Phy 262 1st day slides

Andreas Albrecht
The Keck 10m Telescopes on Mauna Kea, Hawaii
Segments of the Keck 10m Telescope Mirror
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
- \( \Rightarrow \) 107,000,000 galaxy positions

Spectroscopy (3D galaxy positions)
- 68% Complete Mar 15 2005
- \( \Rightarrow \) 680,000 galaxy positions
Plot of a slice of SDSS galaxies
The final SDSS Survey

- Messier 33
- NGC 604

Southern Galactic Cap
Northern Galactic Cap
SDSS-V: Pioneering Panoptic Spectroscopy

**Multi-Object Spectroscopy:** optical & near-IR, all-sky, multi-epoch

**Integral Field Spectroscopy:** optical, 2500 deg², ultra wide-field

(Image Credit: Juna A. Kollmeier and Hans-Walter Rix)
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”)

- 1993 Real
- 2003 Updated after WMAP announcement, Feb 2003
- 2009 Simulated

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

Real Data!

1993

Real

Updated after Planck announcement, 2013

2013

Real Data!

2006

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

1993

Real

March 17 2014! BICEP2 reports signal from primordial gravitation waves in microwave “polarization”
Maps of the microwave sky (the “edge of the observable universe”)

1993

Real Data!

March 17 2014!
BICEP2 reports

May 2 2015 Planck reports better polarization data most likely due to nearby dust
Maps of the microwave sky (the “edge of the observable universe”)

Real Data!

March 17 2014!

Real Data!

May 2 2015

1993

Real

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

1993

Real

Updated after Planck announcement, 2013

September 14 2015! LIGO reports direct detection of gravitational waves from two merging black holes

2013

Real Data!
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
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)

2018
Some Future Plans

New facilities being built

LSST (Large-aperture Synoptic Survey Telescope)

Jan 2016, Tucson AZ
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)

Monday, January 6, 2020

It was announced today that the upcoming Large Synoptic Survey Telescope (LSST), which will conduct a vast astronomical survey for unprecedented discovery of the deep and dynamic Universe, will now be named the NSF (National Science Foundation) Vera C. Rubin Observatory (Rubin Observatory or VRO). The announcement was made today by Ralph Gaume, Director of the NSF Division of Astronomical Sciences; Kathy Turner, DOE (Department of Energy) Office of High Energy Physics program manager; and Steve Kahn, LSST Director during the LSST at the 235th American Astronomical Society meeting in Honolulu, Hawai‘i, USA. The construction and operations of the Rubin Observatory and the DOE LSST Camera is a U.S. federal partnership of the NSF and DOE, with private

Vera Rubin operated the 2.1-meter telescope at Kitt Peak National Observatory. Kent Ford's spectrograph is attached. Image credit:
Scheduled to launch in the mid-2020s
James Webb Space Telescope on Track for March 2021 Launch, NASA Says

Despite numerous setbacks, the $9.7-billion observatory is still on schedule to revolutionize our view of the universe

By Meghan Bartels, SPACE.com on January 7, 2020

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Windows: No Longer Just for Letting In the Light
December 9, 2019

COGNITION
Atlantic Puffins Spotted Using Tools
1 hour ago — Christopher Intagliata

CLIMATE
Report Detailing U.S. Threats Ignores Climate Change
9 hours ago — Thomas Frank and E&E News

SPACE
NASA’s TESS Planet Hunter Finds Its First Earth-Size World in “Habitable Zone”
https://www.lsst.org/

http://jwst.nasa.gov/index.html

http://wfirst.gsfc.nasa.gov/
Outline

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”)
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Distances in the Universe
Measure of distance: One Kilometer ≈ Walk from the Manetti Shrem to Delta of Venus
Measure of distance: One Kilometer ≈ Walk from the *Manetti Shrem* to *Delta of Venus*

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 $\leftrightarrow$ 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 ↔ 1
Physics/Geology Building full of sand
Distance from Earth to Edge of our galaxy = 1,000,000,000,000,000,000,000,000 kilometers ➔ 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
1 km

Earth diameter

Distance to Moon

Earth-Sun distance

Distance to nearest star

Earth-Pluto distance

Distance to edge of galaxy

Average galaxy sep.

