Physics 133 -- Extragalactic Astronomy and **Cosmology**

- Instructor: Prof. Crystal Martin
  - Lectures: M W 2:00-3:15
  - Office hours: TBD (via Zoom)
  - TA: John McCann(via Zoom)
- Textbook:
  - **Introduction to Cosmology**, Barbara S. Ryden, 2nd Edition (required)
- Course covers first 11 chapters in 10 weeks.
- Read Ryden chapters 1-2 (& start 3) this week.

Physics 133

- Prerequisite: Physics 5.
  - *The questions about blackbody radiation on HW1 should all be review.*
- Website: web.physics.ucsb.edu/~phys133/s2021/
  - Course syllabus explains policies (conduct, homework, exams)
  - Lecture Schedule assigns reading that you should do before class.
  - Homework page provides the exercises that will be graded.
  - Supplementary material is also posted for fun. For example, see link to info an ancient cosmology.
- *Hope you enjoy this class. Let me know if I can do anything to make the experience better. You'll find the material challenging.*

Cosmology is the study of the universe as a whole

Cosmology Addresses Questions Fundamental to the Human Condition

- What is the universe made of?
- How big is the universe?
- Is the universe evolving?
- Did it have a beginning?
- If so, how old is the universe?
- Where will it end up?
- Is there an end to the universe?

Cosmology is Based on Observations

An Earth-Centered Cosmos

A reconstruction of the Greek worldview, with Earth circled by the Moon, Sun, planets, and starry zodiac.

Copernicus's *On the Revolutions*

NICOLAI COPERNICI

net, in quo terram cum orbe lunari tanquam epicyclo contineri diximus. Quinto loco Venus nono mense reducitur. Sextum denique locum Mercurius tenet, octuaginta dierum spacio circũ currens. In medio uero omnium residet Sol. Quis enim in hoc

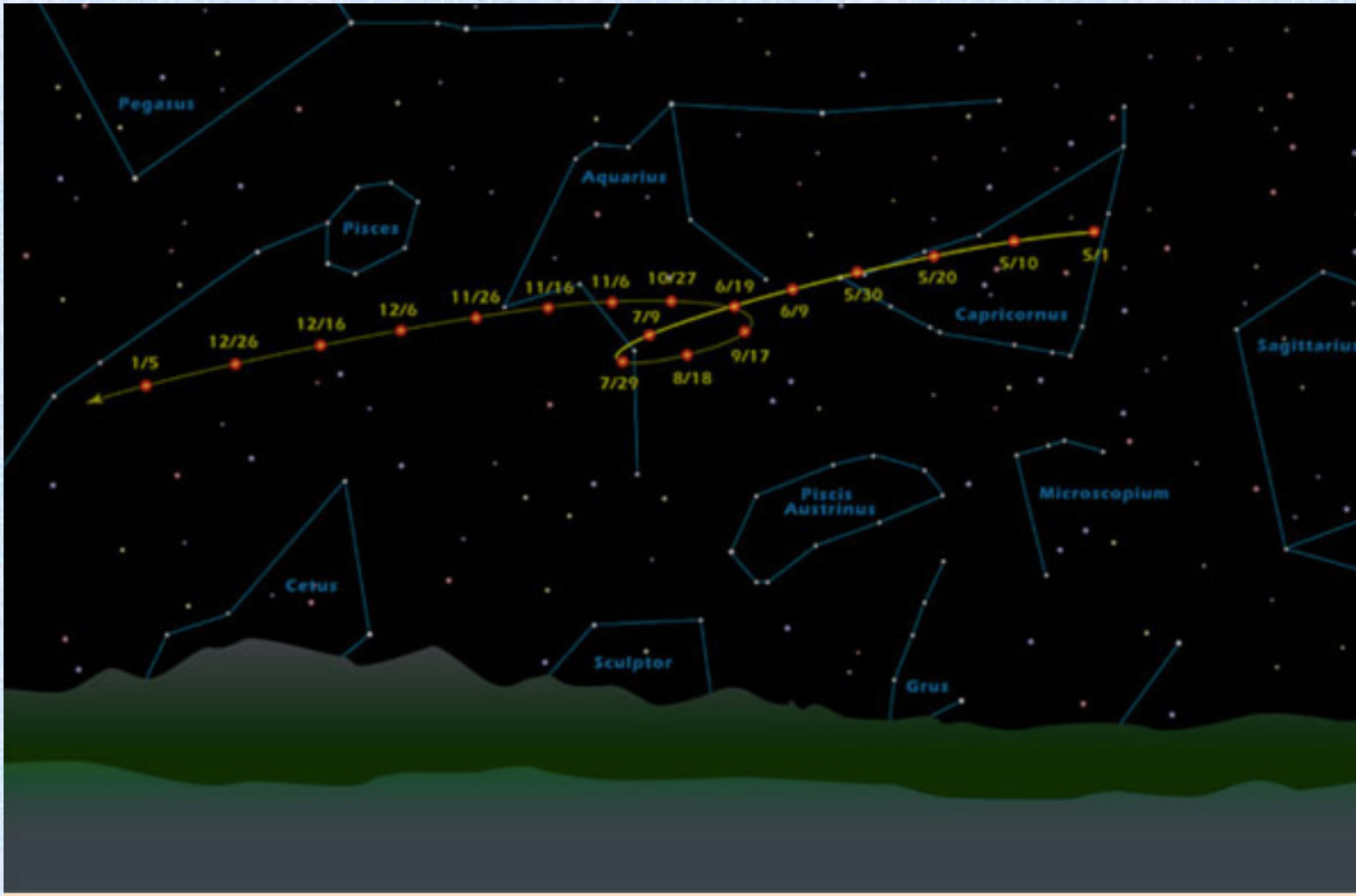
pulcherrimo templo lampadem hanc in alio uel meliori loco poneret, quàm unde totum simul possit illuminare? Siquidem non inepte quidam lucernam mundi, alij mentem, alij rectorem uocant. Trimegistus uisibilem Deum, Sophoclis Electra intuentẽ omnia. Ita profecto tanquam in solio regali Sol residens circum agentem gubernat Astrorum familiam. Tellus quoque minime fraudatur lunari ministerio, sed ut Aristoteles de animalibus ait, maximã Luna cũ terra cognationẽ habet. Concipit interea à Sole terra, & impregnatur annuo partu. Inuenimus igitur sub hac

Page from Copernicus's *On the Revolutions* *(De revolutionibus orbium coelestium)*. Copernicus dedicated his 1543 book to Pope Paul III.

- When data are lacking, we may use aesthetic or philosophical reasons to motivate a model.
- Copernicus explained retrograde motion with a new model that was simpler than the epicycles used by the Greeks.

Observation: Retrograde Motion

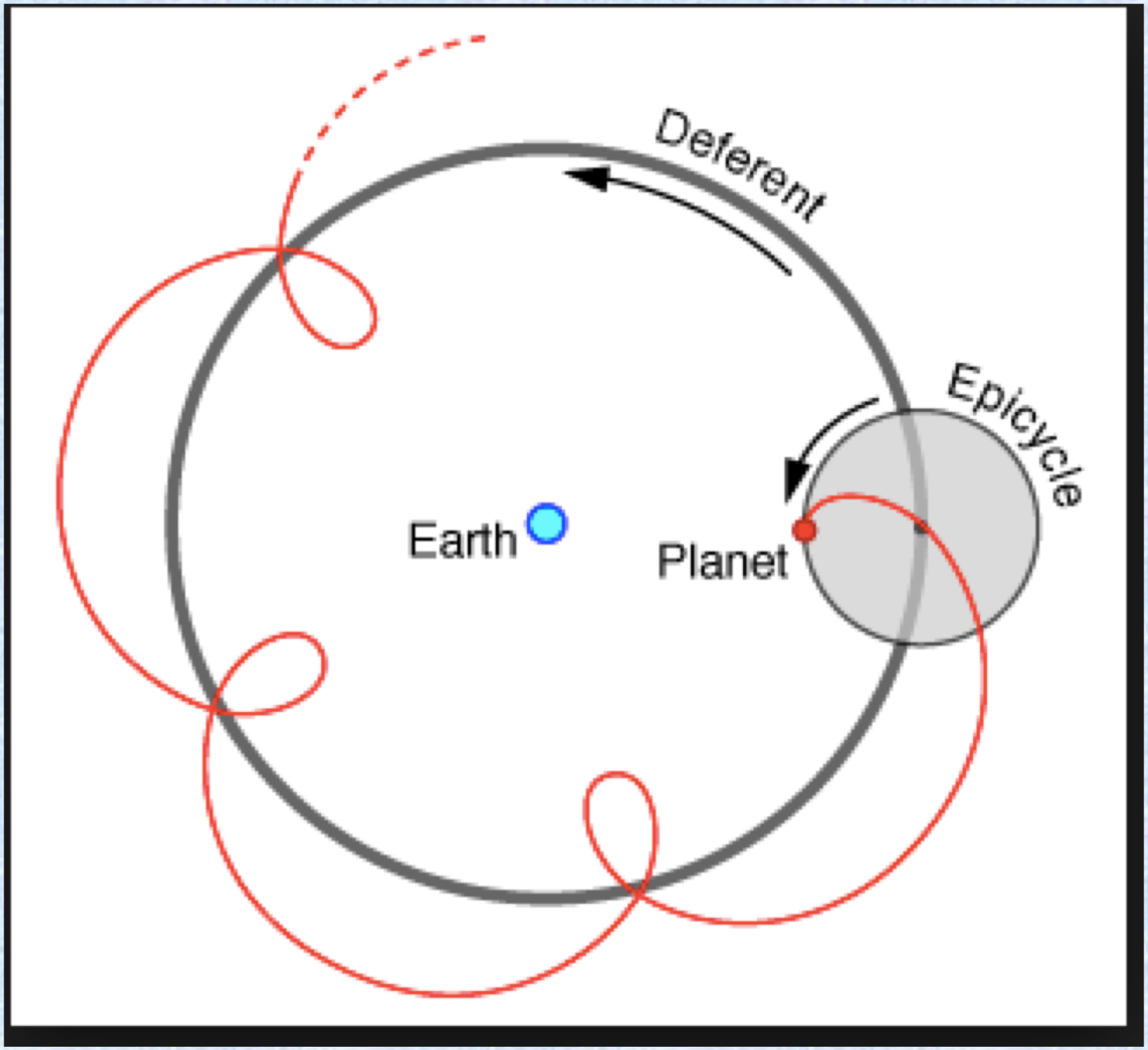
EAST



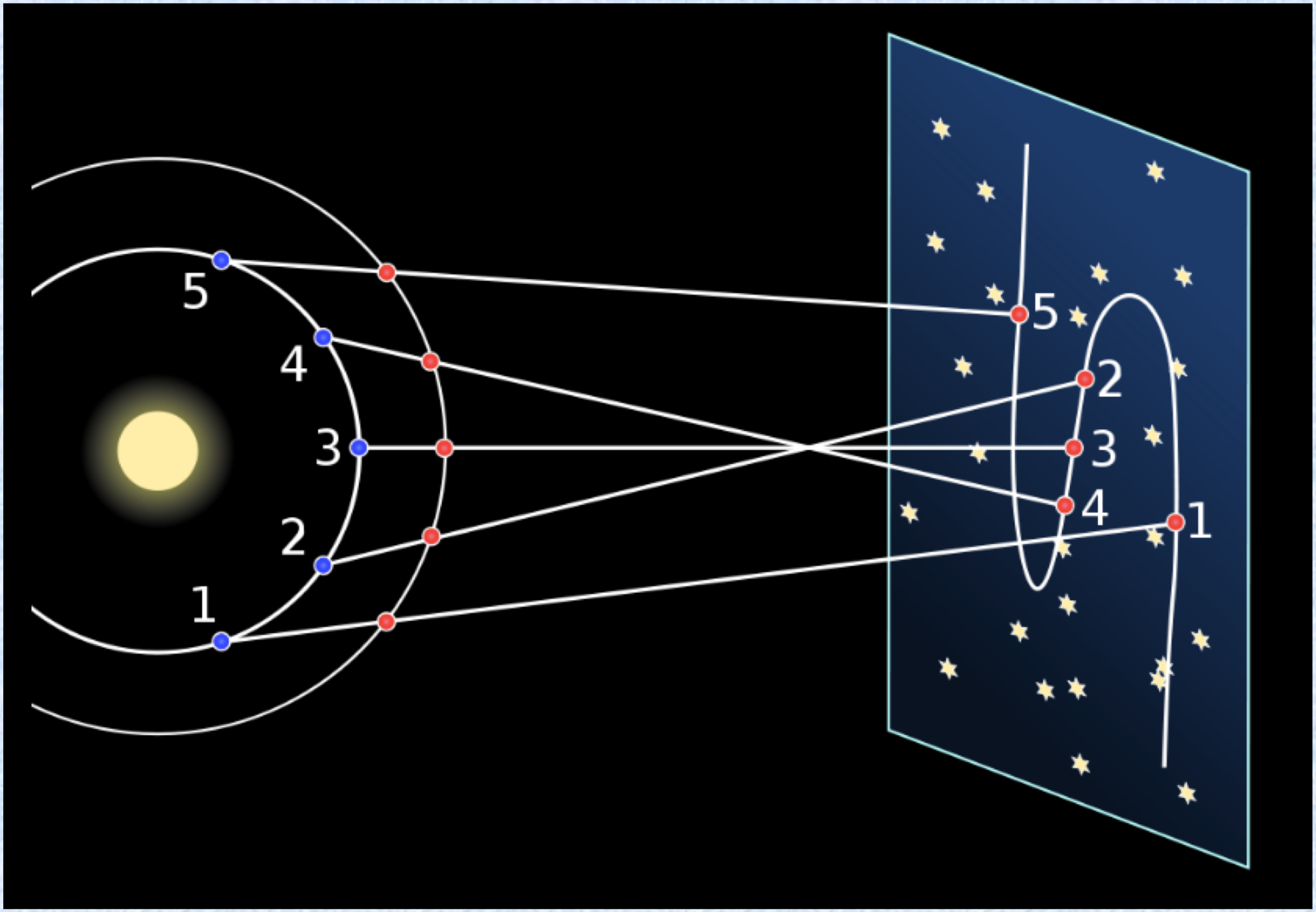
WEST

SOUTH

Geocentric Explanation: Epicycles



Copernican View



The role of observations

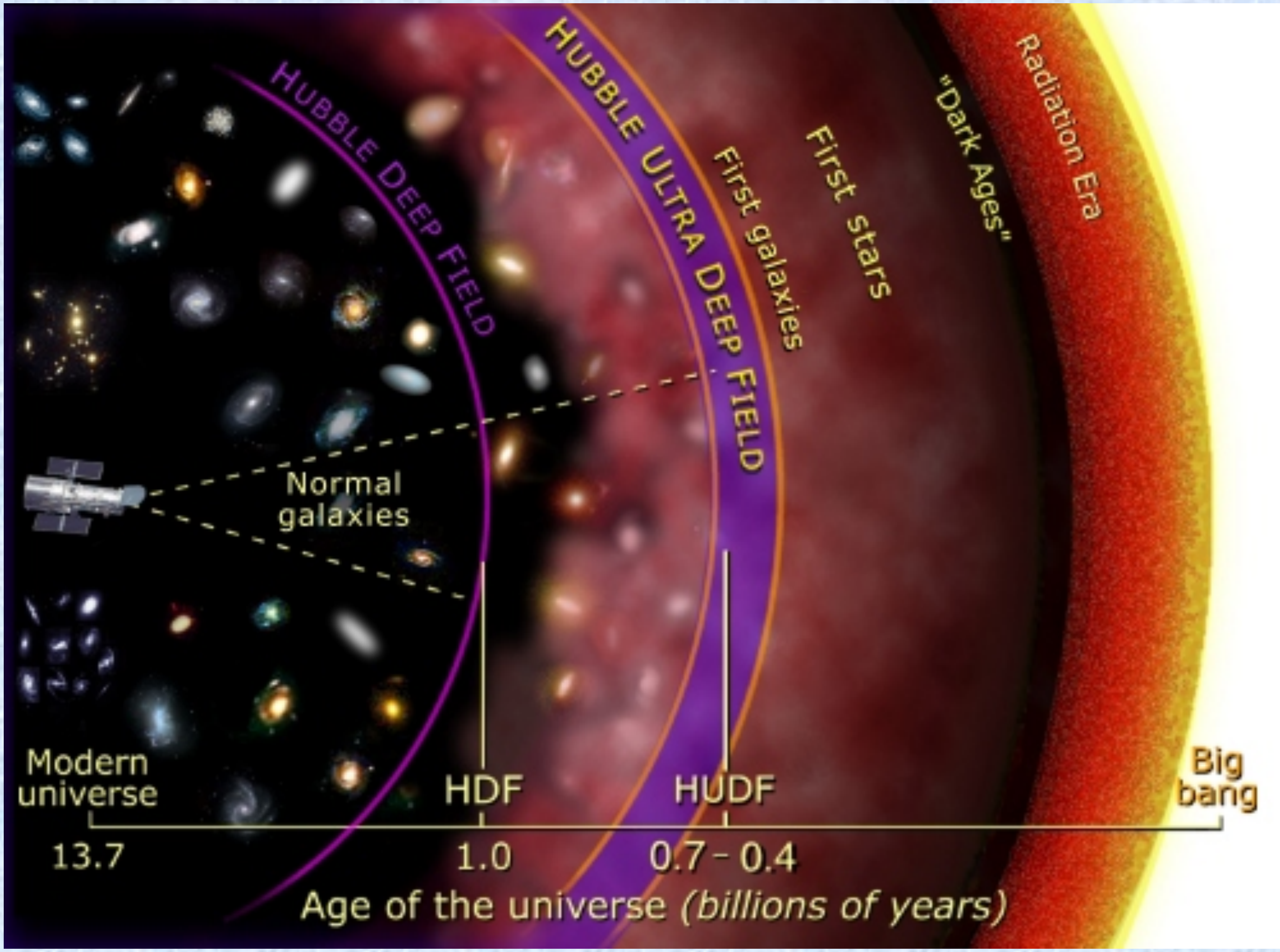
- **Experiments and Observations force us to modify/change our view of the Universe. Examples:**
  - Galileo's observations of sun spots proved that the heavens are not time-invariant
  - Galieo's observations of the phases of Venus proved the earth and venus orbit the sun.
  - Hubble's measurement of galaxy redshifts showed that the Universe is not static
  - High speed motions of stars in galaxies show that either we do not understand gravity or that there is a large amount of "dark matter", i.e. different stuff that the ones that makes you and me (and Earth)

Phases of Venus and evolution of its apparent diameter.

