What do we Know About the Universe?

Andreas Albrecht
UC Davis dept. of Physics
Talk at Lowell Observatory
October 1, 2016

Work supported by UC Davis and the US Department of Energy
Resources

Special Events
Why Physics @ UC Davis Flyer
Resources for Prospective Students
Resources for Current Students
Resources for Faculty and Staff
UC Davis Principles of Community

Department of Physics
UC Davis
One Shields Avenue
Davis, CA 95616
Ph: (530) 752-1500
Fax: (530) 752-4717

Safety
Make a Gift

News

Jack Cunlon has been awarded the APS J. J. Sakurai Prize in Theoretical Particle Physics
Posted: Sep 28, 2016, 11:05 AM
Jack Cunlon has been awarded the APS J. J. Sakurai Prize in Theoretical Particle Physics....

New Graduate Fellowship
Posted: Sep 2, 2016, 2:36 PM
The James D. Cone Graduate Fellowship has been established through a generous donation...

Charles Fadley was elected as Honorary Member of the The International Science Committee for the International Conferences on Vacuum Ultraviolet and X-ray Physics
Posted: Aug 5, 2016, 4:47 PM
The nomination read: "Chuck Fadley is widely regarded as the most inspiring scientist in...
UC Davis Principles of Community

Department of Physics
UC Davis
One Shields Avenue
Davis, CA 95616
Ph: (530) 752-1500
Fax: (530) 752-4717

UCD Physics has hired 11 extraordinary new faculty in last 5 years, many with strong links to the topics presented here, transforming our presence and Impact!
UCD Physics has hired 11 extraordinary new faculty in last 5 years, many with strong links to the topics presented here, transforming our presence and Impact!
UCD Physics has hired 11 extraordinary new faculty in last 5 years, many with strong links to the topics presented here, transforming our presence and Impact!
A Brand New Museum

Doors Open November 13: Free to All

Grounded in the legacy of UC Davis’ world-renowned first generation art faculty, the Jan Shrem and Maria Manetti Shrem Museum of Art will be a hub of creative practice for today’s thinkers, makers and innovators, now and for generations to come.

The museum is under construction and is set to open on November 13, 2016. Check back for more information on opening events this fall.

Be a part of making it happen! Here’s how:
For Students

Possibly useful information for current and prospective students. See also the Special Topics section. Prospective students may also want to look at my For the Public pages as well as the Physics Department and UC Davis web pages.

[Image of cosmic microwave background]
The Keck 10m Telescopes on Mauna Kea, Hawaii

A. Albrecht @ Lowell 10/1/16
Segments of the Keck 10m Telescope Mirror
1. Introduction (The “Golden age of cosmology”)

2. The Big Picture

3. Some Big ideas
   • Cosmic Inflation
   • The String theory landscape
Outline

1. Introduction (The “Golden age of cosmology”)
2. The Big Picture
3. Some Big ideas
   • Cosmic Inflation
   • The String theory landscape
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

r' < 17.55, d > 2", 6° slice

redshift space
62395 galaxies

A. Albrecht @ Lowell 10/1/16
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
Plot of a slice of SDSS galaxies

A. Albrecht @ Lowell 10/1/16
The final SDSS Survey
http://sdss.org
Maps of the microwave sky (the “edge of the observable universe”)

- Real (1993)
- Simulated (2003)
- Simulated (2009)
Maps of the microwave sky (the “edge of the observable universe”)

1993 Real

Updated after WMAP announcement, Feb 2003

Real Data!

2003 WMAP

2009 Simulated
Maps of the microwave sky (the “edge of the observable universe”)

1993

Real

Updated after Planck announcement, 2013

2006

Real Data!

2013

Real Data!

A. Albrecht @ Lowell 10/1/16
Maps of the microwave sky (the “edge of the observable universe”)

March 17 2014! BICEP2 reports signal from primordial gravitation waves in microwave “polarization”

A. Albrecht @ Lowell 10/1/16
Maps of the microwave sky (the “edge of the observable universe”)

1993

Real

March 17 2014! BICEP2 reports

May 2 2015 Planck reports better polarization data most likely due to nearby dust

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

Real Data!

1993

Real

March 17 2014!

May 2 2015

Real Data!

