Astrophysics ASTR 3415

Cosmology and General Relativity

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University of Glasgow, UK

ETSU Basler Chair, Fall 2005

1916. № 7.

ANNALEN DER PHYSIK.
VIERTE FOLGE. BAND 49.

1. *Die Grundlage der allgemeinen Relativitätstheorie;*
von A. Einstein.

Die im nachfolgenden dargelegte Theorie bildet die denkbar weitgehendste Verallgemeinerung der heute allgemein als „Relativitätstheorie" bezeichneten Theorie; die letztere nenne ich im folgenden zur Unterscheidung von der ersteren „spezielle Relativitätstheorie" und setze sie als bekannt voraus. Die Verallgemeinerung der Relativitätstheorie wurde sehr erleichtert durch die Gestalt, welche der speziellen Relativitätstheorie durch Minkowski gegeben wurde, welcher Mathematiker zuerst die formale Gleichwertigkeit der räumlichen Koordinaten und der Zeitkoordinate klar erkannte und für den Aufbau der Theorie nutzbar machte. Die für die allgemeine Relativitätstheorie nötigen mathematischen Hilfsmittel lagen fertig bereit in dem „absoluten Differentialkalkül", welcher auf den Forschungen von Gauss, Riemann und Christoffel über nichteuklidische Mannigfaltigkeiten ruht und von Ricci und Levi-Civita in ein System gebracht und bereits auf Probleme der theoretischen Physik angewendet wurde. Ich habe im Abschnitt B der vorliegenden Abhandlung alle für uns nötigen, bei dem Physiker nicht als bekannt vorauszusetzenden mathematischen Hilfsmittel in möglichst einfacher und durchsichtiger Weise entwickelt, so daß ein Studium mathematischer Literatur für das Verständnis der vorliegenden Abhandlung nicht erforderlich ist. Endlich sei an dieser Stelle dankbar meines Freundes, des Mathematikers Grossmann, gedacht, der mir durch seine Hilfe nicht nur das Studium der einschlägigen mathematischen Literatur ersparte, sondern mich auch beim Suchen nach den Feldgleichungen der Gravitation unterstützte.

Theory of General Relativity,
Published 1916 –
11 years after Einstein's
"Miraculous Year"

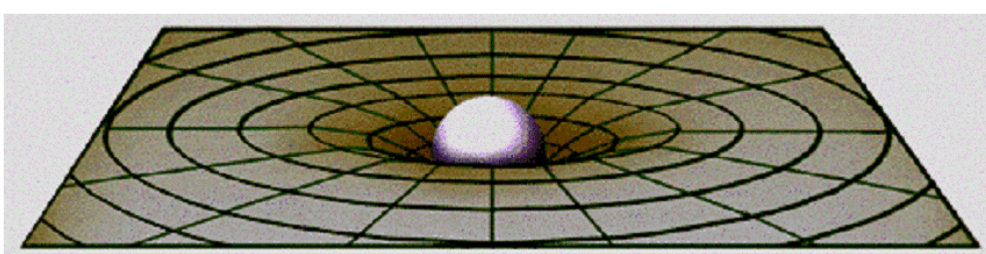
GR provides the mathematical and physical foundations of modern cosmology

Einstein and GR seem topics worthy of the goals of the Basler Chair:

- Einstein's cultural influence extends well beyond science
- GR has profound implications for our modern world

Problem:

bridging the gap between qualitative and rigorous understanding



> "Spacetime tells matter how to move,
> and matter tells spacetime how to curve"

But what do we mean by 'spacetime', 'curvature', 'tells' ?

We need some post-Newtonian physical thinking,
and the mathematical language of **differential geometry**

Course outline:

Week 1

1. *Brief overview of modern cosmology*

- What is cosmology?
- "State of the Universe 2005": the Concordance Model
- Cornerstones of the Big Bang theory

7 - 8 meetings

2. *Introduction to general relativity*

- The equivalence principle and its physical consequences
- Special relativity, spacetime and a first look at tensors
- Manifolds, parallel transport and geodesics
- The energy-momentum tensor and conservation laws in GR
- The curvature tensor and Einstein's equations
- The weak field limit and correspondence with Newtonian gravity

3. *Applications of General Relativity*

- The Schwarzschild metric and the classical tests of GR
- Gravitational lensing: nature's telescope
- Black holes: theory and observations
- Searching for gravitational waves
- GR foundations of cosmology: FRW models and Friedmann's equations

4. *Cosmology Revisited:*

- *Where are we?* The parameters that describe our universe
- *How did we get there?* The formation and evolution of cosmic structure
- *Why are we here?* Inflation and the very early universe;

  Dark energy: Einstein's greatest blunder?...

  Some puzzles for 21st century cosmologists

Course material:

ASTR3415 is a synthesis of several UG- and graduate-level courses I have given recently at Glasgow University

- Level 1 – Introduction to Cosmology (Part 1, 4) ★
- Level 2 – Introduction to GR (Part 2, 3)
- Level 4 – Gravitation and Relativity (Part 2, 3) ★
- Level 4 – Galaxies (Part 3, 4) ★
- Graduate lectures on cosmology (Part 1, 4)

★ I will distribute, and work from, complete sets of lecture notes for these courses (In GU, the notes function as the textbooks)

Notes for all courses available via

http://www.astro.gla.ac.uk/users/martin/basler/astrophysics.html

Course assessment:

Final score = 15% x [Exam 1] / 50 + 15% x [Exam 2] / 50
+ 15% x [Exam 3] / 50

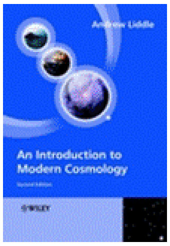
+ 20% x [Project] / 100

+ 30% x [Homework score] / [Homework total]

Final grades will be computed as follows:

A	=	90% or better	B–	=	73 – 75.9%	D+	=	56 – 58.9%
A–	=	88 – 89.9%	C+	=	70 – 72.9%	D	=	50 – 55.9%
B+	=	86 – 87.9%	C	=	62 – 69.9%	F	=	Less than 50%
B	=	76 – 85.9%	C–	=	59 – 61.9%			

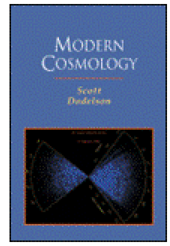
Course material: Books



"An Introduction to modern Cosmology"
Andrew Liddle

ISBN: 0471987581

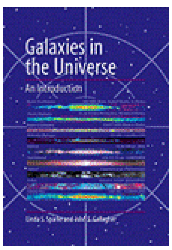
Accessible, concise, clear treatment of most material in part 1 and 4. Very brief discussion of GR



"Modern Cosmology"
Scott Dodelson

ISBN: 022191412

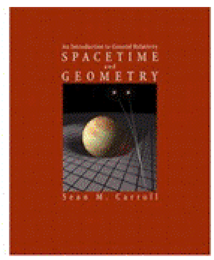
Much more advanced treatment of part 1 and 4; good summary of GR covering part 2 and most of part 3



