The Tools of Cosmology

Andrew Zentner

The University of Pittsburgh

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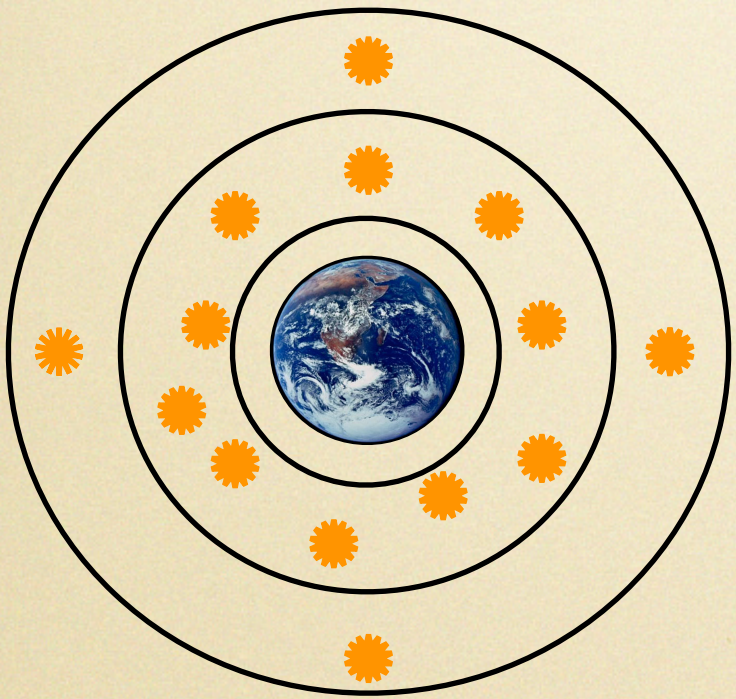
Part One: The Infant Universe

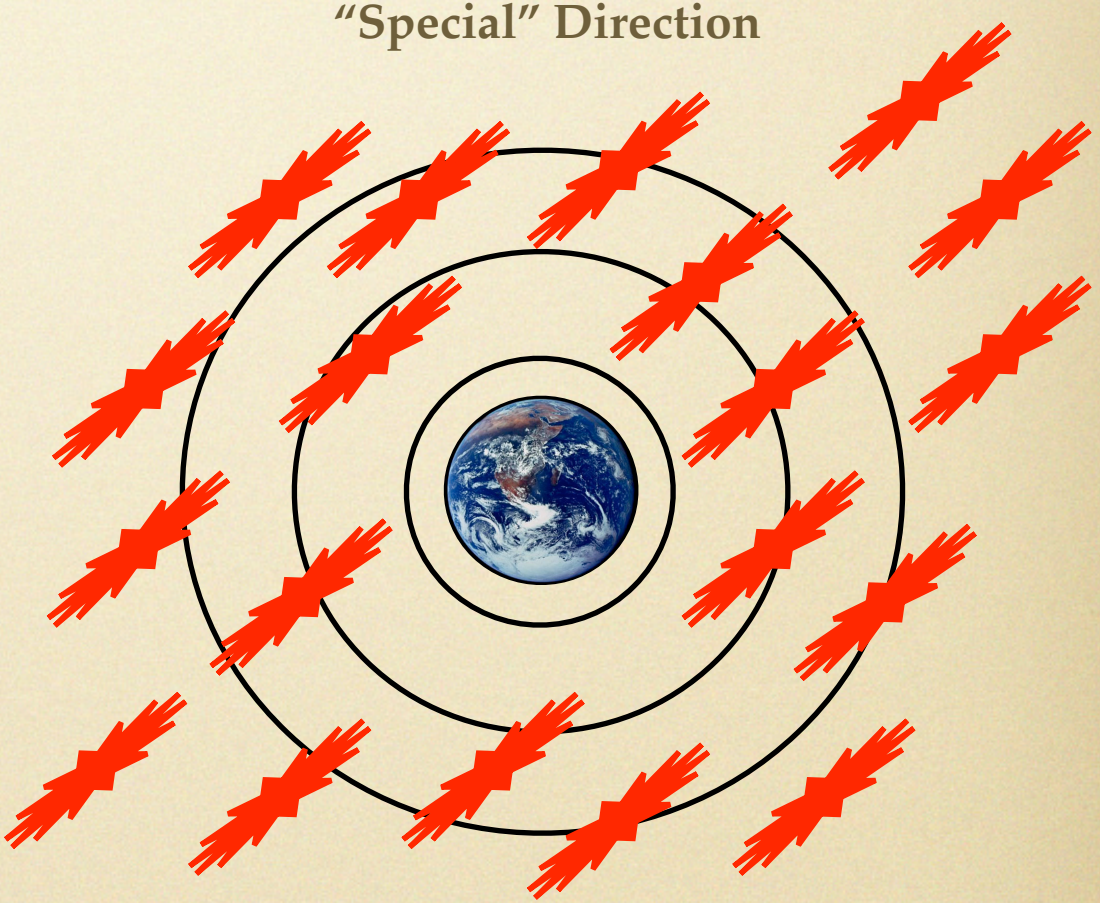
Contents

The Expanding Universe

Not Homogeneous:
Average Density Varies

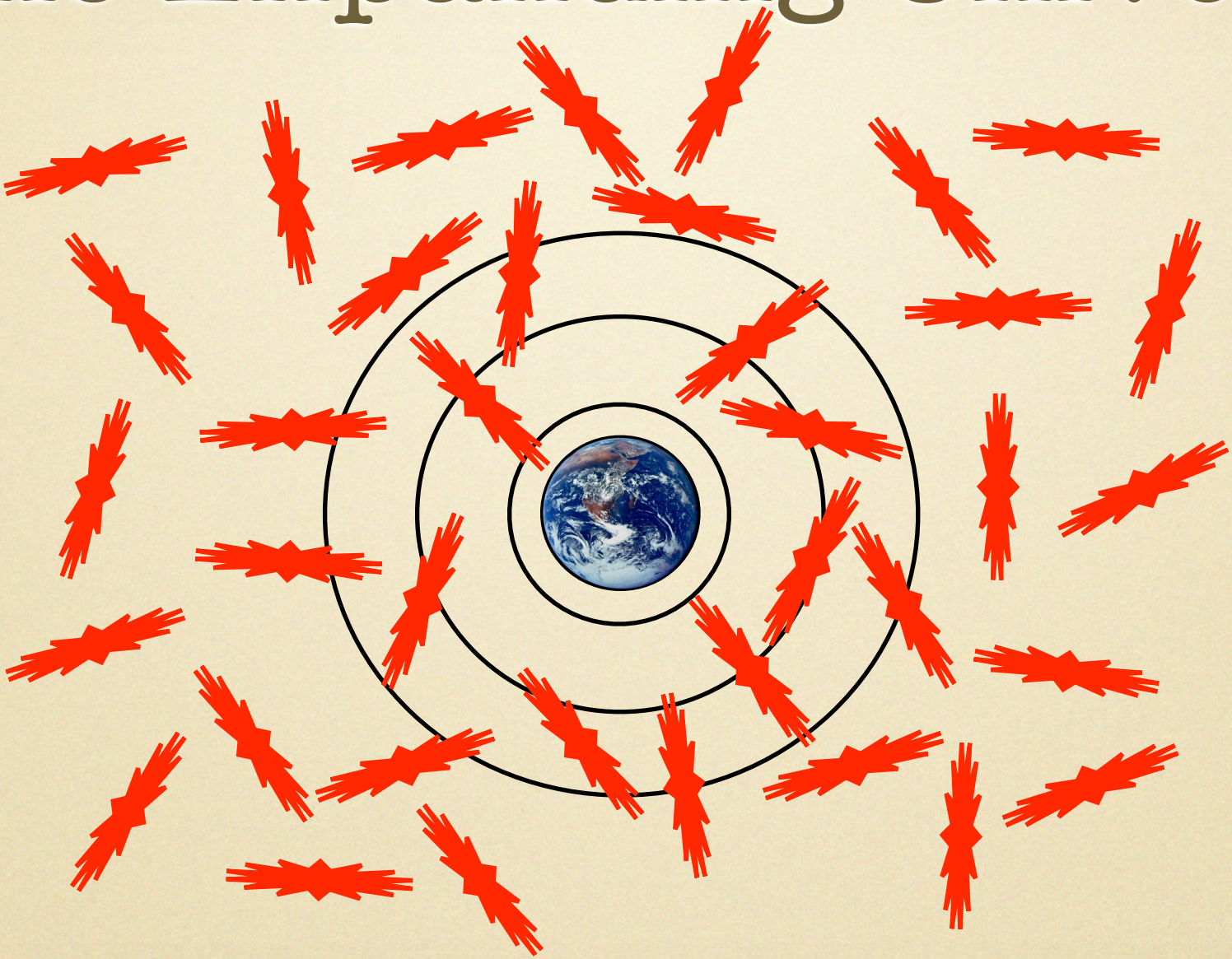


Not Isotropic: There Appears A
"Special" Direction



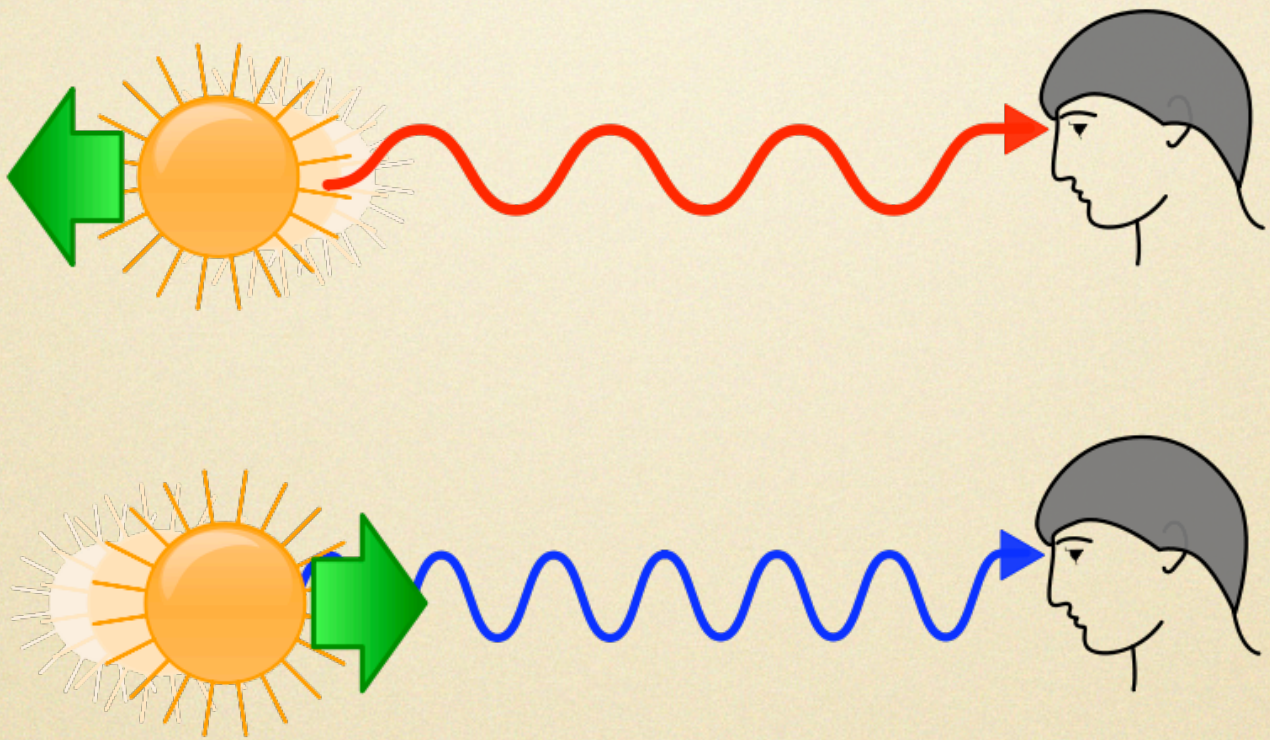
- The Universe Appears Nearly Homogenous and Isotropic on Large Scales

The Expanding Universe



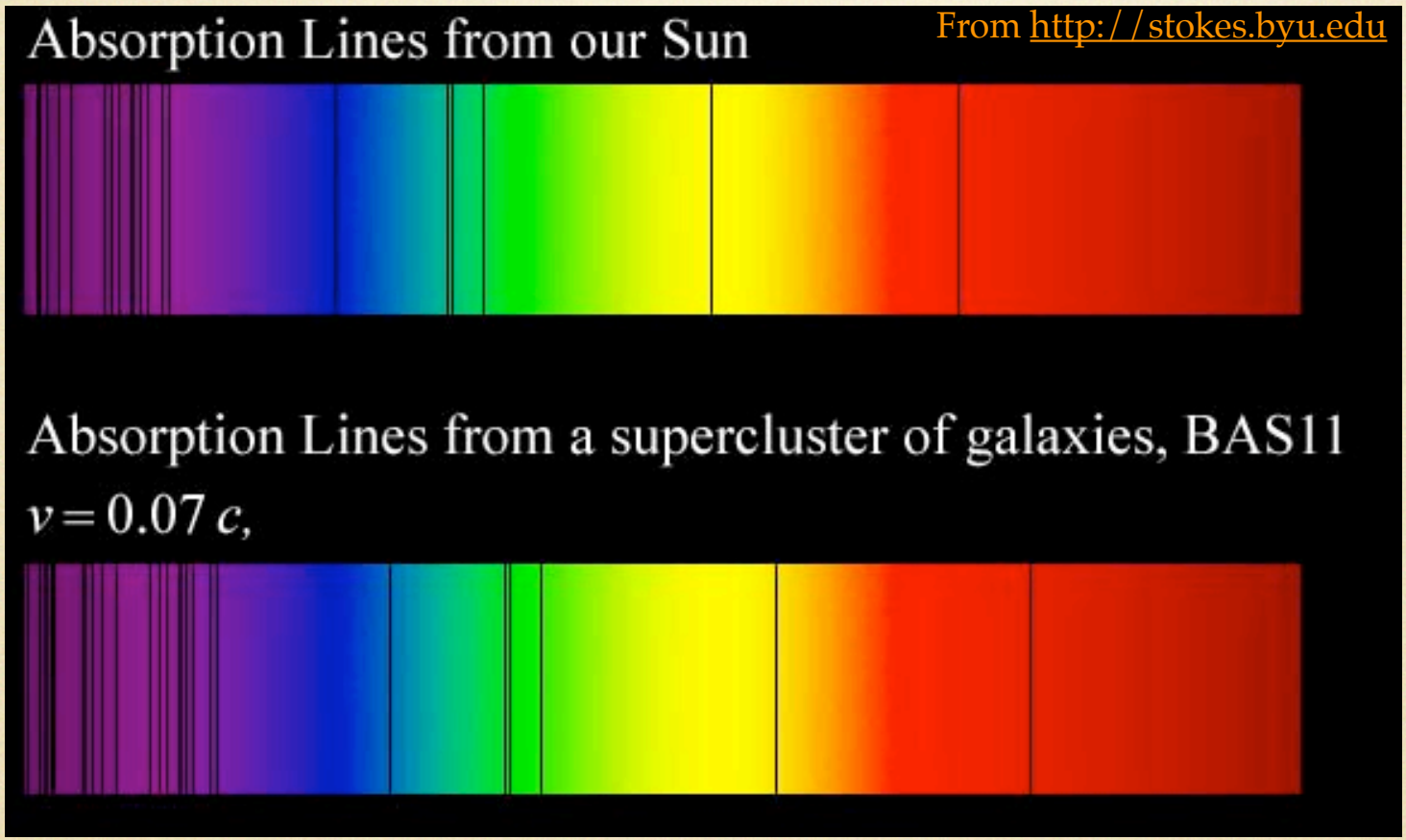
- **The Universe Appears Nearly Homogenous and Isotropic on Large Scales**

The Expanding Universe



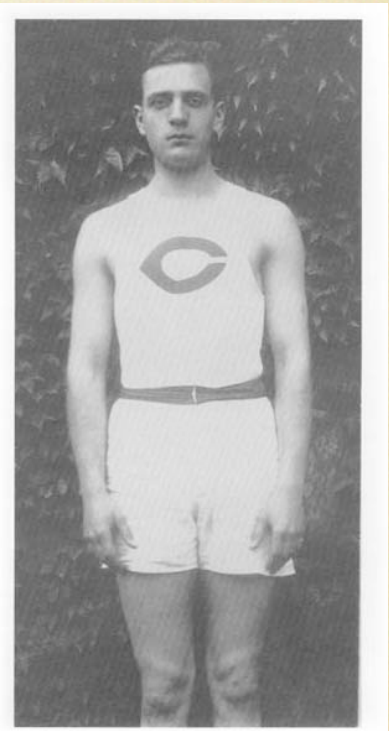
- **Redshift describes the stretching of electromagnetic wavelengths from receding sources**

