The Tools of Cosmology

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Part Two: The Contemporary Universe

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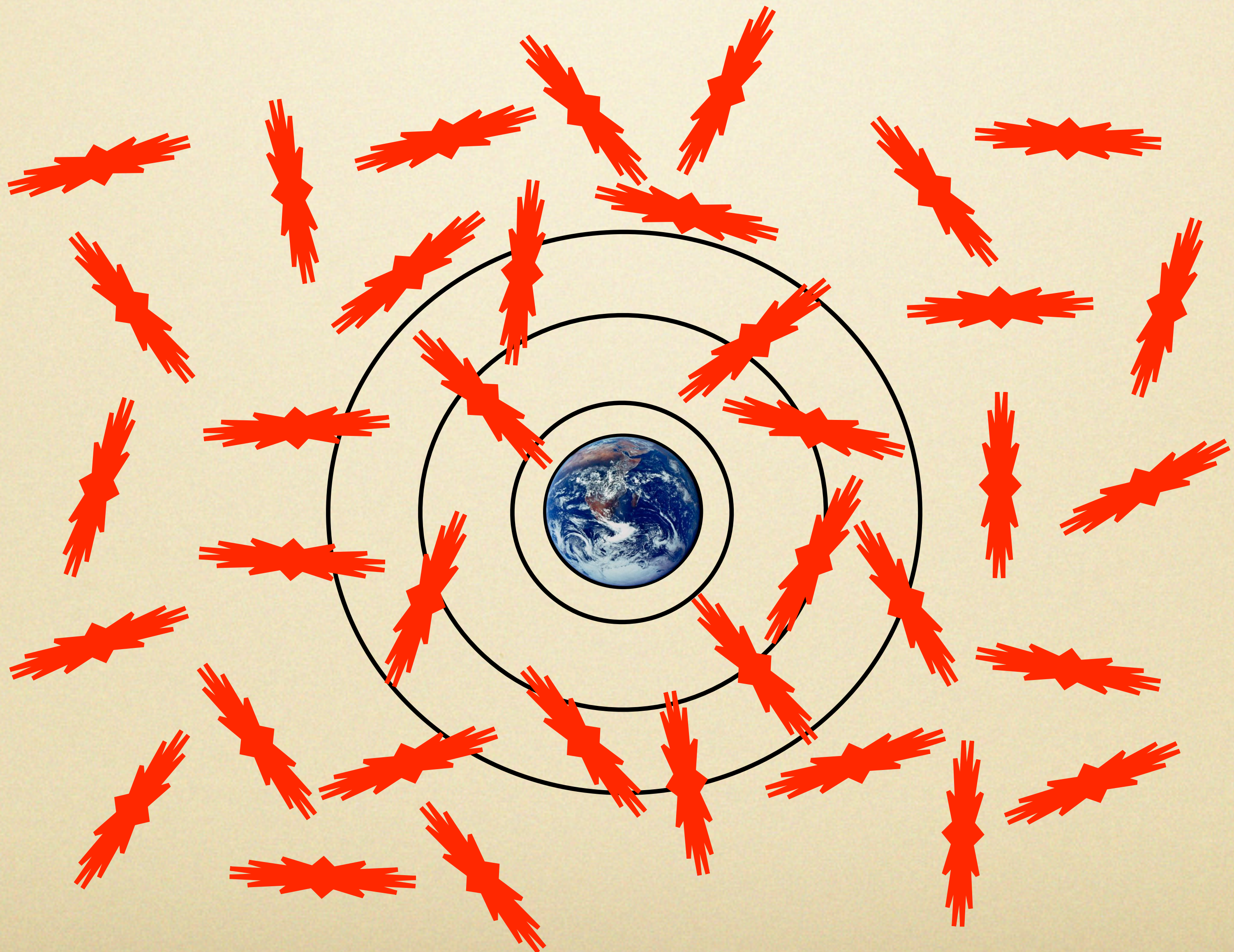
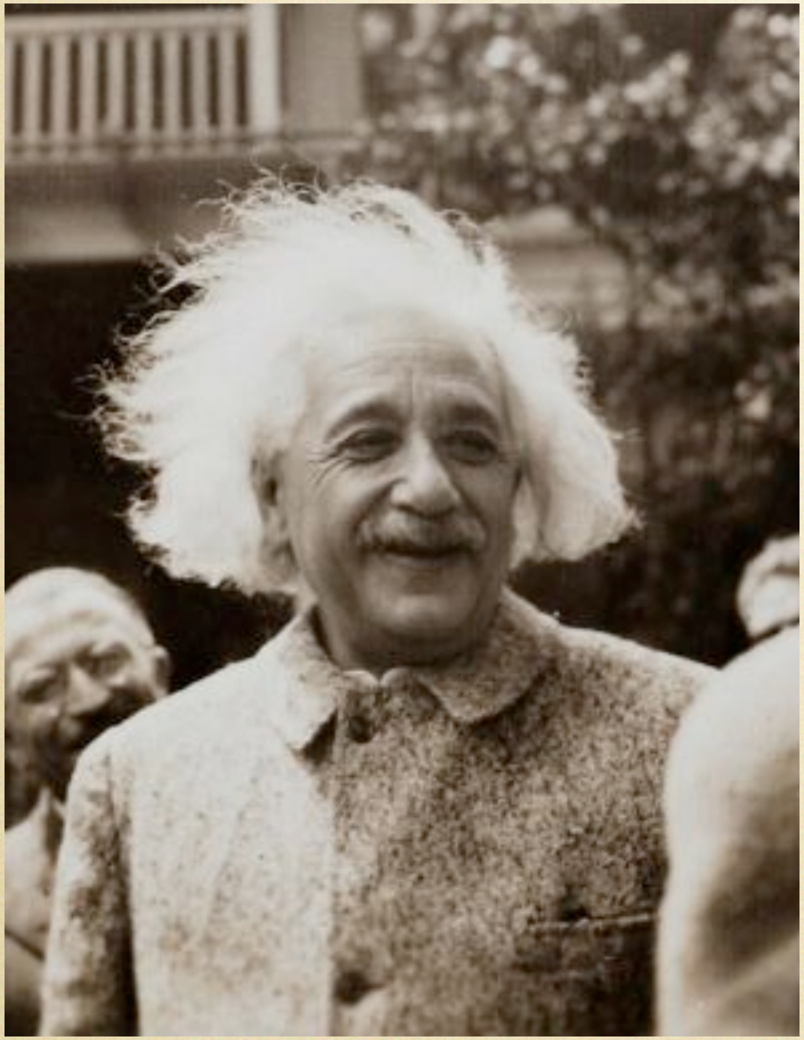
Basic Questions

- **What are the contents of the Universe?**
- **What is the “shape” of the Universe? or What are the rules of geometry on cosmic scales?**

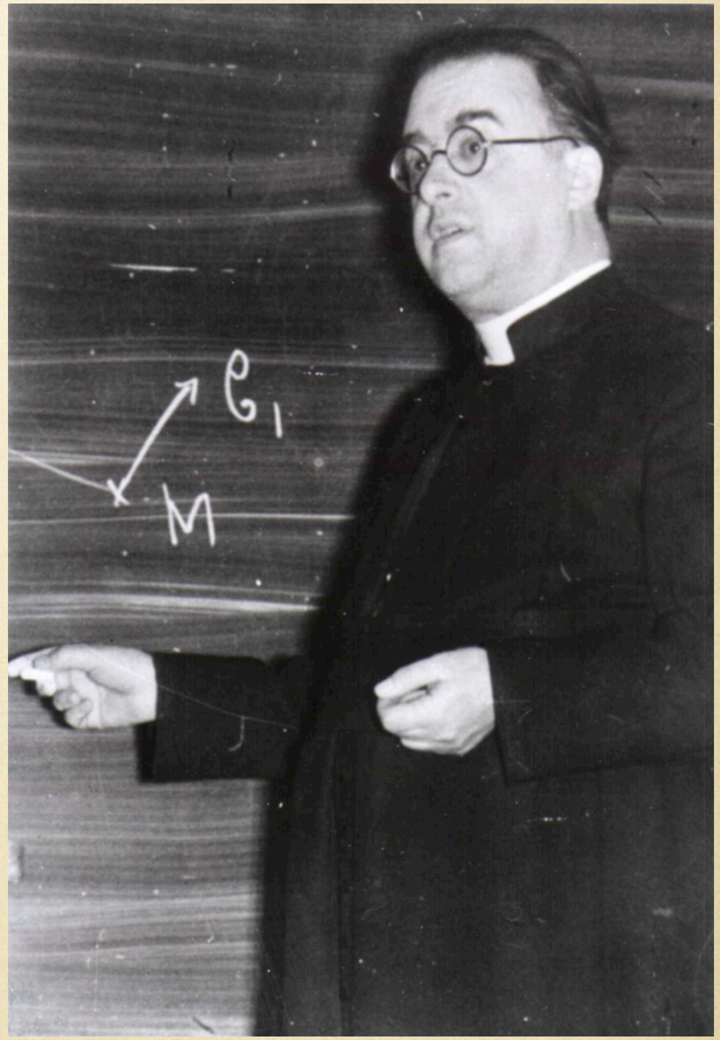
The Homogeneous Universe



The Expanding Universe

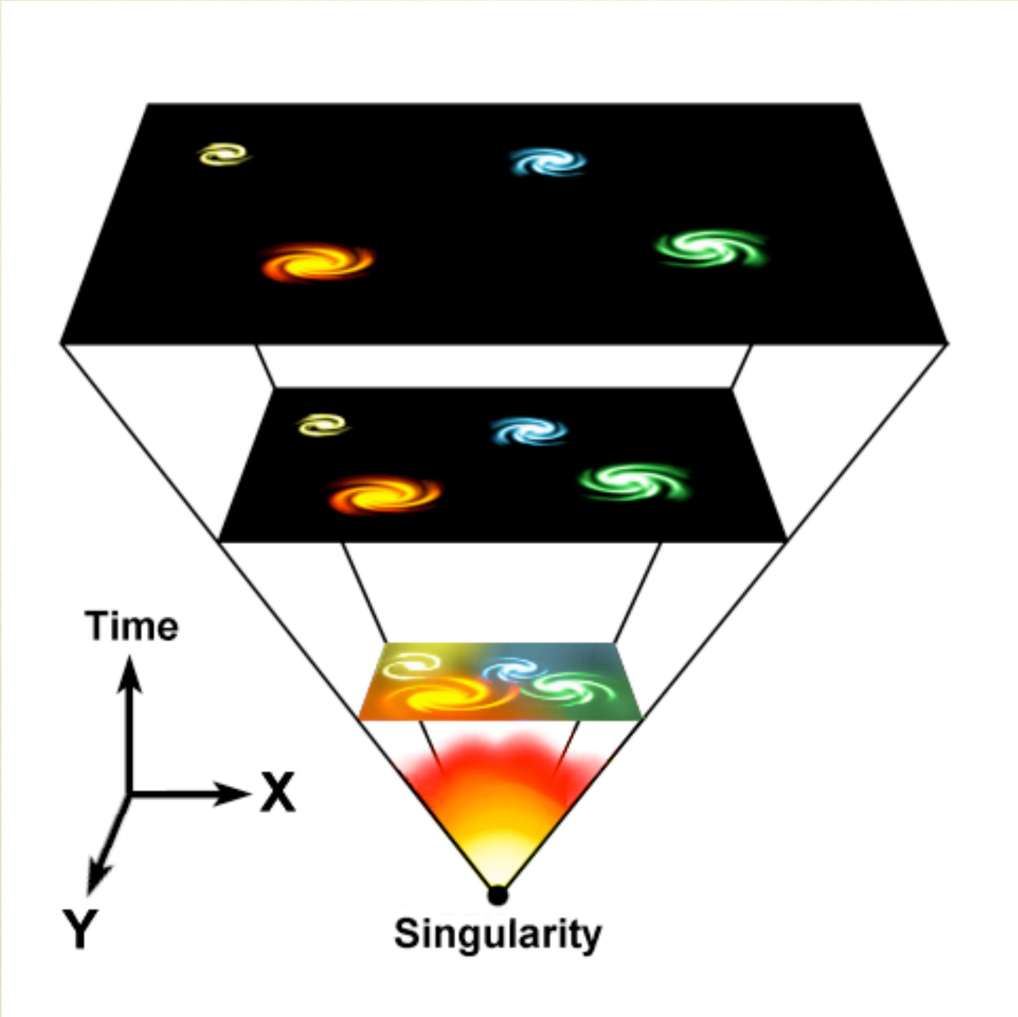


1915 - Einstein:
Theory of Gravity



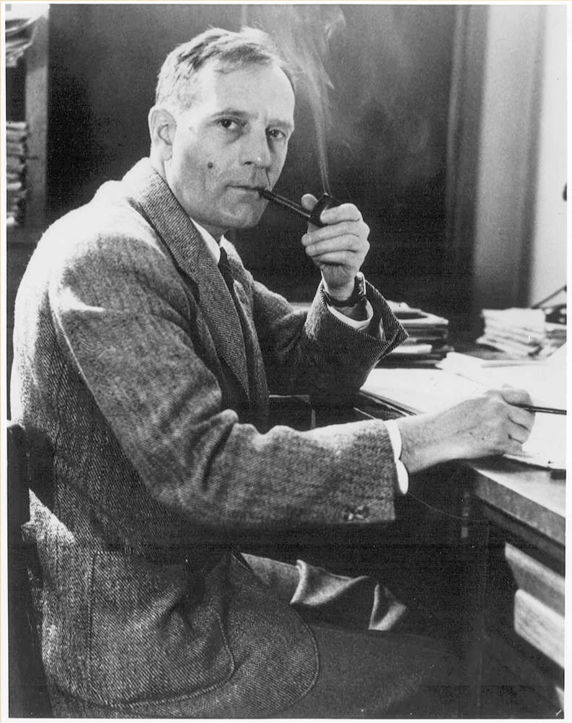
1927 - Georges Lemaître:
Expanding Universe

