Cosmological Beginnings & Endings

Michael S. Turner
Kavli Institute for Cosmological Physics
The University of Chicago
“The New Cosmology”
(aka Concordance Model)

Flat, accelerating Universe

Composition

- 4% baryons (0.5% stars!)
- 26% cold dark matter (~0.1% neutrinos)
- 70% “dark energy”
- < 4% secret ingredients & sauces

Inflation-produced, nearly scale-invariant density perturbations

... Consistent with large & growing body of observations
ORDINARY MATTER: FROM QUARKS TO US

INFLATION

BARYOGENESIS

\( \mathcal{O}_B = 0.045 \pm 0.006 \)

BBN

10^{-5} \text{ sec}

D/H = (3 \pm 2) \times 10^{-5}

\( \Omega_B = 0.04 \pm 0.002 \)

FORMATION OF ATOMS

COSMIC MICROWAVE BACKGROUND

400,000 YRS

FIRST QUASARS

\( \Omega_B/\Omega_m = 0.15 \pm 0.05 \)

\( \Omega_{\text{h}} = 0.20 \pm 0.05 \)

\( \Omega_B = 0.09 \pm 0.02 \)

INTERGALACTIC GAS

ABSORPTION OF QUASAR LIGHT BY HYDROGEN:

\( \Omega_B > 0.04 \)

HERE & NOW

14 Billion yrs

stars, gas, dust,

BBN, NS, Peculiar ...

TRANSITION FROM QUARKS \rightarrow NEUTRONS, PROTONS

BIG-BANG NUCLEOSYNTHESIS

Formation of H, D, He, He-3, Li

100 SEC

DENSITY OF MATTER

\( \mathcal{O}_B = 2/1 \)
Strong Foundation

- Interlocking web of cosmological and lab measurements: from CMB observations to data from particle accelerators

- Sound physics foundation
  - General relativity, atomic & nuclear physics
  - Standard model of particle physics

- Well motivated and well formulated speculations based upon
  - Gauge theory and grand unification
  - Supersymmetry
  - Superstring theory
The thermal history of the universe was traced in Section 15.6 back to an era when the temperature was about $10^{12} \, \text{K}$. At this early time, the universe was filled with particles—photons, leptons, and antileptons—whose interactions are hopefully weak enough to allow this medium to be treated as a more or less ideal gas. However, if we look back a little farther, into the first 0.0001 sec of cosmic history when the temperature was above $10^{12} \, \text{K}$, we encounter theoretical problems of a difficulty beyond the range of modern statistical mechanics. At such temperatures, there will be present in thermal equilibrium copious numbers of strongly interacting particles—mesons, baryons, and antibaryons—with a mean interparticle distance less than a typical Compton wavelength. These particles will be in a state of continual mutual interaction, and cannot reasonably be expected to obey any simple equation of state.

However, the temptation to try to construct some sort of model of the very early universe is irresistible. There are in fact two extremely different simple models that have been widely considered in recent years, and that reflect two divergent views of the nature of the strongly interacting particles. Although neither model can be taken seriously in detail, the hope is that one or the other of these models may come close enough to reality to lead to useful insights about the very early universe.

The first of these two pictures may be called the elementary particle model. It is supposed that all particles are made up of a small number of elementary...
The Fall of the Hadron Wall
The 1970s: Gauge Theory, Asymptotic Freedom and GUTs
Precision Cosmology!

with no apologies!
Some Cosmological Parameters

error bars decreasing, consistency holding

- $T = 2.725 \pm 0.001$ K
- $H_0 = 70 \pm 7$ km/s/Mpc
- $\Omega_0 = 1.01^{+0.009}_{-0.016}$
  - $\Omega_M = 0.27 \pm 0.04$
  - $\Omega_{DE} = 0.65 \pm 0.05$
  - $\Omega_B = (0.022 \pm 0.001)/h^2$
  - $0.001 < \Omega_v h^2 < 0.01$
- $t_0 = 13.7^{+0.13}_{-0.17}$ Gyr
- $n = 0.961 \pm 0.017$
- $\tau = 0.093 \pm 0.03$
- $w = -1 \pm 0.1$

COBE FIRAS
HST, SZ, CMB, ...

WMAP, $H_0$

WMAP, SDSS, SNe, Clusters

WMAP, SDSS, SNe

WMAP, BBN

WMAP, SDSS, SuperK, K2K, ...

