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.

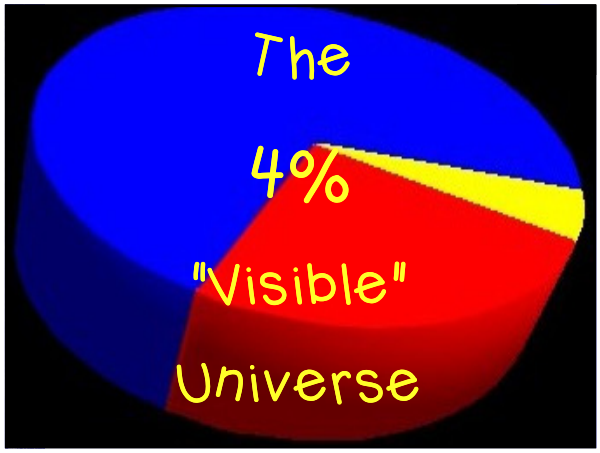
- We will start with a review of our knowledge of our Universe.
- The Big Bang Theory: the discovery of the BBT's footprints.
- What is the CBR? As anyone who wears a tin hat can tell you, metal will shield you from radio waves. Now radio waves..... In 1948 GG ..3,000C→when the universe was 300,000 yrs 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 is science -



Future of Our Universe

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II. What is Physics?
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VI. Critical Tools & Observations: CMB
VII. What is the Stuff that Makes Our Universe?

Future of Our Universe

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XI. Lambda Cold Dark Matter Model (ΛCDM)
XII. Dark Energy Detection - Search Strategies
XIII. One Theory of Dark Energy, Far Future
XIV. What does all this mean? Fine Tuning

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 -

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

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

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

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**

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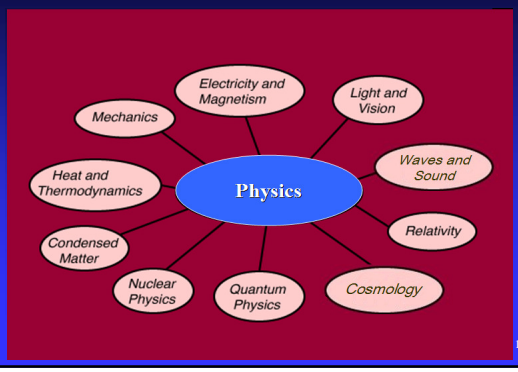
What is Physics?



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Conclusion: Fate of the Universe

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

GRAVITY

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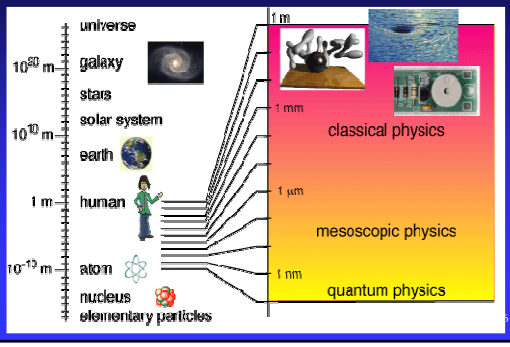
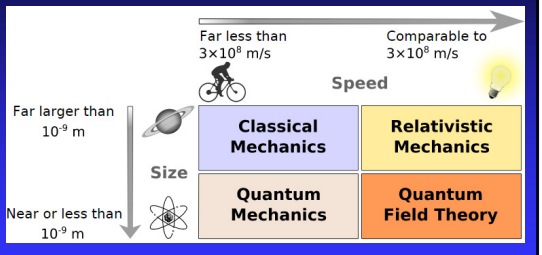
What is Physics? Scale of Physics: Size



What is Physics? Scale of Physics



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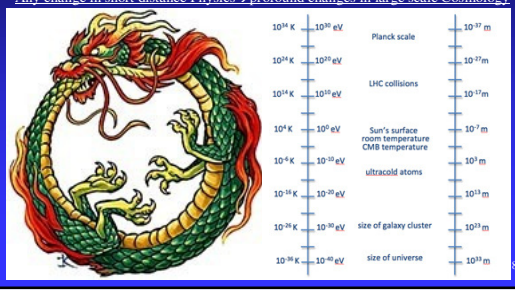
What is Physics? Scale of Physics: Aurubis

The Cosmic Serpent

(The Cosmologist gets Eaten by the Particle Physicist)

Any change in short distance Physics→profound changes in large scale Cosmology



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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

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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.