Most distant “object”

$1.3 \times 10^4 km$

$1.4 \times 10^8 km$

$3.6 \times 10^5 km$

$6 \times 10^9 km$

$4 \times 10^{13} km$

$10^{18} km$

$3 \times 10^{19} km$

$10^{23} km$

$\log (d / km)$
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

We are here

Galaxy surveys
The homogeneity of the universe

Galaxy surveys

We are here

Radial Direction

From 1986

Galaxy surveys
The Hubble law

\[ v = Hr \]

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

Hot, Dense past
Cosmology and High Energy Physics

Upward Arrow: Time (Timeline)

Cooling & Expansion

Today

Atomic Physics ~10 eV

Nuclear Physics ~10 MeV

Quarks ~1 GeV

Weak Interactions

??

Density = 0
Temp = 0

Unification

Superstrings

Phy 262 1st day 2020
The History of the Universe

- Time Since Big Bang
- Present: Today
- 1 billion years: Galaxy Formation
- 300,000 years: Last Scattering
- 3 minutes: Nuclear & HEP
- 10^-10 seconds: Inflation?
- 10^-35 seconds: Dark Energy
- 10^-43 seconds: Extra Dimensions?

- High Energy & Temp

- Present: Today
- 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”)

Time

High Energy & Temp
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

Preferred by modern data

Amount of ordinary matter

Supernova Cosmology Project

Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)

No Big Bang

Supernovae

Clusters

CMB

expands forever
recollapses eventually

open
flat
closed
Supernova

Preferred by modern data

Amount of gravitating matter ➔ Amount of “antigravity” matter ➔ (Dark Energy)

Red line: No anti-gravity matter

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

Surprise factor

Supernova Cosmology Project

CMB

Phy 262 1st day 2020
Mass-Energy of the Universe made *only* out of standard model matter

Preferred by modern data

Need to add dark matter here

Need to add dark energy here

Red line: No anti-gravity matter

Amount of gravitating matter

Amount of "antigravity" matter (Dark Energy)
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 gravitating matter
Cosmic acceleration

Accelerating matter is required to fit current data

“Ordinary” non-accelerating matter

Amount of $w=1$ matter (“Dark energy”) ➔

Amount of “ordinary” gravitating matter ➔

Supernova Cosmology Project

Preferred by data c. 2003

Phy 262 1st day 2020
Cosmic acceleration

Accelerating matter is required to fit current data

Supernova Cosmology Project


Preferred by data c. 2008

“Ordinary” non accelerating matter

Amount of w=1 matter (“Dark energy”)

Amount of “ordinary” gravitating matter

Phy 262 1st day 2020
Cosmic acceleration

Accelerating matter is required to fit current data

Amount of "ordinary" gravitating matter

Preferred by data c. 2008


Phy 262 1st day 2020
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.
95% of the cosmic matter/energy is a mystery. It has never been observed even in our best laboratories.

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

Phy 262 1st day 2020
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.
OCTOBER 5, 2019 - SATURDAY

7:30 AM - 8:30 AM  Registration and Continental Breakfast

8:30 AM - 9:00 AM  Conference opening  
Chair: Rocky Kolb

Simon White, Max-Planck-Institut fuer Astrophysik  
Cosmic controversies: boon or bane? [PDF, 17.79 MB]

9:00 AM - 12:35 PM  PARALLEL SESSIONS

H0 Tension (Room 621)  
Chair: Kimmy Wu

Lloyd Knox, UC Davis  
The Hubble Hunter’s Guide [PDF, 4.08 MB]
The Hubble Hunter’s Guide*

Lloyd Knox
UC Davis


*with apologies to J. Gunion et al.
The Hubble constant / sound horizon problem

From “The Hubble Hunter’s Guide” (LK+Millea 2019)
Also see Bernal, Verde & Riess (2016), and
Arendse et al. (2019)

SH0ES 2019 (Cepheids + Supernovae)  
(no assumption of LCDM)

BOSS BAO + Pantheon SNe  
(no assumption of LCDM*)

Planck (Assumes LCDM)

*assumes 5-parameter spline model for H(z) and zero mean curvature.  
Also see Raveri et al. (2019).
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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 $10^{-40}$ seconds!
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

solid=inflation model
dashed=defect models
(magenta=desperate)
Cosmic Inflation

• A period of accelerated expansion in the very early universe

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

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• 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
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• 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.)

A very exciting place to be!
Cosmic Inflation

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- 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
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Multiverse debate, World Science Festival 2013

https://www.youtube.com/watch?v=2Qt-eGKa34M

A very exciting place to be!
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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 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" where the universe is made of a landscape of different "worlds" with their own laws of physics.

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?

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
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Conclusions

Amazing data and facilities
We have learned a huge amount about the Universe
Conclusions

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Our theories are both remarkably successful and provocative/confusing
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A very exciting place to be!