Interplay of Cosmology and Physics

- Cosmology uses all the knowledge of physics that we learn from laboratory experiments
- Some of the most extraordinary discoveries in physics come from cosmology: dark matter and dark energy, just to name two

Tools of the trade – Telescopes as time machines



Your lifetime could be a golden era for cosmology.

Cosmological Models

- The model must reproduce observations and make falsifiable predictions.
- Can we put together a physical model of the universe and its contents?
- The best we could come up so far is the so-called Standard Cosmological Model (by analogy with particle physics' Standard Model), the Benchmark Model, or the Concordance Model

A fundamental dilemma…

- We only have one Universe! We cannot replicate/alter/reproduce our sample.
- Experiments and Observations can only be made from one specific point in space and time -- Earth now.
- Yet we would like to construct a scientific theory that describes the universe everywhere and at all times.

The solution is called the cosmological principle

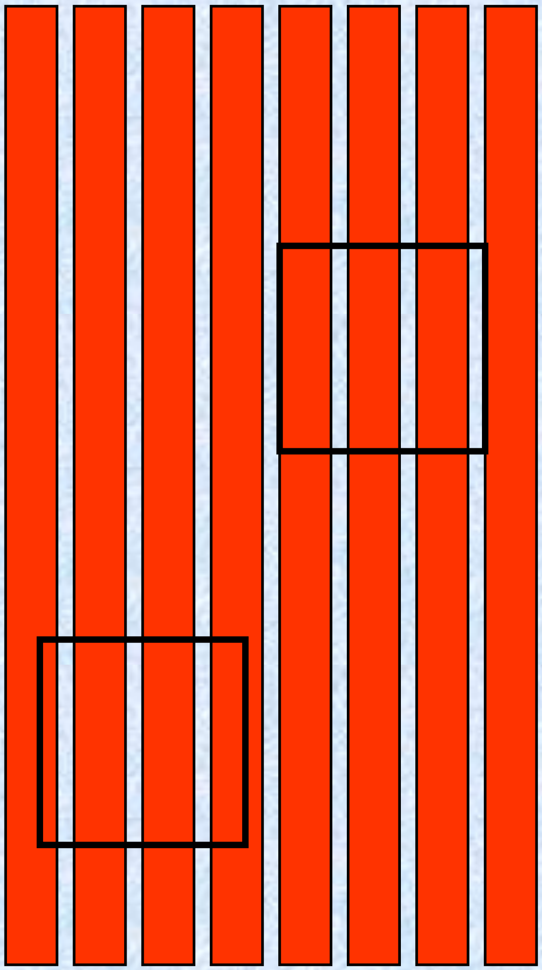
- Physicists postulate a universal principle: our location in the universe is not special.
- This postulate is deeply rooted in two fundamental principles of physics:
  - The laws of physics (whatever they are!) do not depend on space and time
  - Physical explanations of natural phenomena should be as simple as possible (Ockham's razor)

Physics 133: cosmological principle

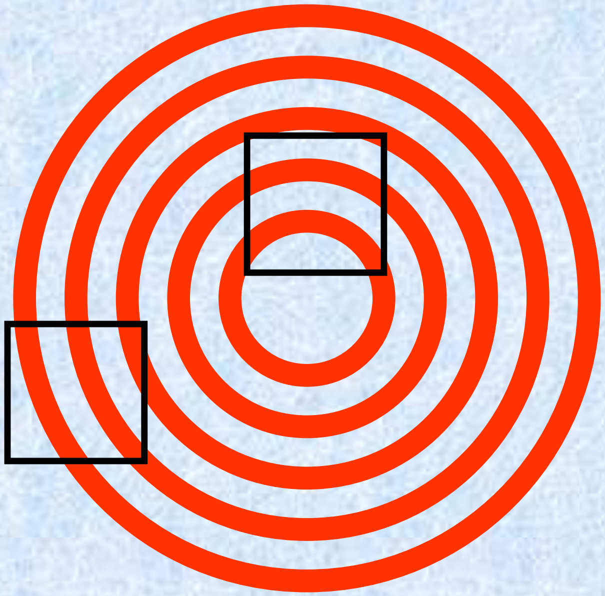
Cosmological Principle:

- **The universe is homogeneous and isotropic.**
  - **Similar to the Copernican Principle: there's no special place in the universe**
- Applies on scales > 100 Mpc
- Does homogeneity imply isotropy?
- Does isotropy imply homogeneity?

Homogeneous but not Isotropic



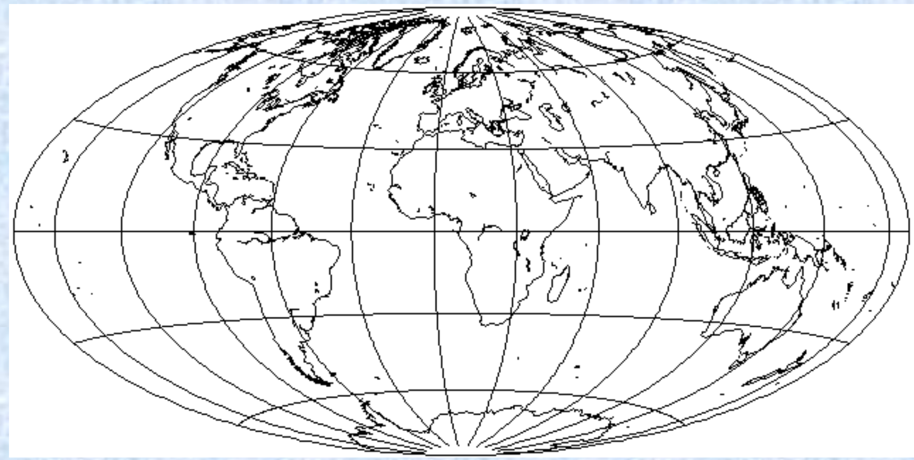
Isotropic (about a point) but not Homogeneous

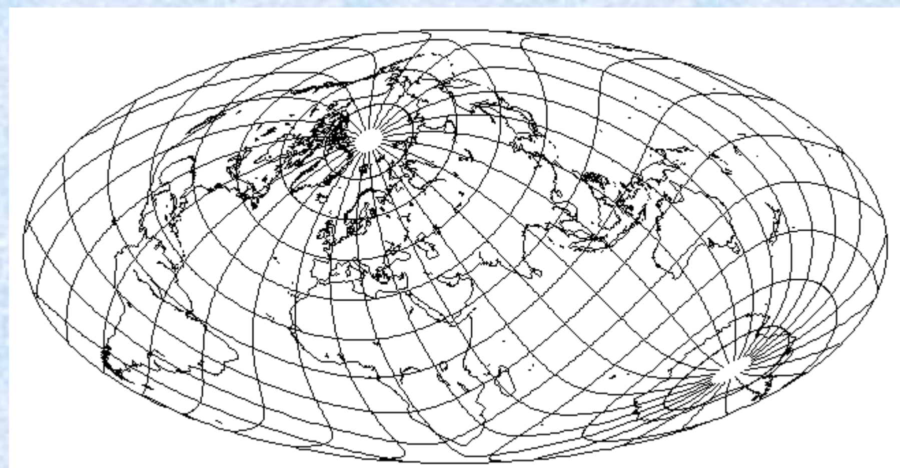


Isotropy at all points in space implies homogeneity

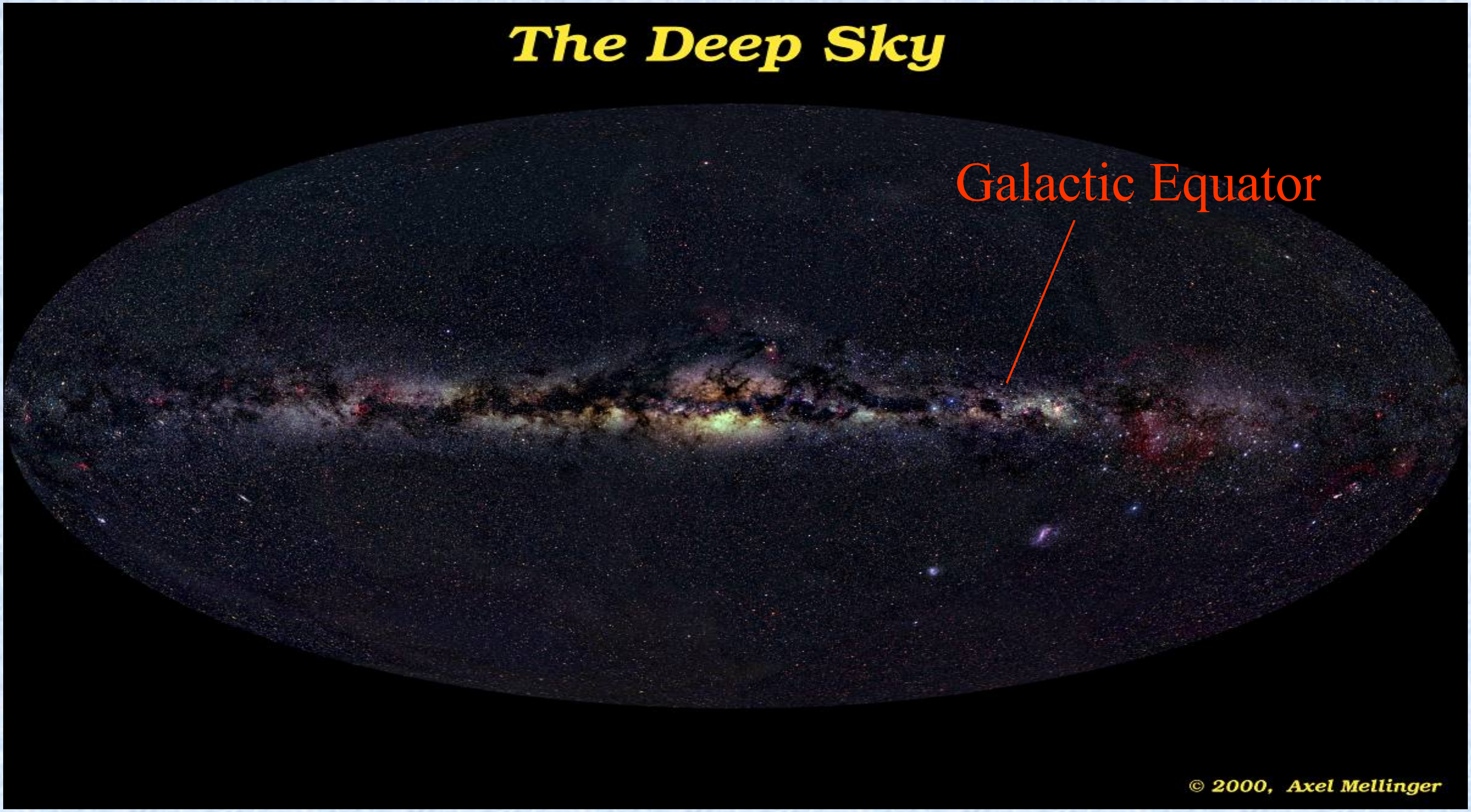
Isotropy and Homogeneity of the Universe: Map Making

