The Keck 10m Telescopes on Mauna Kea, Hawaii
Segments of the Keck 10m Telescope Mirror
Outline

1. Introduction (The “Golden age of cosmology”)
2. The Big Picture
3. The Edge of the observable universe
4. The mysterious dark side
Part 1

Introduction:
The golden age of cosmology
The APM (Automatic Plate Machine) Survey (1992)
Sky positions of 2,000,000 Galaxies
The Sloan Digital Sky Survey
(to locate over 100,000,000 galaxies, 3D positions for 1,000,000)

A simulation of just 65,000 Sloan galaxies
June 5 2001: First release of Sloan data (50,000 galaxies)
Sloan Survey Status

Imaging (Galaxy positions on the sky)
- 47% Complete Jun 21 2002
- 47,000,000 galaxy positions

Spectroscopy (3D galaxy positions)
- 34% Complete Jul 15 2002
- 340,000 galaxy positions
Sloan Survey Status

Imaging (Galaxy positions on the sky)
97% Complete Jun 27 2004
⇒ 97,000,000 galaxy positions

Spectroscopy (3D galaxy positions)
67% Complete Jun 27 2004
⇒ 670,000 galaxy positions
Sloan Survey Status

Imaging (Galaxy positions on the sky)
- 107% Complete Mar 13 2005
- 107,000,000 galaxy positions

Spectroscopy (3D galaxy positions)
- 68% Complete Mar 15 2005
- 680,000 galaxy positions
http://sdss.org
Maps of the microwave sky (the “edge of the observable universe”)

1993
Real

Simulated

2003

2009

Simulated
Maps of the microwave sky (the “edge of the observable universe”)

Real Data!

1993

Real

2003

Updated after WMAP announcement, Feb 2003

2009

Simulated

WMAP
Maps of the microwave sky (the “edge of the observable universe”)

- 1993: Real Data!
- 2006: Real Data!
- 2009: Simulated

Updated after WMAP announcement, Feb 2003
Maps of the microwave sky (the “edge of the observable universe”)

Real Data!

1993

Updated after WMAP announcement, Feb 2003

2006

Real Data!

2009

Simulated
Maps of the microwave sky (the “edge of the observable universe”)

Real Data!

1993

Real

2006

Updated after Planck announcement, 2013

2013

Real Data!
Maps of the microwave sky (the “edge of the observable universe”)

March 17 2014!

Real Data!
Mass inferred from lensing:
Must have dark matter
Using Hubble’s new “advanced camera for surveys” June 2002

Galaxy Cluster Abell 1689

Hubble Space Telescope • Advanced Camera for Surveys

NASA, N. Benitez (JHU), T. Broadhurst (The Hebrew University), H. Ford (JHU), M. Clampin(STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA

STScI-PRC03-01a
http://hubblesite.org/

Some Future Plans

LSST (Large-aperture Synoptic Survey Telescope)

SNAP (Supernova / Acceleration Probe ) ➔
JDEM ➔
WFIRST ➔ WFIRST/AFTA

James Bock / NASA Jet Propulsion Laboratory
Imaging Cosmic Microwave Background Polarization with EPIC
We propose to study a mission concept, the Experimental Probe of Inflationary Cosmology (EPIC), based on a single-aperture telescope and receiver with high-sensitivity polarization-sensitive detector arrays.
Some Future Plans

LSST (Large-aperture Synoptic Survey Telescope)

SNAP (Supernova / Acceleration Probe) → JDEM → WFIRST → WFIRST/AFTA

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Imaging Cosmic Microwave Background Polarization with EPIC

We propose to study a mission concept, the Experimental Probe of Inflationary Cosmology (EPIC), based on a single-aperture telescope and receiver with high-sensitivity polarization-sensitive detector arrays.

LSST Mirror completion event Jan 2015
Some Future Plans

LSST (Large-aperture Synoptic Survey Telescope)

SNAP (Supernova / Acceleration Probe)

JDEM → WFIRST

WFIRST/AFTA

James Bock / NASA Jet Propulsion Laboratory

Imaging Cosmic Microwave Background Polarization with EPIC

We propose to study a mission concept, the Experimental Probe of Inflationary Cosmology (EPIC), based on a single-aperture telescope and receiver with high-sensitivity polarization-sensitive detector arrays.
Hubble ACS (Advanced Camera For Surveys)
Part 2: The big picture
What we know about the big picture

1) On large scales the matter in the Universe is spread out very smoothly ("Homogeneous")

   Mean density: \(10^{-29} \text{ gram} / \text{cm}^3\)

2) The Universe is expanding

   Hubble law: \(v = Hr\)

   \[
   H = \left(\frac{3 \text{m/sec}}{100 \text{lightyears}}\right)
   \]
The homogeneity of the Universe

