

The CMBR Horizon Problem

- The CMBR has the same properties in all directions.
- Consider two portions of the Universe from opposite ends of the sky.
- These two portions are within our observable Universe (horizon), but they are outside each other's horizons.
- Light has not yet had time to travel from one of these portions to the other.
- If they have never been in communication, how do they know to be at the same temperature?

Inflation

- Very early phase of extremely rapid expansion (Guth, Linde, 1980s).
- During this inflationary phase, the Universe expands by a factor of 10^{50} in the time span $t= 10^{-35}$ sec to $t= 10^{-24}$ sec.
- Inflationary phase is immediately after the epoch at which the strong nuclear force froze out, and before the weak nuclear force and electromagnetic force froze apart from each other.
- All of our observable Universe was an infinitesimally small volume $10^{50} \times 10^{50} \times 10^{50} = 10^{150}$ times smaller than we would have guessed from a simple extrapolation of the expansion we observe today.

Solving the Horizon Problem

- Two parts of the Universe on opposite sides of the sky **now** outside each other's horizons.
- Prior to inflationary epoch, these two patches would have been within each other's horizons and therefore 'known' to acquire the same temperature.
- Inflation caused them to expand out of each other's horizon.
- Inflation requires the universe to expand faster than the speed of light.
- Does not violate relativity — STR only applies in flat spacetime (i.e., in weak gravitational fields)
- Special relativity is a special case of General relativity; inflation does obey the equations of General relativity.

Inflation, continued

- Why is the density of the present Universe so close to critical (or why is the geometry of the observable Universe so close to flat)?
- The scale of the observable Universe is much smaller than its 'radius of curvature'.
- What causes the rapid expansion during the inflationary era?
- Inflation may be thought of as a phase transition in the Universe (as in a transition from a liquid to solid phase).
- The 'latent heat' in this phase transition builds up into an extremely high vacuum energy density, and this drives the expansion (analogous to the repulsive effect of Einstein's cosmological constant Λ).

clicker Quiz #19

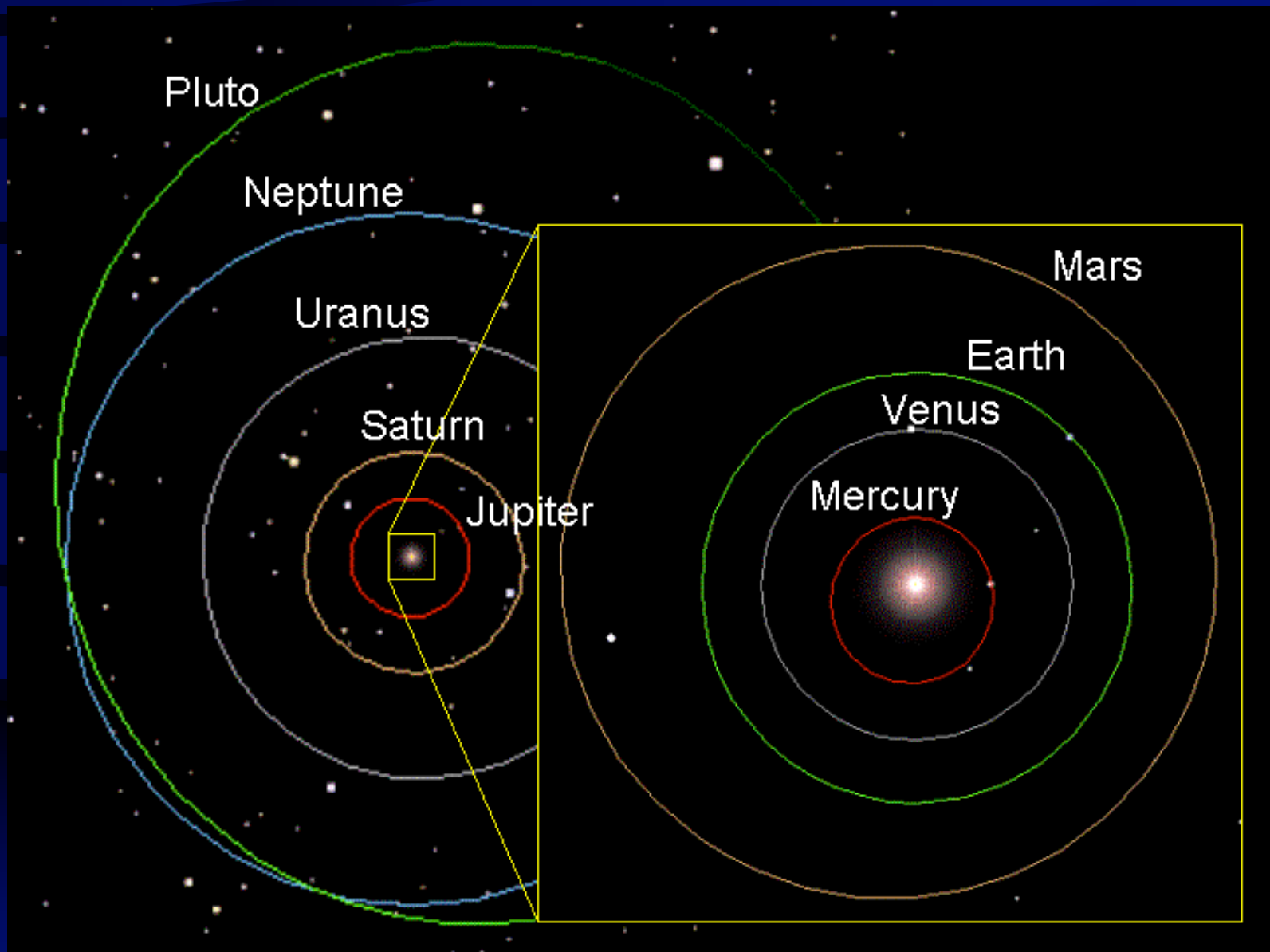
Which of the following statements about the EPOCH OF CONFINEMENT is **TRUE**?

