ASTRONOMY 113 – INTRODUCTION TO COSMOLOGY

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Time/Place: T/Th 3:20–4:55 E&MS B210
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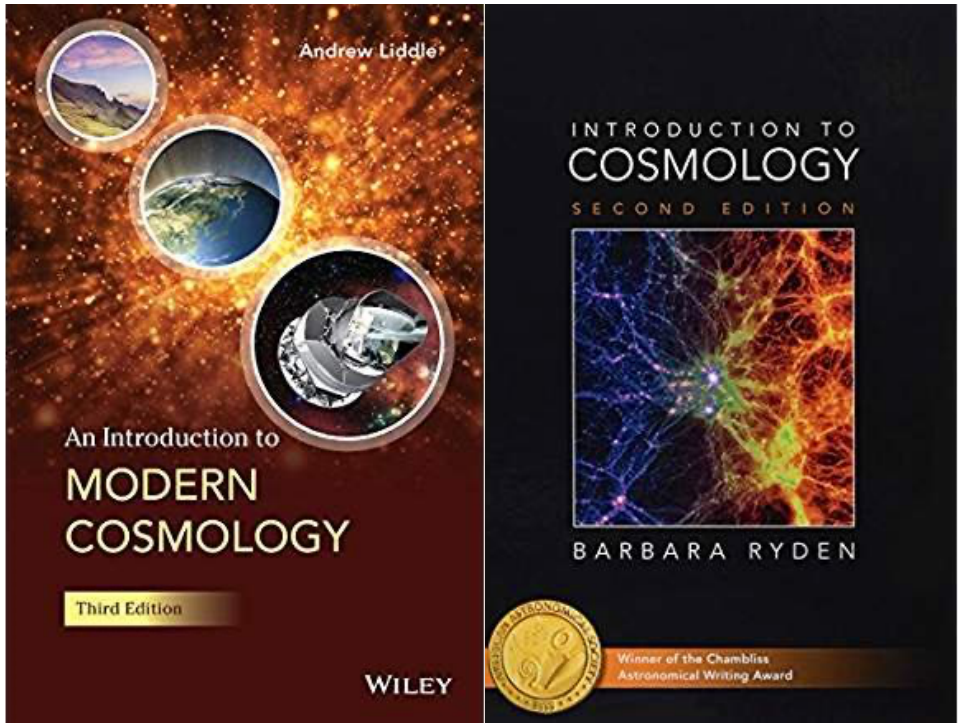
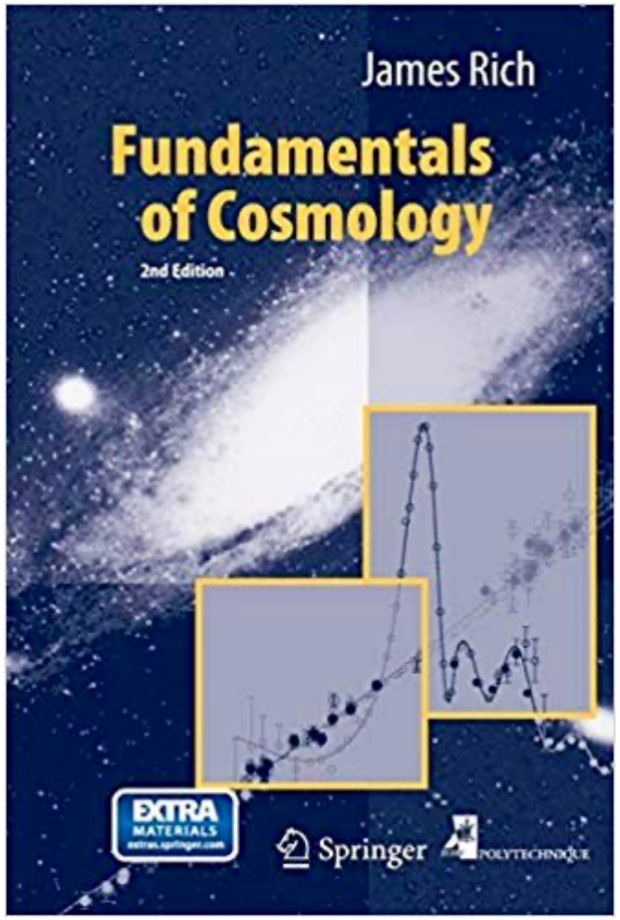
TA: Alexa Villaume (Th 10–11 ISB 126)

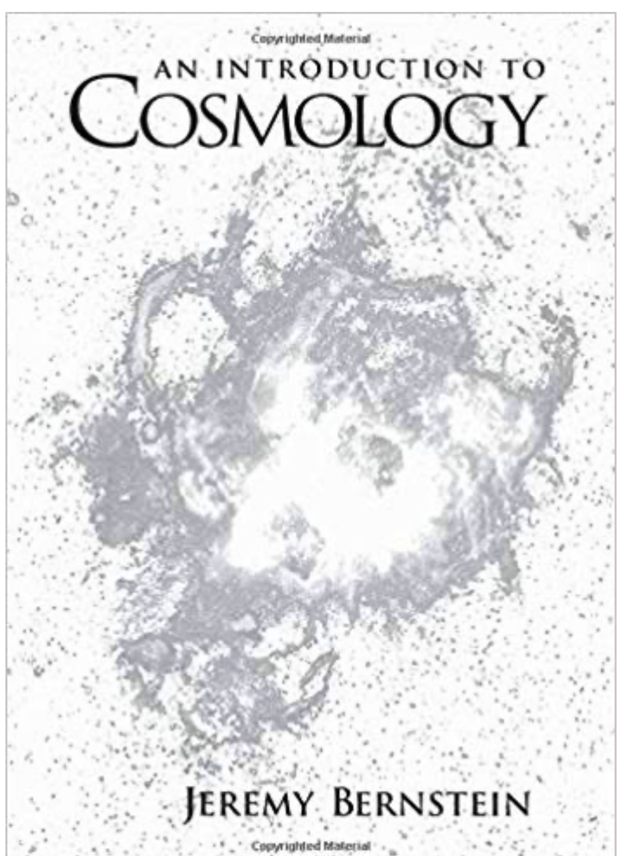
Recommended Books:
B. Ryden, An Introduction to Cosmology
A. Liddle, An Introduction to Modern Cosmology

