INTRODUCTION TO COSMOLOGY

PHYS 76000

WHO I AM

- Professor Maller
- email: amaller@CityTech.Cuny.Edu
- Research: galaxy formation, quasar absorption systems, large scale clustering, gravitational lensing

TEXTS

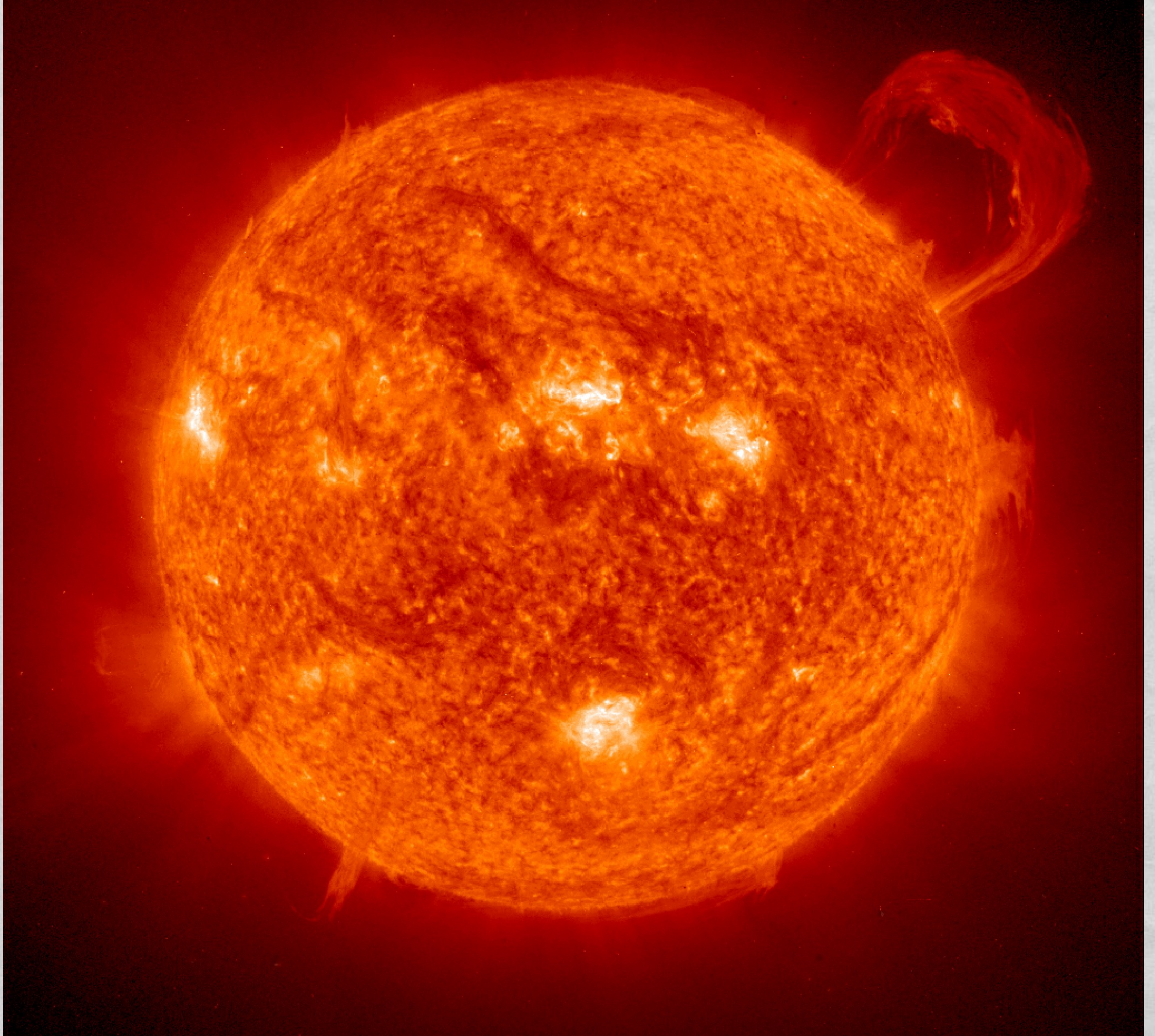
- Modern Cosmology - Scott Dodelson, This is todays standard reference, not so easy to learn from but a good reference to have.
- Introduction to Cosmology - Barbara Ryden, This is an undergrad level book, but very clear good to learn from.
- Cosmological Physics - John Peacock, Good overall coverage of cosmology somewhere in-between the first two books. A bit out of date.

