Astrophysics ASTR 3415

Cosmology
and
General Relativity

Dr Martin Hendry
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

EAST TENNESSEE STATE UNIVERSITY

College of Arts and Sciences

Sunday, Aug 21, 2005Sunday, Aug 21, 2005

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Basler Chair

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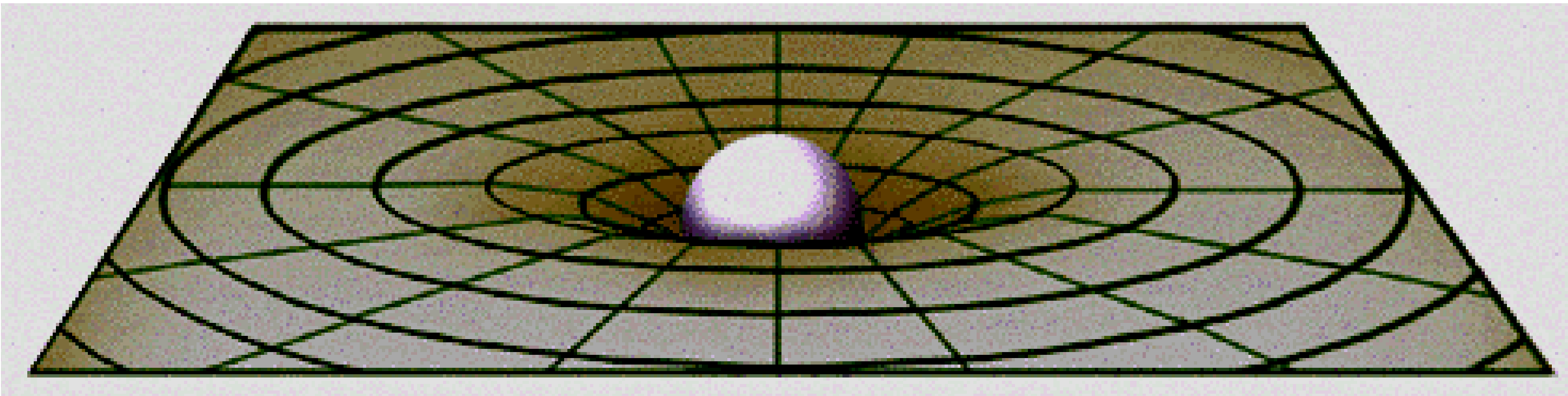
Einstein and GR seem topics worthy of the goals of the Basler Chair:

- 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:

1. *Brief overview of modern cosmology*

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

2. *Introduction to general relativity*

- The equivalence principle and its physical consequences
- Special relativity, spacetime and a first look at tensors
- Manifolds, covariant differentiation 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

Course outline:

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 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

Course outline:

8 - 9 meetings

3. *Applications of General Relativity*

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  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

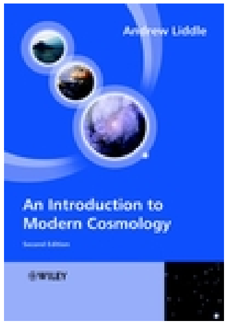
Level 1 – Introduction to Cosmology	(Part 1, 4)	★
Level 2 – Introduction to GR	(Part 2, 3)	
Level 4 – Gravitation and Relativity	(Part 2, 3)	★
Level 4 – Galaxies	(Part 3, 4)	★
Graduate lectures on cosmology	(Part 1, 4)	

★ 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

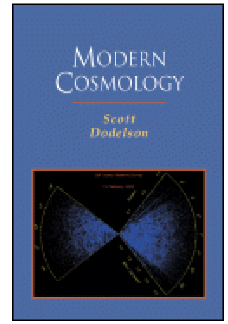
Course material: Books



"An Introduction to modern Cosmology"
Andrew Liddle

ISBN: 0471987581

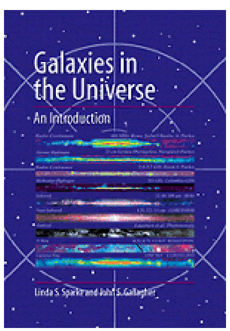
Accessible, concise, clear treatment of most material in part 1 and 4. Very brief discussion of GR



"Modern Cosmology"
Scott Dodelson

ISBN: 022191412

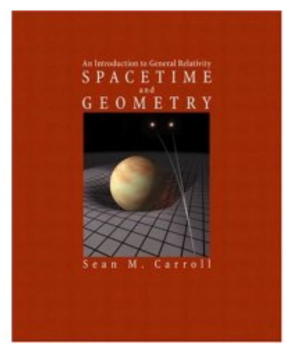
Much more advanced treatment of part 1 and 4; good summary of GR covering part 2 and most of part 3



"Galaxies in the Universe"
Linda Sparke & Jay Gallagher

ISBN: 0521597404

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



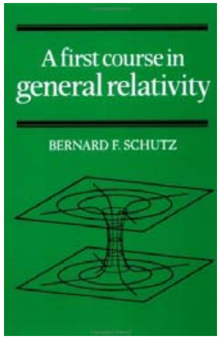
"An Introduction to General Relativity, Spacetime and Geometry"
Sean Carroll

ISBN: 0805387323

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


SPACETIME
GEOMETRY
Sean M. Carroll

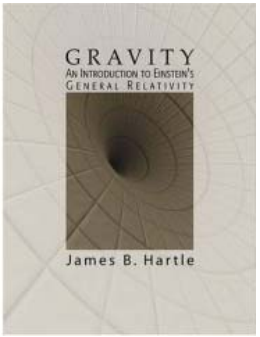
Course material: Books



"A First Course in General Relativity"
Bernard Schutz

ISBN: 052177035

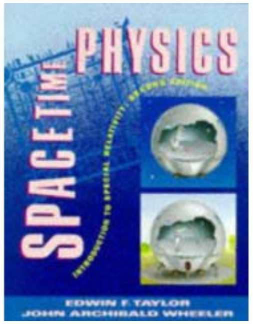
Excellent reference source for part 2 and 3; cosmology sections now well out of date



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

ISBN: 0805386629

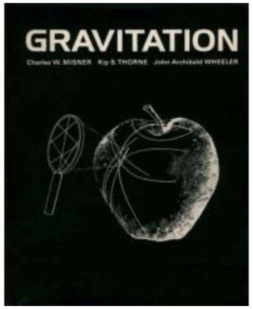
Covers similar material to Carroll (although not quite so good)



"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

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%			

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Room 371, Brown Hall

Email: martin@astro.gla.ac.uk

(ETSU email to follow)

Tel: 94252

Please participate:

Ask questions;

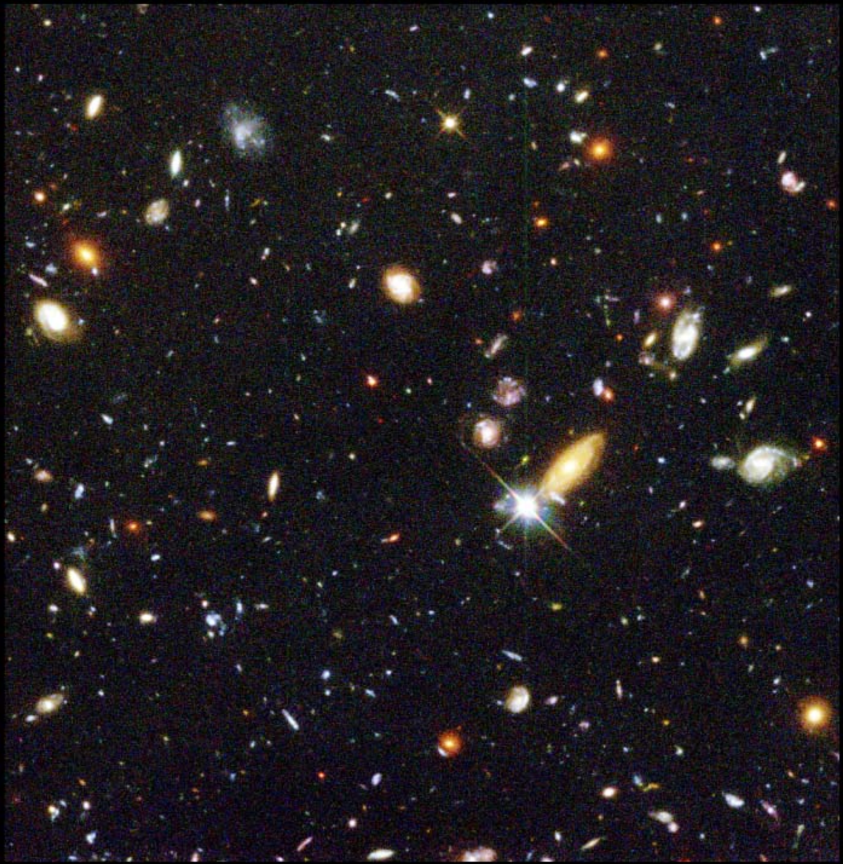
Try the example sheets;

Do the assignments;

Give me feedback!...

Cosmology – the study of the Universe as a whole:

- Origin
- Evolution
- Eventual Fate



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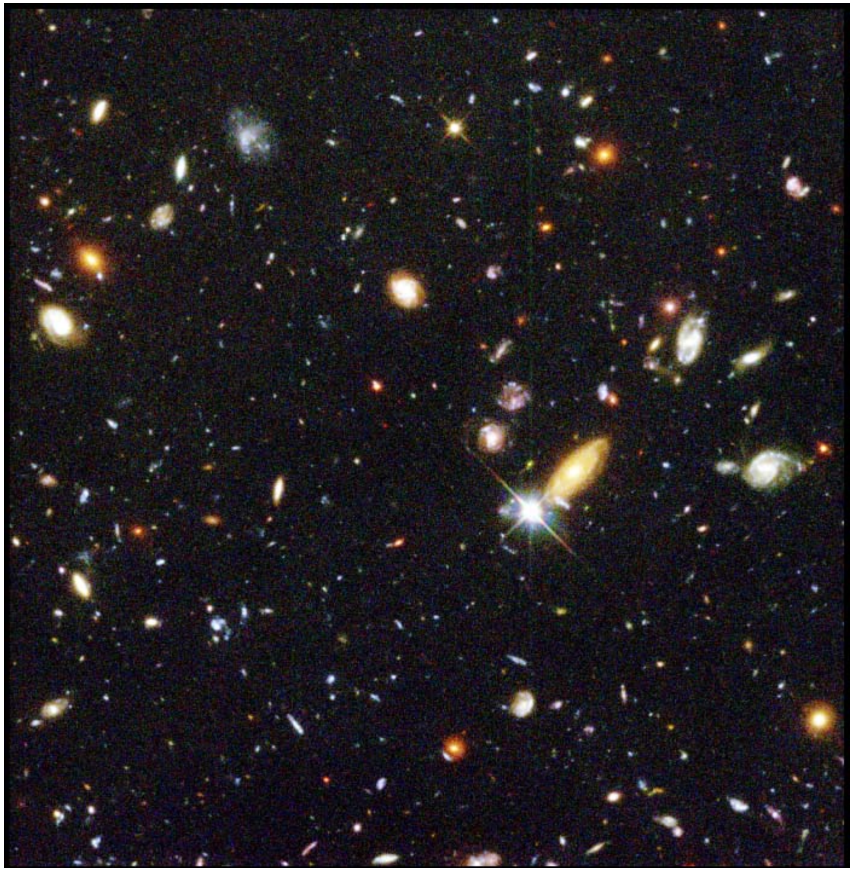
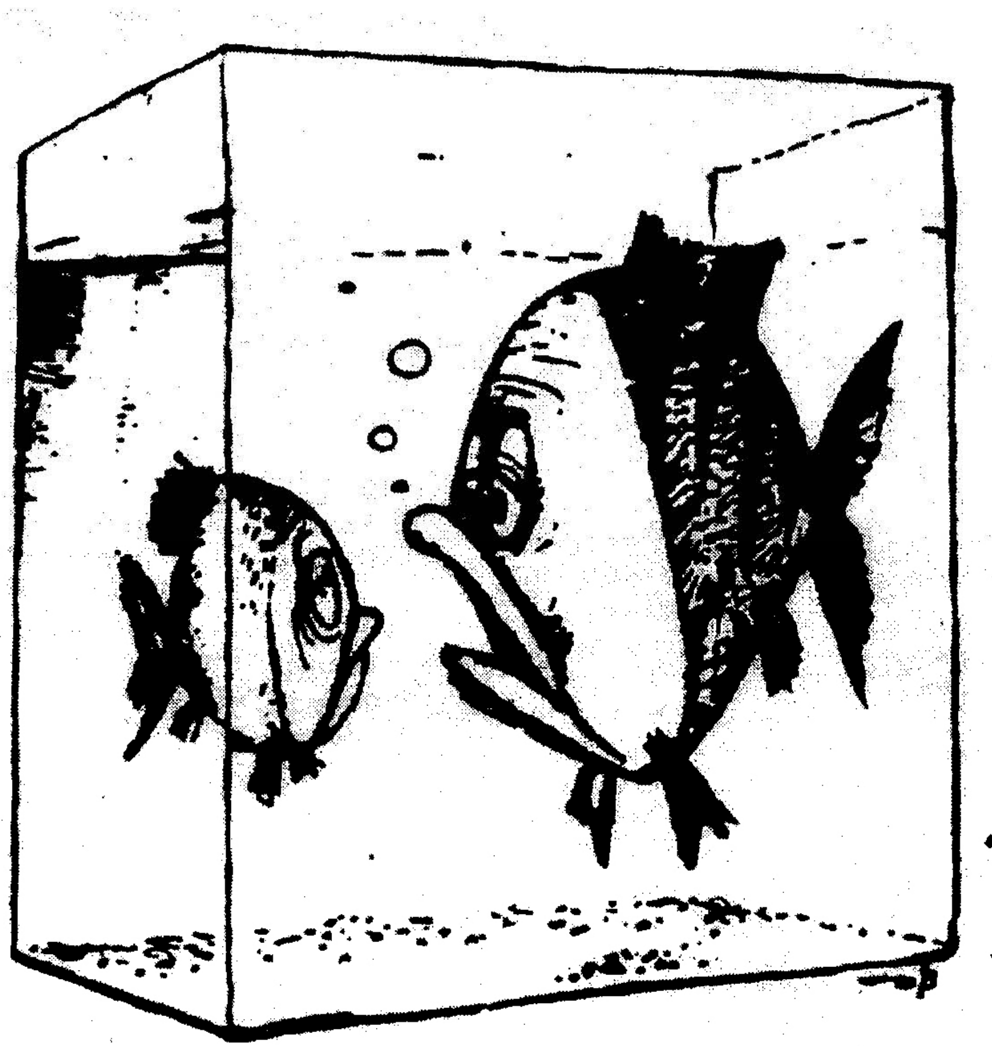
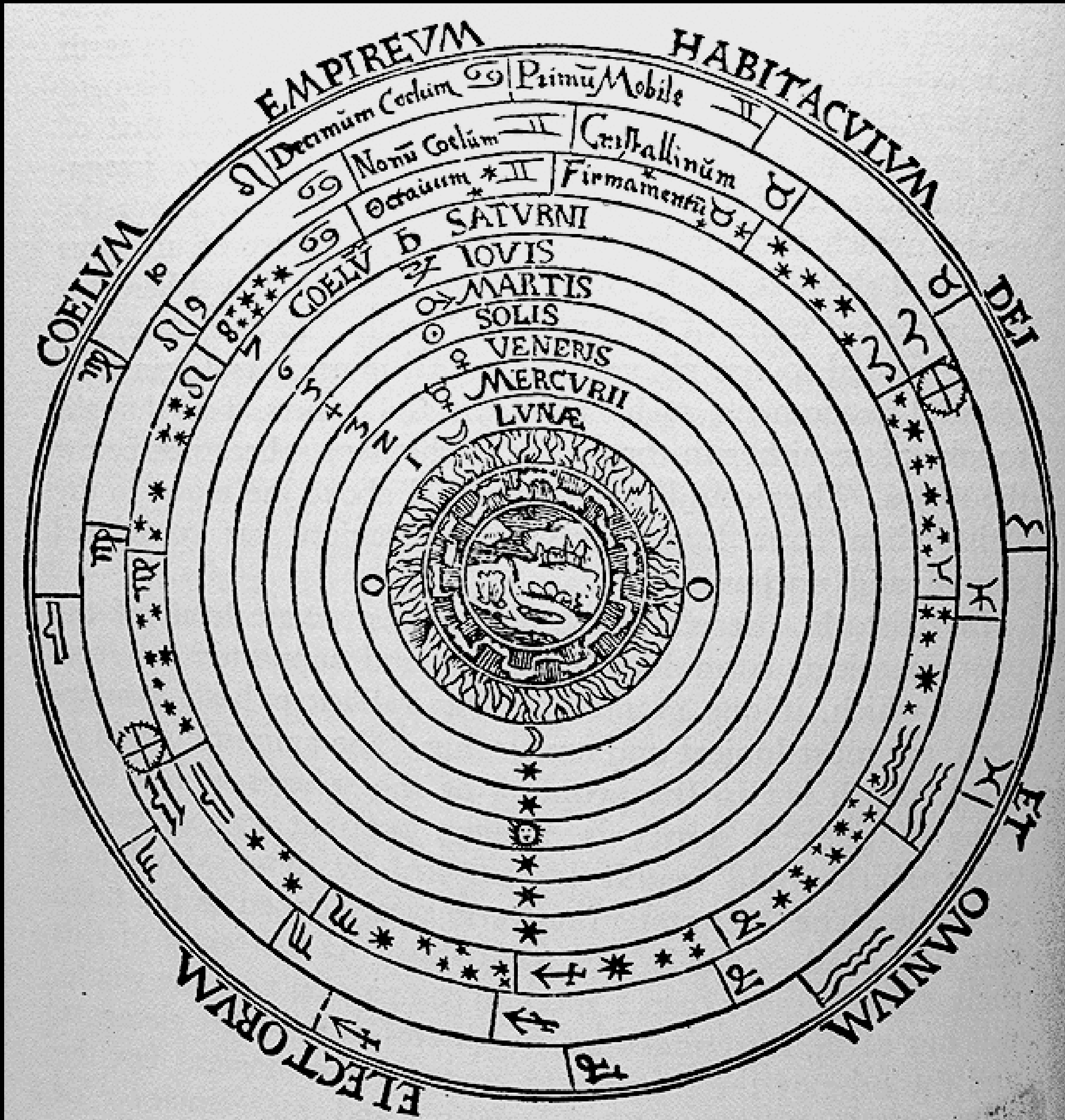


Cosmological theories depend on the available data



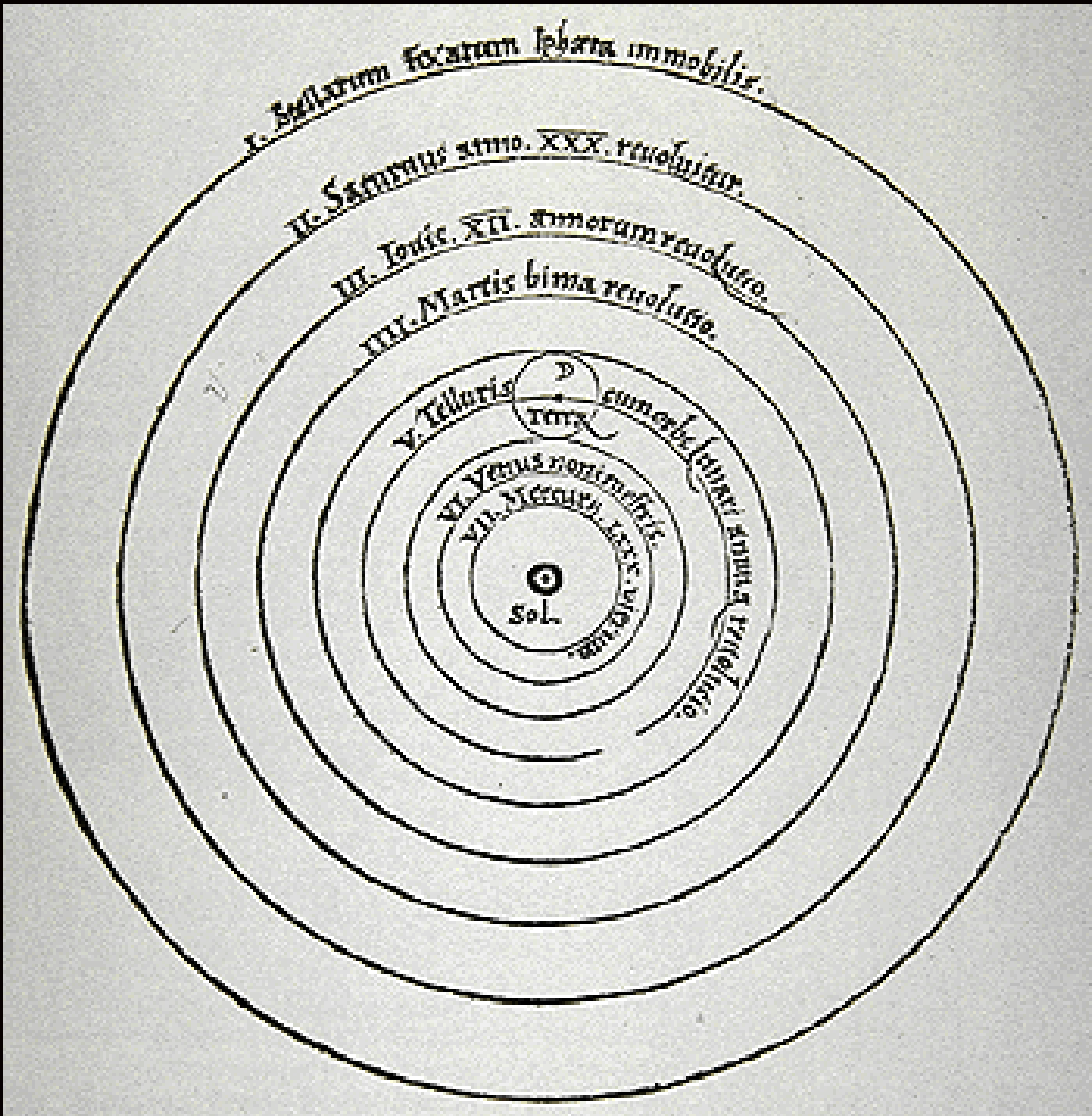
'The universe, my son, is a large tank full of water



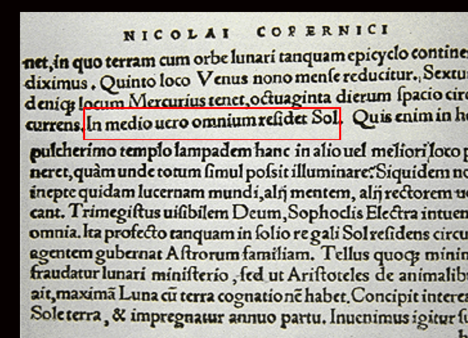
Ptolemy
90 – 168 AD

Almagest (c 140 AD)

