Cosmology today

ASSA: Durban 2008

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- *A summary of our present day knowledge of the nature of the physical cosmos*
- *Comments on its relation to astronomy*

The Universe

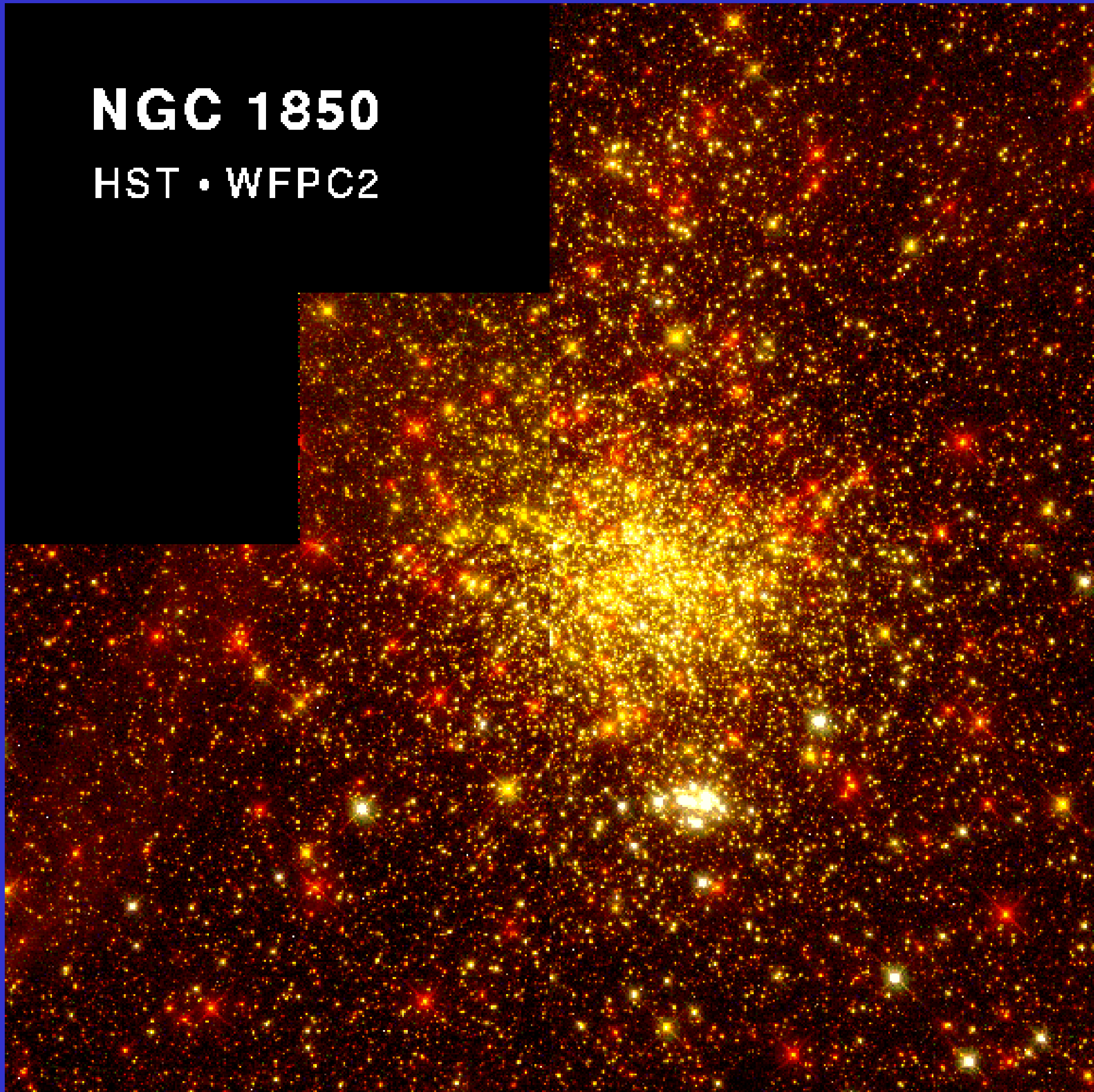
- The universe is of vast scale
- It is expanding
- It started off in a Hot Big Bang
- Structures such as galaxy clusters formed by gravitational attraction
- Stars and planets formed in this environment

1: Observations

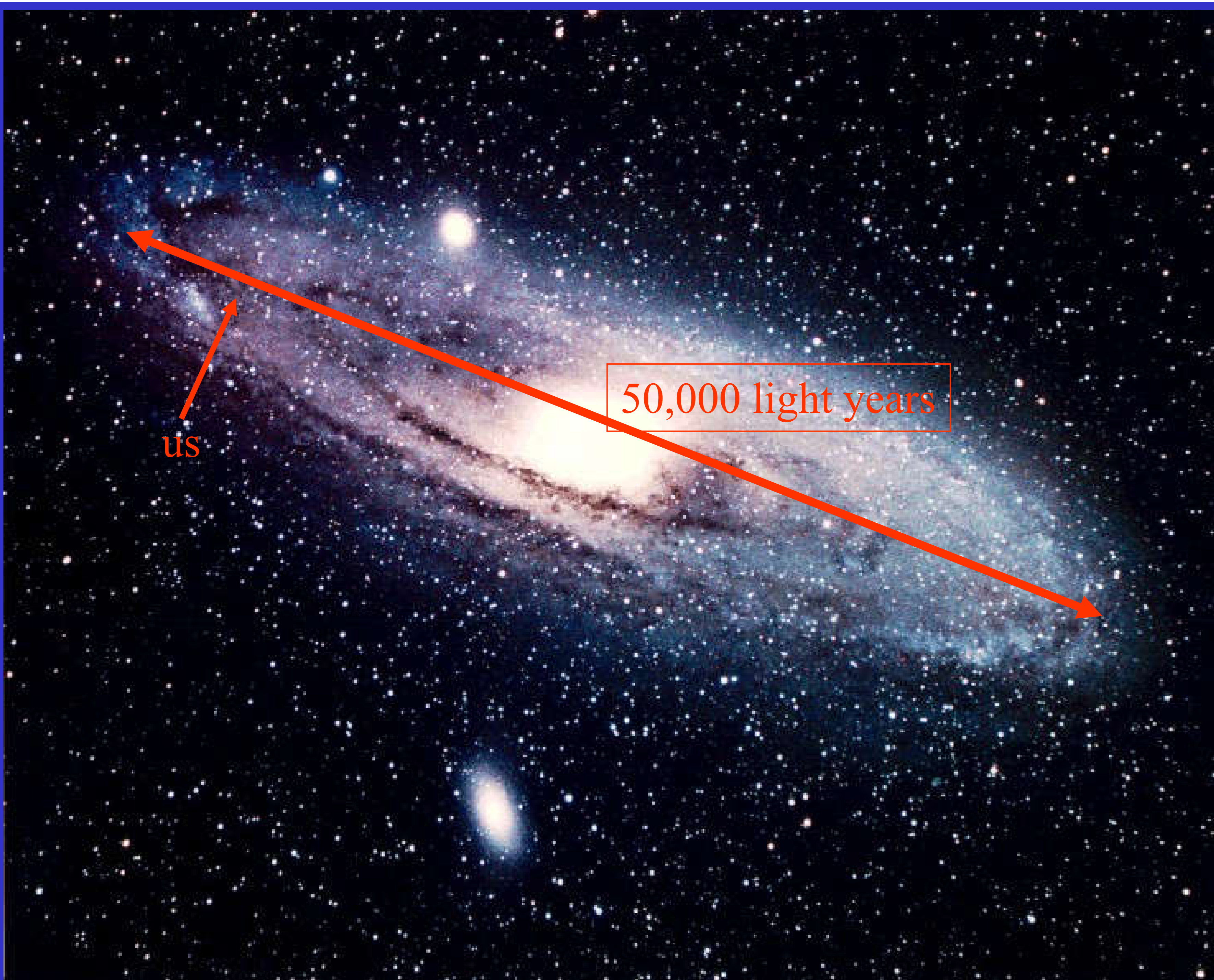
Observational cosmology started in the 1920's through optical observations of galaxies:

Hubble established distances, and showed:

- *faint 'nebulae' are galactic systems equivalent to our own Milky Way*
- *the vast size of the Universe*
- *linear relation between redshift and distance*
- *number counts establish rough homogeneity of the Universe*