The Expanding Universe



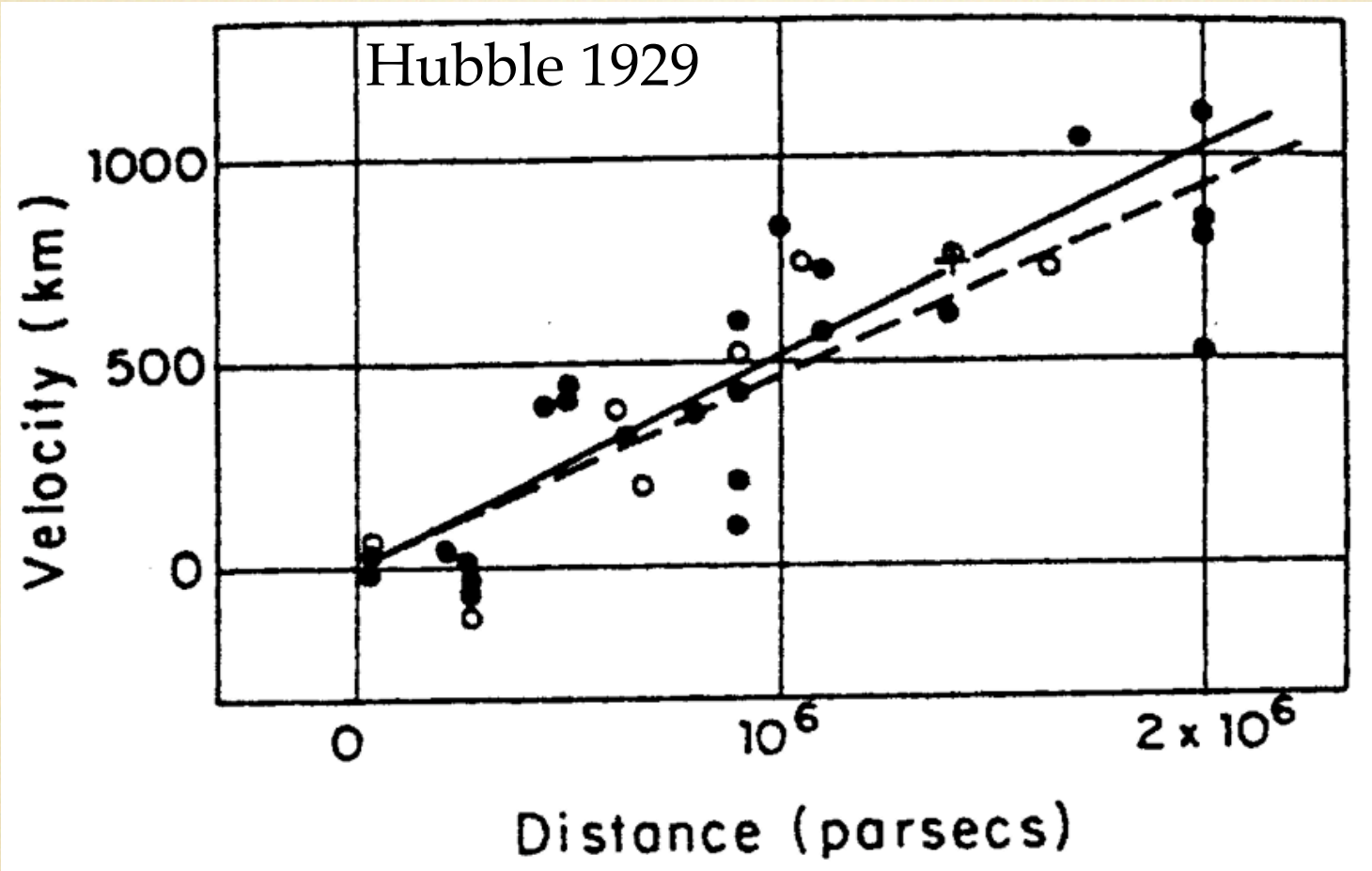
- We measure the redshifts of objects via characteristic patterns in electromagnetic spectra
- The amount of redshift gives the object's speed

The Expanding Universe



- Edwin Hubble made a plot of the distance to galaxies against the velocities that galaxies were receding
- Today the Hubble expansion rate is 22 (km/s) for every million light years of distance

The Expanding Universe



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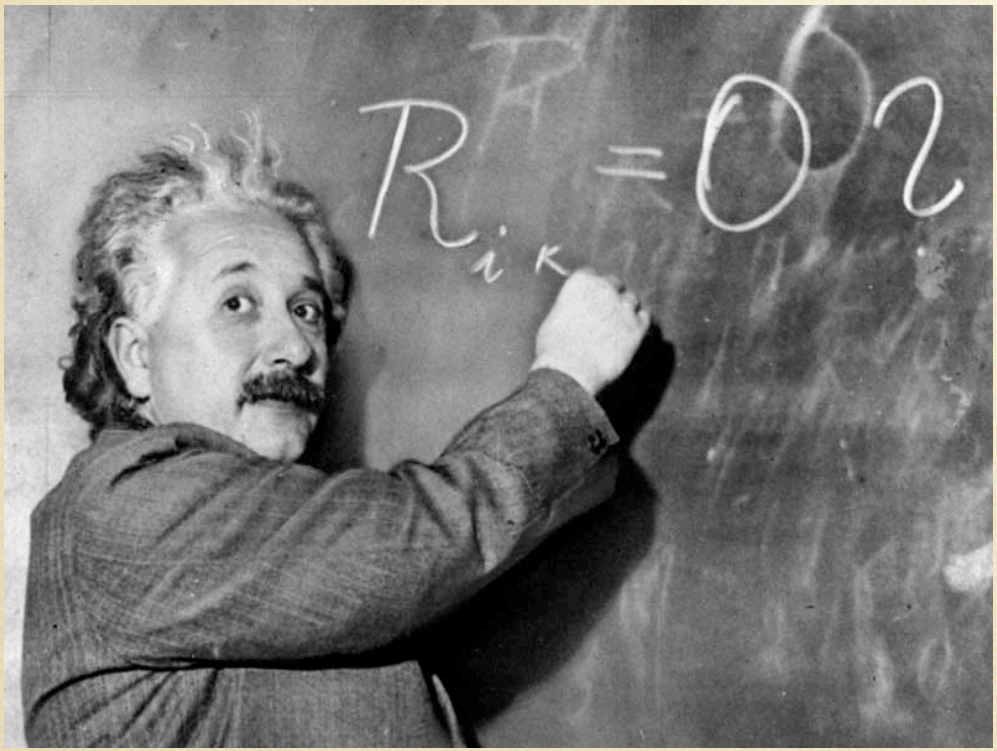
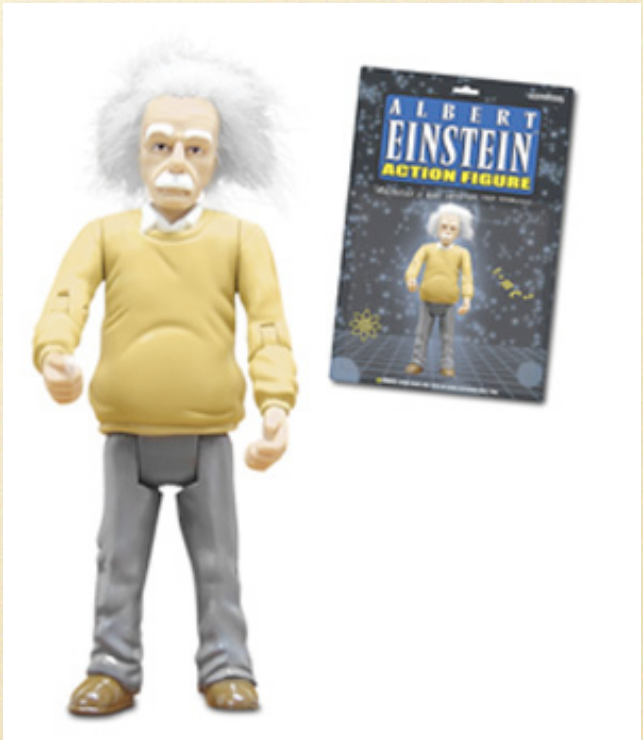
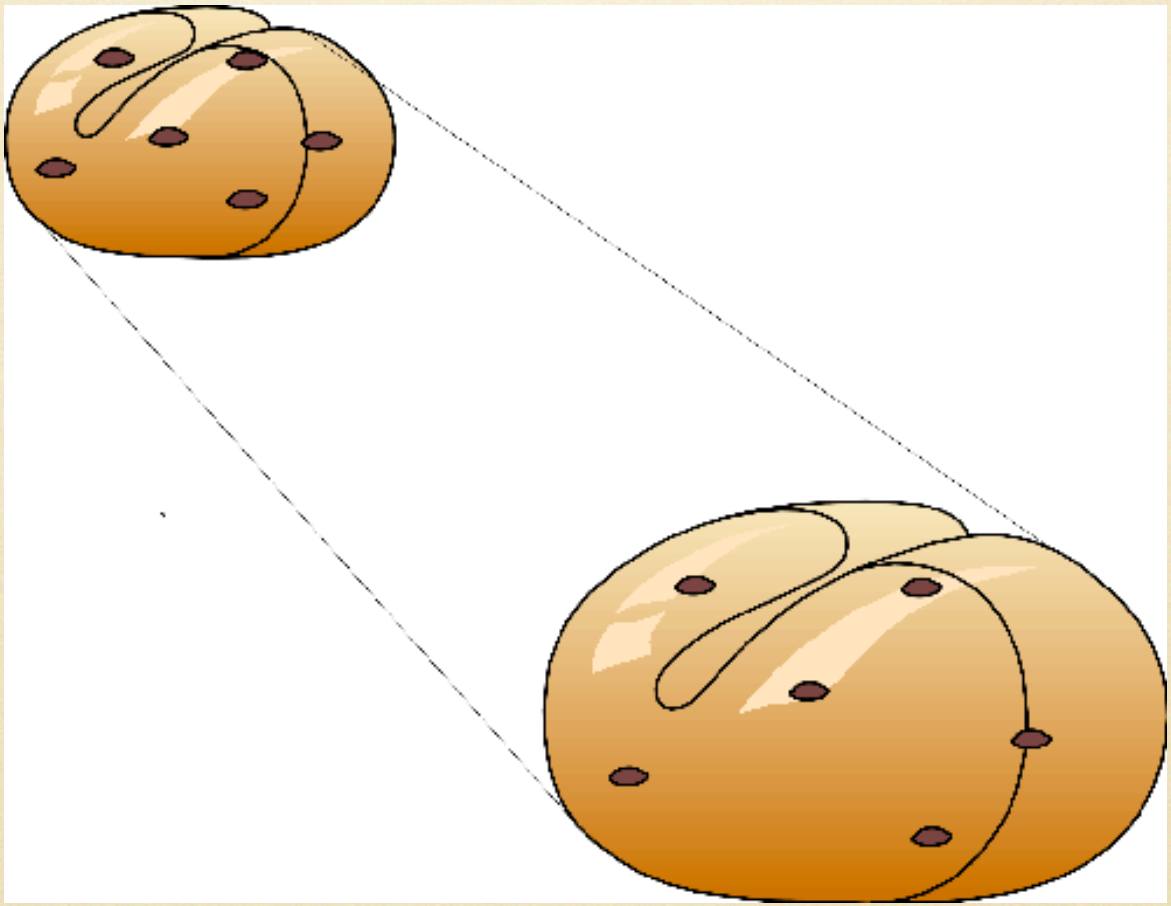




- **Einstein was both pleased and embarrassed by the discovery of the "Hubble Expansion"**

The Expanding Universe

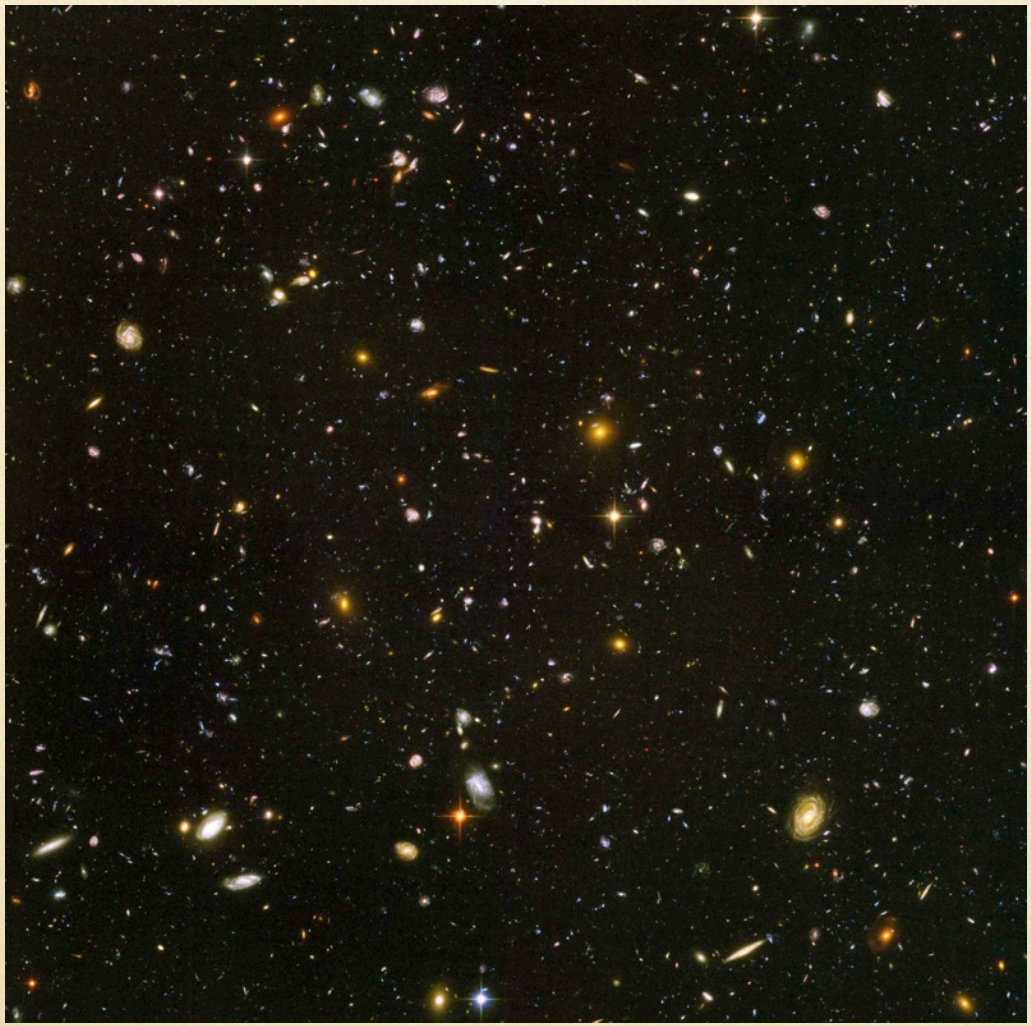


- The Expansion requires no notion of “center”
- All point recede from all other points

The Scale of Cosmology

The Star Closest to the Sun is 4 light-years away, about 24,000,000,000,000 miles

The Scale of Cosmology



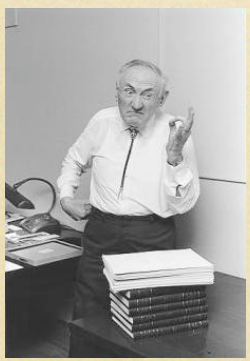
Hubble Space Telescope
http://hst.nasa.gov

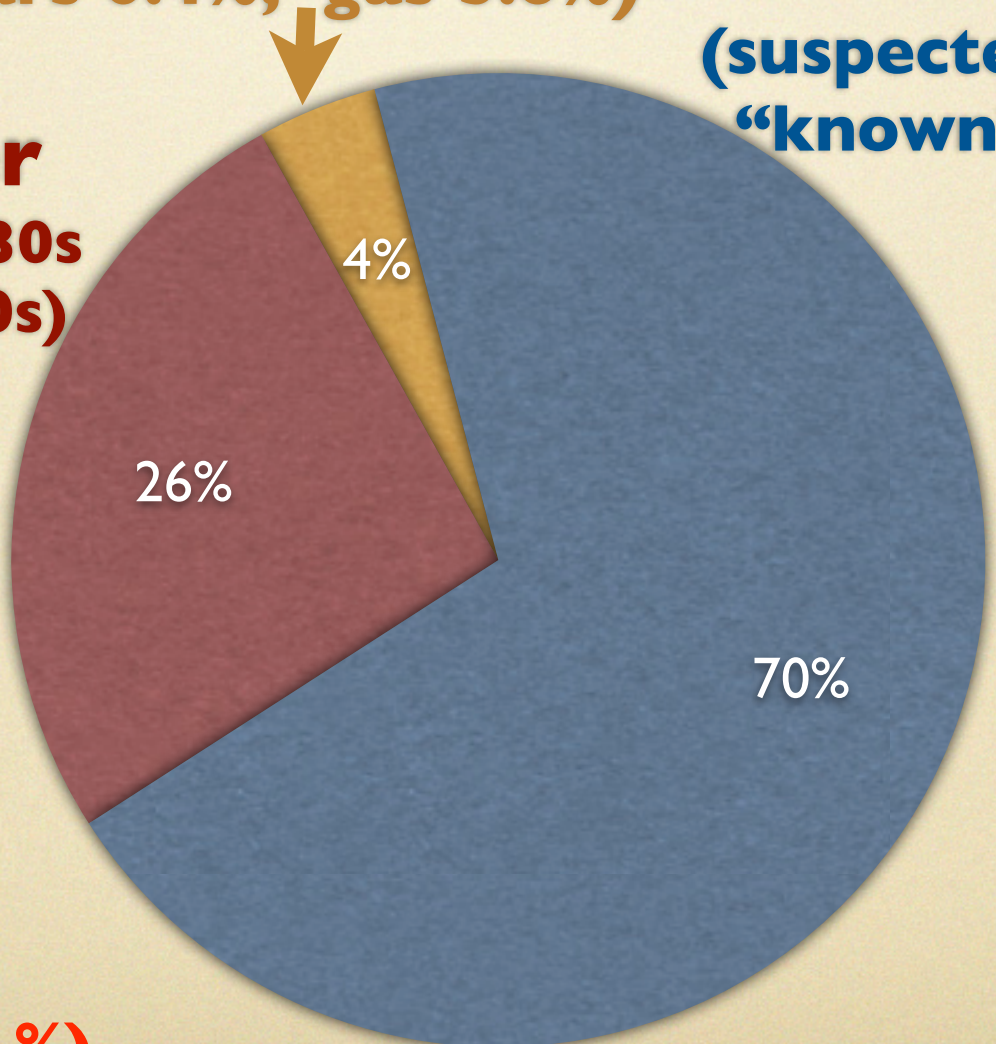
Most Distant Galaxies are ~
200,000,000,000,000,000,000,000 or 2×10^{23}
miles away ~ ten of Billions of light years

