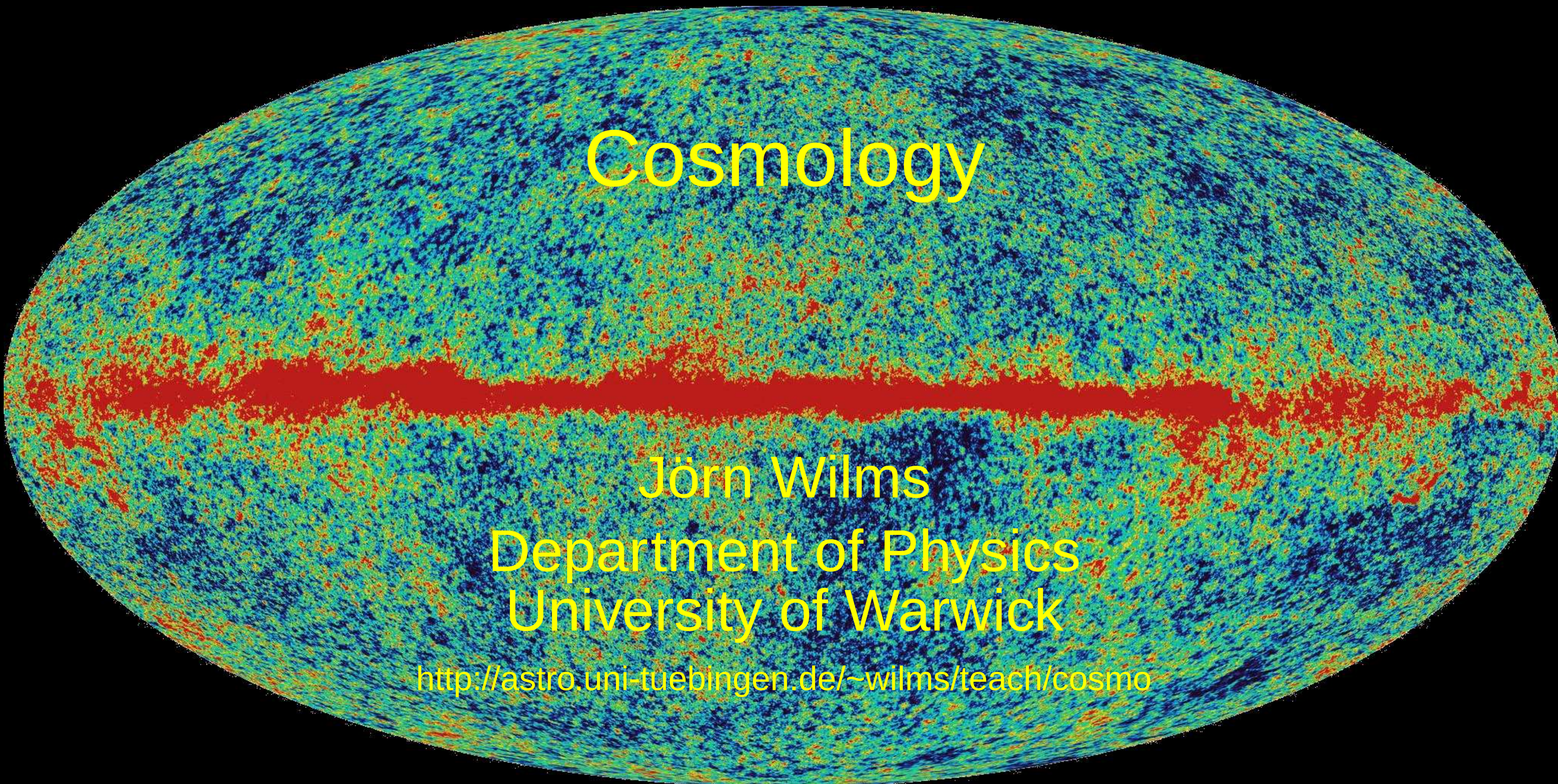

Cosmology

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Contents

Introduction

Cosmology: science of the universe as a whole

How did the universe evolve to what it is today?

Based on four basic facts:

The universe
- expands,
- is isotropic,
- and is homogeneous.

Isotropy and homogeneity of the universe: "*cosmological principle*".

Perhaps (for us) the most important fact is:

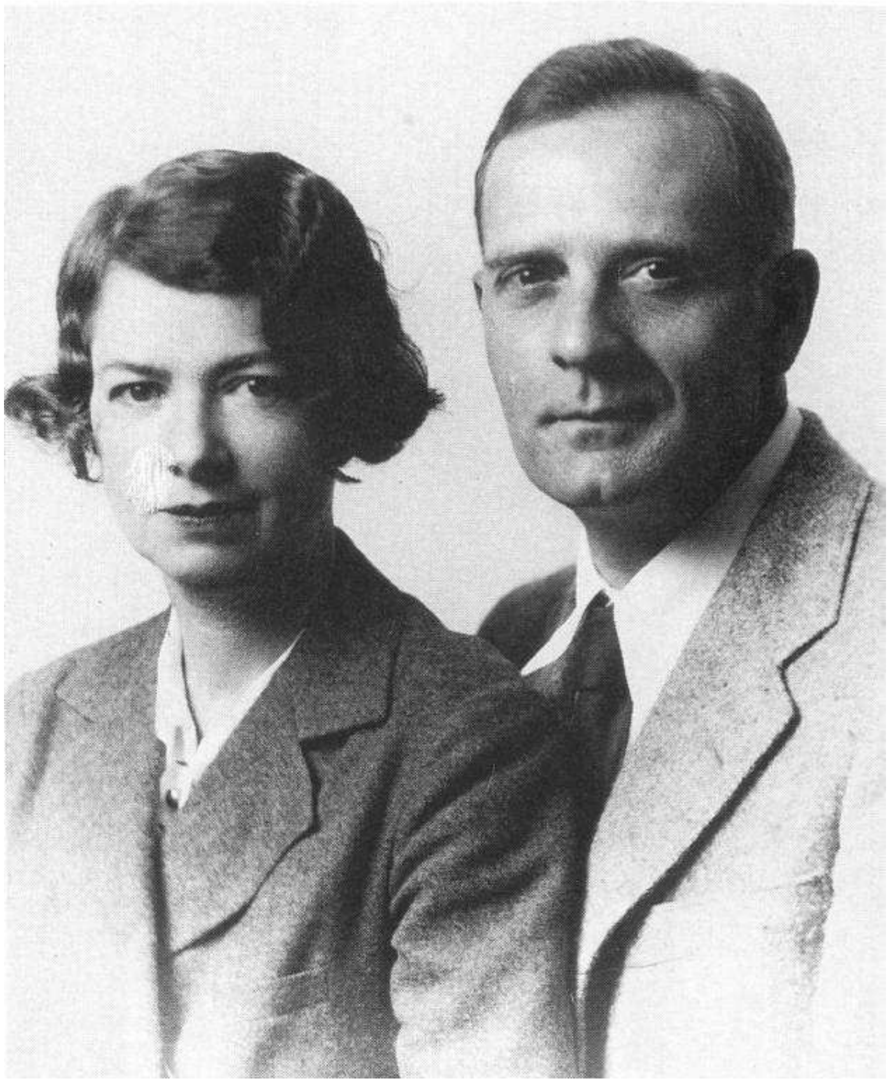
- The universe is habitable for humans.

("*anthropic principle*")

The one question cosmology does not attempt to answer is: How came the universe into being?

$\Longrightarrow$ Realm of theology!

Edwin Hubble



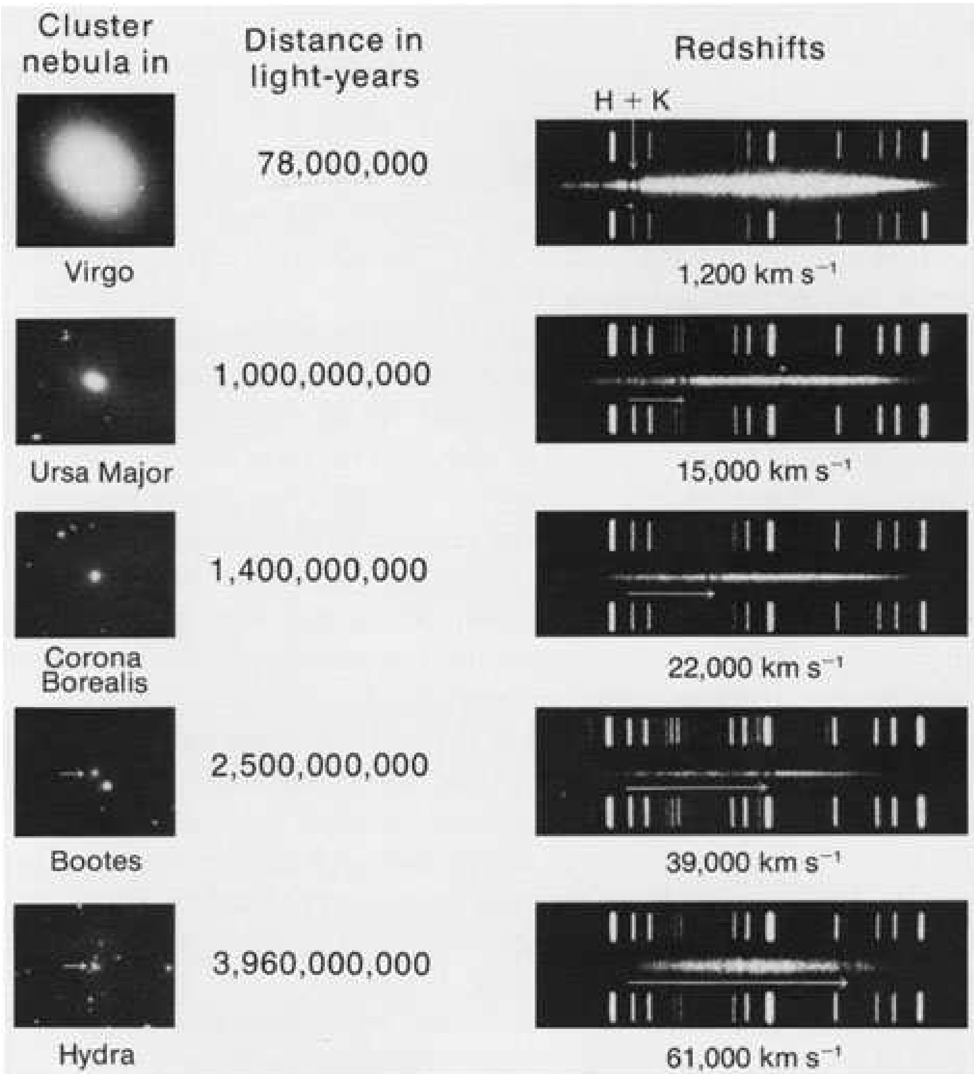
Christianson, 1995, p. 165

Edwin Hubble (1889–1953):

- Realisation of galaxies as being outside of the Milky Way
- Discovery that universe is expanding