NGC 1850
HST • WFPC2

The Milky Way

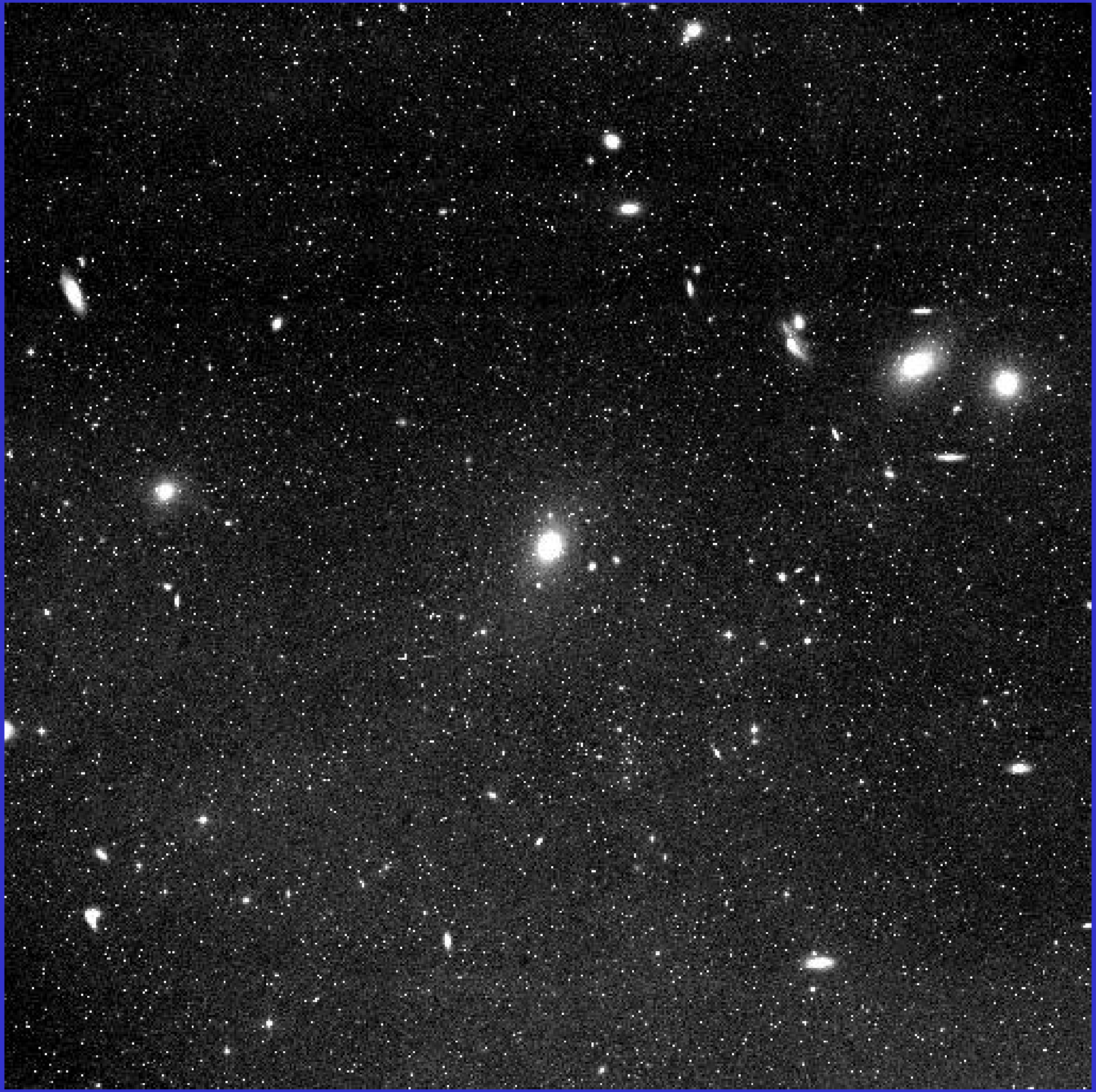

50,000 light years
us


Circinus Galaxy
Hubble Space Telescope • WFPC2
NASA and A. Wilson (University of Maryland) • STScI-PRC00-37