"Galaxies in the Universe"
Linda Sparke & Jay Gallagher

ISBN: 0521597404

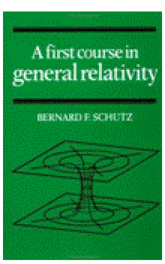
Excellent at linking cosmology to other areas of astrophysics (e.g. stellar evolution, AGN)



"An Introduction to General Relativity, Spacetime and Geometry"
Sean Carroll

ISBN: 0805387323

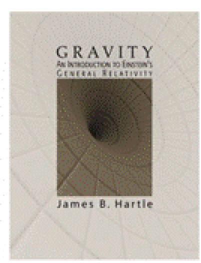
Marvellous book for all parts of the course (but in many places pitches at a significantly higher level)



"A First Course in General Relativity"
Bernard Schutz

ISBN: 052177035

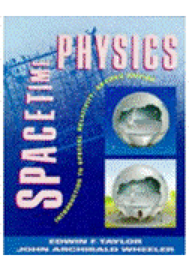
Excellent reference source for part 2 and 3; cosmology sections now well out of date



"Gravity: An Introduction to Einstein's General Relativity"
James Hartle

ISBN: 0805386629

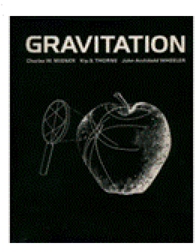
Covers similar material to Carroll (although not quite so good)



"Spacetime Physics"
Edwin Taylor & John Wheeler

ISBN: 0716727371

Very good physical description of special relativity; some good physical insight on curvature and metrics



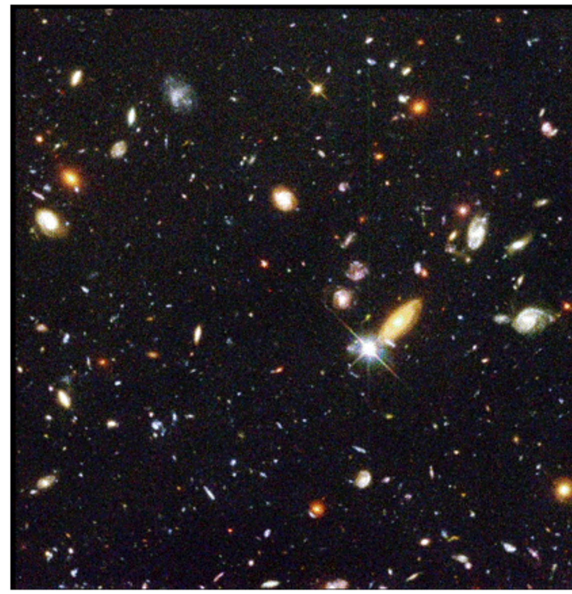
"Gravitation"
Charles Misner, Kip Thorne, John Wheeler

ISBN: 0716703440

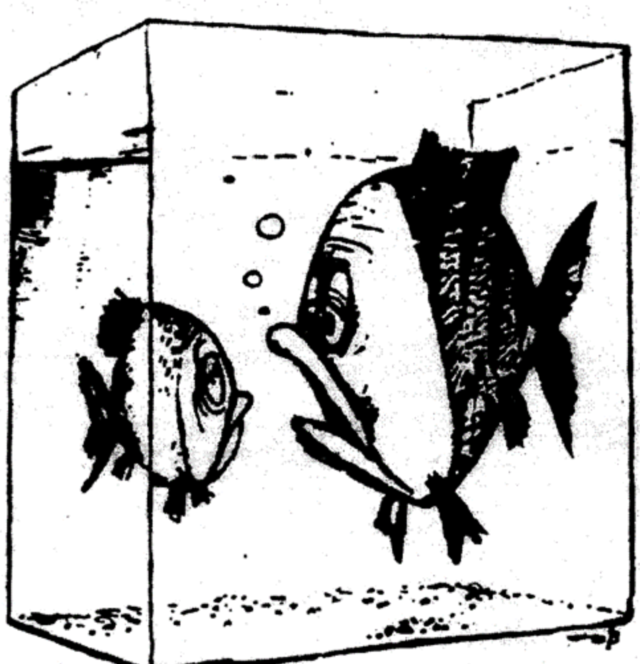
The 'bible' for studying GR

Cosmology – the study of the Universe as a whole:

- Origin
- Evolution
- Eventual Fate



Cosmological theories depend on the available data



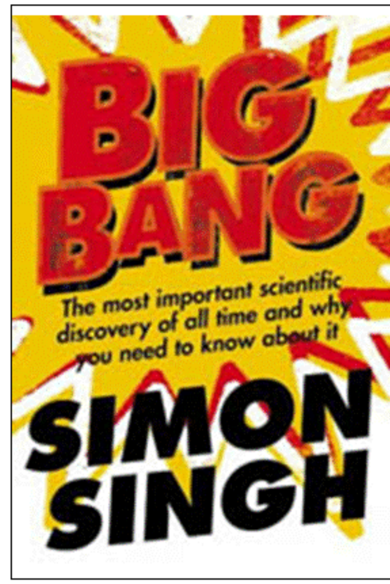
'The universe, my son, is a large tank full of water

The present day:

The Big Bang has become *the* accepted theory for the origin and evolution of the Universe…

…yet in some sense there are *many* Big Bang theories - different parameters control e.g. the age, size, density, temperature, chemical composition of the Universe.

Which parameters describe our Universe?....



The Concordance Model

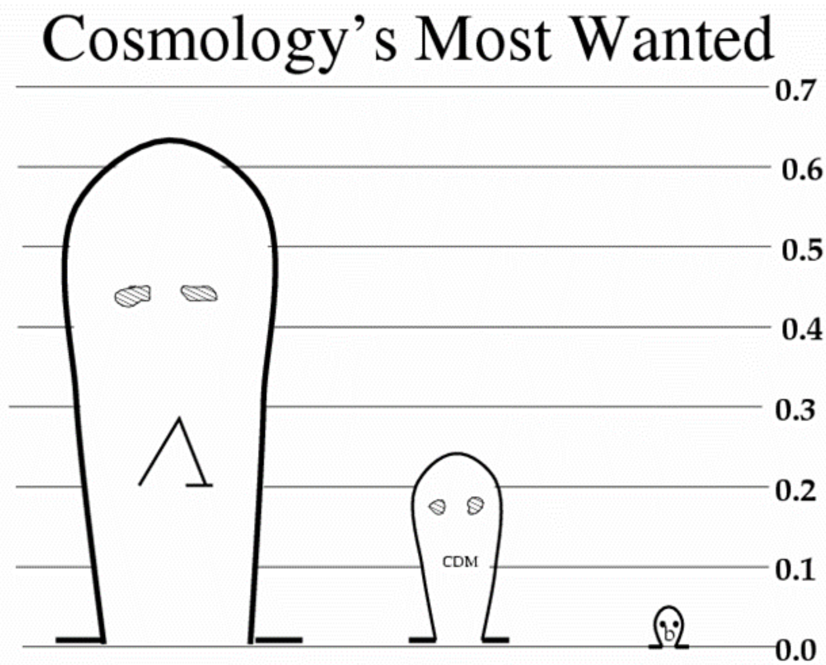
What do we mean by the "Concordance Model" anyway?

Since the late 1990s a remarkably (spookily?) consistent picture has emerged from all sorts of different observations.

