THE BIG BANG

HOW CLOSE
CAN WE COME?

Michael Dine
Final Lecture Physics
171, 2009

Reports a debate among cosmologists about the Big Bang.

lll1.html
Dr. Tyson, who introduced himself as the Frederick P. Rose director of the Hayden Planetarium, had invited five "distinguished" cosmologists into his lair for a roasting disguised as a debate about the Big Bang. It was part of series in honor of the late and prolific author Isaac Asimov (540 books written or edited). What turned out to be at issue was less the Big Bang than cosmologists' pretensions that they now know something about the universe, a subject about which "the public feels some sense of ownership," Dr. Tyson said.

"Imagine you're in a living room," he told the audience. "You're eavesdropping on scientists as they argue about things for which there is very little data."
Rounding out the field were Dr. Lee Smolin, a gravitational theorist at the Perimeter Institute for Theoretical Physics in Waterloo, Ontario, whom Dr. Tyson described as "always good for an idea completely out of left field - he's here to stir the pot."
But Dr. Smolin said the 20th-century revolution was not complete. His work involves trying to reconcile Einstein's general relativity, which explains gravity as the "curvature" of space-time, with quantum mechanics, the strange laws that describe the behavior of atoms. "Quantum mechanics and gravity don't talk to each other," he said, and until they do in a theory of so-called quantum gravity, science lacks a fundamental theory of the world. The modern analog of Newton's Principia, which codified the previous view of physics in 1687, "is still ahead of us, not behind us," he said.

Although he is not a cosmologist, it was fitting for him to be there, he said, because "all the problems those guys don't solve wind up with us."
Today, you are listening to someone seemingly more out in left field
-- a particle physicist.

Particle physics: seeks to determine the laws of nature at a "microscopic" – really submicroscopic, level.

What does this have to do with the Big Bang?

EVERYTHING!
With due respect to the New York Times, articles like this give a very misleading impression.

We know:

• There was a Big Bang (t=0)
• This even occurred about 13 Billion Years Ago
• We can describe the history of the universe, starting at t=3 minutes, and (with less confidence) at t=10^{-35} seconds
• There is now a huge amount of data and a picture with great detail.
There are lots of things we don’t know. With due respect to Lee Smolin, the correct address for these questions is Particle Physics. We can’t answer any of these questions without resolving mysteries of particle physics.

• What is the dark matter?
• Why does the universe contain matter at all?
• What is the dark energy?
• What is responsible for “inflation”?
• What happened at t=0?
Physical Law and the Universe

- Newton: $F = ma$, $F_G = \frac{M_1 M_2}{R^2}$

  **Motion of Planets**

- Laws of electricity and magnetism, nuclear physics: Understanding of Stars

- Einstein: General Relativity – Expansion of the Universe
EINSTEIN

1905: special relativity, photoelectric effect, Brownian Motion
1916: General Relativity

- Culmination of a 9 year struggle to understand Newton’s Gravity, starting with “equivalence principle”
- Tests: Precession of Mercury’s Orbit, Bending of Light

Implications for the universe: COSMOLOGY
Einstein + Copernicus

Assume the universe is homogeneous and isotropic – no special place or direction.

Einstein’s equations have no Static solutions. The universe starts extremely small, then expands!

Einstein was very troubled – remember that at that time (c. 1920) astronomers barely knew about galaxies! Modified his equations by adding ``cosmological constant.”
Edwin Hubble, who first went to study law as a Rhodes scholar, became one of the most important of all astronomers. He convincingly established the existence of galaxies (c. 1925).
HUBBLE (1929)

Galaxies move away from us at a speed proportional to their distance
The Cosmic Microwave Background

For 40 years, only limited evidence for a Big Bang. Gamow, Peebles: if true, there should be a "glow" left over from this huge explosion (but of microwave radiation, not light).

Objects give off a characteristic spectrum of electromagnetic radiation depending on their temperature; "blackbody." The temperature then was 20,000 degrees; today it would be about 3° K.


Today: thanks to COBE satellite, best measured black body spectrum in nature.
Artist’s Rendering of COBE
COBE measured the temperature of the universe:
3 minutes: Synthesis of the Light Elements

• CMBR: A fossil from $t=100,000$ years.
• He, Li, De: Produced at $t=3$ minutes

Neutrino reactions stop; neutrons decay.
Results of Detailed Nucleosynthesis Calculations:

- The fraction of the universe made of "baryons" = protons + neutrons:
- During last few years, an independent measurement from studies of CMBR:

Very impressive agreement!
The CMBR and the Copernican Principle

Just how homogeneous and isotropic is the universe? COBE found at first that the temperature is the same to a part in 1,000 in every direction in the sky!

This high degree of inhomogeneity is hard to understand. Light coming from different directions came from regions which had never been in contact.

