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
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"
- Temperature slightly different on different parts of the sky (Wrinkled or anisotropic at 1 pt in 100000)
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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Very Brief History

Nucleo-Synthesis

Last Scattering

Galaxy Formation

CMB

3 min

3 x 10^5 yrs

5 x 10^9 yrs
Gravitational Instability

"Wrinkles"
or Hills & Valleys

Accumulation in Valleys

Initial

After Infall

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Inflation to Structure Formation

- Present
- Inflation
- Exponential Stretch
- Rapid Expansion
- Gravitational Instability
- Large Scale Structure
- Galaxies

Time

<10^{-35}s

10^{10}\text{yrs}
Inflation to Structure Formation

- Inflation
- Exponential Stretch
- Horizon
- Rapid Expansion
- Horizon Crossing
- Gravitational Instability
- Large Scale Structure
- Galaxies

<10^{-35} \text{s} \quad 10^{10} \text{yrs}

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Inflation to Structure Formation

- Inflation
- Last Scattering
- Horizon Crossing
- Present

<10^{-35}s \quad 3 \times 10^5\text{yrs} \quad 10^{10}\text{yrs}

Gravitational Instability

Large Scale Structure

Galaxies

CMB Observer

Exponential Stretch

Rapid Expansion

Horizon

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Large–Angle Anisotropies

$10^\circ – 90^\circ$ anisotropy
seeing beyond the horizon

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Understanding Maps

COBE's fuzzy vision

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COBE's fuzzy vision

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COBE's imperfect reception
Understanding Maps

Our best guess for the original map

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Small–Angle Anisotropies

$<1^\circ$ anisotropy
seeing inside the horizon

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Small–Angle Anisotropies

Horizon Crossing

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Small–Angle Anisotropies

3x10⁵ yrs

10¹⁰ yrs

Last Scattering

Horizon

Present

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Small–Angle Anisotropies

3x10^5 yrs

10^{10} yrs

CMB Observer

Horizon

Last Scattering

Present

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Harmonic Features:

**Origin** of Fluctuations
(Inflation?)

**Fate** of the Universe
(Eternal expansion?
Big Crunch?)
**Music of Inflation**

- **Inflation**: $3 \times 10^5$ yrs to $10^{10}$ yrs
- **Horizon**: Present
- **CMB Observer**: Fundamental

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Music of Inflation

Exponential Stretch

Inflation

Horizon

Rapid Expansion

Last Scattering

Present

3x10^5 yrs

Overtones 1:2:3...

10^{10} yrs

CMB Observer

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Current CMB Quilt

\[ \Delta T (\mu K) \]

\[ \theta (\text{degrees}) \]

\[ l (\text{multipole}) \]

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Curvature and Fate of Universe

Negative Curvature: Expand Forever
Positive Curvature: Big Crunch
Microwave Background
Triumphs

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

Future

How Microwaves Ring

• **Origin and Evolution of Structure**
  (galaxies...)
  
  *Music of Inflation?*

• **Ultimate Fate and Global Properties**
  of the Universe

  *Curvature, Content (dark matter)*