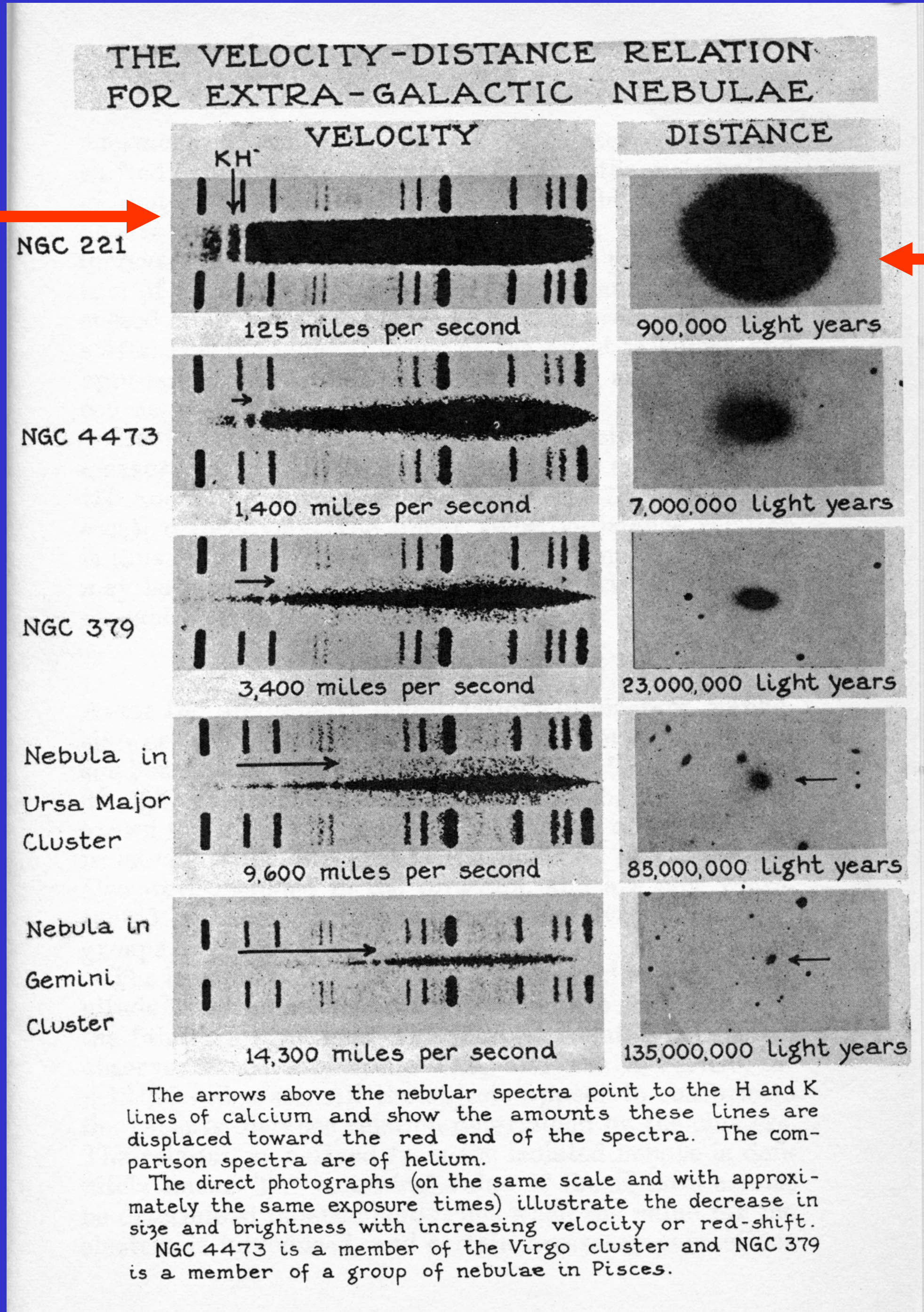

M87 © Anglo-Australian Observatory
Photo by David Malin

Coma cluster

Virgo
cluster



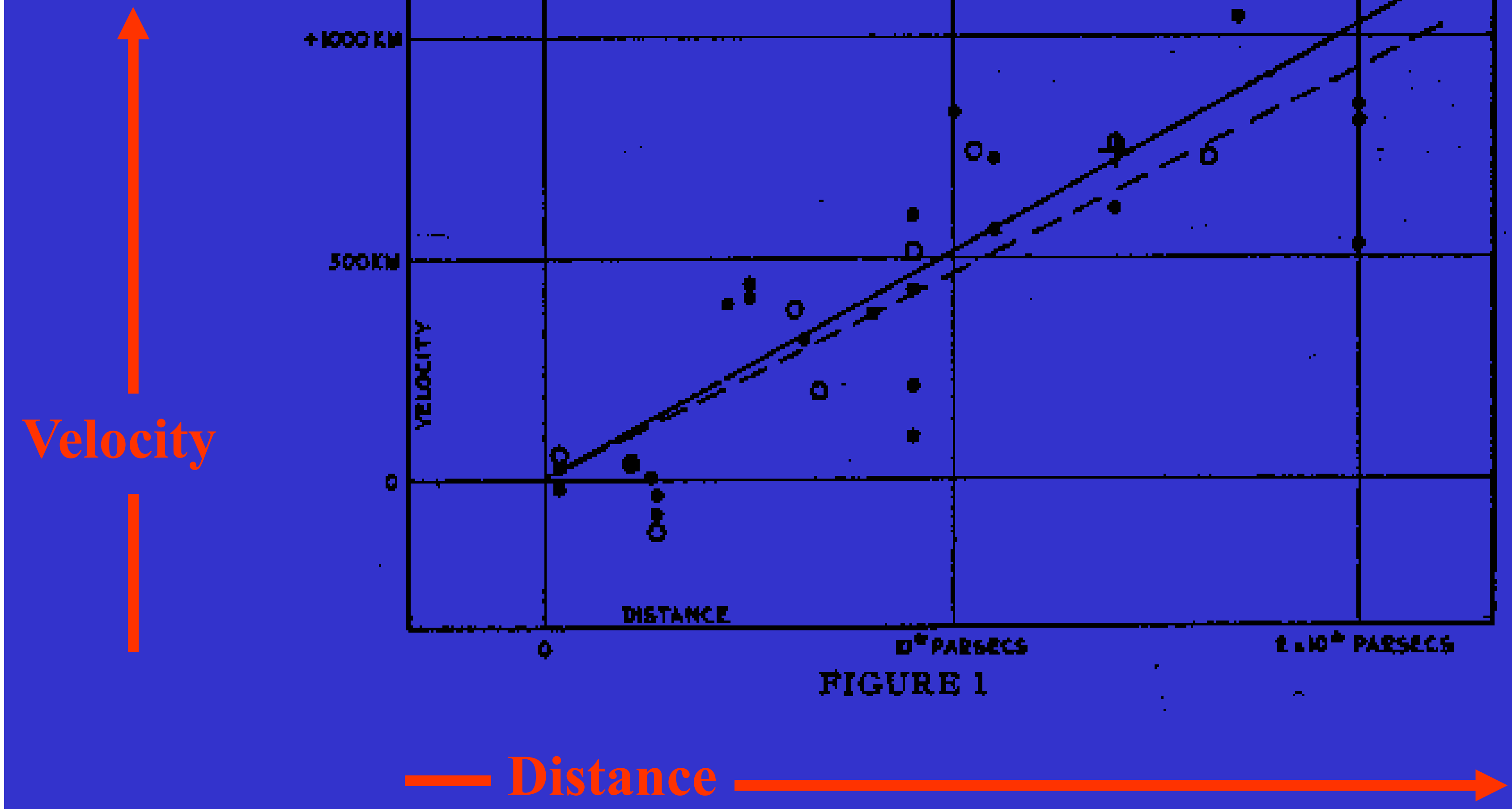
Redshift gives velocity



Apparent size gives distance

Edwin Hubble, 1929

Hubble's data



Velocity is proportional to distance

2. Geometry/relativity

The static cosmologies of Einstein and de Sitter (1917) were replaced, after some initial resistance, by the expanding universes of Friedmann and Lemaitre (`FL')

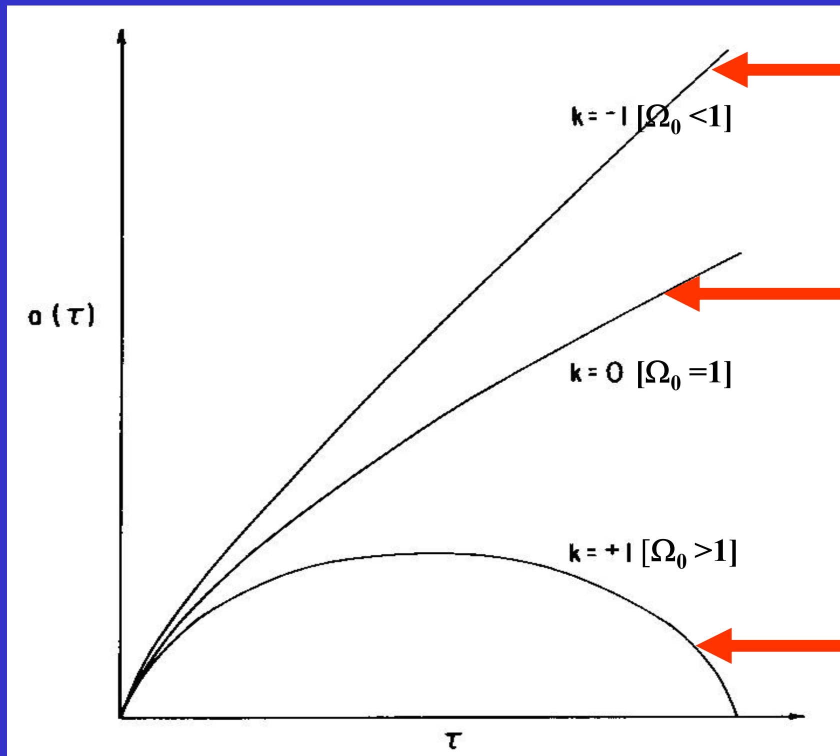
- *a family of exact solutions of the Einstein field equations* (`EFE')
- *with Robertson--Walker* (`RW') *geometry (they are spatially homogenous and isotropic).*
- *Scale factor* S(t) ['size of the universe']
- *Expansion rate* H= (1/S)(dS/dt) ['Hubble parameter']

Size of universe vs time ($\Lambda = 0$)

Gravity is expressed in space-time curvature,
and determines the evolution of space-time:

Dimensionless Density parameter:

$$\Omega_0 = \kappa\,\rho / 3H_0^2$$



Negatively curved 3-spaces

Flat 3-spaces

Positively curved 3-spaces

If $\Lambda = 0$ the critical density $\Omega_0 = 1$ separates the ever-expanding from recollapsing. [More complex when Λ is non-zero].

Observational parameters

- *Hubble constant:* $H_0 = [(1/S)dS/dt]_0$
- *Matter density:* ρ_0
  [different components]
- *Deceleration parameter:*
  $q_0 = - [(1/H^2)(1/S)d^2S/dt^2]_0$
- *Cosmological constant:* Λ
- *Spatial curvature k* (+1, spherical; -1, hyperbolic)

Normalized density parameter: $\Omega_0 = \kappa\rho_0/3 H^2{}_0$

'critical density' $\Omega_0=1$

Observational relations

- *galaxy number counts*: (n,m)
- *galaxy magnitude – redshift relation*: (m,z)