The Contents of the Universe

Normal Matter
(stars 0.4%, gas 3.6%)

Dark Matter
(suspected since 30s
"known" since 70s)





"Dark Energy"
(suspected since 1980s
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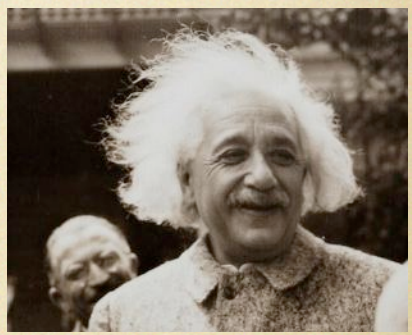

Also Ran:
Radiation (0.01%)

The Contents of the Universe

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Dark Matter
(suspected since 30s
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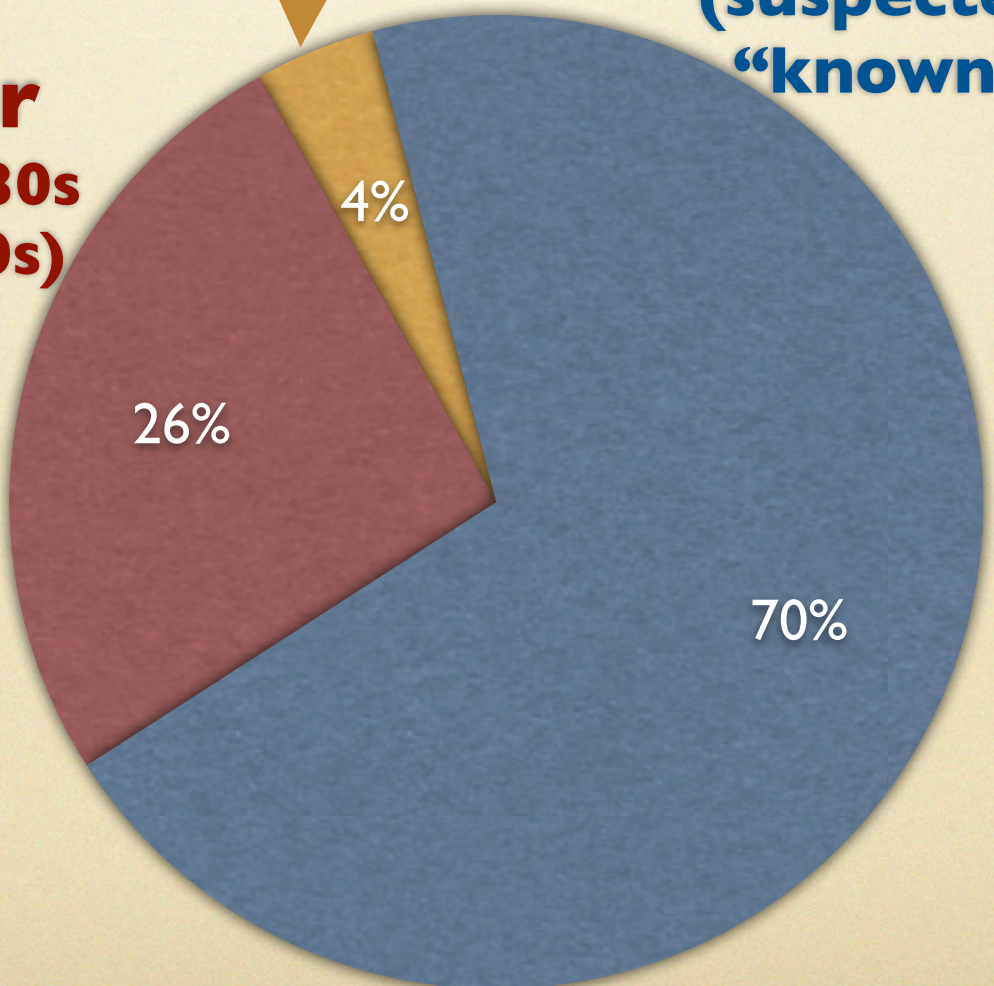
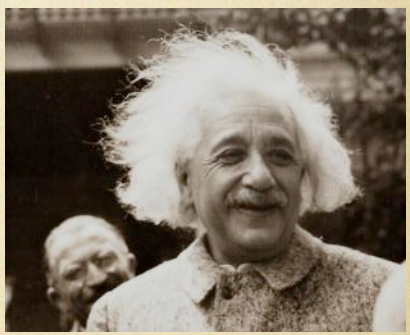
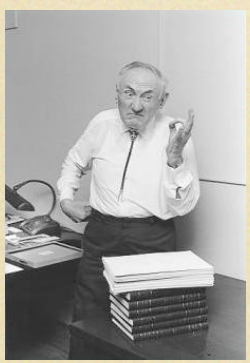


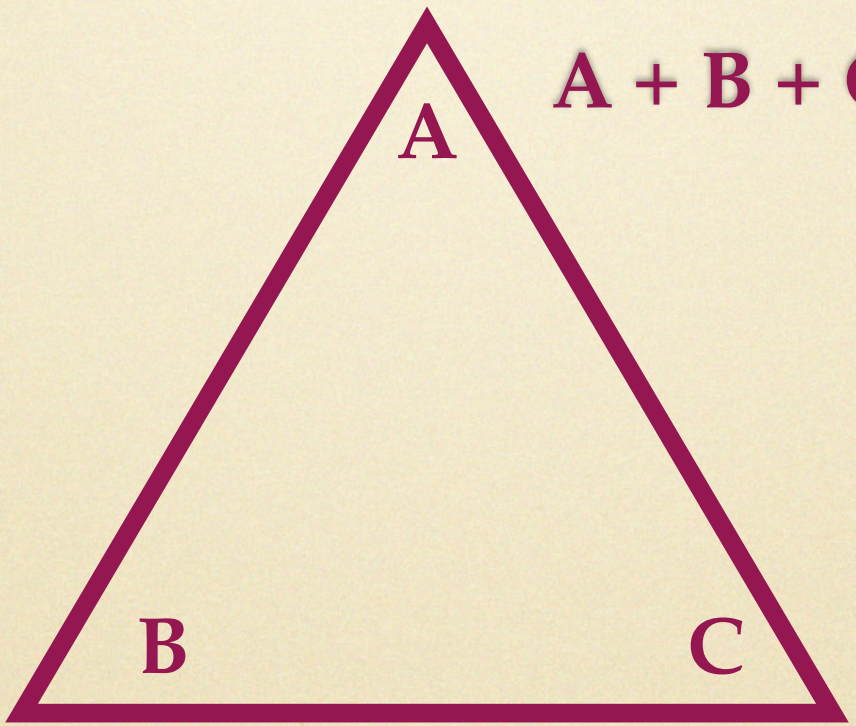




The Geometry of the Universe

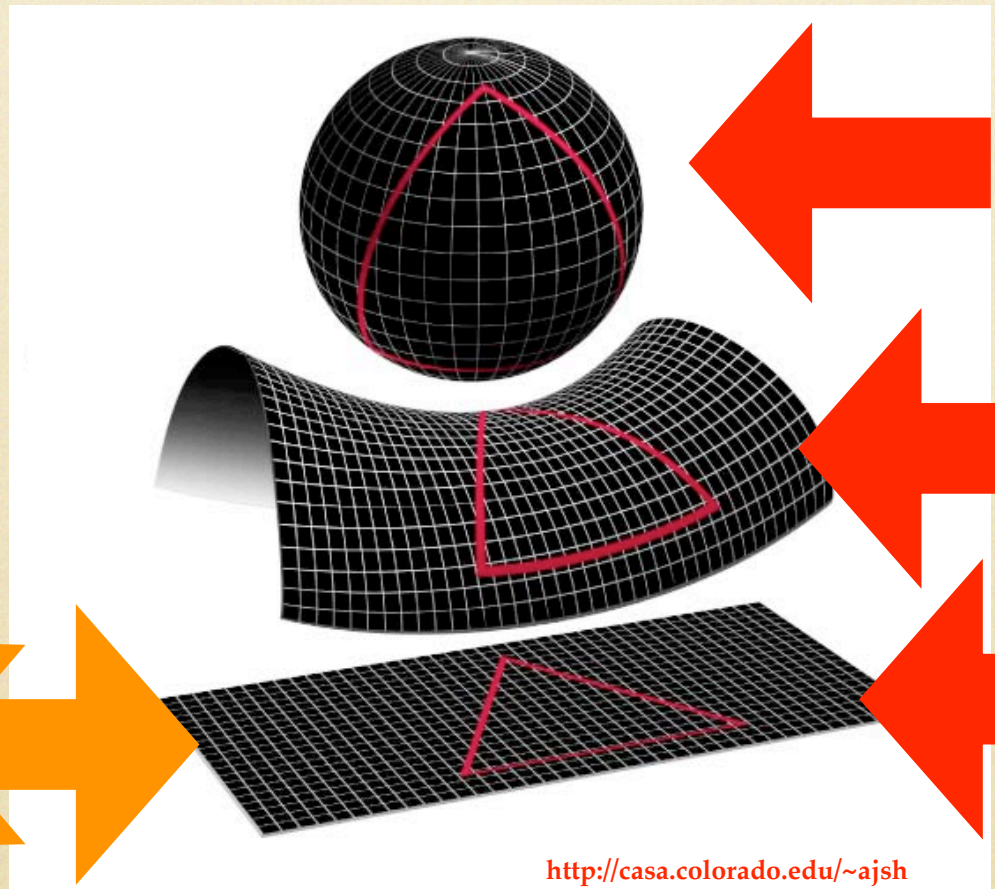
- **Three Options**
  - **The Universe Can Be "Flat"**
  - **The Universe Can Be "Open"**
  - **The Universe Can Be "Closed"**

The Geometry of the Universe



- The Flat Geometry is Familiar
- The angles of a triangle sum to 180°

The Geometry of the Universe



Closed: Angles Sum To > 180°

Open: Angles Sum To < 180°

FLAT (EUCLIDEAN)

Our Universe

The Contents of the Universe

Normal Matter

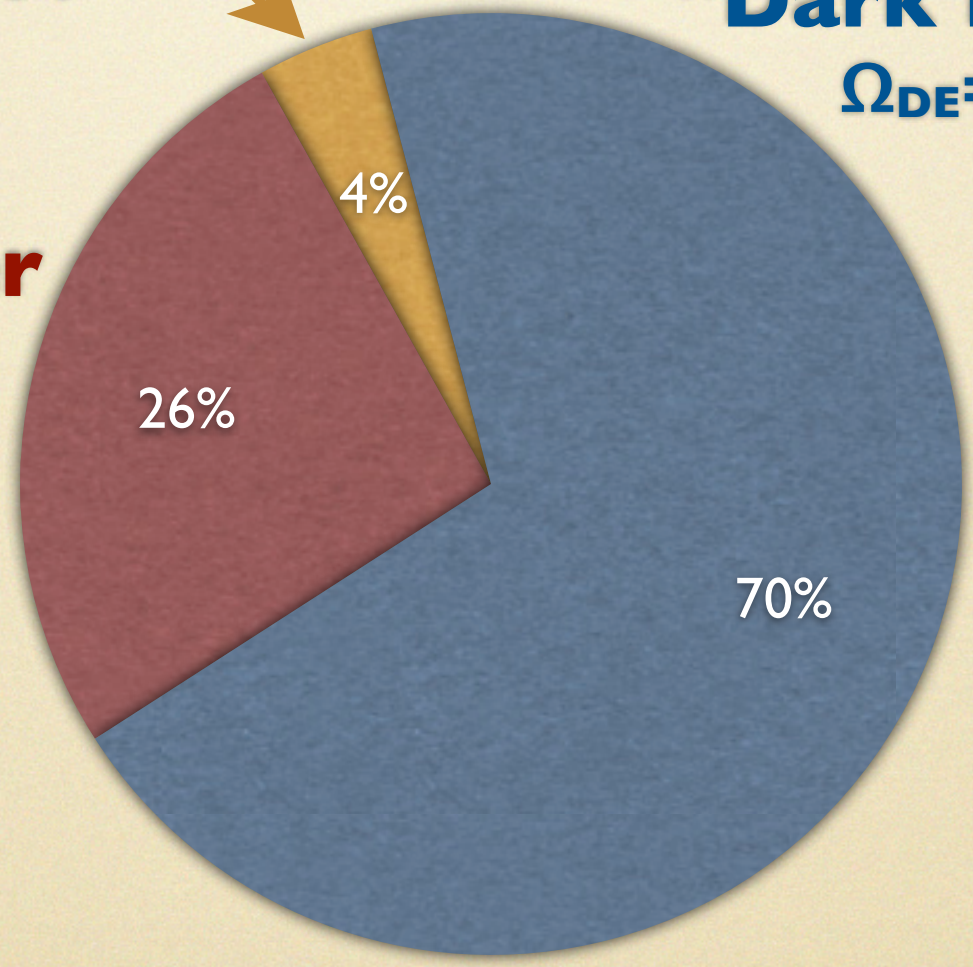
$\Omega_{BARYON} = 0.04$

"Dark Energy"

$\Omega_{DE}=0.70$

Dark Matter

$\Omega_{DM} = 0.26$

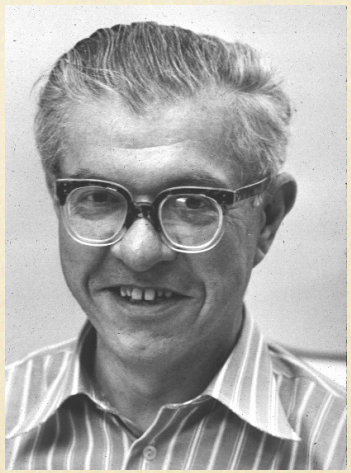


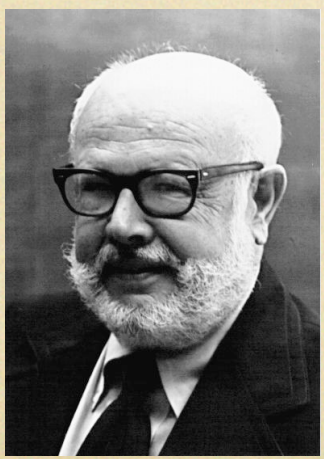
- The Universe is FLAT When $\Omega_{BARYON} + \Omega_{DM} + \Omega_{DE} = 1$

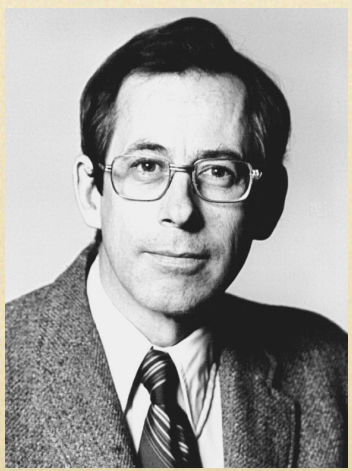
How Do We Know This?

