Sterrewacht Leiden

# Origins & Evolution of the Universe

## an introduction to cosmology – Fall 2014

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http://www.strw.leidenuniv.nl/~hoekstra/TEACHING/OEU/OEU.html

# This course in the cosmology track

Origins and Evolution of the Universe is the introduction to physical cosmology at Leiden Universe. The course can be taken as a stand-alone course and requires a minimum of pre-requisites.

| **Core courses for the MSc cosmology track** | |
|---|---|
| Origin and Evolution of the Universe | 6 EC |
| Particle Physics and Early Universe | 6 EC |
| Large Scale Structure and Galaxy Formation | 6 EC |
| Theory of General Relativity | 6 EC |
| **Related courses** | |
| Observational cosmology | 3 EC |
| Theoretical cosmology | 3 EC |

Although General Relativity is critical to understand our Universe, we can do without for the moment. We will assume a basic BSc level knowledge of astronomy.

# Examination

A written exam is scheduled for December 15th. The material covered in class delimits what will be tested in this exam.

**Do not forget to register for the exam in uSIS!**

To aid in the preparation for the exam, there are three schedule problem classes with homework. This accounts for 30% of the final grade, *if* it is higher than the result from the written exam (so you still need to pass the exam…)

The homework needs to be handed in *before* the start of the problem class to be considered.

# Course outline

As part of the course we adress some of the most fundamental questions:

- What are the basic properties of our Universe (composition, age, origin)?
- What is the origin of the structure in the Universe?

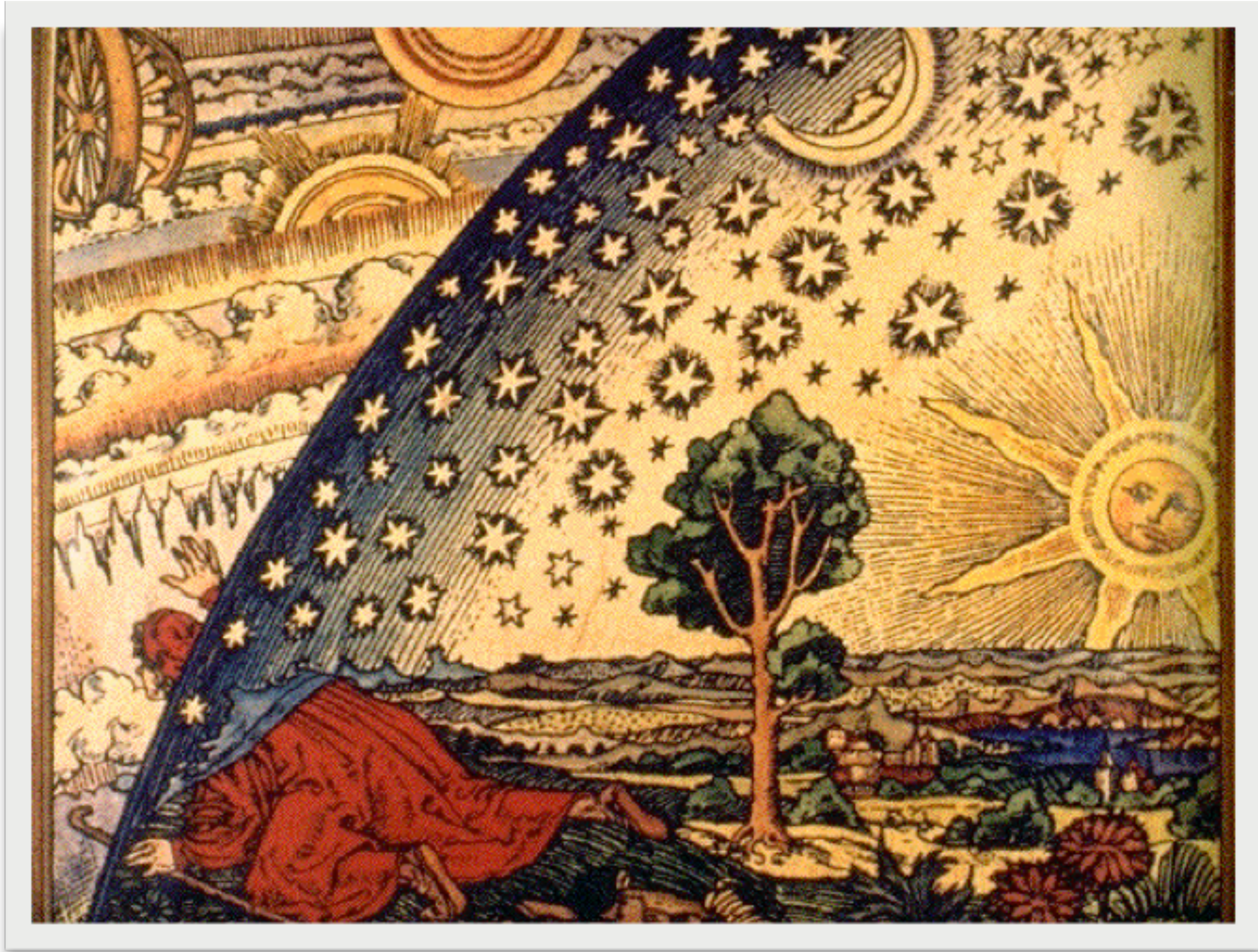
The starting point is the book “An Introduction to Modern Cosmology" (2nd edition) by Andrew Liddle, a basic introduction to cosmology. More detail is provided by "Cosmological Physics" by John Peacock and "Cosmology: The Origin and Evolution of Cosmic Structure" (2nd edition) by Peter Coles and Francesco Lucchin.

# Let's get started…

We start with the reviewing the status of observational cosmology over the past century and how we arrived at the current "standard model" of cosmology.

The aim of this course is to explain these results.

# Let's get started…



# Basic principles

The Universe is enormous and we can observe only a single one…

We cannot carry out experiments to test our ideas: we use our knowledge of terrestrial (or solar system) physics to interpret our observations. This can lead to metaphysical considerations. Only in the past 60 years has cosmology been considered a "real" science.