A. Albrecht @ Lowell 10/1/16
Maps of the microwave sky (the “edge of the observable universe”)

September 14 2015! LIGO reports direct detection of gravitational waves from two merging black holes
Links related to previous slides

http://www.esa.int/esaSC/120398_index_0_m.html

http://www.rssd.esa.int/index.php?project=planck

http://bicepkeck.org/

http://www.esa.int/spaceinimages/Images/2015/02/Polarisation_of_the_Cosmic_Microwave_Background

http://www.esa.int/esaSC/120398_index_0_m.html

http://www.rssd.esa.int/index.php?project=planck

http://albrecht.ucdavis.edu/special-topics/bicep2-story

https://www.ligo.caltech.edu/news
Mass inferred from lensing:
Must have dark matter
Using Hubble’s “advanced camera for surveys” installed 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

A. Albrecht @ Lowell 10/1/16
http://hubblesite.org/

Some Future Plans

LSST (Large-aperture Synoptic Survey Telescope)

WFIRST

James Webb Space Telescope
Some Future Plans

New facilities being built

LSST (Large-aperture Synoptic Survey Telescope)
Some Future Plans

New facilities being built

LSST (Large-aperture Synoptic Survey Telescope)

Jan 2016, Tucson AZ
Some Future Plans

New facilities

LSST (Large-aperture Synoptic Survey Telescope)

James Webb Space Telescope (2018 Launch)
Some Future Plans

New facilities being built

WFIRST
Wide Field Infrared Survey Telescope

Frequently Asked Questions

1. Will the WFIRST mission be a breakthrough in the search for dark matter?

WFIRST will survey large areas of the sky measuring the effects of dark matter on the distribution of galaxies in the universe. It will also observe distant Type Ia supernovae to use them as tracers of dark matter and dark energy. It will provide a huge step forward in our understanding of dark matter and dark energy.

2. In what phase of development is currently the WFIRST spacecraft?

WFIRST is currently in Phase A. The purpose of Phase A is to develop the mission requirements and architecture necessary to meet the programmatic requirements and constraints on the Project and to develop the plans for the Preliminary Design phase.

3. Are the preparations on track for the mid-2020 launch?

Yes, the preparations are on track for a mid-2020 launch.
1. Introduction (The “Golden age of cosmology”)

2. The Big Picture

3. Some Big ideas
   - Cosmic Inflation
   - The String theory landscape
1. Introduction (The “Golden age of cosmology”)

2. The Big Picture

3. Some Big ideas
   • Cosmic Inflation
   • The String theory landscape
Distances in the Universe
Measure of distance: One Kilometer ≈ Walk from Lowell Observatory to Thorpe Park Tennis courts
Measure of distance: One Kilometer ≈ Walk from Lowell Observatory to Thorpe Park Tennis courts

Count cosmic distances as grains of sand: One grain of sand per kilometer.

Grain of sand (enlarged)
Diameter of earth = 12,760 kilometers ↔
1 Teaspoon of sand
Distance to Moon = 356,410 kilometers ↔ 1 Handful of sand
Distance to Moon = 356,410 kilometers ↔
1 Handful of sand

(Also roughly the distance light travels in one second)
Distance from Earth to Sun = 149,600,000 kilometers (8 light minutes) ↔ 1 Milkshake cup of sand
Distance from Earth to Pluto = 6,000,000,000 kilometers \(\longleftrightarrow\) 1 wheelbarrow of sand
Distance from Earth to Nearest Star = 40,000,000,000,000 kilometers ↔ 1 dumpster of sand
Distance from Earth to Edge of our galaxy = 1,000,000,000,000,000,000,000,000 kilometers $\leftrightarrow 1$

Physics/Geology Building full of sand
Average distance between galaxies = $3 \times 10^{19}$ kilometers $\Leftrightarrow$ 1 baseball stadium full of sand
Farthest visible “object” in the universe: $1 \times 10^{23}$ kilometers $\leftrightarrow$ mountain range of sand
\[ \log \left( \frac{d}{\text{km}} \right) \]
What we know about the big picture

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

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

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

Galaxy surveys

We are here

Radial Direction
The homogeneity of the universe

We are here.

Galaxy surveys

From 1986

Radial Direction

A. Albrecht @ Lowell 10/1/16
The Hubble law

\[ v = Hr \]

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

Hot, Dense past

A. Albrecht @ Lowell 10/1/16
Cosmology and High Energy Physics

Today

Atomic Physics ~10eV
Nuclear Physics ~10MeV
Quarks ~1GeV
Weak Interactions TeV

Expansion

Cooling

TIME

??

Unification

Superstrings

Density = 0
Temp = 0

A. Albrecht @ Lowell 10/1/16
The History of the Universe

Time Since Big Bang

Present

1 billion years

300,000 years

3 minutes

0.001 seconds

$10^{-10}$ seconds

$10^{-35}$ seconds

$10^{-43}$ seconds

Particle Era

Electroweak Era

GUT Era

Planck Era

Stars, galaxies, and clusters (made of atoms and plasma)

Era of Galaxies

Nuclear & HEP

Inflation?

Extra Dimensions?

High Energy & Temp

Today

Dark Energy

Galaxy Formation

Last Scattering

Nuclear & HEP

Inflation?