- The Synthesis of the Light Nuclei
- The Cosmic Microwave Background Spectrum

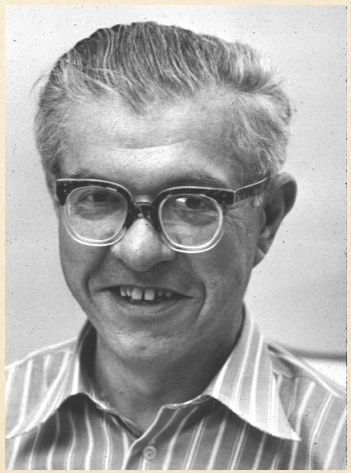
Synthesis of the Light Nuclei

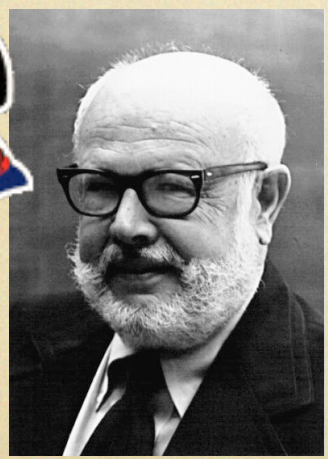


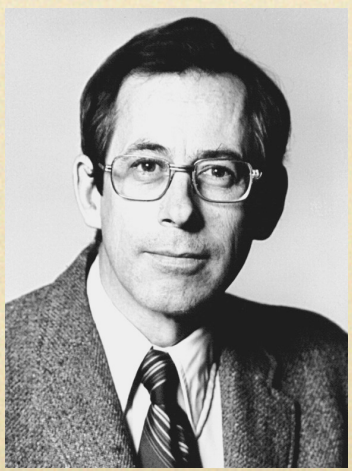




Synthesis of the Light Nuclei







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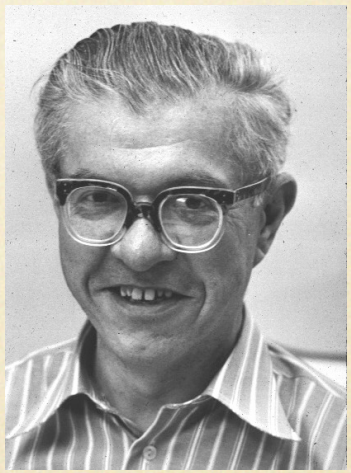

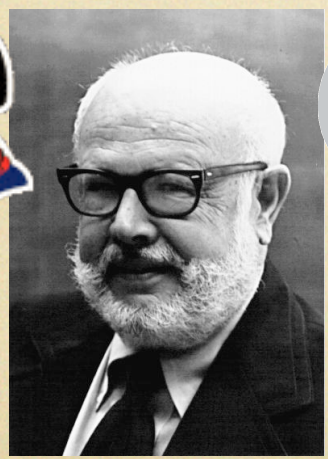

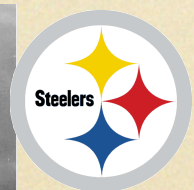

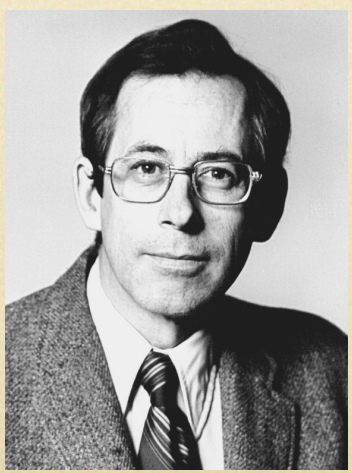

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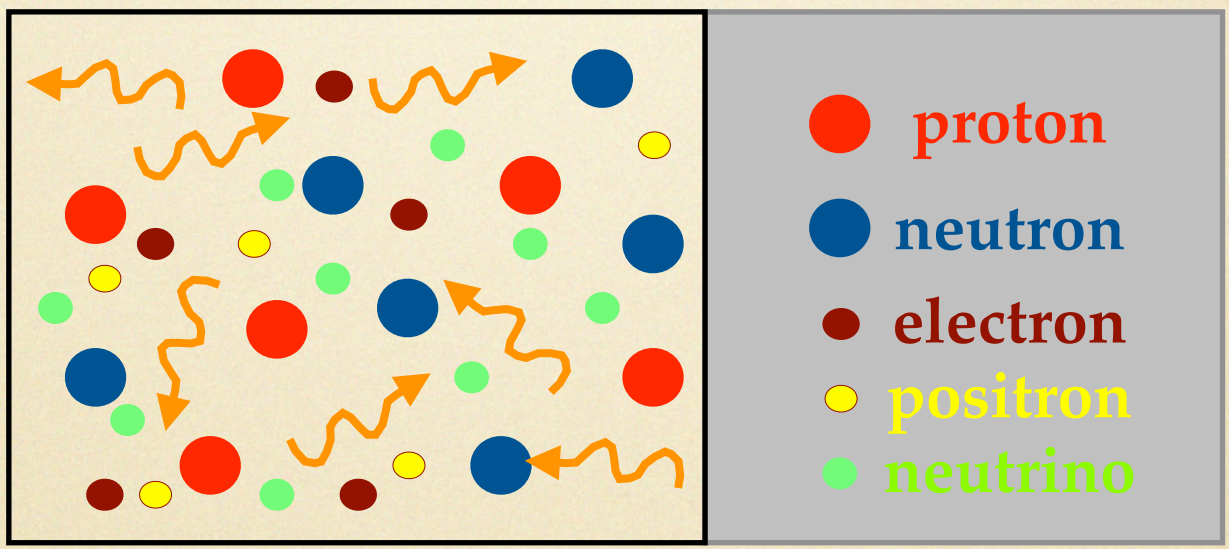
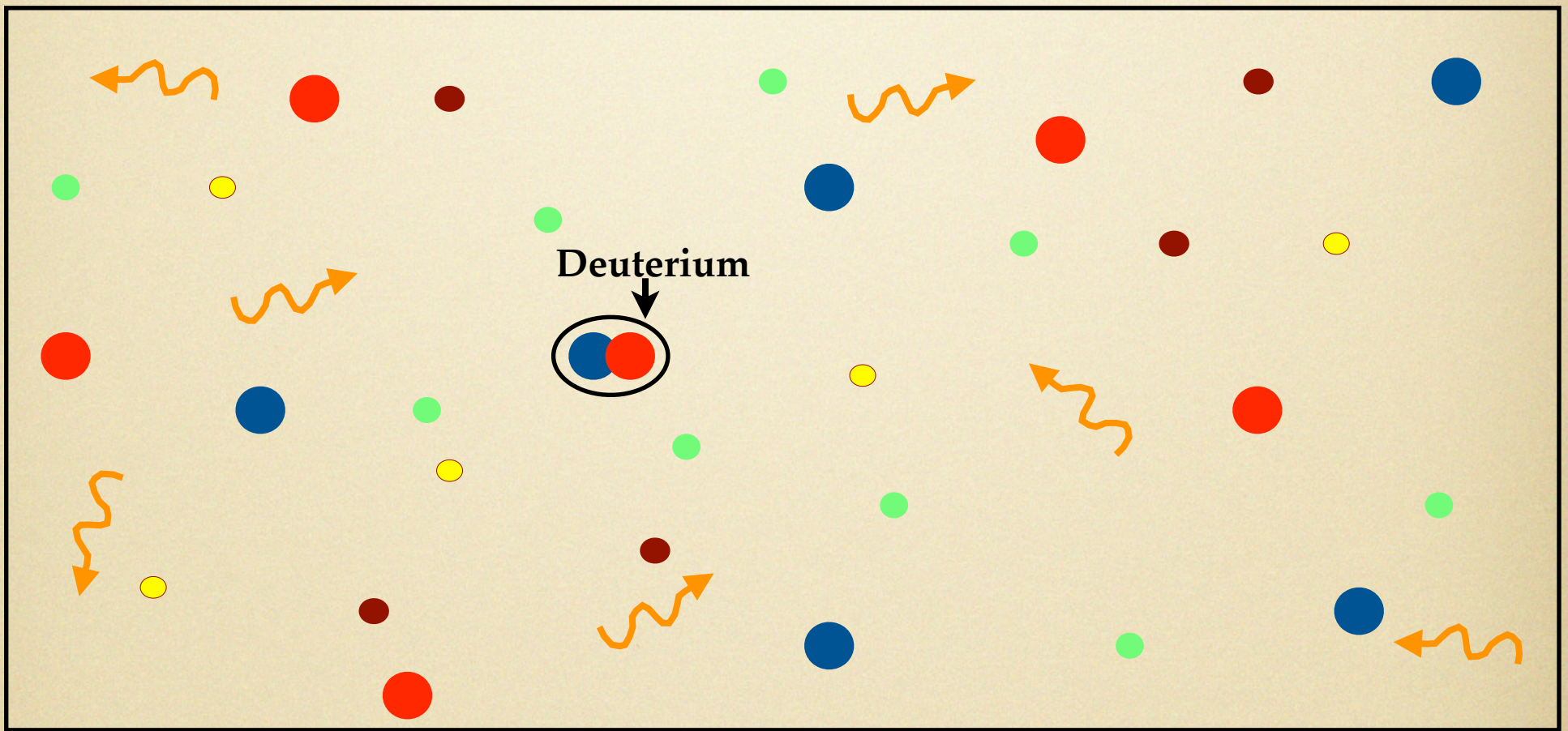


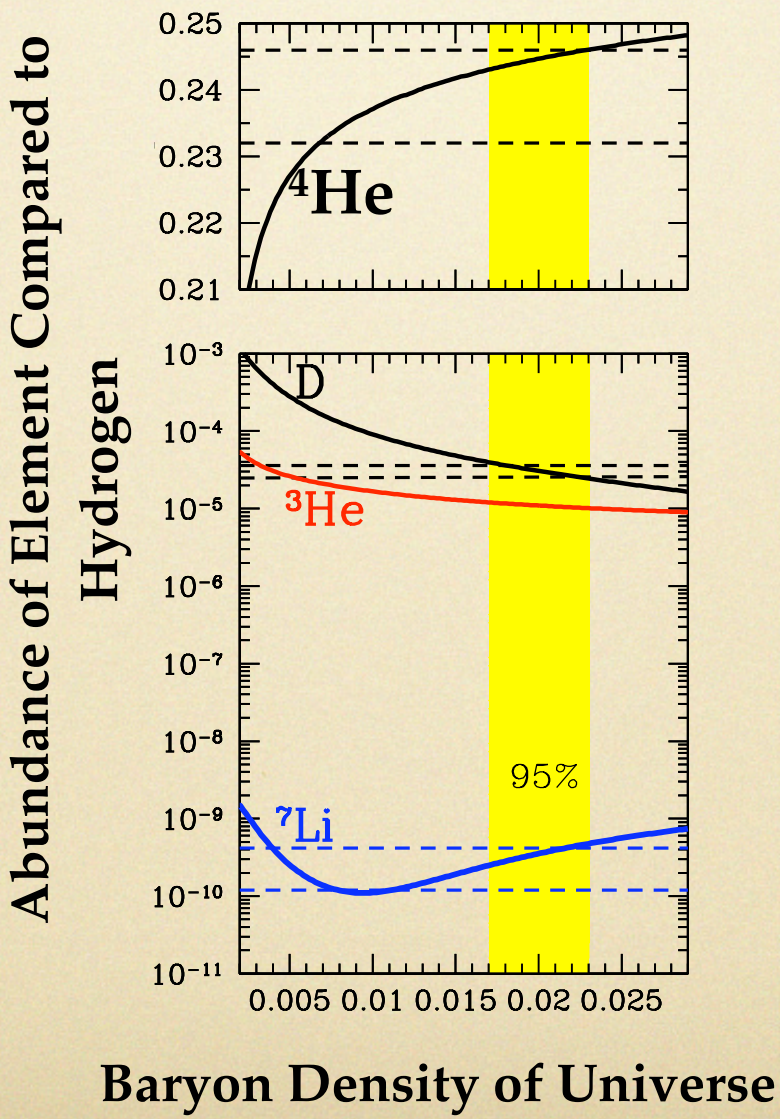
- In the very early universe (t < 1 second)
  - Densities are very high & interactions happen very quickly
  - The weak interactions interconvert protons and neutrons
  - Equilibrium is maintained while interactions are rapid

Synthesis of the Light Nuclei

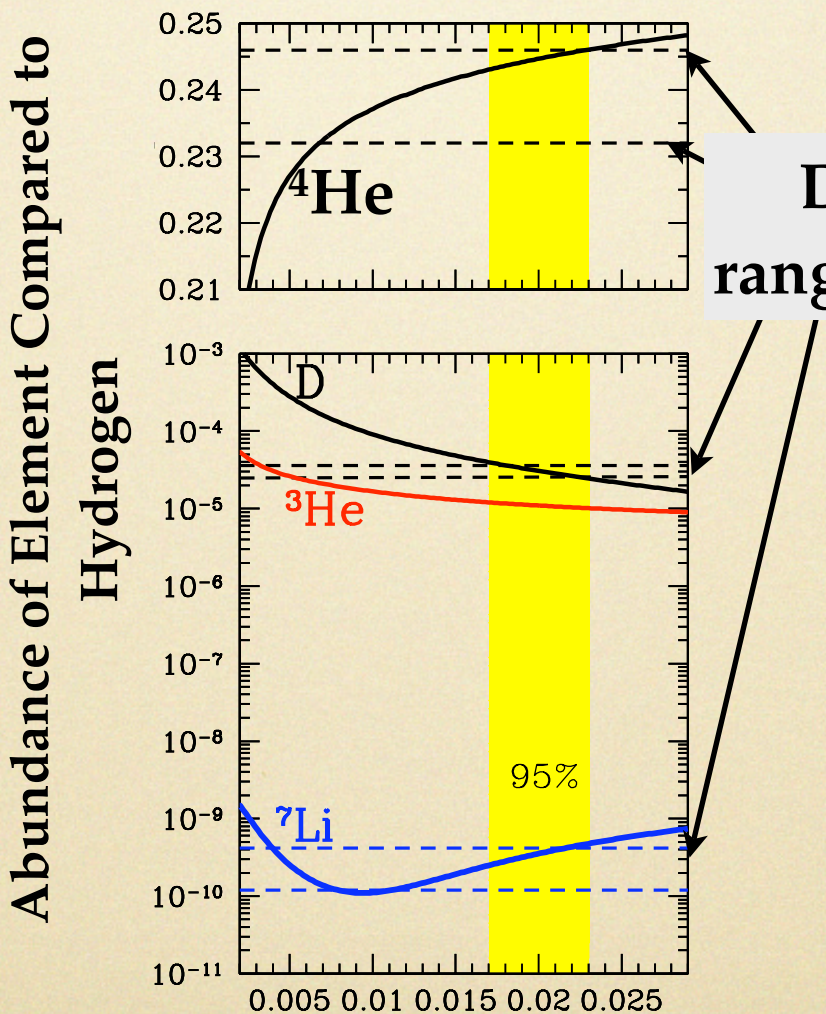


- The Universe expands, cools, and interactions freeze out
- Equilibrium is lost and residual neutrons are incorporated into Deuterium, Helium, & Lithium by t=20 minutes

Abundance of Light Nuclei



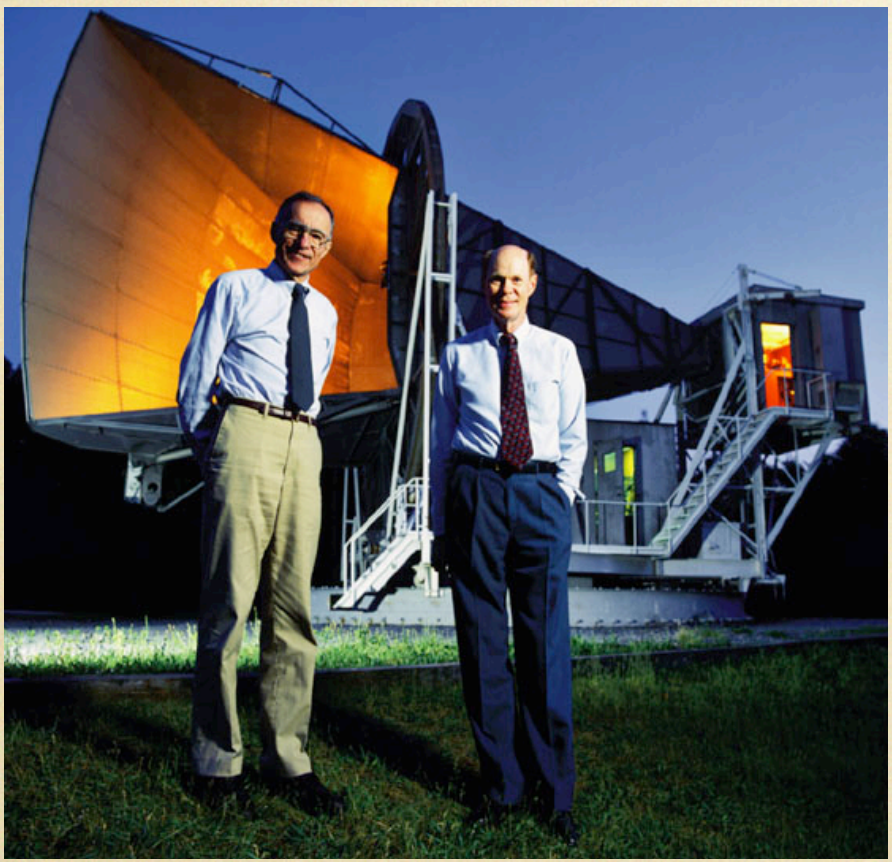
Abundance of Light Nuclei

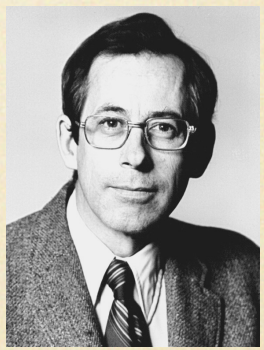


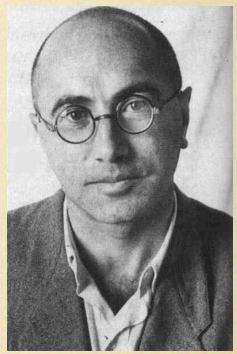
Dashed lines show range of observed values

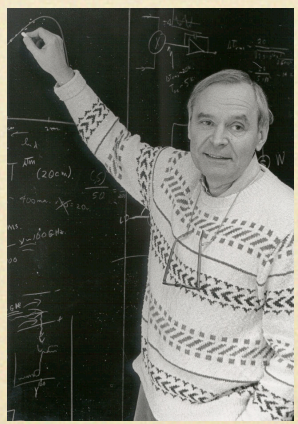
Forward 400,000 years

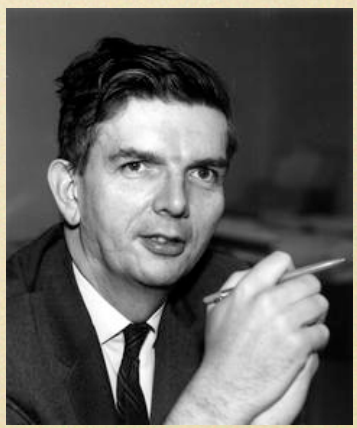
The Cosmic Microwave Background











The Cosmic Microwave Background

We deeply appreciate the helpfulness of Drs. Penzias and Wilson of the Bell Telephone Laboratories, Crawford Hill, Holmdel, New Jersey, in discussing with us the result of their measurements and in showing us their receiving system. We are also grateful for several helpful suggestions of Professor J. A. Wheeler.