Earth-Centred
Universe



Nicolaus Copernicus 1473 – 1543 AD



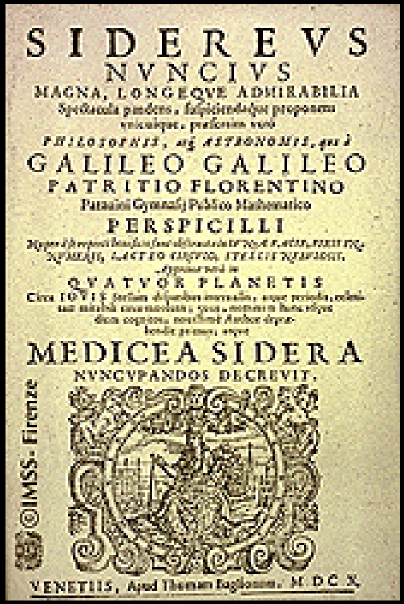
NICOLAI COPERNICI

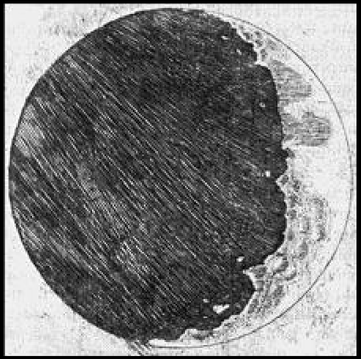
net, in quo terram cum orbe lunari tanquam epicyclo contineri diximus. Quinto loco Venus nono mense reducitur. Sextum denique locum Mercurius tenet, octuaginta dierum spacio circu currens. In medio uero omnium residet Sol. Quis enim in hoc pulcherimo templo lampadem hanc in alio uel meliori loco poneret, quàm unde totum simul possit illuminare? Siquidem non inepte quidam lucernam mundi, alij mentem, alij rectorem uocant. Trimegistus uisibilem Deum, Sophoclis Electra intuentē omnia. Ita profecto tanquam in solio regali Sol residens circum agentem gubernat Astrorum familiam. Tellus quoque minime fraudatur lunari ministerio, sed ut Aristoteles de animalibus ait, maximā Luna cū terra cognationē habet. Concipit interea à Sole terra, & impregnatur annuo partu. Inuenimus igitur sub hac

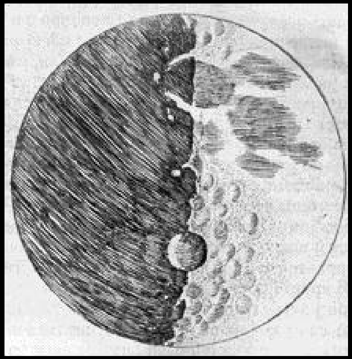
"In the true centre of everything resides the Sun"

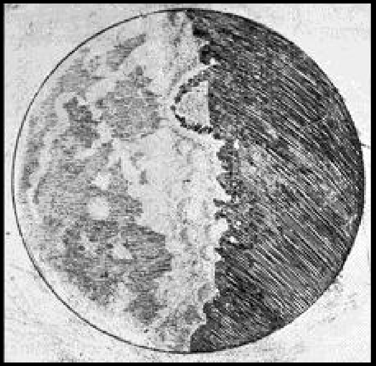
De Revolutionibus Orbis (1543)

Galileo Galilei:
1564 – 1642 AD

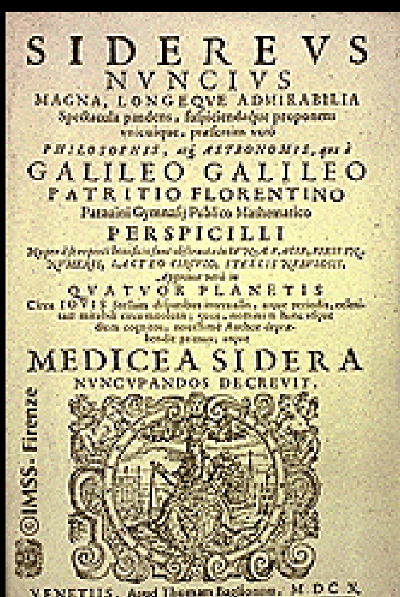

SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
GALILEO GALILEO
PATRITIO FLORENTINO
PERSPICILLI
QVATVOR PLANETIS
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.
VENETIIS, Apud Thomam Baglionum. M DC X.







Galileo Galilei:
1564 – 1642 AD



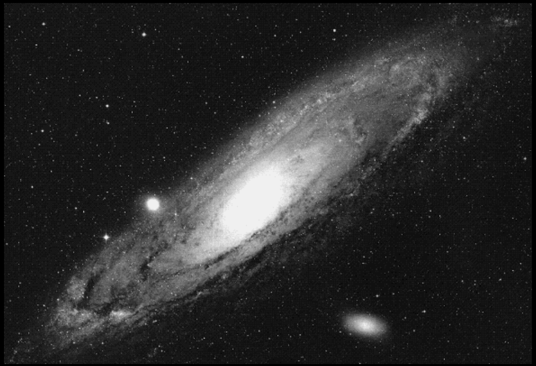
“I have observed the nature and the material of the Milky Way. With the aid of the telescope this has been scrutinized so directly and with such ocular certainty that all the disputes which have vexed philosophers through so many ages have been resolved, and we are at last freed from wordy debates about it.

The galaxy is, in fact, nothing but a collection of innumerable stars grouped together in clusters. Upon whatever part of it the telescope is directed, a vast crowd of stars is immediately presented to view. Many of them are rather large and quite bright, while the number of smaller ones is quite beyond calculation.”

from The Starry Messenger (1610)

Early 20th Century

The nature of the nebulae?...



Gas clouds within the Milky Way,
or Island Universes?....

The Great Debate, 1920

Shapley vs Curtis

at the National Academy of Sciences

The Great Debate, 1920

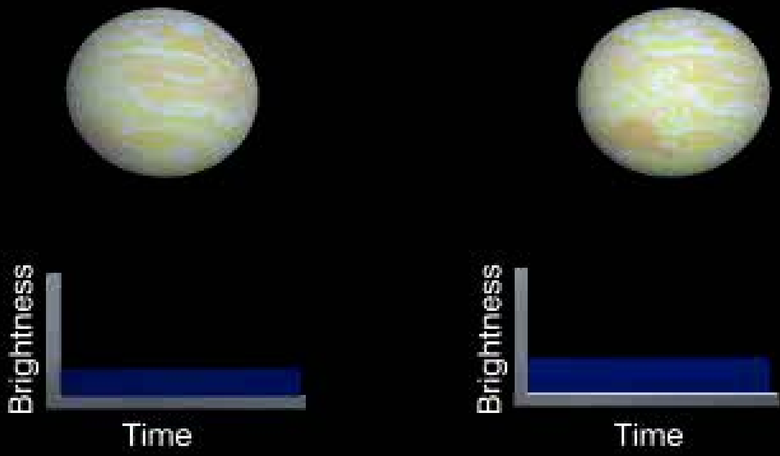
Shapley vs Curtis

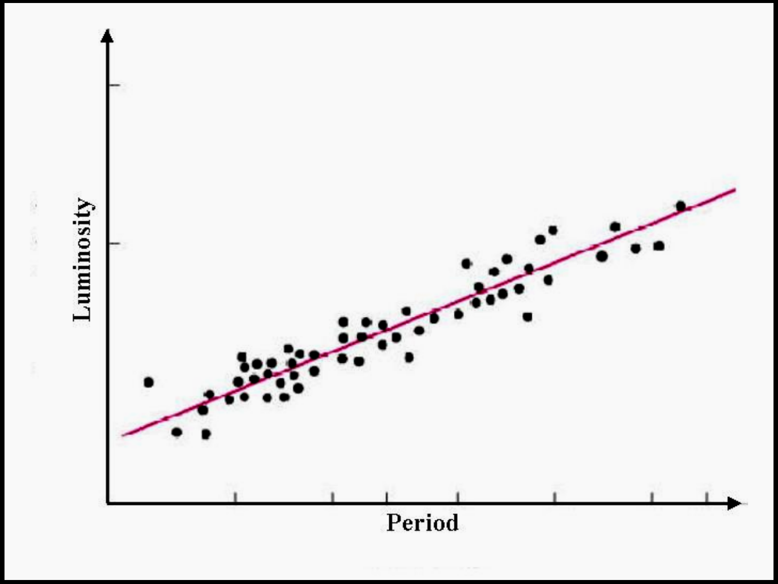
at the National Academy of Sciences

Shapley argues successfully that the nebulae are *within* the Milky Way

Cepheid Variables: Cosmic Yardsticks

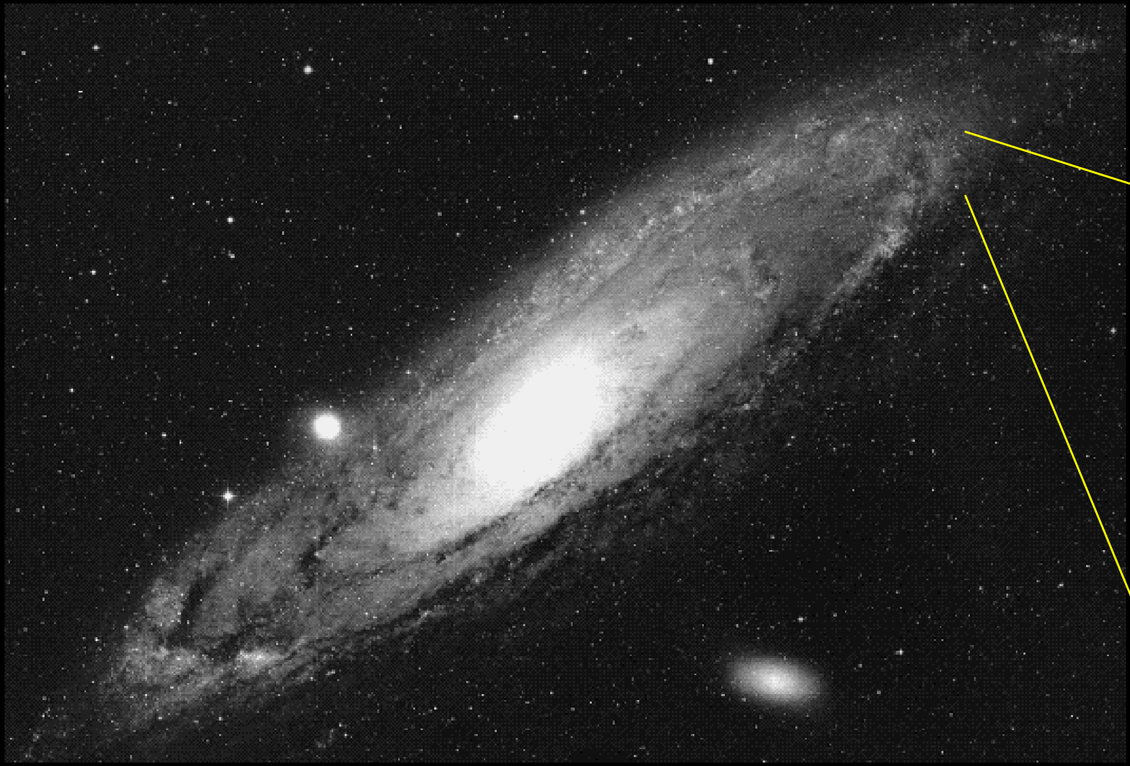
Henrietta Leavitt
1908-1912

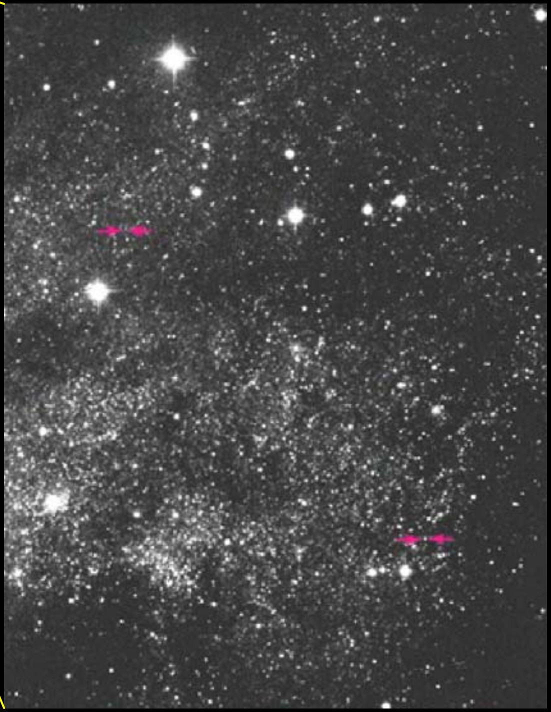


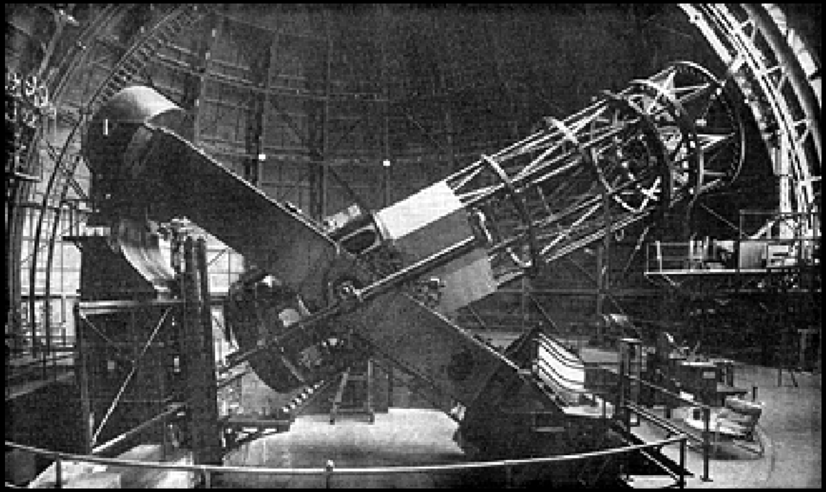


Early 1920s

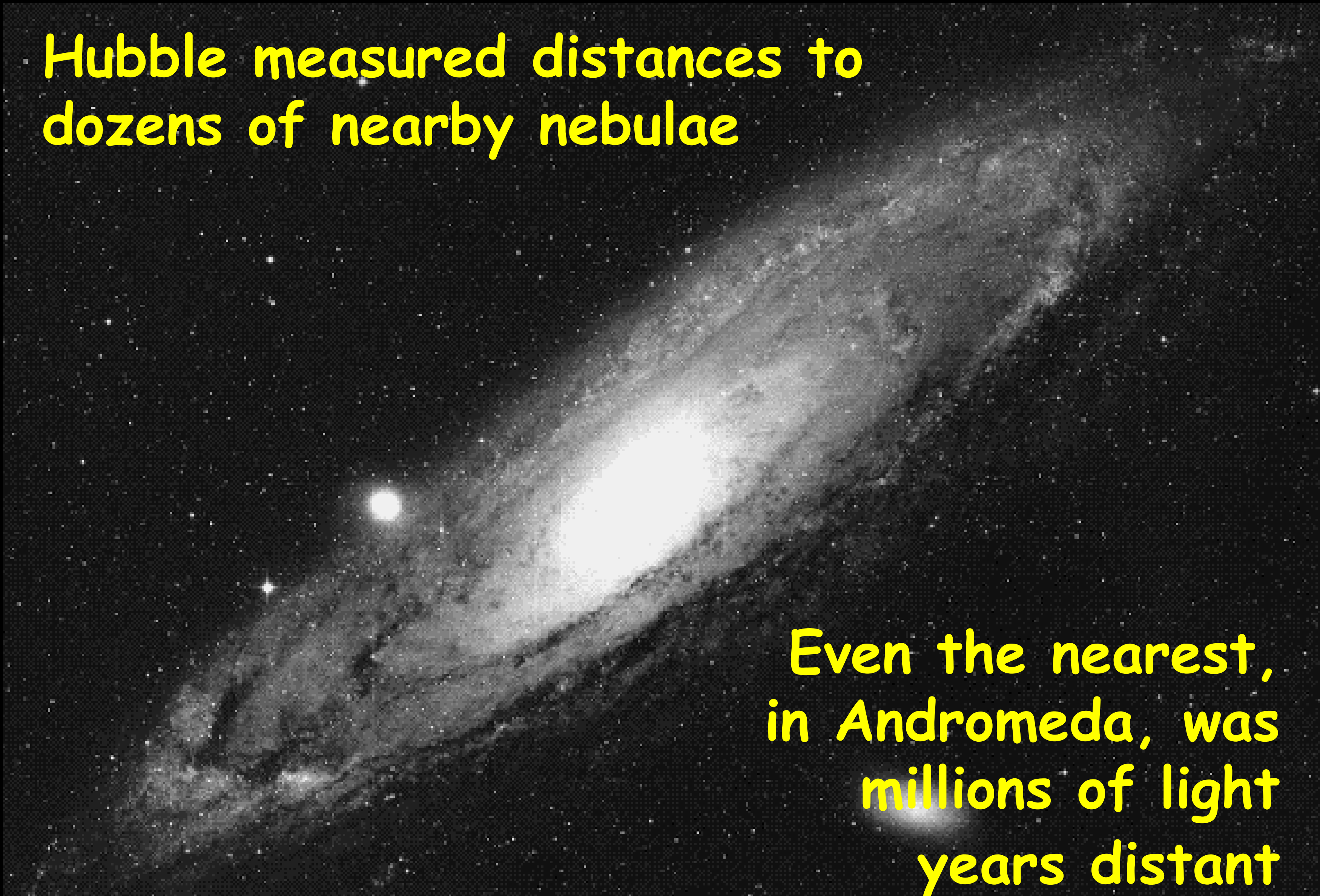
Edwin Hubble tried to measure the distance of the Spiral Nebulae





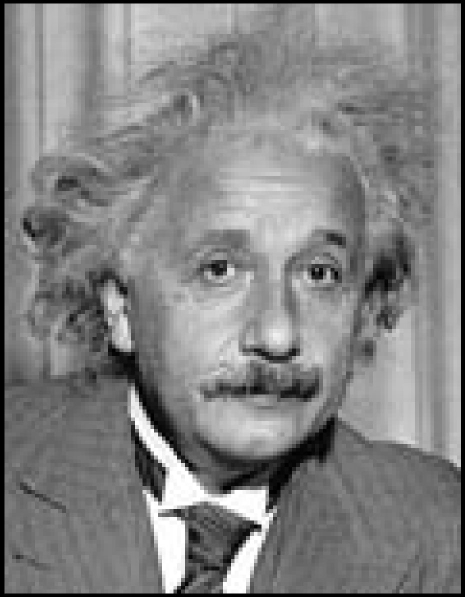


1922: Hubble finds Cepheids in the Great Nebula in Andromeda


Hubble measured distances to dozens of nearby nebulae
Even the nearest, in Andromeda, was millions of light years distant

The Big Bang

1920s - Georges Lemaitre proposes idea of a 'primeval atom'

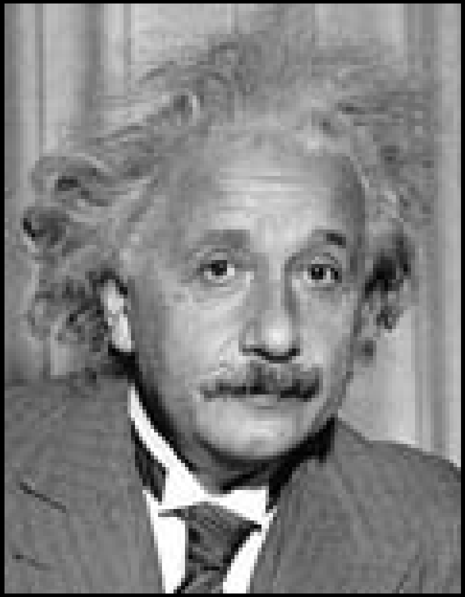


Einstein not impressed!

"your calculations are correct, but your physics is abominable"

The Big Bang

1920s - Alexander Friedmann develops non-static universe models



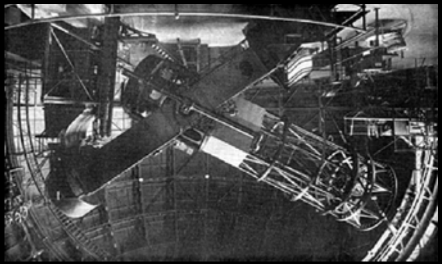
Einstein not impressed!

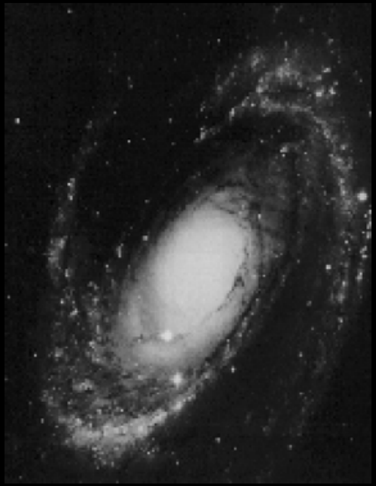
"The results concerning the non-stationary world...appear to me suspicious"

The Big Bang

Late 1920s

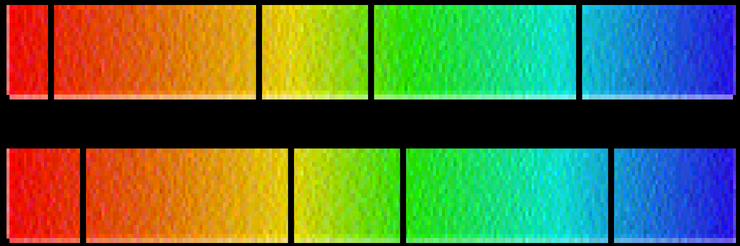
Hubble also measured the shift in colour, or *wavelength*, of the light from distant galaxies.