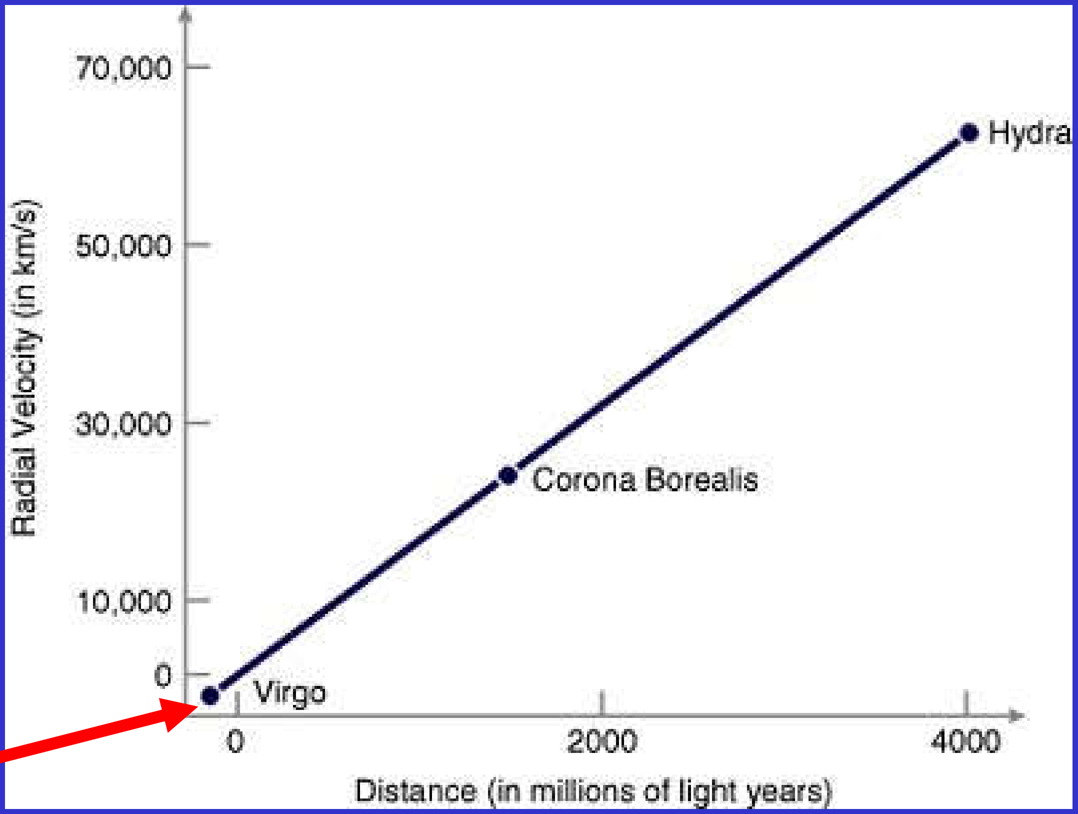
  applied to 'standard candles'
- Major observational programmes

BUT: No good standard candles

- *Source evolution*
- *Source statistics/ variation*

  prevented determining deceleration parameter

Velocity-distance relation



Hubble's data

But consistent with linearity to large distances …

3. Astrophysical cosmology

- *Properties and evolution* of galaxies, clusters of galaxies, intergalactic medium, radio sources, quasi-stellar objects, X-ray sources.

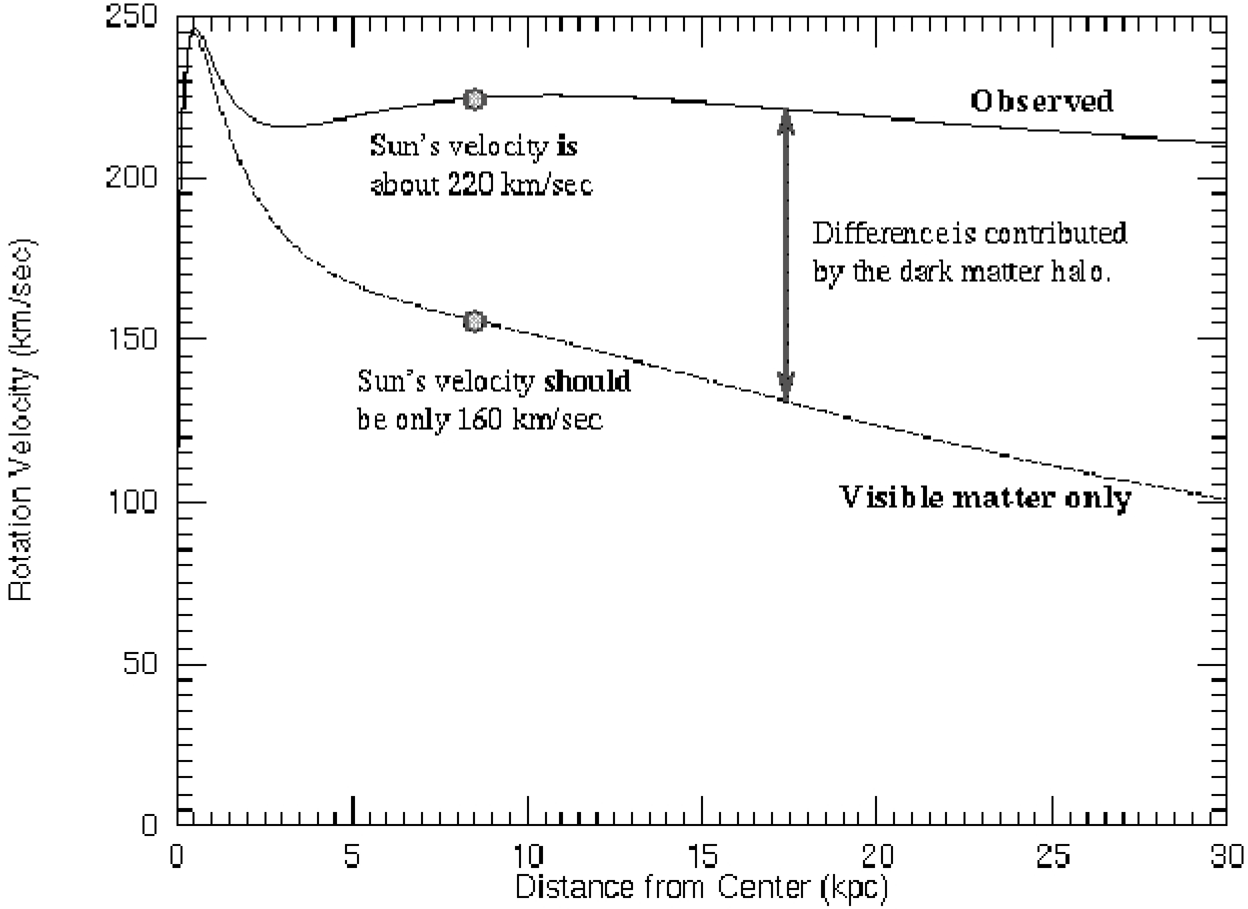
- These sources *evolve with time* (radio source counts are inconsistent with a steady state universe)

- What is the *origin of structures* on various scales? of rotation? of magnetic fields?

Key Discovery

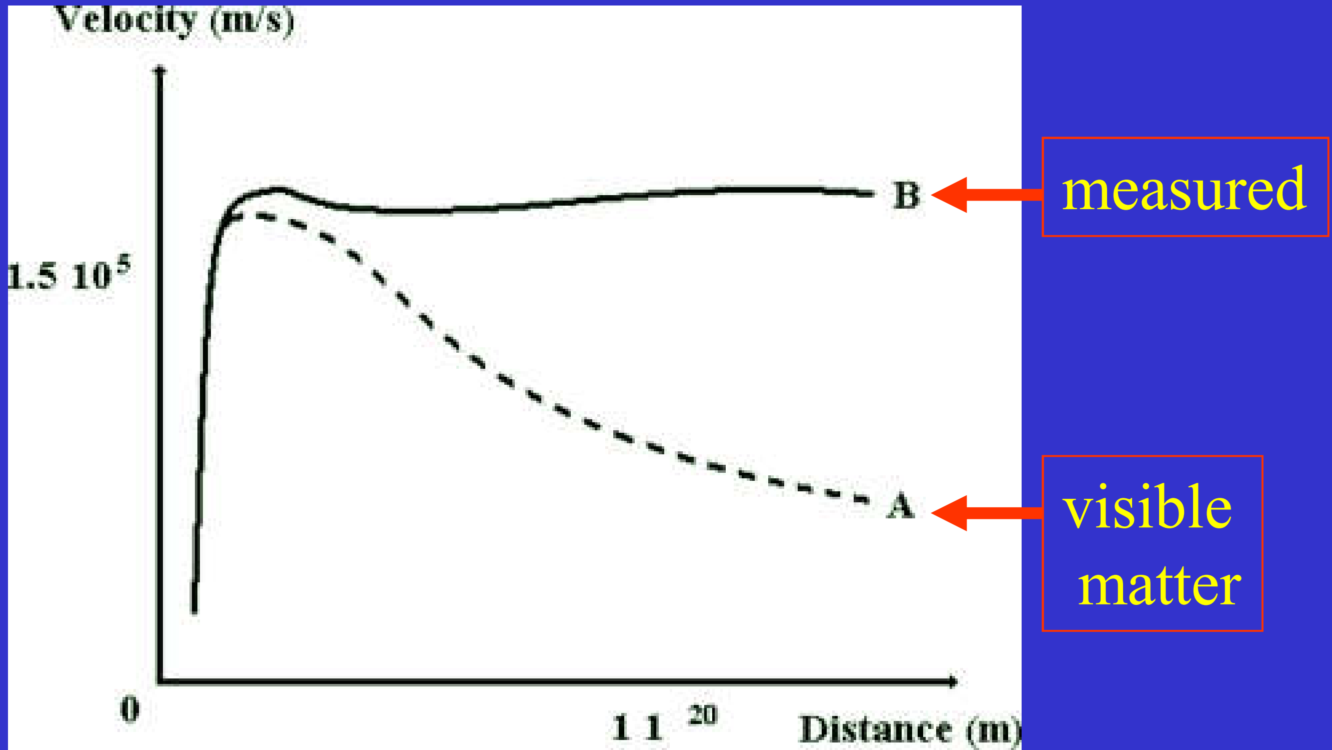
- Rotation curves of galaxies and motions of galaxies in clusters indicate *presence of dark matter*
- Unseen – does not radiate – but felt through its gravitational field
- Density of dark matter varies with scale; cosmologically contributes about $\Omega_0 \sim 0.3$
- Density of luminous (visible) matter much lower: about $\Omega_0 \sim 0.02$