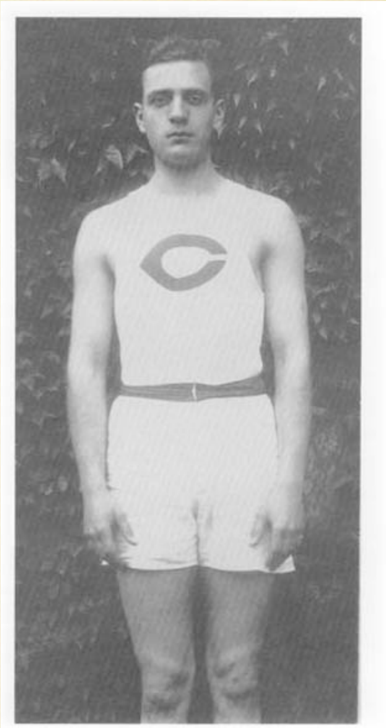
The Expanding Universe



- **The Expansion requires no notion of "center"**
- **All point recede from all other points**

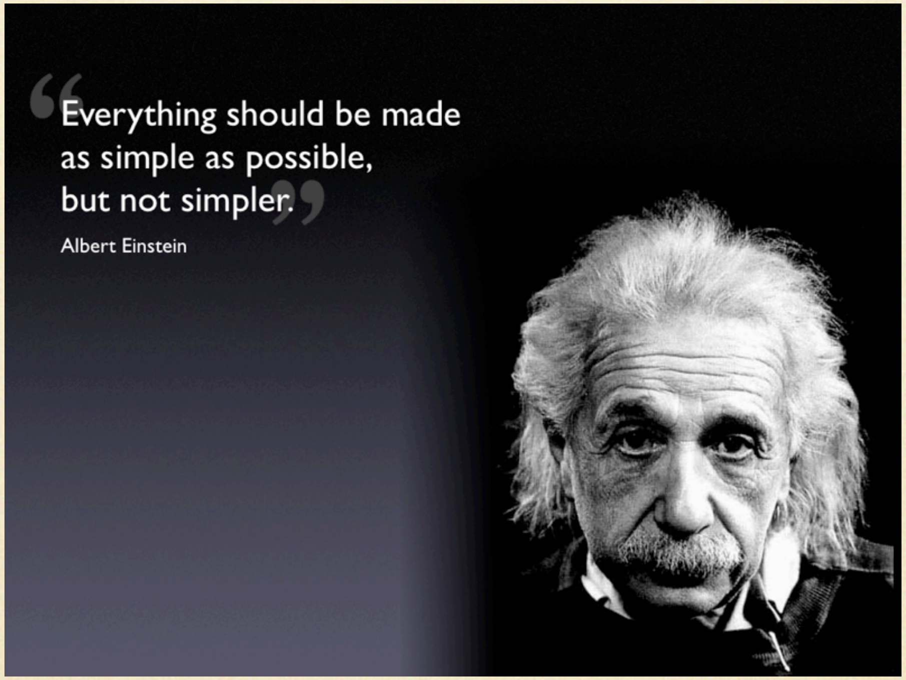
The Expanding Universe





- **1929 - 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**

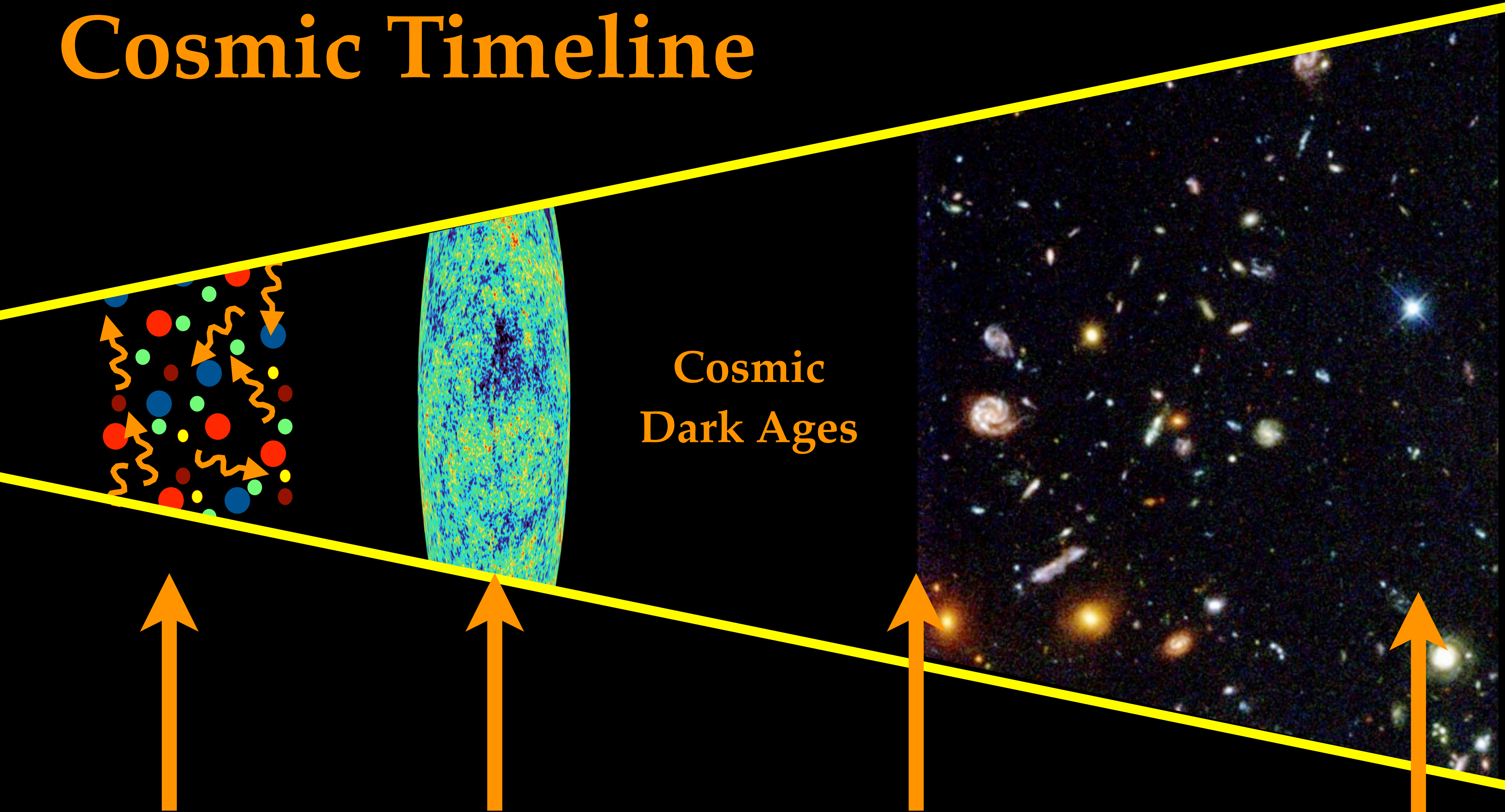
Einstein after Hubble



- "Later, when I was discussing cosmological problems with Einstein, he remarked that the introduction of the cosmological term was the biggest blunder of his life."

- George Gamow

Cosmic Timeline



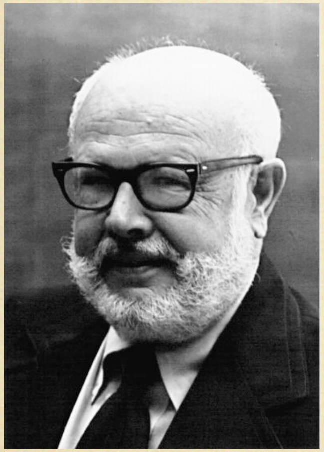
1 sec. to 20 min: Light Element synthesis

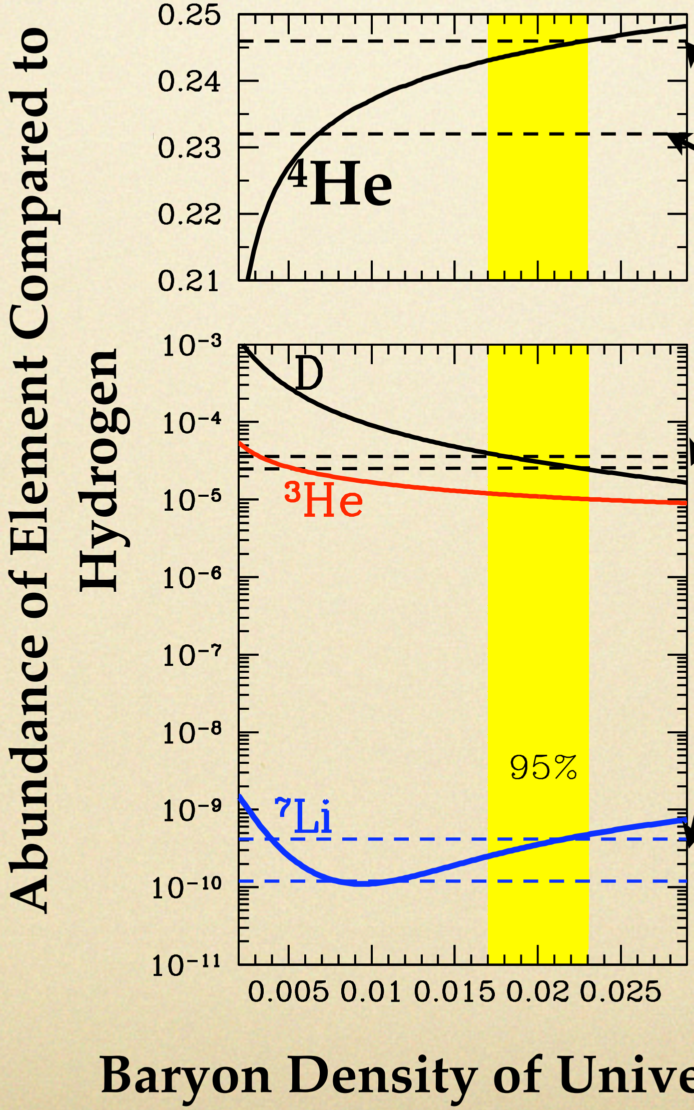
400,000 yr: CMB Produced

200 Million Years: First Stars

13.7 Billion Years: Today

Early Universe Synthesis of Light Nuclei

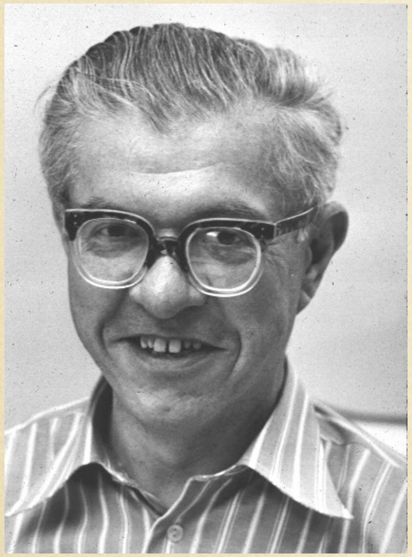




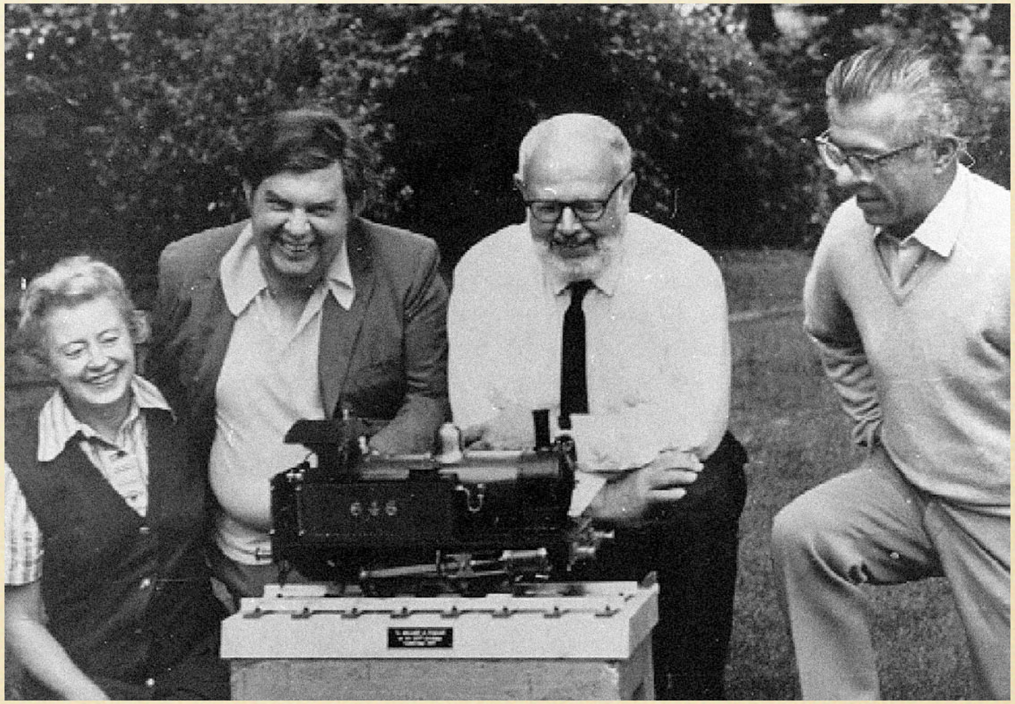
Dashed lines show range of observed values