(This picture is not particularly simple or elegant!)

- The Universe began with a Big Bang, about 15 billion years ago, and has been expanding ever since
- It has a flat geometry (which is a prediction of inflation)
- Energy budget – 1: 30% gravitating matter (a few percent is baryonic, the rest known as CDM – but we don't know what that is)
- Energy budget – 2: 70% 'dark energy' – we *really* don't know what that is but it is now causing the expansion of the Universe to accelerate, and probably has something to do with the energy of the vacuum.
- Energy budget – 3: a few percent probably also comes from massive neutrinos (but those can't be the CDM)
- Large Scale Structure in the Universe grew from tiny quantum fluctuations (probably generated during inflation), first seen in the CMBR, under the influence of gravity.

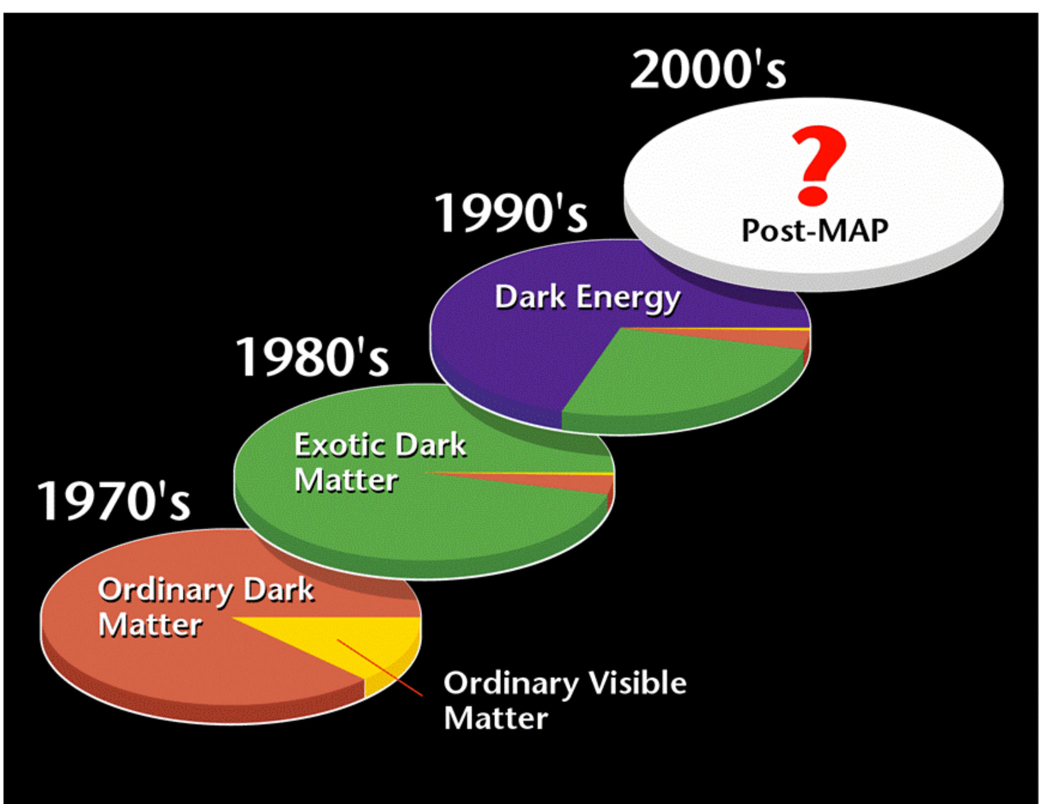
ΛCDM

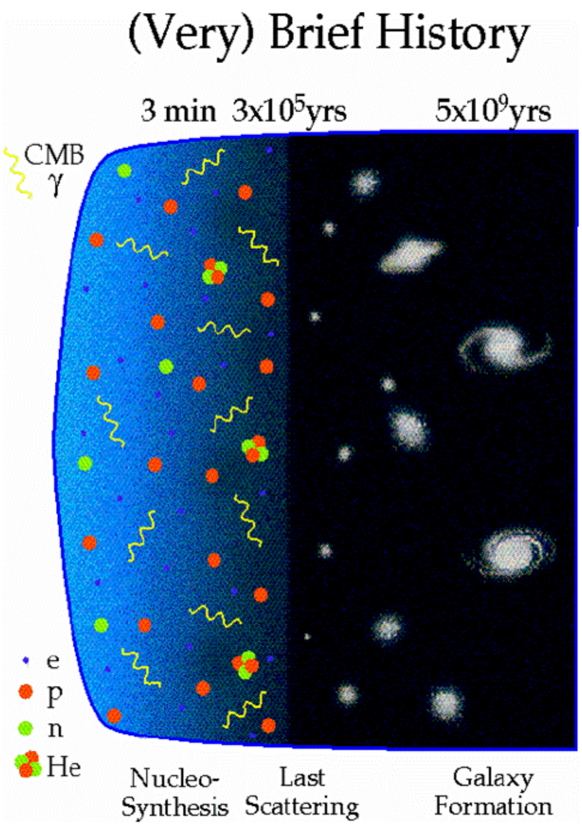


Ω_Λ	Ω_{CDM}	Ω_b
cosmological constant energy of the vacuum He never clumps His evil plan is to blow up the Universe	cold dark matter He likes to clump but has never been detected directly His evil plan is to make the Universe collapse	normal baryonic matter a pawn in the cosmic game who just follows CDM around. He thinks he's a complex life form but is really just a bunch of hydrogen

Figure 3. A line up of cosmological culprits Ω_Λ is the big shot controlling the Universe. He's going to make it blow up. Ω_{CDM} would like to make the Universe collapse but can't compete with Ω_Λ. Ω_b just follows Ω_{CDM} around. Like all dangerous criminals, one can never be sure of Ω_Λ until he is behind bars. The CMB police is being beefed up. Hundreds of heroic CMB observers are now planning his capture.

From Lineweaver (1998)

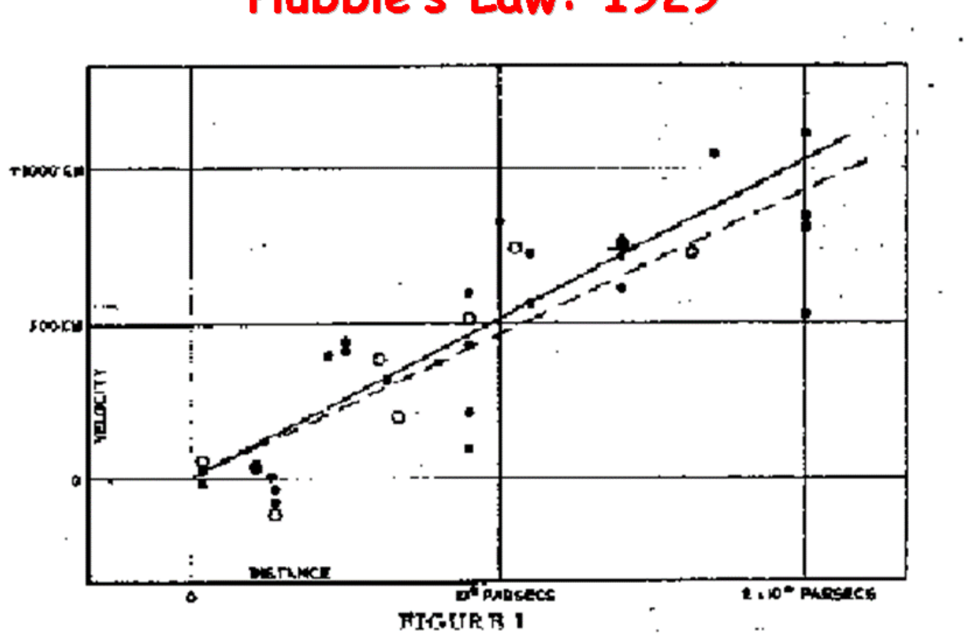




Cornerstones of the Hot Big Bang Model

1.	Expansion of the Universe
2.	Evolution of the Universe
3.	Light Element Abundances
4.	CMBR

Hubble's Law: 1929



Distant galaxies are receding from us with a velocity proportional to their distance