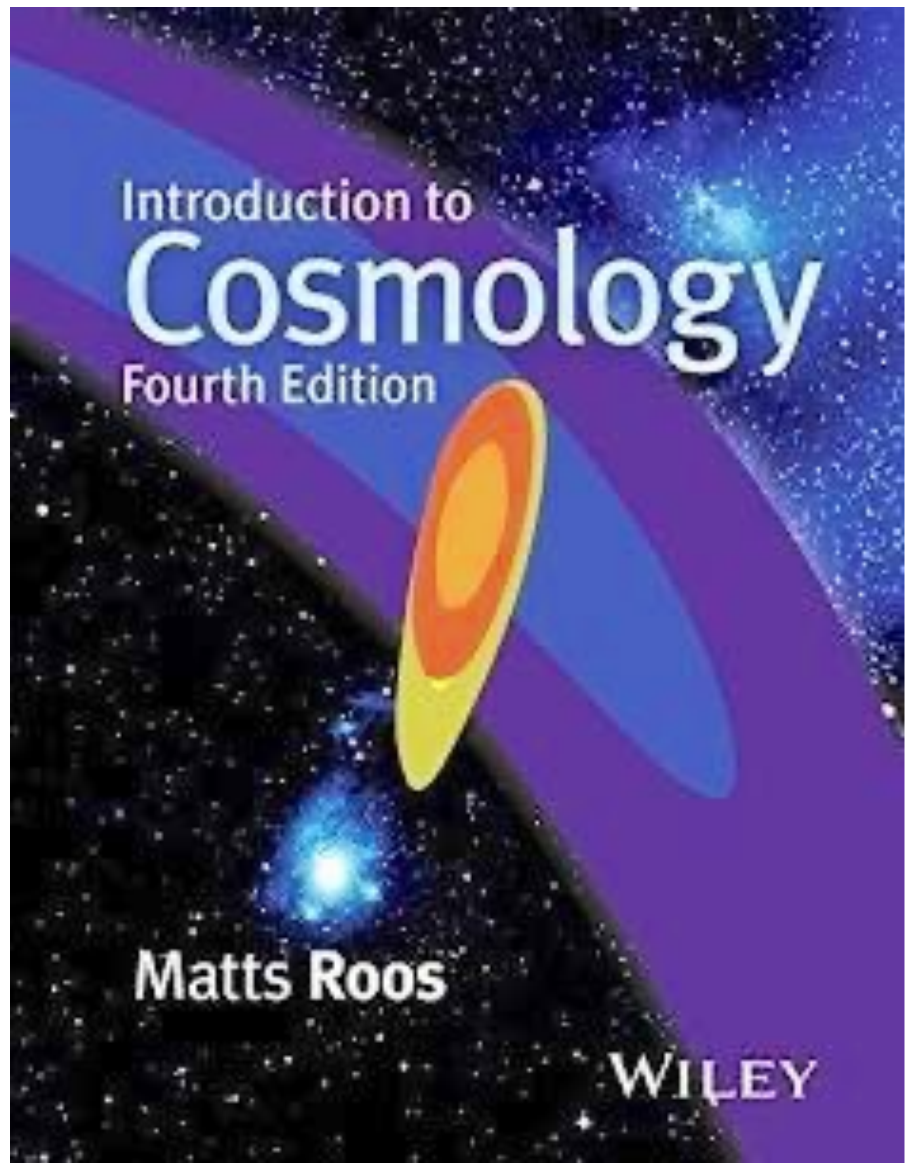


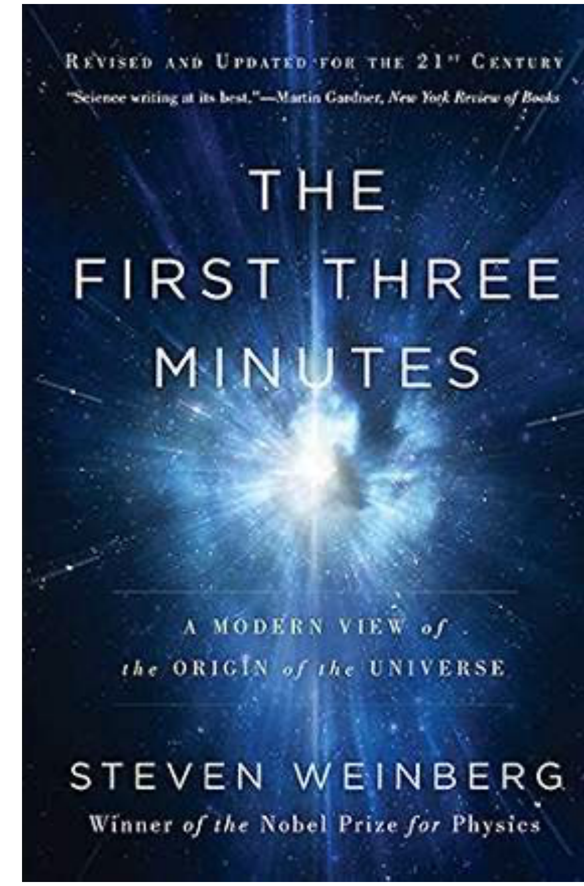
Total Course Grade: 20% class participation, 20% homeworks, 30% midterm, and 30% final exams.

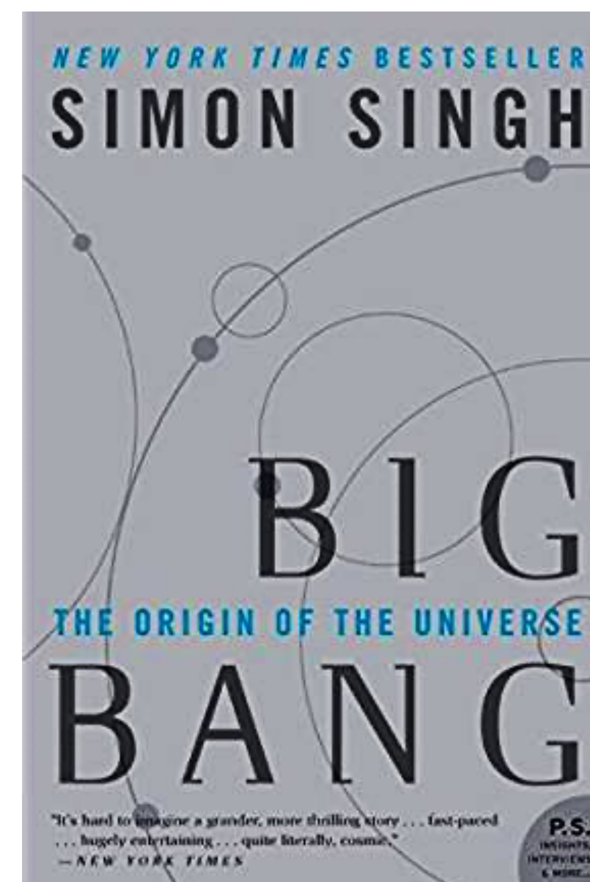
Big Bang: one of the most extraordinary, important, and awe-inspiring theories in science…..











ASTRONOMY 113: INTRODUCTION TO COSMOLOGY

I. INTRODUCTION *(Chapt. 1-2 Liddle, Chapt. 1-2 Ryden)*
1.1 Prologue
1.1 The Cosmological Principle
1.2 Particles in the Universe
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1.5 Doppler effect

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2.1 Homogeneity and Isotropy
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III. NEWTONIAN COSMOLOGY *(Chapt. 3-5 Liddle, Chapt. 4 Ryden)*
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IV. RELATIVISTIC COSMOLOGY *(Chapt. 4 Liddle, AdvTop. 1 Liddle, Chapt. 3 Ryden)*

4.1 A Quick Primer to Non-Euclidean Geometries

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5.1 Tired Light

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VI. MEASURING COSMOLOGICAL PARAMETERS *(AdvTop. 2 Liddle, Chapt. 7 Ryden)*

6.1 Age of the Universe

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VII. COSMIC MICROWAVE BACKGROUND *(Chapt. 9 Ryden, Chapt. 10 Liddle)*

7.1 Discovery of the CMB

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7.3 Origin of the CMB
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VIII. THE EARLY UNIVERSE *(Chapt. 12, AdvTop. 3,4 Liddle, Chapt. 10 Ryden)*

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IX. INFLATION *(Chapt. 13 Liddle, Chapt. 11 Ryden)*

9.1 The Inflation Solution
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X. THE FORMATION OF COSMIC STRUCTURE *(Chapt. 12 Ryden)*

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I. INTRODUCTION

1.1 PROLOGUE

Cosmology is the study of the origin and evolution of the Universe, the all of everything. The word *cosmology* comes from the Greek word *kosmos* meaning harmony or order (same root of the word *cosmetics*!)

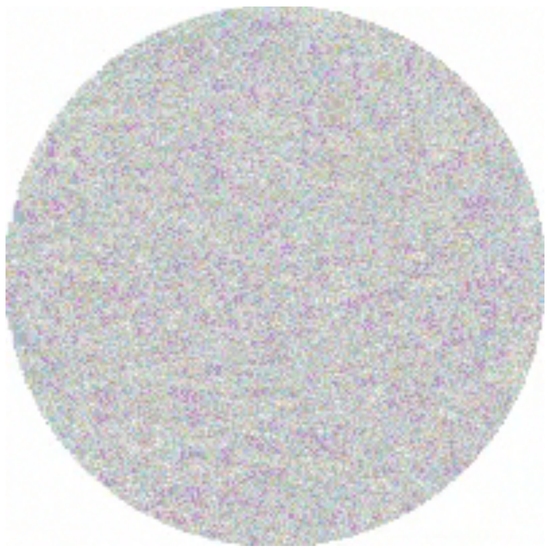
Scientific cosmology — the search for a picture of the Universe that would make sense with no mention of divine beings — began with the Greeks. They sought to look beyond the patterns of numbers to something fundamental.