- A. At this instant, quarks became bound in sets of three to produce protons and neutrons, while matter and radiation continued to interact strongly
- B. The Universe was matter dominated at this epoch
- C. Protons and electrons formed stable hydrogen atoms for the first time at this epoch, and the matter in the Universe became mostly transparent to radiation
- D. This epoch was immediately followed by Inflation

i>clicker Quiz #20

Which of the following statements is **TRUE**?

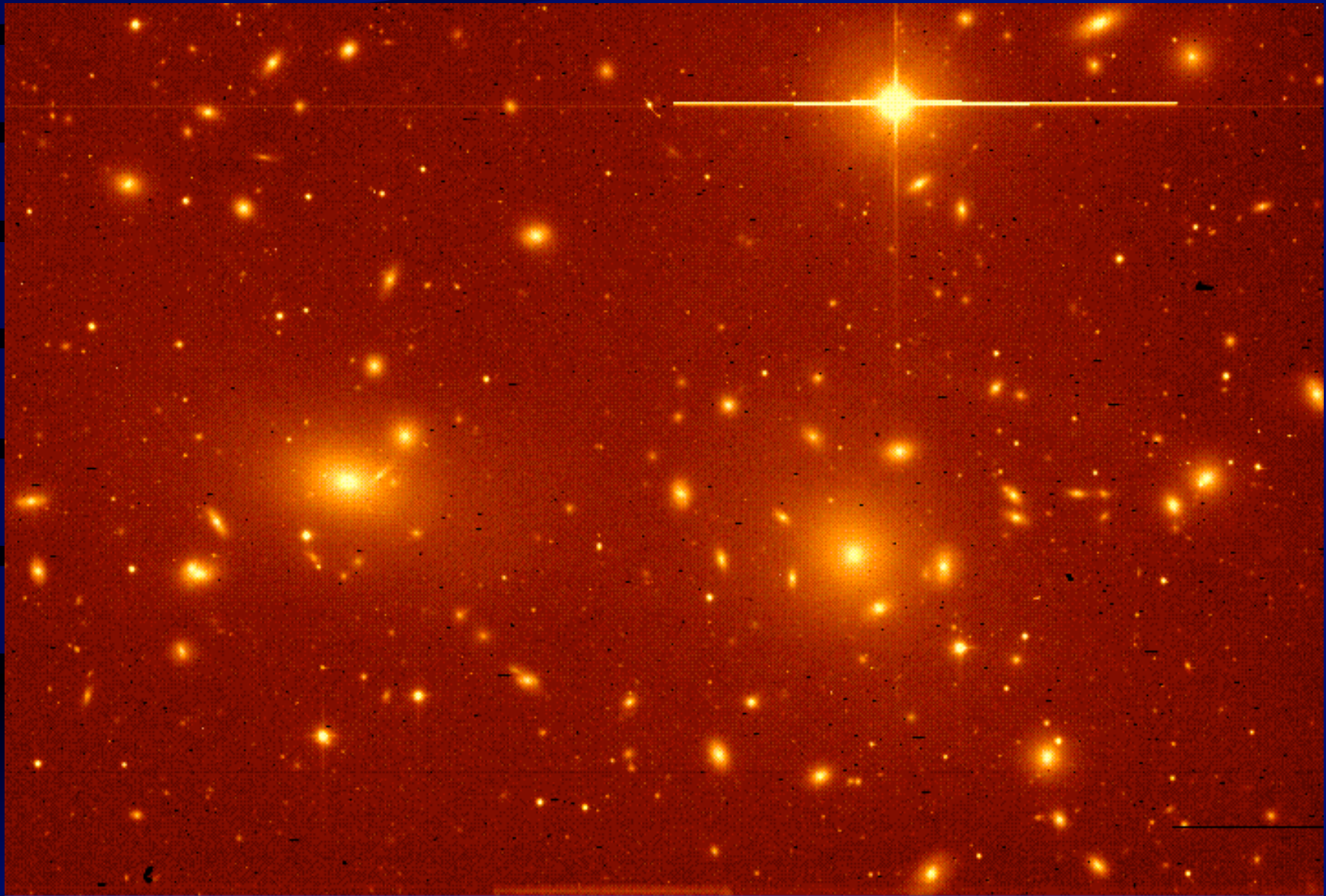
- A. Inflation ended right at Planck time when the Universe was 10^{-50} seconds old
- B. Gravity was the last of the four fundamental forces of Nature to “freeze” out (i.e. develop a unique identity)
- C. Radiation dominated over matter at very early times in the Universe’s history, but matter has dominated over radiation ever since the Universe’s 300,000th birthday
- D. Most of the elements in the periodic table that we learn about in school/college today were synthesized in the early Universe and this is known as Big Bang Nucleosynthesis