Hubble's Law

$$V = H_0 d$$

H_0 has units of (time)$^{-1}$ – usually measured in kilometres per second per Megaparsec

1 pc = 3.26 light years = 3×10^{16} m

H_0^{-1} = **Hubble time** = timescale for the *expansion age* of the Universe

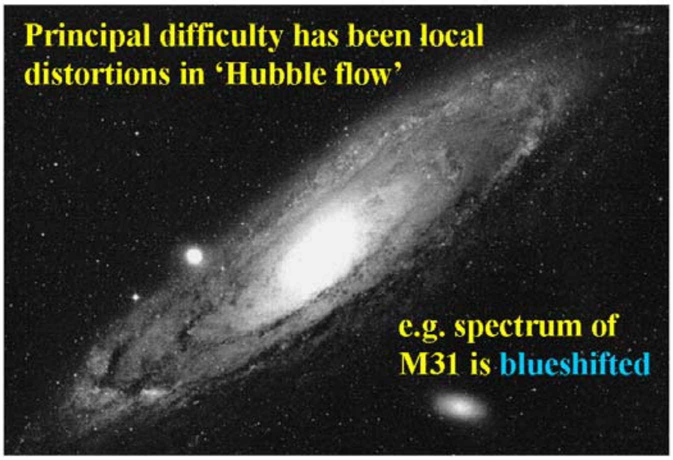
Hubble's original work gave $H_0 = 500$ (in conflict with Geological timescale)

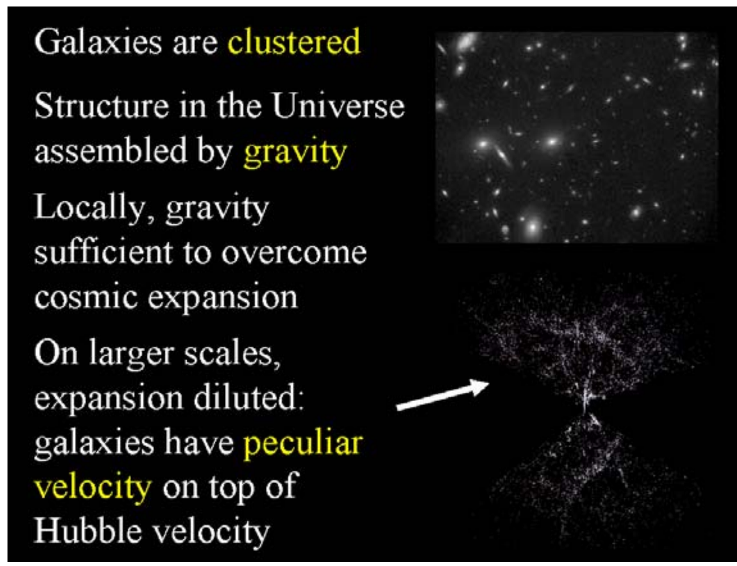
'Modern' values saw dichotomy between $H_0 = 50$, and $H_0 = 100$ (with small statistical error)

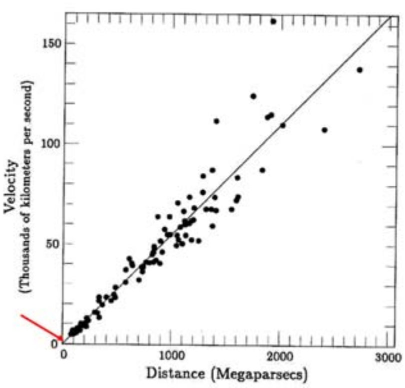
????

How fast is the Universe expanding?

Key Project of the HST

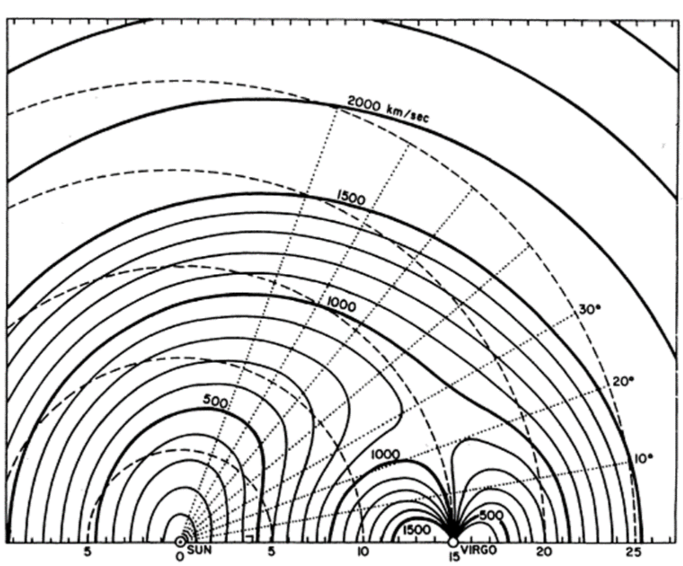






Range probed by Hubble's original work

Main local distortion due to Virgo cluster



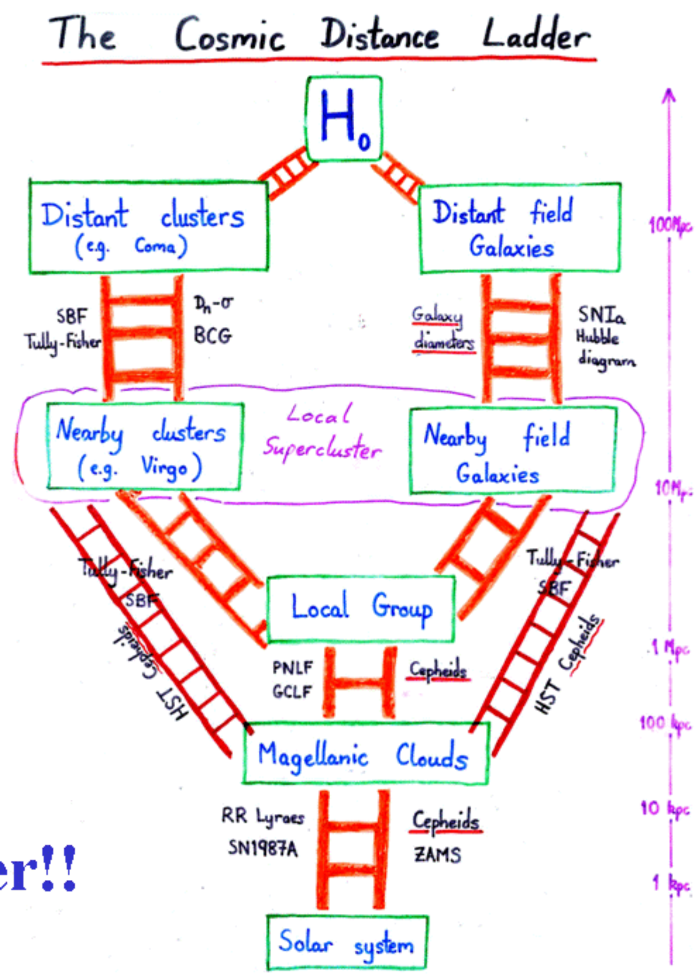
Problem:

Need to determine H_0 from remote galaxies, where peculiar motions are less important….