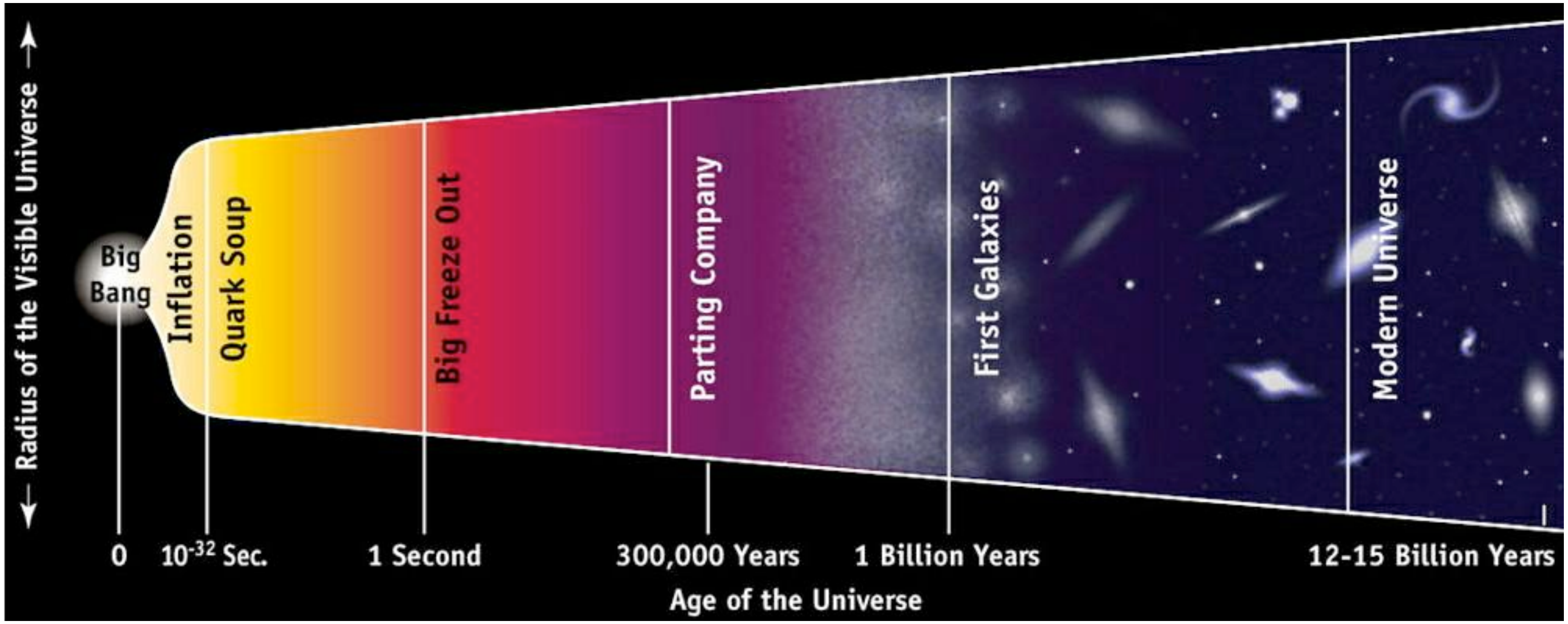
The Greek worldview was the most long-lived in the history of scientific cosmology. Closely tied to the pseudo-science of astrology, it continued from ancient Greece through medieval Islamic civilization to seventeenth-century Europe.

Underlying the Greek worldview was the philosophy of Plato. He sought a deeper level of reality than that accessible to the senses. He also pursued a simple theory about the universe which had incredible explanatory power. The result was a belief in uniform, circular motion. This belief dominated the thinking of many Western astronomers and cosmologists for two thousand years.

An Earth-centered cosmos: A reconstruction of the Greek worldview, with Earth circled by the Moon, Sun, planets, and starry zodiac.

Cosmology is the scientific quest to understand the most salient features of the Universe in which we live. At the beginning of the new millennium we ask about the nature of the *dark matter* that holds the Universe together and of the *dark energy* that is causing the expansion of the Universe to speed up. We are trying to to explain how all structures we see today, from individual galaxies to galaxy superclusters, arose from quantum fluctuations in the early Universe, some 10^{-36} seconds after the Big Bang!





A science that regards galaxies as being small objects may seem, at first glance, extremely remote from the concerns of humanity. And yet cosmology is the oldest of all sciences, as it deals with questions that are fundamental to the human condition: "Where do we come from? What are we? Where are we going?" Cosmology grapples with these questions by describing the past, explaining the present, and predicting the future of the Universe. Cosmologists ask questions such as "What is the Universe made of? Is it finite or infinite in spatial extent? Did it have a beginning some time in the past? Will it come to an end some time in the future?"

This course is about the "theory" of the Big Bang. Only a *theory*? Let's look at what "theory" means. According to the "Oxford English Dictionary":

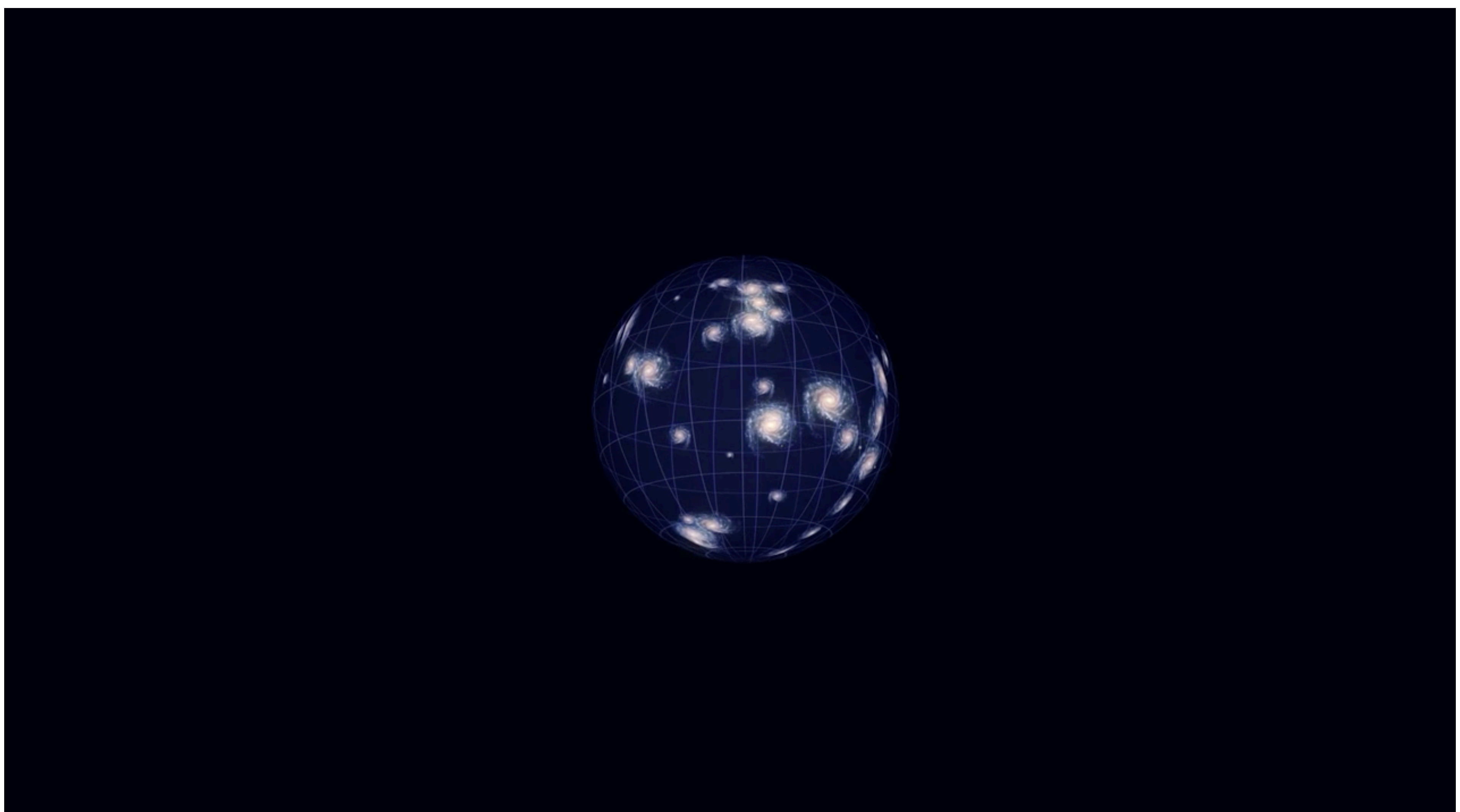
Theory 1. "A scheme or system of ideas or statements held as an explanation or account of a group of facts or phenomena; a hypothesis that has been confirmed or established by observation or experiment, and is propounded or accepted as accounting for the known facts; a statement of what are held to be the general laws, principles, or causes of something known or observed."

Theory 2. "A hypothesis proposed as an explanation; hence, a mere hypothesis, speculation, conjecture; an idea or set of ideas about something; an individual view or notion."

Obviously the two meanings are quite different from one another. And when scientists talk about the *theory* of the Big Bang, they are using Sense 1. "Just a theory" is one of the most annoying phrases ever heard by scientists. In science there is nothing "just" about a theory. A theory is supported by experimental and observational evidence.

What are the pillars of the Big Bang theory?