R. H. Dicke
P. J. E. Peebles
P. G. Roll
D. T. Wilkinson

May 7, 1965
Palmer Physical Laboratory
Princeton, New Jersey

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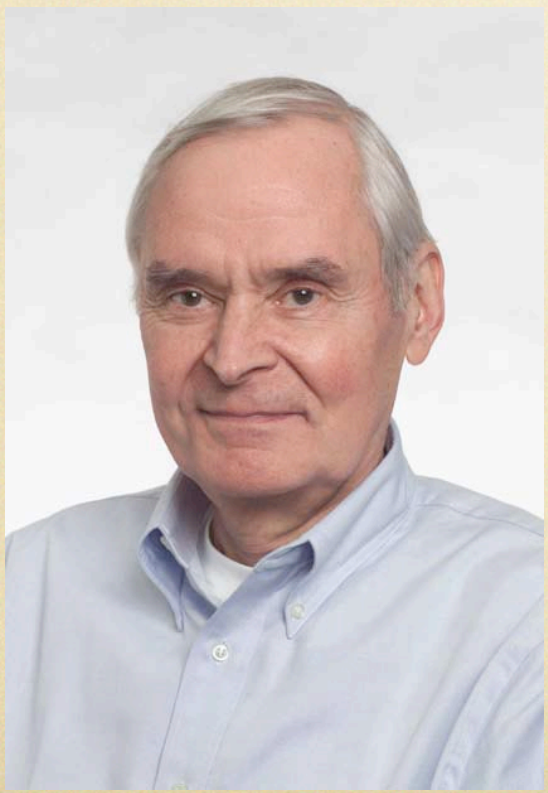
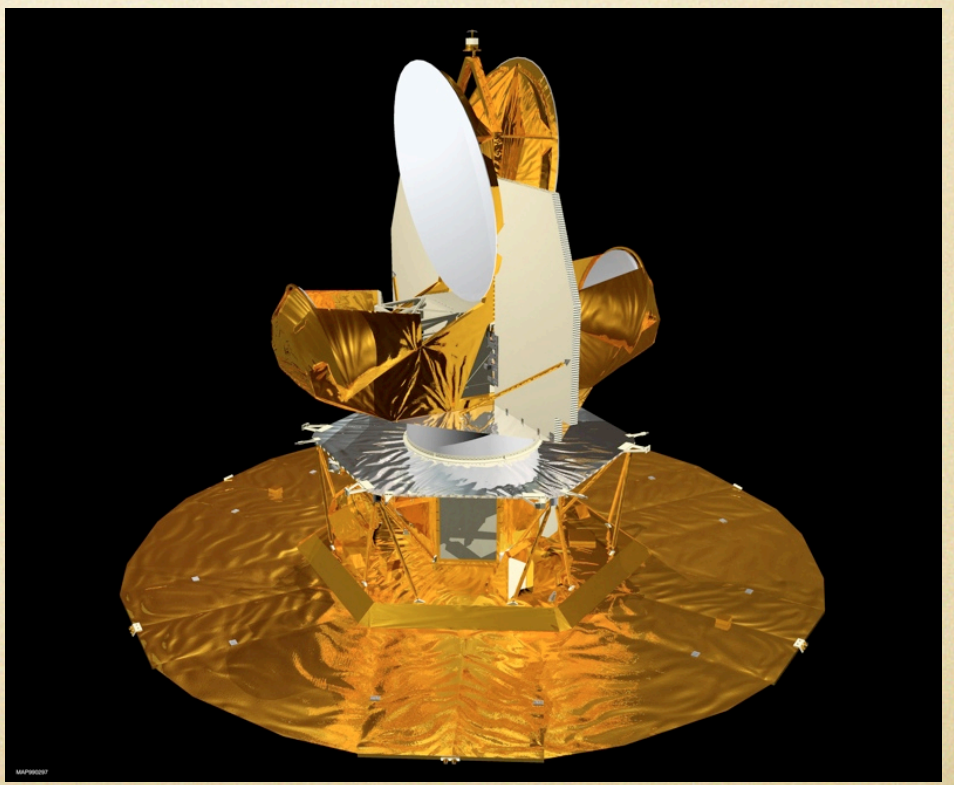
A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

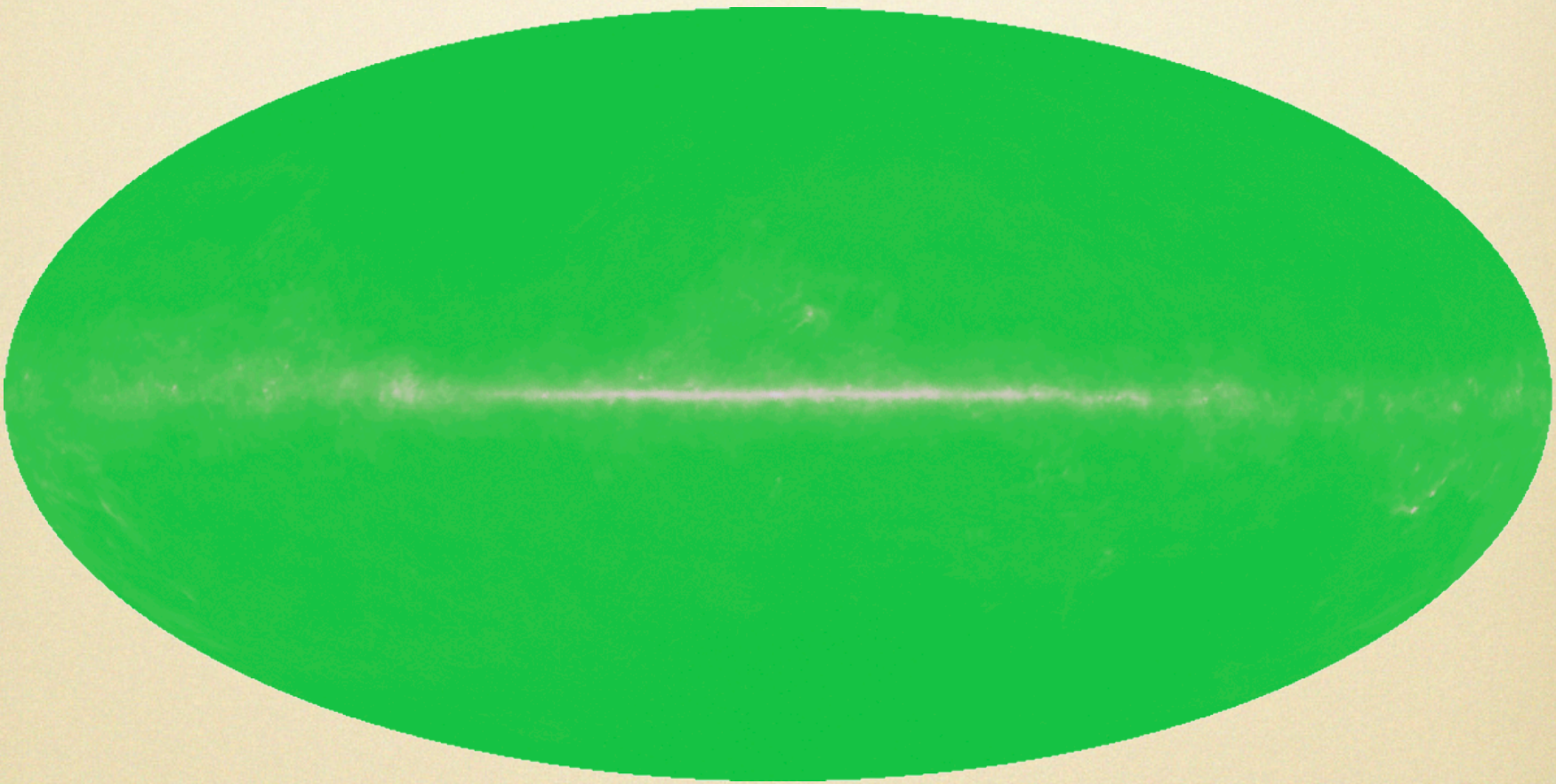
The Wilkinson Microwave Anisotropy Probe





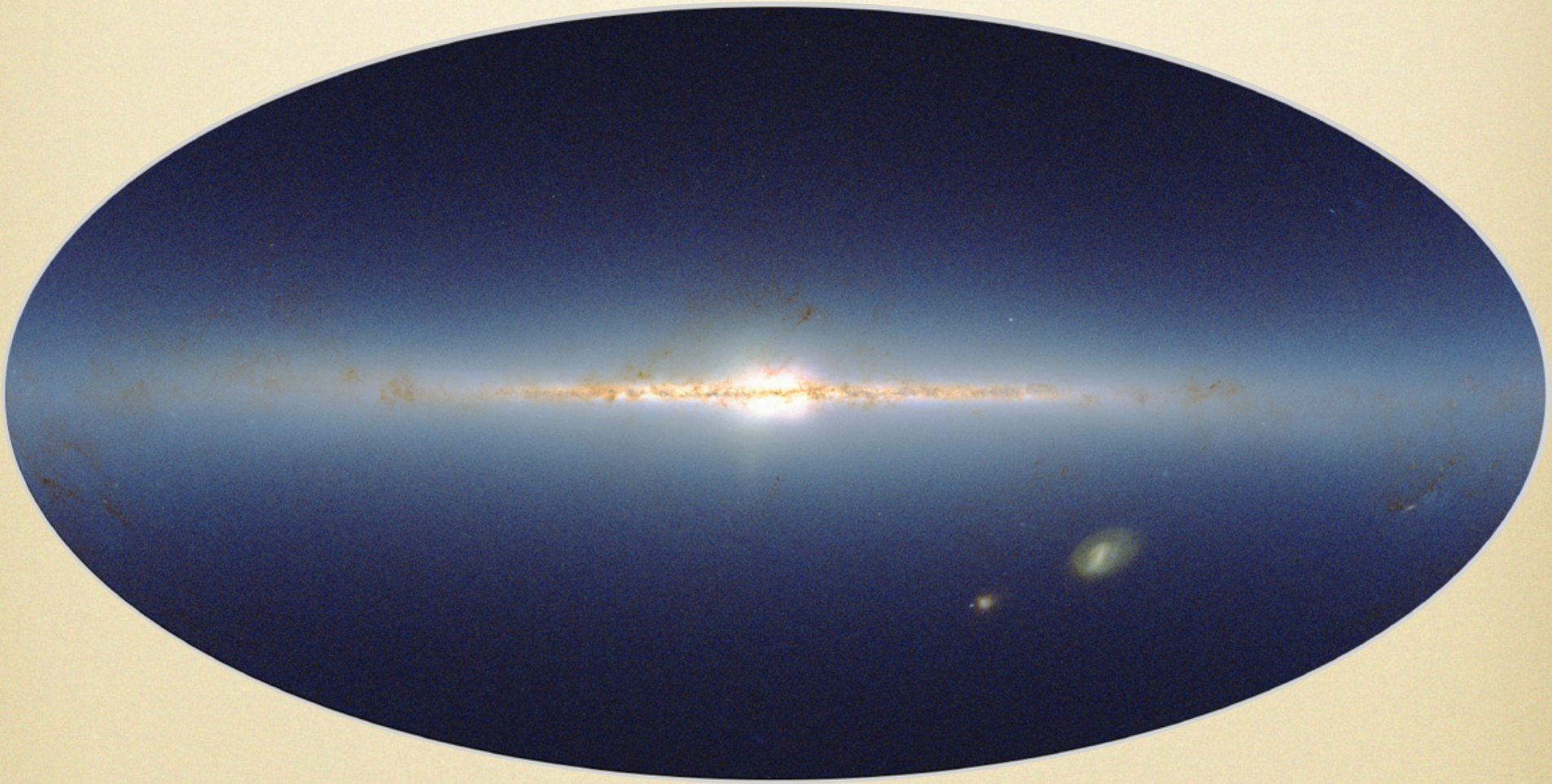
http://map.gsfc.nasa.gov

The Cosmic Microwave Background



- A Map of the CMB on the sky is extremely smooth
- The CMB has a thermal spectrum with T=2.726 K = -454.7 °F

The Cosmic Microwave Background



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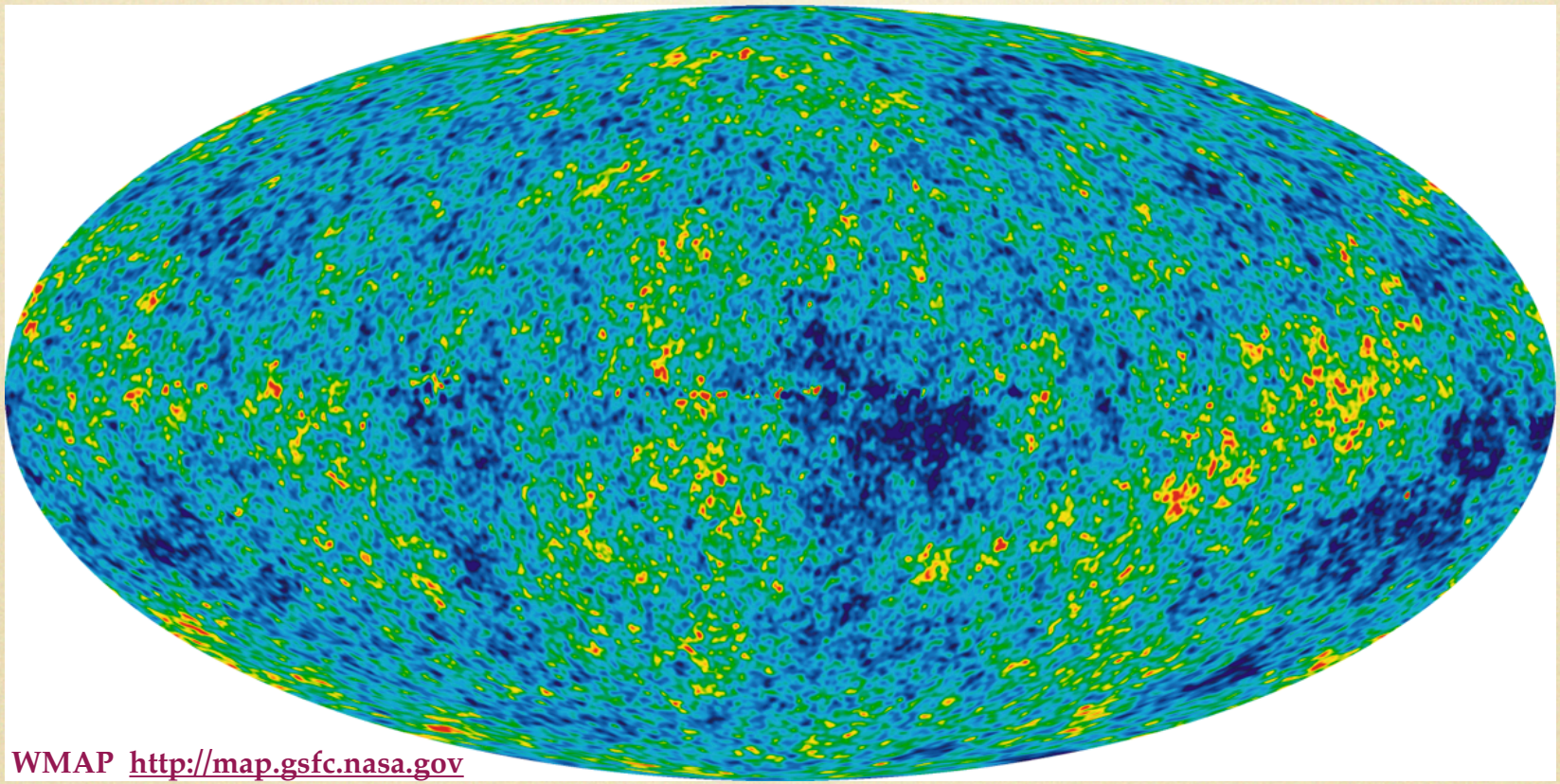
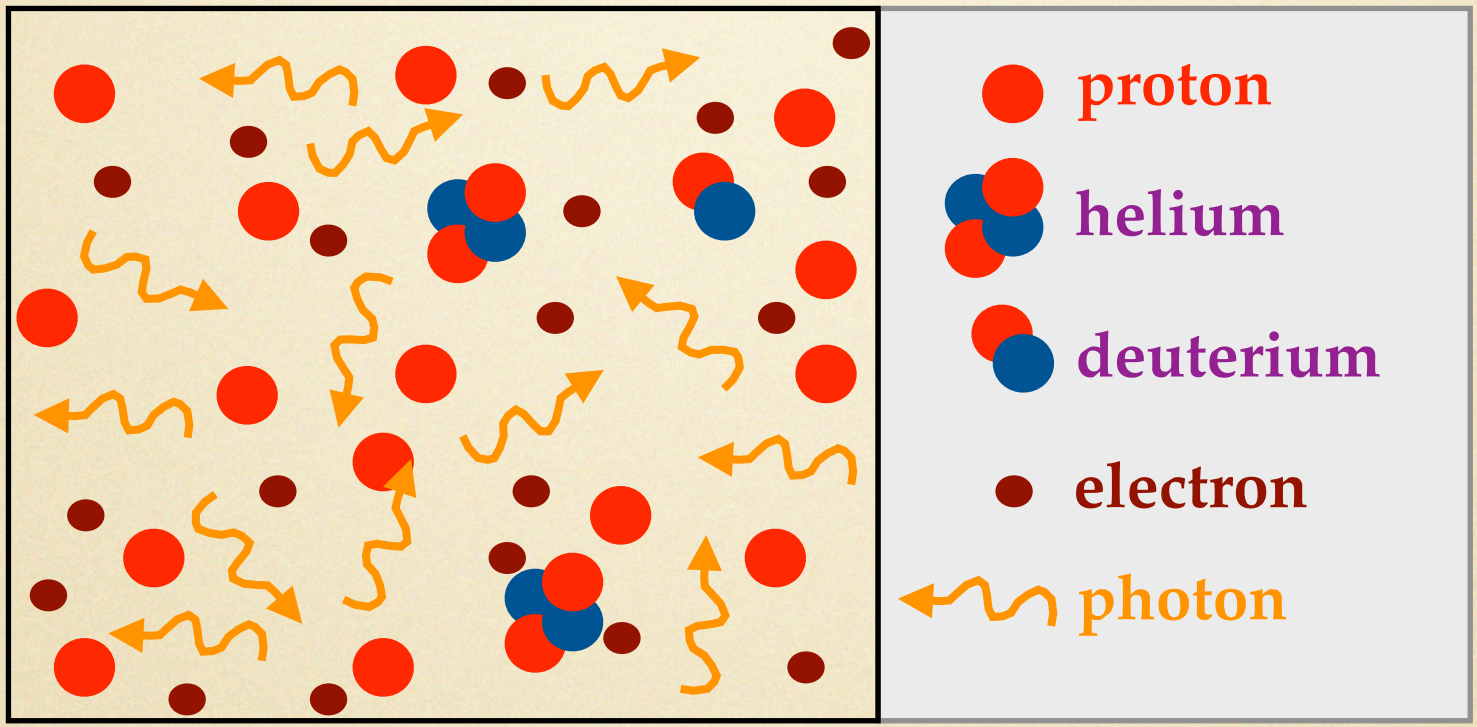


