





Beginning and End of Our Universe



5 Big Ideas

- I. Limitations of human awareness/thinking
- II. How do you know the truth?
- III. Scientific Methodology
- IV. The power of Mathematics
 - The power of Abstraction
 - The power of "n = ..."
 - The Universe is described by Math
- V. Tools for Observations
- VI. Concept of Space & the Fate of the Universe



The Challenge: Truth versus Belief

Oftentimes, our most cherished beliefs are barriers to the discovery of truth

- Truth: the true or actual state of a matter. Conformity with fact or reality.
- I'm here to tell you a story. A very old story that started with the Ancients, and it is not yet finished.
- It is the story of man's thinking and investigation of our being and of the nature of our reality. It is not a story of philosophy (the "arm chair investigation" of the truths and principles of being, knowledge, or conduct); it transcends philosophy. It is the story of the investigation of our universe
- The story starts with each of our birth's, growth, and the exercise of our rational mind.
- We will start with a review of our knowledge of our Universe.
- The Big Bang Theory: the discovery of the BBT's footprints.
- What is the CBR? As anyone who wears a tin hat can tell you, metal will shield you from radio waves. Now radio waves.... In 1948 GG ~3,000C → when the universe was 300,000 yrs old. Universe became transparent to light

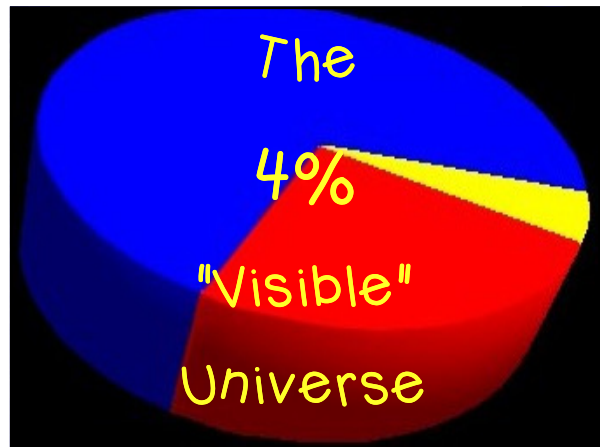
Some of the great unanswered questions

Opening the window of our awareness
Lifting the Veil of Understanding

- Why are we here?
- The nature of reality
- How could the universe evolve beings capable of understanding it?
- Limits of human senses and cognition
 - ◆ Representation of reality is only a metaphor
 - ◆ Limited capacity of short term memory – 3 ideas.
- Math Concepts –
 - ◆ Abstract, symbolic concepts
 - ◆ A reservoir of concepts from best thinkers of ages

This talk is about the latest advances in science -

4



Future of Our Universe

TABLE OF CONTENTS

- I. Lifting the Veil of Understanding
- II. What is Physics?
- III. History of Laws of Physics
- IV. Mathematics of Laws of Physics
- V. **History of Physics of Universe**
- VI. Critical Tools & Observations: CMB
- VII. What is the Stuff that Makes Our Universe?

7

Future of Our Universe

TABLE OF CONTENTS

- VII. Six Evidences for Dark Matter
- VIII. Properties & Detection of Dark Matter
- IX. What is Dark Matter?
- X. Dark Energy
- XI. Lambda Cold Dark Matter Model (Λ CDM)
- XII. Dark Energy Detection - Search Strategies
- XIII. One Theory of Dark Energy, Far Future
- XIV. What does all this mean? Fine Tuning

8

Lifting the Veil of Understanding

Perceiving the World with Our Senses

- Form Model as Child → Model of U developed
- Age 24 brain fully developed
- Perception and Conceptualization **Limited**
- Span of Awareness Limited by Human Scale
- My senses tell me I see YOU with my eyes -

9

Lifting the Veil of Understanding

Perceiving the World with Our Mind - Mathematical Models of our World

- No - See only light scattered from body
- Newton's Laws: Conceptual, Mathematical
- Atomic World. 1 in 10^{-15} space empty space
- Electrostatic Field – the source of interaction
- Understanding Quantum Space – Complex Fields

10

All Science comes out of Truth

One of the most important questions in life and science:

*“The first principle is that you must not fool yourself
—and you are the easiest person to fool.”*

“Be willing to question and doubt your own theories and your own results, and investigate possible flaws in a theory or an experiment. He recommended that researchers adopt an unusually high level of honesty which is rarely encountered in everyday life.”

Richard Feynman

11

All Science comes out of Truth

“Science alone of all the subjects contains within itself the lesson of the danger of belief in the infallibility of the greatest teachers of the preceding generation.”

Richard Feynman

12

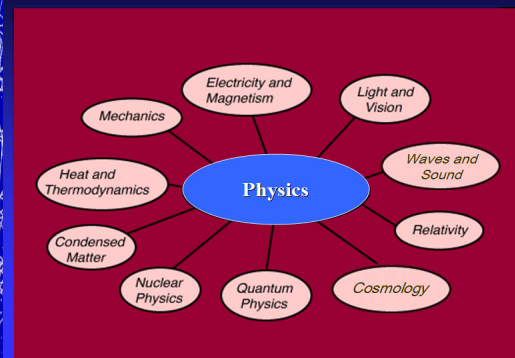
All Science comes out of Truth

How do we determine if something is NOT True, that is, FALSE?

- ◆ Police interrogation methods:
 - **Inconsistent** → Not True
- ◆ **Definition of a False Statement:**
It is Not Consistent

13

What is Physics?



14

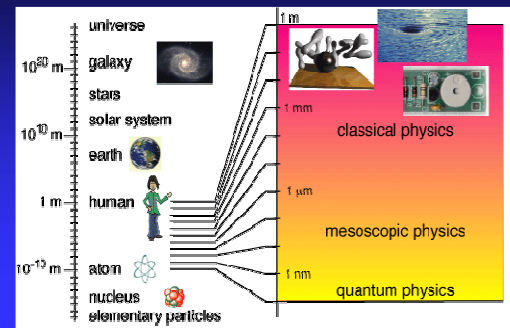
Conclusion: Fate of the Universe

Whether the Universe continues to expand forever or collapse depends on only one thing:

GRAVITY

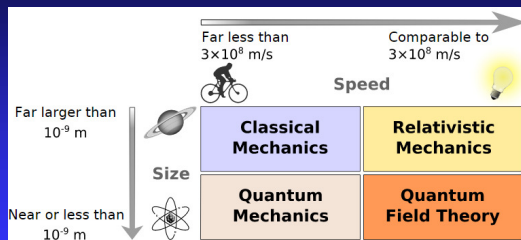
15

What is Physics? Scale of Physics: Size



16

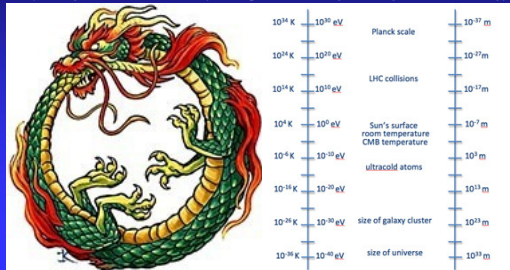
What is Physics? Scale of Physics



17

What is Physics? Scale of Physics: Aurubis The Cosmic Serpent

(The Cosmologist gets Eaten by the Particle Physicist)
Any change in short distance Physics → profound changes in large scale Cosmology



18

What is Physics?

- The scientific study of the basic (**fundamental**) properties of matter and energy ...
 - ◆ Study of **fundamental** structures and interactions in the physical universe
 - ◆ Structures: Sub atomic particle to cosmos

19

What is Physics?

Physics is from Ancient Greek: φύσις *physis* "nature" is a natural science that involves the study of **matter** and its **motion** through **space time**, as well as all related concepts, including **energy and force**.

In the *Assayer* (1622), Galileo noted that **Mathematics is the language in which Nature expresses its laws**. Most experimental results in physics are numerical measurements, and theories in physics use mathematics to give numerical results to match these measurements.

Most pages of text have numbers, charts, equations. 20

History of Laws of Physics

- Astronomy
- Newton's Laws
- Newton's Law of Universal Gravitation
- Maxwell's Equations → Wave Equation.
- Relativity:
 - ◆ Special Relativity (No Effects of Gravity)
 - ◆ General (Includes Effects of Gravitation)
- Quantum Mechanics – 4 Fundamental Forces
- Standard Model of Particle Physics
- Principles of Cosmology
- Tentative Theoretical Models

21

What is Physics?