We live in an expanding Universe that emerged from a beginning some 13.7 billion years ago. **The evidence for this include the universal recession of galaxies at speeds proportional to their distances ("Hubble's law"), and the consistency of the ages of the oldest stars with the time back to the Bang.**



The New York Times

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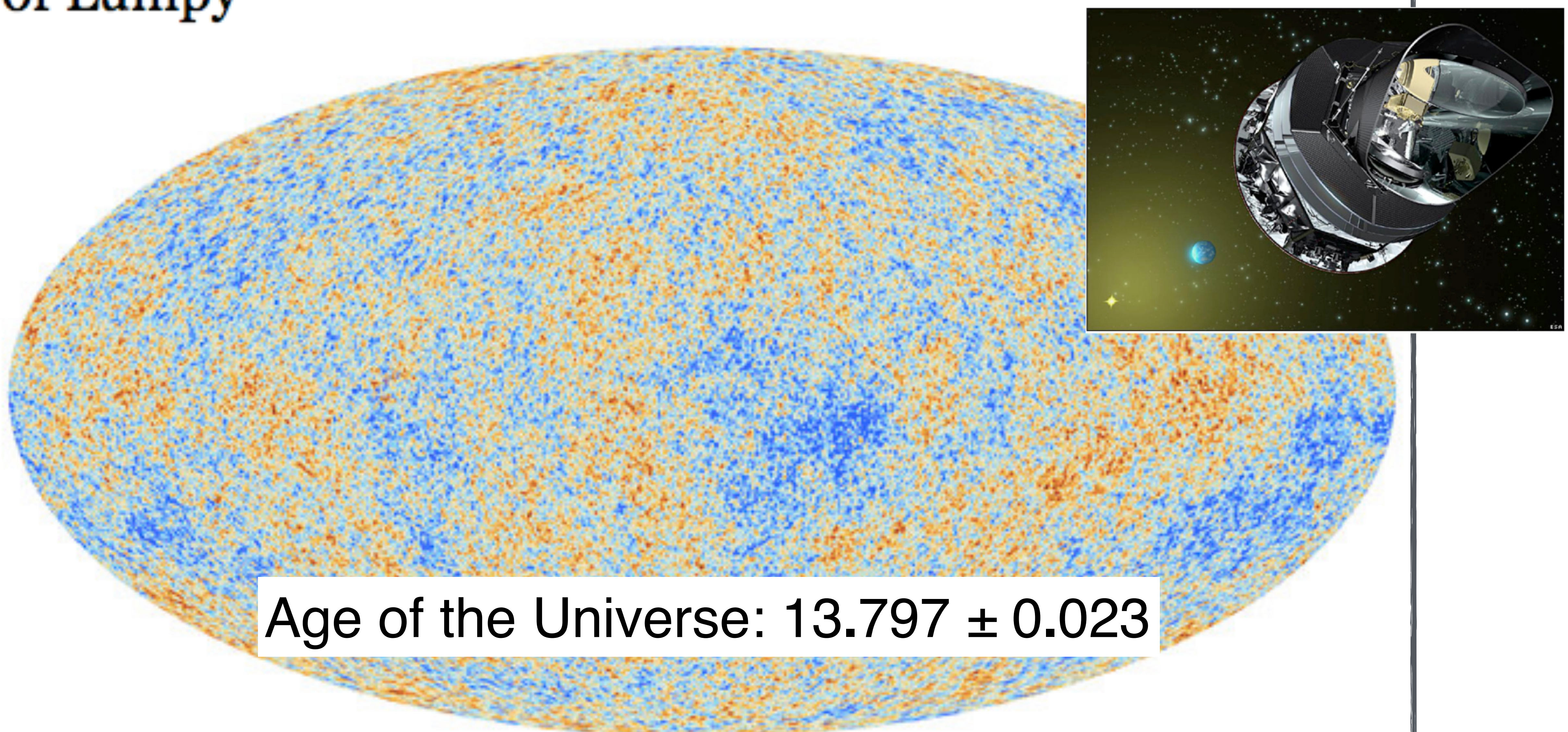
ENVIRONMENT **SPACE & COSMOS**

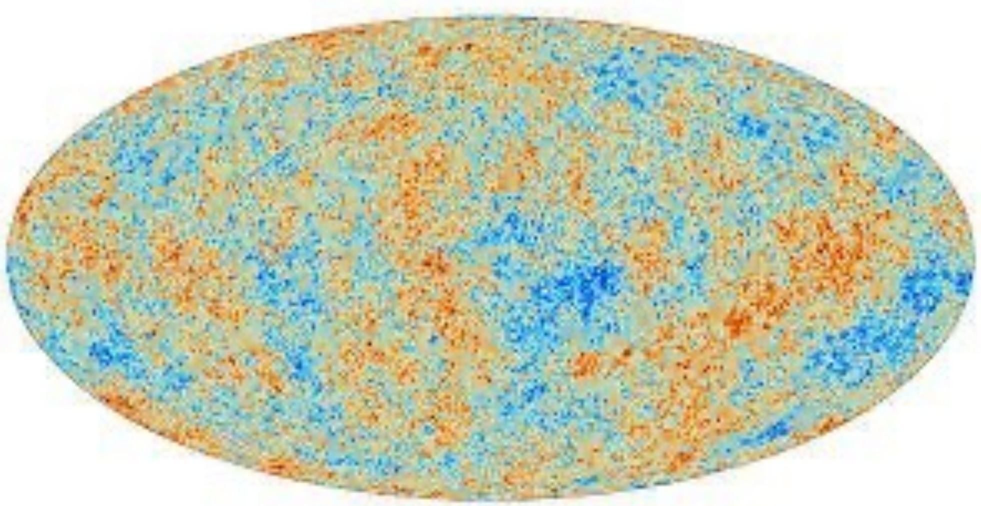
Universe as an Infant: Fatter Than Expected and Kind of Lumpy