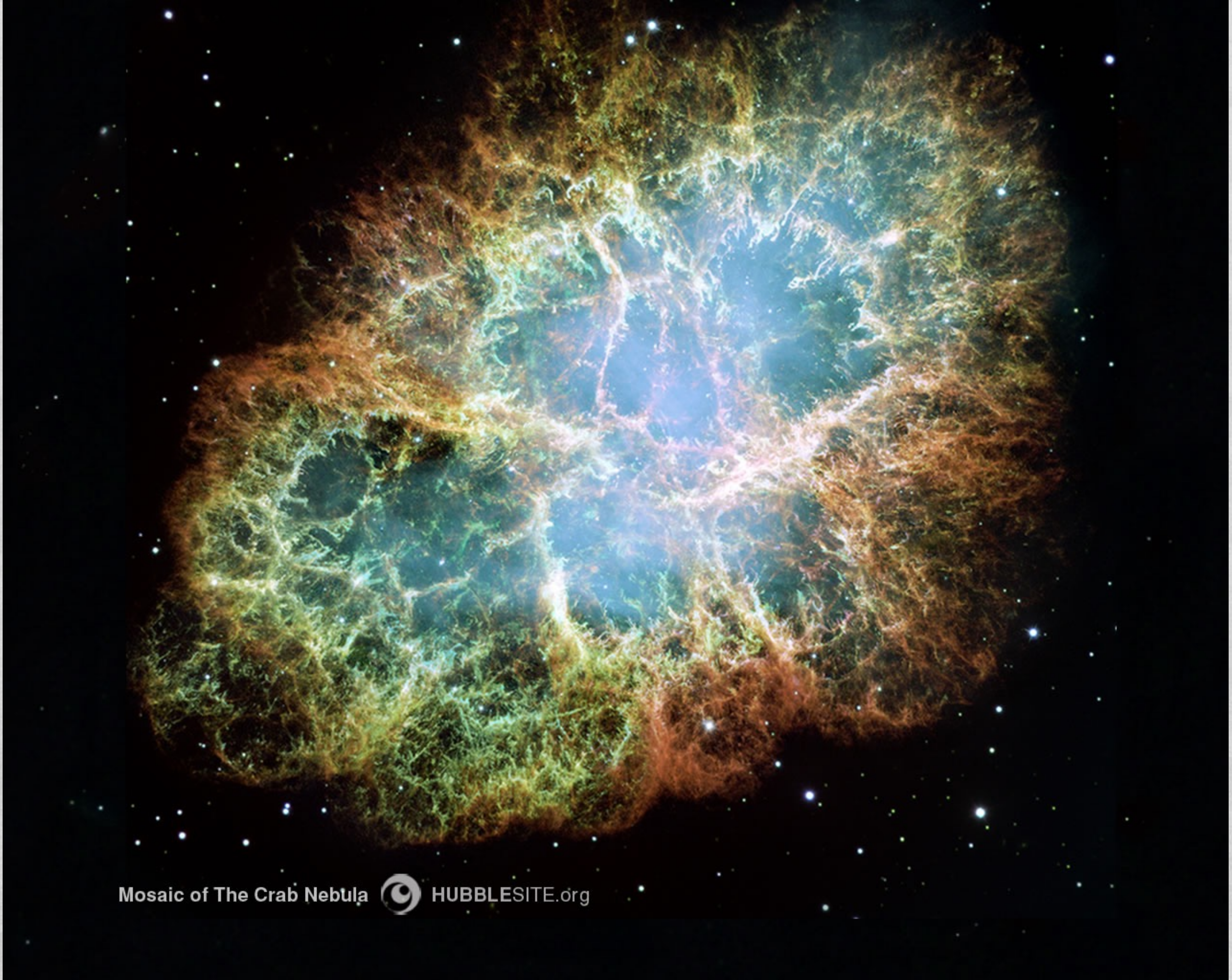
AN INTRODUCTION

- Basic Astronomy Terms
- What is Cosmology?
- The early history
- Observational Cosmology
- What we will cover.

THE NIGHT SKY

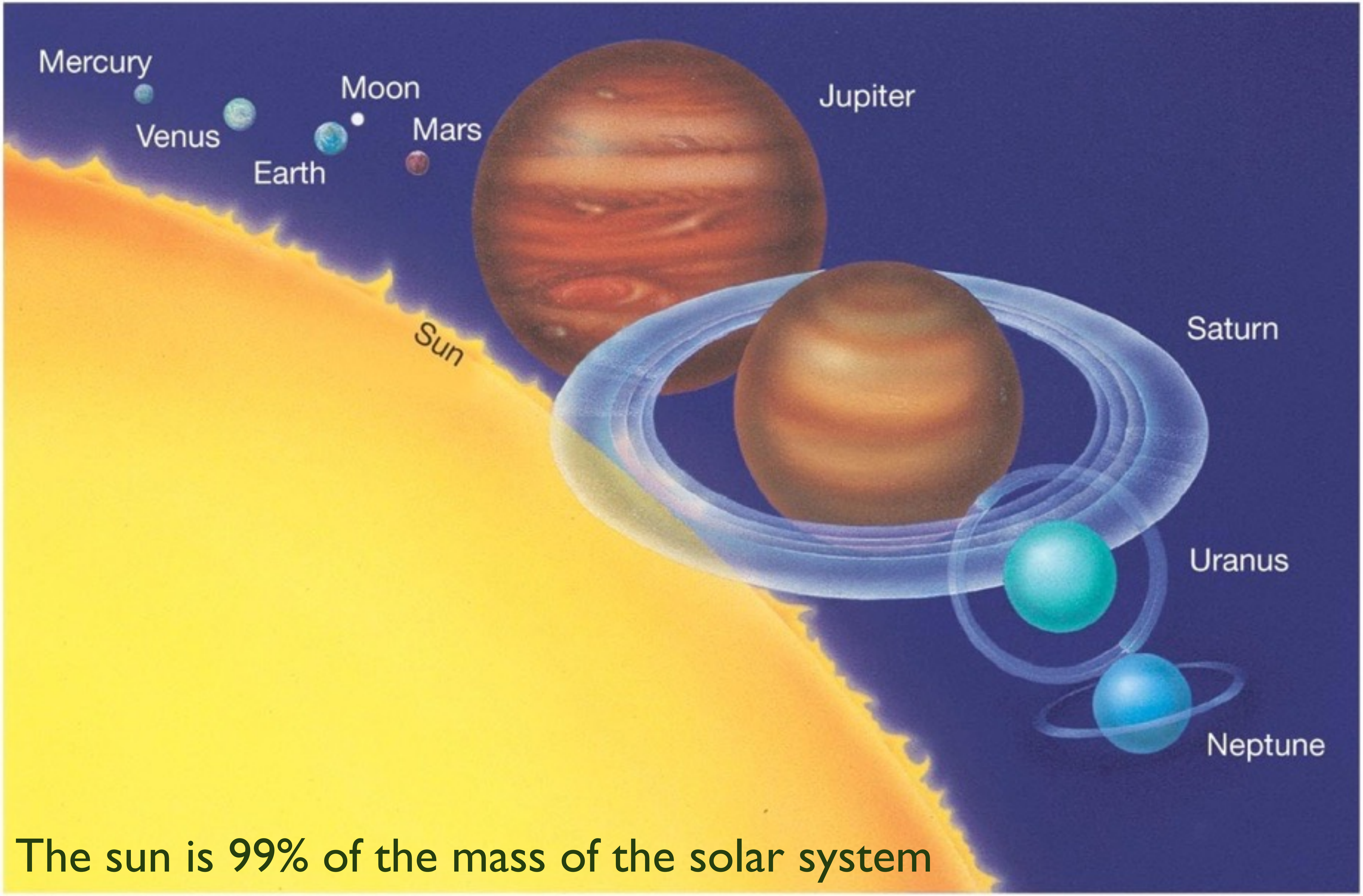
- Looking up at the night sky you may see a few different things; planets, stars and the Milky Way.
- Using a telescope one can see more types of objects including nebula and galaxies.
- This is only using visible light, but modern astronomy makes use of every part of the electromagnetic spectrum, radio, millimeter, infrared, ultraviolet, X-ray and γ-rays.