Galaxy

Laboratory



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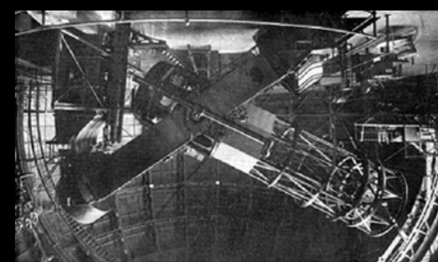
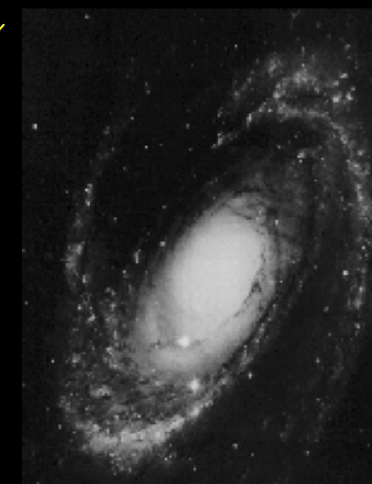
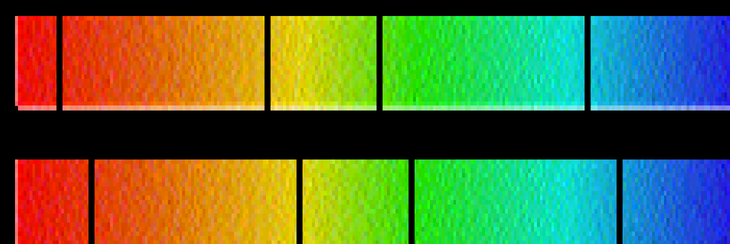




Galaxy

Laboratory



Hubble's Law: 1929

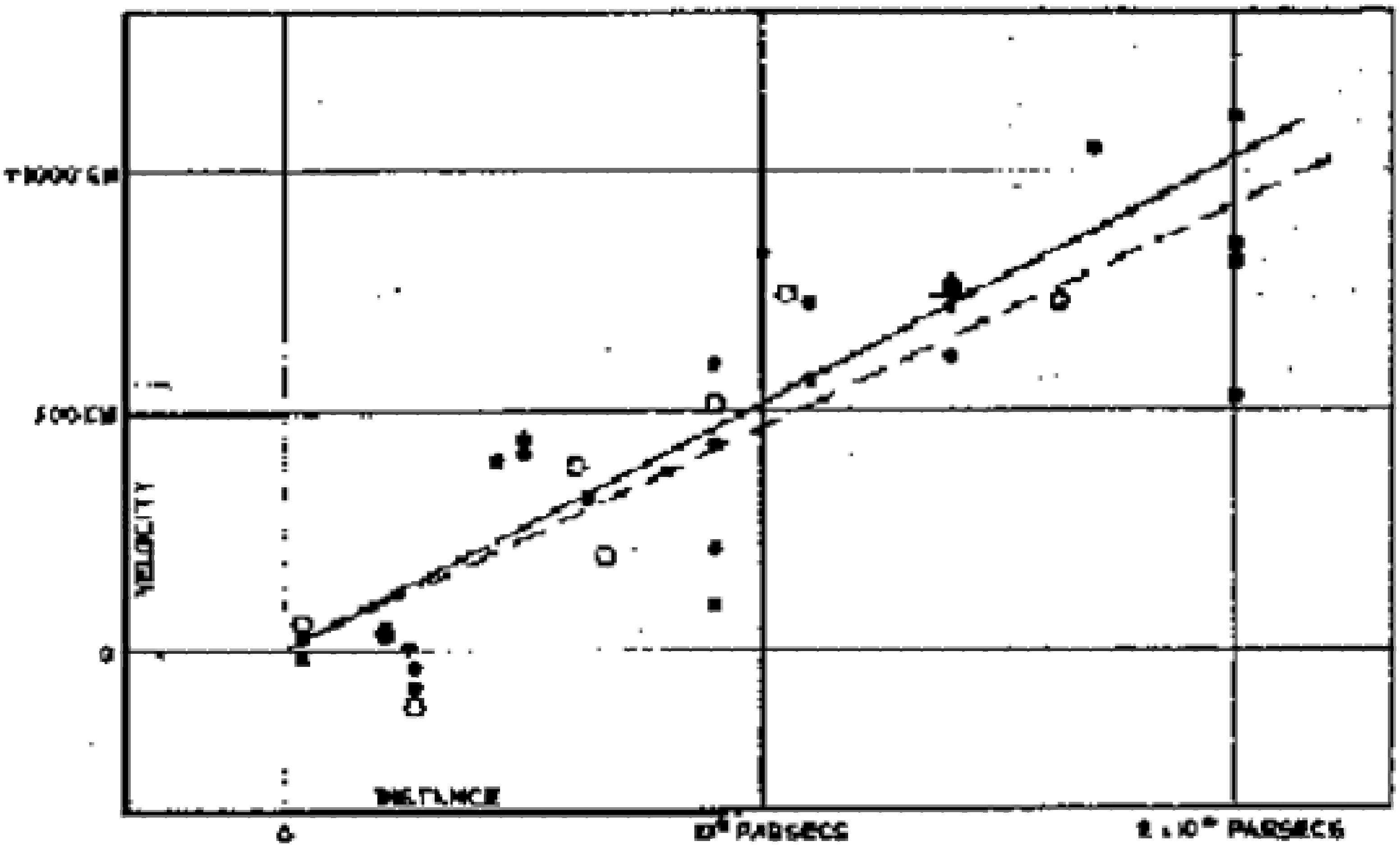
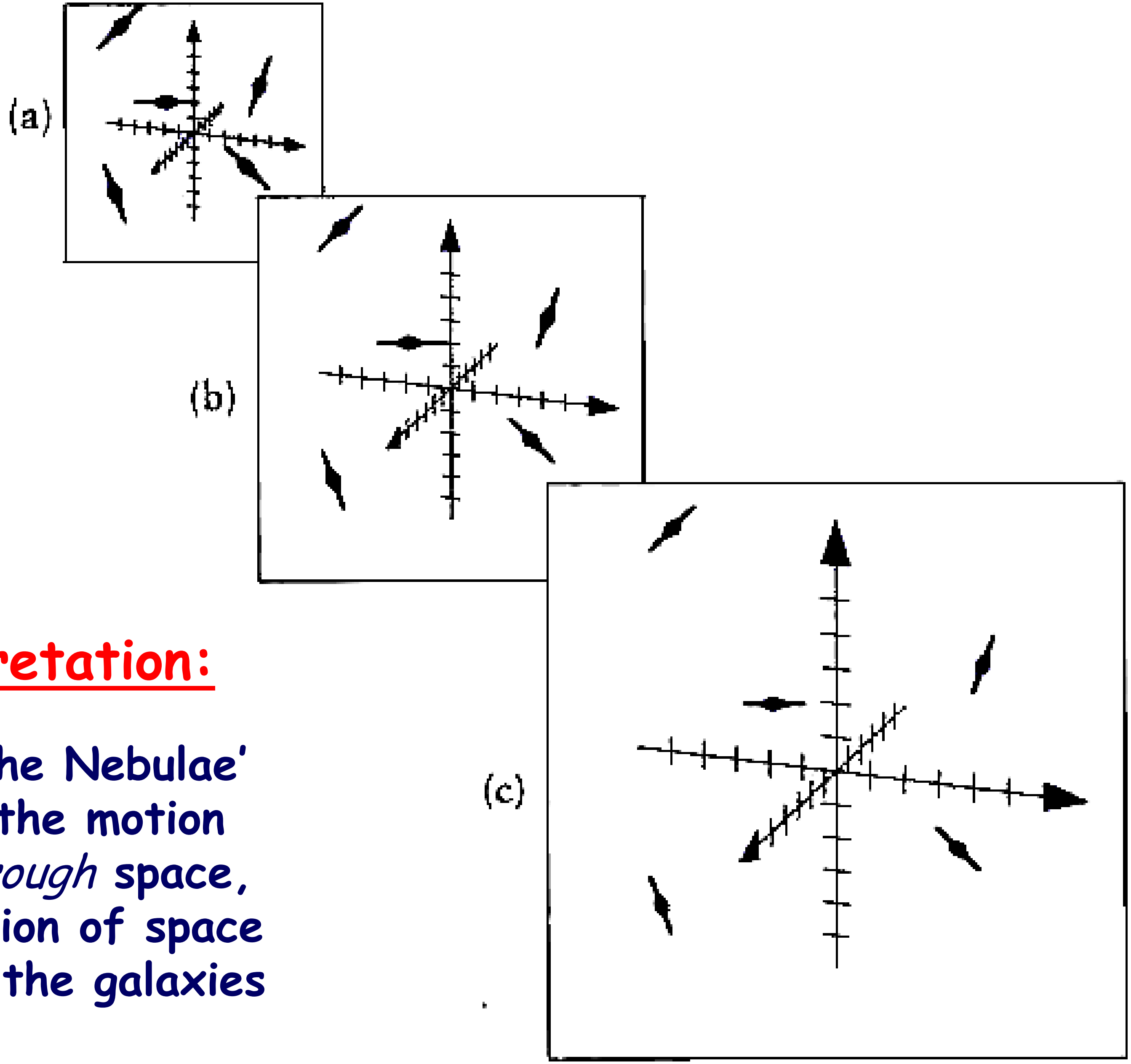


FIGURE 1

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



The interpretation:

'Recession of the Nebulae' caused not by the motion of galaxies *through* space, but the expansion of space itself *between* the galaxies

The Big Bang

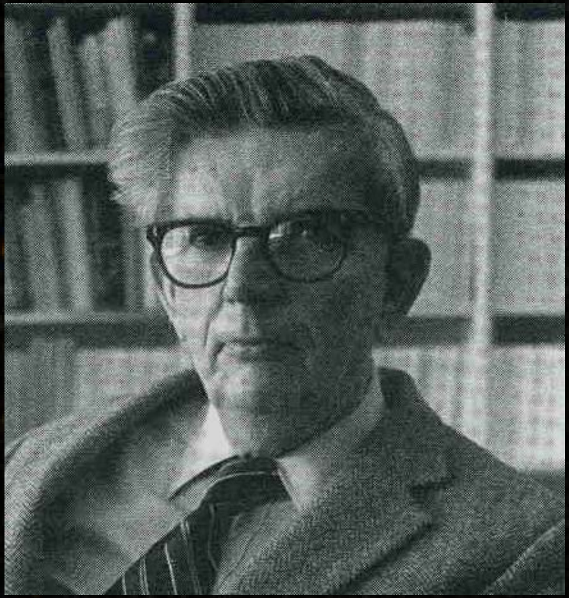
Late 1940s – 1950s:

George Gamow proposes hot early Universe…

…with Alpher and Bethe predicts existence of 'smoking gun' – relic radiation from the primordial Universe…

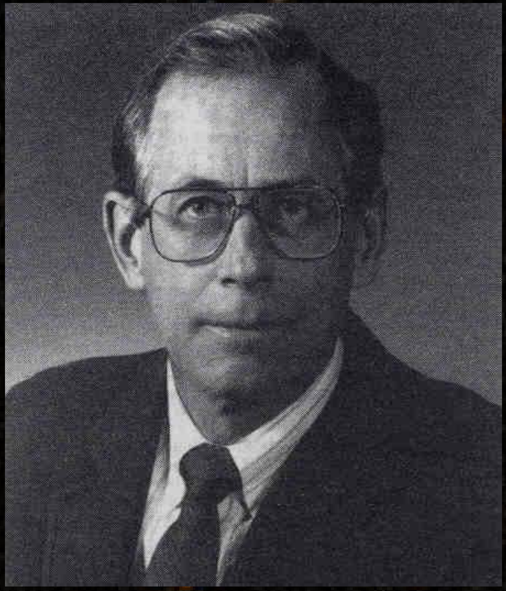
…predicted in more detail by Gamov, Dicke, Peebles, in the 1950s and early 1960s…

…discovered in 1965 by Penzias and Wilson



Robert Dicke

Arno Penzias and Robert Wilson



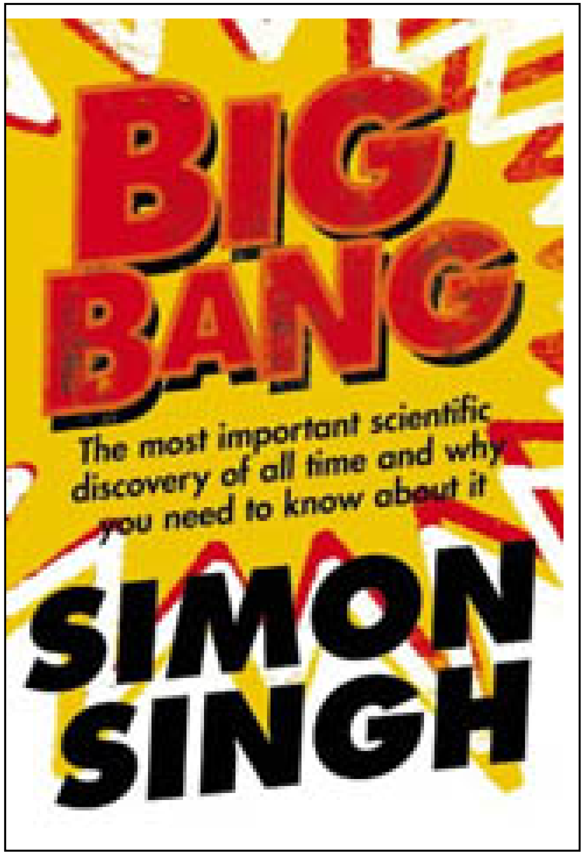
Jim Peebles

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!)

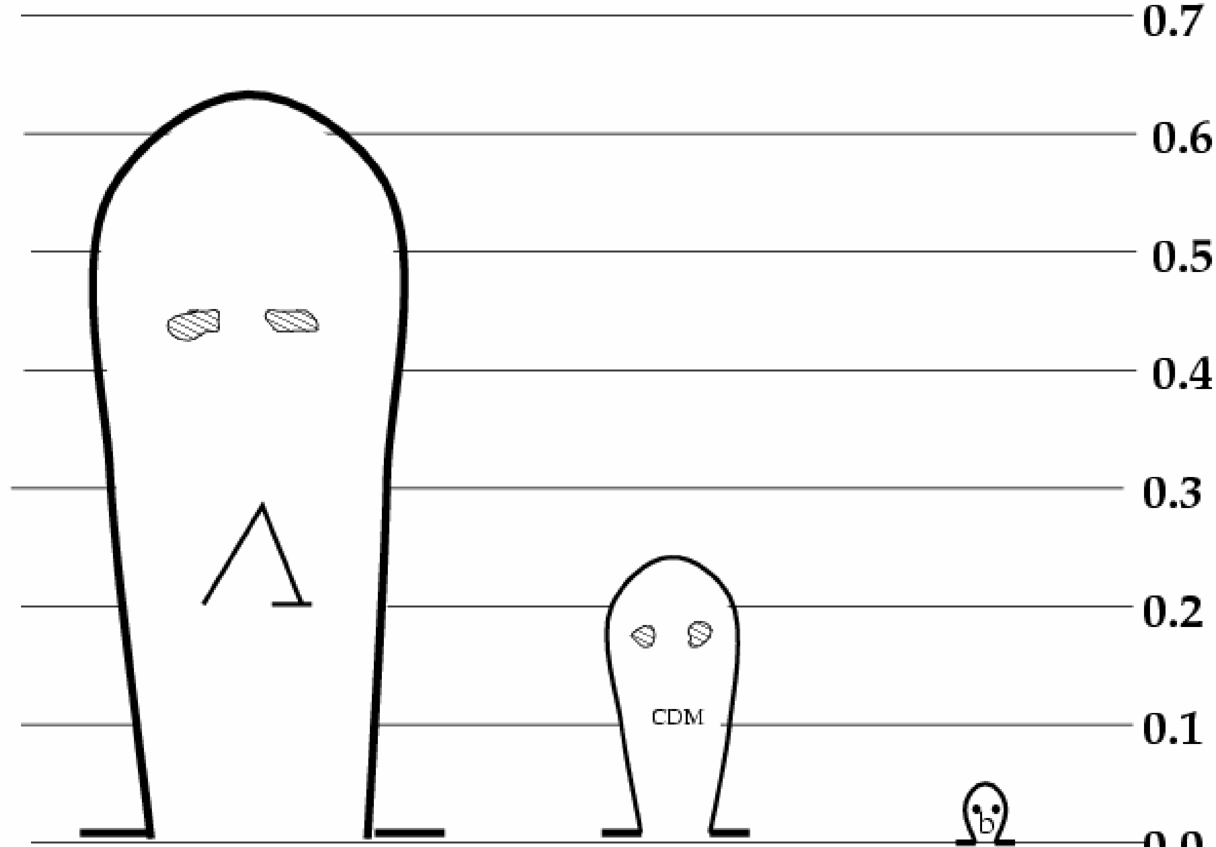
- The Universe began with a Big Bang, about 15 billion years ago, and has been expanding ever since
- It has a flat geometry (which is a prediction of inflation)
- Energy budget – 1: 30% gravitating matter (a few percent is baryonic, the rest known as CDM – but we don't know what that is)
- Energy budget – 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.

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

$$\boxed{\Lambda\,\mathrm{CDM}}$$

ΛCDM

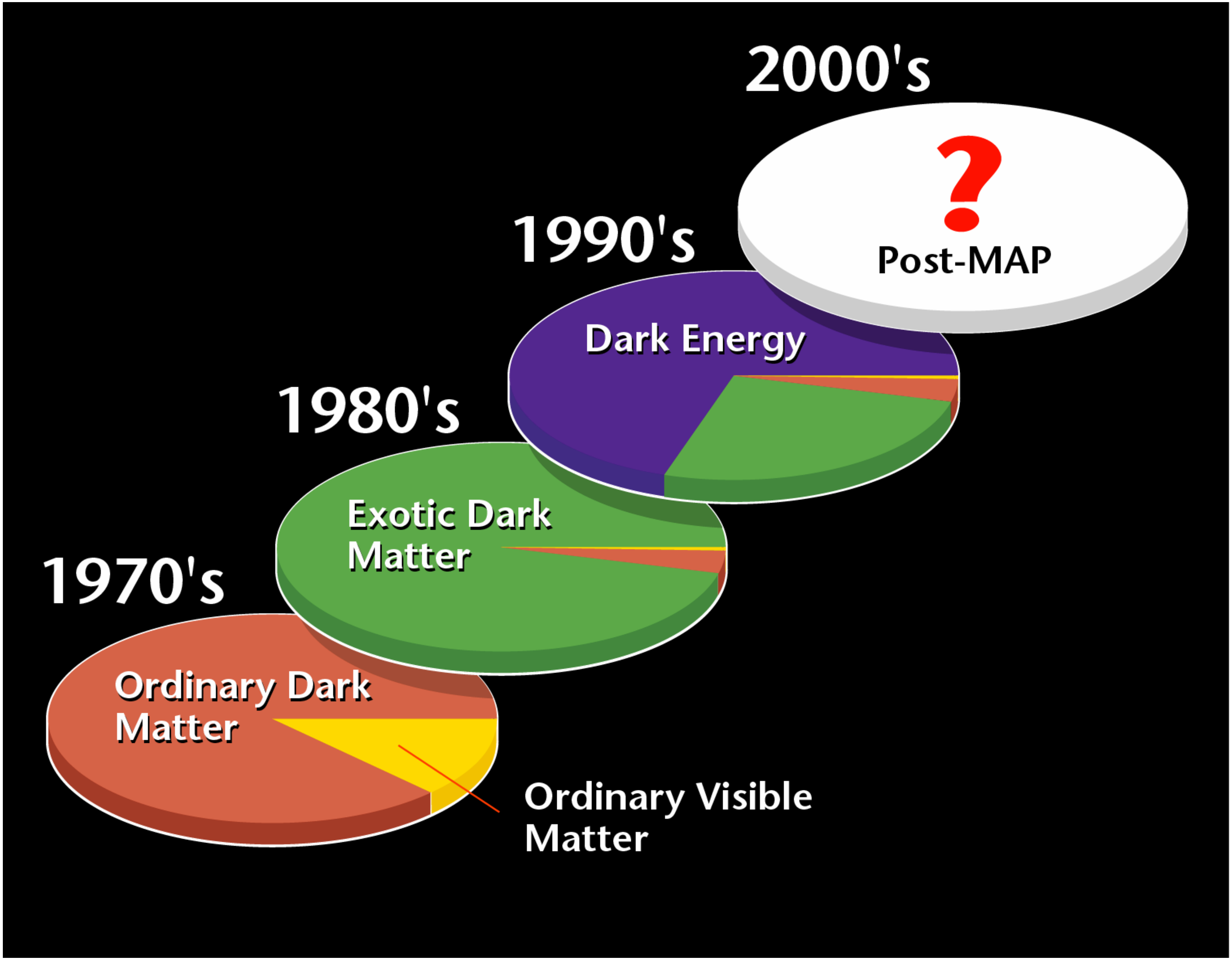
Cosmology's Most Wanted



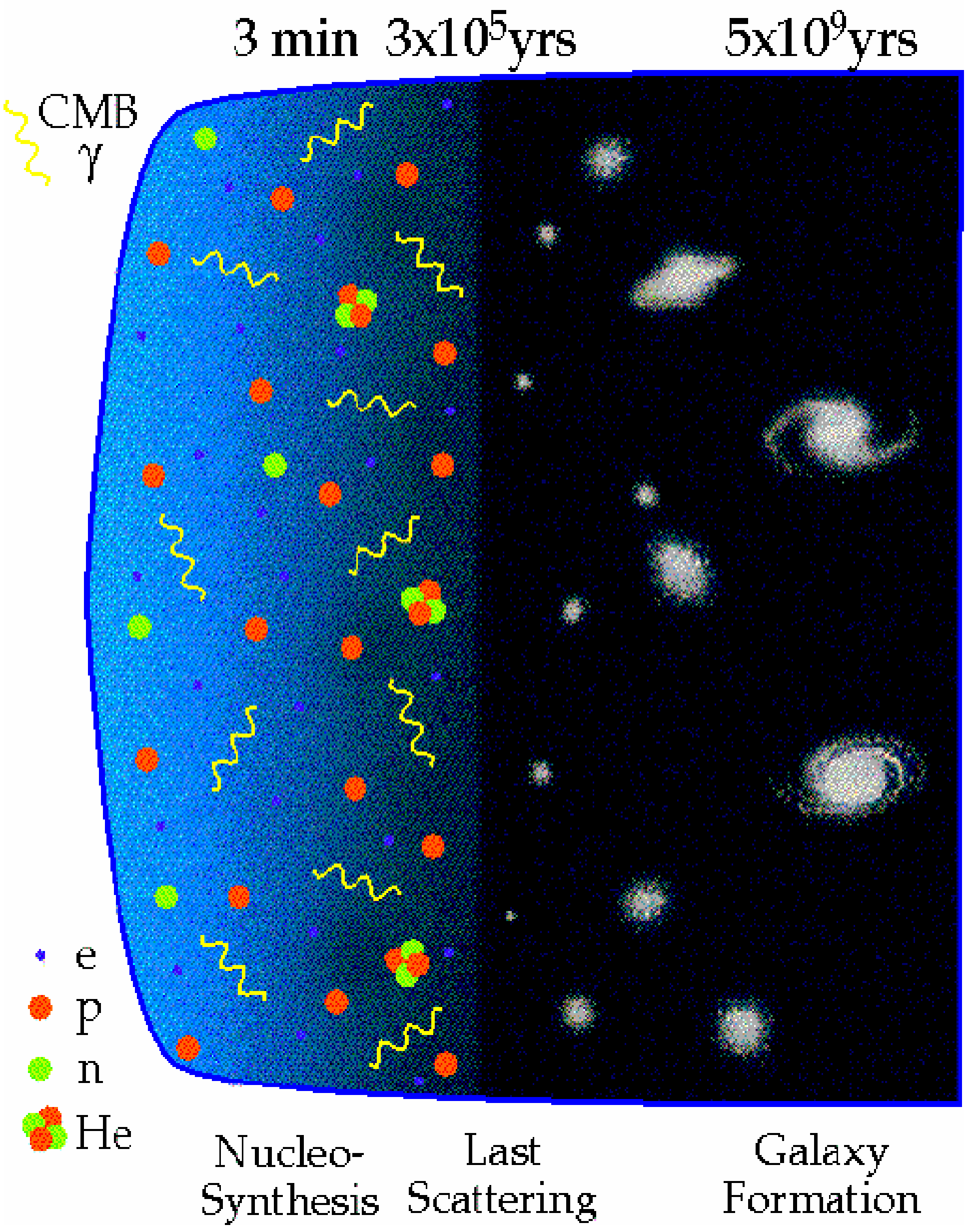
Ω_Λ	Ω_{CDM}	Ω_b
cosmological constant energy of the vacuum He never clumps His evil plan is to blow up the Universe	cold dark matter He likes to clump but has never been detected directly His evil plan is to make the Universe collapse	normal baryonic matter a pawn in the cosmic game who just follows 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)


2000's
?
Post-MAP
1990's
Dark Energy
1980's
Exotic Dark Matter
1970's
Ordinary Dark Matter
Ordinary Visible Matter