- Mapping a sphere onto a plane -- Hammer-Aitoff projection preserves area

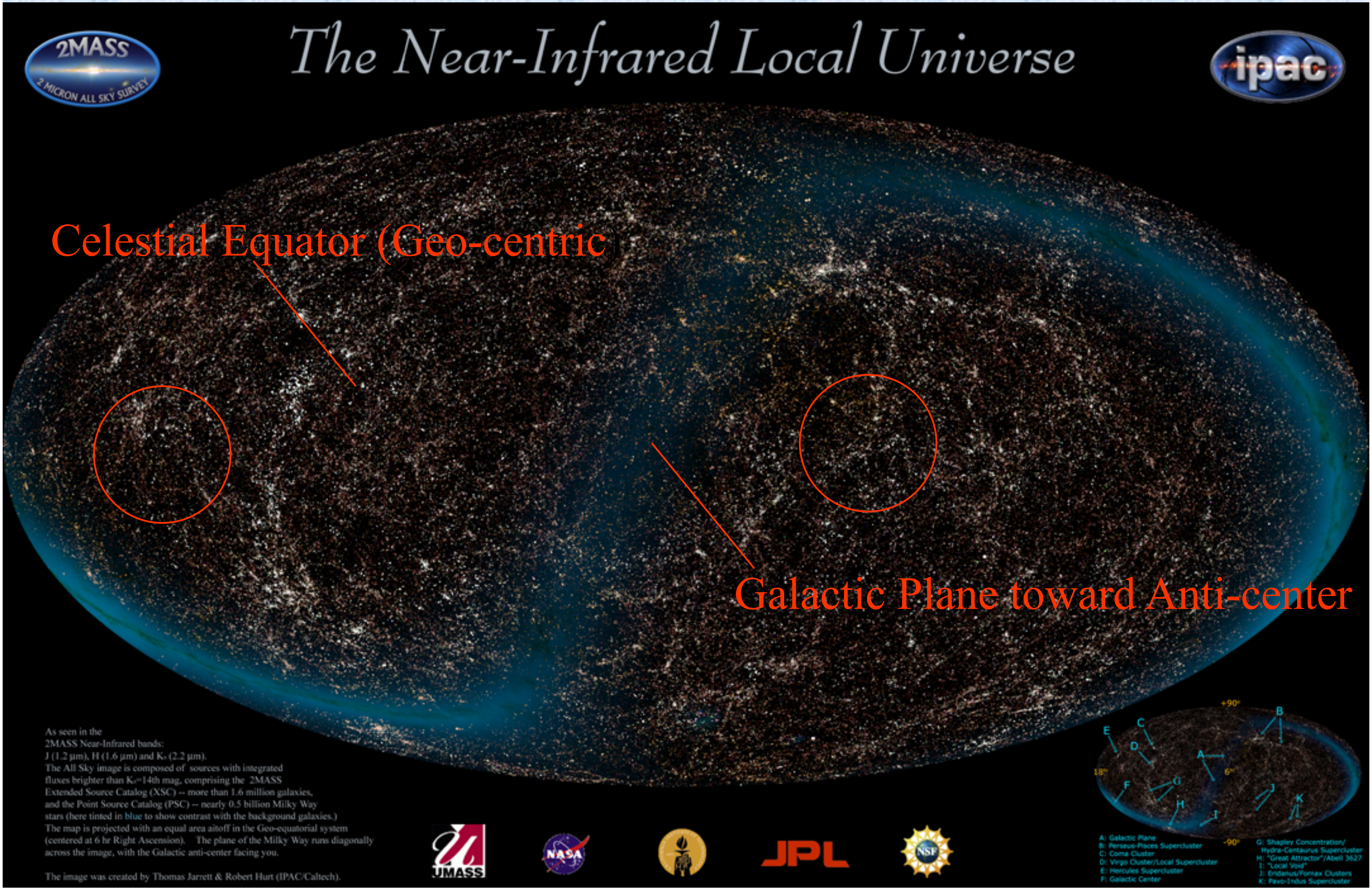




Isotropy and Homogeneity of the Universe: Map Making

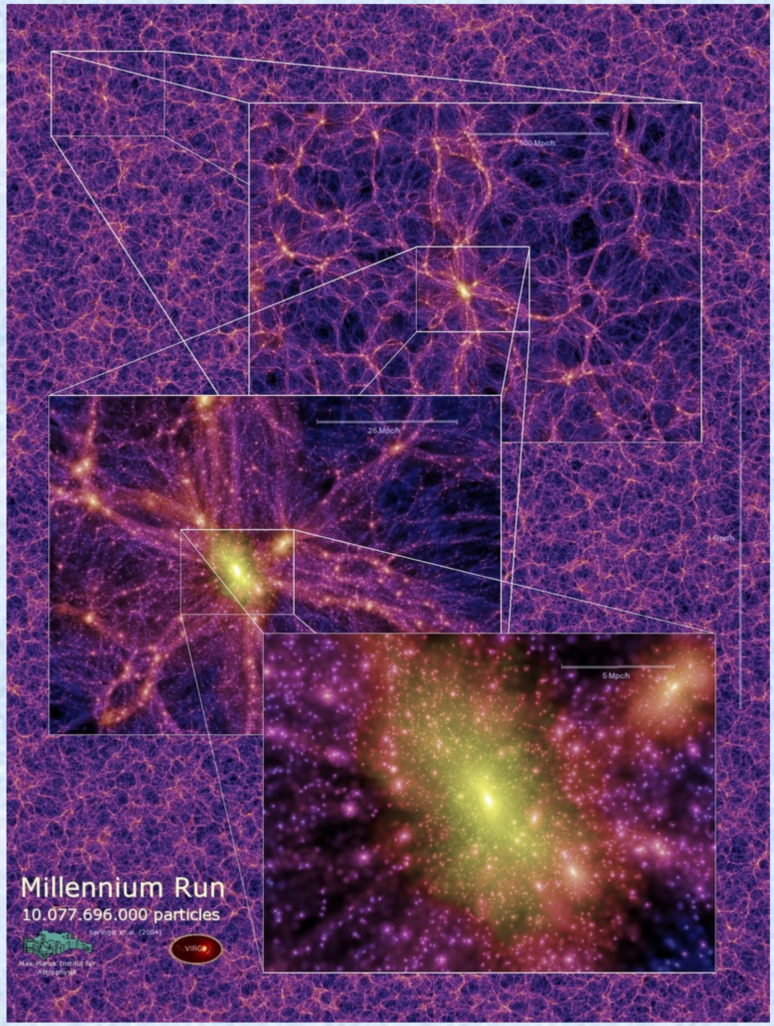


Isotropy and homogeneity: Galaxies



Numerical Model of Structure

100 Mpc ↕



Announcements (3/31/2021)

- TA Office Hours
- Instructor Office Hours
- Can also ask homework questions at the Student Forum on Gaucho Space

- Today: Pillars of Cosmology
  - Olbers' Paradox
  - CMB
  - Hubble Expansion
  - Light Elements

Key Point: Isotropy and homogeneity of the Universe.

- One of the basic assumption of cosmology is that we are observers in a random place. We are not in a special place in any way (Copernican Principle)
- Therefore we CANNOT be at the center of the universe. Thus if the universe is invariant under rotation around a random point it must also be invariant under translation: homogenous.
- **ONLY ON LARGE SCALES. OF COURSE ON SMALL SCALES IT IS NOT!!!**
- **How large?** Scales > roughly 100 Mpc
- *What is a parsec? And why use it to measure distance?*

Stellar Parallax

1 pc is the distance at which a star has a parallax of 1 arcsecond, so

d = 1 AU / [1 asec * radians / asec].

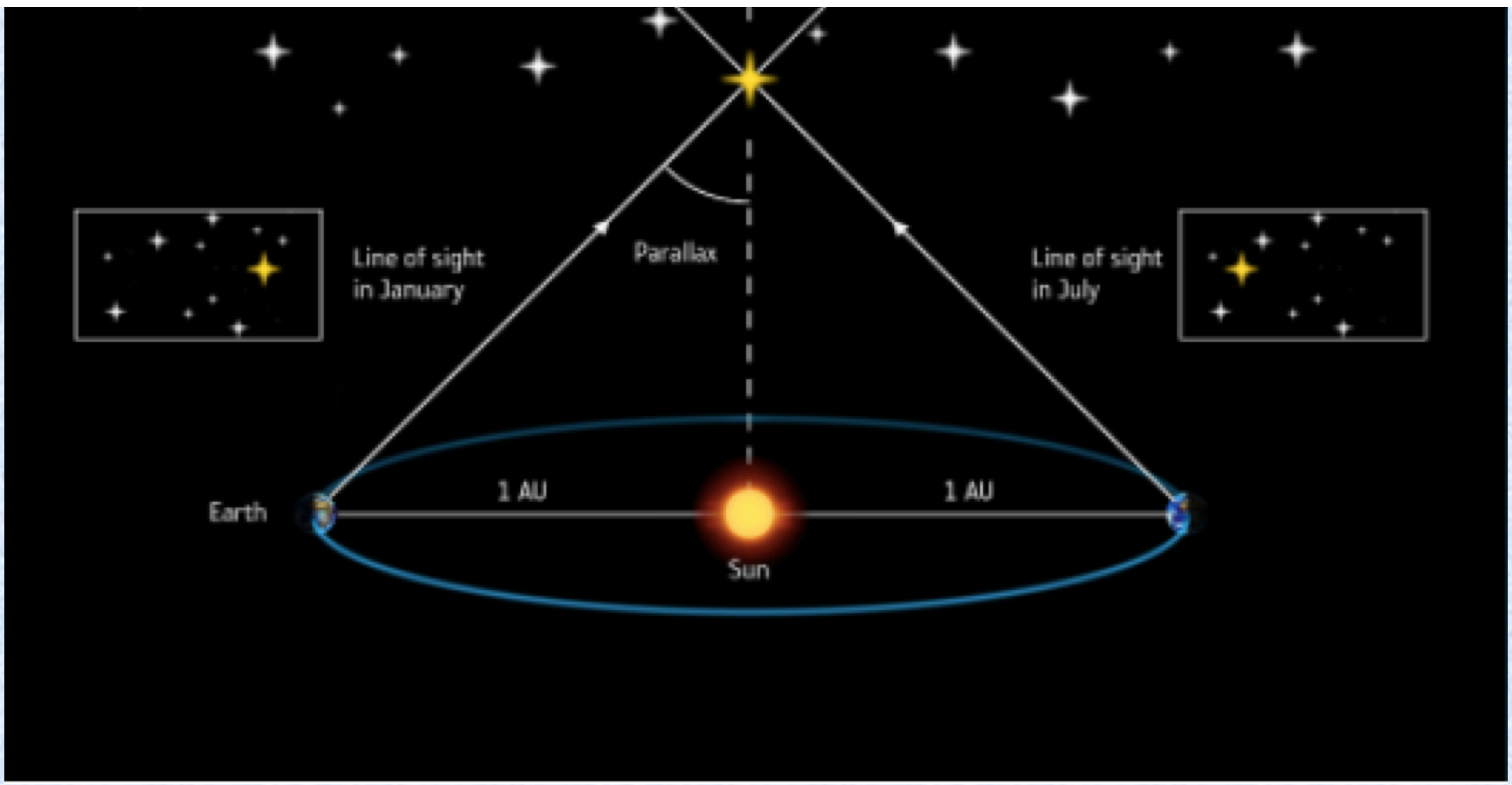
Please note:

π radians is 180°

1° is divided into 60 arcminutes, and

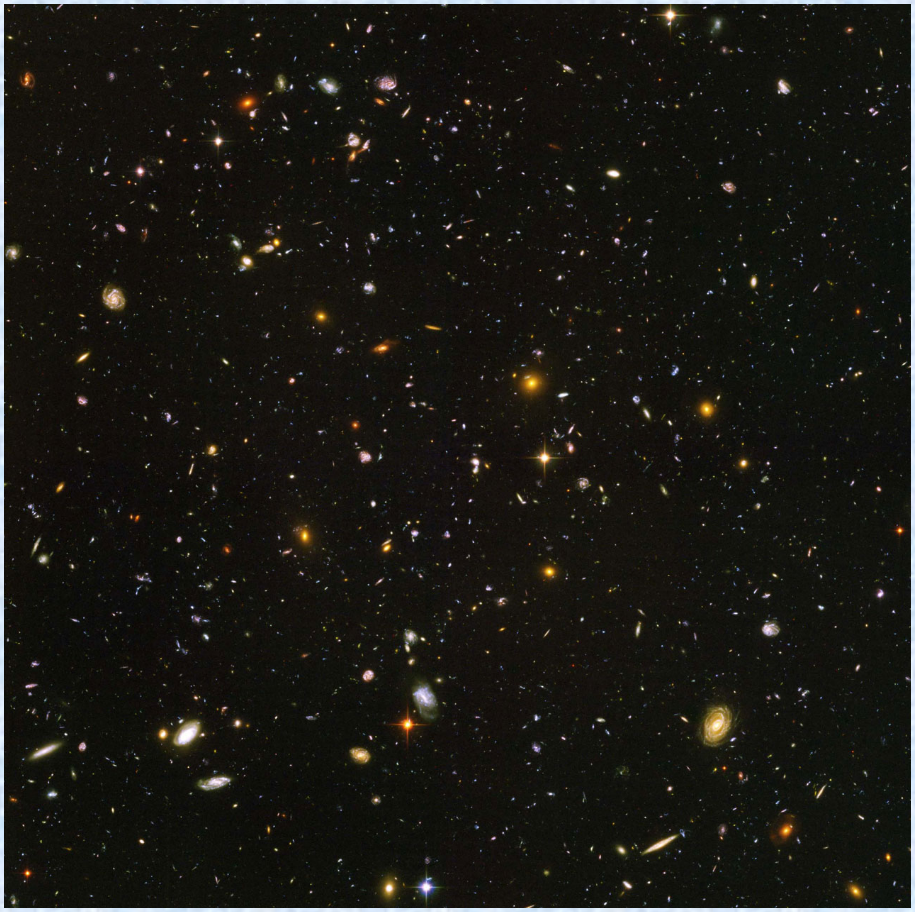
1 arcminute is divided into 60 arcminutes

It follows that **1 parsec = 3.0857e18 cm**, which is the distance that light travels in 3.26 yrs



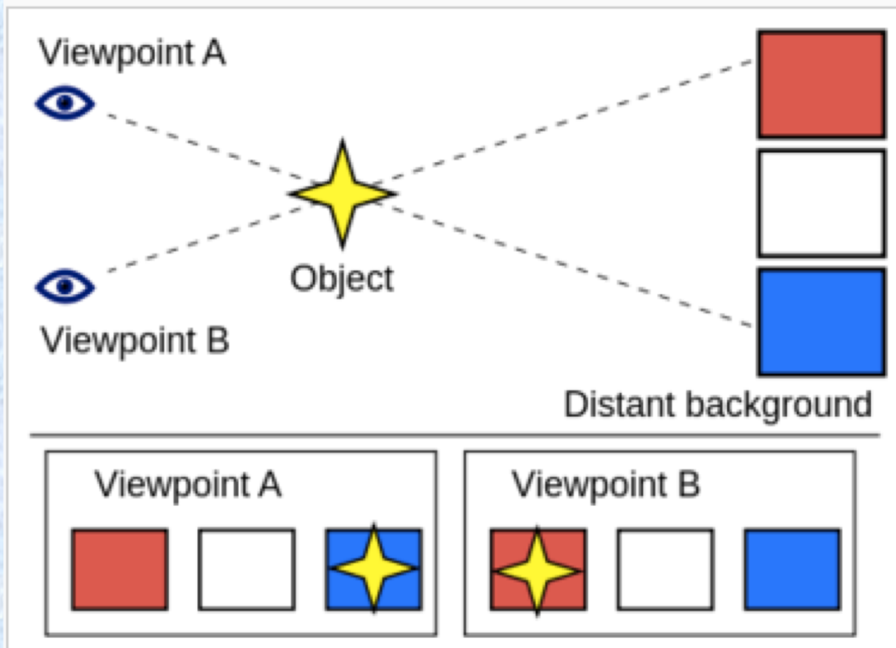
Olbers' paradox.
The night sky is dark!

- This apparently superficial statement has very profound consequences.
- This observational result is evidence in favor of the big bang



Olbers' paradox. A step back..

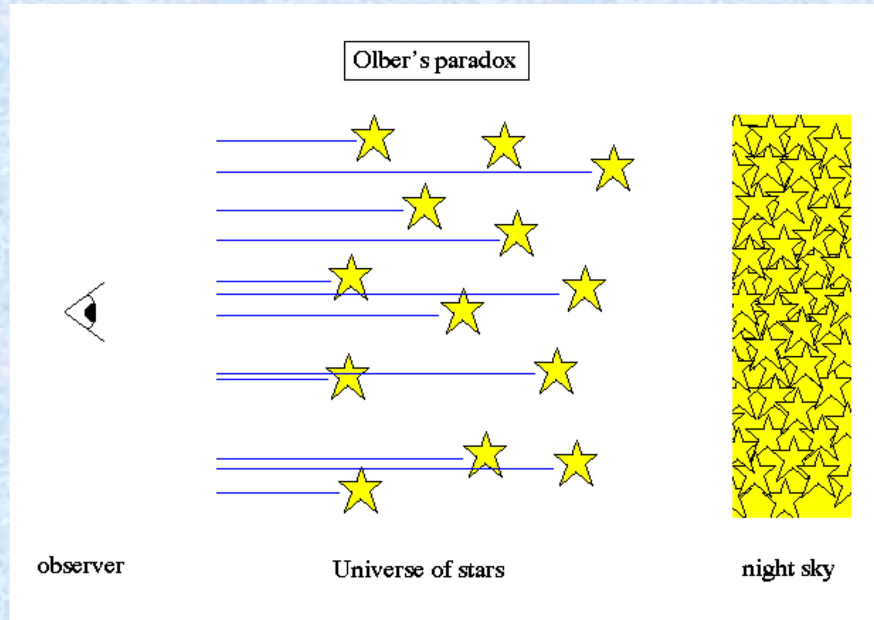
- Copernican system requires the stars to be much further away than the sun; otherwise their parallax would be detected with the naked eye.
- Newton's model of the universe was:
  - Eternal
  - Infinite (otherwise it would collapse gravitationally)
  - Flat Space
  - Time independent
- **So surface brightness is independent of distance**.



A simplified illustration of the parallax of an object against a distant background due to a perspective shift. When viewed from "Viewpoint A", the object appears to be in front of the blue square. When the viewpoint is changed to "Viewpoint B", the object *appears* to have moved in front of the red square.

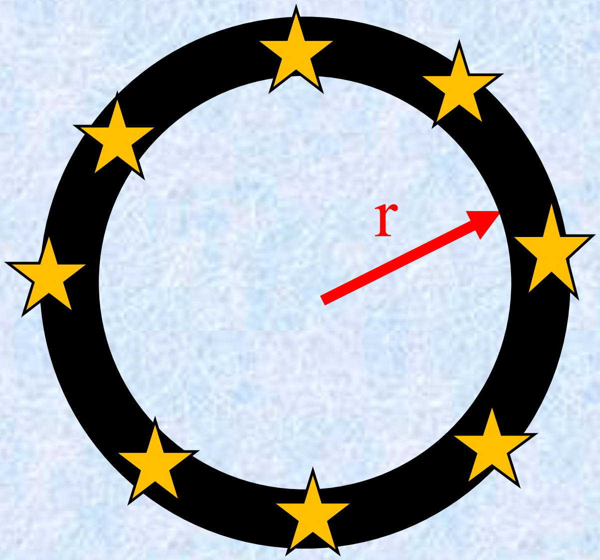
Olbers' s paradox. What does the sky look like in Newton' s model?