Our own galaxy



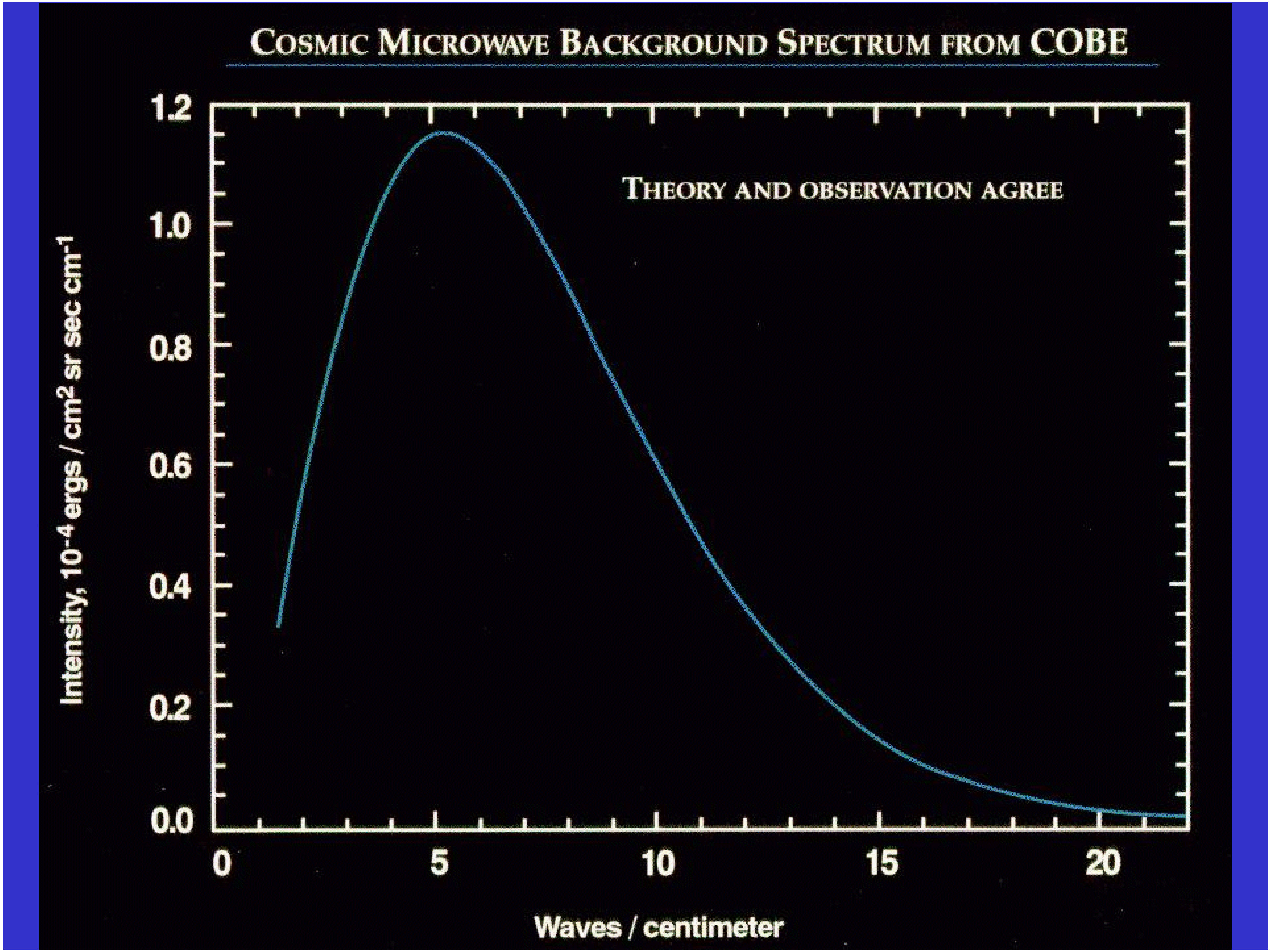
The gravity of the visible matter in the Galaxy is not enough to explain the high orbital speeds of stars in the Galaxy. For example, the Sun is moving about 60 km/sec too fast. The part of the rotation curve contributed by the visible matter only is the bottom curve. The discrepancy between the two curves is evidence for a **dark matter halo.**

Dark matter is required …



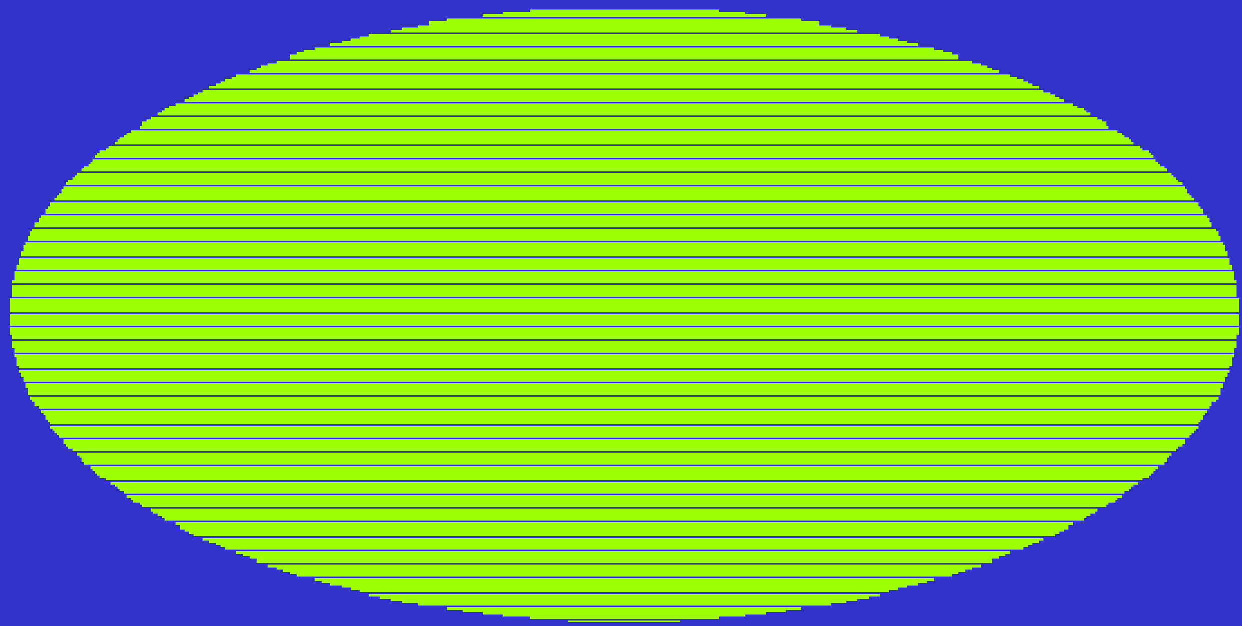
4. Hot Big Bang

- Follow universe back in time: heats up; hence, ***Hot Big Bang (HBB)*** era in early universe
- Equilibrium occurs between matter and radiation, hence ***Cosmic Blackbody Radiation*** (CBR) left over as a remnant of the HBB era; observationally discovered in 1965 at a temperature of 2.75K
- Vindicates application of standard physics to the early Universe
- CBR reaches us from *surface of last scattering at a temperature* of 4000K [a redshift of 1100]