WMAP http://map.gsfc.nasa.gov

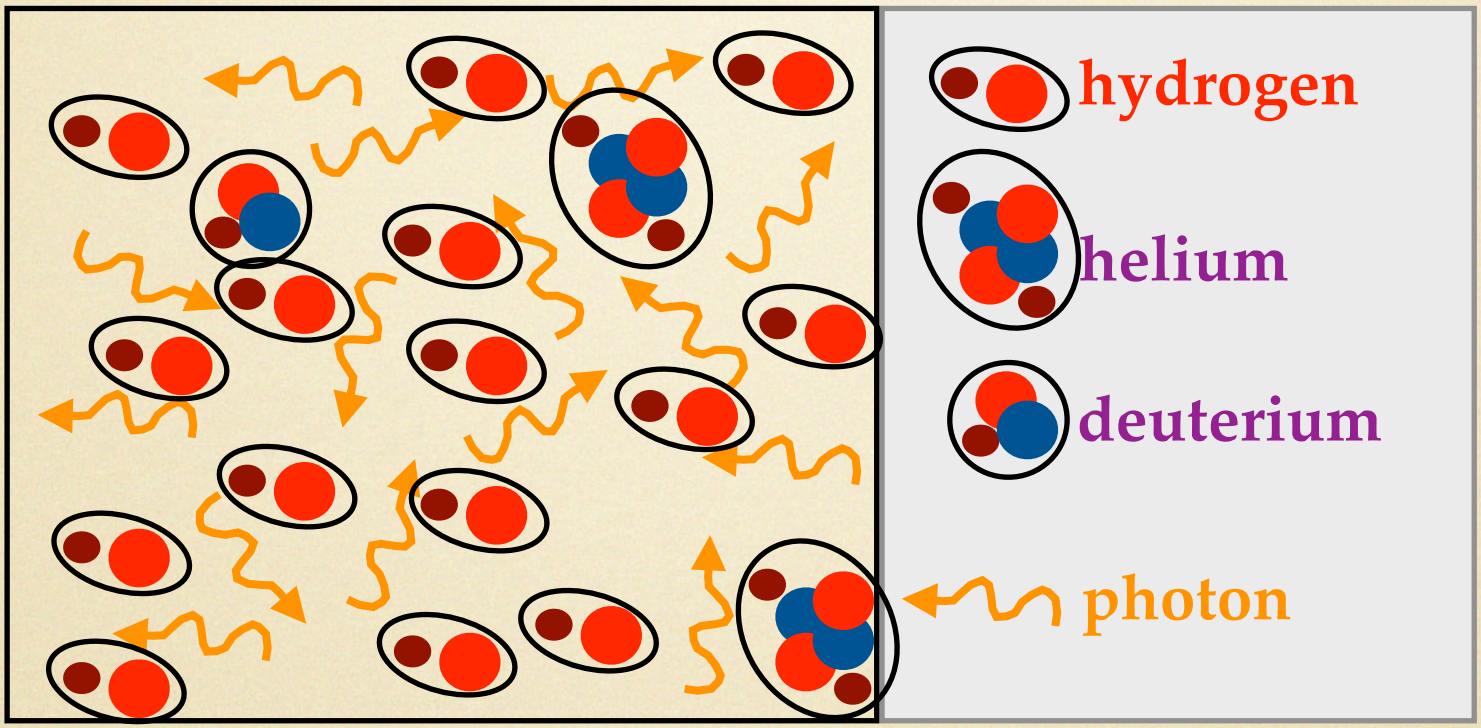
- Turning up the contrast on the map reveals fluctuations of 1 part in 100,000 or temperature changes of ~ 0.00003 K

Producing the CMB



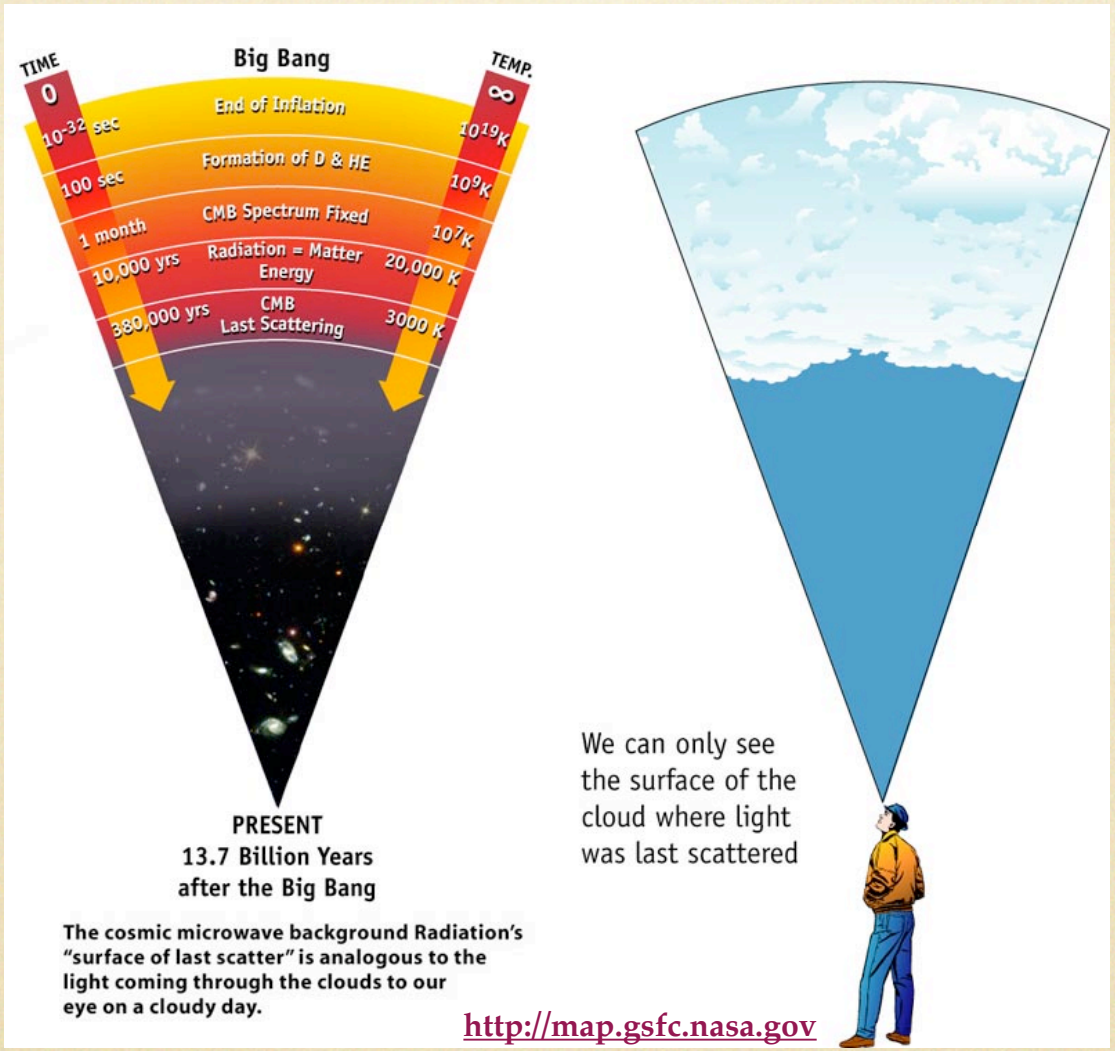
- In the Early Universe, temperatures are high
- Electrons cannot join protons (or Helium nuclei) to form atoms because photons are energetic enough to knock them off
- Photons don't travel far before interacting

Producing the CMB



- When the temperature drops, energies are not high enough to prevent electrons from joining nuclei to form atoms
- Photons no longer interact with the electrically-neutral medium and they move freely through the universe from then on

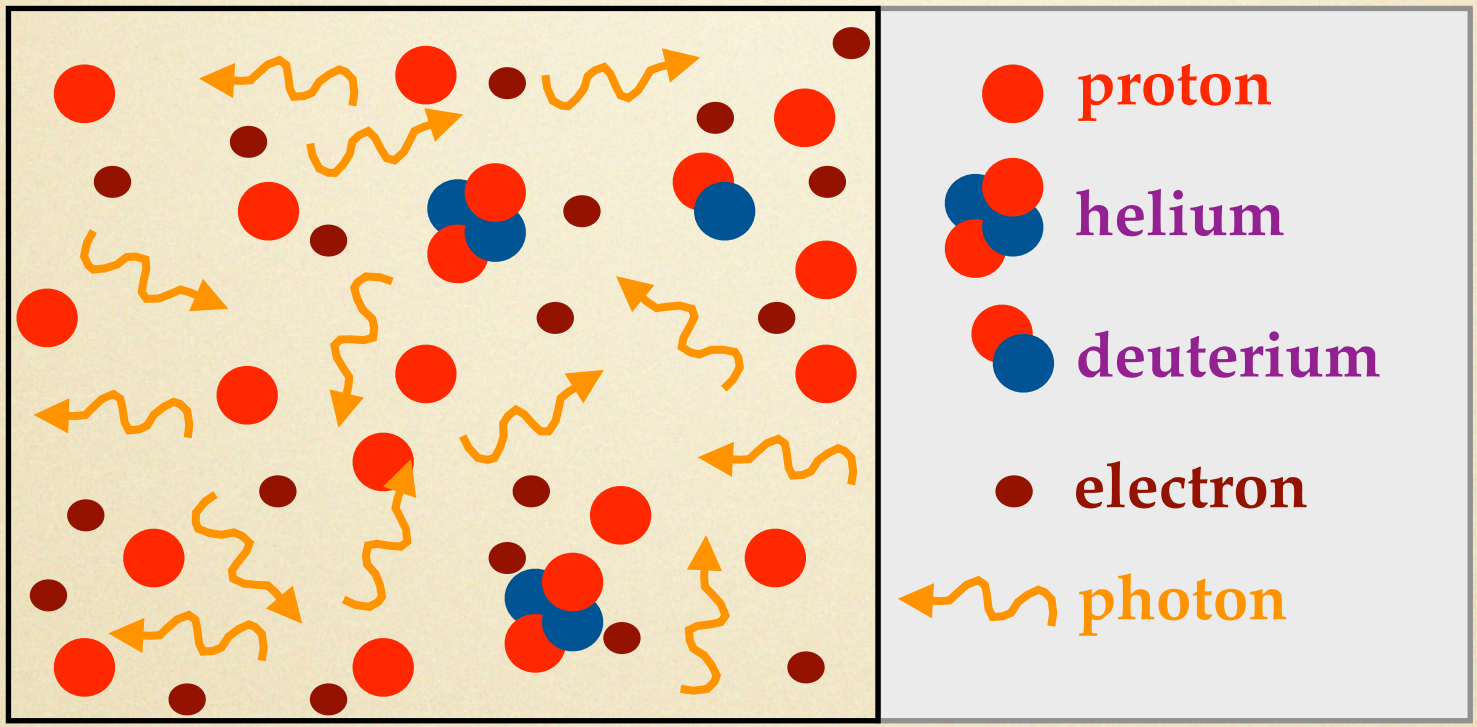
Observing the CMB



- This Cosmic Microwave Background light transmits an image of the infant universe frozen as it was at decoupling

Observing the CMB

http://background.uchicago.edu/~whu



- In the early universe the gravity of density fluctuations tries to compress dense patches
- The pressure of the photons pushes back
- This results in small oscillations in the local density and temperature

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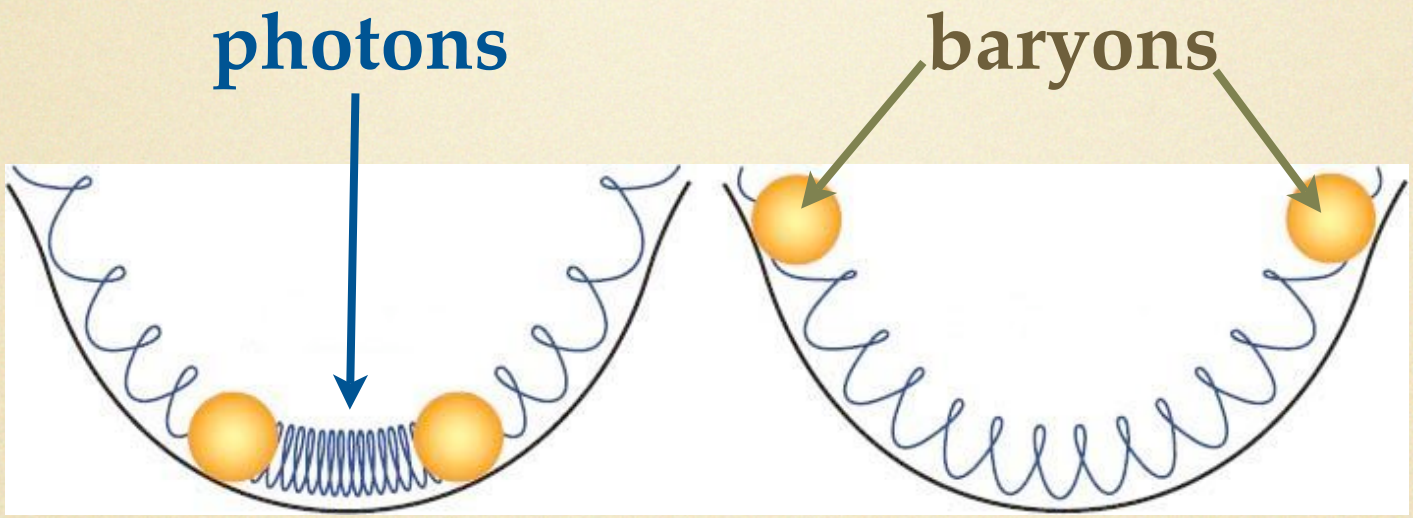

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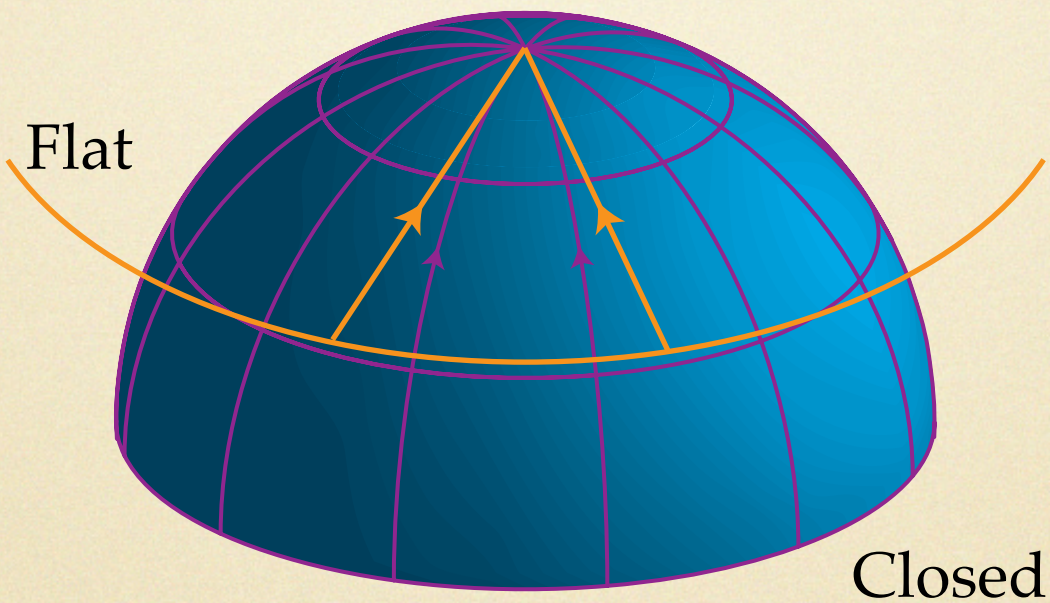
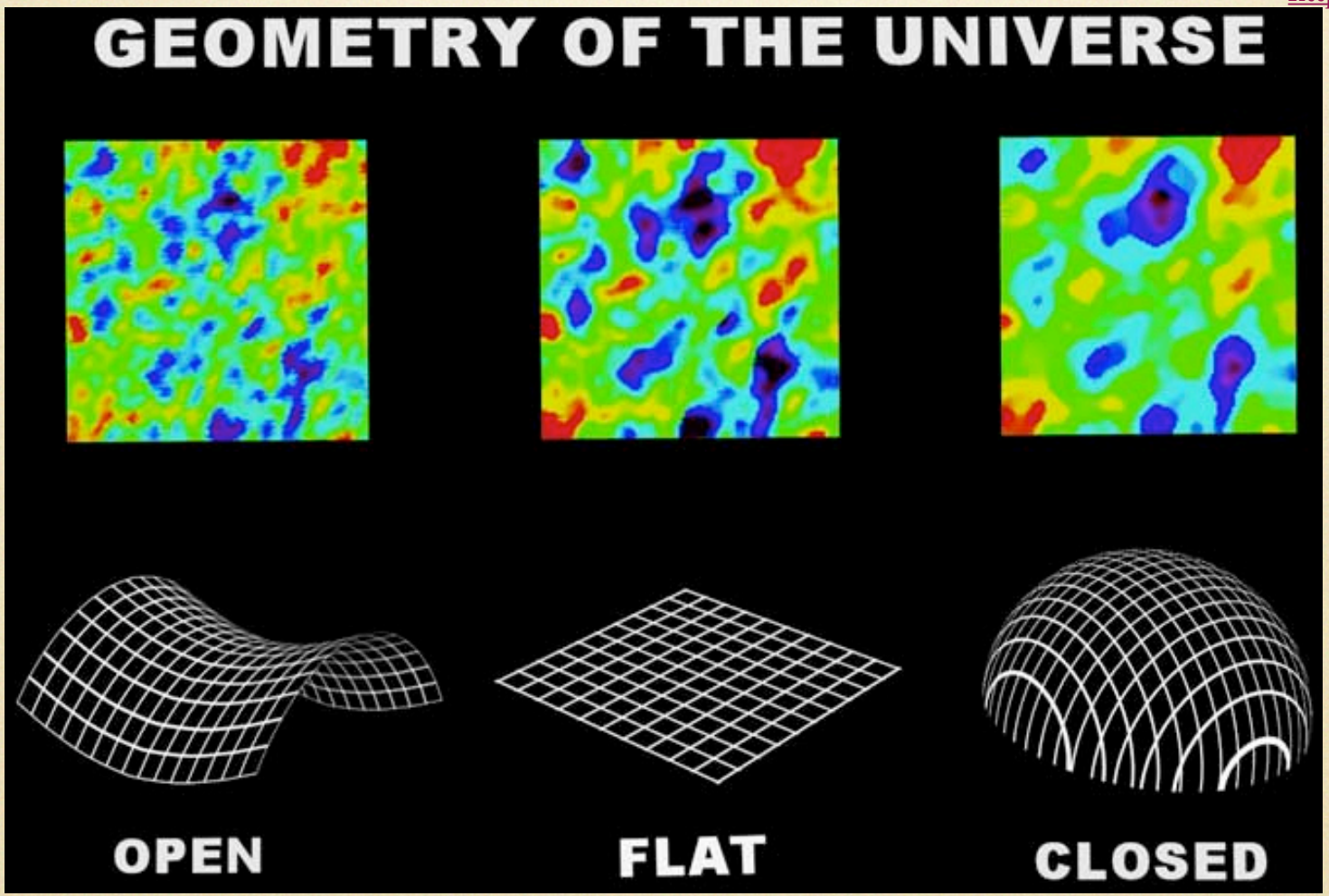