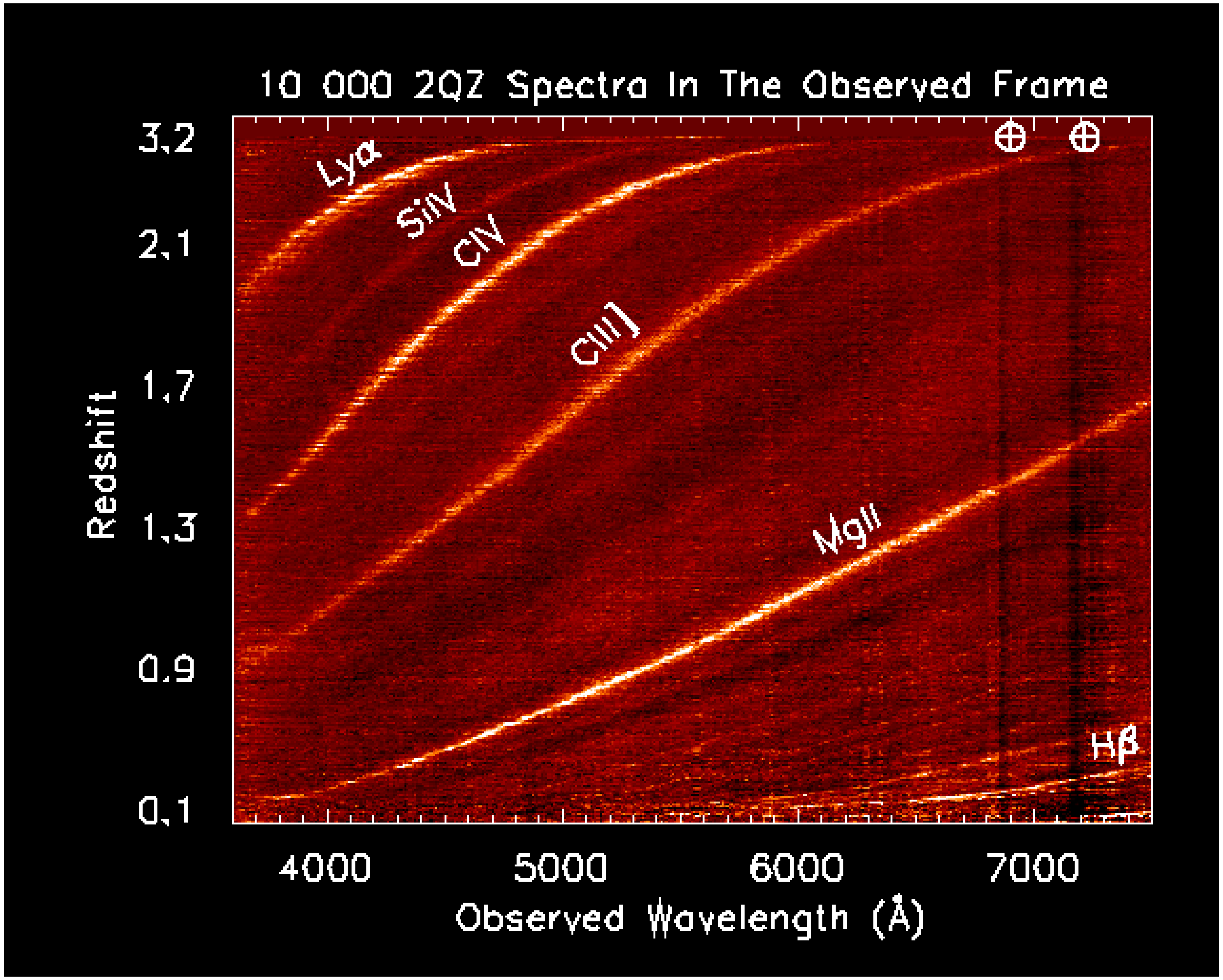
Founder of modern extragalactic astronomy

Redshifts, I



Hubble: spectral lines in galaxies are more and more redshifted with increasing distance.

Redshifts, II



2dF QSO Redshift survey

Redshift:

$$z = \frac{\lambda_{\text{observed}} - \lambda_{\text{emitted}}}{\lambda_{\text{emitted}}}$$

interpreted as velocity:

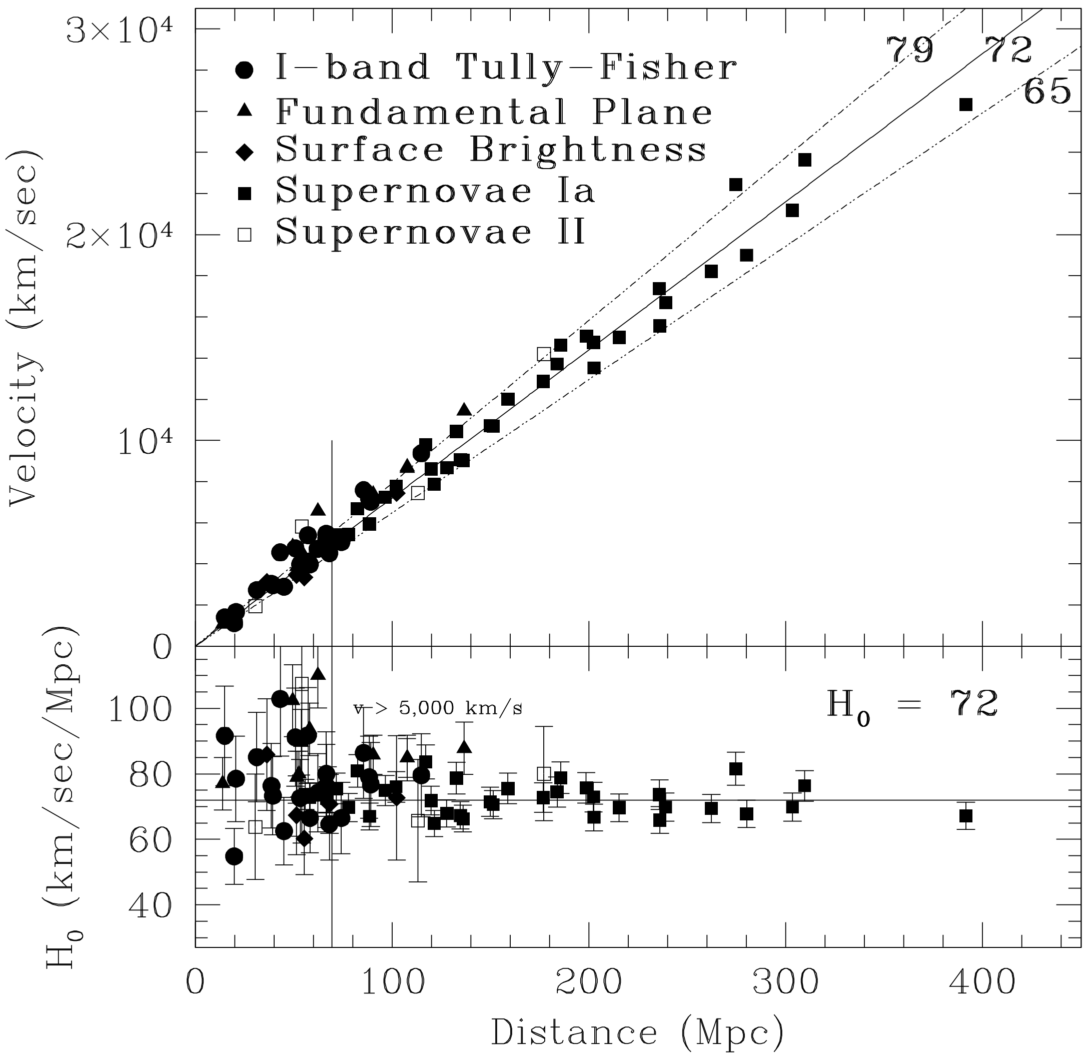
$$v = cz$$

where

$c = 300000\,\text{km}\,\text{s}^{-1}$

(speed of light)

Hubble Relation



(Freedman, 2001, Fig.4)

Hubble relation (1929):

The redshift of a galaxy is proportional to its distance: $v = cz = H_0 d$

where H_0: "Hubble constant".

Measurement: determine v from redshift (easy), d with standard candles (difficult)

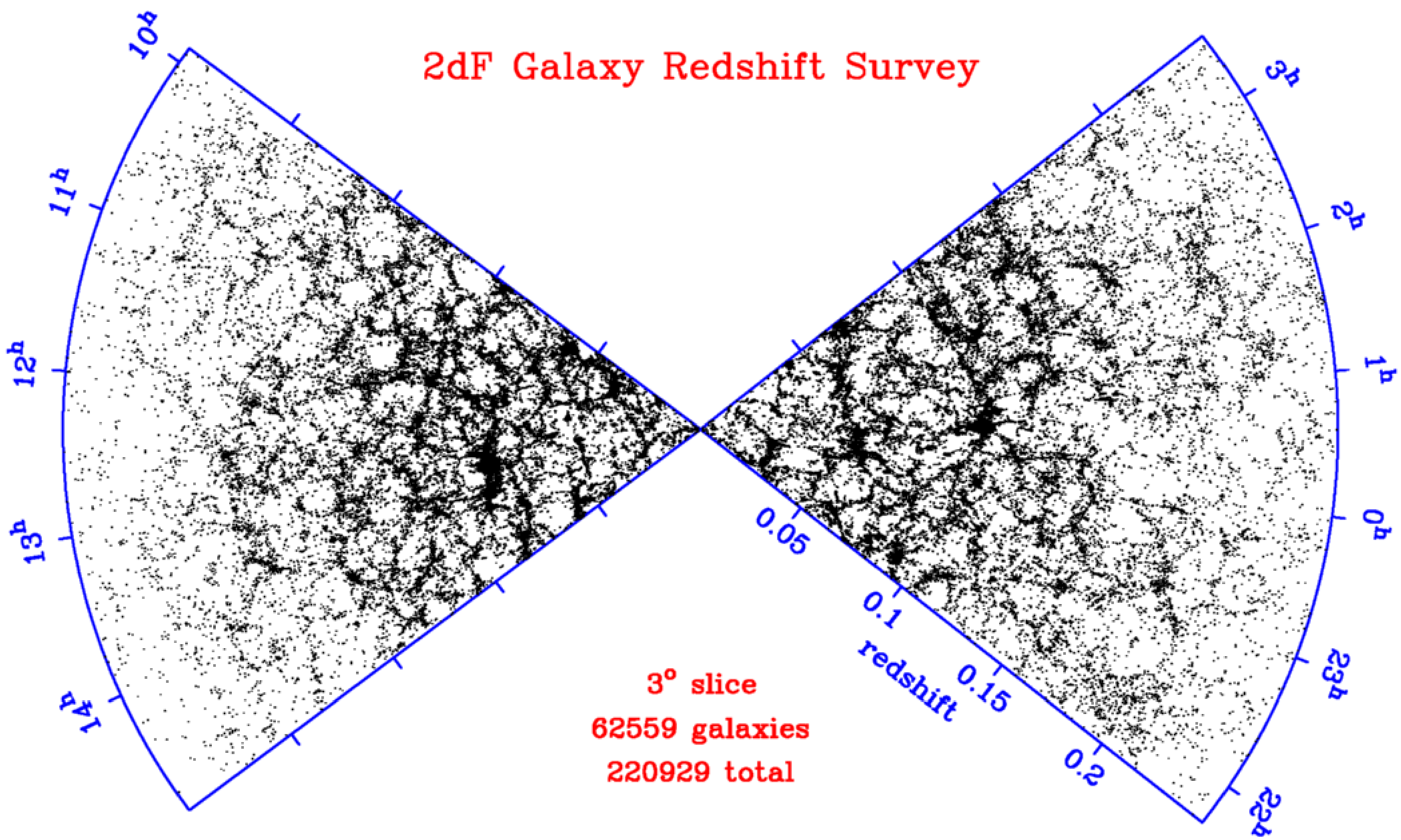
$\Longrightarrow H_0$ from linear regression.

Hubble Space Telescope finds

$$H_0 = 72 \pm 8\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Discussions in previous years on value of H_0 are over...

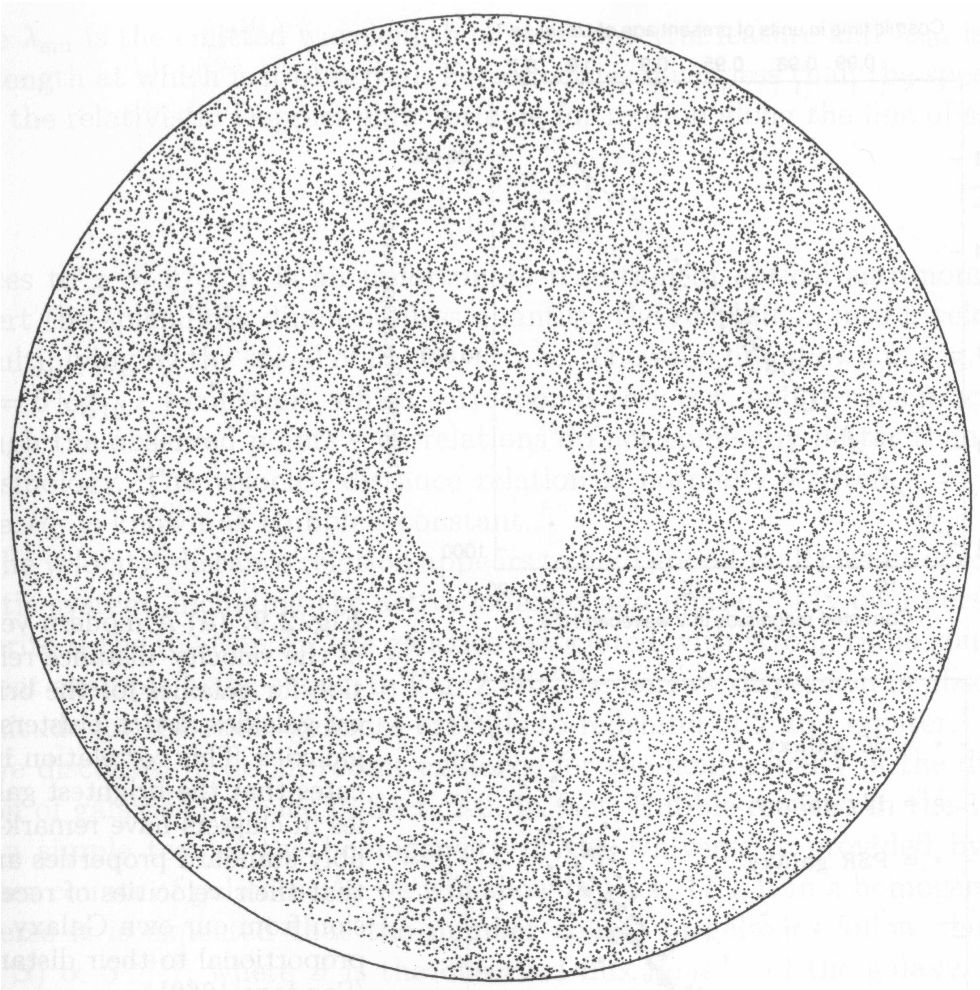
Homogeneity



2dF Survey, $\sim$220000 galaxies total

Homogeneity: “The universe looks the same, regardless from where it is observed” (on scales $\gg$100 Mpc).