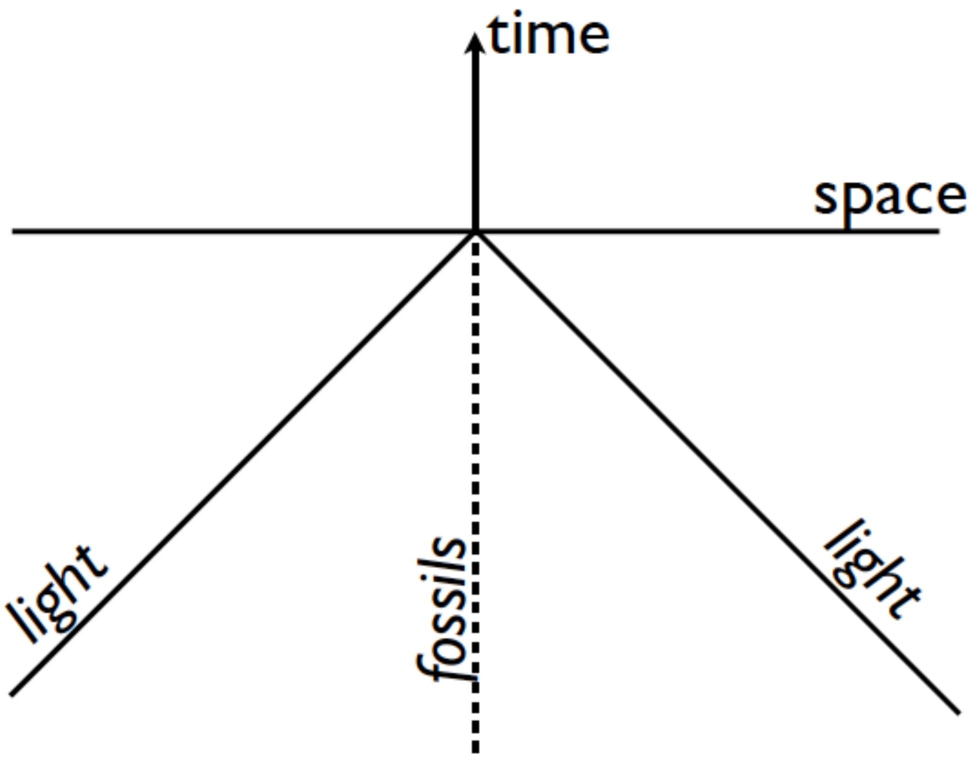
All we observe is the two-dimensional sky: the radial direction is a combination of distance and time into the past.

A critical aspect is the establishment of a distance ladder than can be extended to cosmological scales. This work started in earnest with the work of Hubble, and continues to the present day with the Gaia satellite.

Supporting information may come from the ages of old stars, meteorites, etc.

# Need for homogeneity

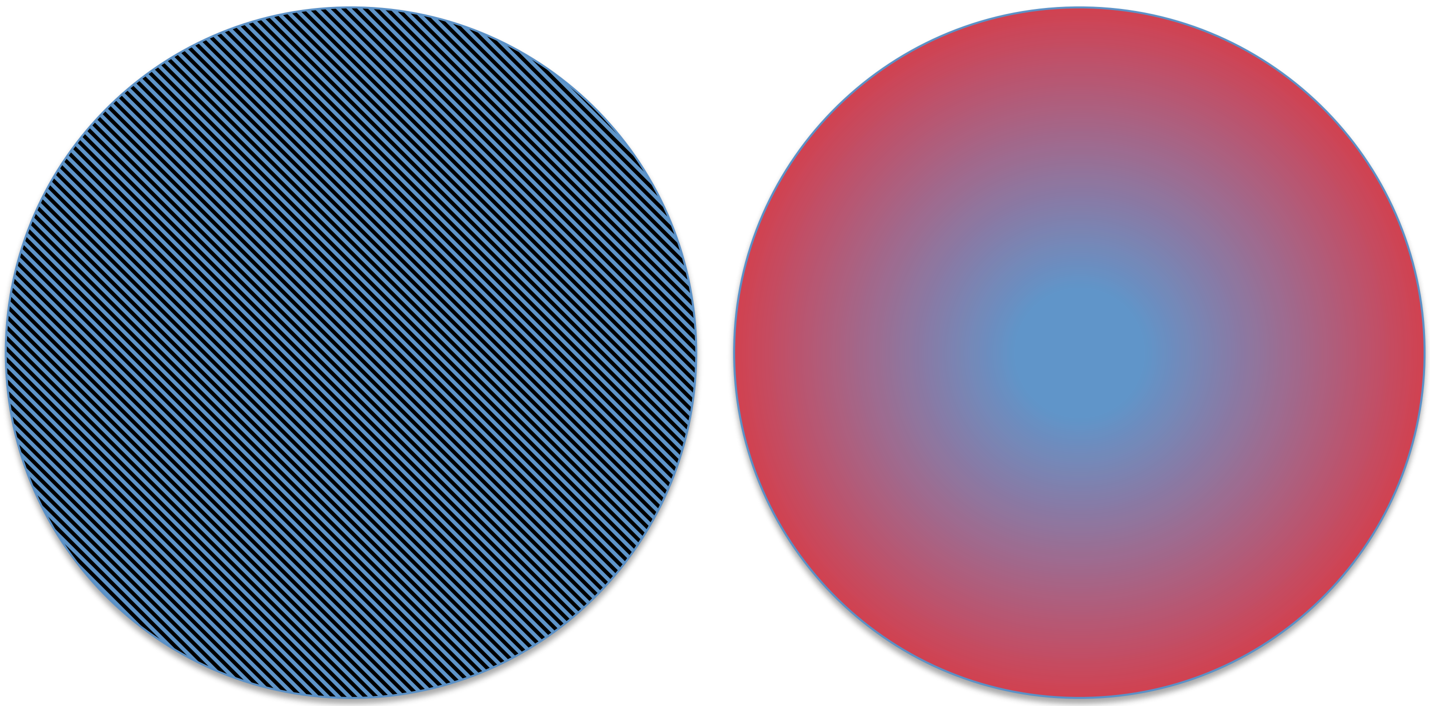
To be able to relate observations along different lines of sight we need to assume **homogeneity**: *without this assumption we cannot interpret observations*.



# Homogeneity and Isotropy

Homogeneity: the Universe looks the same at each point.
Isotropy: the Universe looks the same in all directions.

Homogeneity does not imply isotropy, and isotropy does not imply homogeneity.



# Copernican Principle

The Earth is not a special place in the Universe
(or: we are not privileged observers).

This is a major shift from the Ptolemaic system that formed the basis of medieval cosmology.

This implies that the Universe is isotropic about every point, which implies homogeneity as well.

# Cosmological Principle

The **cosmological principle**:
the Universe is homogeneous *and* isotropic.

'Perfect' Cosmological Principle:

- "The universe is the same in all places, directions and times
- This motivated the 'Steady-State' universe (Bondi, Gold, Hoyle)

In fact it does not apply – the Universe evolves (as we shall see).