- For every line of sight sooner or later you find a star (luminosity L).
- This would mean that the sky should have the same surface brightness of the sun, your average Joe star, e.g. the Sun...
- Assumptions:
  - starlight is not attenuated
  - the density of stars is constant in space and time
  - the universe is infinitely large
  - the universe is infinitely old



Olber's Paradox (Quantitatively)

- For one star a distance r away, the radiative flux received is …



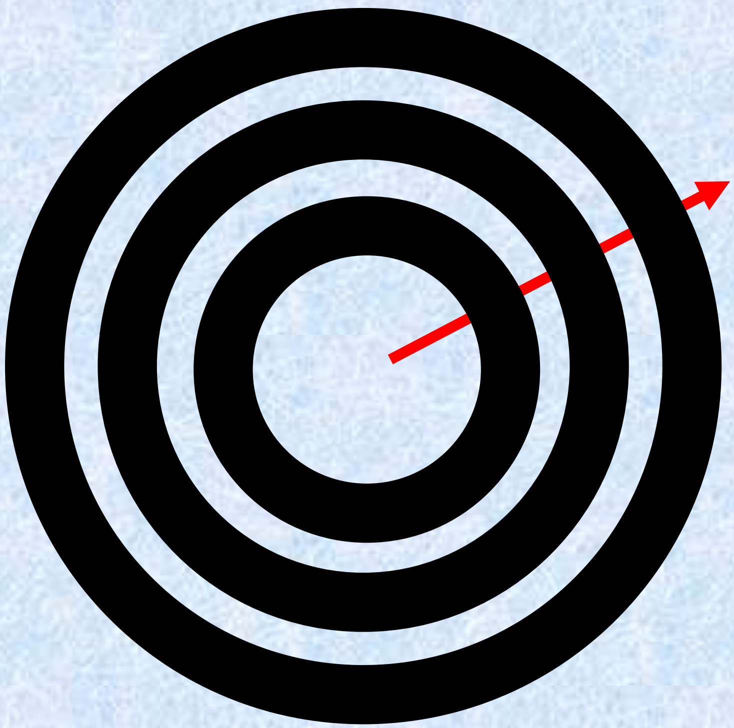
$$F = \frac{L}{4\pi r^2}$$

$$\frac{dF}{dV} = \frac{L}{4\pi r^2} n$$

- The flux contributed by all stars in a volume dV at radius r depends on the density of stars, n, ….

Olber's Paradox (Quantitatively)

- Now let's add up the shells at all distances from r=0 to r = infinity.



$$dF = n\frac{L}{4\pi r^2}4\pi r^2 dr$$

$$dJ = n\frac{L}{4\pi r^2}\frac{4\pi r^2}{4\pi}dr$$

$$dJ = \frac{nL}{4\pi}dr$$

$$J = \frac{nL}{4\pi}\int_0^\infty dr$$

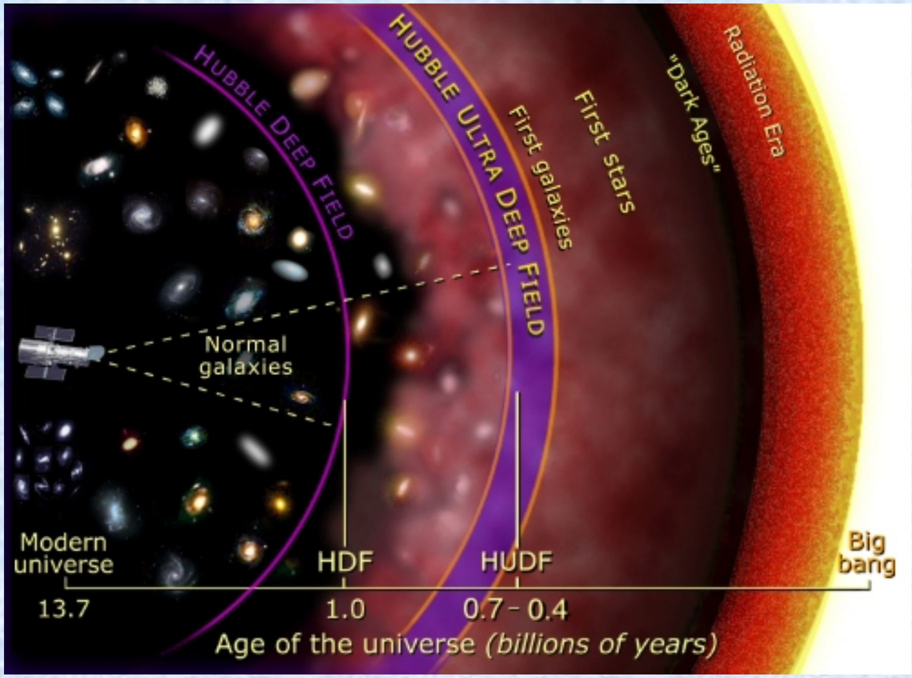
- ***Specific intensity is*** the flux per unit solid angle on the sky.
- For our isotropic example, the mean intensity is dJ = dF / 4π.
- Do the nearby shells or the distant shells contribute more?
- If stars are optically thin ('see through'), then how bright is the sky?

Olbers' paradox. Olbers' solution.

- Olbers postulated that the Universe was filled with an absorbing medium, like fog
- However, if light is absorbed it would heat up the medium, which would re-radiate, producing light albeit at different wavelengths, so this doesn't work!

Olbers' paradox. The Big-Bang's solution

- In the Big Bang model the Universe is finite in TIME (13.7 billion years)
- This means that we can only see as far away as light has had time to travel
- Furthermore stars were not always shining (the sun for example is 4.5 Gyrs old).
- More later..



Olbers' paradox. Summary

- The night sky is dark
- This implies that the emission of starlight in the universe must be finite, in space, time or both.
- This is fundamental test for any cosmological model
- The Big-bang explains Olbers' paradox with the finiteness of the lifetime of the Universe and hence of its stars:
- The universe is NOT eternal in the past! The universe evolves!

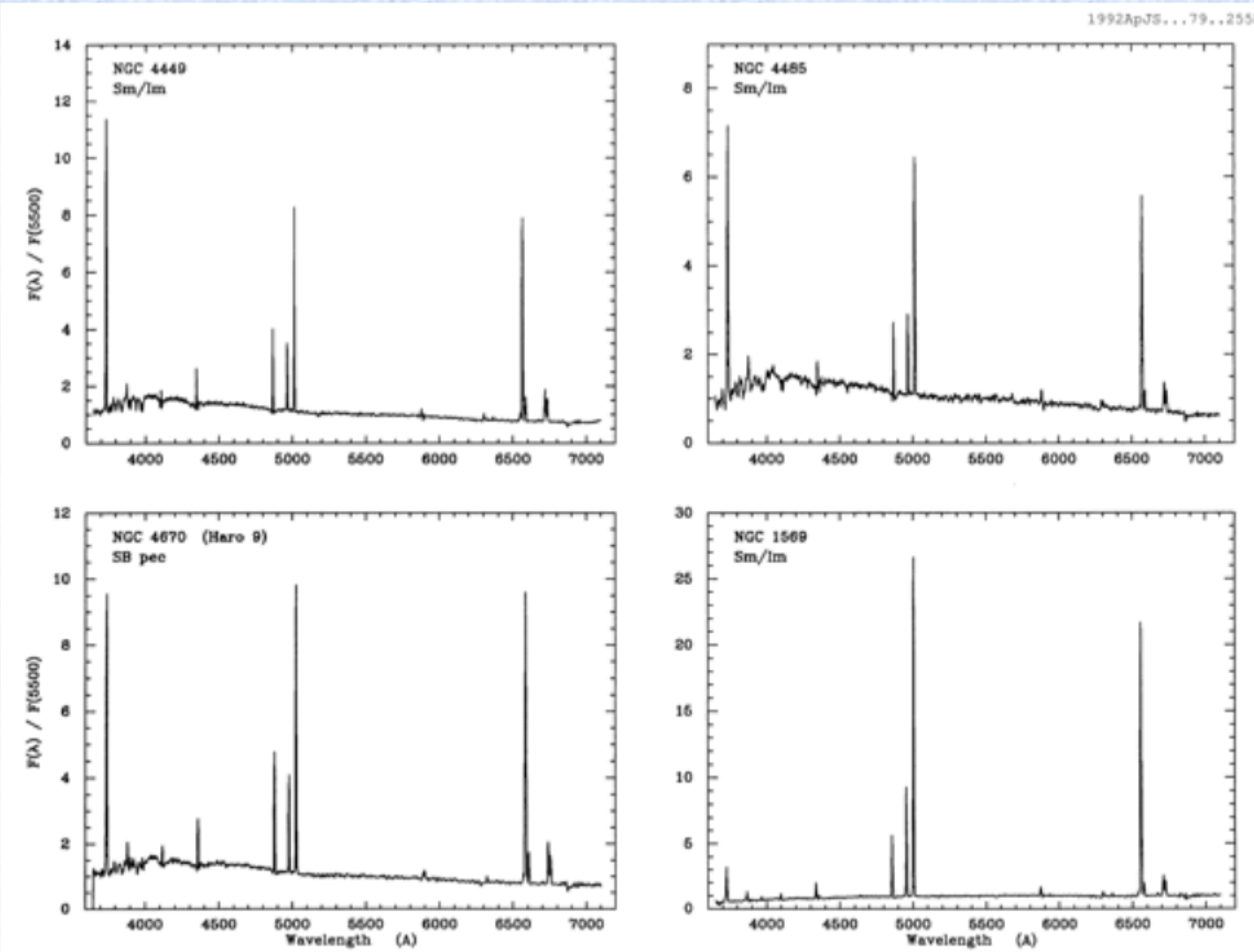
Expansion of the Universe. Empirical facts.

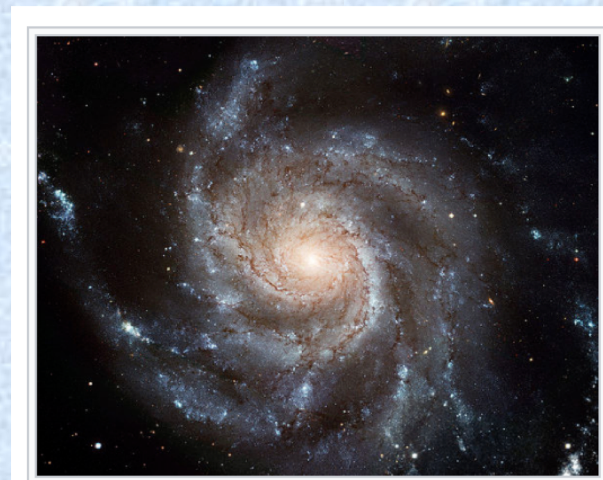
- In the early 20th century, Hubble and Humason found out that the spectra of most galaxies are redshifted.
  - Let λ_0 describe the wavelength of some spectral feature in the laboratory.
  - If that same spectral feature is observed at a longer wavelength, λ, in the galaxy spectrum, then the spectrum is redshifted.
- The redshift, z, is the amount of shift towards longer wavelengths: $z = (\lambda-\lambda_0)/\lambda_0$, which can be written as

$$1 + z = \lambda / \lambda_0,$$

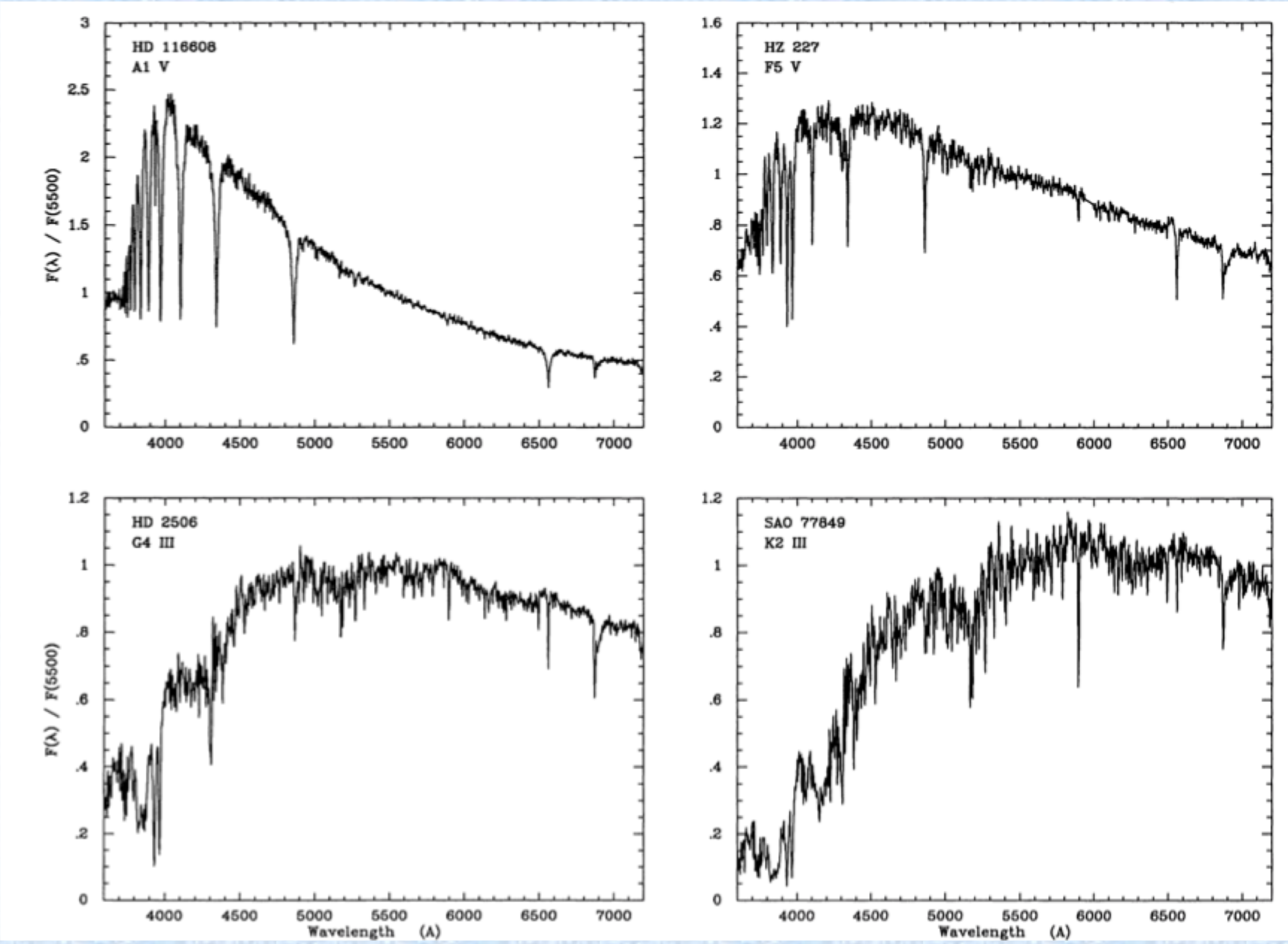
so wavelength stretches by a factor 1 + z.

Measuring Redshifts. 1. Emission Line Galaxies
Spectral Templates (e.g. Kennicutt 1992)





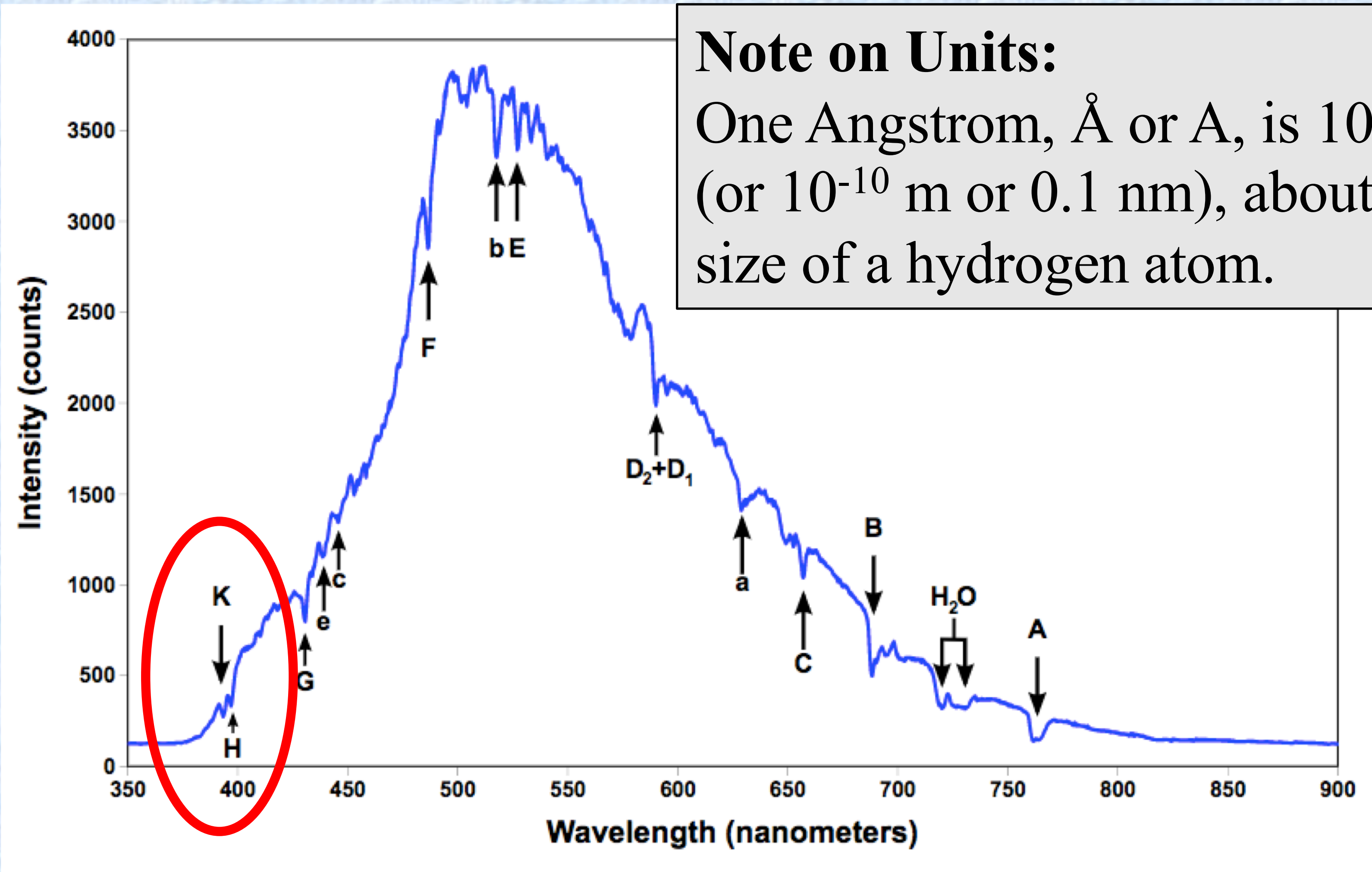
Measuring Redshifts. 2. Passive Galaxies
Spectral Templates (e.g. Kennicutt 1992)



… these spectra are the summation over al the stars in the galaxy.