Mosaic of The Crab Nebula
HUBBLESITE.org

PLANETS

- Planets are made of rock and metal or hydrogen and helium gas. They revolve around stars. The planets we know the best are the ones in our Solar system, Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus and Neptune.
- Other things can orbit stars; astroids, comets and ice balls like Pluto. To be a planet one has to be massive enough to dominate your orbit.
- We now know of thousands of planets around other stars, called exo-planets. And we get closer to finding one similar to Earth.

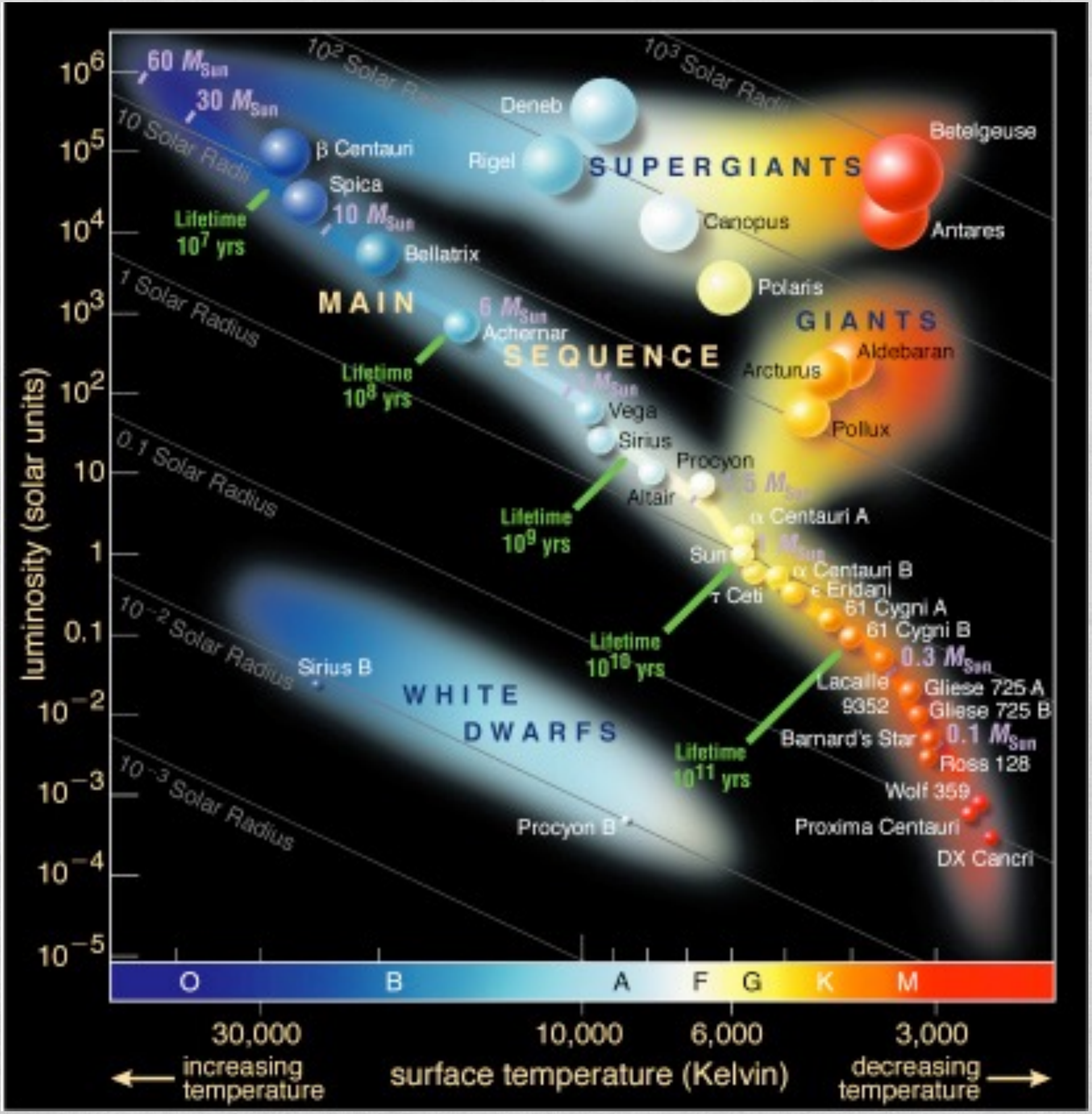


The sun is 99% of the mass of the solar system

STARS

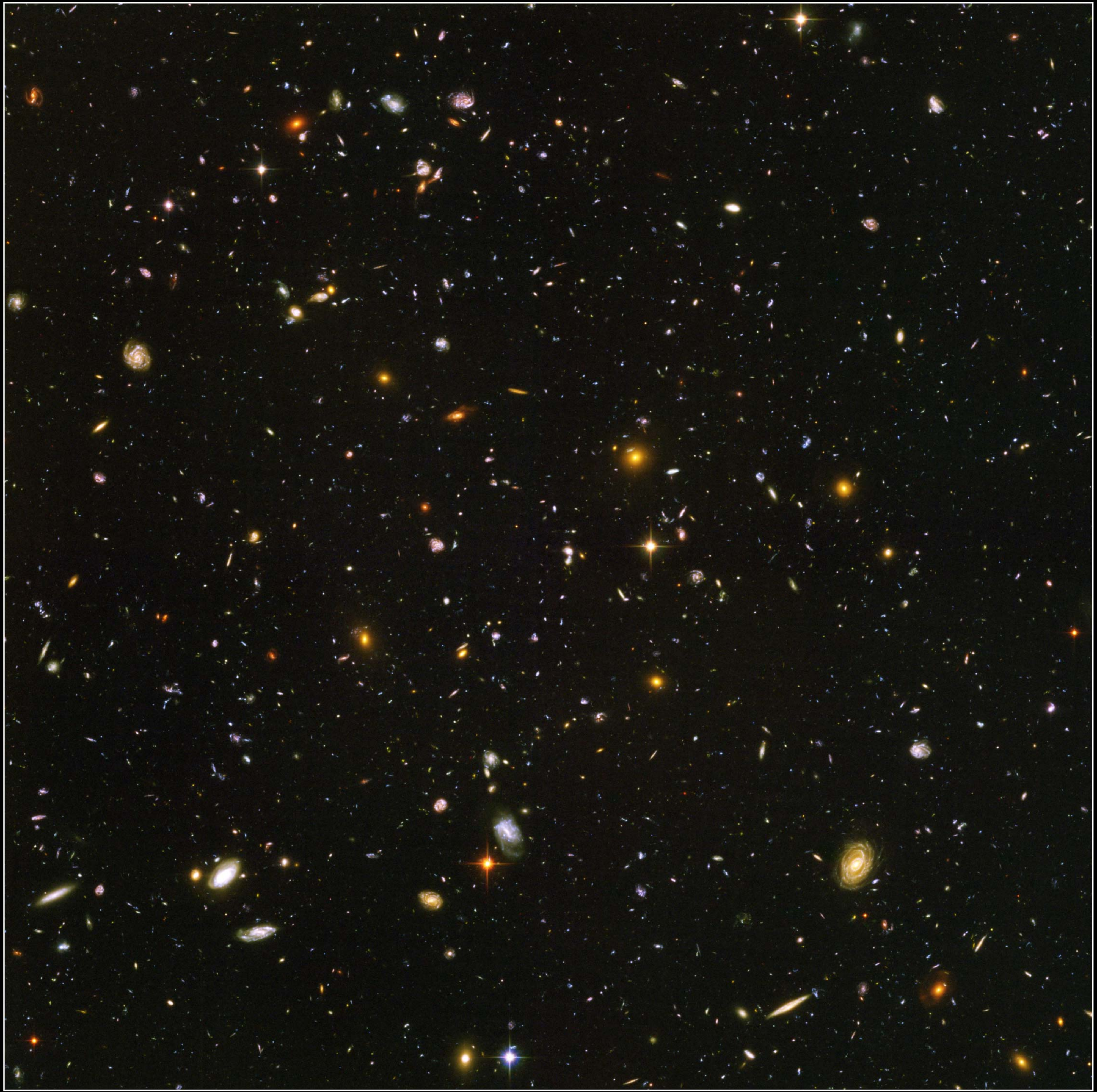