# The Universe 100 years ago

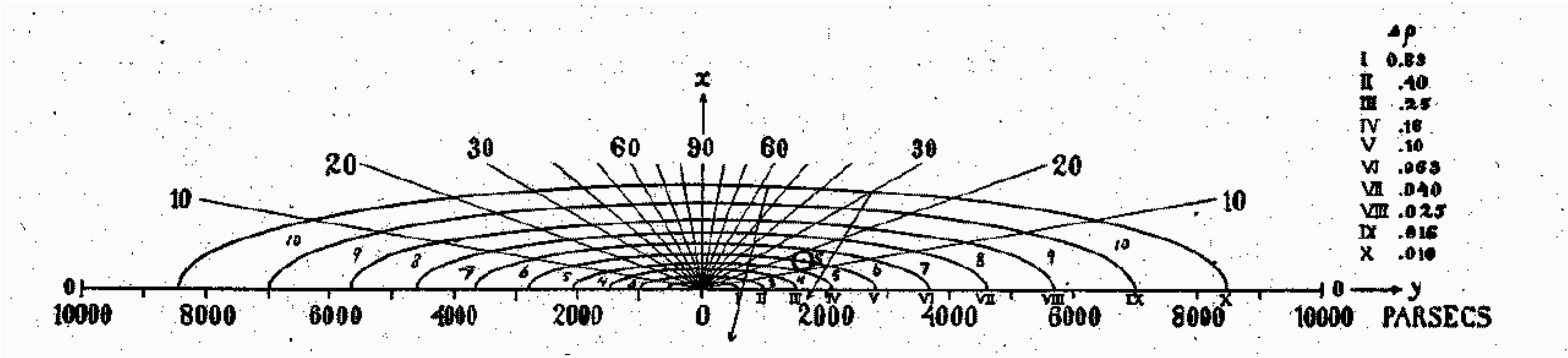



FIG. 1

Kapteyn (1922): used photographic star counts and estimated distances statistically based on parallaxes & proper motions of nearby stars.

He neglected interstellar absorption of starlight (assumes that stars were faint only because they far away, not because interstellar absorption blocks some of the light).

- Milky Way is a flattened disk about 15 kpc across and about 3 kpc thick
- The Sun is located slightly off-center.

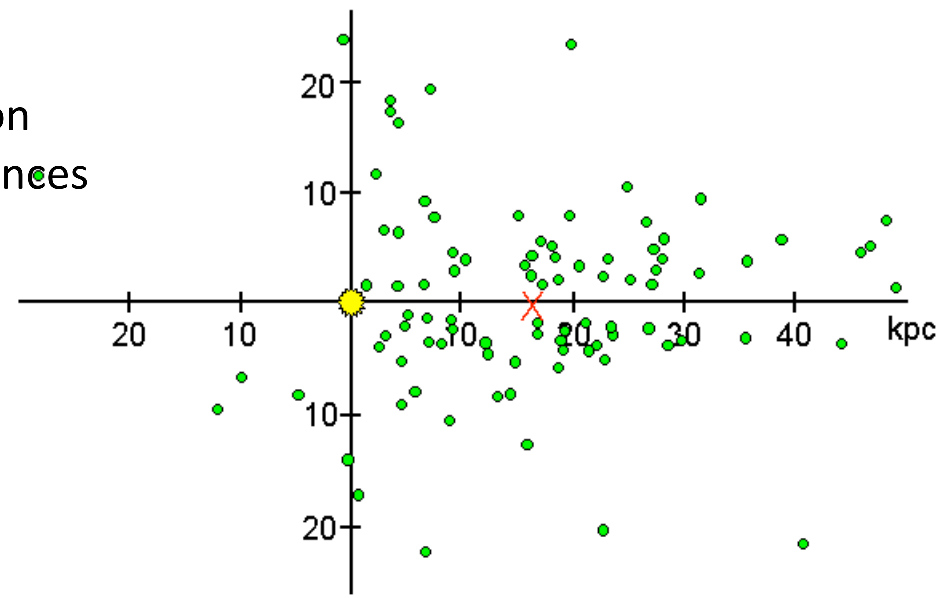
# Shapley's Universe

Shapley's Results (1921):

Globular clusters form a subsystem centered on the Milky Way.
The Sun is 16 kpc from the MW center.
MW is a flattened disk about 100 kpc across

Right basic result, but too big:

Shapley ignored interstellar absorption
Caused him to overestimate the distances



# Distances to other galaxies

At the same time there was an ongoing discussion about the nature of the “nebulae”: are they part of our Galaxy or “island Universes”.

Technology came to the rescue thanks to the construction of the 100-inch (2.5 m) Hooker telescope, which allowed Hubble to identify Cepheid variables in nearby galaxies.

He showed that the “nebulae” are not part of the Milky Way. By combining his distances with redshift measurements by Slipher and Humason he found that:

# Velocity-Distance diagram

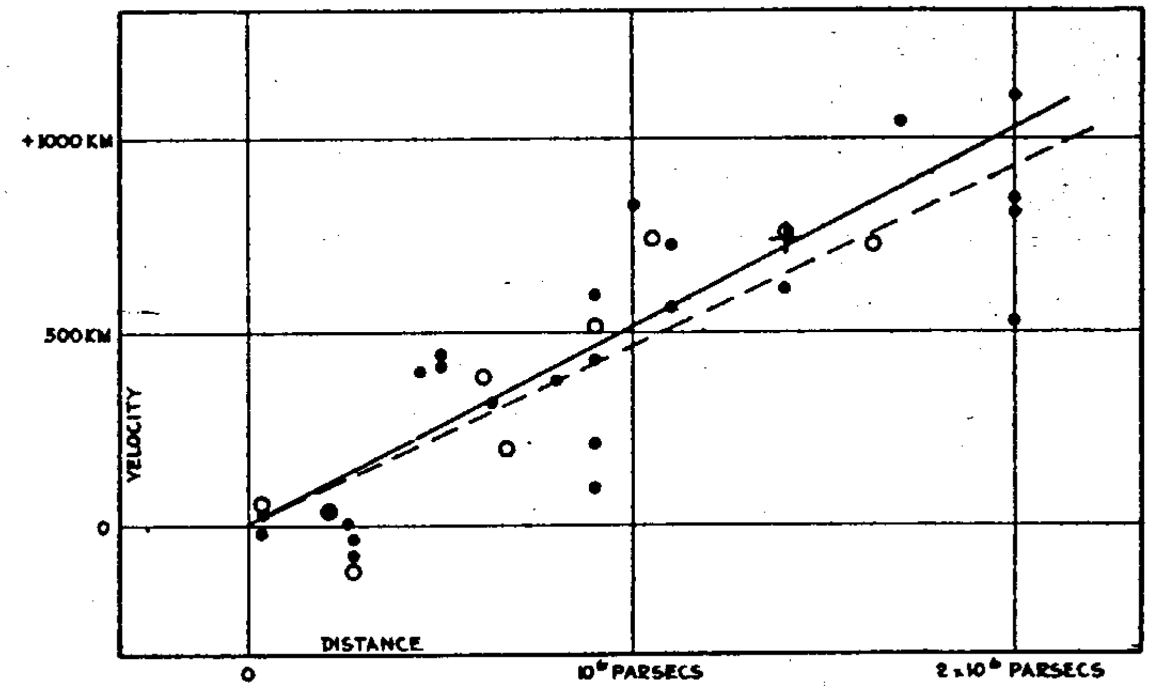


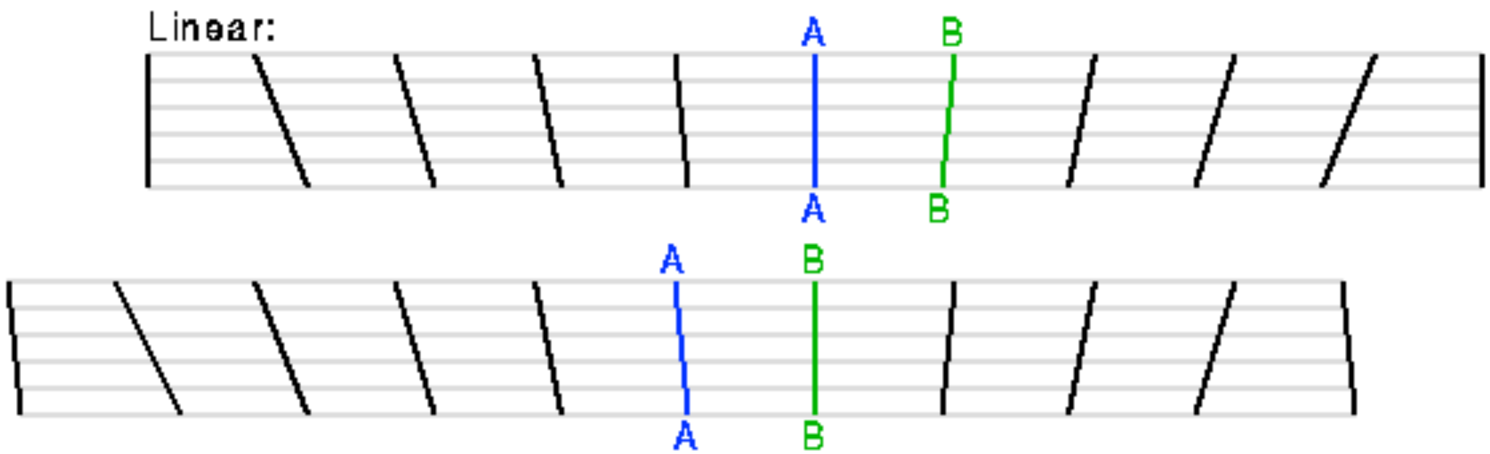

FIGURE 1

Hubble (1929): the recession velocity is proportional to the distance (after allowing for the Sun's motion): $\boldsymbol{v} = H_0\,\boldsymbol{r}$.

Hubble obtained $H_0$ =464 km/s/Mpc.

# Implication of Hubble's discovery

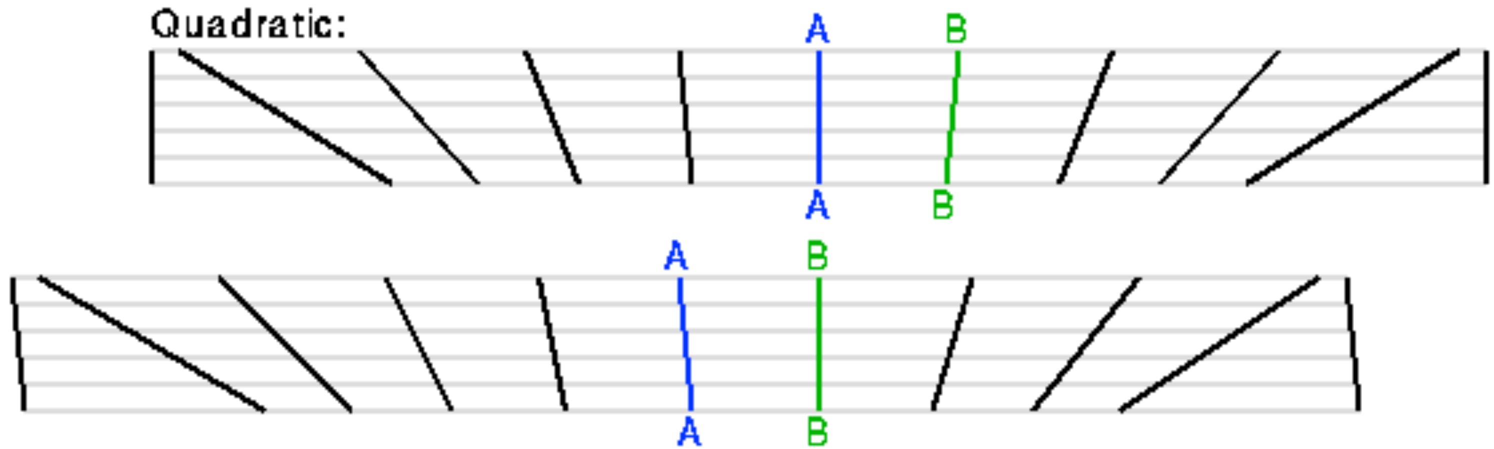
At first glance, this result may violate the Copernican Principle, but this is in fact not true!




The recession velocity is symmetric: if A sees B receding, then B sees that A is receding. The diagrams from the two different points of view are identical except for the names of the galaxies.

# Implication of Hubble's discovery

The linear relation is the only one consistent with the Copernican Principle. For e.g. a quadratic relation different observers would see different relations.



# Implication of Hubble's discovery

The Hubble law produces a **homologous** expansion: shapes of patterns in the Universe are not altered, but are merely scaled isotropically.

scale factor

$$\mathbf{r}(t) = a(t)\mathbf{r}(t_0)$$

$$\Rightarrow \qquad \mathbf{v}(t) = \frac{d\mathbf{r}(t)}{dt} = \frac{da(t)}{dt}\mathbf{r}(t_0)$$

# Age of the Universe

Note that the Hubble constant has dimension 1/time:

$1/H_0$=(978 Gyr)/($H_0$ in km/s/Mpc)

If the expansion velocity is constant then all galaxies were in the same place $t=1/H_0$ years ago. With the current estimates of $H_0=71\pm3$ km/s this implies an age of 14 Gyr.

The expansion rate is not a constant, so the result is only an indication: typically the age of the Universe is $<1/H_0$.

Similarly $c/H_0$ is a natural scale for the Universe.

# Age of the Universe

We can obtain independent constraints on the minimum age of the Universe by dating some of the constituents.

