Einstein, Cosmology and the Universe
From Static to Expanding to Accelerating

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“Spacetime tells matter how to move; matter tells spacetime how to curve.”

John A. Wheeler (1911-2008)
Einstein’s Perfect Universe

Same Everywhere

no evidence for this in 1916
turned out to be correct!

Ever the Same

turned out to be wrong
Expanding Universe

\[ a(t) \]

\[ k=0 \]

\[ k = 0, \text{ flat} \]
\[ k > 0, \text{ closed} \]
\[ k < 0, \text{ open} \]
Redshift $z$

\[
1 + z = \frac{\lambda_{\text{obs}}}{\lambda_{\text{emit}}} = \frac{a_{\text{now}}}{a_{\text{then}}} = \frac{1}{a}
\]
Einstein’s Static Universe

Theory of the Universe in 1920’s

- **Alexander Friedmann**, “Über die Möglichkeiten einer Welt mit konstanter negativer Krümmung”, Zeitschrift für Physik (1924) (Eng: On the possibility of World with constant negative curvature of space)

- **Georges Lemaître**, “Un univers homogène de masse constante et de rayon croissant rendant compte de la vitesse radiale des nébuleuses extra-galactiques”, Annales de la Société Scientifique de Bruxelles (1927)

Observations

- **Henrietta Leavitt** (1912) discovered a relation between the luminosity and the period of Cepheids’ pulsation

- **Cepheids used as “standard candles”**


- **Carl Wirtz** (1924) and **Knut Lundmark** (1925): further nebulae (galaxies) recede faster
A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY AMONG EXTRA-GALACTIC NEBULAE

BY EDWIN HUBBLE

MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON

Communicated January 17, 1929

FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

Meine größte Eselei!
Implication of the expansion:

the universe was dense and hot in the past

We can see the evidence:

looking deep into space = looking back in time
Live, from the Big Bang!
Discovery of the Cosmic Microwave Background

1965: A. Penzias and R. W. Wilson of Bell Labs
1978 Nobel Prize in Physics
The map

Earth Temperatures

-63°  -13°  37°
Centigrade
June 1992

Microwave Sky Temperatures

-270.4252° -270.4250° -270.4248°
Centigrade
380,000 Years after Big Bang
1992 COBE

John Mather and George Smoot, 2006 Nobel Prize in Physics
The wild 90’s

• Working model based on a flat, expanding, decelerating universe

• Only 10%-50% of total energy in the universe is due to matter, where is the rest?

• The Age Problem: some stars are older than the universe
THE COSMOLOGICAL CONSTANT IS BACK

Lawrence M. Krauss\textsuperscript{1} and Michael S. Turner\textsuperscript{2,3}

As we shall discuss, the observational case for a cosmological constant is so compelling today that it merits consideration in spite of its checkered history. On the theoretical side the value of the cosmological constant remains extremely puzzling, and it just could be that cosmology will provide a crucial clue. Fortunately, there are observations that should settle the issue sooner rather than later.

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(submitted to Gravity Research Foundation Essay Competition)

SUMMARY

A diverse set of observations now compellingly suggest that Universe possesses a nonzero cosmological constant. In the context of quantum-field theory a cosmological
1998: the evidence

Standard Candles: Supernovae Type IA

http://supernova.lbl.gov/video.html
Supernovae on Demand

Saul Perlmutter’s idea:

Look at thousands of galaxies for 2-3 nights every 2-3 weeks with a wide-field imager. Follow up with spectroscopy, scheduled in advance

Saul Perlmutter starts the Supernovae Cosmology Project in 1988

Brian Schmidt starts the High-Z SN Search Team in 1994

Adam Riess leads the analysis for HZT

By 1998, SCP reported 42 reliable SNIa, HZT added another 16
Key pieces of information

The redshift of the host galaxy

The distance to the supernovae

\[ \text{Observed Luminosity} = \frac{\text{Intrinsic Luminosity}}{4\pi \text{ Distance}^2} = \frac{L}{4\pi d_L^2} \]

Use Einstein’s equations to find the expansion history and the content of the universe from the way distance changes with redshift

2011 Nobel Prize in Physics

Saul Perlmutter

Brian P. Schmidt

Adam G. Riess

The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess "for the discovery of the accelerating expansion of the Universe through observations of distant supernovae".
Why is it accelerating?

Lambda is a constant energy density of empty space

Vacuum energy is persistent, it is a feature of space itself (the vacuum density does not decrease with expansion)

Constant vacuum density = constant curvature

Curvature causes acceleration
How much energy is in the vacuum?