- Stars are the main thing you see in the Universe, because they emit light.
- A star is basically a ball of hydrogen and helium gas where in the core temperatures are hot enough for fusion to occur.
- The temperatures in the cores of stars range from 10 million to 100 billion K. The surfaces of stars range from 3,000 to 30,000 K.
- Stars live a finite life, eventually they run out of fuel. Then, depending on their mass they may just remain as a glowing ember or they may explode as a supernova.

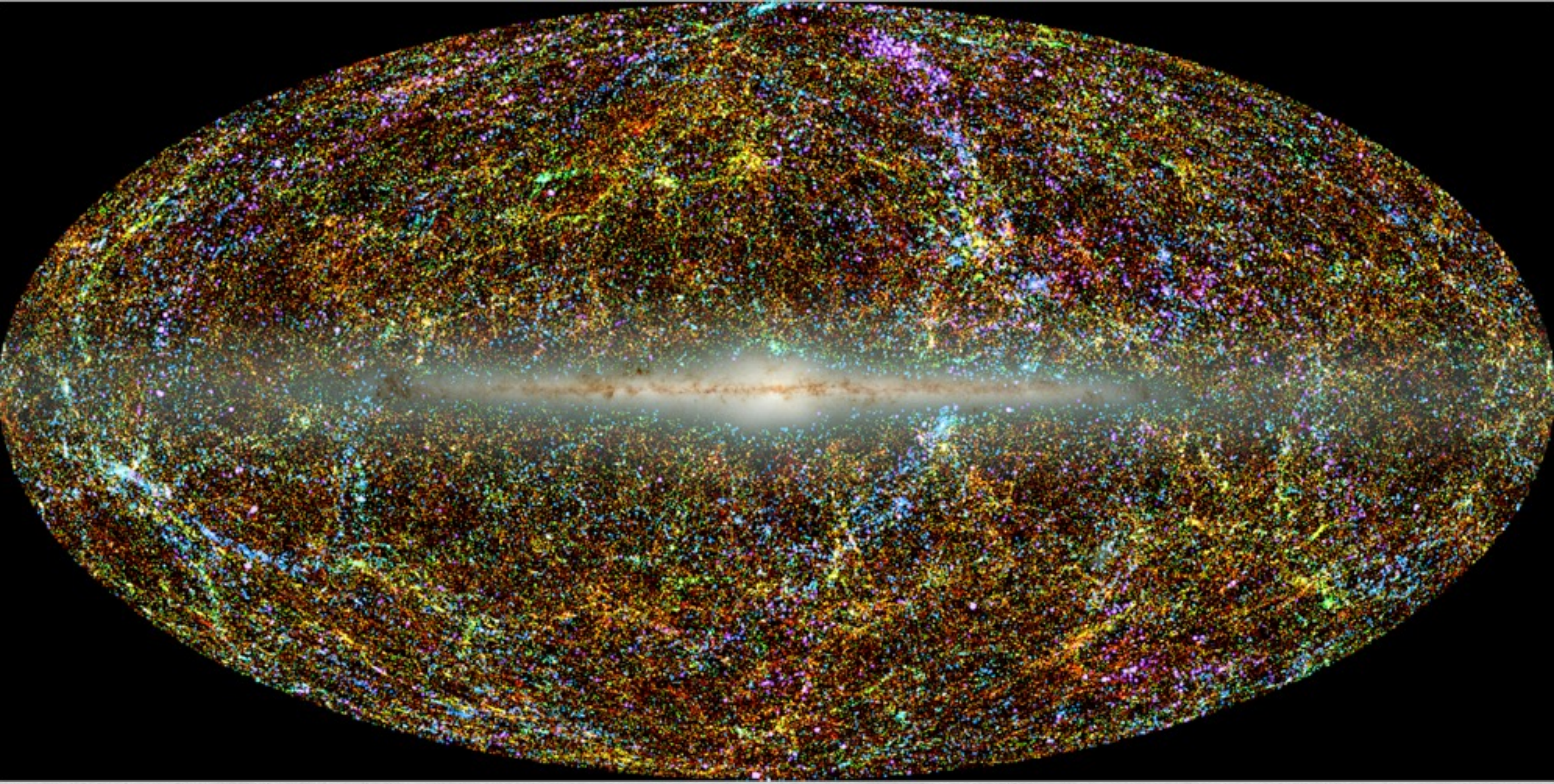
Most stars occupy what is called the main sequence. This means they are burning hydrogen in their core. Stars farther along in their evolution burn heavier elements and are called giants.