➔ 4% of energy in the universe is in "normal" baryonic matter

Early Universe Synthesis of Light Nuclei

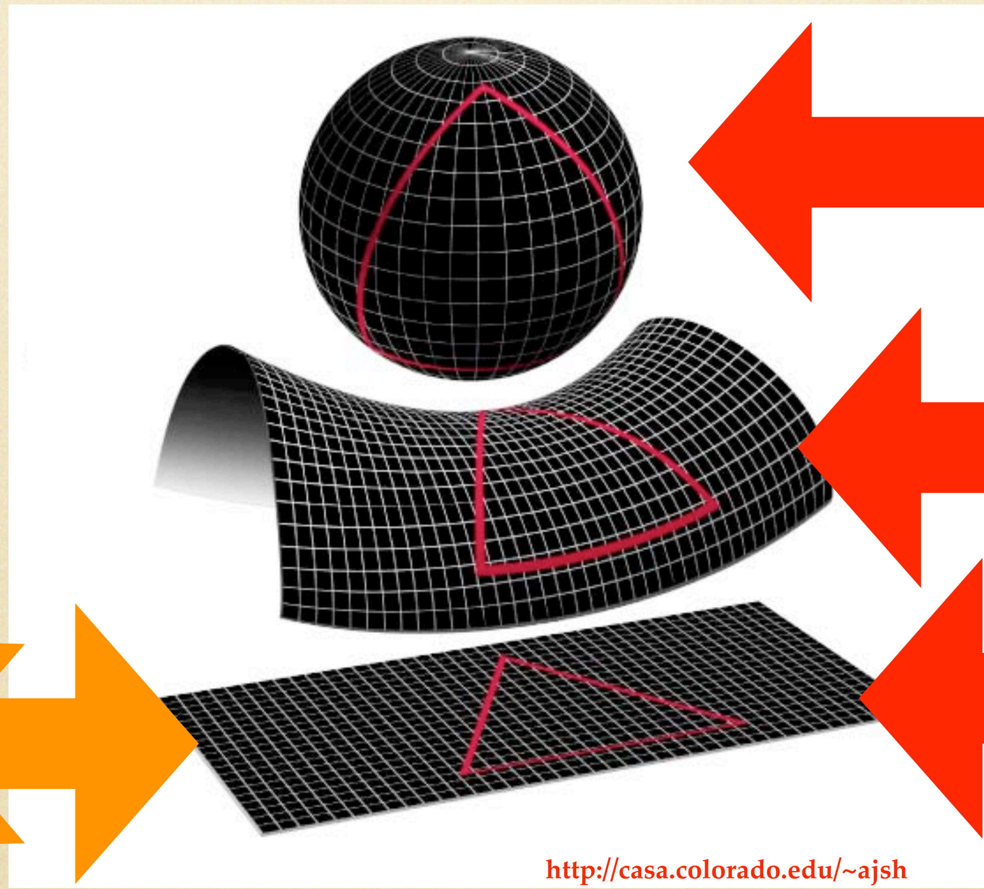


Fred Hoyle



Correctly deduced that heavy elements are synthesized in stars, but never supported the Lemaître "Big Bang" Model

The Geometry of the Universe



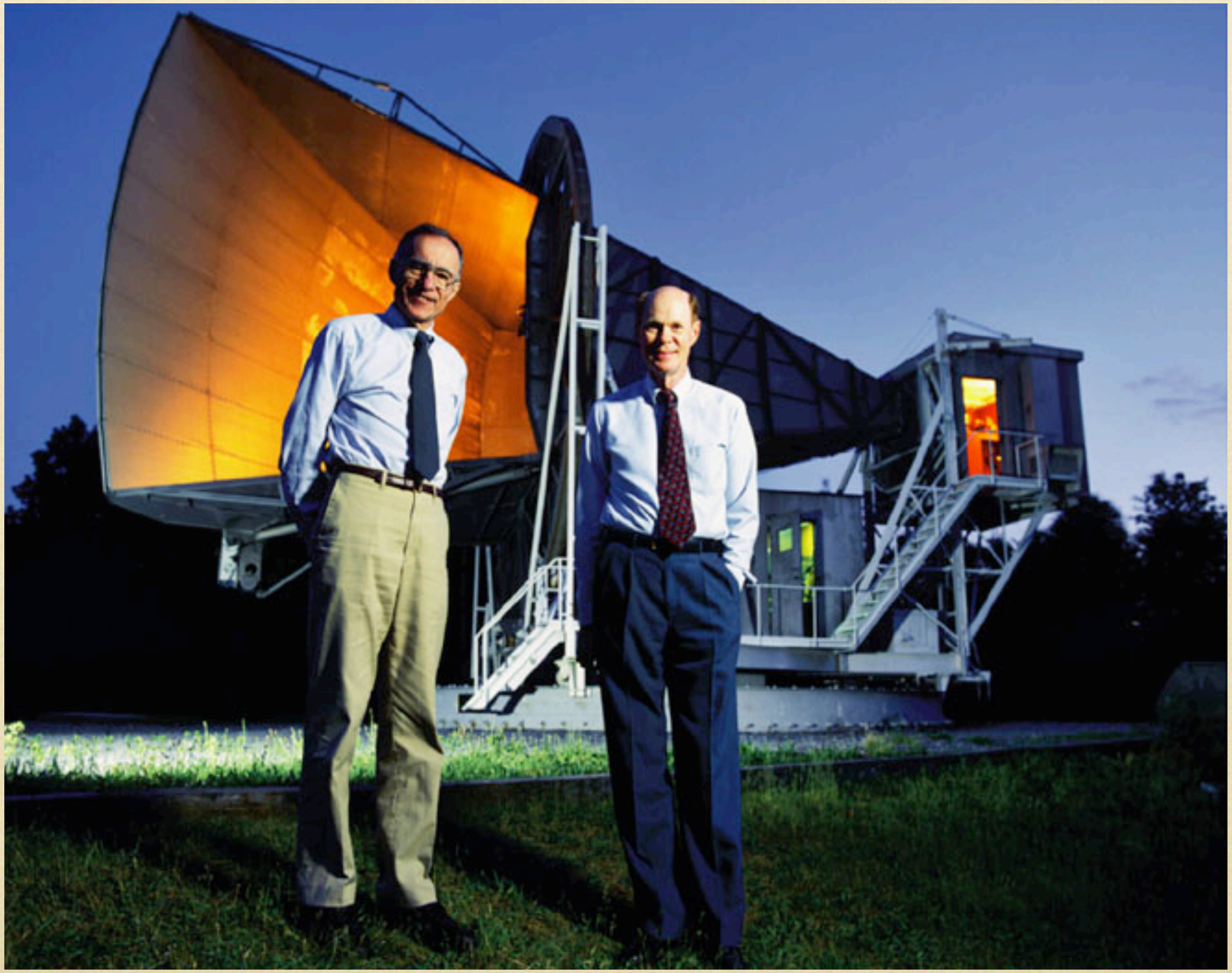
Closed: Angles Sum To > 180°

Open: Angles Sum To < 180°

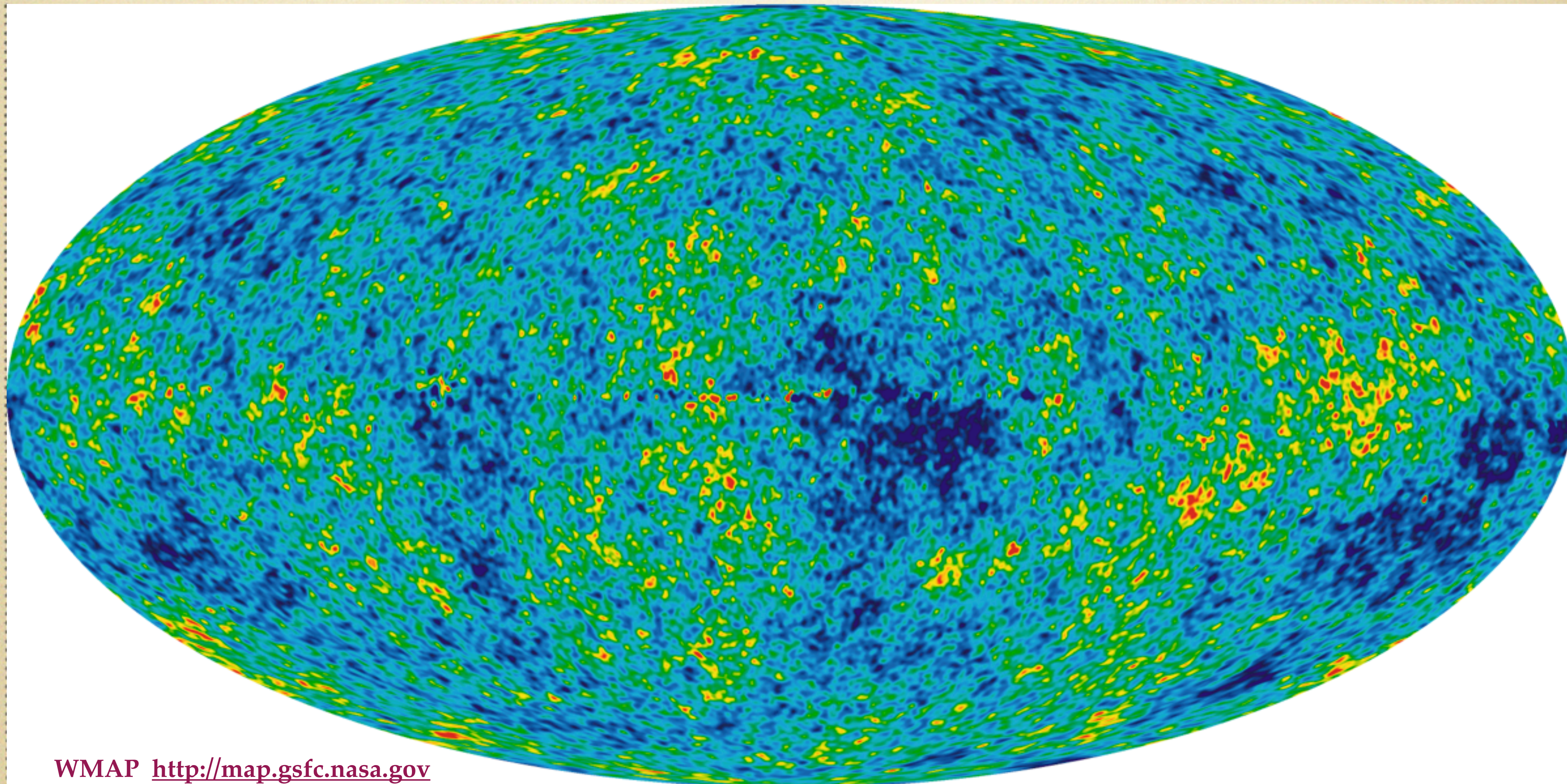
FLAT (EUCLIDEAN)