WMAP, GC, WDs, $H_0$

WMAP, SDSS

WMAP

WMAP, SDSS, SNe
Hubble Constant has been constant for 5+ years!

HST Key Project: $H_0 = 72 \pm 7 \text{ km/s/Mpc}$

WMAP: $H_0 = 73^{+3}_{-4} \text{ km/s/Mpc}$

SZ: $H_0 = 74 \pm 4 \pm 10 \text{ km/s/Mpc}$
The CDM Power Spectrum
Baryon Density

- CMB: $\Omega_B h^2 = 0.022 \pm 0.001$

- D/H and BBN: $\Omega_B h^2 = 0.021 \pm 0.002$
  
  started with “Alpha, Beta, Gamma”

- Mean absorption of IGM: $\Omega_B \sim 0.04$
... much more than quark soup beginning
• Existence of Atoms
• Dark Matter
• Cosmic Acceleration
• Seeds for Structure
• Chemical Elements
• Longlived Stars & Life
• Multiverse

➢ Baryogenesis/Leptogenesis
➢ Axions, Neutrinos, Neutralinos
➢ Dark Energy, New Grav Phys
➢ Inflation
➢ Neutrinos
➢ Hierarchy of Weak/Planck
➢ Superstrings
Linking Inner Space and Outer Space has Profoundly Changed Both Cosmology and Elementary Particle Physics Linking Their Agendas for the Foreseeable Future
The Big Cosmic Questions

- What is the cold dark matter?
- How much of the dark matter is neutrinos?
- How did atoms originate?

WHAT POWERED THE BIG BANG?
Inflation is a modest start

WHAT IS THE DARK ENERGY THAT CONTROLS OUR COSMIC DESTINY?

Validity of general relativity, variation of the constants, ... “precision heavenly lab”
COSMIC BEGINNINGS & ENDINGS

The Middle is in Pretty Good Shape
SPACE-TIME GEOMETRY

our initial geometry
smooth, small ripples

15 Gyr

generic initial geometry

Black holes, anisotropy, ...

10^{-43} sec

"A MESS"

Collins & Hawking '71

NOT LOGICAL INCONSISTENCY!

DILEMMA OF INITIAL DATA

(Why so special?)
Promise of Inflation:

* To lessen dependence of present state upon initial state

“Grander” Big Bang model -- from $10^{-2} \text{sec} \rightarrow 10^{-35} \text{sec}

Underlying Physics

Speculative -- but well defined (classical field theory motivated by grand unification, superstrings, supersymmetry)
All models based upon scalar field dynamics

\[ \ddot{\phi} + 3H \dot{\phi} + V' = 0 \]

**Inflation in the Universe**

Early epoch of tremendous expansion driven by vacuum energy.

Accounts for:
- Smoothness, heat of Big Bang & absence of monopoles

& Predicts:
- "Flat universe" ($\Omega_0 = \frac{\rho_{tot}}{\rho_{cusp}} \approx 1.0$)
- Redshift
- Radio emission
- Nearly scale-invariant density perturbations
- Nearly scale-invariant gravity waves
Density Perturbations

\[ P(k) = \frac{1024 \pi^3}{75} \frac{k}{H_0^4} \frac{V_*^3}{m_{\text{Pl}}^6 V_*''^2} \left( \frac{k}{k_*} \right)^{n-1} T^2(k) \]

\[ n - 1 = -\frac{1}{8\pi} \left( \frac{m_{\text{Pl}} V_*'}{V_*} \right)^2 + \frac{m_{\text{Pl}}}{4\pi} \left( \frac{m_{\text{Pl}} V_*''}{V_*} \right) \]

\[ \frac{dn}{d\ln k} = -\frac{1}{32\pi^2} \left( \frac{m_{\text{Pl}}^3 V_*''}{V_*} \right) \left( \frac{m_{\text{Pl}} V_*''}{V_*} \right)^2 + \frac{1}{8\pi^2} \left( \frac{m_{\text{Pl}}^2 V_*''}{V_*} \right) \left( \frac{m_{\text{Pl}} V_*''}{V_*} \right)^2 - \frac{3}{32\pi^2} \left( \frac{m_{\text{Pl}} V_*'}{V_*} \right)^4 \]

\[ T(q) = \frac{\ln (1 + 2.34q) / 2.34q}{[1 + 3.89q + (16.1q)^2 + (5.46q)^3 + (6.71q)^4]^{1/4}} \]