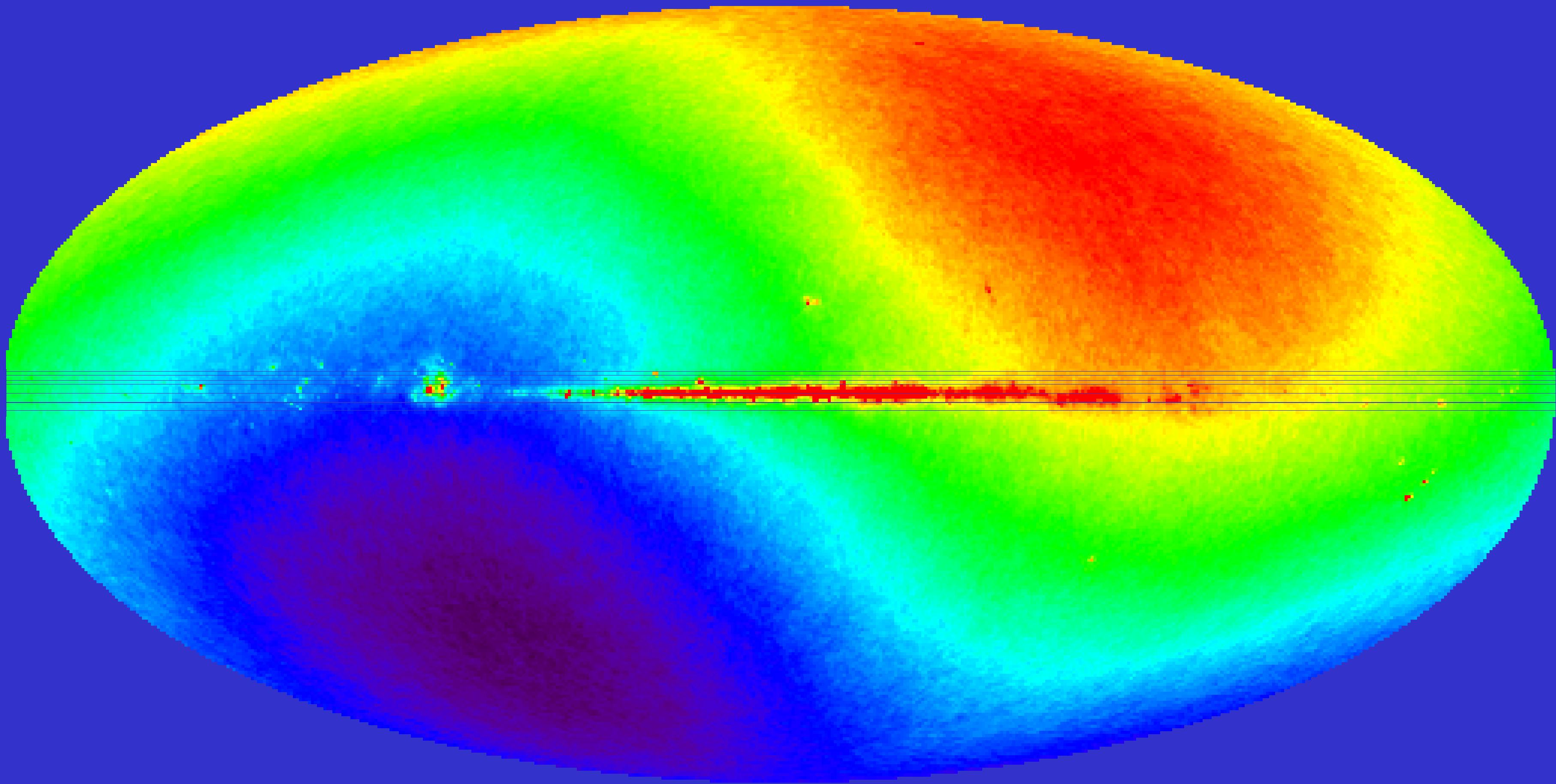


Cosmic Microwave Background Spectrum from COBE
Theory and observation agree
Intensity, 10^{-4} ergs / cm^2 sr sec cm^{-1}
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
Waves / centimeter