Extra Dimensions?
The History of the Universe

Image of the “Last Scattering Surface” or “edge of opaqueness”
The History of the Universe

Image of the “Last Scattering Surface” or “edge of opaqueness” (the most distant “object”)

A. Albrecht @ Lowell 10/1/16
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.

![Graph showing the relationship between the amount of ordinary matter and antigravity matter. Preferred by modern data.]

“Ordinary” non-accelerating matter

A. Albrecht @ Lowell 10/16
Mass-Energy of the a Universe made *only* out of standard model matter

Surprise factor

Preferred by modern data

Red line: No anti-gravity matter
Mass-Energy of the Universe made only out of standard model matter

Amount of gravitating matter

Amount of "antigravity" matter (Dark Energy)

Need to add dark matter here

Need to add dark energy here

Preferred by modern data

Red line: No anti-gravity matter
Cosmic acceleration (newest data)

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

“Gravitating” non accelerating matter

Preferred by modern data

Amount of “antigravity” matter

Amount of gravitating matter
Cosmic acceleration

Accelerating matter is required to fit current data

“Ordinary” non accelerating matter

\[ \text{Amount of } w = -1 \text{ matter ("Dark energy")} \]

\[ \text{Amount of "ordinary" gravitating matter} \]
Cosmic acceleration
Accelerating matter is required to fit current data


Preferred by data c. 2008

Supernova Cosmology Project

Amount of w = -1 matter ("Dark energy")

"Ordinary" non accelerating matter

Amount of "ordinary" gravitating matter

A. Albrecht @ Lowell 10/1/16
Cosmic acceleration

Accelerating matter is required to fit current data

Supernova

Amount of "ordinary" gravitating matter

Preferred by data c. 2008

"Ordinary" non-accelerating matter

Amount of \( w = -1 \) matter ("Dark energy")

\( \zeta \)


(Includes dark matter)

A. Albrecht @ Lowell 10/1/16
In the presence of dark energy, the simple connection between open/closed/flat and the future of the universe no longer holds.
95% of the cosmic matter/energy is a mystery. It has never been observed even in our best laboratories.

- **Dark Energy (accelerating)**: 70%
- **Dark Matter**: 25%
- **Ordinary Matter (observed in labs)**: 5%

A. Albrecht @ Lowell 10/1/16
95% of the cosmic matter/energy is a mystery. It has never been observed even in our best laboratories.

- **Dark Energy (accelerating)**: 70%
- **Dark Matter**: 25%
- **Ordinary Matter (observed in labs)**: 5%

A. Albrecht @ Lowell 10/1/16
95% of the cosmic matter/energy is a mystery. It has never been observed even in our best laboratories.
95% of the cosmic matter/energy is a mystery. It has never been observed even in our best laboratories.
1. Introduction (The “Golden age of cosmology”)

2. The Big Picture

3. Some Big ideas
   - Cosmic Inflation
   - The String theory landscape
Outline

1. Introduction (The “Golden age of cosmology”)
2. The Big Picture
3. Some Big ideas
   - Cosmic Inflation
   - The String theory landscape
Cosmic Inflation

• A period of accelerated expansion in the very early universe

• Motivated by particle physics (related to the recently discovered Higgs particle).
• In most models inflation operates when the temperature was $10^{25}$ times greater than today!

• Conceptually similar in some ways to the acceleration observed today (interesting relationship between the two)
• Cosmic inflation creates features in the universe on all these different lengths.
• The yellow boxes give the time between “feature creation” in units of seconds! $10^{-40}$
Cosmic Microwave Background (CMB) map produced by the Planck satellite (sphere shown using a projection, like in an atlas)

The map shows minute variations in the temperature (just 1 part in 100,000, or in the 5th decimal place).
This plot shows one way to quantify the feature in the CMB map. Roughly, the x-axis labels patch size, and the y-axis show how strongly the temperature typically varies among patches of that size.
Using the CMB to learn about the Universe

Temperature Fluctuation vs. Patch Size (Angular Scale)

solid = inflation model

dashed = defect models

(magenta = desperate)

100

50
Cosmic Inflation

- A period of accelerated expansion in the very early universe

- Motivated by particle physics (related to the recently discovered Higgs particle)

- Conceptually similar in some ways to the acceleration observed today (interesting relationship between the two)

- Extraordinarily successful predictions of features in the observed universe
Cosmic Inflation

• A period of accelerated expansion in the very early universe

• Motivated by particle physics (related to the recently discovered Higgs particle)

• Conceptually similar in some ways to the acceleration observed today (interesting relationship between the two)