….**but….**

We cannot use primary distance indicators to measure their distance

Need Distance Ladder!!



HST has 'bypassed' one stage of the Distance Ladder, by observing Cepheids beyond the Local Group of galaxies

This has dramatically improved measurements of H_0

Must ensure that remote galaxy data are free from **Selection Effects**

e.g. intrinsically brighter or bigger?…

⬇

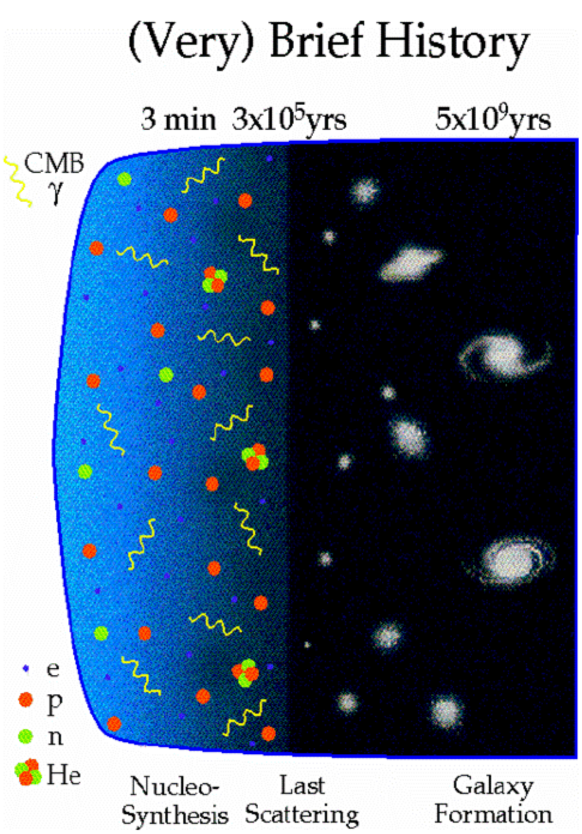
Malmquist Bias

HST Key Project Final Results

Freedman et al. (2001)

$$H_0 = 72 \pm 3 \pm 7 \text{ kms}^{-1}\text{Mpc}^{-1}$$

Combined analysis of several different secondary distance indicators.