GALAXIES

- Stars and planets live in galaxies.
- Also gas, dust, black holes, neutron stars, white dwarfs and pretty much everything interesting lives in a galaxy.
- Between the galaxies is very very low density hydrogen and helium and not much else.
- Thus galaxies are the basic tracer of the universe. When we talk about studying the universe we are mostly talking about studying the behavior of millions and millions of galaxies.





Here color reflects the density of galaxies, not their true colors. The galaxy in the center is supposed to be our own Milky Way, but it is just painted on. We detect the Milky Way by its obscuration of galaxies behind it.

COSMOLOGY

- Cosmology is the study of the evolution of the universe - its past and its future.
- Since the universe changes very slowly on the scales of our lives, we use the finite speed of light to look back in the past by looking at far away objects.
- We can also look for astrophysical relics from an earlier time that are still around today.

ASTRONOMY UNITS

- The standard units in astronomy are:
  - Length - pc, kpc, Mpc (also the AU for solar systems)

    An AU is the Earth - Sun distance.
  - Time - yr, Myr, Gyr
  - Mass - solar mass, $M_\odot$.
  - Luminosity - solar luminosity $L_\odot$, or magnitudes.

LENGTH

- The standard unit of length in astronomy is the parsec, not the light year. 1.0 pc = 3.26 lyr.
- A parsec is the distance an object must be from the sun for it to have a parallax of one arc second.
- Thus it is basically the height of a right triangle whose base is 1 A.U. and angle is 1 arc second.

TIME

- The standard unit of time in astronomy is Myr or Gyr.
- The life time of stars is between 10,000 years and 100Gyr.
- The Universe is 13.7 Gyr old.
- Our Sun is 5Gyr old and has about 5Gyr left to live.

MASS

- The standard unit of mass in astronomy is a solar mass, $M_\odot = 1.9891\times10^{30}$ kg or 1.19×10^{57} times the proton mass.
- The Milky Way is of about $6\times10^{10}\ M_\odot$ and the largest structures in the Universe or of order $10^{15}\ M_\odot$.
- The Earth is 5.97×10^{24} kg so $3\times10^{-6}\ M_\odot$. Jupiter the most massive planet is 318 Earth masses or $0.000955\ M_\odot$.

LUMINOSITY

- In astronomy we usually measure luminosity which is power, or energy per time.
- The Sun is used as a standard unit. The luminosity of the Sun is 3.85×10^{26}W or 1 $L_{\odot}$.
- A common unit for energy in astronomy is the erg, 1 erg = 10^{-7} J. A supernova releases about 10^{51} ergs in a few seconds.

THE BEGININGS OF COSMOLOGY

OVERVIEW OF COSMOLOGY

- 1915 Einstein publishes General Theory of Relativity

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- This allows for the first time for rigorous cosmological models.
- A cosmological model satisfies Einstein’s field equation and the cosmological principle.