(Very) Brief History



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

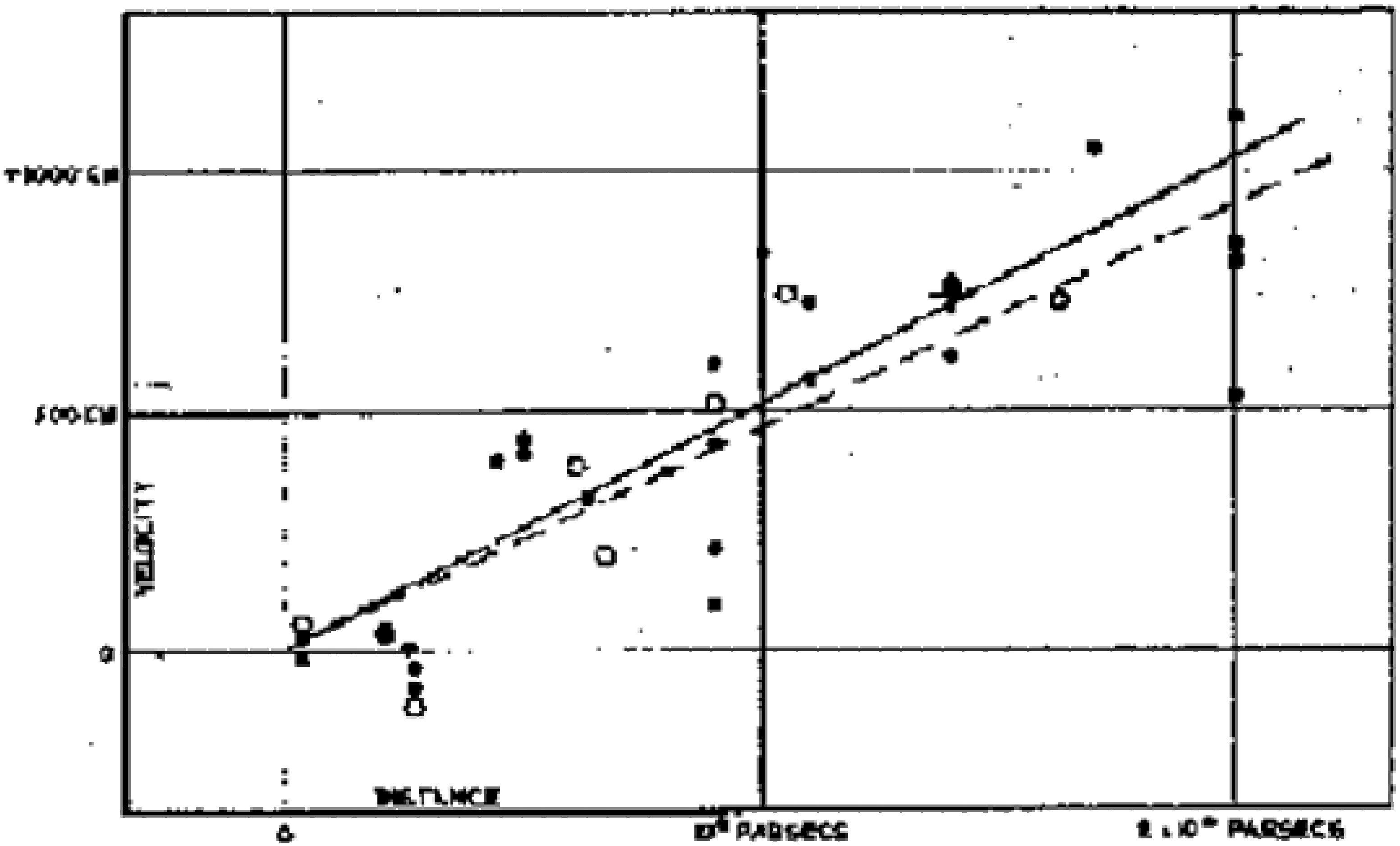


FIGURE 1

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

Hubble's Law

$$\boxed{V = H_0 d}$$

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

Hubble's Law

$$\boxed{V = H_0 d}$$

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1 pc = 3.26 light years = 3×10^{16} m

Hubble's Law

$$\boxed{V = H_0\, d}$$

H_0 has units of $(\text{time})^{-1}$ – 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 Law

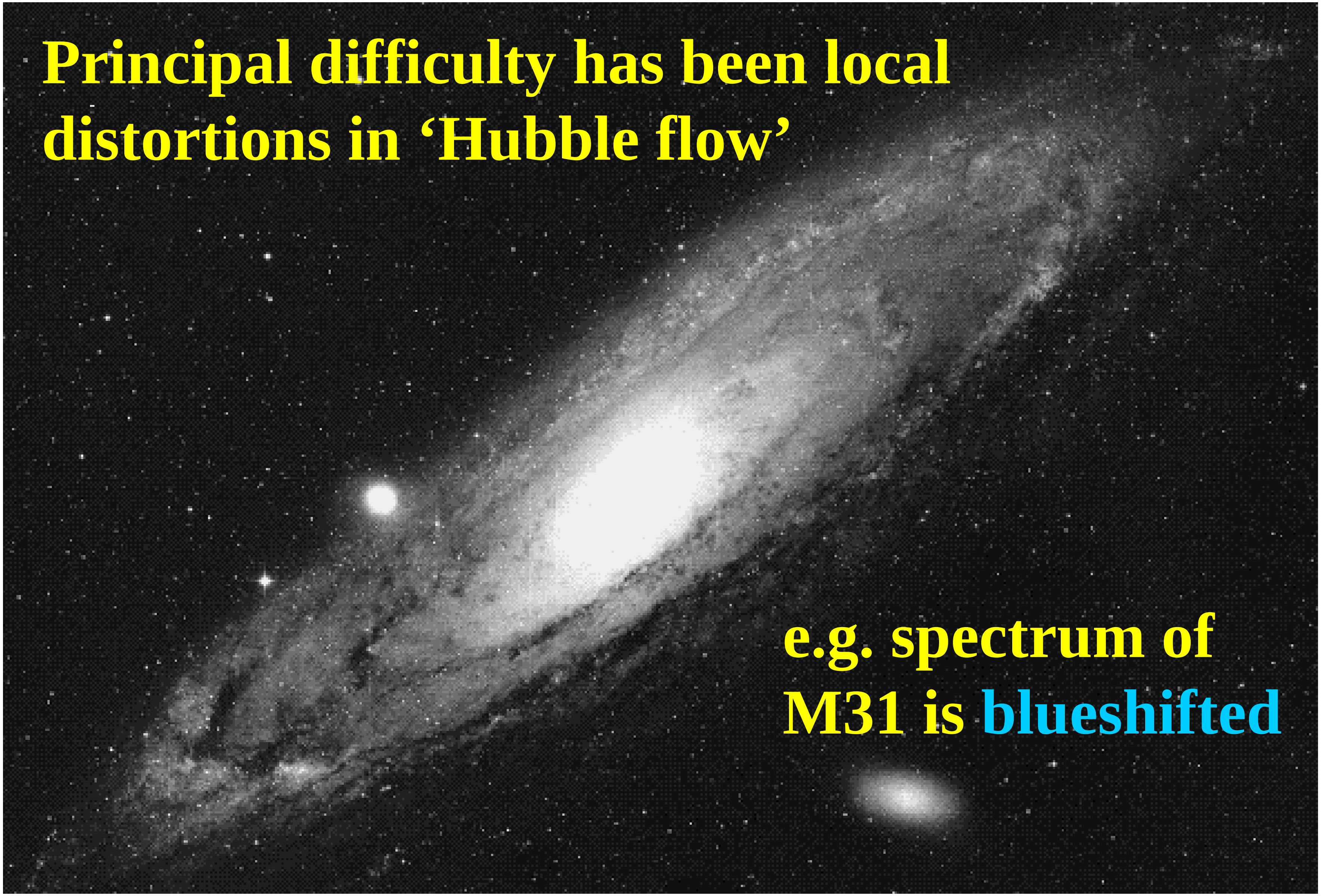
$$\boxed{V = H_0 d}$$

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)

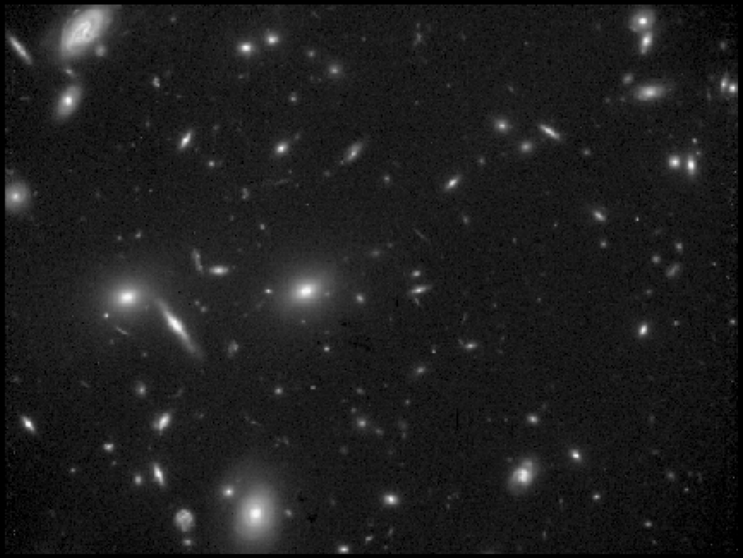
????

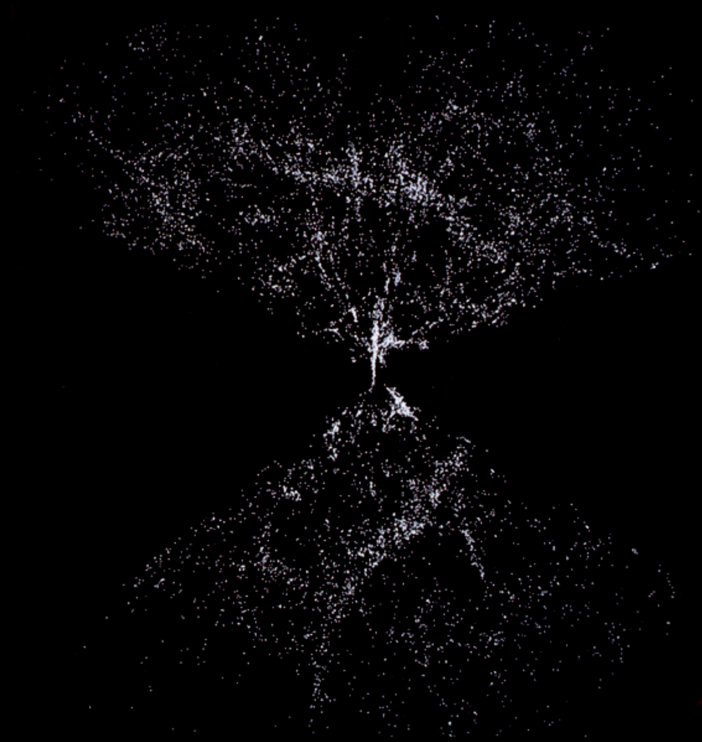
How fast is the Universe expanding?


Principal difficulty has been local distortions in ‘Hubble flow’
e.g. spectrum of M31 is blueshifted

Galaxies are clustered

Structure in the Universe assembled by gravity

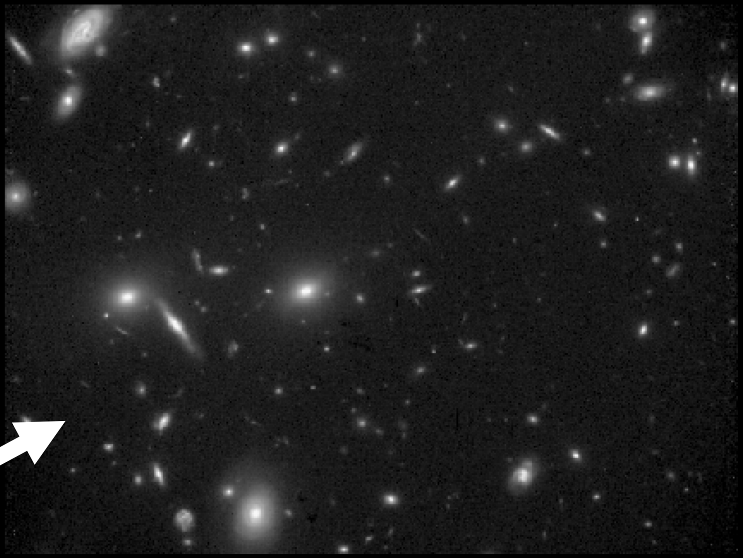


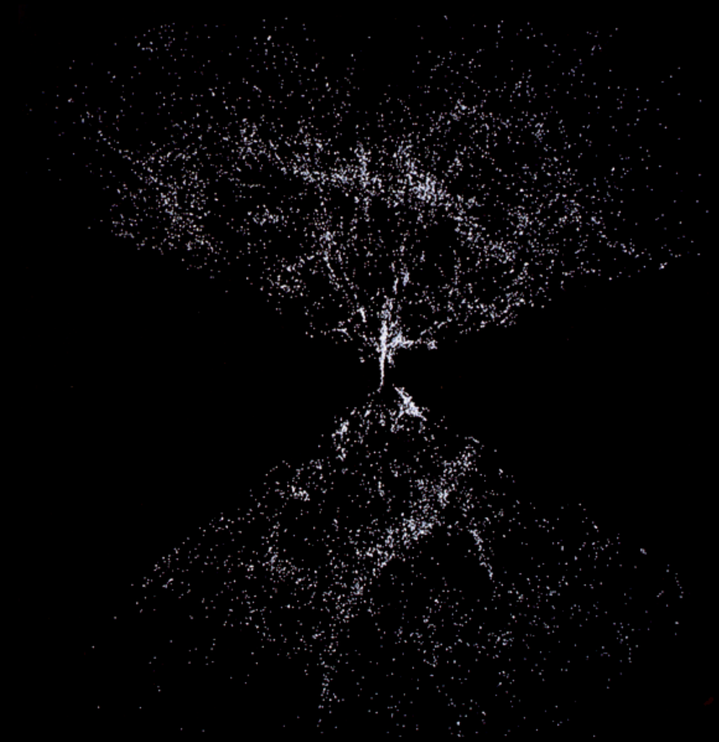


Galaxies are clustered

Structure in the Universe assembled by gravity

Locally, gravity sufficient to overcome cosmic expansion



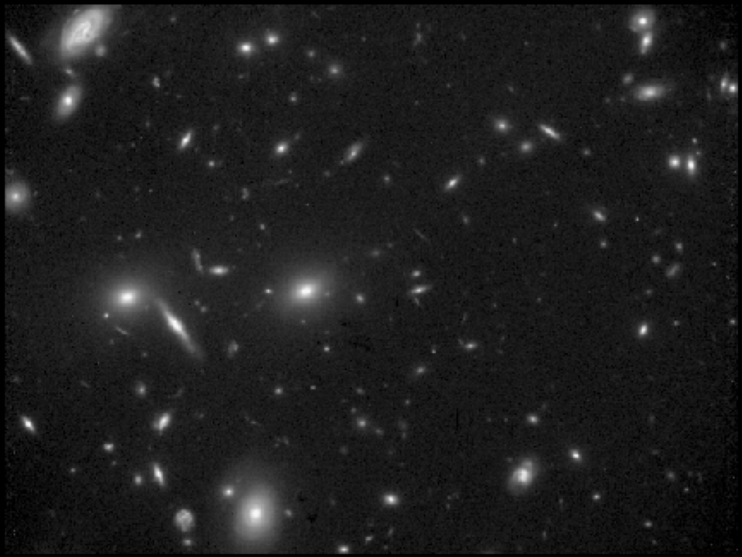


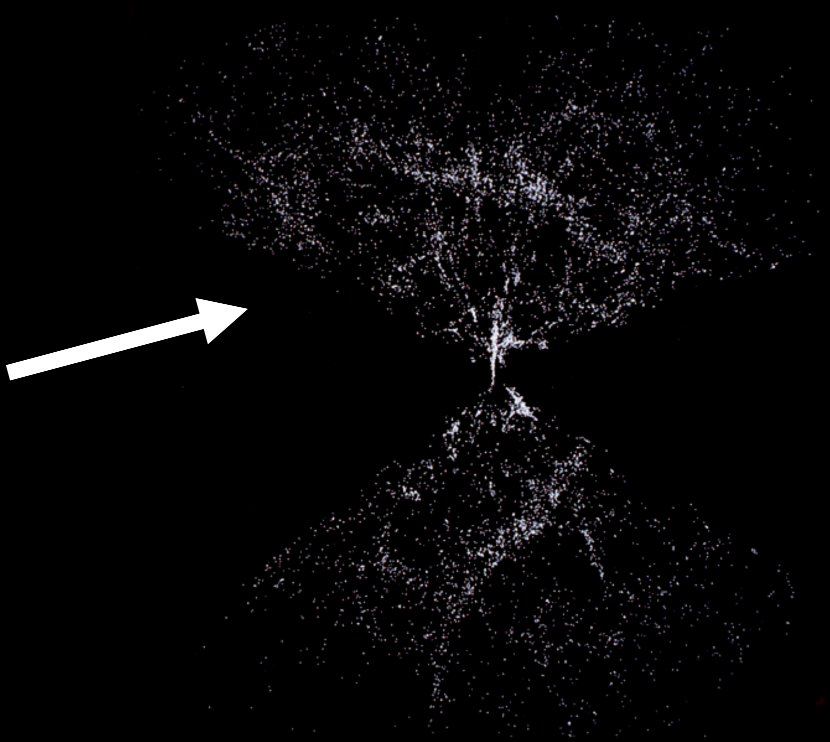
Galaxies are clustered

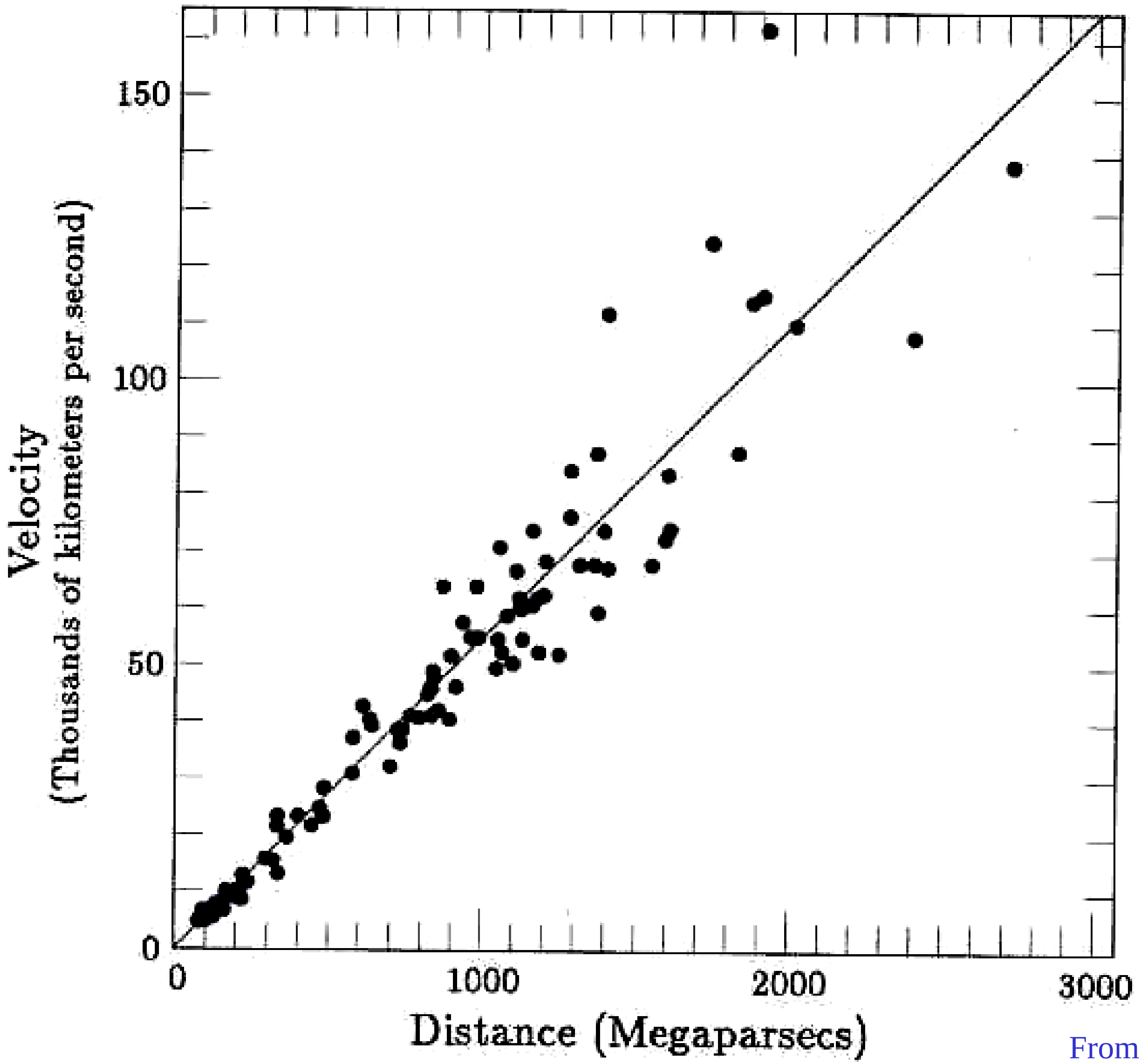
Structure in the Universe assembled by gravity