Laws of Physics: - Mathematics

Newton's Laws of Motion

$$\sum \mathbf{F} = 0 \Rightarrow \frac{d\mathbf{v}}{dt} = 0.$$

$$\mathbf{F} = m \frac{d\mathbf{v}}{dt} = m\mathbf{a},$$

$$\sum \mathbf{F}_{a,b} = -\sum \mathbf{F}_{b,a}$$

Newton's Law of Universal Gravitation

$$\mathbf{F} = \frac{Gm_1m_2}{r^2}$$

22

What is Physics?

Laws of Physics

Maxwell's Equations

$$\nabla \cdot \mathbf{D} = \rho \quad (1) \quad \text{Gauss' Law}$$

$$\nabla \cdot \mathbf{B} = 0 \quad (2) \quad \text{Gauss' Law for magnetism}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (3) \quad \text{Faraday's Law}$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J} \quad (4) \quad \text{Ampère-Maxwell Law}$$

$$\left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) E = 0 \quad (5) \quad \text{Wave Equation}$$

23

What is Physics?

Laws of Physics

➤ Special Relativity

◆ Time Dilation

$$T_0 = \left[1 - \frac{v^2}{c^2} \right]^{1/2} T$$

◆ Length Contraction

$$L = \left[1 - \frac{v^2}{c^2} \right]^{1/2} L_0$$

◆ Mass Increase

$$m(v) = \left[1 - \frac{v^2}{c^2} \right]^{-1/2} m_0$$

➤ General Rel. (Includes Effects of Gravitation)

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

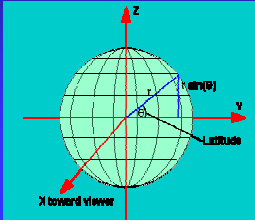
What is Physics? Laws of Physics - Geometry

Euclidean Geometry (EG):

Two parallel line do not meet
Does not describe our earth, solar system,
or our universe.

General Relativity,
Theory of gravity,
Riemann Geometry

(RG)
describes our universe.



What is Physics? Laws of Physics

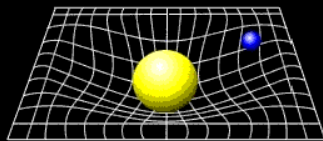
General Relativity

A key concept of General Relativity is that
gravity is no longer described by a
gravitational "field" but rather it is
supposed to be a
distortion of space and time itself.

26

What is Physics? Laws of Physics

General Relativity:
Matter curves space



27

What is Physics? Laws of Physics

General Relativity

Physicist John Wheeler put it well
when he said
"Matter tells space how to curve, and
space tells matter how to move."

28

What is Physics? Laws of Physics

Original Friedmann Equation

Terms: expansion, curvature, density

$$H^2 + \frac{\kappa}{a^2} = \frac{8\pi G}{3} \rho(a)$$

expansion
rate

curvature
of space

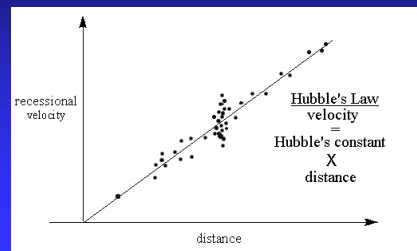
energy
density

29

History of Physics of Universe

Hubble's Law

$$\text{Velocity} = H_0 \times \text{Distance}$$

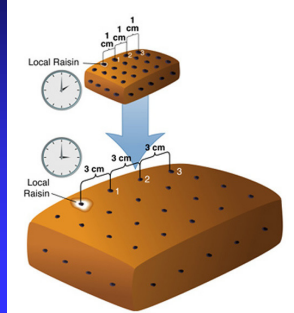


30

History of Physics of Universe

The Center?
This means that all matter seen in the Universe was formed at the same time, at the same place, in the center of the Universe.

Raisin Bread



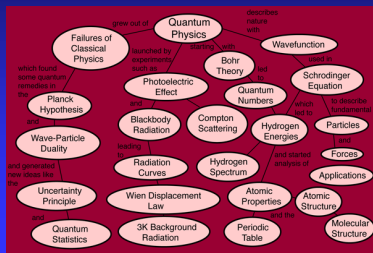
History of Physics of Universe

Cosmological Principle

At any instant of time, the universe must look homogeneous and isotropic to any observer.

What is Physics? Basic Laws of Physics

➤ Experiments of Quantum Mechanics



What is Physics? Basic Laws of Physics

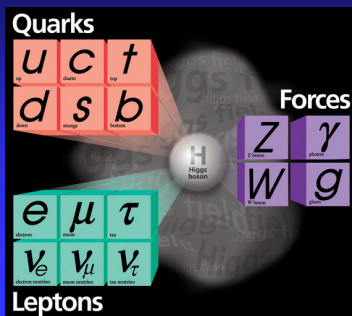
➤ Equations of Quantum Mechanics

$$H(t)|\psi(t)\rangle = i\hbar \frac{\partial}{\partial t} |\psi(t)\rangle$$

$$\frac{1}{c^2} \frac{\partial^2 \psi}{\partial t^2} - \nabla^2 \psi + \left(\frac{m_0 c}{\hbar} \right)^2 \psi = 0.$$

What is Physics? Basic Laws of Physics

➤ Standard Model (SM) Fundamental Particles



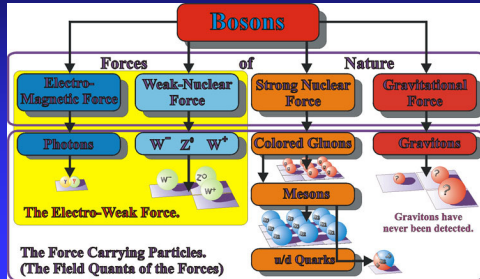
What is Physics? Basic Laws of Physics

➤ SM Fundamental Force Particles

Force	Particles Experiencing	Force Carrier Particle	Range	Relative Strength*
Gravity acts between objects with mass	all particles with mass	graviton (not yet observed)	infinity	much weaker ↓ much stronger
Weak Force governs particle decay	quarks and leptons	W ⁺ , W ⁻ , Z ⁰ (W and Z)	short range	
Electromagnetism acts between electrically charged particles	electrically charged particles	γ (photon)	infinity	
Strong Force** binds quarks together	quarks and gluons	g (gluon)	short range	

What is Physics? Basic Laws of Physics

- Bosons: Fundamental Force Particles



37

What is Physics? Basic Laws of Physics

- Standard Model of Particle Physics

$$\mathcal{L}_{SM} = \underbrace{\frac{1}{4}W_{\mu\nu} \cdot W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu}}_{\text{kinetic energies and self-interactions of the gauge bosons}}$$

$$+ \underbrace{\bar{L}\gamma^\mu(i\partial_\mu - \frac{1}{2}g_T \cdot W_\mu - \frac{1}{2}g'Y B_\mu)L + \bar{R}\gamma^\mu(i\partial_\mu - \frac{1}{2}g'Y B_\mu)}_{\text{kinetic energies and electroweak interactions of fermions}}$$

$$+ \frac{1}{2} \underbrace{[(i\partial_\mu - \frac{1}{2}g_T \cdot W_\mu - \frac{1}{2}g'Y B_\mu)\phi]^2 - V(\phi)}_{W^\pm, Z, \gamma \text{ and Higgs masses and couplings}}$$

$$+ \underbrace{g''(\bar{q}\gamma^\mu T_a q)G_\mu^a}_{\text{interactions between quarks and gluons}} + \underbrace{(G_1 \bar{L}\phi R + G_2 \bar{L}\phi_c R + h.c.)}_{\text{fermion masses and couplings to Higgs}}$$

Discoveries of Physics

- Fine Tuning of fundamental constants
 - ◆ Amount of mass: 1 part in 10^{18}
 - ◆ Same as number of grains of sand on earth
 - ◆ Add one more grain universe would have collapsed.
- BGV Theorem: Classical Inflationary spacetimes are not past complete, e.g. must have an origin in space and time.