Gravitational Waves

\[ P_T(k) = \langle |h_k|^2 \rangle = \frac{8}{3\pi} \frac{V_*}{m_{\text{Pl}}^4} \left( \frac{k}{k_*} \right)^{n_T-3} T_T^2(k) \]

\[ n_T = -\frac{1}{8\pi} \left( \frac{m_{\text{Pl}} V_*'}{V_*} \right)^2 \]

\[ \frac{dn_T}{d\ln k} = \frac{1}{32\pi^2} \left( \frac{m_{\text{Pl}}^2 V_*''}{V} \right) \left( \frac{m_{\text{Pl}} V_*''}{V} \right)^2 - \frac{1}{32\pi^2} \left( \frac{m_{\text{Pl}} V_*'}{V} \right)^4 = -n_T[(n - 1) - n_T] \]

\[ T_T(k) \approx \left[ 1 + \frac{4}{3} \frac{k}{k_{\text{EQ}}} + \frac{5}{2} \left( \frac{k}{k_{\text{EQ}}} \right)^2 \right]^{1/2} \]
Signatures of Inflation

• “Flat,” smooth Universe

• With tiny lumpiness arising from Quantum Fluctuations

• Hot quark soup from decay of vacuum energy
CMB is Key to Testing Cosmic Inflation

- Uncurved (flat) Universe
  - “Spot size”

- Lumpiness from “Quantum Fluctuations”
  - Acoustic peaks, relative heights

- Evidence for inflation produced gravitational waves
  - Polarization (and Anisotropy)
First Evidence for Flat Universe

BOOMERANG 2000

DASI 2001
You Live in a Flat Universe!

WMAP
all sky maps
large angular scales
2003, 2006
WMAP Sea Change

BEFORE WMAP

AFTER WMAP
ACBAR on Viper
2.1 m Telescope
UC Berkeley/Case Western

Probe small angular scales
Complementary to WMAP
ACBAR & WMAP Complementary:
Different Technology & Different Angular Scales

"Acoustic peaks":
signature of inflation-produced lumpiness
Degree Angular Scale Interferometer (DASI)
Chicago/Caltech
DASI Discovers CMB Polarization

• Key Test of Hot Big Bang
• Open Door for the Big Test of Inflation
The Big Prize

“B-Mode” Polarization

Third Critical Test of Inflation
(Gravitational Waves)

Pin Down Energy Scale/Time of Inflation

\[ V = 3.5 \times 10^{16} \text{ GeV } (r=T/S)^{1/4} \text{ or } H^{-1} = 2 \times 10^{-38} \text{ sec}/(r=T/S)^{1/2} \]

Reveal Cause of Inflation
DETECTION OF GRAVITY WAVES

$R = \frac{T}{S}$

$\Omega_{gw}(Hz) h^2$

VERY CHALLENGING!

"DOUBLE DETECTION" $\Rightarrow \eta T$ to $\pm 0.03$

NB:

LIGO: $10^{-8}$

LISA: $10^{-13}$
BICEP* Polarization Experiment
Caltech/JPL, UCSD, UC Berkeley, IAS (Paris), CEA (Grenoble), Cardiff

Optimized for angular scales greater > 1 degree

*Background Imaging of Cosmic Extragalactic Polarization
9 hours BICEP vs. 3 years WMAP
Which is which?
10 m South Pole Telescope (SPT)
Chicago/UC Berkeley/UIUC/Case Western/SAO

Nov 06/Jan 07 Deployment
Planck 2008

$r = 10^{-2}$?
CMB Polarization Satellite?

r = 10^{-3}?
Serious testing of Inflation has \textit{begun}

Key Predictions

1. Flat Universe
2. \textit{Almost} scale-invariant, Gaussian perturbations: \((n-1) \sim \pm 0.1\) and \(dn/d\ln k \sim \pm 0.001\)
3. Gravity waves: spectrum, amplitude not predicted

Key Results (WMAP)

1. \(\Omega_0 = 1.0 \pm 0.01\)
2. \(n = 0.96 \pm 0.017^*; \ dn/d\ln k = -0.1 \pm 0.05; \) no evidence for nonGaussianity
3. \(r < 0.55 \ (95\% \ cl)^*\)