Our Universe

The Cosmic Microwave Background

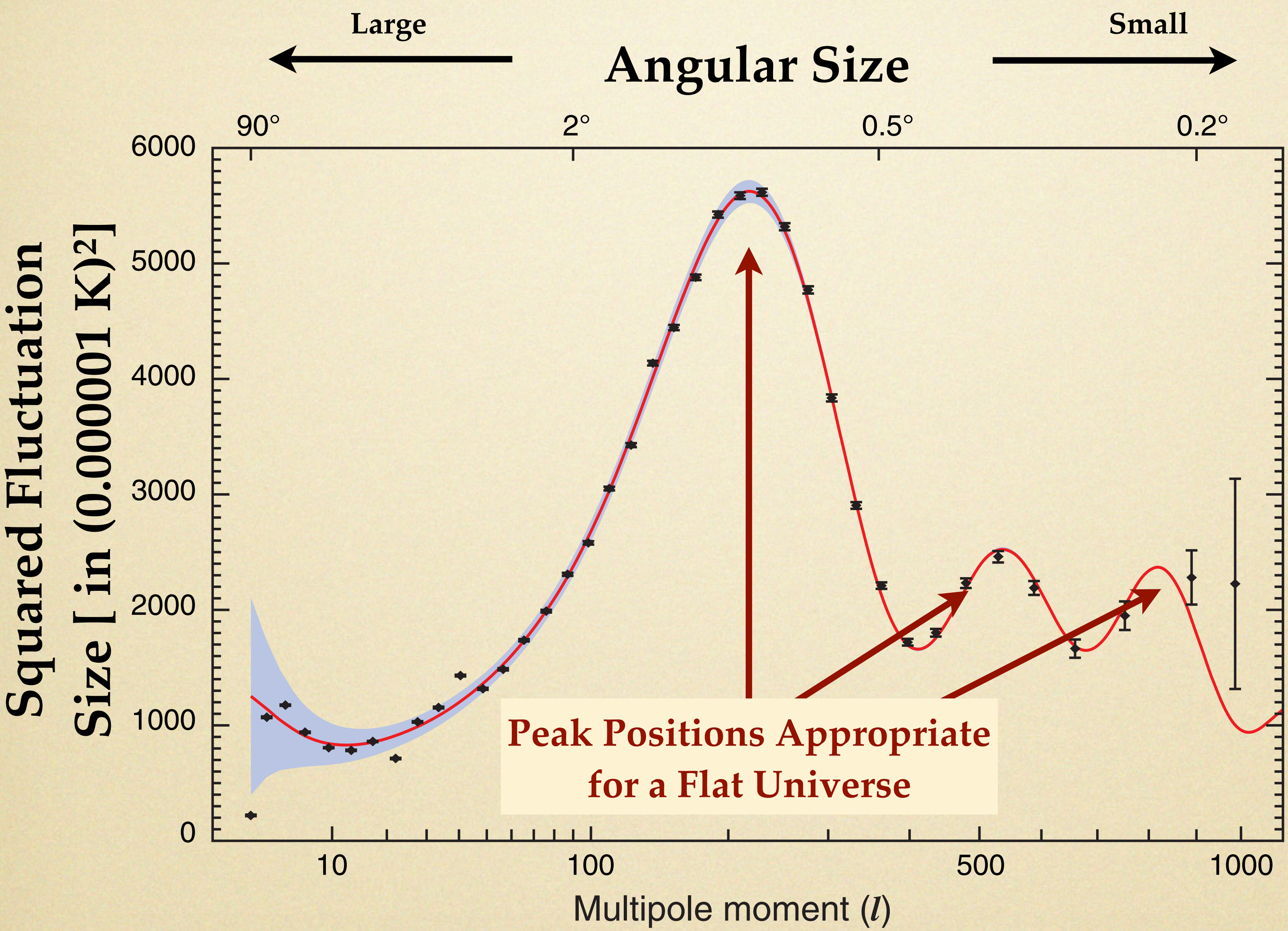


Observing the CMB



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

Observing the CMB



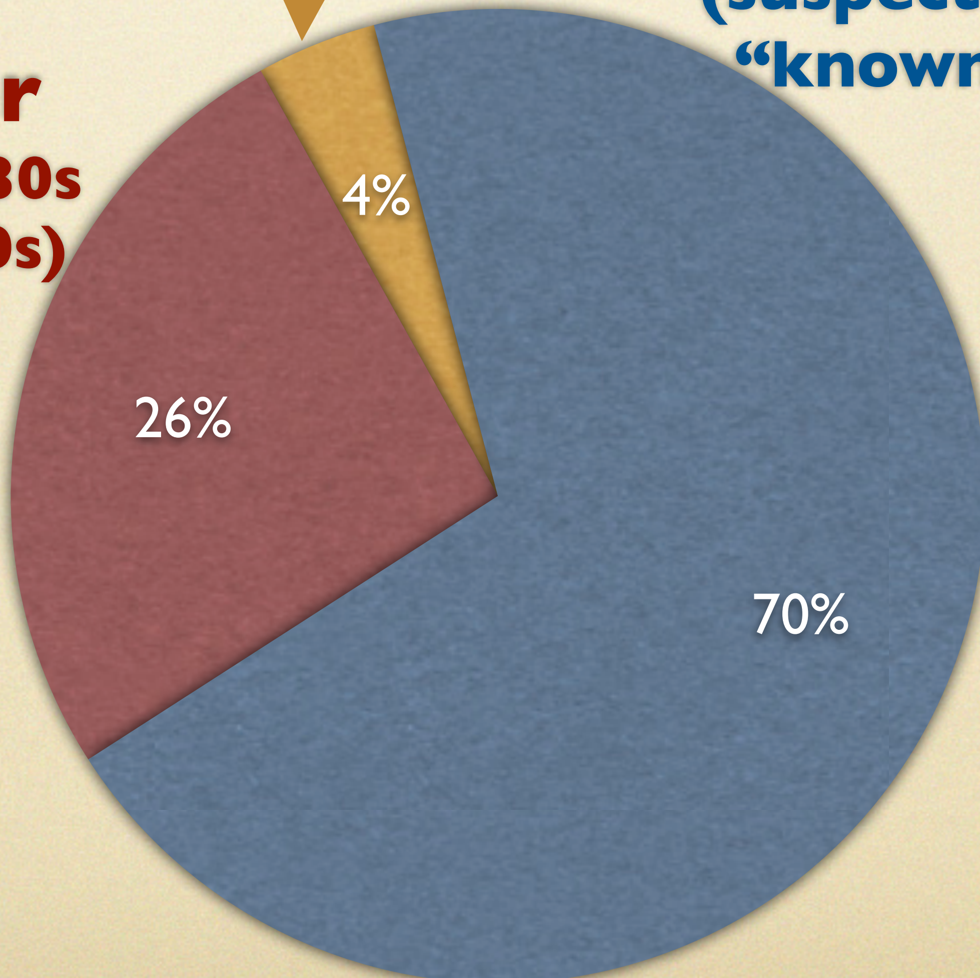
The Universe is Flat ➔ The total density is the critical density for flatness

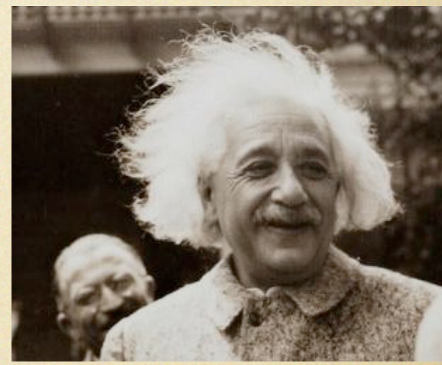
The Contents of the Universe

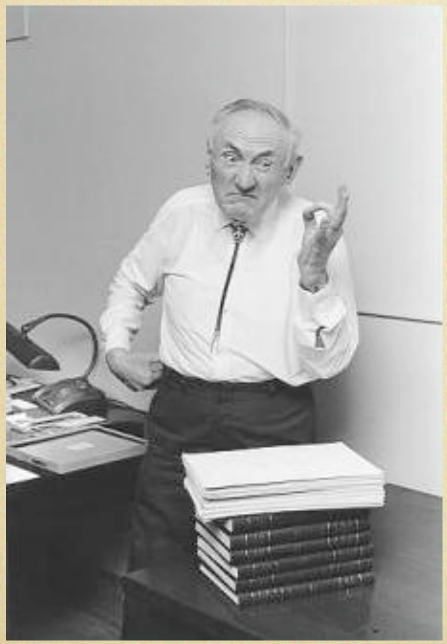
Normal Matter
(stars 0.4%, gas 3.6%)

"Dark Energy"
(suspected since 1980s
"known" since 1998)

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

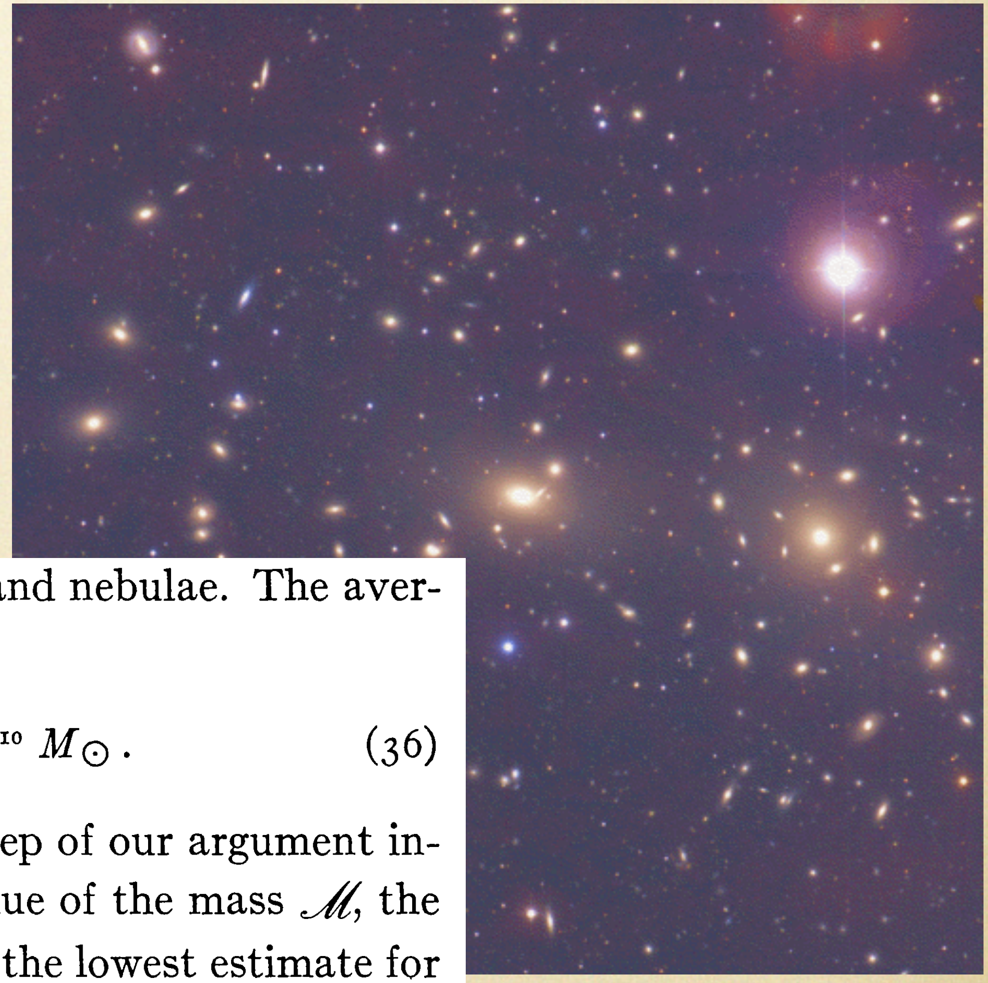






Dark Matter in the Coma Cluster of Galaxies

Dark Matter in the Coma Cluster of Galaxies



The Coma cluster contains about one thousand nebulae. The average mass of one of these nebulae is therefore

$$\overline{M} > 9 \times 10^{43} \text{ gr} = 4.5 \times 10^{10} M_\odot . \qquad (36)$$

Inasmuch as we have introduced at every step of our argument inequalities which tend to depress the final value of the mass $\mathscr{M}$, the foregoing value (36) should be considered as the lowest estimate for the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about 8.5×10^7 suns. According

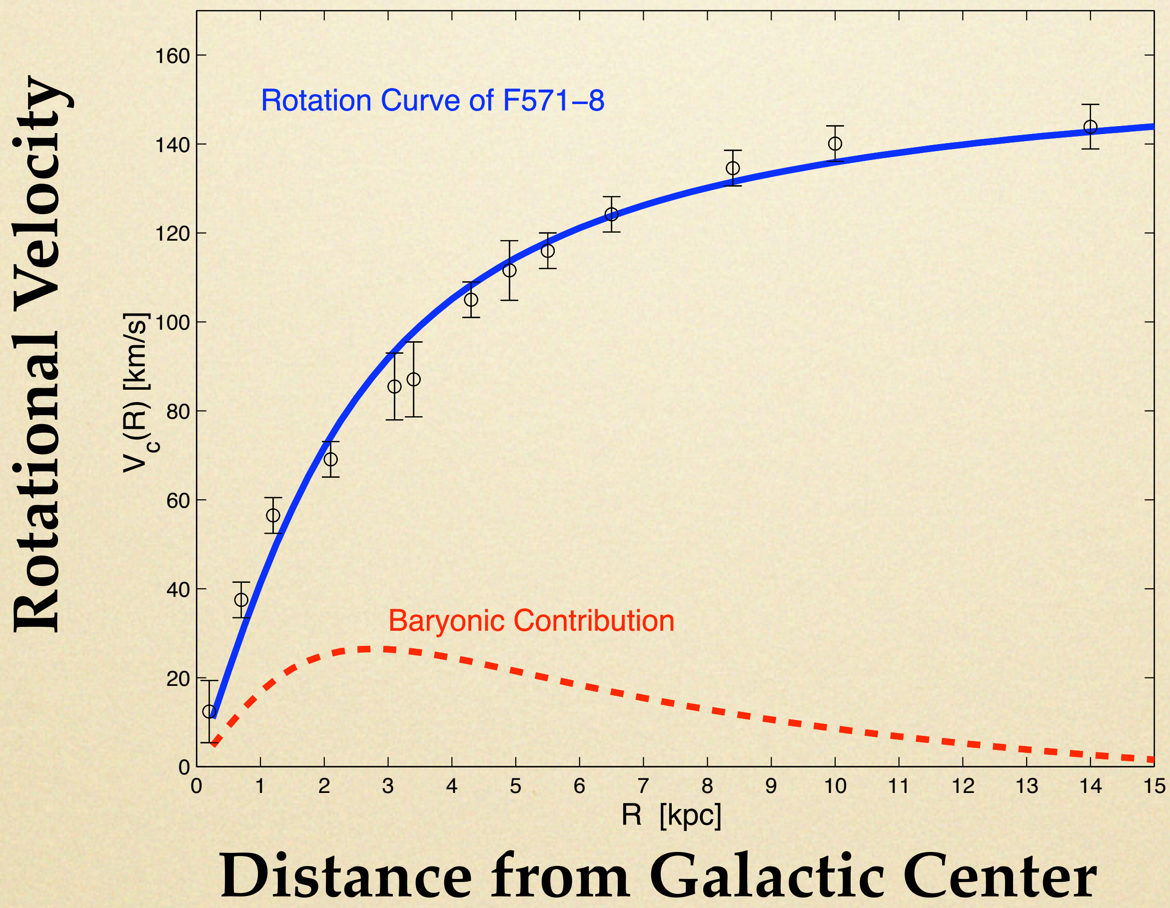
Zwicky 1937

Dark Matter in the Andromeda Galaxy

- The rotation speed of the Andromeda disk (~250 km/s) is much larger than expected from its light output (Rubin & Ford 1970)