Locally, gravity sufficient to overcome cosmic expansion

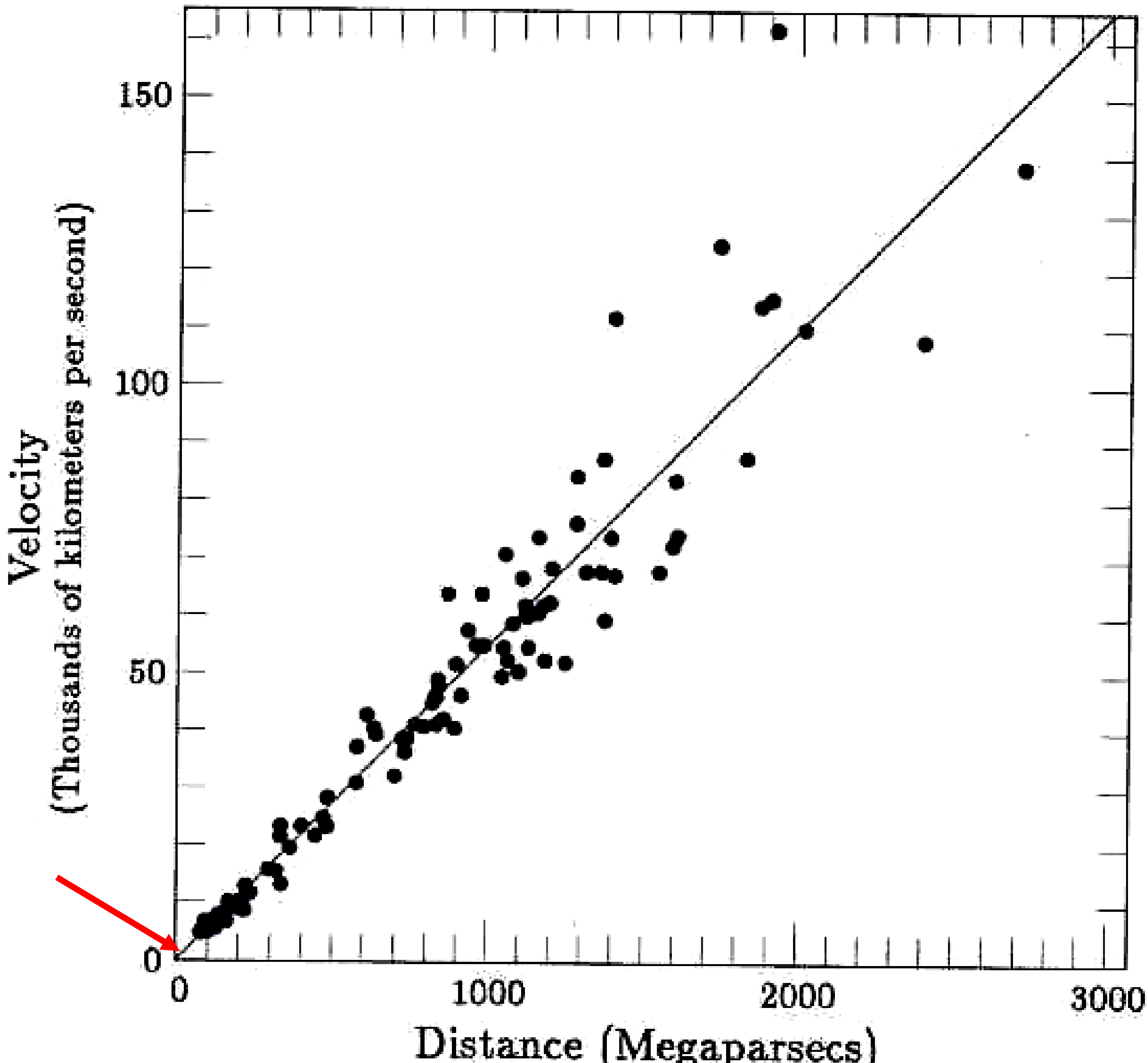
On larger scales, expansion diluted: galaxies have peculiar velocity on top of Hubble velocity





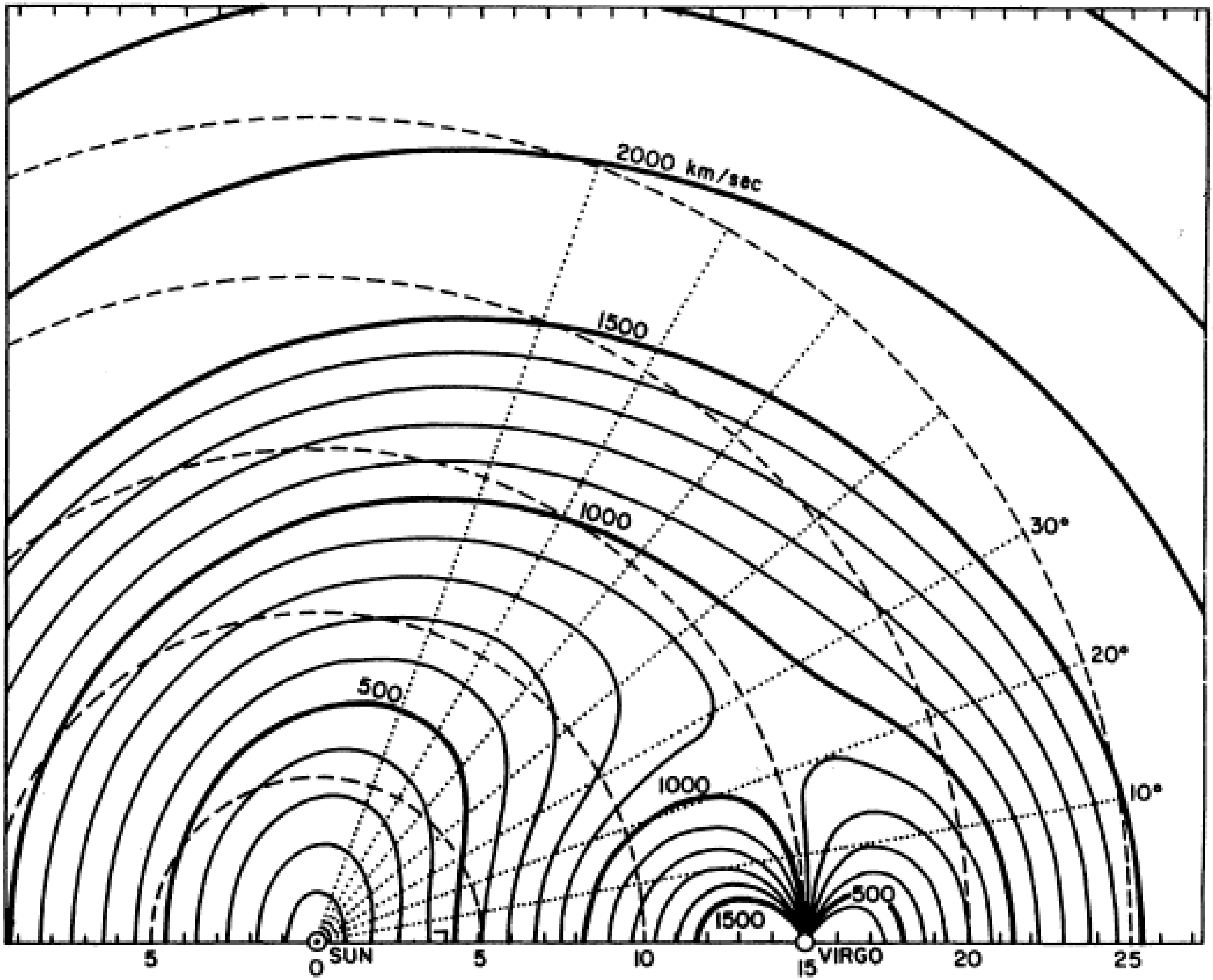


From Guth (1997)



Velocity
(Thousands of kilometers per second)
150
100
50
0
0
1000
2000
3000
Distance (Megaparsecs)

Main local distortion due to Virgo cluster



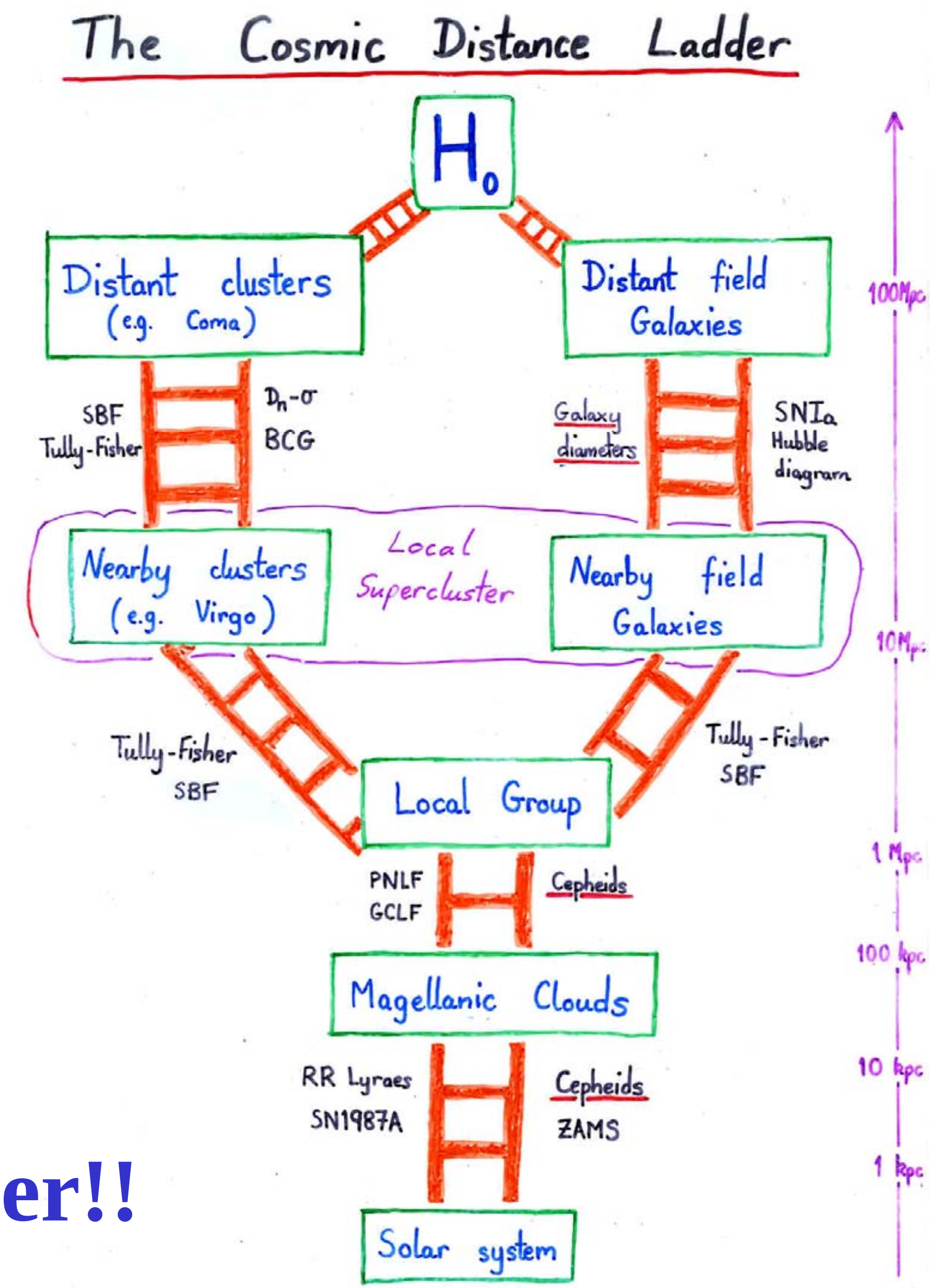
Problem:

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

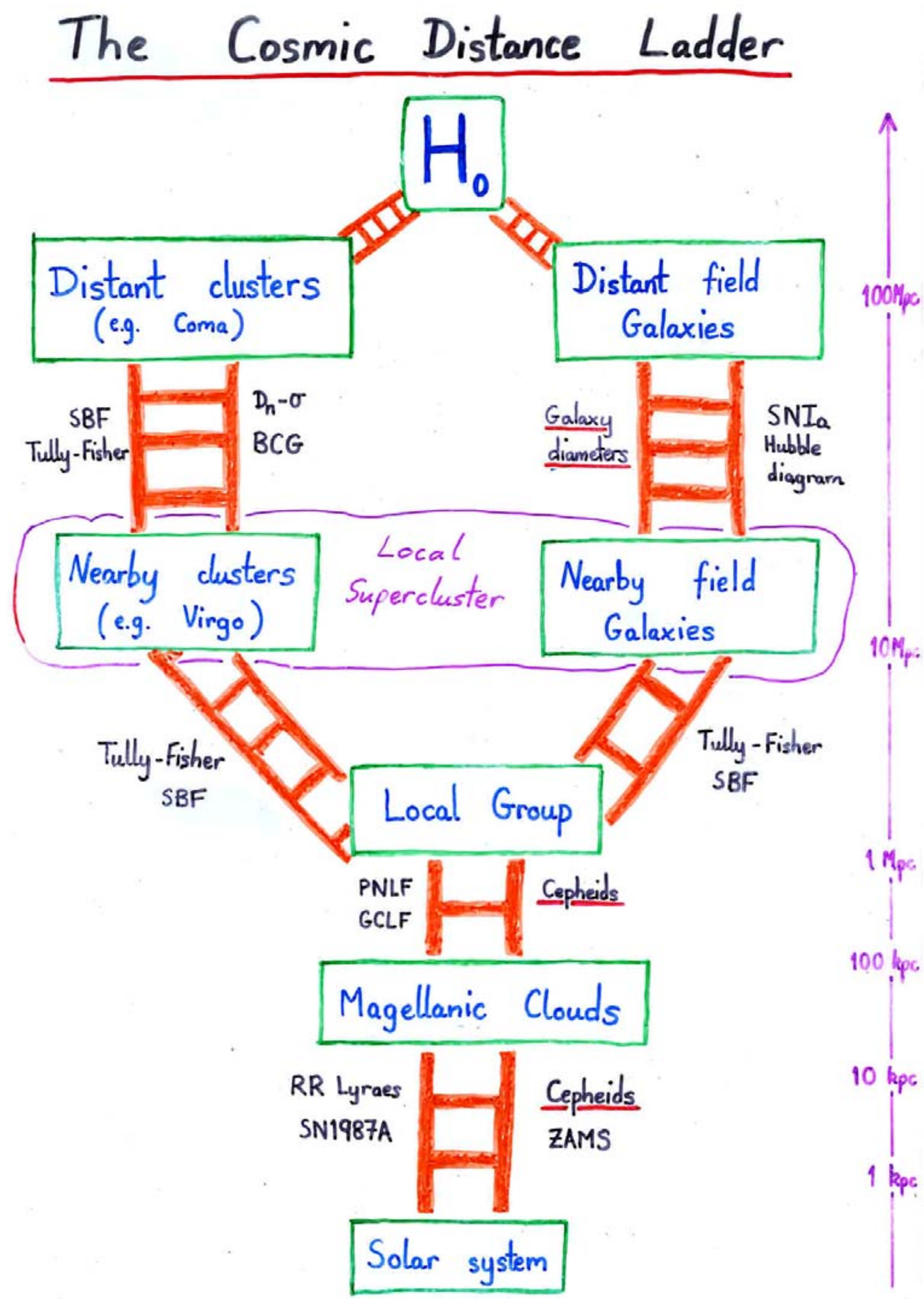
….**but….**

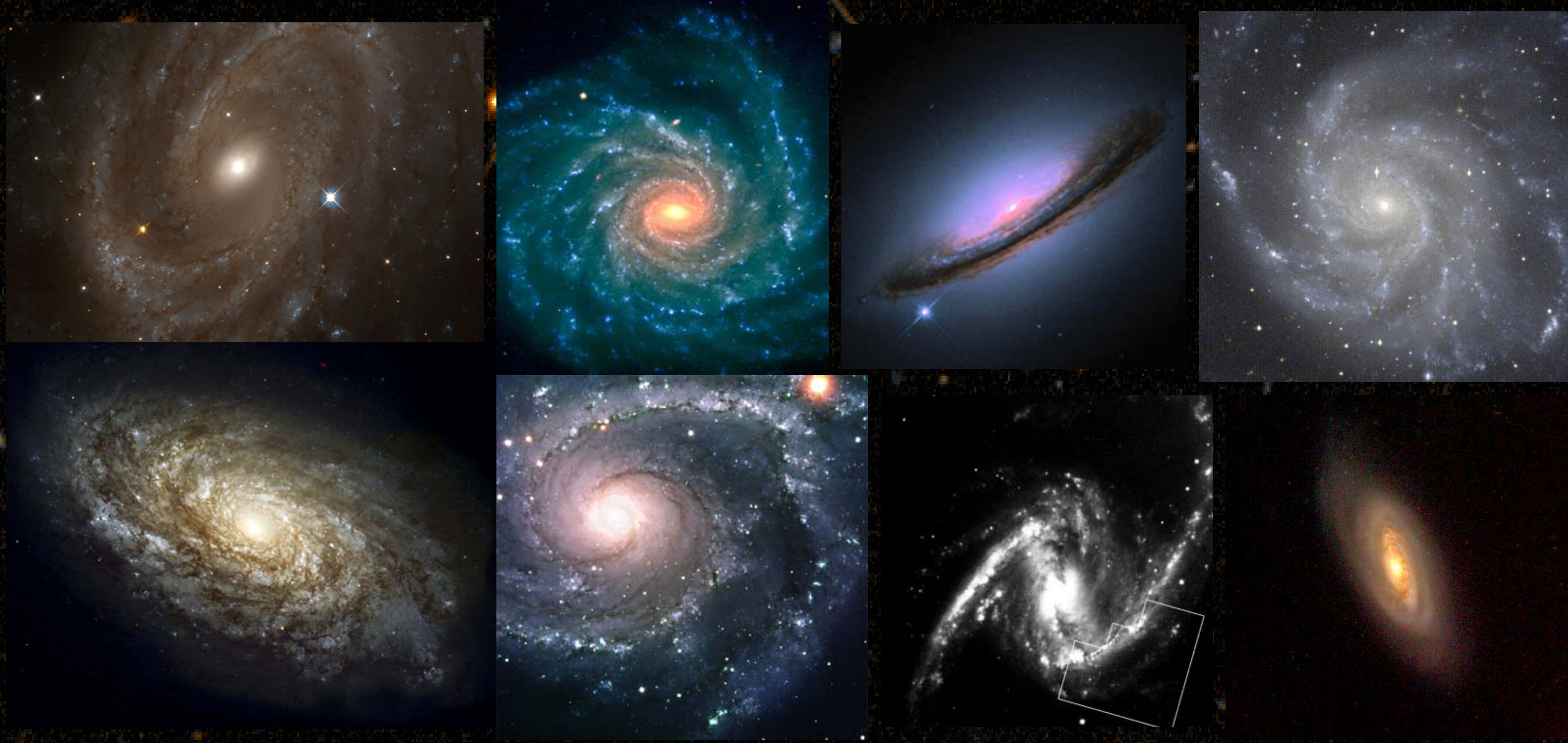
We cannot use primary distance indicators to measure their distance

Need Distance Ladder!!



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

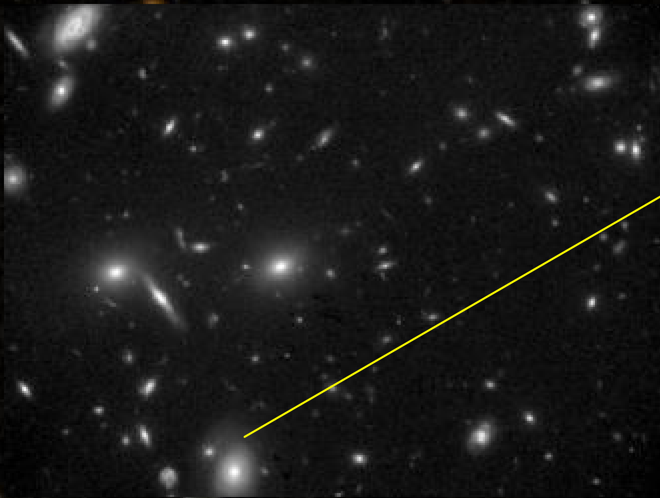




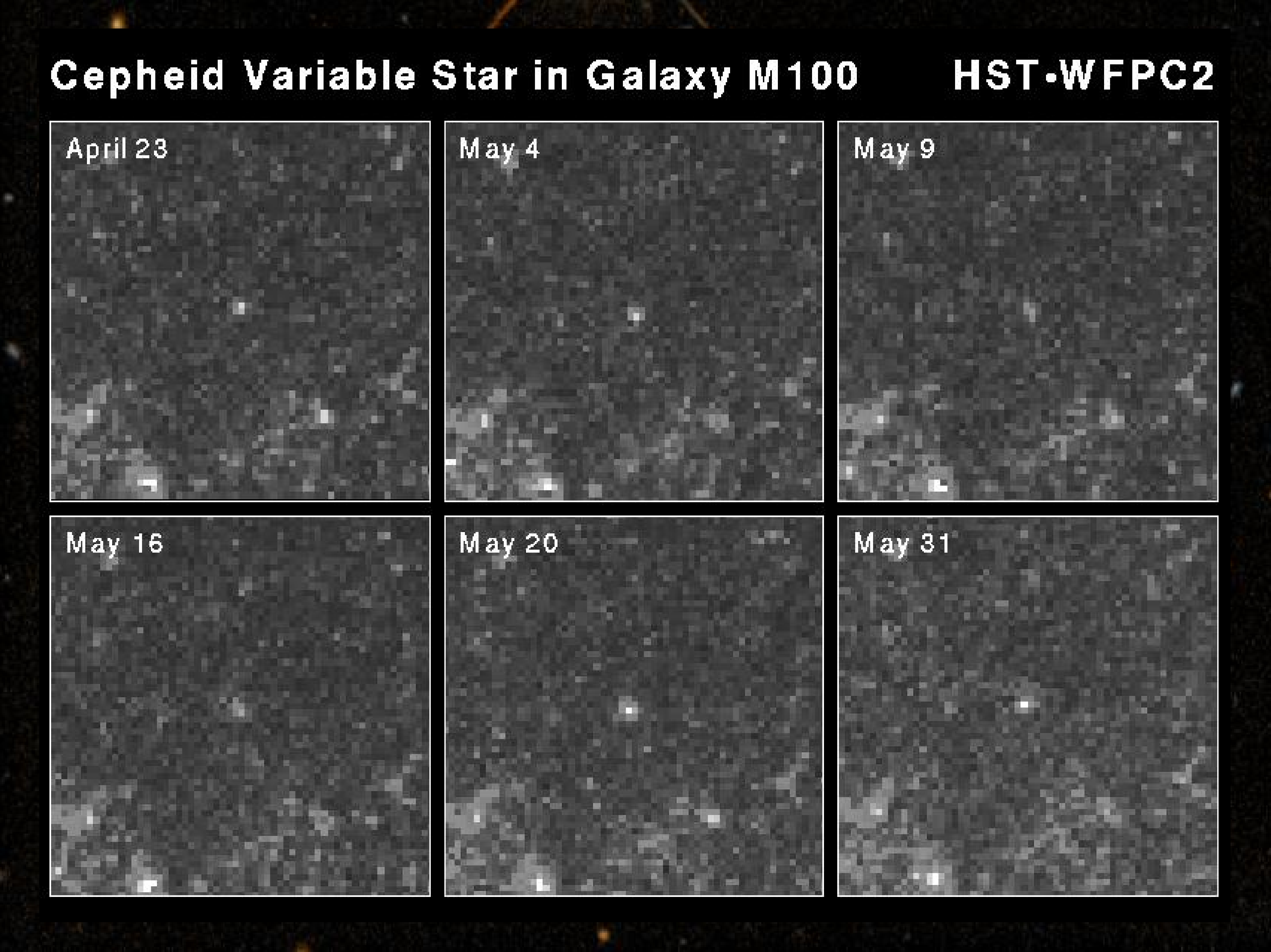
HST Key Project, led by Wendy Freedman

Measure Cepheid distances to ~30 nearby galaxies,

Link Cepheids to Secondary distance indicators

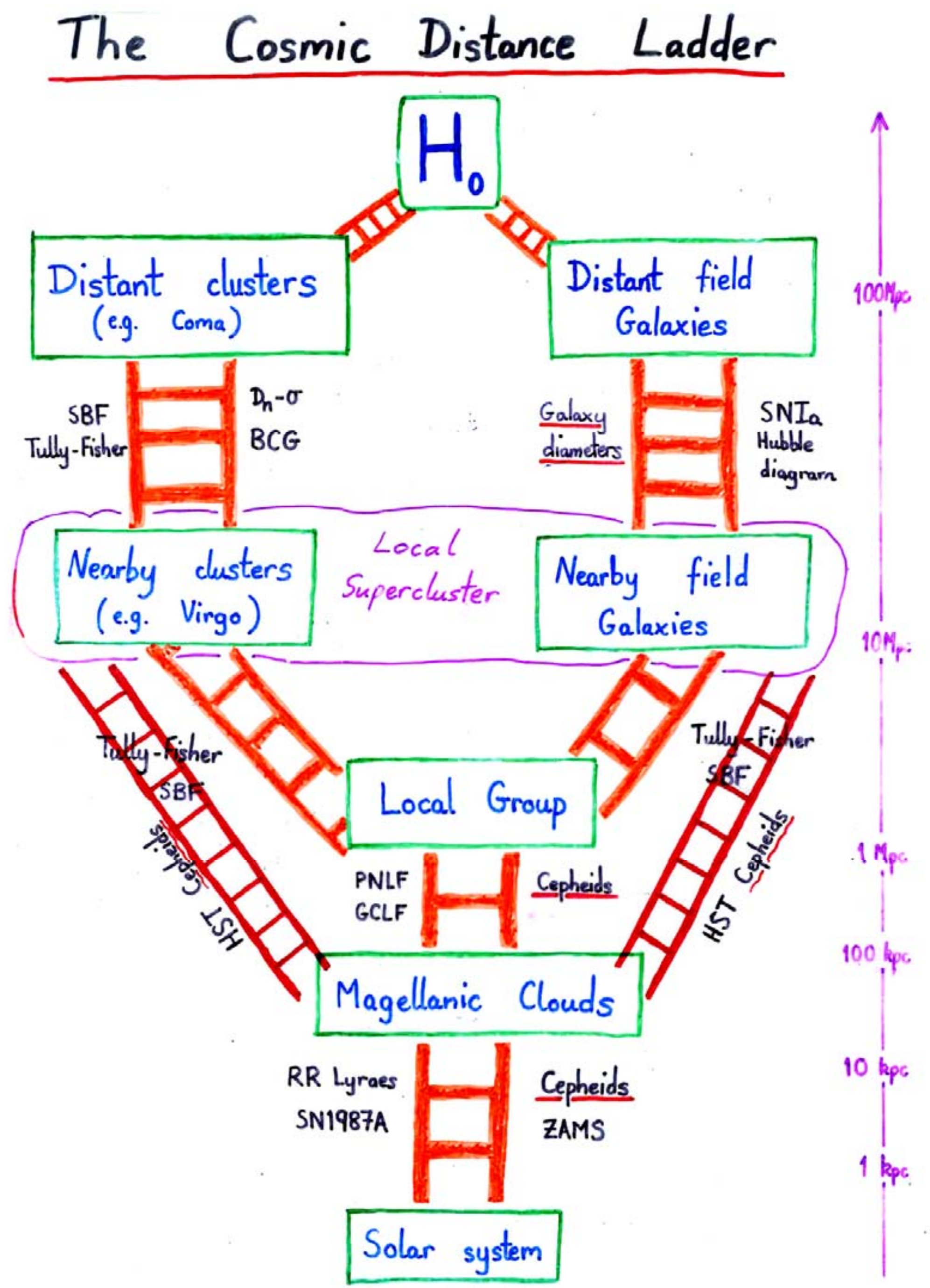


Virgo Cluster galaxy
M100, 60 million light years distant…..


