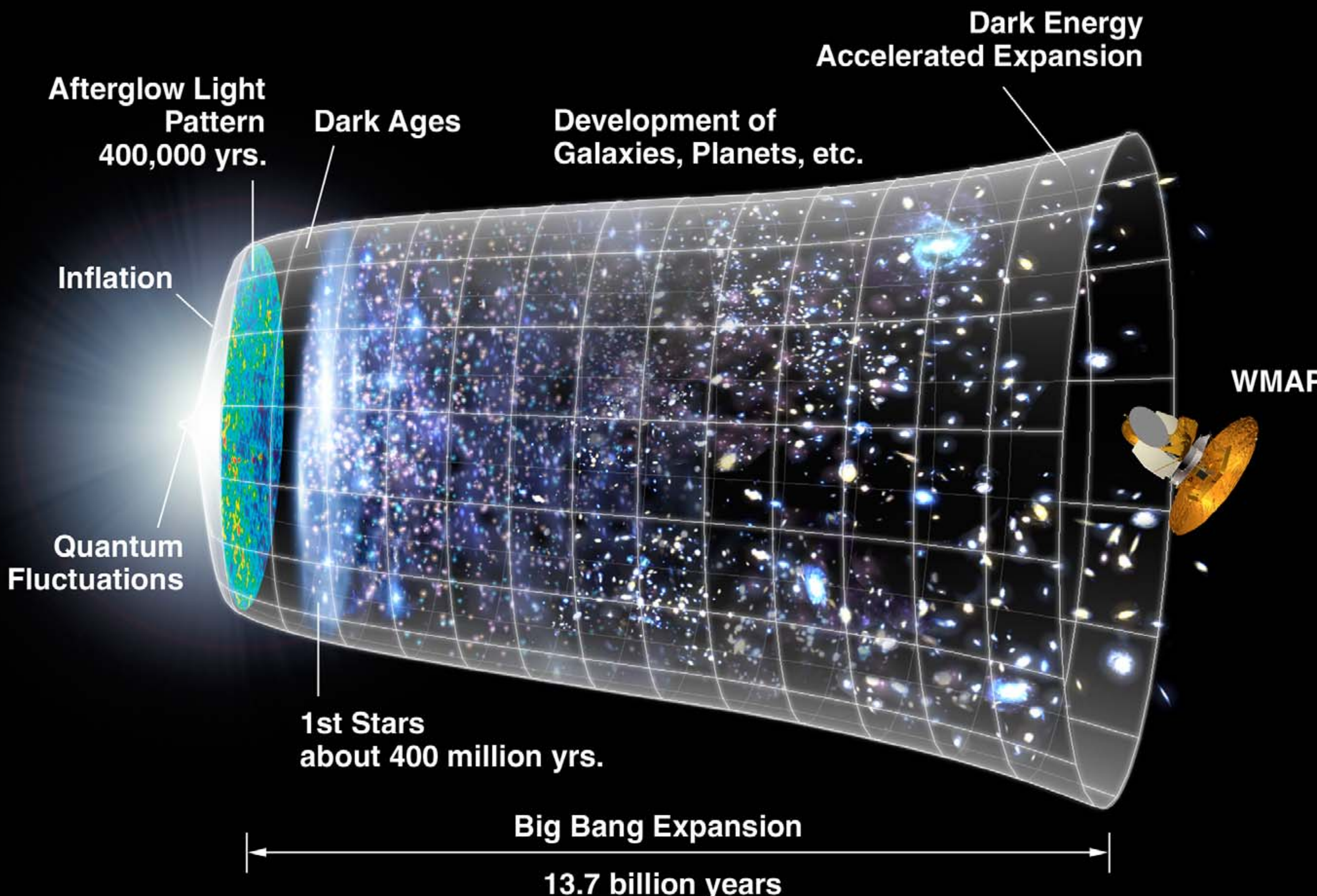
Density Fluctuations of Universe



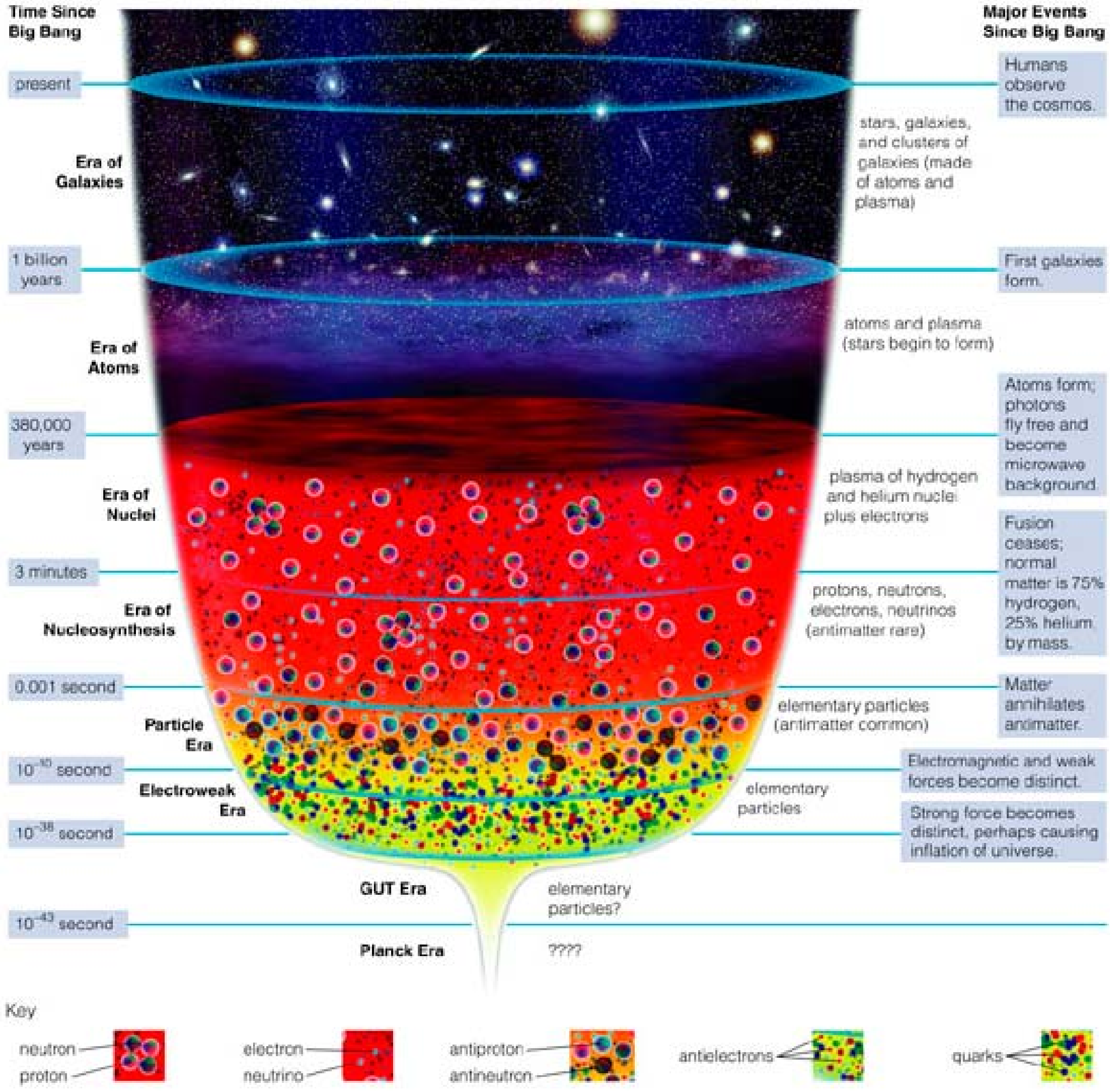


- The Cosmic Calendar

Cosmic Timeline



Cosmic Log Timeline



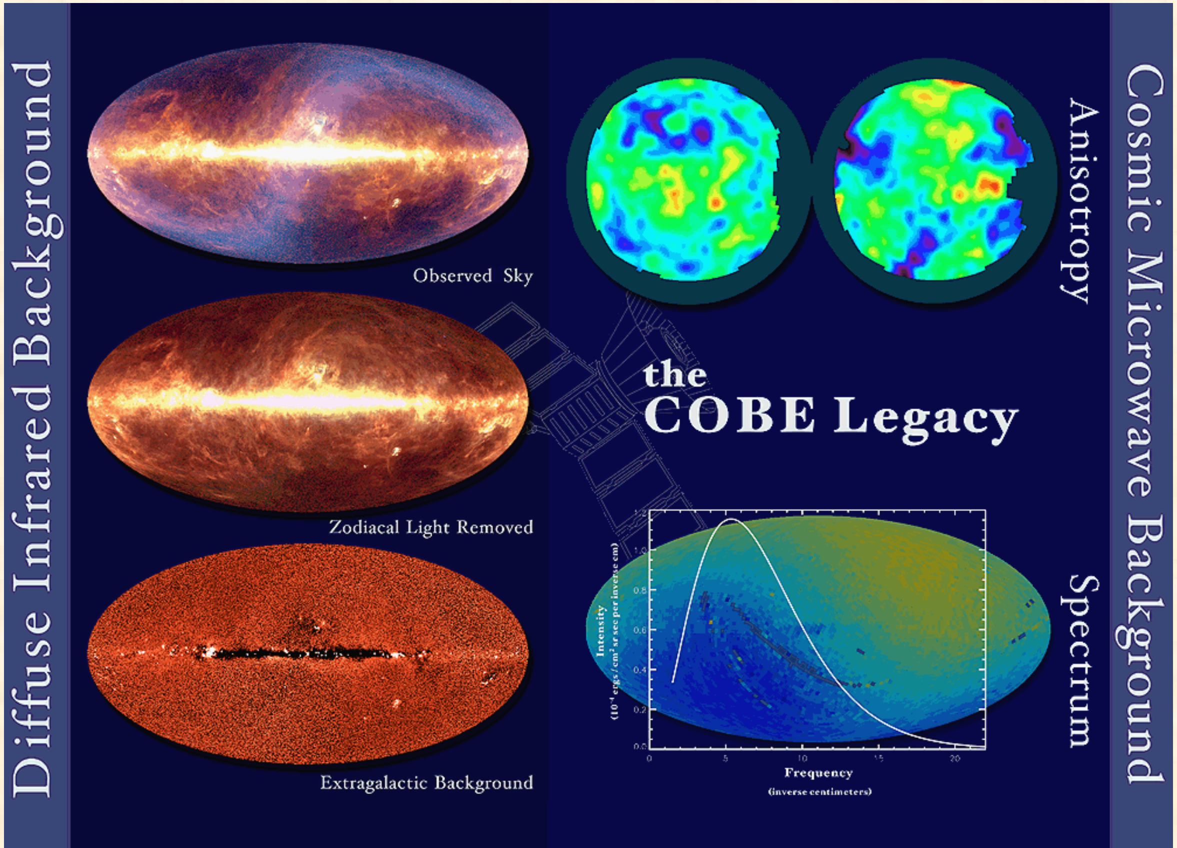
Our Universe

- We live in an…
  - ***Accelerating***
  - ***Cold dark matter-dominated***
  - ***Inflationary***
  - ***Big Bang***

  … Universe
- This model has been conclusively verified in the last few years → the era of **Precision Cosmology**

2006 Physics Nobel Prize to Cosmologists

- George Smoot and John Mather led the development of the COBE satellite: The *COsmic Background Explorer*
- COBE (launched in 1989) detected the "echo of the Big Bang": Background radiation is a perfect blackbody, with the tiniest variations that *precisely* confirmed the Big Bang model



- We live on a hunk of rock and metal that circles a humdrum star that is one of 400 billion other stars that make up the Milky Way Galaxy which is one of billions of other galaxies which make up a universe which may be one of a very large number, perhaps an infinite number, of other universes. That is a perspective on human life and our culture that is well worth pondering. **-- Carl Sagan**

- The important thing is not to stop questioning. Curiosity has its own reason for existing. One cannot help but be in awe when he contemplates the mysteries of eternity, of life, of the marvelous structure of reality. It is enough if one tries merely to comprehend a little of this mystery every day. Never lose a holy curiosity. **-- Albert Einstein**

