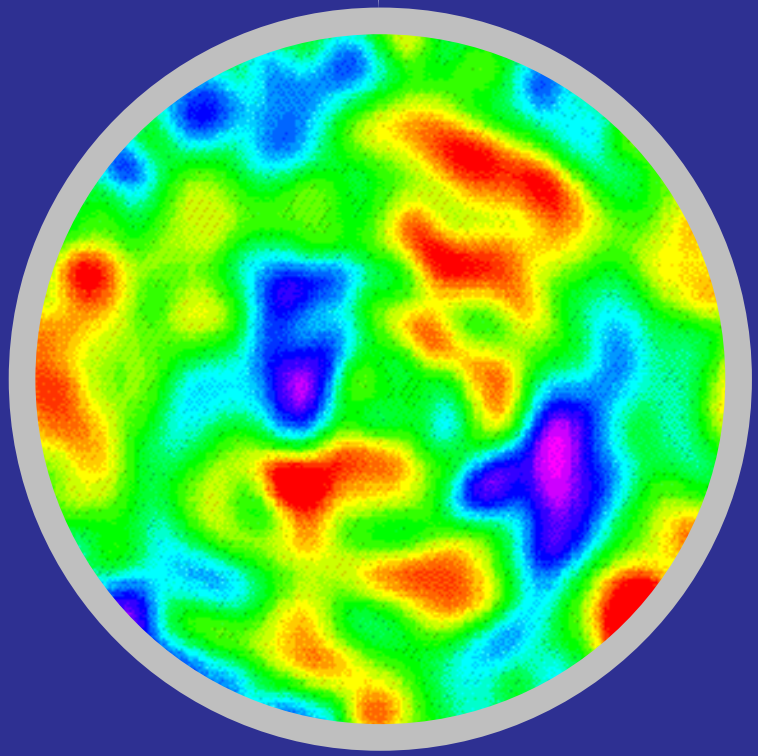
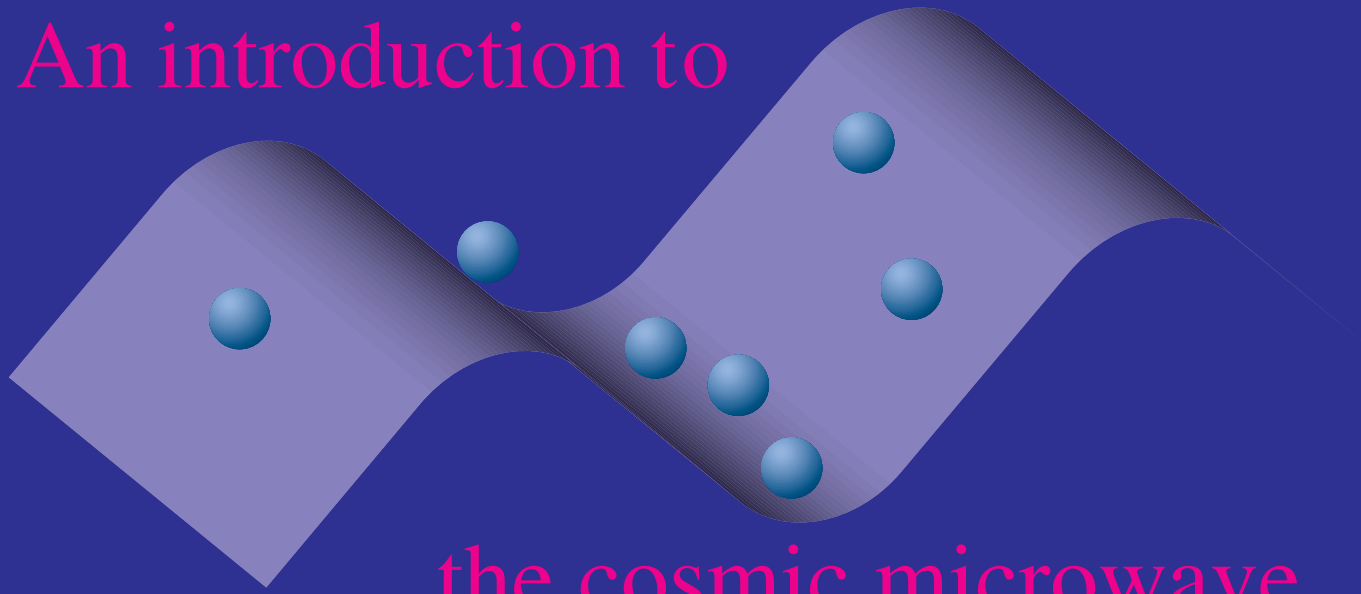


An introduction to



the cosmic microwave background

W. Hu

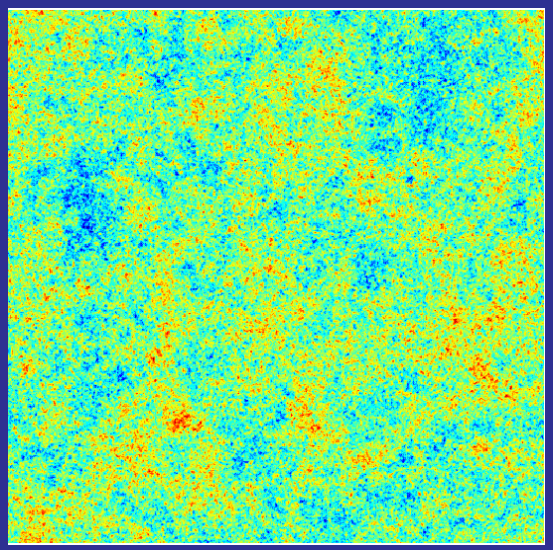
Cosmological Background

"Big Bang"

- Universe Began Hot and Dense
- Expands and Cools

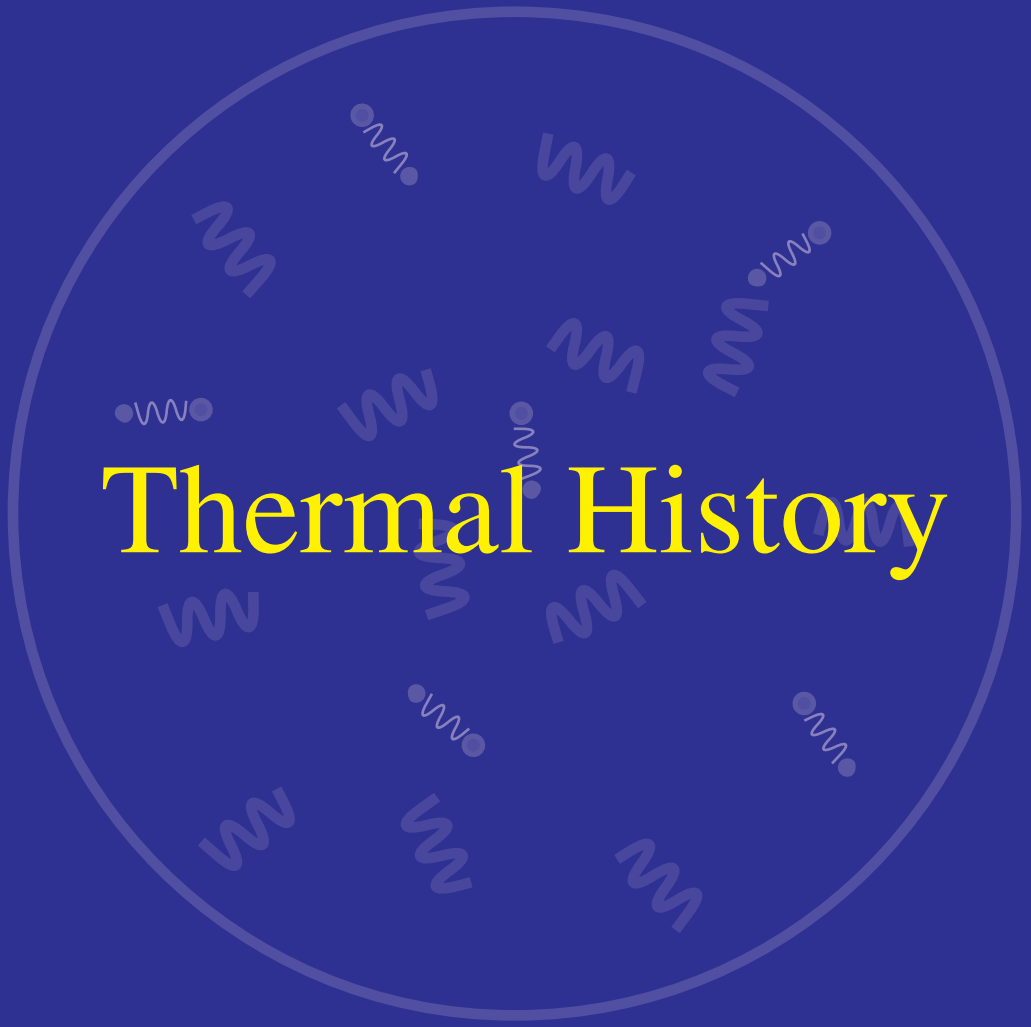
"Gravitational Instability"

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



gravity

Cosmological Expansion

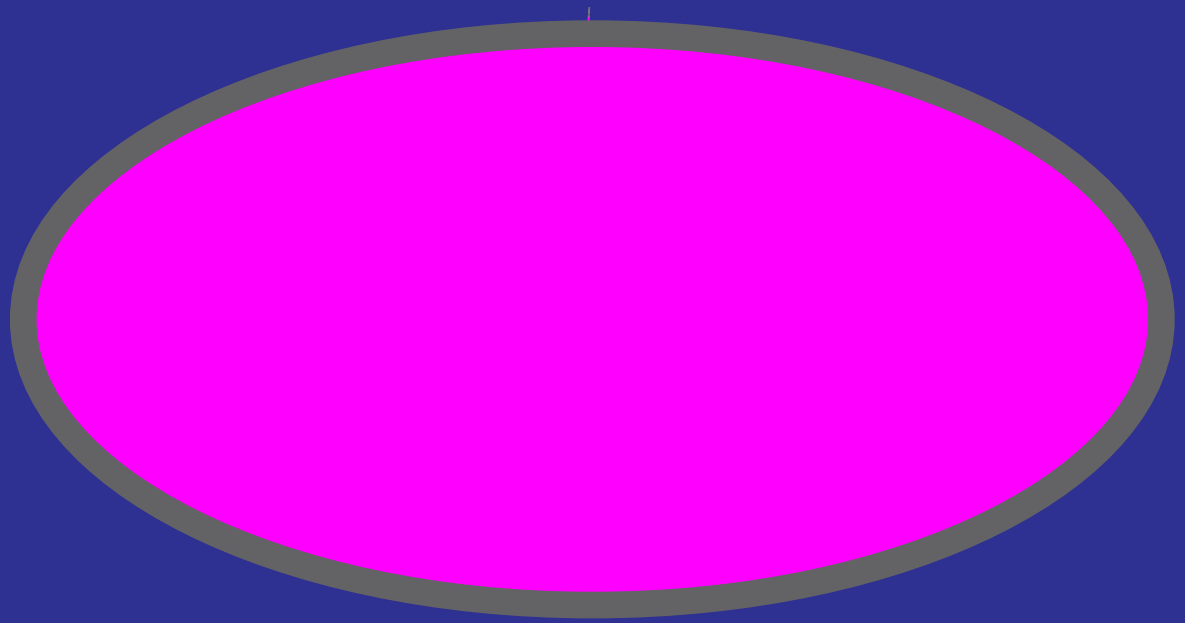

Thermal History

CMB Properties

- 3 degrees above absolute zero (-270˚C)
- mm-cm wavelength (1-10% microwave oven)