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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

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What is Physics?
Laws of Physics: - Mathematics

Newton's Laws of Motion

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

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

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

Newton's Law of Universal Gravitation

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

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What is Physics?
Laws of Physics

Maxwell's Equations

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

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

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

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

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

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What is Physics?
Laws of Physics

- Special Relativity
  - Time Dilation
  - Length Contraction
  - Mass Increase

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

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

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

- General Rel. (Includes Effects of Gravitation)

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

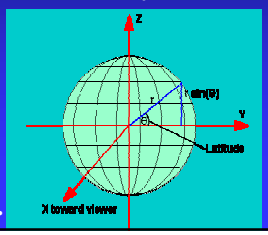
What is Physics?
Laws of Physics - Geometry

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

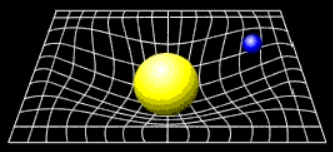
General Relativity

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.

What is Physics?
Laws of Physics

General Relativity:
Matter curves space



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."

What is Physics?
Laws of Physics

Original Friedmann Equation

Terms: expansion, curvature, density

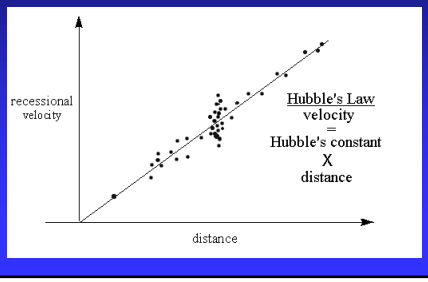
$$H^2 + \frac{\kappa}{a^2} = \frac{8\pi G}{3}\rho(a)$$

expansion rate | curvature of space | energy density

History of Physics of Universe

Hubble's Law

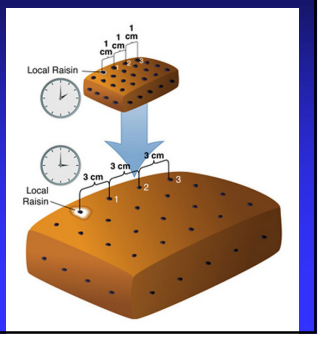
Velocity = H_o x Distance



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



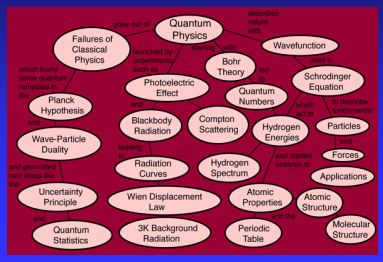
History of Physics of Universe

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

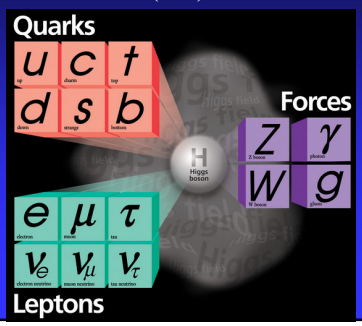
- Equations of Quantum Mechanics

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

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

What is Physics?
Basic Laws of Physics

- Standard Model (SM) Fundamental Particles



What is Physics?
Basic Laws of Physics

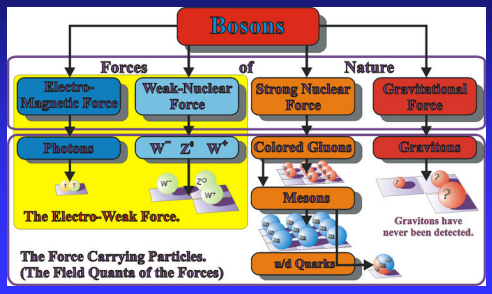
- SM Fundamental Force Particles

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
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	γ (photon)	infinity	
Strong Force** binds quarks together	quarks and gluons	g (gluon)	short range	much stronger