- Radioactive dating of the Solar system: > 4.6 billion years

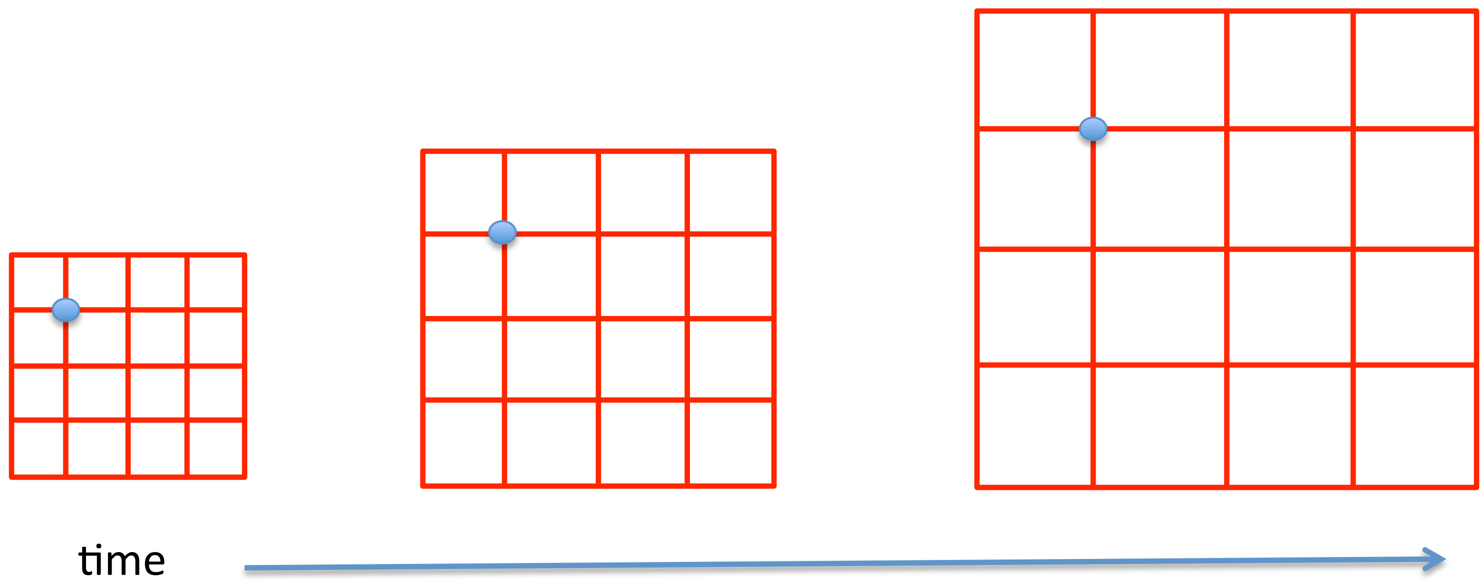
- Cooling ages of old white dwarfs: best models give ages up to 11 Gyr

- Ages of star clusters: globular clusters have ages of 11 Gyr

Main Sequence stars: $L \propto M^4 \Rightarrow M/L \propto M^{-3} \propto L^{-3/4}$
Typical distance errors are 10% $\Rightarrow$ 20% in L, or 15% in age.

# Implication of Hubble's discovery

The Hubble law defines a special frame of reference at any point in the Universe. A **comoving** observer is at rest in this special frame of reference.

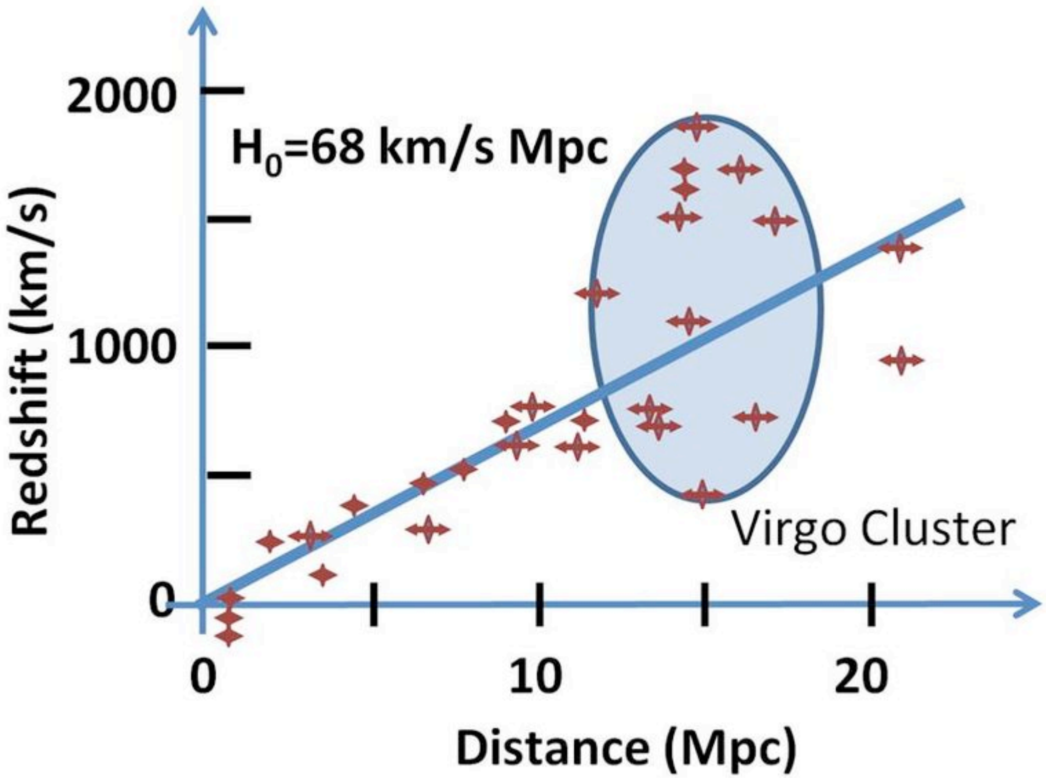


# Reaching the Hubble flow

Our Solar System is not quite comoving: it moves with a **peculiar velocity** of 370 km/s relative to the observable Universe.