The Inflationary universe hypothesis: The Universe, perhaps as early as $10^{-35}$ seconds, underwent a period of extremely rapid expansion.

Predicts: should see small variations in the temperature (part in 100,000).
1993: COBE MAP OF THE SKY
Detailed Confirmation

From satellites and earth based (balloon) experiments. Most recently the WMAP satellite.
Detailed information about the universe:
Dark Matter -- evidence
Dark Matter in the Milky Way:

The gravity of the visible matter in the Galaxy is not enough to explain the high orbital speeds of stars in the Galaxy. For example, the Sun is moving about 60 km/sec too fast. The part of the rotation curve contributed by the visible matter only is the bottom curve. The discrepancy between the two curves is evidence for a dark matter halo.
Bullet Cluster:

Dark Energy – Einstein’s Cosmological Constant

Studies of Supernovae (Type Ia)

Stars, in their final stages, can have varied fates. Some collapse and then explode. Type Ia: “``Standard Candles’’: can determine their distance, light output. Amount of dimming tells about structure of space-time nearby.
Type Ia Supernovae: Dark Energy

![Graph showing mag. residual from empty cosmology vs. redshift z]

- $\Omega_M, \Omega_\Lambda$
  - 0.25, 0.75
  - 0.25, 0
  - 1, 0

The graph illustrates the relationship between the magnitude residual from an empty cosmology and the redshift $z$. The data points and error bars suggest a trend that can be modeled with different combinations of $\Omega_M$ and $\Omega_\Lambda$. The significance of these parameters for understanding dark energy is highlighted.
COMPOSITION OF THE UNIVERSE

If 5% of the Universe is Baryons, What is the Rest?

From studies of CMBR, of distant Supernova explosions, and from Hubble and Ground-Based observations we know:

- 5% Baryons (protons, neutrons)
- 30% Dark Matter (zero pressure)
- 65% Dark Energy (negative pressure)
A Confusing Picture: Where Do We Stand?

We have a good understanding of the history of the universe, both from observations and well understood physical theory, from $t=180$ seconds.

BUT:

• We don’t know why there are baryons at all!
• We don’t know what constitutes 95% of the energy of the universe.
• We know that the universe underwent a period of inflation. But we have little idea what inflation is.
What’s the Problem?

- To answer these questions, we need to know how the universe behaved when the temperature was extremely high.
  
  $\text{Temperature} = \text{energy}$

  So we need to know about high energies.

- In quantum mechanics, high energies $=$ short distances. We need to know about the laws of physics which operate at very short distances.
What do we know?

- Particle physicists know the laws of nature on scales down to one-thousandth the size of an atomic nucleus. The "Standard Model". This corresponds to temperatures about 1,000,000 times those of nucleosynthesis.

**BUT THIS IS NOT ENOUGH TO ANSWER OUR QUESTIONS**

- Experiments at higher energy accelerators at CERN (Geneva) and Fermilab (Chicago) are testing our understanding at even shorter distances. Expect to discover new phenomena.
Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

<table>
<thead>
<tr>
<th>Matter Constituents</th>
<th>Spin</th>
<th>Flavor</th>
<th>Mass (GeV/c^2)</th>
<th>Electric Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptons spin = 1/2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e electron</td>
<td>1</td>
<td>&lt;1x10^{-8}</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>ν_e neutrino</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e electron</td>
<td>-1</td>
<td>0.000511</td>
<td>-1</td>
<td></td>
</tr>
<tr>
<td>ν μ neutrino</td>
<td></td>
<td>&lt;0.0002</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>μ electron</td>
<td>-1</td>
<td>0.106</td>
<td>-1</td>
<td></td>
</tr>
<tr>
<td>ν τ neutrino</td>
<td></td>
<td>&lt;0.02</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>τ electron</td>
<td>-1</td>
<td>1.7771</td>
<td>-1</td>
<td></td>
</tr>
</tbody>
</table>

Quarks spin = 1/2

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass (GeV/c^2)</th>
<th>Electric Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>u up</td>
<td>0.003</td>
<td>2/3</td>
</tr>
<tr>
<td>d down</td>
<td>0.006</td>
<td>-1/3</td>
</tr>
<tr>
<td>c charm</td>
<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>s strange</td>
<td>0.1</td>
<td>-1/3</td>
</tr>
<tr>
<td>t top</td>
<td>175</td>
<td>2/3</td>
</tr>
<tr>
<td>b bottom</td>
<td>4.3</td>
<td>-1/3</td>
</tr>
</tbody>
</table>

Spin is the intrinsic angular momentum of particles. Spin is given in units of h, which is the quantum unit of angular momentum, where \( h = 6.626 \times 10^{-34} \text{ Kg m}^2\text{ s} \).

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is \( 1.60 \times 10^{-19} \) coulombs.