CBR isotropy 1

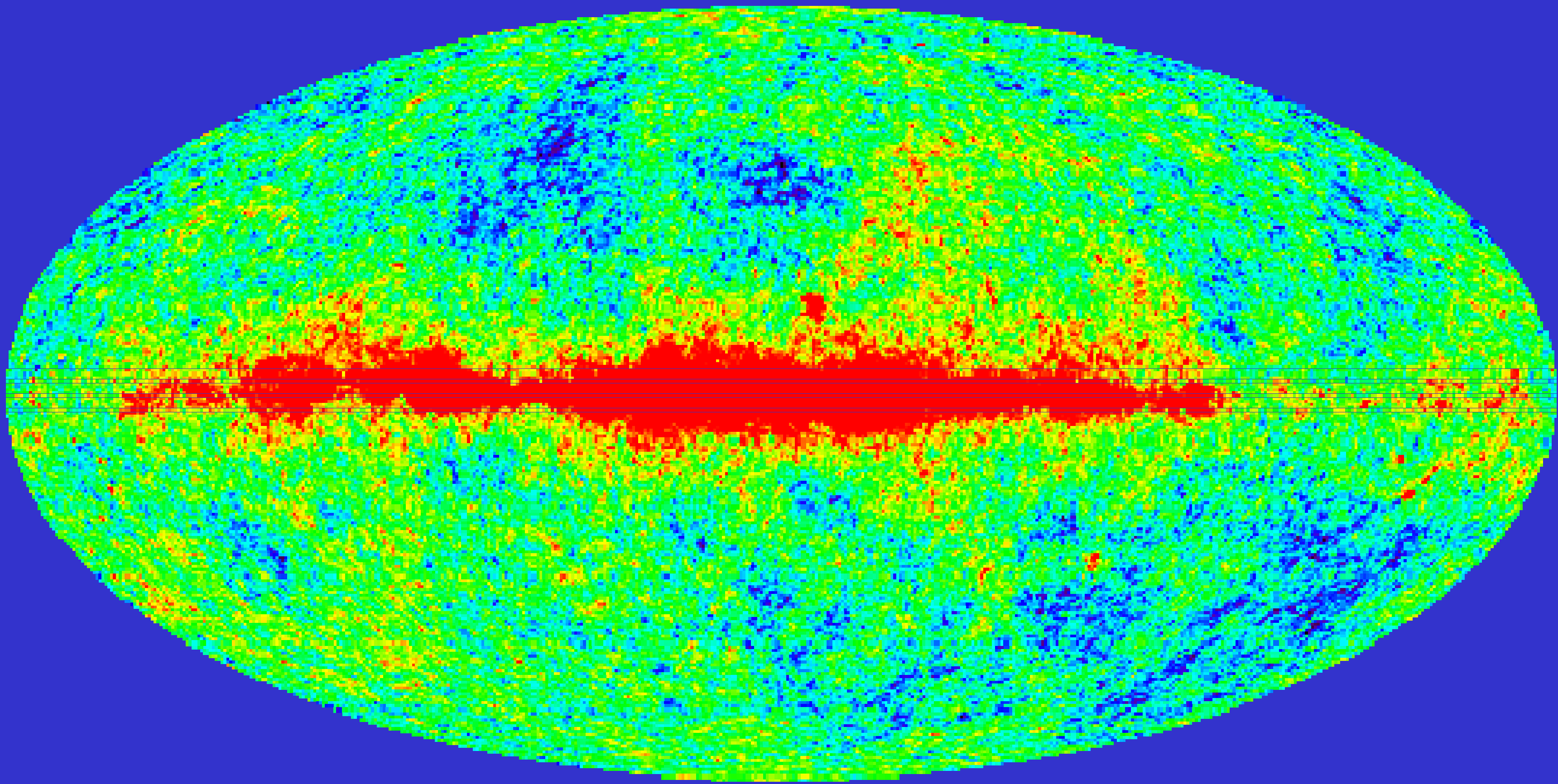


Isotropic at 1 part in 100



Microwave background radiation anisotropy: dipole measured by MAP

Anisotropy at 1 part in 1000:
Our motion relative to the universe

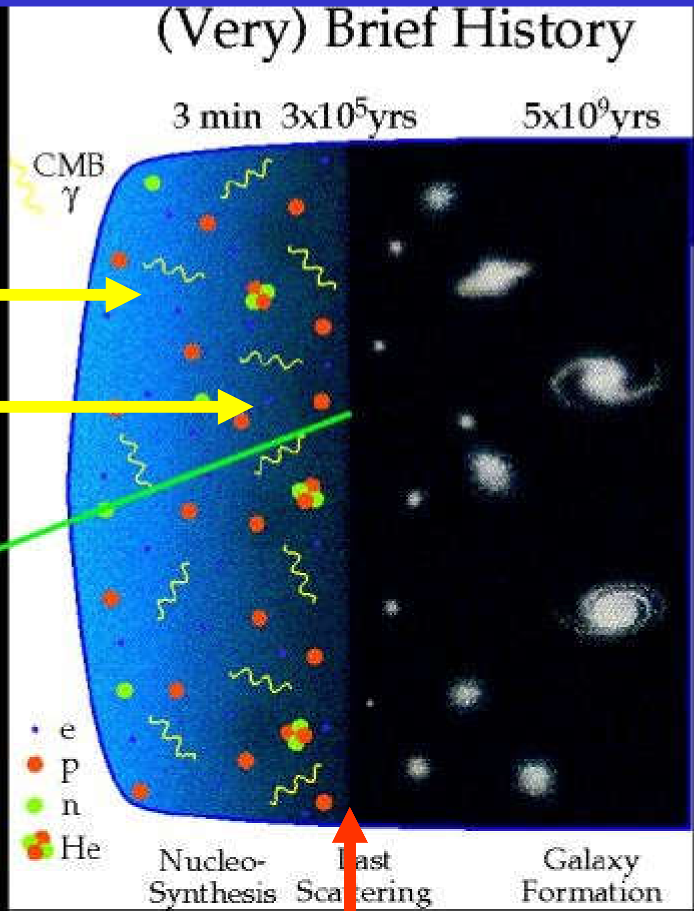


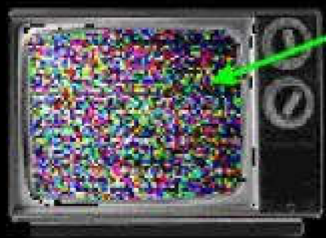
Microwave background radiation anisotropy: dipole removed

Anisotropy at one part in 100,000

Elementary particles combine to give protons and neutrons

Then light elements are formed





About 1% of the "snow" on a tv is due to CMB photons.

opaque transparent

Last scattering surface:
Electrons and nuclei form atoms

Origin of the elements

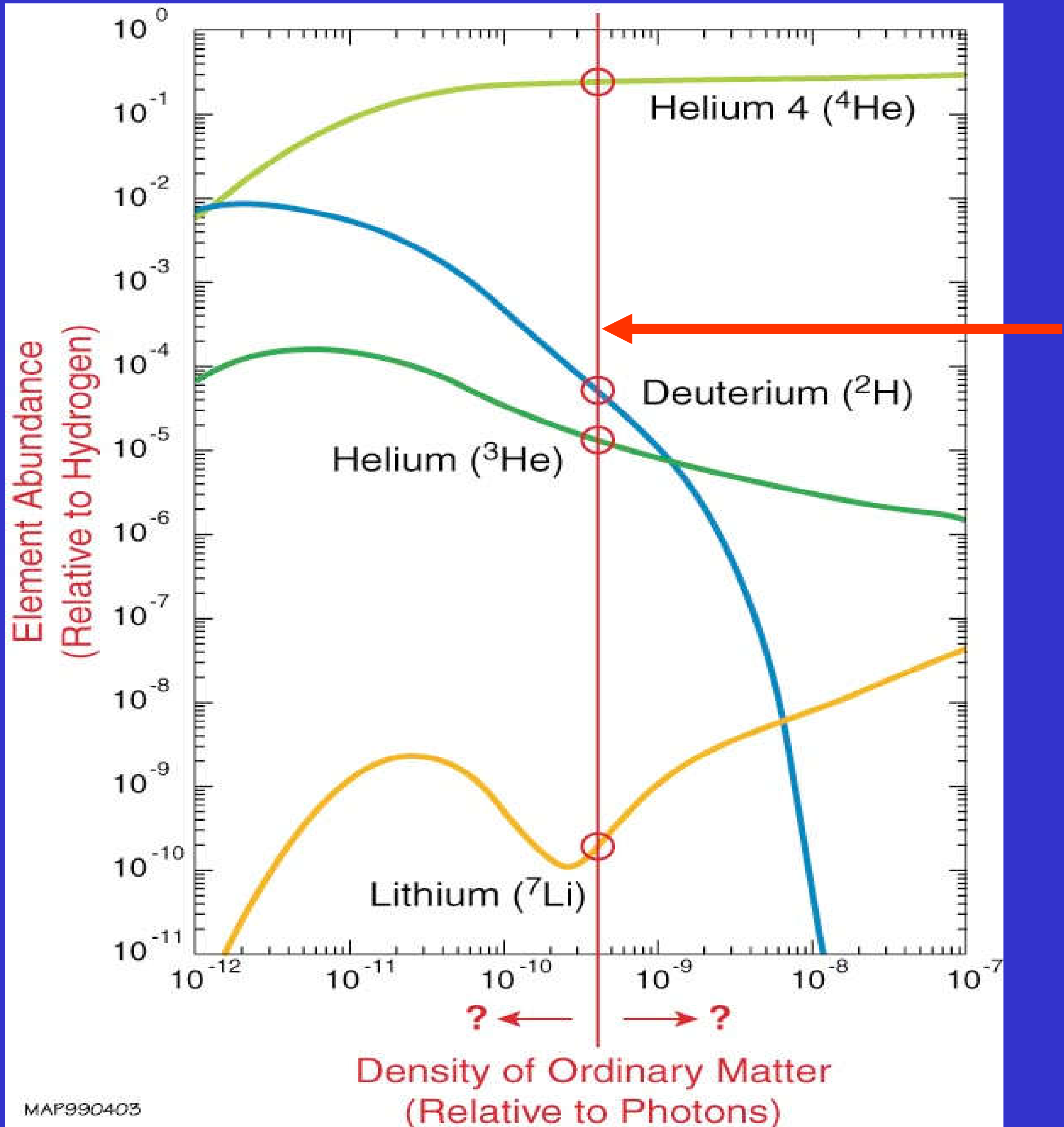
- nuclear physics processes during the HBB era

- The unbounded temperature in this era implies *matter-radiation equilibrium*:

  Previous state is then irrelevant

- an epoch of *nucleosynthesis* when the light elements form in the early Universe at a temperature of about 10^9K [neutrons and protons combine to form nuclei]

- heavy elements form much later in stars



All four observations agree

Relation to observations

- nucleosynthesis *theory and element abundance observations agree* provided the baryon density in the early Universe is low: $\Omega_{b0} \sim 0.04$

- together with the density estimates from astrophysical cosmology $\Omega_0 \sim 0.3$, provides evidence for *much more non-baryonic dark matter than baryonic matter* in the Universe

- requires there be *no more than three neutrino species*, a conclusion confirmed later by experiments at CERN