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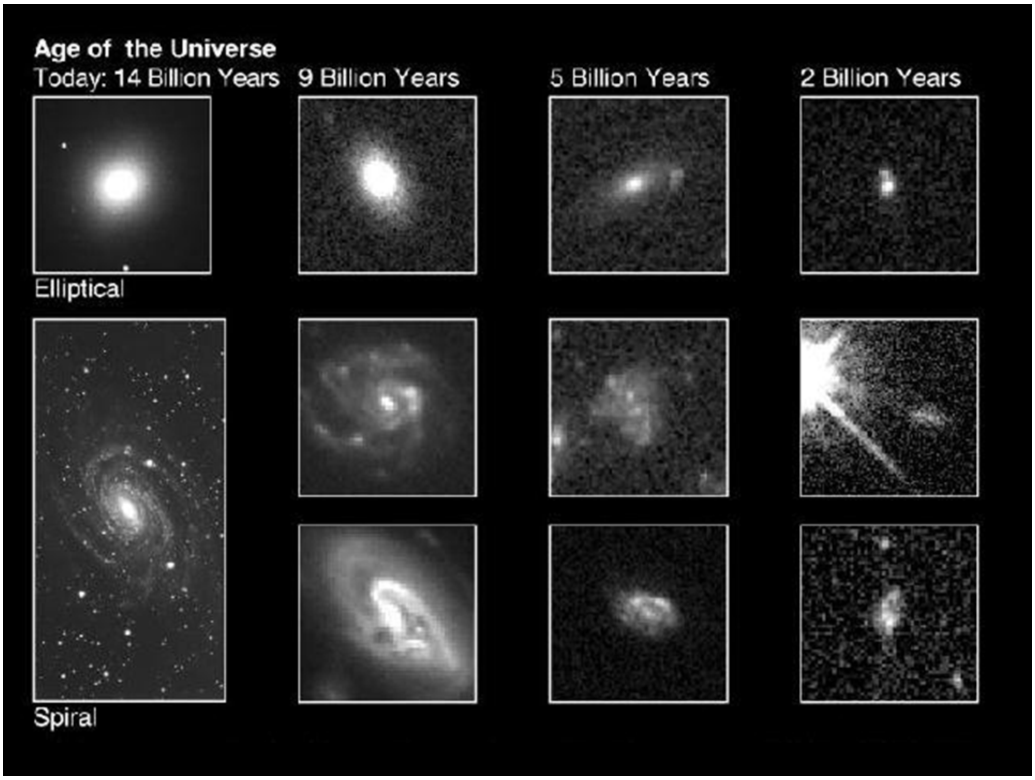
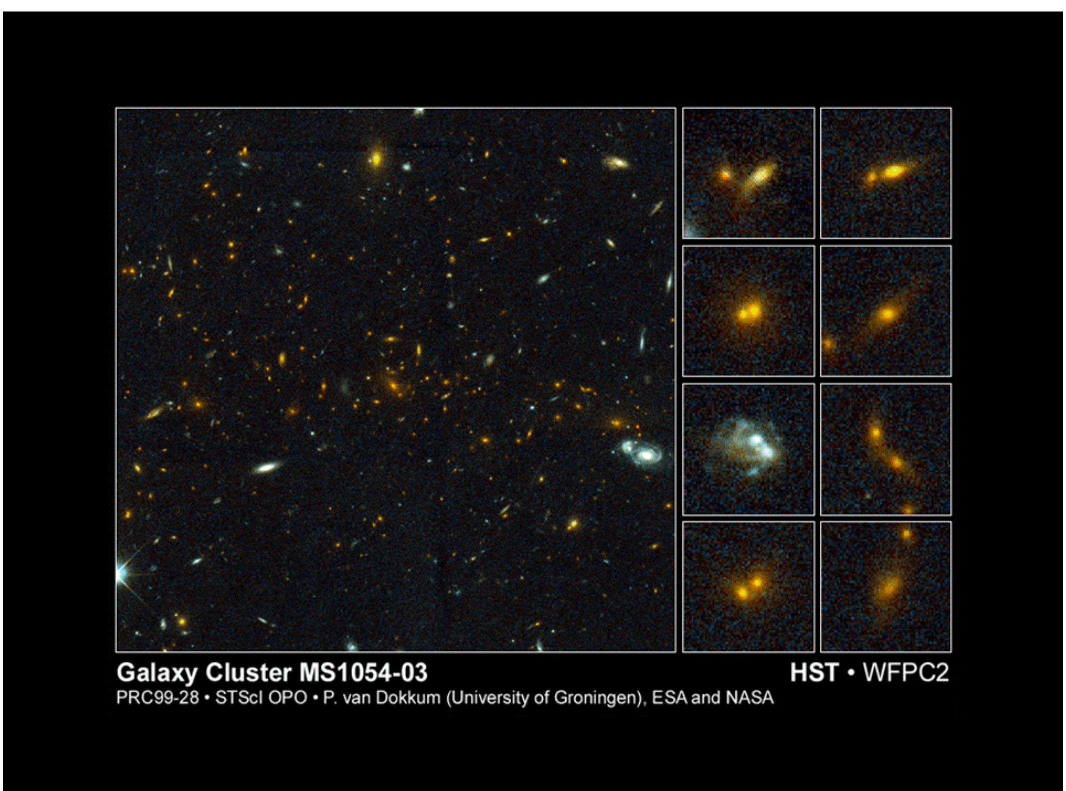
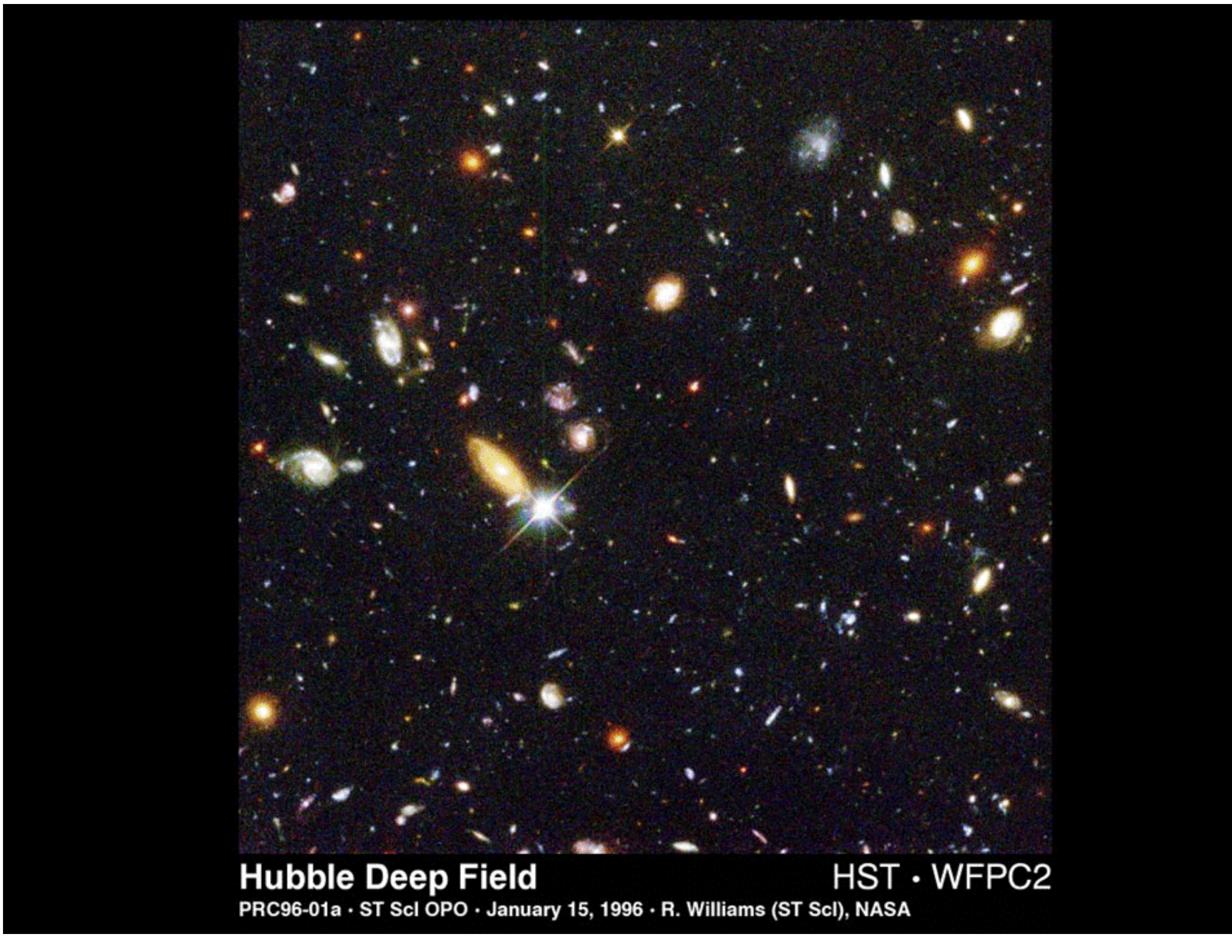
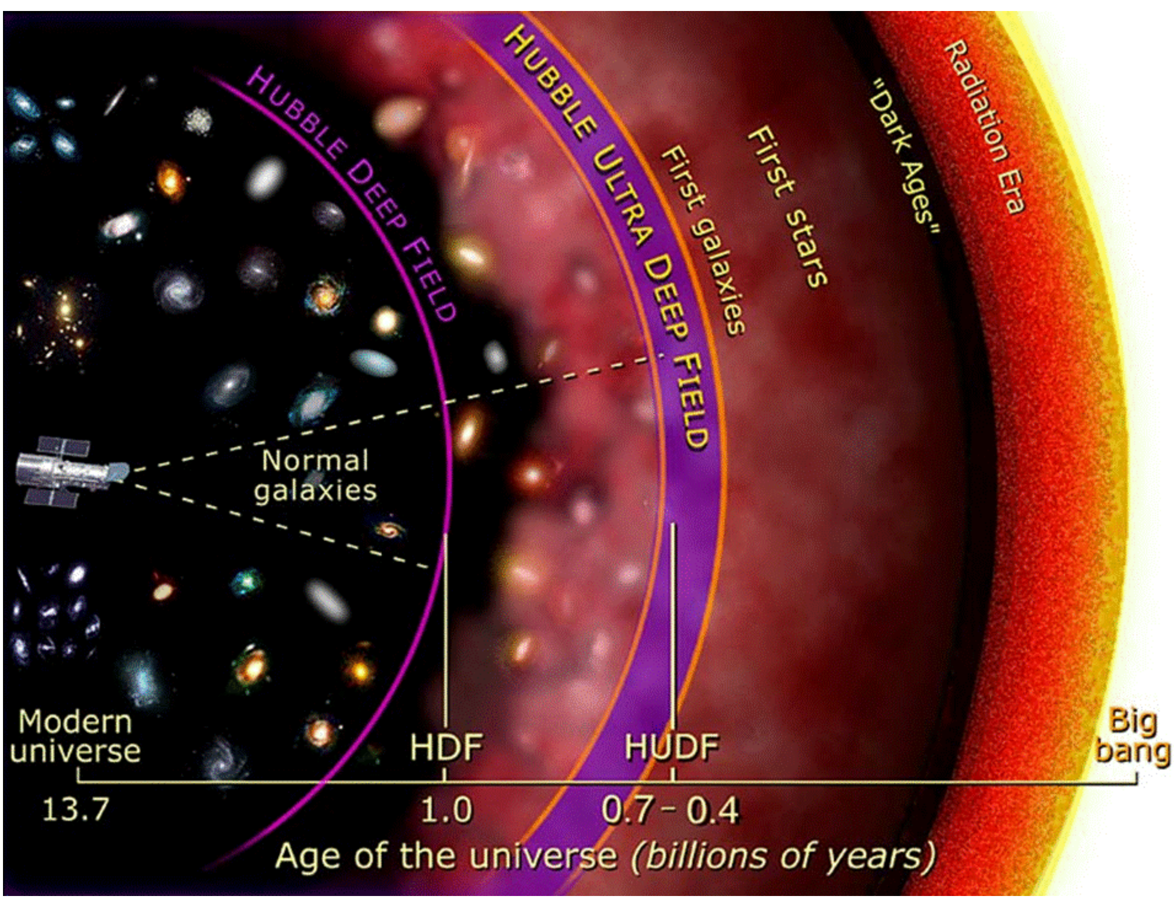
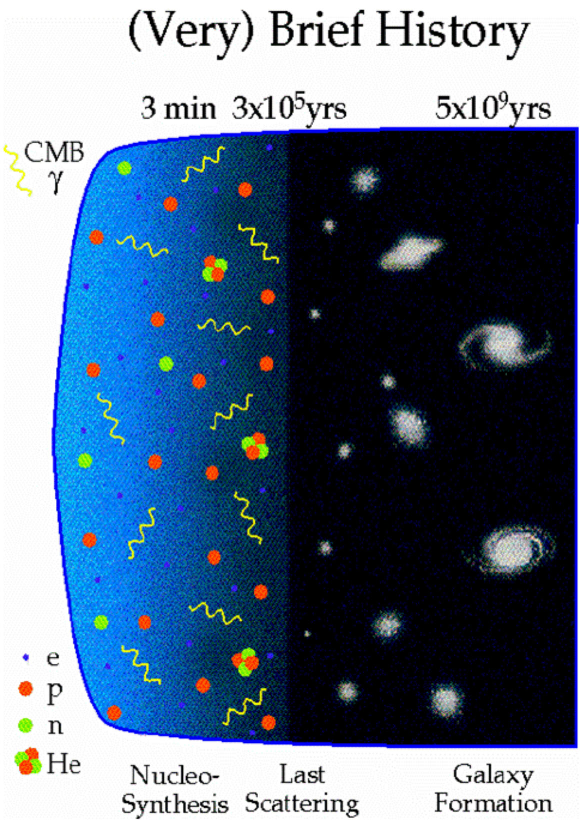

