An introduction to
the cosmic microwave background

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Cosmological Background

"Big Bang"
- Universe Began Hot and Dense
- Expands and Cools

"Gravitational Instability"
- Galaxies ("Structure") from the self-attraction of primordial fluctuations

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Cosmological Expansion

Recession
Velocity

Expansion
Redshift

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Thermal History
CMB Properties

- 3 degrees above absolute zero (-270°C)
- mm-cm wavelength (1-10% microwave oven)
- 400 photons/cm³ (10 trillion photons/sec/cm²)
- Few percent of TV "snow"
Large–Angle Anisotropies

Actual Temperature Data Really Isotropic!

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Large–Angle Anisotropies

dipole anisotropy
1 part in 1000

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Large–Angle Anisotropies

10°–90° anisotropy
1 part in 100000

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Anisotropies: A Time Machine

• Reversing time:
A Brief Thermal History

- CMB photons hotter at high redshift $z$
- At $z \sim 1000$, $T \sim 3000$K: photons ionize hydrogen
Very Brief History

Nucleo-Synthesis

3 min 3\times 10^5 \text{ yrs}

CMB

3\times 10^9 \text{ yrs}

Galaxy Formation

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Gravitational Instability
Gravitational Instability

"Wrinkles"
or Hills & Valleys

Accumulation in Valleys
Inflation to Structure Formation

Quantum Fluctuations

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Inflation to Structure Formation

<10^{-35}s

Exponential Stretch

Rapid Expansion

Inflation

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Inflation to Structure Formation

<10^{-35}s

Exponential Stretch

Rapid Expansion

Inflation

Gravitational Instability
Inflation to Structure Formation

- Inflation: $<10^{-35}$s
- Present: $10^{10}$ yrs
- Exponential Stretch
- Gravitational Instability
- Galaxies
- Large Scale Structure

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Inflation to Structure Formation

Inflation

<10^{-35}s

3 \times 10^5 \text{ yrs}

Gravitational Instability

Large Scale Structure

CMB Observer

Galaxies

Exponential Stretch

Rapid Expansion

Horizon

Horizon Crossing

Last Scattering

Present

10^{10} \text{ yrs}

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Temperature Maps
Large–Angle Anisotropies

10°–90° anisotropy
seeing beyond the horizon

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Understanding Maps

COBE's fuzzy vision

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Understanding Maps

COBE's fuzzy vision

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Understanding Maps

COBE's imperfect reception
Understanding Maps

Our best guess for the original map

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Small–Angle Anisotropies

<1° anisotropy seeing inside the horizon

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New DASI Data

[Image: A grid of circular maps representing cosmic microwave background (CMB) radiation data. The maps show variations in temperature with a color scale ranging from -100μK to 100μK. The maps are spread across a 3.5° x 3.5° area.]
MAP Satellite has Launched!
What MAP Should See

Simulated Data

http://map.gsfc.nasa.gov
Ringing in the New Cosmology
Projected MAP Errors

$\Delta T$ (µK) vs. $l$ (multipole) and $\theta$ (degrees)

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Thermal History II
Small–Angle Anisotropies

Horizon Crossing

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Small–Angle Anisotropies

3x10^5 yrs 10^{10} yrs

Horizon

Last Scattering Present

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Small–Angle Anisotropies

3x10^5 yrs

10^{10} yrs

CMB Observer

Horizon

Last Scattering

Present

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A Brief Thermal History

- Rapid **scattering** couples **photons** and **baryons**
- Plasma behaves as **perfect fluid**
Acoustic Oscillations
Gravitational Ringing

• Potential wells = inflationary seeds of structure

• Fluid falls into wells, pressure resists: acoustic oscillations
Seeing Sound

- Oscillations *frozen at recombination*
- Compression=*hot spots*, Rarefaction=*cold spots*
Harmonic Modes

• **Frequency proportional to wavenumber**: \( \omega = kc_s \)

• **Twice the wavenumber = twice the frequency of oscillation**
Angular Peaks
Why Anisotropies?

- Spatial temperature perturbation oscillating in time and frozen in at recombination
Peaks in Angular Power

• Standing wave acoustic oscillations in local temperature
Peaks in Angular Power

- Oscillations frozen in at recombination
- Prompt release of photons
Peaks in Angular Power

• Photons arriving at observer show an anisotropy whose angular scale decreases with time

• Temperature inhomogeneity $\rightarrow$ anisotropy
Peaks in Angular Power

- The Anisotropy Formation Process
Acoustic Landscape
The First Peak
Curvature and Fate of Universe

Negative Curvature: Expand Forever
Positive Curvature: Big Crunch
Curvature in the Power Spectrum

- Features scale with angular diameter distance
- Angular location of the first peak
The Second Peak
Baryon & Inertia

• Baryons add inertia to the fluid

• Equivalent to adding mass on a spring

• Same initial conditions

• Same null in fluctuations

• Unequal amplitudes of extrema
Baryons in the Power Spectrum
Second Peak Detected
Score Card
Higher Peaks
Radiation and Dark Matter

- **Radiation domination:**
  potential wells created by CMB itself
- **Pressure support** $\Rightarrow$ potential decay $\Rightarrow$ driving
- **Heights measures** when dark matter dominates
Dark Matter in the Power Spectrum
Third Peak Constrained
Microwave Background Past

Validation of

• **Big Bang**  
  (Hot, Expanding Univ.)  
  Thermal Spectrum  
  Temp. at early times

• **Gravitational Instability**  
  (wrinkles → galaxies)  
  Amplitude and Spectrum of Anisotropies

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Microwave Background Present

How Microwaves Ring

• **Origin and Evolution of Structure** (galaxies...)

  Music of Inflation?

• **Global Properties of the Universe**

  Curvature, Content (dark energy, dark matter baryons)

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Microwave Background

Future

How Inflation Works

- Particle physics of the Early Universe
  Polarization

Understanding the Dark Side

- Evolution of Structure and Dark Matter and Dark Energy
  Secondary Anisotropies
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Outtakess
http://background.uchicago.edu