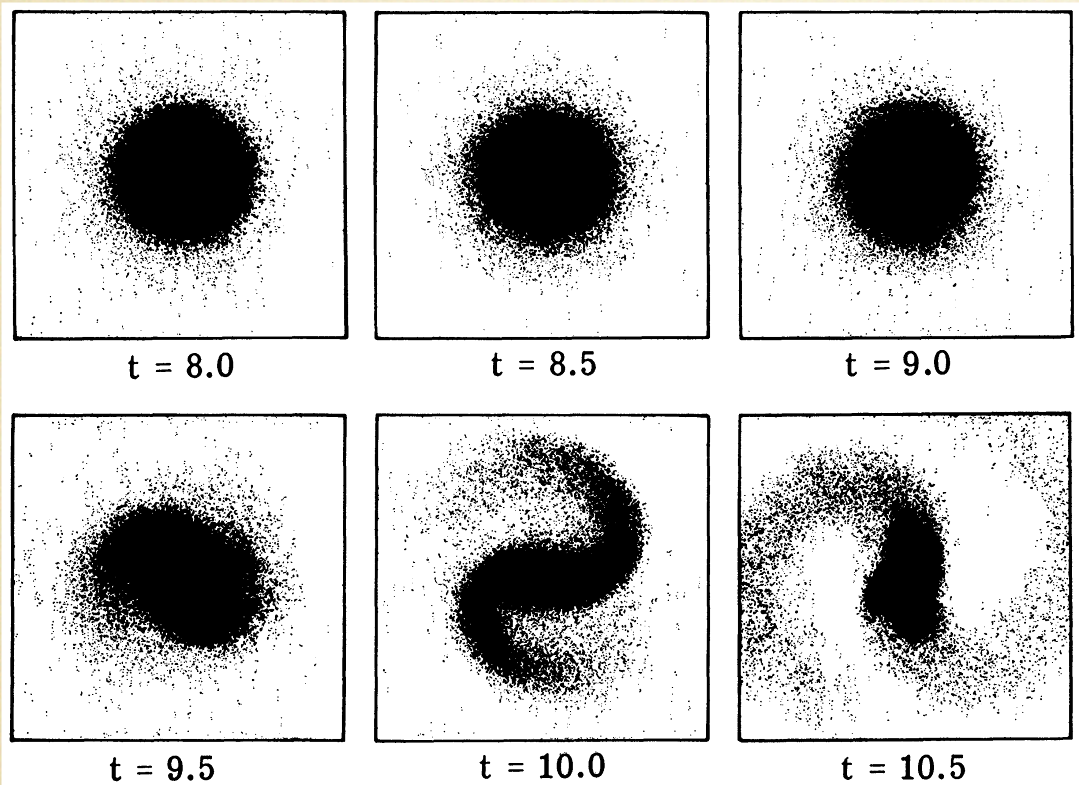
Dark Matter in Disk Galaxies

Velocities: Observed vs. Expected from Light



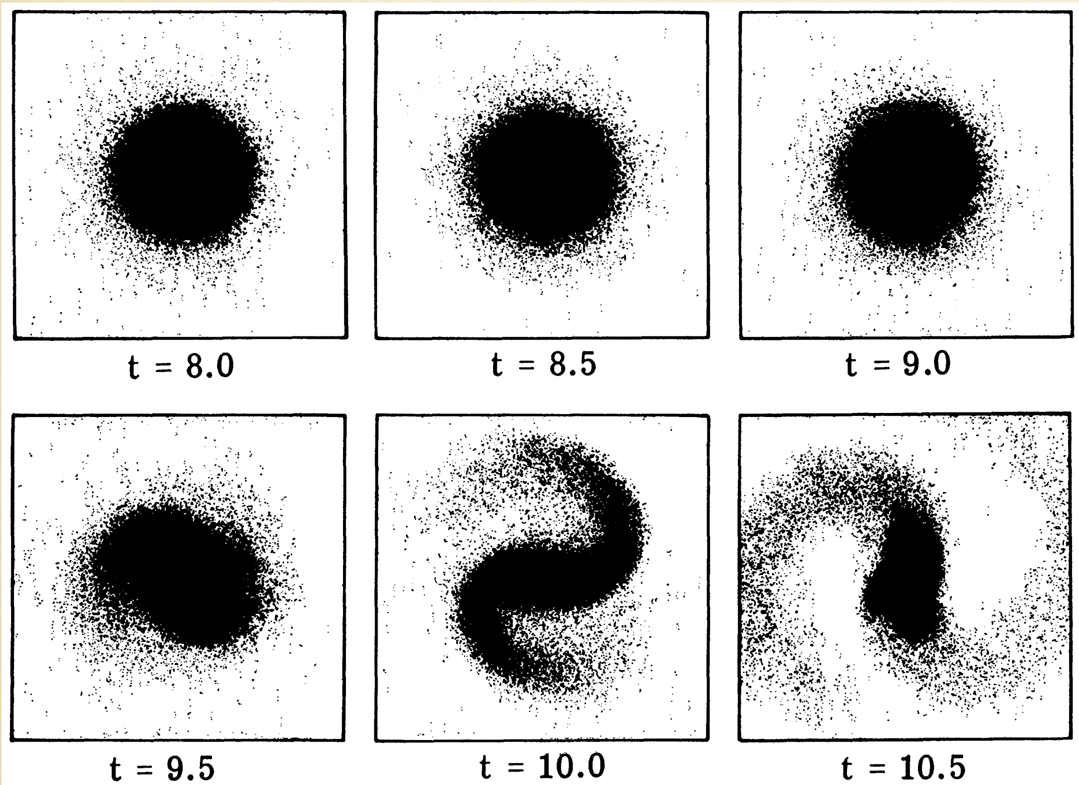
- This problem of excessive rotation speeds is typical of disk galaxies

Dark Matter and the Stability of Disk Galaxies



Hohl 1970: Disk galaxies will evolve into strong bars in millions of years ➔ puzzling for a 14 Billion year old Universe

Dark Matter and the Stability of Disk Galaxies



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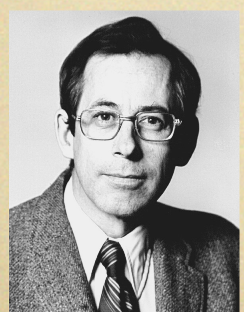
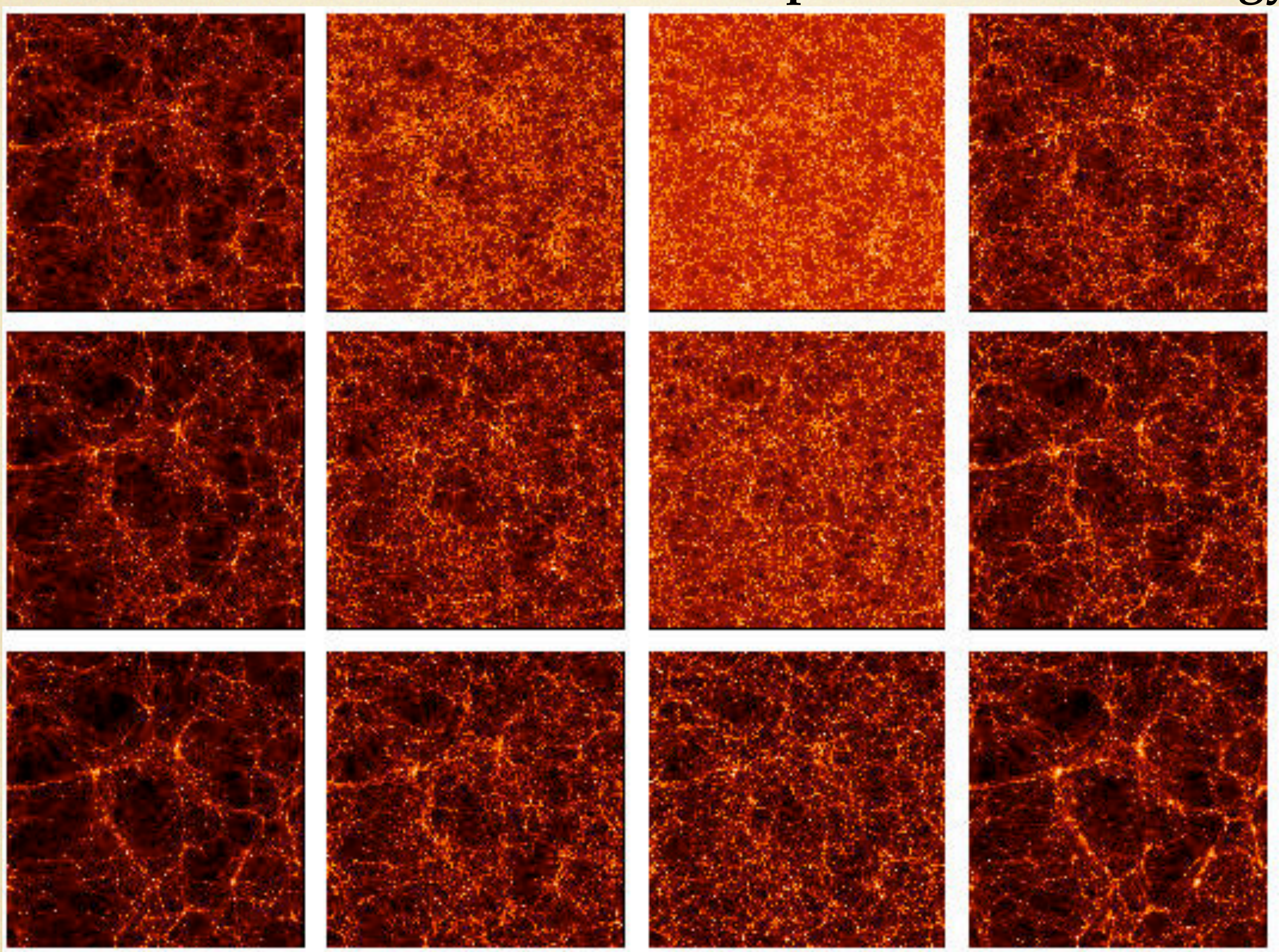


Ostriker & Peebles 1973: This problem could be mitigated if galaxies sit in halos of dark matter

The Modern Era

Curved Universe | Matter only Universe | Matter only & slow expansion | Matter & Dark Energy



z=3, 11 billion year ago

z=1 8 billion year ago

today

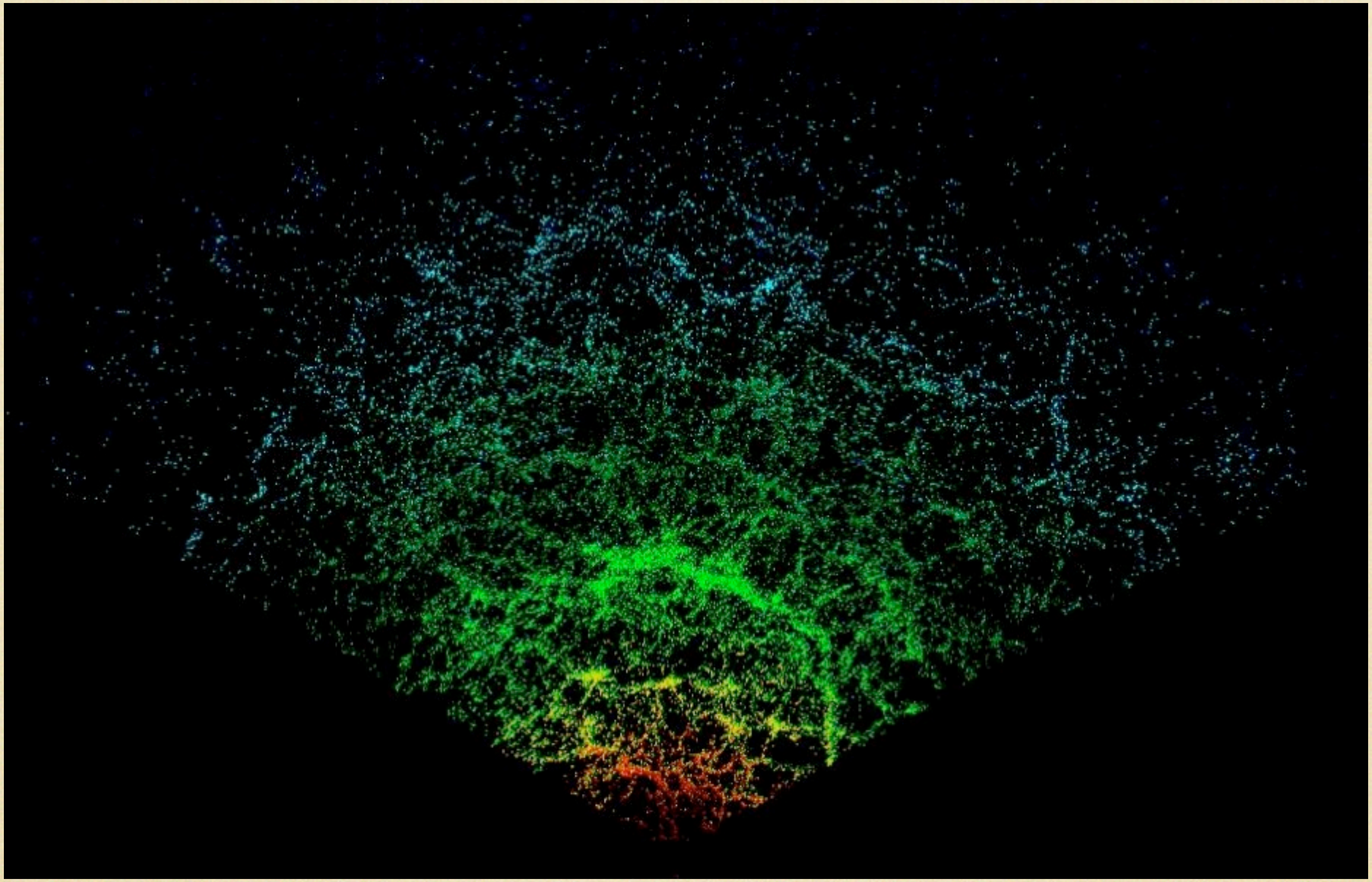
- Large calculations predict the patterns of galaxies that we should observe