- 400 photons/cm^3 (10 trillion photons/sec/cm^2)
- Few percent of TV "snow"

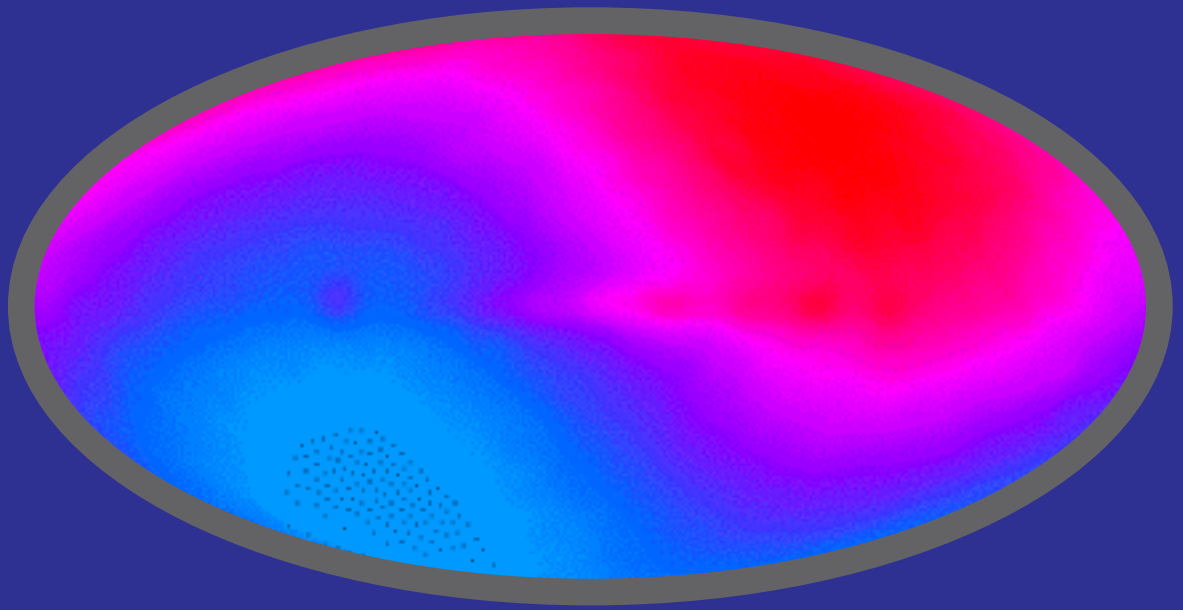
Large–Angle Anisotropies



Actual Temperature Data

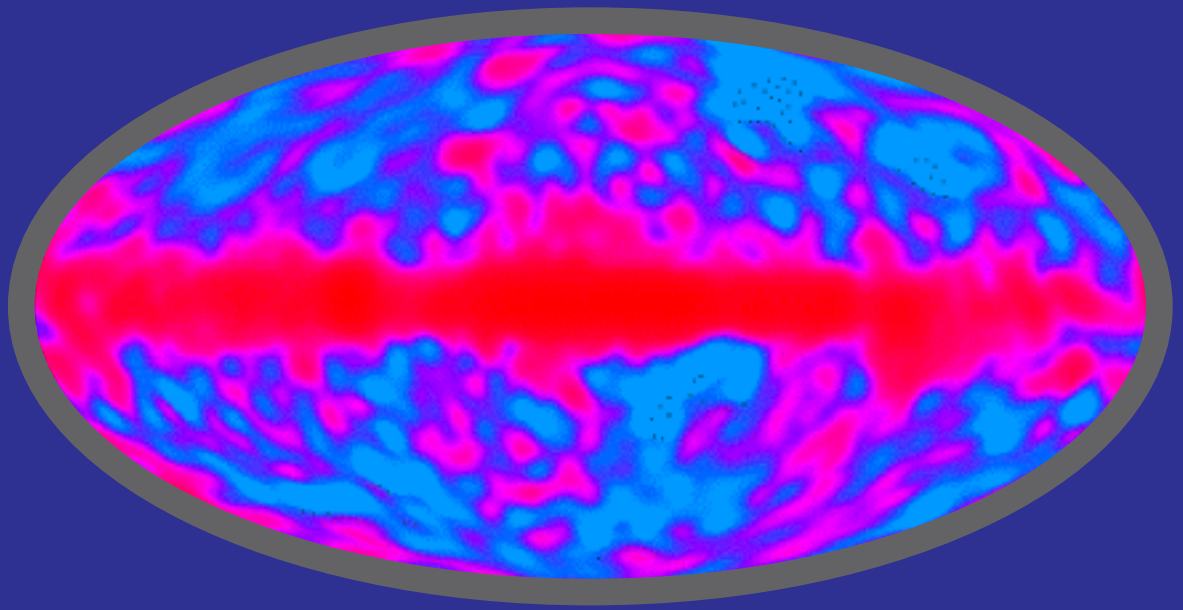
Really Isotropic!

Large–Angle Anisotropies



dipole anisotropy
1 part in 1000

Large–Angle Anisotropies



10°–90° anisotropy

1 part in 100000

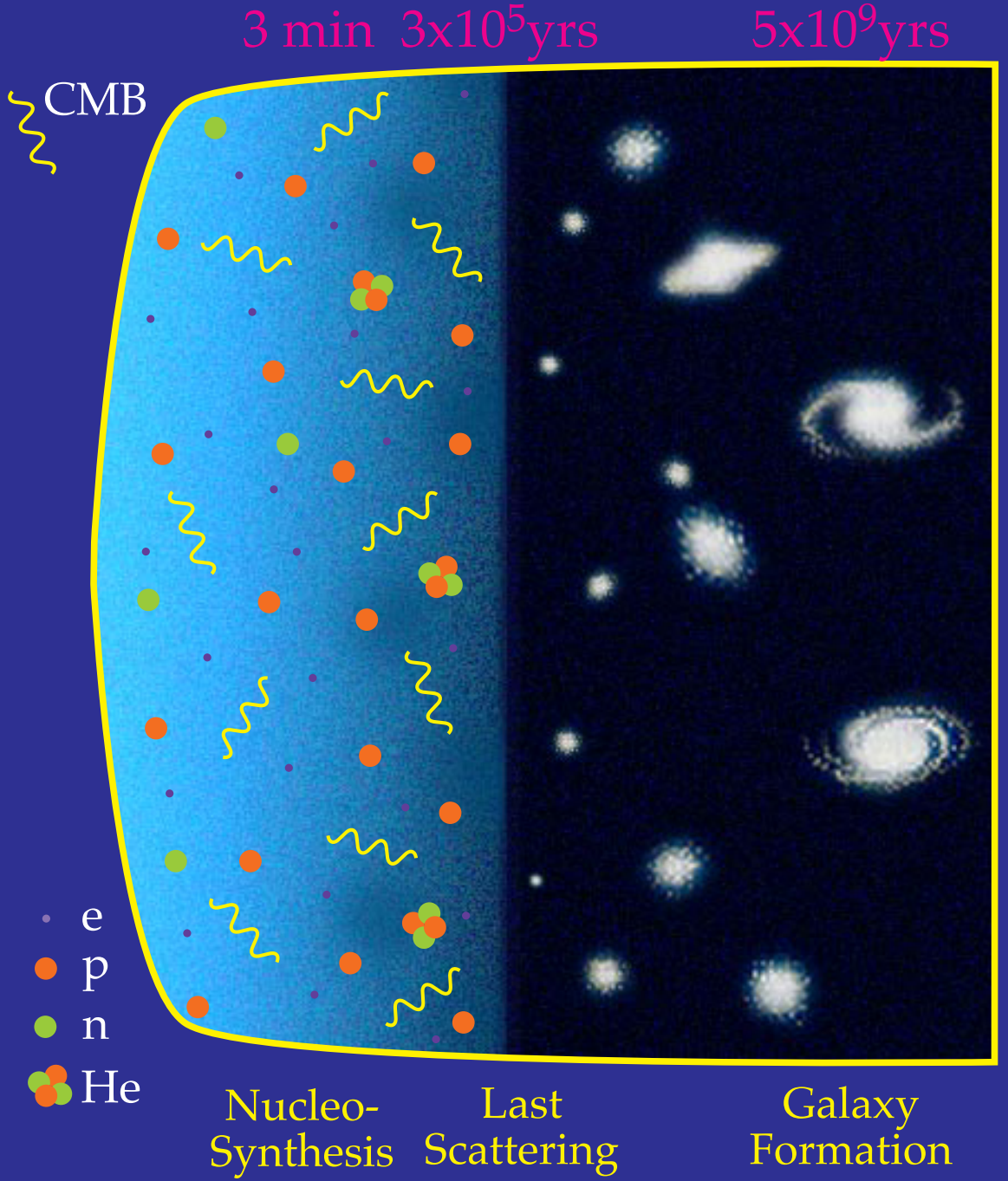
Anisotropies: A Time Machine

- Reversing time:

A Brief Thermal History

- CMB photons hotter at high redhift z
- At z~1000, T~3000K: photons ionize hydrogen