Cepheid Variable Star in Galaxy M100
HST•WFPC2
April 23
May 4
May 9
May 16
May 20
May 31

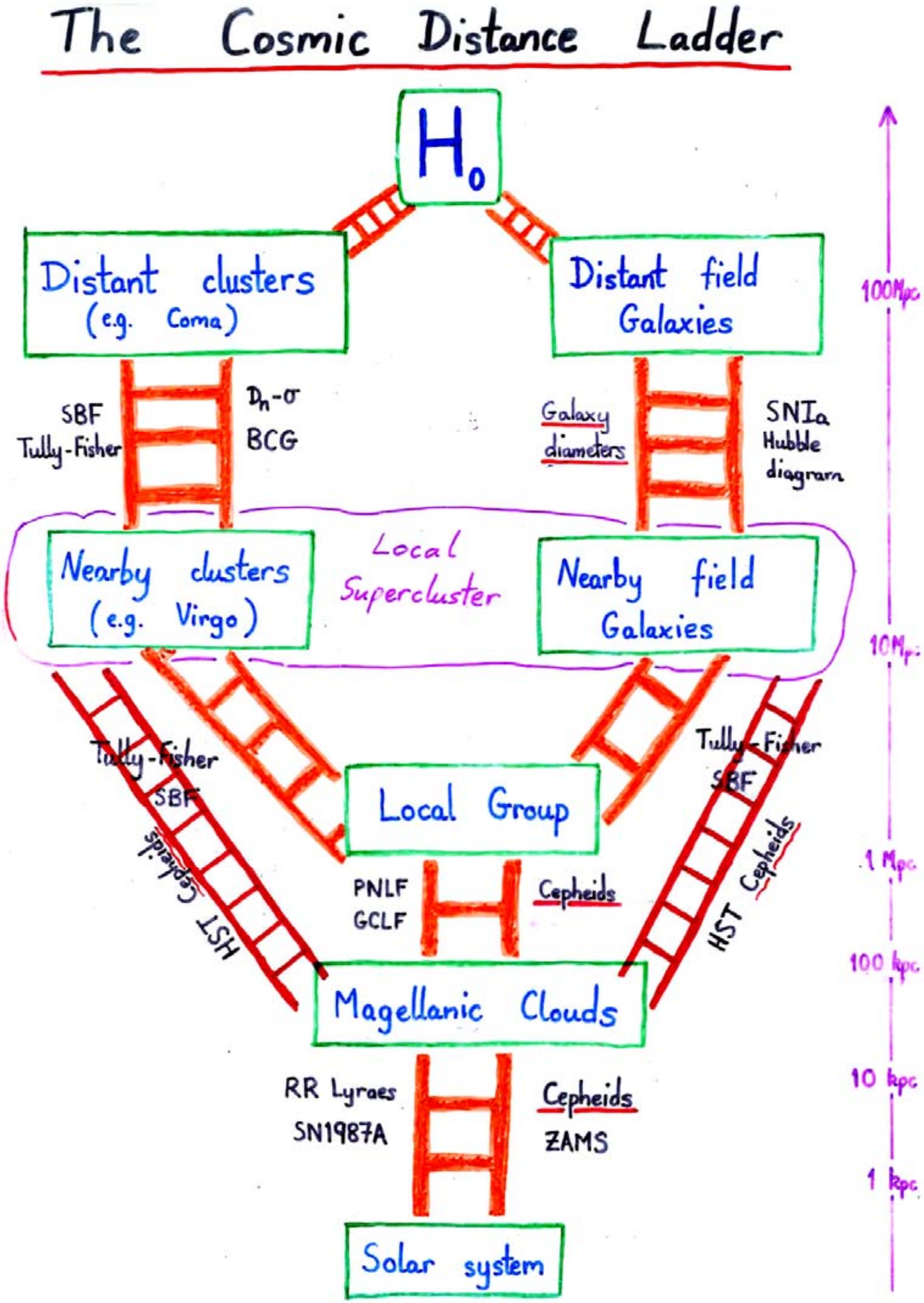
HST has 'bypassed' one stage of the Distance Ladder, by observing Cepheids beyond the Local Group of galaxies

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?…

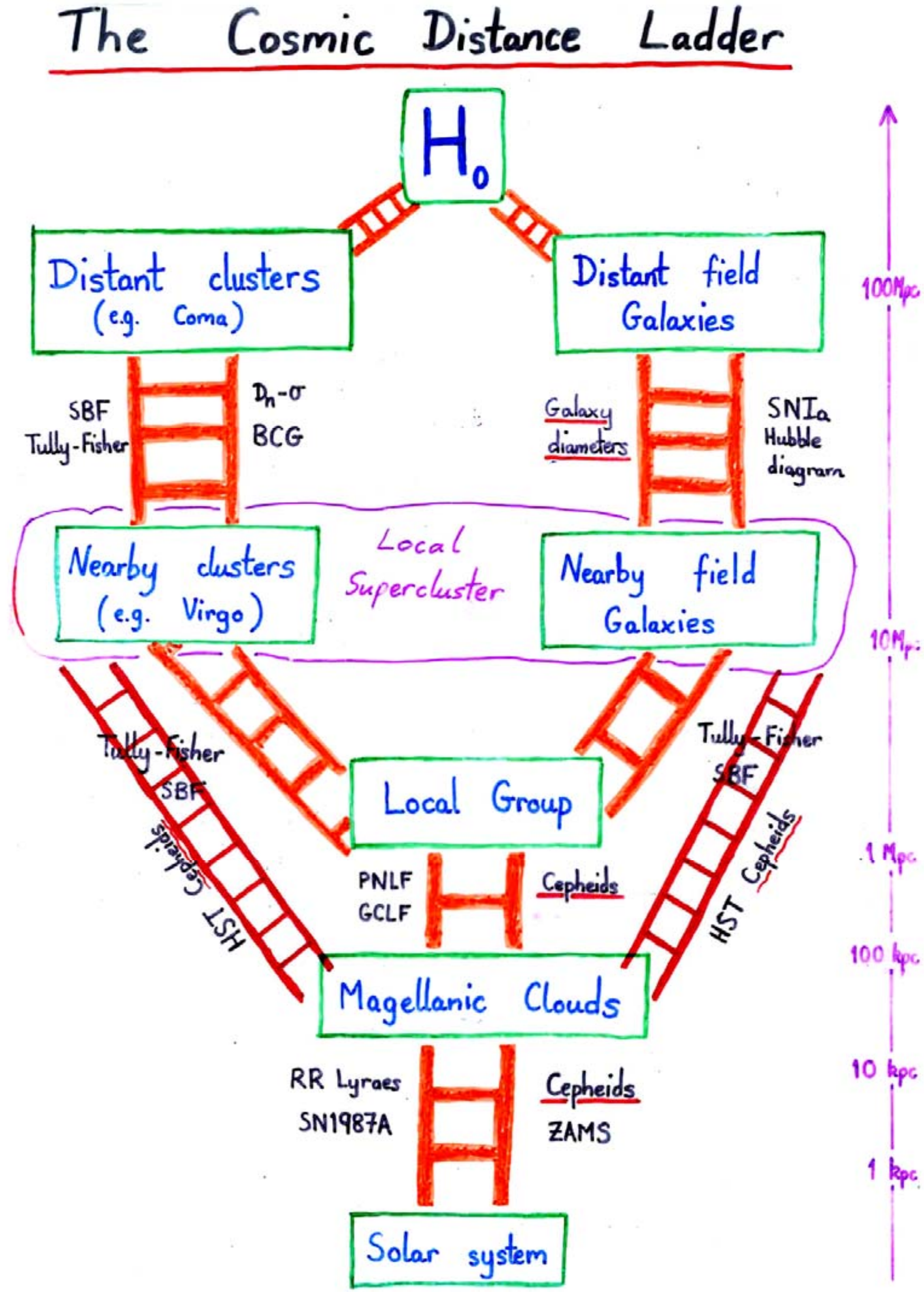


Must ensure that remote galaxy data are free from **Selection Effects**

e.g. intrinsically brighter or bigger?…

⬇

Malmquist Bias



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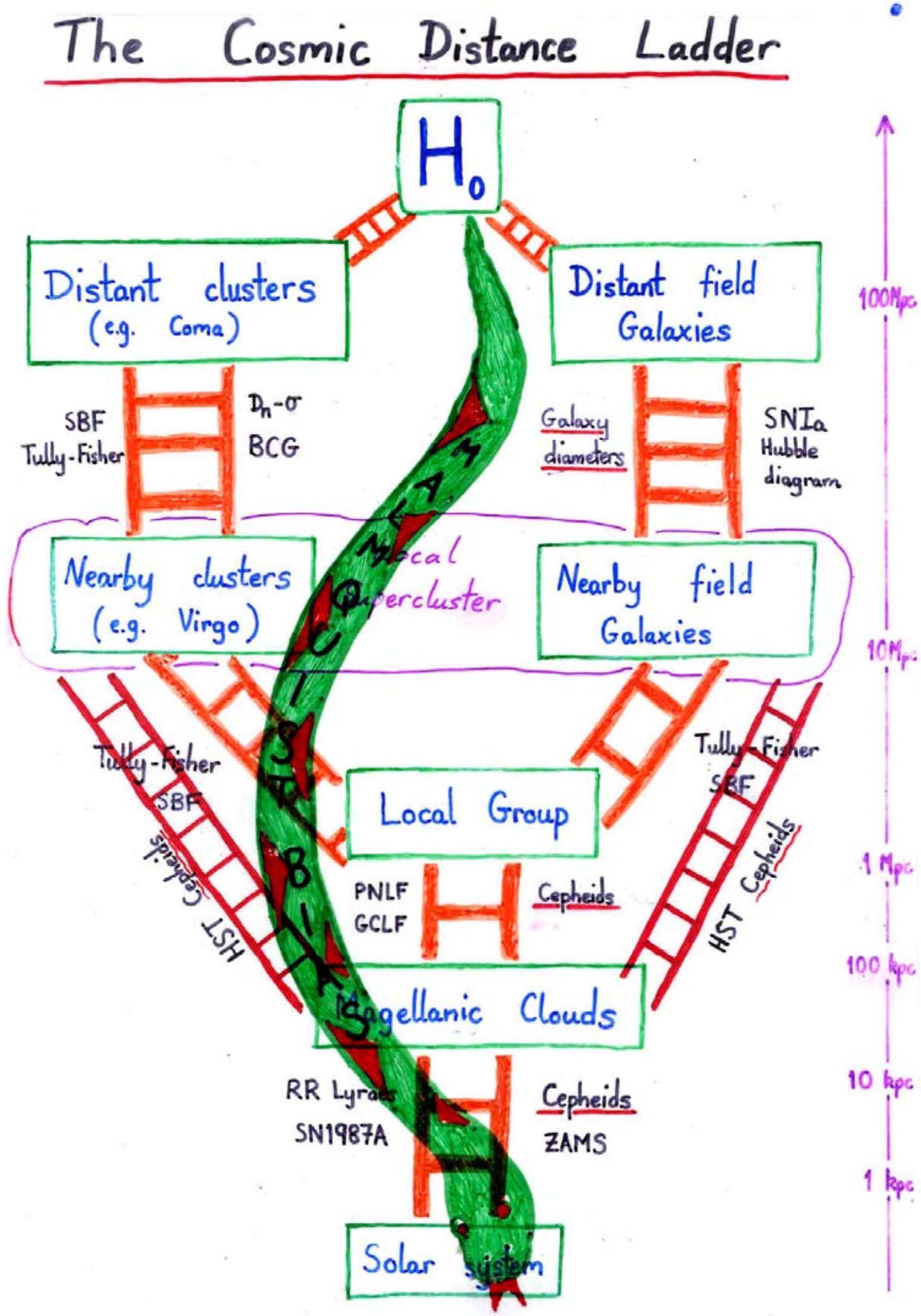
Malmquist Bias

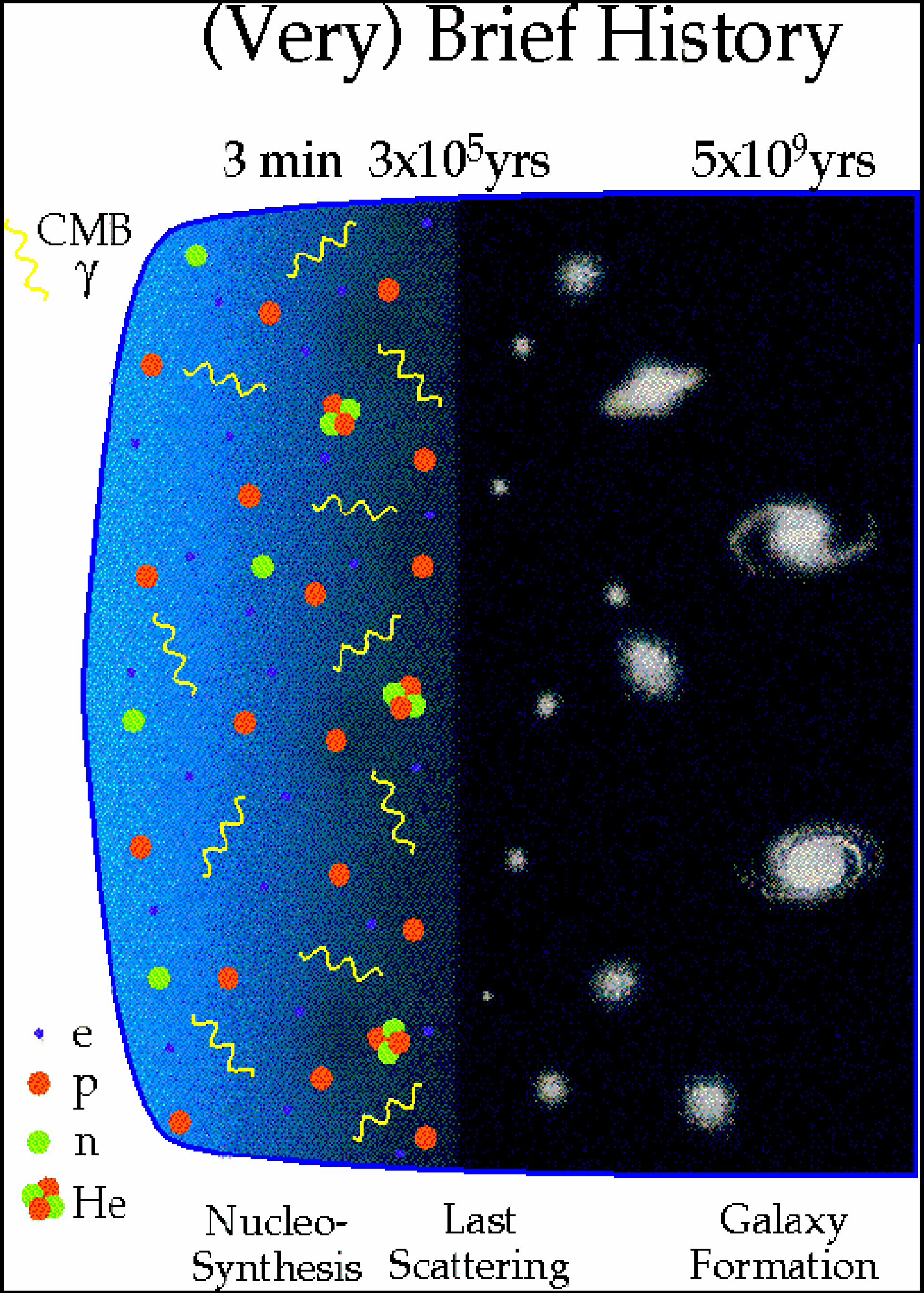


HST Key Project Final Results

Freedman et al. (2001)

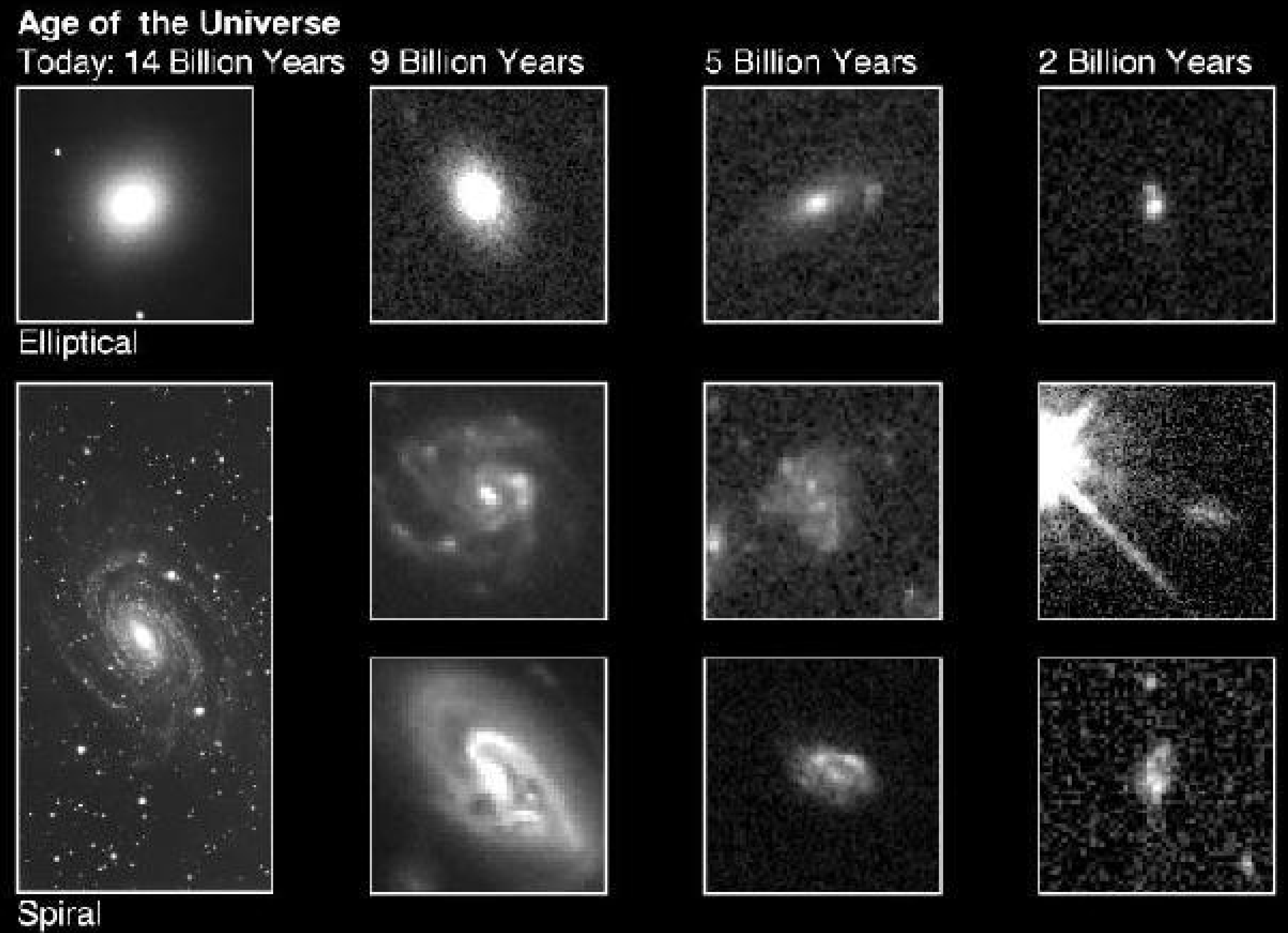
$$\boxed{H_0 = 72 \pm 3 \pm 7 \ \mathrm{km s^{-1} Mpc^{-1}}}$$

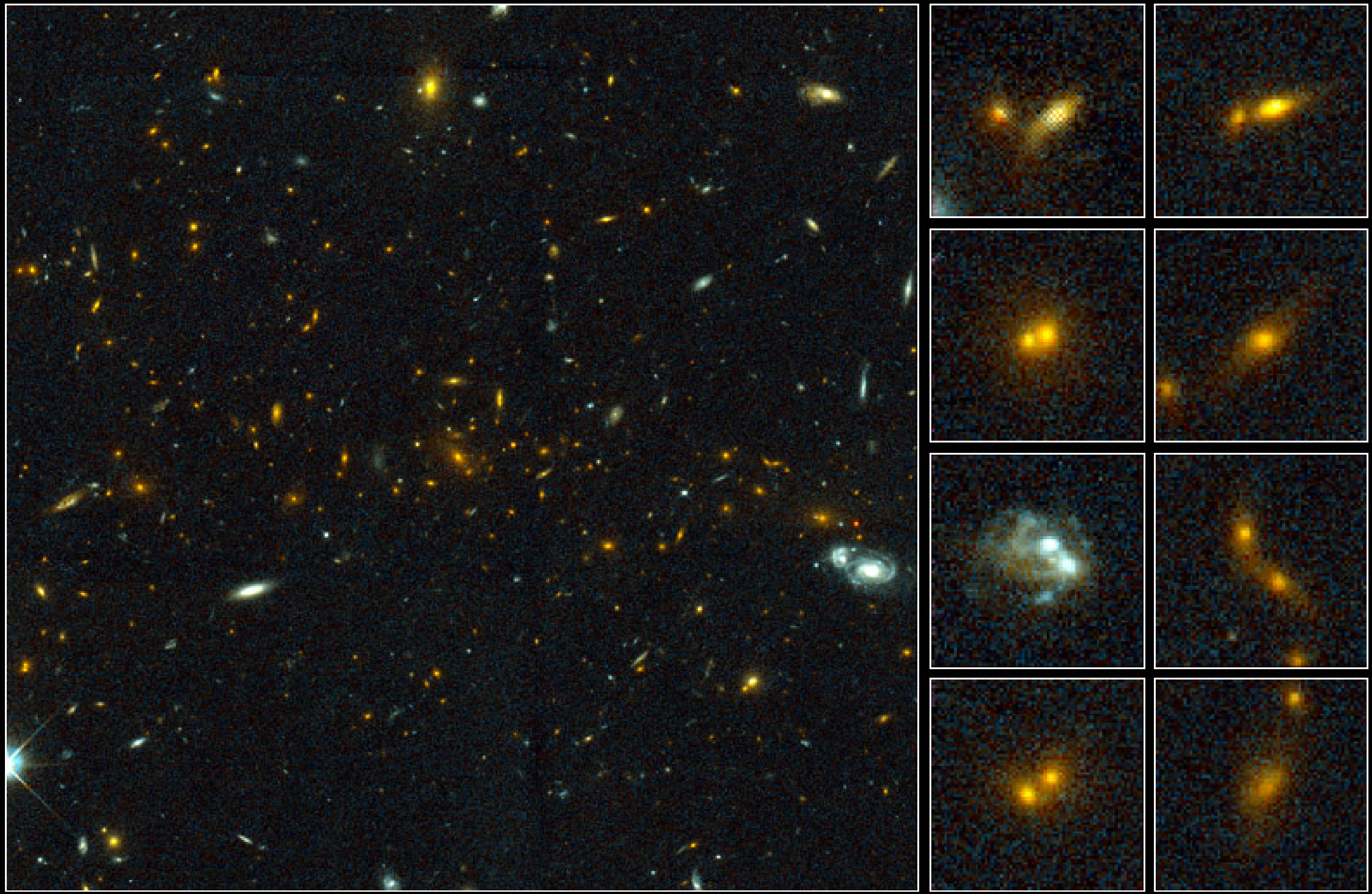
Combined analysis of several different secondary distance indicators.