The Modern Era

The Sloan Digital Sky Survey (Pitt. is part of the collaboration) in New Mexico

- Observatories can map out the positions of millions of galaxies

A Universe Map

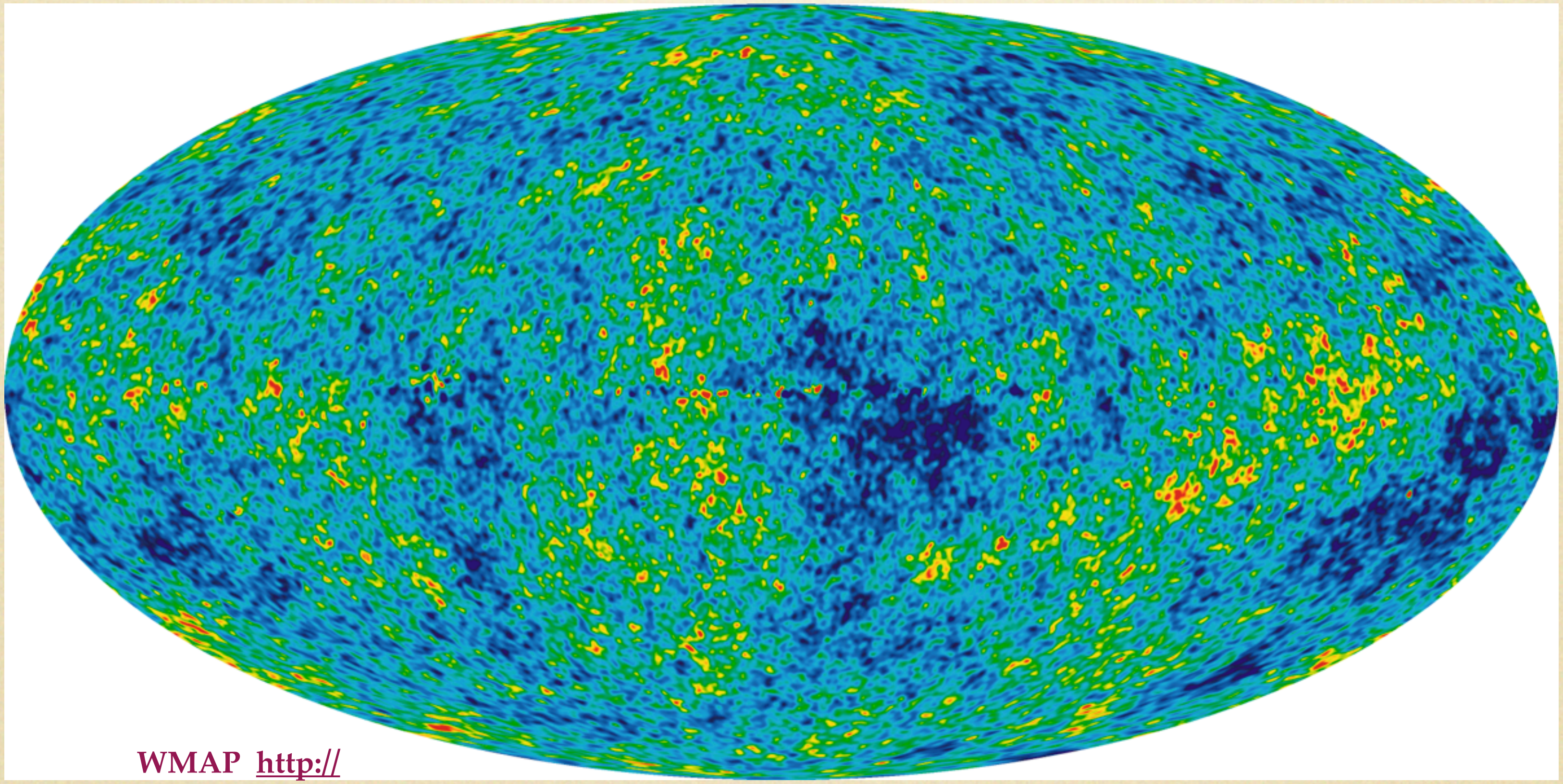


- The Sloan Digital Sky Survey has mapped the positions of millions of galaxies

Galaxy Clustering Patterns

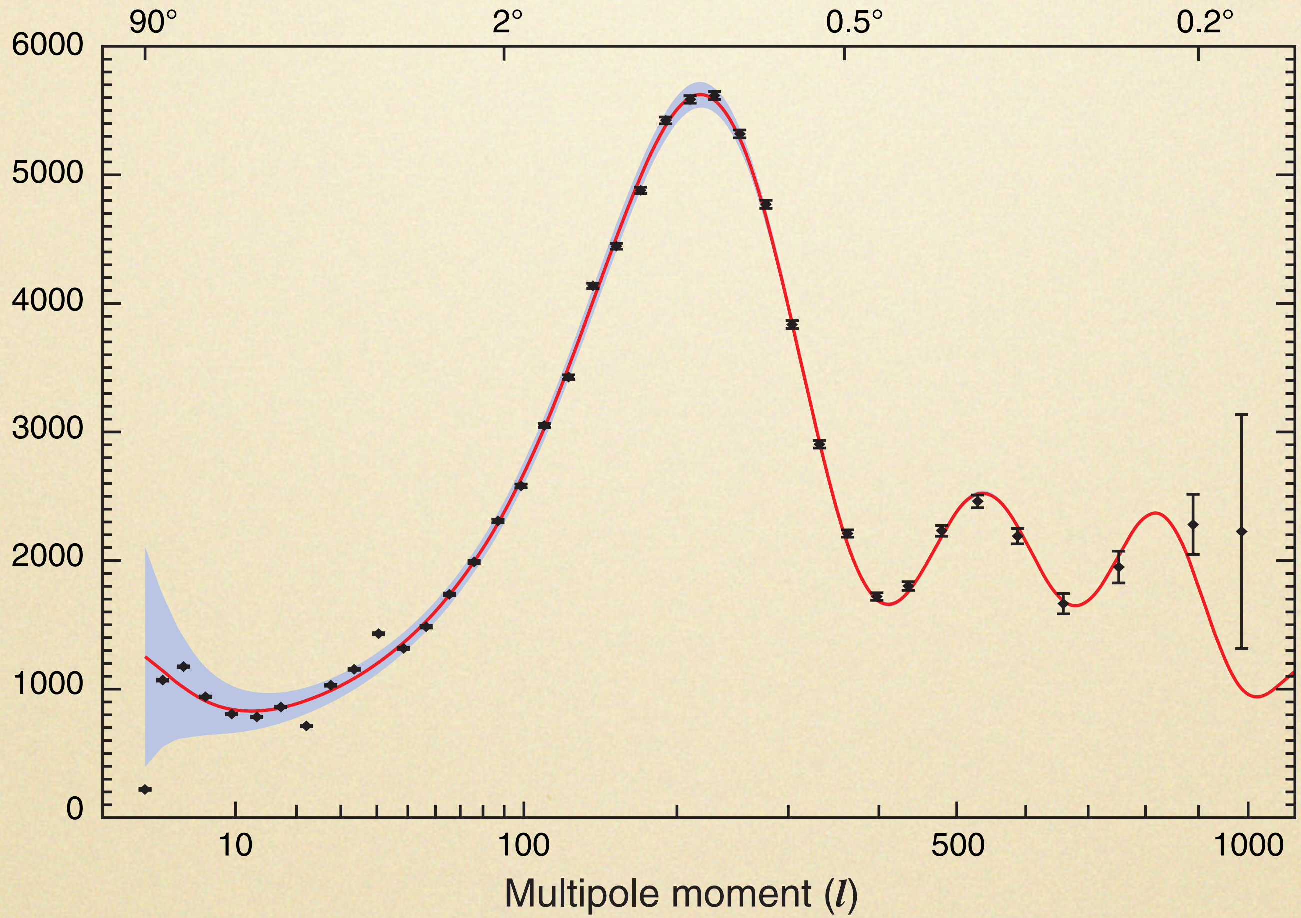
- Comparing the patterns in the way galaxies are distributed throughout the Universe

The CMB Bump in Galaxies



- The "Bump" in the CMB Anisotropy Spectrum leaves an imprint on the pattern of galaxies

The CMB Bump in Galaxies



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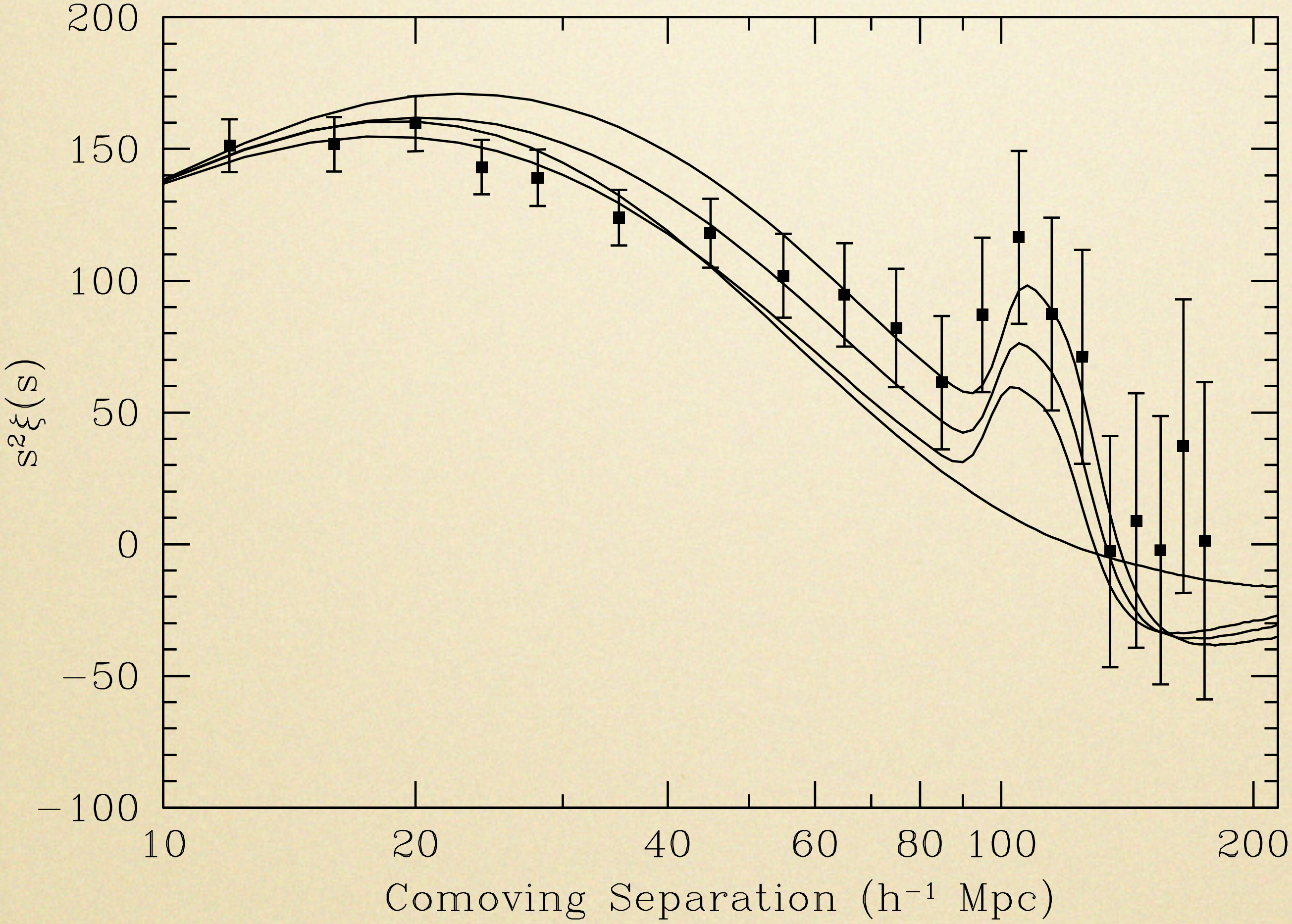
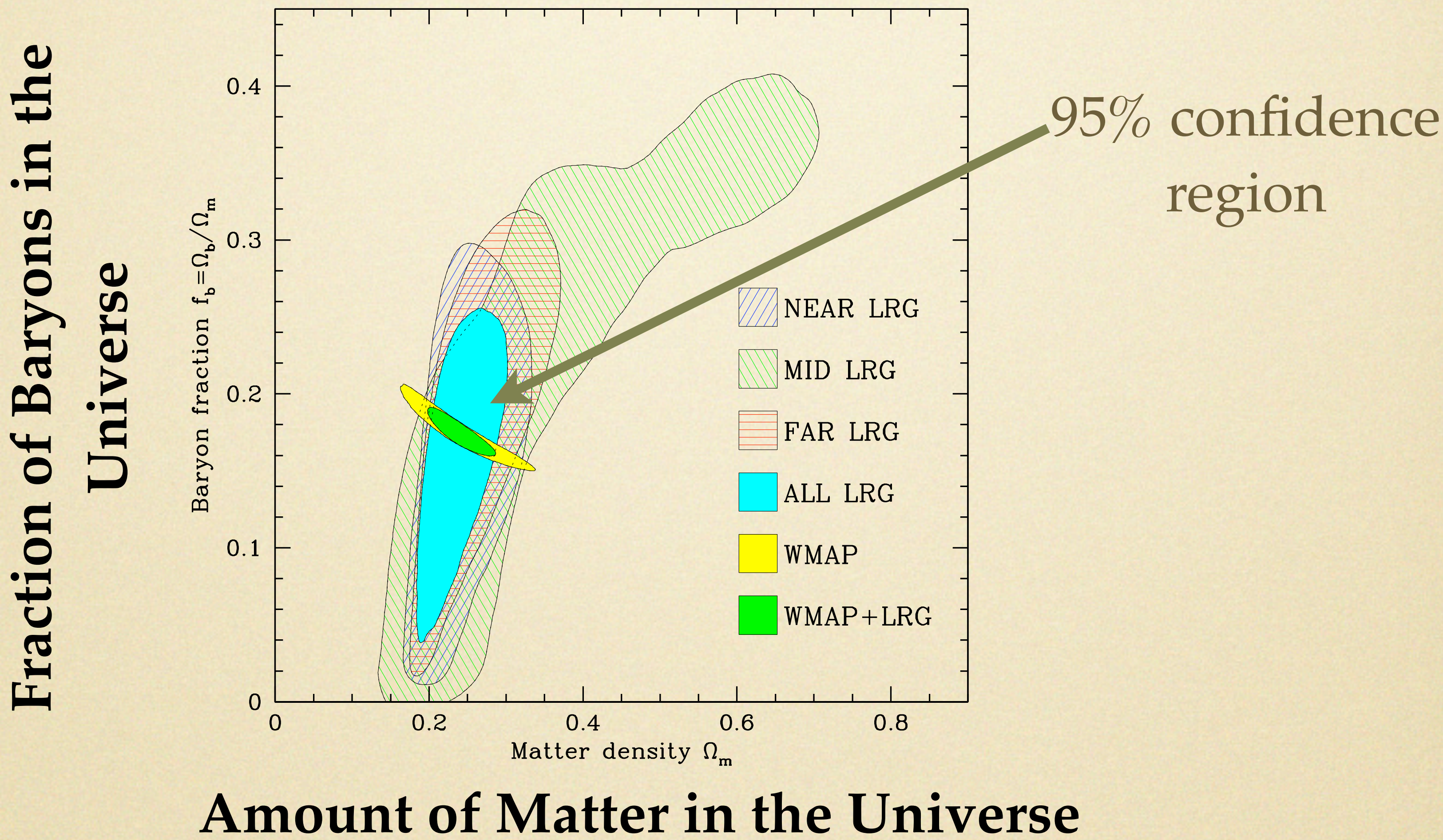