Isotropie



Peebles (1993): Distribution of 31000 radio sources on northern sky (wavelength $\lambda = 6$ cm)

Isotropy $\Longleftrightarrow$ The universe looks the same in all directions.

N.B. Homogeneity *does not* imply isotropy, and isotropy around one point does not imply homogeneity!

World Models

A. Einstein (1879–1955)

Albert Einstein: Presence of mass leads to curvature of space (=gravitation) $\Longrightarrow$ General Theory of Relativity (GRT)

GRT is applicable to Universe as a whole!

World Models

A. Einstein (1879–1955)

Theoretical cosmology:

Combination of

1. relativity theory

World Models

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Theoretical cosmology:

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$\Longrightarrow$ complicated

World Models

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Theoretical cosmology:

Combination of

1. relativity theory
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$\Longrightarrow$ complicated

Typically calculation performed in three steps:

1. Describe metric following the cosmological principle
2. Derive evolution equation from GRT
3. Use thermodynamics and quantum mechanics to obtain equation of state

. . . and then do some maths

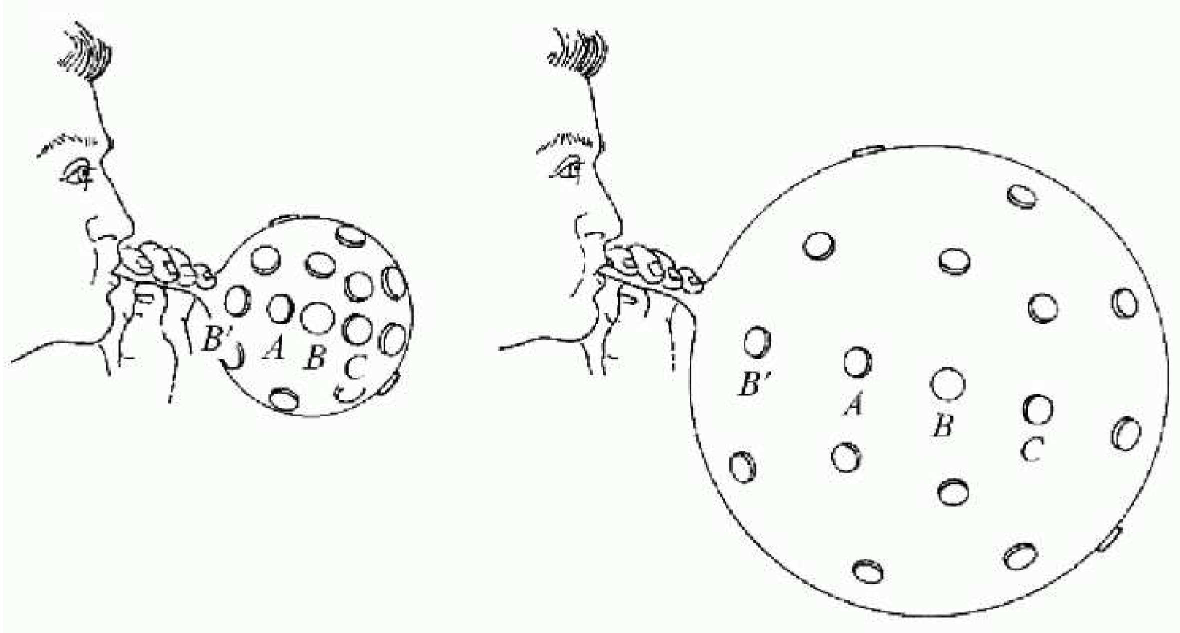
World Models

A.A. Friedmann

(1888–1925)

Friedmann: Mathematical description of the Universe using normal “fixed” coordinates (“comoving coordinates”), plus scale factor R which describes evolution of the Universe.

World Models



R small R large

Misner, Thorne, Wheeler

Friedmann: Mathematical description of the Universe using normal "fixed" coordinates ("comoving coordinates"), plus scale factor R which describes evolution of the Universe.

World Models

Using GR, derive equation for evolution of scale factor ("Friedmann equations").

World Model: Evolution of R as a function of time

Equations depend on

1. Value of H as measured today (note: H is time dependent!)
2. Density of universe, $\Omega = \Omega_\mathrm{m} + \Omega_\Lambda$

Density: universe evolves under its self gravitation, typically parameterised in units of critical density, ρ_crit (density when universe will collapse in the future):

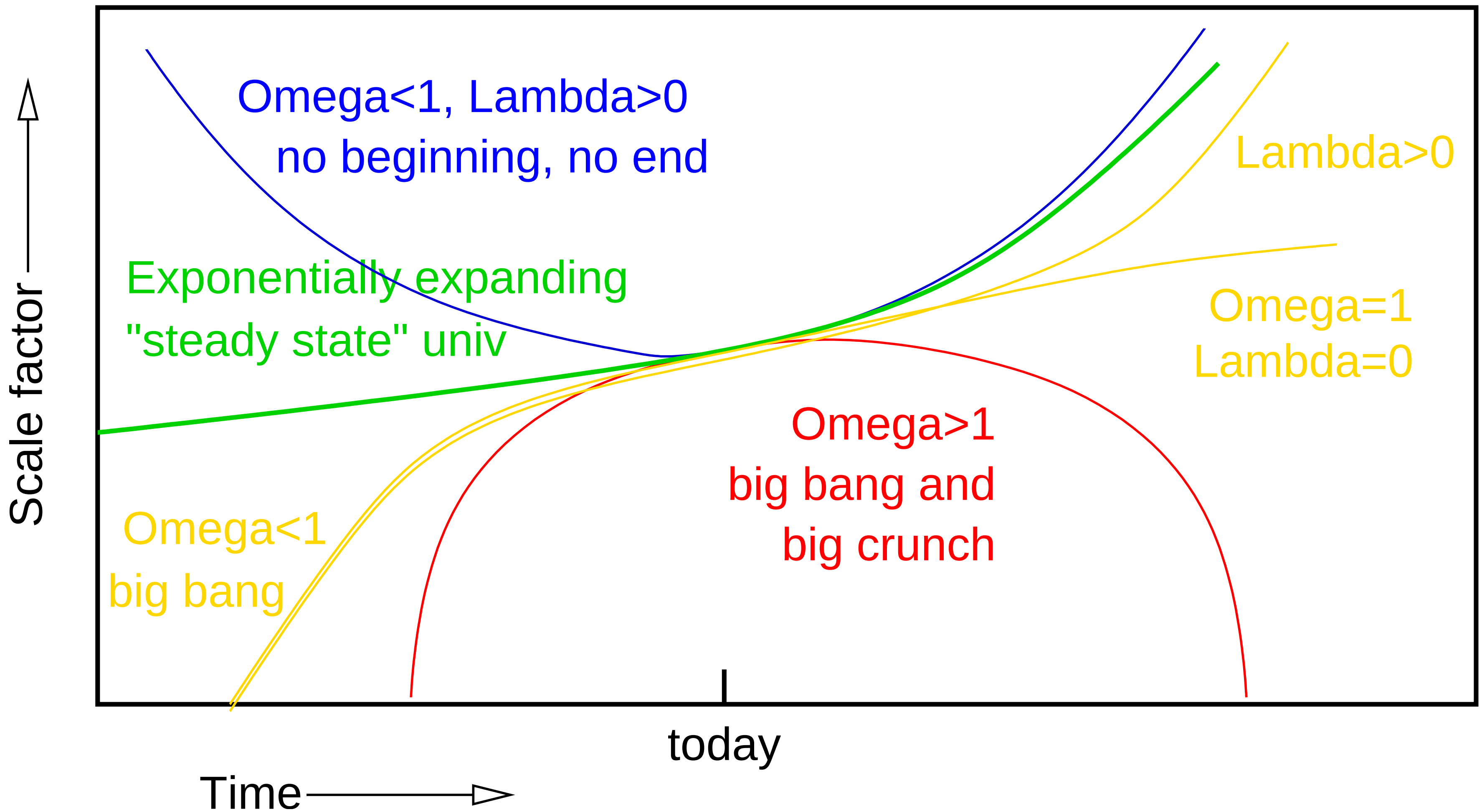
$$\Omega = \frac{\rho}{\rho_\mathrm{crit}} \qquad \text{where} \qquad \rho_\mathrm{crit} = \frac{3H_0^2}{8\pi G}$$

currently: $\rho_\mathrm{crit} \sim 1.67 \times 10^{-24}\,\mathrm{g\,cm^{-3}}$ ($3\ldots10\,\mathrm{H\text{-}Atoms\,m^{-3}}$).

Total Ω is sum of:

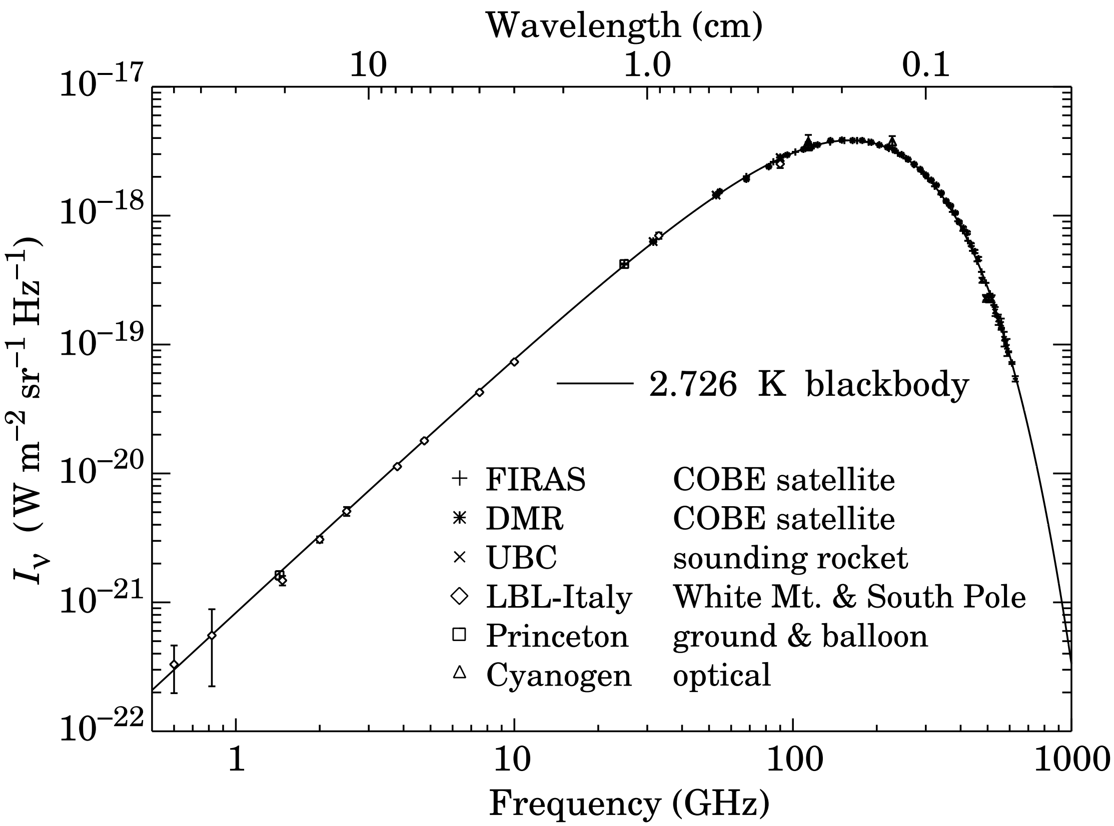
1. Ω_m: Matter, i.e., everything that leads to gravitative effects, $\lesssim$3% is baryonic, i.e., not "dark matter" but matter as we know it
2. $\Omega_\Lambda = \Lambda c^2/3H^2$: contribution caused by vacuum energy density Λ ("dark energy")

World Models



Many different kinds of world models are possible, behaviour of universe depends on Ω und Λ.