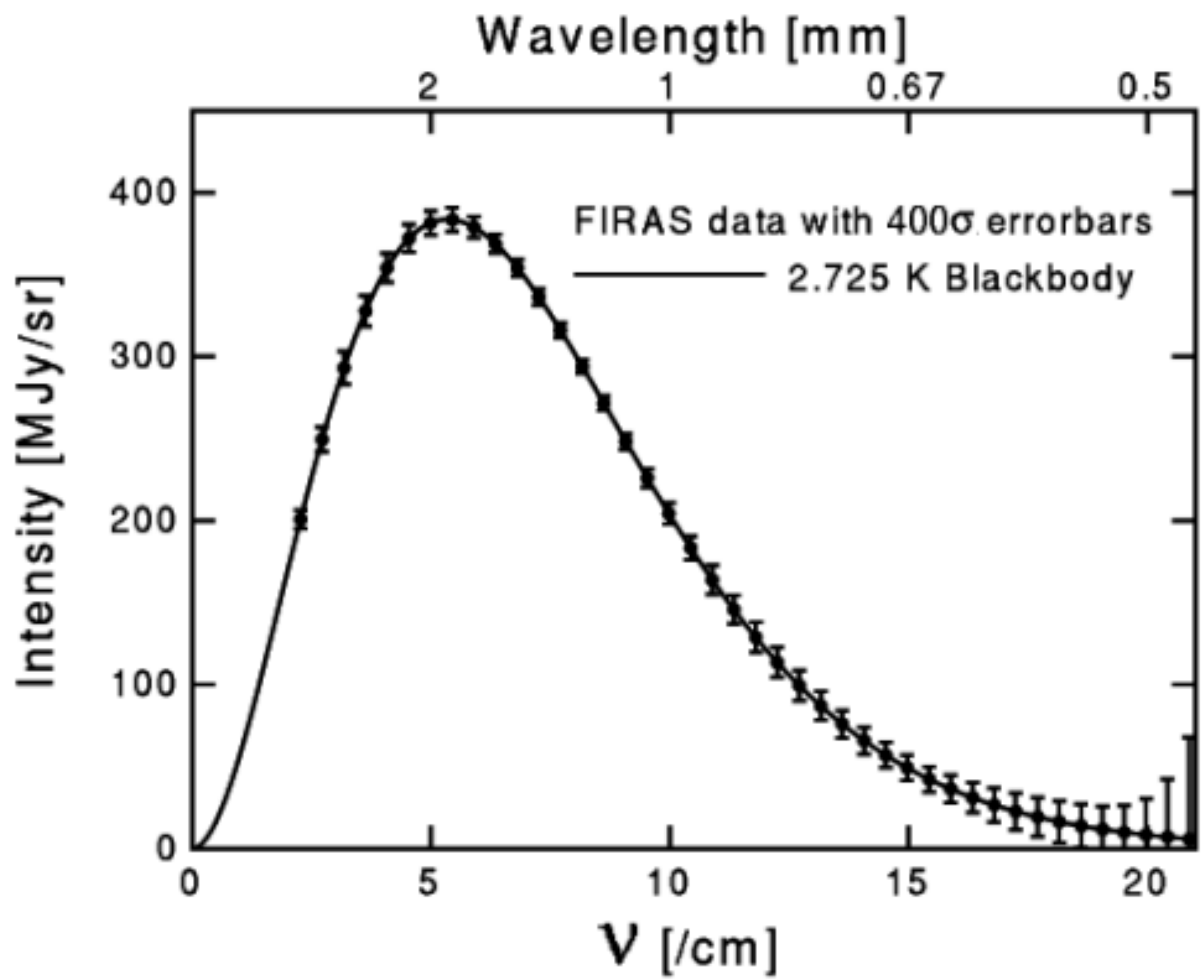


European Space Agency; Planck Collaboration

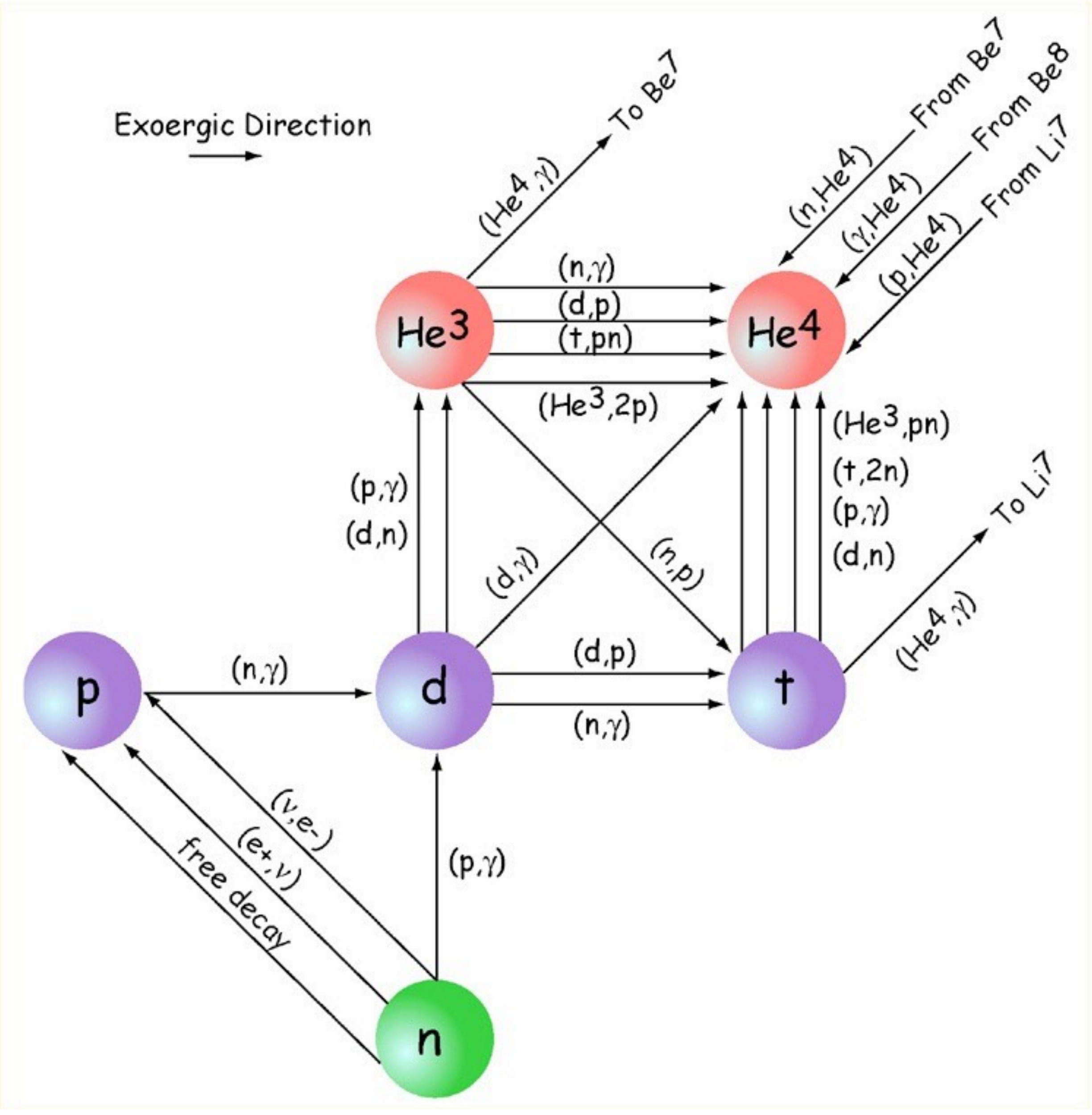
A view of the cosmic microwave background collected by the European Space Agency's Planck satellite. The heat map of the cosmos was imprinted on the sky when the universe was just 380,000 years old.

During its first million years the Universe was a hot, dense, smooth plasma. **The evidence for this comes form the existence today of the 2.725 ± 0.001 K Cosmic Microwave Background (CMB) that pervades the observable Universe with its very nearly perfect blackbody spectrum, the fossil record of the early heat.**





The Universe at an age of seconds, when thermal energies were in the MeV range, was a nuclear furnace operating out of thermal equilibrium. **The evidence comes in the abundance pattern of H (about 76% by mass), D (a few parts in 10^{-5} relative to H), ^{3}He (similar to D), ^{4}He (about 24% by mass), and ^{7}Li (a few parts in 10^{-10} relative to H) seen in the most pristine samples of the cosmos.**



The abundance of cosmic structure seen in the Universe today, from individual galaxies to superclusters of galaxies, emerged from the tiny (0.001%) primeval inhomogeneity in the distribution of matter. **The evidence for this comes from the tens of microKelvin fluctuations in the CMB measured on different angular scales.**

nature of DM and DE?

Yet there is much we remain unsure about, like the ultimate fate of the Universe. The expansion may reverse in the future, and the world as we know it end in a collapse to a hot, dense, big crunch. Or it may continue to expand forever, to an arbitrarily low mean density, but with most of the matter trapped in galaxies and clusters of galaxies that will eventually contract and end up as black holes.

For 70 years astronomers have been trying to measure the slowing effect of gravity on the expansion of the Universe to determine the total amount of matter in the Universe. In a surprising and exciting turn of events, two teams independently studying supernovae at high redshift (corresponding to great distances) recently found that the expansion of the Universe is speeding up, not slowing down!

Why is the expansion of the Universe speeding up? The acceleration requires something new, as matter in any amount should cause the Universe to decelerate. According to Einstein's theory, in unusual circumstances mass-energy can extert a repulsive force. What is needed is a form of energy that is elastic (negative pressure), like the energy of the quantum vacuum. The exact nature of this new component, called "dark energy", is not understood!!

Physical Cosmology is the study of the very largest scales of the material world around us by the methods of the natural sciences. In the attempt to make sense of the Universe we shall use physical principles from particle physics, nuclear physics, atomic physics, thermodynamics, statistical physics, electromagnetism, and gravitation.