Isotropy of the microwave background (from the “edge of the observable universe”) to one part in 100,000
The homogeneity of the universe

We are here

Galaxy surveys
The homogeneity of the universe

Galaxy surveys

We are here

Radial Direction

From 1986
The Hubble law

\[ v = Hr \]

\[ H = \left( \frac{3 \text{m/sec}}{100 \text{lightyears}} \right) \]
Hubble Expansion

Hot, Dense past
Cosmology and High Energy Physics

- Today
- Atomic Physics ~10eV
- Nuclear Physics ~10 TeV
- Quarks ~1 GeV
- Weak Interactions
- Unification
- Superstrings

Density = 0
Temp = 0
The History of the Universe

High Energy & Temp

Time Since Big Bang

present

1 billion years

300,000 years

3 minutes

$10^{-10}$ seconds

$10^{-35}$ seconds

$10^{-43}$ seconds

Galaxy Formation

Last Scattering

Nuclear & HEP

Inflation?

Extra Dimensions?

Today

Anti-Gravity?*!
The History of the Universe

- Time
- High Energy & Temp
- Present
- 1 billion years
- 300,000 years
- 3 minutes
- 10^{-10} seconds
- 10^{-35} seconds
- 10^{-43} seconds

Research at UCD in all these areas!

Today
- Anti-Gravity?*
- Galaxy Formation
- Last Scattering
- Nuclear & HEP
- Inflation?
- Extra Dimensions?
Part 3: The Edge of the observable universe
The Edge of the Observable Universe:

As we look back in space we look back in time. We see:

- Light traveling from far away = from distant past

Long ago (about 14 Billion years) the Universe was so hot and dense it was opaque: The edge of the observable universe
Properties of the Edge of the Observable Universe:

Today:
- Only 2.726K above absolute Zero
- "Microwave Radiation" (The "Cosmic Microwave Background": CMB)
- 1,000,000 times weaker than ambient radiation in a pitch dark room.

Similar to surface of Sun at time of emission (~ 6000°K)
Observing the Microwave Background, Past, present and future:

1965
Penzias and Wilson

1992
COBE

2001
MAP (Simulated)
The History of the Universe

New Image of the “Last Scattering Surface” from NASA’s WMAP satellite released Feb 11 2003
Maps of the microwave sky (the “edge of the observable universe”)

1993

Real data!

COBE

Updated after WMAP announcement, Feb 2003

2009

Simulated data
WMAP map of the “edge of the observable universe” plotted as a sphere
WMAP map of the “edge of the observable universe” plotted as a sphere

Note: we are really on the inside looking out
NASA’s WMAP
(Microwave Anisotropy Probe)

-Launched June 30 ’01
-Reached “L2” Oct 1 ’01
Using the CMB to learn about the Universe

solid=inflation model
dashed=defect models
(magenta=desperate)
I.1 Successes

Characteristic oscillations in the CMB power

Adapted from Bennett et al. Feb 11 '03

Inflation

“Active” models

Angular scale

Temperature Power

WMAP

TT Cross Power Spectrum

Adapted from Bennett et al Feb 11 '03
The Mysterious Dark Side
Cosmic acceleration

Using supernovae (exploding stars) as cosmic “mileposts”, acceleration of the Universe has been detected.
The Hubble law at great distances depends on the variations of the Hubble “constant” $H$ with time.
Cosmic acceleration

Using supernovae (exploding stars) as cosmic “mileposts”, acceleration of the Universe has been detected.

“Ordinary” non accelerating matter
Cosmic acceleration

Using supernovae (exploding stars) as cosmic “mileposts”, *acceleration* of the Universe has been detected.
Supernova

Preferred by modern data

\[ \text{Amount of gravitating matter} \rightarrow \]
\[ \text{Amount of "antigravity" matter} \rightarrow (\text{Dark Energy}) \]

Red line: No anti-gravity matter

Mass-Energy of the Universe made only out of standard model matter

Surprise factor

Preferred by modern data

Red line: No anti-gravity matter

Amount of gravitating matter
Mass-Energy of the Universe made only out of standard model matter

Amount of gravitating matter

Need to add dark matter here

Need to add dark energy here

Preferred by modern data

Red line: No anti-gravity matter
95% of the cosmic matter/energy is a mystery. It has never been observed even in our best laboratories.
THE GOLDEN AGE

1) Dramatic progress in our understanding

2) Deep mysteries yet to be resolved
   (probably a revolution is required!)

3) A clear path forward
For the future:

- Feel free to come around to my office hours at any time in the future with questions.

- Perhaps some of you would like to make a career in cosmology research (feel free to see me & discuss that).