3K CMB



(Smoot et al., 1997, Fig. 1)

Penzias & Wilson (1965): "Measurement of Excess Antenna Temperature at 4080 Mc/s"

$\Longrightarrow$ Cosmic Microwave Background radiation (CMB)

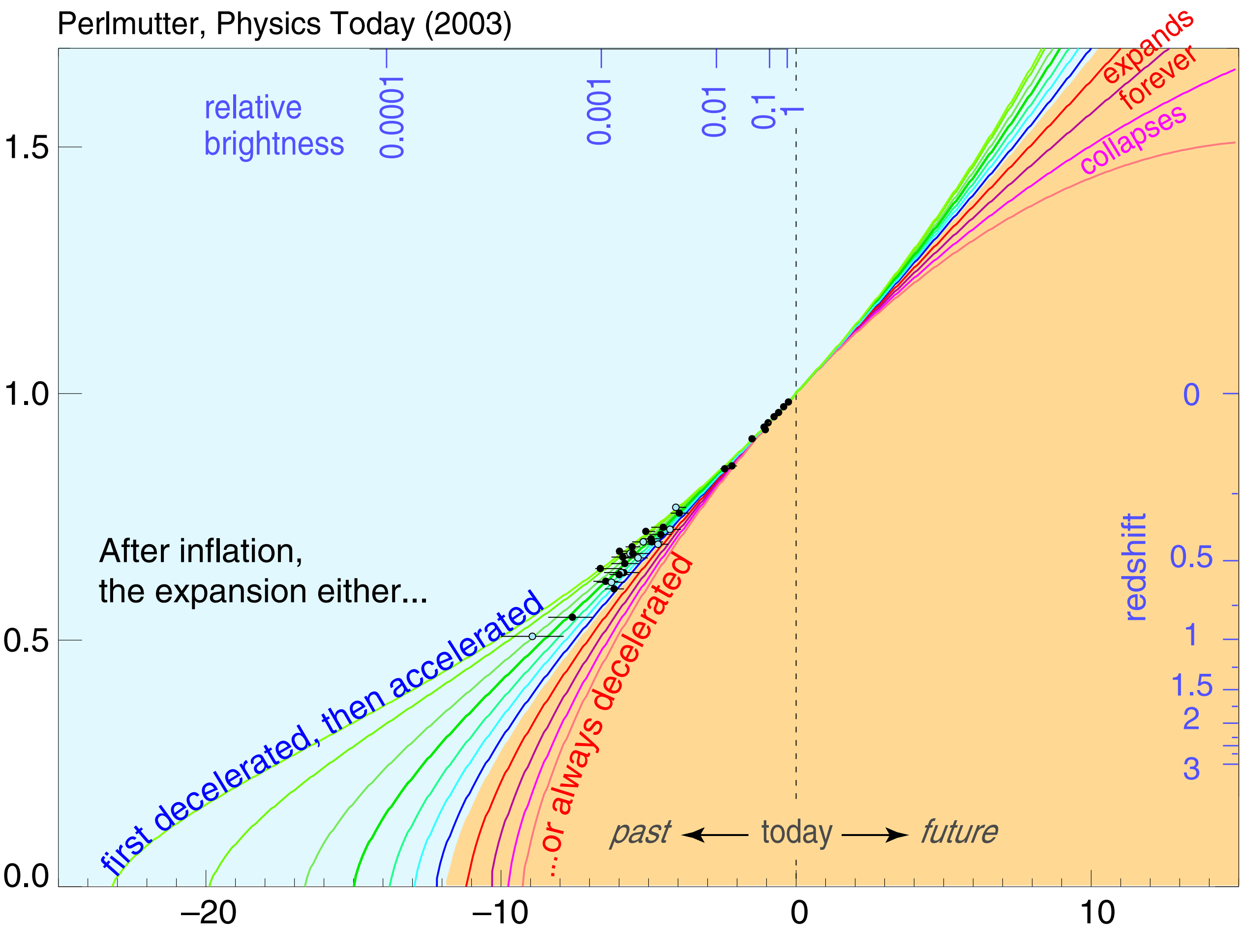
CMB spectrum is blackbody with temperature $T_{\rm CMB} = 2.728 \pm 0.004$ K.

Extrapolating CMB temperature back in time shows:

Universe started with a hot big bang, has since cooled down.

World Models

Perlmutter, Physics Today (2003)



Note: Extrapolation backwards gives age of universe as *roughly* $1/H_0$!

for $H_0 = 72\,\mathrm{km\,s^{-1}\,Mpc^{-1}} = 2.3 \times 10^{-18}\,\mathrm{s^{-1}}$, giving an age of 13.6 Gyr.

History of the universe

$R(t)$	t since BB	T[K] [K]	ρ_{matter} [g cm^{-3}]	Major Events
	10^{-42}	10^{30}		Planck era, "begin of physics"
	$10^{-40\ldots-30}$	10^{25}		Inflation (IMPLIES $\Omega = 1$)
10^{-13}	$\sim 10^{-5}$ s	$\sim 10^{13}$	$\sim 10^{9}$	generation of p-p^{-}, and baryon anti-baryon pairs from radiation background
3×10^{-9}	1 min	10^{10}	0.03	generation of e^{-}-e^{+} pairs out of radiation background
10^{-9}	10 min	3×10^{9}	10^{-3}	nucleosynthesis
$10^{-4} \ldots 10^{-3}$	$10^{6\ldots7}$ yr	$10^{3\ldots4}$	$10^{-21\ldots-18}$	End of radiation dominated epoch
7×10^{-4}	380000 yr	4000	10^{-20}	Hydrogen recombines, decoupling of matter and radiation
	200×10^{6} yr			first stars formed
1	13.7×10^{9} yr	3	10^{-30}	now

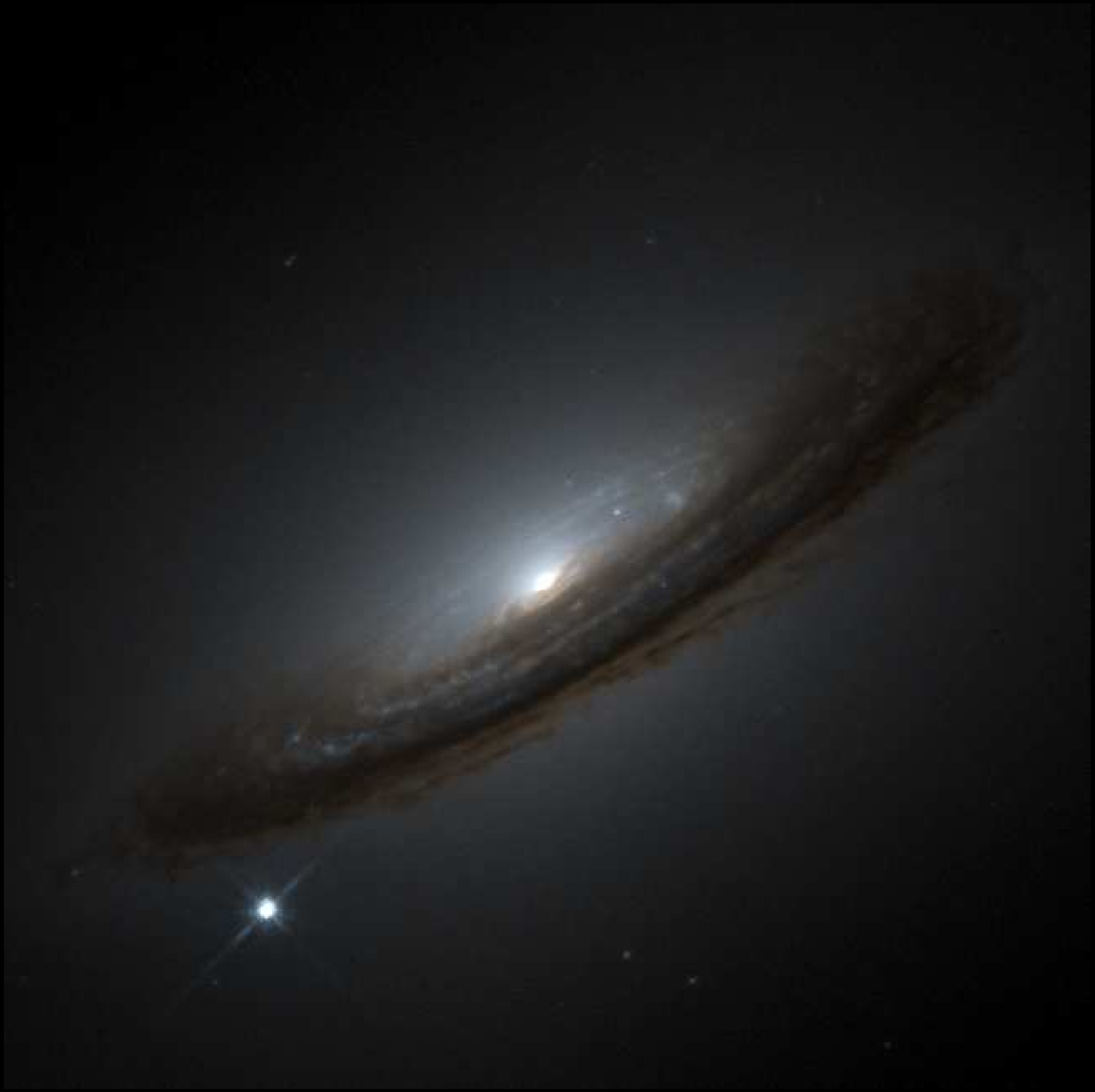
Conclusions

Modern Cosmology: Determination of H_0, Ω and Λ from observations and comparison with theory

In the following: Examples for new measurements to determine Ω and Λ:

- Supernova observations and
- Cosmic Microwave Background (WMAP).

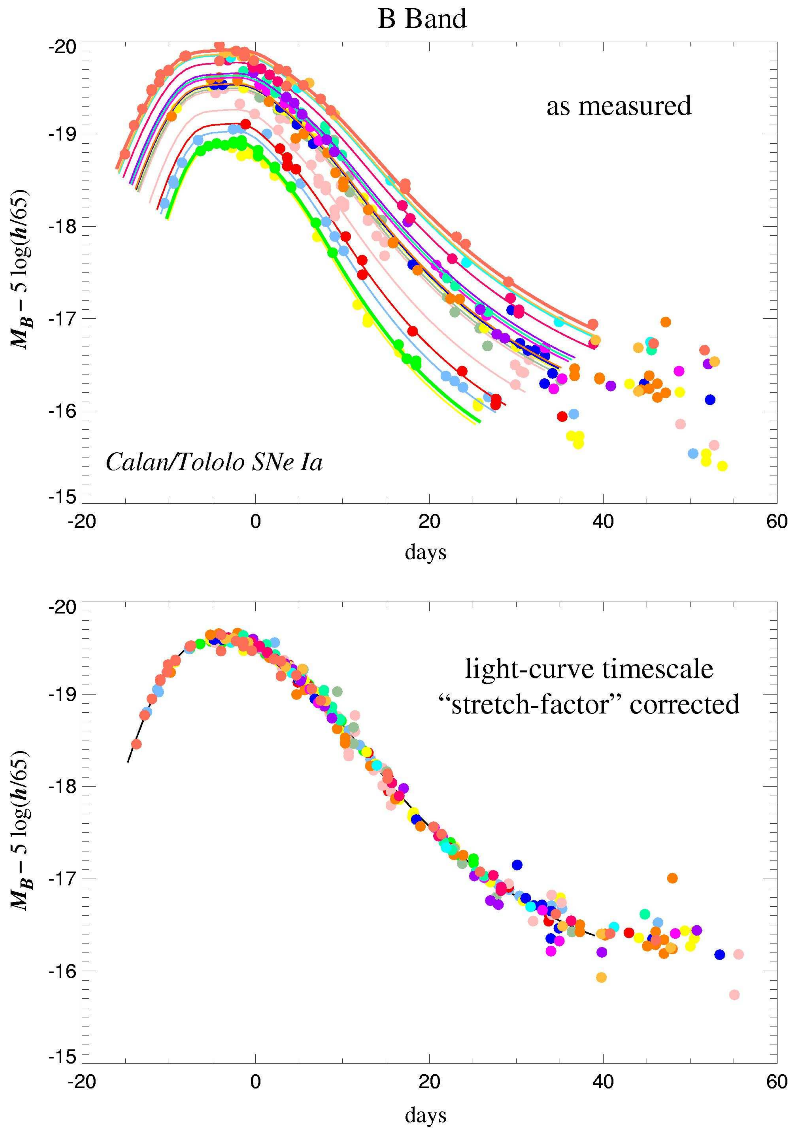
General hope: confirmation that $\Omega_\mathrm{m} + \Omega_\Lambda = 1$ as predicted by theory of inflation (this implies a *flat* universe).