39



History of Physics of Universe

I. Ancient, Medieval, Renaissance: EG

- Ancients 20th Century BC– The Firmament
- Aristotle (300 BC): Perfection of Celestial Spheres
- Ptolemaic System (150 AD) – Circles around Circles
- Copernicus – (1540) Heliocentric

History of Physics of Universe

II. Early Modern (EG, Pre EM, QM, and GR)

- Galileo (1609) First Telescope: Universe greater than Solar System
- Kepler (1610) - Observational: Kepler's Laws
- Newton (1687) – Math Laws of Forces and Universal Gravitation
- Philosophy - Kant (1724): Pure Reason → Transcendental – Non Observational

History of Physics of Universe

III. Modern: EM Theory, Quantum Mechanics, and Relativity

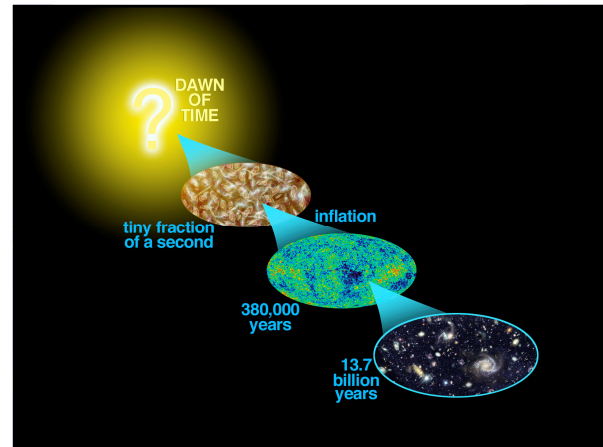
- Maxwell's Equations (1879): Electro-Magnetic Theory
- Planck (1900), Bohr (1913), ... Quantum Mechanics
- Einstein – GR (RG) + Cosmological (Λ) for Infinite Universe
- Friedmann – (1925) % Critical Mass \rightarrow Expand, Flat, Contract
- Hubble (1929) - Expansion of Universe \rightarrow U had an origin
- Zwicky (1933) - Galaxy Cluster Rotation Insufficient Mass
- Penzias & Wilson (1963) Discovery of 2.7 K CMBR @ 7.3 cm
- Vera Rubin (1970) - Galactic Rotation Andromeda, 60 More
- Allan Guth (1980) – Theory of Inflation
- 1989 Cosmic Background Explorer (COBE) satellite
- 1998 Expansion of Universe is *Accelerating* \rightarrow Dark Energy
- Fine Tuning of Universe

Three Pillars of Observational Cosmology

- Universal Expansion. Hubble 1920s
- Primordial Nucleosynthesis: Gamow 1940s
 - ◆ Relative abundances of light elements formed by hot dense phase
- Microwave Background Radiation – BB red fireball
 - ◆ The relic thermal radiation discovered by Penzias and Wilson (1965) the “missing link” between the primordial fire-ball of the young Big Bang universe and its present day mature phase dominated by evolved astronomical objects.
 - ◆ CBR Analysis: Paradigm for understanding universe at large

Origins of the Big Bang Theory

- Georges Lemaître (1927) expanded on idea of **expanding universe**, realizing that the **universe was smaller yesterday** than today, and so on until a “day that would not have had a yesterday”: the moment of creation.
 - ◆ The moment of creation would be the sudden expansion that started the expansion of the universe as we know it today.
- This idea wasn't widely accepted at first: **Fred Hoyle** dismissed “this hot Big Bang”, noting that there **wasn't any record or remnants**. He argued for a “steady state” universe.



THE BIG BANG THEORY

Timeline from **TIME BEGINS** to **PRESENT DAY**.

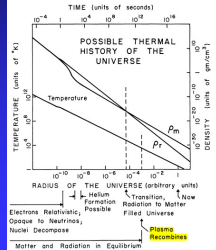
Time	Temperature	Major Events
10^{-43} sec	10^{32} °C	1 The cosmos goes through a superfast "inflation" as it expands from a subatomic size to a size of a grapefruit in a tiny fraction of a second.
10^{-32} sec	10^{27} °C	2 The expansion slows as the universe begins to cool. A hot soup of electrons, quarks and gluons forms.
10^{-12} sec	10^{12} °C	3 A rapidly cooling universe permits quarks to clump into protons and neutrons.
3 min.	10^9 °C	4 Still too hot for atoms, charged electrons and protons prevent light from shining. The universe is a glowing fog.
300,000 yrs.	10^4 °C	5 Electrons combine with protons and neutrons to form atoms, mostly hydrogen and helium. Light can finally shine.
1 billion yrs.	10^3 °C	6 Gravity makes hydrogen and helium gas clump together to form the giant clouds that will become galaxies. Smaller clumps of gas collapse to form the first stars.
15 billion yrs.	10^2 °C	7 As galaxies cluster together under gravity, the first stars die and spew heavy elements into space. More stars will eventually form into new stars and planets.

Labels: Quarks, Neutron, Hydrogen nucleus, Hydrogen atom, Protogalaxy, Electron, Proton, Helium nucleus, Helium atom, Galaxy.