Solar system: 9 light hours diameter

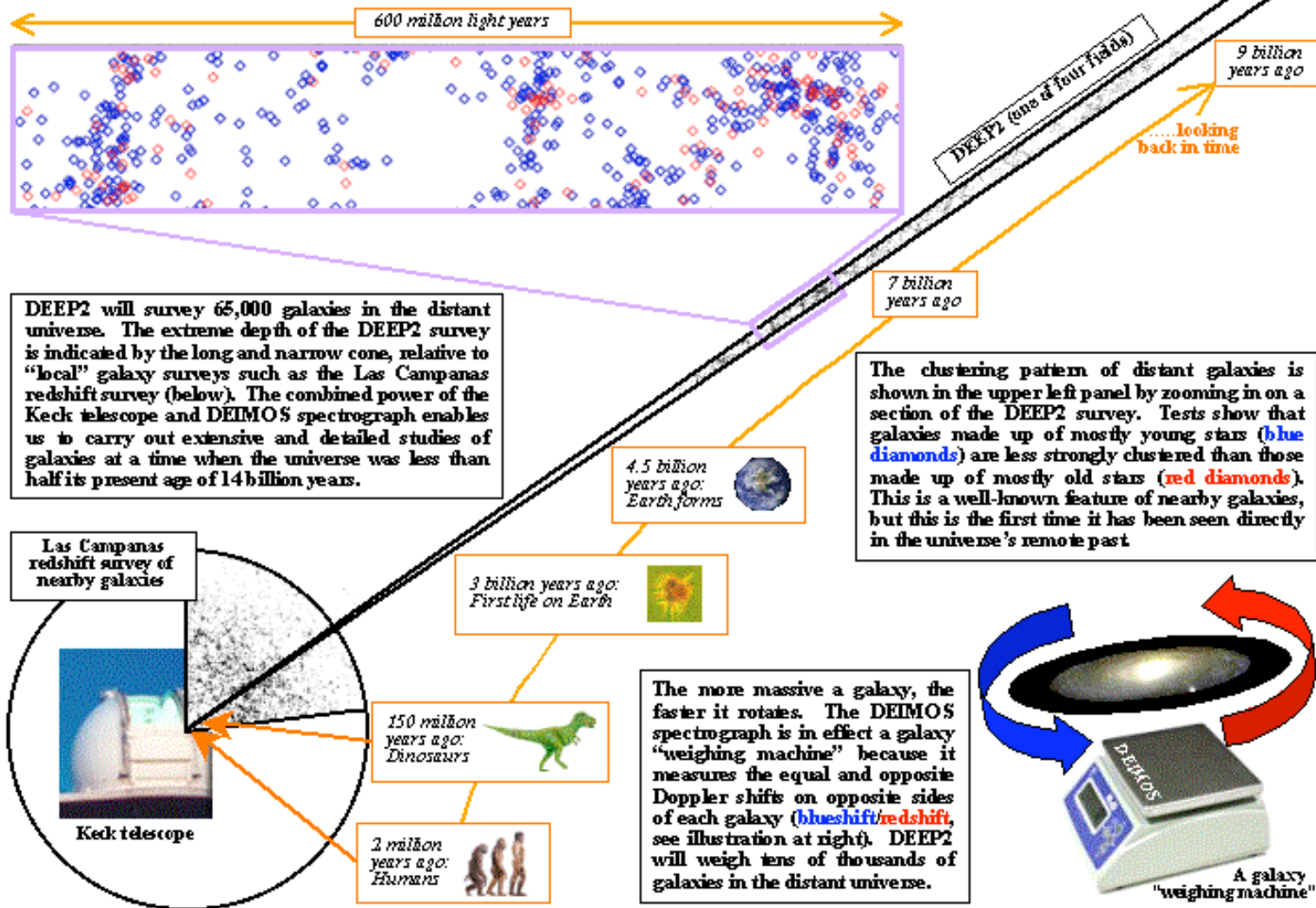


Spiral galaxy: 80,000 light years diameter