SN1994d (HST WFPC)

Supernovae have luminosities comparable to whole galaxies: $\sim 10^{51}$ erg/s in light, $100\times$ more in neutrinos.

Supernovae



Kim, *et al.* (1997)

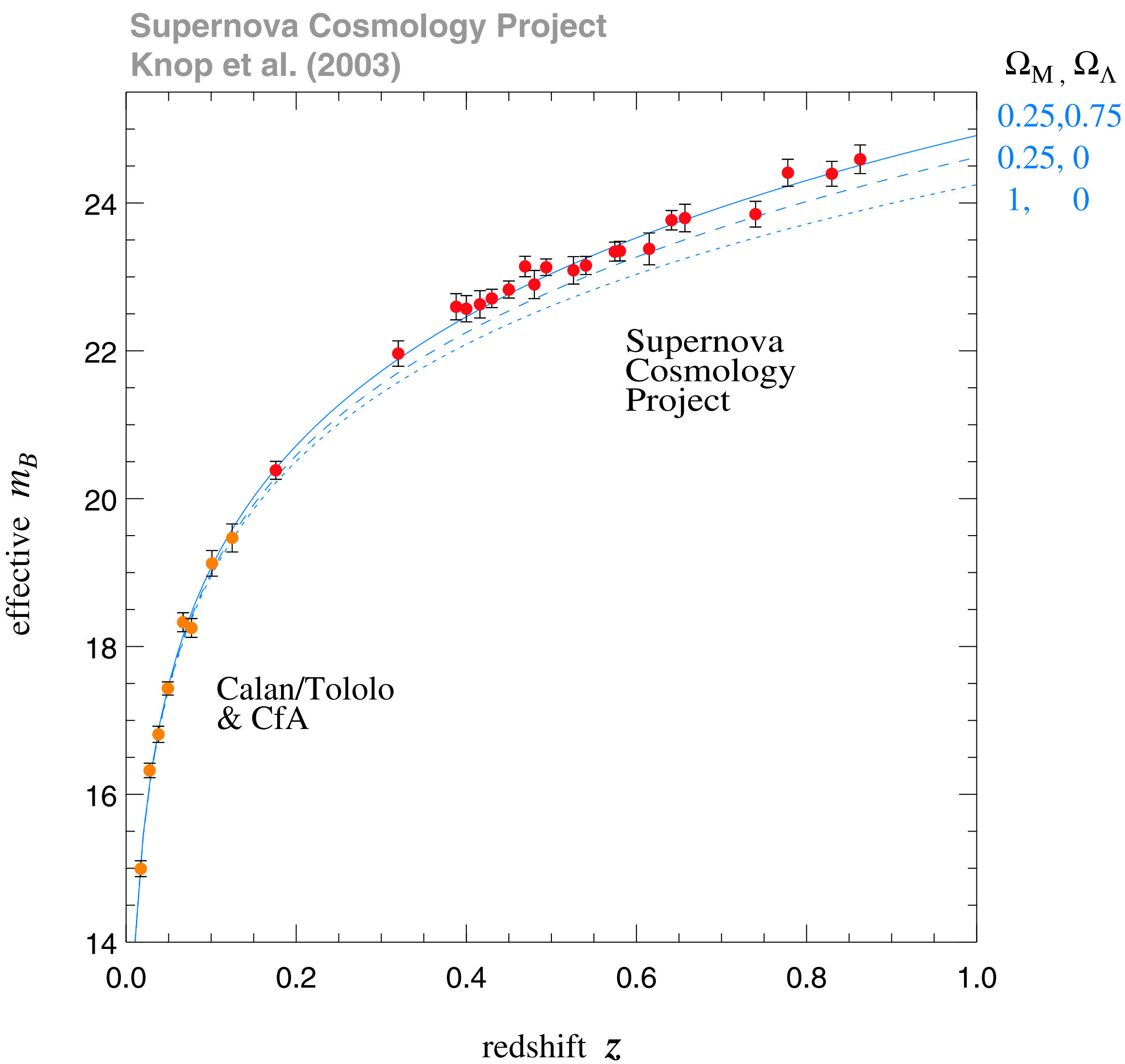
After correction of systematic effects:

SN Ia lightcurves all look the same

$\Longrightarrow$ standard candle

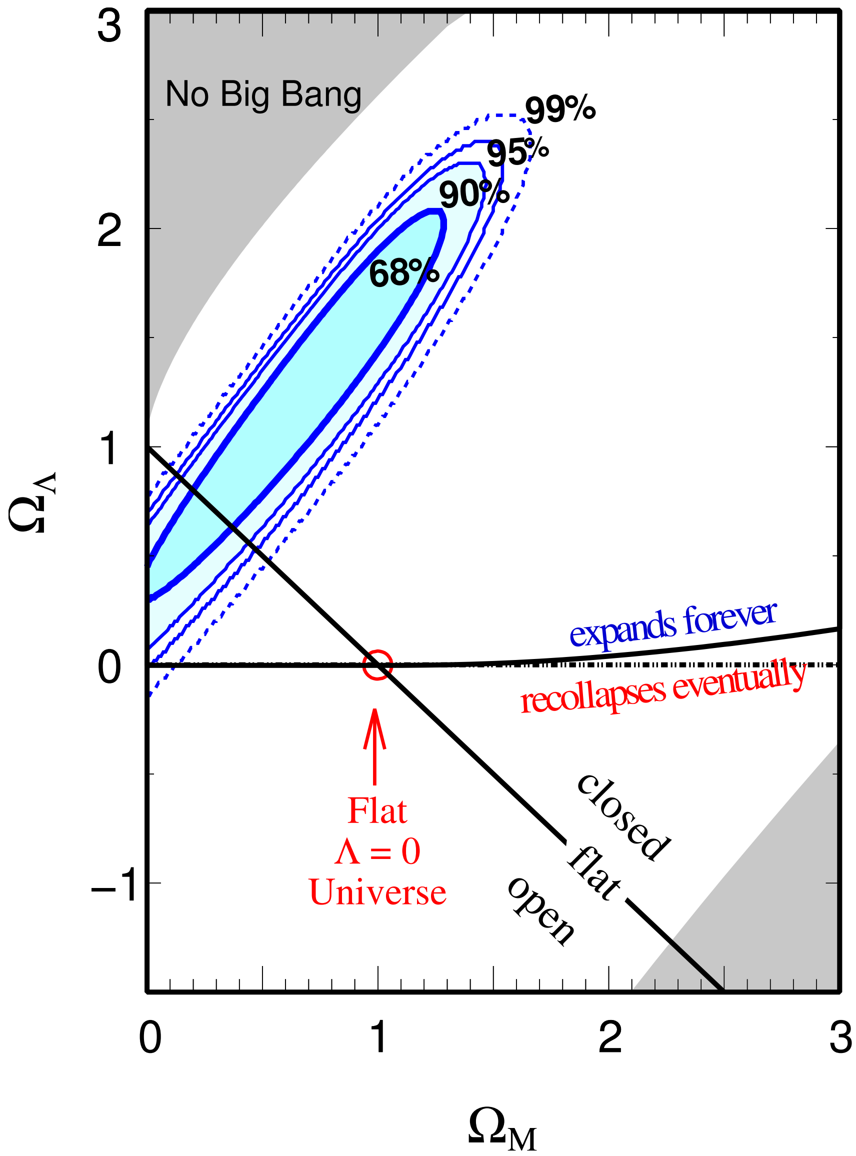
$\Longrightarrow$ can measure their distances

Supernovae



Supernova observations are well explained by models with $\Omega_{\rm m} = 0.25$ and $\Omega_\Lambda = 0.75$.

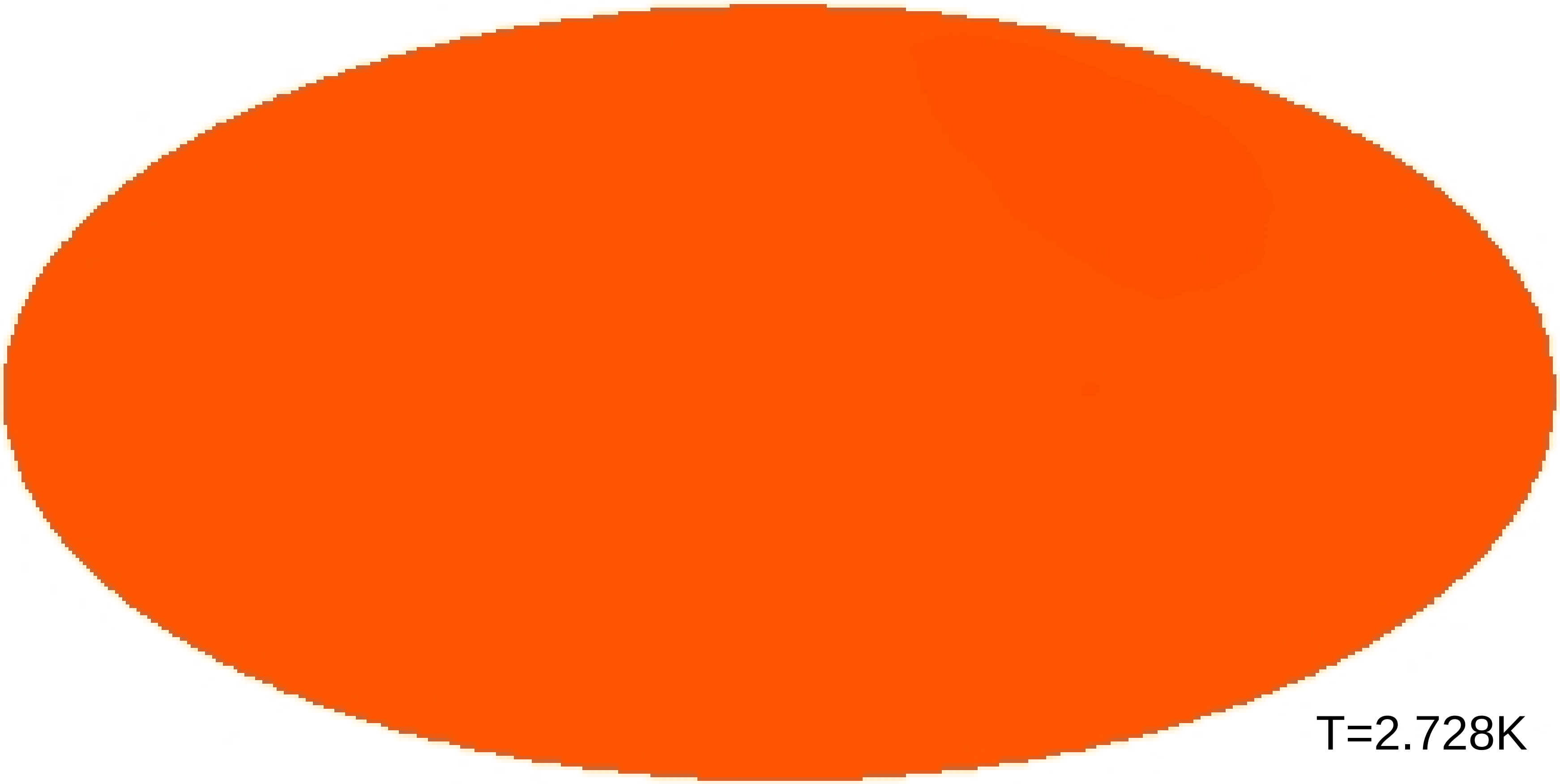
Supernovae



Supernova observations are well explained by models with $\Omega_m = 0.25$ and $\Omega_\Lambda = 0.75$.

$\Omega_\Lambda = 0$ is *excluded* by data!