NOTE: The numbers for cosmology are to great and the numbers for subatomic physics are too small to fit. All numbers are approximate. Time measured in Planck (10⁻⁴³), 10⁻³², 10⁻¹², 10⁹, 10¹², 10¹⁸, 10²¹, 10²⁴, 10²⁷, 10³⁰, 10³³, 10³⁶, 10³⁹, 10⁴², 10⁴⁵, 10⁴⁸, 10⁵¹, 10⁵⁴, 10⁵⁷, 10⁶⁰, 10⁶³, 10⁶⁶, 10⁶⁹, 10⁷², 10⁷⁵, 10⁷⁸, 10⁸¹, 10⁸⁴, 10⁸⁷, 10⁹⁰, 10⁹³, 10⁹⁶, 10⁹⁹, 10¹⁰², 10¹⁰⁵, 10¹⁰⁸, 10¹¹¹, 10¹¹⁴, 10¹¹⁷, 10¹²⁰, 10¹²³, 10¹²⁶, 10¹²⁹, 10¹³², 10¹³⁵, 10¹³⁸, 10¹⁴¹, 10¹⁴⁴, 10¹⁴⁷, 10¹⁵⁰, 10¹⁵³, 10¹⁵⁶, 10¹⁵⁹, 10¹⁶², 10¹⁶⁵, 10¹⁶⁸, 10¹⁷¹, 10¹⁷⁴, 10¹⁷⁷, 10¹⁸⁰, 10¹⁸³, 10¹⁸⁶, 10¹⁸⁹, 10¹⁹², 10¹⁹⁵, 10¹⁹⁸, 10²⁰¹, 10²⁰⁴, 10²⁰⁷, 10²¹⁰, 10²¹³, 10²¹⁶, 10²¹⁹, 10²²², 10²²⁵, 10²²⁸, 10²³¹, 10²³⁴, 10²³⁷, 10²⁴⁰, 10²⁴³, 10²⁴⁶, 10²⁴⁹, 10²⁵², 10²⁵⁵, 10²⁵⁸, 10²⁶¹, 10²⁶⁴, 10²⁶⁷, 10²⁷⁰, 10²⁷³, 10²⁷⁶, 10²⁷⁹, 10²⁸², 10²⁸⁵, 10²⁸⁸, 10²⁹¹, 10²⁹⁴, 10²⁹⁷, 10³⁰⁰, 10³⁰³, 10³⁰⁶, 10³⁰⁹, 10³¹², 10³¹⁵, 10³¹⁸, 10³²¹, 10³²⁴, 10³²⁷, 10³³⁰, 10³³³, 10³³⁶, 10³³⁹, 10³⁴², 10³⁴⁵, 10³⁴⁸, 10³⁵¹, 10³⁵⁴, 10³⁵⁷, 10³⁶⁰, 10³⁶³, 10³⁶⁶, 10³⁶⁹, 10³⁷², 10³⁷⁵, 10³⁷⁸, 10³⁸¹, 10³⁸⁴, 10³⁸⁷, 10³⁹⁰, 10³⁹³, 10³⁹⁶, 10³⁹⁹, 10⁴⁰², 10⁴⁰⁵, 10⁴⁰⁸, 10⁴¹¹, 10⁴¹⁴, 10⁴¹⁷, 10⁴²⁰, 10⁴²³, 10⁴²⁶, 10⁴²⁹, 10⁴³², 10⁴³⁵, 10⁴³⁸, 10⁴⁴¹, 10⁴⁴⁴, 10⁴⁴⁷, 10⁴⁵⁰, 10⁴⁵³, 10⁴⁵⁶, 10⁴⁵⁹, 10⁴⁶², 10⁴⁶⁵, 10⁴⁶⁸, 10⁴⁷¹, 10⁴⁷⁴, 10⁴⁷⁷, 10⁴⁸⁰, 10⁴⁸³, 10⁴⁸⁶, 10⁴⁸⁹, 10⁴⁹², 10⁴⁹⁵, 10⁴⁹⁸, 10⁵⁰¹, 10⁵⁰⁴, 10⁵⁰⁷, 10⁵¹⁰, 10⁵¹³, 10⁵¹⁶, 10⁵¹⁹, 10⁵²², 10⁵²⁵, 10⁵²⁸, 10⁵³¹, 10⁵³⁴, 10⁵³⁷, 10⁵⁴⁰, 10⁵⁴³, 10⁵⁴⁶, 10⁵⁴⁹, 10⁵⁵², 10⁵⁵⁵, 10⁵⁵⁸, 10⁵⁶¹, 10⁵⁶⁴, 10⁵⁶⁷, 10⁵⁷⁰, 10⁵⁷³, 10⁵⁷⁶, 10⁵⁷⁹, 10⁵⁸², 10⁵⁸⁵, 10⁵⁸⁸, 10⁵⁹¹, 10⁵⁹⁴, 10⁵⁹⁷, 10⁶⁰⁰, 10⁶⁰³, 10⁶⁰⁶, 10⁶⁰⁹, 10⁶¹², 10⁶¹⁵, 10⁶¹⁸, 10⁶²¹, 10⁶²⁴, 10⁶²⁷, 10⁶³⁰, 10⁶³³, 10⁶³⁶, 10⁶³⁹, 10⁶⁴², 10⁶⁴⁵, 10⁶⁴⁸, 10⁶⁵¹, 10⁶⁵⁴, 10⁶⁵⁷, 10⁶⁶⁰, 10⁶⁶³, 10⁶⁶⁶, 10⁶⁶⁹, 10⁶⁷², 10⁶⁷⁵, 10⁶⁷⁸, 10⁶⁸¹, 10⁶⁸⁴, 10⁶⁸⁷, 10⁶⁹⁰, 10⁶⁹³, 10⁶⁹⁶, 10⁶⁹⁹, 10⁷⁰², 10⁷⁰⁵, 10⁷⁰⁸, 10⁷¹¹, 10⁷¹⁴, 10⁷¹⁷, 10⁷²⁰, 10⁷²³, 10⁷²⁶, 10⁷²⁹, 10⁷³², 10⁷³⁵, 10⁷³⁸, 10⁷⁴¹, 10⁷⁴⁴, 10⁷⁴⁷, 10⁷⁵⁰, 10⁷⁵³, 10⁷⁵⁶, 10⁷⁵⁹, 10⁷⁶², 10⁷⁶⁵, 10⁷⁶⁸, 10⁷⁷¹, 10⁷⁷⁴, 10⁷⁷⁷, 10⁷⁸⁰, 10⁷⁸³, 10⁷⁸⁶, 10⁷⁸⁹, 10⁷⁹², 10⁷⁹⁵, 10⁷⁹⁸, 10⁸⁰¹, 10⁸⁰⁴, 10⁸⁰⁷, 10⁸¹⁰, 10⁸¹³, 10⁸¹⁶, 10⁸¹⁹, 10⁸²², 10⁸²⁵, 10⁸²⁸, 10⁸³¹, 10⁸³⁴, 10⁸³⁷, 10⁸⁴⁰, 10⁸⁴³, 10⁸⁴⁶, 10⁸⁴⁹, 10⁸⁵², 10⁸⁵⁵, 10⁸⁵⁸, 10⁸⁶¹, 10⁸⁶⁴, 10⁸⁶⁷, 10⁸⁷⁰, 10⁸⁷³, 10⁸⁷⁶, 10⁸⁷⁹, 10⁸⁸², 10⁸⁸⁵, 10⁸⁸⁸, 10⁸⁹¹, 10⁸⁹⁴, 10⁸⁹⁷, 10⁹⁰⁰, 10⁹⁰³, 10⁹⁰⁶, 10⁹⁰⁹, 10⁹¹², 10⁹¹⁵, 10⁹¹⁸, 10⁹²¹, 10⁹²⁴, 10⁹²⁷, 10⁹³⁰, 10⁹³³, 10⁹³⁶, 10⁹³⁹, 10⁹⁴², 10⁹⁴⁵, 10⁹⁴⁸, 10⁹⁵¹, 10⁹⁵⁴, 10⁹⁵⁷, 10⁹⁶⁰, 10⁹⁶³, 10⁹⁶⁶, 10⁹⁶⁹, 10⁹⁷², 10⁹⁷⁵, 10⁹⁷⁸, 10⁹⁸¹, 10⁹⁸⁴, 10⁹⁸⁷, 10⁹⁹⁰, 10⁹⁹³, 10⁹⁹⁶, 10⁹⁹⁹, 10¹⁰⁰², 10¹⁰⁰⁵, 10¹⁰⁰⁸, 10¹⁰¹¹, 10¹⁰¹⁴, 10¹⁰¹⁷, 10¹⁰²⁰, 10¹⁰²³, 10¹⁰²⁶, 10¹⁰²⁹, 10¹⁰³², 10¹⁰³⁵, 10¹⁰³⁸, 10¹⁰⁴¹, 10¹⁰⁴⁴, 10¹⁰⁴⁷, 10¹⁰⁵⁰, 10¹⁰⁵³, 10¹⁰⁵⁶, 10¹⁰⁵⁹, 10¹⁰⁶², 10¹⁰⁶⁵, 10¹⁰⁶⁸, 10¹⁰⁷¹, 10¹⁰⁷⁴, 10¹⁰⁷⁷, 10¹⁰⁸⁰, 10¹⁰⁸³, 10¹⁰⁸⁶, 10¹⁰⁸⁹, 10¹⁰⁹², 10¹⁰⁹⁵, 10¹⁰⁹⁸, 10¹¹⁰¹, 10¹¹⁰⁴, 10¹¹⁰⁷, 10¹¹¹⁰, 10¹¹¹³, 10¹¹¹⁶, 10¹¹¹⁹, 10¹¹²², 10¹¹²⁵, 10¹¹²⁸, 10¹¹³¹, 10¹¹³⁴, 10¹¹³⁷, 10¹¹⁴⁰, 10¹¹⁴³, 10¹¹⁴⁶, 10¹¹⁴⁹, 10¹¹⁵², 10¹¹⁵⁵, 10¹¹⁵⁸, 10¹¹⁶¹, 10¹¹⁶⁴, 10¹¹⁶⁷, 10¹¹⁷⁰, 10¹¹⁷³, 10¹¹⁷⁶, 10¹¹⁷⁹, 10¹¹⁸², 10¹¹⁸⁵, 10¹¹⁸⁸, 10¹¹⁹¹, 10¹¹⁹⁴, 10¹¹⁹⁷, 10¹²⁰⁰, 10¹²⁰³, 10¹²⁰⁶, 10¹²⁰⁹, 10¹²¹², 10¹²¹⁵, 10¹²¹⁸, 10¹²²¹, 10¹²²⁴, 10¹²²⁷, 10¹²³⁰, 10¹²³³, 10¹²³⁶, 10¹²³⁹, 10¹²⁴², 10¹²⁴⁵, 10¹²⁴⁸, 10¹²⁵¹, 10¹²⁵⁴, 10¹²⁵⁷, 10¹²⁶⁰, 10¹²⁶³, 10¹²⁶⁶, 10¹²⁶⁹, 10¹²⁷², 10¹²⁷⁵, 10¹²⁷⁸, 10¹²⁸¹, 10¹²⁸⁴, 10¹²⁸⁷, 10¹²⁹⁰, 10¹²⁹³, 10¹²⁹⁶, 10¹²⁹⁹, 10¹³⁰², 