• Extraordinarily successful predictions of features in the observed universe

• Very problematic aspects emerge when we attempt to complete the picture. (The cause of intensive research and debate among the experts.)
May cosmologists believe in “eternal inflation” (our universe exists in a “pocket” with eternal inflation all around us).
• May cosmologists believe in “eternal inflation” (our universe exists in a “pocket” with eternal inflation all around us).
• Eternal inflation theory predicts infinitely many pocket universes, some like ours, some different
• May cosmologists believe in “eternal inflation” (our universe exists in a “pocket” with eternal inflation all around us).
• Eternal inflation theory predicts infinitely many pocket universes, some like ours, some different

But Which one is really ours?
• May cosmologists believe in “eternal inflation” (our universe exists in a “pocket” with eternal inflation all around us).
• Eternal inflation theory predicts infinitely many pocket universes, some like ours, some different

This question appears to lead to deep ambiguities and problems with the theory that cause some to reject the idea of cosmic inflation altogether

But Which one is really ours?
Cosmic Inflation

• A period of accelerated expansion in the very early universe

• Motivated by particle physics (related to the recently discovered Higgs particle)

• Conceptually similar in some ways to the acceleration observed today (interesting relationship)

• Extraordinarily successful predictions of features in the observed universe

• Very problematic aspects emerge when we attempt to complete the picture. (The cause of intensive research and debate among the experts.)
Cosmic Inflation

- A period of accelerated expansion in the very early universe
- Motivated by particle physics (related to the recently discovered Higgs particle)
- Conceptually similar in some ways to the acceleration observed today (interesting relationship)
- Extraordinarily successful predictions of features in the observed universe
- Very problematic aspects emerge when we attempt to complete the picture. (The cause of intensive research and debate among the experts.)

Multiverse debate, World Science Festival 2013

A very exciting place to be!
Outline

1. Introduction (The “Golden age of cosmology”)
2. The Big Picture
3. Some Big ideas
   • Cosmic Inflation
   • The String theory landscape
1. Introduction (The “Golden age of cosmology”)

2. The Big Picture

3. Some Big ideas
   • Cosmic Inflation
   • The String theory landscape
The cosmic acceleration observed today has proven very difficult to incorporate into our fundamental theories of physics.
The cosmic acceleration observed today has proven very difficult to incorporate into our fundamental theories of physics.

These difficulties have caused some theorists to embrace the “string theory landscape”
• The cosmic acceleration observed today has proven very difficult to incorporate into our fundamental theories of physics.

• These difficulties have caused some theorists to embrace the “string theory landscape”

• Instead of the physical world around us exhibiting “the fundamental laws”, according to the STL picture the universe is made of a landscape of different “worlds” which with their own laws of physics.
The cosmic acceleration observed today has proven very difficult to incorporate into our fundamental theories of physics. These difficulties have caused some theorists to embrace the "string theory landscape". Instead of the physical world around us exhibiting "the fundamental laws", according to the STL picture the universe is made of a landscape of different "worlds" which with their own laws of physics.

Where are we?
The cosmic acceleration observed today has proven very difficult to incorporate into our fundamental theories of physics. These difficulties have caused some theorists to embrace the “string theory landscape.”

Instead of the physical world around us exhibiting “the fundamental laws”, according to the STL picture the universe is made of a landscape of different “worlds” which with their own laws of physics.

A radical change from how we thought we should be doing physics.
Conclusions

- The search for a “big picture” of the Universe that explains why the region we observe should take this form has proven challenging, but has generated exciting ideas.

- We know we can do science with the Universe

- It appears that there is something right about cosmic inflation

- dSE cosmology offers a finite alternative to the extravagant (and problematic) infinities of eternal inflation

- Predictions of observable levels of cosmic curvature from dSE cosmology will give an important future test
1. Introduction (The “Golden age of cosmology”)

2. The Big Picture

3. Some Big ideas
   - Cosmic Inflation
   - The String theory landscape
Conclusions

1. Introduction (The “Golden age of cosmology”)
2. The Big Picture
3. Some Big ideas
   • Cosmic Inflation
   • The String theory landscape

Amazing data and facilities
Conclusions

1. Introduction (The “Golden age of cosmology”)
2. The Big Picture
3. Some Big ideas
   • Cosmic Inflation
   • The String theory landscape

We have learned a huge amount about the Universe
Conclusions

1. Introduction (The “Golden age of cosmology”)

2. The Big Picture

3. Some Big ideas
   • Cosmic Inflation
   • The String theory landscape

Our theories are both remarkably successful and provocative/confusing
1. Introduction (The “Golden age of cosmology”)

2. The Big Picture

3. Some Big ideas
   - Cosmic Inflation
   - The String theory landscape

Conclusions

- Amazing data and facilities
- We have learned a huge amount about the Universe
- Our theories are both remarkably successful and provocative/confusing

A very exciting place to be!
Conclusions

A very exciting place to be!

- Amazing data and facilities
- We have learned a huge amount about the Universe
- Our theories are both remarkably successful and provocative/confusing

Our theories are both remarkably successful and provocative/confusing