Solar Spectrum

Fraunhofer lines



Note on Units:
One Angstrom, Å or A, is 10^{-8} cm (or 10^{-10} m or 0.1 nm), about the size of a hydrogen atom.

The K line at 3933 Å comes from the element Calcium. Let's use it as an example.

Measuring Redshifts, an example.

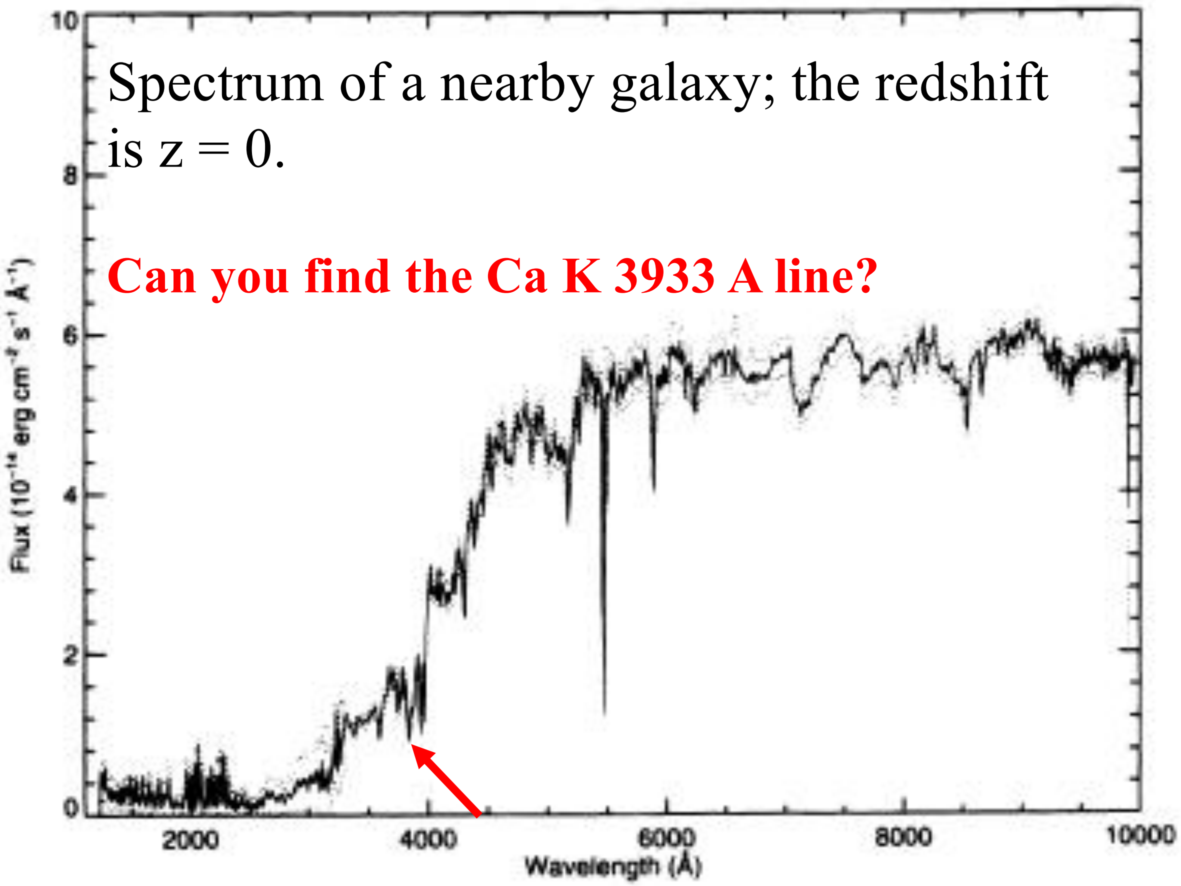
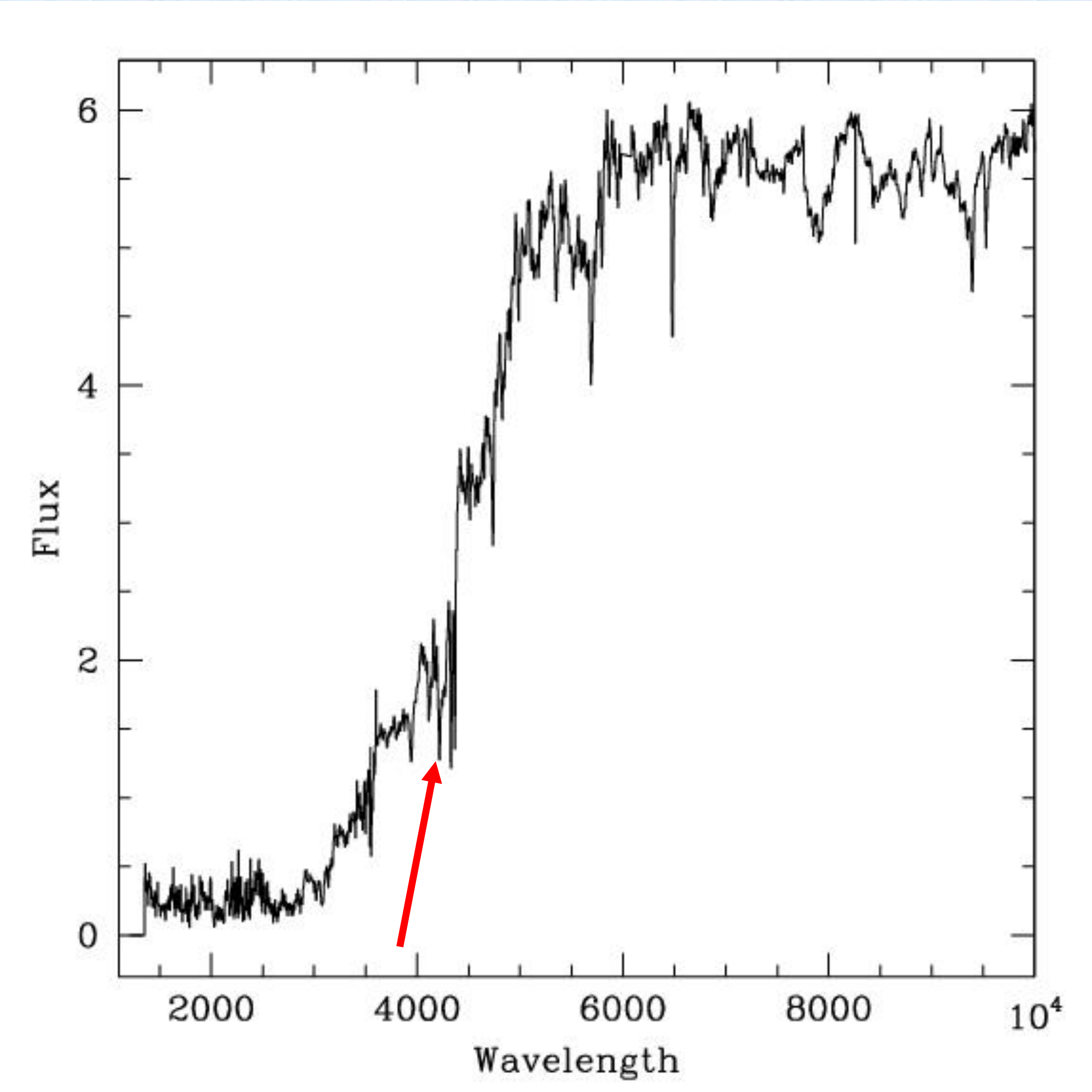


FIG. 2*a*

Now consider a redshifted galaxy that contains a similar population of stars. Every spectral feature will shift to longer wavelength.

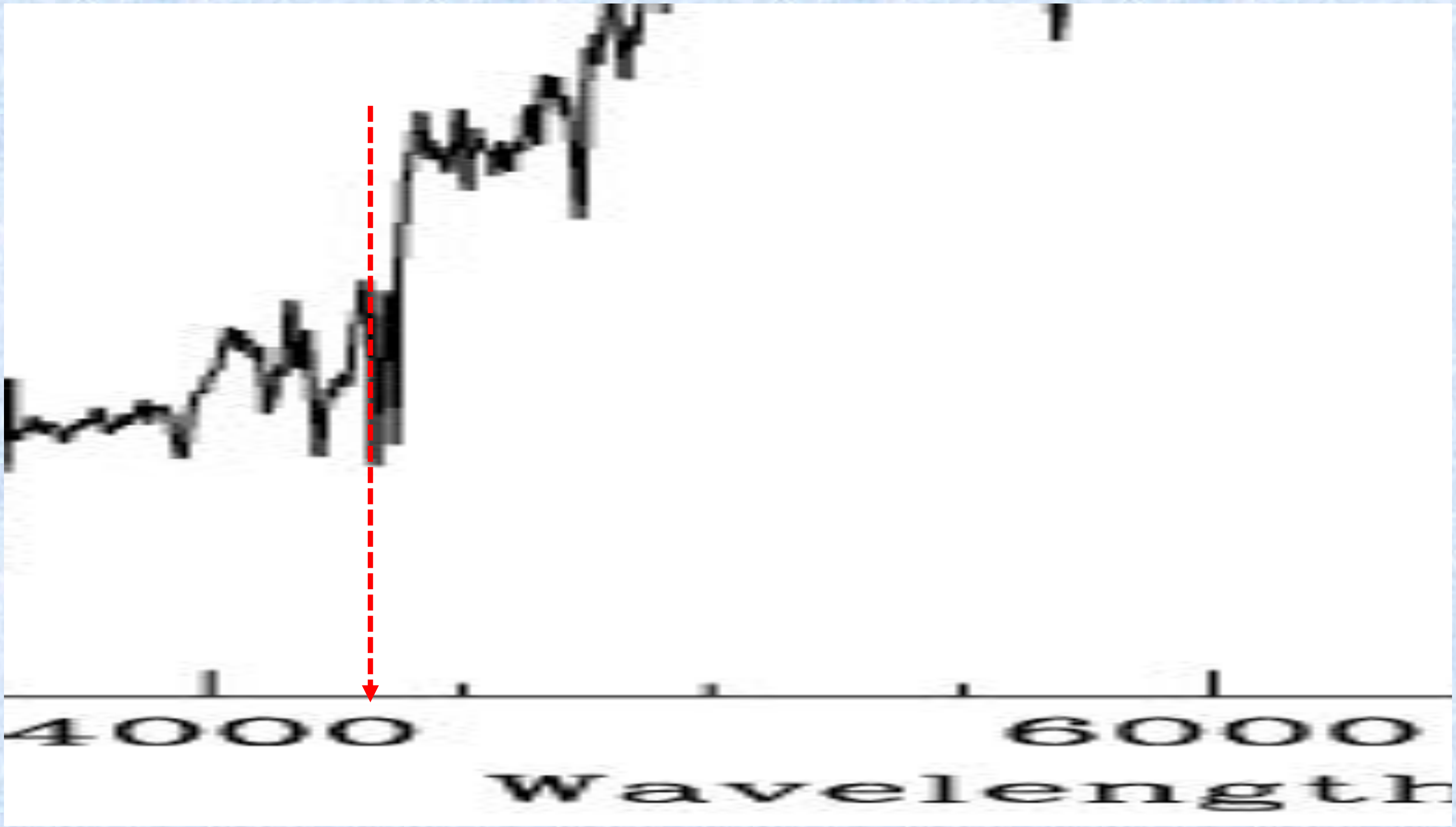
Quiz: Measure the Redshift



- Here is such a spectrum.
- Find the Ca K spectral line. (Hint: it is no longer at 3933 A.)
- How much has the Ca K line shifted?
- The definition of redshift is simple:

$$1 + z = \lambda / \lambda_0,$$

Quiz Answer



$1 + z = \lambda / \lambda_0$

$1 + z = 4330 / 3933$

$z \sim 0.1$

What is Redshift?

- Cosmological redshift is the shift caused by the expansion of space between the time of photon emission (by a distant galaxy) and photon detection (on earth).
  - We will show this shortly.
  - This is NOT relative motion THROUGH space.

- Relative motion through space causes a Doppler shift, which would also shift the spectrum.
  - The spectrum of a galaxy pulled toward the Milky Way by gravity will be blueshifted.

- The distinction was not clear when Hubble & Humason obtained galaxy spectra. They observed a redshift, which they expressed as a velocity, **$v \sim cz$**, by analogy with the Doppler effect.

Hubble and Humason’s Observations

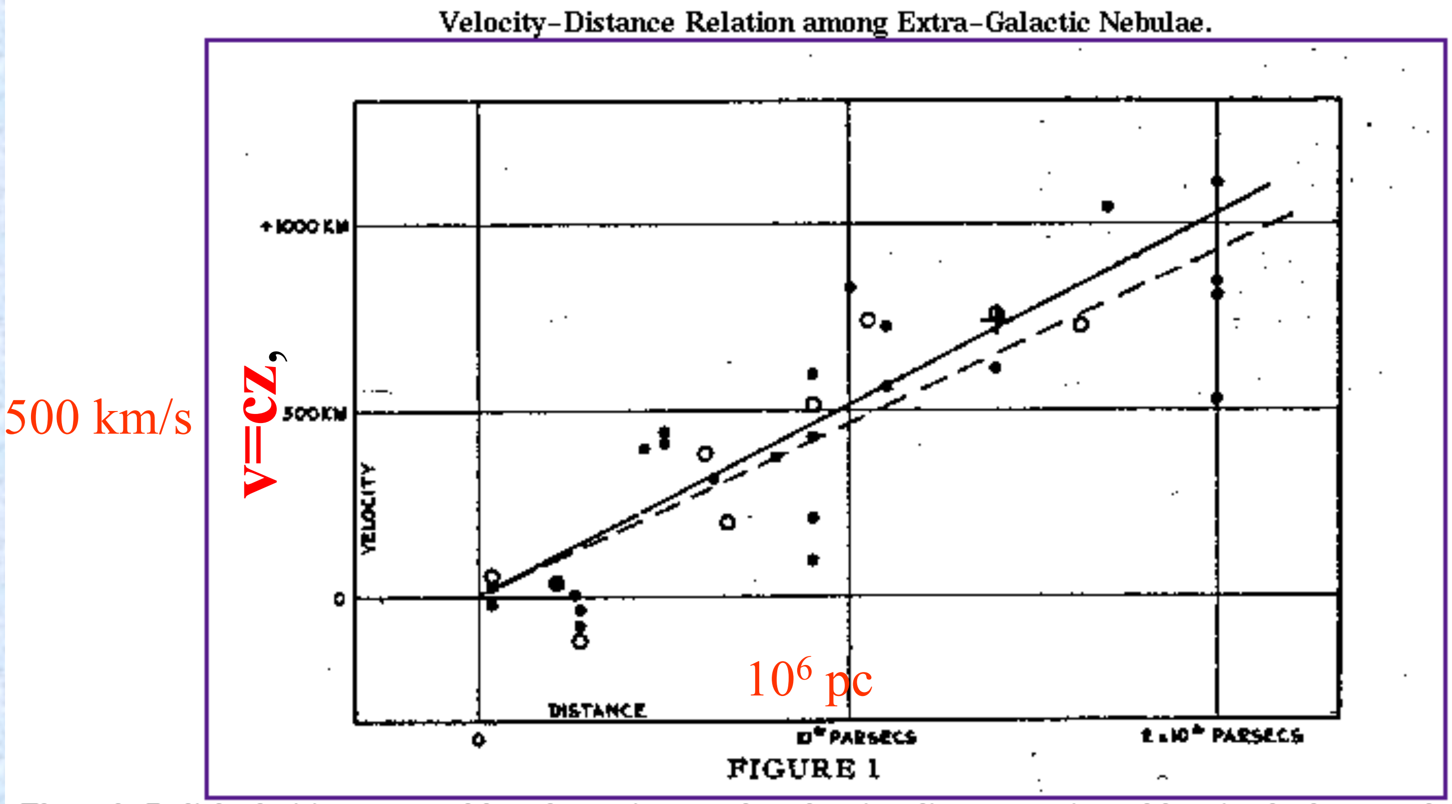


Figure 1: *Radial velocities, corrected for solar motion, are plotted against distances estimated from involved stars and mean luminosities of nebulae in a cluster. The black discs and full line represent the solution for solar motion using the nebulae individually; the circles and broken line represent the solution combining the nebulae into groups; the cross represents the mean velocity corresponding to the mean distance of 22 nebulae whose distances could not be estimated individually.*

- Most of the ”velocities” were redshifted ; very few were blueshifted.
- They measured distances to the galaxies using the Cepheid period -- luminosity relation.
- Spectra of the more distant galaxies had larger redshifts.