The energy unit of particle physics is the electronvolts (eV), the energy gained by one electron crossing a potential difference of one volt. Masses are given in GeV/c\(^2\) (remember \( E = mc^2\)), where 1 GeV = \( 1.60 \times 10^{-16} \) eV = 1.60 \( 10^{-12} \) joules. The mass of the proton is 0.938 GeV/c\(^2\) = 1.67 \( 10^{-27} \) kg.

The strong binding of protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

BOSONS

<table>
<thead>
<tr>
<th>Force Carriers</th>
<th>Spin</th>
<th>Flavor</th>
<th>Mass (GeV/c^2)</th>
<th>Electric Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon</td>
<td>1</td>
<td>γ</td>
<td>80.4</td>
<td>-1</td>
</tr>
<tr>
<td>W^+</td>
<td>1</td>
<td>W^+</td>
<td>80.4</td>
<td>+1</td>
</tr>
<tr>
<td>Z^0</td>
<td>0</td>
<td>Z^0</td>
<td>91.187</td>
<td>0</td>
</tr>
</tbody>
</table>

Color Charge

Each quark carries one of three types of "strong charge" (also called "color charge.") These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons, just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and W and Z bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called hadrons. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pair (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: mesons \( \eta \) and \( \eta' \) and baryons \( qqq \).

Residual Strong Interaction

Properties of the Interactions

<table>
<thead>
<tr>
<th>Property</th>
<th>Gravitational</th>
<th>Weak</th>
<th>Electromagnetic</th>
<th>Strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acts on:</td>
<td>Mass – Energy</td>
<td>Flavor</td>
<td>Electric Charge</td>
<td>Color Charge</td>
</tr>
<tr>
<td>Particles experiencing:</td>
<td>All</td>
<td>Quarks, Leptons</td>
<td>Electrically charged</td>
<td>Quarks, Gluons</td>
</tr>
<tr>
<td>Particles mediating:</td>
<td>Graviton (not yet observed)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strength relative to electron:</td>
<td>( 10^{-18} ) m</td>
<td>( 10^{-4} )</td>
<td>0.8</td>
<td>1</td>
</tr>
<tr>
<td>for two ( u ) quarks:</td>
<td>( 10^{-17} ) m</td>
<td>10^{-4}</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>for two protons in nucleus:</td>
<td>( 10^{-36} )</td>
<td>10^{-7}</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

The Particle Adventure

Visit the award-winning web feature The Particle Adventure at http://ParticleAdventure.org

This chart has been made possible by the generous support of:

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One possible new phenomenon: Supersymmetry

If correct, all of the particles we know have "superpartners" (same electric charge and other properties, but different "spin")

If this idea is right, then it explains what the dark matter is!
<table>
<thead>
<tr>
<th>Electrons</th>
<th>Selectrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quarks</td>
<td>Squarks</td>
</tr>
<tr>
<td>Photons</td>
<td>Photinos</td>
</tr>
<tr>
<td>Higgs particles</td>
<td>Higgsinos</td>
</tr>
</tbody>
</table>
Aerial view of LHC
Muon superconducting Toroids in the ATLAS Detector at the LHC
GLAST (Fermi) launch, June
Tracker Pictures

Tracker

Inserting silicon detector into tracker

Inserting solenoid into calorimeter
Muon superconducting toroids.
Endcap Muon Sectors
SCALE OF THE PROJECT

- The stored energy in the beams is equivalent roughly to the kinetic energy of an aircraft carrier at 10 knots (stored in magnets about 16 times larger).
- There will be about a billion collisions per second in each detector.
- The detectors will record and stores “only” around 100 collisions per second.
- The total amount of data to be stored will be 15 petabytes (15 million gigabytes) a year. It would take a stack of CDs 20Km tall per year to store this much data.
Collide two protons each with energy 7 TeV.
(1 TeV is roughly the kinetic energy of a flying mosquito. This energy is squeezed into a region $10^{-12}$ of a mosquito.)

The total energy in the beam is comparable to an aircraft carrier moving at about 10 knots.
• So a better understanding of the laws of nature – in the not too distant future – might answer two of the puzzles in our list.

What about the others?

Harder: But over time, we may have answers. All require, as Smolin says, an understanding of quantum mechanics and gravity (general relativity). Particle physicists do have a theory which reconciles both: String Theory. This is the subject of another talk. But String Theory does have

• Supersymmetry (dark matter, baryogenesis)
• Candidate mechanisms for inflation
• A possible explanation of the dark energy.
String Theory

• For reasons that are still not understood, assuming that the fundamental entities are strings rather than point particles automatically gives a sensible quantum theory of gravity (General Relativity).
• These theories are hard. Many features are qualitatively right, but the details are hard to get straight.
Could the LHC discover string theory?

Maybe. String theory may predict supersymmetry, the spectrum (masses) of the new particles. It might predict (a real long shot, but terribly exciting if true) extra dimensions of space which could be observed, black holes...