Steven Hawking, while closing his book “A Brief History of Time”, wrote,

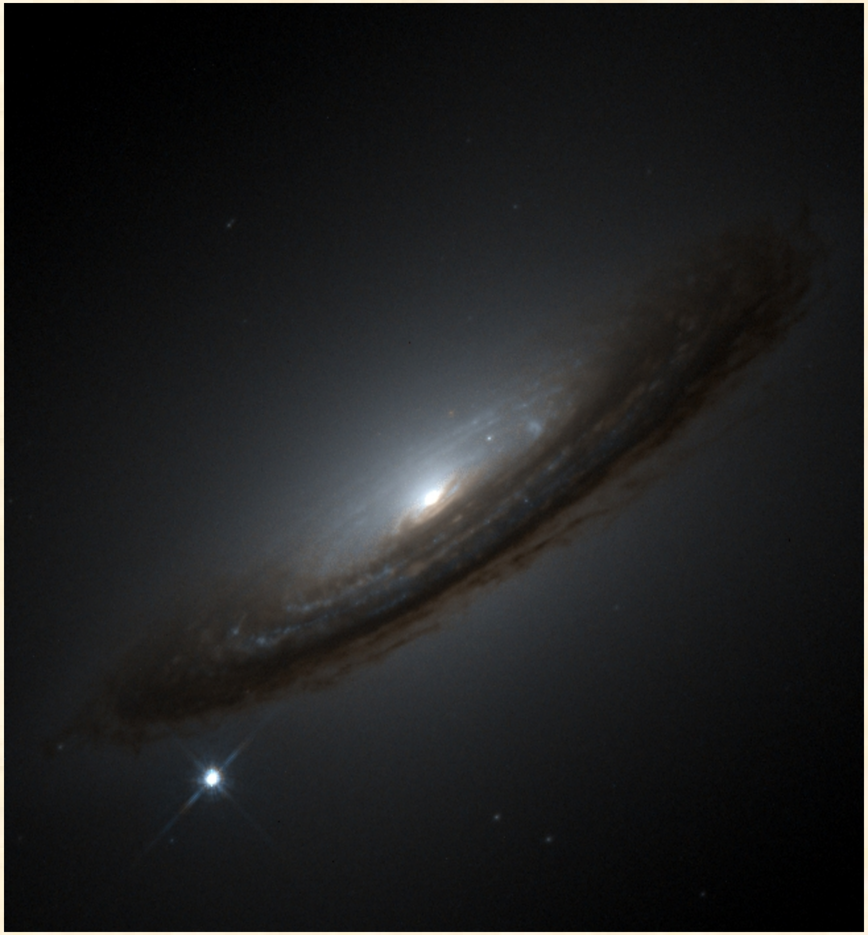
“if we do discover a complete theory, it should in time be understandable in broad principle by everyone, not just a few scientists. Then we shall all, philosophers, scientists, and just ordinary people, be able to take part in the discussion of the question of why it is that we and the universe exist. If we find the answer to that, it would be the ultimate triumph of human reason - for then we would know the mind of God.”

The Observable Universe

- Our universe is 13.7 billion years old.
- This means we cannot see further away than 13.7 billion light-years!
- This is called our "observable universe". There may be (and likely is) a universe far beyond that, but we can never hope to observe it (at least with light).
- When astronomers say "universe" they typically mean "observable universe", since it's a bit pointless to discuss things you can't observe!
- We are at the center of our *observable*

SN Type Ia

- Giant star accreting onto white dwarf
- Standard candles
- Compare observed luminosity with predicted
- Too faint
- From z → expansion rate of distant SN < closer SN



- Describe the basic motions of “spaceship Earth.”
  - ✓ Earth rotates on its axis once each day and orbits around the Sun once each year. Our Solar System orbits the center of the Milky Way Galaxy about every 230 million years. Galaxies in the Local Group move relative to one another, while all other galaxies are moving away from us with expansion of the Universe.
- How do we know that the Universe is expanding?
  - ✓ We observe nearly all other galaxies to be moving away from us, with more distant ones moving faster.