Age of the Universe
Today: 14 Billion Years
9 Billion Years
5 Billion Years
2 Billion Years
Elliptical
Spiral


Galaxy Cluster MS1054-03
HST • WFPC2
PRC99-28 • STScI OPO • P. van Dokkum (University of Groningen), ESA and NASA


Hubble Deep Field
HST • WFPC2
PRC96-01a • ST ScI OPO • January 15, 1996 • R. Williams (ST ScI), NASA


Hubble Deep Field
Hubble Ultra Deep Field
First galaxies
First stars
"Dark Ages"
Radiation Era
Normal galaxies
Modern universe
HDF
HUDF
Big bang
13.7
1.0
0.7 – 0.4
Age of the universe (billions of years)



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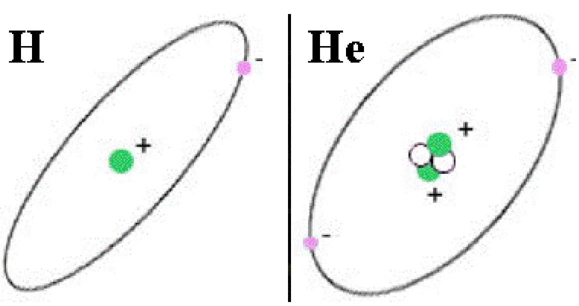
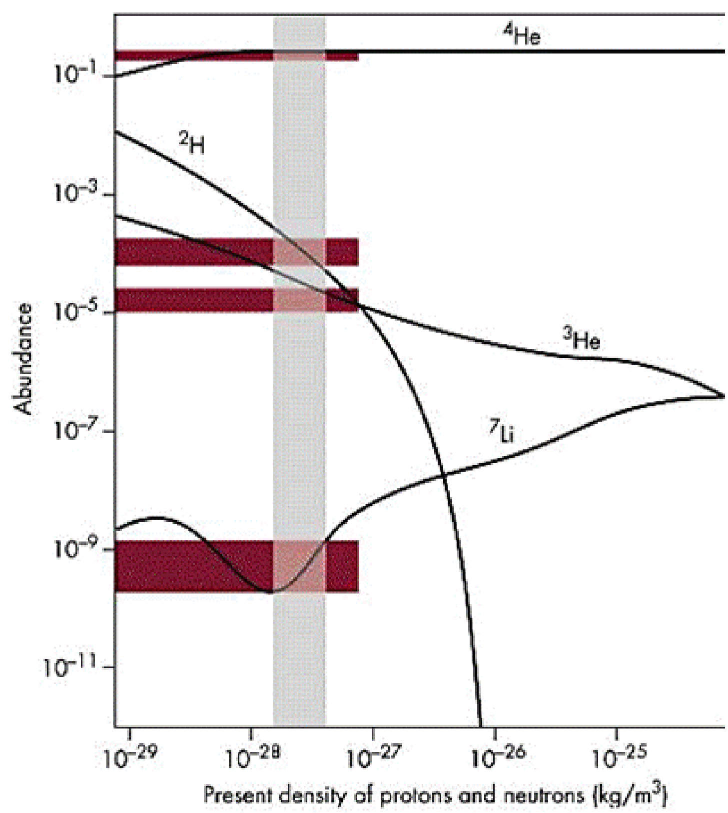


Helium cooked during first Three minutes

(also trace amounts of Lithium, Deuterium, Tritium and Beryllium

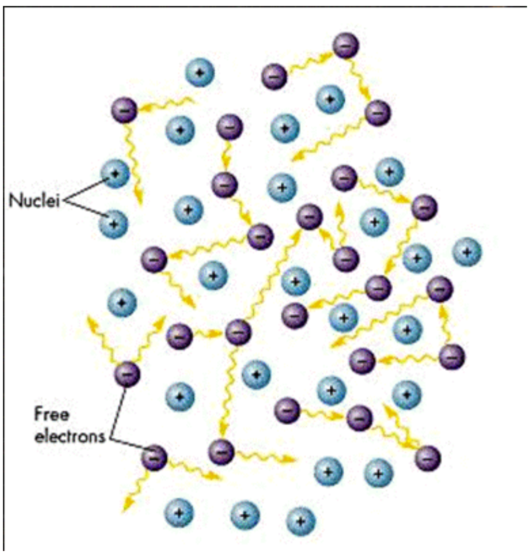
Big Bang theory predicts correct amounts of all of these elements