10¹³⁰⁵, 10¹³⁰⁸, 10¹³¹¹, 10¹³¹⁴, 10¹³¹⁷, 10¹³²⁰, 10¹³²³, 10¹³²⁶, 10¹³²⁹, 10¹³³², 10¹³³⁵, 10¹³³⁸, 10¹³⁴¹, 10¹³⁴⁴, 10¹³⁴⁷, 10¹³⁵⁰, 10¹³⁵³, 10¹³⁵⁶, 10¹³⁵⁹, 10¹³⁶², 10¹³⁶⁵, 10¹³⁶⁸, 10¹³⁷¹, 10¹³⁷⁴, 10¹³⁷⁷, 10¹³⁸⁰, 10¹³⁸³, 10¹³⁸⁶, 10¹³⁸⁹, 10¹³⁹², 10¹³⁹⁵, 10¹³⁹⁸, 10¹⁴⁰¹, 10¹⁴⁰⁴, 10¹⁴⁰⁷, 10¹⁴¹⁰, 10¹⁴¹³, 10¹⁴¹⁶, 10¹⁴¹⁹, 10¹⁴²², 10¹⁴²⁵, 10¹⁴²⁸, 10¹⁴³¹, 10¹⁴³⁴, 10¹⁴³⁷, 10¹⁴⁴⁰, 10¹⁴⁴³, 10¹⁴⁴⁶, 10¹⁴⁴⁹, 10¹⁴⁵², 10¹⁴⁵⁵, 10¹⁴⁵⁸, 10¹⁴⁶¹, 10¹⁴⁶⁴, 10¹⁴⁶⁷, 10¹⁴⁷⁰, 10¹⁴⁷³, 10¹⁴⁷⁶, 10¹⁴⁷⁹, 10¹⁴⁸², 10¹⁴⁸⁵, 10¹⁴⁸⁸, 10¹⁴⁹¹, 10¹⁴⁹⁴, 10¹⁴⁹⁷, 10¹⁵⁰⁰, 10¹⁵⁰³, 10¹⁵⁰⁶, 10¹⁵⁰⁹, 10¹⁵¹², 10¹⁵¹⁵, 10¹⁵¹⁸, 10¹⁵²¹, 10¹⁵²⁴, 10¹⁵²⁷, 10¹⁵³⁰, 10¹⁵³³, 10¹⁵³⁶, 10¹⁵³⁹, 10¹⁵⁴², 10¹⁵⁴⁵, 10¹⁵⁴⁸, 10¹⁵⁵¹, 10¹⁵⁵⁴, 10¹⁵⁵⁷, 10¹⁵⁶⁰, 10¹⁵⁶³, 10¹⁵⁶⁶, 10¹⁵⁶⁹, 10¹⁵⁷², 10¹⁵⁷⁵, 10¹⁵⁷⁸, 10¹⁵⁸¹, 10¹⁵⁸⁴, 10¹⁵⁸⁷, 10¹⁵⁹⁰, 10¹⁵⁹³, 10¹⁵⁹⁶, 10¹⁵⁹⁹, 10¹⁶⁰², 10¹⁶⁰⁵, 10¹⁶⁰⁸, 10¹⁶¹¹, 10¹⁶¹⁴, 10¹⁶¹⁷, 10¹⁶²⁰, 10¹⁶²³, 10¹⁶²⁶, 10¹⁶²⁹, 10¹⁶³², 10¹⁶³⁵, 10¹⁶³⁸, 10¹⁶⁴¹, 10¹⁶⁴⁴, 10¹⁶⁴⁷, 10¹⁶⁵⁰, 10¹⁶⁵³, 10¹⁶⁵⁶, 10¹⁶⁵⁹, 10¹⁶⁶², 10¹⁶⁶⁵, 10¹⁶⁶⁸, 10¹⁶⁷¹, 10¹⁶⁷⁴, 10¹⁶⁷⁷, 10¹⁶⁸⁰, 10¹⁶⁸³, 10¹⁶⁸⁶, 10¹⁶⁸⁹, 10¹⁶⁹², 10¹⁶⁹⁵, 10¹⁶⁹⁸, 10¹⁷⁰¹, 10¹⁷⁰⁴, 10¹⁷⁰⁷, 10¹⁷¹⁰, 10¹⁷¹³, 10¹⁷¹⁶, 10¹⁷¹⁹, 10¹⁷²², 10¹⁷²⁵, 10¹⁷²⁸, 10¹⁷³¹, 10¹⁷³⁴, 10¹⁷³⁷, 10¹⁷⁴⁰, 10¹⁷⁴³, 10¹⁷⁴⁶, 10¹⁷⁴⁹, 10¹⁷⁵², 10¹⁷⁵⁵, 10¹⁷⁵⁸, 10¹⁷⁶¹, 10¹⁷⁶⁴, 10¹⁷⁶⁷, 10¹⁷⁷⁰, 10¹⁷⁷³, 10¹⁷⁷⁶, 10¹⁷⁷⁹, 10¹⁷⁸², 10¹⁷⁸⁵, 10¹⁷⁸⁸, 10¹⁷⁹¹, 10¹⁷⁹⁴, 10¹⁷⁹⁷, 10¹⁸⁰⁰, 10¹⁸⁰³, 10¹⁸⁰⁶, 10¹⁸⁰⁹, 10¹⁸¹², 10¹⁸¹⁵, 10¹⁸¹⁸, 10¹⁸²¹, 10¹⁸²⁴, 10¹⁸²⁷, 10¹⁸³⁰, 10¹⁸³³, 10¹⁸³⁶, 10¹⁸³⁹, 10¹⁸⁴², 10¹⁸⁴⁵, 10¹⁸⁴⁸, 10¹⁸⁵¹, 10¹⁸⁵⁴, 10¹⁸⁵⁷, 10¹⁸⁶⁰, 10¹⁸⁶³, 10¹⁸⁶⁶, 10¹⁸⁶⁹, 10¹⁸⁷², 10¹⁸⁷⁵, 10¹⁸⁷⁸, 10¹⁸⁸¹, 10¹⁸⁸⁴, 10¹⁸⁸⁷, 10¹⁸⁹⁰, 10¹⁸⁹³, 10¹⁸⁹⁶, 10¹⁸⁹⁹, 10¹⁹⁰², 10¹⁹⁰⁵, 10¹⁹⁰⁸, 10¹⁹¹¹, 10¹⁹¹⁴, 10¹⁹¹⁷, 10¹⁹²⁰, 10¹⁹²³, 10¹⁹²⁶, 10¹⁹²⁹, 10¹⁹³², 10¹⁹³⁵, 10¹⁹³⁸, 10¹⁹⁴¹, 10¹⁹⁴⁴, 10¹⁹⁴⁷, 10¹⁹⁵⁰, 10¹⁹⁵³, 10¹⁹⁵⁶, 10¹⁹⁵⁹, 10¹⁹⁶², 10¹⁹⁶⁵, 10¹⁹⁶⁸, 10¹⁹⁷¹, 10¹⁹⁷⁴, 10¹⁹⁷⁷, 10¹⁹⁸⁰, 10¹⁹⁸³, 10¹⁹⁸⁶, 10¹⁹⁸⁹, 10¹⁹⁹², 10¹⁹⁹⁵, 10¹⁹⁹⁸, 10²⁰⁰¹, 10²⁰⁰⁴, 10²⁰⁰⁷, 10²⁰¹⁰, 10²⁰¹³, 10²⁰¹⁶, 10²⁰¹⁹, 10²⁰²², 10²⁰²⁵, 10²⁰²⁸, 10²⁰³¹, 10²⁰³⁴, 10²⁰³⁷, 10²⁰⁴⁰, 10²⁰⁴³, 10²⁰⁴⁶, 10²⁰⁴⁹, 10²⁰⁵², 10²⁰⁵⁵, 10²⁰⁵⁸, 10²⁰⁶¹, 10²⁰⁶⁴, 10²⁰⁶⁷, 10²⁰⁷⁰, 10²⁰⁷³, 10²⁰⁷⁶, 10²⁰⁷⁹, 10²⁰⁸², 10²⁰⁸⁵, 10²⁰⁸⁸, 10²⁰⁹¹, 10²⁰⁹⁴, 10²⁰⁹⁷, 10²¹⁰⁰, 10²¹⁰³, 10²¹⁰⁶, 10²¹⁰⁹, 10²¹¹², 10²¹¹⁵, 10²¹¹⁸, 10²¹²¹, 10²¹²⁴, 10²¹²⁷, 10²¹³⁰, 10²¹³³, 10²¹³⁶, 10²¹³⁹, 10²¹⁴², 10²¹⁴⁵, 10²¹⁴⁸, 10²¹⁵¹, 10²¹⁵⁴, 10²¹⁵⁷, 10²¹⁶⁰, 10²¹⁶³, 10²¹⁶⁶, 10²¹⁶⁹, 10²¹⁷², 10²¹⁷⁵, 10²¹⁷⁸, 10²¹⁸¹, 10²¹⁸⁴, 10²¹⁸⁷, 10²¹⁹⁰, 10²¹⁹³, 10²¹⁹⁶, 10²¹⁹⁹, 10²²⁰², 10²²⁰⁵, 10²²⁰⁸, 10²²¹¹, 10²²¹⁴, 10²²¹⁷, 10²²²⁰, 10²²²³, 10²²²⁶, 10²²²⁹, 10²²³², 10²²³⁵, 10²²³⁸, 10²²⁴¹, 10²²⁴⁴, 10²²⁴⁷, 10²²⁵⁰, 10²²⁵³, 10²²⁵⁶, 10²²⁵⁹, 10²²⁶², 10²²⁶⁵, 10²²⁶⁸, 10²²⁷¹, 10²²⁷⁴, 10²²⁷⁷, 10²²⁸⁰, 10²²⁸³, 10²²⁸⁶, 10²²⁸⁹, 10²²⁹², 10²²⁹⁵, 10²²⁹⁸, 10²³⁰¹, 10²³⁰⁴, 10²³⁰⁷, 10²³¹⁰, 10²³¹³, 10²³¹⁶, 10²³¹⁹, 10²³²², 10²³²⁵, 10²³²⁸, 10²³³¹, 10²³³⁴, 10²³³⁷, 10²³⁴⁰, 10²³⁴³, 10²³⁴⁶, 10²³⁴⁹, 10²³⁵², 10²³⁵⁵, 10²³⁵⁸, 10²³⁶¹, 10²³⁶⁴, 10²³⁶⁷, 10²³⁷⁰, 10²³⁷³, 10²³⁷⁶, 10²³⁷⁹, 10²³⁸², 10²³⁸⁵, 10²³⁸⁸, 10²³⁹¹, 10²³⁹⁴, 10²³⁹⁷, 10²⁴⁰⁰, 10²⁴⁰³, 10²⁴⁰⁶, 10²⁴⁰⁹, 10²⁴¹², 10²⁴¹⁵, 10²⁴¹⁸, 10²⁴²¹, 10²⁴²⁴, 10²⁴²⁷, 10²⁴³⁰, 10²⁴³³, 10²⁴³⁶, 10²⁴³⁹, 10²⁴⁴², 10²⁴⁴⁵, 10²⁴⁴⁸, 10²⁴⁵¹, 10²⁴⁵⁴, 10²⁴⁵⁷, 10²⁴⁶⁰, 10²⁴⁶³, 10²⁴⁶⁶, 10²⁴⁶⁹, 10²⁴⁷², 10²⁴⁷⁵, 10²⁴⁷⁸, 10²⁴⁸¹, 10²⁴⁸⁴, 10²⁴⁸⁷, 10²⁴⁹⁰, 10²⁴⁹³, 10²⁴⁹⁶, 10²⁴⁹⁹, 10²⁵⁰², 10²⁵⁰⁵, 10²⁵⁰⁸, 10²⁵¹¹, 10²⁵¹⁴, 10²⁵¹⁷, 10²⁵²⁰, 10²⁵²³, 10²⁵²⁶, 1