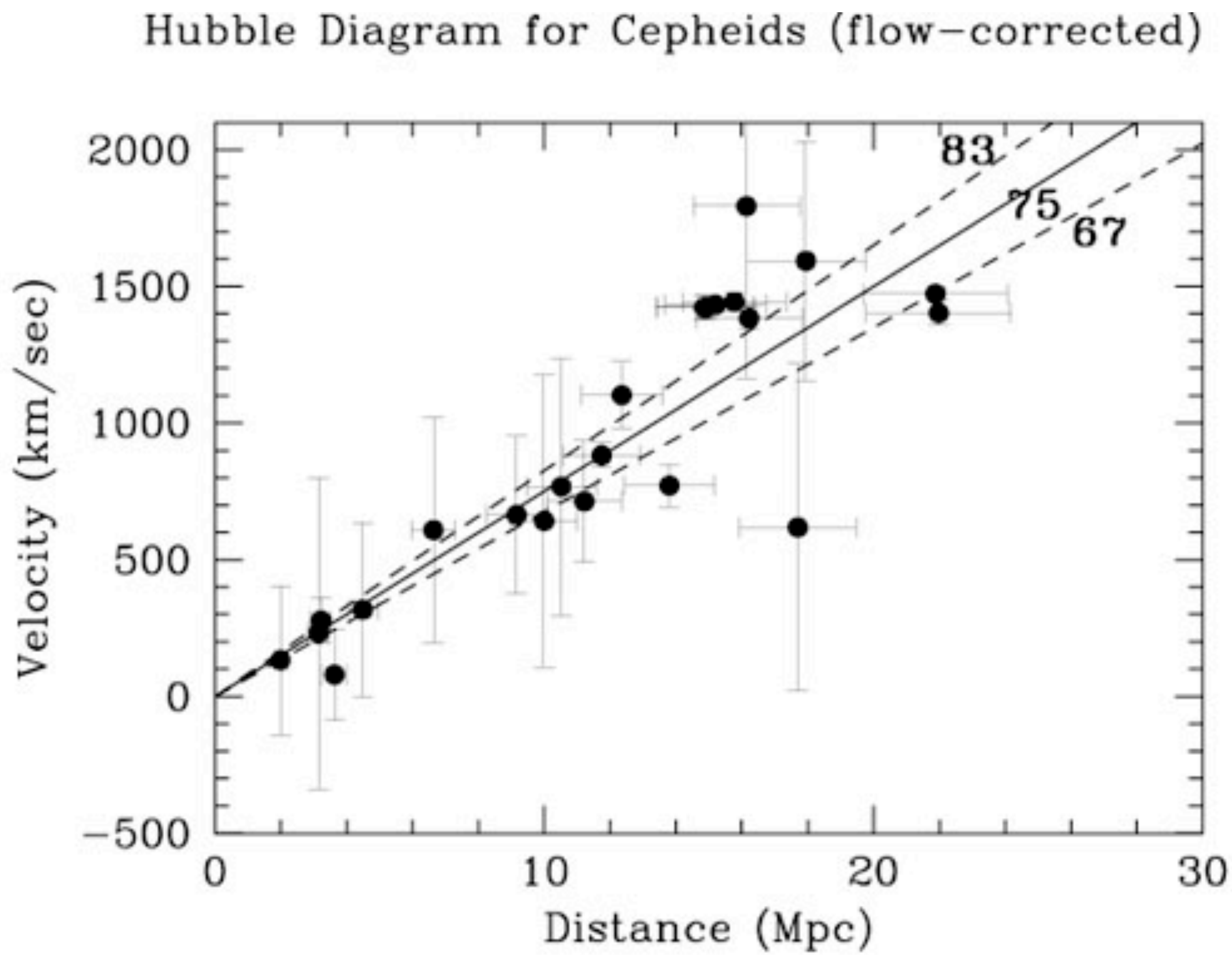
The Local Group of galaxies, which includes the Milky Way, appears to be moving at 600 km/sec relative to the observable Universe.

# Reaching the Hubble flow

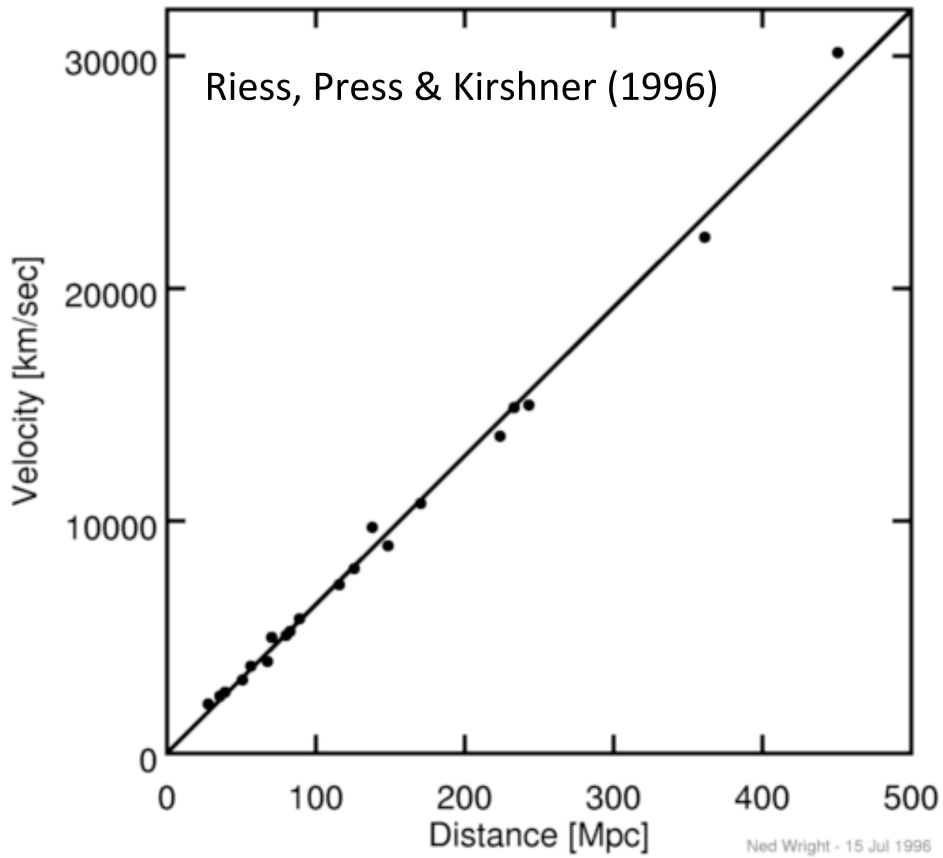



How far out do we need to measure to get a reliable measurement of $H_0$ if galaxies have **peculiar velocities** of 600 km/s?