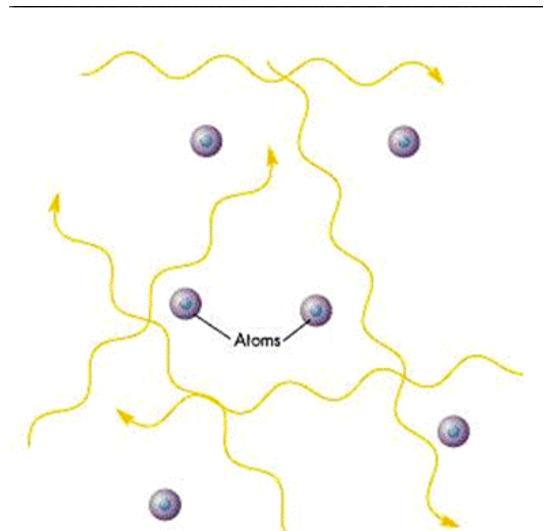


Early Universe too hot for neutral atoms

Free electrons scattered photons (as in a fog)

After ~300,000 years, cool enough for atoms; fog clears!

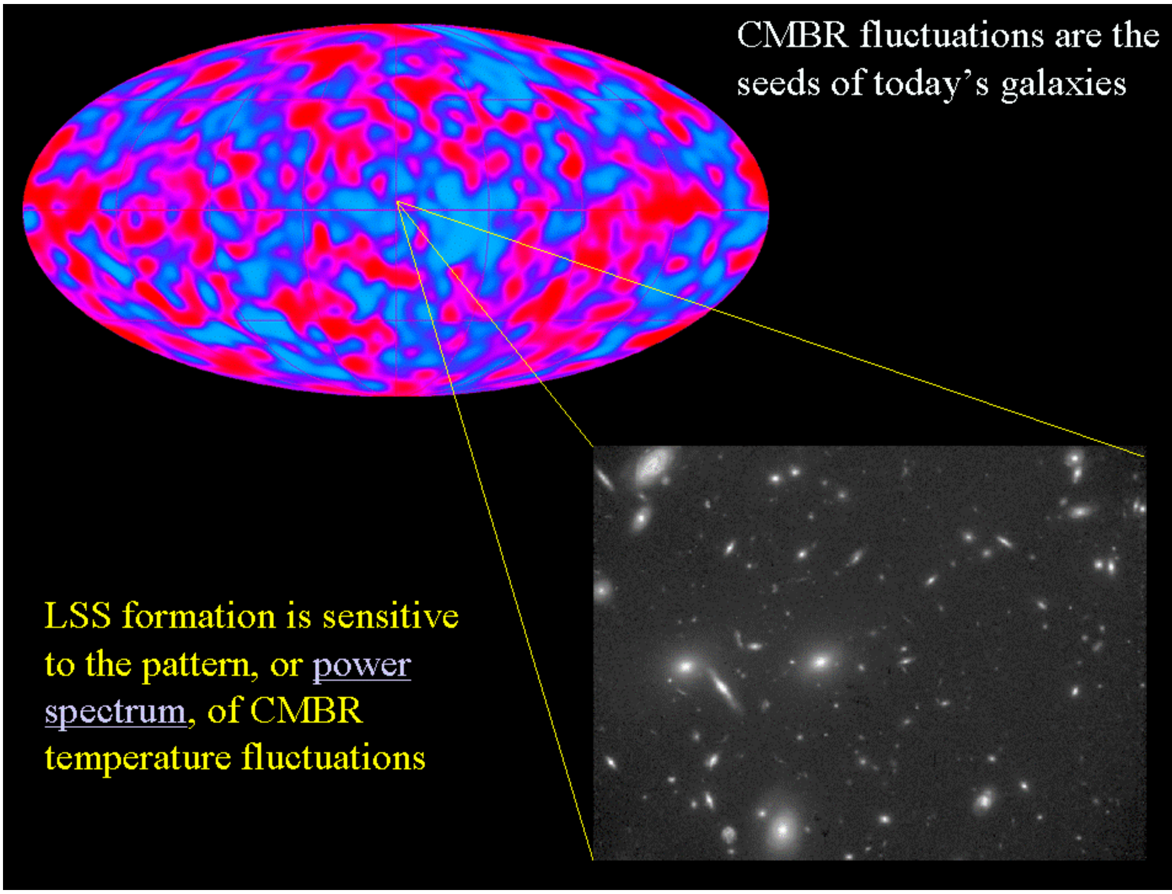




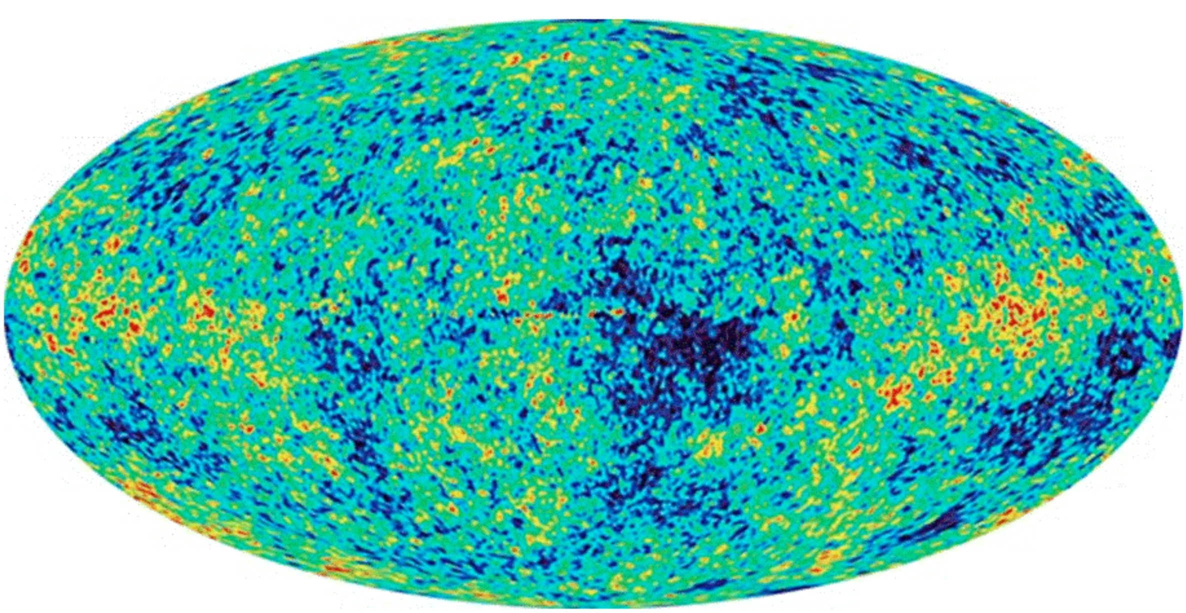
T ~ 3K

Strong support for the Cosmological Principle:

"The Universe is homogeneous and isotropic on large scales"



From Bennett et al (2003)



WMAP results, published early 2003