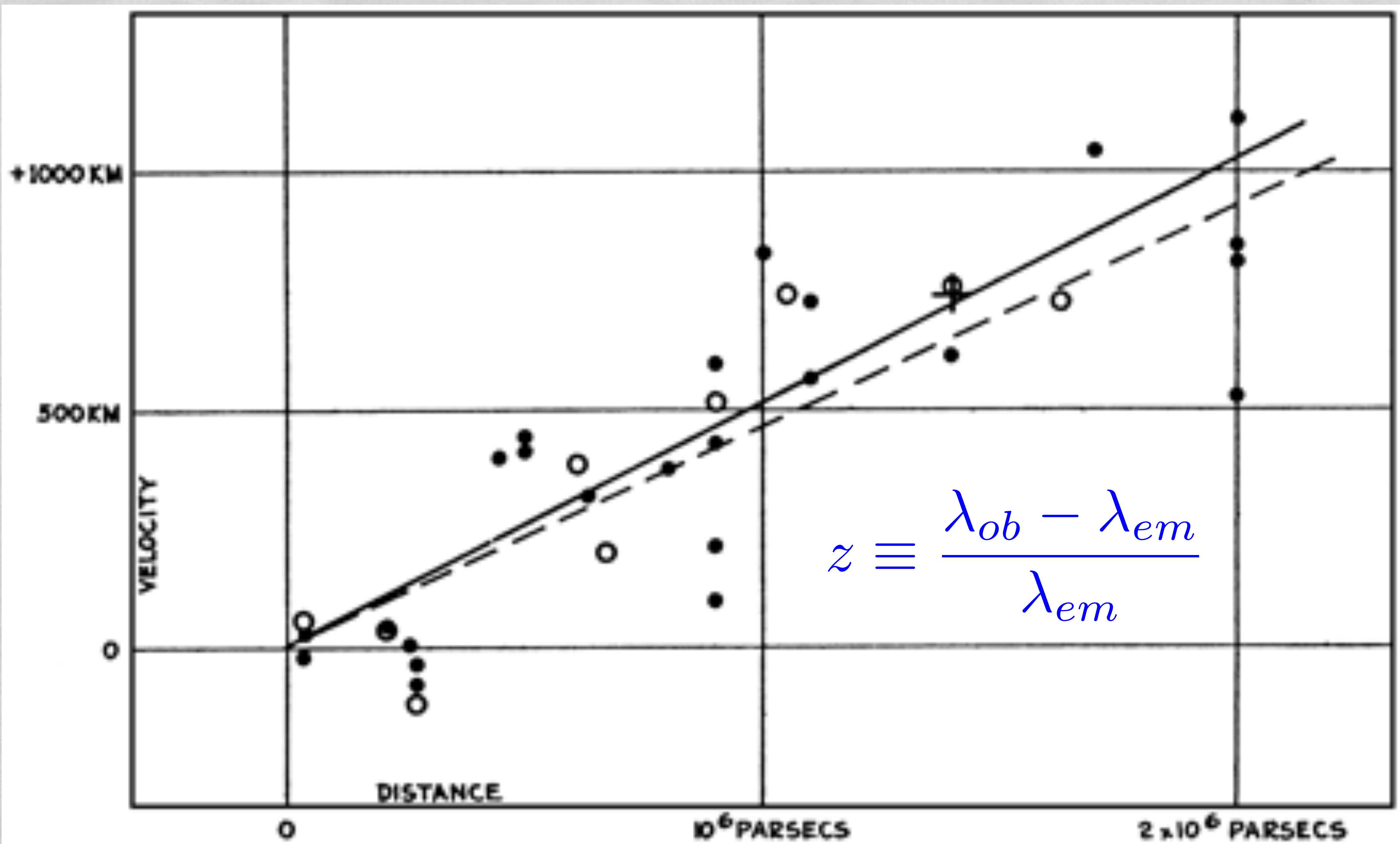
THE COSMOLOGICAL PRINCIPLE

- The assumptions of cosmology are that the Universe is homogenous (on large scales) and isotropic.
- Homogenous - that the universe is the same everywhere.
- Isotropic - that the universe looks the same in every direction.

THEORETICAL COSMOLOGY

- In 1917, Einstein wrote down the first cosmological model, a static universe. But to get the universe to be static he had to introduce a new force to counteract gravity, the cosmological constant.
- Shortly afterwards de Sitter pointed out that the universe could also be undergoing constant acceleration. Both were concerned that the Universe not evolve with time.
- In 1922-1924, Friedman found the solution for an expanding or contracting universe, but the importance of this was not widely recognized.
- In 1927, Lemaitre publishes a theory of expanding Universe, he even includes support from observation.
- In 1929, Hubble shows the Universe is expanding, Hubble's Law.

HUBBLE'S LAW


+1000 KM
500 KM
0
VELOCITY
DISTANCE
0
10^6 PARSECS
2 x 10^6 PARSECS
$z \equiv \frac{\lambda_{ob} - \lambda_{em}}{\lambda_{em}}$

FLRW COSMOLOGY

- In 1935, Robertson and Walker proved that the metric used by Friedman and Lemaitre is the only isotropic metric for space-time.

$$ds^2 = a(t)^2[dr^2 + S_k(r)^2 d\Omega^2]$$

- Taken together this is called the 'standard' cosmology, or the Friedman-Lemaitre-Robertson-Walker cosmology.
- Often the metric is called the Robertson-Walker metric while the equations of motion are called the Friedman or Friedman-Lemaitre equations.
- The special case of a Universe that also has time symmetry (like Einstein's first model) is called de Sitter space.

OBSERVATIONAL COMSOLOGY

OBSERVATIONAL COSMOLOGY

- So far we have discussed cosmology as a metric for a space-time that follows the cosmological principle.
- At the time there where two competing interpretations of this theory. One, the Universe could be expanding but new matter constantly appears to keep it basically unchanged. This was called the steady state theory. In the other you trace the universe back till it becomes so hot and dense eventually you have just a singularity called a big bang.

THE BIG BANG THEORY

- The big bang theory made a couple of observable predictions, though at the time no one actually thought they would be observed.
- First, at some point the Universe's average density would be the same as the surfaces of stars, at this point radiation would be trapped with the matter.
- Only as the Universe expanded would the density decrease and light escape. This relic radiation is referred to as the cosmic microwave background.