# Hubble key project

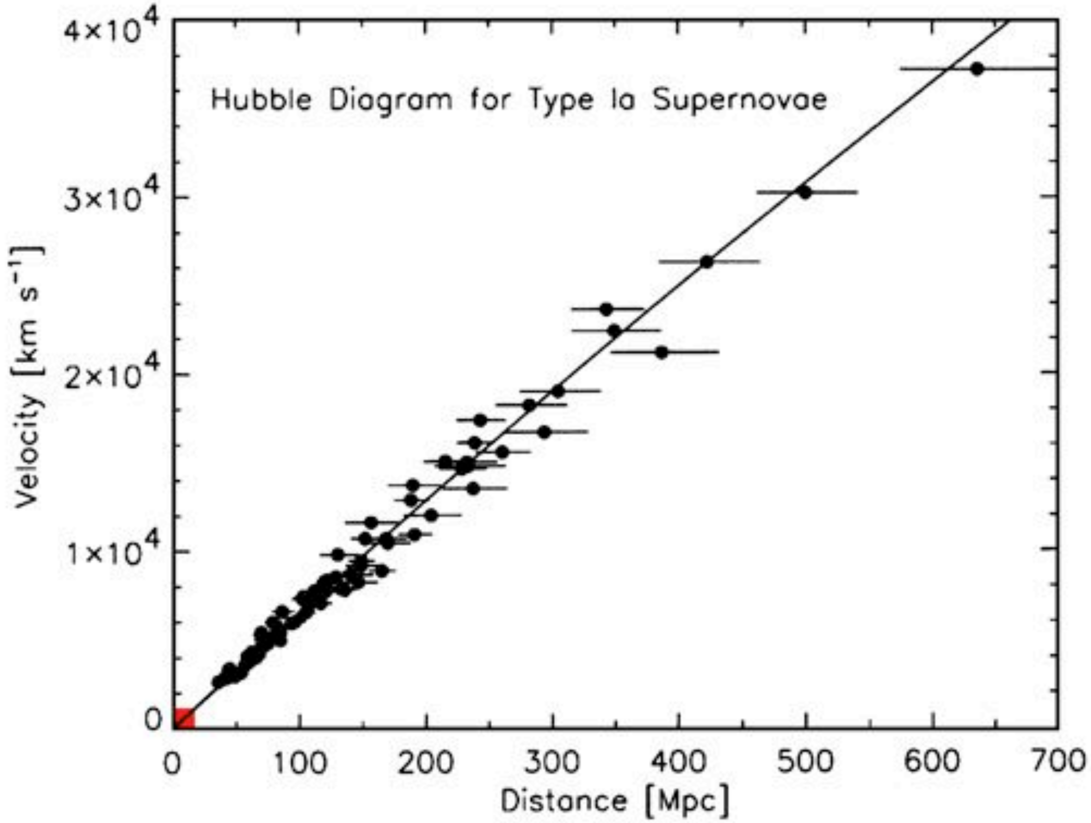


# Linear relation on large scales




Riess et al. (1996) used type Ia SNe to extend the measurements beyond 30,000 km/sec and provide a dramatic confirmation of the Hubble law

# Linear relation on large scales

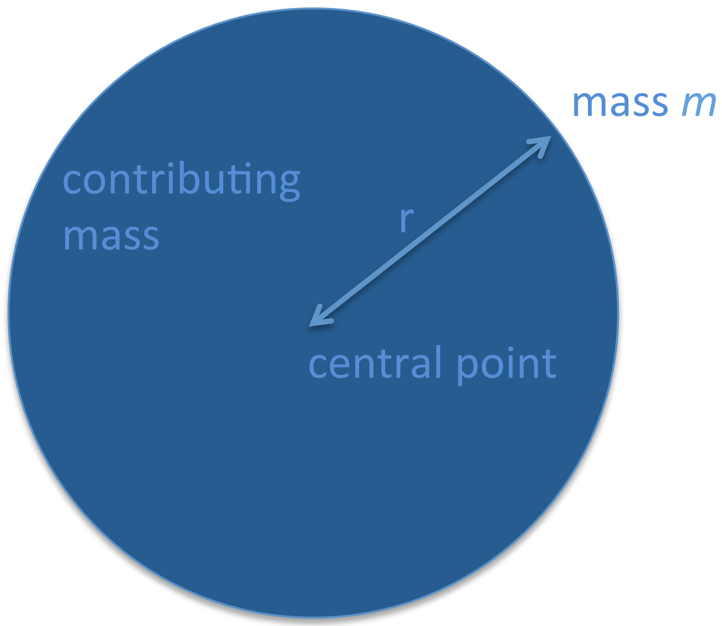



**Kirshner, Robert P. (2004) Proc. Natl. Acad. Sci. USA 101, 8-13**

Type Ia SNe  allow us to extend the measurements beyond 30,000 km/sec and provide a dramatic confirmation of the Hubble law

# The expanding Universe

It is possible to derive the equations that describe an expanding homogeneous Universe using Newtonian gravity. Note that a correct physical interpretation does require General Relativity.




A particle feels no force from material at radii $>r$ and the mass inside $r$ can be treated as if all concentrated in the central point.