CBR Evidence for Big Bang Theory

Detection of Cosmic Background Radiation - 1963.
Thermal black body spectrum at a temperature of $3.5 \pm 1K$: Proof of primordial fireball, i.e. Big Bang .



49

What is the Stuff that Makes Our Universe?

- Greek Model: Earth, Air, Fire, and Water
- Atoms - Mendeleev Periodic Table
- Quantum Mechanics gives a "Standard Model"
 - ◆ Fundamental Forces (Felt by Baryonic Matter)
 - ◆ Baryonic Matter – The stuff out of which we, atoms, planets, stars, and galaxies are made.
 - ◆ That is, the visible universe

50



Dark Matter – Physics Discovery in Action!

(Historical Significance)

- Physicists get excited about inconsistencies
- **Inconsistencies** → Discover New Physics
- Cosmology, The Cosmic Serpent –
 - ◆ Physics at Shortest Distance Scales affects Largest Distance scales → Cosmology

52

Six Evidences (Observations) for Dark Matter (23%)

1. Galactic Rotation
 2. Gravitational Lensing
 3. Simulation of Evolution
 4. Galactic Collision
 5. CMBR: COBE Angular Spectrum
 6. Structure Formation Galaxy Clusters: Cosmology Models
- ◆ DM Theory Detection Tools: Observation

53

What is the Stuff that Makes 4% Universe?

We see stuff because it is
Electromagnetic Radiation – has an electric charge.
Examples of EMR:
Sun, stars, light bulbs (BB radiation)
Lecture screen
Radio waves
Cosmic Background Radiation (CBR).
Seeing stuff, you can't see, i.e. Dark Matter, isn't easy.
How can we "see" Dark Matter things.

54

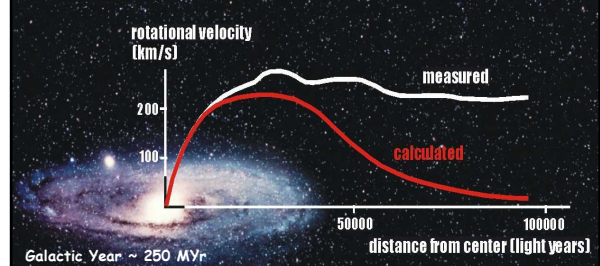
Properties of Dark Matter

- ◆ Dark matter neither emits nor absorbs light or any other electromagnetic radiation.
- ◆ Dark matter's existence is inferred from gravitational effects on visible matter and gravitational lensing of background radiation, etc.
- ◆ Non Baryonic, i.e., not atoms (charges).

55

Evidence for Dark Matter:

1. Motion of Stars Within Galaxies



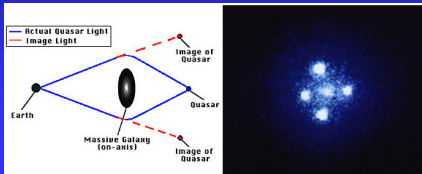
- Need more gravity to balance $v \rightarrow$ Dark Matter
- Dark Matter 5X Baryonic Matter. Figure E.8
- Dark – does not interact. Not like atoms.

Evidence for Dark Matter

2. Gravitational Lensing: Galaxy

Gravitational Lensing: Gravity bends light.

Produces more than one image of distant quasars, as seen in this shot from the Hubble Space Telescope.



57

Evidence for Dark Matter

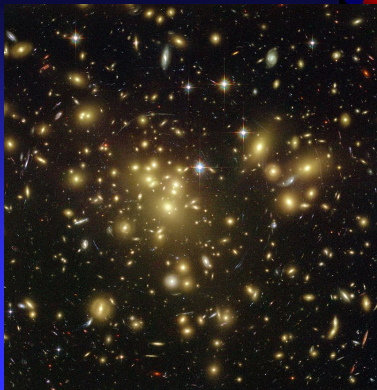
2. Gravitational Lensing: Within a Galaxy



58

Evidence for Dark Matter

2. Gravitational Lensing: Galaxy Clusters



59

Evidence for Dark Matter

3. Dark matter and normal matter have been wrenched apart by the tremendous Collision of two large Clusters of Galaxies.

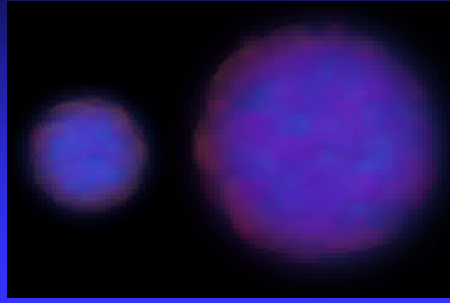
The discovery, using NASA's Chandra X-ray Observatory and other telescopes, gives direct evidence for the existence of dark matter.



60

Evidence for Dark Matter

3. Cluster with Dark Matter Collision Simulation



Hot gas, containing most of the normal matter in the cluster, is shown in red and dark matter is in blue. During the collision the hot gas in each cluster is slowed and distorted by a drag force, similar to air resistance. A bullet-shaped cloud of gas forms in one of the clusters. In contrast, the dark matter is not slowed by the impact, because it does not interact directly with itself or the gas except through gravity, and separates from the normal matter. The animation ends by dissolving into an image showing the hot gas (seen with Chandra) (pink) and the cluster mass as inferred by gravitational lensing (blue), which is mostly dark matter.

61

Evidence for Dark Matter

4. Why galaxies and clusters of galaxies come in the Structures that we observe?

After the BB, the U was fairly uniformly distributed everywhere. How did structures form?

62

Evidence for Dark Matter

4. Dark Matter Simulation –

Why galaxies and clusters of galaxies come in the Patterns that we observe.

After the BB, the density of matter in the Universe was fairly uniformly distributed everywhere.

How Large Scale Structure of U evolves over time:

You can see matter collapses under the pull of gravity
A single dot is a galaxy halo.