Very Brief History

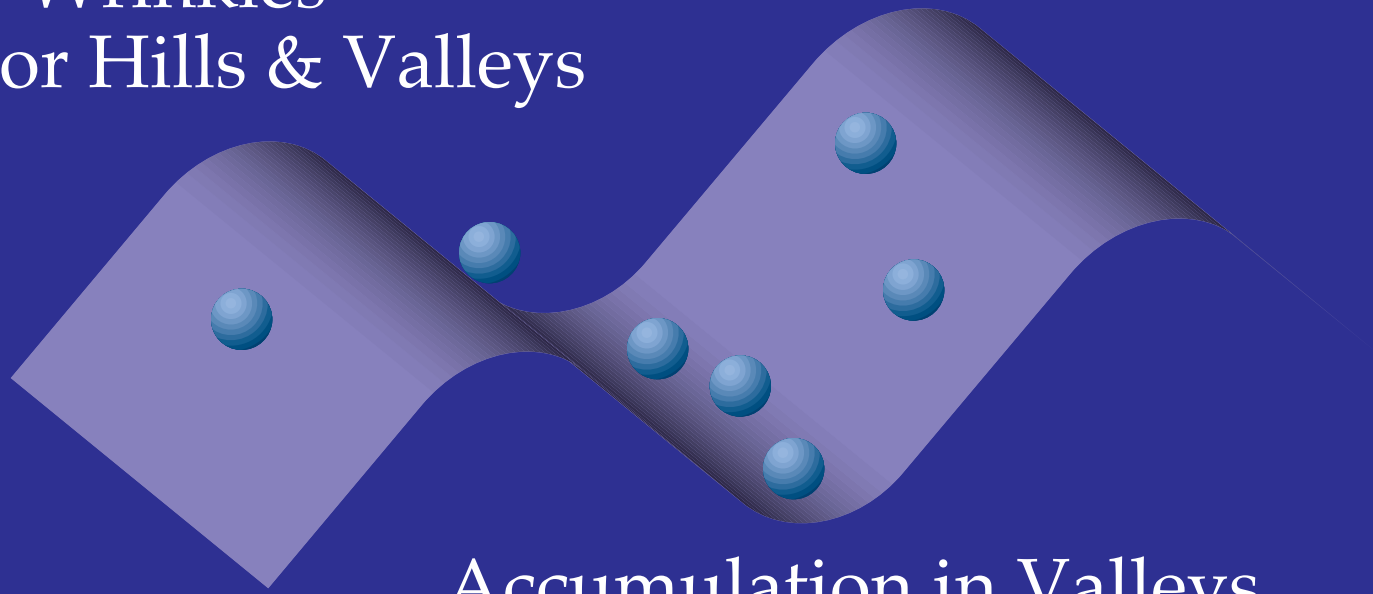


W. Hu

Gravitational Instability

Gravitational Instability

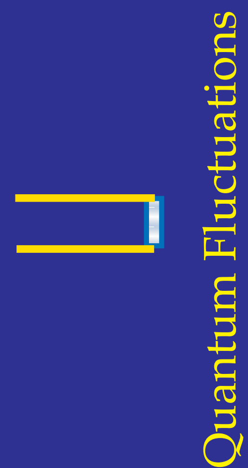
"Wrinkles"
or Hills & Valleys



Accumulation in Valleys

Cosmological Simulations

Inflation to Structure Formation



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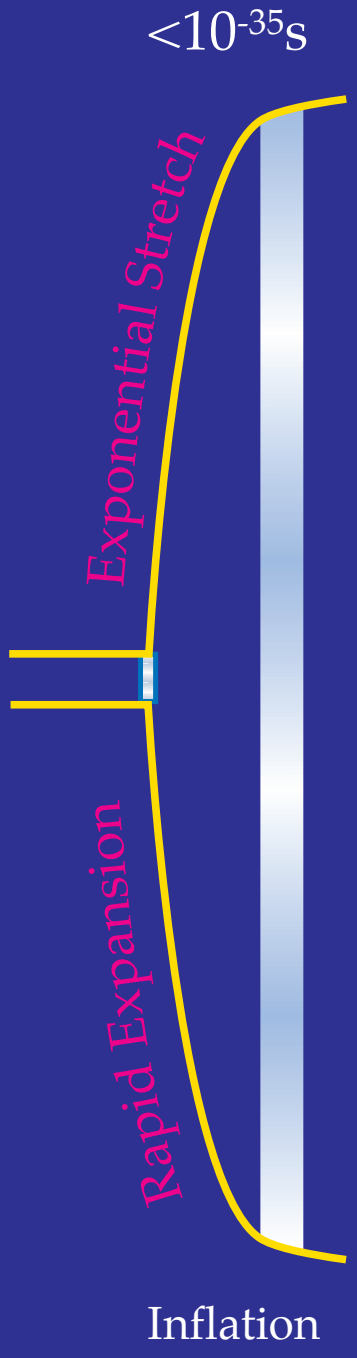
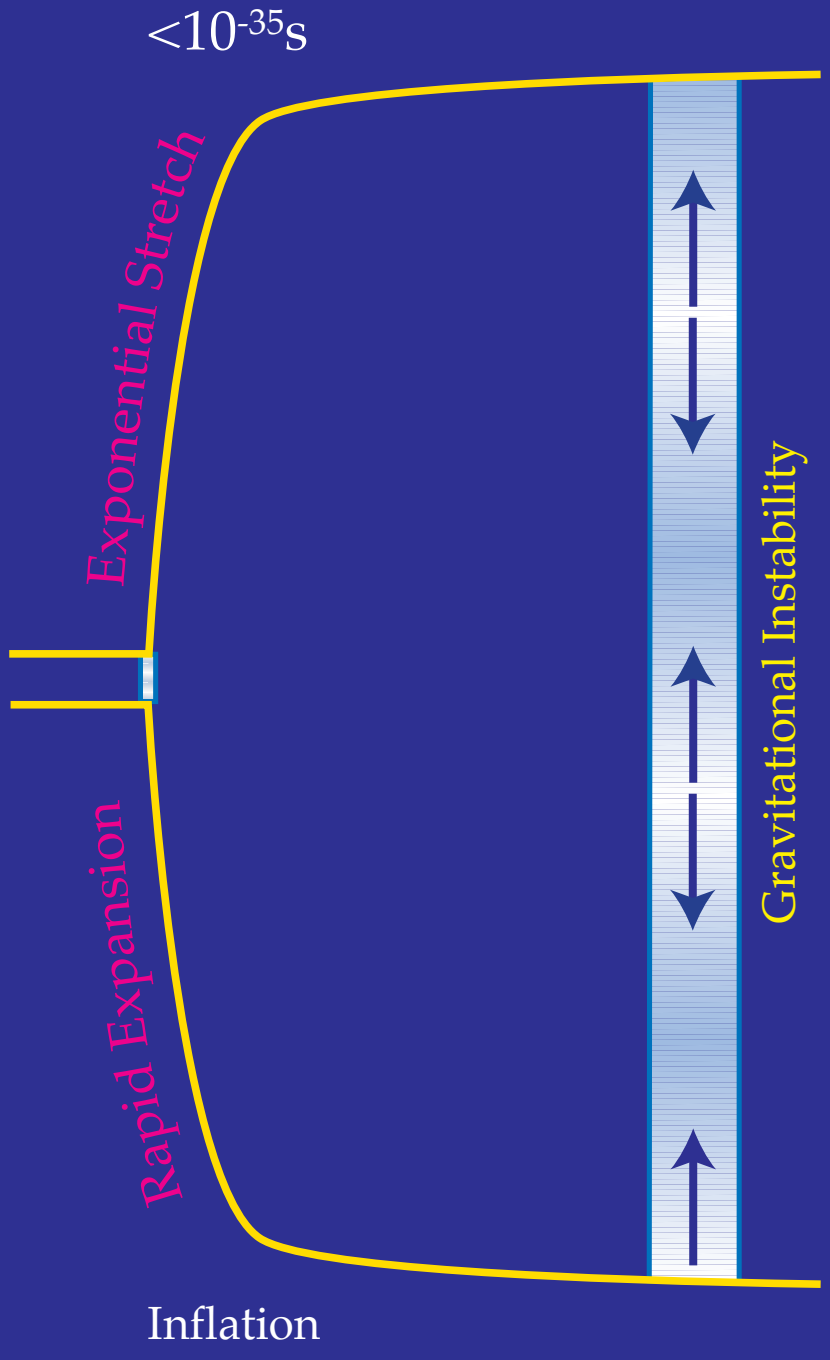
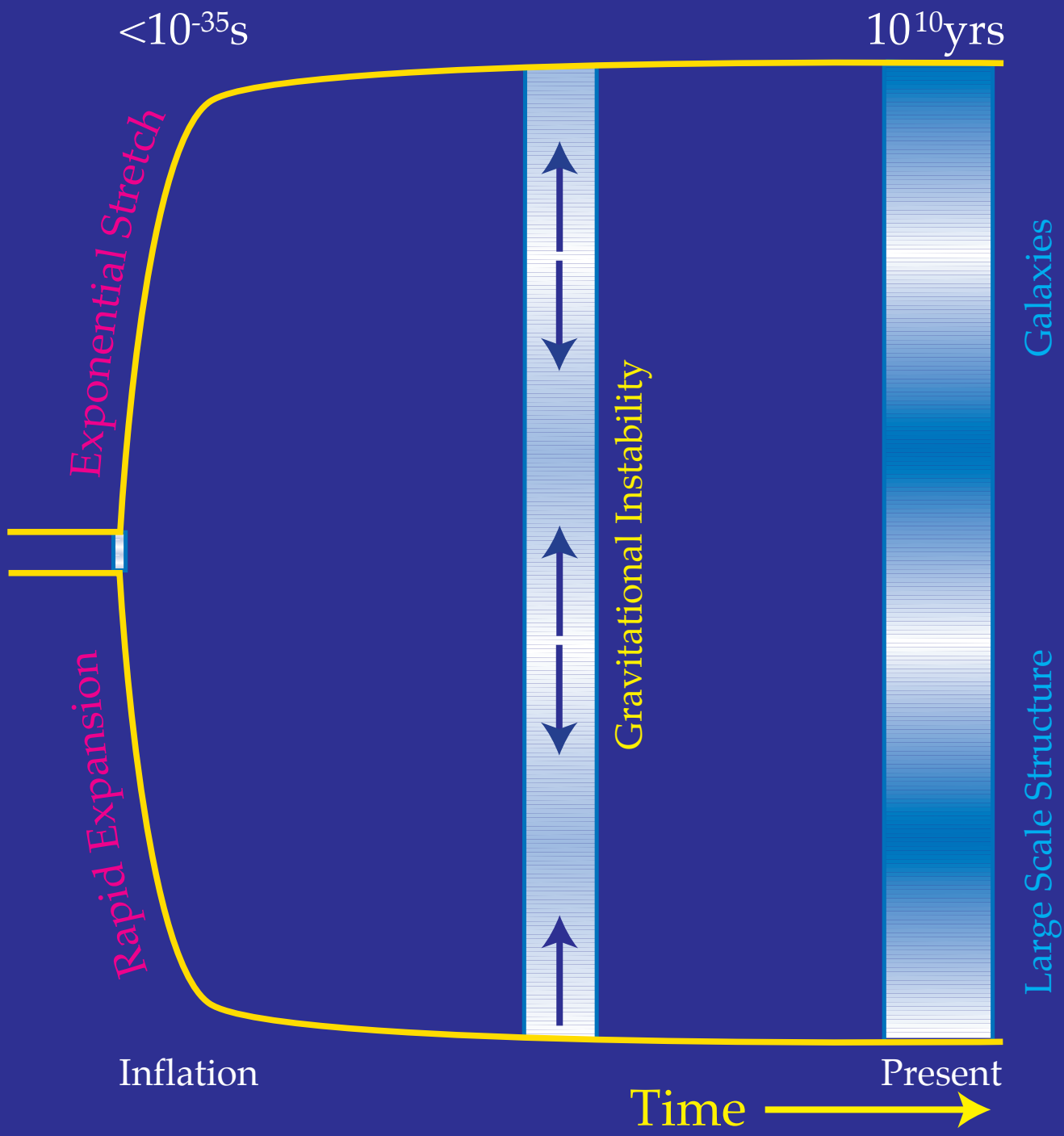
Inflation to Structure Formation