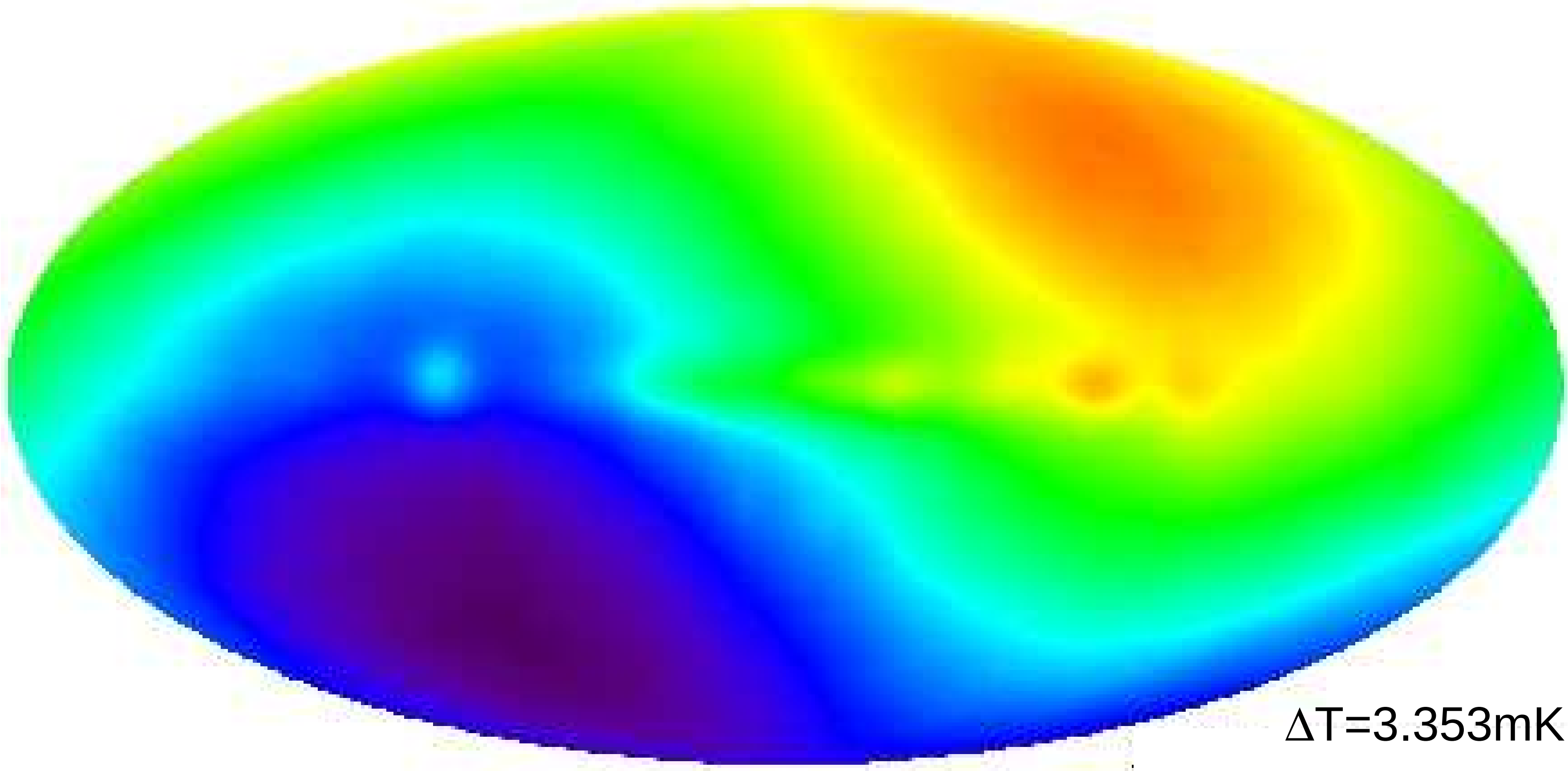
CMB, I



COBE (1992): First map of 3K-CMB

$T = 2.728\,\mathrm{K}$

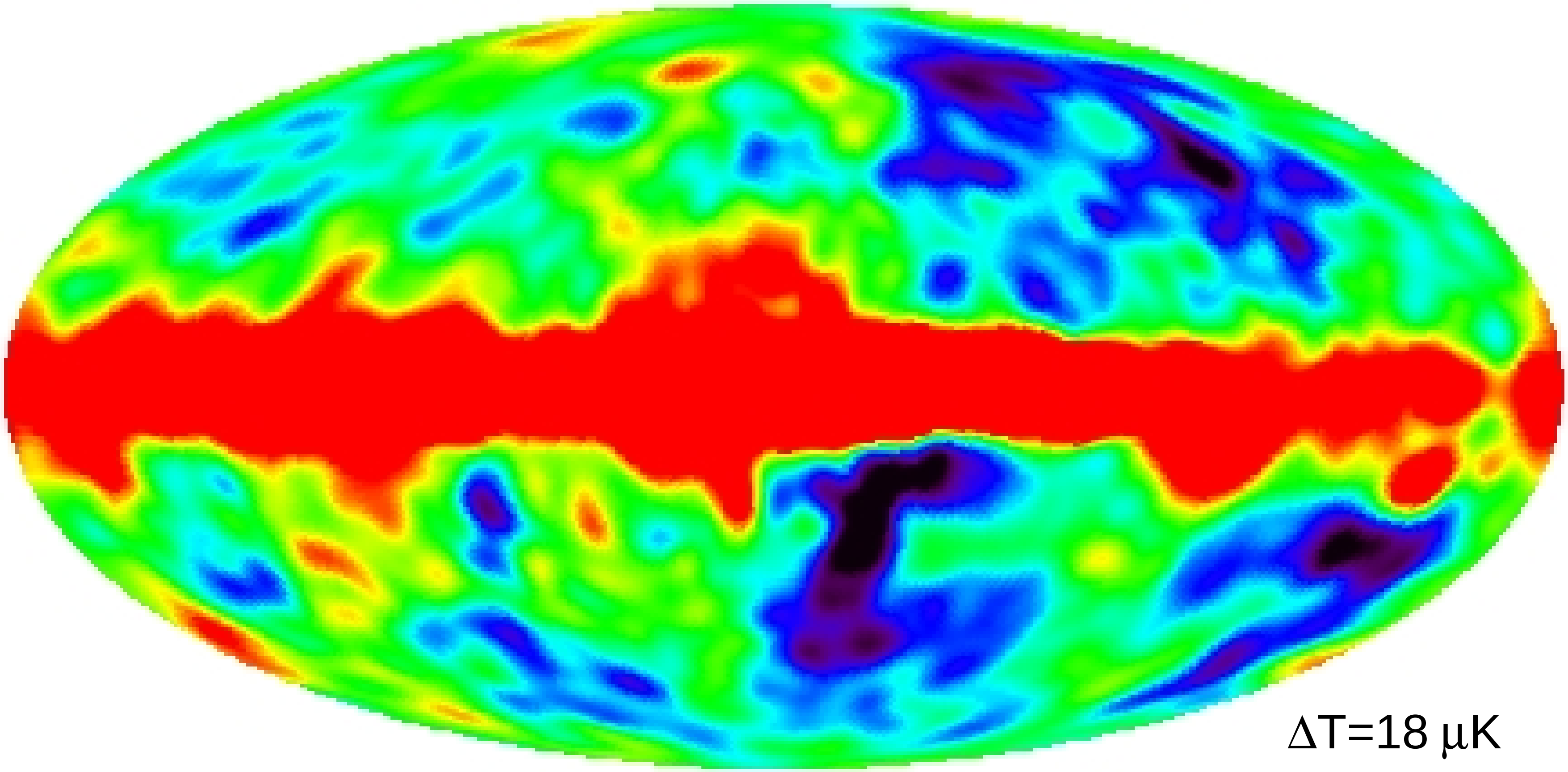
CMB, II



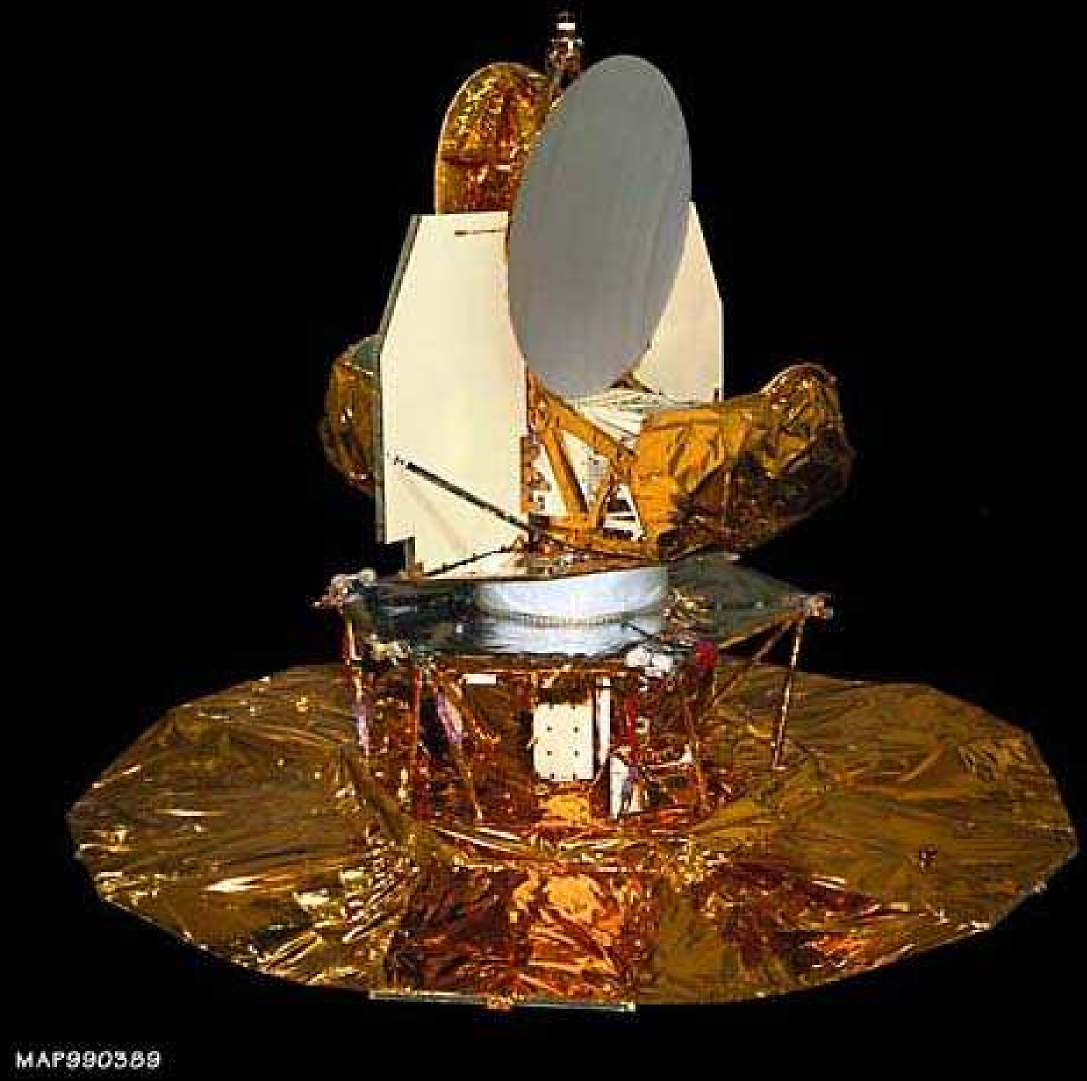
Overlaid: Dipole anisotropy caused by motion of the solar system

Temperature fluctuation: $\Delta T/T \sim 10^{-4}$

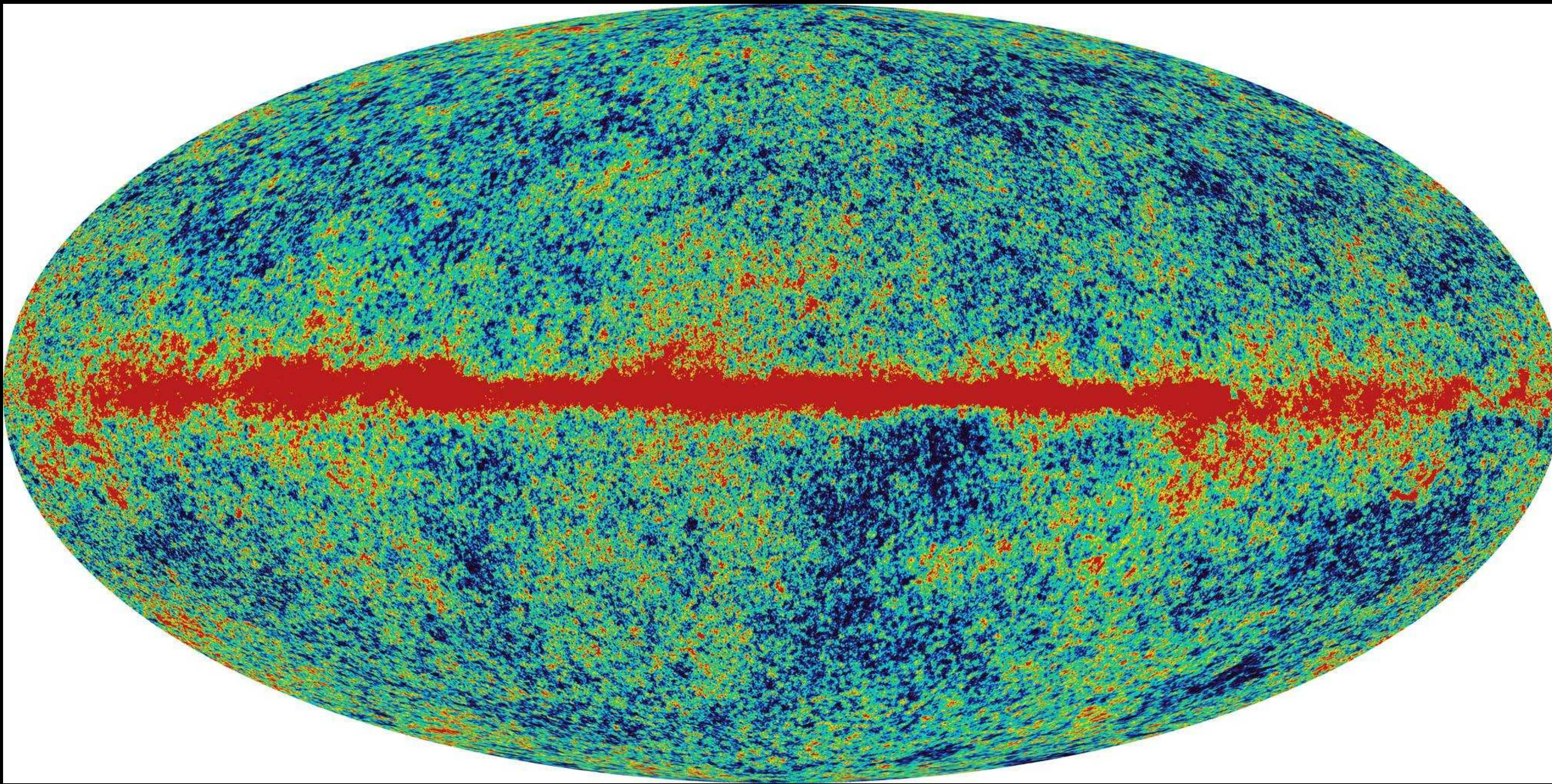
CMB, III



At level of $\Delta T/T \sim 10^{-5}$: Deviations from isotropy due to structure formation