1.2 THE COSMOLOGICAL PRINCIPLE

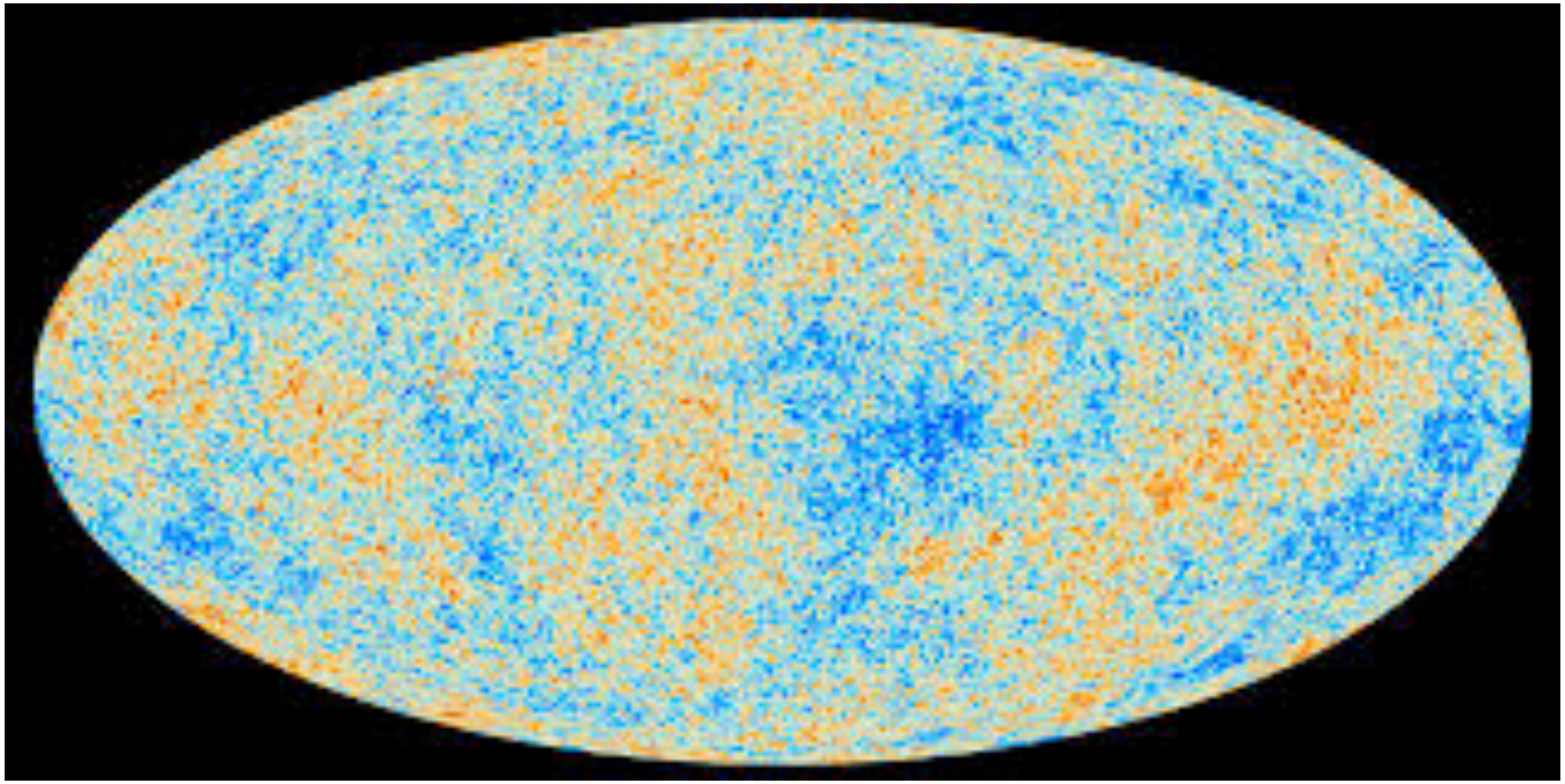
Any cosmological consideration must be based on one or more *cosmological principles* -- a seemingly trivial simplifying set of assumptions. Six of them are described below: The *Ancient Hindu*, the *Ancient Greek*, the *Genuine Copernican*, the *Generalized Copernican*, the *Perfect*, and the *Anthropic CP*.

The Ancient Hindu Cosmological Principle: The Universe is infinitely heterogeneous; our Earth is not an exceptional place, neither in space nor in time, but it is also not typical, not average (it is impossible to obtain any mean, any average value out of infinitely dispersed parameters).

The Ancient Greek Cosmological Principle: *The natural center of the Universe is the Earth, which is a unique feature in time and space. Several geometrical figures possessing centers were already known to ancient Greeks. Thus many mathematical cosmological models based on this principle have been developed starting from antiquity, like the systems of Hipparchus, Ptolemy and Tycho Brahe.*

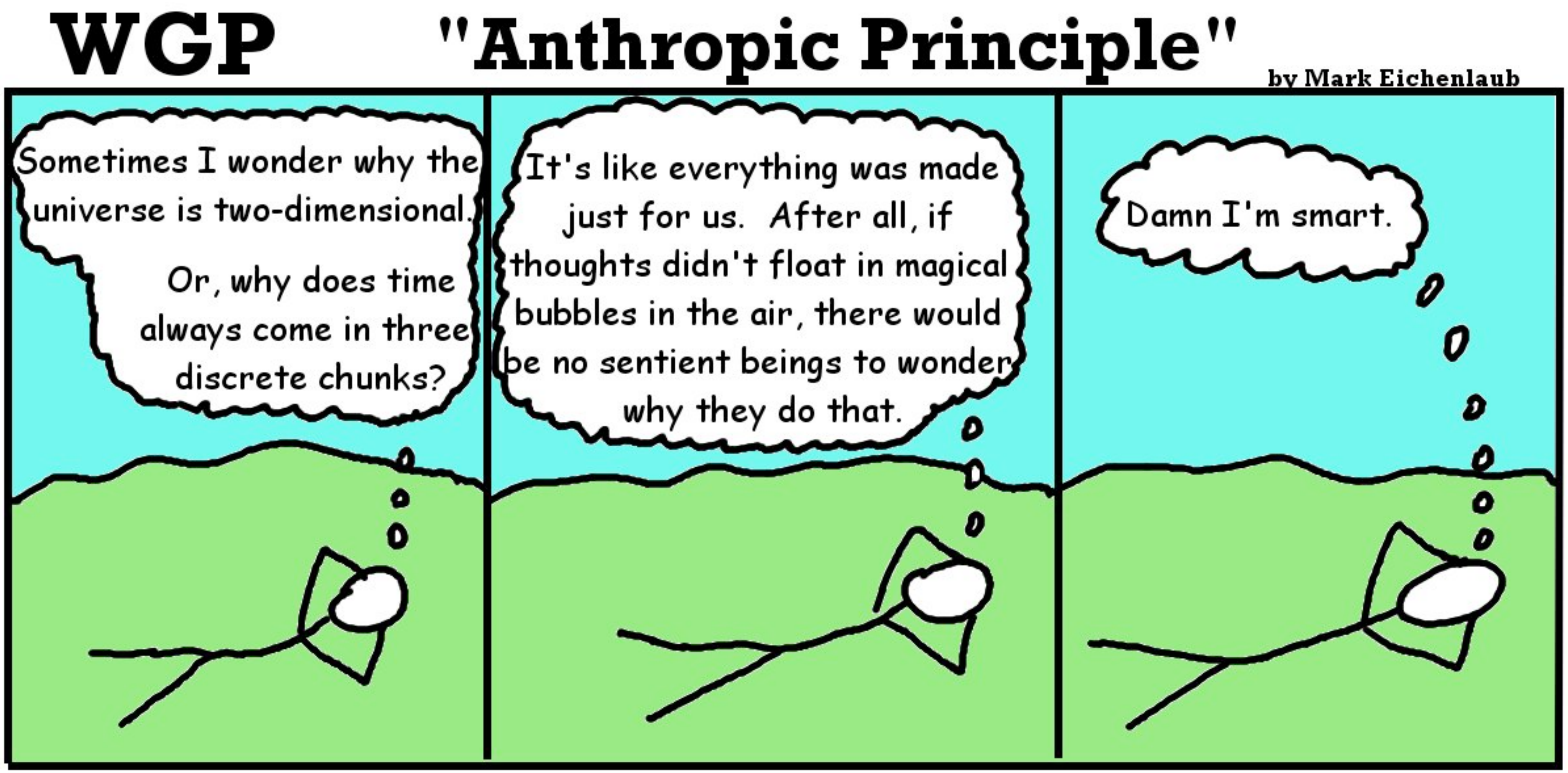
The Genuine Copernican Cosmological Principle: *The Universe observed from every planet looks roughly the same. The original cosmological model of Copernicus was based on it (Sun was at the center of the Universe.)*

The Generalized Copernican Cosmological Principle: The Universe looks roughly the same not only when seen from every planet but from every point in every direction (Universe is homogeneous and isotropic). Introduced in the beginning of the 20th century by Einstein, Friedmann, Lemaitre, and others, as a seemingly harmless simplification when solving equations. It produces the Hubble Law.



The Perfect Cosmological Principle: The Universe observed from every point in every direction and at every time looks roughly the same. Introduced by Herman Bondi and Thomas Gold (1948), this principle brings more restrictions on the possible solutions than the former principle does. The only solution based on this principle is the Steady State model, ruled out by the discovery of the CMB in 1964!

The Anthropic Principle: There exists in the Universe a physical being, intelligent and striving to knowledge; out of this assumption all the physical laws and physical constants can be deduced in narrow intervals of their values. Formulated by various authors in various manners (e.g., Carr 1982).