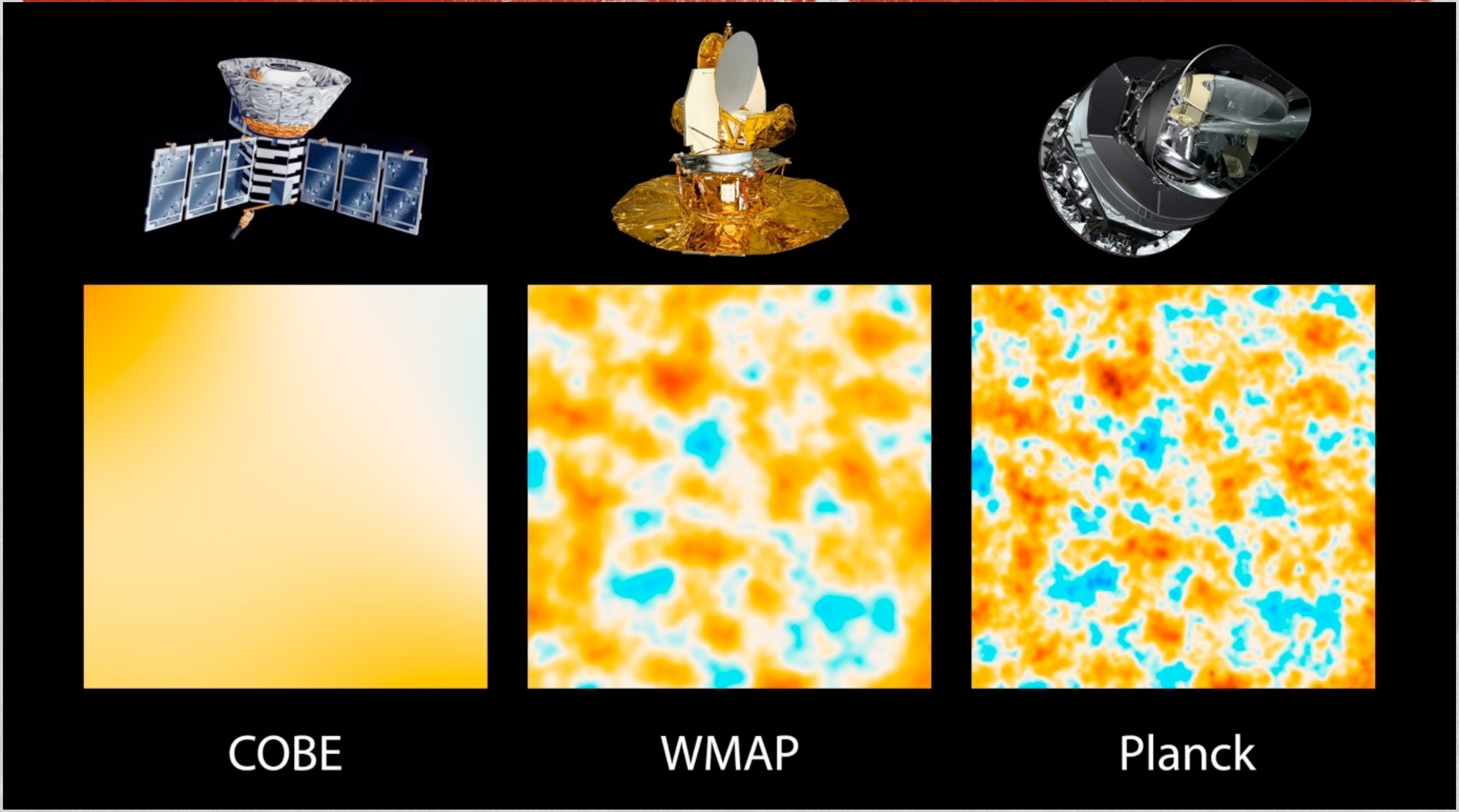
THE BIG BANG THEORY

- The big bang theory made a couple of observable predictions, though at the time no one actually thought they would be observed.
- Second, even farther back in time the Universe would be so dense it would be as dense as the cores of stars. This means fusion would occur.
- Big Bang Nucleosynthesis predicts the amount of helium and other light elements that would be formed in this first 3 minutes.

THE COSMIC MICROWAVE BACKGROUND

- In 1965 Penzias and Wilson were two scientist working on microwave transmission for Bell Labs.
- They had a large, for the time, microwave antenna and had this problem that they were getting background noise no matter what they did.
- The background was uniform and from all directions. Not knowing what to make of this they went down the road to the Princeton Physics Department where they were told they had just discovered the cosmic microwave background.

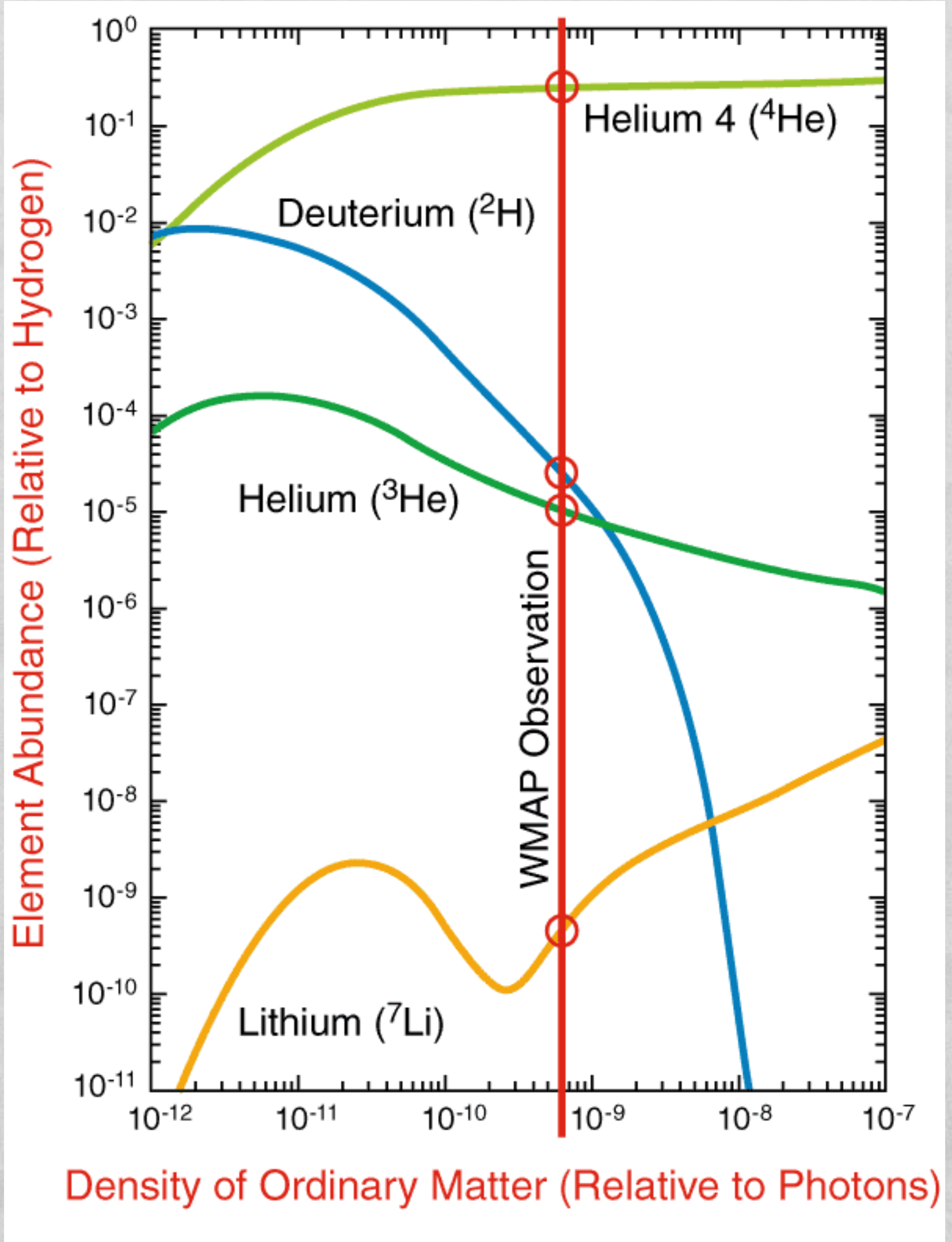
THE COSMIC MICROWAVE BACKGROUND



Big Bang Nucleosynthesis predicts the relative abundances of light elements depending on other cosmological parameters.