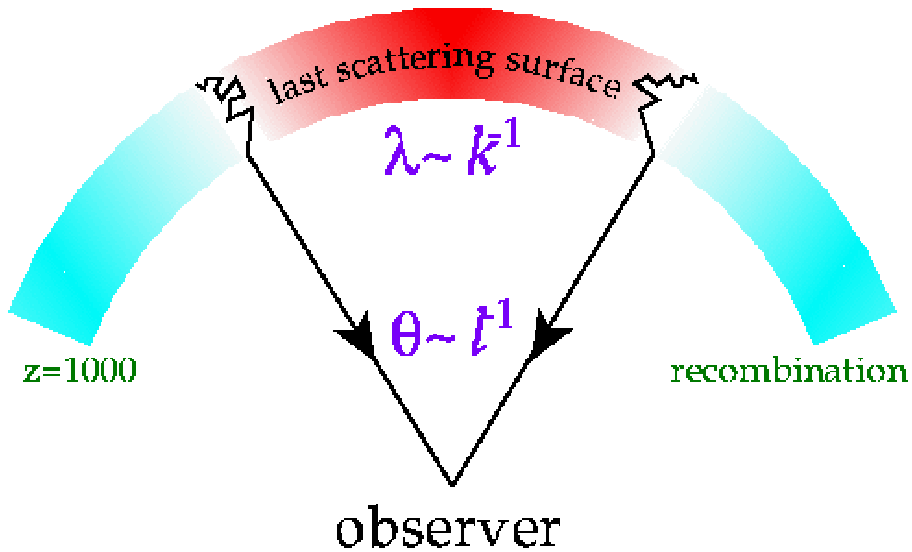


Wilkinson Microwave Anisotropy Probe (WMAP):
Launch 2001 June 30,
first publications 2003 February



WMAP, W-Band, $\lambda = 3.2\,\mathrm{mm}$, $\nu = 93.5\,\mathrm{GHz}$, resolution 0.21°

Results



courtesy Wayne Hu

After Big Bang: universe dense ("foggy"), photons efficiently scatter off electrons $\Longrightarrow$ coupling of radiation and matter

Universe cools down: recombination of protons and electrons into hydrogen

$\Longrightarrow$ no free electrons

$\Longrightarrow$ scattering far less efficient

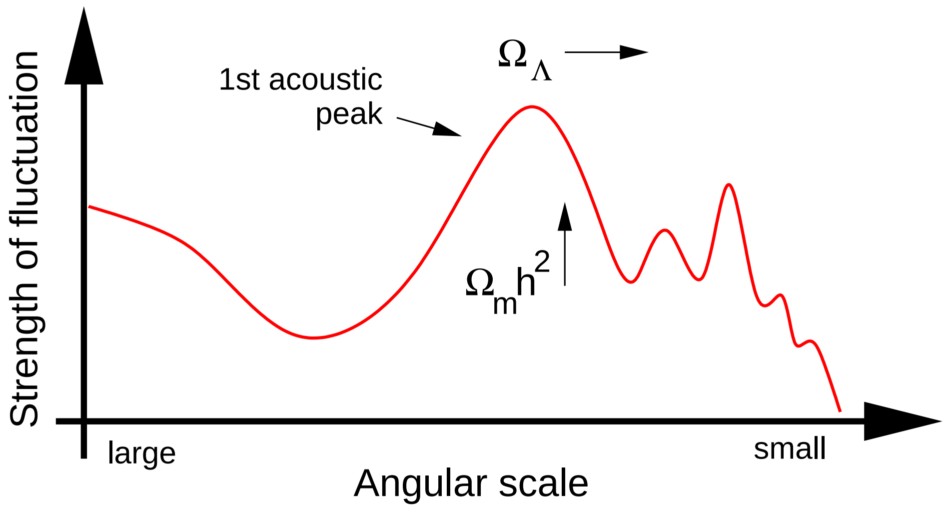
$\Longrightarrow$ Photons: "free streaming"

Photons escaping from overdense regions loose energy (gravitational red shift)

$\Longrightarrow$ Observable as temperature fluctuation (Sachs Wolfe Effect)

CMB Fluctuations $\sim$ Gravitational potential at $z \sim 1100 \Longrightarrow$ structures

Results

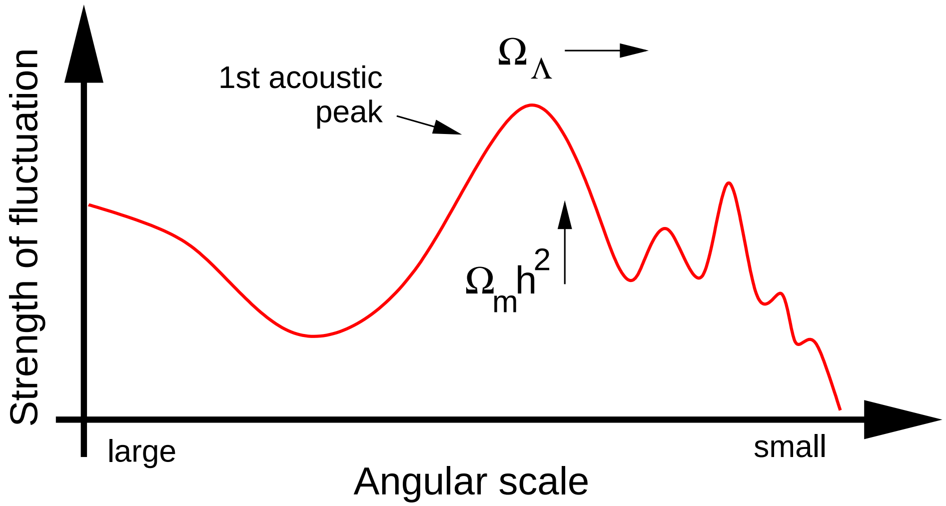


(after Hu et al., 1995)

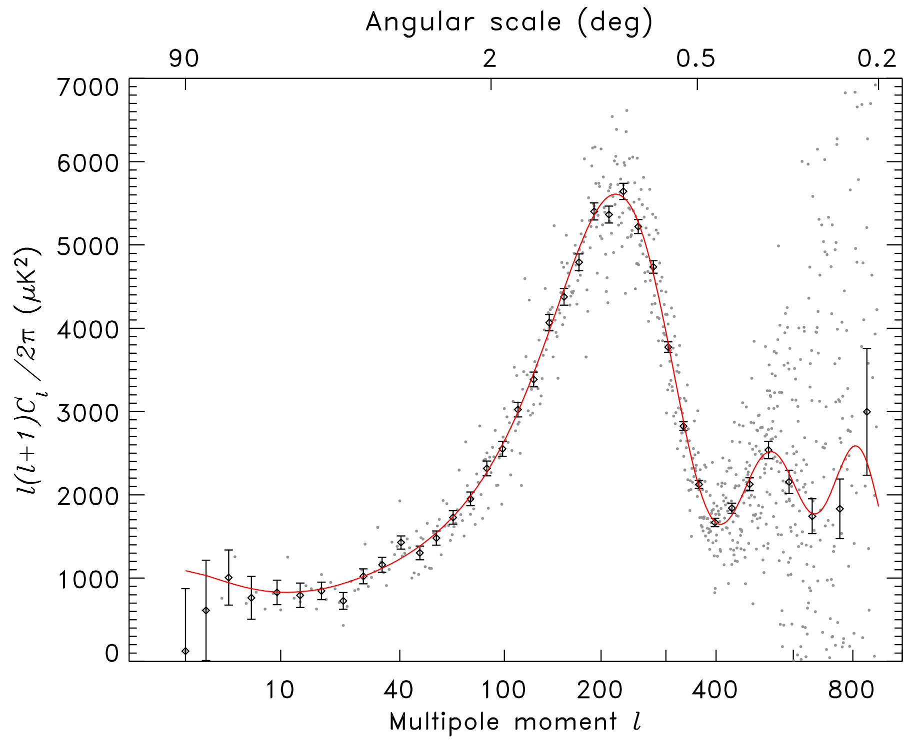
Power spectrum of CMB depends on

Ω_{m} H_0 Ω_Λ

Results



(after Hu et al., 1995)



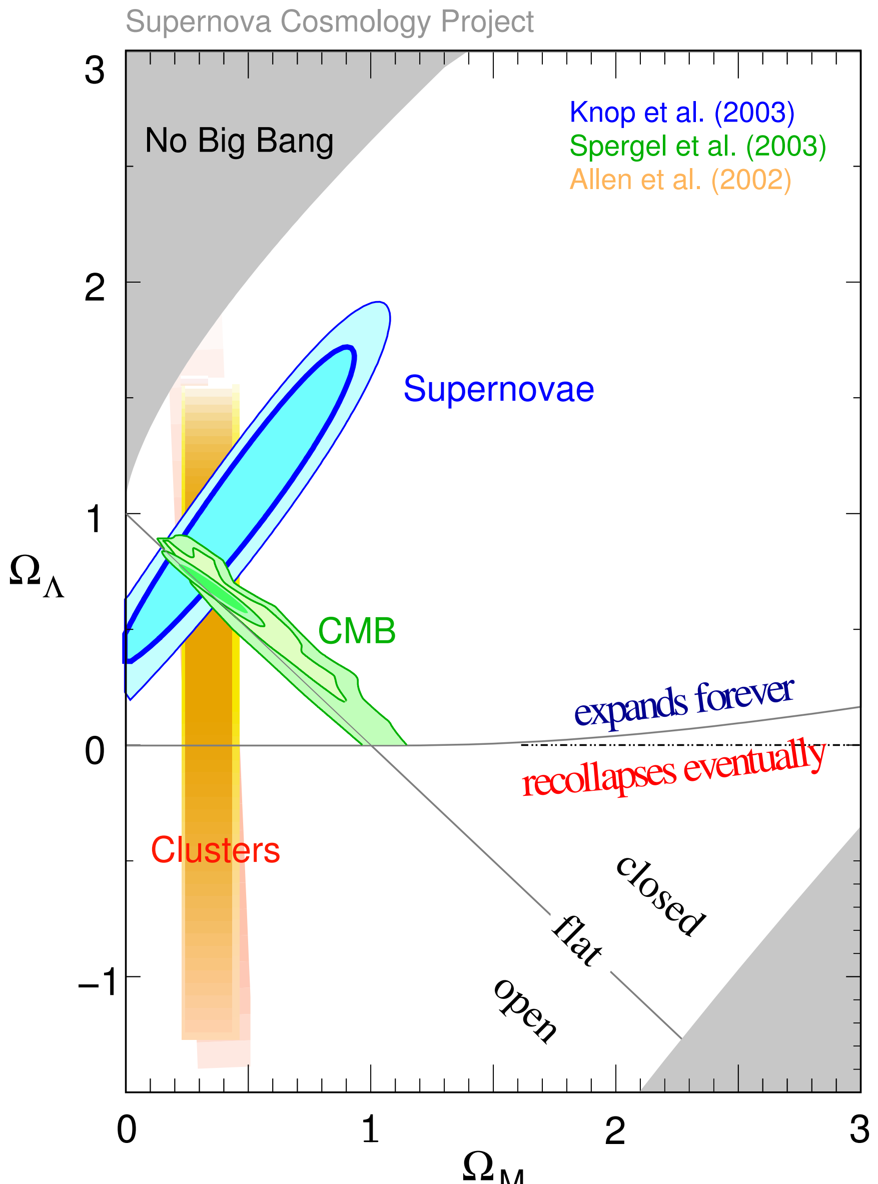
Power spectrum of CMB depends on

Ω_m H_0 Ω_Λ

WMAP best fit parameters (assuming $\Omega = 1$, $H_0 =: h \cdot 100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$):

$$h = 0.72 \pm 0.05$$
$$\Omega_m h^2 = 0.14 \pm 0.02$$

Results



Confidence regions for Ω_Λ and Ω_m.