Inflation to Structure Formation

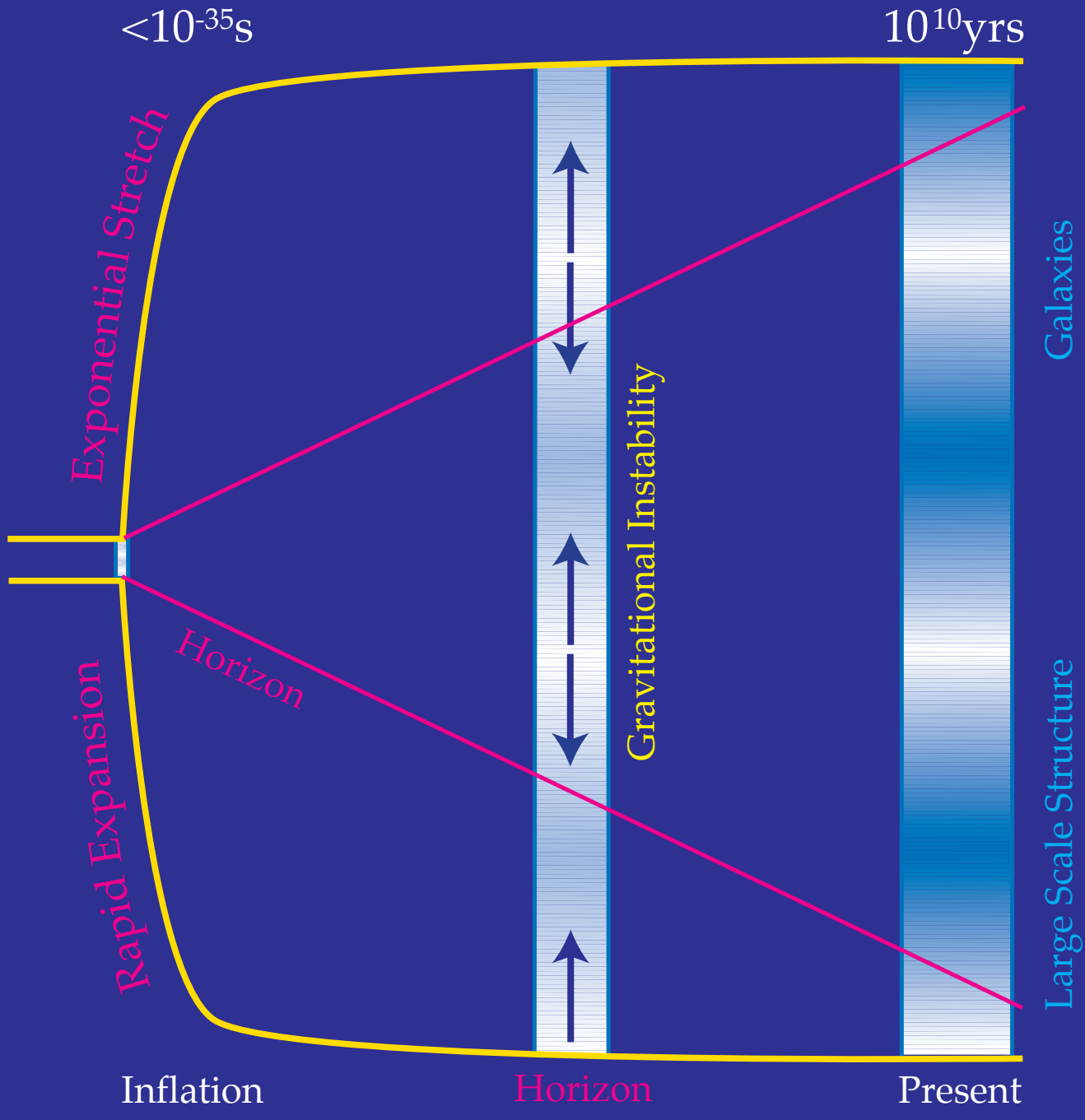


Inflation to Structure Formation



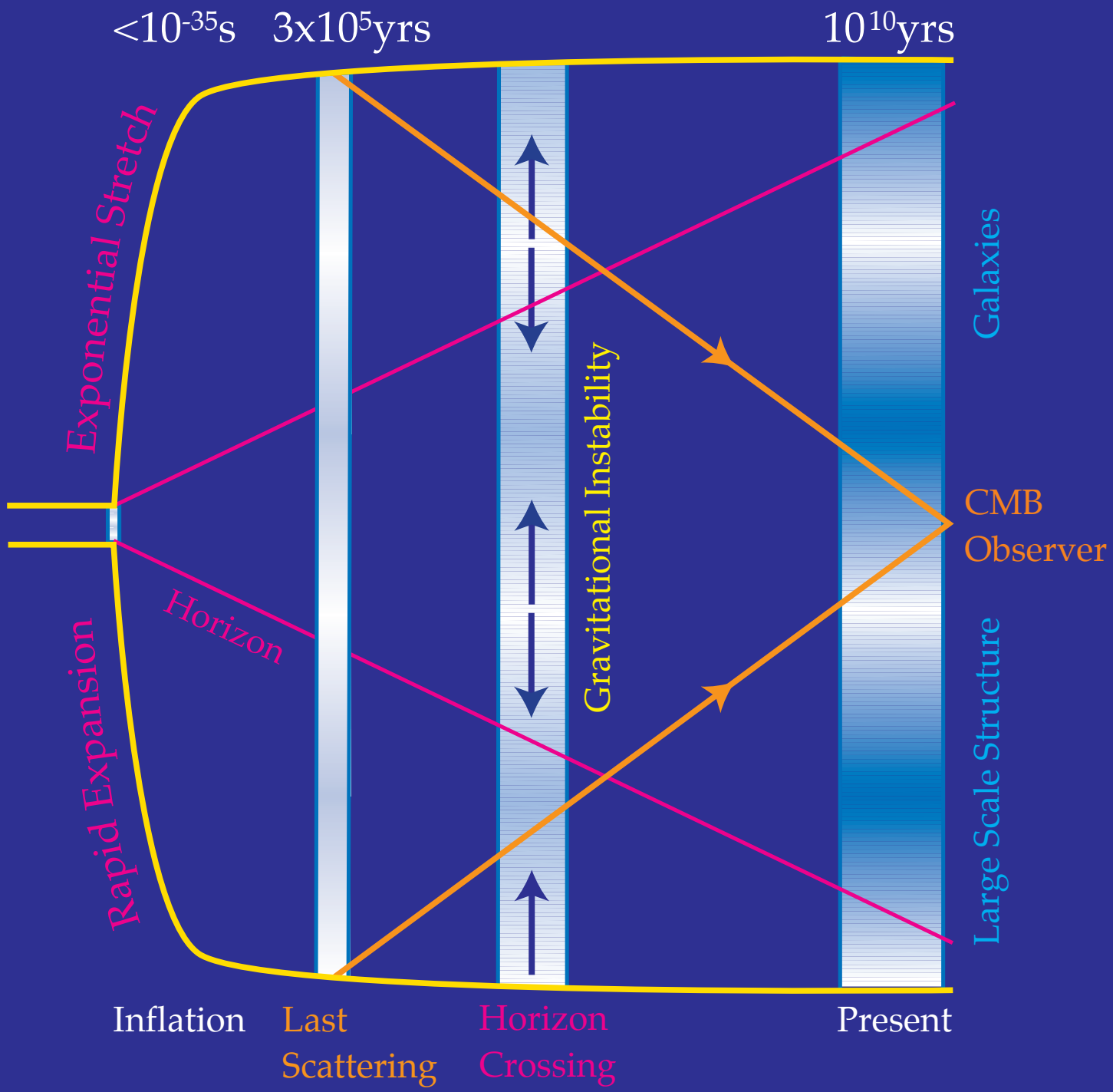
W. Hu

Inflation to Structure Formation



W. Hu

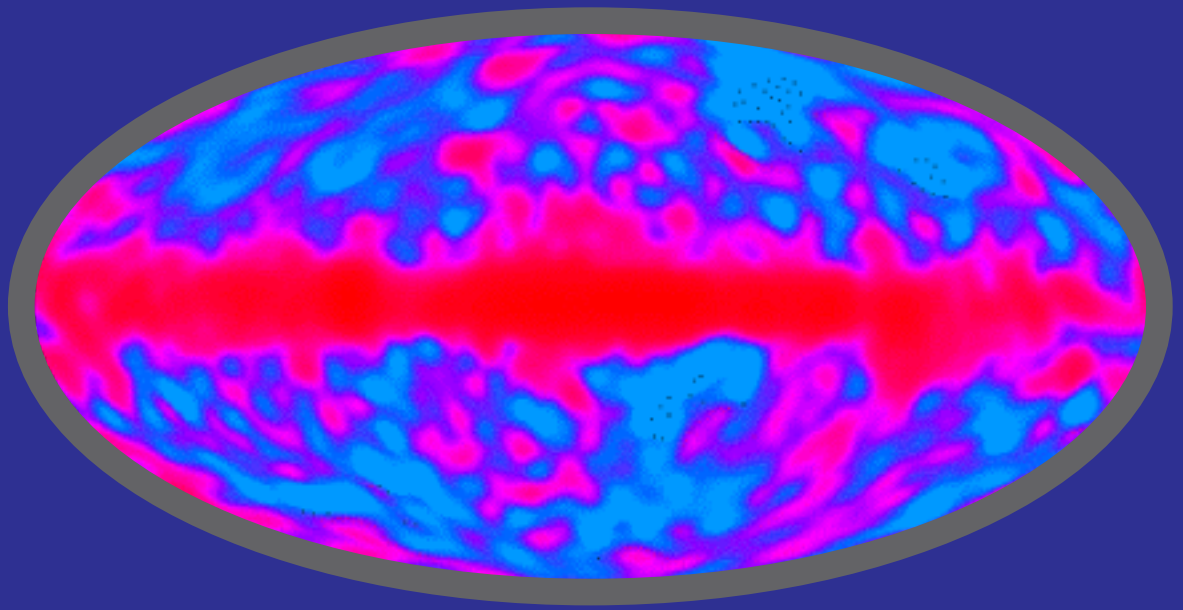
Inflation to Structure Formation



W. Hu

Temperature Maps

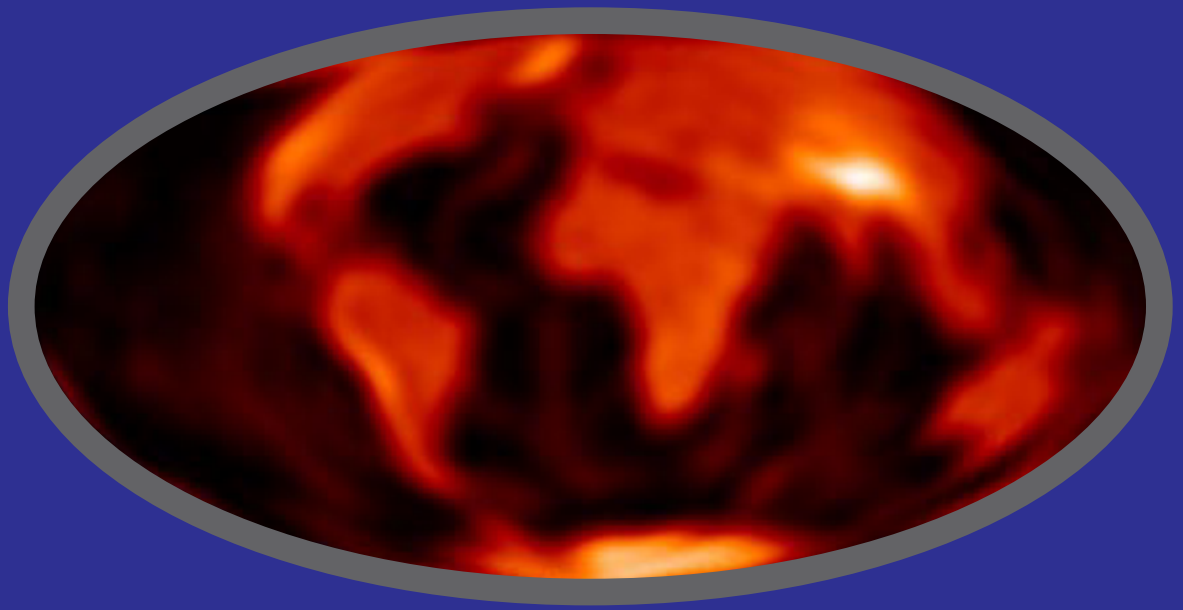