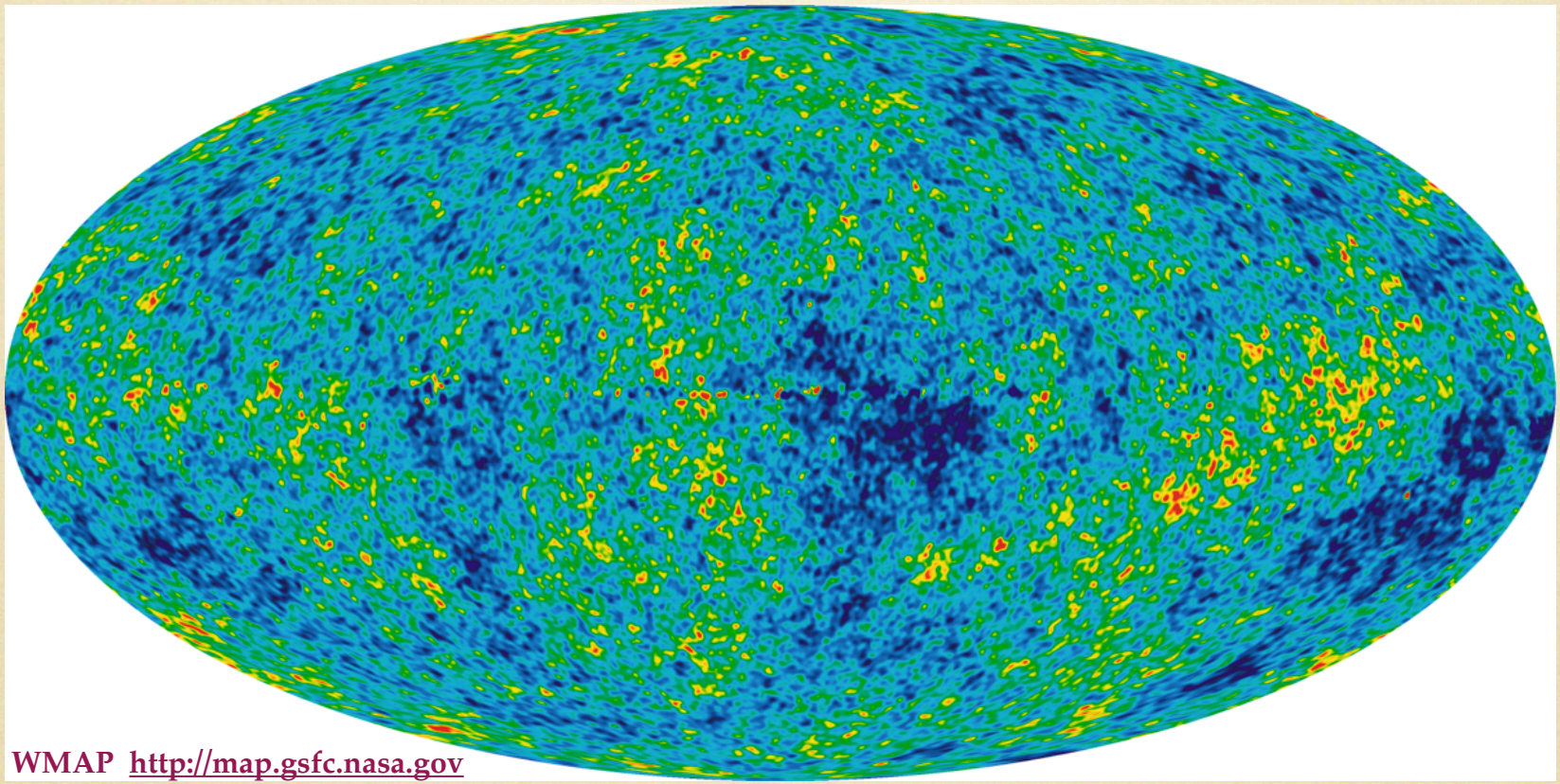
- Hot & Cold patches reflect the time needed to compress
- Hot & Cold patches have a typical physical size
- The angle subtended by such patches on the sky is a function of the geometry of the space