What is Physics?
Basic Laws of Physics

- Bosons: Fundamental Force Particles



What is Physics?
Basic Laws of Physics

- Standard Model of Particle Physics

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

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

$$+ \underbrace{\frac{1}{2}\left|(i\partial_{\mu} - \frac{1}{2}g\tau\cdot\mathbf{W}_{\mu} - \frac{1}{2}g'YB_{\mu})\,\phi\right|^{2} - V(\phi)}_{W\pm, Z, \gamma \text{ and Higgs masses and couplings}}$$

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

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.

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→Expand,Flat,Contract**
- **Hubble (1929) - Expansion of Universe → 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* → 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

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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.

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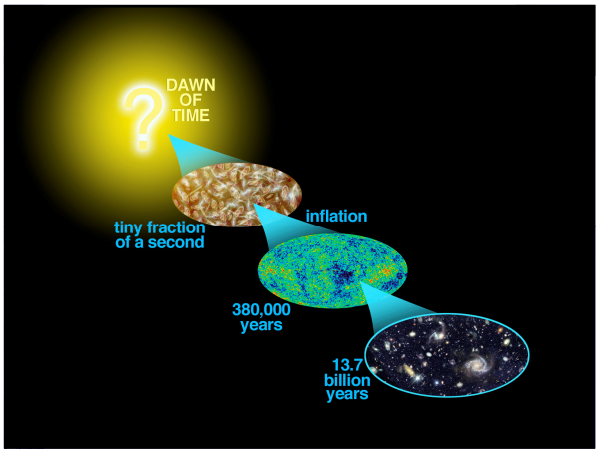
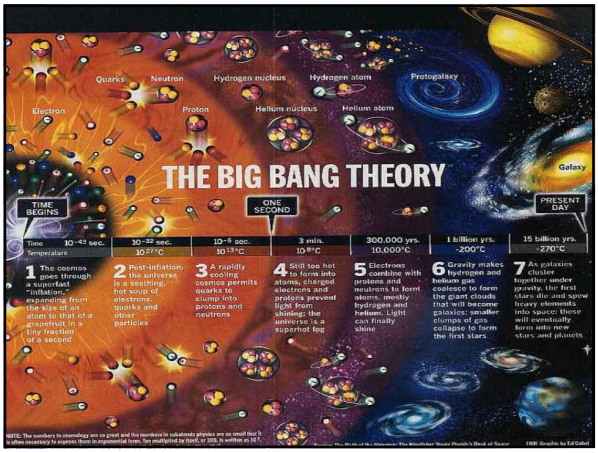
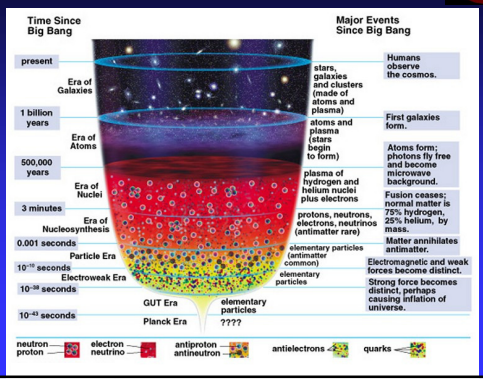