Hubble's Law

- The ratio between velocity v and distance d is a constant, called the Hubble Constant,

$$v = H_0 d$$

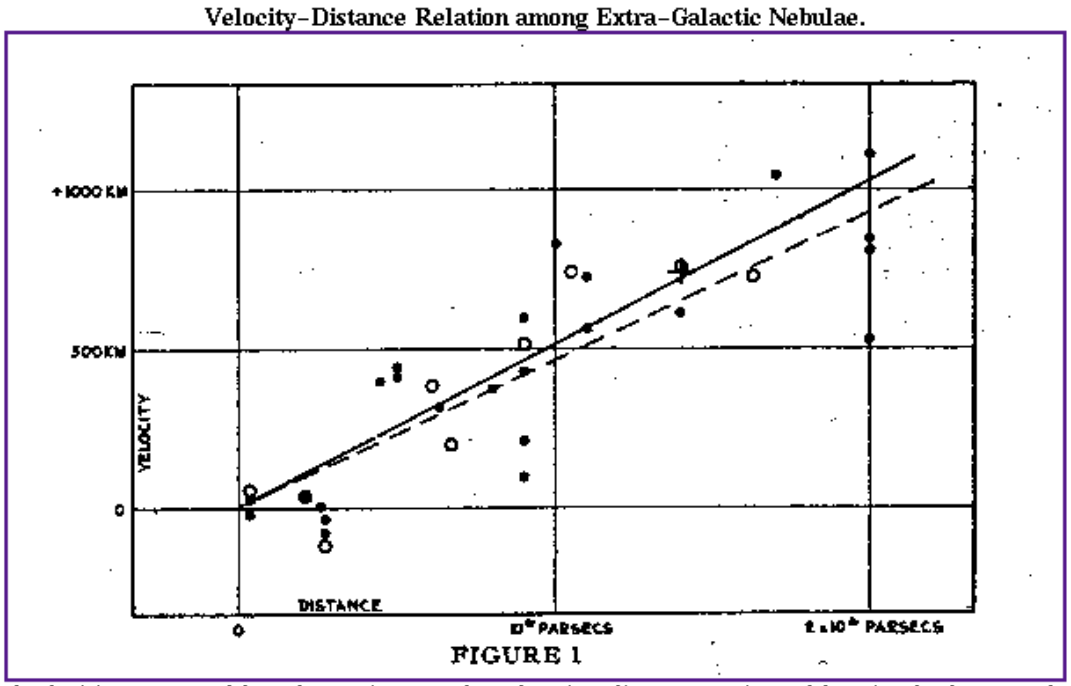
$$H_0 = v/d = cz/d,$$

which is measured in km/s/Mpc, around 70 km/s/Mpc.

- This is phenomenal! If we know H_0, then it is sufficient to measure redshift, which is easy, as we saw earlier, to find out the distance to any galaxy!

- Astronomers prefer to *use redshift instead of velocity* because this is what we measure.

Even Hubble makes mistakes….



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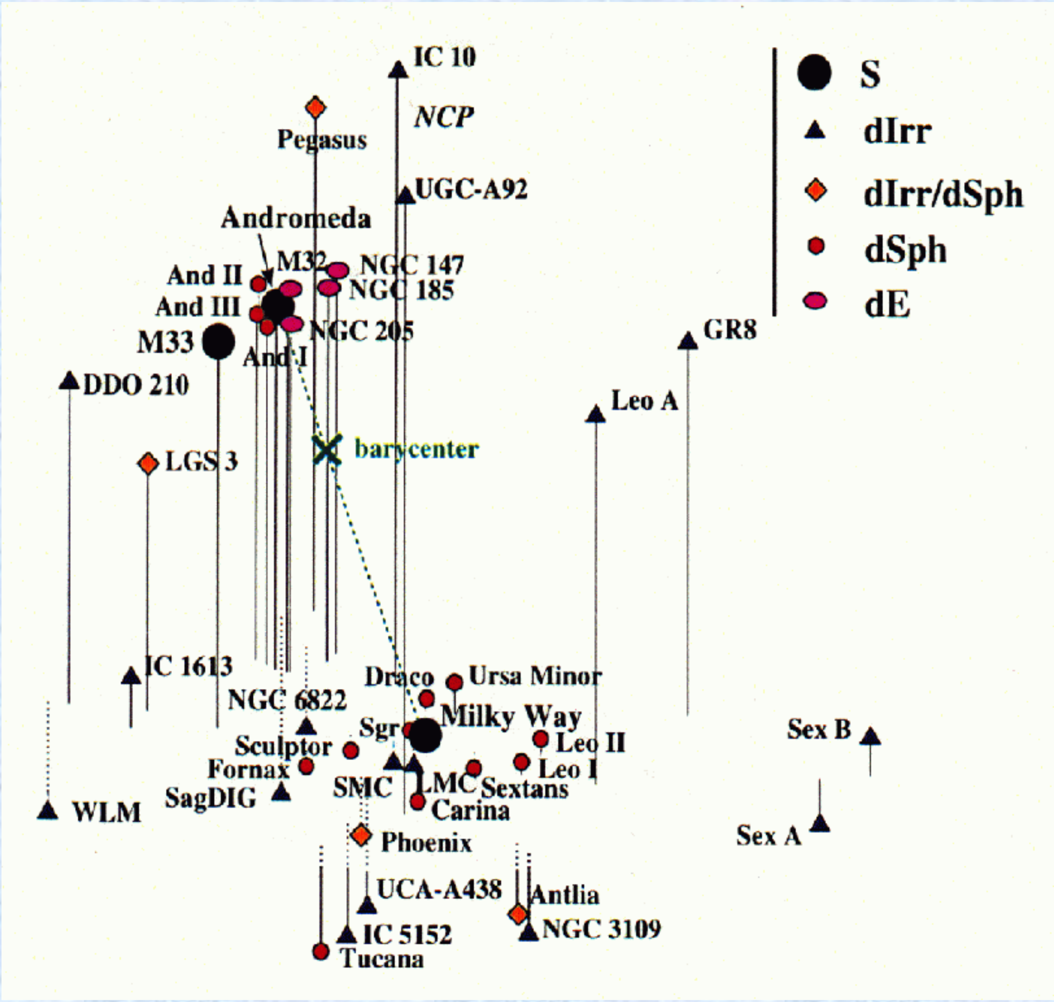
- Hubble's first measurement of the Hubble constant was wrong: 500 km/s/Mpc, instead of the current best estimate of 70 km/s/Mpc
- Hubble's mistake was due to various reasons including that he used as standard candles things that were not standard candles

Are All Galaxies Redshifted?

- No. Only those galaxies whose relative motion from cosmological expansion is larger than the motion caused by the gravitational attraction of the Milky Way.

- We saw that galaxies are strongly clustered on scales < 100 Mpc, and that the gravitational forces acting between galaxies describe that clustering.



The Universe is expanding

- Hubble's law is not only a convenient way to obtain distances to galaxies from their redshifts
- Hubble's law has a much more profound significance
- In the current standard cosmological model, Hubble's law is believed to be the result of the expansion of the Universe
- Expansion in an isotropic model = Hubble's law [Blackboard]

Meaning of the Hubble constant

- In the standard model the Hubble constant represents the current expansion rate of the Universe

- If the expansion rate were constant, the Universe would be of finite age, 14 Gyrs since the Big Bang. (We will see later that the actual age is closer to 13.7 Gyr.)

- The horizon distance is the distance a photon travels in the finite age of the universe.

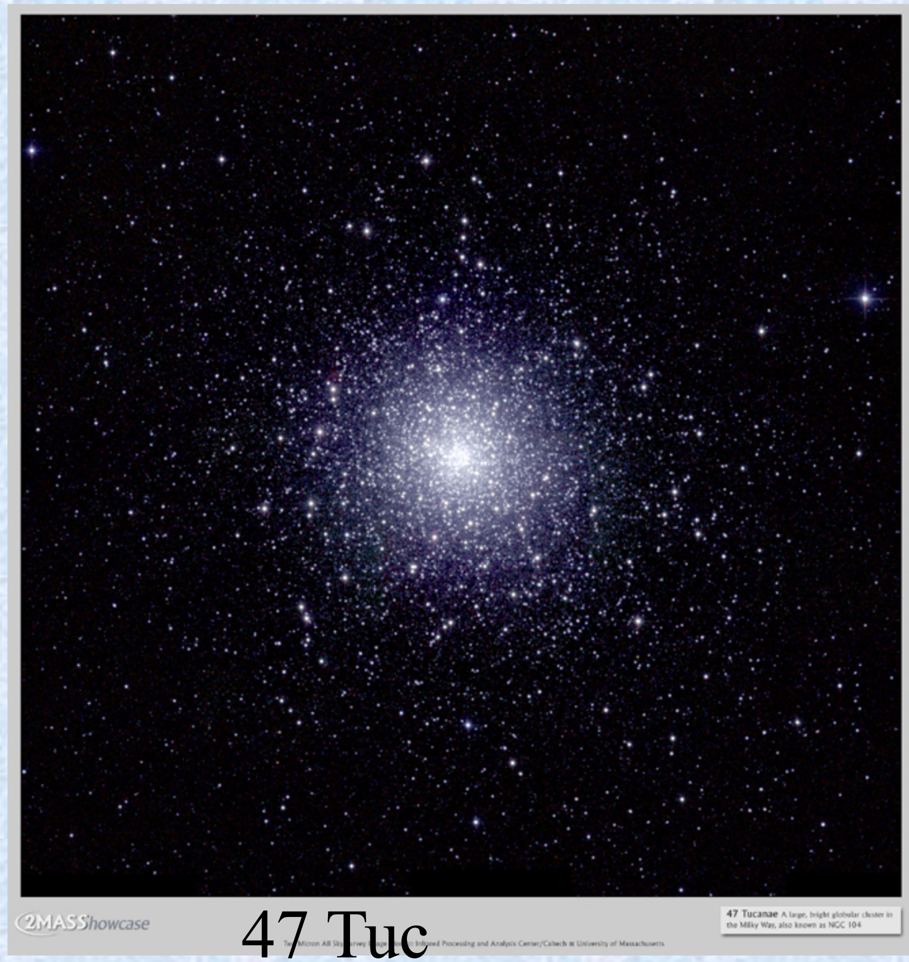
- This solves Olbers' paradox . The size of the visible universe is limited to $r_H \sim c\ (1/H_0)$. [Blackboard]

Is there an age problem?

The large value of the Hubble constant obtained by Hubble implied a much shorter life of the Universe, of order 1-2 Gyrs. This caused problems as it was inconsistent with the age of the Earth (4.5 Gyrs), for example.

- The age of stars can be inferred from stellar evolution models, by analyzing the luminosity and temperatures of stars.

- Globular clusters are made of very old stars, all in the same location. Their ages are consistent, i.e. less than or equal to 13.7 Gyr.



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Is there an age problem?

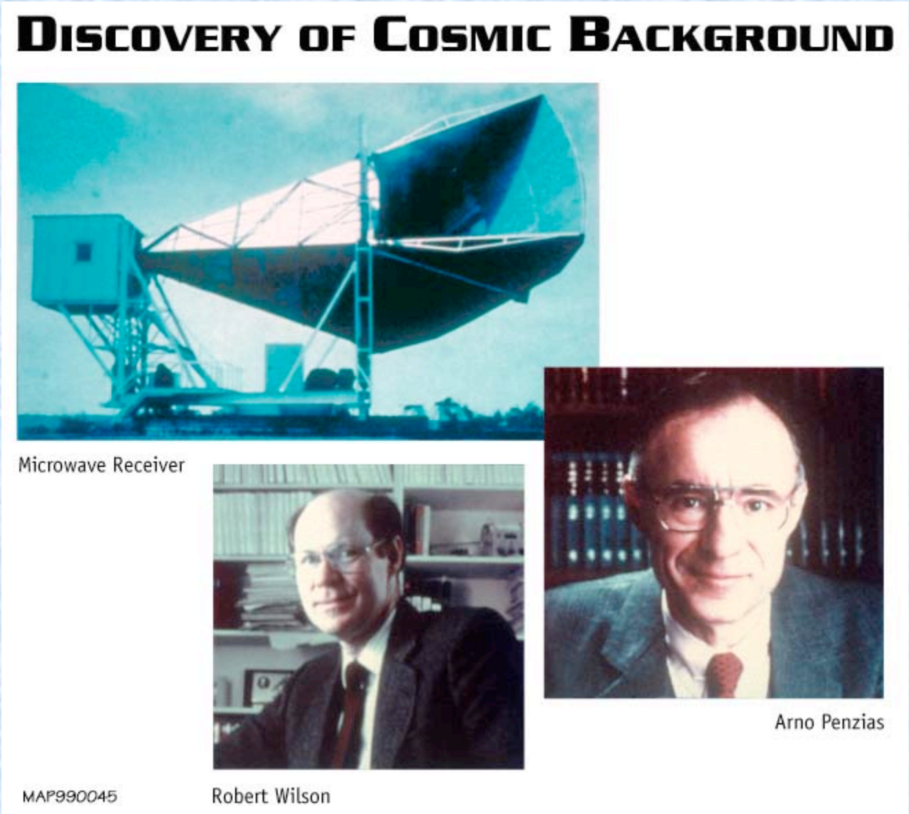
- No
- Quite the opposite, the age of the oldest stars in the Universe are remarkably consistent with the age of the universe itself, at any redshift where we can measure it.
- This does not prove that the model is right, but is a great triumph of the theories of the big bang and that of stellar evolution.