Observing the CMB

http://map.gsfc.nasa.gov

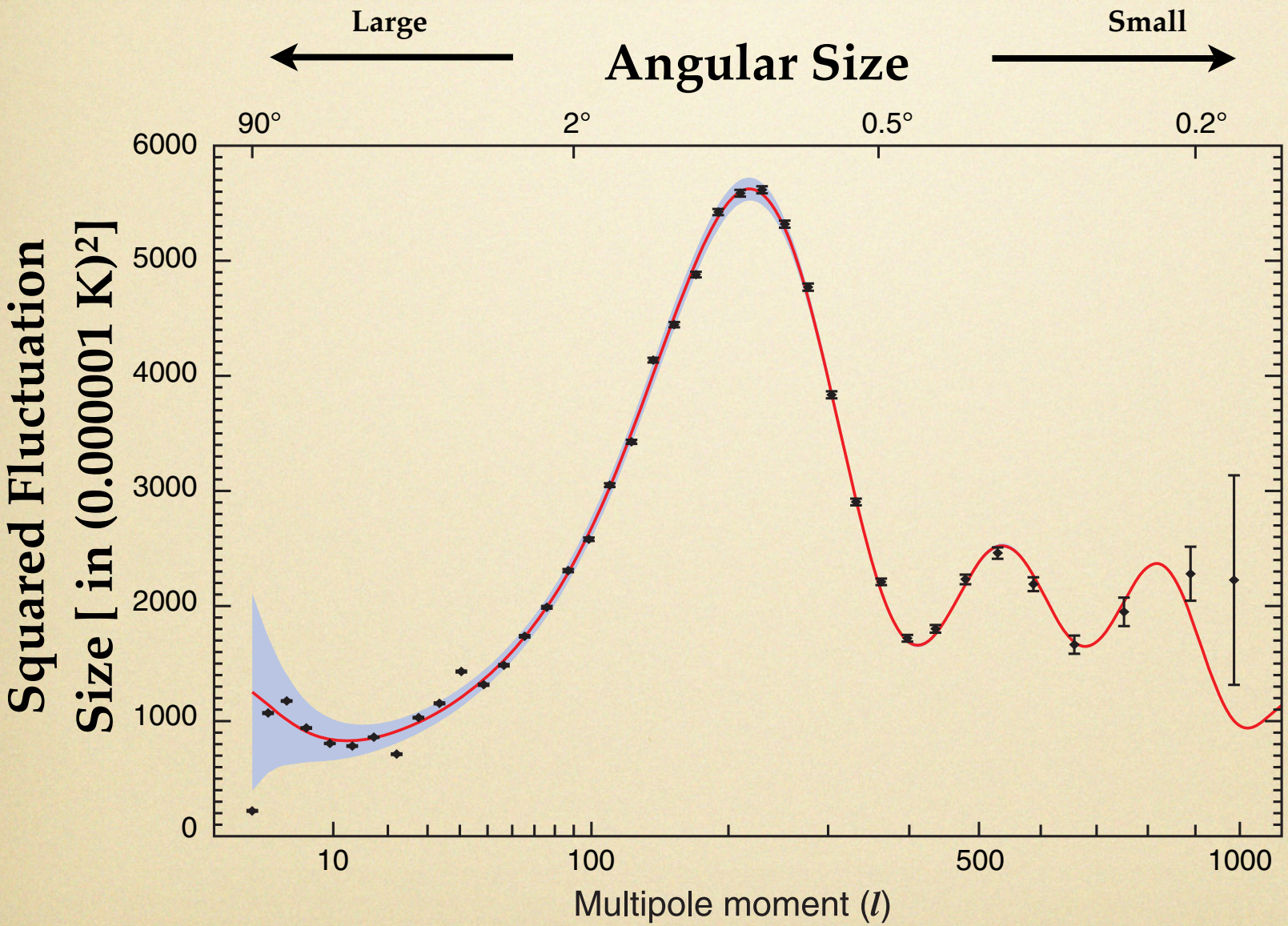


Observing the CMB

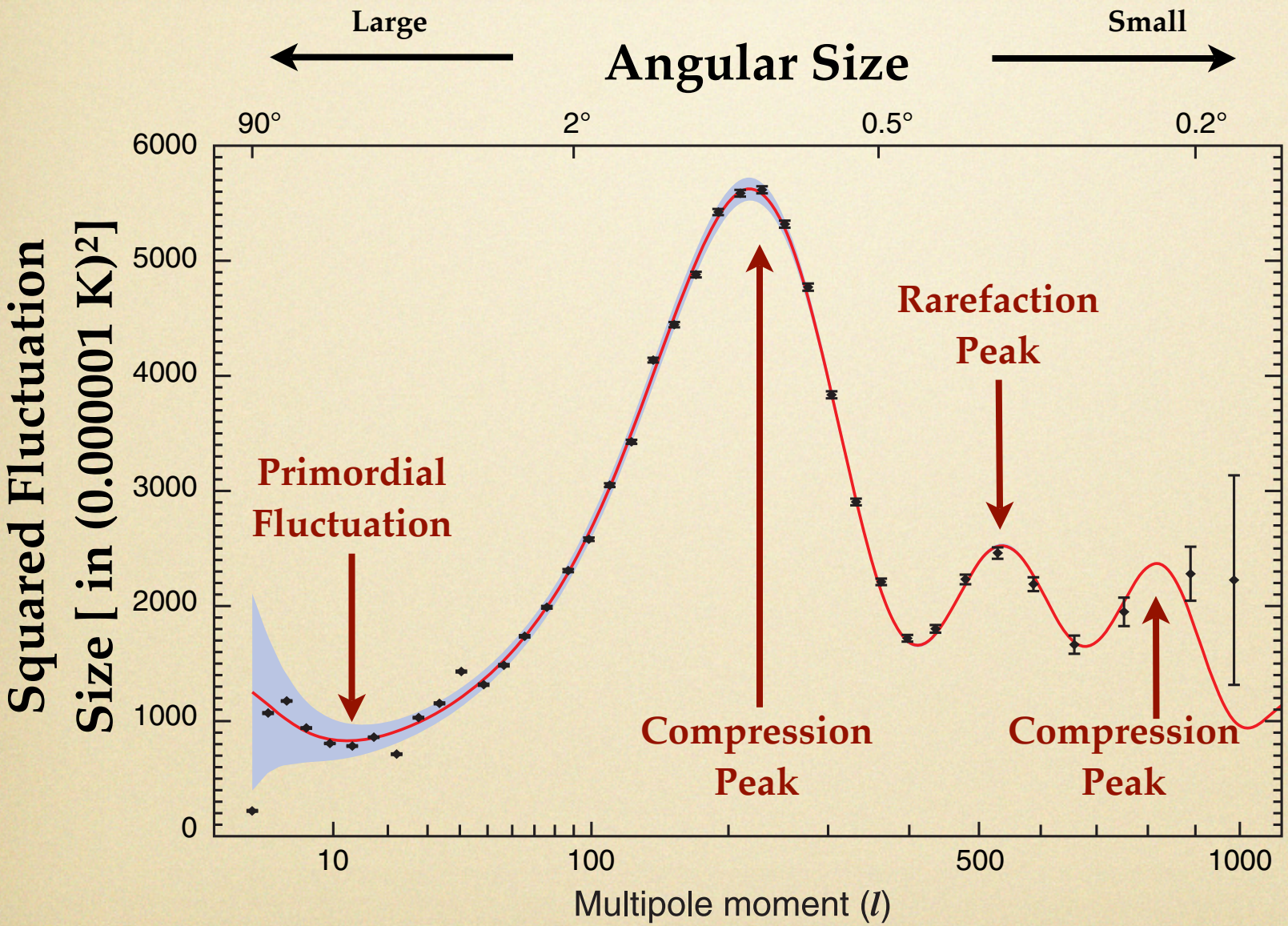


WMAP http://map.gsfc.nasa.gov

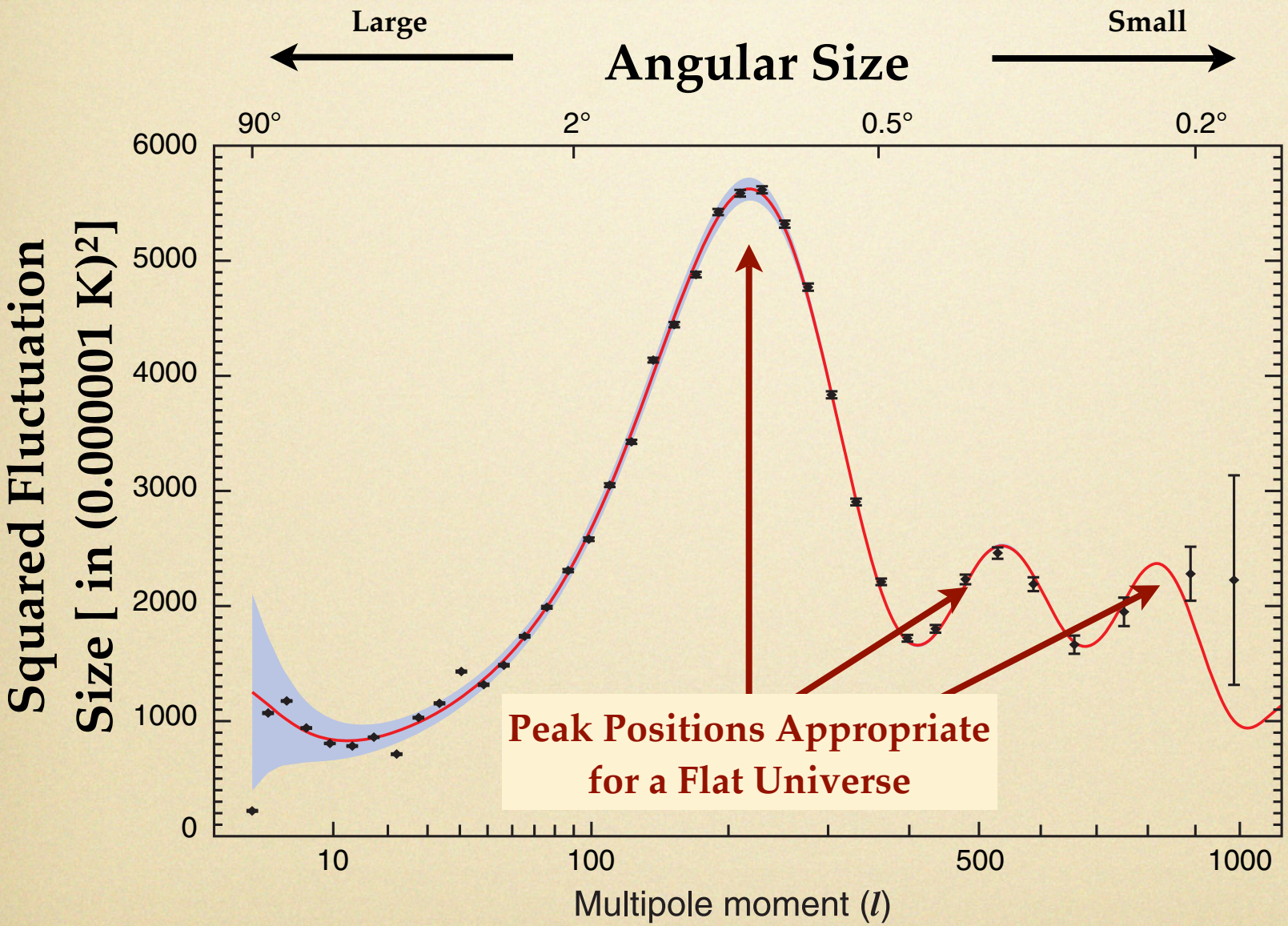
Observing the CMB



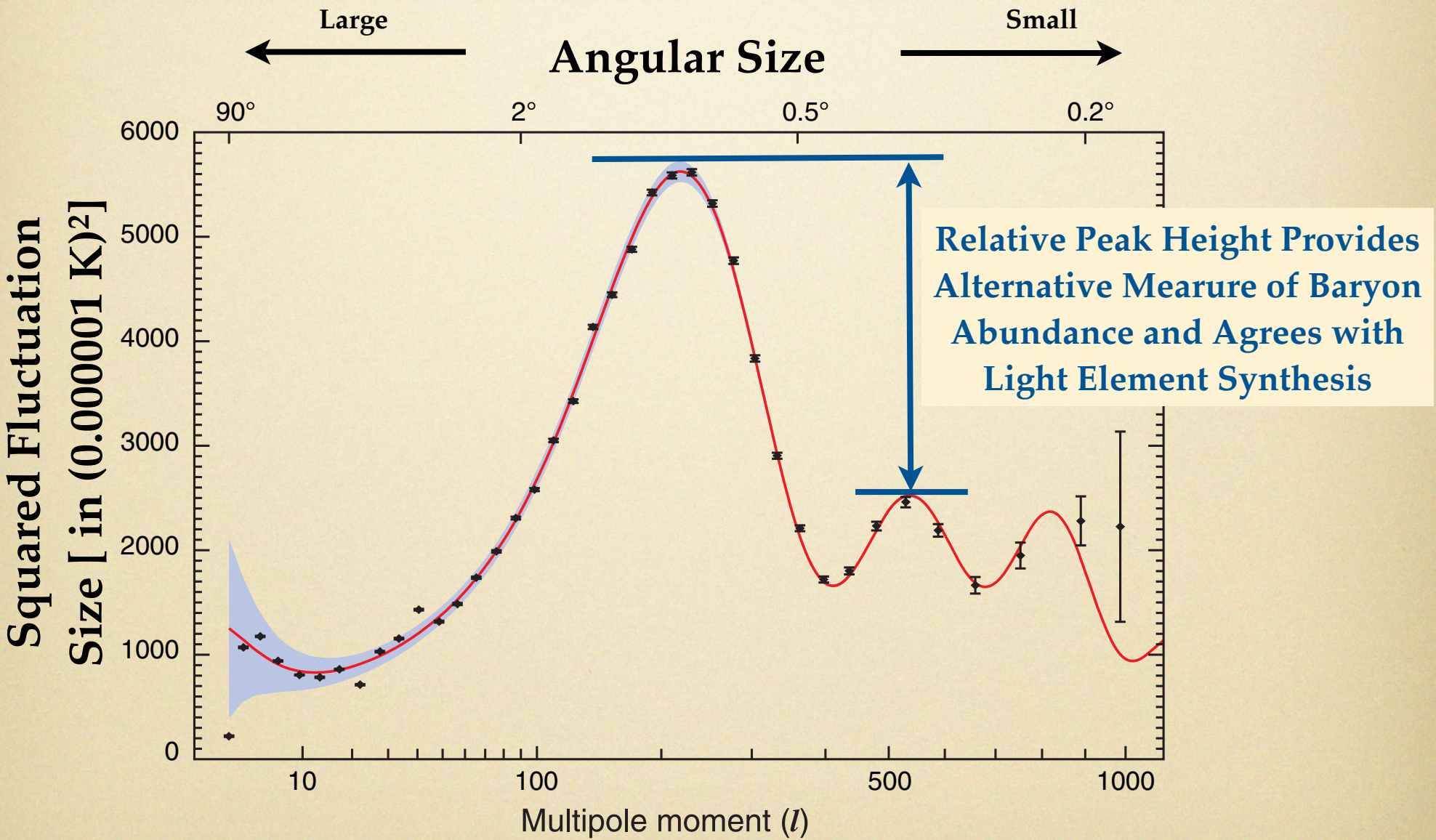
Observing the CMB



Observing the CMB



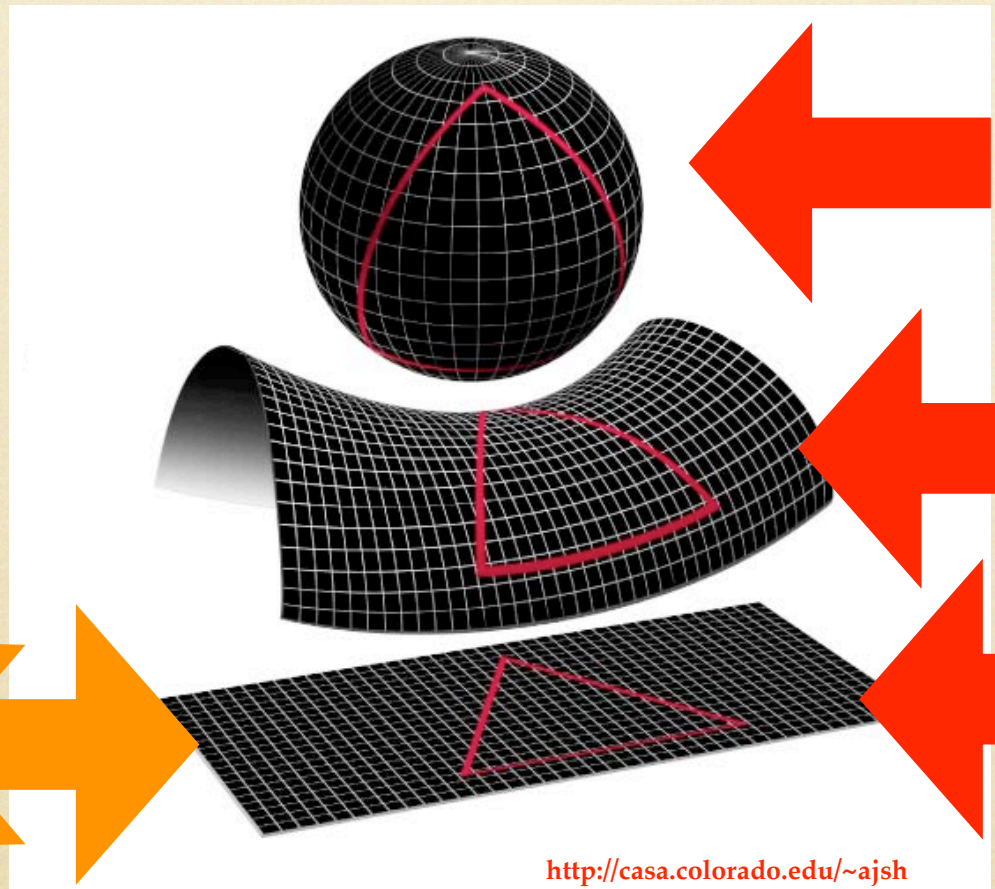
Observing the CMB



Summary

- Light Element Synthesis & Cosmic Microwave Background Studies:
  - Support Extrapolation of Expanding Universe Picture to a time 13.7 Billion Years Ago!
  - Provide Measurements of the Geometry and Total Matter Content of the Universe!

Summary



Closed: Angles Sum To > 180°

Open: Angles Sum To < 180°

FLAT (EUCLIDEAN)

Our Universe

Summary & Next Step

Normal Matter

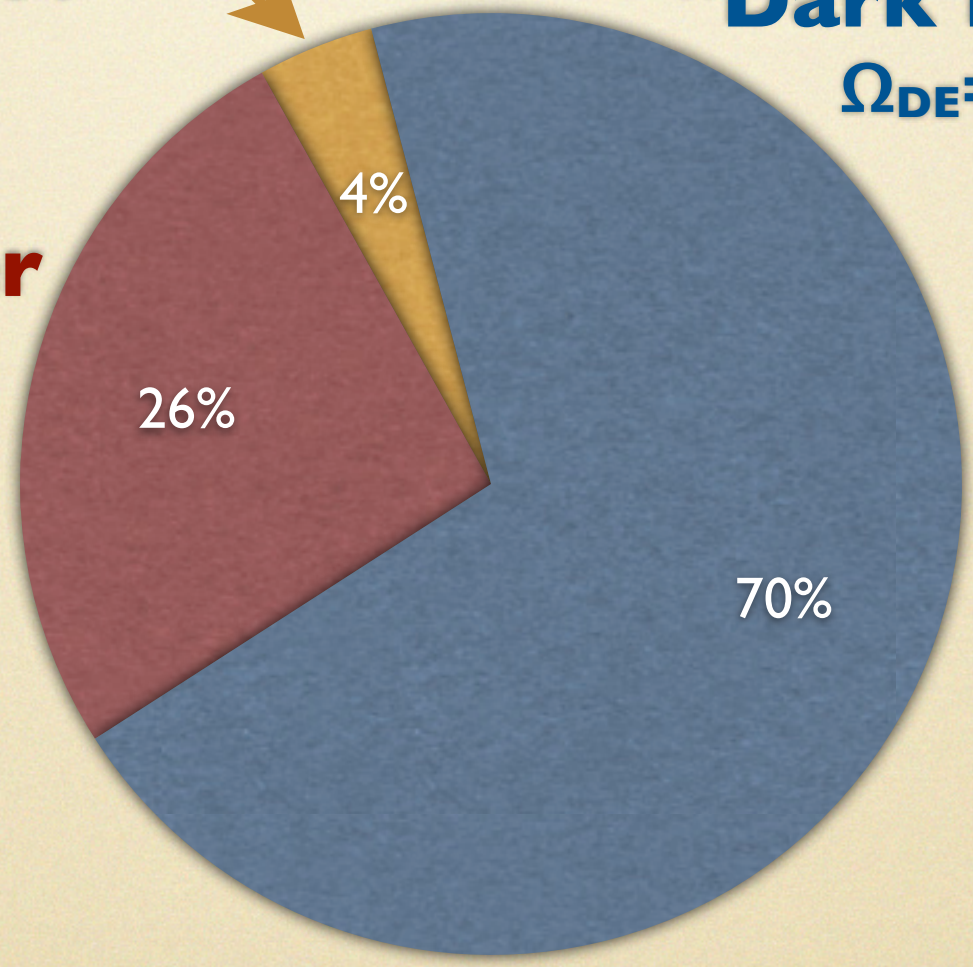
$\Omega_{BARYON} = 0.04$

"Dark Energy"

$\Omega_{DE}=0.70$

Dark Matter

$\Omega_{DM} = 0.26$



- The Universe is FLAT When $\Omega_{BARYON} + \Omega_{DM} + \Omega_{DE} = 1$

Summary & Next Step

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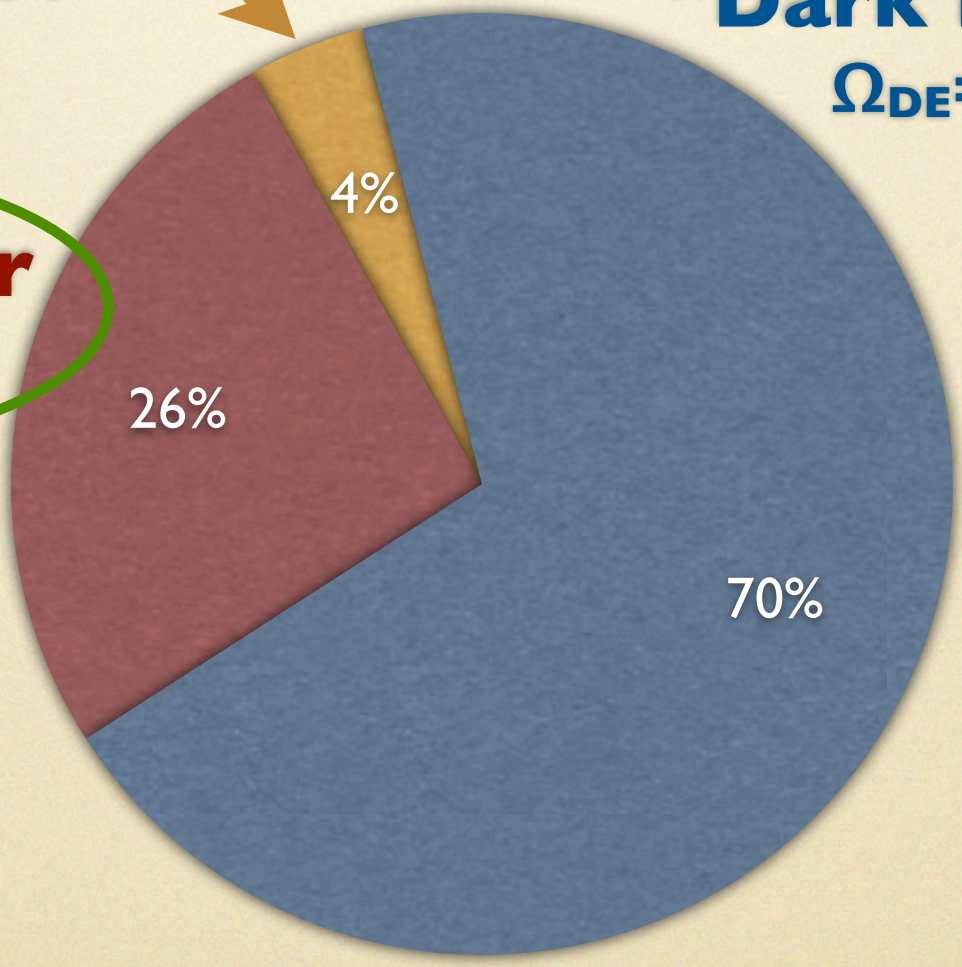
WHY?



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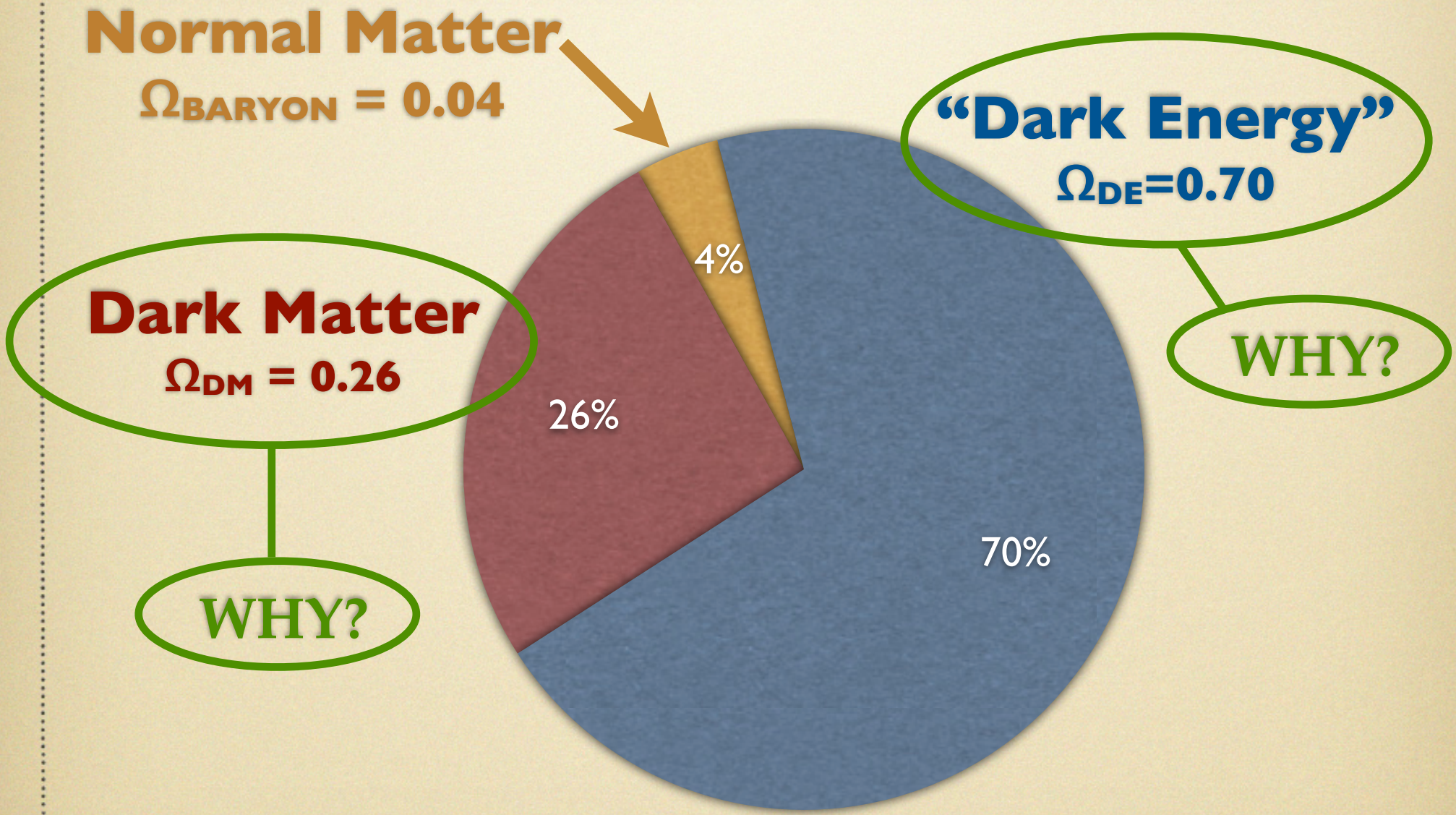
Summary & Next Step



- The Universe is FLAT When $\Omega_{BARYON} + \Omega_{DM} + \Omega_{DE} = 1$