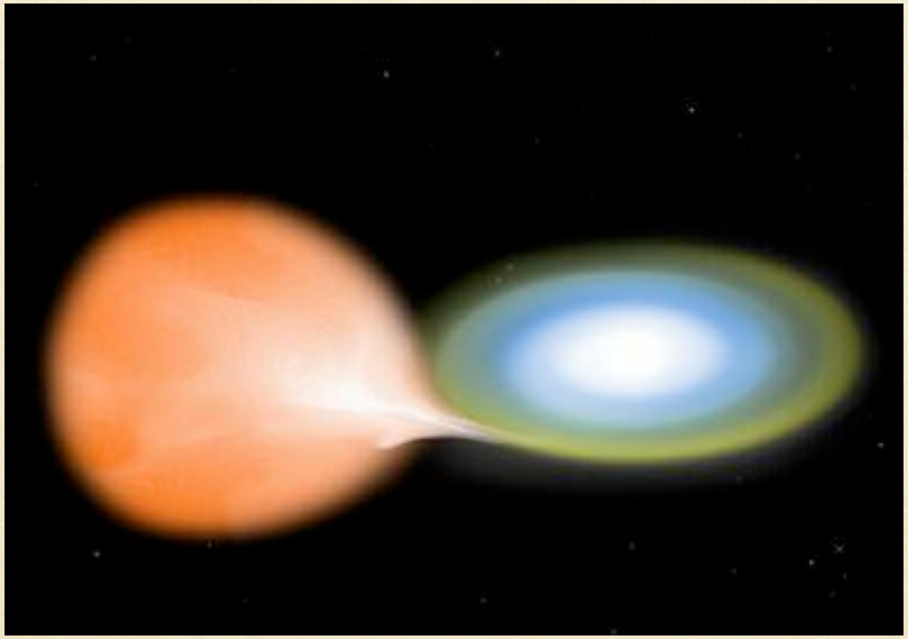
- The "Bump" in the CMB Anisotropy Spectrum leaves an imprint on the pattern of galaxies

The Oscillation Bump



- With the rules of geometry fixed by the CMB, the size of the bump tells us the amount of matter in the Universe

Type Ia Supernovae

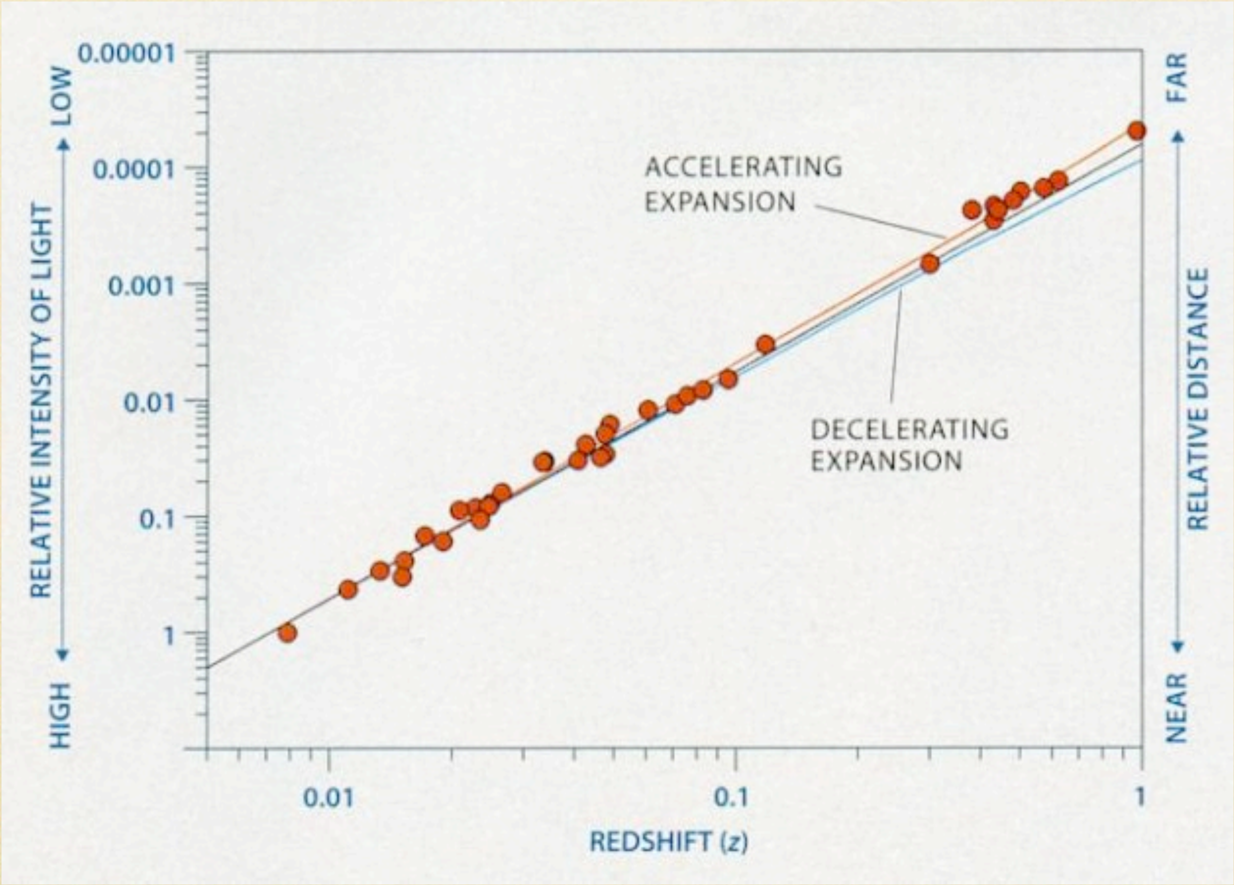


- Occur when a white dwarf accretes mass from a companion that pushes it up to **1.3 times the mass of the sun**
- Because they always occur at this **critical mass**, they have a **fixed luminosity**

Type Ia Supernovae

- Objects with a fixed luminosity are called "standard candles"
- They measure effective distances in the Universe

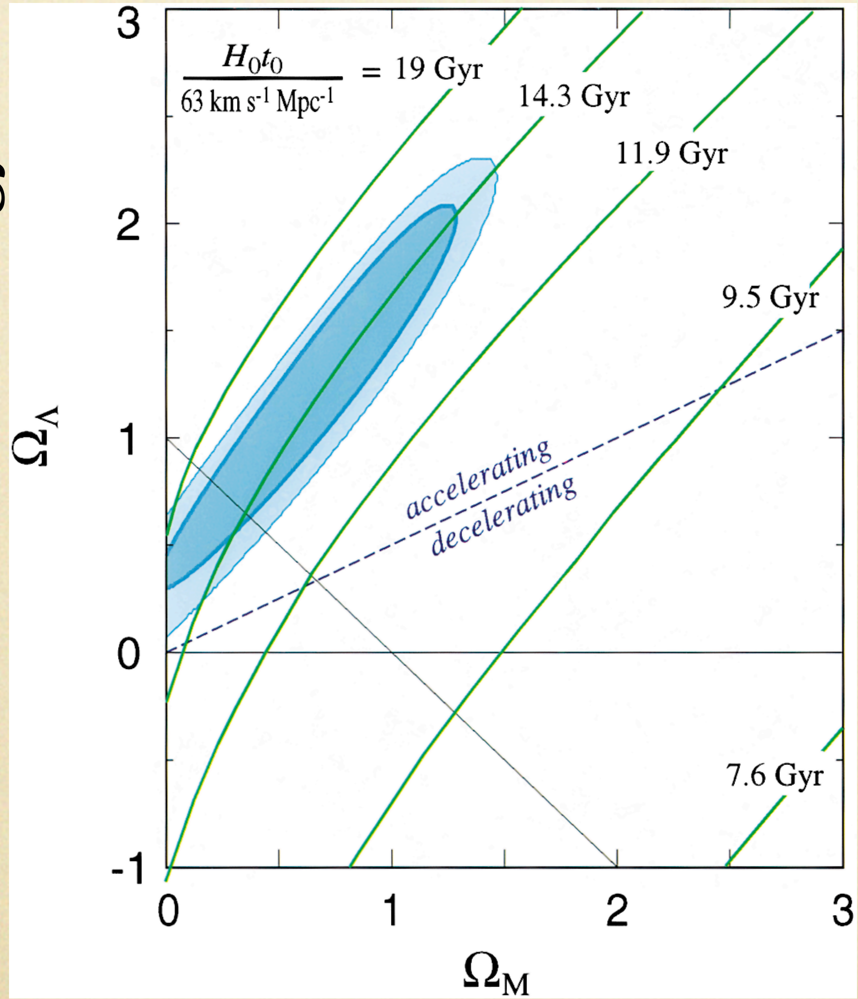
The Accelerating Universe



- Supernova appear dimmer than naively expected ➔ The Universal Expansion is Accelerating!

