Our universe’s story
from chaos to cosmos

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Zachary Slepian
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Harvard University Department of Astronomy
Harvard-Smithsonian Center for Astrophysics
Copernican Revolution (c. 1600)

Uraniborg Observatory and Tycho Brahe

Heliocentric Solar System

Tycho Brahe
Nicolaus Copernicus
Galaxies and Nebulae (c. 1800)

Milky Way is a galaxy

What are spiral nebulae?
Shapley-Curtis Debate (c. 1920)

Mt. Wilson Observatory and Edwin Hubble

Spiral nebulae are galaxies

Exploratorium
Adam Evans / CC BY 2.0
The Big Bang Cosmology

Part I: State of the Cosmos

Part II: Growth of Structure + Galaxy Clustering

Part III: Inflation

hot + dense
nearly formless
chaos

cool + sparse
structured
cosmos

Adapted from NASA
Our universe’s story

Part I: State of the Cosmos

Stephen Portillo
State of the Cosmos

1. The universe is expanding
2. Galaxies are arranged in structures
3. These structures are made of dark matter
Hubble’s Law

Velocity-Distance Relation among Extra-Galactic Nebulae.

Exploratorium
Hubble (1929)
The Universe is Expanding

hot and dense

cold and sparse

NASA
State of the Cosmos

1. The universe is expanding
2. Galaxies are arranged in structures
3. These structures are made of dark matter
The Distribution of Galaxies

CNRS, Margaret Geller, John Huchra de Lapparent, Geller, and Huchra (1986)
Questions?
State of the Cosmos

1. The universe is expanding
2. Galaxies are arranged in structures
3. These structures are made of dark matter
Baryonic (Visible) Matter

emits light

reflects & absorbs light

re-emits light
Visible Matter

emits light

reflects & absorbs light
re-emits light
Dark Matter in Galaxies

Adapted from Joe Parks, Adam Evans / CC BY 2.0
Rubin, Burstein, Ford, and Thonnard (1984), Vera Rubin
Dark Matter in Galaxy Clusters
Dark Matter

DOES NOT emit light

DOES NOT reflect, absorb, or re-emit light

Adapted from Stefan Wernli / CC BY-SA 2.5, Brighton Science Festival / CC BY-NC-SA 2.0, Rainer Klute / CC BY-SA 3.0
The game is afoot
How important is visible matter?

The visible matter just follows the dark matter.
But everything we see is visible matter.

The universe used to be hotter and denser.
Visible matter and light interacted much more.
Summary

What is the state of the cosmos?

• The Universe is expanding
• There is a large-scale structure of galaxies
• These structures are made of dark matter

*Our cosmology is only as precise as our observations*
Our universe’s story

Part II: Why do galaxies cluster as they do?

Zachary Slepian
SDSS Galaxies

distance from us

SDSS telescope

Each point is a galaxy!

SDSS galaxies; images: Michael Blanton, NRAO
Each point is a galaxy!
Each sphere has a characteristic diameter
Why do galaxies cluster?

Extra galaxies over random

Correlation function of galaxies

black = data

green = predicted

distance from us (units of 30 X width of our galaxy)

Eisenstein et al. 2005

Daniel Eisenstein
Why do galaxies cluster?

Correlation function of galaxies

Extra galaxies over random

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Eisenstein et al. 2005
Why is the Enterprise the way it is?

Look at the blueprints!
Astronomy with Kitchen Devices
The Cosmic Microwave Background

map of temperature of left over radiation from moment Universe became neutral

Planck collaboration hi-resolution map; Planck website
Zooming in

Galaxies today!

Cosmic Microwave Background
14 billion years ago

Simulation
Understand why Cosmic Microwave Background has these structures

• Since CMB is blueprint for structures today
• … understanding why these features are in the CMB …
• should tell us why they are here today

So what gives the Cosmic Microwave Background these hot and cold spots?
Let’s focus on one hot spot

- Hot spot = more matter there
- We call that “overdense”
- How does one overdense region evolve in time from nearly the beginning of the Universe . . .
- to the formation of the CMB?
2 important forces

Gravity

Pressure

Image: Guardian Liberty Voice, Science Section
Gravity

Mass in sphere is proportional to overdensity.

Gravitational force is proportional to the mass.

Sphere contracts.

This raises density.

Overdensity grows!
Gravity

Mass in sphere is proportional to overdensity

Gravitational force is proportional to the mass

Sphere contracts

This raises density

Overdensity grows!
Pressure

Pressure is proportional to the overdensity

Pressure leads to expansion of sphere

Expansion lowers density of sphere

Overdensity gets diluted!
These 2 forces both work on regular matter

- Gravity causes initial contraction
- But then pressure pushes regular matter out

What provides the pressure?
- Early times: pressure from radiation (light)
- Electrons interact strongly with light
- Electrons pull protons along for the ride
- So all the regular matter follows the light!
What about the Dark Matter?

• Why is DM the most relaxed substance in the Universe?
• Doesn’t interact with light
• Therefore . . .
• DM doesn’t feel pressure
• Only feels gravity
Putting it together

• Start with an overdense region at some very early time

• How does it evolve?

• Regular matter: gravity compresses, pressure pushes outwards

• Pressure is due to photons’ interaction with electrons

• Dark matter feels only gravity, so always compresses
Questions?
Universe is expanding . . . and cooling! 

Temperature of Universe vs. Time: 
- Ionized 
- Neutral
Initial conditions

Mass within a sphere of radius $r$ at $z=80000$

- Regular matter
- Dark matter
- Radiation

$r$ [units of $30 \times$ width of our galaxy]
Later

Mass within a sphere of radius $r$ at $z=6400$

- **Regular matter**
- **Dark matter**
- **Radiation**

Temperature of Universe

- Ionized
- Neutral

Time

$r$ [units of $30 \times$ width of our galaxy]
Even later . . .