Large–Angle Anisotropies



10°–90° anisotropy

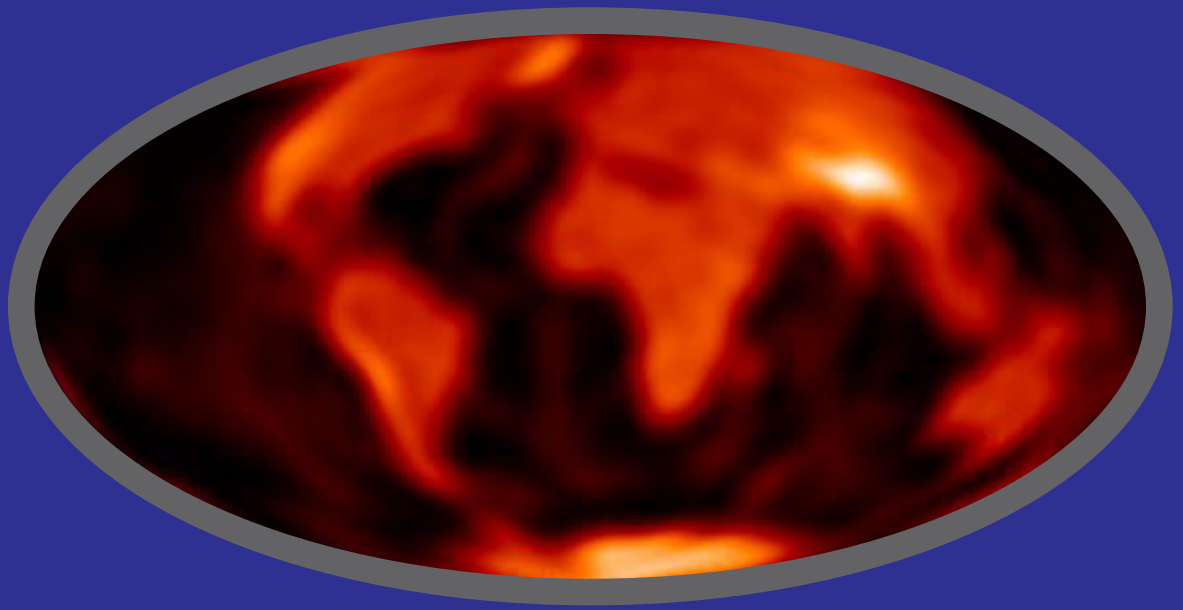
seeing beyond the horizon

Understanding Maps



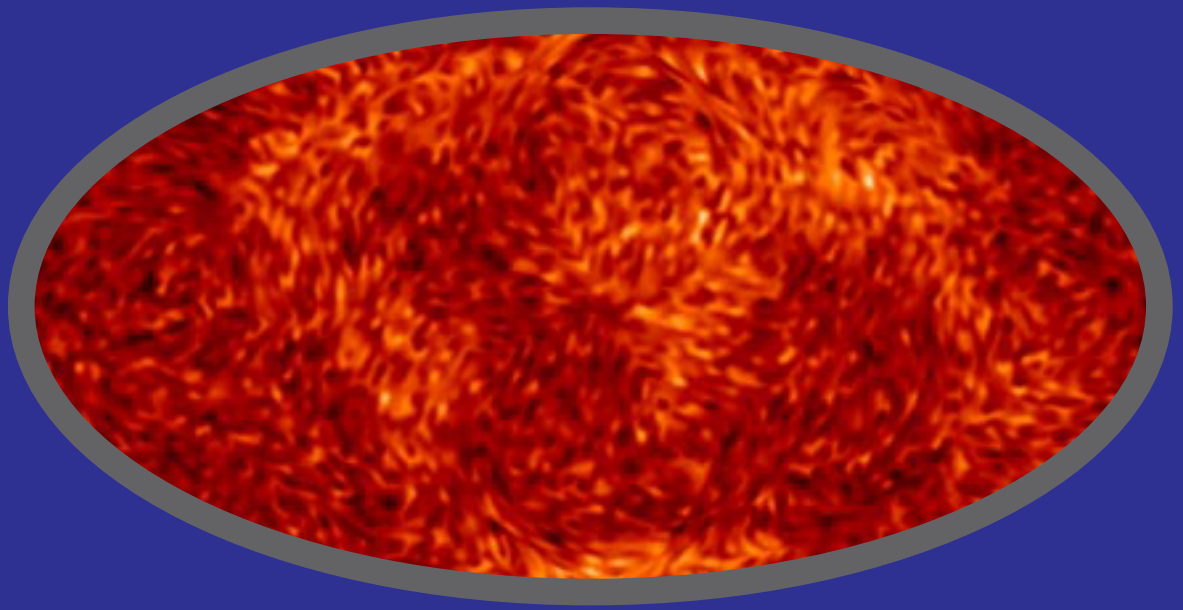
COBE's fuzzy vision

Understanding Maps



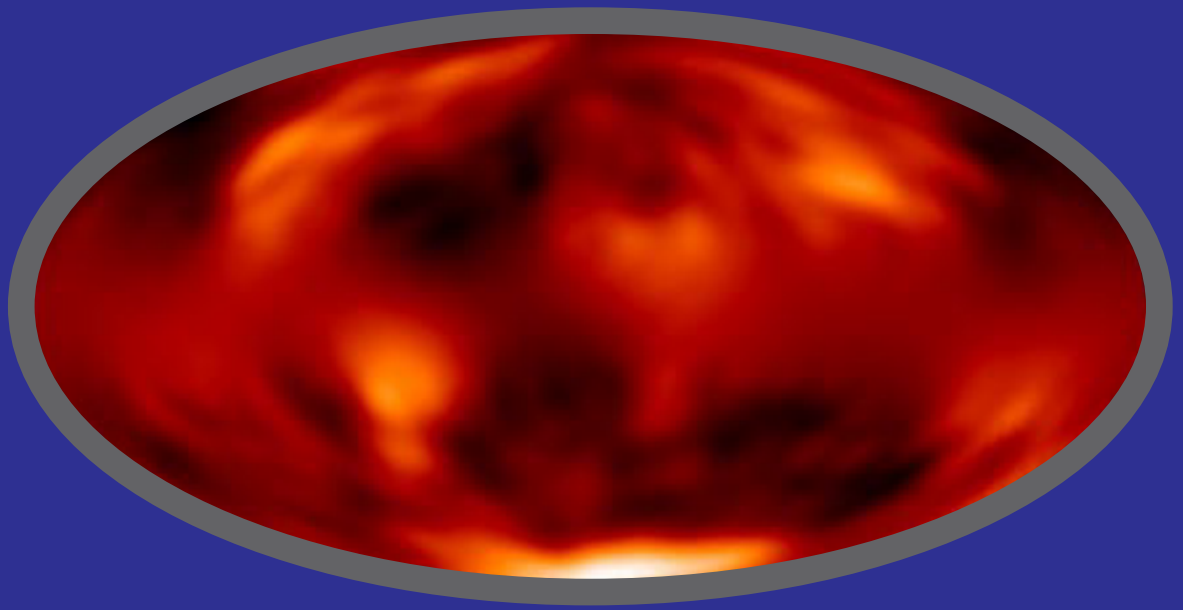
COBE's fuzzy vision

Understanding Maps