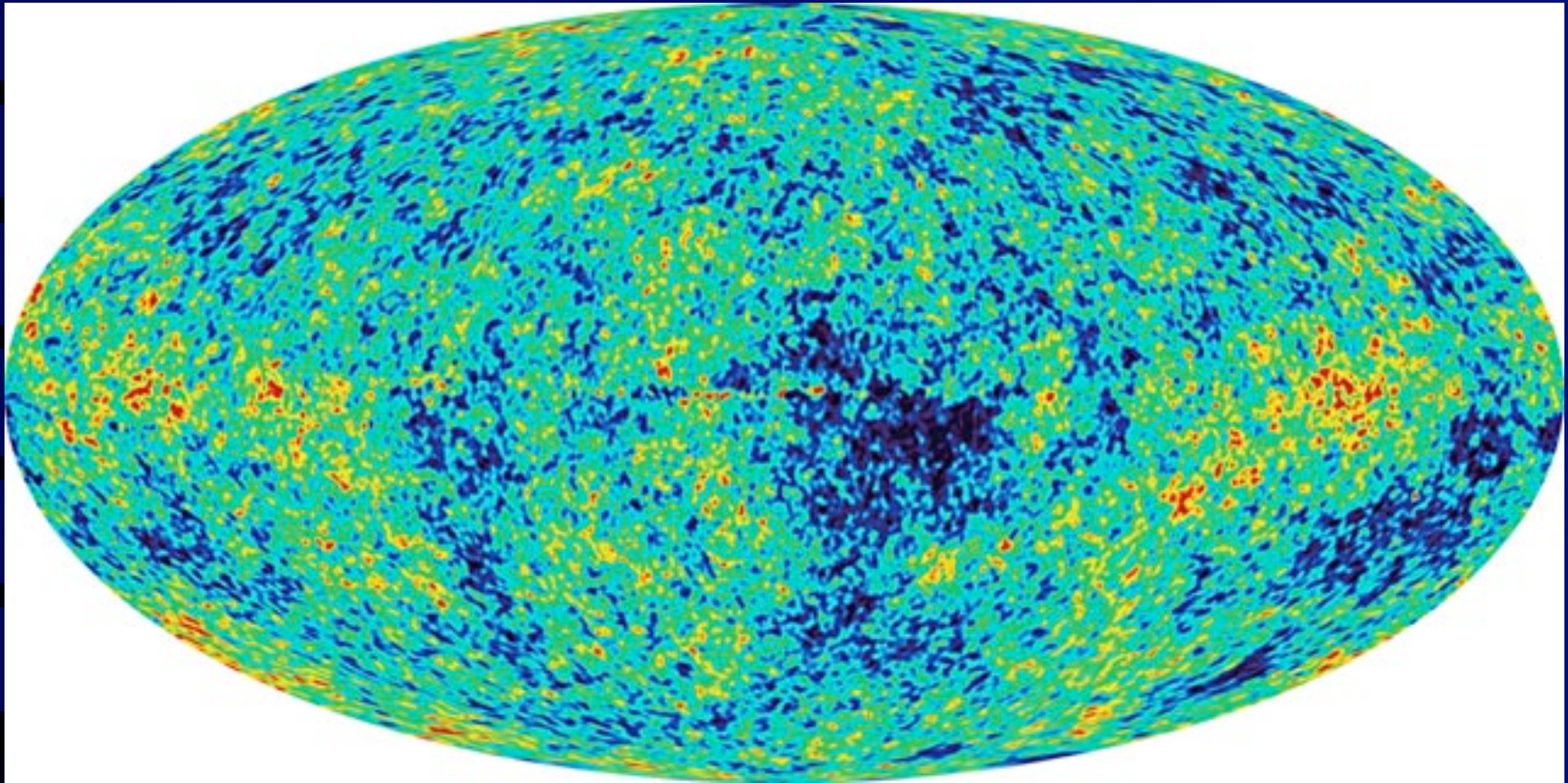


Coma cluster of galaxies: 2.5 million light years across

First Results from the