Scale of Physics: Time Since BB



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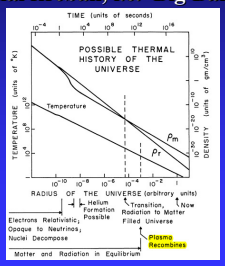
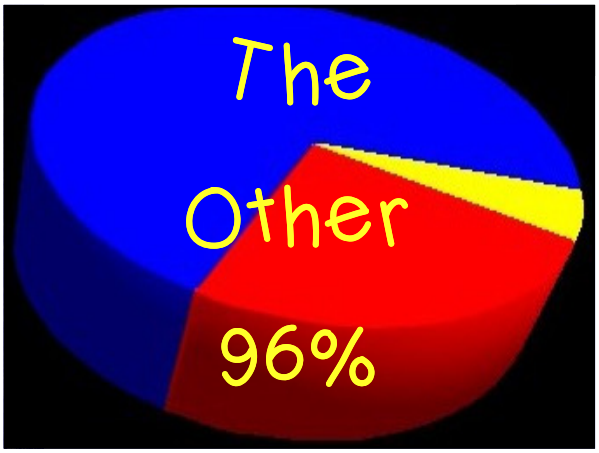
CBR Evidence for Big Bang Theory

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



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



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

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

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.

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).

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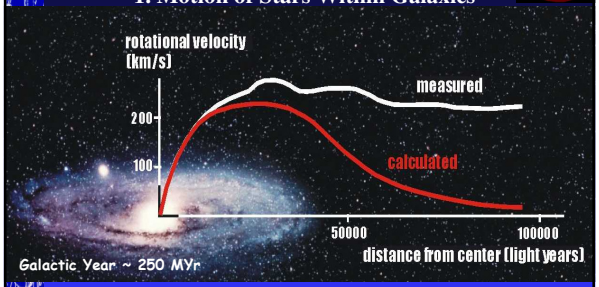
Evidence for Dark Matter:

1. Motion of Stars Within Galaxies



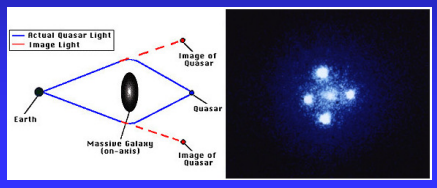
- Need more gravity to balance v → Dark Matter
- Dark Matter 5X Baryonic Matter. Figure E.8
- Dark – does not interact. Not like atoms.

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.



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Evidence for Dark Matter

2. Gravitational Lensing: Within a Galaxy

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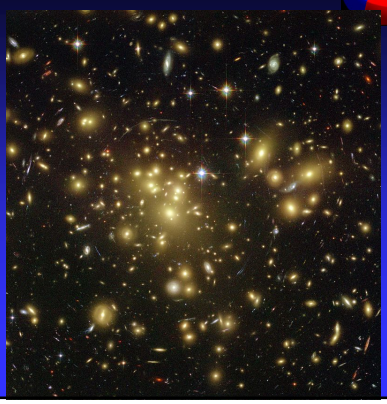
Evidence for Dark Matter

2. Gravitational Lensing: Galaxy Clusters



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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.

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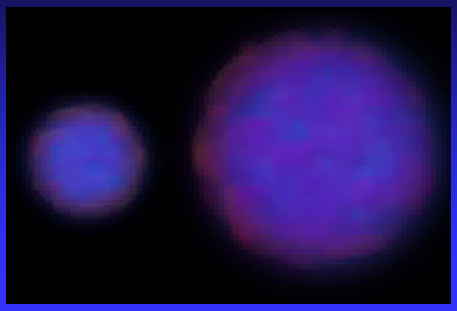
Evidence for Dark Matter

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.

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?

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

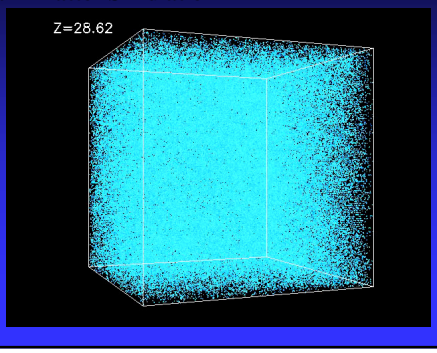
A single dot is a galaxy halo.