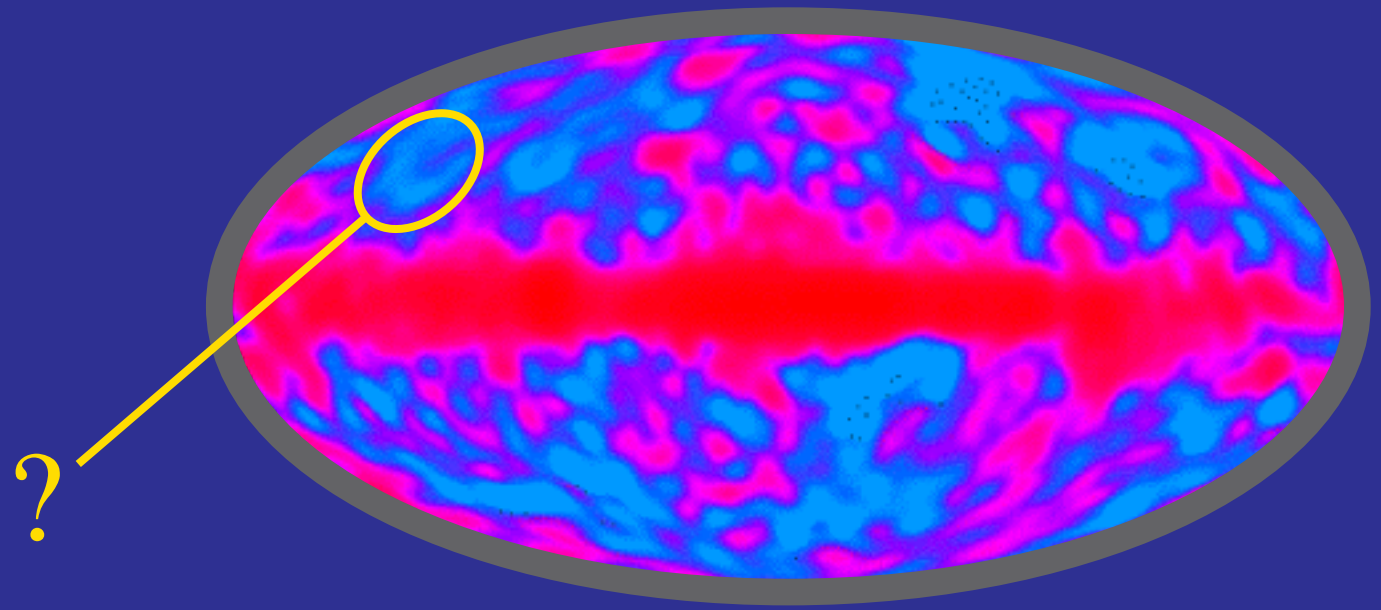
COBE's imperfect reception

Understanding Maps



Our best guess for the original map

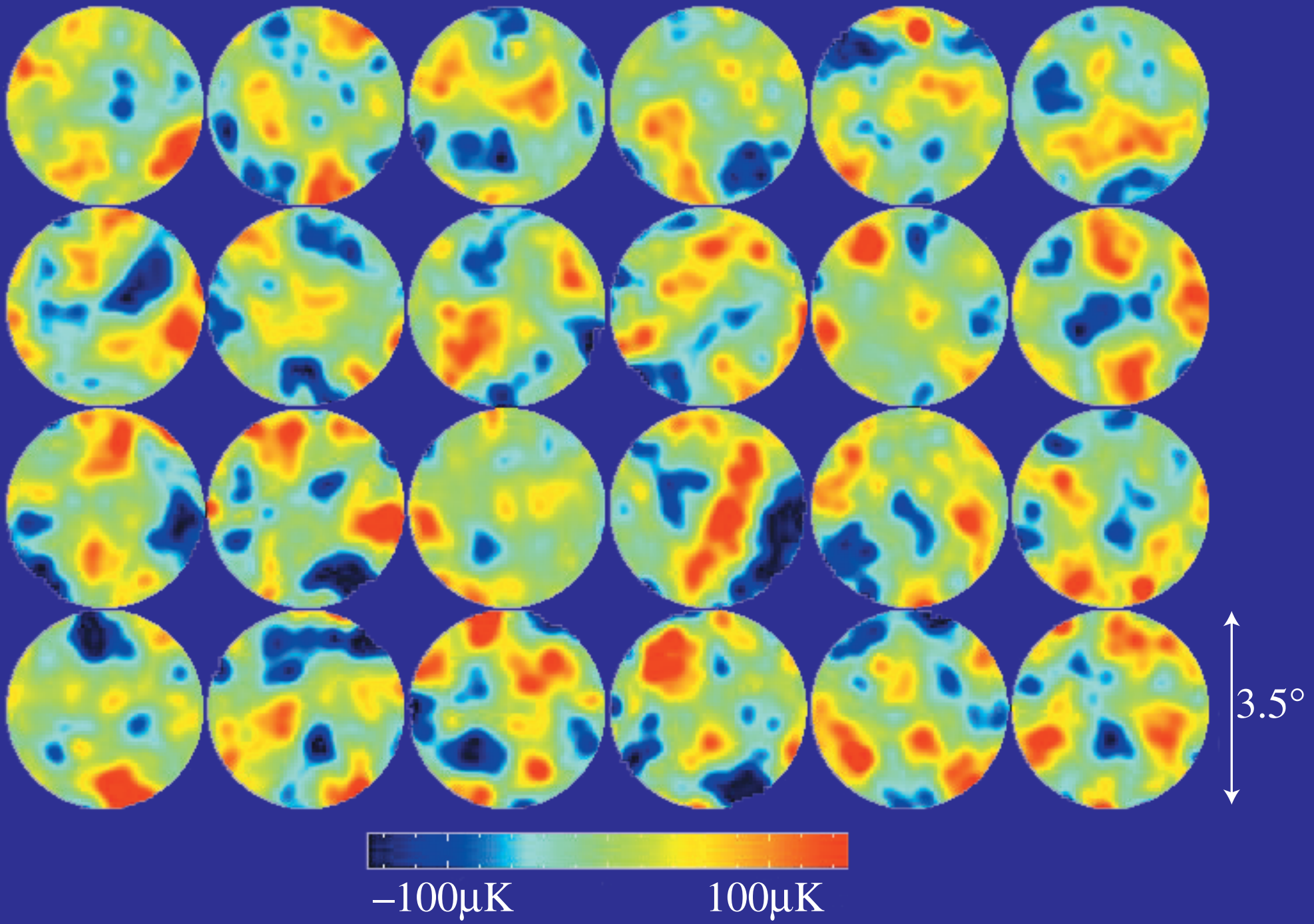
Small–Angle Anisotropies



<1° anisotropy

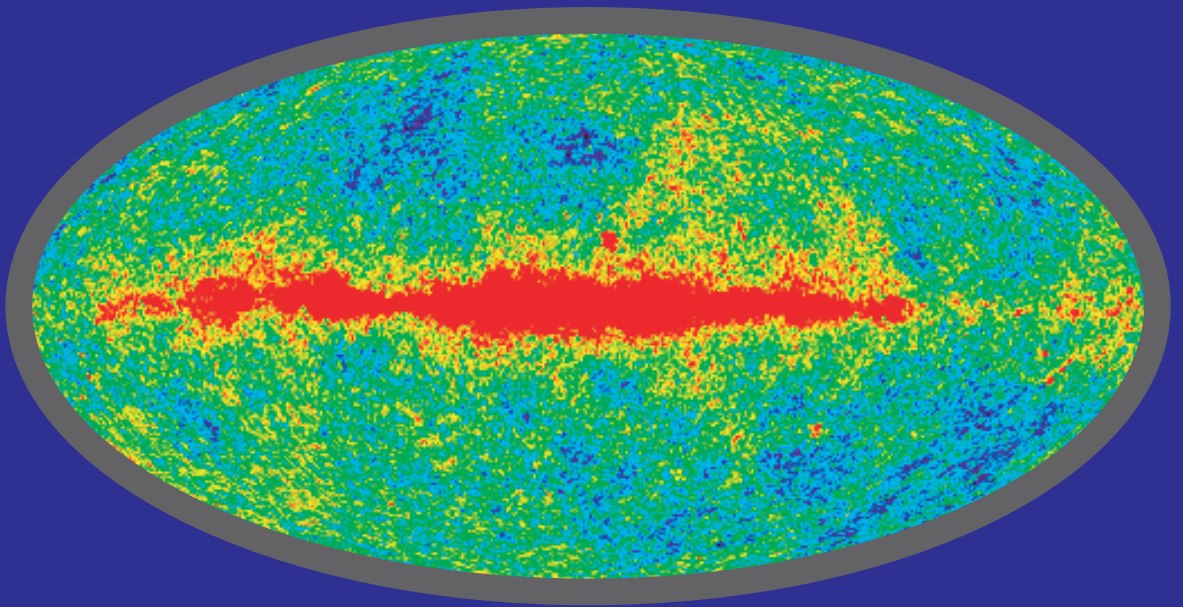
seeing inside the horizon

New DASI Data



MAP Satellite has Launched!