*Depends significantly upon the priors assumed
**Inflation Scorecard**

**Predictions**

**Flat Universe**
- $\Omega = 1.000$

**Density Perturbations From**
- Adiabatic
- Nearly Scale-Invariant $(\eta-1) \sim \theta(\pm 0.1)$
- Nearly Power-Law $d\eta/d\ln k \sim 10^{-3}$
- Gaussian

**QM Fluc**
- 33 Acoustic Peaks
- $n = 1.05 \pm 0.04$
- $d\eta/d\ln k = -0.02 \pm 0.04$
- "No Evidence Against"

**CDM**
- "Has much of the truth"

**Grav Waves from QM Metric Fluc**
- $T/S \geq 10^{-3}$
- Nearly Scale Invariant $n_T = -1/2 \times T/S$
- $T/S \leq 0.4$
- $0.71 (95\% c.l.)$
- $T/S \geq 10^{-4}$
- $\pm 0.03$

**Now**
- $n = 1.03 \pm 0.03$
- $\pm 0.001$

**Grade**
- **++**

**Goal**
- $\pm 0.001$
STATUS OF INFLATION: EXCELLENT!
How much truth does inflation have?

Cosmic Inflation

DID THE UNIVERSE INFLATE?

Test the three predictions

What powered inflation?

Who is \( \phi \)?

Multiverse! #?

Science?

Lab evidence
Inflation is Modest –– More Like Duct Tape

BEFORE THE BIG BANG

Three Ideas – All Probably Wrong
Einstein's Big Bang

- No before the Big Bang

The Big Bang
Creation of space, time, matter, and energy
INFLATIONARY MULTIVERSE

INFINITE NUMBER OF BEGINNINGS

“COSMIC RIVER OF TIME”
Some Features of String Theory

• Extra “dimensions” (big & small)
• Multiple vacua (landscape, etc)
• Variable constants (moduli field)
• Unification of particles and forces
• Strings
Some Cosmic Aspirations of String Theory

- Fundamental theory of inflation
- Explanation of cosmic acceleration
- Emergent space and time
- Variable constants (moduli field)
- Foundation for multiverse
String Theory’s Big Bang

- No before the Big Bang

Creation of space, time, matter & energy
Bouncing Universe

Size

¡Biff! Bam! Pow!

Pow! Wow! Time
THE MULTIVERSE
DARK ENERGY
MAY BE THE MOST
PROFOUND PROBLEM
IN ALL OF SCIENCE TODAY
A LOT AT STAKE!

COSMIC DESTINY
(CAN'T UNDERSTAND)

INFLATION
(RELATED?)

NARCISSISTIC
SYMMETRY

NEUTRAL
MASS
SAME SCALE

QUANTUM VACUUM
ENERGY

(WHY SO SMALL?)

SURPRISE

???

DARK ENERGY

WHAT IS IT?

SUPER SYMMETRY

SUPER SYMMETRY
(SOLUTION?)

SUSY \Rightarrow \rho_{vac} = 0
SUSY \Rightarrow \rho_{vac} \neq 0

NEW GRAVITY
PHYSICS

OF ACCELERATION

WHY NOW?

... SWEDISH GOLD OPPORTUNITIES
In the Presence of Dark Energy, a Flat Universe Can Expand Forever, Re-collapse, or Even Experience a Big Rip!

Cannot Understand Our Cosmic Destiny Until We Understand What Dark Energy Is!
Cosmic Acceleration
Dark Energy

• Evidence for cosmic acceleration has gotten stronger (HST, CFHTLS, Essence, WMAP, XMM/Chandra…)
• Still no understanding – “theorists continue to explore phase space”
• No evidence that dark energy is not the energy of the quantum vacuum
• Very significant probes on the horizon
GR allows for repulsive gravity:

Source of gravity in GR:

$\rho + 3p$

(Spherical symmetry)

Black holes when $\rho \geq p/3$

Repulsive gravity when $\rho < -p/3$

Feature not a bug!
The Gravity of Nothing Is Repulsive

… But How Much Does Nothing Weigh?