1.2 PARTICLES IN THE UNIVERSE

Everything in the Universe is made by fundamental particles, and the behavior of the Universe as a whole depends on the properties of these particles. (We shall see how, in cosmology, the equation of state of an ideal fluid is characterized by $p = w\rho c^2$, and that the dimensionless number w depends on whether the fluid is relativistic or non-relativistic).

Any particle has 2 contributions to its total energy, one being the kinetic energy and the other being the rest-mass energy,

$$E_{\text{total}}^2 = m_0^2 c^4 + p^2 c^2,$$

where m_0 is the particle mass at rest and p its momentum. (Note that in Ch. 2.5.1 Liddle mass m is our m_0.)

The above expression can be derived by expressing the relativistic momentum as

$$p = mv = \frac{m_0 v}{\sqrt{1 - v^2/c^2}} \equiv \gamma m_0 v$$

where m is the relativistic mass and $\gamma \equiv (1 - v^2/c^2)^{-1/2}$, and the relativistic total energy as

$$E_{\rm total} = mc^2 = \gamma m_0 c^2.$$

Rewriting γ^2 as

$$\gamma^2 = 1 + \gamma^2 (v^2/c^2) = 1 + \frac{p^2}{m_0^2 c^2}$$

one obtains

$$E_{\rm total}^2 = m_0^2 c^4 + p^2 c^2.$$

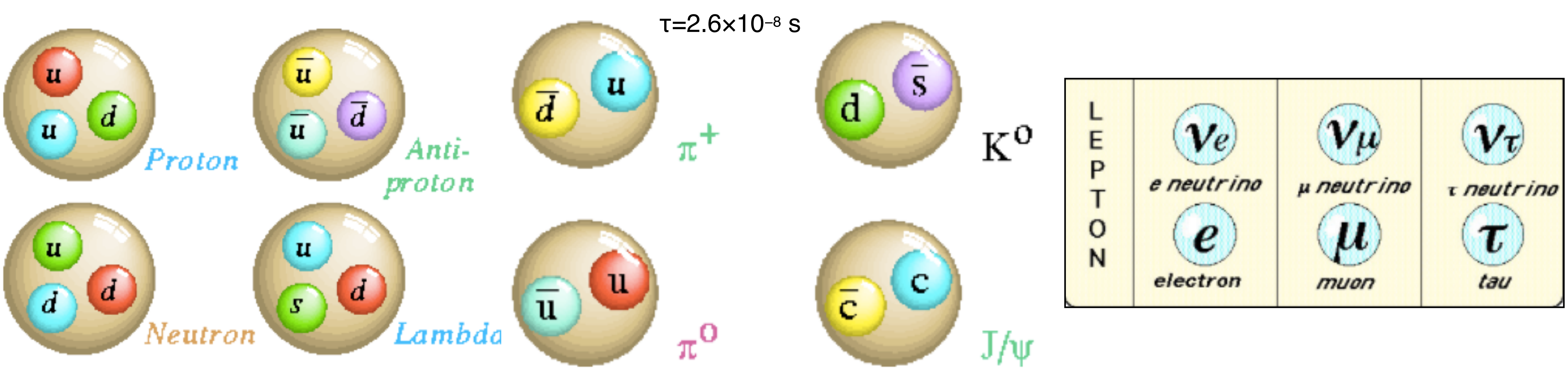
If the mass-energy dominates, the particle will be moving at much less than the speed of light, and we say it is non-relativistic. In that limit we can carry out an expansion

$$E_{\rm total} = m_0 c^2 \left(1 + \frac{p^2}{m_0^2 c^2}\right)^{1/2} \approx m_0 c^2 + \frac{p^2}{2m_0}.$$

The first term (Einstein's famous $E = mc^2$) is the energy of the particle when it is stationary, the second term is the usual kinetic energy ($p = m_0 v$ in the non-relativistic limit). If the mass-energy does not dominate, the particle will be moving at a substantial fraction of the speed of light, and so is relativistic. Any particle with zero mass (like photons, neutrinos) is always relativistic and moves at c.

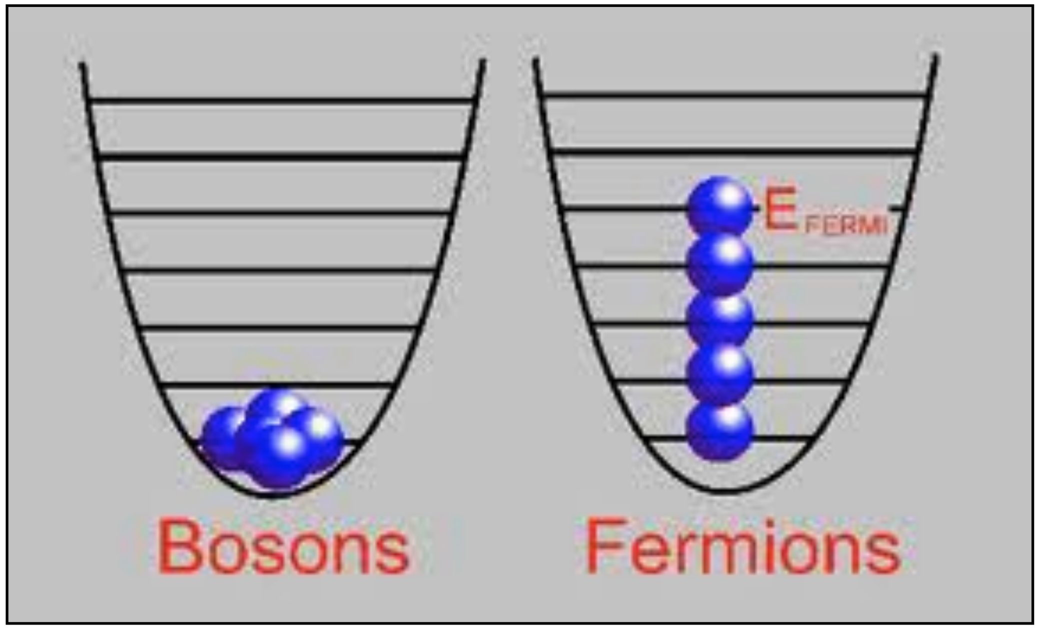
Baryons

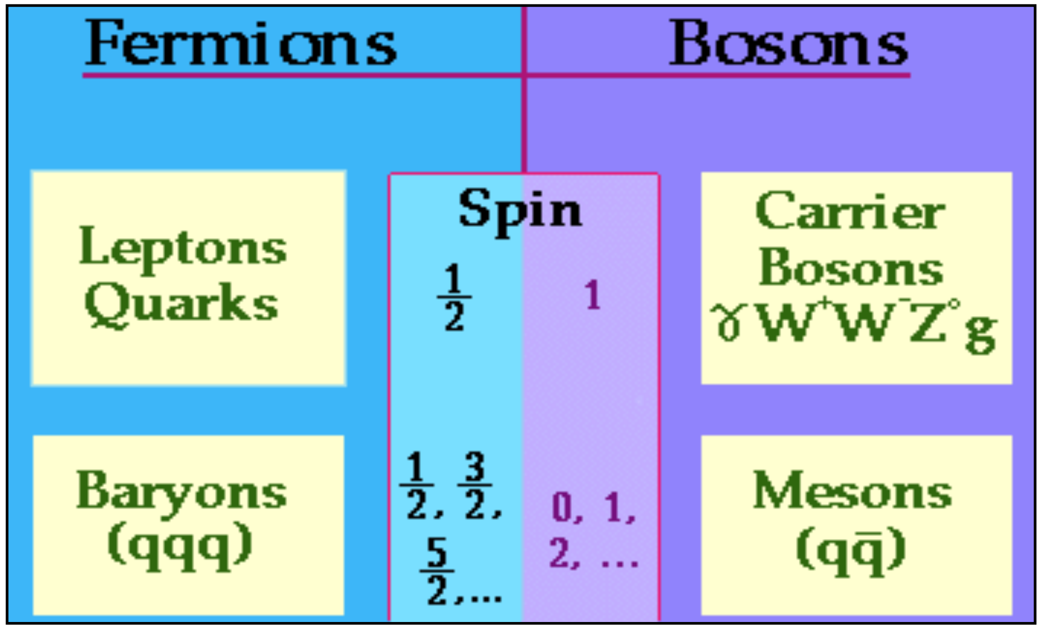
A BARYON is a composite particle made of three QUARKS. Baryons are opposed to MESONS which are made of one quark and one antiquark. Both baryons and mesons belong to the HADRON family, which are the particles made of quarks. Since baryons are composed of quarks, they participate in the strong interaction. LEPTONS, on the other hand, are not composed of quarks and as such do not participate in the strong interaction. The most well known baryons are the PROTONS and NEUTRONS that make up most of the mass of the visible matter in the universe, whereas ELECTRONS (the other major component of atoms) are leptons. Each baryon has a corresponding ANTIPARTICLE (antibaryon) where quarks are replaced by their corresponding antiquarks. For example, a proton is made of two UP quarks and one DOWN quark; and its corresponding antiparticle, the antiproton, is made of two up antiquarks and one down antiquark.