This map looks the same as actual observations

- **Interactions-Observation: Structure- Galaxies**

Evidence for Dark Matter

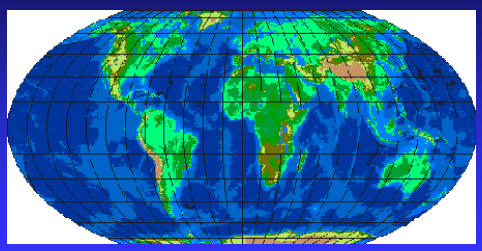
4. Dark Matter Simulation



Evidence for Dark Matter

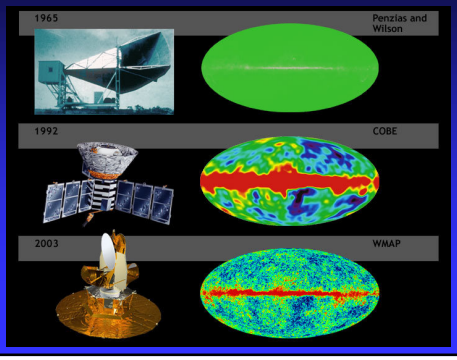
5. Angular Spectrum of CBR

Projection of 3D Sky (Sphere) onto Plane



Evidence for Dark Matter

5. Angular Spectrum of CBR



Evidence for Dark Matter

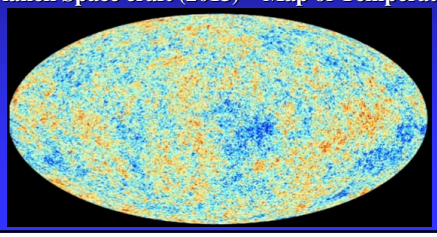
5. Angular Spectrum of CBR

Detect this with Satellites

Cosmic background explorer, COBE (1989)

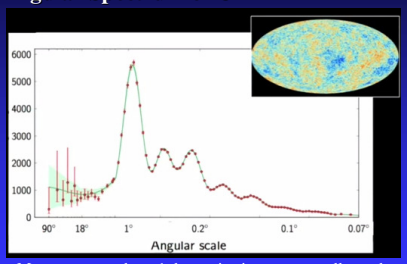
WMAP - Wilkinson Microwave Anisotropy Probe (2001)

Planck Space craft (2013) – Map of Temperatures



Evidence for Dark Matter

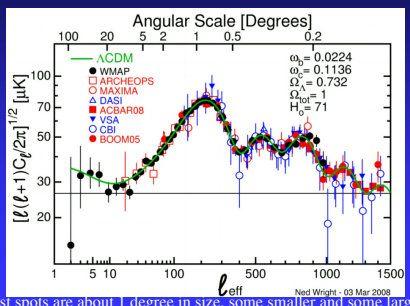
5. Angular Spectrum of CMR



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

Evidence for Dark Energy, ΛCDM

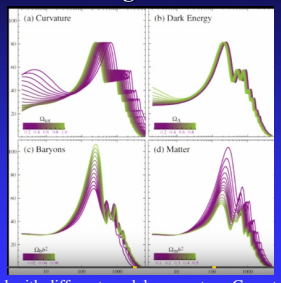
5. Map of Cosmic Background Radiation, Ω_Λ



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

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.

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

What is Dark Matter?