DEEP2 Redshift Survey



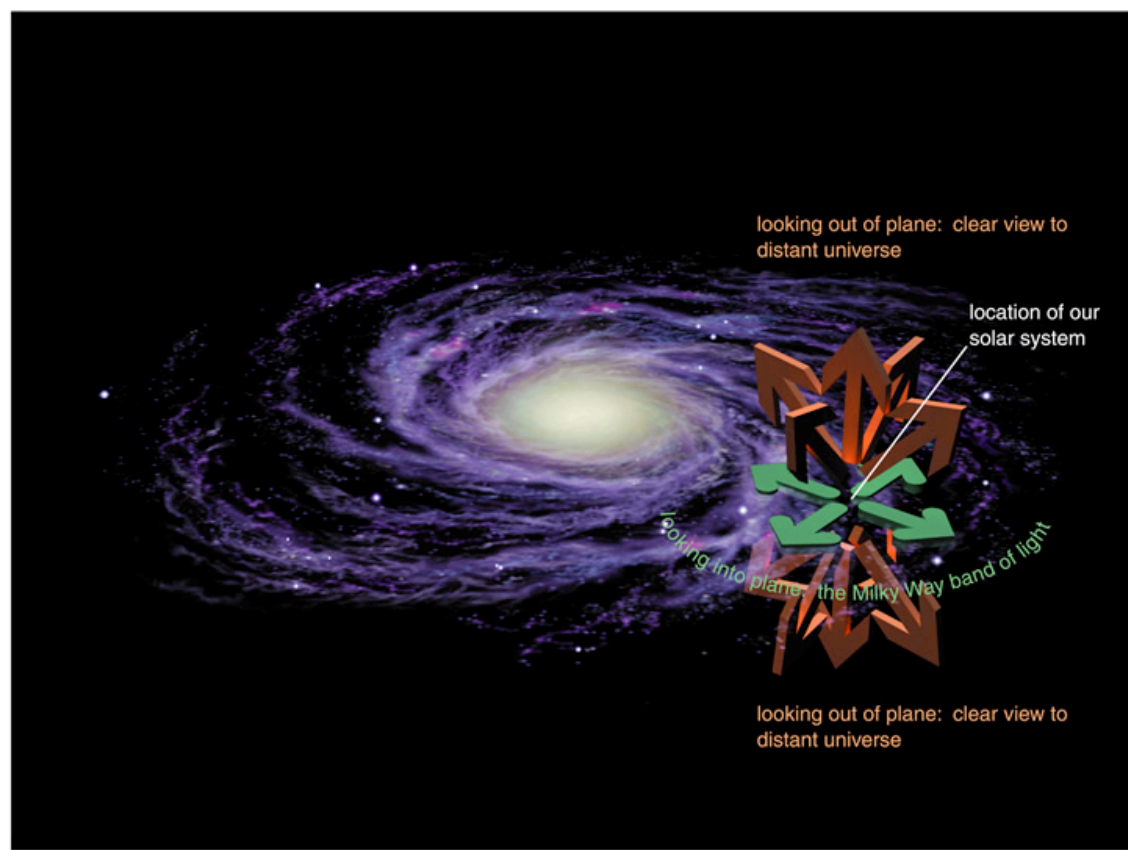
Survey of distant galaxies: 5 to 9 billion light-years away