Elements are also produced in stars, so it is hard to find pristine gas that reflects the abundances 3 minutes after the big bang.

However, astronomers beleive they have done this and the abundances match up perfectly with the cosmology parameters measured from the CMB.



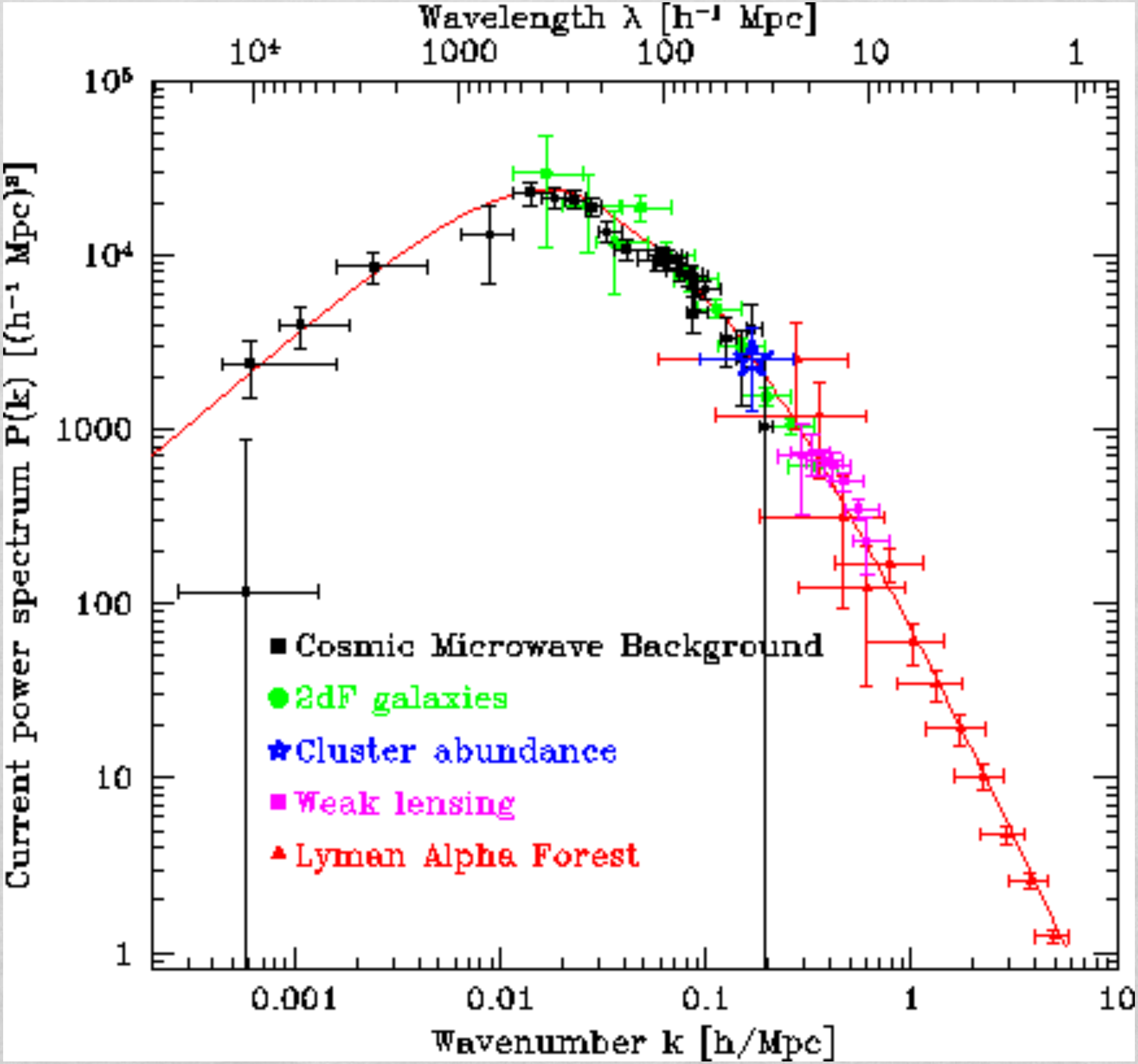
DENSITY FLUCTUATIONS

- If the Universe was truly how we have been describing it, perfectly smooth and homogenous, then there would be no people.
- In fact the Universe is very inhomogenous on small scales.
- How does this come about?

DENSITY FLUCTUATIONS

- Any over-dense region in the universe will become denser as gravity wins over expansion, while under-dense regions will become less dense as expansion wins over gravity.
- Thus the initial density fluctuations in the Universe are the seeds for all future structure.
- The spectrum of density fluctuations tells us about the physics of the very early universe and the growth of fluctuations tells us about the forces in the universe.

Measuring the amplitude of fluctuations on different scales is one of the main diagnostics of cosmological models.



DARK MATTER

- Finally, through other observations we have learned of the necessity for dark matter.
- Basically, the light emitted from stars does not account for sufficient mass to account for the motions of stars and galaxies.
- Very detailed studies have ruled out just about any other from of ordinary matter.
- Dark matter seems to be something that fundamentally does not interact with electromagnetic fields.

THE ΛCDM MODEL

- Our current best cosmological model is called the ΛCDM model because the energy/mass terms include both dark energy and dark matter.
- This model has 6 parameters; Ω_{dm}, Ω_b, Ω_Λ, H_0, σ_8 and n_s.
- This 6 seem to be sufficient to describe the current observations, but there are also many open questions.

COURSE OUTLINE

1. GR and the RW metric
2. The Friedman Equation
3. Single component universes
4. Multiple-component universes
5. Cosmological Parameters
6. Dark Matter
7. Alternatives to GR
8. Cosmic Microwave Background
9. Big Bang Nucleosynthesis
10. Inflation
11. The Very Early Universe
12. Structure Formation
13. Galaxy Formation