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

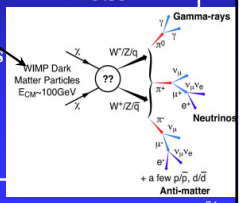
- Particle Candidates

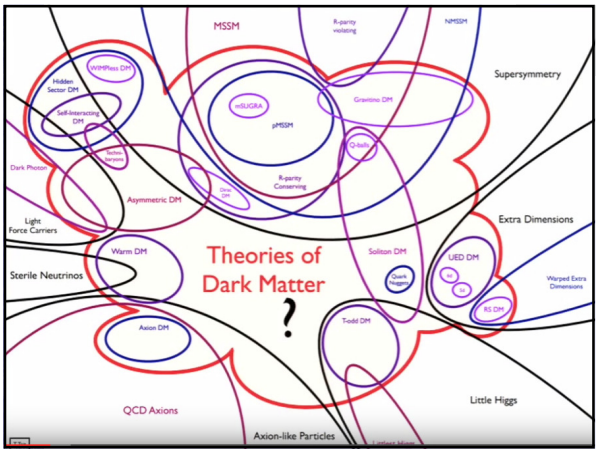
Candidates for Dark Matter: WIMPs

- The most attractive picture for dark matter is that it is some kind of weakly interacting, massive particle (WIMP).
- E.g. Neutralinos in supersymmetry
- WIMPs are particularly exciting, because they have "large" interactions with the Standard Model.
- Large here means roughly electroweak strength -- much larger than gravity.
- The interesting implication is that we have many handles to search for such particles.
- A non-gravitational observation would teach us a lot about the nature of dark matter!

Search for Direct Evidence of DM
Detection of Dark Matter
Particle Search Strategies

- LHC Particle Production
- Detection of Dark Matter
  - Dark Matter-Homogenous to Filaments
  - Starwatch_NGC5754_1507. Dark Matter Lensing.jpg
- Interaction Products
- Cryogenic Crystal Detectors
- Noble Gas Scintillators
- Bubble Chambers





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)

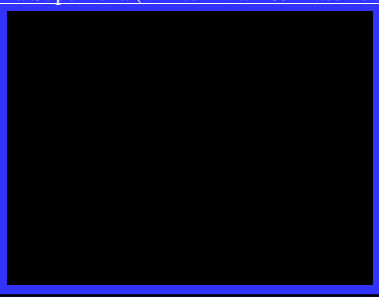
Chandrasekhar Limit
The threshold that make life possible.

Gas is being stripped from a giant star to form an accretion disc around a compact companion (such as a white dwarf star).
Simulation

Evidence for Dark Energy – Star Death

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

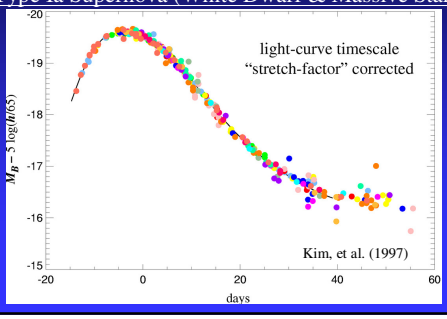
Type Ia Supernova (White Dwarf & Massive Star)



Evidence for Dark Energy

Type Ia Supernova Event

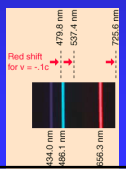
Type Ia Supernova (White Dwarf & Massive Star)



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.

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

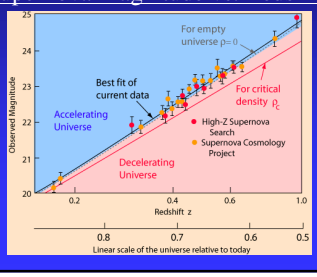


Evidence for Dark Energy

Supernova Cosmology: Probing Dark Energy

The Principal Evidence Dark Energy is

Type Ia Supernova Magnitude vs. Redshift (1998)