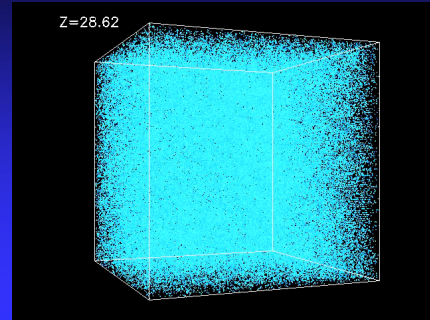
This map looks the same as actual observations

➤ Interactions-Observation: Structure- Galaxies

63

Evidence for Dark Matter

4. Dark Matter Simulation

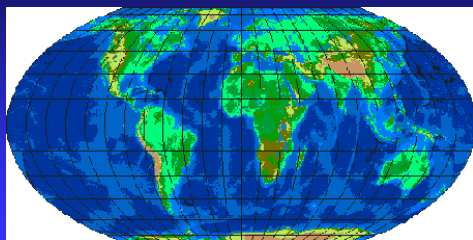


64

Evidence for Dark Matter

5. Angular Spectrum of CBR

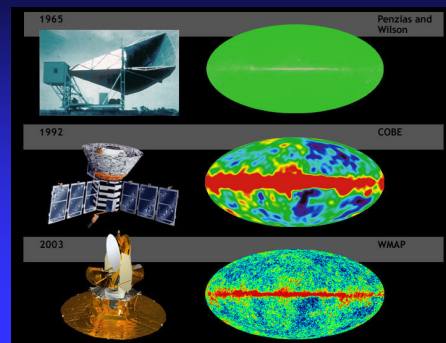
Projection of 3D Sky (Sphere) onto Plane



65

Evidence for Dark Matter

5. Angular Spectrum of CBR



66

Evidence for Dark Matter

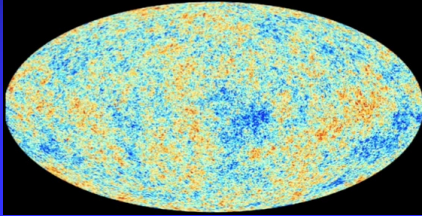
5. Angular Spectrum of CBR

Detect this with Satellites

Cosmic background explorer, COBE (1989)

WMAP - Wilkinson Microwave Anisotropy Probe (2001)

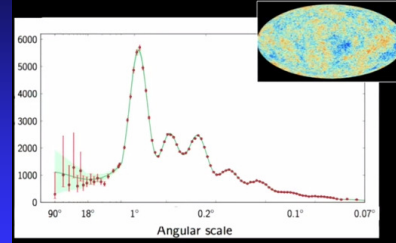
Planck Space craft (2013) – Map of Temperatures



67

Evidence for Dark Matter

5. Angular Spectrum of CMR

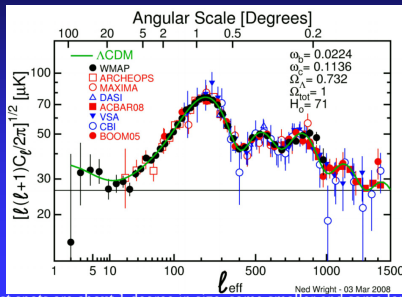


Most spots are about 1 degree in size, some smaller and some larger
Dark Energy and Matter determined by large angular scales

68

Evidence for Dark Energy, Λ CDM

5. Map of Cosmic Background Radiation, Ω_Λ

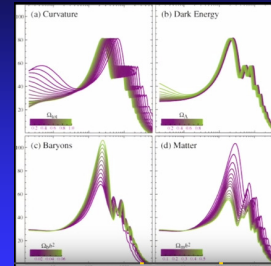


Most spots are about 1 degree in size, some smaller and some larger
Dark Energy and Matter determined by large angular scales

69

Evidence for Dark Matter

5. Map of Cosmic Background Radiation



Can tune model with different model parameters: Curvature,
% matter, % dark matter to get best fit.
Best match: 84% of matter in our universe is not atoms, but dark matter.

70

Evidence for Dark Matter

6. CBR -Weighing the Universe: Models

ρ = mass-energy density of Universe

ρ_c = critical density

$\Omega = \rho/\rho_c$

$\Omega < 1$ OPEN

$\Omega = 1$ FLAT

$\Omega > 1$ CLOSED

71

What is Dark Matter?

To decipher the nature of dark matter is one of the great enigmas still unsolved

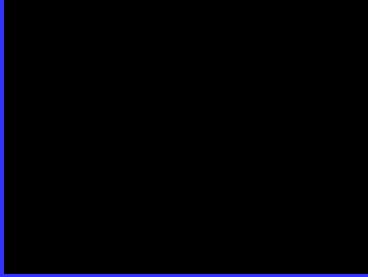
➤ Particle Candidates

72

Evidence for Dark Energy – Star Death

Supernova Cosmology: Need bright stars with same brightness to study early history

Type Ia Supernova (White Dwarf & Massive Star)

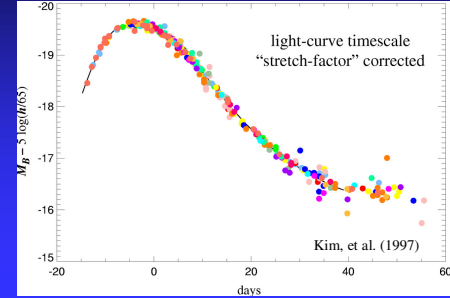


79

Evidence for Dark Energy

Type Ia Supernova Event

Type Ia Supernova (White Dwarf & Massive Star)



80

Evidence for Dark Matter

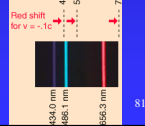
Light from distant stars and more distant galaxies is not featureless. It has a distinct spectral features characteristic of the atoms in the gases around the stars.

When these spectra are examined, the wavelength, λ , are found to be shifted toward the red end of the spectrum. This shift is apparently a **Doppler shift** and indicates that essentially all of the galaxies are moving away from us. Example below for hydrogen.

This shift is expressed in terms of the **Redshift parameter z**

For today, time t_0 , distance R_0 is equal to 1.

$$1 + z = \frac{\lambda_{observed}}{\lambda_{emitted}} = \frac{R(t_0)}{R(t)} = \frac{1}{R(t)}$$



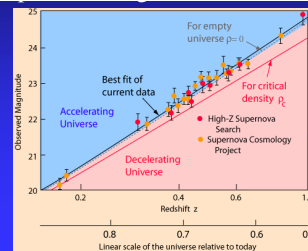
81

Evidence for Dark Energy

Supernova Cosmology: Probing Dark Energy

The Principal Evidence Dark Energy is

Type Ia Supernova Magnitude vs. Redshift (1998)



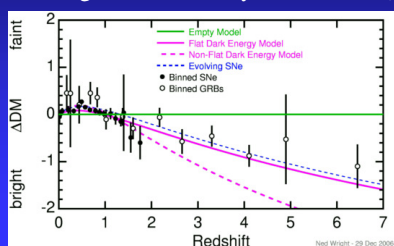
82

Evidence for Dark Energy

Supernova Cosmology: Probing Dark Energy

The Principal Evidence Dark Energy is

Rate of change of DM density vs. Redshift (2006)



83

Original Hypothesis of Dark Energy

Original Friedmann Equation

3 terms: expansion, curvature, density

$$H^2 + \frac{\kappa}{a^2} = \frac{8\pi G}{3} \rho(a)$$

expansion rate curvature of space energy density

84

What is Physics?

Basic Laws of Physics

Original Friedmann Models

ρ = mass-energy density

ρ_c = critical density

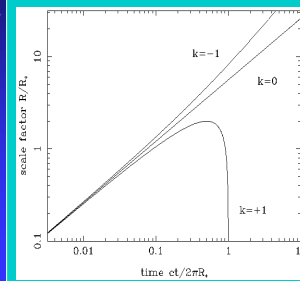
k = curvature

$\Omega = \rho/\rho_c$

$\Omega < 1$ OPEN, $k = -1$

$\Omega = 1$ FLAT, $k = 0$

$\Omega > 1$ CLOSED, $k = 1$



Original Hypothesis of Dark Energy

Friedmann Models with Λ

3 terms: matter density, curvature, and Λ

$$H^2 = \frac{8\pi G}{3} \rho - \frac{kc^2}{R^2} + \frac{\Lambda}{3}$$

H = Hubble's constant
 c = speed of light
 G = gravitational constant
 R = radius of the Universe
 ρ = matter density of the Universe
 k = curvature of the Universe
 Λ = cosmological constant

$$\frac{H^2}{H_0^2} = \Omega_R a^{-4} + \Omega_M a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda$$

Original Hypothesis of Dark Energy

Lambda Cold Dark Matter Model (Λ CDM):

A Parametrization of the Big Bang Model-

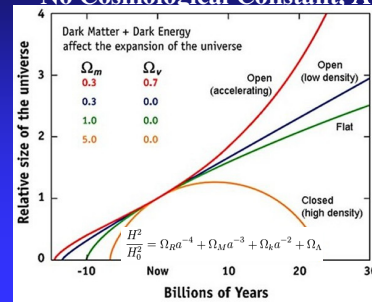
The universe contains a Cosmological Constant, Lambda (Greek Λ), associated with Dark Energy and Cold Dark Matter

Based on 6 parameters:

Baryon density; dark matter density; age of the universe; scalar spectral index; curvature fluctuation; and reionization optical depth.