dark: 68% confidence, outer region: 90%

$$\Omega = 1.02 \pm 0.02$$
$$\Omega_\mathrm{m} = 0.14 \ldots 0.3$$
$$H_0 = 72 \pm 5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

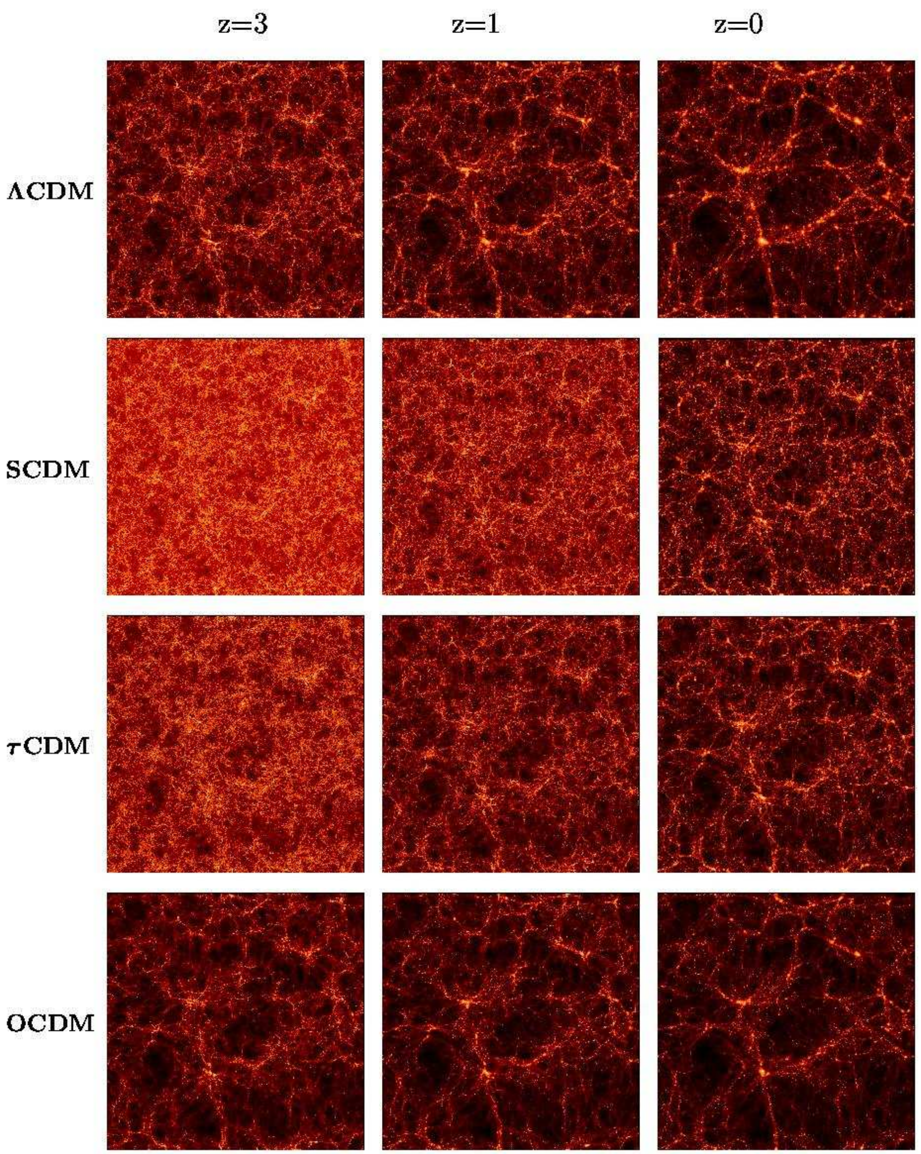
leading to an age of the universe of 13.7 billion years.

This means:

$\sim$70% of the universe is due to "dark energy"

. . . and what this is: we have no clue

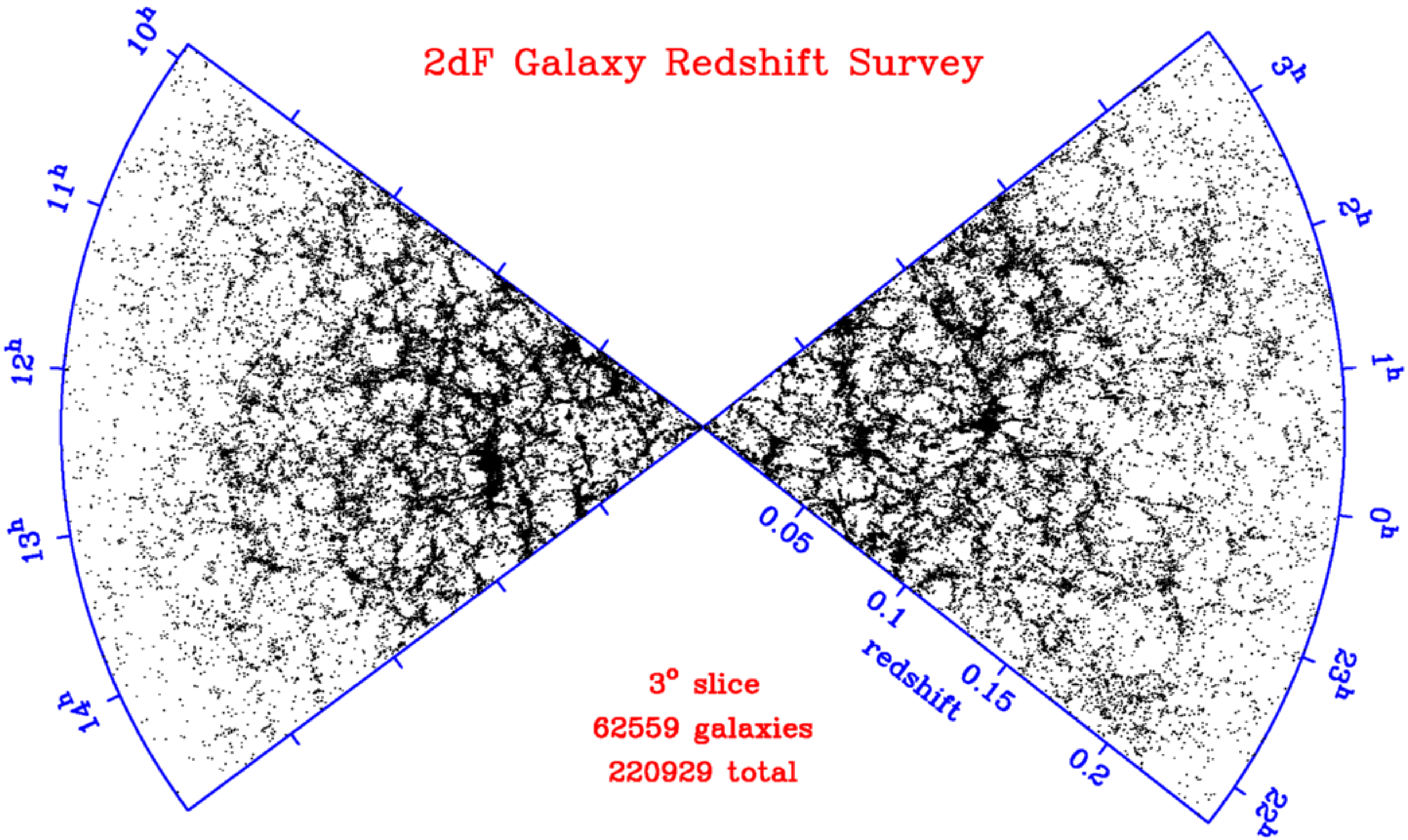
Large Scale Structures, I



Virgo collaboration

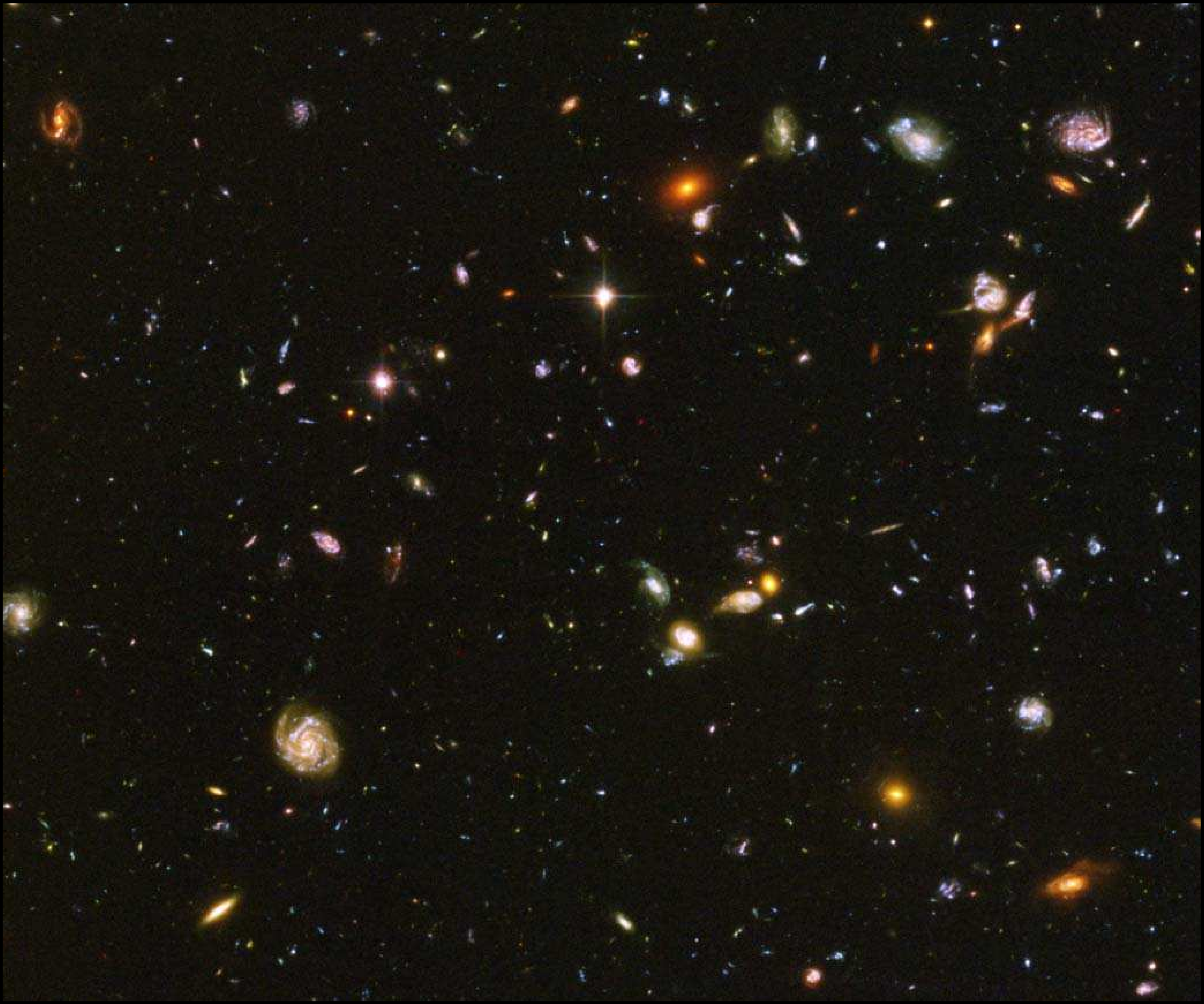
We can use theories for nature of Λ and measured values of H_0 and Ω to predict how galaxies evolve in the universe.

Large Scale Structures, II



2dF Survey, ∼220000 galaxies total $\Longrightarrow$ structures

Hubble Ultra Deep Field (11 days exposure!)



Hubble Ultra Deep Field (11 days exposure!)