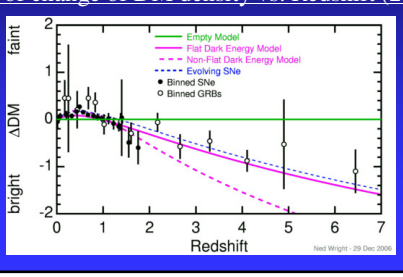


Evidence for Dark Energy

Supernova Cosmology: Probing Dark Energy

The Principal Evidence Dark Energy is

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



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

What is Physics?
Basic Laws of Physics

Original Friedmann Models

ρ = mass-energy density

ρ_c = critical density

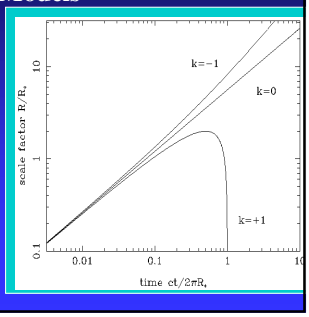
k = curvature

$\Omega = \rho/\rho_c$

$\Omega < 1$ 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

$$H^2 = \underbrace{\frac{8\pi G}{3}\rho}_{\text{matter density}} - \underbrace{\frac{kc^2}{R^2}}_{\text{curvature}} + \underbrace{\frac{\Lambda}{3}}_{\text{dark energy}}$$

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

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

Original Hypothesis of Dark Energy

Lambda Cold Dark Matter Model (ΛCDM):

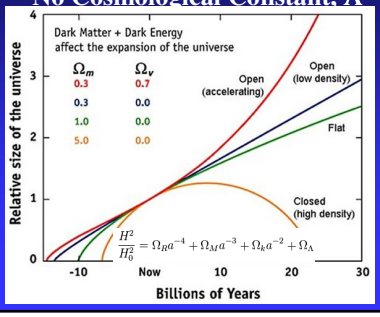
- **A Parametrization of the Big Bang Model-**
- **The universe contains a Cosmological Constant, Lambda (Greek Λ), associated with Dark Energy and Cold Dark Matter**

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

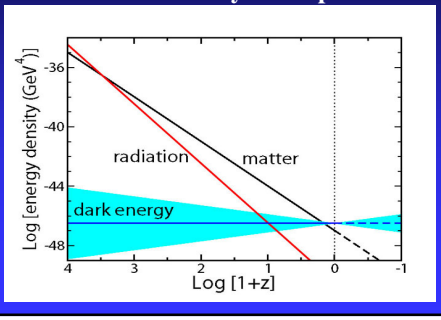
Original Friedmann Models: Matter Only, No Cosmological Constant, Λ



Original Hypothesis of Dark Energy

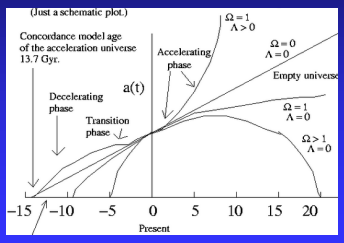
Friedmann Models with Λ,

Plot of Density vs. Expansion



Original Hypothesis of Dark Energy

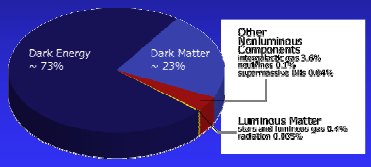
Friedmann Models with Λ



Evidence for Dark Energy

Supernova Cosmology:

Physicists, based on cosmological measurements the following composition of matter.



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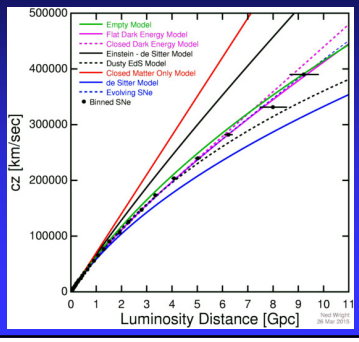
ΛCDM Concordance Modeling:

http://www.astro.ucla.edu/~wright/sne_cosmology.html

Measuring the Curvature of the Universe by
Measuring the Curvature of the Hubble Diagram



11 Parameter ΛCDM Model Simulation

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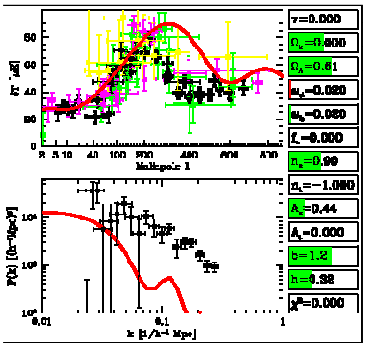
ΛCDM Concordance Modeling: 11 Parameters from CMB to Large Scale