Baryons are strongly interacting FERMIONS – that is, they experience the strong nuclear force and are described by FERMI-DIRAC statistics, which apply to all particles obeying the Pauli EXCLUSION PRINCIPLE: no two identical fermions may occupy the same quantum state simultaneously.

This is in contrast to the BOSONS, which do not obey the exclusion principle. All fermions possess HALF-INTEGER SPIN, meaning that they possess an intrinsic angular momentum whose value is $\hbar = h/(2\pi)$ (reduced Planck's constant) times a half-integer (1/2, 3/2, 5/2, etc.). In the theory of quantum mechanics, fermions are described by antisymmetric states. Particles with INTEGER SPIN have a symmetric wave function and are called bosons; in contrast to fermions, they may share the same quantum states. Examples of bosons include the photon, the Cooper pairs (which are responsible for superconductivity), and the W and Z bosons.





Force	Electromagnetism	Gravity	Strong Nuclear	Weak Nuclear
	strength=1	strength=10^{-36}	strength=100 at 1 fermi	strength=10^{-4}
Number of Bosons	1	1	1	3
Bosons	Photon	Graviton**	Gluon	W^+, W^-, Z^0
Boson Mass*	0	0	0	80
Boson Charge	0	0	0	±1, 0
Acts on	Anything With Charge	Anything With Mass	Anything With Colour	Left Handed particle or Right Handed anti-particle with Flavour

helicity of a particle is right-handed if the direction of its spin is the same as the direction of its motion

Baryonic matter is matter composed mostly of baryons (by mass), which includes atoms of any sort (and thus includes nearly all matter that we may encounter or experience in everyday life, including our bodies). NON-BARYONIC matter, as implied by the name, is any sort of matter that is not primarily composed of baryons. This might include such ordinary matter as NEUTRINOS; however, it may also include EXOTIC species of non-baryonic DARK MATTER, such as SUPERSYMMETRIC particles (NEUTRALINO), or AXIONS. The distinction between baryonic and non-baryonic matter is important in cosmology, because Big Bang nucleosynthesis models set tight constraints on the amount of baryonic matter present in the early universe.

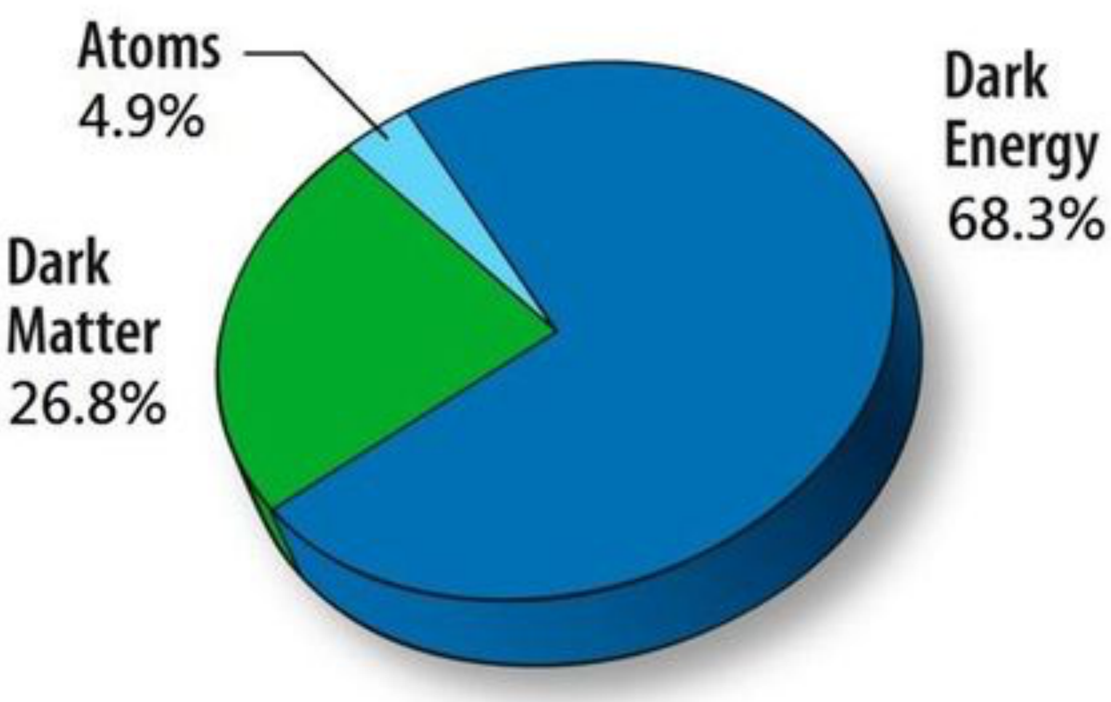
+CMB

The very existence of baryons is also a significant issue in cosmology because we have assumed that the Big Bang produced a state with equal amounts of baryons and antibaryons. The process by which baryons come to outnumber their antiparticles is called BARYOGENESIS.

The rest-mass energies of a proton and a neutron are 938.3 MeV and 939.6 MeV.

Although electrons are not made of quarks, they are traditionally included under the title *baryon*. A property of the Universe is that it is charge neutral, so there must be one electron for every proton. Weighing only 0.511 MeV, the contribution of electrons to the total mass is negligible.

Energy Content of the Universe



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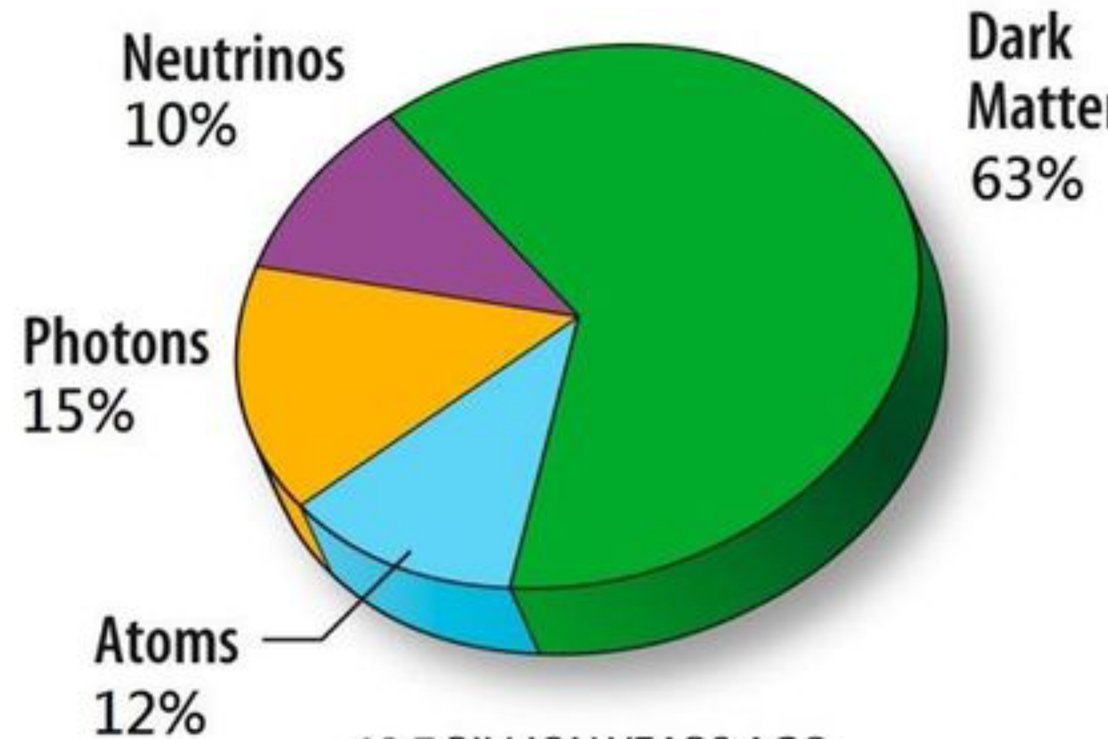

13.7 BILLION YEARS AGO
(Universe 380,000 years old)