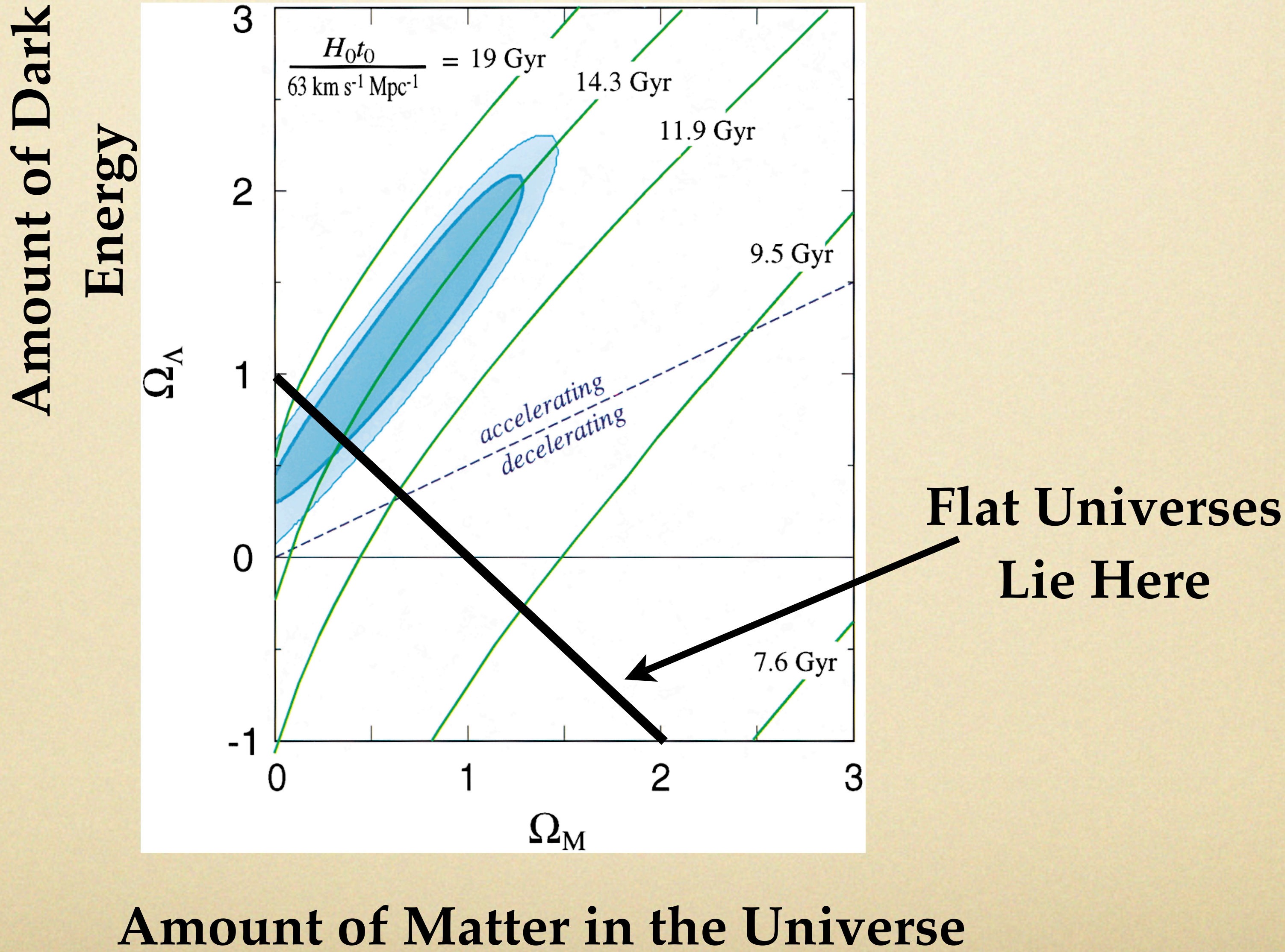
The Accelerating Universe

Amount of Dark Energy

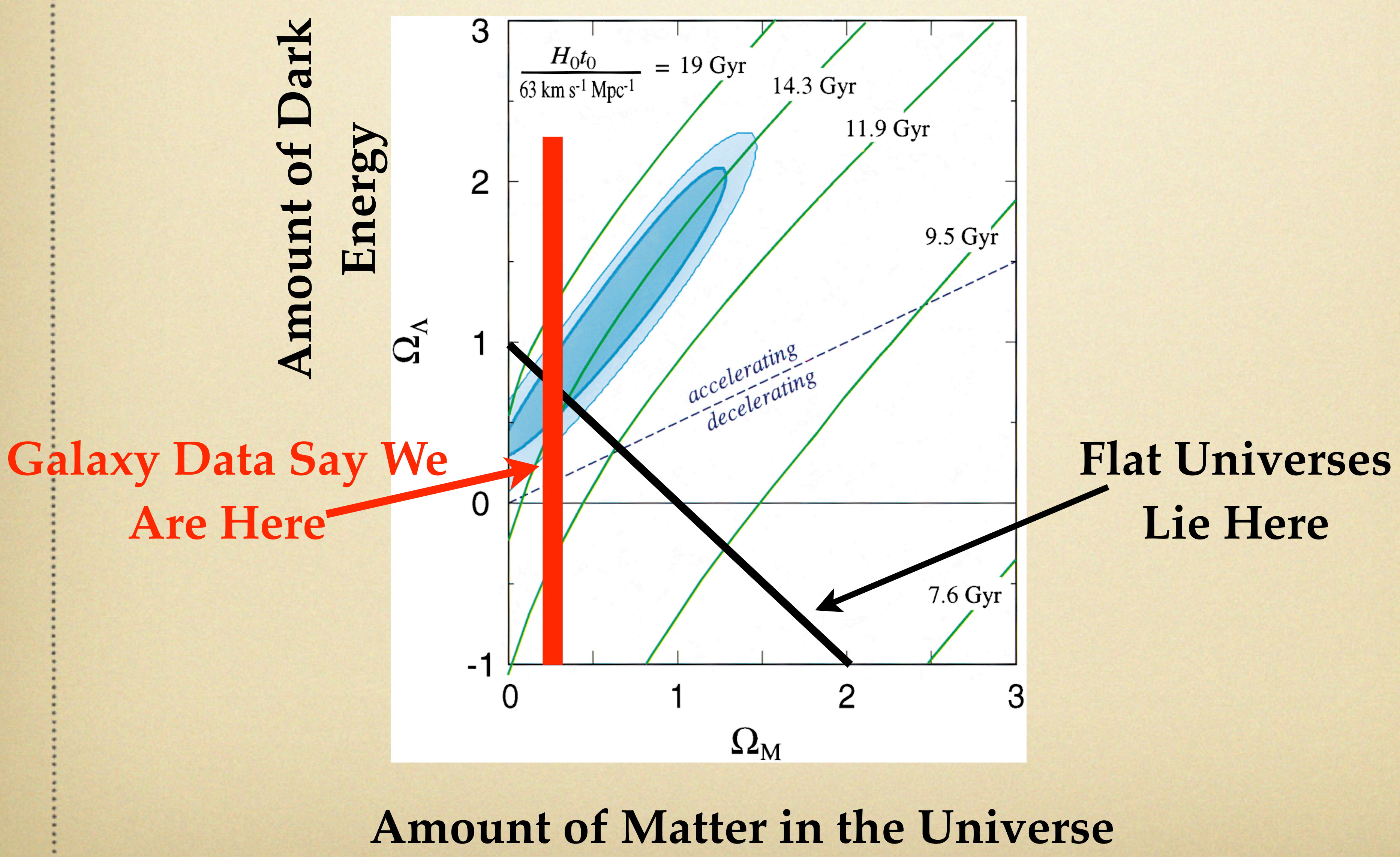


Amount of Matter in the Universe

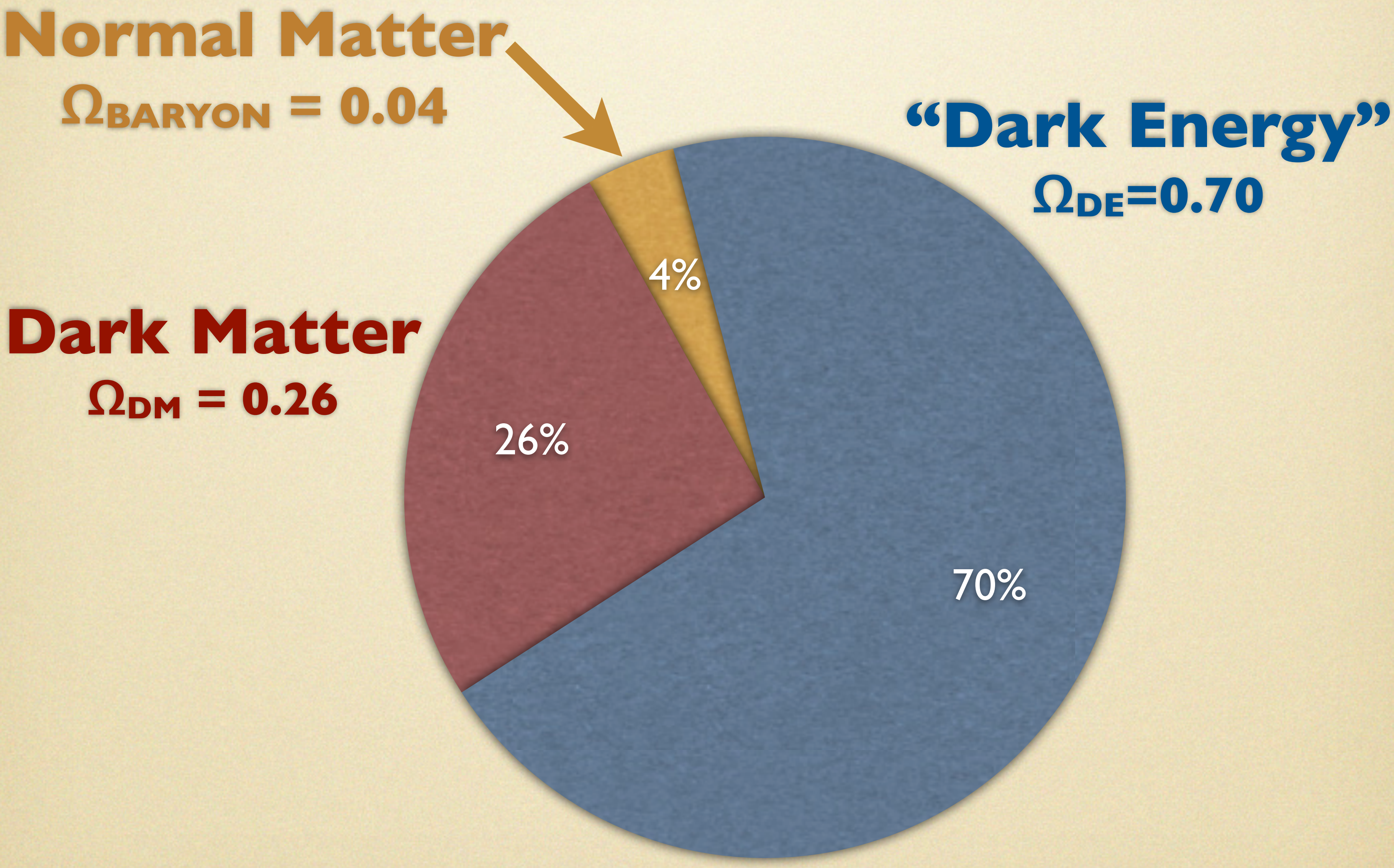
The Accelerating Universe



The Accelerating Universe



The Full Pie



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

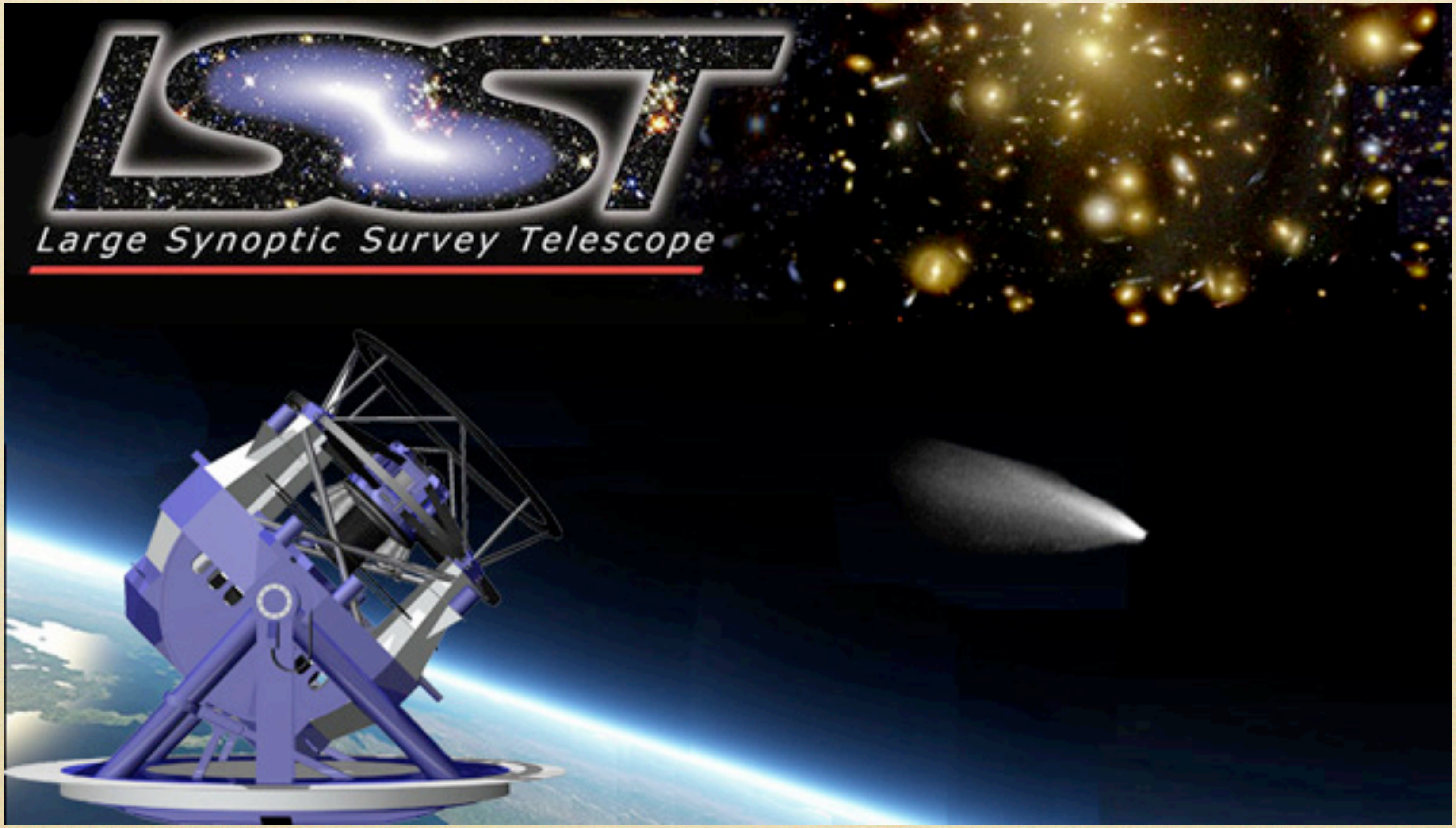
Lensing Support for Dark Matter

Lensing Support for Dark Matter

The Future

- Both Dark Energy and Dark Matter effect the efficiency of gravitational lensing
- Detailed surveys measuring the effects of gravitational lensing on galaxies will hopefully give us clues to the properties of Dark Matter and Dark Energy

The Future



Summary

- We have **good evidence** that:
  - The Universe is only **4% normal matter**
  - The Universe is **24% dark matter**
  - The Universe is **72% dark energy**
  - The Universe if **flat**
  - Structure in the Universe has been around for only about **13.7 Billion years**
  - We can **trace most of this history reliably!**
- This is an impressive achievement
- The future will lead to more fundamental insights into the nature of the dark stuff