- Heavy elements form later in stars

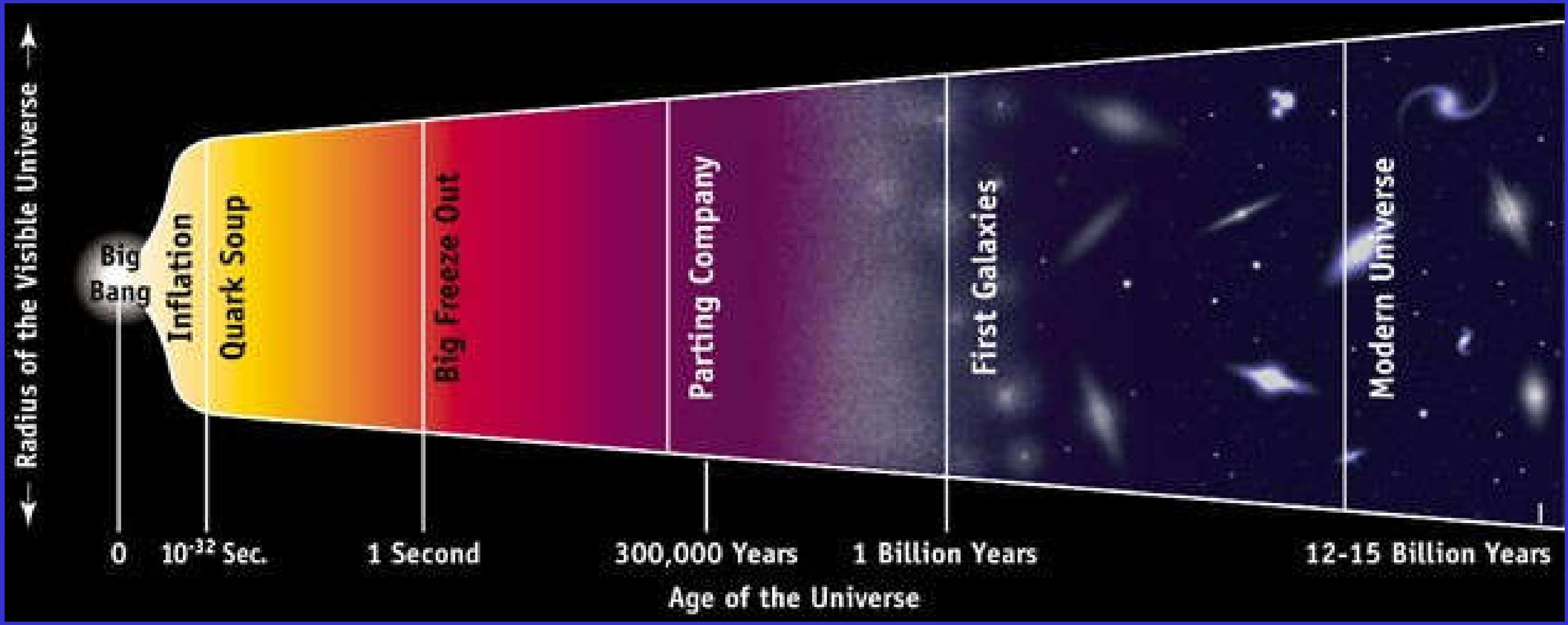
5: Particle cosmology and inflation

- In the very early Universe particle physics plays a major role.

- Because quantum field theory allows a violation of the standard energy condition $\rho+3p > 0$, at very early times there can be a *period of accelerated expansion* driven by scalar fields

- ***'inflation'*** with expansion accelerating rapidly takes place through many e-foldings before a subsequent HBB era begins (when the inflationary field has decayed to ordinary matter and radiation).

a(t)
versus



time

Inflation (continued)

- The power of this concept was demonstrated in 1980 by Guth: in principle gives an explanation of the *smoothness*, *flatness*, and *horizon* problems

- structure formation theories based on inflation predict a scale-free power spectrum for the matter distribution and a series of peaks in the power spectrum of CBR anisotropies *[verified!]*

- 'chaotic inflation' predicts pockets of inflation surround ordinary expanding Universe regions, resulting in an overall fractal-like structure

6: Quantum cosmology

- Before the inflationary era, some kind of quantum gravity effects will dominate the dynamics of the Universe and provide the initial conditions for inflation

Attempts to describe this quantum cosmology era include:

- the *wave function of the Universe*, either through the Wheeler-DeWitt equation or path integral methods
- *'pre-big bang'* theory based on string dualities
- *brane cosmology* : our Universe lives on a 4-dimensional 'brane' imbedded in a 5-dimensional spacetime
- the *ekpyrotic universe* where two such branes collide

Quantum cosmology

- In all cases the problem is making a solid link to observational tests, because the proposed particle interactions and/or extension of classical gravitational theory is not directly testable

- however, these theories are indirectly testable via their effects on the inflationary perturbation spectrum, and so on structure formation

- there is no fully formulated theory of quantum gravity

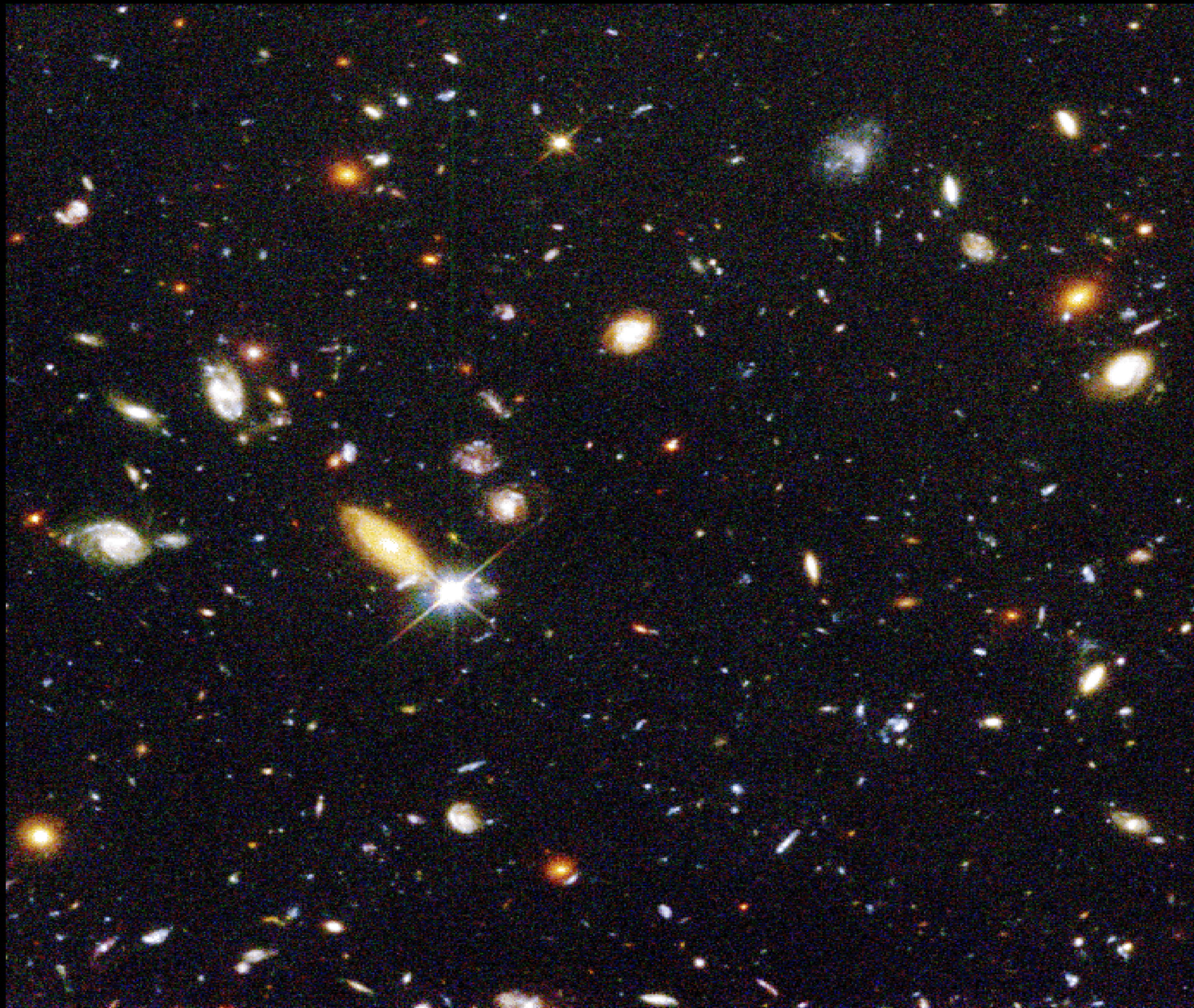
- *In the end we do not know if there was a start to the universe or not*

7: Observational transformation

Since the 1960's, observational cosmology has gone through a major transformation: discovery of quasi-stellar objects, X-ray sources, gravitational lenses, and so on. This has been made possible by a revolution in observational technology

- new telescopes, both ground-based (e.g. Keck) and borne aloft in balloons and satellites (e.g. IRAS, the Hubble Space Telescope)
- operating at all wavelengths from radio to γ-ray
- with features such as multiple-mirrors and adaptive optics

- improved detectors have allowed much deeper observations and number counts than before.



Hubble Deep Field HST • WFPC2

PRC96-01a • ST ScI OPO • January 15, 1996 • R. Williams (ST ScI), NASA