Cornerstones of the Hot Big Bang Model

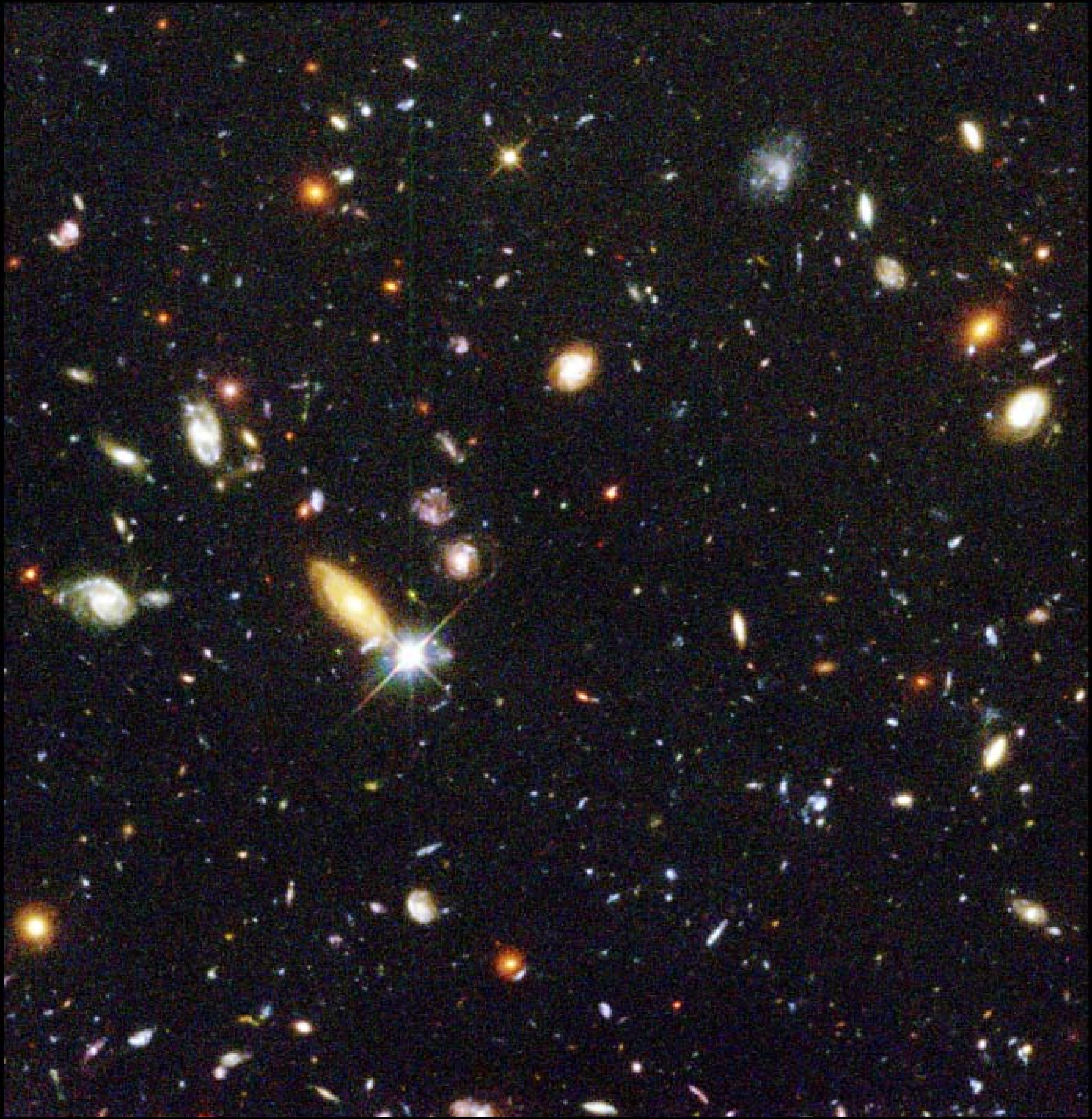
1. Expansion of the Universe
2. Evolution of the Universe
3. Light Element Abundances
4. CMBR


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



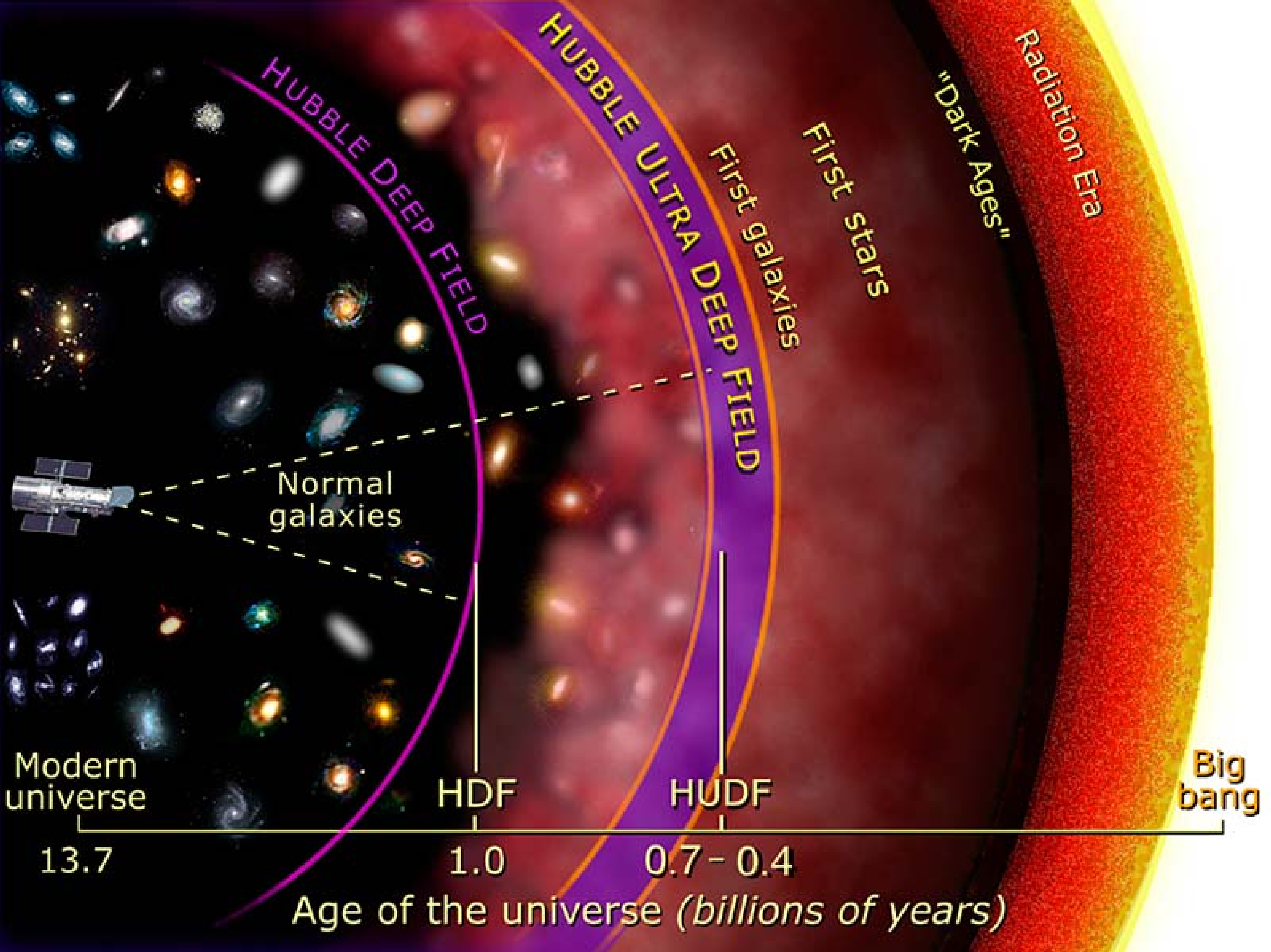
Galaxy Cluster MS1054-03 **HST • WFPC2**

PRC99-28 • STScI OPO • P. van Dokkum (University of Groningen), ESA and NASA

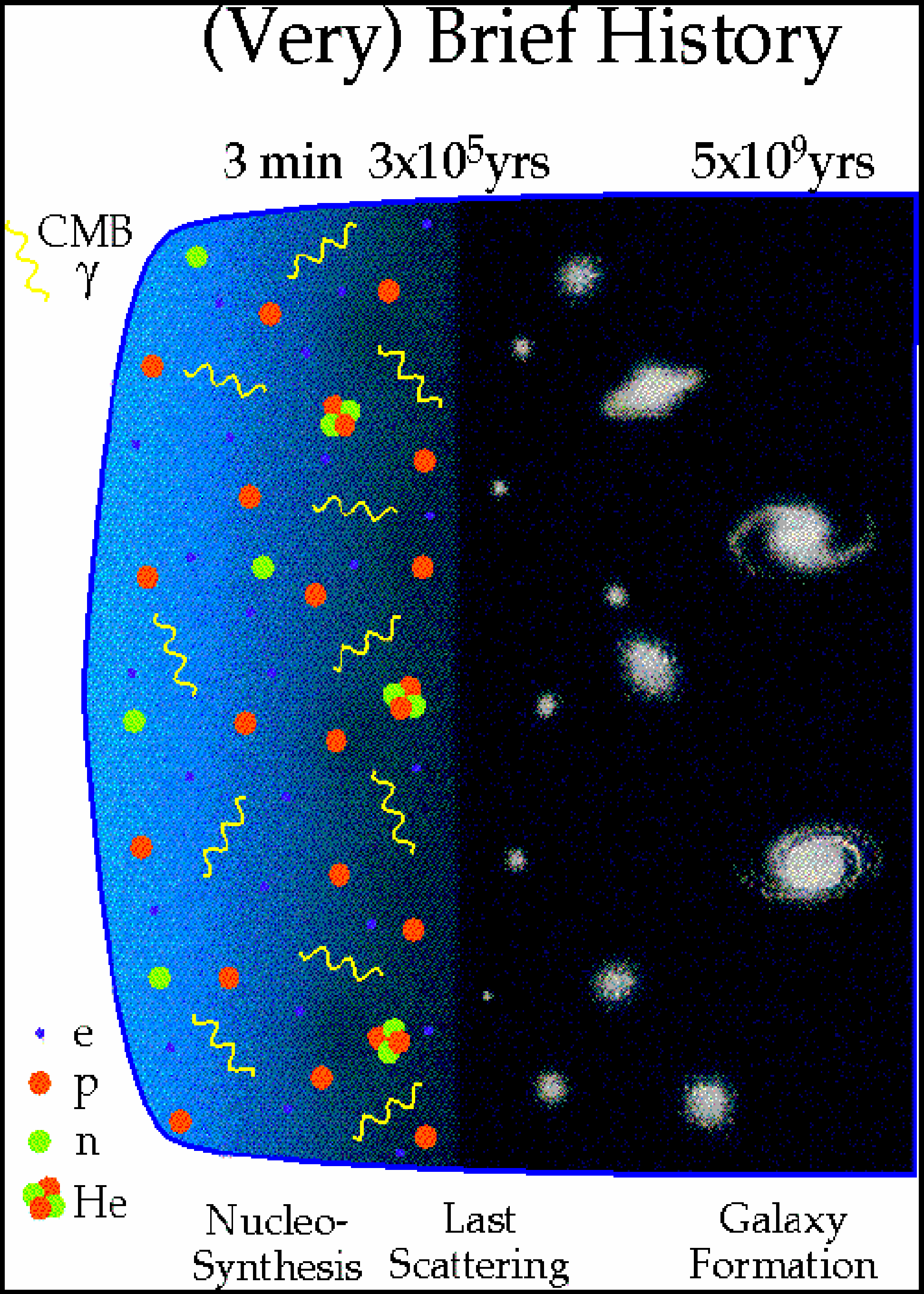


Hubble Deep Field HST • WFPC2

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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1. Expansion of the Universe
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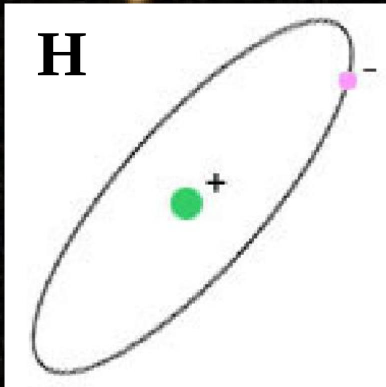
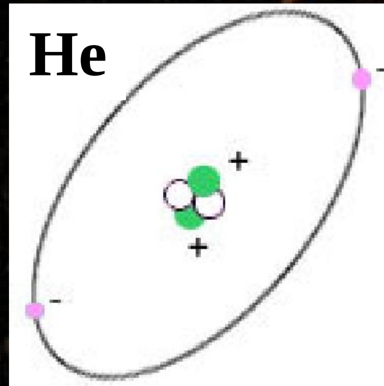
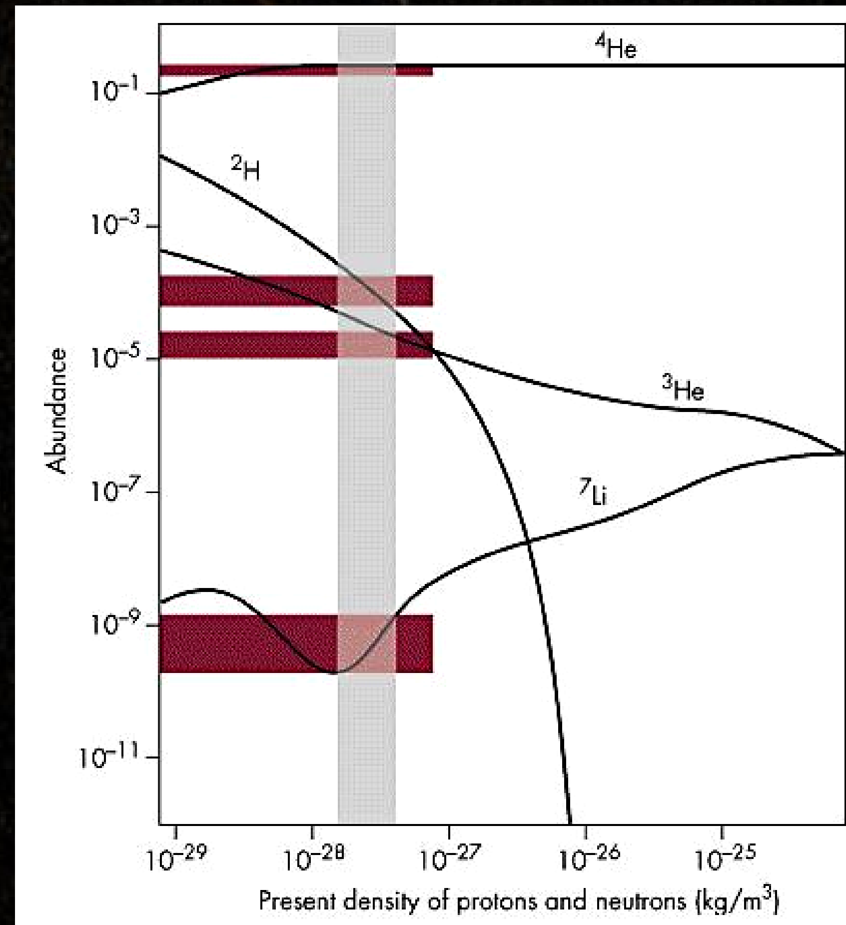


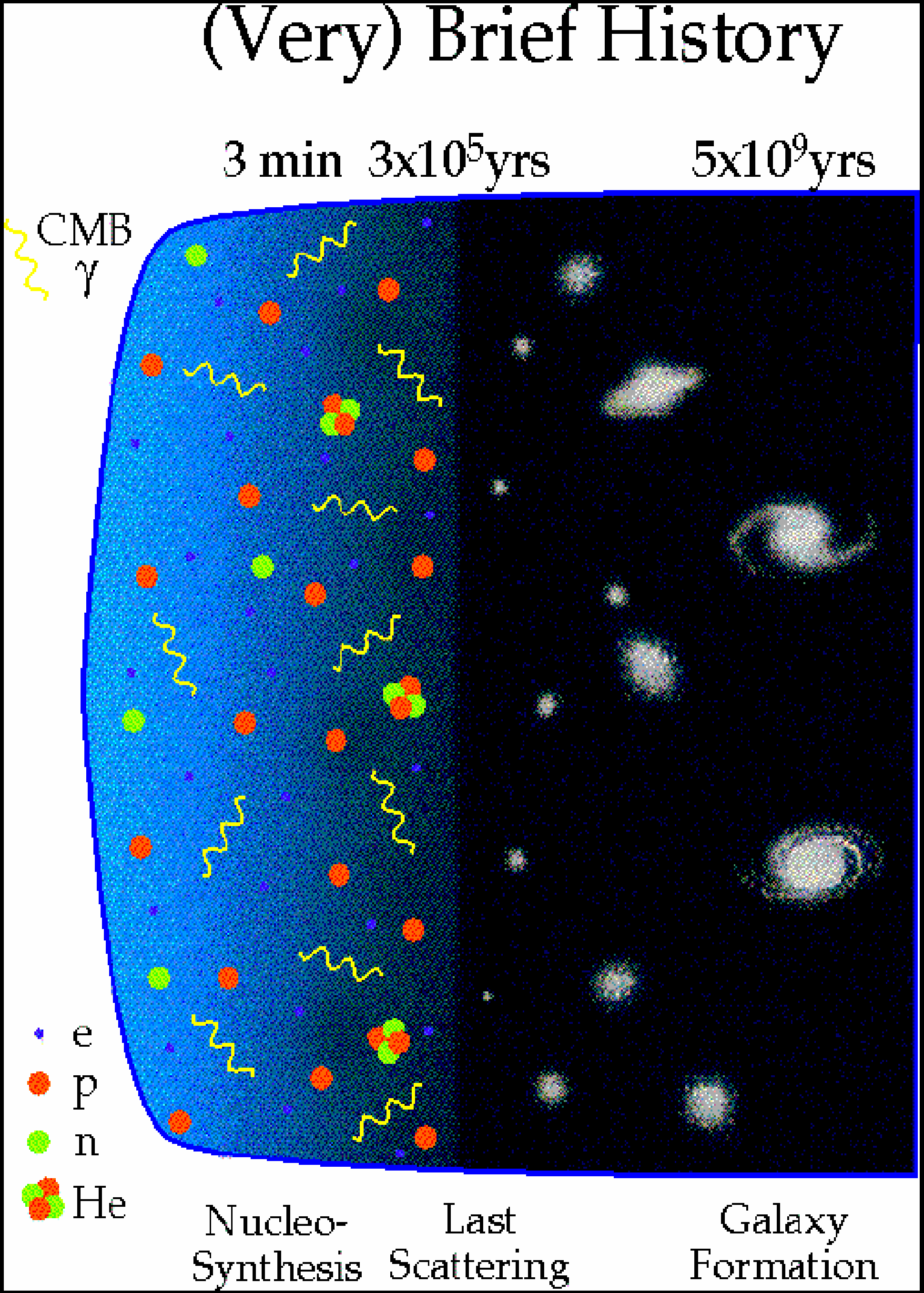


Helium ‘cooked’ during first three minutes

(Also trace amounts of Lithium Deuterium, Tritium, Beryllium)