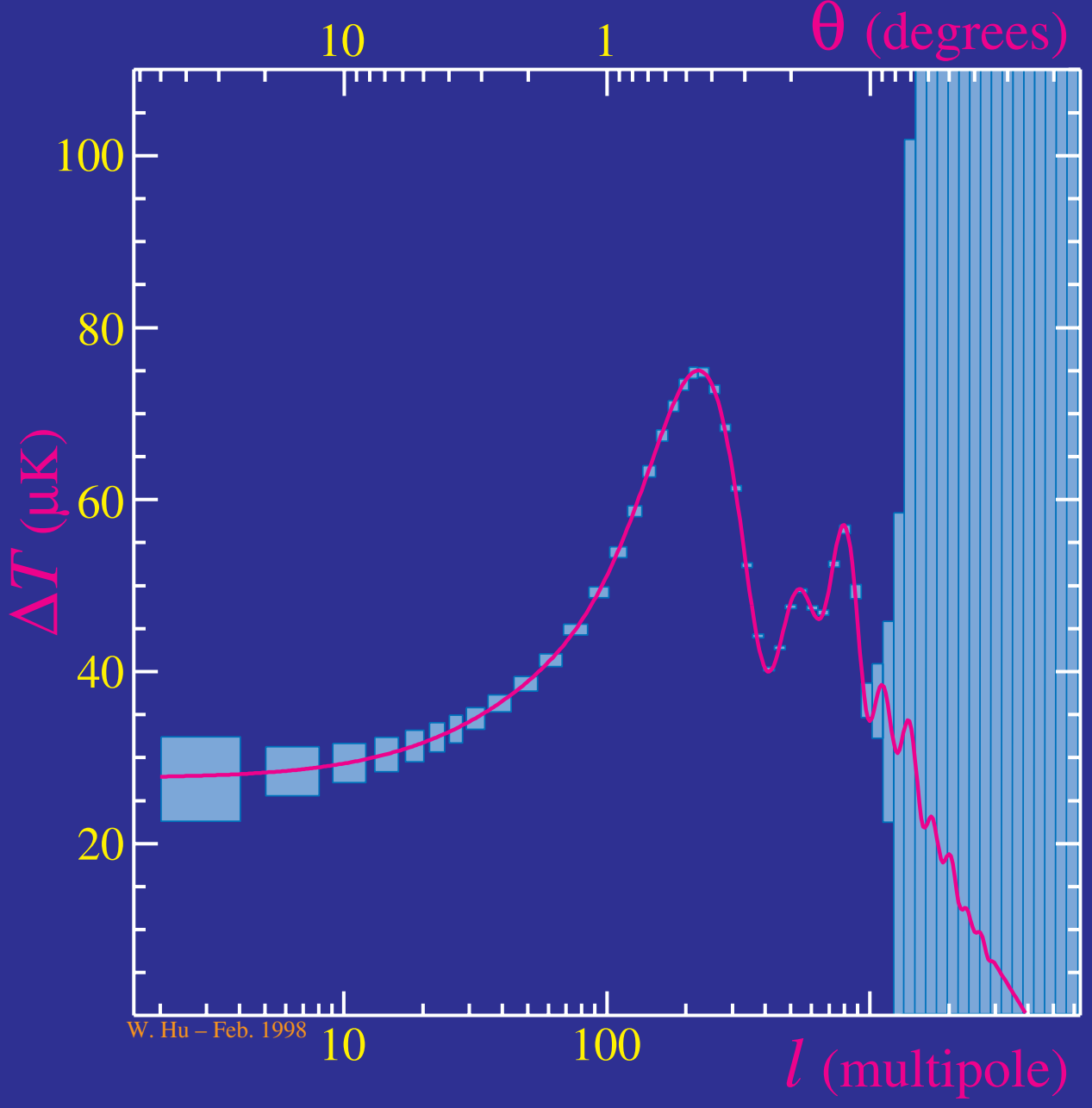
What MAP Should See

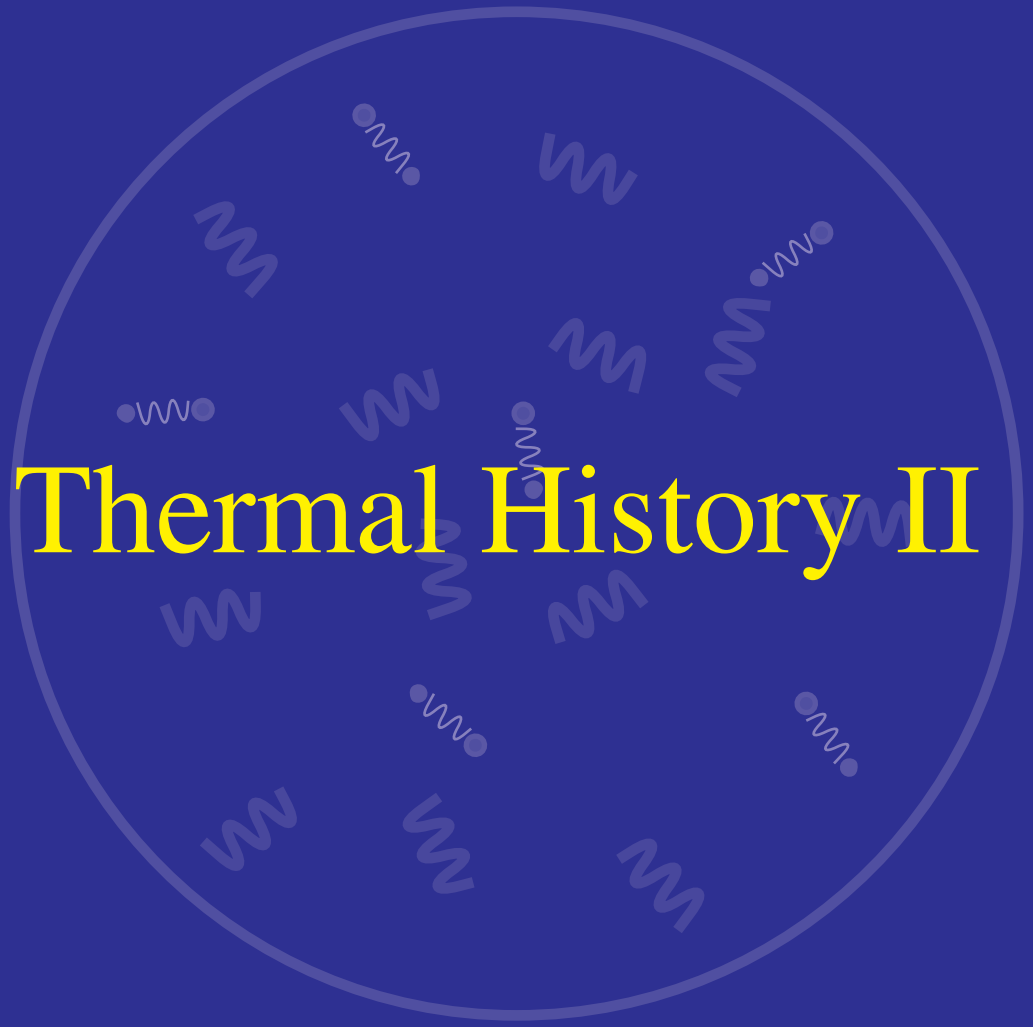


Simulated Data

Ringing in the New Cosmology

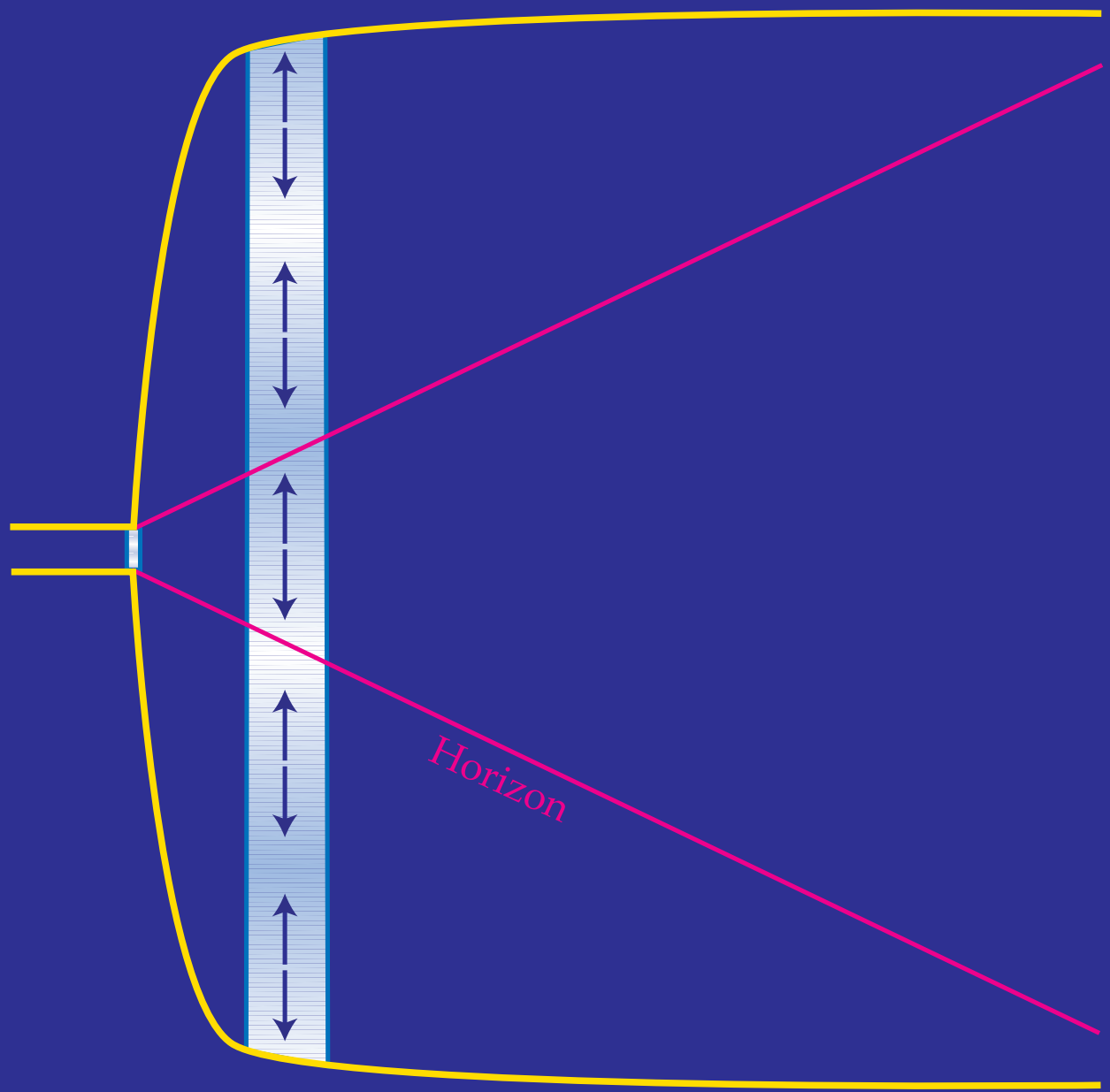
Projected MAP Errors



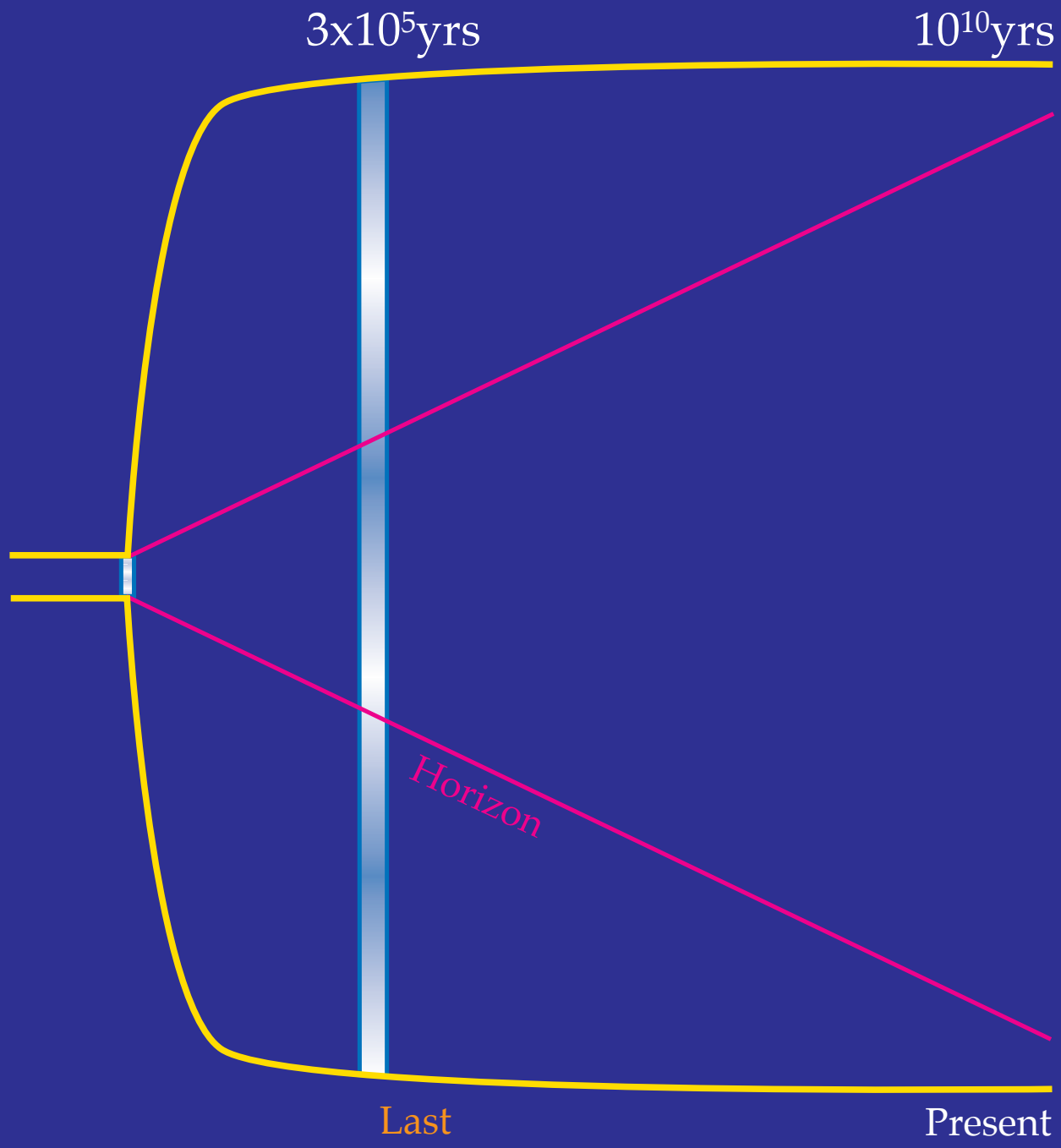


Thermal History II

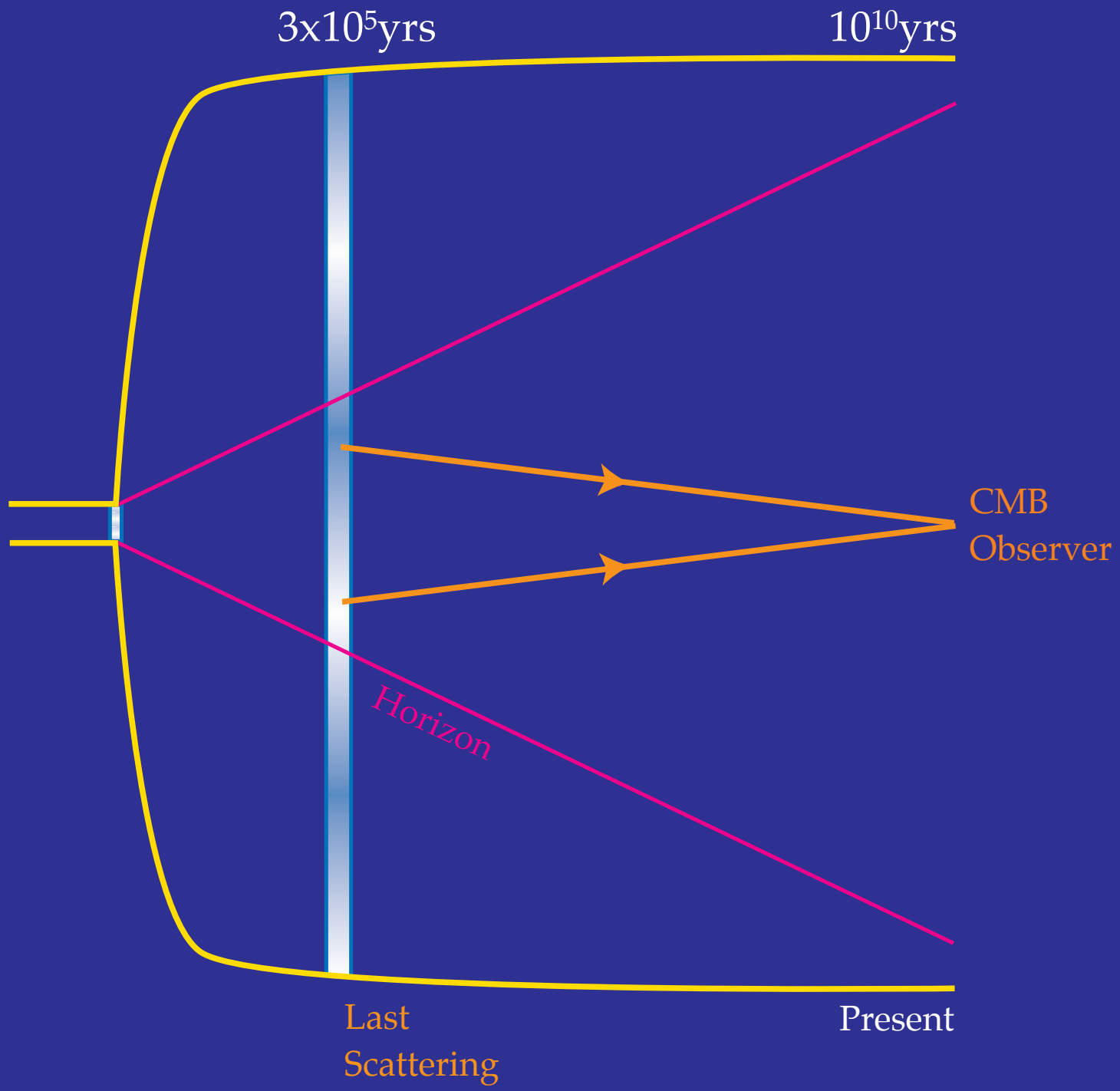
Small–Angle Anisotropies



Small–Angle Anisotropies



Small–Angle Anisotropies



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

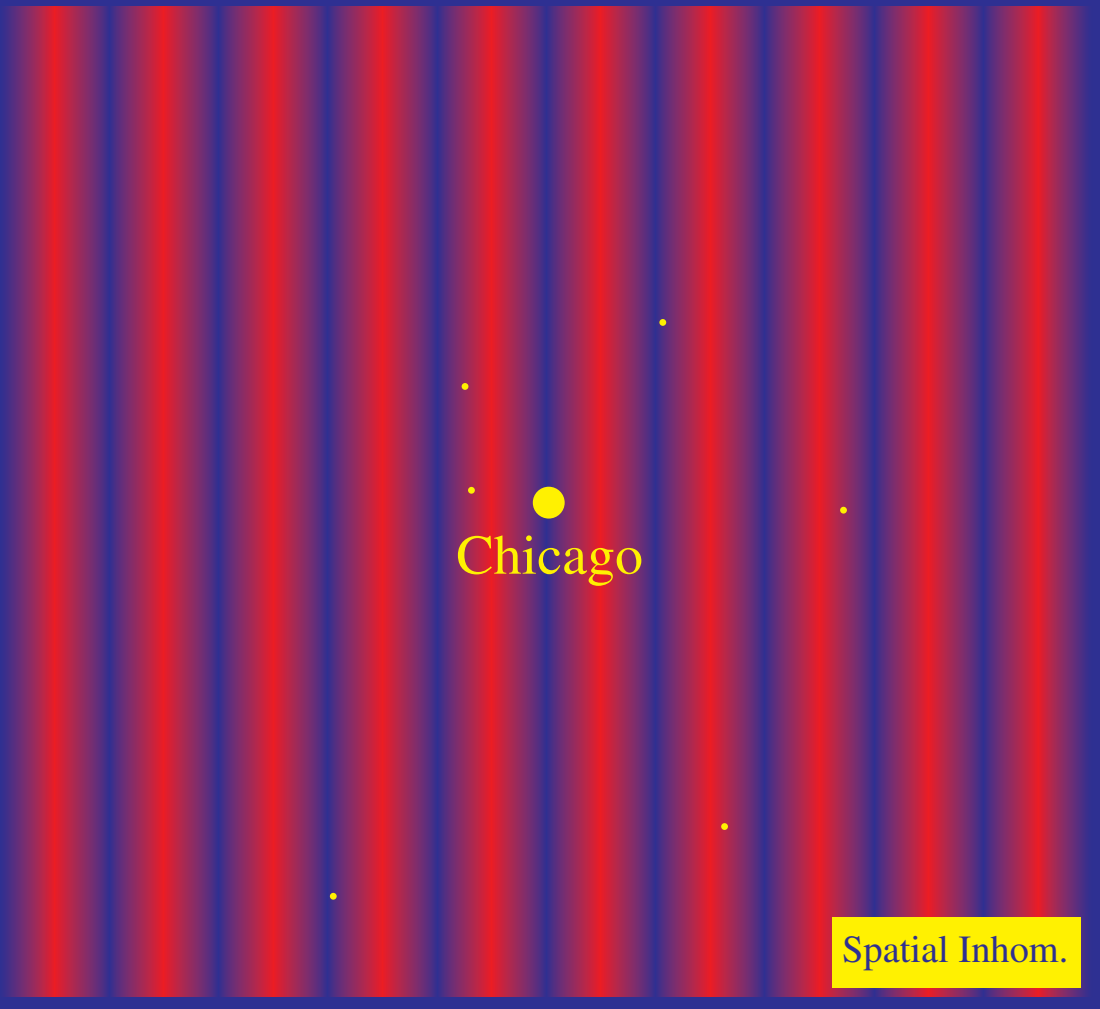
Harmonic Modes