Apparently, Way Too Much or Possibly Nothing

Quantum Vacuum is NOT Empty!

sea of virtual particles

Whose existence has been detected (shifting of atomic levels in H)

W. Lamb, Nobel Prize '55

Quantum vacuum is elastic ($p = -\rho$) & its gravity is repulsive! ($p + 3\rho = -2\rho$)

Just what is needed -- but...

Theoretical estimates of amount $10^{55} \times$ what is needed to explain accelerating Universe

"Houston, we have a problem"
Dark Energy Theory

SOLVING THE COSMIC ACCELERATION RIDDLE WILL REQUIRE A CRAZY, NEW IDEA!

NB: NOT EVERY CRAZY IDEA IS A SOLUTION TO A PROFOUND PROBLEM.
**Rolling Scalar Field**

(a.k.a. decaying cosmological constant, pseudo Nambu Goldstone boson, quintessence, not there yet)

Bronstein 1933 (executed by Stalin 1935)
Hill Schramm Fry 1986
Freese et al. 1987
Ratra-Peebles 1988
Figueroa et al. 1995
Caldwell et al. 1998

& others

A. Greenspan 1998: “... Brief Episodes of Inflation Are Unavoidable.”

\[ V(\phi) \]

\[ p = \frac{1}{2} \dot{\phi}^2 + V \]

\[ p = \frac{1}{2} \dot{\phi}^2 - V \]

\[ w = -1 \rightarrow 1 \]

\[ (10^{-2} eV)^4 \]

**TRUE VACUUM**
**ZERO ENERGY**
Everyone Wants to Play!

**A BRIEF EPISODE OF INFLATION**

(aka decaying cosmological constant, quintessence, rolling scalar field)

...mild episodes of inflation are unavoidable

A. GREENSPAN

![Diagram](image)

$V(\phi)$

$m, \nu$

Pressure varies with time, but typically negative
Network of (frustrated) topological defects

**String**

A. Vilenkin '84
Pan-Spergel '98

Very elastic: \( p = -p/3 \)

In general: \( p = -n/3 \)
NO DARK ENERGY
NEW ASPECT OF GRAVITY

"EMPTY" UNIVERSE UNDERGOES ACCELERATED EXPANSION!

AVERAGE MATTER DENSITY TODAY $\approx 10^{-29}$ g/cm$^3$
$\approx 10^{-100} \times$ DENSITY AFTER INFLATION
Summary of Dark Theory

• No compelling model (to say the least)

• Current Menu
  – Quantum Vacuum Energy
    + it exists (!)
    - 55 orders-of-magnitude discrepancy (or more!)
  – Quintessence
    + temporary, related to cosmic inflation, great variety of models
    - doesn’t solve vacuum energy, coupling to the world
  – Modified Gravity
    + Einstein didn’t get last word, superstring inspired, no dark energy
    - No workable/compelling model
  – “Conventional solution” (Riotto et al)
    - Doesn’t work?, no fun!
Describing Dark Energy

- Defining feature of dark energy: negative pressure, smooth distribution
- \( w \), not perfect, but nothing is better, connects to the physics

\[
\rho_{\text{DE}} \sim (1 + z)^{3(1+w)}
\]

1. Not necessarily constant
2. Vacuum energy = -1
3. Quintessence -1 to 1
4. Ghostly quintessence < -1
5. Modified gravity, \( w \) can be imaginary
Probing Dark Energy

• Primary effect is on the expansion and it controls:
  – cosmic distances
  – evolution of cosmic structure

• Powerful Probes:
  – Supernovae, baryon acoustic oscillations
  – Clusters, large-scale structure

• Where we are: \( w = 1 \pm 0.1 \); no evidence for variation

• Where we could be by the end of next decade:
  – \( w = xx \pm 0.03 \) and \( \frac{dw}{dz} = yy \pm 0.1 \)
  – Multiple complementary techniques
  – Evidence for supersymmetry (from LHC)
Baryon Acoustic Oscillations as a Standard Ruler

Eisenstein et al, 2005
3 Critical Probes of Dark Energy
WE KNOW MUCH

INFLATION

STYLING COSMOLOGY

HOT BIG BANG MODEL

MASSIVE NEUTRINOS

DARK ENERGY

COSMIC ACCELERATION

COLD DARK MATTER

CAN WE PUT IT ALL TOGETHER?
WE KNOW MUCH

INFLATION

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THE BIG PICTURE

OUR UNIVERSE