Mass within a sphere of radius $r$ at $z=2097$

- Blue: Regular matter
- Black: Dark matter
- Red: Radiation

Temperature of Universe vs. Time

Ionized, Neutral
So close to neutral!

Mass within a sphere of radius $r$ at $z=1342$

- Regular matter
- Dark matter
- Radiation

Temperature of Universe

Ionized
Neutral
Time

$0.0014$
$0.0012$
$0.0010$
$0.0008$
$0.0006$
$0.0004$
$0.0002$
$0.0000$

$r$ [units of $30 \times$ width of our galaxy]
Video!

Mass within a sphere of radius $r$ at $z=10000$

- Regular matter
- Dark matter
- Radiation

$r$ [units of 30 x width of our galaxy]
What happens when Universe becomes neutral?
Cosmic Microwave Background forms at moment Universe becomes neutral
And photons release regular matter

• Neutral means “no more electrons”

• So no more strong interaction between regular matter and light

• No more radiation (light) pressure!
Universe is now neutral

Mass within a sphere of radius $r$ at $z=47$

- Blue: Regular matter
- Black: Dark matter
- Red: Radiation

Temperature of Universe

- Ionized
- Neutral

Time

$r$ [units of $30 \times$ width of our galaxy]
Each sphere has a characteristic diameter
Questions?
Our universe’s story

Part III: Back to the beginning

Kate Alexander
Outline

• What is inflation and why do we need it?

• How do we test inflation?

• Recent scientific results
Recall the picture thus far…

1. Today the Universe is full of structure: galaxies, clusters, dark matter

2. These structures began as tiny perturbations, which grew over time because gravity overcame pressure and the expansion of the Universe
Looking back in time

CMB

First Stars

380,000 years

~200 million years

13.8 billion years

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Outstanding Questions
Outstanding Questions

• How did the initial perturbations form?
Outstanding Questions

• How did the initial perturbations form?

• The **Horizon Problem**: Why does the Universe look the same in every direction?

20 billion light years
Outstanding Questions

• How did the initial perturbations form?
• The **Horizon Problem**: Why does the Universe look the same in every direction?
• The **Flatness Problem**: How did the Universe end up almost perfectly flat?
Stepping back even further…

CMB

First Stars

380,000 years

~200 million years

13.8 billion years

Present Day
Stepping back even further…

- **INFLATION**
- Fraction of a second
- 380,000 years
- CMB
- First Stars
- ~200 million years
- Present Day
- 13.8 billion years

Present Day

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What is inflation?

- A brief time period where the size of the Universe increased very quickly (exponentially)
- **Space itself** expanded – like blowing up a balloon
This solves the horizon and flatness problems

A and B close together

A and B further apart

A

B

Strongly curved surface

Flatter surface
The initial density perturbations come from small-scale physics.
What caused inflation?
What caused inflation?

• We still don’t know for sure!
What caused inflation?

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• Theoretical physicists model a particle called an “inflaton” that decayed into more familiar light and matter particles when inflation ended.
What caused inflation?

• We still don’t know for sure!
• Theoretical physicists model a particle called an “inflaton” that decayed into more familiar light and matter particles when inflation ended.
• Today the Universe is entering another period of accelerated expansion – caused by the equally mysterious “dark energy.”
Inflation Summary

• During inflation, space itself doubled its size many times very quickly

• It explains the flatness problem, the horizon problem, and the origin of structure

• We still don’t know what caused it, but a similar effect is causing the Universe to expand increasingly quickly today.
Questions?
How do we prove it?
How do we prove it?

• Inflation solves a lot of problems. But to be a proper scientific theory, it needs to also make **experimentally testable predictions**.

• This is harder than you might think…
  – Must be something we don’t know already
  – Must be something we can actually measure
Problem: We need to observe the very beginning...
...but we can only use light to see back in time as far as the CMB.

Hidden – the Universe is too hot and dense for light to travel freely.
Solution: Look for a different kind of signal
What are Gravitational Waves?

• “Stretching” and “squeezing” of space
• Produced during inflation, propagate freely throughout the Universe

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How do we see them?

• Gravitational waves create a unique polarization pattern in the CMB ("B-mode" polarization)
• But first, let’s talk about what polarization is…
Light Polarization: A Brief Intro

Light Source

Light Beam

Polarizer (vertical)

Vertically polarized light waves
How do we see them?

A single gravitational wave

Polarization pattern from this wave
How do we see them?

- The overall polarization pattern comes from many waves traveling in different directions.
Questions?
How do we see them?

- Gravitational waves can test inflation – now we have to detect them.
- We need a microwave telescope and a really great observing site...
The South Pole

South Pole CMB telescopes

10m South Pole Telescope
BICEP1
BICEP2
BICEP3
DASI
QUAD
Keck
Array

Copyright Steffen Richter, BICEP2 Collaboration
BICEP2
BICEP2 results

• March 17, 2014 – B modes detected!
Comparison to earlier results
Comparison to earlier results

![Comparison to earlier results chart](image-url)
Is it really inflation?

- Gravitational waves...or dust?
- Need more data – results coming soon!
Summary

• Gravitational waves are a “smoking gun” for inflation
• BICEP2 detected a signal that could be gravitational waves!
• Scientists around the world are still working hard to figure out the signal’s origin – dust, gravitational waves, or both?
Final Summary

Part I: State of the Cosmos

Part II: Growth of Structure + Galaxy Clustering

Part III: Inflation

hot + dense
nearly formless
chaos

cool + sparse
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