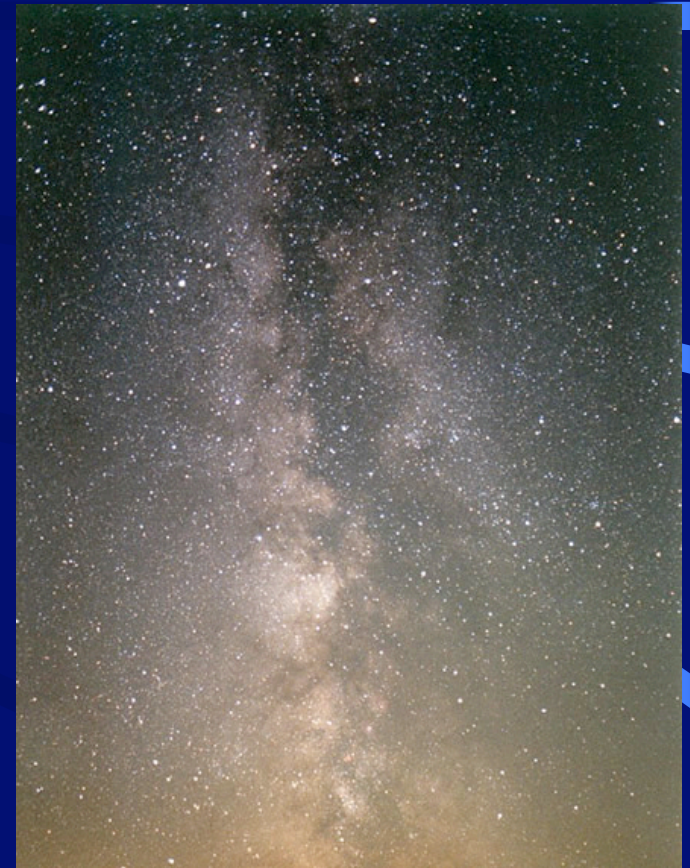
Cosmic Microwave Background Radiation (after-glow from the Big Bang) - edge of the observable Universe:

14 billion light years away

The Detailed Structure of a Spiral Galaxy



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clicker Quiz #21

Which of the following statements about INFLATION is **FALSE**?

- A. The Universe expands faster than the speed of light during Inflation
- B. The rapid expansion during Inflation naturally explains why spacetime appears to be “flat” in terms of its geometric properties
- C. Inflation solves the CMBR horizon problem
- D. Inflation violates the principles of Einstein’s General Theory of Relativity
- E. The theory of Inflation predicted that there should be fluctuations at the level of 1 part in 10^5 in the CMBR

clicker Quiz #22

Which of the following statements is **FALSE**?

- A. The Michelson-Morley experiment established that light is bent in a strong gravitational field
- B. Einstein received the Nobel Prize in Physics for explaining the photo-electric effect and the “particle” (photon) nature of light given by the law: $E = h\nu$
- C. Kepler’s laws can be used to describe the motion of planets around the Sun
- D. Hubble is credited with the discovery of the expansion of the Universe
- E. Guth and Linde formulated the theory of Inflation

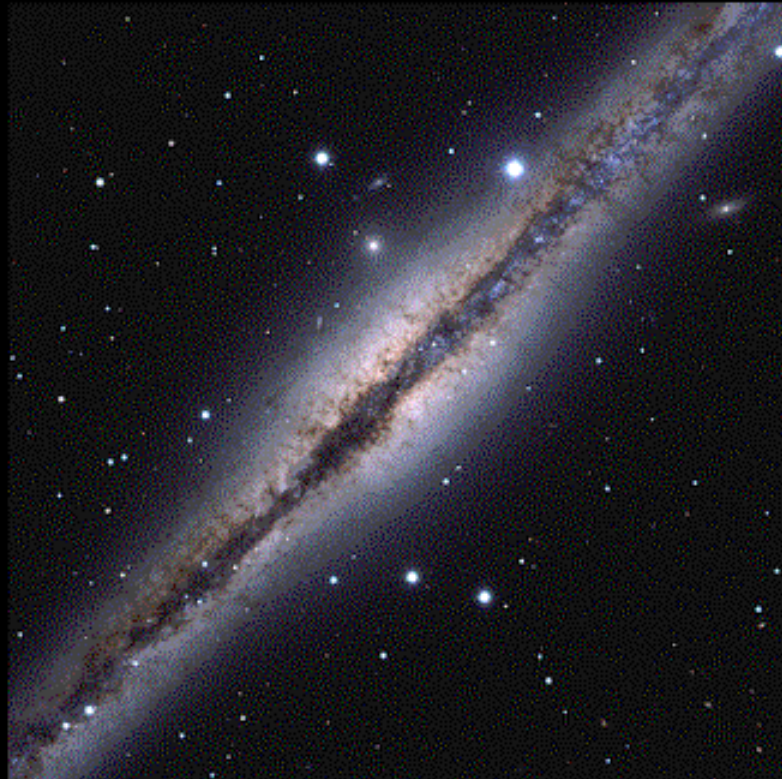
Introduction to Galaxies

Basic Structure

- How densely packed are stars in a galaxy?
 - Size (diameter) of a typical star: 10^6 km
 - Distance between stars: $1 \text{ pc} = 3 \times 10^{13}$ km
 - Analogy: 1 cm sized marbles separated by 300 km !
- What fills in the space between stars?
 - Interstellar medium: gas, dust