The universe is expanding. Frequently asked questions…

- What is the universe expanding into?
- Nothing, the universe is all there is, spacetime is expanding
- Where is the center of the expansion?
- Nowhere, there is no center, the universe is homogenous and isotropic
- Do we expand as well?
- No, because we are bound by electromagnetic forces
- Do galaxies expand?
- No because they are bound by gravity and they detach from the Hubble Flow

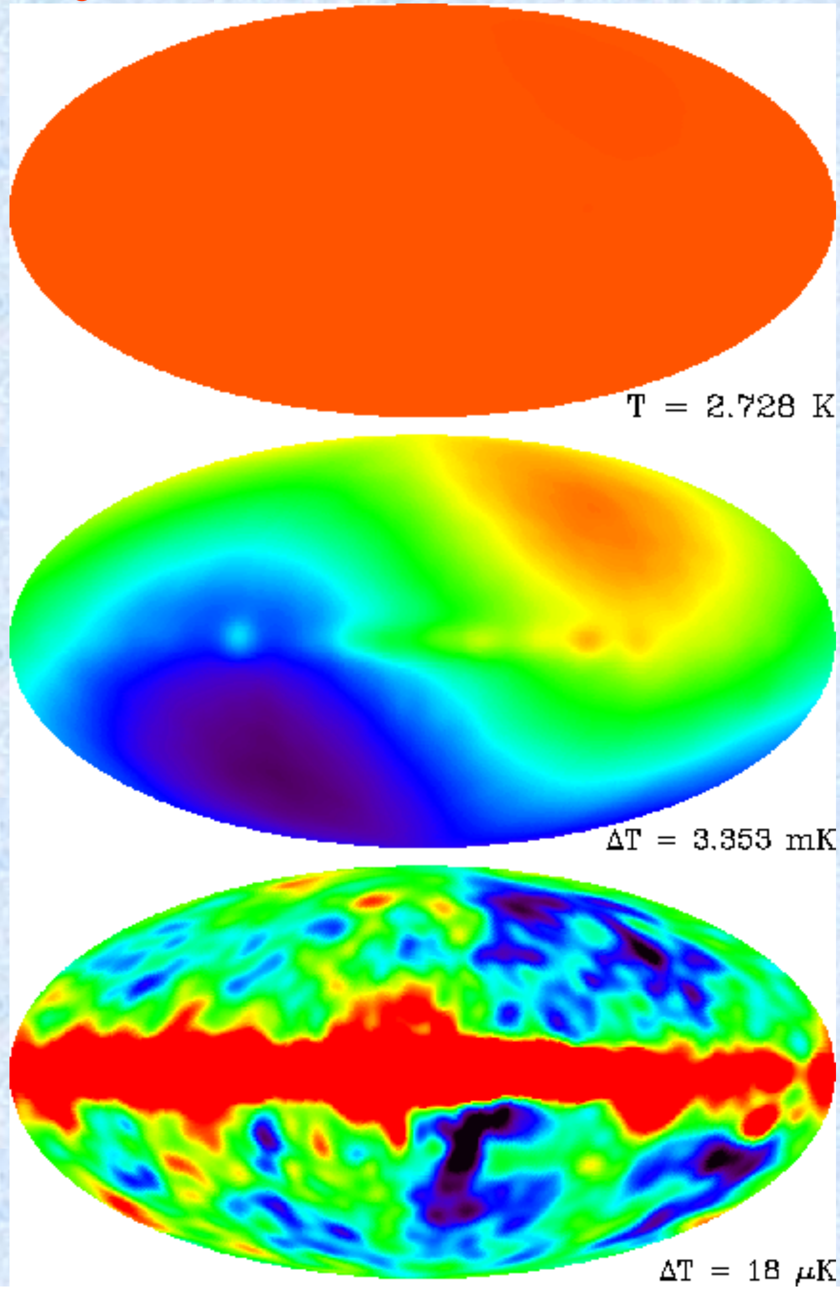
Cosmic Microwave Background

- The cosmic microwave background was discovered as a background “noise” a real problem for telecommunication satellites (1965)
- Wherever Penzias and Wilson pointed their antenna they would detect a microwave signal, very uniform across the sky
- This signal is now called the cosmic microwave background…

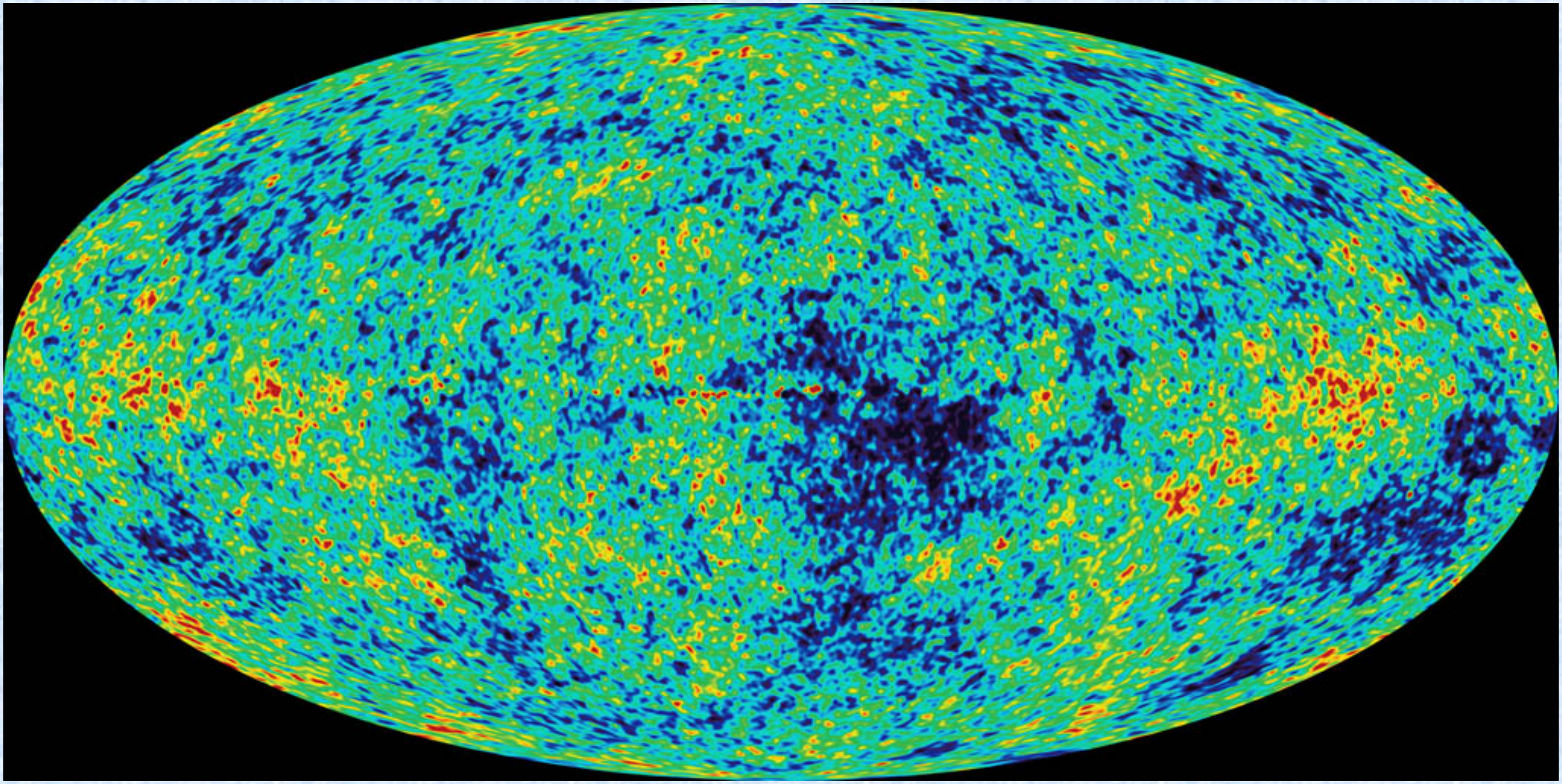


Isotropy and homogeneity of the CMB

- Smooth
- What does the dipole mean?
- What is the horizontal band?
- And what are the small temperature fluctuations?



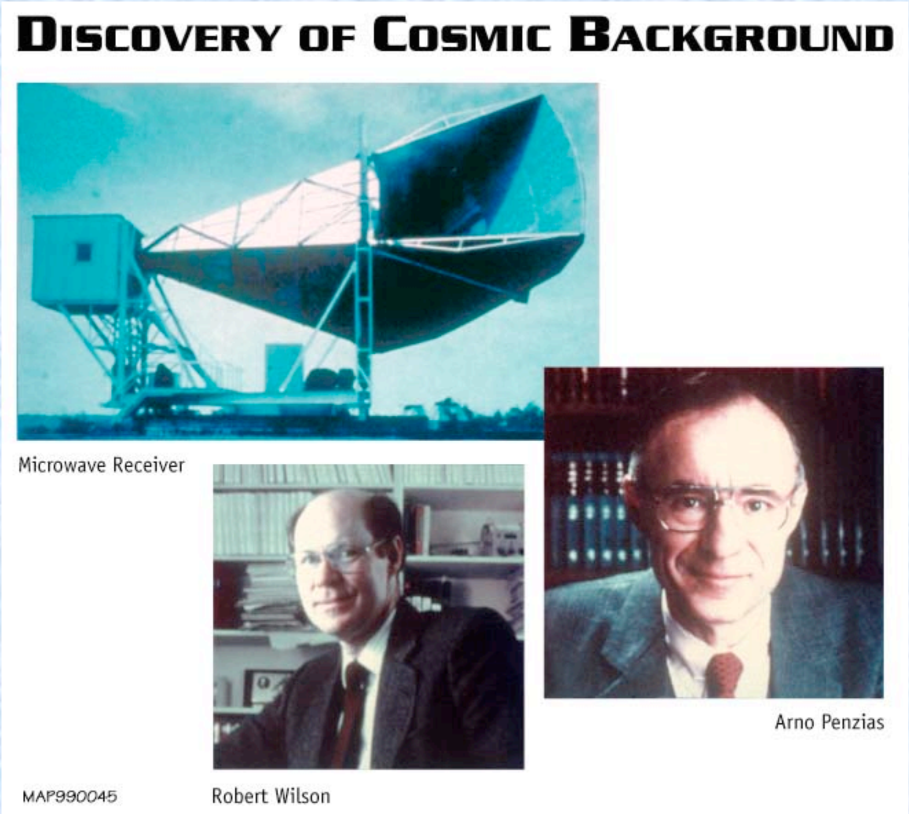
Cosmic Microwave Background. Anisotropies from WMAP



The CMB sky, circa 2002…

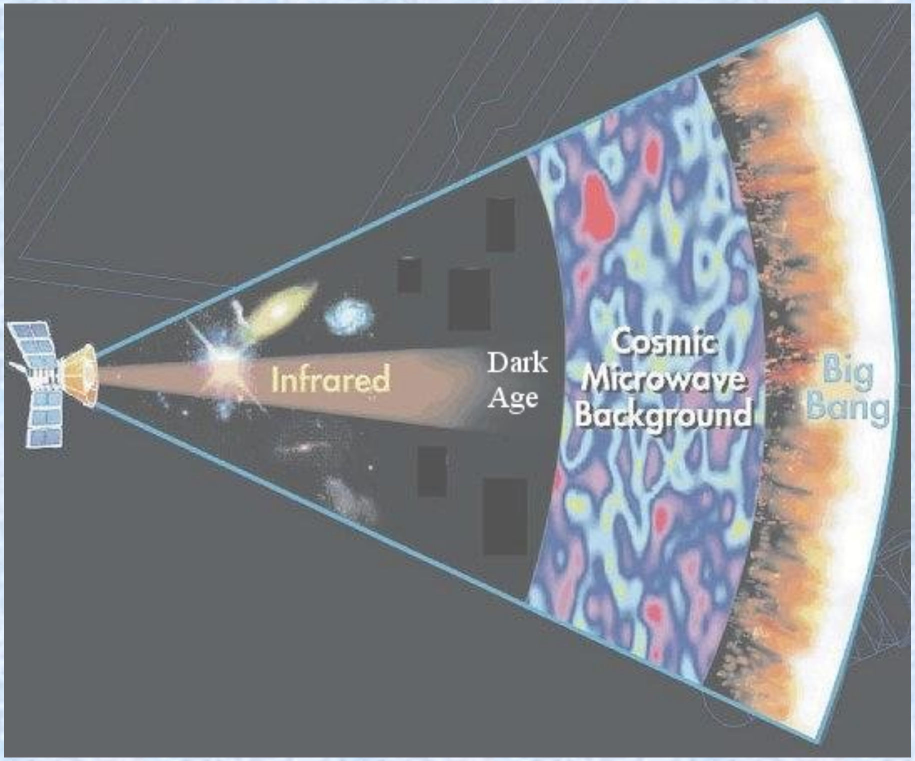
Cosmic Microwave Background

- The CMB was already visible in the data taken by Dunham and Adams of the properties of CN in the interstellar medium …back in 1937
- The saw that CN was excited as if it was immersed in a thermal bath of radiation of temperature T~3K…
- But nobody realized it.. So the Nobel Prize went to Penzias & Wilson… and not to Dunham and Adams.. Such is life..



Cosmic Microwave Background

- A group of physicists (initially Gamow (1948) and then Alpher and Hermann (1950) and then Dicke and his group at Princeton) had predicted such radiation, from the so-called big bang nucleosynthesis theory (later in the class..)
- The CMB was predicted to be:
  - Thermal
  - At a temperature of about 5K
  - Isotropic



Dicke was devising a CMB search when the discovery was made. His paper with Peebles, Roll, and Wilkinson presented the cosmological interpretation along-side the Penzias and Wilson paper.

Cosmic Microwave Background

- Discovery of CMB settled debate between Steady-State and Big Band models.
- Why?
  – CMB photons are a relic of the epoch when matter and radiation were in equilibirum, i.e. interacted frequently.
  – And the background radiation was much hotter then. Hot enough to ionize hydrogen and create free electrons.

Cosmic Microwave Background. Thermal "Blackbody" Radiation

- We know Penzias and Wilson detected isotropic radiation, so that was consistent with the Big Bang model and the Cosmological Principle
- The theory predicted it to be thermal, i.e. a blackbody.

Plank's Equation

$$B_\lambda = \frac{2hc^2}{\lambda^5} \frac{1}{\exp\frac{hc}{\lambda kT} - 1}$$

Where:

B_λ = Magnitude of Radiation per Wavelength.

λ = Wavelength.

h = Plank's Constant ($6.6238 * 10^{-34}$ Js).

c = Speed of Light ($3.0 * 10^8$ m/s).

k = Boltzmann Constant ($1.3807 * 10^{-23}$ J/K).

Properties of Blackbody Radiation

1. Matter and radiation in equilibrium produces a characteristic spectral shape

2. Radiative emissivity

   $F = \sigma T^4$, where

   $\sigma = 5.67e\text{-}8\ J/s/m^2/K^4$

3. Wien's Law - hotter body produces higher energy photons;

   $\lambda_{max} T = 0.3$ cm * deg

4. Energy density -

   $\varepsilon = a_{rad} T^4$, where

   $a_{rad} = 7.56e\text{-}16\ J/m^3/K^4$

But is the CMB radiation really a perfect blackbody spectrum?