Observations measure the sum of vacuum energy and Lambda

\[ \rho_{\text{obs}}^{(\text{vac}+\Lambda)} \approx 2.4 \times 10^{-12} \text{ kCal/m}^3 \]

Quantum theory predicts a huge vacuum energy

\[ \rho_{\text{theory}}^{(\text{vac})} \sim 10^{120} \rho_{\text{obs}}^{(\text{vac}+\Lambda)} \]

Something is NOT right
The Two Cosmological Constant Problems

THE OLD PROBLEM:

What is the vacuum energy and how does it gravitate?

THE NEW PROBLEM (Dark Energy)

What sets the observed value of Lambda?

The only existing “solution” to both problems is “anthropic” (Weinberg 1989, Vilenkin 1995):

IF Lambda could take on ANY value, its value should be consistent with existence of galaxies like ours
Since 1998

WMAP and Planck satellite provided spectacular CMB measurements

Sloan Digital Sky Survey provided millions of galaxy redshifts

Around 1000 supernovae, compared to 42±17 in 1998
We have a working model of the visible universe
CMB Theory vs Data

Planck best-fit
Need dark matter
Gravitational mass of the galaxies within the Coma cluster are at least 400 times greater than expected from their luminosity.

Fritz Zwicky (1898–1974)
Gravity Bends Light

1. A Distant Source
   - Light leaves a young, star-forming blue galaxy near the edge of the visible universe.

2. A Lens of ‘Dark Matter’
   - Some of the light passes through a large cluster of galaxies and surrounding dark matter, directly in the line of sight between Earth and the distant galaxy. The dark matter’s gravity acts like a lens, bending the incoming light.

3. Focal Point: Earth
   - Most of this light is scattered, but some is focused and directed toward Earth. Observers see multiple, distorted images of the background galaxy.

Source: Del Lab, Lucent Technologies

Tony Tyson, Greg Kroesen, and Jon DeFiore
Frank O’Connell and Jon McCann
The New York Times
Gravitational Lensing

from Hubble telescope
The “Bullet” cluster

Chandra, VLT, Hubble, Magellan, 2006
A working theory of an accelerating universe

two key ingredients:

Dark Matter (25%)
Dark Energy (70%)

just a couple of remaining unknowns:

Dark Matter
Dark Energy

Fig. 1. The “four elements” of modern cosmology (adapted from a figure in a 1519 edition of Aristotle’s *Libri de Caelo*)
Is there a reason to doubt Einstein?
Dark Matter vs Modified Gravity

1:0
Discovery of Neptune in 1846

Urbain Jean Joseph Le Verrier
1811 – 1877

John Couch Adams
1819-1892
Precession of Mercury

1:1
Precession of Mercury’s perihelion

Dark Matter vs Modified Gravity

Urbain Jean Joseph Le Verrier
1811 – 1877
Modified Gravity

- Extra d.o.f
- Higher derivatives
- Non-locality
- Extra dimensions

- Scalar
- Vector
- Tensor

- Massive gravity
- Bigravity, Eddington-Born-Infeld
- Einstein-Aether
- TeVeS

- Horndeski, Brans-Dicke, Galileons, KGB

- f(R)
- Horava-Lifshitz
- Noncritical gravity

- Generalisations of $S_{EH}$
- Scalar-Gauss-Bonnet
- Lovelock gravity
- Gauss-Bonnet

- $f(\Box^{-1} R)$ models

- Compact
- Extended
- Kaluza-Klein,
  String compactifications
- DGP,
  Randall-Sundrum

Credit: Tessa Baker's PhD Thesis
The Smoking Gun of Modified Gravity

“Spacetime tells matter how to move; matter tells spacetime how to curve.”

John A. Wheeler (1911-2008)

Einstein: photons (light) and free falling matter follow same paths

General Relativity posits that the curvature of space is the same as the gravitational potential

In modified gravity theories the two are typically different

Check if trajectories of light are consistent with the motion of matter
By studying lensed images of distant galaxies we test trajectories of light

By studying redshifts of galaxies we test the motion of matter
Euclid, ESA, 2019 launch

- L2 Orbit
- 5-6 year mission
- galaxy shapes, photo-z’s, redshifts

Dark Energy Survey (DES) ongoing

- Blanco 4-meter telescope
- 5 years
- galaxy shapes, photo-z’s, redshifts, SNe
• 8.4 meter mirror
• half of the sky to redshift z=3
• galaxy shapes, photo-z’s, SNe
Summary

100 years of scientific breakthroughs and big surprises

Acceleration of cosmic expansion is beyond reasonable doubt

Einstein’s theory of General Relativity is yet to be seriously tested outside our solar system

We do not know how Vacuum gravitates

We do not know what Dark Matter is

A key test of Einstein:

Differences between trajectories of light and matter

New data is coming, big potential for new discoveries