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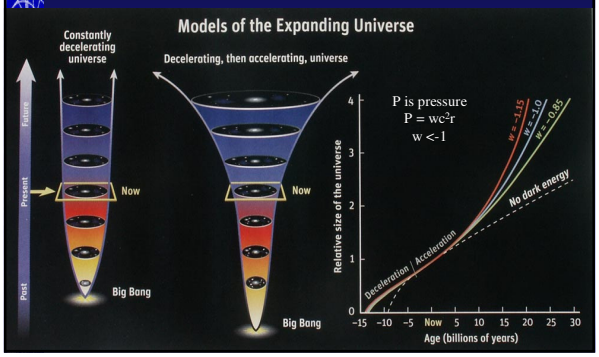
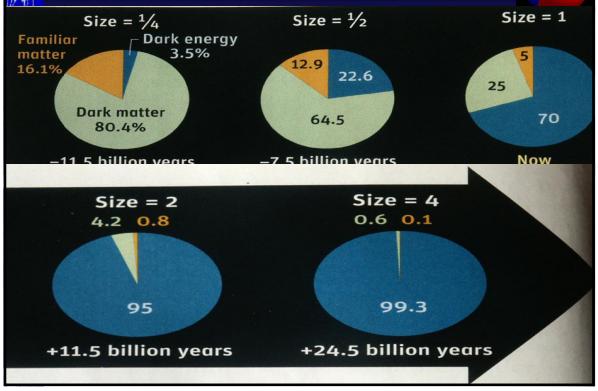
ΛCDM Model

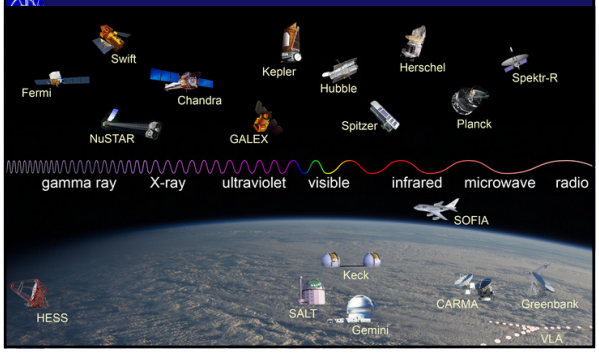


ΛCDM Model



Evidence for Dark Matter

5. Observatories across the electromagnetic spectrum



Dark Energy Detection

- 570-megapixel Dark Energy Camera
- Microwave kinetic inductance detectors
- Can dark energy and matter be detected and studied in labs?
  - Terrestrial Experiment Using Atom Interferometry

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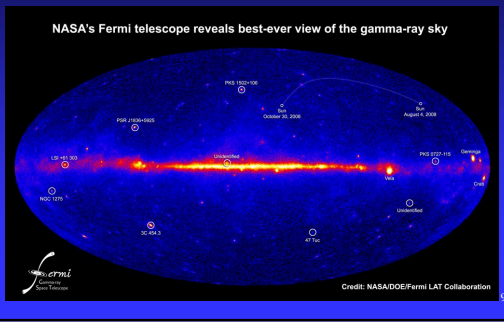
Dark Energy Detection
Fermilab Dark Energy Camera

Dark Energy Detection – Gamma Rays



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One Theory of Dark Energy

Most of the Mass of Our Universe is from Quantum (Empty) Space

Simulation

100

One Theory of Dark Energy

Most of the Mass of Our Universe is from Quantum (Empty) Space

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Theory of Dark Energy: Far Future

- **The Stelliferous (Star Bearing) Age**
- **The Degenerate Age (Dead Stars)**
- Proton Decay
- Black Hole Age – 10^{100} Years to Evaporate
- Dark Age
  - Photons, neutrinos, electrons and positron

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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

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}.