Big Bang theory predicts correct amounts of all of these elements





Cornerstones of the Hot Big Bang Model

1. Expansion of the Universe
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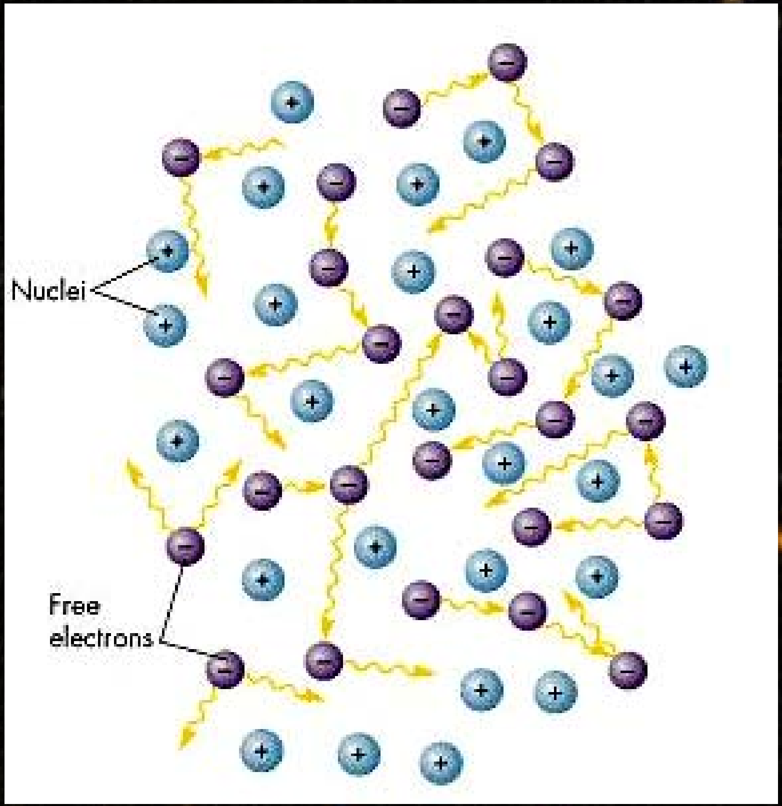
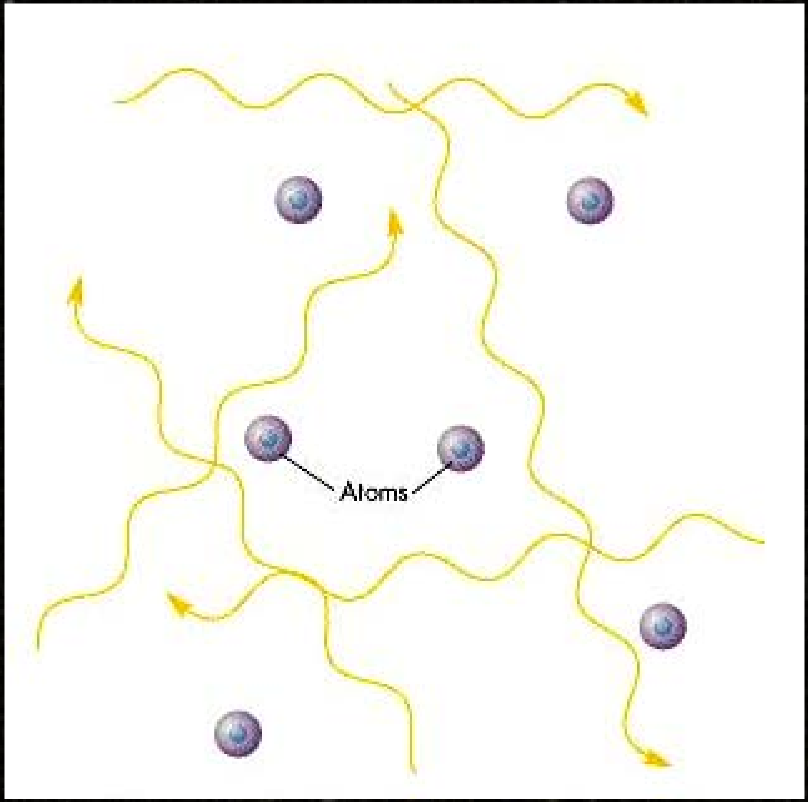
4. CMBR

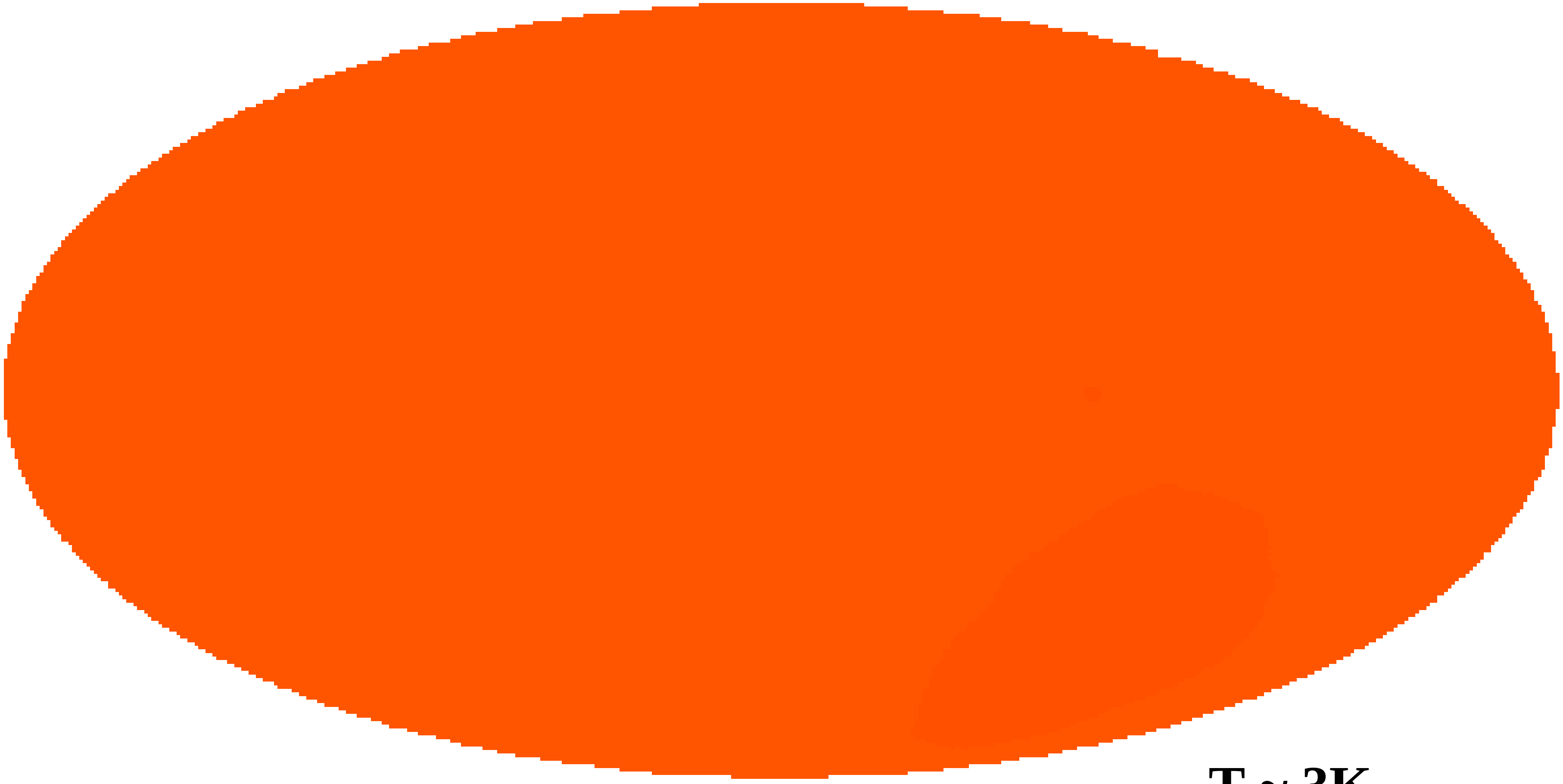
Early Universe too hot for neutral atoms

Free electrons scattered light (as in a fog)

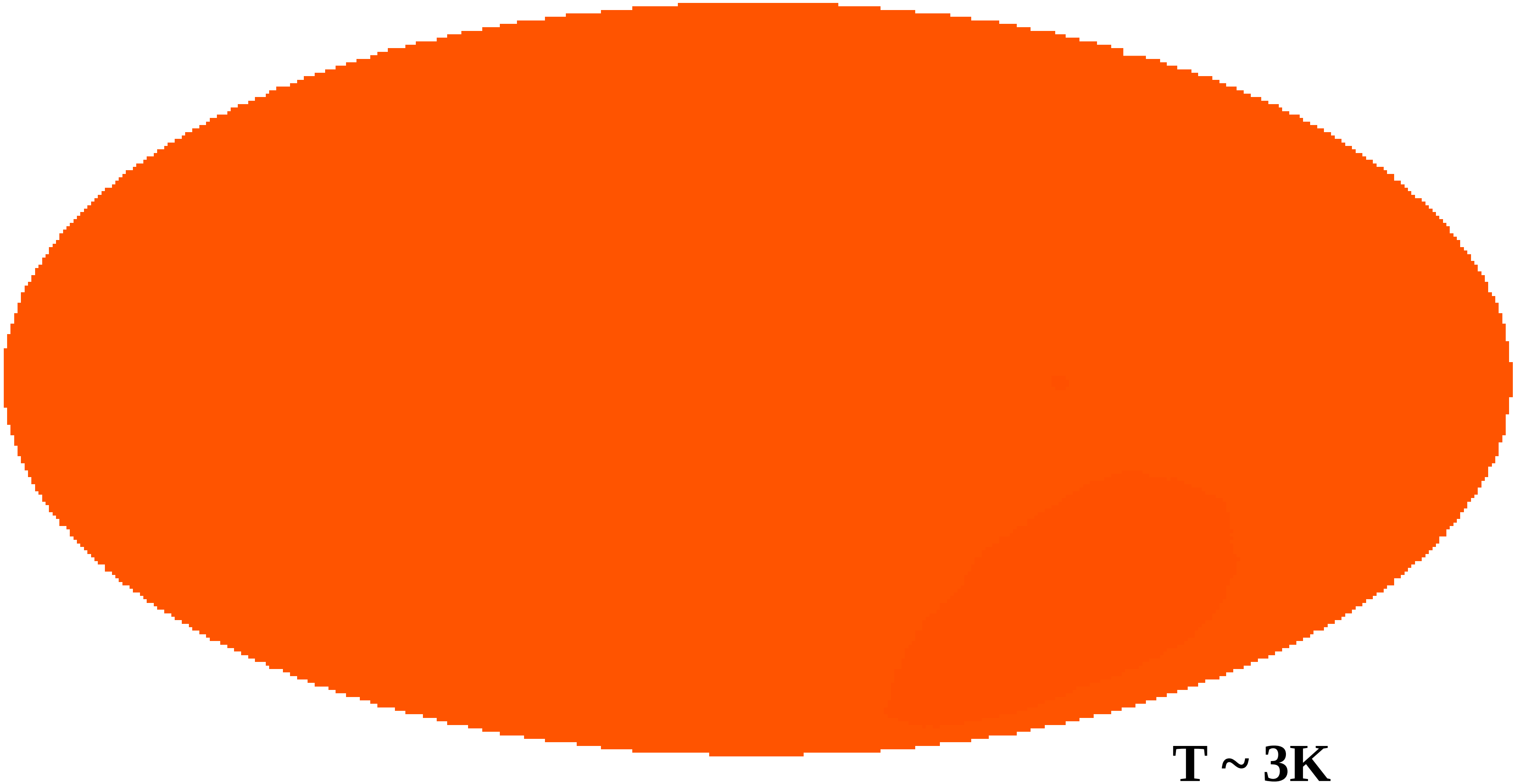
After ~300,000 years, cool enough for atoms; fog clears!







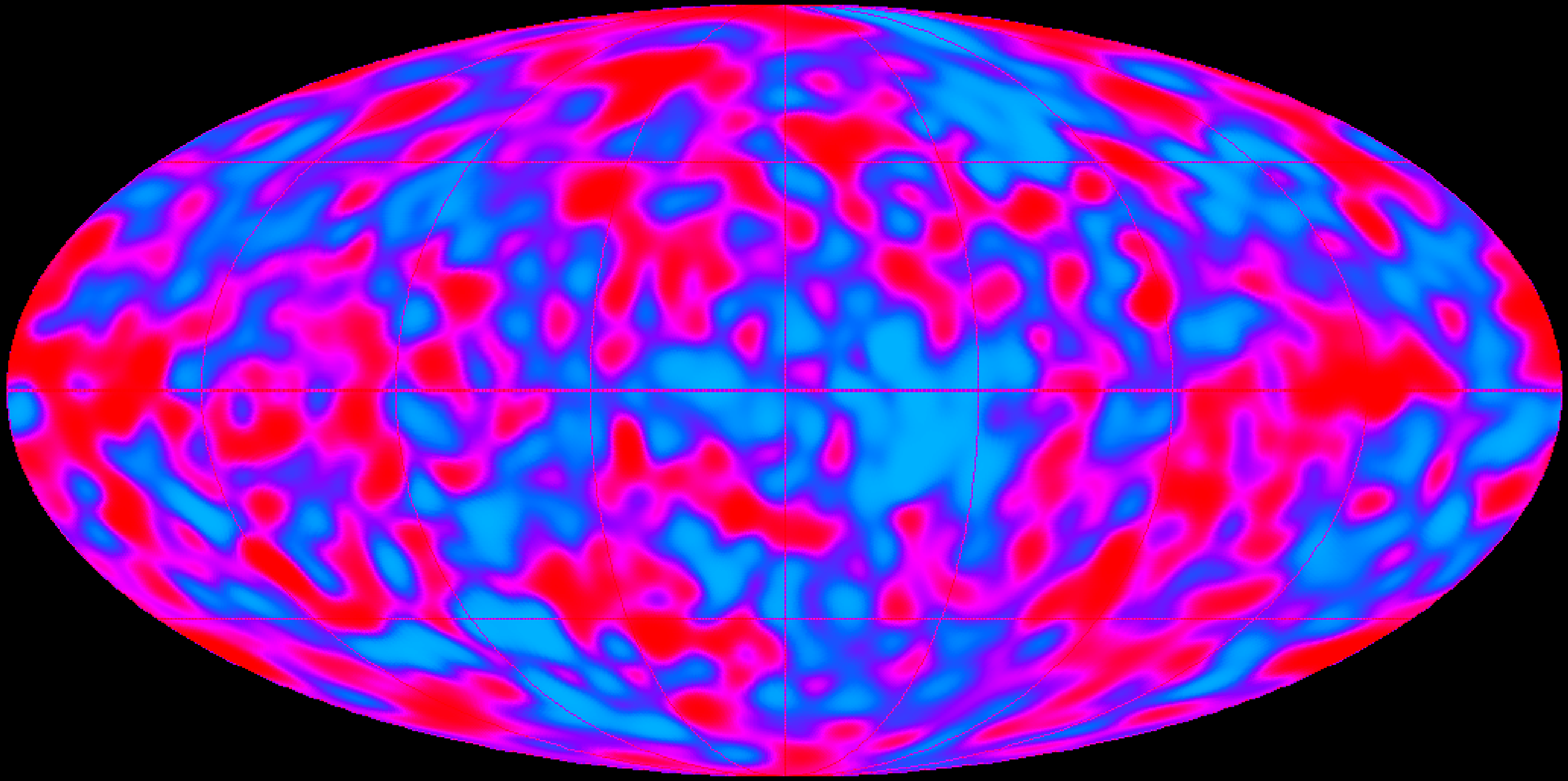
T ~ 3K

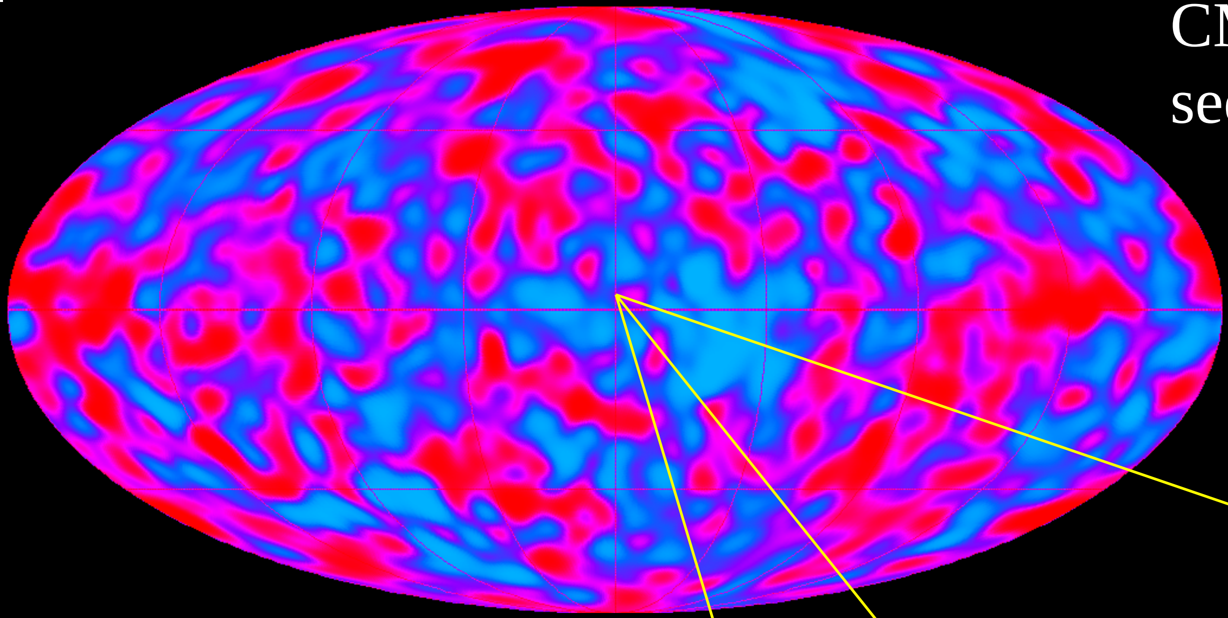


Strong support for the Cosmological Principle:

"The Universe is homogeneous and isotropic on large scales"

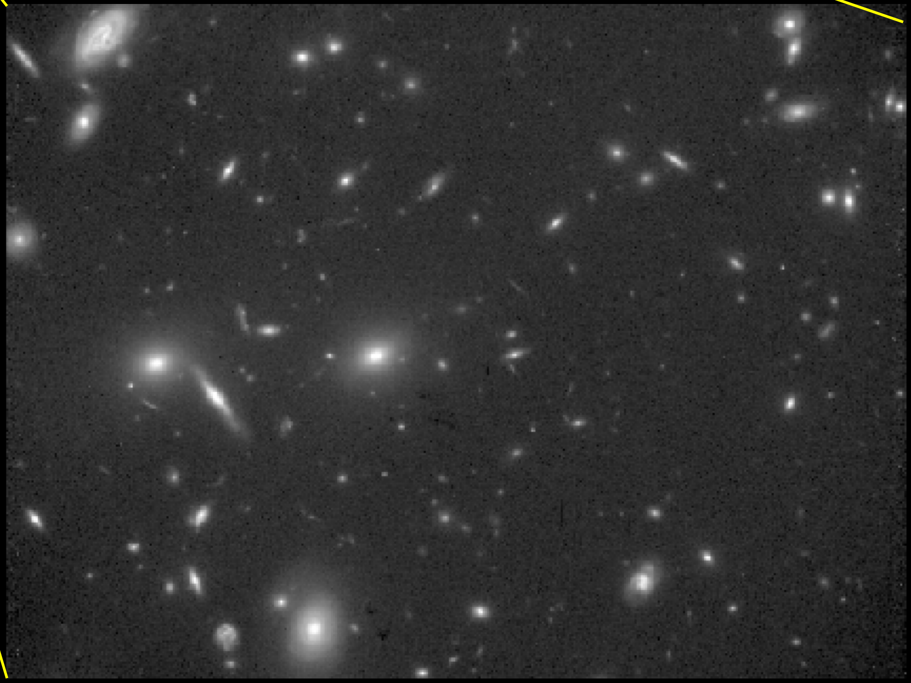
CoBE map of temperature across the sky



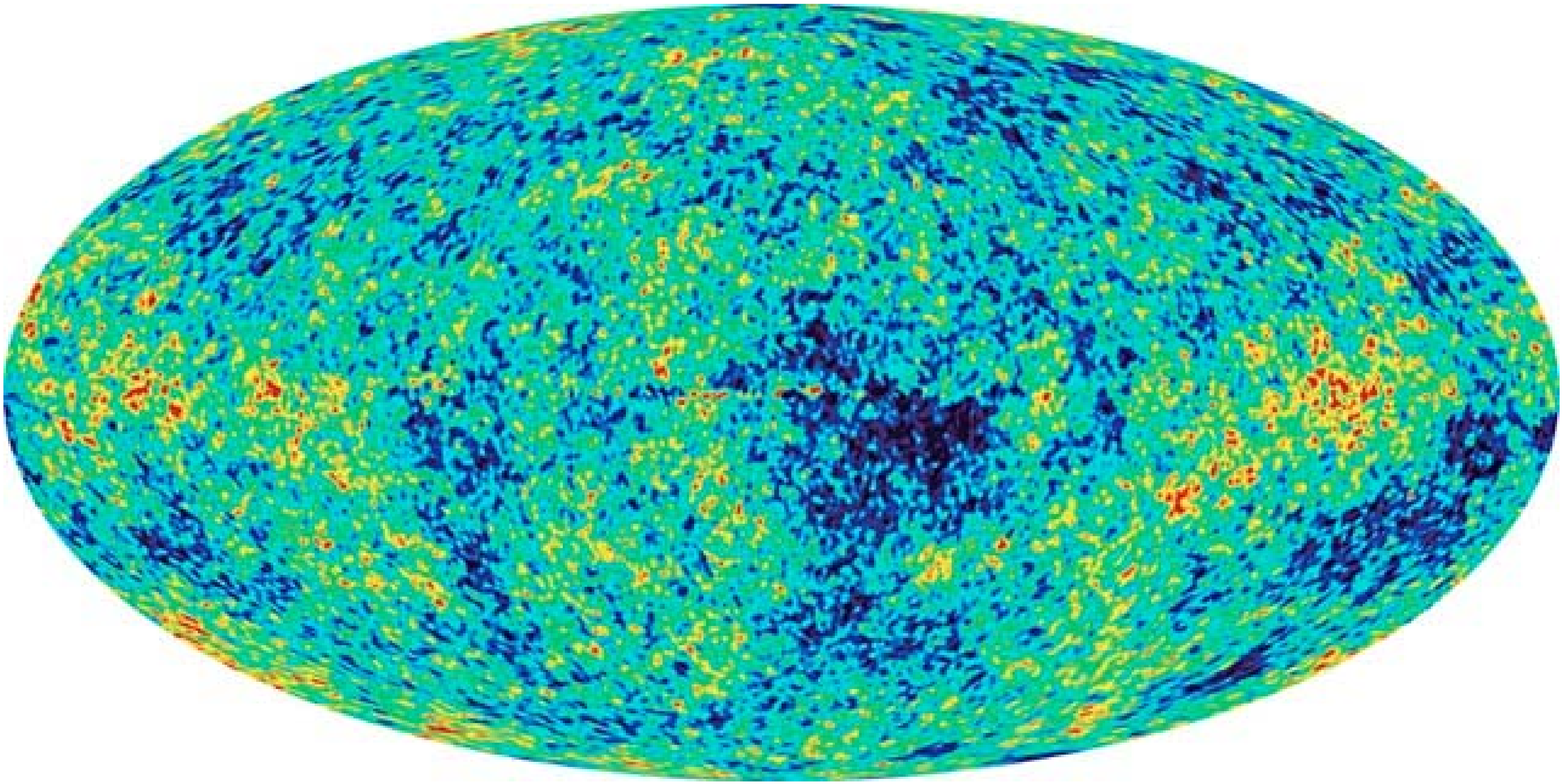


CMBR fluctuations are the seeds of today's galaxies

LSS formation is sensitive to the pattern, or power spectrum, of CMBR temperature fluctuations



From Bennett et al (2003)



WMAP results published early 2003