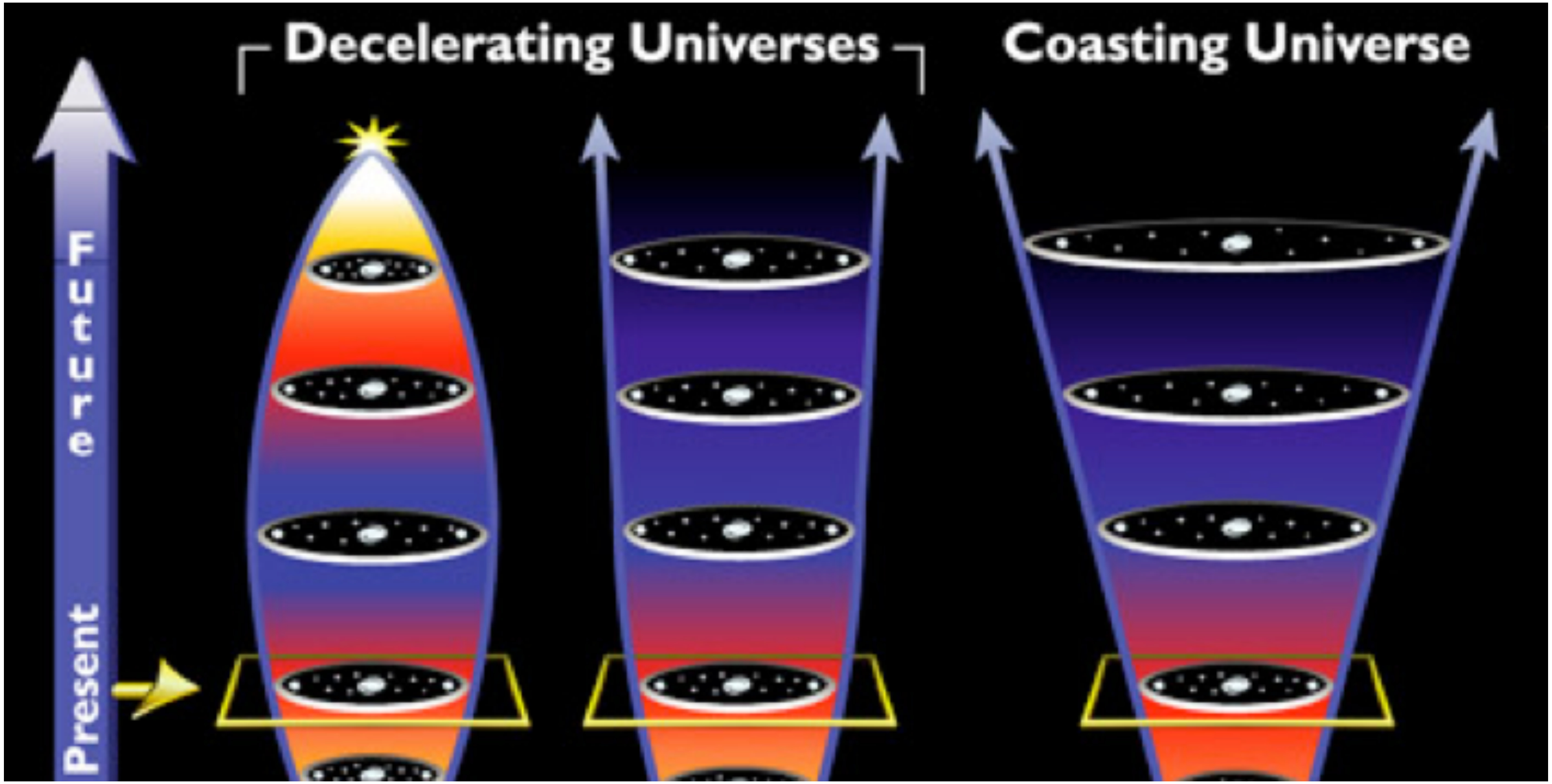
# Friedmann equation

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2}$$

Three cases:

k<0: expansion never stops, as a→∞, da/dt > 0
k=0: assymptotically slow expansion, as a→∞, da/dt→0
k>0: expansion stops and recollapses, as a→∞, da/dt < 0

# The fate of the Universe




What sets the value of $k$?

# The expanding Universe

Note that $\ddot{a} < 0$, so that extrapolating backwards always leads to $a$=0!

# Deceleration

The expansion rate is expected to slow down due to the gravity of matter in the Universe. Therefore by measuring the rate of change we can “weigh” the Universe.

Therefore the Hubble constant is not constant, but varies with time: it is better to talk about the **Hubble parameter**.

To measure the deceleration, we need to extend the measurements to much larger distances, which became possible in the 1990s using type Ia supernovae.

# Particles in the Universe

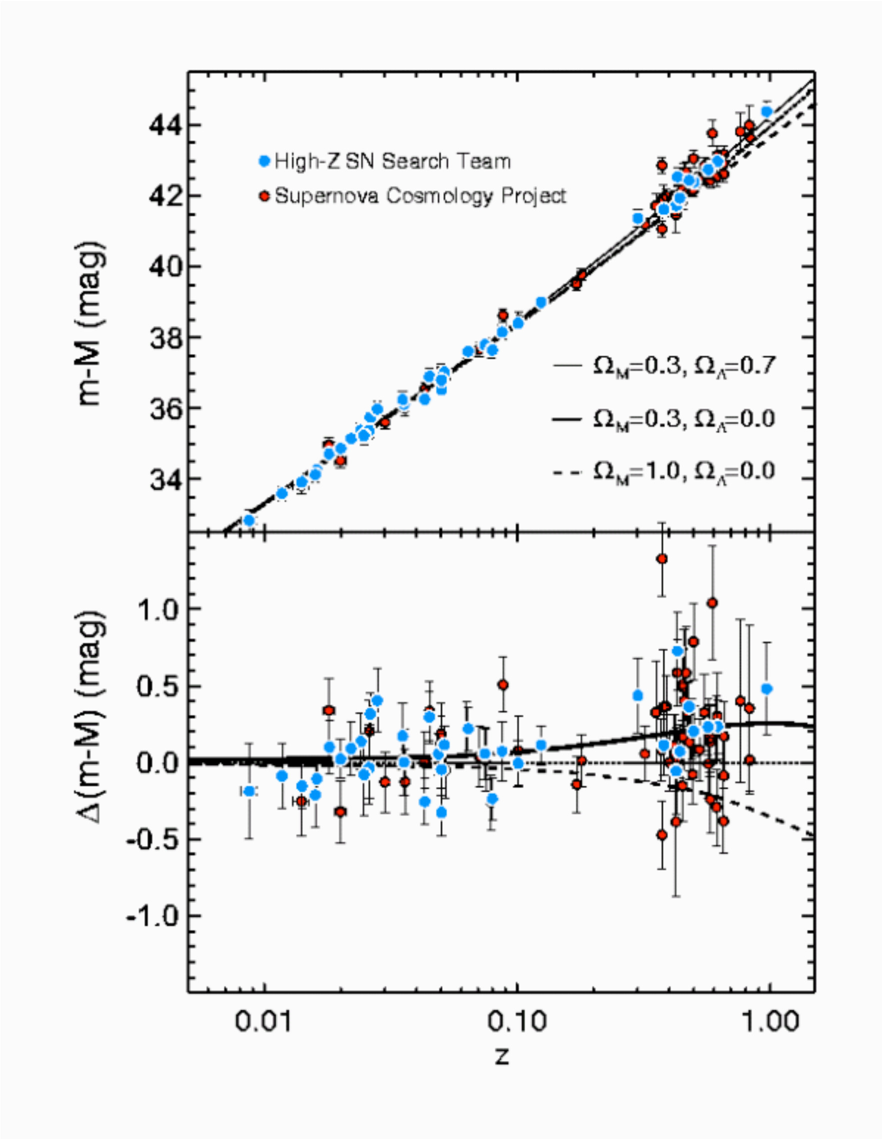
Later we will explore what determines the expansion rate, but note here that it depends whether a particle is moving relativistically or not.

For a particle with rest mass $m$: $E^2=m^2c^4+p^2c^2$

If the mass-energy dominates, the particle will be moving at much less than the speed of light, and is said to be non-relativistic.

Relativistic: photons and neutrinos
Non-relativistic: baryons and dark matter (?)

# Very distant supernovae




The discovery in 1998 was that the distances to the supernovae were larger than expected:

Instead of decelerating, the expansion is actually accelerating!

Explaining this result is the biggest question in cosmology to date.

# Evolving Universe!

The positive value for $H_0$ implies the Universe is expanding, which is a natural consequence of General Relativity.

The Universe was smaller in the past, as were the physical conditions; observations of distant objects show a different epoch.

*The Universe is evolving.*