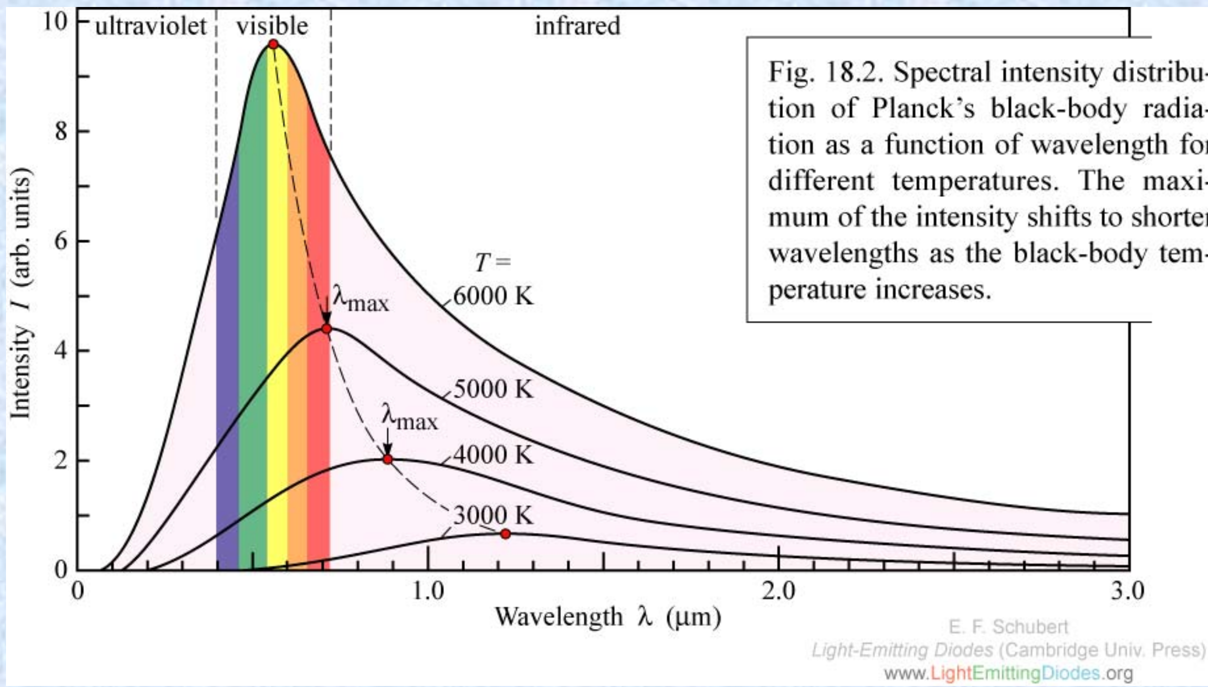
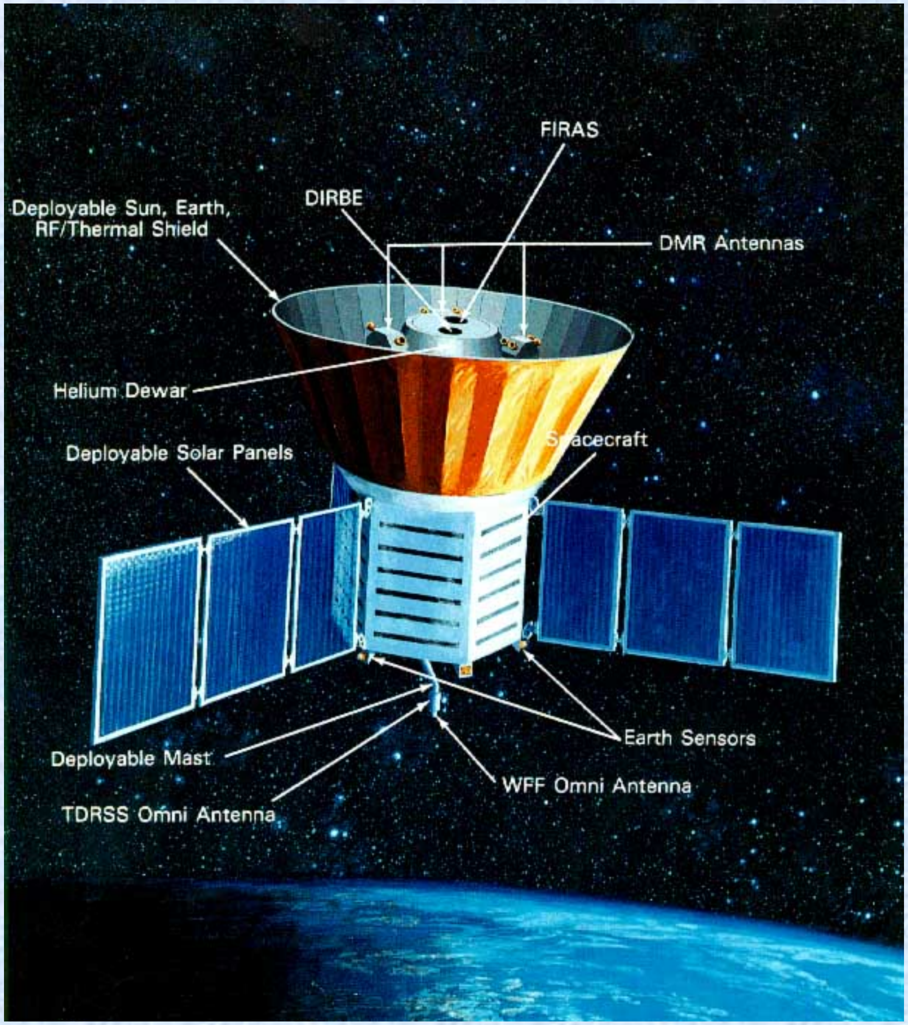


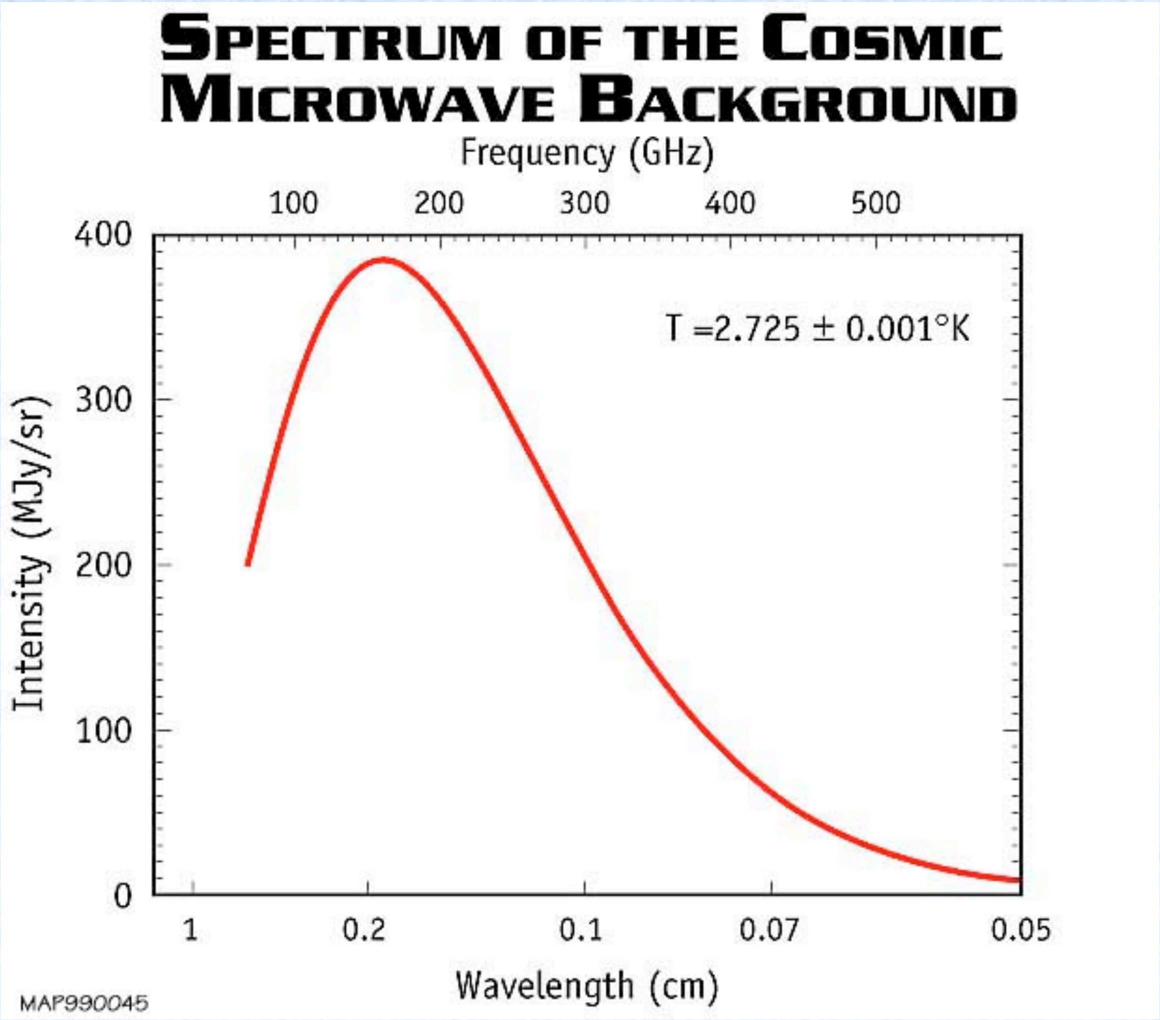
Fig. 18.2. Spectral intensity distribution of Planck's black-body radiation as a function of wavelength for different temperatures. The maximum of the intensity shifts to shorter wavelengths as the black-body temperature increases.

Is the Microwave Background Radiation Thermal?

COBE got the answer



Cosmic Microwave Background.
The CMB is a “perfect” Blackbody



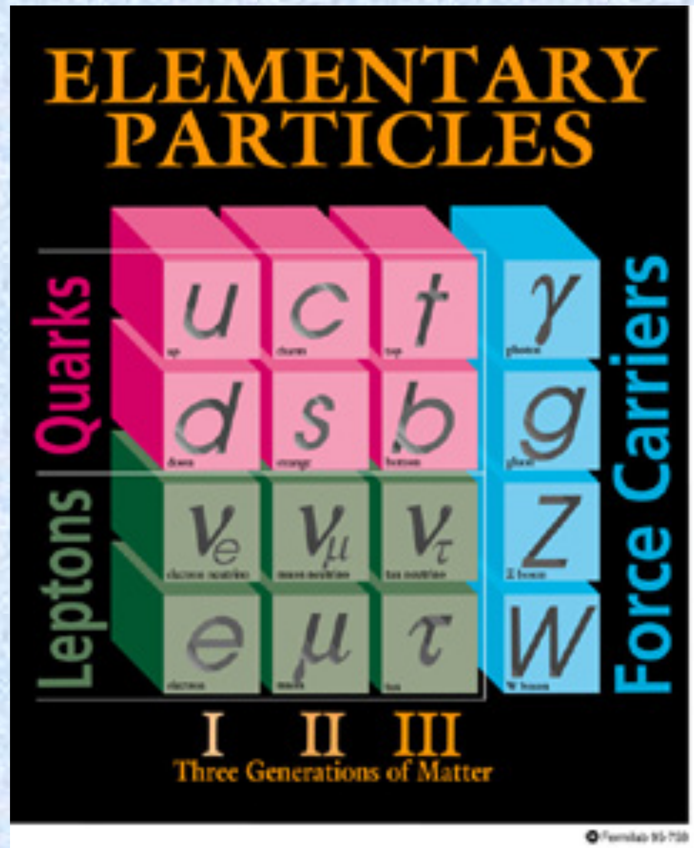
COBE FIRAS 1989

CMB properties [Blackboard]

- CMB T = 2.725 K today.
- A hot, dense universe provides an environment where matter and radiation are in **Thermodynamic Equilibrium.**
- Universe becomes transparent at T < 3000 K.
- **The photon gas cooled due to the expansion of the universe.**
  - Expansion is adiabatic
  - Scaling of T with scale factor (or redshift)
  - Expansion preserves blackbody
  - CMB photons are a relic of the epoch when matter and radiation were in equilibirum, I.e. interacted frequently. And the background radiation was much hotter then. Hot enough to ionize hydrogen and create free electrons.

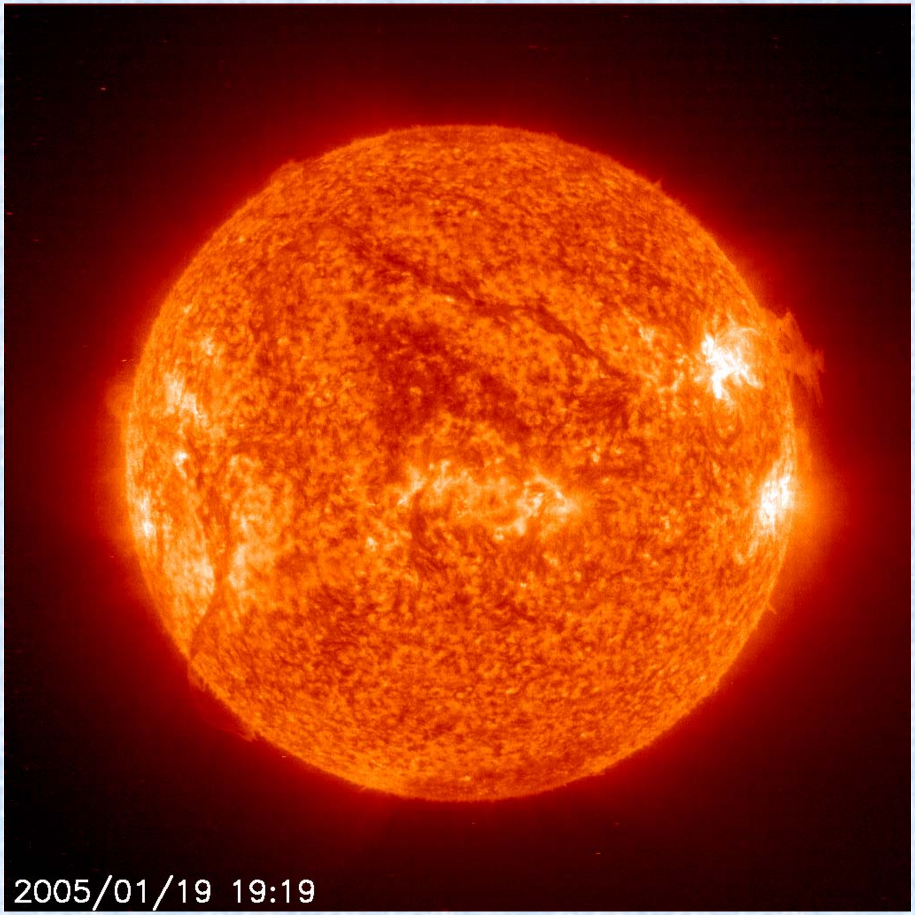
What is the universe made of? "normal" matter

- Ordinary matter is made for the most part of protons and neutrons, i.e. quarks up and down.
- For this reason we refer to ordinary matter as baryonic matter (the electrons contribute only a small fraction of the mass)
- Neutrinos should not have mass in the standard model, but they do (neutrino oscillations) [See HW problem 4]
- No antimatter is observed!



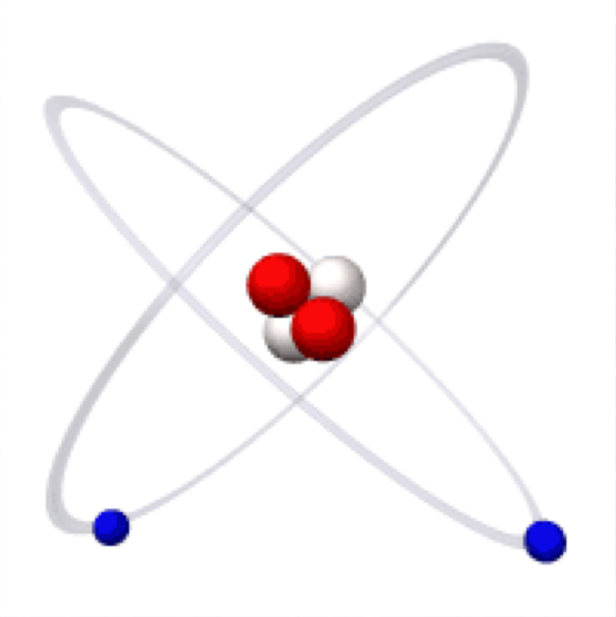
What baryons? Chemical composition of stars.

- The sun is made of:
- Hydrogen (74% by mass)
- Heavier elements (1%) commonly referred to as "metals" by astrophysicists
- Helium (25%)
- This is way more He than expected from a universe initially made of Hydrogen where Helium is produced in stars…
- This is a common problem: Helium abundance is always ~25%



Helium abundance. The Big Bang solution

- He is produced in the early Universe when T was high enough (above ~10^9 K) to allow for nuclear fusion. *Recall* $T(t) = T_0\, a_o / a(t)$, *so the scale factor was ~3e5 times smaller during the epoch of nucleosynthesis than at the surface of last scattering.*
- Why do you need high temperature to do fusion?
- We will see later on that the Big Bang theory predicts exactly the abundance of all heavy elements. Note: this is the third pillar of the Big Bang theory (+ Hubble Expansion + CMB)



Week 1: Review

1. Cosmological models use the same physical laws that we study in the laboratory and are both motivated and tested by observations.
2. Copernican, or Cosmological, Principle.
   - The Universe is the same throughout.
   - **ONLY ON LARGE SCALES ≥ 100 MPC. ON SMALL SCALES IT IS NOT!!!**
   - Observations of CMB and galaxy surveys are the same in every direction (isotropic). Since there is no special place, it is the same in every direction from every point, and therefore homogeneous.
3. The Universe is not time invariant. Only the weak form of the cosmological principle applies.

Week 1: Review

- Empirical foundations of the Big Bang theory. I:
  - The night sky is dark.
    - Inconsistent with an eternal, static and infinite Universe
  - The spectra of distant galaxies appear "redshifted" as if the distance between us and them was increasing with time.
    - In the Big Bang theory this is interpreted as due to the expansion of the Universe.
  - The ages of stars (and galaxies) are found to be less than $1/H_0$, consistent with the finite lifetime of the universe.

Week 1: Review

- Empirical foundations of the Big Bang theory. II:
  - The Universe is filled with an almost perfectly isotropic blackbody radiation at a temperature of 2.7 K. This is interpreted in the Big Bang theory as the remnant of an hot state when radiation and matter were in thermal equilibrium.
    - **[Note: You should be able to derive the scaling of the temperature of BB radiation with scale factor or redshift.]**
  - The baryonic matter in the universe is found to have a very regular chemical composition, mostly H, He and tiny amounts of heavier matter. Stars cannot produce all the He. Hence the universe must have been hot enough and dense enough for nucleosynthesis to occur before the first stars formed.

End Week 1

- HW #1 due Friday; please upload pdf file through Gaucho Space.
- Read [R] ch. 3.
- See you on Monday!