Disk Galaxies: Structural Components

- Flattened **differentially-rotating disk**
- Dense centrally-concentrated **bulge** with mostly **disordered** orbits
- Extended, not centrally concentrated, mostly **dark halo**
- Bulge + Halo = “**Spheroid**”



NGC 891
Edge-On Sb



NGC 628
Face-On Sc

Spiral Galaxy Properties

- Bulge stars are **older** on average than disk stars
- **Youngest** disk stars lie in very **thin plane**
- **Older** disk stars lie in a **thicker disk**
- Disk stars, particularly young ones, are organized into **spiral arms**
- **Spiral density waves** in the disk: the most successful explanation of spiral structure

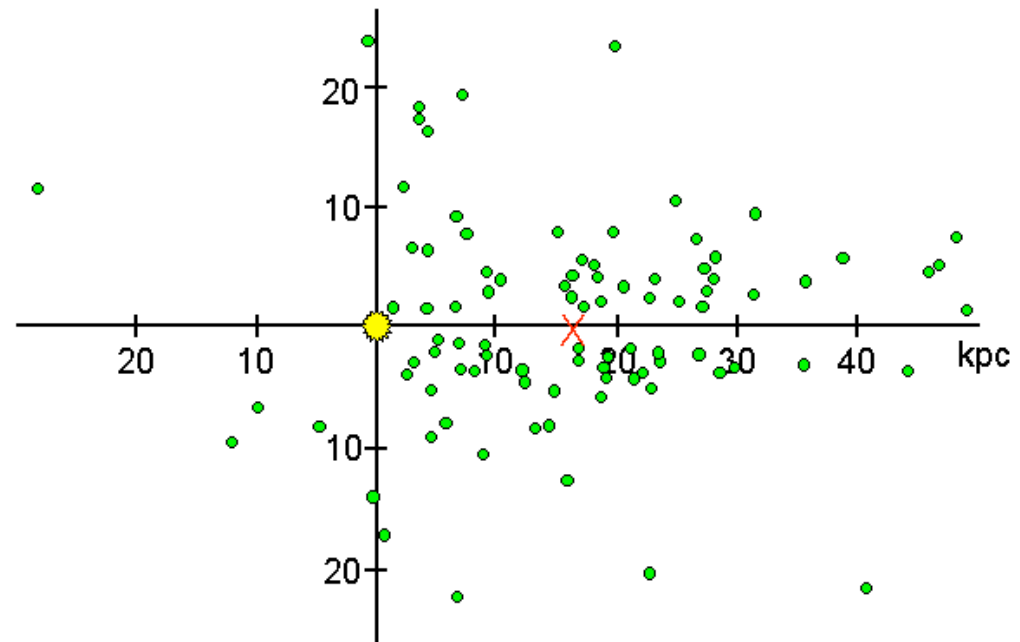
Globular Clusters



Globular Clusters

- Most galaxies, including our own, contain dense clusters of $10^3 - 10^6$ stars known as **globular clusters**
- The observed distribution of globular clusters tells us that the Sun is **NOT** at the center of the Milky Way galaxy

Shapley's Globular Cluster Distribution



Galaxy Types

- Spirals & irregulars (disk galaxies); ellipticals

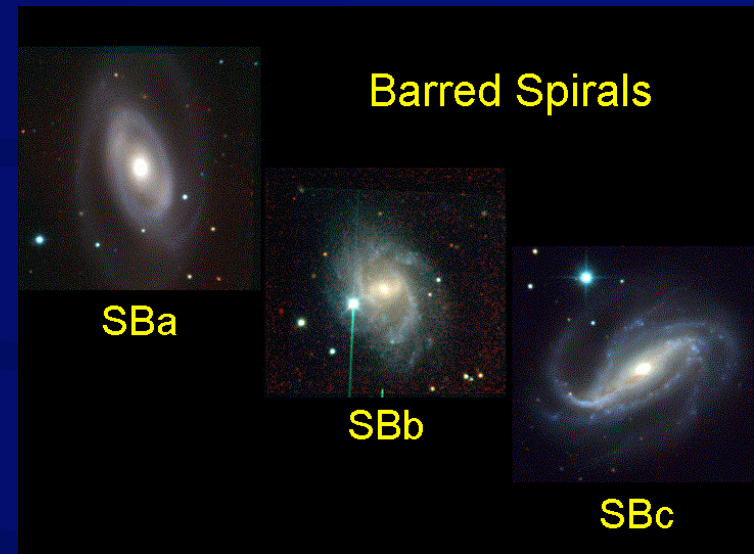
- Morphological (structural) features:

Disk, bulge, bulge+disk, presence/absence of **central bar**

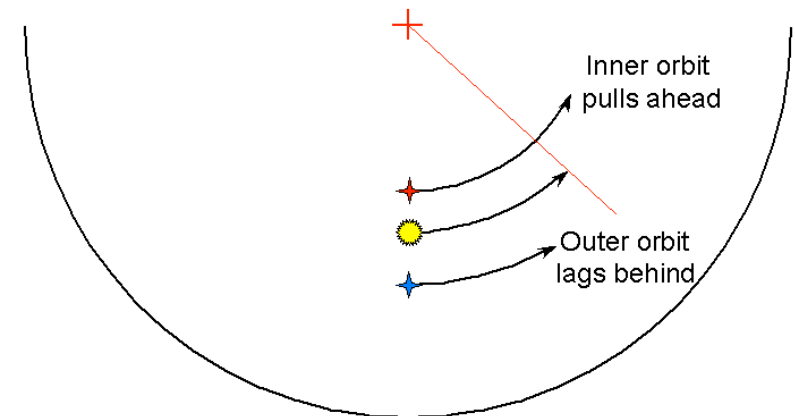
- Nature of kinematics (internal motion of stars and gas):

Coherent rotation of stars and gas in a disk; **differential rotation**

Random motion of stars in the bulge of a spiral galaxy or elliptical



Differential Rotation





Irregular Galaxies



UKS 14

Large Magellanic Cloud



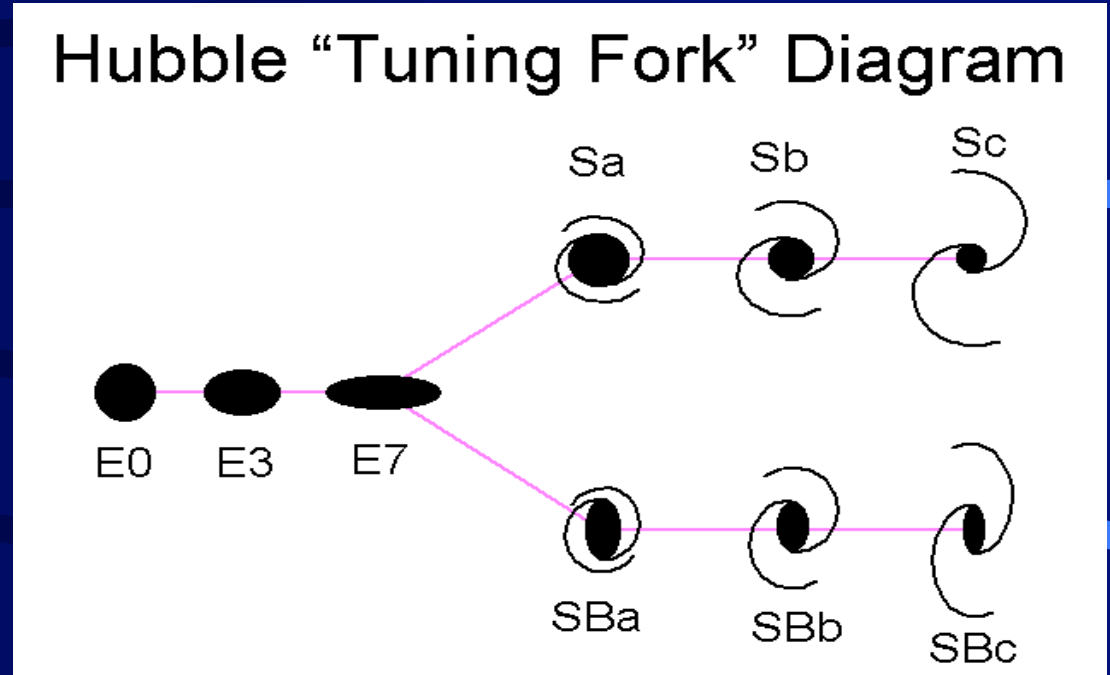
UKS 17

Small Magellanic Cloud

Hubble Sequence of Galaxies

- Tuning fork diagram:
E0-E7, S0
Sa-Sd / SBa-SBd, Irr

- Morphological trends along the sequence:
Shape (flattening)
Bulge-to-disk ratio
Spiral arms



- Kinematical trends along the sequence:
Ellipticals: mostly **random motion**, hardly any rotation
Spirals: mostly **rotation**, hardly any random motion
- Trends in the stellar mix:
Ellipticals: mostly **cool (old)** stars
Spirals: dominated by **hot (young)** stars