Original Hypothesis of Dark Energy

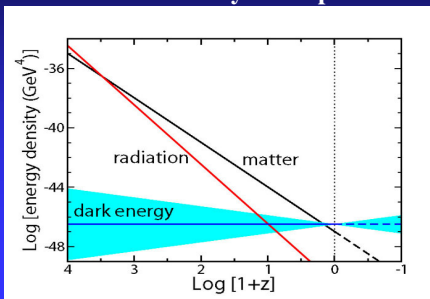
Original Friedmann Models: Matter Only, No Cosmological Constant, Λ



Original Hypothesis of Dark Energy

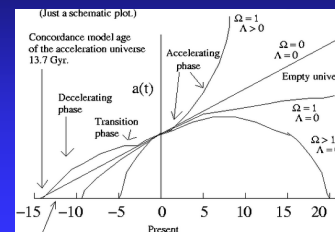
Friedmann Models with Λ ,

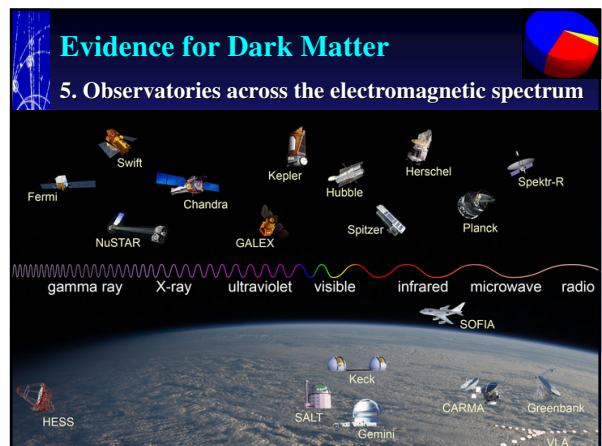
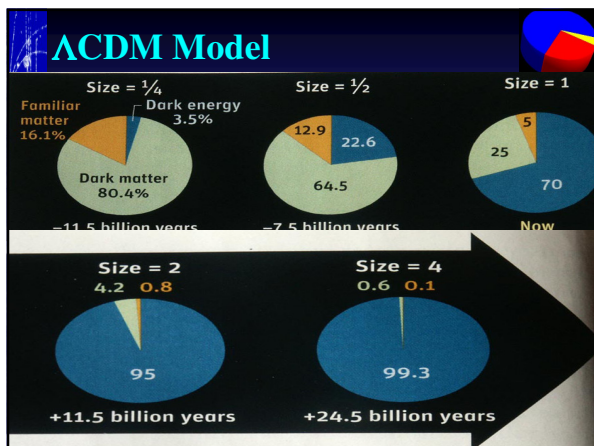
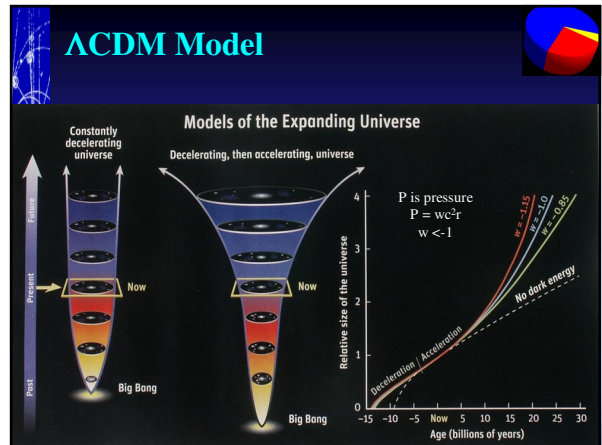
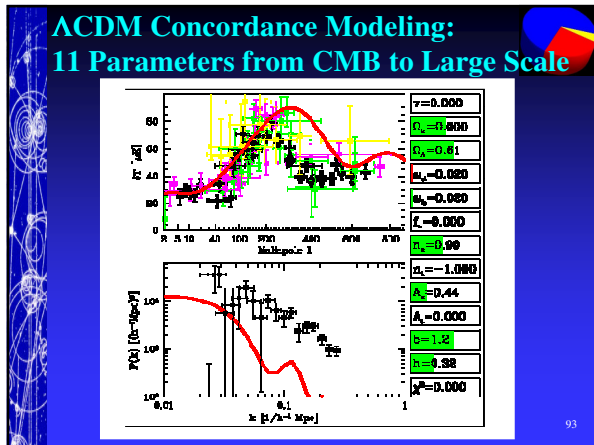
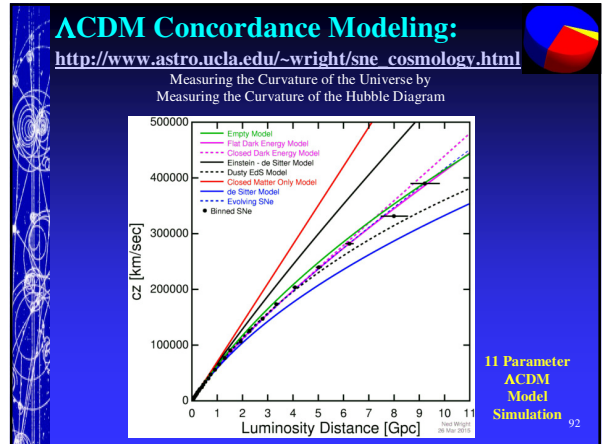
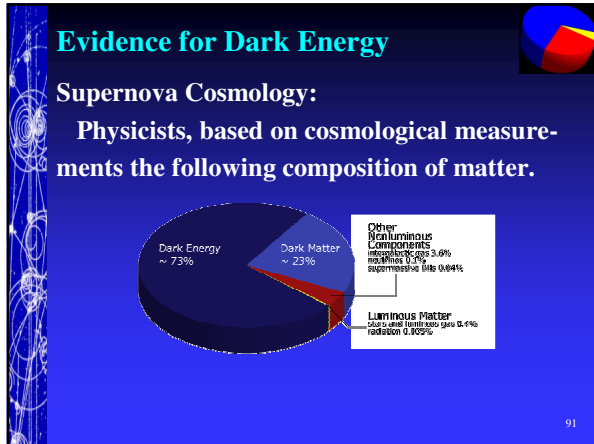
Plot of Density vs. Expansion



Original Hypothesis of Dark Energy

Friedmann Models with Λ





Does Dark Energy Violate the Law of Conservation of Energy?

- DE is Negative Energy/Work
 - ◆ Negative pressure, $P = -\rho c^2$
- Effect of DE is that it reduces gravity
- It takes energy to produce space
- Satisfies Noether's theorem - time for GR

103

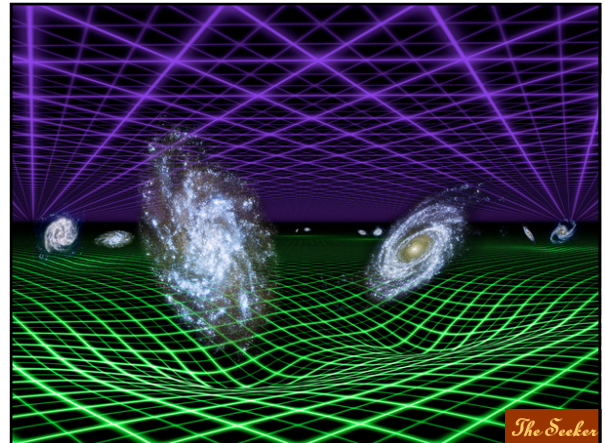
What does all this mean?

- Nothing special about any location in space
- Era in time is special
- Able to observe distant - primordial stars
- Able to discern the model of universe
- Fine Tuning

What does all this mean?

Fine Tuning

- To achieve the precise rate and timing of the cosmic slowing down and speeding up, two characteristics of the universe must be fixed with exacting precision.
- The **mass density** cannot vary by more than one part in 10^{60} .
- The **space energy density** cannot vary by more than one part in 10^{120} .



The Seeker