- 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 ariving at observer show an anisotropy whose angular scale decreases with time
- Temperature inhomogeneity $\rightarrow$ anisotropy

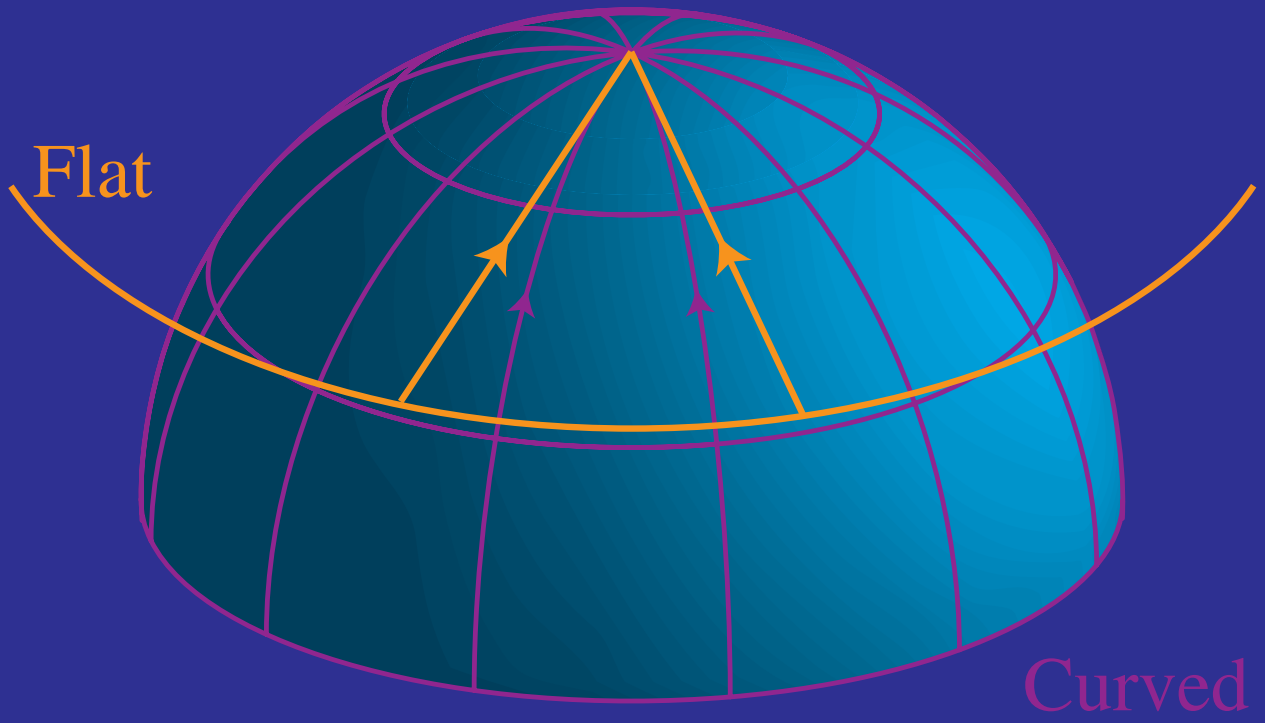
Peaks in Angular Power

- 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

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)

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

Index

- Properties
- Thermal History
- Gravitational Instability
- Temperature Maps
- Acoustic Oscillations
- Peaks
- First Peak
- Second Peak

Outtakes

http://background.uchicago.edu